The role of KLOE and KLOE-2 in the search for a secluded gauge sector

Fabio Bossi

\textsuperscript{a}Laboratori Nazionali di Frascati dell’INFN, Frascati, Italy.

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Abstract

The hypothesis of the existence of an hidden or secluded gauge sector with manifestations at low or intermediate energies is motivated by several different recent astrophysical observations. At low and medium energy $e^+e^-$ colliders this sector gives clear signatures with cross sections that can be as large as 1 pb at 1 GeV. Some of these signatures are straightforward, and can be relatively easily isolated against background. Therefore, KLOE, with its collected 2.5 fb\(^{-1}\), and KLOE-2 with its foreseen detector’s upgrades and larger data sample are and will be able to test these models in deep detail.

1 Introduction

In recent years, several astrophysical observations have failed to find easy interpretations in terms of standard astrophysical and/or particle physics sources. A non exhaustive lists of these observations includes the 511 keV photon signal from the galactic center observed by the INTEGRAL satellite \cite{1}, the excess in the cosmic ray positrons reported by PAMELA \cite{2}, the total electron and positron flux measured by ATIC \cite{3} and the annual modulation of the DAMA/LIBRA signal \cite{4}.

An intriguing feature of these observations is the fact that all of them can be interpreted in terms of the existence of WIMP Dark Matter (DM) candidates belonging to a secluded gauge sector, under which the Standard Model (SM) particles are uncharged, but can still weakly couple through a kinetic mixing mechanism with typical mixing parameters $k$ naturally of the order $10^{-2}$-$10^{-3}$. More interestingly, from the point of view of the present note, the typical mass scale of the vector bosons related to the secluded symmetry is of order 1 GeV.
A dramatic consequence of the above hypotheses is that they must induce observable effects in medium energy $e^+e^-$ colliders, such as the existing or future B-factories and the Frascati $\phi$-factory DAΦNE. A rather comprehensive discussion of these effects can be found in references [5] and [6]. Although the two papers differ slightly in some detail of the underlying theoretical framework, the conclusion of the two are essentially the same.

In the present note, I will move from the phenomenological basis suggested by these two articles, to discuss in a little detail the actual potentials of the KLOE experiment [7] at DAΦNE, and of its proposed continuation, KLOE-2 [8]. The paper is organized as follows. In the next section, a very qualitative description of the physics models inspiring it is given. This description is not meant to be fully comprehensive, neither in the details of the single model nor in the variety of them, so I refer to the bibliography reported therein, for a more complete panorama. In the following section, a short description of the KLOE apparatus and of its main performance is given. Also, the plans for its usage in the near future are reported. Then, I concentrate on three possible signatures of this new physics at KLOE, namely the vector boson plus $\gamma$ signal, the dilepton plus missing energy, and the multilepton events. Since the physics potentials of KLOE, at least for some of these signals are already discussed in other papers, I concentrate mostly on the main experimental issues for all of them. Although this discussion is only semi-quantitative, we will see that one can safely conclude that there is an ample margin for KLOE and KLOE-2 to appreciably contribute to the field, by testing (some of) these models for a large part of the allowed free-parameters space. It is also important to stress that the searches at KLOE and at the B-factories are largely complementary, so that it would be desirable to set-up some kind of networking among the various experiments, as well as between experiments and theorists in the field, to enhance the efficiency of the analysis process.

2 Main features of the secluded sector

As stated above, there exist several different models with different gauge structures, which are interesting for the present discussion [9] [10] [11]. A common feature of all of them is the existence of at least a vector boson, the “$U$” from now on, of mass around 1 GeV, responsible for mediating a new abelian $U(1)_S$ interaction. Together with it, it is also natural to conceive the existence of an elementary Higgs-like boson, the $h'$, which spontaneously breaks the symmetry. The existence of the $h'$ is not strictly required by the observational inputs mentioned in the previous section. In fact the authors of reference [6] do consider also a model without it. However, the existence of the $h'$ is on the one hand rather natural theoretically, and on the other it has important consequences in terms of observable phenomenology, as it will be seen later on.
The mass hierarchy between these two particles is not constrained. However it has important consequences in terms of possible decay channels, so that one has to consider different detection strategies for the two cases $m_{h'} < m_U$ and $m_{h'} > m_U$.

Another ansatz that has relevant consequences in what follows, which is particularly stressed by the authors of reference [5], is that the mass of the $U$ boson satisfies the relation $m_U << m_{WIMP}$, $m_{WIMP}$ being the mass of the DM weakly interacting candidate; this relation naturally leads to an enhanced WIMP annihilation cross section in the galaxy, as required by the data, and, more importantly for the present discussion, to an enhancement or dominance of the leptonic branching ratios in the annihilation products.

Both the $U$ and the $h'$ can be produced at DAΦNE, provided that their masses are less than $m_{\phi}$. This is somewhat a disadvantage with respect to the B-factories, since the available phase-space is lower. Also, the luminosity of DAΦNE is about two orders of magnitude lower than the one of PEP-II and KEK-B. However there are two main advantages with respect to the B factories. On the one hand, the production cross sections scale as $1/s$, which essentially compensates the lower luminosity of DAΦNE. On the other hand, DAΦNE is better suited for detecting particles with masses lower than 1 GeV, since the main physical backgrounds are typically due to QED radiative processes, whose cross sections increase with the distance between the 'new particle' mass and the collision energy.

3 KLOE and KLOE-2

The KLOE detector consists mainly of a cylindrical drift chamber (DC) with momentum resolution $\sigma_{p_t}/p_t < 0.4\%$, and a highly hermetic electromagnetic calorimeter with energy resolution of $\sigma_E/E = 5%/\sqrt{E(\text{GeV})}$. The DC [13] has its first sensitive layer at a radius of 30 cm from the interaction point (IP); this fact, combined with a B field value of 0.52 T, results in an effective cut-off value for the transverse momentum of the detectable charged particles produced at the IP of $\sim 40$ MeV/c. Photons and electrons of energy down to $\sim 20$ MeV and polar angle in the range $20^\circ < \theta < 160^\circ$ can be detected with good efficiency by the calorimeter [14]. Inefficiencies below the per mil level are obtained for energies above $\sim 100$ MeV.

The trigger [15] uses both calorimeter and DC information. In the first case, two energy deposits above 50 MeV in the barrel or 150 MeV in the endcaps are required. In the second, the trigger is produced by the count of $\sim 100$ wires accumulated over an interval of 1 $\mu$s.
KLOE has so far acquired 2.5 fb$^{-1}$ of data at the $\phi(1020)$ resonance peak. A further run is foreseen for the beginning of year 2010 with the goal of acquiring other $\sim 5$ fb$^{-1}$, as a first part of the so called KLOE-2 program. Soon after a program for upgrading the detector is planned. For the purpose of the present discussion, the main upgrades will consist in the insertion of a very light internal tracking device (the Inner Tracker, IT), which would allow detection of charged particles down to a radius of $\sim 12$ cm. Crystal calorimeters (CCALT), placed in front of the low-$\beta$ focussing quadrupoles, will help detecting photons emitted in the very forward direction, down to $\theta=9^\circ$. The total integrated luminosity for this second stage of operation should reach at least 20 fb$^{-1}$.

4 $U\gamma$ events

One interesting process to be studied is $e^+e^- \rightarrow U\gamma$. It has the advantage of being independent of the existence and on the details of the Higgs sector. Also, its expected cross section can be as high as 0.1 pb at DAΦNE energies, as shown in figure 5 of reference [6]. The on-shell boson can decay into a lepton pair, giving rise to a $l^+l^-\gamma$ signal.

The most relevant physics background comes from the parent QED radiative process, which has a much higher cross section but can be rejected by cutting on the invariant mass of the lepton pair, as already discussed in reference [12]. There is however a relevant instrumental background that has to be taken into consideration for the electron channel, namely $e^+e^- \rightarrow \gamma\gamma$ with subsequent conversion of one of the two photons on the beam pipe, with a probability of $\sim 2\%$. This effect can be identified and rejected cutting on the reconstructed invariant mass and vertex of the pair as done for instance in the analysis of [10]. For $m_U$ larger than $\sim 200$ MeV, the rejection factor is around $10^2$. Taking into account that the calorimeter energy resolution is $\sim 35$ MeV for photons of 510 MeV, and that the cross section of the $e^+e^- \rightarrow \gamma\gamma$ events is of a few hundreds nanobarns, one obtains that a reasonable background rejection can be obtained only for $m_U \geq 500$ MeV.

The insertion of the IT can be rather beneficial in this case, since it would help in a better definition of the pair production vertex. A quantitative statement on this issue, however, needs the use of a detailed Monte Carlo simulation, which is at present unavailable.

For the muon channel, the above mentioned background is not present. One has to take into account however, the physical process $e^+e^- \rightarrow \pi\pi\gamma$, that is relevant, since $\pi-\mu$ separation in highly untrivial at DAΦNE energies.
A further consideration has to be done, concerning the final detection efficiency. Actually, the process under study, as well as its backgrounds, has an angular distribution proportional to \((1 + \cos^2(\theta))/\sin^2(\theta)\), which results in a limited geometrical acceptance, since most of the events are in the forward direction. Again, the proposed modification for the second phase of KLOE-2 should be beneficial, since they increase acceptance for both charged tracks, thanks to the IT, and for photons, thanks to the CCALT.

All considered, one can conclude that the \(l^+l^-\gamma\) signature at KLOE has reasonable chances to be useful to explore the region \(m_U > 400-500\) MeV, \(k \sim 10^{-2}\). Some improvement can be obtained with KLOE-2, thanks to the higher expected statistics and to a better background rejection capability.

A final note has to be made on the possibility that the \(U\) boson decays into two neutral long lived (or stable) particles, either DM WIMPs or neutrinos (as discussed for instance in [12]). In this case the signal would be a single photon plus missing energy. This signal fails to satisfy the KLOE trigger conditions, so it cannot be in the present KLOE data set. Moreover, even assuming the implementation of a dedicated trigger for the future, it would be affected by copious physical as well as machine backgrounds, that produce a single photon signal in the calorimeter at a much higher rate. Here, a key requirement is a very high energy resolution which would help isolating the signal peak over a broad background. Unfortunately the KLOE calorimeter is not conceived for such an high resolution, so that the observation of this signature at KLOE is essentially hopeless.

5 The higgs'-strahlung process

Assuming the existence of a higgs’ boson, a particularly interesting process from the experimental point of view is the higgs'-strahlung \(e^+e^- \rightarrow Uh'\), which can be observed at KLOE if \(m_U + m_{h'} < m_\phi\). As stated above, the signature of this process heavily depends on the existing relation between \(m_U\) and \(m_{h'}\). In this paragraph we assume that the \(h'\) is lighter than the \(U\) boson; in this case it turns out to be very long-lived (see [5]), so that the signature of the process will be a lepton pair, generated by the \(U\) boson decay, plus missing energy.

There are several advantages for this type of signal. Firstly, there are no other physical processes with the same signature. The background due to QED \(l^+l^-\gamma\) events with a photon lost by the calorimeter, is suppressed by a relevant factor due to the high detection efficiency of this device. Moreover, this kind of background would give rise to a missing momentum equal to the missing energy, while in the case of the signal these two quantities will be sizeably different, due to the non-zero \(h'\) mass. In this case, differently from the one discussed in
the previous paragraph, the key ingredient is the very high resolution of the
DC as compared to the calorimeter one. A third advantage in terms of both
background rejection and detection efficiency is that the angular distribution
of the process is proportional to \( \sin^3(\theta) \), which peaks at \( \theta = \pi/2 \). Finally, for a
wide choice of \( m_U \) and \( m_{h'} \) the trigger efficiency should exceed 90%.

The only physical process that can give rise to a dangerous background at
DAΦNE, is the process \( \phi \rightarrow K^0_S K^0_L \) followed by a \( K^0_S \rightarrow \pi^+\pi^- \) decay and
the \( K^0_L \) flying through the apparatus without interacting. This decay chain is
relevant only for the \( U \rightarrow \mu^+\mu^- \) channel and its amount can be well calibrated
by using the events in which the \( K^0_L \) is observed in the apparatus. If this
background turns out to be a problem, however, one can always take data at
\( \sqrt{s} < 2m_K \), that can be easily done at DAΦNE, without loss of luminosity.

As a side note to the present discussion, it can be added that KLOE is also
particularly well suited for the observation of events with a displaced decay
vertex of the \( h' \). These events might happen for particular combinations of the
parameters which can make the decay path of the \( h' \) lower than a few meters.
Actually the detector was conceived to maximize the efficiency for the decays
of the \( K^0_L \)'s, that have a mean free path of 3.5 m at DAΦNE.

6 Multilepton events

In the case \( m_{h'} > m_U \), then, it more frequently decays to a pair of real or
virtual \( U \)'s. In this case one can observe events with 6 leptons in the final
state, due to the higgs'-strahlung process, or 4 leptons and a photon, due to
the \( e^+e^- \rightarrow h'\gamma \) reaction.

Albeit very spectacular, these kind of events suffer of the fact that at KLOE
they have a relatively limited allowed phase-space, especially for the muon
channel. Also, the higher the multiplicity, the lower is the value of the mim-
imum transverse momentum for the charged particles, resulting in a possible
sizeable loss of acceptance, since one has to reconstruct completely the events.
Clearly, the all-electron channel is privileged at KLOE. In order to make more
quantitative statements, however, a detailed Monte Carlo simulation is needed.

It is important to stress that multilepton events are foreseen also in more
complex models, with respect to the one we have so far taken into consideration.
For instance in models with a confined sector, such as the one of reference [11]
one has the presence of vector 'hidden' mesons that can easily decay to leptons,
and scalar ones that cannot, so that a possible resulting signal is a multilepton
plus missing energy one\textsuperscript{1}. This model is very appealing since it reconciles well with the hypothesis that the dark matter is done by scalar particles, as suggested by the authors of reference \textsuperscript{17}. Obviously, the detectability of such kind of signals is very much dependent on the details of the model, so that, once again, quantitative statements can be made only after a dedicated Monte Carlo study has been performed.

7 Overview and conclusions

The hypothesis of the existence of an 'hidden' or 'secluded' gauge sector with manifestations at low or intermediate energies is motivated by several different recent astrophysical observations. This new physics can have escaped detection so far by particle physics experiments, due to its weak coupling to ordinary matter. Actually, the best limits on it are presently due to the measured value of the electron $g - 2$, as discussed for instance in references \textsuperscript{6} \textsuperscript{12}. At low and medium energy $e^+e^-$ colliders this sector gives clear signatures with cross sections that can be as large as 1 pb at 1 GeV. Although this value is relatively high with respect to present day standards, it must be stressed that previous generation collider experiments at or around this energy, such as those at ACO, ADONE and VEPP, have collected statistics of a few inverse picobarns at maximum, so that they could not have been able to observe anything.

KLOE at DAΦNE, with its collected 2.5 fb\textsuperscript{−1}, and KLOE-2 with its foreseen detector’s upgrades and larger data sample are and will be able to test these models in deep detail. Since the typical masses of these hypothetical particles range between a few MeV up to $\sim$10 GeV, searches must be performed at different facilities. KLOE can be the front-runner in the range between a few hundreds MeV to $\sim$1 GeV, while for higher mass values the present and future B-factories will play a crucial role.

A common effort between theorists and experimentalists, in terms of production of Monte Carlo generators, discussion on measurement strategies and interpretation of the data would be highly desirable.

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