Search for a vector gauge boson in $\phi$ meson decays with the KLOE detector

The KLOE-2 Collaboration

F. Archilli$^{p,q}$, D. Babusci$^f$, D. Badoni$^{p,q}$, I. Balwierz$^e$, G. Bencivenni$^f$, C. Bini$^{n,o}$, C. Bloise$^f$, V. Bocci$^o$, F. Bossi$^f$, P. Branchini$^s$, A. Budano$^{r,s}$, S. A. Bulychjev$^i$, L. Caldeira Balkestål$^u$, P. Campana$^f$, G. Capon$^f$, F. Ceradini$^{r,s}$, P. Ciambrone$^f$, E. Czerwiński$^f$, E. Dané$^f$, E. De Lucia$^f$, G. De Robertis$^b$, A. De Santis$^{n,o}$, G. De Zorzi$^{n,o}$, A. Di Domenico$^{n,o}$, C. Di Donato$^{j,k}$, D. Domenici$^f$, O. Erriquez$^{a,b}$, G. Fanizzi$^{a,b}$, G. Felici$^f$, S. Fiore$^o$, P. Franzini$^{n,o}$, P. Gauuzzi$^{n,o}$, G. Giardina$^{g,h}$, S. Giovannella$^{f,*}$, F. Gonnella$^{p,q}$, E. Graziani$^g$, F. Happacher$^f$, B. Höistad$^u$, L. Iafolla$^f$, E. Iarocci$^{l,f}$, M. Jacewicz$^u$, T. Johansson$^u$, A. Kowalewska$^v$, V. Kulikov$^i$, A. Kupsc$^u$, J. Lee-Franzini$^{f,t}$, F. Loddo$^b$, G. Mandaglio$^{g,h}$, M. Martemianov$^i$, M. Martini$^{f,m}$, M. Mascolo$^{p,q}$, M. Matsuuck$^i$, R. Messi$^{p,q}$, S. Miscetti$^f$, G. Morello$^f$, D. Moricci$^{n,q}$, P. Moskal$^e$, F. Nguyen$^{r,s}$, A. Passeri$^s$, V. Patera$^{l,f}$, I. Prado Longhi$^{r,s}$, A. Ranieri$^b$, C. F. Redmer$^u$, P. Santangelo$^f$, I. Sarra$^f$, M. Schioppa$^{c,d}$, B. Sciascia$^f$, A. Sciubba$^{l,f}$, M. Silarski$^e$, S. Stucci$^{c,d}$, C. Taccini$^{r,s}$, L. Tortora$^s$, G. Venanzoni$^f$, R. Versaci$^{f,w}$, W. Wiślicki$^v$, M. Wolke$^u$, J. Zdebik$^e$.

$^a$Dipartimento di Fisica dell’Università di Bari, Bari, Italy.
$^b$INFN Sezione di Bari, Bari, Italy.
$^c$Dipartimento di Fisica dell’Università della Calabria, Cosenza, Italy.
$^d$INFN Gruppo collegato di Cosenza, Cosenza, Italy.
$^e$Institute of Physics, Jagiellonian University, Cracow, Poland.
$^f$Laboratori Nazionali di Frascati dell’INFN, Frascati, Italy.
$^g$Dipartimento di Fisica dell’Università di Messina, Messina, Italy.
$^i$Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia.

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Abstract

The existence of a light dark force mediator has been tested with the KLOE detector at DAΦNE. This particle, called $U$, is searched for using the decay chain $\phi \rightarrow \eta U$, $\eta \rightarrow \pi^+\pi^-\pi^0$, $U \rightarrow e^+e^-$. No evidence is found in 1.5 fb$^{-1}$ of data. The resulting exclusion plot covers the mass range $5 < M_U < 470$ MeV, setting an upper limit on the ratio between the $U$ boson coupling constant and the fine structure constant, $\alpha'/\alpha$, of $\leq 2 \times 10^{-5}$ at 90% C.L. for $50 < M_U < 420$ MeV.

Key words: $e^+e^-$ collisions, dark forces, gauge vector boson

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1 Introduction

In recent years, several unexpected astrophysical observations have failed to find a common interpretation in terms of standard astrophysical or particle physics sources. A non-exhaustive list of these observations includes the 511 keV gamma-ray signal from the galactic center observed by the INTEGRAL
satellite [1], the excess in the cosmic ray positrons reported by PAMELA [2],
the total electron and positron flux measured by ATIC [3], Fermi [4], and
HESS [5,6], the annual modulation of the DAMA/LIBRA signal [7,8] and the
low energy spectrum of nuclear recoil candidate events observed by CoGeNT
[9].

Although there are alternative explanations for some of these anomalies, they
could be all explained with the existence of a dark matter weakly interacting
massive particle, WIMP, belonging to a secluded gauge sector under which the
Standard Model (SM) particles are uncharged [10,11,12,13,14,15,16,17,18,19].
An abelian gauge field, the \( U \) boson with mass near the GeV scale, couples the
secluded sector to the SM through its kinetic mixing with the SM hyper-charge
gauge field. The kinetic mixing parameter, \( \epsilon \), is expected to be of the order
\( 10^{-4} \)–\( 10^{-2} \) [11,20], so that observable effects can be induced in \( O(\text{GeV}) \)-energy
e\( \gamma \) colliders [20,21,22,23,24] and fixed target experiments [25,26,27,28]. The
possible existence of a new light boson gauging a new symmetry with a small
coupling was in fact already introduced on general grounds in [29], and re-
discussed in models postulating also the existence of light spin 0 or 1/2 dark
matter particles [30,31]. This boson can have both vector and axial-vector cou-
lings to quark and leptons, however axial couplings are strongly constrained
by data, leaving room to vector couplings only.

The \( U \) boson can be produced at \( e^+e^- \) colliders via different processes:
\( e^+e^- \rightarrow U\gamma \), \( e^+e^- \rightarrow Uh' \) (\( h' \)-strahlung), where \( h' \) is a higgs-like particle responsible
for the breaking of the hidden symmetry, and \( V \rightarrow P\gamma \) decays, where \( V \) and
\( P \) are vector and pseudoscalar mesons, respectively. In this work, we study
the process \( \phi \rightarrow \eta U \), using a sample of \( \phi \) mesons produced resonantly at the
DA\( \Phi \)NE collider. The \( U \) boson can be observed by its decay into a lepton pair,
while the \( \eta \) can be tagged by one of its main decays. An irreducible background
due to the Dalitz decay of the \( \phi \) meson, \( \phi \rightarrow \eta \ell^+\ell^- \), is present. This decay
has been studied by the SND and CMD-2 experiments, which measured a
branching fraction of \( \text{BR}(\phi \rightarrow \eta e^+e^-) = (1.19 \pm 0.19 \pm 0.07) \times 10^{-4} \)
and \( \text{BR}(\phi \rightarrow \eta e^+e^-) = (1.14 \pm 0.10 \pm 0.06) \times 10^{-4} \), respectively [32,33]. This
corresponds to a cross section of \( \sigma(\phi \rightarrow \eta \ell^+\ell^-) \sim 0.7 \) nb, with a di-lepton
mass range \( M_{\ell\ell} < 470 \) MeV. For the signal, the expected cross section is
expressed by [22]:

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

where \( F_{\phi\eta}(m_U^2) \) is the \( \phi\eta\gamma^* \) transition form factor evaluated at the \( U \) mass
while the following term represents the ratio of the kinematic functions of the
involved decays.\(^1\)

\(^1\) \( \lambda(m_1^2, m_2^2, m_3^2) = [1 + m_3^2/(m_1^2 - m_2^2)]^2 - 4m_1^2m_2^2/(m_1^2 - m_2^2)^2.\)
\( \sigma(\phi \rightarrow \eta U) \sim 40 \text{ fb} \) is obtained. Despite the small ratio between the overall cross section of \( \phi \rightarrow \eta U \) and \( \phi \rightarrow \eta \ell^+ \ell^- \), their different di-lepton invariant mass distributions allow to test the \( \epsilon \) parameter down to \( 10^{-3} \) with the KLOE data set.

The best \( U \) decay channel to search for the \( \phi \rightarrow \eta U \) process at KLOE is in \( e^+e^- \), since a wider range of \( U \) boson masses can be tested and \( e^\pm \) are easily identified using a time-of-flight (ToF) technique. The \( \eta \) can be tagged by the three-pion or two-photon final state, which represent \( \sim 85\% \) of the total decay rate. We have used the \( \eta \rightarrow \pi^+\pi^-\pi^0 \) decay channel, which provides a clean final state with four charged particles and two photons.

## 2 The KLOE detector

The KLOE experiment operated from 2000 to 2006 at DAΦNE, the Frascati \( \phi \)-factory. DAΦNE is an \( e^+e^- \) collider running at a center-of-mass energy of \( \sim 1020 \text{ MeV} \), the mass of the \( \phi \) meson. Equal energy positron and electron beams collide at an angle of \( \pi-25 \text{ mrad} \), producing \( \phi \) mesons nearly at rest. The detector consists of a large cylindrical Drift Chamber (DC), surrounded by a lead-scintillating fiber electromagnetic calorimeter (EMC). A superconducting coil around the EMC provides a 0.52 T field. The beam pipe at the interaction region is spherical in shape with 10 cm radius, it is made of a Beryllium-Aluminum alloy of 0.5 mm thickness. Low beta quadrupoles are located at about \( \pm 50 \text{ cm} \) distance from the interaction region. The drift chamber \[34\], 4 m in diameter and 3.3 m long, has 12,582 all-stereo tungsten sense wires and 37,746 aluminum field wires. The chamber shell is made of carbon fiber-epoxy composite with an internal wall of \( \sim 1 \text{ mm} \) thickness, the gas used is a 90\% helium, 10\% isobutane mixture. The spatial resolutions are \( \sigma_{xy} \sim 150 \mu\text{m} \) and \( \sigma_z \sim 2 \text{ mm} \). The momentum resolution is \( \sigma(p_\perp)/p_\perp \approx 0.4\% \). Vertexes are reconstructed with a spatial resolution of \( \sim 3 \text{ mm} \). The calorimeter \[35\] is divided into a barrel and two endcaps, for a total of 88 modules, and covers \( 98\% \) of the solid angle. The modules are read out at both ends by photomultipliers, both in amplitude and time. The readout granularity is \( \sim (4.4 \times 4.4) \text{ cm}^2 \), for a total of 2440 cells arranged in five layers. The energy deposits are obtained from the signal amplitude while the arrival times and the particles positions are obtained from the time differences. Cells close in time and space are grouped into energy clusters. The cluster energy \( E \) is the sum of the cell energies. The cluster time \( T \) and position \( \vec{R} \) are energy-weighted averages. Energy and time resolutions are \( \sigma_E/E = 5.7\%/\sqrt{E} \text{ (GeV)} \) and \( \sigma_t = 57 \text{ ps}/\sqrt{E} \text{ (GeV)} \oplus 100 \text{ ps} \), respectively. The trigger \[36\] uses both calorimeter and chamber information. In this analysis the events are selected by the calorimeter trigger, requiring two energy deposits with \( E > 50 \text{ MeV} \) for the barrel and \( E > 150 \text{ MeV} \) for
the endcaps. A cosmic veto rejects events with at least two energy deposits above 30 MeV in the outermost calorimeter layer. Data are then analyzed by an event classification filter \cite{37}, which selects and streams various categories of events in different output files.

3 Event selection

The analysis of the decay chain $\phi \rightarrow \eta U$, $\eta \rightarrow \pi^+\pi^-\pi^0$, $U \rightarrow e^+e^-$, has been performed on a data sample of 1.5 fb$^{-1}$, corresponding approximately to $5 \times 10^9$ produced $\phi$ mesons. The Monte Carlo (MC) simulation of the irreducible background $\phi \rightarrow \eta e^+e^-$, $\eta \rightarrow \pi^+\pi^-\pi^0$ has been produced with $d\Gamma(\phi \rightarrow \eta e^+e^-)/dm_{ee}$ weighted according to Vector Meson Dominance model \cite{38}, using the form factor parametrization from the SND experiment \cite{32}. The MC simulation for the $\phi \rightarrow \eta U$ decay has been developed according to \cite{22}, with a flat distribution in $M_{ee}$. All MC productions, including all other $\phi$ decays, take into account changes in DAΦNE operation and background conditions on a run-by-run basis. Data-MC corrections for cluster energies and tracking efficiency, evaluated with radiative Bhabha events and $\phi \rightarrow \rho\pi$ samples, respectively, have been applied.

As a first step of the analysis, a preselection is performed requiring:

1. two positive and two negative tracks with point of closest approach to the beam line inside a cylinder around the interaction point (IP), with transverse radius $R_{FV} = 4$ cm and length $Z_{FV} = 20$ cm;
2. two photon candidates i.e. two energy clusters with $E > 7$ MeV not associated to any track, in an angular acceptance $|\cos \theta_\gamma| < 0.92$ and in the expected time window for a photon ($|T_\gamma - R_\gamma/c| < \text{MIN}(5\sigma_T, 2 \text{ ns})$);
3. best $\pi^+\pi^-\gamma\gamma$ match to the $\eta$ mass in the pion hypothesis to assign $\pi^\pm$ tracks.\(^2\) the other two tracks are then assigned to $e^\pm$;
4. loose cuts of about $\pm 4\sigma$'s on $\eta$ and $\pi^0$ invariant masses ($495 < M_{\pi^+\pi^-\gamma\gamma} < 600$ MeV, $70 < M_{\gamma\gamma} < 200$ MeV).

After this selection, a clear peak corresponding to $\phi \rightarrow \eta e^+e^-$ events is observed in the distribution of the recoil mass to the $e^+e^-$ pair, $M_{\text{recoil}}(ee)$, as shown in Fig. 1. The second peak at $\sim 590$ MeV is due to $K_S \rightarrow \pi^+\pi^-$ events with a wrong mass assignment. Events in the $535 < M_{\text{recoil}}(ee) < 560$ MeV window are retained for further analysis.

A residual background contamination, due to $\phi \rightarrow \eta\gamma$ events with photon

\(^2\) The invariant mass of $\pi^+\pi^-\gamma\gamma$ for each positive/negative track pair, $M_{\text{test}}$, is evaluated in the hypothesis that the two tracks belong to charged pions. The track pair with the smaller $|M_{\text{test}} - M_\eta|$ value is assigned to $\pi^+$ and $\pi^-$. 

5
conversion on beam pipe (BP) or drift chamber walls (DCW), is rejected by tracing back the tracks of the two $e^+, e^-$ candidates and reconstructing their invariant mass ($M_{ee}$) and distance ($D_{ee}$) at the BP/DCW surfaces. As both quantities are small in case of photon conversions, $\phi \rightarrow \eta \gamma$ background is removed by rejecting events with: $M_{ee}(BP) < 10$ MeV and $D_{ee}(BP) < 2$ cm, $M_{ee}(DCW) < 80$ MeV and $D_{ee}(DCW) < 10$ cm. A further relevant background, originated by $\phi \rightarrow K \bar{K}$ decays surviving analysis cuts, has more than two charged pions in the final state and is suppressed using time-of-flight (ToF) to the calorimeter. When an energy cluster is connected to a track, the arrival time to the calorimeter is evaluated both using the calorimeter timing ($T_{\text{cluster}}$) and the track trajectory ($T_{\text{track}} = L_{\text{track}} / \beta c$). The $\Delta T = T_{\text{track}} - T_{\text{cluster}}$ variable is then evaluated in both electron ($\Delta T_e$) and pion ($\Delta T_\pi$) hypotheses. Events with an $e^+, e^-$ candidate outside a 3$\sigma$’s window on the $\Delta T_e$ variables are rejected. In Fig. 2 the $M_{ee}$ distribution evaluated at different steps of the analysis is shown. The peaks at $\sim 30$ MeV and $\sim 80$ MeV are due to photon conversions on BP and DCW, respectively. The ToF cut reduces the tail at high $M_{ee}$ values while the conversion cut removes events in the low invariant mass region. The analysis efficiency, defined as the ratio between the number of events surviving analysis cuts and that of all generated events, is shown in Fig. 3 as a function of $M_{ee}$, ranging between 10% and 20%. The main contribution to the loss of efficiency is due to preselection cuts, being $\varepsilon_{\text{presel}} = (24.73 \pm 0.04)\%$.

In Fig. 4 the comparison between data and Monte Carlo events for $M_{ee}$ and $\cos \psi^*$ distributions is shown. Here $\psi^*$ is the angle between the $\eta$ and the $e^+$ in the $e^+e^-$ rest frame. About 14,000 $\phi \rightarrow \eta e^+e^-$, $\eta \rightarrow \pi^+\pi^-\pi^0$ candidates are present in the analyzed data set, with a negligible residual background.
4 Upper limit evaluation

As an accurate description of the background is crucial for the search of the $U$ boson, its shape is extracted directly from our data. A fit is performed to the $M_{ee}$ distribution, after applying a bin-by-bin subtraction of the $\phi \to \eta \gamma$ background and efficiency correction. The parametrization of the fitting function has been taken from Ref. [38].
Fig. 4. Invariant mass of the $e^+e^-$ pair (top) and $\cos\psi^*$ distribution (bottom) for $\phi \rightarrow \eta e^+e^-$, $\eta \rightarrow \pi^+\pi^-\pi^0$ events. Dots are data, the black solid line is the sum of all MC expectations while signal and residual background contamination from $\phi \rightarrow \eta\gamma$ are shown in colors.

\[
\frac{d\Gamma(\phi \rightarrow \eta e^+e^-)}{dq^2} = \frac{\alpha}{3\pi} \frac{|F_{\phi\eta}(q^2)|^2}{q^2} \sqrt{1 - \frac{4m^2}{q^2}} \left(1 + \frac{2m^2}{q^2}\right) \lambda^{3/2}(m^2_{\phi}, m^2_{\eta}, m^2_U) \tag{2}
\]

with $q = M_{ee}$ and the transition form factor described by

\[
F_{\phi\eta}(q^2) = \frac{1}{1 - q^2/A^2}. \tag{3}
\]

Free parameters of the fit are $\Lambda$ and an overall normalization factor. A good description of the $M_{ee}$ shape is obtained except at the high end of the spectrum (see Fig. 5), where a residual background contamination from multi-pion events is still present.

As mentioned in Sec. 3, the $\phi \rightarrow \eta U$ MC signal has been produced according to Ref. [22], with a flat distribution of the $U$ boson invariant mass, $M_U$. This sample has been used to evaluate the resolution on the $e^+e^-$ invariant mass as a function of $M_U$, applying a Gaussian fit to the $M_{ee} - M_U$ distributions. Results are reported in Fig. 6. The resolution is $\sim 2$ MeV for $M_U < 350$ MeV and then improves to 1 MeV for higher values. The upper limit on $\phi \rightarrow \eta U$ signal as a function of $M_U$ is then obtained in the following way:
Fig. 5. Fit to the corrected $M_{ee}$ spectrum for the Dalitz decays $\phi \rightarrow \eta e^+e^-$. 

(a) MC events are divided in sub-samples of 1 MeV width in the range $5 < M_U < 470$ MeV; 
(b) for each $M_U$ sub-sample, the average value of the $\phi \rightarrow \eta e^+e^-$ background, $b(M_{ee})$, is obtained by fitting the reconstructed $M_{ee}$ spectrum with 5 MeV binning, removing five bins centered at $M_U$; 
(c) for each fit, the maximum variation of $b(M_{ee})$ events, $\Delta b(M_{ee})$, is obtained changing by $\pm 1\sigma$ the fit parameters; 
(d) for each $M_U$ value, the signal hypothesis is tested comparing observed data, $b(M_{ee})$ and MC signal in the five reconstructed bins excluded in (b). The exclusion plot is obtained applying the CLs method \[39\]. A Gaussian spread of width $\Delta b(M_{ee})$ on the background distribution is applied while evaluating CLs. 

In Fig. 7 the exclusion plot at 90% C.L. on the number of events for the decay chain $\phi \rightarrow \eta U, \eta \rightarrow \pi^+\pi^-\pi^0, U \rightarrow e^+e^-$, is shown. Using Eq. (1) and taking into account the analysis efficiency this result is then reported in terms of the parameter $\alpha'/\alpha = \epsilon^2$, where $\alpha'$ is the coupling of the $U$ boson to electrons and $\alpha$ is the fine structure constant. The opening of the $U \rightarrow \mu^+\mu^-$ threshold, in the hypothesis that the $U$ boson decays only to lepton pairs and assuming equal coupling to $e^+e^-$ and $\mu^+\mu^-$, has been included. In Fig. 8 the smoothed exclusion plot at 90% C.L. on $\alpha'/\alpha$ is compared with existing limits from the muon anomalous magnetic moment $a_\mu$ \[40\] and from recent measurements of the MAMI/A1 \[41\] and APEX \[42\] experiments. The gray line is where the $U$ boson parameters should lay to account for the observed discrepancy between measured and calculated $a_\mu$ values. Our result greatly improves existing limits in a wide mass range, resulting in an upper limit on the $\alpha'/\alpha$ parameter of
Fig. 6. Resolution on $M_{ee}$ as a function of the $U$ boson invariant mass for $\phi \rightarrow \eta U$ MC events.

Fig. 7. Upper limit at 90% C.L. on the number of events for the decay chain $\phi \rightarrow \eta U$, $\eta \rightarrow \pi^+\pi^-\pi^0$, $U \rightarrow e^+e^-$. $\leq 2 \times 10^{-5}$ @ 90% C.L. for $50 < M_U < 420$ MeV, thus covering part of the expected $\epsilon$ range (see Sec. [1]). We exclude that the existing $a_\mu$ discrepancy is due to a $U$ boson with mass ranging between 90 and 450 MeV.

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Fig. 8. Exclusion plot at 90% C.L. for the parameter $\alpha'/\alpha = \epsilon^2$, compared with existing limits in our region of interest.

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References

[1] P. Jean et al., Astron. Astrophys. 407, L55 (2003).
[2] O. Adriani et al., Nature 458, 607 (2009).
[3] J. Chang et al., Nature 456, 362 (2008).
[4] A.A. Abdo et al., Phys. Rev. Lett. 102, 181101 (2009).
[5] F. Aharonian et al., Phys. Rev. Lett. 101, 261104 (2008).
[6] F. Aharonian et al., Astron. Astrophys. 508, 561 (2009).
[7] R. Bernabei et al., Int. J. Mod. Phys. D 13, 2127 (2004).
[8] R. Bernabei et al., Eur. Phys. J. C 56, 333 (2008).
[9] C. E. Aalseth et al., Phys. Rev. Lett. 107, 141301 (2011).
[10] M. Pospelov, A. Ritz, M.B. Voloshin, Phys. Lett. B 662, 53 (2008).
[11] N. Arkani-Hamed, D.P. Finkbeiner, T.R. Slatyer, N. Weiner, Phys. Rev. D 79, 015014 (2009).
[12] D.S.M. Alves, S.R. Behbahani, P. Schuster, J.G. Wacker, Phys. Lett. B 692, 323 (2010).
[13] M. Pospelov, A. Ritz, Phys. Lett. B 671, 391 (2009).
[14] J. Hisano, S. Matsumoto, M.M. Nojiri, Phys. Rev. Lett. 92, 031303 (2004).
[15] M. Cirelli, M. Kadastik, M. Raidal, A. Strumia, Nucl. Phys. B 813, 1 (2009).
[16] J. March-Russell, S.M. West, D. Cumberbatch, D. Hooper, JHEP 07, 058 (2008).
[17] I. Cholis, G. Dobler, D.P. Finkbeiner, L. Goodenough, N. Weiner, Phys. Rev. D 80, 123518 (2009).
[18] I. Cholis, D.P. Finkbeiner, L. Goodenough, N. Weiner, JCAP 0912, 007 (2009).
[19] N. Arkani-Hamed, N. Weiner, JHEP 12, 104 (2008).
[20] R. Essig, P. Schuster, N. Toro, Phys. Rev. D 80, 015003 (2009).
[21] B. Batell, M. Pospelov, A. Ritz, Phys. Rev. D 79, 115008 (2009).
[22] M. Reece, L.T. Wang, JHEP 07, 051 (2009).
[23] N. Borodatchenkova, D. Choudhury, M. Drees, Phys. Rev. Lett. 96, 141802 (2006).
[24] P.F. Yin, J. Liu, S.h. Zhu, Phys. Lett. B 679, 362 (2009).
[25] J.D. Bjorken, R. Essig, P. Schuster, N. Toro, Phys. Rev. D 80, 075018 (2009).
[26] B. Batell, M. Pospelov, A. Ritz, Phys. Rev. D 80, 095024 (2009).
[27] R. Essig, P. Schuster, N. Toro, B. Wojtsekhowski, JHEP 1102, 009 (2011).
[28] M. Freytsis, G. Ovanesyan, J. Thaler, JHEP 01, 111 (2010).
[29] P. Fayet, Phys. Lett. B 95, 285 (1980); P. Fayet, Phys. Lett. B 187, 184 (1981).
[30] C. Boehm and P. Fayet, Nucl. Phys. B 683, 219 (2004).
[31] P. Fayet, Phys. Rev. D 70, 023514 (2004).
[32] M. N. Achasov et al., Phys. Lett. B 504, 275 (2001).
[33] R. R. Akhmetshin et al., Phys. Lett. B 501, 191 (2001).
[34] M. Adinolfi et al., Nucl. Inst. and Meth. A 488, 51 (2002).
[35] M. Adinolfi et al., Nucl. Inst. and Meth. A 482, 364 (2002).
[36] M. Adinolfi et al., Nucl. Inst. and Meth. A 492, 134 (2002).
[37] F. Ambrosino et al., Nucl. Inst. and Meth. A 534, 403 (2004).
[38] L.G. Landsberg, Phys. Rep. 128, 301 (1985).
[39] T. Junk, Nucl. Instr. Meth. A 434, 435 (1999).
[40] M. Pospelov, Phys. Rev. D 80, 095002 (2009).
[41] H. Merkel et al., Phys. Rev. Lett. 106, 251802 (2011).
[42] S. Abrahamyan et al., Phys. Rev. Lett. 107, 191804 (2011).