The Physics Case for Low Energy Photon Experiments
—
Axions, WIMPs, WISPs and other weird stuff

Joerg Jaeckel

Institute for Particle Physics and Phenomenology, Durham University, Durham DH1 3LE, UK

Due to their enormous precision low energy experiments with photons provide a unique window towards fundamental physics. More generally, low energy but high precision experiments may provide for a powerful probe of new physics beyond the Standard Model which is complementary to collider experiments. In these notes we argue that Axions, WIMPs and WISPs are phenomena that can be tested in low energy experiments. At the same time these particles are motivated by experimental and observational evidence as well as the desire to test theoretical model building. This provides an excellent 'physics-case'to search for new phenomena at the low energy frontier.

1 Introduction – Hints for new physics

Over the years both theoretical as well as experimental evidence has accumulated that strongly suggests the existence of physics beyond the current standard model of particle physics (SM). The Large Hadron Collider currently starting up at CERN will test many of the ideas for such physics beyond the standard model (BSM) and hopefully will provide us with a wealth of new information. In this note we argue that there is also a very good motivation to search for new physics in low energy experiments that can provide us with powerful complementary information on currently open questions and in particular on how the standard model is embedded into a more fundamental theory.

Let us begin by briefly repeating some of the main reasons why we believe that there must be physics beyond the standard model.

On the theoretical side there are a number of deficiencies in the SM. Some of them could be just aesthetic defects but some may go deeper. First of all the SM has a relatively large number $\mathcal{O}(30)$ free parameters that cannot be determined from theory alone but must be measured experimentally. Although this does not indicate an inconsistency of the theory it certainly is not in line with the hope that a fundamental theory of everything should have very few, possibly only 1 or even 0, free parameters. Moreover, some of the parameters seemingly need to require an enormous degree of finetuning or appear unnaturally small. Well known examples are the Higgs mass but also the θ parameter of QCD (which must be extremely small in order not to be in conflict with the observed smallness of strong CP violation). Another dissatisfying feature is that gravity is not incorporated into the SM but rather treated as a separate part. This is not just an aesthetic defect but also an expression of the fact that the quantization of gravity is still not (fully) understood. Finally, strictly speaking the SM will most likely not be valid up to arbitrary high energy scales. On the one hand this is due to our current inability to properly quantize gravity. But even the non-gravity parts are probably encountering problems in the form of Landau poles (places where the coupling becomes infinite) in the QED sector (at a very high scale much beyond the Planck scale) but probably also in the Higgs sector (where the problem is much more immediate and will occur at scales much below the Planck scale - depending on the Higss mass possibly even not much above the electroweak scale).

Next there are quite a few phenomena which are experimentally well established but for which there is no good explanation within the standard model. The most shocking of which is probably the realization that most of the matter and energy in the universe actually is not made up of SM particles. Cosmological and astrophysical observations give strong evidence that about 70 % of the energy in the universe is dark energy and another 25 % is dark matter [1]. These are things that simply do not appear in the current SM (although they could be accommodated see, e.g., [2]). But even within the standard model there are things which are experimentally well established but for which a good explanation is lacking. These are, e.g., the existence of three generations of SM particles, the mass hierarchies for the SM particles and the small parameters such as, e.g., the already mentioned θ parameter [3]. The latter is, of course, a repetition of some of the problems already mentioned as 'theoretical' problems showing that they actually arise from experimental results.

Finally, there is the direct experimental evidence for BSM physics. At the moment most of this is still relatively circumstantial but it definitely demonstrates that low energy experiments can provide information on BSM physics as well as opening new directions which can be explored (or close others). Examples are the deviation [4] of the muon $(g-2)$ from the SM expectation, the excess in the event rate of the DAMA [5] experiment and the PVLAS anomaly [6] (which has been retracted [7] but, as we will see, has inspired a lot of fruitful experimental and theoretical activity). Most recently, a lot of interest has been generated by the observation of a positron excess by the PAMELA satellite [8]. This has led to great interest in the existence of new "Dark Forces" which are relatively long range with force carries of mass $\sim$ GeV (see, e.g., [9]).

2 Bottom-up/phenomenological arguments

In this section we will present several examples for physics at the low energy frontier that arise from more phenomenological arguments - a line of thought that could be called 'bottom-up' and that follows a hands-on approach on fixing problems step by step.

Axions are a good example for this approach [10]. The extreme smallness of the θ-angle is unexplained in the standard model. This can be solved by introducing a new symmetry - the Peccei Quinn symmetry. As a consequence one predicts a pseudo-Goldstone boson, the axion. This is already a good motivation to experimentally search for the axion, for example in light shining through a wall experiments [11–14] (see also next section), laser polarization experiments (as, e.g., PVLAS) [6, 7, 15] or axion helioscopes [16]. The case for this search is then strengthened by the finding that the axion is also a valid candidate for dark matter [17]. This prediction, however, not only strengthens the physics case for searching axions but it also opens new ways to do so. One can search for axion dark matter, for example using resonant cavity techniques [18] or looking in the sky for axions decaying into photons.

Another example are WIMPs (for a review see [19]). As a solution for the hierarchy problem in the SM one can, again, introduce a symmetry: SUSY. Introducing SUSY leads to many new particles, notably the heavy supersymmetric partners of the SM particles, which are weakly interacting and massive, i.e. WIMPs. Some of them are good candidates for dark matter. Again good motivation to perform a WIMP search. Another incentive is that SUSY also allows

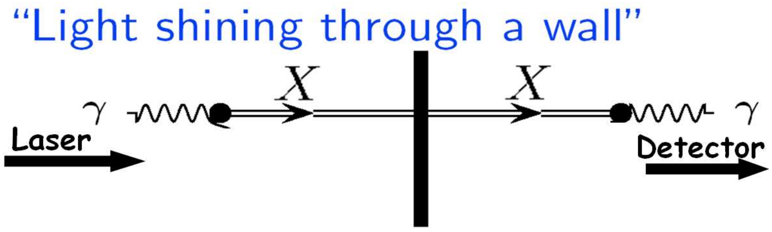

Figure 1: Schematic setup of a "light shining through a wall experiment". A laser is shone on an opaque wall. After the wall a detector is placed to search for photons that somehow make it through the wall. The idea is that some of the photons are converted into very weakly interacting particles X which can simply traverse the wall. After the wall the X particles reconvert into ordinary photons and can be detected. In some cases (e.g. Axions) the conversion can be stimulated by the presence of a magnetic field. In other cases (e.g. extra hidden, massive U(1) gauge bosons the conversion results from an oscillation between the photon and the new particle which is very similar to neutrino oscillations. Then it can happen even in vacuum.

to explain the deviation of the muon $(g-2)$ from its SM value that was already mentioned in the introduction. SUSY might be discovered at a collider such as LHC. Such an experiment may even find a dark matter candidate. But in order to know that such a candidate really makes up all or most of the dark matter, i.e. if it was produced in sufficient quantities, one needs the low energy WIMP searches [5, 20] which therefore give us crucial information.

The PVLAS anomaly which was in contradiction to the SM expectation led to the introduction of several types of WISPs (weakly interacting slight (or sub-eV) particles). To check their result and to search for these WISPs the PVLAS group then improved their apparatus finding that the original result was probably an artifact of the apparatus [7]. However, this is not the end of the story. The introduction of WISPs also led people to realize that there is a large amount of unexplored parameter space for new physics that (e.g., due to the extremely weak interactions involved) cannot be tested in conventional colliders [21][1]. Yet, new ideas how to access this parameters space in low energy experiments and observations have been put forward [23]. Moreover, it was (re-)discovered that the extremely weak interactions of WISPs are often connected to very high energy scales $\gtrsim 10^5$ GeV, in some cases even as high as the string or the even Planck scale $\sim 10^{18}$ GeV. Showing that the new and improved low energy experiments can give us complementary information on very high energy physics. Let us see in the next section how the precision of low energy photon experiments turns them into a probe for very high energy scales.

3 Low energy photon probes

Let us look a little bit more closely how we can use low energy photon experiments to search for Axions and more general WISPs.

One of the most intriguing idea is a so-called light shining through a wall experiments [11–14]. The schematic setup is shown in Fig. 1. The power of this type of experiment lies in its enormous

[1] Astrophysical arguments are, however, a different matter. For an overview over pre-PVLAS work in this direction see, e.g., [22].

precision. Laser powers of the order of ~ 100W corresponding to 10^{21} photons per second are easily achievable. Moreover, it is certainly possible to detect as little as 1 photon per second. This allows us to search for particles with a transition probability as low as 10^{-21}!

Let us further illustrate this with an example. Axions and axion like particles (a) couple to two photons with an interaction

$$\mathcal{L}_{\rm int} \sim \frac{1}{M} a F^{\mu\nu} \tilde{F}_{\mu\nu} \sim \frac{1}{M} a \mathbf{E} \cdot \mathbf{B}. \tag{1}$$

Here M roughly gives the energy scale where the new physics connected to the axion (like particle) happens. (In some cases there is an additional (small) coupling constant involved, e.g. the electromagnetic coupling, then we probe a scale $\sim \alpha M$.)

Experimentally the electric field is provided by the laser photons and a strong magnet (typically a recycled accelerator magnet) provides the magnetic field. In this situation the probability for a photon to traverse the wall is given by

$$P_{\gamma \to a \to \gamma} \sim N_{\rm pass} \left(\frac{|\mathbf{B}| L}{M} \right)^4, \tag{2}$$

where L is the length of the magnetic field region. Moreover, we have included a factor $N_{\rm pass}$ accounting for the fact that we can use mirrors to reflect the light back and forth inside the interaction region to enhance the transition probability (see [11, 14] for experiments that have implemented this feature). $N_{\rm pass} \sim 100$, $B \sim 5\,{\rm T} \sim 1000\,{\rm eV}^2$ and $L \sim$ few $\times$ m $\sim (10^7 - 10^8)\,{\rm eV}^{-1}$ are realistic values. Inserting this into Eq. (2) and remembering that we can detect probabilities $\lesssim 10^{-21}$ we find that the experiments are sensitive to

$$M \sim (10^6 - 10^7){\rm GeV}. \tag{3}$$

In other words we are probing for new physics connected to energy scales $(10^4 - 10^7)$GeV, much higher than the scale of current accelerator experiments.

The enormous precision is what makes photon experiments such a powerful tool to search for new physics. Here, we demonstrated this precision using light shining through a wall experiments searching for axion like particles as an example. This precision can also be exploited in a wide variety of other experiments [6, 7, 15, 23], including laser polarization experiments, experiments with microwave cavities, but also traditional tests of the Coulomb's law. These experiments can search for a huge variety of different WISPs such as hidden sector photons, minicharged particles and chameleon particles, as well as many other interesting things.

4 Top-down/theory arguments

Instead of taking small steps and fixing the problems, in the process often creating a more and more baroque model, one can also go back to the drawing board and rethink the very principles on which the original model was based. One such attempt (among others) is string theory. One of the main motivations for string theory is to unify the SM with gravity. To achieve this point particles are replaced by extended strings. Currently string theory is not yet in a state where it provides a first principle derivation of the SM and corrections to the same. Nevertheless, it has a variety of general features that suggest avenues for model building and also specific phenomena.

One such general feature is that for consistency string theory likes SUSY. Following the arguments from the previous section SUSY provides a good physics case for WIMP searches. Accordingly string theory strengthens the physics case for such searches.

Another property of string theory is that in order to be consistent it needs the existence of extra (space) dimensions. In order to be in agreement with observation all except the well known three have to be compactified. However, compactification leaves its traces[2]. Shape and size deformations of the compactified dimensions correspond to scalar fields, so-called moduli. These could be very light (it is actually often difficult to give them any mass at all) and provide excellent WISP candidates (and may also be searched for in fifth force experiments [24]). In a similar manner also various types of axions appear in string theory (see, e.g., [25]). The physics of these particles (e.g. the small size of their interactions) is inherently linked to the string scale. Hence, suitable low energy experiments searching for such WISPs may give us the opportunity to probe the fundamental theory and its associated fundamental energy scale.

String theory also tends to have whole sectors of extra matter in addition to the ordinary SM matter. This matter often lives in so-called hidden sectors which have only extremely weak interactions with the SM particles. Accordingly particles in these sectors may avoid detection in collider experiments even if they are light, i.e. these hidden sector provide good candidates for WISPs[3]. Typical WISP candidates arising from such hidden sectors are extra 'hidden' U(1) gauge bosons and 'hidden' matter charged under those U(1)s [28, 29][4]. In many models these hidden sectors are located at a different place in the extra dimension than the SM sector[5]. Accordingly searching and testing these hidden sectors can give us crucial global information on the compactification that can hardly be obtained from collider experiments which probe the local structure that has relatively strong interactions.

Finally, string theory also motivates some surprising things. In particular, some models predict non-commutativity and other Lorentz symmetry violating effects [34]. This then can also be tested in low energy experiments and observations such as, e.g., comparing the spectrum of hydrogen and anti hydrogen atoms [35] or by observing if light from gamma-ray bursts arrives at (slightly) different times depending on its polarization [36]. These experiments and observations (see [37] for an overview) again provide an ultra high precision that can then give us insights into the fundamental theory at very high energy scales.

Let us again illustrate the power of precision by an example. In some models of non-commutativity the two polarizations of light move at slightly different speed,

$$\frac{\Delta c}{c} \sim 10^{-34} \left(\frac{M_P}{M_{\rm NC}}\right)^2. \tag{4}$$

Now assume that we observe light from a very distant source. For example, a gamma ray burst

[2]If the size of the extra dimension is large enough there could actually be a very direct consequence: the inverse square law of the gravitational force would be modified. This, too, can be tested in low energy experiments [24].

[3]If the hidden sector particles are somewhat heavier they can also be WIMP candidates [26] (which in some cases can also be searched for at colliders [26,27]). However, this also depends on how strict one takes the 'Weak' in the name WIMP. Often it is constraint to be the weak of electroweak. Then hidden sector particles cannot really be WIMPs.

[4]The hidden U(1)'s can interact with the SM via a kinetic [30], magnetic [31] or mass mixing [32] with the ordinary photon. The kinetic or magnetic mixing can then also lead to a small electric charge for the hidden matter [30, 31].

[5]An alternative to truly hidden sectors are sectors with hyperweak interactions [33]. Although in these models the new particles can have tree-level interactions with the standard model particles these are extremely weak. Effectively they are diluted because the hyperweak sector extends more into the extra dimensions. Accordingly these, too, contain more information about the global structure.

at a distance of $\sim 10^9$ lightyears. If the two polarization directions move with slightly different speeds one will arrive earlier than the other. If we can measure time differences of the order of 1 second we already have an enormous precision of 1 part in 10^{16} in the speed of light. In our example this means that we are probing energy scales of the order of 10^9 GeV. However, we can actually do much better. Using polarimetric measurements one can search for time differences corresponding to one wavelength or less. This gives us another amazing factor of $\gtrsim 10^{15}$ in the precision. Overall we can test for differences in the speed of light of the order of 1 part in $\gtrsim 10^{32}$. Comparing with Eq. (4) we see that this really tests Planck scale physics!

5 Conclusions

Both the phenomenological bottom-up and the more theory oriented top-down approach provide an excellent physics case motivating further experiments at the low-energy frontier such as searches for axions, WIMPs and WISPs and other interesting effects such as Lorentz violation. These phenomena are often connected to energy scales much higher than those reachable in near future accelerators. They provide experimental access to hidden sectors that may contain crucial information on the underlying global structure of a more fundamental theory. Moreover, they give us reasons to challenge and experimentally check basic assumptions as, e.g., Lorentz symmetry. In conclusion, low energy but high precision experiments provide crucial complementary information to uncover the nature of a more fundamental theory beyond the standard model.

Acknowledgements

The author wishes to thank the organizers of the *Photon 2009* for a very enjoyable meeting.

References

[1] E. Komatsu *et al.* [WMAP Collaboration], arXiv:0803.0547 [astro-ph].

[2] H. Davoudiasl, R. Kitano, T. Li and H. Murayama, Phys. Lett. B **609** (2005) 117.

[3] N. F. Ramsay, Phys. Rept. **43** (1977) 409; C. A. Baker *et al.*, Phys. Rev. Lett. **97** (2006) 131801.

[4] G. W. Bennett *et al.* [Muon g-2 Collaboration], Phys. Rev. Lett. **92** (2004) 161802.

[5] R. Bernabei *et al.* [DAMA Collaboration], Eur. Phys. J. C **56** (2008) 333 [arXiv:0804.2741 [astro-ph]].

[6] E. Zavattini *et al.* [PVLAS Collaboration], Phys. Rev. Lett. **96** (2006) 110406 [Erratum-ibid. **99** (2007) 129901].

[7] E. Zavattini *et al.* [PVLAS Collaboration], Phys. Rev. D **77** (2008) 032006.

[8] O. Adriani *et al.* [PAMELA Collaboration], Nature **458** (2009) 607.

[9] N. Arkani-Hamed, D. P. Finkbeiner, T. R. Slatyer and N. Weiner, Phys. Rev. D **79** (2009) 015014.

[10] R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. **38**, 1440 (1977); Phys. Rev. D **16**, 1791 (1977); S. Weinberg, Phys. Rev. Lett. **40**, 223 (1978); F. Wilczek, Phys. Rev. Lett. **40**, 279 (1978); J. E. Kim, Phys. Rept. **150** (1987) 1.

[11] R. Cameron *et al.* [BFRT Collaboration], Phys. Rev. D **47** (1993) 3707;

[12] P. Sikivie, Phys. Rev. Lett. **51**, 1415 (1983) [Erratum-ibid. **52**, 695 (1984)]; A. A. Anselm, Yad. Fiz. **42**, 1480 (1985); M. Gasperini, Phys. Rev. Lett. **59**, 396 (1987); K. Van Bibber, N. R. Dagdeviren, S. E. Koonin, A. Kerman and H. N. Nelson, Phys. Rev. Lett. **59**, 759 (1987).

[13] K. Ehret *et al.*, arXiv:hep-ex/0702023; C. Robilliard,*et al* [BMV Collaboration], Phys. Rev. Lett. **99** (2007) 190403; A. S. Chou *et al.* [GammeV (T-969) Collaboration], Phys. Rev. Lett. **100** (2008) 080402; P. Pugnat *et al.* [OSQAR Collaboration], arXiv:0712.3362 [hep-ex]. M. Fouche *et al.* [BMV Collaboration], Phys. Rev. D **78** (2008) 032013; A. Afanasev *et al.* [LIPSS Collaboration], arXiv:0806.2631 [hep-ex]; arXiv:0810.4189 [hep-ex].

[14] K. Ehret *et al.* [ALPS collaboration], arXiv:0905.4159 [physics.ins-det].

[15] S. J. Chen, H. H. Mei and W. T. Ni [Q& A Collaboration], Mod. Phys. Lett. A **22** (2007) 2815; P. Pugnat *et al.* [OSQAR Collaboration], Czech. J. Phys. **55**, A389 (2005); Czech. J. Phys. **56**, C193 (2006); R. Battesti *et al.* [BMV Collaboration], Eur. Phys. J. D **46**, 323333 (2008); R. Battesti *e*t al. [BMV Collaboration], Eur. Phys. J. D **46** (2008) 323.

[16] K. Zioutas *et al.* [CAST Collaboration], Phys. Rev. Lett. **94** (2005) 121301; S. Andriamonje *et al.* [CAST Collaboration], JCAP **0704** (2007) 010; M. Minowa, Y. Inoue, Y. Akimoto, R. Ohta, T. Mizumoto and A. Yamamoto, arXiv:0809.0596 [astro-ph].

[17] L. F. Abbott and P. Sikivie, Phys. Lett. B **120** (1983) 133; J. Preskill, M. B. Wise and F. Wilczek, Phys. Lett. B **120** (1983) 127; M. Dine and W. Fischler, Phys. Lett. B **120** (1983) 137.

[18] P. Sikivie, Phys. Rev. Lett. **51** (1983) 1415 [Erratum-ibid. **52** (1984) 695]; S. Asztalos *et al.*, Phys. Rev. D **64** (2001) 092003; L. D. Duffy *et al.*, Phys. Rev. D **74** (2006) 012006.

[19] G. Jungman, M. Kamionkowski and K. Griest, Phys. Rept. **267** (1996) 195.

[20] F. Probst *et al.*, Nucl. Phys. Proc. Suppl. **110** (2002) 67; D. S. Akerib *et al.* [CDMS Collaboration], Phys. Rev. Lett. **93** (2004) 211301; G. Angloher *et al.* [CRESST Collaboration], Astropart. Phys. **23** (2005) 325; V. Sanglard *et al.* [The EDELWEISS Collaboration], Phys. Rev. D **71** (2005) 122002; J. Angle *et al.* [XENON Collaboration], Phys. Rev. Lett. **100** (2008) 021303; Z. Ahmed *et al.* [CDMS Collaboration], arXiv:0802.3530 [astro-ph].

[21] E. Masso and J. Redondo, JCAP **0509** (2005) 015; P. Jain and S. Mandal, Int. J. Mod. Phys. D **15** (2006) 2095; J. Jaeckel, E. Masso, J. Redondo, A. Ringwald and F. Takahashi, hep-ph/0605313; Phys. Rev. D **75** (2007) 013004; E. Masso and J. Redondo, Phys. Rev. Lett. **97** (2006) 151802; H. Gies, J. Jaeckel and A. Ringwald, Phys. Rev. Lett. **97** (2006) 140402; R. N. Mohapatra and S. Nasri, Phys. Rev. Lett. **98** (2007) 050402; P. Brax, C. van de Bruck and A. C. Davis, Phys. Rev. Lett. **99** (2007) 121103; P. Brax, C. van de Bruck, A. C. Davis, D. F. Mota and D. J. Shaw, Phys. Rev. D **76** (2007) 085010; I. Antoniadis, A. Boyarsky and O. Ruchayskiy, Nucl. Phys. B **793** (2008) 246; M. Ahlers, H. Gies, J. Jaeckel, J. Redondo and A. Ringwald, Phys. Rev. D **76** (2007) 115005; Phys. Rev. D **77** (2008) 095001.

[22] G. G. Raffelt, Stars As Laboratories For Fundamental Physics: The Astrophysics of Neutrinos, Axions, and other Weakly Interacting Particles, University of Chicago Press, Chicago, 1996; S. Davidson, S. Hannestad and G. Raffelt, JHEP **0005** (2000) 003.

[23] A. Dupays, C. Rizzo, M. Roncadelli and G. F. Bignami, Phys. Rev. Lett. **95** (2005) 211302; H. Gies, J. Jaeckel and A. Ringwald, Europhys. Lett. **76** (2006) 794; A. Badertscher *et al.*, Phys. Rev. D **75** (2007) 032004; A. Dupays, E. Masso, J. Redondo and C. Rizzo, Phys. Rev. Lett. **98** (2007) 131802; M. Fairbairn, T. Rashba and S. V. Troitsky, Phys. Rev. Lett. **98** (2007) 201801; E. G. Adelberger, B. R. Heckel, S. A. Hoedl, C. D. Hoyle, D. J. Kapner and A. Upadhye, Phys. Rev. Lett. **98** (2007) 131104; M. Ahlers, H. Gies, J. Jaeckel and A. Ringwald, Phys. Rev. D **75** (2007) 035011; S. N. Gninenko, N. V. Krasnikov and A. Rubbia, Phys. Rev. D **75** (2007) 075014; A. Mirizzi, G. G. Raffelt and P. D. Serpico, Phys. Rev. D **76** (2007) 023001; A. Melchiorri, A. Polosa and A. Strumia, Phys. Lett. B **650** (2007) 416; J. Jaeckel and A. Ringwald, Phys. Lett. B **653** (2007) 167; D. Hooper and P. D. Serpico, Phys. Rev. Lett. **99** (2007) 231102; J. Jaeckel and A. Ringwald, Phys. Lett. B **659** (2008) 509; A. De Angelis, O. Mansutti and M. Roncadelli, Phys. Lett. B **659** (2008) 847; K. A. Hochmuth and G. Sigl, Phys. Rev. D **76** (2007) 123011; M. Ahlers, A. Lindner, A. Ringwald, L. Schrempp and C. Weniger, Phys. Rev. D **77** (2008) 015018; H. Gies, D. F. Mota and D. J. Shaw, Phys. Rev. D **77** (2008) 025016; S. N. Gninenko, arXiv:0802.1315 [hep-ph]. S. N. Gninenko and J. Redondo, Phys. Lett. B **664** (2008) 180; J. Jaeckel, J. Redondo and A. Ringwald, arXiv:0804.4157 [astro-ph]; A. S. Chou *et al.*, arXiv:0806.2438 [hep-ex]; J. Jaeckel and J. Redondo, 0806.1115 [hep-ph]; P. L. Slocum, talk at the *4th Patras Workshop on Axions, WIMPs and WISPs* 2008, Hamburg, http://axion-wimp.desy.de/e30; M. Ahlers, J. Jaeckel, J. Redondo and A. Ringwald, arXiv:0807.4143 [hep-ph]; J. Jaeckel, arXiv:0807.5097 [hep-ph]. P. Williams, talk at the 5th Patras Workshop on Axions, WIMPs and WISPs, Durham 2009, http://axion-wimp.desy.de; M. Tobar, talk at the 5th Patras Workshop on Axions, WIMPs and WISPs, Durham 2009, http://axion-wimp.desy.de; J. Jaeckel, Phys. Rev. Lett. **103** (2009) 080402; F. Caspers, J. Jaeckel and A. Ringwald, arXiv:0908.0759 [hep-ex].

[24] C. D. Hoyle, U. Schmidt, B. R. Heckel, E. G. Adelberger, J. H. Gundlach, D. J. Kapner and H. E. Swanson, Phys. Rev. Lett. **86** (2001) 1418; J. Chiaverini, S. J. Smullin, A. A. Geraci, D. M. Weld and A. Kapitulnik, Phys. Rev. Lett. **90** (2003) 151101; V. V. Nesvizhevsky *et al.*, Nature **415** (2002) 297; E. G. Adelberger, B. R. Heckel and A. E. Nelson, Ann. Rev. Nucl. Part. Sci. **53** (2003) 77; J. C. Long, H. W. Chan, A. B. Churnside, E. A. Gulbis, M. C. M. Varney and J. C. Price, Nature **421** (2003) 922; V. V. Nesvizhevsky and K. V. Protasov, Class. Quant. Grav. **21** (2004) 4557; C. D. Hoyle, D. J. Kapner, B. R. Heckel, E. G. Adelberger, J. H. Gundlach, U. Schmidt and H. E. Swanson, Phys. Rev. D **70** (2004) 042004;

[25] P. Svrcek and E. Witten, JHEP **0606** (2006) 051.

[26] B. Kors and P. Nath, Phys. Lett. B **586** (2004) 366; B. Kors and P. Nath, JHEP **0507** (2005) 069; D. Feldman, B. Kors and P. Nath, Phys. Rev. D **75** (2007) 023503; D. Feldman, Z. Liu and P. Nath, AIP Conf. Proc. **939** (2007) 50; D. Feldman, Z. Liu and P. Nath, AIP Conf. Proc. **939** (2007) 50.

[27] C. Coriano, A. E. Faraggi and M. Guzzi, Phys. Rev. D **78** (2008) 015012.

[28] B. Batell and T. Gherghetta, Phys. Rev. D **73** (2006) 045016.

[29] K. R. Dienes, C. F. Kolda and J. March-Russell, Nucl. Phys. B **492** (1997) 104; D. Lüst and S. Stieberger, hep-th/0302221; S. A. Abel and B. W. Schofield, Nucl. Phys. B **685** (2004) 150; M. Berg, M. Haack and B. Kors, Phys. Rev. D **71** (2005) 026005; [arXiv:hep-th/0404087]; R. Blumenhagen, S. Moster and T. Weigand, Nucl. Phys. B **751** (2006) 186; S. A. Abel, J. Jaeckel, V. V. Khoze and A. Ringwald, Phys. Lett. B **666** (2008) 66; S. A. Abel, M. D. Goodsell, J. Jaeckel, V. V. Khoze and A. Ringwald, JHEP **0807** (2008) 124.

[30] B. Holdom, Phys. Lett. B **166** (1986) 196.

[31] F. Brummer, J. Jaeckel and V. V. Khoze, JHEP **0906** (2009) 037.

[32] L. B. Okun, Sov. Phys. JETP **56** (1982) 502 [Zh. Eksp. Teor. Fiz. **83** (1982) 892]; R. Foot and X. G. He, Phys. Lett. B **267** (1991) 509.

[33] C. P. Burgess, J. P. Conlon, L. Y. Hung, C. H. Kom, A. Maharana and F. Quevedo, JHEP **0807** (2008) 073.

[34] V. A. Kostelecky and S. Samuel, Phys. Rev. D **39** (1989) 683. N. Seiberg and E. Witten, JHEP **9909** (1999) 032; V. A. Kostelecky and R. Lehnert, Phys. Rev. D **63** (2001) 065008; M. S. Berger and V. A. Kostelecky, Phys. Rev. D **65** (2002) 091701; S. A. Abel, J. Jaeckel, V. V. Khoze and A. Ringwald, JHEP **0609** (2006) 074.

[35] R. Lehnert, hep-ph/0602097.

[36] V. A. Kostelecky and M. Mewes, Phys. Rev. Lett. **97** (2006) 140401.

[37] V. A. Kostelecky and M. Mewes, Phys. Rev. D **66** (2002) 056005; V. A. Kostelecky and N. Russell, arXiv:0801.0287 [hep-ph].