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Dark Forces and Dark Matter in a Hidden Sector

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Hidden sectors in connection with GeV-scale dark forces and dark matter are not only a common feature of physics beyond the Standard Model such as string theory and SUSY but are also phenomenologically of great interest regarding recent astrophysical observations. The hidden photon in particular is also searched for and constrained by laboratory experiments, the current status of which will be presented here. Furthermore, several models of hidden sectors containing in addition a dark matter particle will be examined regarding their consistency with the dark matter relic abundance and direct detection experiments.

1 Motivation

Hidden sectors are often predicted in string theories and contained in various supersymmetric models as the source of SUSY breaking. As the hidden sector (HS) is not charged under the Standard model (SM) gauge groups and vice versa the two sectors are not directly connected and only interact via messenger particles. An example for a messenger is the hidden photon γ' which is a frequent feature of SM extensions as extra hidden U(1) symmetries for example often remain in the breaking of larger gauge groups or appear in string compactifications.

On the other hand there are several observations in indirect and direct dark matter detection experiments like PAMELA, Fermi, DAMA and CoGeNT which favour dark matter (DM) models with light messenger particles. Such a messenger, despite mediating the DM scattering on nuclei, most importantly ensures that the DM annihilation is at the same time leptophilic and greatly enhanced by the Sommerfeld effect.

A GeV-scale mass for the hidden photon can be obtained quite naturally both through the Stückelberg and the Higgs mechanism. The former, being the simplest mechanism to give mass to abelian gauge bosons, can give for example in certain string compactifications with D7-branes a mass to the hidden photon according to $m_{\gamma'} \gtrsim M_{\rm S}^2/M_{\rm Pl}$, which depends on the volume of the extra dimension, i.e. the string-scale $M_{\rm S}$, and the Planck scale $M_{\rm Pl}$ [1, 2]. For intermediate string-scales $M_S \sim 10^9 - 10^{10}$ GeV, which are preferred by the axion decay constant and SUSY breaking scales, this leads to $m_{\gamma'} \sim$ GeV-scale. In the case of the Higgs mechanism where the symmetry breaking is transferred by the kinetic mixing from the visible to the hidden sector the hidden photon mass can be estimated by $m_{\gamma'} \simeq \sqrt{g_Y g_h c_{2\beta}}\; v\sqrt{\chi}$ [3, 4]. Assuming that the kinetic mixing χ is generated supersymmetrically at high scales, without light fields charged under both U(1)s, it is of the order of a loop factor [1] and we impose the following relation with the hidden gauge coupling g_h

$$\chi = \frac{g_Y g_h}{16\pi^2}\;\kappa \tag{1}$$

where κ is an $\mathcal{O}(1)$ factor leading typically to $\chi \sim 10^{-3} - 10^{-4}$ and thus $m_{\gamma'} \sim$ GeV-scale.

2 Hidden Photon: Constraints and future experiments

We consider the most simple hidden sector containing only an extra U(1) symmetry and the corresponding hidden photon γ' which kinetically mixes with the ordinary photon. The most general Lagrangian for such a scenario, including a mass-term $m_{\gamma'}$ for the hidden photon and the kinetic mixing between γ and γ' parameterized by χ, is given by

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\chi}{2}X_{\mu\nu}F^{\mu\nu} + \frac{m_{\gamma'}^2}{2}X_\mu X^\mu + g_Y j_{\rm em}^\mu A_\mu, \qquad (2)$$

where $F_{\mu\nu}$ is the field strength of the ordinary electromagnetic field A_μ and $X_{\mu\nu}$ the field strength of the hidden U(1) field X_μ. The hidden photon can be constrained by and searched for in experiments through its coupling to SM fermions which is possible due to the kinetic mixing with the photon. SM precision measurements (SM PM) [5], the muon and electron anomalous magnetic moment (a_μ, a_e) [6] and a reinterpretation of the BaBar search for the $\Upsilon(3S)$ decay to a pseudoscalar in the process $e^+e^- \to \gamma\mu^+\mu^-$s [7] exclude large values of kinetic mixing as shown in grey in the left plot of Fig. 1. Fixed-target experiments where γ' can be produced in Bremsstrahlung off e^-/p-beams place additional constraints from the non-observation of the decay $\gamma' \to e^+e^-$. Limits from past e^--beam dump searches that have been studied in [8] are shown in the left plot of Fig. 1 as grey areas. The same graph also contains as coloured lines the new limits set by currently running (MAMI [9], KLOE-2 [10], APEX [11]) and reanalyzed older experiments (Serpukhov [12], Orsay [13]). Experiments are closing in on the remaining region of the parameter space and more is to be tested in the (near) future by presently operating or planned fixed-target experiments at JLab (APEX [7], HPS [14], DarkLight [15, 16]), Mainz (MAMI, MESA [17]) and DESY (HIPS [18]). The expected sensitivities of those experiments are shown as coloured lines in the right plot of Fig. 1.

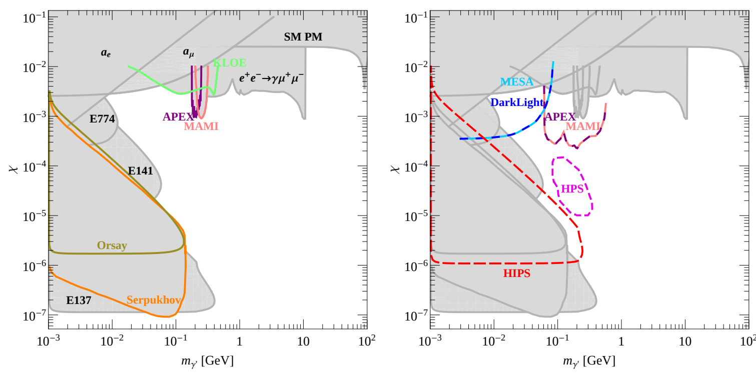

Figure 1: Hidden photon parameter space with past and new exclusion regions *(left)* as well as projected sensitivities *(right)*.

3 Hidden Dark Matter

The results of this section are based on an analysis that has been presented in detail in [19].

Hidden Sector toy model: Dirac fermion dark matter

The simplest possible extension of the hidden sector studied in the previous section is the addition of a Dirac fermion as dark matter candidate (cf. [20, 21, 22, 23]). As the hidden photon mediates both the DM annihilation and the DM scattering on nuclei it is essential for the determination of the DM relic abundance and direct detection rate respectively.

Using relation (1) with $\kappa = 0.1$ we find that for a DM mass of 6 GeV the correct relic abundance can be obtained on the dark green stripe in Fig. 2 while in the light green area the contribution to the total DM density is only subdominant. The spin-independent (SI) scattering on nuclei of the Dirac fermion DM can explain the CoGeNT [24] signal in the purple band (90% CL lighter 99% CL darker purple). The plotted cross section σ_{SI} has been rescaled by the relic abundance for subdominant DM and fits the one found in [25] to be compatible with CoGeNT for a Standard Halo Model. Constraints from CDMS [26] and XENON [27] are not shown as they do not apply to DM masses as light as 6 GeV. The excluded grey areas and coloured lines for sensitivities of future experiments are the same as in Fig. 1. A scan over the DM mass allows to fill the complete parameter space as shown in Fig. 3 on the left for $\kappa = 1$ where dark green corresponds to the correct relic abundance, light green to subdominant and purple to CoGeNT allowed points (all points are compatible with other direct detection limits). The effects of varying the DM mass, the parameter κ and the details of the halo model have been studied in more detail in [19].

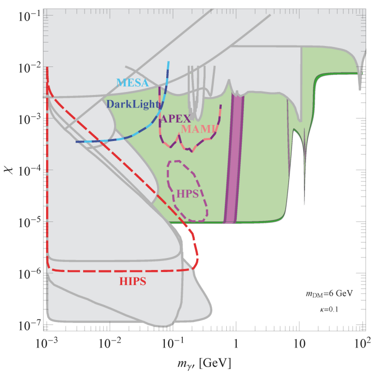

Figure 2: Toy model HS with relic abundance (green) and CoGeNT region (purple) for the Dirac fermion DM.

Supersymmetric hidden sector: Majorana and Dirac fermion dark matter

As a more sophisticated and better motivated model, we consider three chiral superfields S, H_+, H_- with H_+ and H_- charged under the hidden U(1). Taking the superpotential $W \supset \lambda_S S H_+ H_-$ and the dimensionless coupling λ_S this is the simplest anomaly-free model possible without adding dimensionful supersymmetric quantities. While we assume the MSSM in the visible sector, the DM phenomenology of the HS depends on the details of the SUSY breaking. If the breaking of the hidden gauge symmetry is via the effective Fayet-Iliopoulos

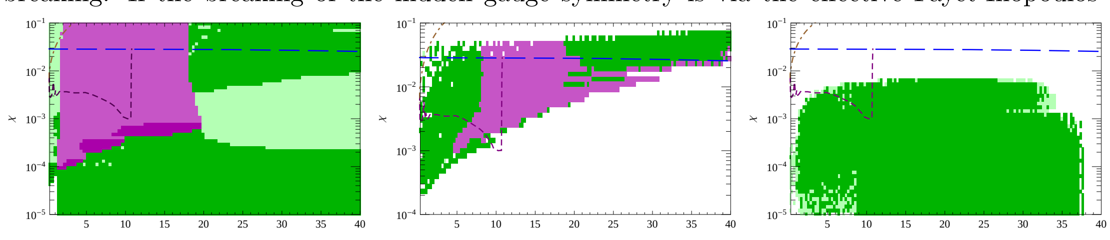

Figure 3: Scatter plots for the toy model *(left)* and the SUSY HS with visible sector induced breaking *(middle)* as well as radiative breaking domination *(right)*. Lines are constraints from EWPT (long dashed), BaBar (short dashed) and muon g-2 (dash-dotted) similar to Fig. 1.

term induced in the HS by the kinetic mixing with the visible Higgs D-term we find that the DM can be either a Dirac or a Majorana fermion. The former has similar prospects for SI scattering as in the toy model as shown in the middle plot of Fig. 3 where the parameter κ has been scanned over in the range $0.1 \leq \kappa \leq 10$. The axial couplings of the latter lead to dominantly spin-dependent (SD) scattering which is partly constrained by experiments but without any chance of explaining any of the signals in SI direct detection experiments. In the case where the hidden gauge symmetry breaking is induced by the Yukawa coupling λ_S, we find only a Majorana fermion as lightest particle in the spectrum. As before this only shows in SD direct detection experiments, hence the missing purple colour for CoGeNT in the right plot of Fig. 3.

4 Conclusions

Hidden sectors are motivated by various aspects from top-down (string theory, SUSY) and bottom-up (DM) and have a potentially rich content like dark forces and dark matter which despite their weak coupling can be phenomenologically interesting. We reviewed past constraints on hidden photons as dark force and showed the reach of future experiments. A simple toy model for a HS with DM is found to be consistent with relic abundance and direct detection and additionally provides the correct cross section for explaining CoGeNT. The better-motivated supersymmetric hidden sectors show some similarities with the toy model but have a more complicated phenomenology where spin-dependent scattering must also be taken into account. Nevertheless, they also give viable models for DM with interesting signatures in experiments.

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References

[1] M. Goodsell, J. Jaeckel, J. Redondo, A. Ringwald, JHEP **0911** (2009) 027. [arXiv:0909.0515].
[2] M. Cicoli, M. Goodsell, J. Jaeckel, A. Ringwald, JHEP **1107** (2011) 114. [arXiv:1103.3705].
[3] M. Baumgart, C. Cheung, J.T. Ruderman, L.-T. Wang, I. Yavin, JHEP **0904** (2009) 014. [arXiv:0901.0283].
[4] D. E. Morrissey, D. Poland, K. M. Zurek, JHEP **0907** (2009) 050. [arXiv:0904.2567].
[5] A. Hook, E. Izaguirre, J. G. Wacker, [arXiv:1006.0973].
[6] M. Pospelov, Phys. Rev. **D80** (2009) 095002. [arXiv:0811.1030].
[7] R. Essig, P. Schuster, N. Toro, B. Wojtsekhowski, JHEP **1102** (2011) 009. [arXiv:1001.2557].
[8] J. D. Bjorken, R. Essig, P. Schuster, N. Toro, Phys. Rev. **D80** (2009) 075018. [arXiv:0906.0580].
[9] H. Merkel *et al.* [A1 Collaboration], Phys. Rev. Lett. **106** (2011) 251802. [arXiv:1101.4091].
[10] F. Archilli *et al.*, [KLOE-2 Collaboration], [arXiv:1107.2531] and [arXiv:1110.0411].
[11] S. Abrahamyan *et al.* [APEX Collaboration], [arXiv:1108.2750].
[12] J. Blumlein, J. Brunner, Phys. Lett. **B701** (2011) 155-159. [arXiv:1104.2747].
[13] S. Andreas, J. Jacobsohn,, C. Niebuhr A. Ringwald, *work in preparation.*
[14] T. Maruyama, talk given at the SLAC - Dark Forces Workshop, 2009.
[15] M. Freytsis, G. Ovanesyan and J. Thaler, JHEP **1001** (2010) 111 [arXiv:0909.2862].
[16] J. Thaler and P. Fisher, talk given at the SLAC - Dark Forces Workshop, 2009.
[17] A. Denig, talk given at the JLab Workshop - Searching for a New Gauge Boson at JLab, 2010.
[18] S. Andreas, A. Ringwald, [arXiv:1008.4519].
[19] S. Andreas, M. D. Goodsell, A. Ringwald, [arXiv:1109.2869].
[20] D. Feldman, B. Kors, P. Nath, Phys. Rev. **D75** (2007) 023503. [hep-ph/0610133].
[21] M. Pospelov, A. Ritz and M. B. Voloshin, Phys. Lett. B **662** (2008) 53 [arXiv:0711.4866].
[22] E. J. Chun, J. C. Park and S. Scopel, JHEP **1102** (2011) 100 [arXiv:1011.3300].
[23] Y. Mambrini, JCAP **1009** (2010) 022 [arXiv:1006.3318].
[24] C. E. Aalseth *et al.* [CoGeNT Collaboration], Phys. Rev. Lett. **106** (2011) 131301. [arXiv:1002.4703].
[25] C. Arina, J. Hamann, Y. Y. Y. Wong, JCAP **1109** (2011) 022. [arXiv:1105.5121].
[26] Z. Ahmed *et al.* [CDMS-II Collaboration], Phys. Rev. Lett. **106** (2011) 131302. [arXiv:1011.2482].
[27] E. Aprile *et al.* [XENON100 Collaboration], [arXiv:1104.2549].