Status of sub-GeV Hidden Particle Searches

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DOI: http://dx.doi.org/10.3204/DESY-PROC-2010-03/andreas_sarah

Hidden sector particles with sub-GeV masses like hidden U(1) gauge bosons, the NMSSM CP-odd Higgs, and other axion-like particles are experimentally little constrained as they interact only very weakly with the visible sector. For masses below the muon threshold, we present constraints from meson decays, $g-2$ as well as beam-dump and reactor experiments. The NMSSM CP-odd Higgs and generally any pseudoscalar is required to be heavier than 210 MeV or couple to fermions much weaker than the SM Higgs. Hidden photons are less constrained and can be searched for at future fixed-target experiments, e.g. HIPS at DESY.

1 Motivation for a sub-GeV dark sector

Hidden sectors are frequently proposed as part of the physics beyond the standard model. Since their interactions with the visible sectors are very weak, so are the current experimental bounds. In fact, motivated both from a bottom-up and a top-down perspective, those sectors might even contain light particles with masses in the sub-GeV range that have so far escaped detection. Among those weakly interacting slim particles (WISPs) are hidden U(1) gauge bosons, the CP-odd Higgs of the NMSSM, and other axion-like particles (ALPs).

Such particles are of great interest in many models that seek to interpret recent terrestrial and astrophysical anomalies in terms of dark matter (DM). The rise in the positron-fraction with energy as observed by PAMELA (cf. [1]) and the deviation from the power-law in the $e^+ + e^-$ spectrum measured by FERMI (cf. [2]) together with the absence of an excess in anti-protons require the DM candidate to annihilate dominantly into leptons *(leptophil)* with a cross section much larger than the one giving the correct relic abundance. Different direct detection measurements like the annual modulation observed by DAMA/LIBRA [3] and the null results of CDMS and XENON [4, 5] seem somewhat contradicting. Consistency might still be possible if either the DM candidate is light ($m \sim 5 - 10$ GeV) with elastic scattering or heavy with excited states (mass splitting $\Delta m \sim 100$ keV) generating inelastic scattering. Those properties are challenging for standard DM candidates and alternative scenarios like hidden sectors with light messenger particles have been considered because of the following advantageous features. A long range attractive force mediated by such a light messenger generates a so called Sommerfeld enhancement of the annihilation cross section. Dark matter annihilation proceeding through this messenger – if light enough – is naturally leptophilic due to kinematics. Inelastic scattering on nuclei can also be mediated by such a light particle. Possible examples of messenger particles that have already been studied are ALPs like the NMSSM CP-odd Higgs [6] and hidden U(1) photons of a generic hidden sector [7, 8, 9, 10] or of asymmetric mirror worlds [11].

From a top-down perspective, hidden sectors appear naturally in various supersymmetric models descending from string theory. Mediator particles are generally weakly coupled to the visible sector and can also be light. Specifically in [12] it was found that the heterotic string can reproduce the NMSSM in a Peccei-Quinn limit with a light Pseudo-Goldstone boson, an axion-like particle. The breaking of larger groups down to the SM gauge group can in general yield hidden U(1) symmetries which may remain unbroken down to small energy scales. Their hidden photon may be light and couple weakly to the visible sector through kinetic mixing [13, 14].

In the following we present various constraints on the NMSSM CP-odd Higgs as representative of an axion-like particle and the hidden photon for masses below the muon threshold.

2 NMSSM CP-odd Higgs

The extension of the MSSM with an additional scalar field S to the NMSSM has been motivated as it solves the μ-problem by replacing the μ-parameter with a SM singlet S [15]. Additionally, the enlargement of the particle content by an additional CP-odd Higgs A^0 alleviates the little hierarchy problem if A^0 is light by opening an additional Higgs decay channel $h \to 2A^0$, thereby reducing the LEP limit on the Higgs mass. We focus our analysis on the Z_3-symmetric NMSSM, a special version without direct μ-term, with superpotential

$$W = \lambda S H_u H_d + \frac{1}{3}\kappa S^3.$$

In the limit $\kappa \to 0$, the Higgs potential possesses an approximate Peccei-Quinn symmetry and a naturally light pseudoscalar A^0 arises with $m_{A^0}^2 \simeq \kappa \cdot \mathcal{O}(\text{EW scale})^2$ where $\kappa \ll 1$. In the heterotic string example of [12], κ can be as small as 10^{-6} resulting in a 100 MeV pseudoscalar. Its couplings to fermions are according to [16] given by

$$\Delta\mathcal{L} = -i\frac{g}{2m_W}\, C_{Aff}\left(m_d\, \bar{d}\gamma_5 d + \frac{1}{\tan^2\beta} m_u\, \bar{u}\gamma_5 u + m_l\, \bar{l}\gamma_5 l\right) A^0.$$

We treat C_{Aff} as free parameter focusing on the range $10^{-2} \lesssim C_{Aff} \lesssim 10^2$ to avoid violation of perturbativity and/or finetuning and summarize the constraints derived in [17] in the following.

Different meson-decays set bounds for two distinct cases depending on the lifetime of A^0. If it is sufficiently long lived to escape the detector, invisible decays $X \to Y + A^0 \to Y +$ inv. place limits requiring $\Gamma^{X\to YA^0}/\Gamma^{\text{tot}} < \mathcal{B}^{\text{exp}}_{\text{inv}}$. Larger values of C_{Aff} for which A^0 decays within the detector are constrained by visible decays $X \to Y + A^0 \to Y + e^+e^-$ demanding $\text{BR}^{\text{X}\to\text{YA}^0}\text{BR}^{\text{A}^0\to\text{e}^+\text{e}^-} < \mathcal{B}^{\text{exp}}_{\text{e}^+\text{e}^-}$. Together with the limit from a search for a peak in the π^+ momentum spectrum in $K^+ \to \pi^+ + X$, meson decays cover most of the parameter space in Fig. 1.

Complementary constraints arising from the pion-decay $\pi^0 \to e^+e^-$ and the muon anomalous magnetic moment a_μ completely close the available parameter space. The former process which proceeds in the SM through loop diagrams receives a tree level contribution from A^0 and sets a limit requiring $\Gamma^{\pi^0 \xrightarrow{A^0} e^+e^-}/\Gamma^{\text{tot}} < \mathcal{B}^{\text{exp}}_{\pi^0\to e^+e^-}$. As there are several NMSSM contributions to a_μ of both signs, even though the negative loop-contribution from A^0 worsens the current discrepancy $a_\mu^{\text{exp}} > a_\mu^{\text{SM}}$, we derive a constraint demanding A^0 not to worsen it beyond 5σ.

Additional constraints can be derived from beam-dump and reactor experiments (lines and shaded regions, respectively, in Fig. 1, right) searching for the decay $A^0 \to e^+e^-$. Like any ALP, A^0 can be emitted in the former via bremsstrahlung from an e- or p-beam and in the latter in place of photons in transitions between nuclear levels.

In summary, for masses below the muon threshold, the CP-odd Higgs is excluded or required to couple to matter at least 4 orders of magnitude weaker than the SM Higgs which can hardly be achieved in the NMSSM. Those constraints as they are plotted in Fig. 1 apply in general to the coupling of a light pseudoscalar to matter.

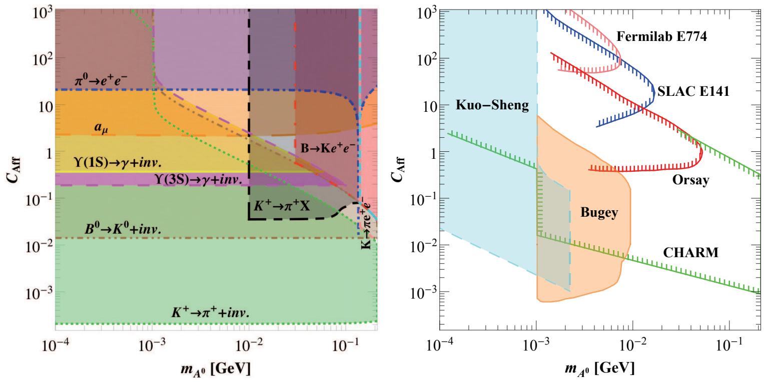

Figure 1: Excluded regions for the NMSSM CP-odd Higgs [17].

3 Hidden U(1) gauge boson

Many SM extensions contain additional U(1) symmetries in the hidden sector under which the SM is neutral. The corresponding gauge boson, the hidden photon γ' and the ordinary photon kinetically mix [13, 18] induced by loops of heavy particles charged under both U(1) groups.

The most general Lagrangian is

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{\chi}{2}X_{\mu\nu}F^{\mu\nu} + \frac{m_{\gamma'}^2}{2}X_\mu X^\mu$$

where $F^{\mu\nu}$ is the usual electromagnetic field strength and $X^{\mu\nu}$ the one corresponding to the hidden gauge field X^μ. The kinetic mixing χ is typically of the size of a radiative correction $\sim \mathcal{O}(10^{-4} - 10^{-3})$. Kinetic mixing allows γ' to couple and decay to SM fermions thereby making it accessible for experimental searches, the constraints of which are presented in the following.

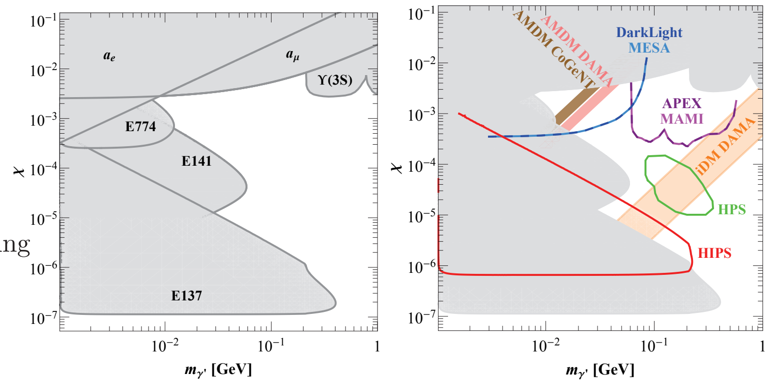

Figure 2: Exclusion regions *(left)* as well as projected sensitivities and phenomenological motivations *(right)* for the hidden photon.

Similarly to the CP-odd Higgs, limits arise from one-loop contributions of the hidden photon to the muon and electron anomalous magnetic moment [19]. Also beam-dump experiments in which γ' is emitted through bremsstrahlung from an e-beam can set constraints by searching for the decay $\gamma' \to e^+e^-$ [20]. The resulting limits (shaded in Fig. 2) leave an unexplored region in the parameter space which is best explored by fixed-target experiments [20, 21]. Dedicated proposals are being developed at DESY (HIPS, see also [22]), JLab (APEX [23, 24], HPS [25], DarkLight [21, 26]), and Mainz (MAMI, MESA [27]), with complementary sensitivities (cf. lines in Fig. 2, right).

The whole allowed parameter range in Fig. 2 is phenomenologically interesting for DM with dark photons of a generic hidden U(1) [7] or mirror photons in asymmetric mirror DM models (AMDM) [11]. The former can reproduce DAMA for inelastic DM [28] (orange "iDM" band) and achieve naturally the leptophilic DM annihilation required for PAMELA [29], while the latter is able to explain the DAMA and CoGeNT measurements with mirror neutrons as DM [30] (colored "ADMD" bands).

4 Conclusions

Hidden sectors are well motivated by DM, SM extensions, and string theory. They might contain light particles that despite their very weak couplings to the SM can be constrained experimentally. In particular, the NMSSM CP-odd Higgs has to be heavier than 210 MeV or couple much weaker to fermions than the SM Higgs. Hidden photons on the contrary are less constrained and can be searched for in complementary experiments at DESY, JLab and Mainz.

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