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Particle Physics of the Dark Sector

Oliver Baker [1,*,†], Andrei Afanasev [2,†], Theodota Lagouri [3,†], Jingjing Pan [1,†] and Christian Weber [4,†]

[1] Department of Physics, Yale University, New Haven, CT 06520, USA
[2] Department of Physics, The George Washington University, Washington, DC 20052, USA
[3] Instituto de Alta Investigacion, Universidad de Tarapaca (CL), Arica 1000000, Chile
[4] Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA
* Correspondence: oliver.baker@yale.edu
† These authors contributed equally to this work.

Abstract: The mystery associated with a proposed Dark Sector of phenomena that are separate from the standard model of particle physics is described. A Dark Sector may possess matter particles, force carriers which mediate their interactions, and new interactions and symmetries that are beyond the standard model of particle physics. Various approaches for Dark Sector searches are described, including those at the energy frontier at the Large Hadron Collider, in astrophysical interactions with both terrestrial experiments and those in space-born platforms. Searches using low energy photons from microwave energies in cryogenic environments to x-ray energies are also described. While there is no noncontroversial evidence for Dark Sector phenomena presently, new searches with more modern equipment and analysis methods are exploring regions of phase space that have not been available before now, indicating ongoing interest and excitement in this research.

Keywords: dark matter; standard model; elementary particles; hidden-sector particles; large hadron collider

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1. Historical Overview

Experimental and theoretical research in physics, astrophysics, cosmology, and astronomy has provided strong indication of physical phenomena that is not well understood fundamentally. These new universal phenomena appear to interact only very weakly with our detectors, with particles and fields that exist which we understand well, and with itself. Evidence for this exists in such large scale structures as the Bullet Cluster, the velocity of celestial bodies in our galaxy, the manner that visible light from distance galaxies is distorted by this new phenomena, in the photons' travel to our experiments on or near earth, to name a few general examples. Furthermore, while we see the photons of light that result from interactions we understand fundamentally, this new set of unknown particles and fields (from a physics perspective) is not visible to us or our detectors. These new phenomena are therefore, in this manuscript, referred to as Dark Sector phenomena. It may include Dark Matter particles, Dark Force carriers, along with new, not-well-understood interactions and interaction strengths. It appears to constitute about 27% of all the matter in the universe, according to the Cosmological model. In addition to this Dark Sector of proposed particles and fields, there is also a separate family of phenomena that resists the gravitational energy, resulting in the accelerated expansion of our universe. It is called Dark Energy, since it is known to exist, however its fundamental nature is unknown.

This Dark Sector of phenomena is an intriguing mystery, as it is the dominant component of our universe. In this article, we give a non-exhaustive account of both theoretical and experimental research that aims to detect and define the fundamental nature of this Dark Sector, from a physics perspective.

2. Brief Status of the Standard Model

The ATLAS [1] and CMS [2] collaborations at CERN's Large Hadron Collider discovered the Higgs boson in 2012. The standard model (SM) of particle physics [3–7] is now complete. It unifies the strong, electromagnetic, and weak interactions involving both fermions and bosons. However, there are physical phenomena that appear to require an explanation that is beyond the standard model (BSM): The accelerated expansion of the universe, dark matter and possibly dark force carriers, the unexpectedly small value of the neutron electric dipole moment (strong CP violation) and more than a dozen free parameters within the SM, are examples. There are several BSM physics proposals that may clarify some of these mysteries.

Searches for indication of Dark Sector phenomena constitute a vibrant space of research at the highest accelerator energies—the Energy Frontier—at the Large Hadron Collider, the Intensity Frontier at Fermi National Laboratory, along with CERN's and Jefferson Lab's fixed target experiments.

Dark matter (DM) and dark energy (DE) dominate the Universe, with ordinary baryonic matter limited only to less than five per cent of Universe's mass-energy content. Therefore DM is central to understanding our Universe, its composition and evolution since Big Bang, as well as its future. A historical overview of DM may be found, for example, in [8].

Constraints for the baryonic content come from element abundances in primordial nucleosynthesis and from measurements of anisotropy in Cosmic Microwave Background (CMB). Convincing evidence for DM is due to a variety of astrophysical observations. As a result, DM is presently a part of a standard model of modern cosmology. On the other hand, existence of DM in a form of elementary particles [9] remains an open question and currently is a subject of high-priority scientific efforts and future plans.

In this current document, we describe a non-exhaustive set of theoretical and experimental studies of Dark Sector phenomena. The description includes studies and searches in particle, nuclear, atomic, molecular and optical, and astro-particle, physics. These communities pursue research that covers several energy and particle mass ranges. Recent progress in theoretical research is given in Section 2. Searches for phenomena that can be attributed to Dark Sector interactions with SM fields and particles at the Energy Frontier is described for specific cases in Sections 3 and 4. Astrophysical data from space telescopes and non-terrestrial experiments have shown results and behavior that can be ascribed to BSM interactions. An overview of Dark Sector searches along with theoretical motivation is provided in Section 5. There is, additionally, strong motivation for Dark Sector particles and fields in low energy experiments that use probes having masses or energies in the electron-volt range, or lower, described in Sections 6 and 7.

3. Theory Motivation for Dark Matter Particles

Three of the four fundamental forces of nature, the strong nuclear, the weak nuclear, and the electromagnetic interactions are described theoretically with great success and accuracy by the SM. Experimental studies and results have validated predictions and post-dictions in atomic, nuclear, particle, and astro-particle, physics. This realization exists over many orders of magnitude in energy, from sub-electron-volt to greater than Terra-electron-volts, and over length scales less than a fermi to galactic scales or more.

However, the not-well-known experimental results described in Section 2 suggest that there are limitations to the SM theory. There may be an even more structured theory that includes the SM describing known interactions, and additional particles that interact via BSM force carriers. Furthermore, these may exist at larger or smaller masses and interaction strengths with different symmetries than are described by the SM. For example, there may be a DS of particles and fields that interact with the 'Visible Sector' SM fields via small couplings that are much weaker than that of photons coupling to charge [10,11]

This hidden sector hypothesis may be probed using SM particles at high energy accelerators at the TeV scale, and also by laser and microwave photon probes at long wavelengths [12–23]. Hidden, dark sector photons may also be related to a BSM cosmic microwave background. This may have bearing on the mystery of high energy gamma rays propagating large distances in the interstellar medium. If there is photon dark-photon resonant kinetic mixing, then a measurement of this mixing may provide new constraints on the effective number of neutrinos produced after nucleosynthesis and before CMB decoupling [24].

This low energy supposition involves SM mass-less electromagnetic force mediator photons, and Dark Sector photons with a finite mass [10].

$$L = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{2}\chi F^{\mu\nu}B_{\mu\nu} + \frac{1}{2}m^2_{\gamma'}B_\mu B^\mu \quad (1)$$

In this equation $F_{\mu\nu}$ represents the electromagnetic gauge field strength tensor, $B^{\mu\nu}$ the Dark Sector field strength tensor for the Dark Sector field B^μ, and m_γ the BSM dark photon mass. Equation (1) shows the kinetic terms for the SM photon and Dark Sector photon fields, in that order. The third term in (1) corresponds to (kinetic) mixing between these two photon fields, while the final term of the Lagrangian indicates the possibility that the Dark Sector photon has mass. The mixing parameter χ in this last term may have a (unit-less) strength of as small as 10^{-16} or smaller, and as large as 10^{-4} in some string theory based calculations [17–24]. Future experimental Dark Sector or Dark photon search results should narrow this mixing range.

4. Dark Sector Searches at Colliders

One avenue for such dark sector searches enabled by mixing between dark and SM particles is provided by particle colliders. Here the mixing provides an effective coupling between the colliding particles and a dark sector particles, enabling the production of the latter. This allows for two types of direct production searches at colliders. In one the dark sector particles are presumed to decay, at least partially, back into detectable SM particles. Alternatively the produced dark sector particles remain detector stable or decay into other dark sector states, leaving an imbalance in the reconstructed particle momenta.

The direct production searches with missing transverse momentum generally rely on the detection of some initial state radiation in order to tag events of interest. Hence they are refereed to as mono-photon or mono-jet searches. These mono-X searches constrain the effective coupling between Standard Model and dark matter particles ξ for dark matter masses m_ξ between a few GeV—depending on the detector resolution—and up to half the collider beam's center of mass energy. With that collider experiments can exclude regions in the plane of Standard Model–dark sector mediator coupling and mediator mass.

This approach allows to constrain, for example, the coupling between electrons and dark matter by re-interpreting [25] mono-photon searches from LEP's DELPHI experiment [26,27]. The authors of this re-interpretation use LEP data to place limits on scalar, vector, and other couplings between leptons and DM, for DM masses between 1 GeV and 100 GeV, as well as exclude light thermal relic dark matter ($m_\xi < 10$ GeV) with universal couplings exclusively to charged leptons. These limits are able to rule out the DAMA favored region [28] as well as the CoGeNT [29] excess.

Complementary direct production limits come from mono-jet searches at the Tevatron and the LHC. These probe the effective coupling of dark sector particles to quarks and gluons. Reference [30] reinterprets mono-jet measurements [31] of pp collisions recorded at the Tevatron's CDS experiment. Assuming a Dirac fermion dark matter, the authors arrive at limits on dark matter–proton scattering rates between 1×10^{-42} and 1×10^{30}, depending on the presumed dark matter mass, interaction type, and mediator mass. Reference [32] uses the same CDF results to place limits on the single nucleon cross section on for Majorana Dark matter between 1×10^{-41} to 1×10^{-38} for spin-independent interactions, and 1×10^{-40} to 1×10^{-37} for spin-dependent interactions. Both for dark matter particle masses between 1 GeV and 300 GeV.

More recent mono-jet limits are being reported by the LHC's CMS and ATLAS experiments. The former published multiple recent mono-jet searches with data from the LHC Runs 1 [33] and 2 [34] with cross section limits on the interactions between DM and nucleons, for DM masses from 1 to ∼2000 GeV. In these studies the CMS collaboration ruled out relevant cross sections from 10^{-42} (vector interactions), to 10^{-43} (axial-vector interactions), and to the level 10^{-45} for scalar particle mediators. Another set of results from CMS [35] uses 36 fb^{-1} integrated luminosity for pp collisions at 13 TeV collision energy to place exclusion limits in the two-dimensional plane given by dark matter and mediator mass for purely axial or vector like couplings to quarks.

Additional limits on dark sector physics from searches with missing transverse energy were also published by both collaboration. These include missing transverse energy di-jet final states [36–38], missing transverse energy concurrent with a reconstructed (vector) particle [39–42], final states with leptons and jets together with missing transverse momentum [43,44], mono-photon searches at the LHC [45], and lastly, missing transverse momentum in association with the production of a Higgs boson [46–49].

An indirect way of probing dark sector physics that is unique to colliders is the measurement of the Higgs → invisible branching ratio. In the Standard Model the Higgs boson has a non-zero branching ratio into neutrino final states via the processes $H \to \nu\bar{\nu}$ and $H \to ZZ \to 4\nu$. These final states are pratically 'invisible' due to the low interaction cross section of neutrinos with any detector material. The Higgs boson can acquire additional invisible decay modes if the dark sector contains another scalar particle; via mixing with it the Higgs can attain an effective coupling to other dark sector particles. Thus, measurements of the Higgs's invisible decay branching ratio [50,51] can constrain dark sector models indirectly.

Additional constrains to dark sector physics can come with searches with SM final states. These include searches for exotic visible decays of the Higgs [52,53], which can be used to constrain the mixing parameter χ, among others.

Both, the ATLAS and the CMS experiments at the LHC conducted searches for dark photons γ_d, or Z_d in the massive case, in Higgs decays. The ATLAS collaboration examined data from searches for dark photons decaying into (both) displaced or prompt lepton-jets. Additionally, both the ATLAS and CMS experiments searched for unstable particles that have long lifetimes, referred to as Long-Lived Particles (LLPs), decaying to displaced di-leptons. Furthermore, lastly, both the CMS and LHCb experiments conducted searches for low mass di-muon resonances.

The ATLAS collaboration recently published [54] results from a search for exotic SM Higgs boson decays into two new Dark Sector, negative parity (Z_d), vector particles $H \to Z_d Z_d$, two new BSM spin-0 negative parity (α), pseudoscalar particles $H \to \alpha\alpha$, or a SM vector boson together with either a single Dark Sector Z_d or an α boson. The final search results were based upon recorded data of 139 fb^{-1} integrated luminosity in proton-proton collision data at $\sqrt{s}$ = 13 TeV center of mass energy by the ATLAS experiment in Run 2 at the LHC.

The first process described in the reference of the preceding paragraph is the exotic Higgs boson decay $H \to XX \to \ell^+\ell^-\ell'^+\ell'^-$, where X is either a Z_d vector boson or an α pseudoscalar boson, with a mass range of $15\,\text{GeV} < m_X < 60\,\text{GeV}$, and l refers to either a muon or electron with the charge indicated by the superscript. The exotic $H \to XX \to 4\mu$ decay process was described next, where $1\text{ GeV} < m_X < 15\text{ GeV}$. An $H \to ZX \to \ell^+\ell^-\ell'^+\ell'^-$ exotic Higgs boson decay search follows, where $15\text{ GeV} < m_X < 55\text{ GeV}$ was the third process in the previous paragraph. In these searches, the reaction $H \to Z_d Z_d$ proceeds theoretically via SM Higgs boson mixing with a BSM Dark Higgs. This mixing is parametrized by a mixing parameter κ [55–57] and given by the interaction lagrangian

$$L = \frac{1}{2}\,\kappa\,S^2\,|H|^2 \tag{2}$$

where S is a dark sector singlet scalar, and H denotes the SM Higgs doublet. The $H \to ZZ_d$ reaction on the other hand involves the kinetic mixing between the BSM Z_d vector boson and the SM Z boson with mixing parameter χ. Upper limits are also set on the branching ratio of the Higgs boson decays to Z_d Z_d and $\alpha\alpha$ as a function of intermediate vector boson mass, for gluon-gluon fusion production of SM Higgs bosons along with prompt Z_d /α boson decays.

The ATLAS collaboration used these results to provide constraints on dark Higgs boson–SM Higgs boson mixing parameter κ, and the kinetic mixing parameter χ of the Z-Z_d interaction, along with the mass mixing parameter δ [55,58]. Each case presumes the Hidden Abelian Higgs Model (HAHM) [56] is introduced at the Higgs portal level. The limits provided in the most recent analysis outperformed those in the prior publications [59,60].

Furthermore, the CMS collaboration reported on a generic search for di-lepton resonances in Higgs boson decays to the four-lepton final state [61]. The two decay topologies $pp \to H \to ZX$ and $pp \to H \to XX$ resulting from the proton-proton collisions were explored in the search. Substantial limitations on model-independent branching fractions and model parameters of these two well-motivated BSM models were set with no major deviation from SM expectations in the study. Analyses were carried out on products of model independent branching fractions B($H \to ZX$), B($H \to XX$), and B($X \to$ ee or $\mu\mu$), assuming flavor-democratic decays of X to di-muons and di-electrons, along with exclusive decays of X to di-muons, and exclusive decays of X to di-electrons. The search also provided unique constraints on the Higgs-mixing parameter $\kappa < 0.004$ in a dark photon model with the XX selection, in Higgs-mixing-dominated scenarios, while searches for Z_d in Drell-Yan processes provided better exclusion limits on χ in kinematic-mixing-dominated scenarios. A further search was carried out by the CMS collaboration for a Higgs boson that is created in conjunction with a Z boson and decays to an undetected particle and an isolated photon [53] with an integrated luminosity of 137 fb^{-1} at a center-of-mass energy of 13 TeV at the LHC. No substantial excess of events compared to the SM background was found. This translated into an observed (expected) upper limit on the branching fraction of 4.6 (3.6)% at 95% confidence level for a mass of 125 GeV, assuming the SM production cross section.

The CMS collaboration [62] also used a data sample corresponding to an integrated luminosity of 35.9 fb^{-1} of proton-proton collisions at the same center-of-mass energy in a model agnostic search for new light bosons decaying into muon pairs. The search was carried out over a range of new light boson masses from 0.25 GeV to 8.5 GeV. No significant deviation from the expected background was found.

The ATLAS collaboration at the LHC carried out a search for the production of displaced dark-photon jets also at $\sqrt{s}$ =13 TeV, collision energy with 36.1 fb^{-1} integrated luminosity [63]. No significant excess of events were seen as compared to the background expectation at 95% confidence level upper bounds on the production cross section times branching fraction. In comparison to previous ATLAS searches using 7 and 8 TeV pp center of mass collision data [64,65], dark photon decays were excluded at 95% confidence level for $c\tau \in [1.5, 307]$ mm and $c\tau \in [3.7, 178]$ mm for production of two and four dark photons, respectively. An additional search for light (approximately 1 GeV mass) bosons that decay to collimated lepton jets using used 20.3 fb^{-1} of integrated luminosity and pp collisions with an eight TeV center-of-mass energy was conducted by the ATLAS collaboration [66]. This ATLAS search showed no statistically significant deviation from SM predictions and set 95% confidence level upper limits on the contribution of (model dependent) beyond the SM phenomena. Results interpreted in terms of a 90% confidence-level exclusion region were also obtained in kinetic mixing and dark-photon mass parameter space, results that extended beyond the reach of prior searches.

A search for BSM long-lived particles decaying into two muons of opposite-sign electric charge was implemented by the ATLAS collaboration with pp collisions at center-of-mass energy of $\sqrt{s}$ =13 TeV and an integrated luminosity of 32.9 fb^{-1} [67]. There is no substantial excess in the number of vertices in either signal region as compared to the predicted background. As a result, upper limits at 95% confidence level on the product of cross section and branching fraction were calculated, as a function of lifetime, for production of long-lived particles in either a dark-sector model with dark-photon masses in the range 20–60 GeV, produced from decays of the Higgs boson, or in a general gauge-mediated SUSY model with a gluino mass of 1100 GeV and neutralino masses in the range 300 GeV–1000 GeV.

Data gathered by the CMS collaboration [68] at pp collision energy of $\sqrt{s} = 8$ TeV, also was used in a search for Long-Lived particles (LLPs) that decay to a final state containing a pair of electrons or a pair of muons. No similar events were observed. A CMS search for a narrow resonance decaying to a pair of muons was also done at $\sqrt{s} = 13$ TeV pp collision energy with an integrated luminosity of 137 fb^{-1} [69]. The search was made for resonance mass ranges of 45 GeV–75 GeV and 110 GeV–200 GeV

Using pp collision data recorded by the CMS experiment at $\sqrt{s} = 13$ TeV, a search for a narrow resonance decaying to a pair of muons has been presented. Fully reconstructed data containing a pair of muons with transverse momenta greater than 20 and 10 GeV, corresponding to an integrated luminosity of 137 fb^{-1}, was utilized to . Data collected with high-rate di-muon triggers yielded an integrated luminosity of 96.6 fb^{-1}, which was used to search for resonances in the mass range of 11.5 GeV–45.0 GeV. In the mass ranges of about 30 GeV–75 GeV and 110 GeV–200 GeV, the search had yielded the lowest upper bounds on the kinetic mixing coefficient of a dark photon to date.

At a center-of-mass energy of 13 TeV, searches for prompt as well as long-lived dark photons created in pp collisions were conducted by the LHCb collaboration at 13 TeV center of mass energy [70]. Each of the searches used a data sample size of 5.5 fb^{-1} integrated luminosity during the period 2016–2018. The focus was on $Z_d \rightarrow \mu^+\mu^-$ decays. No evidence for a signal was detected in either search, and 90% confidence level exclusion regions were placed on the Z-Z_d kinetic mixing strength. The prompt search produced the most rigorous restrictions on dark photons from near the di-muon threshold up to 70 GeV. The long-lived search was limited to the mass range between 214 and 350 MeV, where the data sample had sensitivity, and placed world-leading limitations on low-mass dark photons with O(1) ps lifetimes. The results provided substantially improved sensitivity to dark photons than the previous LHCb results [71], mainly due to increased integrated luminosity than before, and improved analysis techniques.

Collider are a unique tool to probe dark sector searches. For one they enable searches for dark matter and other BSM particles with masses at and above the GeV threshold. Colliders at the energy frontier also provide use of the Higgs boson as a window to the dark sector via its potential couplings to dark sector phenomena.

5. Dark Sector Searches in Space

Where colliders can constrain dark matter candidates at higher masses, astrological observations can yield insights at the other end of the mass spectrum. Axions [72] are theorized light, weakly interacting, pseudo scalar bosons that are a candidate Dark Matter particle.

Theoretical work by P. Sikivie [73,74] demonstrates that in the presence of sufficiently strong magnetic fields axions can convert into radio-frequency photons. Conditional on the axion's existence, one can then expect to detect a nearly monochromatic radio frequency signature in the vicinity of strong magnetic fields, as for example created by neutron stars. The frequency of that signature is then solely determined by the axion mass.

Detection of cosmic radio-frequency EM radiation inevitably comes with more challenging backgrounds compared to laboratory-based axion searches using haloscopes. However, is has been recently shown that the strong magnetic field on the order of 10^{11} T still makes neutron stars competitive and promising candidates for detection of axion particles [75,76]. In addition, they are massive compared to most other astrophysical objects and are therefore expected to attract large amounts of axions. An analysis looking for signals of axion-photon conversion in the magnetospheres surrounding two neutron stars and at the center of the Milky Way galaxy has recently been accomplished [77]. The analysis was able to set constraints on the existence of axion DM at the 95% Confidence Level in the mass range from 5 to 11 μev, corresponding to radio frequencies range 1.1 to 2.7 GHz and including the strongest constraint to date in the mass range of 10 to 11 μev. No observation of axion signal were reported, but instead limits on the mass-dependent axion-photon coupling $g_{a\gamma}$ were by this analysis. These are stronger than the previous limits obtained from the CAST telescope at CERN by about one order of magnitude [78].

Searches for axion-dark matter have been broadened to also including axion-like particles [79] (ALPs), weakly interacting, pseudo scalar bosons even lighter than the predicted axion. These are predicted to be continually produced during and preceding supernovae. Conversion of such produced ALPs to photons photons in the Galactic magnetic field could then be detectable in the X-ray spectrum at photon energies above 10 keV. Betelgeuse is a red super-giant in earth's galactic vicinity that is expected to go supernova in the near cosmological future. Recent observations of Betelgeuse by the NuSTAR satellite telescope placed new limits at the 95% C.L. on the ALP-photon coupling in the range $g_{a\gamma} < (0.5 \sim 1.8) * 10^{-11}$ GeV^{-1} (which depends on model of the magnetic field model in that region of space) and on the ALP mass $m_a < (5.5 \sim 3.5) * 10^{-11}$ eV [80].

Another property of ALPs is that they can form domain walls or topological defects. The typical size of these regions can be much bigger than planetary scales, but small enough that Earth crosses them on human time scales. In such a scenario the crossing between domains should be detectable, for example, via the ALPs ability to interact with atomic spins. The GNOME collaboration operates a suitable network of spin-based magnetometers that is capable to detect such domain crossings. It recently published [81] a search for signals consistent with domain walls crossing using more than dozen globally distributed optical magnetometers covering a month long data taking period, during which no domain crossings were detected though.

6. Dark Sector Searches Using Low Energy Photons

Additional regions of BSM Dark Sector phase space are accessible in experiments that make use of low energy probes such as laser and microwave photon experiments. These benefit from electron-volt to sub-electron-volt energy probes, play an important and prominent role in Dark Sector searches [10,12–14,16–22,82]. Additionally they allow for better control of backgrounds and noise than collider based experiments and astrophysical observations.

There have been several experiments that collected data in this search for Dark Sector signatures even given the small mixing parameter or coupling strength with SM fields in the low energy range: GammeV [83], BMV [84], OSQAR [85,86], and PVLAS [87] are recent examples. These first three of these experiments are based upon the technique of "light shining through a wall" (LSW) due to photon regeneration [15,88]. In these (proposed) processes laser light impinges upon a wall that it cannot penetrate. Only the weakly interacting, small mass, BSM particles that are the result of photon regeneration could penetrate the barrier ("wall") and give rise to a regenerated photon signal. In addition, vacuum oscillations of photons (γ) into dark-sector or Dark Sector photons (γ_d) with masses that are less than an electron-volt can produce detectable regeneration rates in a carefully designed experiment [10]. In addition to predictions about Dark Sector photons (vector bosons), predictions that the effect of BSM scalar (spin-zero) bosons exist in theories of particle physics as well as cosmology [10,89].

Chameleon particles are a candidate for a class of scalars whose mass depends on their environment [19]. If they are created in the vacuum vessel of the experiment by photons passing through a magnetic field, they will be trapped in the vessel due to energy conservation. They may be reconverted back into photons via coupling to the magnetic field, even when the photon source is turned off, giving an afterglow that is a smoking gun for these kinds of particles [90]. A recent analysis by the XENON1T experiment [91] found slight evidence for chameloen-screened dark energy at the 2σ level. This is currently providing renewed impetus in the search for chameleons of solar origin.

The groups referred to above searched for evidence of photons coupling to light, neutral pseudo-scalar bosons as well. See a sketch of the LIPSS collaboration experimental setup, for example, in Figure 1 The searches for the scalar coupling of photons to a hypothetical light neutral boson (LNB) in a regeneration experiment are similar in the experiments referenced here. Previous LIPSS results in the search for pseudo-scalar couplings to photons had already been reported by the BMV collaboration, and as carried out originally by the BFRT collaboration [92]. First results in searches for both scalar and pseudo-scalar couplings to photons in the same region of coupling-versus-mass parameter space were reported by the GammeV collaboration at FNAL and by the OSQAR collaboration at CERN. The limits, see [93] were augmented with the results from the CAST collaboration [94] where searches for solar produced axions (light, weakly interacting, pseudo scalar bosons) using the photon regeneration technique. New limits were placed on the possible existence of dark matter halo axions in the galaxy, as well as constraints on BSM couplings and masses from tests of the gravitational inverse-square law.

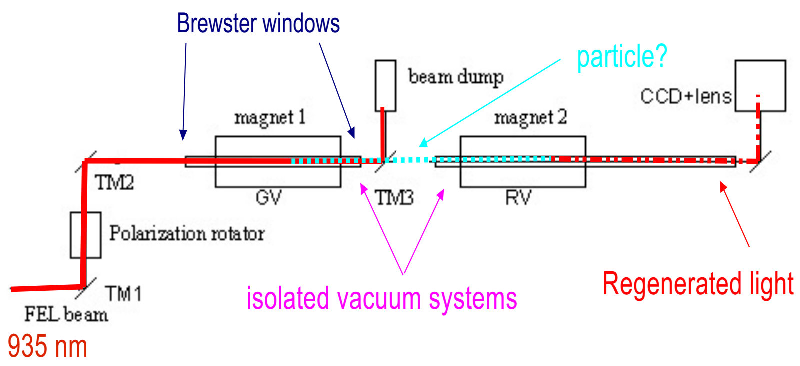

Figure 1. The LIPSS photon regeneration ("light shining through a wall") experimental setup at Jefferson Laboratory.

7. Microwave Cavity Search for Dark Sector Phenomena

Here, achievable fields of a few Teslas are many orders of magnitude smaller than around stellar bodies. However if a microwave cavity is placed in the interaction region, when the produced photon frequency is resonant with a mode of the cavity, the signal power is enhanced. This, together with state of the art amplification techniques, can more then compensate for the reduced magnetic field strength. As the axion mass is not known, the resonant frequency of the cavity must be swept to search for possible converted photons. This method has been used to constrain the axion-photon interaction strength for masses between 1 and 3 μeV, with plans to search up to 12 μeV.

The experiments and collaborations that are most sensitive to axion detection using this approach are (i) ADMX that made use of a microwave cavity, a high field solenoid magnet, along with quantum electronics [95], and (ii) HAYSTAC which employs a microwave cavity search for cold dark matter (CDM) axions with masses above 20 μeV [96] using new quantum sensor techniques.

Prior to the work in the experiment described here, the microwave cavity method had not been applied to look for axions of higher mass in the 0.1 meV–1.0 meV range. It was important to search for axions in this mass range in order to cover new regions of parameter space; the QCD axion is constrained to have mass roughly between 1 μeV and 1 meV. Presented here is the first microwave cavity search for dark matter ALPs with mass m_a = 140 μeV. The experiment measured the power in the Ka-band frequency range from the TM020 mode of a cryogenicaly cooled cavity in a 7 Tesla background magnetic field. HEMT amplifiers were employed to decreased the system noise-temperature to approximately 20 Kelvin. Data was taken for six months and the microwave cavity resonant frequency was swept from 33.9 GHz to 34.5 GHz, which is a hypothetical axion mass range of 140.2 μeV–42.7 μeV. No statistically significant signals were observed. Upper bounds on the photon coupling to axions, $g_{\gamma\gamma}$, of less than 8.75×10^{-11} GeV^{-1}, was set, marginally improving on the previous best limit obtained from the CAST experiment [97]. With the same data set new limits were obtained on dark photon-photon interactions of $\chi < 10^{-10}$, significantly improving upon previous bounds. In conclusion, as with the first generation of microwave cavity experiments that searched for axions in the μeV mass range, there were several technical challenges that had to be overcome in order to reach the sensitivity to observe or exclude canonical axion models. However, since the axion mass is not known a priori, a search for them in the entire possible mass range is valuable. If observed, axion (and ALP) dark matter would not only represent an important advance in our knowledge of dark matter but also provide clues about processes at high energy scales inaccessible to collider experiments.

Among the accomplishments and results from this experimental effort are: 1. The first narrow-band search for axions, axion-like particles, and dark sector photons in the mass range around 0.1 milli-electron volt mass, part of the region favored for Cold Dark Matter. 2. The first cryogenically-cooled, tune-able, radio-frequency cavity operated at Ka band frequencies used in these searches. 3. New limits were set on coupling parameters that had never been achieved previously.

Experimental Apparatus and Overview

The apparatus consisted of a tunable resonant oxygen-free copper cavity (Q $\sim 10^4$), a HEMT cryogenic amplifier located at the bottom of a vertically oriented cold gas cryostat that is cooled to approximately 4 K, and coupled by a few centimeters of WR28 waveguide. The cryostat was positioned inside the vertical bore of a solenoidal cryogenic magnet, see Figure 2.

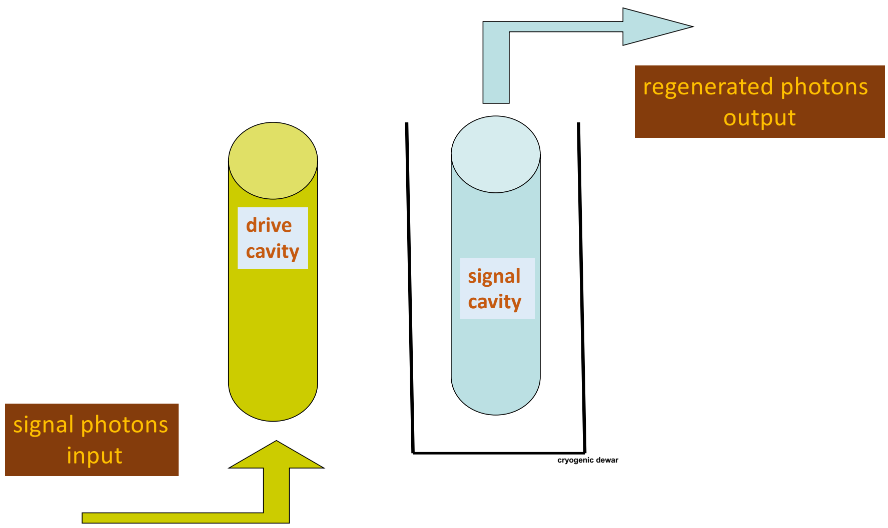

Figure 2. The experimental setup on the Yale University campus. Microwave photons from the signal generator are directed into the copper resonant cavity (drive cavity) as shown. No incident photons pass through the walls of the drive cavity. An identical copper cavity (the signal cavity) sits inside the liquid helium cooled cryogenic Dewar separated from the drive cavity.

A separate gas-flow cryostat from Cryo Industries housed the cavity and cryogenic amplifier assembly. This cryostat was situated in the bore of the magnet, with an inner diameter of 39.88 mm (1.57 inches), and offset from the bore center so that there was enough space for a second cavity to be placed in the bore but outside of the cryostat. For a sketch of the components placed inside the cryostat, see Figure 3.

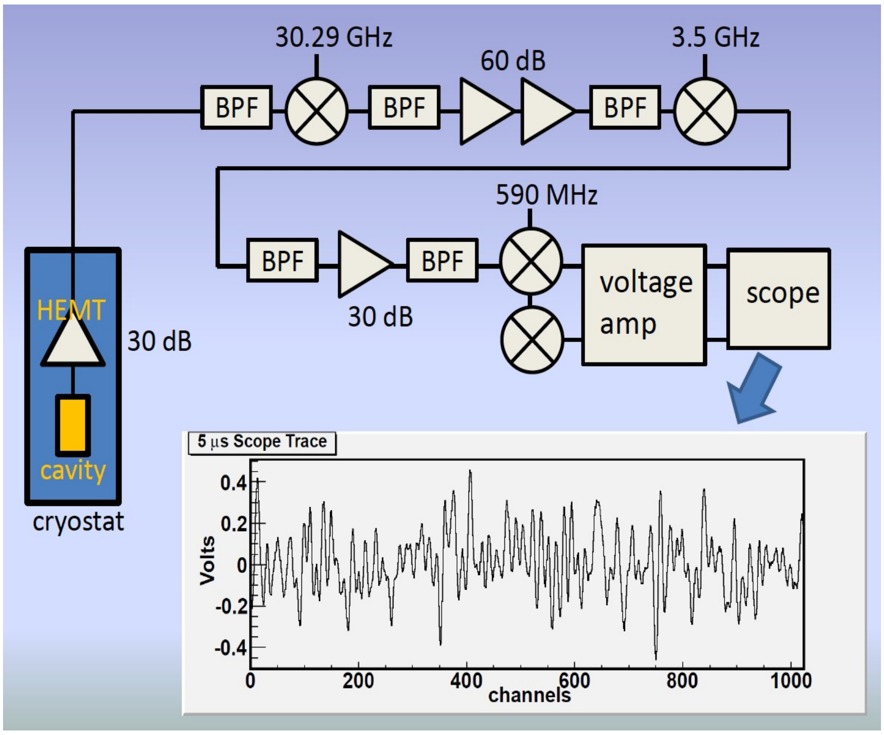

Figure 3. A schematic of the experimental setup on the Yale University campus. The copper cavity is held at cryogenic temperature (4 K liquid helium) inside a seven Tesla magnetic field. The signal from the cavity, resonant at 34 GHz, is fed into a HEMT, the LNA, who's output feeds into the sensitive receiver chain shown. The latter uses a triple heterodyne technique to translate the 34 GHz signal down to the audio range, suitable for acquisition and storage, and later analysis.

The experiment monitored the power in the transverse magnetic TM020 mode; the oscillating electric field creates currents that run vertically; hence it is important to have good contact between the cap and the cavity body. The bottom cap therefore has a knife-edge on the surface to ensure good electrical contact. The form factor was shown to be a decreasing function of the mode index n for the TM0n0 modes. This would imply that it is favorable to work in the lowest order TM010 mode. However, the full expression for the signal power depends not only on the form factor, but also the volume and quality factor. Even though the form factor is smaller for higher order modes, for two modes at the same frequency the volume will be larger for the higher order mode. The cavity resonance frequency is adjusted by vertically inserting a dielectric rod into the cavity. This perturbs the fields, with the net effect being that the resonance frequency decreases. This is the same technique as used by the first dark matter axion searches using microwave cavities. This tuning method is straightforward but also degrades the form factor as the rod insertion depth increases, due to mode localization. This limits the tuning range one can access with a single rod. The ADMX experiment achieves a wide tuning range by using a combination of metal and dielectric posts and moving them sideways; for the frequency range covered in this work, the vertical insertion method did not measurably degrade the form factor and so was deemed an acceptable solution. Results of the sensitivities achieved in this microwave cavity setup can be found in [98–100].

8. Summary

This year (2022) registers the submission of the current article for publication and also marks the 10th anniversary of the Higgs boson discovery. It is a new particle that, unlike any other in the SM, may provide a portal to new phenomena, including, possibly, Dark Sector particles and fields (if the particle physics picture of the interactions is valid). In this article, descriptions have been presented about how this new particle physics tool can be used in such a search. Moreover, it has been shown that new, powerful technology advances and innovative thinking and analysis techniques by researchers can also improve searches for fundamental new Dark Sector particles and their properties. An extensive, but not comprehensive, listing and explanation of these research activities includes Dark Sector searches at the Energy Frontier (the LHC at CERN) in particle physics, in astrophysical inquiries carried out in space, at fixed target experiments carried out with mainly medium energy probes, and also at low energies using laser and microwave photon probes to search for indications of new interactions and particles. The latter included photon regeneration experiments (the so called "light shining through a wall" technique) and cryogenic magnets along with cavities. To date, no conclusive sighting of Dark Sector particles has been achieved, even though the phase space covered in such searches continues to increase with each new experiment. This is an exciting field of study for both theorists and experimentalists that may very likely continue for the foreseeable future!

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