PROCEEDINGS OF SCIENCE

Dark Sectors - Theory review

Daniele Barducci

Dipartimento di Fisica "Enrico Fermi", Università di Pisa and INFN Section of Pisa, Largo Bruno Pontecorvo 3, I-56127 Pisa, Italy

E-mail: daniele.barducci@pi.infn.it

The framework of *portal interactions* between the Standard Model and a hypothetical invisible sector has gained renewed attention in recent years, with particular focus on light beyond the Standard Model states, which are ideal candidates to be tested at high-intensity experiments. In this contribution we review three main portals between the Standard Model and the invisible sectors: the dark photon portal, the sterile neutrino portal and the dark Higgs portal. After introducing their main characteristics we review current exclusions and projected limits on these theories, highlighting the existing complementarity between high-intensity and high-energy experimental probes.

Workshop Italiano sulla Fisica ad Alta Intensità (WIFAI2023)
8-10 November 2023
Dipartimento di Architettura dell'Università Roma Tre, Rome, Italy

https://pos.sissa.it/

PoS(WIFAI2023)008

1. Introduction

The Standard Model (SM) of particle physics is a remarkably successful theory, able to explain a pletora of experimental measurements down to a length scale of $O(10^{-19})$ m, which is currently being tested at the Large Hadron Collider (LHC) through multi-TeV pp scatterings. Despite its enormous successes, the SM is so far unable to explain three observational evidences that require it to be embedded in a more complete theory: *i)* the non vanishing masses of at least two of the three neutrinos *ii)* the observed matter-antimatter asymmetry *iii)* the existence of dark matter (DM) and dark energy, making up $\sim 25\%$ and $\sim 70\%$ of the Universe energy budget respectively.

As far as DM is concerned, one of the most popular candidates is a massive particle in thermal equilibrium with the SM plasma in the early Universe, which then undergoes thermal freeze-out at a temperature T close to its mass. The observed DM relic abundance $\Omega h^2 \sim 0.120 \pm 0.001$ [1] is reproduced for a value of the thermally averaged cross-section $\langle \sigma v \rangle \simeq 1$pb. Further assuming that this state interacts with the SM via electroweak (EW) interactions fixes its mass m_χ and couplings strength $g_\chi = \sqrt{4\pi\alpha_\chi}$ to satisfy

$$\langle \sigma v \rangle \simeq 1 \text{ pb} \left(\frac{\alpha_\chi}{10^{-2}}\right)^2 \left(\frac{\text{TeV}}{m_\chi}\right)^2 . \tag{1}$$

Eq. (1) is the well-known weakly interacting massive particle (WIMP) miracle relation, which states that a TeV scale DM particle with EW strength interactions provides the correct relic density. For DM masses lighter than the EW scale Eq. (1) gets modified to

$$\langle \sigma v \rangle \simeq 1 \text{ pb} \left(\frac{m_\chi}{3 \text{ GeV}}\right)^2 , \tag{2}$$

which implies that the smaller m_χ is, the larger is the DM abundance, up to the point that for $m_\chi \lesssim$ GeV the DM turns out to be overproduced. This lower limit is known as the Lee-Weinberg bound [2]. It can, however, be evaded by postulating the DM to interact with the SM fields via a new beyond the SM (BSM) state. For example, by assuming the existence of a new spin-1 singlet mediator Z'_μ whose interaction strengths with SM and DM fields are g_f and g_χ respectively, one has

$$\langle \sigma v \rangle \simeq 1 \text{ pb} \left(\frac{g_\chi}{0.5}\right)^2 \left(\frac{g_f}{0.001}\right)^2 \left(\frac{m_\chi}{100 \text{ MeV}}\right)^2 \left(\frac{1 \text{ GeV}}{m_{Z'}}\right)^4 , \tag{3}$$

which implies that the observed relic density can be reproduced with a light DM particle if the mediator is a light BSM state.

Relaxing the assumption on the nature of the mediator, naturally leads to framing the discussion in terms of *portal interactions* between the SM and the dark sector, to which the DM particle belongs but which can comprise more states that the DM alone. The *portal framework* is given by the following generic setup. Let O_{SM} and O_{DS} be two operators built solely from SM and dark sector fields respectively. The portal framework combines them as

$$\mathcal{L} = \sum O_{\text{SM}} \times O_{\text{DS}} , \tag{4}$$

where the sum goes over various possibile operators with different mass dimensions and built from different fields. Typically, one categorises the portals in terms of their mass dimension. Restricting to mass dimensions $d = 4$ the number of possibilities is extremely limited and one has only the following options

- **Vector portal**: $\mathcal{L} \supset \epsilon B^{\mu\nu} A'_{\mu\nu}$
- **Fermion portal**: $\mathcal{L} \supset y_N LHN$
- **Scalar portal**: $\mathcal{L} \supset (\mu_S S + \lambda_S S^2) H^\dagger H$

where A'_μ, N and S are BSM vector, fermion and scalar fields respectively, total singlet under the SM gauge group[1]. We'll now discuss the three $d = 4$ portals in turn, highlighting the main experimental signatures that can be searched for at low-energy experiments up to multi-TeV colliders.

2. Vector portal: the dark photon

The idea of an additional gauge boson arising from a new $U(1)$ local symmetry goes back to the 1980s [3]. In its minimal setup the theory is described by

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} A'^{\mu\nu} A'_{\mu\nu} + \frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - \frac{1}{2} A'_\mu A'^\mu \,, \tag{5}$$

where the UV origin of the A'_μ mass is left unspecified. Massless dark photons do not interact with the SM fields at the $d = 4$ level [4], while massive dark photons might be a DM candidate themselves if light and produced non thermally [5, 6] or if produced during inflation [7, 8]. In the massive case, after diagonalising the interaction of Eq. (5), the dark photon inherits universal couplings to the SM fields with a coupling strength proportional to their electric charge Q_f

$$\mathcal{L} = -\epsilon e A'_\mu \sum_f Q_f J^\mu_f \,, \tag{6}$$

where J^μ_f is the electromagnetic current and e the elementary electric charge. Dark photons can thus be produced in the same way as ordinary photons. The simplicity of the dark photon parameter space, described in its minimal incarnation by only two parameters ($m_{A'}$ and ϵ), makes this model an ideal framework to design experimental searches. Postulating extra interactions with states belonging to the invisible sector, for example a coupling of the dark photon with a DM particle, adds additional parameters and new decay channels for the dark photon. Crucially, the dark photon experimental search strategies depend on its decay modes. With the electron being the lightest charged SM state, a natural threshold is $m_{A'} \sim 1$ MeV, which divides the decay regime between visible and invisible decay modes. As regarding the dark photon production mechanisms, we can divide them among high-intensity beam-dump experiments, where bremsstrahlung and SM meson decays allow to test light dark photons and small kinetic mixings ϵ, and collider experiments, probing higher masses and higher ϵ values. A summary of current limits and future prospects for the case of visible and invisible dark photons is shown in Fig. 1, taken from [9], where one can see the interplay between high- and low-energy experiments, covering different portions of the dark photon parameter space.

---

[1] Allowing for operators of higher mass dimensions, of particular interest is the case of the axion portal $\mathcal{L} \supset a/f F_{\mu\nu} \tilde{F}^{\mu\nu}$, due to its relation with the resolution of the strong CP problem.

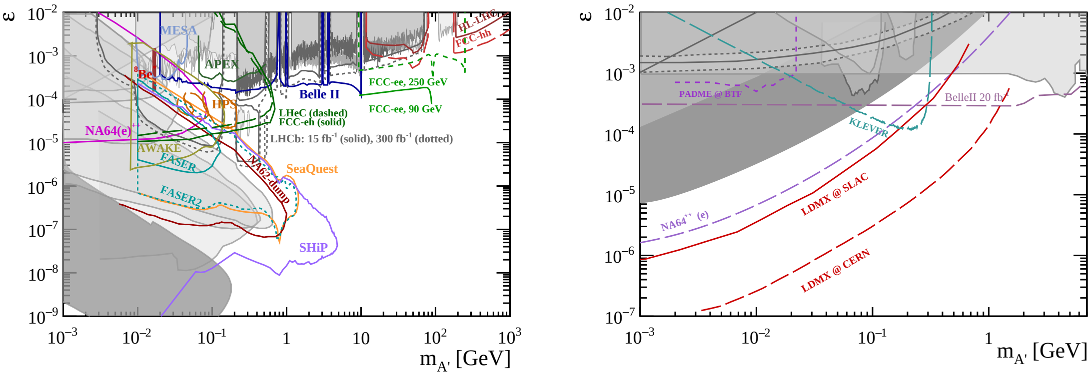

Figure 1: Existing exclusions (shaded gray areas) and projected limits (colored lines) on the dark photon parameter space in the $m_{A'} - \epsilon$ plane for the case of visible (left panel) and invisible (right panel) decays. The figure is taken from [9].

3. Fermion portal: the sterile neutrino

The case of the fermion portal is of paramount interest since new SM fermion singlets can account for the observed non-zero SM neutrino masses via the see-saw mechanism [10]. The vanilla theory is described by

$$\mathcal{L} = \mathcal{L}_{\rm SM} - y_N LHN - \frac{1}{2} M N^2 + h.c.\,, \tag{7}$$

where we have added a Majorana mass term M for the sterile fermion N and the fermion fields are two components left-handed Weyl spinors. Upon diagonalization, Eq. (7) gives rise to two mass eigenstates with masses $m_N \sim M$ and $m_\nu \sim y^2 v^2/M$ respectively. The sterile neutrino N interacts with the SM fields thanks to a mixing with the active neutrino

$$\theta_{\nu N} \sim \frac{y_N v}{m_N} = \sqrt{\frac{m_\nu}{m_N}} \ll 1\,, \tag{8}$$

which is then suppressed by the smallness of the active neutrino mass. This implies a small production rate and a large decay length for N. For example, for $m_N < m_W$ the decay width into SM states proceeds via on off-shell W with a rate

$$\Gamma \simeq \frac{1}{192\pi^3} \theta^2_{\nu N} \frac{m_N^5}{m_W^4}\,, \tag{9}$$

which can imply a macroscopic decay length in laboratory experiments where the sterile neutrino is produced with energy E_N

$$L_{\rm lab} \simeq 5\ {\rm m} \left(\frac{\rm GeV}{m_N}\right)^6 \left(\frac{10^{-2}}{\theta_{\nu N}}\right)^2 \left(\frac{E_N}{10\ {\rm GeV}}\right)\,, \tag{10}$$

making the sterile neutrino portal the ideal dark sector prototype. Sterile neutrinos can be produced in all processes involving a SM neutrino, with a $\theta^2_{\nu N}$ rescaling of the rates. As for the dark photon case, in its simplest version the sterile neutrino portal is described by only two parameters[2]: m_N and $\theta_{\nu N}$. Current limits and projected exclusions for future experiments are shown in Fig. 2, taken from [11], for the case of exclusive mixings with the first and second lepton flavor generation.

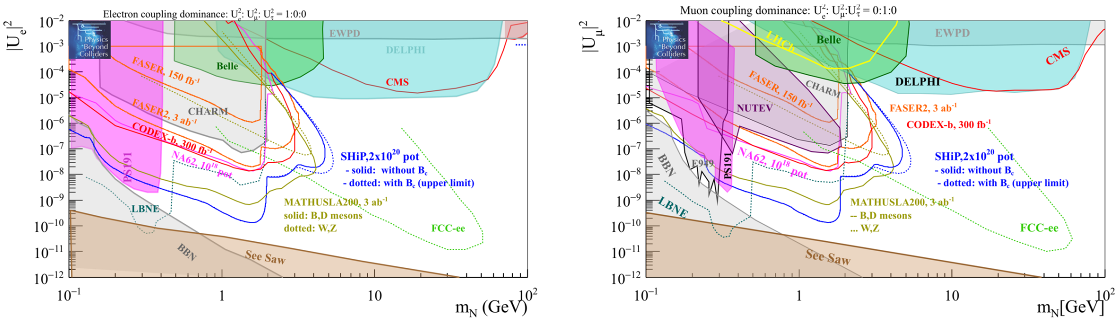

Figure 2: Existing exclusions (shaded colored areas) and projected limits (colored lines) on the sterile neutrino parameter space in the $m_N - \theta$ plane for the case of exclusive mixing with the first (left panel) and second (right panel) lepton flavor generation. The figure is taken from [11].

4. Scalar portal: the dark Higgs

Additional neutral scalar bosons are predicted by many extensions of the SM. At the renormalizable level their interactions are described by

$$\mathcal{L} = \mathcal{L}_{\rm SM} + (\mu_S S + \lambda_S S^2) H^\dagger H \,, \tag{11}$$

through which, after electroweak symmetry breaking, the new scalar S can mix with the SM Higgs boson h via a mixing angle

$$\theta_{hS} = \frac{\mu_S v}{m_h^2 - m_S^2} \,. \tag{12}$$

Despite the simplicity of this model, its phenomenology is extremely rich. The couplings of the Higgs boson to SM fields are universally rescaled by $\cos\theta_{hS}$, while the new scalar inherits coupling to the SM degrees of freedom proportional to the Higgs boson ones, with a $\sin\theta_{hS}$ rescaling. Moreover, depending on the mass hierarchy between h and S, new Higgs decay modes, $h \to SS$, or new di-Higgs production mechanisms, $S \to hh$, can be realized. For high m_S masses, the experimental targets are those typical of heavy Higgs searches performed at the LHC while, once again, in the case of a light S scalar the more relevant probes are high-intensity beam dumps experiments. Existing limits and future projections for sub-GeV dark scalars are shown in Fig. 3, taken from [12].

5. Conclusions

The indirect evidence for the existence of Dark Matter calls for an explanation. Among the various options, the concept of *portal interactions* between the Standard Model and a hypothetical

---

[2] Eq. (8) actually implies that there is only one free parameter. Theories with more than one sterile neutrino relax this relation and allows to treat m_N and $\theta_{\nu N}$ as independent parameters.

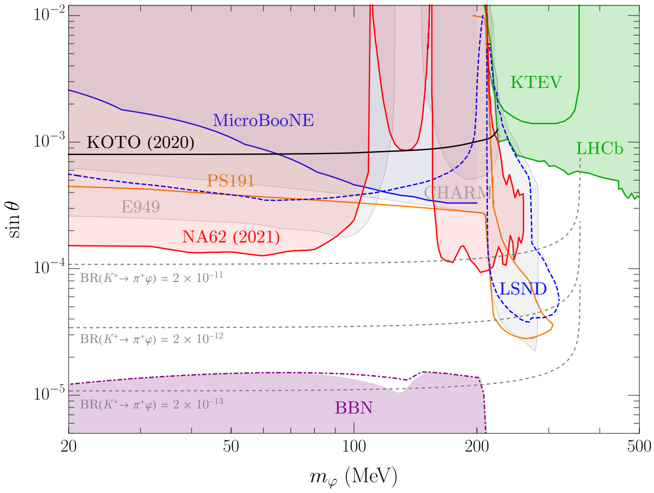

Figure 3: Existing exclusions (shaded colored areas) and projected limits (colored lines) on the dark scalar parameter space in the $m_S - \theta_{hS}$ plane. The figure is taken from [12].

invisible sector has gained renewed attention in recent years, with particular focus on light beyond the Standard Model states, which are ideal candidates to be tested at high-intensity experiments.

In this contribution we have reviewed the three main portals between the Standard Model and the dark sectors. These are the vector or dark photon portal, the fermion or the sterile neutrino portal and the scalar or dark Higgs portal. After introducing their main characteristics, we have reviewed current exclusions and projected limits on the parameter space of these theories. We have in particular highlighted the existing complementarity between high-intensity and high-energy experiments, which are able to cover different regions in the portals' parameter spaces. Crucially, these dark sectors theories will be deeply tested in the near future, possibly allowing the scientific community to shed light on one of the darkest mystery of our Universe.

References

[1] N. Aghanim *et al.* [Planck], Astron. Astrophys. **641** (2020), A6 [erratum: Astron. Astrophys. **652** (2021), C4] doi:10.1051/0004-6361/201833910 [arXiv:1807.06209 [astro-ph.CO]].

[2] B. W. Lee and S. Weinberg, Phys. Rev. Lett. **39** (1977), 165-168 doi:10.1103/PhysRevLett.39.165

[3] B. Holdom, Phys. Lett. B **166** (1986), 196-198 doi:10.1016/0370-2693(86)91377-8

[4] B. A. Dobrescu, Phys. Rev. Lett. **94** (2005), 151802 doi:10.1103/PhysRevLett.94.151802 [arXiv:hep-ph/0411004 [hep-ph]].

[5] A. E. Nelson and J. Scholtz, Phys. Rev. D **84** (2011), 103501 doi:10.1103/PhysRevD.84.103501 [arXiv:1105.2812 [hep-ph]].

[6] P. Arias, D. Cadamuro, M. Goodsell, J. Jaeckel, J. Redondo and A. Ringwald, JCAP **06** (2012), 013 doi:10.1088/1475-7516/2012/06/013 [arXiv:1201.5902 [hep-ph]].

[7] P. W. Graham, J. Mardon and S. Rajendran, Phys. Rev. D **93** (2016) no.10, 103520 doi:10.1103/PhysRevD.93.103520 [arXiv:1504.02102 [hep-ph]].

[8] Y. Nakai, R. Namba and Z. Wang, JHEP **12** (2020), 170 doi:10.1007/JHEP12(2020)170 [arXiv:2004.10743 [hep-ph]].

[9] M. Fabbrichesi, E. Gabrielli and G. Lanfranchi, doi:10.1007/978-3-030-62519-1 [arXiv:2005.01515 [hep-ph]].

[10] P. Minkowski, Phys. Lett. B **67** (1977), 421-428 doi:10.1016/0370-2693(77)90435-X

[11] J. Beacham, C. Burrage, D. Curtin, A. De Roeck, J. Evans, J. L. Feng, C. Gatto, S. Gninenko, A. Hartin and I. Irastorza, *et al.* J. Phys. G **47** (2020) no.1, 010501 doi:10.1088/1361-6471/ab4cd2 [arXiv:1901.09966 [hep-ex]].

[12] E. Goudzovski, D. Redigolo, K. Tobioka, J. Zupan, G. Alonso-Álvarez, D. S. M. Alves, S. Bansal, M. Bauer, J. Brod and V. Chobanova, *et al.* Rept. Prog. Phys. **86** (2023) no.1, 016201 doi:10.1088/1361-6633/ac9cee [arXiv:2201.07805 [hep-ph]].