Feebly-interacting particles: experimental landscape

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Abstract. Feebly-interacting particles represent an alternative paradigm with respect to the traditional strongly-coupled Beyond the Standard Model physics explored at the LHC and can provide an answer to many fundamental open questions in particle physics. This document presents the state of the art of searches for feebly-interacting particles at accelerator-based experiments including projects proposed at CERN and currently discussed in the European Strategy for Particle Physics update.

1. Introduction
Unknown particles or interactions are needed to explain a number of observed phenomena and outstanding questions in particle physics, astrophysics, and cosmology. While there is a vast landscape of theoretical models that try to address these puzzles, on the experimental side most of the efforts have so far concentrated on the search for new particles with sizeable couplings to SM particles and masses above the EW scale.

An alternative possibility, largely unexplored, is that particles responsible for the still unexplained phenomena are below the EW scale and have not been detected because they interact too feebly with SM particles. These Feebly-Interacting Particles (FIPs) would belong to an entirely new sector, the so-called hidden or dark sector.

While masses and interactions of particles in the dark sector are largely unknown, the mass range between the MeV and tens of GeV appears particularly interesting, both theoretically and experimentally. An important motivation for new physics in this mass range is Dark Matter (DM), which could be made of light particles, with either a thermal or non-thermal cosmological origin. Thermal DM in the MeV−GeV range with SM interactions is overproduced in the early Universe and therefore viable scenarios require additional SM neutral mediators to deplete the overabundance [1, 2, 3, 4, 5, 6, 7, 8, 9].

Accelerator experiments represent a unique tool to test models with light dark matter (LDM) in the MeV-GeV range, under the hypothesis that DM annihilates directly to SM particles via new forces/new dark sector mediators. The advantage of accelerator experiments is that the DM is produced in a relativistic regime, and therefore its abundance depends very weakly on the assumptions about its specific nature, while the rates can be predicted from thermal freeze-out.

In addition to the DM in the MeV−GeV range, accelerator based experiments can probe the existence of Heavy Neutral Leptons (HNLs) with masses between 100 MeV and ∼100 GeV in a range of couplings phenomenologically motivated and challenge the seesaw mechanism in the freeze-in regime.
2. The portal formalism

The mediators between LDM and SM, which must be singlets under the SM gauge symmetry, can lead to couplings of feebly-interacting particles to the SM fields through portal operators.

The portal operators considered in this document are the following:

| Portal          | Coupling                                                                 |
|-----------------|--------------------------------------------------------------------------|
| Dark Photon, $A_\mu$ | $-\frac{e}{2\cos \theta_W} F^\mu_\nu B^{\mu \nu}$                   |
| Dark Higgs, $S$  | $(\mu S + \lambda S^2) H H$                                            |
| Axion, $a$       | $\frac{a}{f_a} F^\mu_\nu F^{\mu \nu}$, $\frac{a}{f_a} G_{i \mu \nu} \tilde{G}^{i \mu \nu}$, $\frac{\partial_a a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$ |
| Sterile Neutrino, $N$ | $y_N LHN$                                                               |

Here, $F^\mu_\nu$ is the field strength for the dark photon, which couples to the hypercharge field, $B^{\mu \nu}$; $S$ is a new scalar singlet that couples to the Higgs doublet, $H$, with dimensionless and dimensional couplings, $\lambda$ and $\mu$; and $N$ is a new neutral fermion that couples to one of the left-handed doublets of the SM and the Higgs field with a Yukawa coupling $y_N$. These three cases are the only possible renormalizable portal interactions. While many new operators can be written at the non-renormalizable level, a particularly important example is provided by the axion (or axion-like) particle $a$ that couples to gauge and fermion fields at dimension five.

From the portal formalism, the Physics Beyond Colliders (PBC) Beyond the Standard Model (BSM) Study Group [10] has identified a set of benchmark physics cases that have been used to investigate experimental sensitivities of current and future experiments. In this document we briefly report the outcome of this study. It is worth noting that this formalism has been also used to evaluate the sensitivity to FIPs of future collider experiments, as described in the Briefing Book of the European Strategy for Particle Physics update [11], but the results of this investigation go beyond the scope of these proceedings.

3. Proposals at CERN and experimental sensitivities

Heavy neutral leptons, LDM and corresponding light mediators (dark photons, dark scalars, etc.) with masses in the MeV-GeV mass range can be searched for using the interactions of proton, electron and muon beams available (or proposed) at the PS and SPS CERN accelerator complex and at the LHC interaction points.

A multitude of experimental proposals has been presented within the PBC framework. A concise description of these projects has been discussed in Ref. [10] along with beam request, key requirements for the detectors, open questions, and feasibility studies. Here we simply list the main proposals, and in the following Section we will present their sensitivity to FIPs and put them into a worldwide landscape.

- **NA64**$-e$, **NA64**$-\mu$ @ SPS
  
  The NA64 is a hermetic general purpose detector to search for dark sector particles [12, 13] in missing energy events from high-energy ($\sim 100$ GeV) electrons, muons, and hadrons scattering off nuclei in an active dump. NA64 is currently taking data at the H4 beam line of the SPS [14, 15, 16]. The collaboration has collected about $3 \times 10^{11}$ electrons-on-target (eot), and aims at reaching $5 \times 10^{12}$ eot during Run 3.

  A new detector served by the M2 beam line and located in the EHN2 experimental hall in the CERN North Area is proposed to investigate dark sector predominantly coupled to the second and third generation and Lepton-Flavor-Violating (LFV) $\mu - \tau$ conversion with a high energy muon beam. The M2 line, currently serving the COMPASS experiment, is able to provide muons with momentum of $\sim (100 - 160)$ GeV/c, and intensity up to $\sim 10^8 \mu$/spill.
- **NA62-dump @ SPS**
  NA62 [17] is a fixed target experiment at the CERN SPS with the main goal of measuring the BR of the ultra-rare decay $K^+ \rightarrow \pi^+\nu\bar{\nu}$ with 10% precision. It is currently taking data at the K12 beam line at the CERN SPS. NA62 proposes to integrate $\sim 10^{18}$ pot operating the detector in dump mode for few months during Run 3 [18].

- **SHiP @ SPS**
  The SHiP project [19] proposed to run at the Beam Dump Facility (BDF) [20] is a proton beam dump experiment aiming at testing a wide variety of models [21] containing feebly-interacting particles with masses below $\mathcal{O}(10)$ GeV with unprecedented sensitivity, via either visible decays of hidden sector mediators, or via direct detection of LDM through its scattering with the detector medium. The BDF, if approved, can provide $2 \times 10^{20}$ 400 GeV protons on target (pot) in five years of operation.

- **LDMX @ eSPS**
  The Light Dark Matter eXperiment (LDMX) [22] aims to probe DM parameter space far below expectations from the thermal freeze-out mechanism by exploiting the missing-momentum technique in a fixed-target experiment with a primary electron beam of modest GeV-range energy, low current and high duty-cycle. A high-intensity primary electron beam can be provided via an X-band linac that could accelerate electrons to 3.5 GeV and fill the SPS in 1-2 sec. The beam could be further accelerated up to 16 GeV by the SPS and then slowly extracted to serve the LDMX detector.

- **CODEX-b @ LHC**
  The CODEX-b detector [23] is proposed as a new, shielded subdetector for LHCb to be placed in what is currently the LHCb data acquisition room, 25 m away from the LHCb interaction point (IP). CODEX-b plans to accumulate 300 fb$^{-1}$ of integrated luminosity starting in Run 5.

- **MATHUSLA @ LHC**
  The MATHUSLA proposal, as discussed in the Letter of Intent [24] and in Refs. [25, 26], is a very large $(200 \times 200 \text{ m}^2)$ area detector (MATHUSLA200) built on the surface, situated 100 m horizontally and vertically away from a LHC interaction point (IP) (either ATLAS or CMS IP), and a decay volume height of 20 m above the ground. It aims at collecting an integrated luminosity of 3 ab$^{-1}$ corresponding to the full HL-LHC period, with a hypothetical start of the data taking during Run 4.

- **FASER @ LHC**
  FASER will be located 480 m downstream from the ATLAS IP in service tunnel TI12 in time to collect data during Run 3. FASER’s cylindrical active decay volume has a radius $R = 10$ cm and length $L = 1.5$ m. If FASER is successful, a larger version, FASER2, with an active decay volume with $R = 1$ m and $L = 5$ m, could be installed during LS3 and take data in the HL-LHC era.

4. **Experimental sensitivities**

The physics reach of these proposals has been evaluated using benchmark cases which are strictly connected to the portals. These benchmark cases do not pretend to be exhaustive but only to provide a common ground to compare sensitivities of different experiments. They should be considered as the starting point towards a comprehensive investigation of hidden sector models in the MeV-GeV mass range to be performed in the future. The results are shown in this section as 90% CL exclusion limits and compared to the existing bounds and the physics reach of other similar initiatives proposed worldwide in the same timescale.
4.1. Benchmark cases connected to the Vector Portal

New light vector particles mixed with the photon are not uncommon in BSM models containing hidden sectors, possibly related to the DM problem. The parameters describing this class of models are $\epsilon$, $\alpha_D$, $m_{A'}$ and $m_\chi$, where $\epsilon$ is the mixing parameter between the dark and ordinary photon; $\alpha_D = g_D^2/4\pi$ is the coupling strength of the dark photon with DM; and $m_{A'}$ and $m_\chi$ are the dark photon and DM particle mass, respectively. The study of experimental sensitivities can be performed either in the plane of $\epsilon$ versus $m_{A'}$ (assuming $\alpha_D$ to be negligible with respect to $\epsilon$) and in the $y$ versus $m_\chi$ plane, where the yield variable $y = \alpha_D \epsilon^2 (m_\chi/m_{A'})^4$ is argued to contain a combination of parameters relevant for the freeze-out and DM-SM particles scattering cross section.

In the latter case, the yield variable $y$ can be put in direct connection to the DM thermal relic abundance. In fact, the direct DM annihilation responsible of the thermal relic abundance, is driven by the same couplings that define the direct DM scattering, leading to rather well defined predictions: $\langle \sigma \cdot v \rangle \sim y/m_\chi$. The measured DM abundance imposes a minimum bound on this cross-section, $\langle \sigma \cdot v \rangle_{\text{relic}}$. This lower bound can be translated in turn into a lower bound on the strength of the SM-mediator and DM-mediator couplings, and, as a consequence, opens up the possibility to link results obtained at accelerator-based experiments to those coming from DM direct detection experiments, depending on the nature of the DM candidate.

Figures 1 and 2 show the current bounds and future prospects in the plane $\epsilon$ versus $m_{A'}$ for experiments included and not included in the PBC activity, respectively. Visible decays of vector mediators are mostly constrained from searches for di-electron or di-muon resonances, and re-interpretation of data from fixed target or neutrino experiments in the low ($< 1$ GeV) mass region: NA48/2 [27], A1 [28] and BaBar [29] experiments put the strongest bounds for $\epsilon > 10^{-3}$ in the 0.01 – 10 GeV mass range. These results are complemented by those from beam dump experiments, such as E141 [30] and E137 [31, 32] at SLAC, E774 at Fermilab [33], CHARM [34, 35] and NuCal [36].

The low-mass range (0.01 – 1 GeV) is best covered by beam-dump experiments (SHiP [19], NA62 in dump mode [37]), and by FASER at the ATLAS interaction point [38], in the very low-coupling regime ($\epsilon < 10^{-4}$). These are complemented by the LHCb Upgrade [39] and Belle-II [40] in a slightly higher mass range (1-10 GeV).

The current bounds and future perspectives in the plane ($m_\chi, y$) are shown in Fig. 3 under the hypothesis that DM is a Pseudo-Dirac fermion. Future initiatives that could explore a still uncovered parameter space for DM masses below 1 GeV are all those who have sensitivity in the plane ($\epsilon, m_{A'}$) and, in addition, experiments exploiting DM scattering with nucleons and/or electrons, both accelerator-based and from direct detection searches. Among the accelerator-based experiments, there are BDX at JLab [41], MiniBooNE at FNAL [42] and COHERENT at ORNL [43]. PBC projects able to put bounds on the $y$ versus $m_\chi$ plane are NA64–e and, on a longer time scale, LDMX and SHiP.

4.2. Benchmark case connected to the Scalar Portal

In the scalar or Higgs portal, the dark sector is coupled to the Higgs boson via the bilinear $H^\dagger H$ operator of the SM. The minimal scalar portal model operates with one extra singlet field $S$ and two types of couplings, $\mu$ (or $\sin \theta$) and $\lambda_{HS}$ [44]. The coupling constant $\lambda_{HS}$ leads to pair-production of $S$ but cannot induce its decay, which requires a non-vanishing $\sin \theta$. This portal has several theoretical motivations. The new scalar can generate the baryon asymmetry of the Universe [45] and play the role of mediator between SM particles and light DM in case
Figure 1. Future upper limits at 90% CL for dark photons in visible decays in the plane $\epsilon$ versus $m_A'$ for PBC projects. Figure taken from Ref. [10].

Figure 2. Future upper limits at 90% CL for dark photons in visible decays in the plane $\epsilon$ versus $m_A'$ for experiments and proposals not included in the PBC activity. Figure taken from Ref. [10].

Figure 3. Dark Photon decaying to DM Pseudo-Dirac fermion particle. Prospects for PBC projects are compared to the current bounds (solid areas) and future experimental landscape (other solid and dashed lines). In the limit computation we assume a dark coupling constant value $\alpha_D = 0.1$ and a ratio $m_A'/m_\chi = 3$. Figure taken from Ref. [10].

of secluded annihilations ($\chi\chi \rightarrow \phi\phi$, where $\chi$ is the light DM particle and $\phi$ the light scalar mediator) [46].

It can also address the Higgs fine-tuning problem (via the relaxion mechanism [47]), which generically leads to relaxion-Higgs mixing [48] and provides an alternative baryogenesis mechanism [49] and a DM candidate [50, 51].

Figure 4 shows the current bounds and future sensitivity curves on the mixing parameter $\sin^2 \theta$ versus the mass of the dark scalar $m_S$. Bounds on this scenario come from recast of data from old beam dump experiments [52, 53], bump hunt in visible $B$ meson decays [54, 55, 56] and cosmological and astrophysical arguments.

Searches in the near ($\sim 5$ years) future will be performed by SeaQuest at FNAL [57] and LHCb with $\sim 15$ fb$^{-1}$ expected to be collected during Run 3. NA62 will be able to explore the
mass range below the kaon mass, as a side product of the measurement at $\mathcal{O}(10\%)$ accuracy of the rare decay $K^+\rightarrow\pi^+\nu\bar{\nu}$, by interpreting it as $K^+\rightarrow\pi^+S$.

On a longer timescale (10-15 years) the explored parameter space will be significantly extended by bigger PBC projects, as SHiP, MATHUSLA200, FASER2, and CODEX-b.

**Figure 4.** Current bounds and prospects on 10-15 year timescale for PBC projects for the dark scalar mixing with the Higgs in the plane mixing angle $\sin^2\theta$ versus dark scalar mass $m_S$. The sensitivity curves have been obtained assuming $BR(h\rightarrow SS) = 10^{-2}$. Figure taken from Ref. [10].

### 4.3. Benchmark case related to the Fermion Portal

All fermions in the Standard Model with the exception of neutrinos are known to exist with both left handed and right handed chirality. A particularly strong motivation for the existence of right handed neutrinos $\nu_R$ or Heavy Neutral Leptons (HNLs) comes from the fact that they can explain the smallness of neutrino masses [58, 59, 60, 61, 62, 63] via the type I seesaw mechanism.

Particularly interesting are models, as the $\nu$MSM [64] predicting the existence of these particles below the electroweak breaking scale where they can be searched for experimentally.

Figure 5 shows the current bounds and future sensitivities for HNL coupled to the first lepton generation. Strong constraints on couplings for HNLs with masses below the kaon mass are set by past experiments, in particular PS191 [65], CHARM [66], NuTeV [67], E949 [68], PIENU [69], TRIUMF-248 [70] and NA3 [71]. An interesting search has been also performed recently by the NA62 Collaboration [72] and updated in these proceedings.

A significant improvement in the entire mass range below the $B$-meson mass could be achieved by SHiP. The same mass range could also be probed by FASER2 [73], CODEX-b [23] and MATHUSLA200 [25]. Above the $B$-meson mass, displaced vertex searches at high energy hadron or lepton colliders would be more sensitive, see Ref. [11] for a summary.

### 5. Conclusions

The absence, so far, of unambiguous signals of new physics from direct searches at the LHC, indirect searches in flavor physics and direct DM detection experiments invigorates the need of broadening the experimental effort in exploring ranges of interaction strengths and masses different from what is already covered by existing or planned projects.
Figure 5. Sensitivity to Heavy Neutral Leptons with coupling to the first lepton generation only: current bounds (filled areas) and 10-15 years prospects for PBC projects (SHiP, MATHUSLA200, CODEX-b and FASER2) (solid lines). Figure taken from Ref. [10].

Feebly-Interacting Particles (FIPs) represent an alternative paradigm with respect to the traditional (strongly-coupled) BSM physics explored at the LHC. The investigation of this paradigm over a large range of couplings and masses requires a great variety of experimental facilities. As far as accelerator based experiments are concerned, the physics reach of experiments at colliders is complemented by beam-dump, fixed-target facilities which typically cover the range of low masses and extremely feeble couplings.

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