Summary plots from FIPs 2022 workshop

In the following we shortly present the state of the art for the search for feebly interacting particles at accelerator based experiments and the current worldwide situation and timescales of running or proposed experiments in all the main laboratories worldwide. This short write-up is completed with Tables and Figures, aiming at showing the status of these searches on the international landscape. Similar set of plots will be produced for ultra-light FIPs in the near future.

1 The Physics Case

The search for feebly-interacting particles is currently one of the most debated and discussed topics in fundamental physics. These particles can provide elegant explanations to several unresolved problems.

The theoretical framework widely used to describe the phenomenology of FIPs, is a general effective field theory formalism, called the *portal formalism* (see *e.g.* Refs. [1–3]). Let $O_{\rm SM}$ be an operator composed from the SM fields, and $O_{\rm DS}$ is a corresponding counterpart composed from the dark sector fields. Then the portal framework combines them into an interaction Lagrangian,

$$\mathcal{L}_{\rm portal} = \sum O_{\rm SM} \times O_{\rm DS}. \tag{1.1}$$

The sum goes over a variety of possible operators and of different composition and dimension. According to the general logic of quantum field theories, the lowest canonical dimension operators are going to be addressed as the most important. The minimal "portals" are the collection of lowest canonical-dimension operators that mix new dark-sector states with gauge invariant (but not necessarily Lorentz-invariant) combinations of SM fields. Following these general principles, it turns out that the collection of such portals is rather simple, as shown in Table 1. To each portal it is possible to connect one or more complete models that could answer one or more open problems in particle physics, as discussed below.

Table 1. The portal formalism.

Portal	Coupling
(1) Vector: Dark Photon, A'	$-\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
(2) Scalar: Dark Higgs, S	$(\mu S + \lambda_{\rm HS} S^2) H^\dagger H$
(3) Pseudo-scalar: Axion, a	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$
(4) Fermion: Heavy Neutral Lepton, N	$y_N L H N$

- Light DM with thermal origin: If DM is a non-relativistic thermal relic from the hot early universe, non-gravitational interactions can arise between dark and ordinary matter. The experimental value of DM density from the CMB and large scale structures, $\Omega_{\rm DM}h^2 = 0.1198 \pm 0.00015$ [4] can be associated to more or less complex scenarios with extended feebly-interacting sectors and several mediators [5–7]. The canonical example of a minimal SM extension involves a heavy particle with mass between [0.1-1] TeV interacting through the weak force, the WIMP. However a thermal origin is possible even if DM is not a WIMP: DM with any mass in the MeV-100 TeV range can achieve the correct relic abundance by annihilating directly into SM matter. Thermal DM in the MeV-GeV range with SM interactions is overproduced in the early Universe so viable scenarios require additional SM neutral mediators to deplete the overabundance [8–13]. These "dark sector mediators" could be light, long-lived, feebly-interacting particles mixing/interacting with SM fields that do not carry electromagnetic charge, like the Higgs, the Z^0, and the photon. *Most of the models describing light (sub-GeV) DM interacting with the SM fields belong to the vector and scalar portals.*

- Solution to the strong CP problem: The axion, introduced to solve the apparent lack of CP violation in strong interactions, is a Goldstone boson associated with the breaking of the Peccei-Quinn (PQ) symmetry and it could be a natural DM candidate below 10^{-3} eV. Since the axion interaction couplings are suppressed by the high symmetry-breaking scale f_a, ($10^9 < f_a < 10^{12}$ GeV), the axion is a natural FIP candidate. The QCD axion can be heavier if the QCD behavior at higher energies changes (see [14] for a short review of original papers), rendering the QCD axion possibly accessible at accelerator-based experiments. Natural extensions of the axion paradigm bring to a wide range of interesting pseudo-scalar particles which typically have very similar interactions as the axion but without a strict relation between the mass and coupling, the Axion-Like Particles or ALPs. ALPs appear in any theory with a spontaneously broken global symmetry [15–17]. *Axions and ALPs naturally belong to the pseudo-scalar portal.*

- Hierarchy of scales, cosmological inflation, and EW symmetry breaking: The SM Higgs is especially sensitive to the potential existence of new light degrees of freedom. In fact the Higgs portal operator, $H^\dagger H$, is a low-dimensional operator and a singlet under all known symmetries of the SM. This is exactly what lies at the root of the hierarchy problem and simultaneously what generically enables the Higgs to couple to all NP to some degree. A light scalar field very feebly coupled to the Higgs, appears in many extensions of the SM as a possible explanation of dark matter [18–20], the $(g-2)_\mu$ anomaly [11, 21], inflation [22], naturalness [23–26], and neutrino masses [27]. In a minimal model, the new singlet scalar has predominantly a quadratic coupling and a mixing term to the Higgs that regulate its production at accelerators. The hidden scalar couples to SM fermions and vector bosons as a SM Higgs, but with strength reduced by a factor of $sin\theta$, being θ the mixing angle between the two sectors. *A light scalar mixing to the Higgs is naturally described by the scalar portal.*

- The origin of neutrino masses and leptogenesis: The origin of the neutrino masses and oscillations may be deeply interconnected with the origin of matter antimatter asymmetry in the universe [28]. Right-handed neutrinos ν_R or Heavy Neutral Leptons (HNLs) could account for both. They might explain the light neutrino masses and oscillations via a type I seesaw mechanism [29–31] and generate a lepton asymmetry in the primordial plasma via CP-violating transitions. HNL in the MeV - few GeV region are full compatible with the data coming from active neutrinos, and with the constraints coming from astroparticle and cosmology. *HNLs naturally belong to the fermion portal.*

2 Benchmark models

In the subsequent sections, we formulate the benchmark models in some detail, repeating the prescriptions detailed by Maxim Pospelov for the PBC BSM Report [32].

2.1 Vector portal models

A large class of BSM models includes interactions with light new vector particles. Such particles could result from extra gauge symmetries of BSM physics. New vector states can mediate interaction both with the SM fields, and extra fields in the dark sector that *e.g.* may represent the dark matter (DM) states.

The most minimal vector portal interaction can be written as

$$\mathcal{L}_{\text{vector}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} - \frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B_{\mu\nu}, \tag{2.1}$$

where $\mathcal{L}_{\text{SM}}$ is the SM Lagrangian, $B_{\mu\nu}$ and $F'_{\mu\nu}$ are the field stengths of hypercharge and new $U(1)'$ gauge groups, ϵ is the so-called kinetic mixing parameter [33], and $\mathcal{L}_{\text{DS}}$ stands for the dark sector Lagrangian that may include new matter fileds χ charged under $U'(1)$,

$$\mathcal{L}_{\text{DS}} = -\frac{1}{4}(F'_{\mu\nu})^2 + \frac{1}{2} m_{A'}^2 (A'_\mu)^2 + |(\partial_\mu + i g_D A'_\mu)\chi|^2 + \ldots \tag{2.2}$$

If χ is stable or long-lived it may constitute a fraction of enteriety of dark matter. At low energy this theory contains a new massive vector particle, a dark photon state, coupled to the electromagnetic current with ϵ-proportional strength, $A'_\mu \times \epsilon J^\mu_{EM}$.

We define the following important benchmark cases (denoted for further concvenience as $BC\#$) for the vector portal models.

- *BC1, Minimal dark photon model*: In this case the SM is augmented by a single new state A'. DM is assumed to be either heavy or contained in a different sector. In that case, once produced, the dark photon decays back to the SM states. The parameter space of this model is then $\{m_{A'}, \epsilon\}$.

- *BC2, Light dark matter coupled to dark photon*: this is the model where minimally coupled viable WIMP dark matter model can be constructed [9, 10]. Preferred values of dark coupling $\alpha_D = g_D^2/(4\pi)$ is such that the decay of A' occurs predominantly into $\chi\chi^*$ states. These states can further rescatter on electrons and nuclei due to ϵ-proportional interaction between SM and DS states mediated by the mixed AA'

propagator [2, 34]. The parameter space for this model is $\{m_{A'}, \epsilon, m_\chi, \alpha_D\}$ with further model-dependence associated with properties of χ (boson or fermion). The suggested choices for the PBC evaluation are 1. ϵ vs $m_{A'}$ with $\alpha_D \gg \epsilon^2\alpha$ and $2m_\chi < m_{A'}$, 2. y vs. m_χ plot where the "yield" variable y, $y = \alpha_D\epsilon^2(m_\chi/m_{A'})^4$, is argued [35] to contain a combination of parameters relevant for the freeze-out and DM-SM particles scattering cross section. One possible choice is $\alpha_D = 0.1$ and $m_{A'}/m_\chi = 3$.

- *BC3, Millicharged particles*: this is the limit of $m_{A'} \to 0$, in which case χ of $\bar{\chi}$ have an effective electric charge of $|Q_\chi| = |\epsilon g_D e|$ [33, 36]. The suggested choice of parameter space is $\{m_\chi, Q_\chi/e\}$, and χ can be taken to be a fermion.

Note that the decays of the dark photon to the SM hadrons cannot be calculated *ab-initio*. This, however, does not lead to significant uncertainty, as $A' \to$ hadrons partial decay width can be inferred from the experimentally measured R-ratio (see *e.g.* the treatment in Ref. [37]).

The kinetic mixing coupling of A' to matter is the simplest and most generic, but not the only possible vector portal. Other cases considered in the literature include gauged $B - L$ and $L_\mu - L_\tau$ models, and somewhat less motivated leptophylic and leptophobic cases, when A' is assumed to be coupled to either total lepton current, or total baryon current with a small coupling g'. We encourage experimental collaborations to assess their sensitivity to these cases as well.

2.2 Scalar portal models

The 2012 discovery of the BEH mechanism, and the Higgs boson h, prompts to investigate the so called scalar or Higgs portal, that couples the dark sector 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, μ and λ [38],

$$\mathcal{L}_{\text{scalar}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} - (\mu S + \lambda S^2)H^\dagger H, \tag{2.3}$$

The dark sector Lagrangian may include the interaction with dark matter χ, $\mathcal{L}_{\text{DS}} = S\bar{\chi}\chi + \ldots$. Most viable dark matter models in the sub-EW scale range imply $m_\chi > m_S$ [20].

At low energy, the Higgs field can be subsituted for $H = (v+h)/\sqrt{2}$, where $v = 246\,\text{GeV}$ is the the EW vacuum expectation value, and h is the field corresponding to the physical 125 GeV Higgs boson. The nonzero μ leads to the mixing of h and S states. In the limit of small mixing it can be written as

$$\theta = \frac{\mu v}{m_h^2 - m_S^2}. \tag{2.4}$$

Therefore the linear coupling of S to SM paarticles can be written as $\theta S \times \sum_{\text{SM}} O_h$, where O_h is a SM operator to which Higgs boson is coupled. (For an elementary fermion, *e.g.* $O_h = (m_\psi/v) \times \bar{\psi}\psi$). The sum goes over all type of SM operators coupled to the Higgs field.

Coupling constant λ leads to the coupling of h to a pair of S particles, λS^2. It can lead to pair-production of S but cannot induce its decay. An important property of the scalar portal is that at a loop level it can induce flavour-changing transitions, and in particular lead to decays $K \to \pi S$, $B \to K^{(*)} S$ etc [22, 38, 39] and similarly for the hS^2 coupling [40].

We define the following benchmark cases for the scalar portal models:

- *BC4, Higgs-mixed scalar:* in this model we assume $\lambda = 0$, and all production and decay are controlled by the same parameter θ. Therefore, the parameter space for this model is $\{\theta, m_S\}$.

- *BC5, Higgs-mixed scalar with large pair-production channel:* in this model the parameter space is $\{\lambda, \theta, m_S\}$, and λ is assumed to dominate the production via *e.g.* $h \to SS$, $B \to K^{(*)} SS$, $B^0 \to SS$ etc. We suggest taking the value of $\lambda \simeq 5 \times 10^{-4}$ such that $Br_{h \to SS}$ is close to 10^{-3}, and therefore safely outside the reach of the direct LHC searches for the Higgs invisible decay channels.

We also provide comments on treatment of strong interaction uncertainties. For the flavour-changing decays, the effective $b - s - S$ and $s - d - S$ vertices are dominated by the short-distance contribution and therefore are uncertainty-free. The $K \to \pi$ transitional matrix elements can be obtained using chiral theory, while for the $B \to K^*$ transitions we recommend using the QCD sum rule derived form factors [41, 42].

The flavour diagonal transitions such as $S \to$ *hadrons* decays contain significant hadronic uncertainty. Our recommendation is to use the chiral perturbation theory calculation, including the region with enhacement of the pion decay channel around the mass of f_0 resonance [43]. (Fig 6b of Ref. [43] can be used as an input below 1.4 GeV) Above $m_S = 1.4$ GeV we recommend using perturbative input [44, 45], *i.e.* S decays to heavy quarks, gluons and strange quarks, for definitiveness.

We also note that while the 125 GeV Higgs-like resonance has properties of the SM Higgs boson within errors, the structure of the Higgs sector can be more complicated and include *e.g.* several scalar doublets. In the two-Higgs doublet model the number of possible couplings grows by a factor of three, as S can couple to 3 combinations of Higgs field bilinears, $H_1^\dagger H_1$, $H_2^\dagger H_2$ and $H_1 H_2$. Therefore, the experiments could investigate their sensitivity to a more complicated set of the Higgs portal couplings.

2.3 Neutrino portal models

Netrino portal extension of the SM is very motivated by the fact that it can be tightly related with the neutrino mass generation mechanism. The neutrino portal operates with one or several dark fermions N, that can be also called "heavy neutral leptons" or HNLs. The general form of the neutrino portal can be written as

$$\mathcal{L}_{\text{vector}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} + \sum F_{\alpha I} (\bar{L}_\alpha H) N_I \tag{2.5}$$

where the summation goes over the flavour of lepton doublets L_i, and the number of available HNLs, N_J. The F_{iJ} are the corresponding Yukawa couplings. The dark sector

Lagrangian should include the mass terms for HNLs, that can be both Majorana or Dirac type. For more extended review, see Ref. [3, 46]. Setting Higgs field to its v.e.v., and diagonalizing mass terms for neutral fermions, one arrives at $\nu_i - N_J$ mixing, that is usually parametrized by a matrix called U. Therefore, in order to obtain interactions of HNLs, inside the SM interaction terms, one can replace $\nu_\alpha \to \sum_I U_{\alpha I} N_I$. In the minimal HNL models, both the production and decay of an HNL are controlled by the elements of matrix U.

The PBC suggests the following benchmark cases:

- *BC6, Single HNL, electron dominance:* Assuming one Majorana HNL state N, and the predominant mixing with electron neutrinos, all production and decay can be determined as function of parameter space $\{m_N, |U_e|^2\}$. Parameter space is $\{m_N, |U_e|^2\}$.
- *BC7, Single HNL, muon dominance:* Assuming one Majorana HNL state N, and the predominant mixing with muon neutrinos, all production and decay can be determined as function of parameter space $\{m_N, |U_\mu|^2\}$.
- *BC8, Single HNL, tau dominance:* One Majorana HNL state with predominant mixing to tau neutrinos. Parameter space is $\{m_N, |U_\tau|^2\}$.

These are representative cases which do not exhaust all possibilities. Multiple HNL states, and presence of comparable couplings to different flavours can be even more motivated than the above choices. The current choice of benchmark cases is motivated by simplicity.

2.4 Axion portal models

QCD axions are an important idea in particle physics [47–49] that allows for a natural solution to the strong CP problem, or apparent lack of CP violation in strong interactions. Current QCD axion models are restricted to the sub-eV range of axions. However, a generalization of the minimal model to *axion-like particles* (ALPs) can be made [36]. Taking a single pseudoscalar field a one can write a set of its couplings to photons, quarks, leptons and other fields of the SM. In principle, the set of possible couplings is very large and we take only the flavour-diagonal subset,

$$\mathcal{L}_{\rm axion} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DS} + \frac{a}{4f_\gamma} F_{\mu\nu}\tilde{F}_{\mu\nu} + \frac{a}{4f_G}{\rm Tr} G_{\mu\nu}\tilde{G}_{\mu\nu} + \frac{\partial_\mu a}{f_l}\sum_\alpha \bar{l}_\alpha \gamma_\mu\gamma_5 l_\alpha + \frac{\partial_\mu a}{f_q}\sum_\beta \bar{q}_\beta\gamma_\mu\gamma_5 q_\beta \tag{2.6}$$

The DS Lagrangian may contain new states that provide UV completion to this model (for the case of the QCD axion they are called the PQ sector). All of these interactions do not lead to large additive renormalization of m_a, making this model technically natural. Note, however, that the coupling to gluons does lead to the non-perturbative contribution to m_a.

The PBC committee proposes to consider the following benchmark cases:

- *BC9, photon dominance:* Assuming a single ALP state a, and the predominant coupling to photons, all phenomenology (production, decay, oscillation in the magnetic field) can be determined as functions on $\{m_a, g_{a\gamma\gamma}\}$ parameter space, where $g_{a\gamma\gamma} = f_\gamma^{-1}$ notation is used.

- *BC10, fermion dominance:* Assuming a single ALP state a, and the predominant coupling to fermions, all phenomenology (production and decay) can be determined as functions on $\{m_a, f_l^{-1}, f_q^{-1}\}$. Furthermore, for the sake of simplicity, we recommend taking $f_q = f_l$.

- *BC11, gluon dominance:* this case assume an ALP coupled to gluons. Parmeter space is $\{m_a, f_G^{-1}\}$. Notice that in this case the limit of $m_a < m_{a,QCD}|_{f_a=f_G}$ is unnatural as it requires fine tuning and therefore is less motivated.

The ALP portals, $BC\,9-11$, are *effective* interactions, and would typically require UV completion at or below f_i scales. This is fundamentally different from vector, scalar and neutrino portals that do not require external UV completion. Moreover, the renormalization group (RG) evolution is capable of inducing new couplings. The PBC recommends that all three cases, $9-11$, be considered as input at the renormalization scale of $\Lambda = 1\,\mathrm{TeV}$. Therefore, the low-energy phenomenology at an appropriate scale μ, (*e.g.* $\mu = 1\,\mathrm{GeV}$) will contain new couplings developed by the RG flow with $\log(\Lambda/\mu)$ dependence. In particular, RG effecs will induce $b-s-a$ and $s-d-a$ vertices at low energy.

PBC also recommends perturbative approach for calculating $a \to hadrons$ for $m_a > 1\,\mathrm{GeV}$, while neglecting hadronic widths below that scale, $\Gamma_{a\to hadrons}(m_a < 1\,\mathrm{GeV}) \simeq 0$.

Experimental results

FIPs physics is currently at the forefront of fundamental physics and all the main laboratories in the world host one or more experiments able to cover a region of the parameter space allowed by portal formalism. Tables 2 and Table 3 show past, existent and future (proposed or approved) experiments running at accelerators that will search for FIPs in a mass range between ~ MeV and 100 GeV. Figures 1-11 show the state of the art of existing limits and future projections (both at 90 % CL) for all the accelerator-based experiments worldwide. The legenda is as follows: filled areas are existing limits; dotted line are projections obtained using a toy monte carlo; dashed lines are projections obtained using a full Monte Carlo with background simulated (at different levels); solid lines are extrapolation from existing datasets.

Table 2. Main past accelerator-based experiments sensitive to FIPs searches. Legend for portals: 1: Vector; 2: Scalar; 3: Pseudo-scalar; 4: Fermion. The techniques used are: i) visible decays; ii) invisible decays; e^- or nucleon recoil; missing mass $\not{M}$, missing momentum $\not{p}$ and missing energy $\not{E}$.

Experiment	lab	beam	particle yield/$\mathcal{L}$	technique	portals
past					
BaBar [50]	SLAC	e^+e^-, 10.58 GeV	514 fb^{-1}	visible, invis.	(1)
Belle [51]	KEK	e^+e^-, 10.58 GeV	0.6-0.8 fb^{-1}	visible	(1,2,4)
CHARM [52]	CERN	p, 400 GeV	$2.4 \cdot 10^{18}$	visible	(1,2,3,4)
E137 [53]	SLAC	e^-, 20 GeV	$2 \cdot 10^{20}$ (30 C)	visible	(1,3)
E141 [54]	SLAC	e^-, 9 GeV	$2 \cdot 10^{15}$	visible	(1,3)
E774 [55]	FNAL	e^-, 275 GeV	$2 \cdot 10^{15}$	visible	(1)
KLOE [56, 57]	LNF	e^+e^-, 1 GeV	up to 1.7 fb^{-1}	visible, inv.	(1)
LSND [58]	LANL	p, 800 MeV	10^{23} pot	e^- recoil	(1)
MiniBooNE [**?**]	FNAL	p, 8 GeV	$1.9 \cdot 10^{20}$	recoil e, N	(1)
NA48/2 [59]	CERN	π^0	$2 \cdot 10^7$	$\not{M}$	(1)
NuCAL [60, 61]	Serpukhov	p, 70 GeV	$1.7 \cdot 10^{18}$	visibile	(1,3)
PIENU [62]	TRIUMF	π^+, 75 MeV	10^7	missing mass	(4)

Table 3. Main current, and future (proposed or approved) accelerator-based experiments sensitive to FIPs searches. Legend for portals: 1: Vector; 2: Scalar; 3: Pseudo-scalar; 4: Fermion.

Experiment	lab	beam	particle yield/$\mathcal{L}$	technique	portals	timescale
current						
APEX [63]	JLAB	e^+, 2.2 GeV	up to 150 μA	visible	(1)	unknown
ATLAS [64]	CERN	pp, 13-14 TeV	up to 3 ab^{-1}	visible, invis.	(1,2,3,4)	2042
Belle II [65]	KEK	e^+e^-, 11 GeV	up to 50 ab^{-1}	visible, invis.	(1,2,3,4)	2035
CMS [66]	CERN	pp, 13-14 TeV	up to 3 ab^{-1}	visible, invis.	(1,2,3,4)	2042
Dark(Sea)Quest [67]	FNAL	p, 120 GeV	$10^{18} \to 10^{20}$	visible	(1,2,3,4)	2025?
FASER [68]	CERN	pp, 14 TeV	150 fb^{-1}	visible	(1,2,3,4)	2025 HPS [69]
JLAB	e^-, 2-6 GeV	$\sim 10^{20}$ eot	visible	(1,3)	unknown	
LHCb [70]	LHC	pp, 13-14 TeV	up to 300 fb^{-1}	visible	(1,2,3,4)	2042
MicroBooNE [71]	FNAL	p, 8 GeV	$\sim 10^{21}$ pot	visible	(1)	2015-2021
NA62 [72]	CERN	K^+, 75 GeV	up to 10^{13} K decays	visible, invis.	(1,2,3,4)	2025
NA62-dump [73]	CERN	p, 400 GeV	$\sim 10^{18}$ pot	visible	(1,2,3,4)	2025
NA64$_e$ [74]	CERN	e^-, 100 GeV	up to $3 \cdot 10^{12}$ eot/year	$\not{E}$, visible	(1,3)	2025?
PADME [75]	LNF	e^+, 550 MeV	$5 \cdot 10^{12}$ e^+ot	missing mass	(1)	$<$ 2023
T2K-ND280 [76]	JPARC	p, 30 GeV	10^{21} pot	visible	(4)	running
proposed						
BDX [77]	JLAB	e^-, 11 GeV	$\sim 10^{22}$	recoil e	(1,3)	2024-2025
CODEX-b [78]	CERN	pp, 14 TeV	300 fb^{-1}	visible	(1,2,3,4)	2042
Dark MESA [79]	Mainz	e^-, 155 MeV	150 μA	visible	(1)	$<$ 2030
FASER2 [80]	CERN	pp, 14 TeV	3 ab^{-1}	visible	(1,2,3,4)	2042
FLaRE [80]	CERN	pp, 14 TeV	3 ab^{-1}	visible, recoil	(1)	2042
FORMOSA [80]	CERN	pp, 14 TeV	3 ab^{-1}	visible	(1)	2042
HIKE-dump [81]	CERN	p, 400 GeV	$5 \cdot 10^{19}$ pot	visible	(1,2,3,4)	$<$2038
HIKE-K$^+$ [81]	CERN	K, 75 GeV	n. of K?	visible, inv.	(1,2,3,4)	$<$2038
LBND (DUNE) [82]	FNAL	p, 120 GeV	$\sim 10^{21}$ pot	recoil e, N	(1,2,3,4)	$<$ 2040
LDMX [83]	SLAC	e^-, 4,8 GeV	$2 \cdot 10^{16}$ eot	$\not{p}$, visible	(1)	$<$ 2030
M^3 [84]	FNAL	μ, 15 GeV	10^{10} (10^{13}) mot	$\not{p}$	(1)	proposed
MATHUSLA [85]	CERN	pp, 14 TeV	3 ab^{-1}	visible	(1,2,3,4)	2042
milliQan [86]	CERN	pp, 14 TeV	0.3-3 ab^{-1}	visible	(1)	$<$ 2032
MoeDAL/MAPP [87]	CERN	pp, 14 TeV	30 fb^{-1}	visible	(4)	$<$ 2032
Mu3e [88]	PSI	29 GeV	$10^{18} \to 10^{20} \mu$/s	visible	(1)	$<$ 2038
NA64$_\mu$ [89]	CERN	μ, 160 GeV	up to 10^{13} mot/year	$\not{p}$	(1)	$<$ 2032
PIONEER [90]	PSI	55-70 MeV, π^+	$0.3 \cdot 10^6 \pi$/s	visible	(4)	phase I approved
SBND [91]	FNAL	p, 8 GeV	$6 \cdot 10^{20}$ pot	recoil Ar	(1)	$<$ 2030
SHADOWS [92]	CERN	p, 400 GeV	$5 \cdot 10^{19}$ pot	visible	(2,3,4)	$<$2038
SHiP [93]	CERN	p, 400 GeV	$2 \cdot 10^{20}$ pot	visible, recoil	(1,2,3,4)	$<$2038

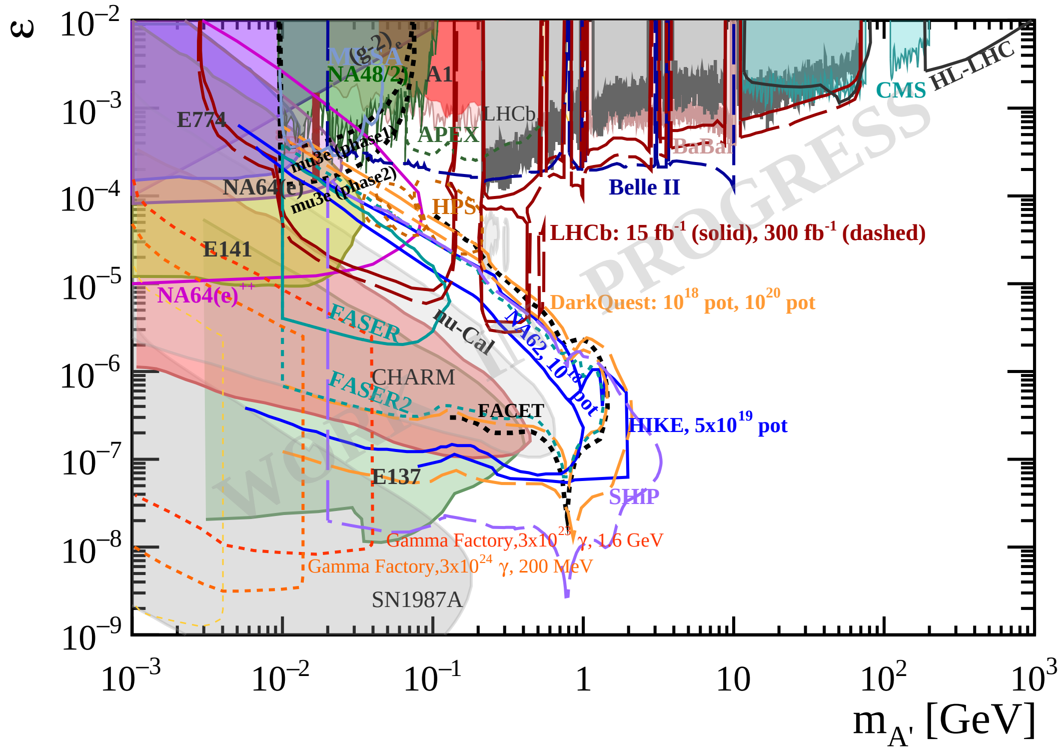

Figure 1. **Dark photon into visible final states (BC1):** ε versus $m_{A'}$. Filled areas are existing limits from searches at experiments at collider/fixed target (A1 [94], LHCb [95],CMS [96],BaBar [97], KLOE [98–101], and NA48/2 [102]) and old beam dump: E774 [55], E141 [54], E137 [53, 103, 104]), ν-Cal [60, 61], CHARM (from [105]), and BEBC (from [106]). Bounds from supernovae [107] and $(g-2)_e$ [11] are also included. Coloured curves are projections for existing and proposed experiments: Belle-II [108]; LHCb upgrade [109, 110]; NA62 in dump mode with 10^{18} [111] and HIKE with 5×10^{19} pot [81]; NA64(e)$^{++}$ [112, 113]; FASER [114] and FASER2 [80, 115]; FACET [116]; DarkQUEST [117]; HPS [118]; DarkMESA [119]; Mu3e [120]; HL-LHC [121]; Gamma Factory [122].

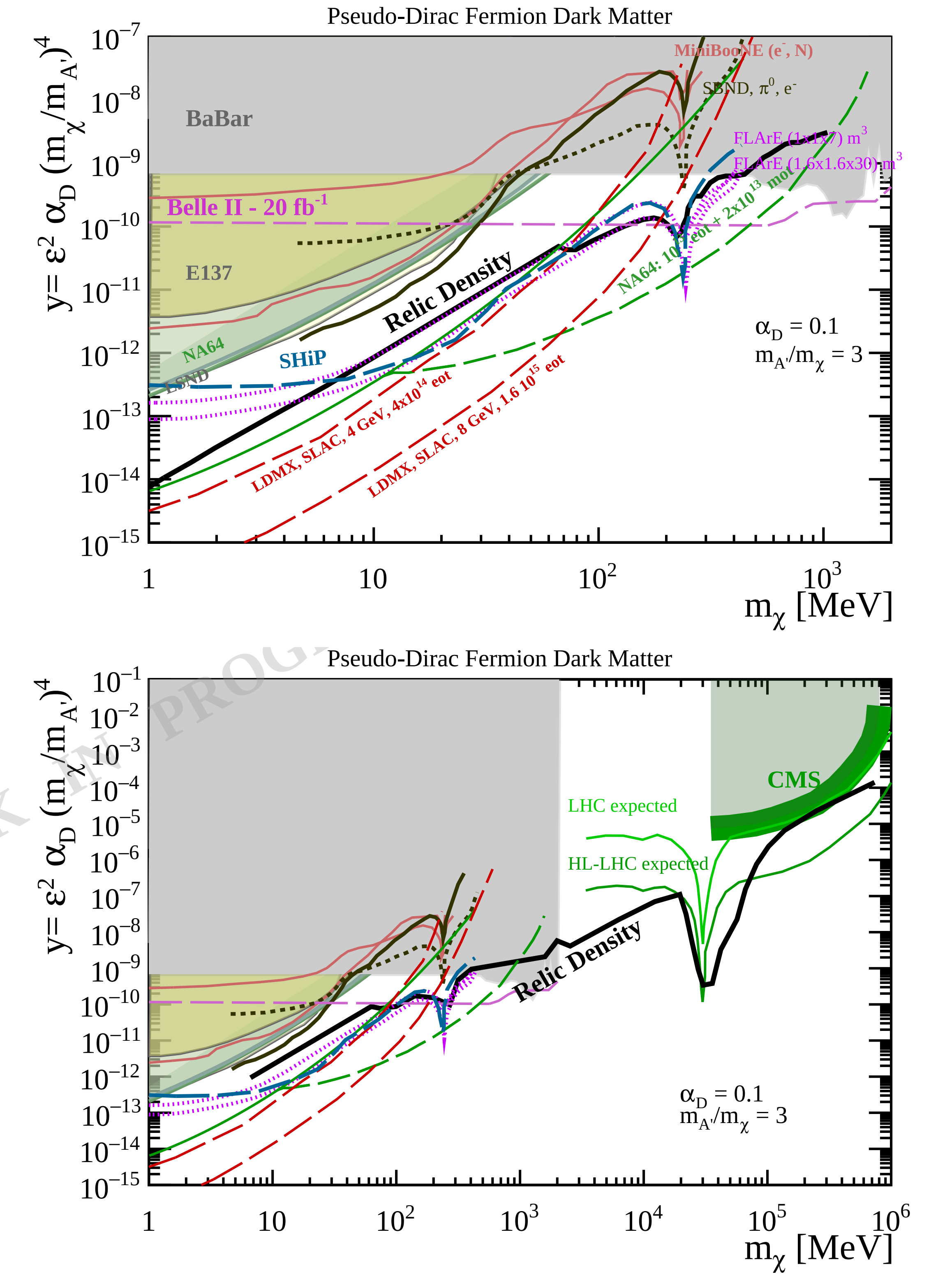

Figure 2. Existing limits (filled areas) and future sensitivities of existing or proposed experiments (coloured curves) to light dark matter production through a dark photon in the plane defined by the yield variable y as a function of DM mass m_χ for a specific choice of $\alpha_D = 0.1$ and $m_{A'}/m_\chi = 3$. The DM candidate is assumed to be a pseudo-Dirac fermion. Top plot shows the DM mass range up to a few GeV, bottom plot up to 1 TeV. Current limits shown as filled areas come from: BaBar [123]; CMS [124]; NA64$_e$ [125]; reinterpretation of the data from E137 [103] and LSND [58]; result from MiniBooNE [126]. The projected sensitivities, shown as solid, dashed, or dotted lines, come from: SHiP [93], SBND [127], FLArE [115],LDMX [83, 128],Belle-II [108]. The "LHC expected" and "HL-LHC expected" sensitivities come from [129].

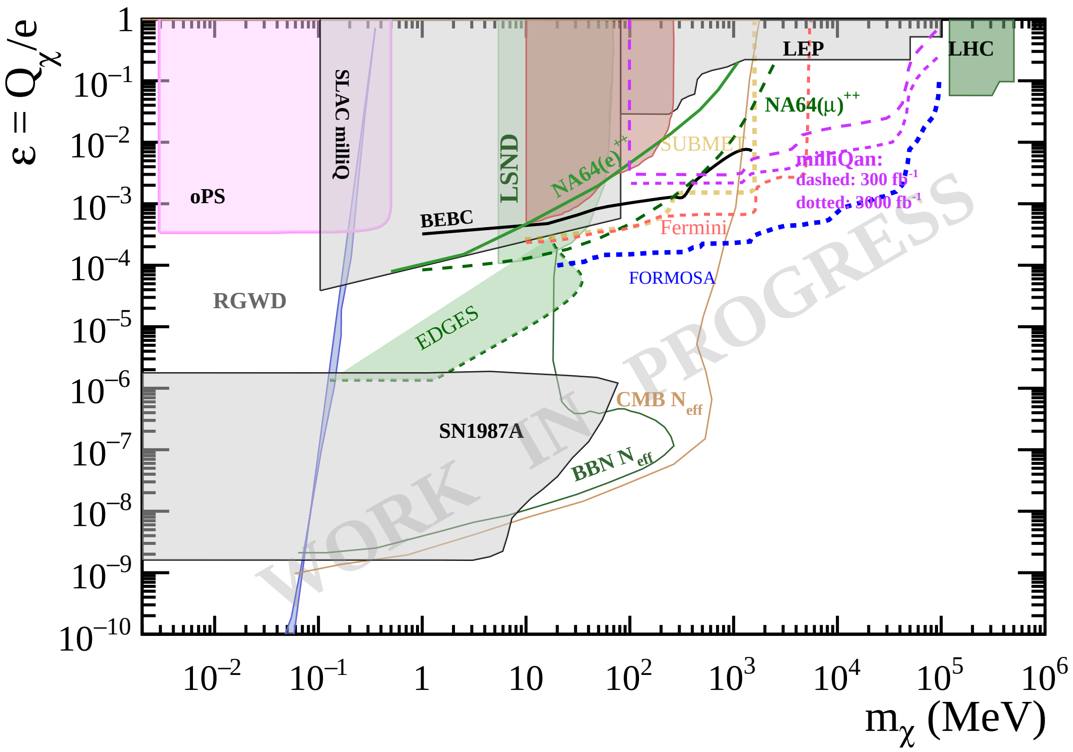

Figure 3. **Dark Photon milli-charged particles (BC3)**. Existing limits (filled areas) and future sensitivities for existing or proposed experiments (curves). Existing limits: stellar evolution (RGWD [130] and SN1987 [131]); N_{eff} during BBN and CMB [130]; invisible decays of ortho-positronium (oPS) [132]; SLAC milliQ experiment [133]; reinterpretation of data from LSND and MiniBooNE [134]; interpretation of the anomalous 21 cm hydrogen absorption signal by EDGES [135]; searches at LEP [136] and LHC [137]. Future sensitivities: NA64(e)$^{++}$ [74]; NA64(μ) [138]; FerMINI [139]; milliQAN [86].

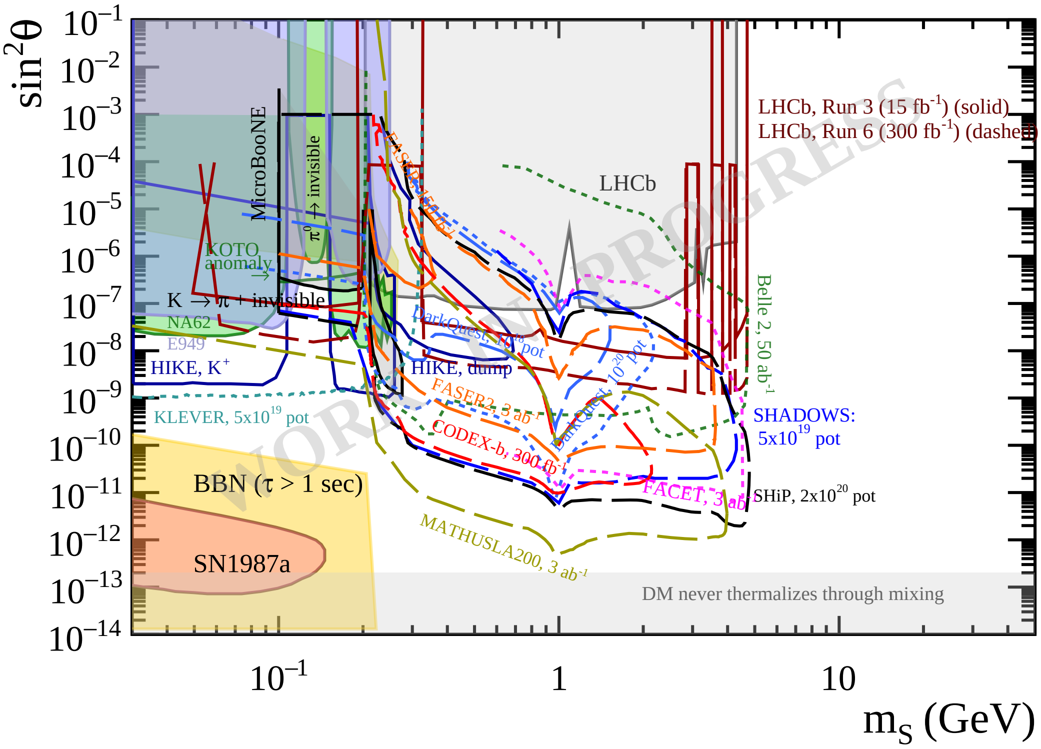

Figure 4. **Sensitivity to light dark scalar (BC4).** Current bounds and future projections for 90% CL exclusion limits. Shaded areas come from: reinterpretation [27] of results from CHARM experiment [140]; NA62 [141]; E949 [142, 143]; MicroBooNE [144] that excludes a light dark scalar as interpretation [145] of the KOTO anomaly and MicroBooNE from Numi data [146]; LHCb [147, 148] and Belle [149]. Coloured lines are projections of existing or proposed experiments: SHiP [93]; HIKE-K$^+$ and HIKE-dump [81]; HIKE-K_L/KLEVER [81]; SHADOWS [92]; DarkQuest [117, 150], Belle 2 [151], LHCb run3 and run6 [152], FASER2 [80], CODEX-b [78, 153], MATHUSLA [154], and FACET [116]. BBN and SN 1987A are from [155] and [156].

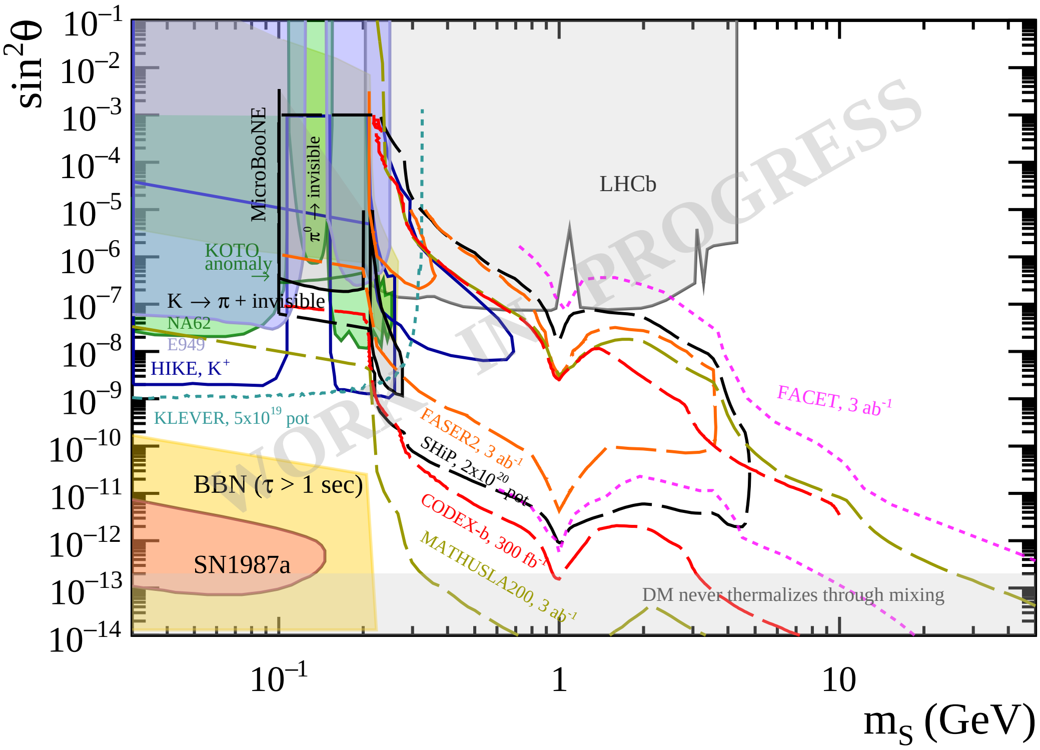

Figure 5. **Sensitivity to light dark scalar (BC5).** Current bounds and future projections for 90% CL exclusion limits. Shaded areas come from: reinterpretation [27] of results from CHARM experiment [140]; NA62 [141]; E949 [142, 143]; MicroBooNE [144] that excludes a light dark scalar as interpretation [145] of the KOTO anomaly and MicroBooNE from Numi data [146]; LHCb [147, 148] and Belle [149]. Coloured lines are projections of existing or proposed experiments: SHiP [93]; HIKE-K$^+$ [81]; HIKE-K_L/KLEVER [81]; SHADOWS [92]; FASER2 [80], CODEX-b [78, 153], MATHUSLA [154], and FACET [116]. BBN and SN 1987A are from [155] and [156].

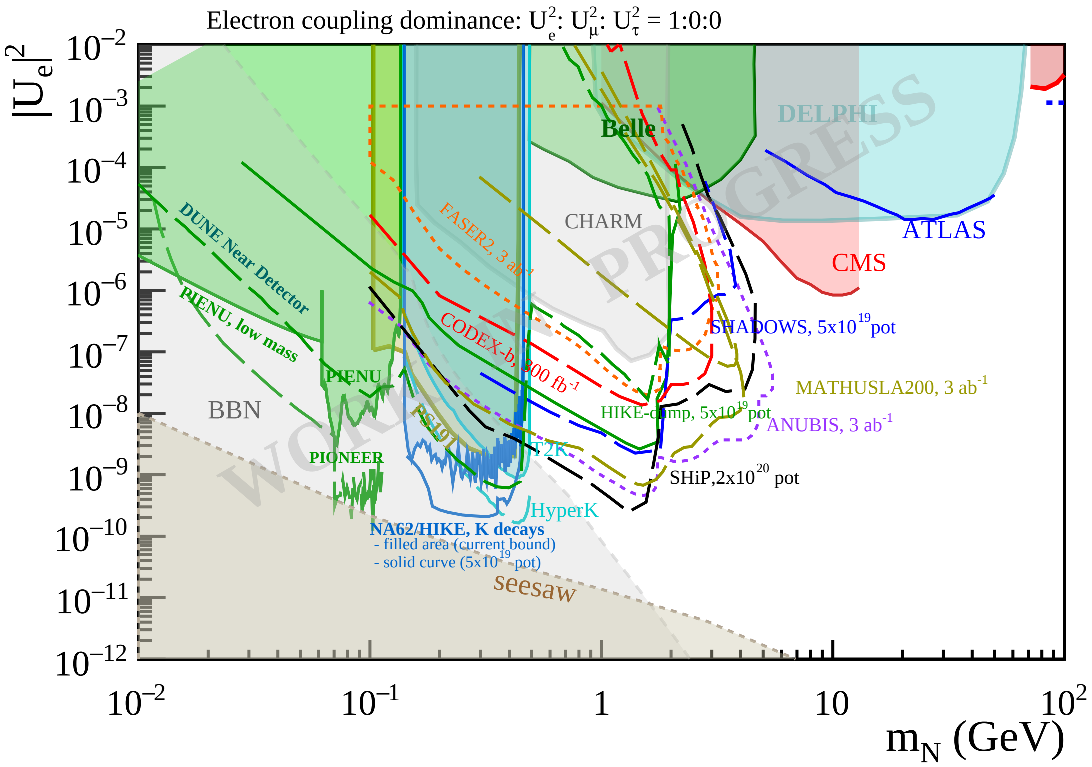

Figure 6. **Sensitivity to HNL with electron coupling (BC6).** Current bounds and future projections for 90% CL exclusion limits. Filled areas are existing bounds from: PS191 [157], CHARM [140], PIENU [158], NA62 (K_{eN}) [159], NA62 ($K_{\mu N}$) [160], T2K [161], Belle [162], DELPHI [163], ATLAS [164], and CMS [165]. Coloured curves are projections from: PIONEER [166], HIKE [81], DarkQuest [150], Belle-II [167], FASER2 [114]; DUNE near detector [168], Hyper-K (projections based on [169]), CODEX-b [78], SHiP [93], SHADOWS [92] and MATHUSLA200 [154]. The BBN bounds are from [170]. The seesaw bounds are computed under the hypothesis of two HNLs mixing with active neutrinos, and should be considered only indicative.

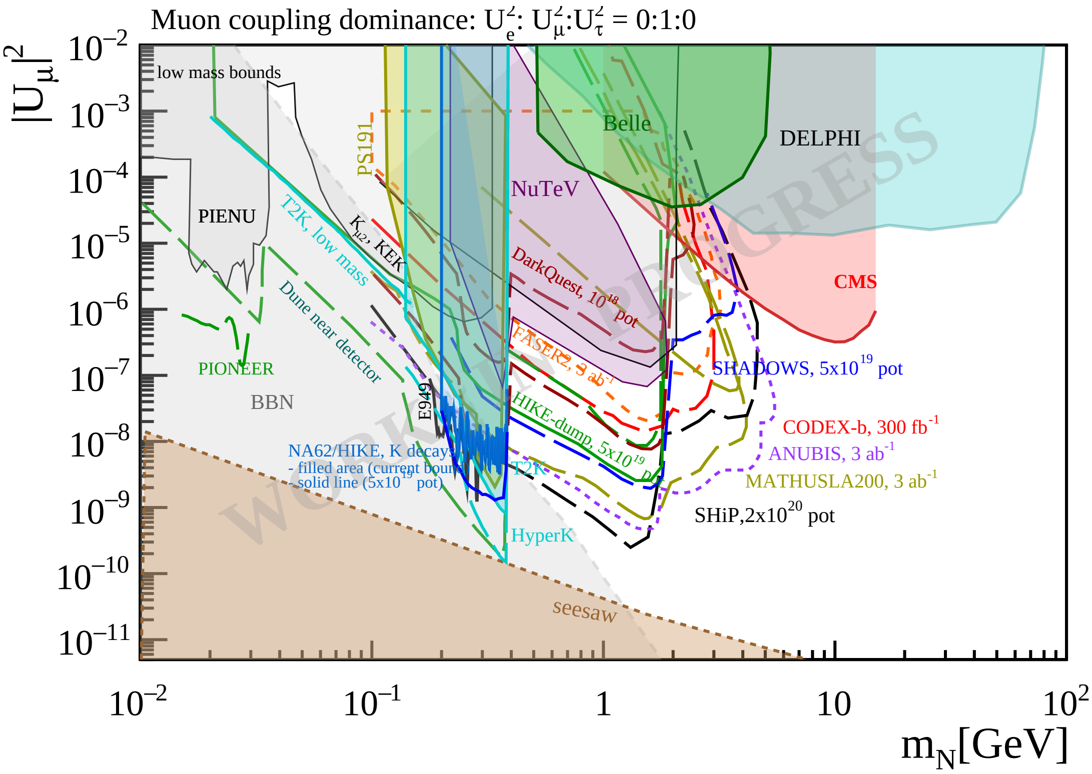

Figure 7. **Sensitivity to HNL with muon coupling (BC7).** Current bounds and future projections for 90% CL exclusion limits. Filled areas are existing bounds from: PS191 [157], CHARM [140], PIENU [158], NA62 (K_{eN}) [159], NA62 ($K_{\mu N}$) [160], T2K [161], Belle [162]; DELPHI [163], ATLAS [164] and CMS [165]. Coloured curves are projections from: NA62-dump [32, 111], DarkQuest [150], Belle-II [167]; FASER2 [114]; DUNE near detector [168]; Hyper-K (projections based on [169]); SHiP [93], CODEX-b [78], and MATHUSLA200 [154]. The BBN bounds are from [170]. The seesaw bounds are computed under the hypothesis of two HNLs mixing with active neutrinos, and should be considered only indicative.

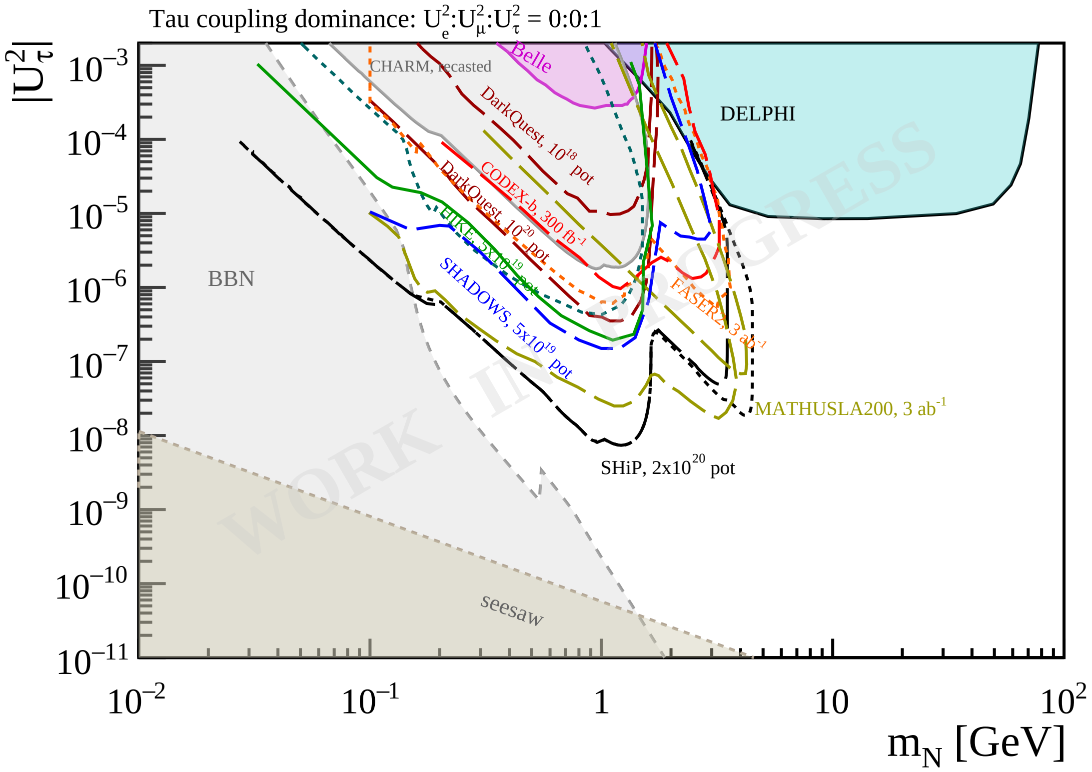

Figure 8. **Sensitivity to HNL with tau coupling (BC8).** Current bounds and future projections for 90% CL exclusion limits. Filled areas are existing bounds from: CHARM [140]; Belle [162]; DELPHI [163],; T2K [161] Coloured curves are projections from: HIKE-dump [81], SHiP [93], DarkQuest [150], Belle-II [167], DUNE [171], FASER2 [114]; CODEX-b [78], and MATHUSLA200 [154]. The BBN bounds are from [170]. The seesaw bounds are computed under the hypothesis of two HNLs mixing with active neutrinos, and should be considered only indicative.

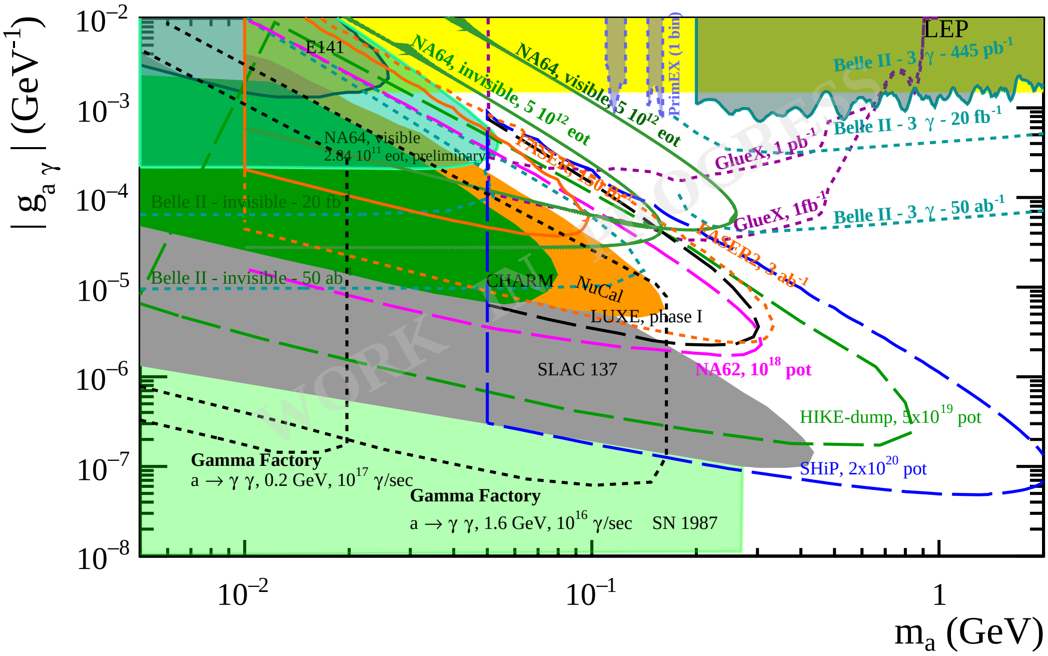

Figure 9. **Axions/ALPs with photon coupling (BC9).** Region of interest for accelerator-based experiments up to a few GeV. Shaded areas are excluded regions from: LEP (data: [172–175]; interpretation: [176]); Belle II [177]; E137 [53]; NA64 [178]; CHARM [105]; NuCal [179]. Curves are projections from: NA62-dump [73]; Belle II [180] for 20 fb^{-1} and 50 ab^{-1}; SHiP [93]; FASER [114] and FASER2 [80]; NA64$_e^{++}$ [74] in visible and invisible modes; LUXE-phase 1 [181]; HIKE-dump [81]; Gamma Factory [182].

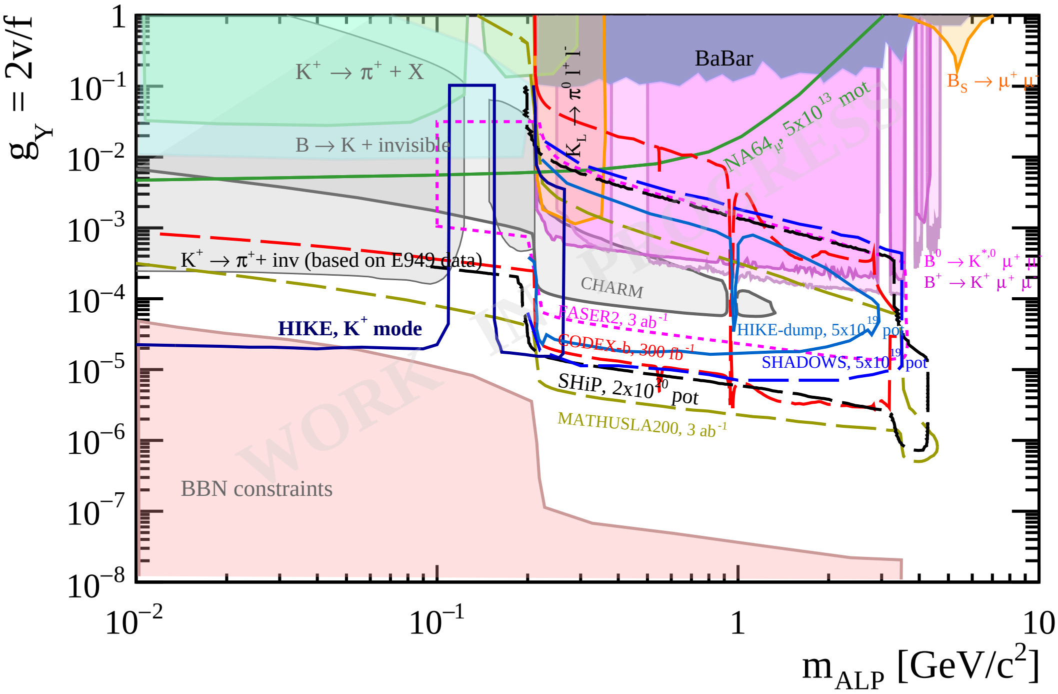

Figure 10. **Sensitivity to ALPs with fermion couplings (BC10).** Current bounds and future projections for 90% CL exclusion limits. Current bounds (filled areas) and prospects (solid lines) from FASER2 [114], CODEX-b [78], MATHUSLA [32], HIKE-K^+ and in dump mode [81], SHADOWS [92], and SHiP [93]. CHARM and LHCb filled areas have been adapted by F. Kahlhoefer, following Ref. [183].

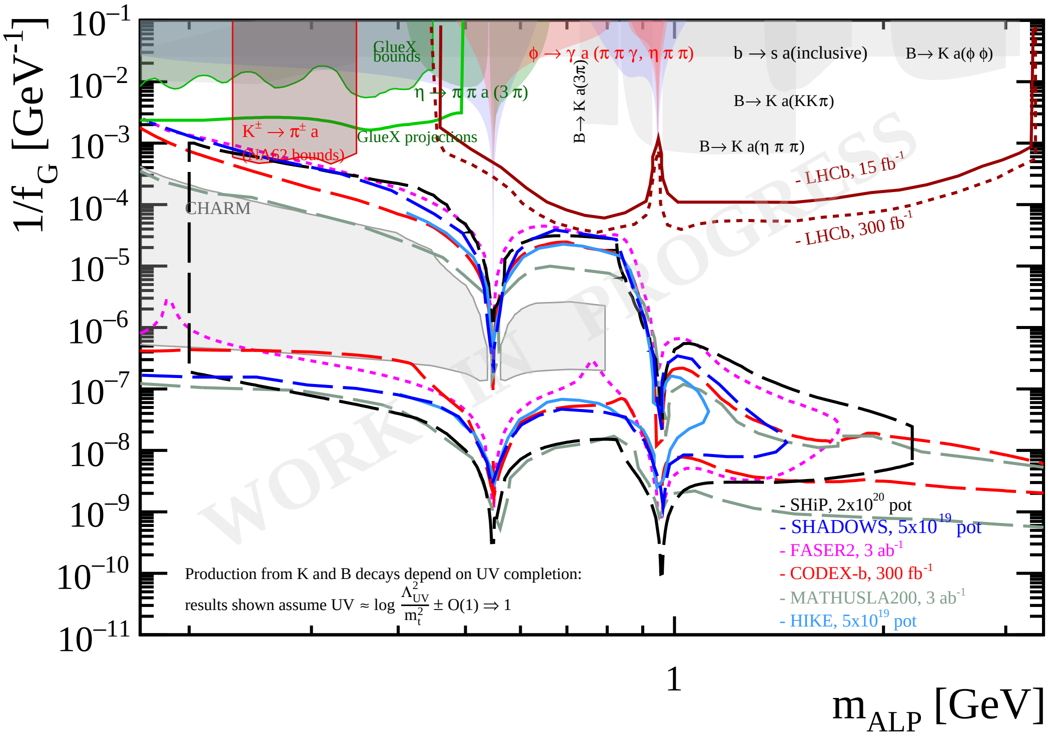

Figure 11. **Sensitivity to ALPs with gluon coupling (BC11).** Current bounds and future projections for 90% CL exclusion limits. Current bounds are shown as filled areas, projections as lines. **Current bounds:** CHARM gray filled area has been computed by F. Kling, recasting the search for long-lived particles decaying to two photons performed at CHARM [140]. Other coloured filled areas are kindly provided by Mike Williams and revisited from Ref. [184]. The gray areas depend on UV completion and the results shown assume $\approx [\log\Lambda^2_{\rm UV}/m_t^2 \pm \mathcal{O}(1)] \Rightarrow 1$. **Projections:** LHCb with 15 fb^{-1} and 300 fb^{-1} [152]; CODEX-b with 300 fb^{-1} [153]); MATHUSLA with 3 ab^{-1} (estimate from [153]); FASER2 with 3 ab^{-1} [80]; SHiP with 2×10^{20} pot [93]; SHADOWS [92] and HIKE-dump [81] with 5×10^{19} pot each.

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