Features of new physics in FIPs searches

at LHC-based LLP detectors

for the ANUBIS Experiment

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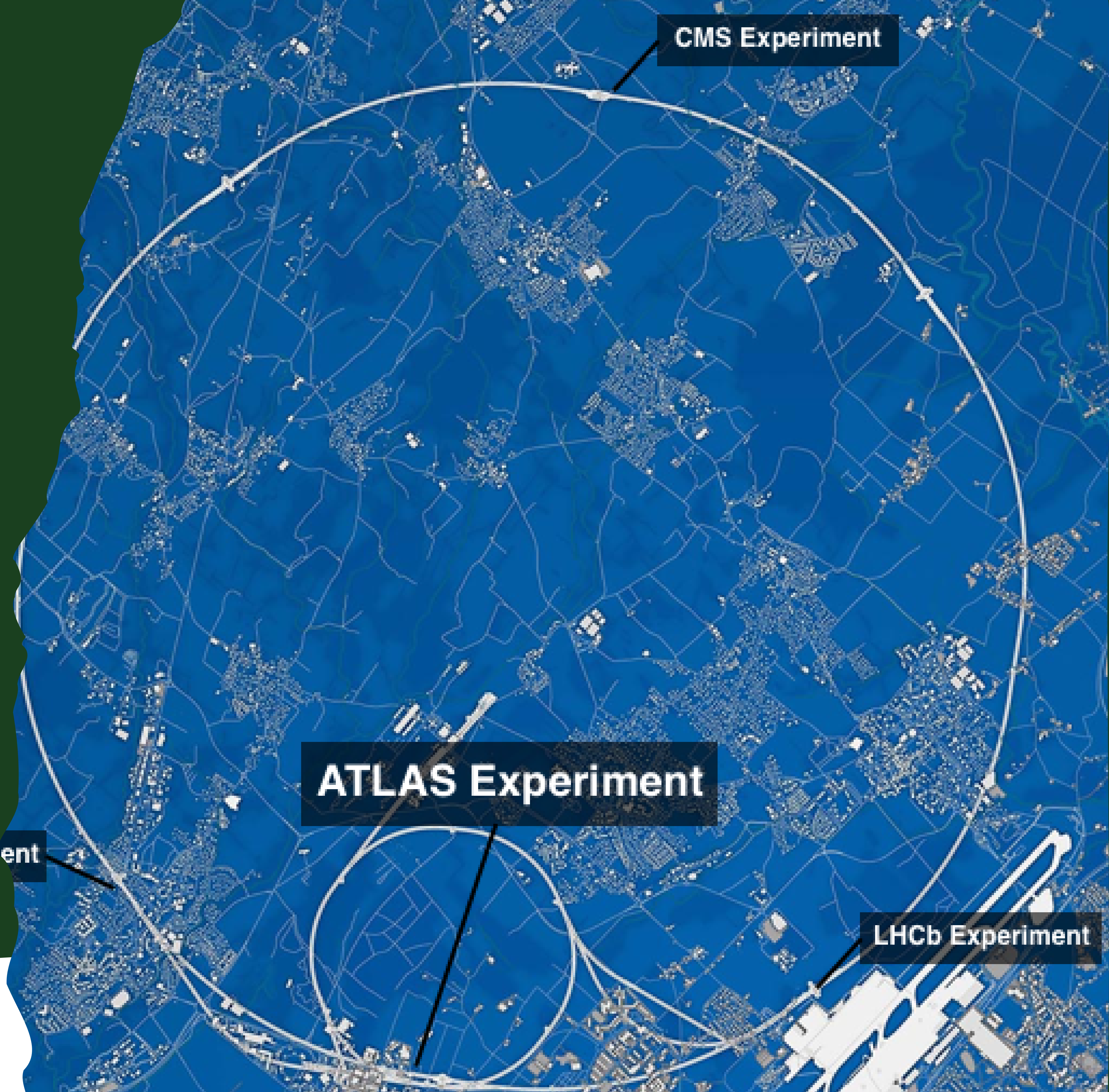

ATLAS EXPERIMENT

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Physics Beyond Colliders

FIPs & LLP models

Hidden Valley / Sector / FIP revolution reshaped the theoretical and experimental particle physics landscape

- Shift away from focus only on states at ever higher energies

- Hidden sectors appear generically in many UV complete theories (e.g. strings)

- Heavy mediators can mediate rare decays / flavour violating processes

Generic physics features:

- Light DS hidden by high barrier to interactions with SM
- Explains DM using some symmetry to stabilise at least one hidden sector state
- Results in neutral bound states with low masses and long lifetimes
- DS states decay to SM through heavy mediators
- Mechanisms to set the DM relic abundance

Classes of models:

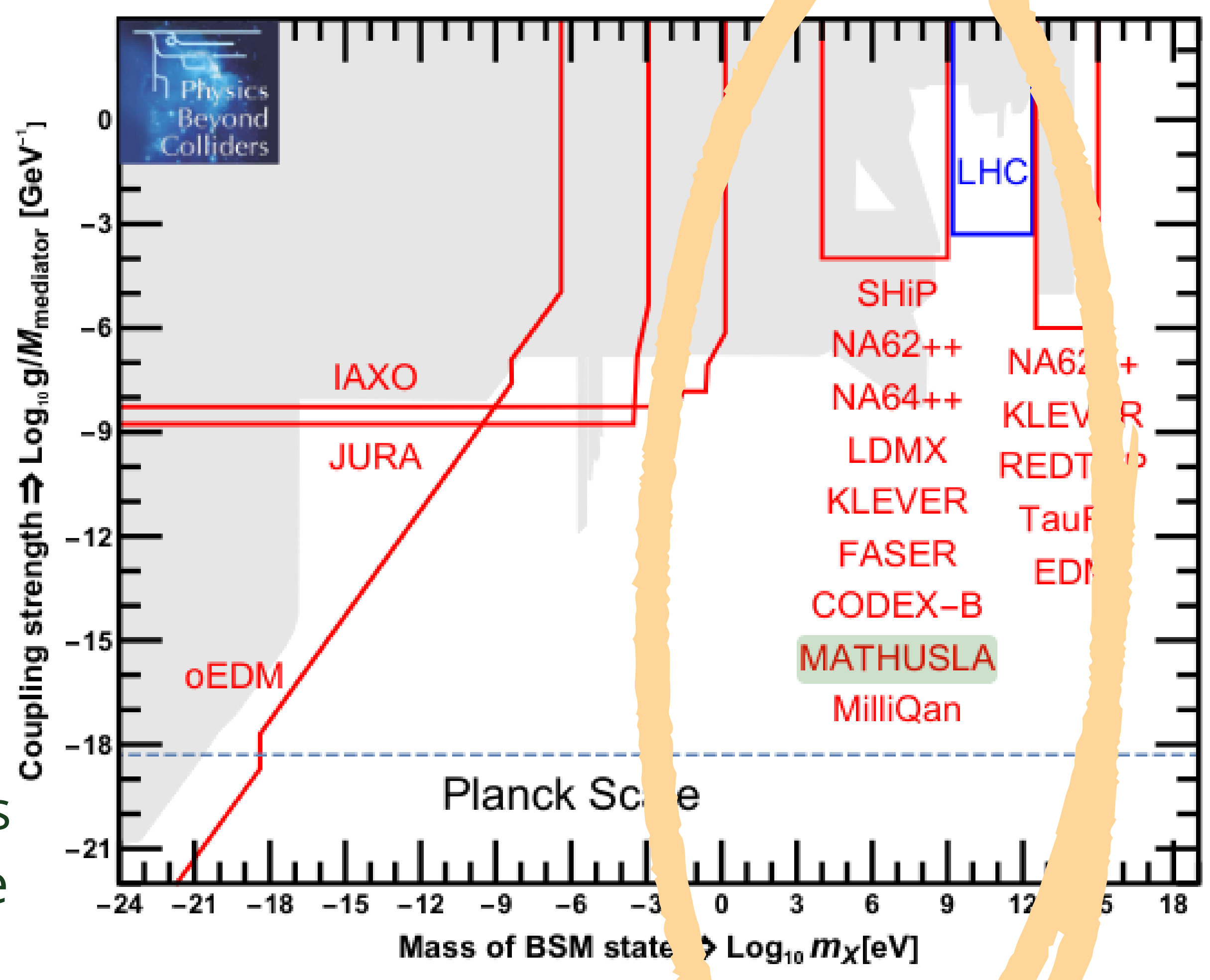
- Common benchmark models for comparison across experiments
- Simplicity: minimal vs. non-minimal models

Flexible structure of hidden sector → wide range of models. How should we organise our search at ANUBIS?

Experiments & search strategies

Strategies for covering remaining LLP parameter space
Target mass & lifetime of LLP

- Filling gaps in parameter space
  - E.g. lifetimes longer than 10^8 seconds are less constrained by LHC experiments
  - Lifetimes shorter than a few minutes are less constrained by BBN
  - Sensitivity in MeV-GeV range



Transverse vs forward LHC LLP detectors

- Forward:
  - Light, weakly interacting particles produced dominantly along beam axis
- Transverse:
  - Heavier / more strongly interacting LLPs

Concentrating on ANUBIS:

- Focus on scenarios predicting LLPs boosted in transverse direction
- Signatures from production of unstable portal/DS particle with displaced decay to SM
- Signatures from extended DS with additional Higgs/Z boson couplings

Contents

Models – generic features

Aims:

- Organise our search for specific models
  - by comparing sensitivity projections with other LLP detectors
  - and identifying interesting model parameter space

The search for thermal relic DM so far:

- GeV-TeV scale: null results in direct/indirect/LHC DM experiments
- MeV-GeV scale: thermal relic DM is much less constrained

Link to dark matter:

- If **thermal / freeze-out** (direct thermal contact with SM) → small set of highly predictive portal models
- If **non-thermal / freeze-in** (DM never reached equilibrium with thermal bath) → many complicated & less constrained models

⇒ Focus on predictive thermal DM models

PBC benchmark models:

- Motivated by Dark Sector / Hidden Valleys
- Categorising the dimension-4 and -5 portal interactions allowing a total SM singlet to interact with SM fields
- 11 benchmarks

Generic search strategies:

- **Direct freeze-out:** DM freezes out directly to SM final states
  - Mediator decays into DM which is lightest state
  - **Mainly invisible decays**
  - Missing energy, sharply-characterised production targets
- **Secluded freeze-out:** DM freezes out into mediator particles
  - Mediator/at least one DS particle is lighter than DM
  - **Mediator decays visibly**

Hidden Valleys – PBC

General classification for LLP scenarios

- Hidden sector states with mass scales below the weak scale are hidden from the visible sector due to a high barrier (i.e. sub-weak interactions between sectors)
- Flexible structure: strongly or weakly coupled, dark photons or Higgses, a dark SU(N) with N_f flavours, sterile neutrinos or asymmetric dark matter, wide range of dynamics

Lowest-dimensional renormalisable portals

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$
Sterile Neutrino, N	$y_N L H N$

Vector portal (dark photon/Z')
Scalar portal (dark Higgs)
Axion portal (ALPs)
Neutrino portal (HNLs)

PBC benchmarks

- Motivated by simplicity
  - E.g. 3 cases identified for HNL benchmarks, all with only 1 HNL state and single-flavour couplings
- BC1-BC11 describe cases for all 4 above portals

[hep-ph/0604261]

Dark scalar & dark photon/Z'

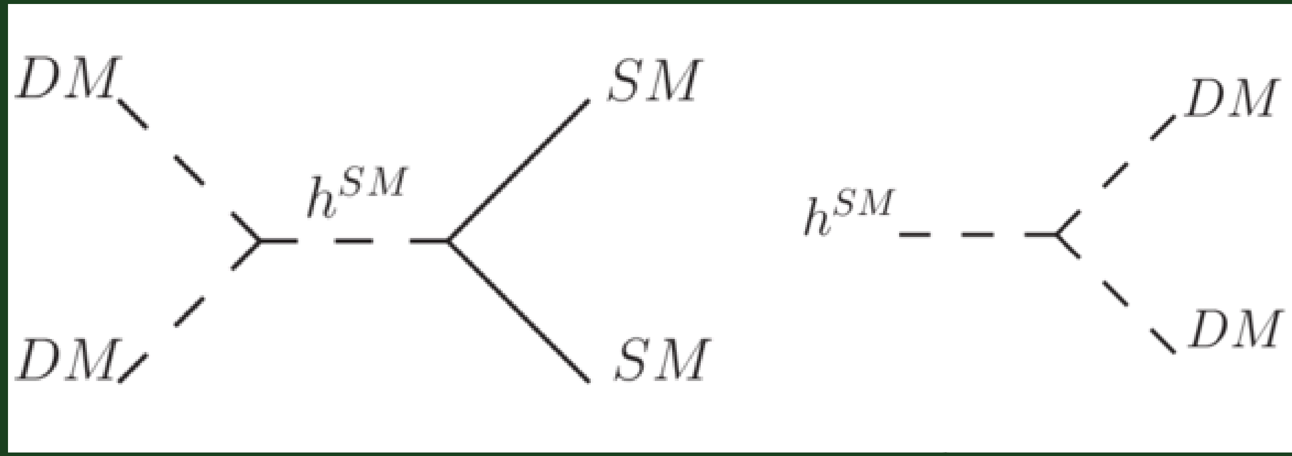
- Renormalizable vector portals mediated by a dark vector boson; scalar portals mediated by a new scalar mixing with the SM Higgs boson
- New vector provides simplest possible thermal freeze-out scenario producing correct relic abundance with MeV-GeV DM masses

Dark scalar/Higgs

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

$$\mathcal{L}_{\text{DS}} = S\bar{\chi}\chi + \ldots.$$

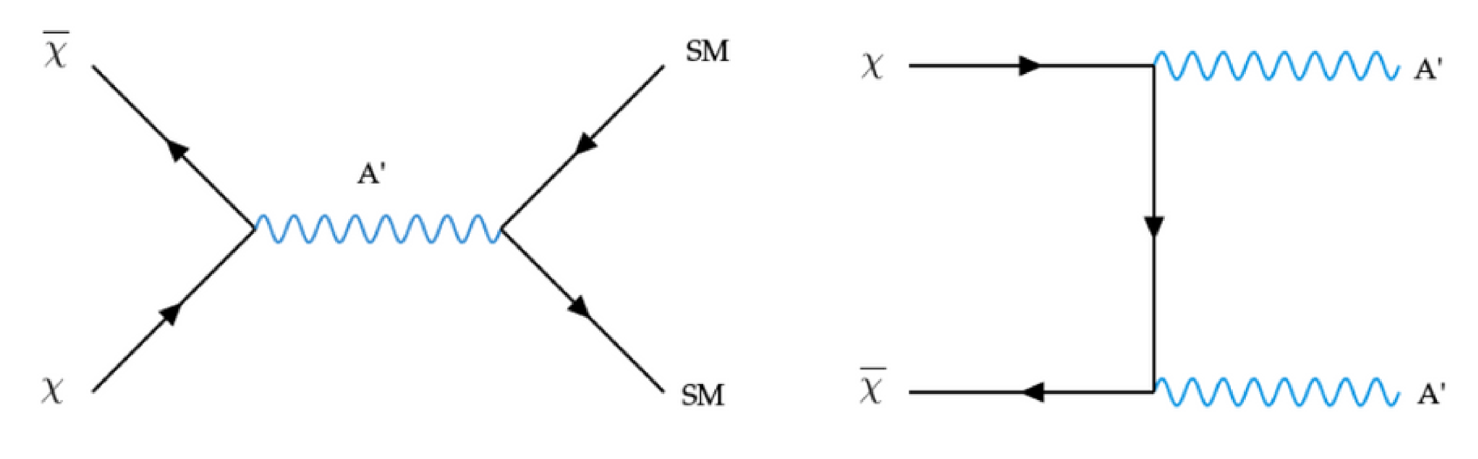
- E.g. if scalar is Higgs boson



Dark vector/photon

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

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



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Heavy Neutral Leptons

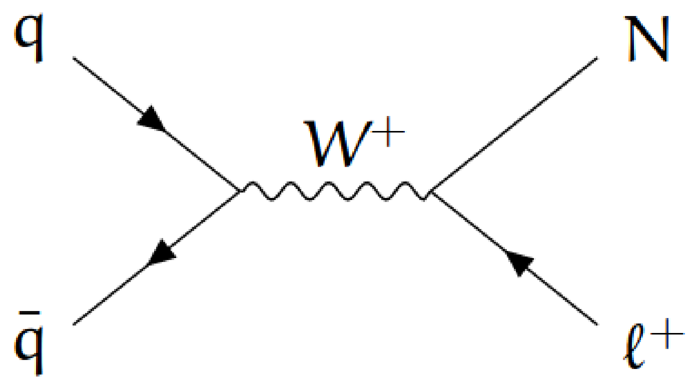
Minimal & non–minimal HNL scenarios

- Explain nonzero neutrino masses via the seesaw mechanism
- Mechanism for generating matter-antimatter asymmetry
- Object of ATLAS and CMS searches covering mass range from a few GeV to several TeV

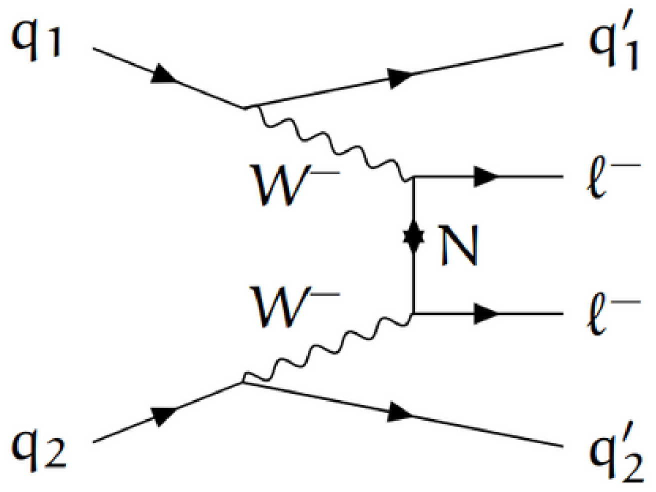
- Take into account different production channels: **D–mesons, B-mesons, W-bosons, Z-bosons, SM Higgs bosons, and the top quark**

- For meson decays, include three-body and two-body decays

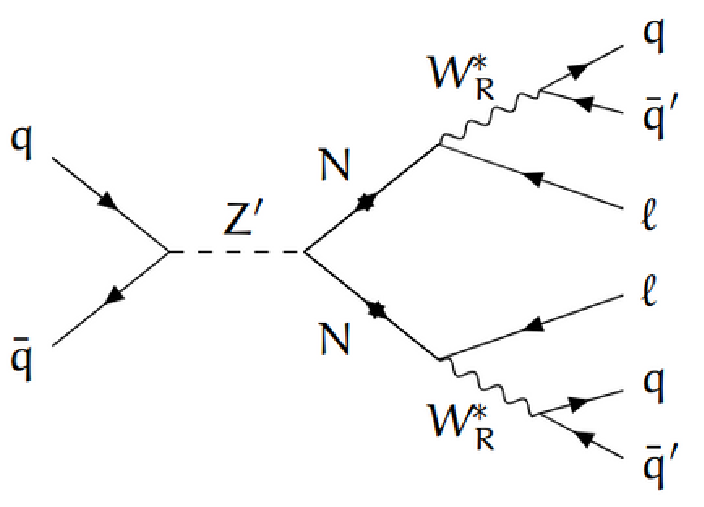
Drell-Yann process in type-I seesaw models



VBF t-channel process in type-I seesaw models



Z' decays



RH sector neutrino mixing matrix

E.g. gauge group with simple SM extension

CC and NC interactions relevant to later analysis

$$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$\mathcal{L} = \frac{g_R}{\sqrt{2}}\left(\bar{d}\gamma^\mu P_R u + V^R_{\alpha N} \cdot \bar{l}_\alpha \gamma^\mu P_R N\right) W^-_{R\mu} + \frac{g_R}{\sqrt{1 - \tan^2\theta_W (g_L/g_R)^2}} \times Z^\mu_{LR} \bar{f} \gamma_\mu \left[T_{3R} + \tan^2\theta_W (g_L/g_R)^2 (T_{3L} - Q)\right] f$$

Interesting scenario:

- Targeting scenarios with large mass gap between HNL and Z' such that HNLs and decay products are highly boosted

Non–minimal LLP models

Rich structure and phenomenology

Inelastic DM

- DM + mediator + additional particles
- Best probed at high intensity experiments

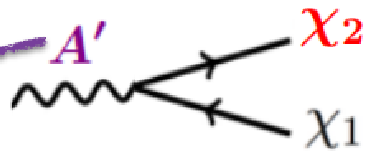
The only relevant interaction is inelastic:

$$\mathcal{L} \supset \frac{i e_D \, m_D}{\sqrt{m_D^2 + (\delta_\xi - \delta_\eta)^2/4}} A'_\mu \left(\bar{\chi}_1 \gamma^\mu \chi_2 - \bar{\chi}_2 \gamma^\mu \chi_1\right)$$

The elastic piece is very small $(\delta_{\eta,\xi} \ll m_D)$:

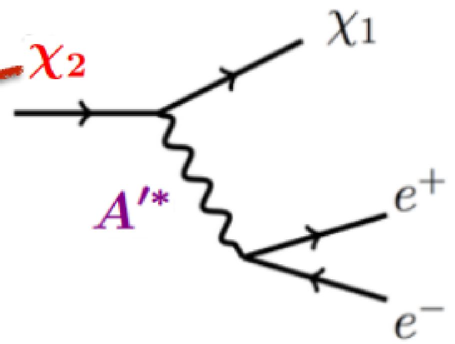
$$\mathcal{L} \supset \frac{e_D \, (\delta_\xi - \delta_\eta)}{\sqrt{4 m_D^2 + (\delta_\xi - \delta_\eta)^2}} A'_\mu \left(\bar{\chi}_2 \gamma^\mu \chi_2 - \bar{\chi}_1 \gamma^\mu \chi_1\right)$$

$m_\chi < m_{A'}$



Copiously produced at high intensity experiments

with



$$\Gamma(\chi_2 \to \chi_1 e^+ e^-) \simeq \frac{4\epsilon^2 \, \alpha_{em} \, \alpha_D \, \Delta^5 m_1^5}{15 \pi m_{A'}^4}$$

E.g: BC_{iDM}

Complex DM of BC2 split into 2 non-degenerate real states

SIMPs

- Standard thermal freeze-out via 2 --> 2 annihilation
  - Predicts a TeV scale mass range

$$m_{\rm DM} \sim \alpha_{\rm ann} \left(T_{\rm eq} M_{\rm Pl}\right)^{1/2} \sim \ {\rm TeV}$$

matter-radiation equality temperature

- In SIMP models, freeze-out via 3 --> 2 annihilation
  - Points to sub-GeV scale DM

$$m_{\rm DM} \sim \alpha_{\rm eff} \left(T_{\rm eq}^2 M_{\rm Pl}\right)^{1/3} \sim 100 \ {\rm MeV}$$

effective strength of SIMP self-interaction (order 1)

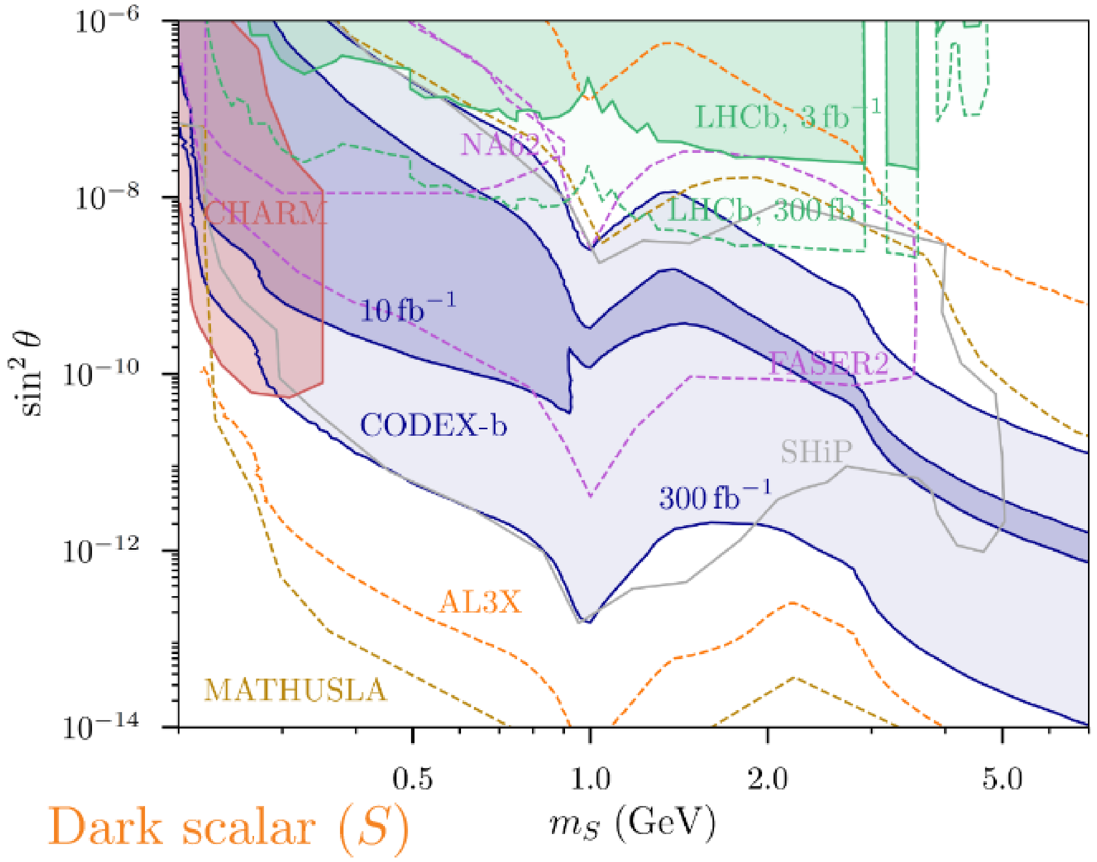
1402.5143.pdf

LHC transverse LLP detectors

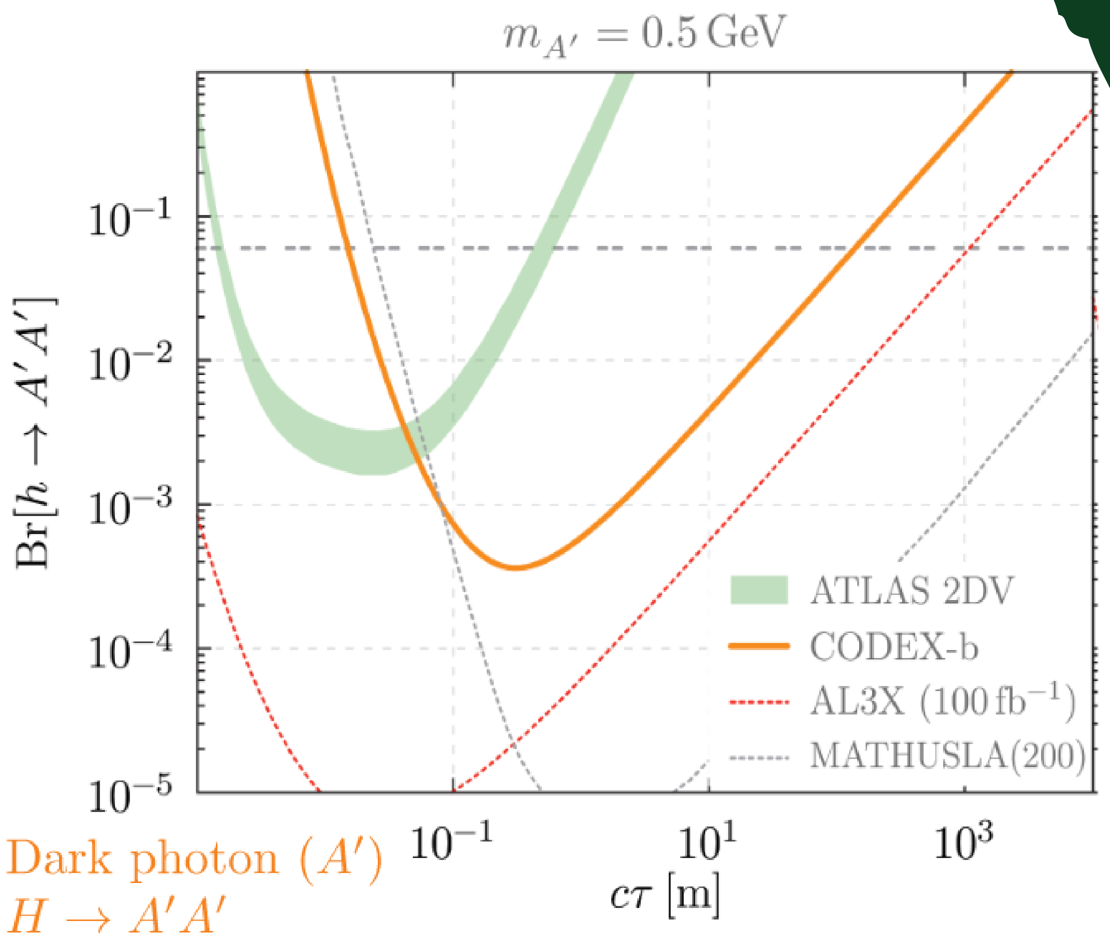
	MATHUSLA Massive Timing Hodoscope for Ultra-Stable neutral particles	**CODEX-b** A Compact Detector for Exotics at LHCb
Experimental setup	• large decay volume 200 m x 200 m x 20 m near CMS • RPCs as sensor technology	• smaller acceptance and luminosity than MATHUSLA but closer proximity to IP so overall competitive in low-lifetime regime • 10 m x 10 m x 10 m tracker box
Combined analysis	• supply an L1 trigger to ensure retention of relevant info at CMS • allows to determine production mode, decay mode, parent particle mass (if applicable)	• proximity to LHCb permits interface with LHCb's planned triggerless readout, allowing identification and partial reconstruction of LLP event
Shielding / backgrounds	• located above ground but partly excavated, 100m horizontally and vertically away from IP • relying on shielding to deliver small/zero backgrounds	• behind a 3.2 m thick shield • largest gains in reach for relatively light LLPs (<10 GeV) ◦ where backgrounds in ATLAS and CMS are prohibitive

Portal models – projections

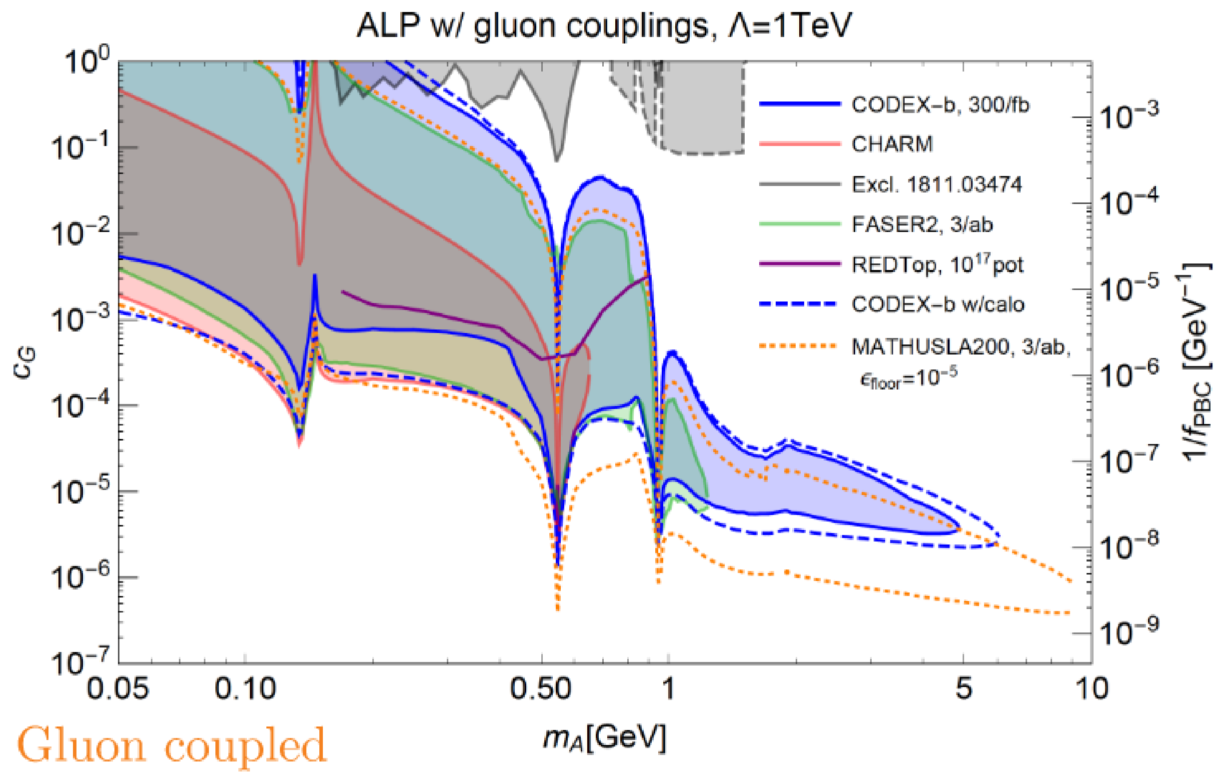
MATHUSLA, CODEX-b 2251269/3819001/CODEX-b



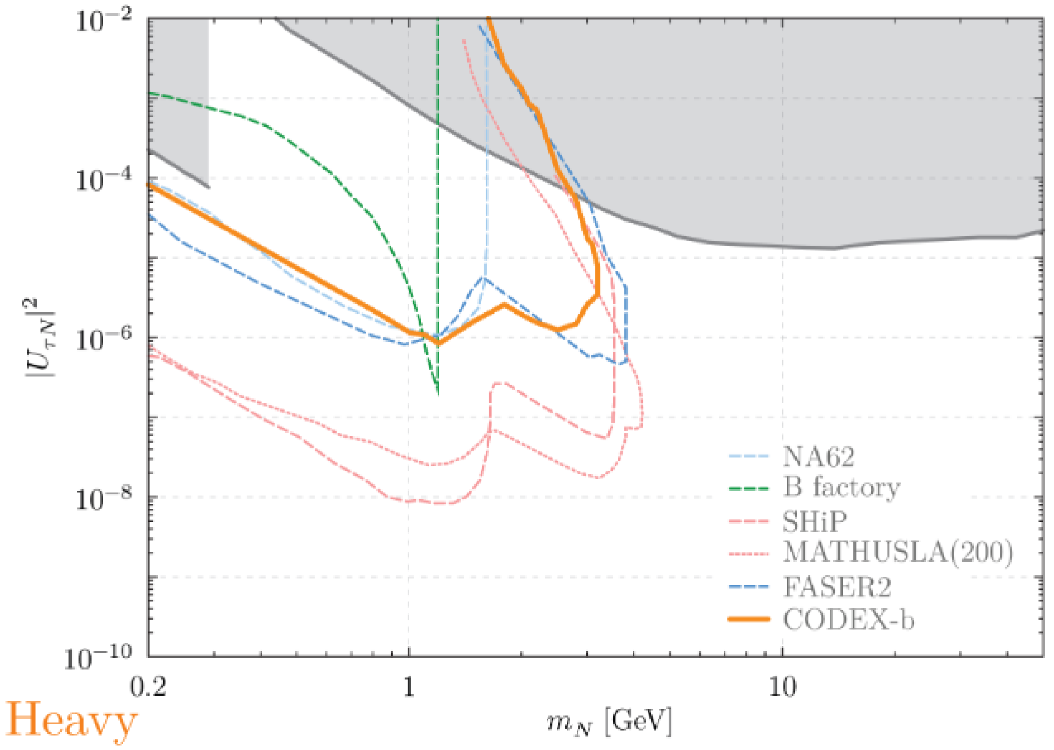
Dark scalar (S)
$H \to SS$



Dark photon (A')
$H \to A'A'$



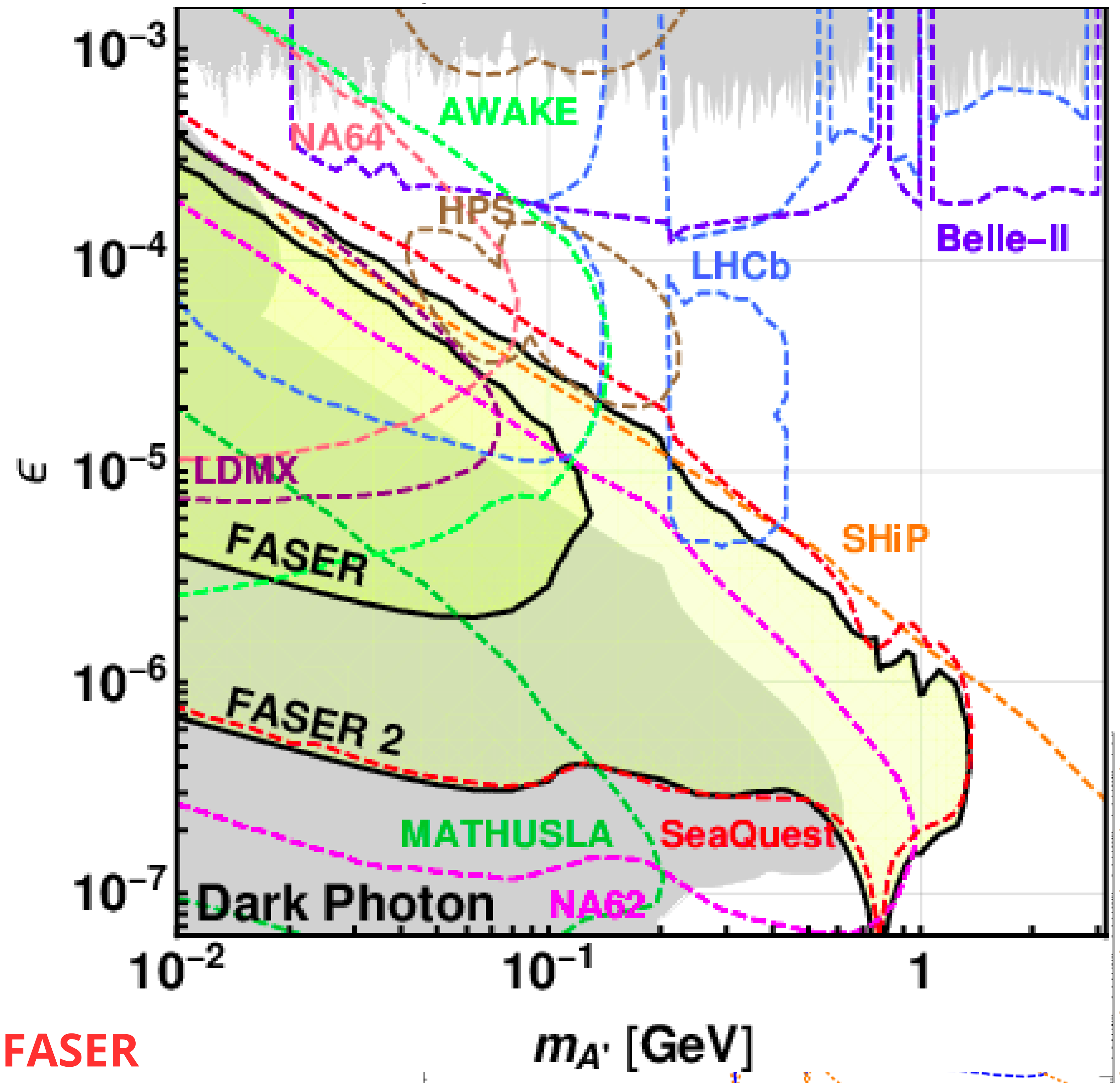
Gluon coupled ALPs



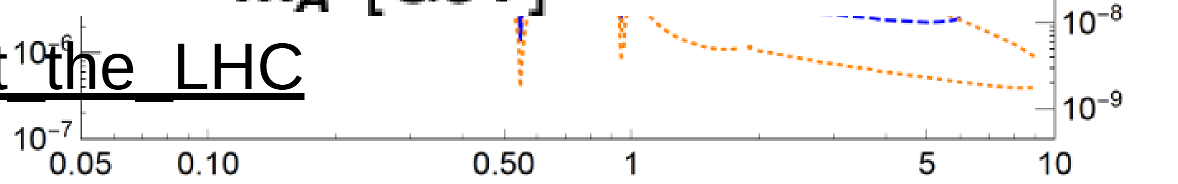
Heavy neutral leptons

Portal models – projections

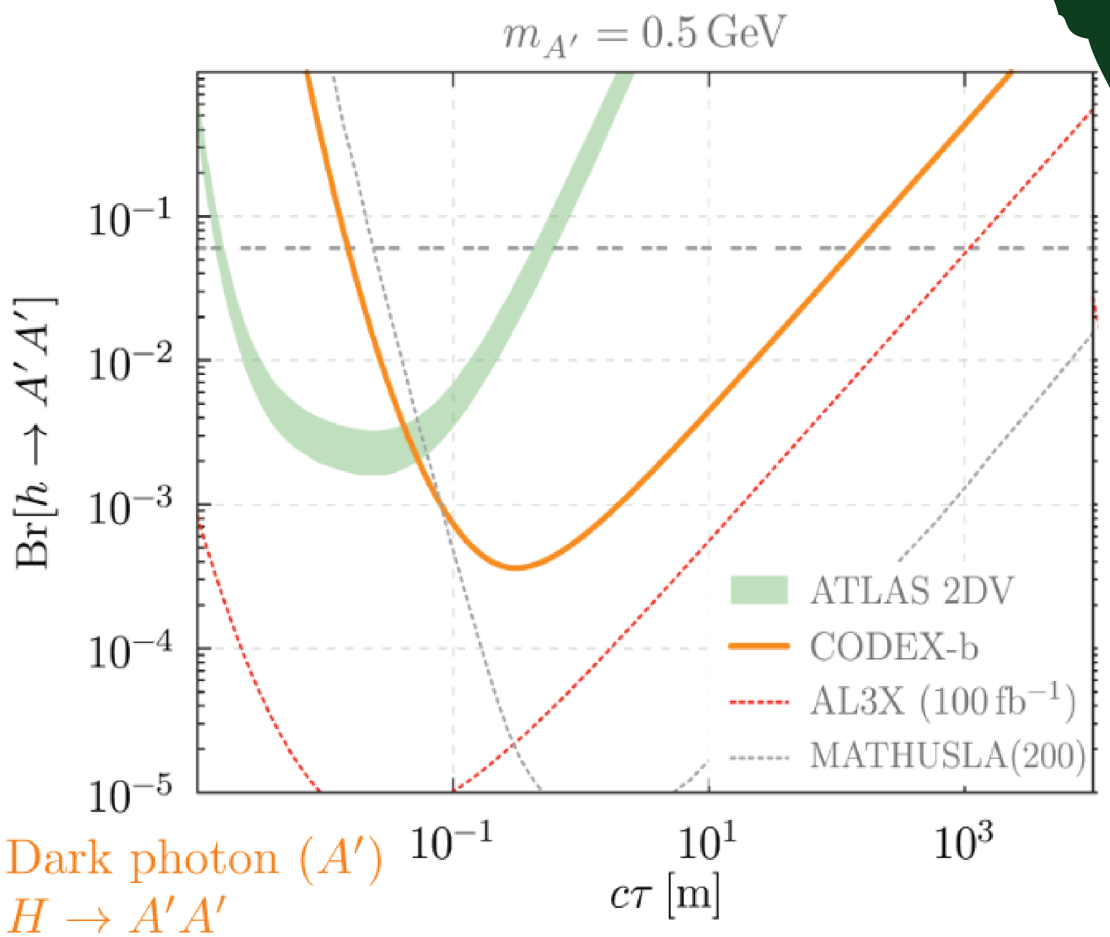
MATHUSLA, CODEX-b 2251269/3819001/CODEX-b



FASER
BSM_Particles_at_the_LHC



Gluon coupled ALPs



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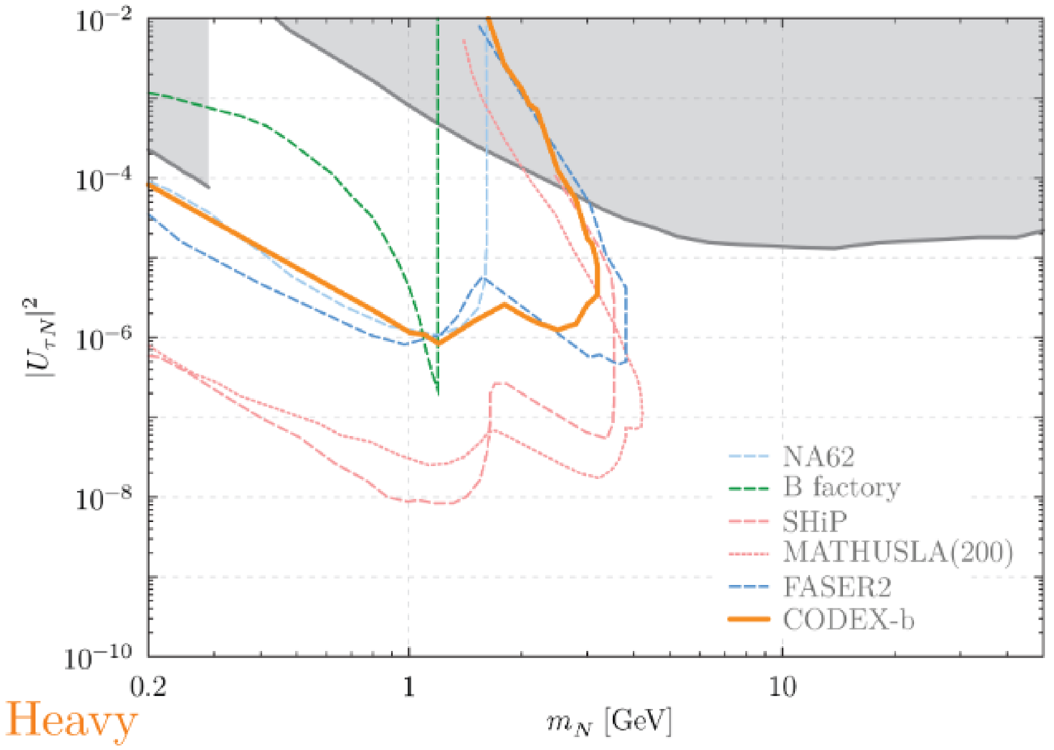
$H \to A'A'$

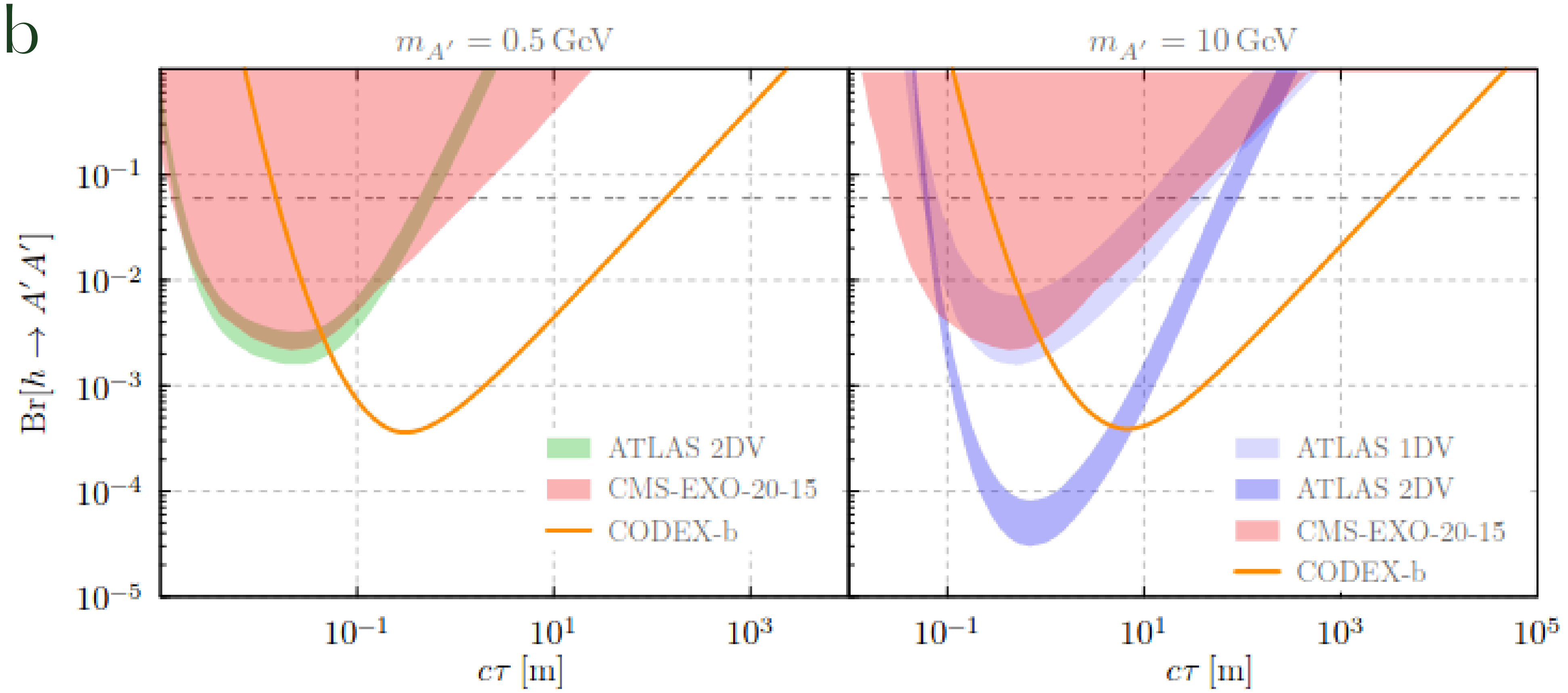


Heavy neutral leptons

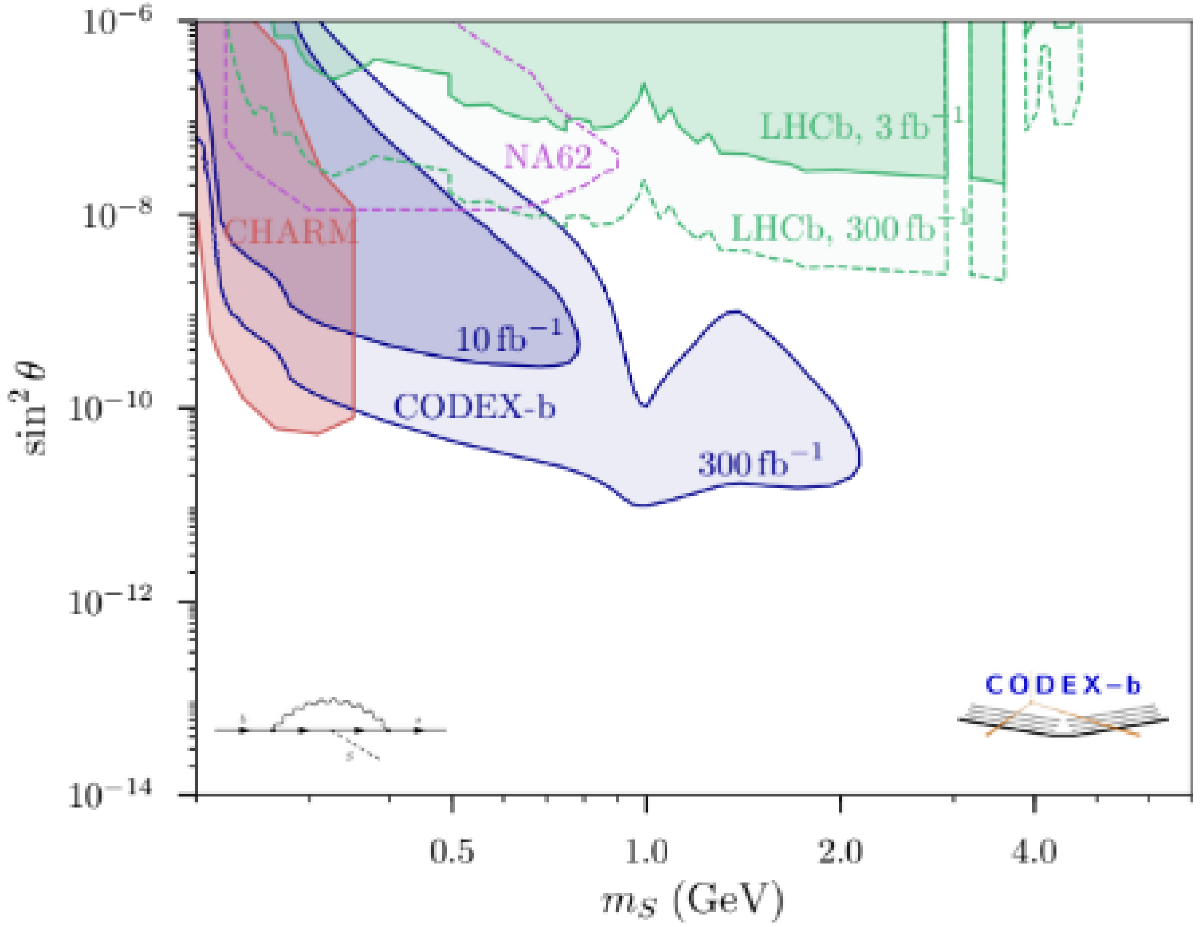
Scalar & vector portal bounds

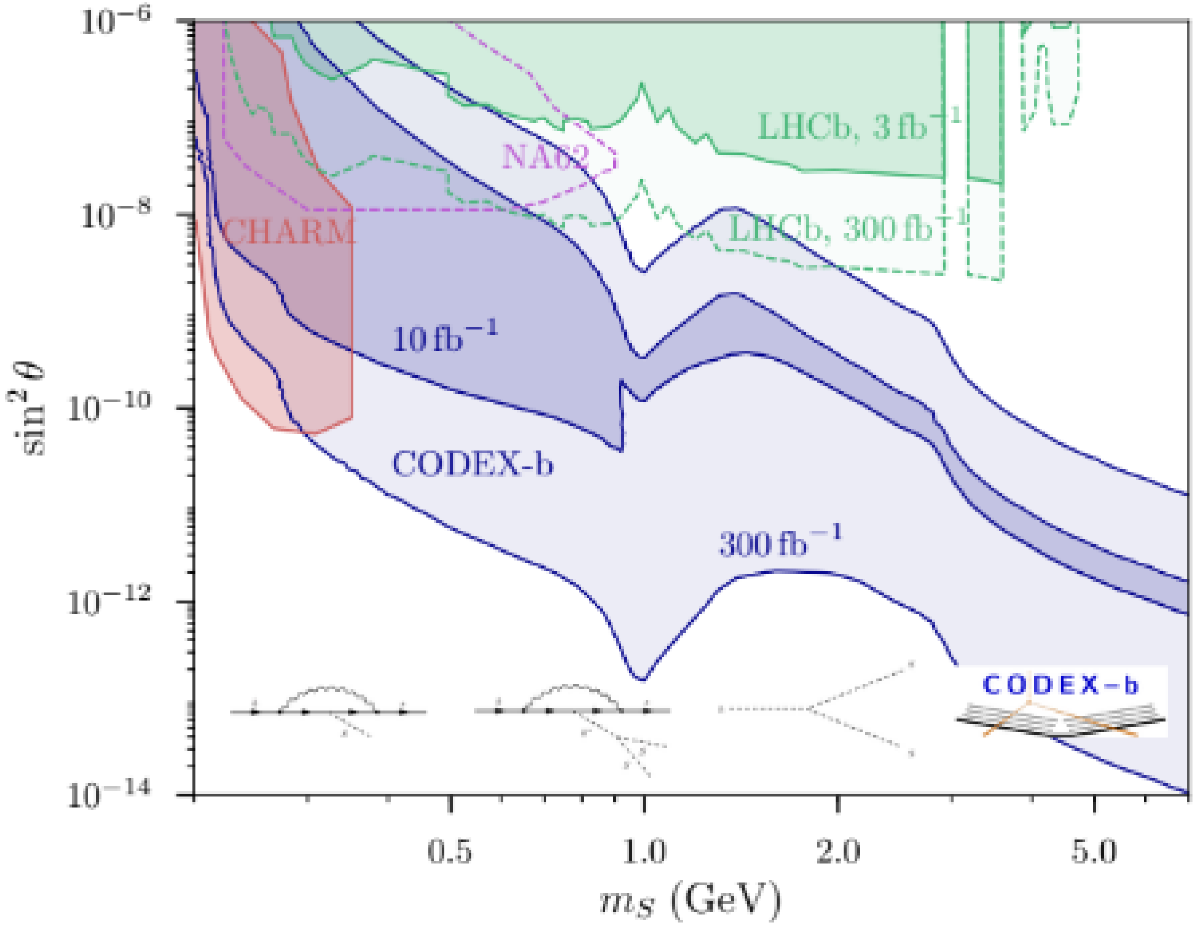
More detail on CODEX-b

Dark Higgs



Dark photon





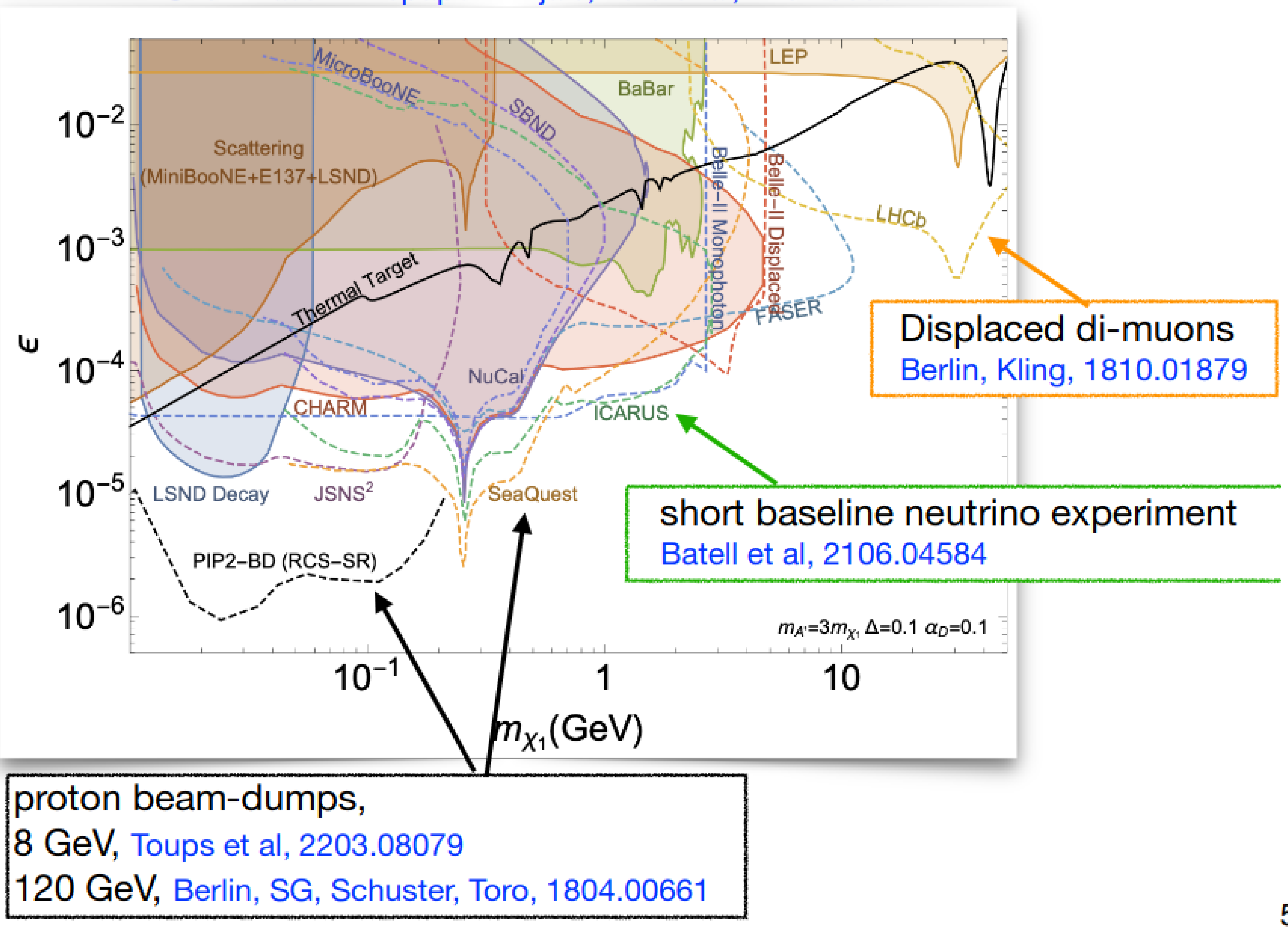
Non–minimal model – projections

MATHUSLA, CODEX-b

Fermionic inelastic DM:

- small mass splitting between 2 DM states -> require high intensity collider searches
- off-diagonal coupling of dark photon to 2 DM states motivates semi-visible search strategy

Snowmass whitepaper Krnjaic, Toro et al, 2207.00597



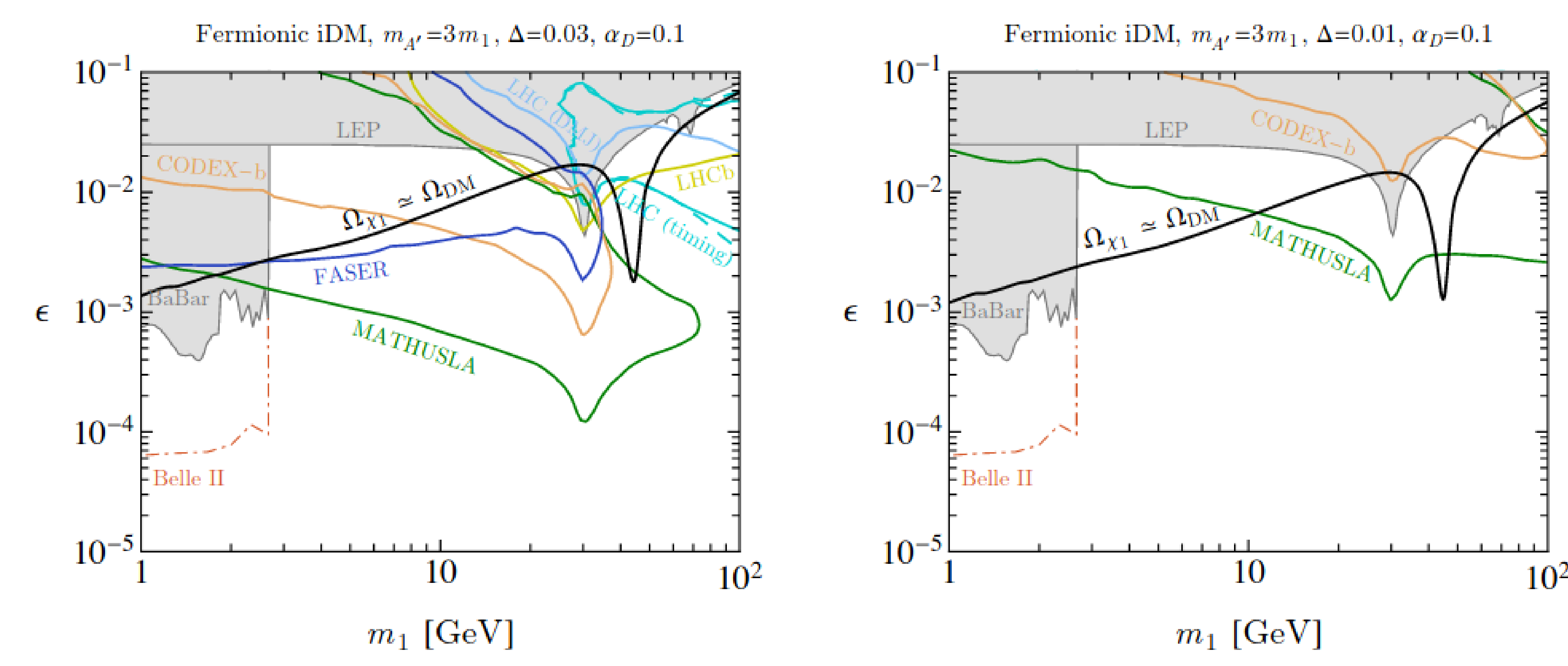


Figure 72: Reach of MATHUSLA and other LHC experiments and searches for inelastic Dark Matter (iDM) with a dark photon of mass $m_{A'}$ that has kinetic mixing ϵ with the SM photon, and mass splittings Δ in the percent range. The black curve indicates where thermal co-annihilations $\chi_2\chi_1 \to A' \to f\bar{f}$ SM fermions give the observed DM relic density. Figure taken from [851].

SIMP: future aims to add MATHUSLA, CODEX-b (& ANUBIS?) to SIMP model plots

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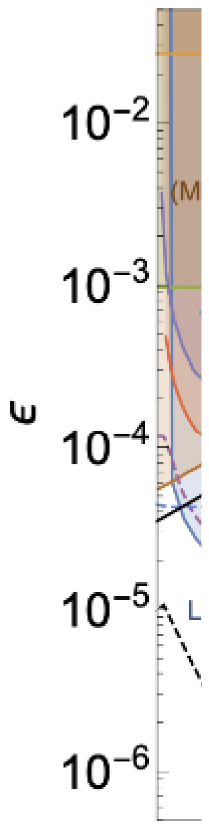
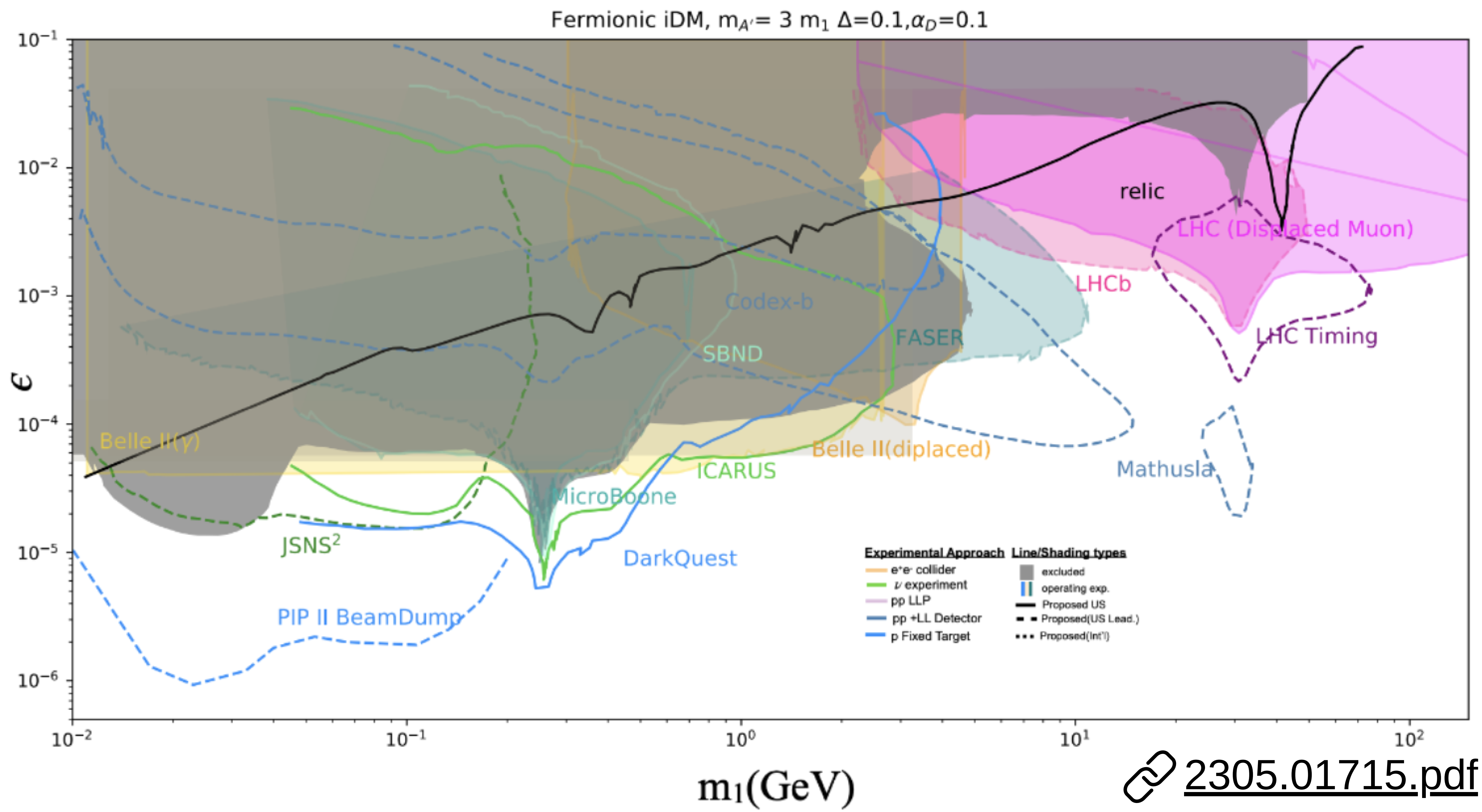


proton be
8 GeV, To
120 GeV,



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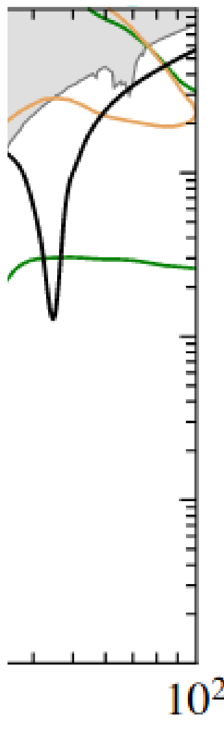
the dark photon decays to an unstable particle with a mass splitting between the excited particle(m_2) and dark matter particle(m_1) given by $\Delta = \frac{m_2 - m_1}{2(m_2+m_1)} = 0.1$ and a dark matter coupling given by $\alpha_D = 0.1$.

DEX-b



k Matter
splittings
$\to f\bar{f}$

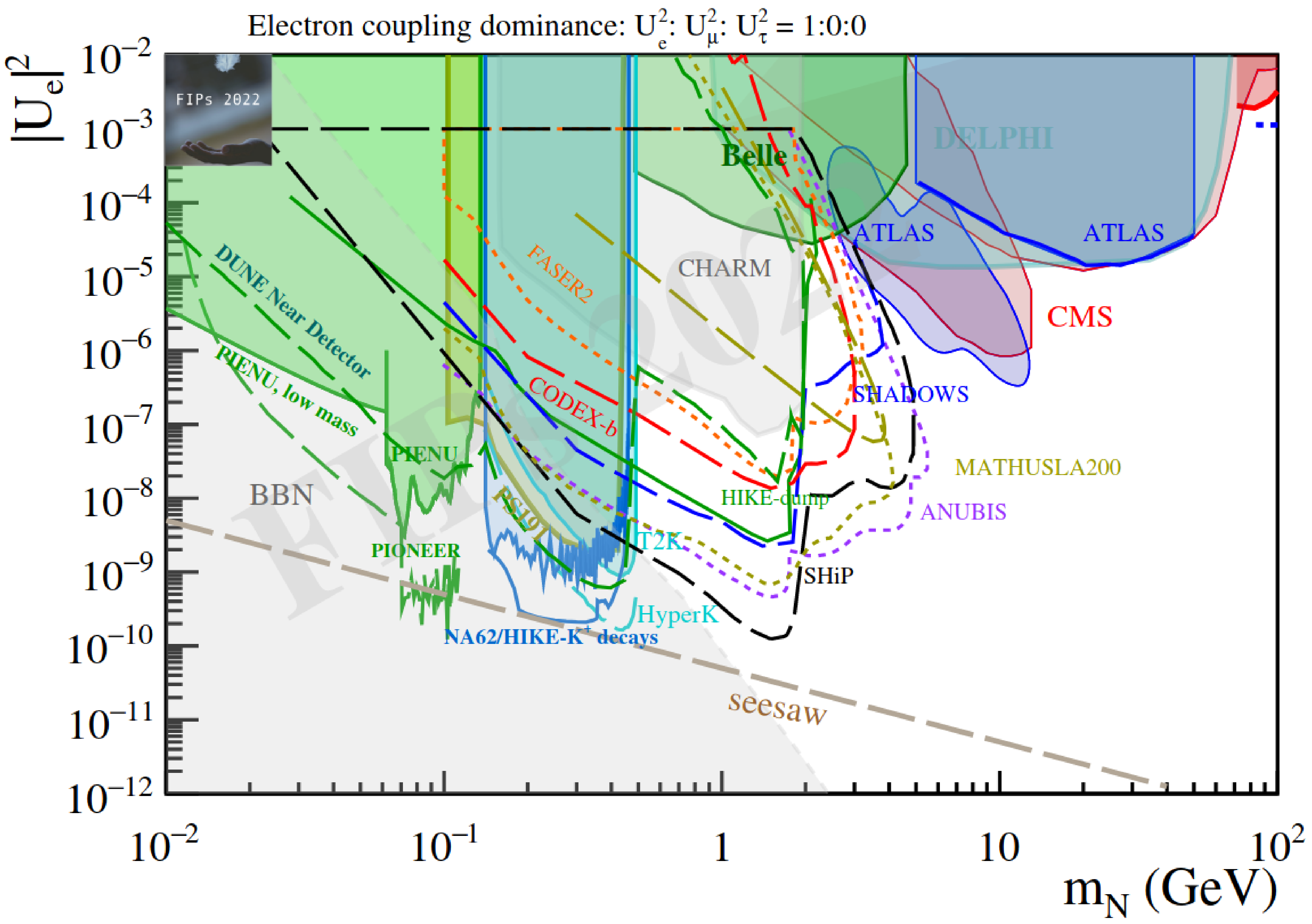
SIMP: future aims to add MATHUSLA, CODEX-b (& ANUBIS?) to SIMP model plots

HNLs – ANUBIS

- For the minimal HNL scenario, the contributions from W's decaying to HNLs are more important at ANUBIS than at MATHUSLA, extending the sensitivity to slightly larger HNL masses at ANUBIS

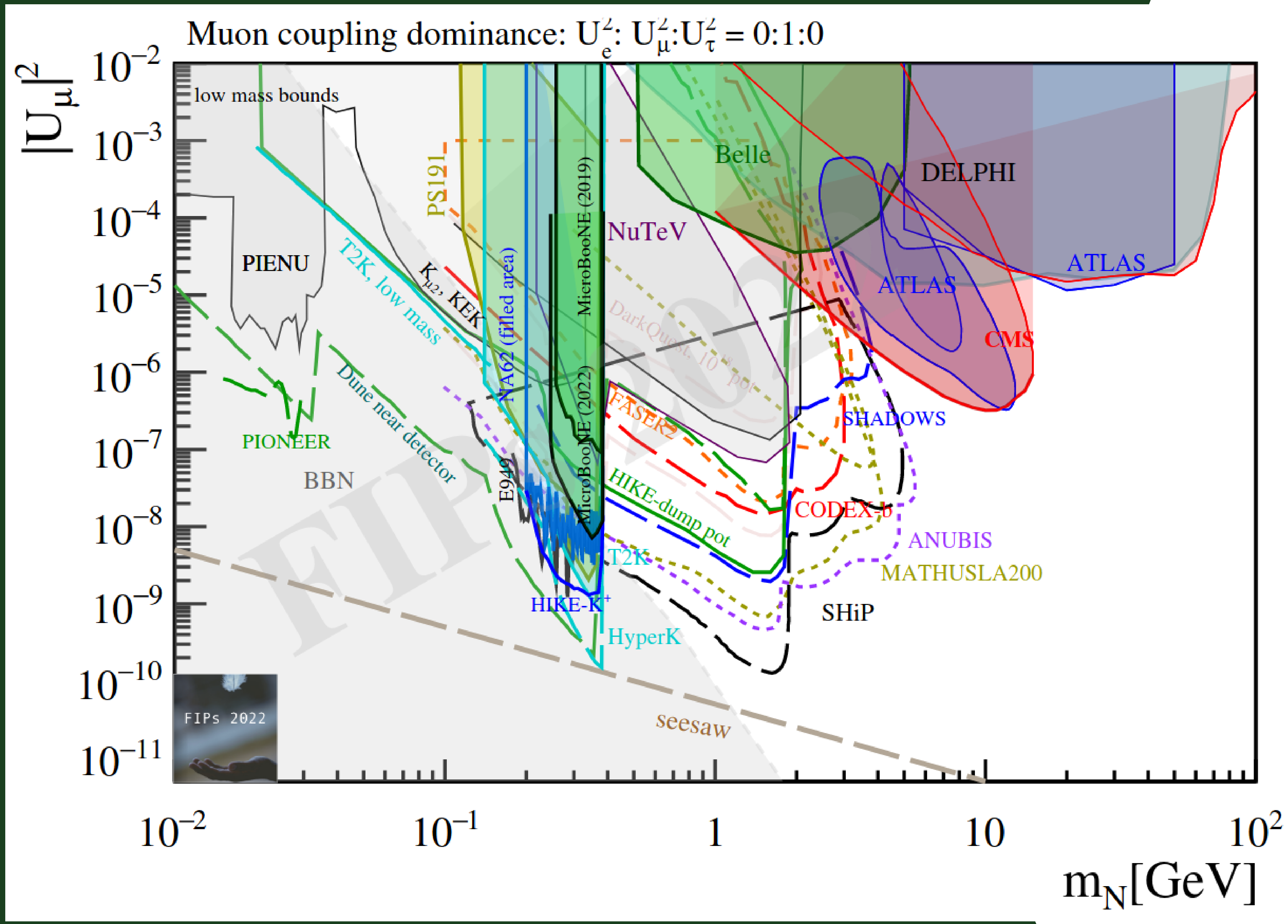
- Plots assume previous (shaft not cavern) geometry of ANUBIS so must be recalculated
  - Cavern configuration: sensitive to the products of neutral LLP decays occuring between the ATLAS muon spectrometer and the cavern ceiling
  - Shaft configuration (outdated): sensitive to decays which occur within the PX14 service shaft

Sensitivity to HNL with electron coupling (BC6)



Filled grey areas: bounds from interpretation of old data sets or astrophysical data,
Filled coloured areas: bounds set by experiment,
Solid lines: projections based on existing data sets,
Dashed coloured lines: projections based on full MC simulations,
dotted coloured lines: projections based on toy MC simulations.

HNLs – ANUBIS



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- ANUBIS has comparable sensitivity with MATHUSLA for both muon and electron coupling HNLs
- Stronger exclusion potential than forward detectors e.g. FASER2
- Note that these simplified benchmarks are not consistent with neutrino oscillation data in minimal seesaw scenarios (until flavour mixing pattern is expanded to include mixing with >1 flavour - **proposed additional benchmarks**)

Sensitivity to HNL with muon coupling (BC7)

2305.01715

HNLs – ANUBIS

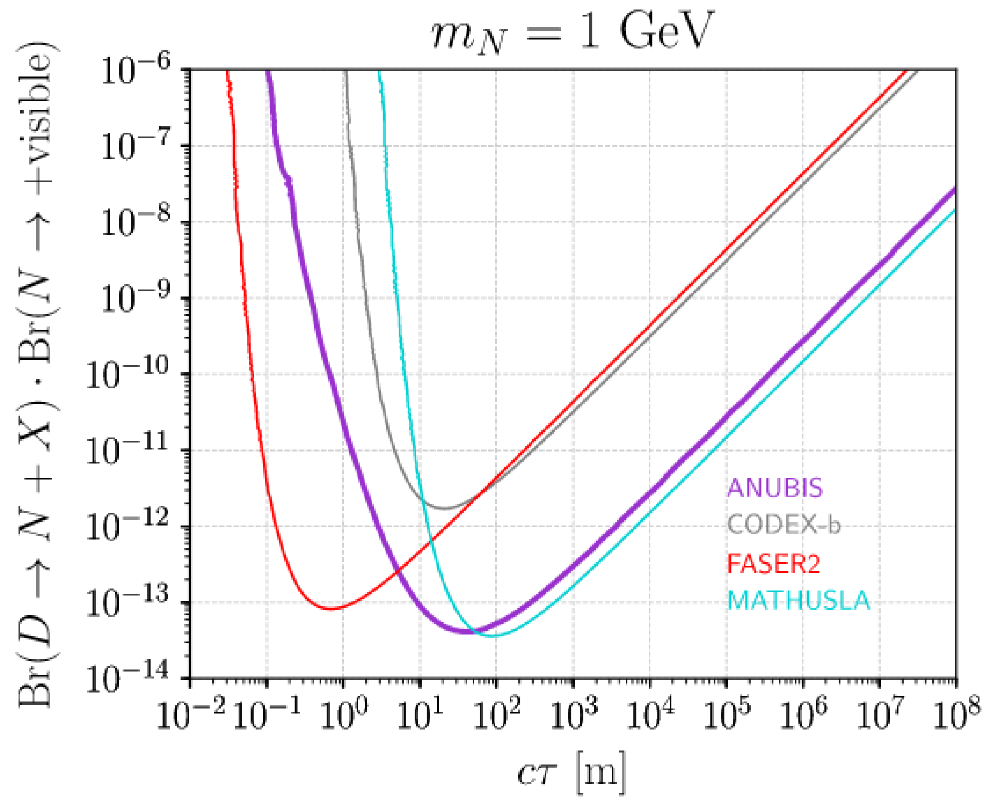
HNL bounds: minimal model

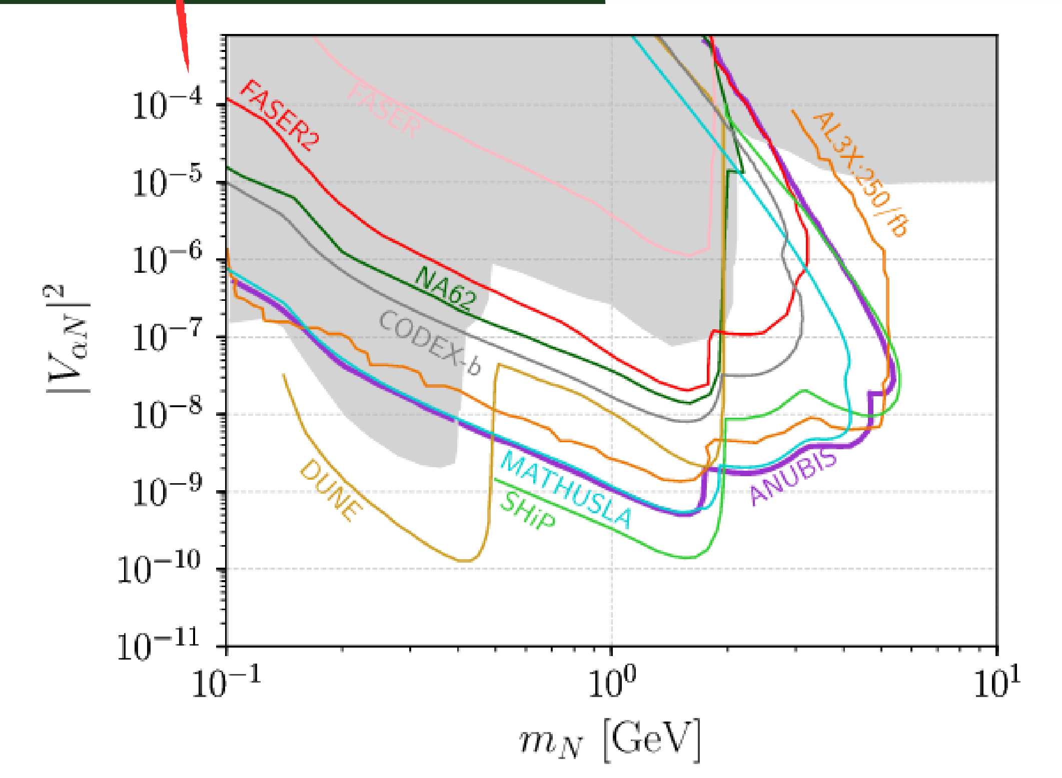
Minimal scenario where production and decay of HNLs controlled by active-sterile neutrino mixing

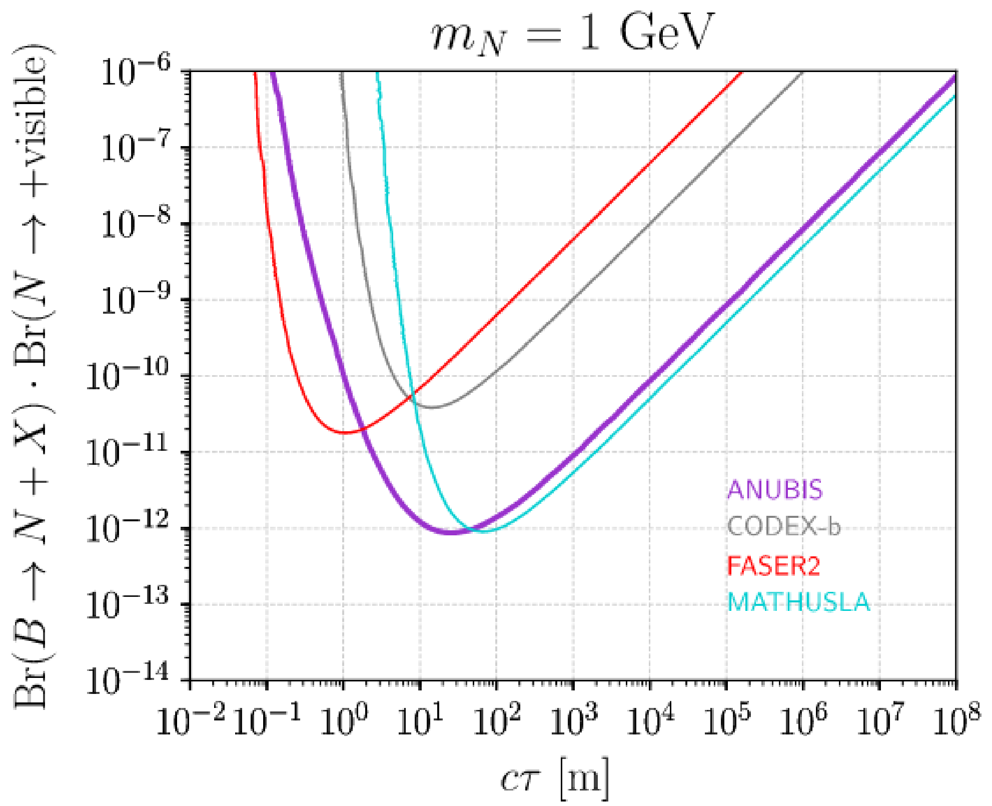
- Despite much smaller instrument volume of ANUBIS, see similar minimum branching ratios to MATHUSLA for B- and D-decays to HNLs
  - Due to smaller distance to IP

Includes dominant production modes: B-, D-mesons and W-bosons

- MATHUSLA has max sensitivity at larger lifetimes for HNLs from both B- and D-decays
  - Due to distance to IP
  - & due to how HNLs of mass 1 GeV travelling inside MATHUSLA typically have boost factors larger than HNLs travelling towards ANUBIS (by factor <2)
- FASER in forward position detects lighter particles, has vastly different sensitivity here







HNLs from D-decays (top) and B-decays (bottom right) in the minimal HNL scenario. HNLs from combined channels (bottom left). HNLs with one generation of N mixing with one of either electron or muon neutrino for combined sensitivities of dominant production modes.

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HNLs – ANUBIS

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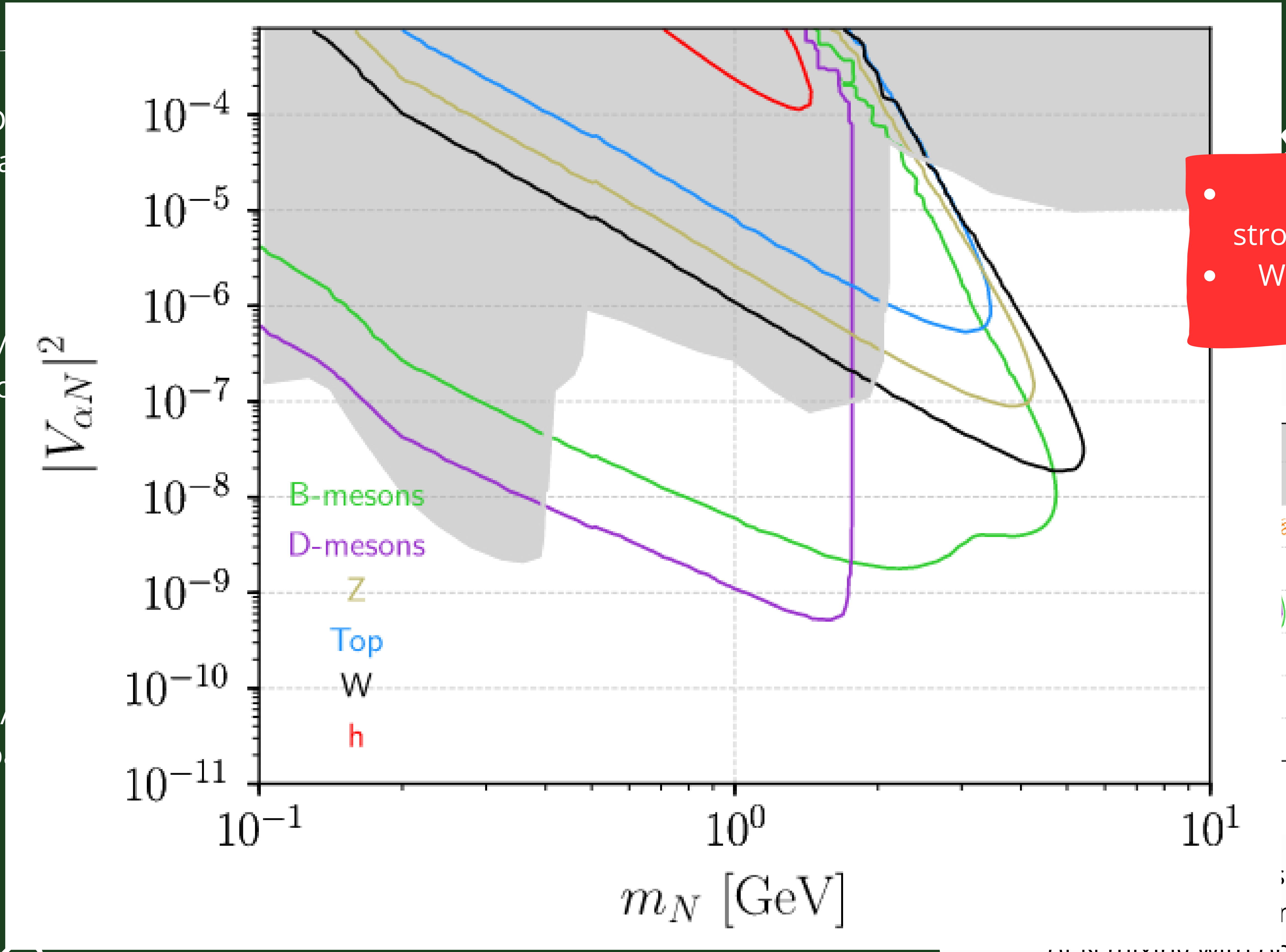
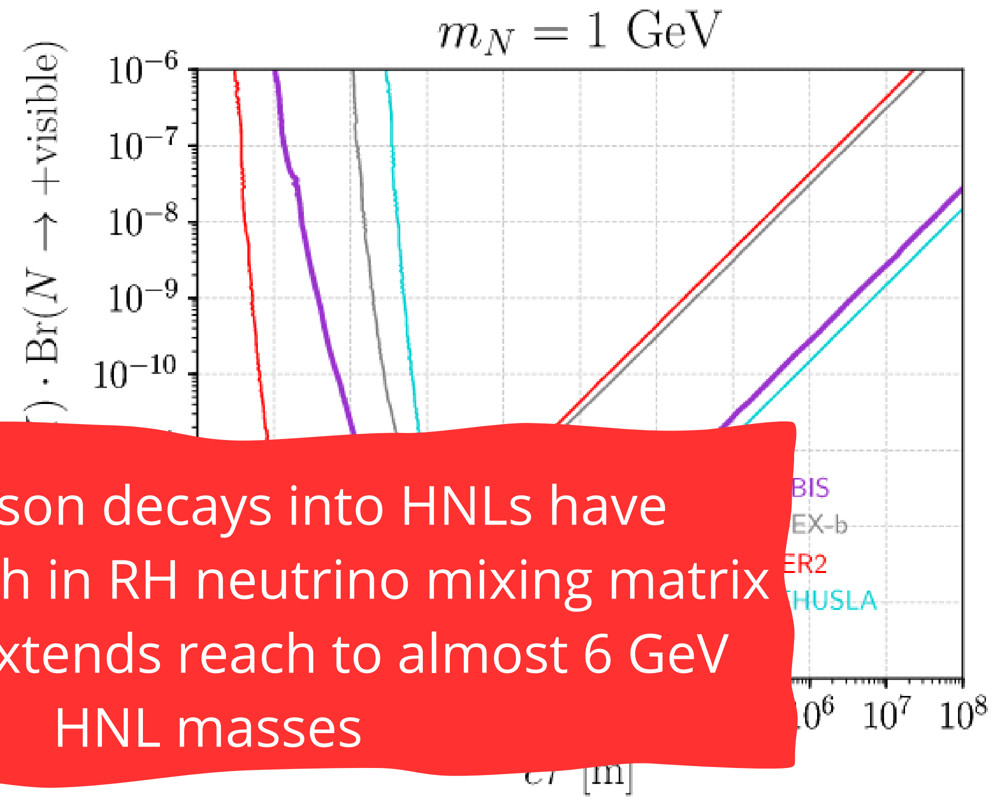
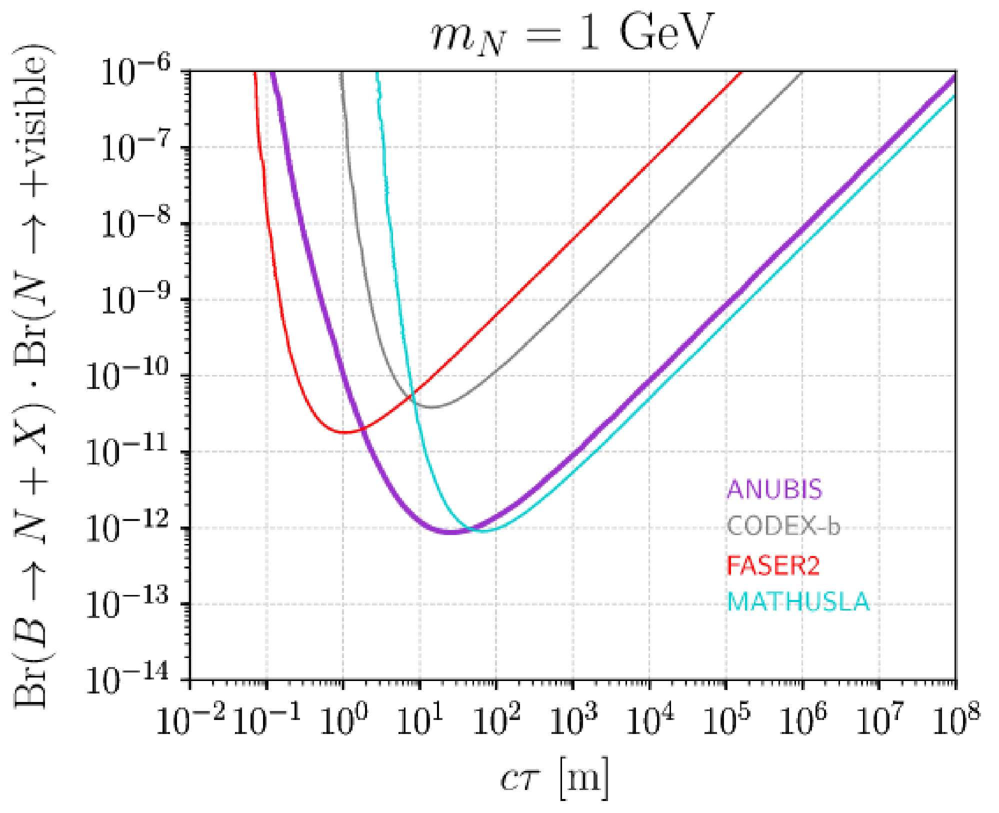




- Heavy meson decays into HNLs have strongest reach in RH neutrino mixing matrix
- W channel extends reach to almost 6 GeV HNL masses



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sensitivities of dominant production modes.

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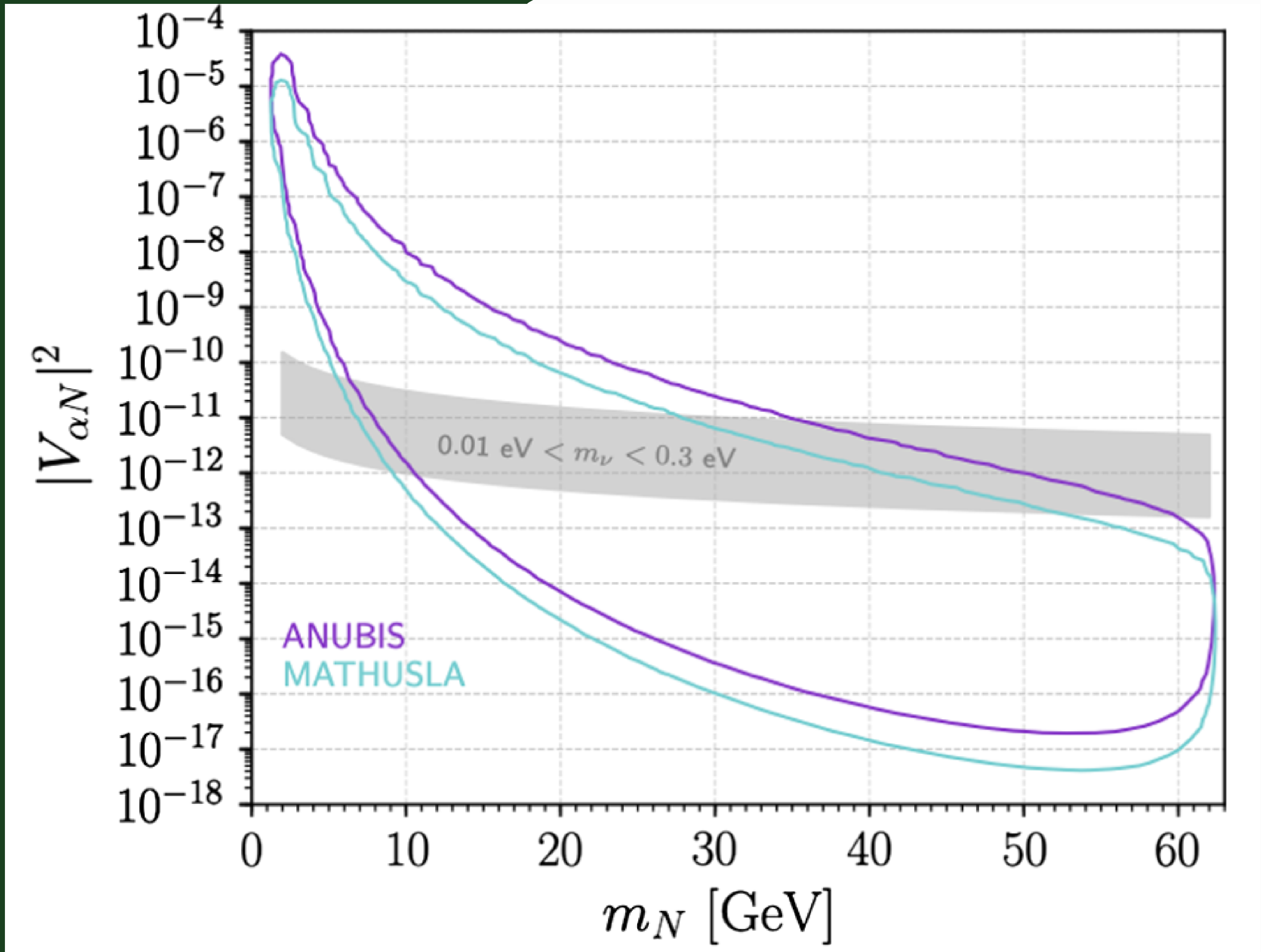
HNLs – ANUBIS

Non-minimal extended scenario where gauge group extended by new U(1) B-L

Non–minimal scenario

- SM-like Higgs decay into a pair of HNLs which mix with electron or muon neutrino
- Grey band: interesting parameter space where **type-I seesaw limits** for light neutrino masses are between 0.01 eV and 0.3 eV
- ANUBIS sensitive to slightly **larger values of the neutrino mixing matrix squared** because closer to IP



HNLs produced from SM-like Higgs decays

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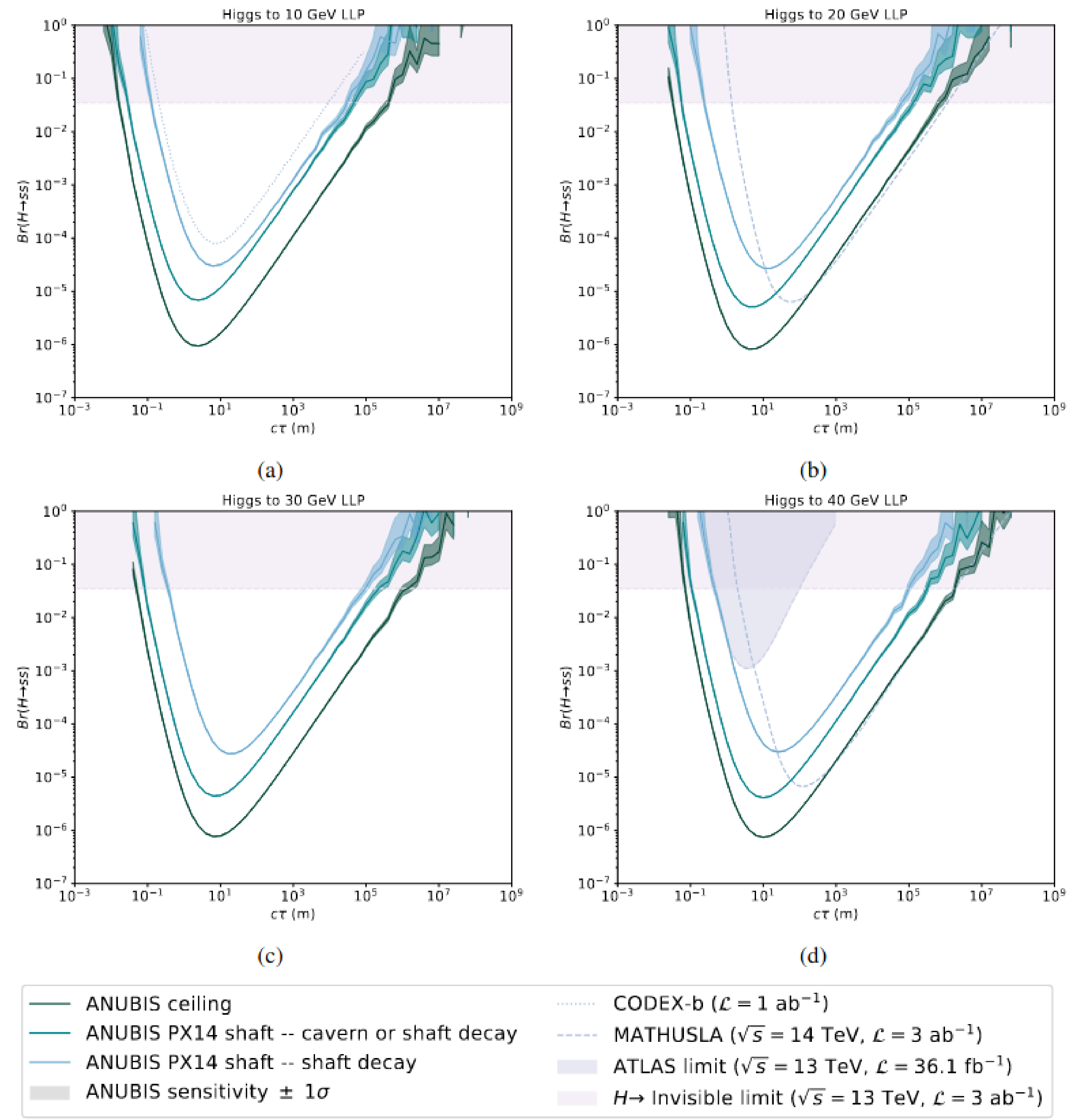
Our initial steps

- towards further develop these sensitivity studies,
- identifying most promising regions of parameter space
- and including simulations of the updated ANUBIS design

Review of Toby's calculations

- Sensitivity to LLPs produced at electroweak scale
  - benchmark model neutral LLPs from Higgs decays
- Gluon fusion and VBF Higgs boson production modes at NLO with Powheg
  - Higgs decays into LLPs with masses 10, 20, 30 and 40 GeV
  - subsequent decay into bb~, showered and hadronised with Pythia
- Investigate what fraction of decays would occur between ATLAS detectors and ANUBIS, and what fraction of events would produce >=2 final-state, charged-jet particles with trajectories permitting detection with ANUBIS
- Ceiling configuration of ANUBIS sensitive to branching ratios of LLPs with masses of 10, 20, 30 and 40 GeV reaching a limit of order 10^(-6) for particles with ctau of 2, 4, 6 or 10 m respectively



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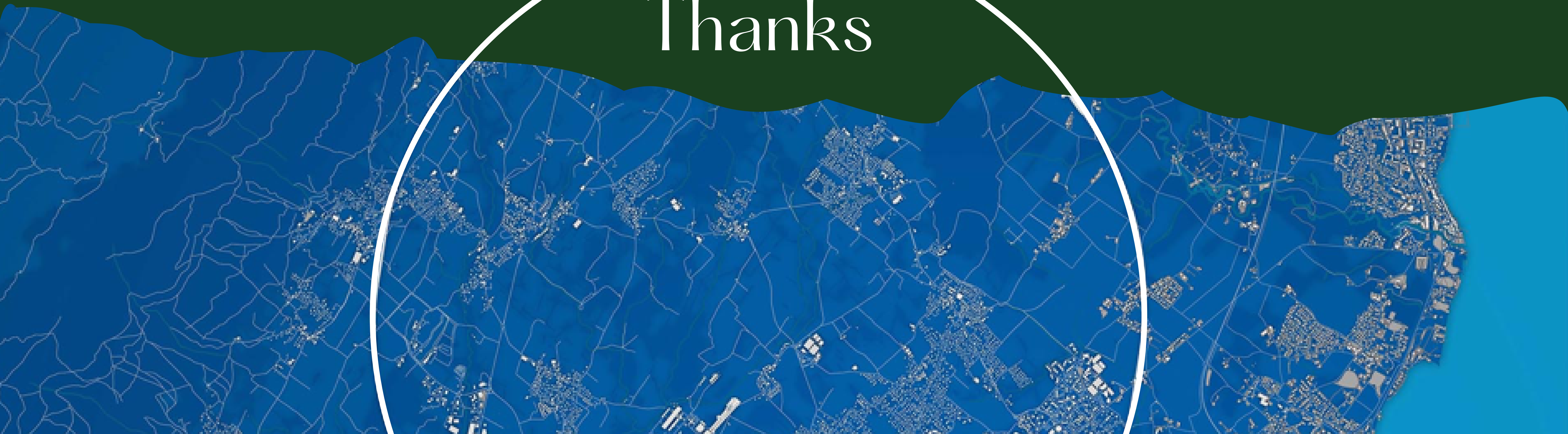
Outlook

Currently working towards...

- Best ways to simulate meson decays for HNL production
  - Pythia, MadSpin
- FeynRules parameters for producing UFOs consistent with those used by other experiments
  - Starting with simplest configurations of scalar and vector portal models
- Understanding axion portal model of interest to ANUBIS

Thanks



Backup

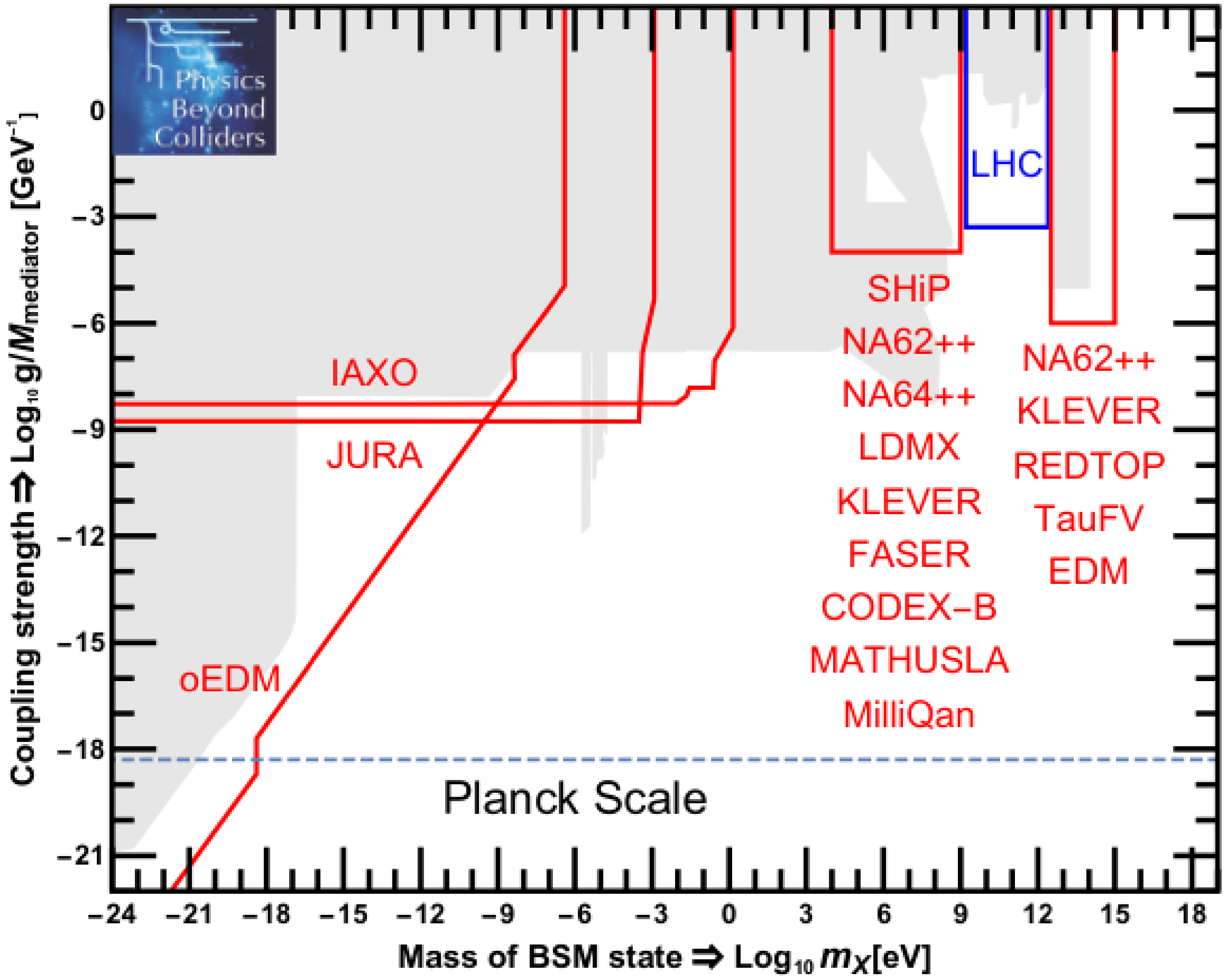


Figure 1: Schematic overview of the BSM landscape, based on a selection of specific models, with a rough outline of the areas targeted by the PBC experiments. The $x-$axis corresponds to the mass m_X of the lightest BSM state, and the $y-$axis to the scale of the effective new interaction $f = M_{\text{Mediator}}/g$, where M_{Mediator} is the mass of a heavy mediator and g its (dimensionless) coupling constant to the Standard Model. The grey shaded area outlines the currently excluded regions for a class of models corresponding to the benchmarks BC9 and BC11 (see Refs [27, 37, 38]).

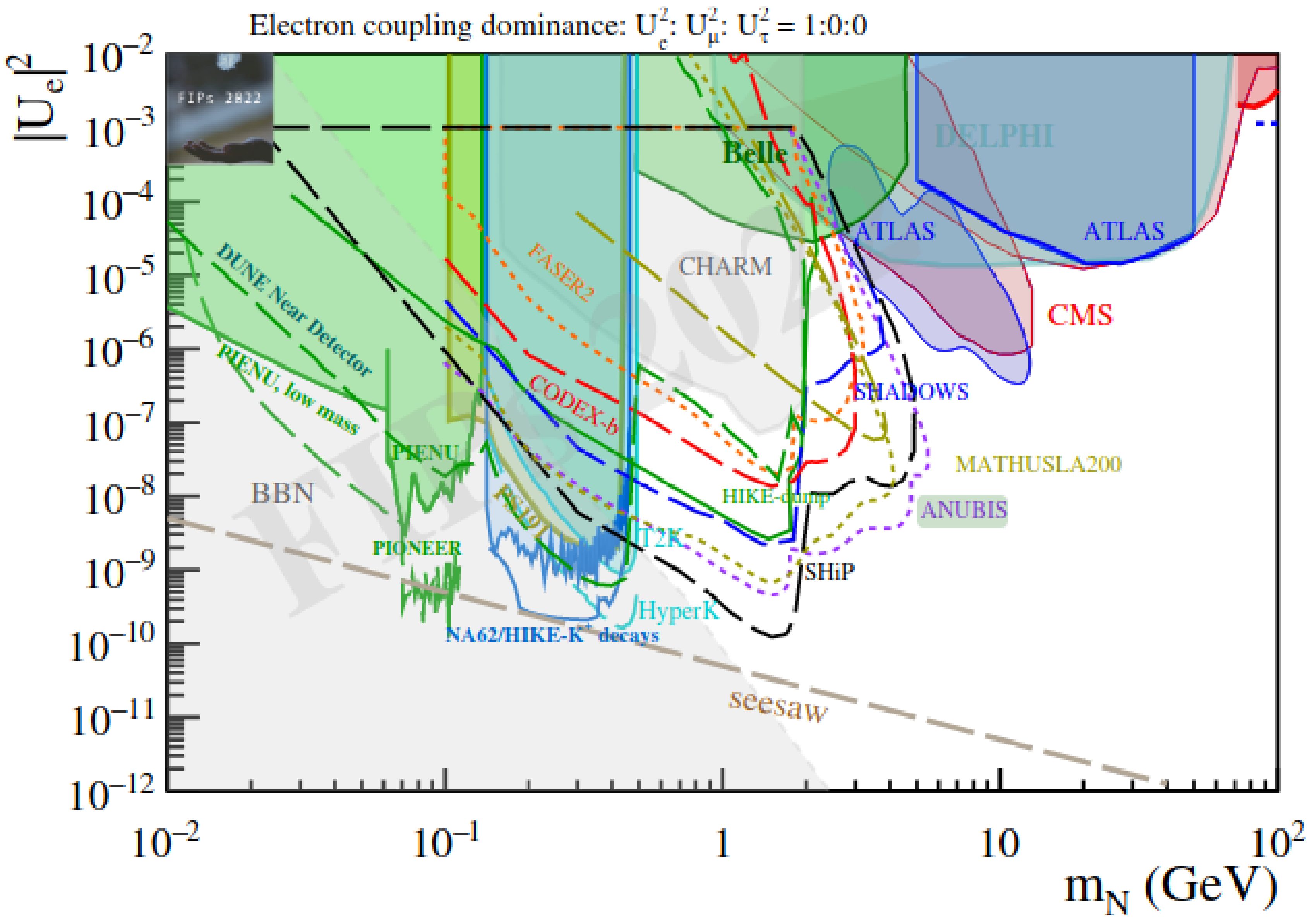


Figure 174: **Sensitivity to HNL with electron coupling (BC6).** Current bounds and future projections for 90% CL exclusion limits. **Legend:** filled gray areas are bounds coming from interpretation of old data sets or astrophysical data; filled coloured areas are bounds set by experimental collaborations; Solid coloured lines are projections based on existing data sets; Dashed coloured lines are projections based on full Monte Carlo simulations; Dotted coloured lines are projections based on toy Monte Carlo simulations. Filled areas are existing bounds from: PS191 [1561], CHARM [1432], PIENU [1785], NA62 (K_{eN}) [1177], T2K [1786], Belle [1787], DELPHI [1788], ATLAS [1627, 1621], and CMS [1625, 1620]. Coloured curves are projections from: PIONEER [1789], HIKE-K^+ [1392, 1191]; HIKE-dump [1392, 1191]; DarkQuest [1258], Belle II [1782], FASER2 [1416]; DUNE near detector [1172], Hyper-K (projections based on [1562]), CODEX-b [1030], SHiP [1402], SHADOWS [1401] and MATHUSLA200 [1441]. The BBN bounds are from [1686]The dashed seesaw line is given by $|U_\alpha|^2 = \sqrt{\Delta m^2_{atm}}/m_N$ corresponding to the naive seesaw scaling and should be considered only as indicative.