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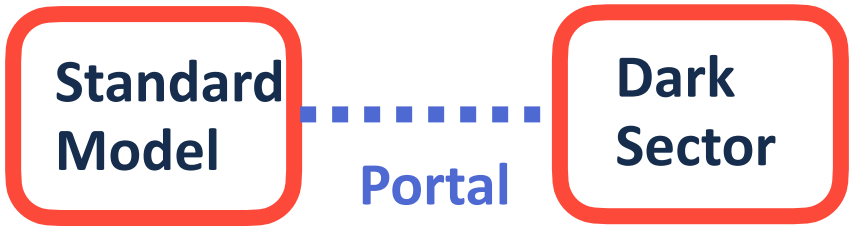
Probing right-handed neutrinos dipole operators

Motivation

- Long-lived particles arise in a variety of models beyond the Standard Model
- Specific experimental strategies and facilities needed for their discovery
- Examples of such particles arise in dark sectors communicating with the SM through feeble portal interactions



$\frac{\epsilon}{2} F'_{\mu\nu} B_{\mu\nu}$ Vector portal

$H^\dagger H(\mu S + \lambda S^2)$ Scalar portal

$yLHN$ Neutrino portal

$\frac{1}{\Lambda^2} J_\mu^{SM} J_\mu^{DS}, \ldots$ Higher dimensional operators portals

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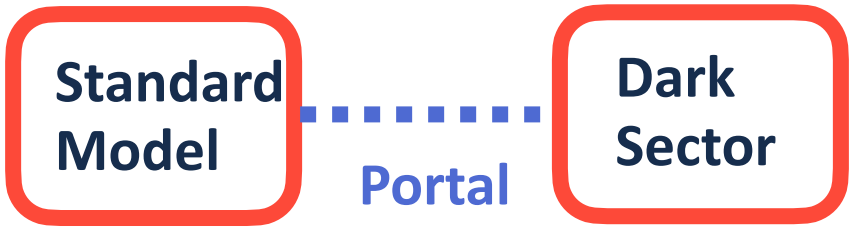

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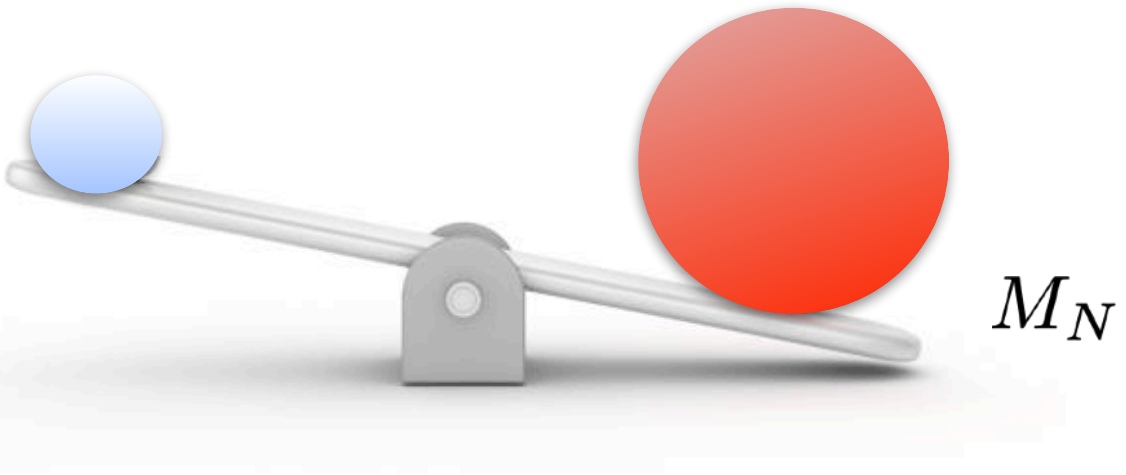
Motivation

- The see-saw mechanism is the simplest SM extension explaining neutrino masses

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\bar{N}\partial\!\!\!/ N - \bar{L}_L Y_\nu \tilde{H} N - \frac{1}{2}\bar{N}^c M_N N + h.c.$$

- Small active-sterile mixings imply long lifetime for the RH neutrinos

$$m_\nu \sim \frac{Y_\nu^2 v^2}{M_N}$$



Motivation

- νSMEFT

  New physics at scales >> EW encapsulated by higher-dimensional operators.

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\bar{N}\partial\!\!\!/ N - \bar{L}_L Y_\nu \tilde{H} N - \frac{1}{2}\bar{N}^c M_N N + \sum_{n>4} \frac{\mathcal{O}^n}{\Lambda^{n-4}} + h.c.$$

- At d=5 in addition to the Weinberg operator we have

$$\mathcal{O}^5_{NH} = \bar{N}^c N H^\dagger H \qquad \mathcal{O}^5_{NB} = \bar{N}^c \sigma^{\mu\nu} N B_{\mu\nu}$$

Aparici et al. PRD 80 (2009) 01310, Balaji et al. JHEP 12 (2020) 090, Barducci et al. JHEP 06 (2020) 185, Cho et al. PRD 105 (2022) 1, Delgado et al. JHEP 09 (2022) 079

- At d=6: many more operators and a lot of recent works

Our minimal scenario

- We consider two RH neutrinos whose phenomenology is determined by the dipole operator

$$\mathcal{O}^5_{NB} = \frac{g_Y}{16\pi^2}\frac{e^{i\alpha}}{\Lambda}\bar{N}_1^c\sigma^{\mu\nu}N_2 B_{\mu\nu} + h.c.$$

Loop factor in a weakly coupled UV completion

- The dipole induced the radiative decay $N_{\text{heavy}} \to N_{\text{light}} + \gamma$

$$c\tau \simeq 0.4\,\text{m}\left(\frac{0.1}{\delta}\right)^3\left(\frac{0.5\,\text{GeV}}{m_{N_1}}\right)^3\left(\frac{\Lambda}{1\,\text{TeV}}\right)^2 \qquad \delta = \frac{m_{N_2} - m_{N_1}}{m_{N_1}}$$

- We assume suppressed active-sterile mixing, leading to the decay of the lightest state

- Another motivation is inelastic dipole dark matter

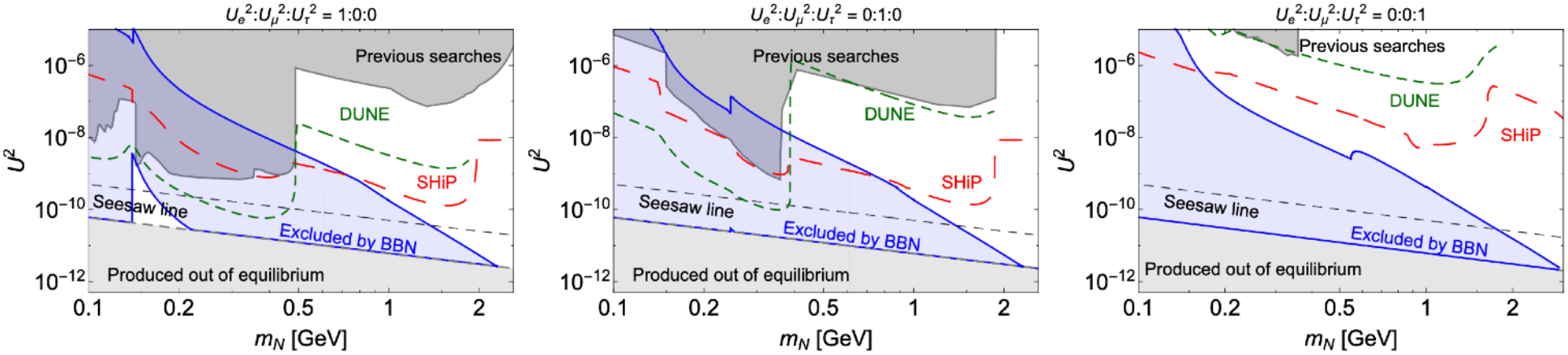
  Lightest neutrino state is replaced by dark matter

  Same pheno at colliders as long as the lightest sterile neutrino is collider-stable

Dienes, Feng, Fieg, Huang, Lee and Thomas, PRD 107 (2023) 11

Astrophysics and cosmology

- We assume suppressed active-sterile neutrino mixing
- Bounds arise from decays of sterile neutrino around the BBN epoch
- We check that these constraints are satisfied



Boyarsky, Ovchynnikov, Ruchayskiy and Syvolap, PRD 104 (2021) 2

- Bounds from supernovae marginally affect the parameter space under consideration

Collider experiments

- Our experimental signature is a single photon from decays of N_2
- Different searches apply depending on the lifetime of the sterile states

- Detector stable. Mono-photon + MET, LEP limits on invisible Z width

  Weak bound which is beyond the validity of the EFT $\Lambda \gtrsim 9\,\mathrm{GeV}$

- Displaced decays. Searches for non-pointing photons at ALEPH, ATLAS, CDF and DELHPI

  With a simplified recasting analysis we find quite weak bounds

- Prompt decays. Monophoton searches from Babar and LEP

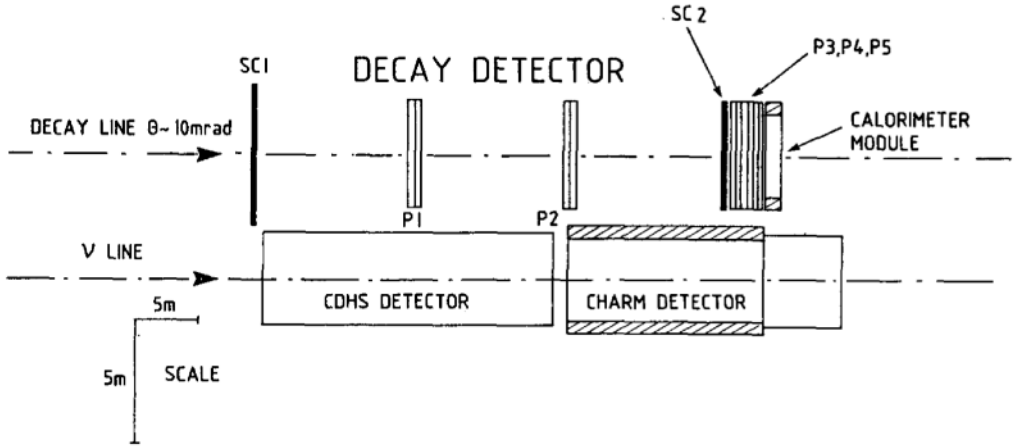
- For all the cases we find **very weak bounds**

See also **Delgado, Duarte, Jones-Perez,Manrique-Chavil, Peña JHEP 09 (2022) 079**

Past fixed-target experiments

- **CHARM**

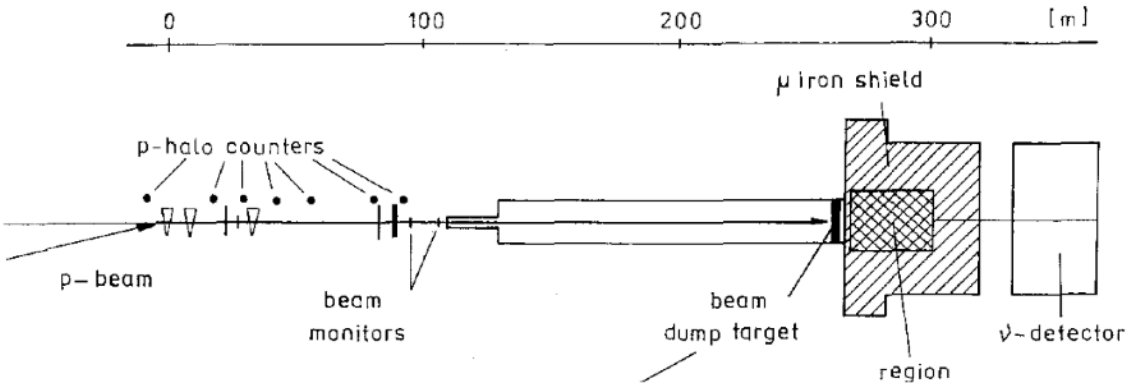
  400 GeV proton beam on a fixed target with a detector at 480 m from the IP



Recast analysis **Bergsma et al. PLB 157 (1985) 458**

- **NuCal**

  70 GeV proton beam dumped into iron target
  Detector placed at 64 m from the target



Recast analysis **Blumlein et al. Z. Phys. C 51 (1991) 341**

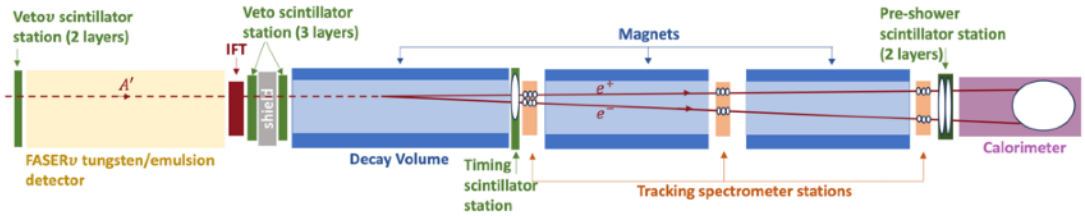
Projected sensitivities

- **FASER 2**

FASER: new detector at the LHC

dedicated to LLPs searches in the forward

direction, 476 m from ATLAS IP



Recent: new FASER bounds on dark photon!

FASER coll. arXiv: 2308.05587

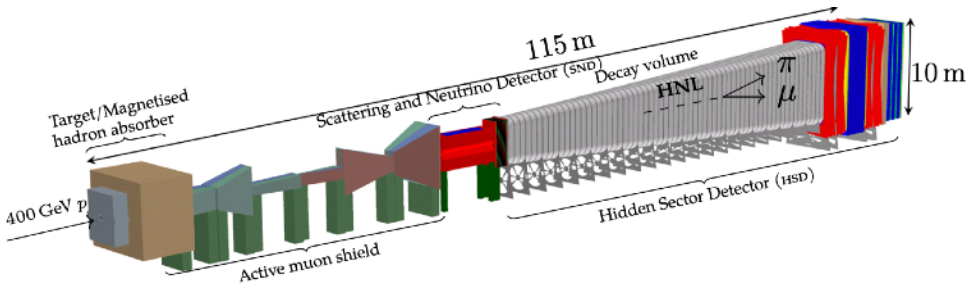
FASER 2: planned upgrade

Meson decays: dominant sterile-neutrino production channel

ρ, ω, J/ψ, Υ mesons simulated with Pythia 8 and EPOS-LHC

Good agreement with the FORESEE package

- **SHiP**



Proposed 400 GeV proton

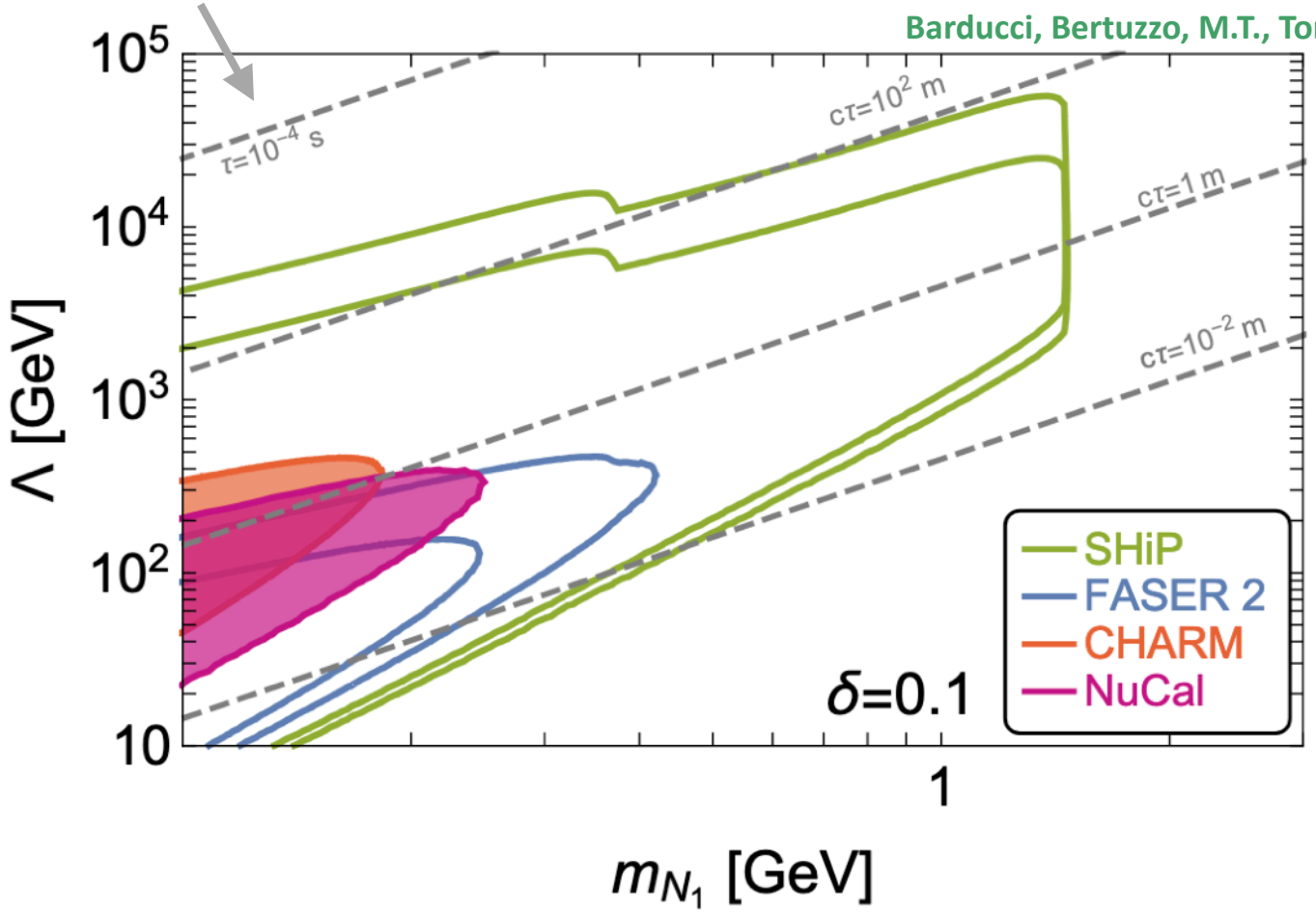
beam-dump experiment at the CERN SPS

ρ, ω, J/ψ, Υ mesons simulated with Pythia 8

Results

BBN requires $\tau \lesssim 10^{-2}$ s

Barducci, Bertuzzo, M.T., Toni, JHEP 03 (2023) 239



FASER 2 and SHiP: 95% CL exclusion limit assuming no background

Alternative choice for SHiP: assume conservative estimate for bkg in Magill et al. PRD 98 (2018) 11

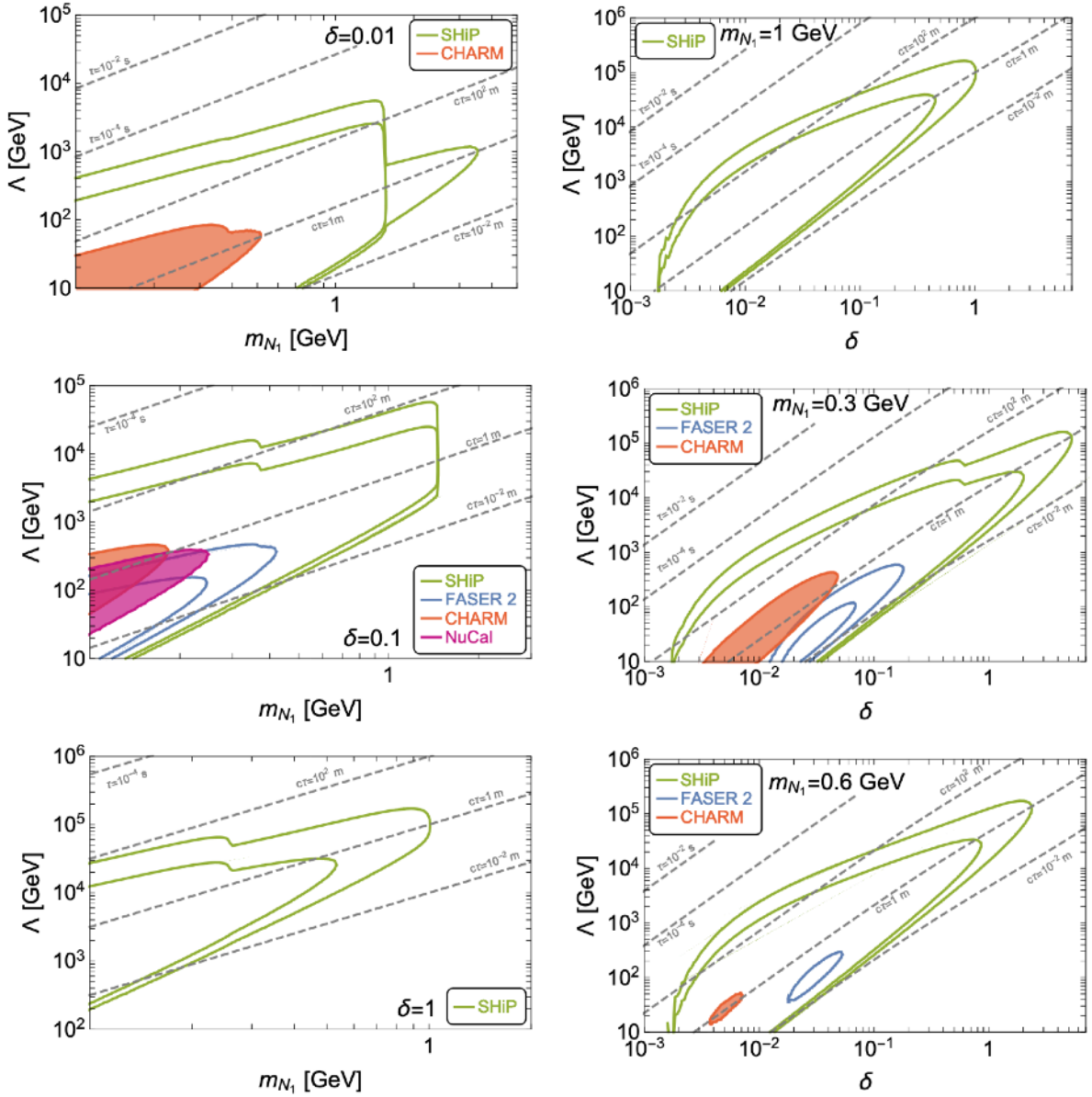
Alternative choice for FASER 2: isocontour of 30 events

Results

Barducci, Bertuzzo, M.T., Toni, JHEP 03 (2023) 239

Energy of the photon correlates with the mass splitting

$$E_\gamma^{\rm lab} = \left(P_{N_2} + \sqrt{m_{N_2}^2 + P_{N_2}^2}\right) \frac{\delta}{2} \frac{2+\delta}{(1+\delta)^2} \simeq 2P_{N_2}\delta$$

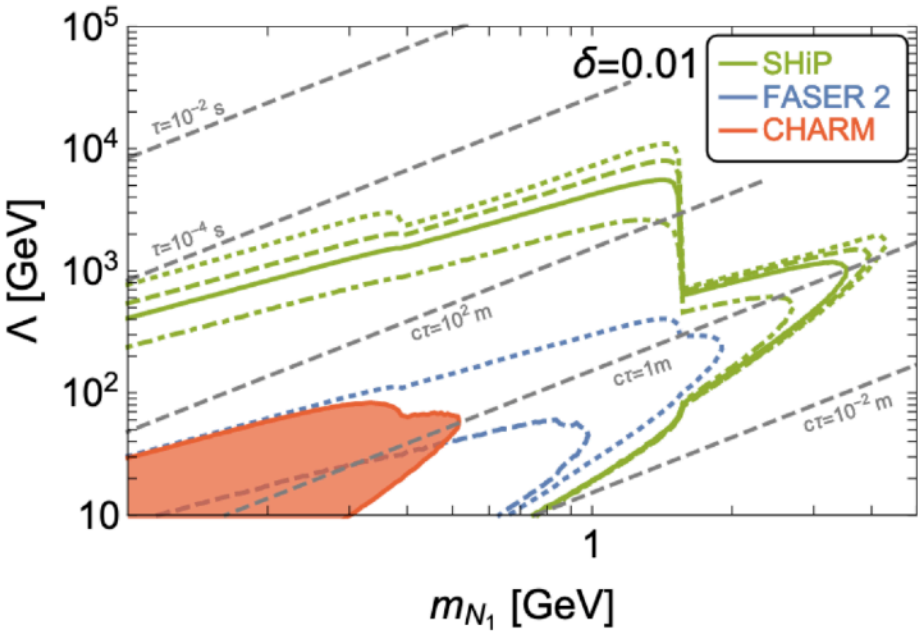


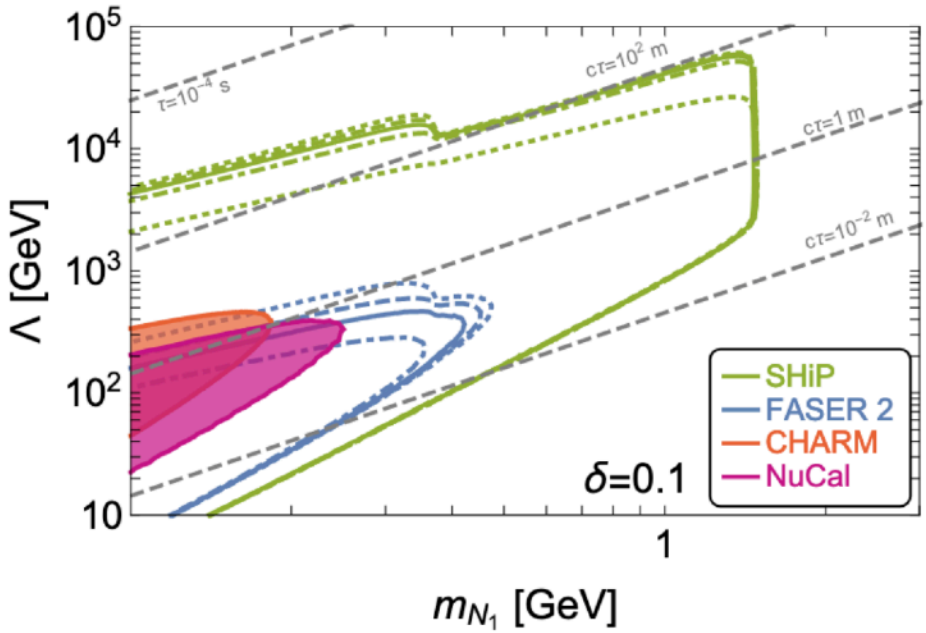
Energy threshold

Minimum photon energy: 10, 50, 100, 200 GeV

Minimum photon energy: 0.1, 0.5, 1, 2, 10 GeV

Barducci, Bertuzzo, M.T., Toni, JHEP 03 (2023) 239

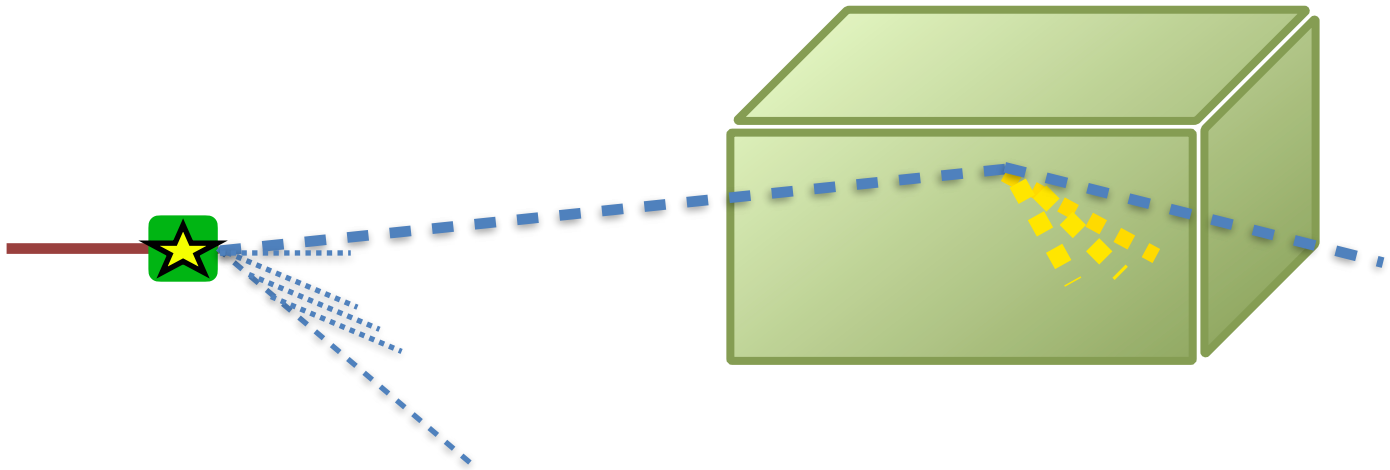




Energy threshold is crucial for small splittings

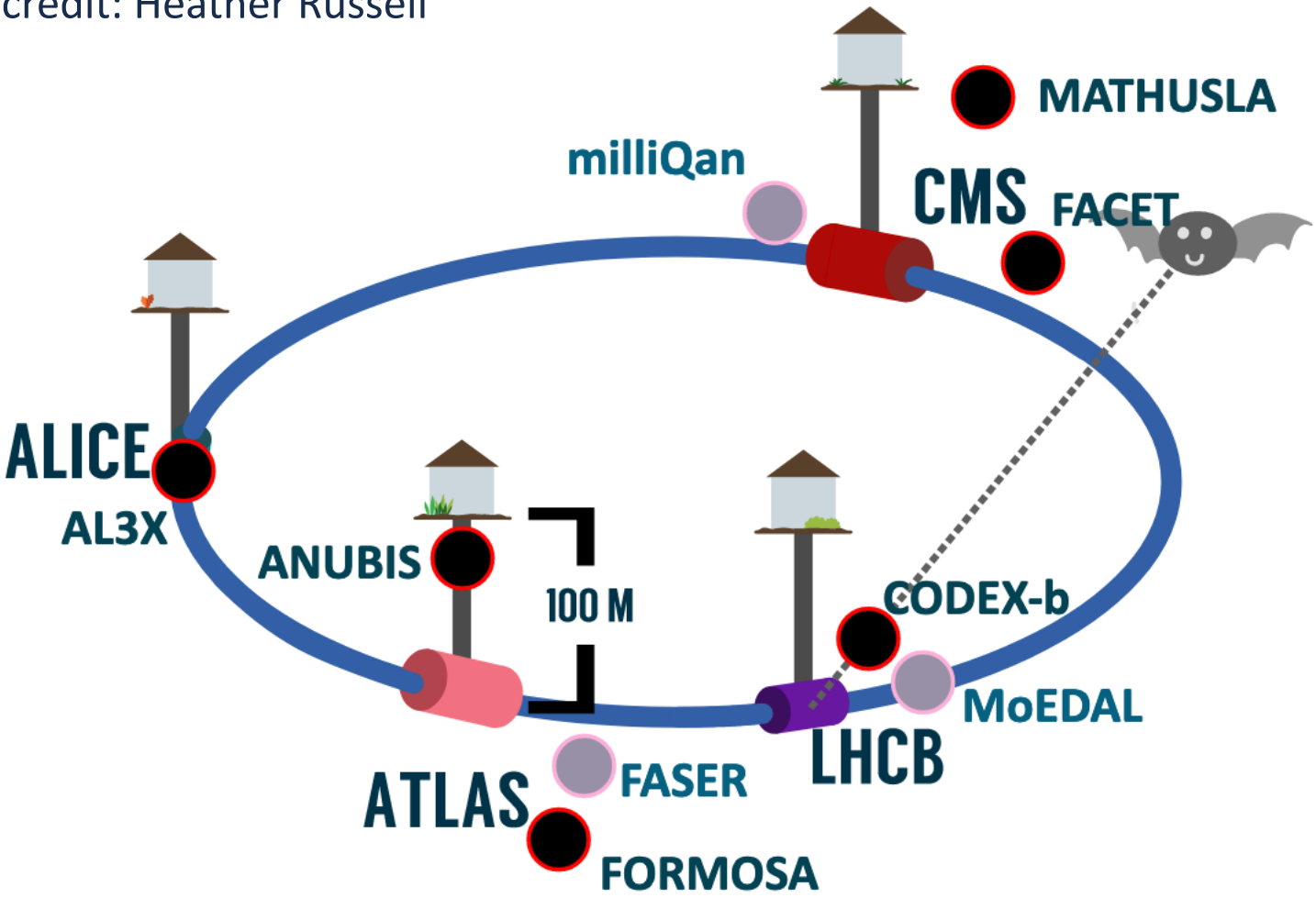
Conclusions

- We have considered sterile neutrinos in the GeV range acting as long-lived particles
- A mono-photon signal is induced by a dipole operator
- We have evaluated the reach of experiments targeting long lived particles, in particular FASER 2 and SHiP
- They can probe regions of the parameter space inaccessible by conventional collider searches



Proposed LLPs experiments

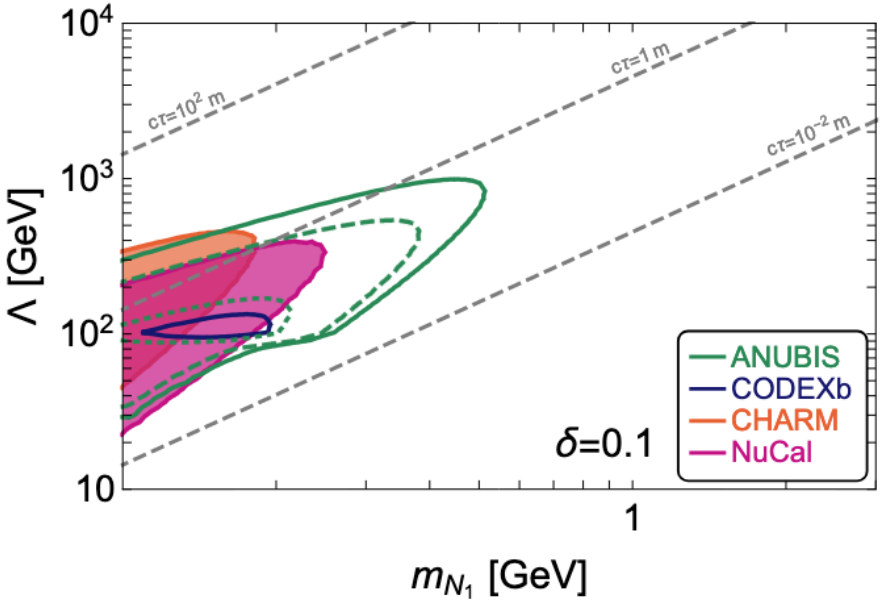
Image credit: Heather Russell

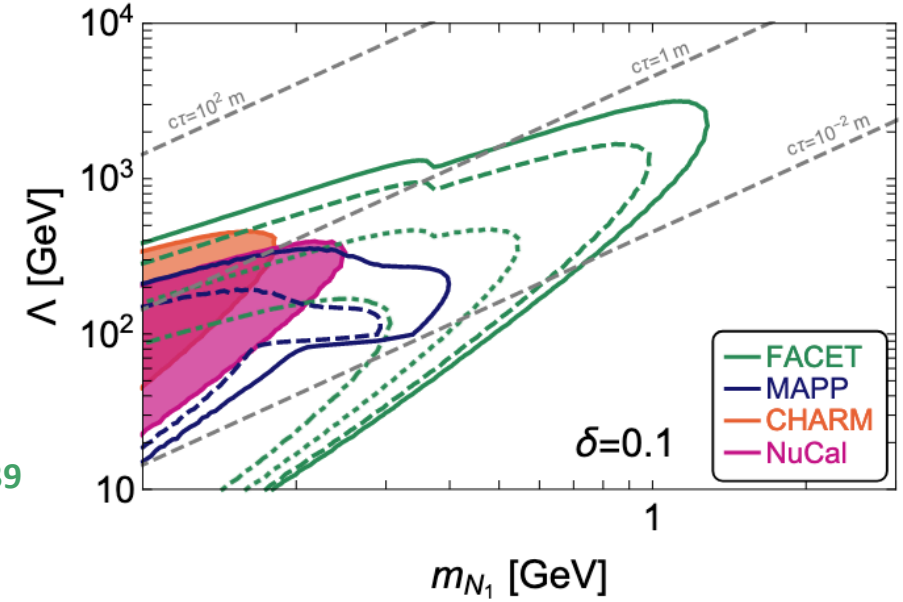


Results

Isocontours of

N_{signal} = 3, 10, 100, 1000





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