SHiP and searches for new physics

Quarks workshop

Maksym Ovchynnikov (Leiden University)

June 8, 2021

Intensity frontier experiments

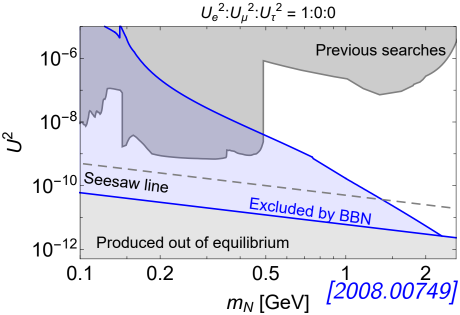
- New physics particles may couple to SM via
  1. Effective higher-dimensional operators (**Energy frontier**),
  2. Portals – operators with dimension ≤ 4 (**Intensity frontier**): dark scalars, dark photons, Heavy Neutral Leptons (HNLs)
- Searches for the Higgs boson at the LHC pushed the energy frontier. The intensity frontier has remained unexplored
- HL-LHC as well as future colliders such as FCC will be able to explore Intensity frontier
- However, domain of "low" masses $m \lesssim m_B$ is complicated to explore

Parameter space to be probed

For the given mass range, what is the couplings range to be probed?

- Consider **HNLs** for instance. The upper bound comes from old experiments (such as PS191, CHARM, DELPHI)
- A natural lower bound on couplings (seesaw bound): HNLs must provide masses to active neutrinos

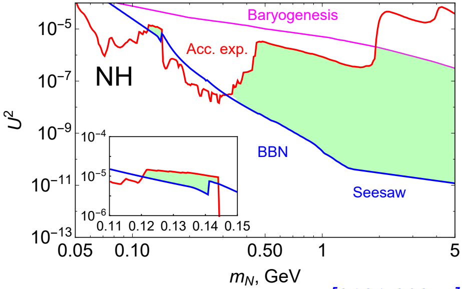
- Another bound comes from BBN
- HNLs with masses $m_N > m_\pi + m_l$ lead to an overproduction of primordial He if their lifetimes $\tau_N > 0.02$ s – **a factor of 5 improvement** as compared to previous estimate $\tau_N > 0.1$ s



[2008.00749]

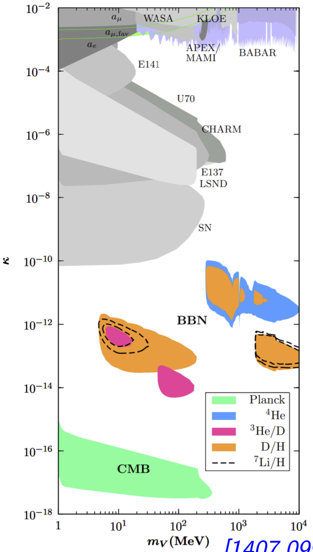
Parameter space to be probed

- Combination of old experiments, neutrino oscillations data and cosmological bounds $\to$ minimal mass in Neutrino Minimal Standard Model (νMSM)

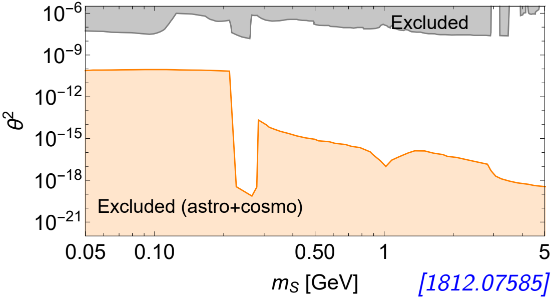


[2101.09255]

Parameter space to be probed



[1407.0993]

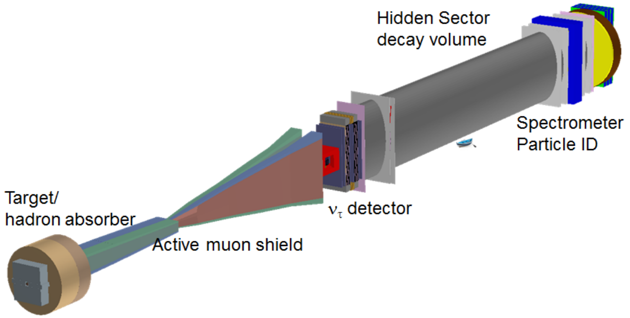


[1812.07585]

- Similar estimates exist for other portal models

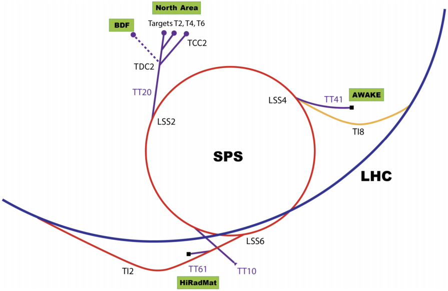
One needs an experiment that may cover the unprobed domain

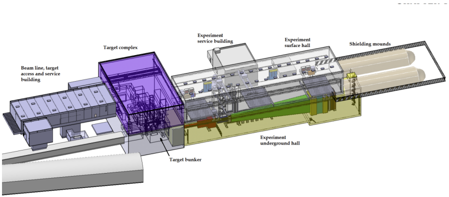
SHiP [1504.04956]



- 1 m long W target, $N_{\mathrm{PoT}} = 2 \times 10^{20}$ during 5 years of operation
- Hadronic absorber followed by muon shield
- $l_{\mathrm{min}} = 50$ m, $l_{\mathrm{fid}} = 50$ m
- The detector angle is $\theta \in (0; 25)$ mrad

SHiP





[1912.06356]

- SHiP is planned to be installed at the Beam Dump Facility (BDF)

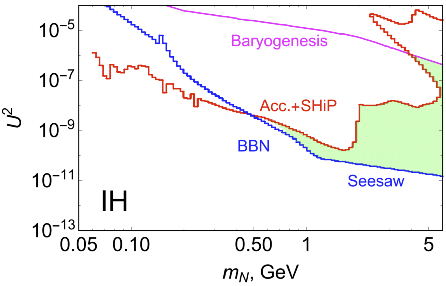
What SHiP may tell about portals?

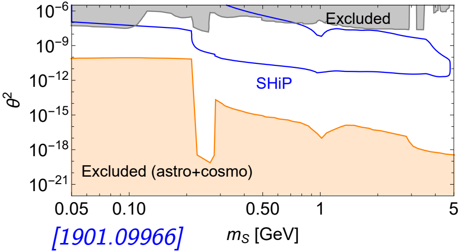
Two "types" of sensitivity:

- Based on the number of events
- Based on the ability to reconstruct parameters of model

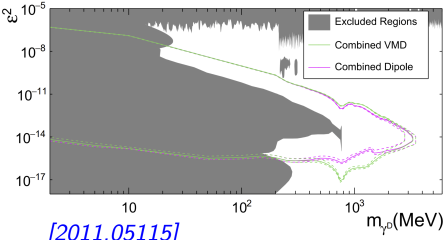
The number of events sensitivity for HNLs:

- Significantly extends the probed mass range up to $m_N = m_B$
- Probes couplings very close to BBN/seesaw line





[1901.09966]



[2011.05115]

- Similarly, SHiP may probe unexplored parameter space for other portals

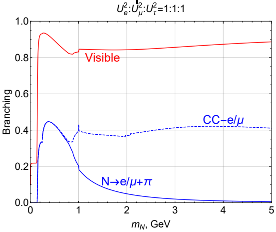
SHiP and portals

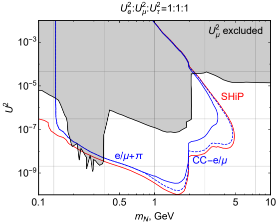
- HNLs may be clearly distinguished from other portal particles by decays $N \to l + \pi$. HNLs with masses $m_N < m_l + m_\pi$ may be identified by 3-body decays $N \to e + \bar{e} + \nu$
- The properties to be probed are:
  1. HNL mass M_N
  2. the mixing angles U^2_α
  3. number of HNLs
- To explain neutrino oscillations and baryogenesis, one needs two mass degenerate HNLs [0505013]. It is important to
  1. distinguish two quasi-degenerate HNLs
  2. measure the mass splitting $\Delta M = |M_1 - M_2|$ and mixing angle differences $|U^2_{\alpha 1} - U^2_{\alpha 2}|$
  3. Check consistency with active neutrino oscillations

SHiP may probe all of these parameters

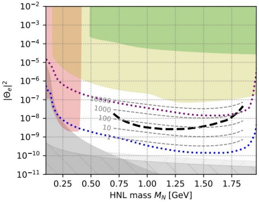
SHiP and portals

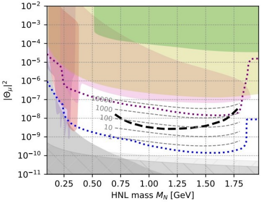
- Mass measurements: from neutrinoless decays, e.g., $N \to l + \text{hadrons}$. At least $O(10)$ events are required





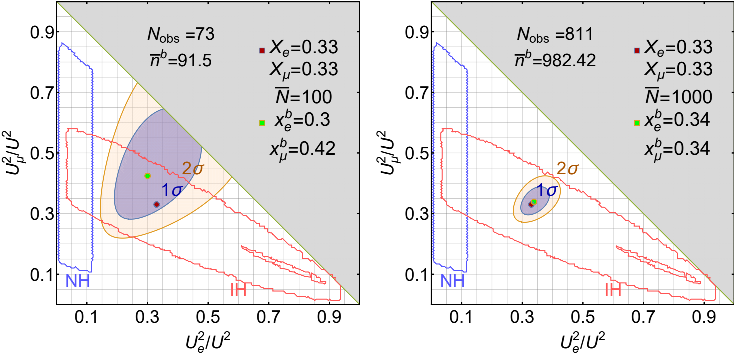
- Dirac/Majorana HNLs: distinguishing lepton number violating/conserving processes (LNV/LNC) by spectra of decay products. $O(100)$ events is required





[1912.05520]

- measure U_e^2, U_μ^2, U_τ^2 and check their consistency with active neutrino mixing by distinguishing different decay modes. For simulated results for an HNL with $U_e^2 : U_\mu^2 : U_\tau^2 = 1 : 1 : 1$ and 100 (left) or 1000 (right) expected decay events the bounds are:



SHiP and other experiments

- SHiP is not currently approved
- After its proposal, a lot of other Intensity Frontier experiments searching for displaced decays have been proposed:
  1. SPS-based (NA62-BD, SHADOWS)
  2. LHC-based (FASER, MATHUSLA, Codex-b,...)
  3. DUNE
  4. ...

How to compare qualitatively their sensitivities?

SHiP and other experiments

The sensitivity to decays of particles N with mass M_N and coupling U:

$$N_{\text{decay events}} \approx N_{\text{prod}} \times \epsilon_{\text{tot}} \times P_{\text{decay}} > N_{\text{min}},$$

where

- N_{prod} is the number of produced particles,

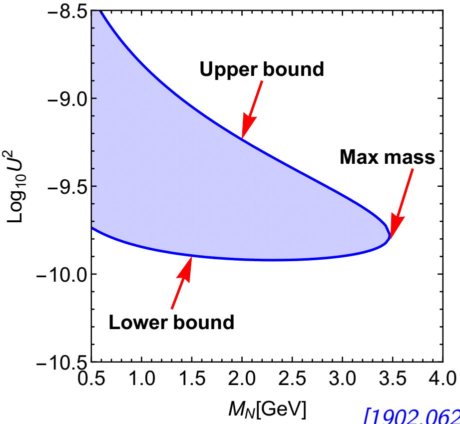
$$N_{\text{prod}} \approx N_{\text{mother}} \cdot \text{Br}_{N\text{ prod}} \propto U^2 \tag{1}$$

- ϵ_{tot} is the efficiency, $\epsilon_{\text{tot}} = \epsilon_{\text{geom}} \times \epsilon_{\text{decay}} \times \epsilon_{\text{det}} \times \text{Br}_{\text{vis}}$
- P_{decay} is the decay probability,

$$P_{\text{decay}} \approx e^{-\frac{l_{\text{min}}\Gamma_N}{c\gamma_N}} - e^{-\frac{l_{\text{max}}\Gamma_N}{c\gamma_N}} \approx \begin{cases} l_{\text{fid}}\Gamma_N/c\gamma_N, & \ell_{\text{decay}} \gg \ell_{\text{max}}, \\ \exp\left[-\ell_{\text{min}}\Gamma_N/c\gamma_N\right], & \ell_{\text{decay}} < \ell_{\text{min}} \end{cases} \tag{2}$$

where $l_{\text{decay}} = c\gamma_N/\Gamma_N$

SHiP and other experiments



[1902.06240]

- Lower bound ($l_{\text{decay}} \gg l_{\max}$):

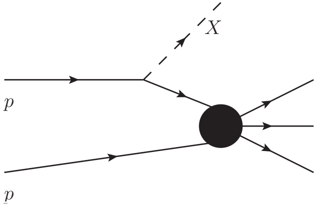
$$U^2_{\text{lower}} \propto \chi_{\text{lower}} = = \sqrt{\frac{N_{\text{prod}}}{\text{Br}_{N\ \text{prod}}} \times \epsilon \times \frac{l_{\text{fid}}}{\langle p \rangle} \times \frac{1}{N_{\min}}} \quad (3)$$

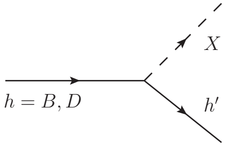
- Upper bound ($l_{\text{decay}} \lesssim l_{\min}$):

$$U^2_{\text{upper}} \propto \chi_{\text{upper}} = \frac{\langle p \rangle}{l_{\min}} \quad (4)$$

SHiP and other experiments

- Using the analytic estimates, let us compare SHiP with other SPS current/proposed experiments (NA62, SHADOWS), and LHC-based experiments (FASER2, MATHUSLA)





- We will consider main production channels for GeV scale HNLs, dark scalars, dark photons and ALPs with fermion coupling:
  1. decays of B, D mesons
  2. proton bremsstrahlung

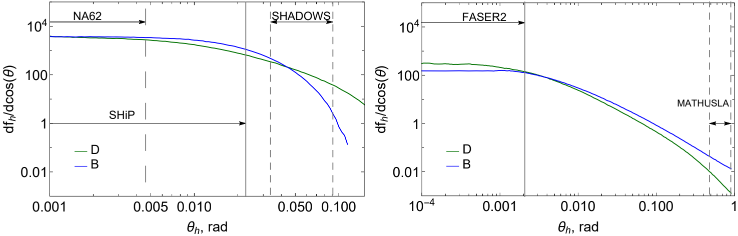
Analytic estimates: basic parameters

	SHiP	NA62x4	SHADOWS	MATHUSLA	FASER2
N_{PoT}	$2 \cdot 10^{20}$	$\sim 5 \cdot 10^{19}$	$\sim 5 \cdot 10^{19}$	$2.2 \cdot 10^{17}$	$2.2 \cdot 10^{17}$
$\frac{l_{\text{min}}}{\text{m}}$	50	100	10	40	480
$\frac{\langle l_{\text{fid}} \rangle}{\text{m}}$	50	100	20	100	5
$\frac{\theta_{\text{det}}}{\text{rad}}$	$(0, 0.025)$	$(0, 5 \cdot 10^{-3})$	$(0.03, 0.09)$	$(0.48, 0.9)$	$(0, 2.1 \cdot 10^{-3})$

	$\chi_{c\bar{c}}$	$\chi_{b\bar{b}}$
SPS	0.004	$3 \cdot 10^{-7}$
LHC	0.1	$7 \cdot 10^{-3}$

- LHC-based experiments: smaller intensity but larger meson production probability

Analytic estimates: ϵ_{geom}



Obtained using FONLL, SIBYLL and FairShip simulations

- $p_{T,\mathrm{mesons}} \sim m_h \Rightarrow$ distribution of mesons is peaked at the forward direction
- Bremsstrahlung: $p_T \lesssim \Lambda_{QCD}$ MATHUSLA and SHADOWS have poor sensitivity to dark photons

	SHiP	NA62x4	SHADOWS	MATHUSLA	FASER2
$N_B \cdot \epsilon^B_{\mathrm{geom}}$	$8 \cdot 10^{13}$	$1 \cdot 10^{12}$	$5 \cdot 10^{11}$	$3 \cdot 10^{13}$	10^{13}
$N_D \cdot \epsilon^D_{\mathrm{geom}}$	$8 \cdot 10^{17}$	$2 \cdot 10^{16}$	$2 \cdot 10^{16}$	$5 \cdot 10^{14}$	$2 \cdot 10^{14}$
$N_{\mathrm{PoT}} \cdot \epsilon^{\mathrm{brem}}_{\mathrm{geom}}$	10^{20}	$5 \cdot 10^{18}$	–	–	$2 \cdot 10^{16}$

Analytic estimates: ϵ_{decay}

- ϵ_{decay}: compare the angular size of the detector θ_{det} with characteristic angle between decay products $\xi \simeq m_X/E_X$
- MATHUSLA, FASER: $\epsilon_{\text{decay}} = \mathcal{O}(1)$
- Not the case for SHiP, NA62, SHADOWS

	SHiP	NA62x4	SHADOWS	MATHUSLA	FASER2
$\epsilon_{\text{decay},\ B}$	0.4	$\mathcal{O}(10^{-2})$	< 0.4	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$\epsilon_{\text{decay},\ D}$	0.4	$\mathcal{O}(0.1)$	$\simeq 0.3$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$\epsilon_{\text{decay},\ \text{brem}}$	$\mathcal{O}(1)$	$\mathcal{O}(0.1)$	–	–	$\mathcal{O}(1)$

A toy Monte-Carlo estimate of ϵ_{decay}: decays of particles with $m = m_{B/D}$ (and $m = 1$ GeV for bremsstrahlung) into two massless particles and requiring them to point to detectors

Analytic estimates: lower bound

	SHiP	NA62x4	SHADOWS	MATHUSLA	FASER2
$\chi_{\text{lower},\ B}$	$4\cdot 10^{-7}$	$8\cdot 10^{-6}$	$6\cdot 10^{-6}$	10^{-7}	$2\cdot 10^{-6}$
$\chi_{\text{lower},\ D}$	$3\cdot 10^{-9}$	$2\cdot 10^{-8}$	$8\cdot 10^{-8}$	$4\cdot 10^{-8}$	$5\cdot 10^{-7}$
$\chi_{\text{lower, brem}}$	10^{-10}	10^{-9}	–	–	10^{-7}

$$U^2_{\text{lower}} \propto \chi_{\text{lower}} = \sqrt{\frac{N_{\text{prod}}}{\text{Br}_{N\ \text{prod}}} \times \epsilon \times \frac{l_{\text{fid}}}{\langle p \rangle} \times \frac{1}{N_{\text{min}}}} \quad (5)$$

- All of the experiments have worse sensitivity than SHiP for the production from D mesons
- SHiP is better for everything except for the production from B

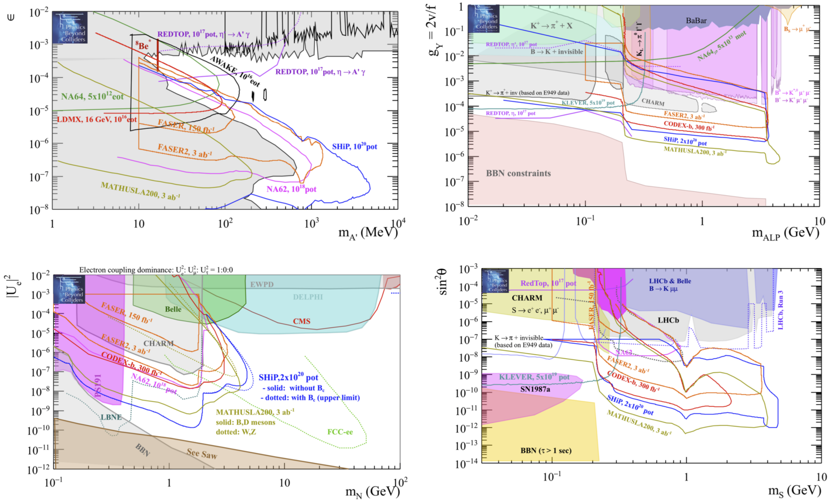
  Disclaimer: LHC-based experiments may use benefits of production of h, W, Z at LHC

Analytic estimates: upper bound

	SHiP	NA62x4	SHADOWS	MATHUSLA	FASER2
$\chi_{\text{upper}, B}$	2	1	6	0.1	3
$\chi_{\text{upper}, D}$	1	1	2	0.03	2
$\chi_{\text{upper, brem}}$	3	1	–	–	2

- At on-axis experiments, particles have larger energies
- Upper bound probed by MATHUSLA is significantly weaker than the one probed by SHiP $\Rightarrow$ smaller maximal mass probed

Analytic estimates: summary



[1901.09966]

Conclusions

- SHiP is a "golden standard" of the Intensity frontier experiment
- It suits perfectly for probing parameter space of all portal models (HNLs, dark photons, dark scalars, ALPs) with masses $m < m_B$