Searches for Heavy Neutral Leptons at Intensity Frontier Experiments

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Structure of the Standard Model

In the past the structure of the Standard Model was predicting where to expect new physics

We searched for new particles required for the consistency of our explanation of all the previous experiments

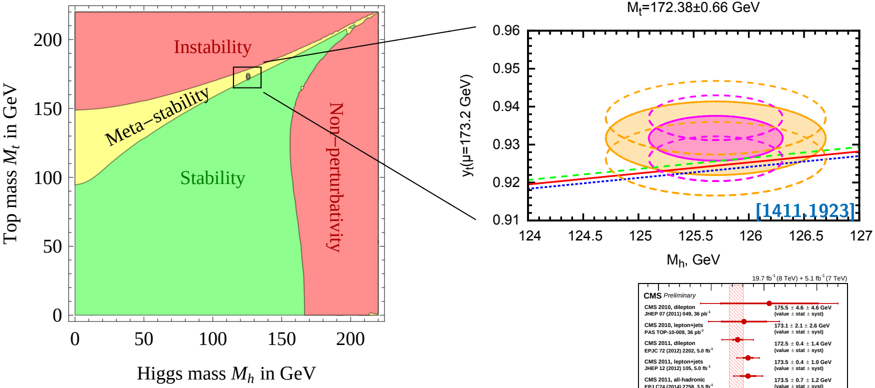
- We knew that something should— be found at energies below $E < G_{\text{Fermi}}^{-1/2}$
- Without the top quark the Standard Model would be **non-unitary**
- Without the Higgs boson the Standard Model would be **non-unitary**

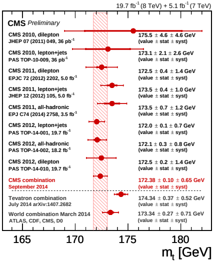
Higgs boson was the last predicted but unseen particle

- **Did century long quest come to its end?**
- **Where do we need to look for something else?**

Standard Model is consistent up to very high scales

Possibly all the way to the Planck scale





"It is expected that the difference between the MC mass definition and the formal pole mass of the top quark is up to the order of 1 GeV" (from *First combination of Tevatron and LHC measurements of the top-quark mass* [1403.4427]

Bezrukov et al. "Higgs boson mass and new physics" [1205.2893]

Degrassi et al. [1205.6497], Buttazzo et al. [1307.3536]

Should we believe that new particles exist?

Physics **Beyond** the Standard Model

Neutrino masses and oscillations

What makes neutrinos disappear and then re-appear in a different form? Why do they have mass?

- Neutrino oscillations do not tell us what is the scale of new physics
- It can be **anywhere** between sub-eV and 10^{15} GeV

Dark matter

What is the most prevalent kind of matter in our Universe?

- Physics at high scales (10^{12} GeV for axions), at intermediate scales (TeVs for WIMPs) or at low scales (keV-ish sterile neutrino, physics below electroweak scale) can be responsible for this

Baryon asymmetry of the Universe

what had created tiny matter-antimatter disbalance in the early Universe?

- Physics on the very different scales can be responsible for it

Question about the evolution of the Universe as a whole

Cosmological inflation:

What sets the initial conditions for all the structure that we see in the Universe? (possibly Higgs field)

Dark Energy:

What drives the accelerated expansion of the universe now (possibly this is just Λ-term)

Deep theoretical questions

- Strong CP problem
- Why Planck scale 10^{19} GeV is much higher than the electroweak scale (100 GeV)?
- How to describe gravity quantum mechanically?

(Fundamental questions, but it is possible to be agnostic about them for quantitative description of what was observed so far)

Unsolved problems mean that new particles probably exist

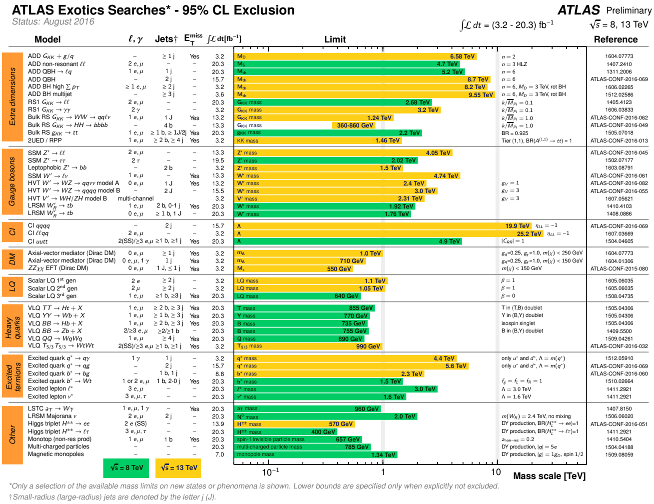
We did not detect them because

they are **heavy**

OR

they are light but
very weakly interacting

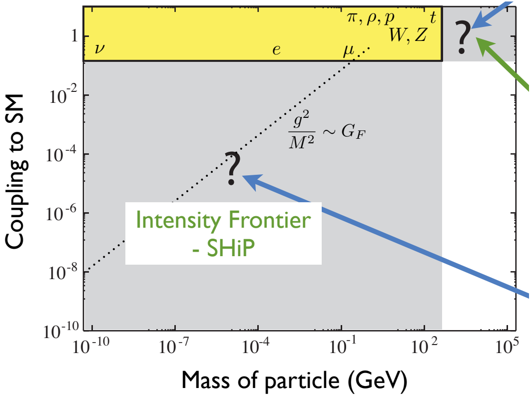
Heavy particles: active LHC searches



Probed scale

$\ll 10^{19}$ GeV

Intensity frontier searches for feebly interacting particles



Intensity frontier has been paid much less attention in the recent years:

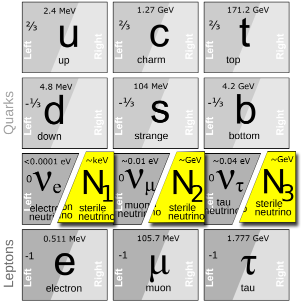
- PS 191 (early 1980s)
- CHARM: 1980s
- NuTeV: 1990s
- DONUT: late 1990s – early 2000

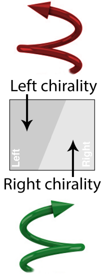
Portal operators — the gate to new physics

Light messengers couple Standard Model to "hidden sectors" via portals

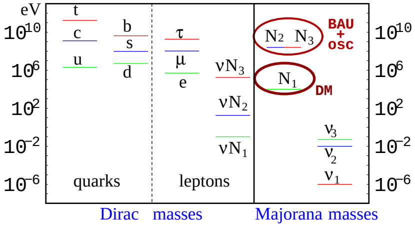
- **Scalar** portal (new particles are neutral singlet scalars, S_i that couple the Higgs field: $(\lambda_i S_i^2 + g_i S_i)(H^\dagger H)$)
- **Vector** portal (new particles are Abelian fields, A'_μ with the field strength $F'_{\mu\nu}$, that couple to the hypercharge field $F_Y^{\mu\nu}$ via $F'_{\mu\nu}F_Y^{\mu\nu}$)
- **Neutrino** portal (the singlet operators $(\bar{L}\cdot\tilde{H})$ couple to new neutral singlet fermions N_I $F_{\alpha I}(\bar{L}_\alpha \cdot \tilde{\Phi})N_I$)
- **Chern-Simons*** portal (coupling of SM vectors to new vector X through the interaction of form $\varepsilon^{\mu\nu\sigma\rho}X_\mu V_\nu \partial_\sigma V'_\rho$)
- **Axion-like*** portal (couplings of pseudo Nambu-Goldstone bosons a, associated with the breaking of approximate global symmetries: $aF_{\mu\nu}\tilde{F}^{\mu\nu}$, $\partial_\mu a\bar{\psi}\gamma^\mu\gamma^5\psi$)

Neutrino minimal Standard Model (νMSM)



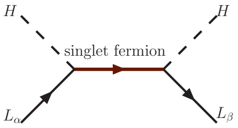


- **Neutrino oscillations:** particles N_2, N_3
- **Baryon asymmetry:** same particles N_2, N_3
  - masses $\mathcal{O}(100)$ MeV – $\mathcal{O}(80)$ GeV
- **Dark matter:** particle N_1
  - mass $1 - 50$ keV
- **Inflation:** Higgs field coupled to gravity
  - Inflationary parameters for $M_{\mathrm{Higgs}} \sim 126$ GeV in perfect agreement with observations



- **Neutrino Minimal Standard Model (νMSM)**
- Masses of right-handed neutrinos as of other order of masses of other leptons
- Yukawas as those of electron or smaller
- Review: Boyarsky, Ruchayskiy, Shaposhnikov Ann. Rev. Nucl. Part. Sci. (2009), [0901.0011]

Heavy Neutral Leptons



Majorana mass term

$$\mathcal{L}_{\mathrm{HNL}} = \mathcal{L}_{\mathrm{SM}} + i\bar{N}\partial\!\!\!/ N + Y\,\bar{N}(\tilde{H}\cdot L) + \frac{1}{2}\bar{N}MN^c + \mathrm{h.c.}$$

Dirac mass term

- States that propagate (**mass eigenstates**) do not have a definite weak charges – oscillations

- Neutrinos are light because $M_D \ll \boldsymbol{M}$:

$$\boxed{m_\nu \simeq \frac{(M_D)^2}{\boldsymbol{M}}} = U^2\boldsymbol{M}$$

- **active-sterile mixing angle**

$$\boxed{U = \frac{M_D}{\boldsymbol{M}} \ll 1}$$

The new particle is called "Sterile neutrino" or "heavy neutral lepton" or **HNL**

Properties of HNLs

Heavy neutral lepton inherits the interactions from neutrinos

Charged current-like: $$\tilde{\mathcal{L}}_{CC} = \frac{g\, U}{\sqrt{2}} \bar{e}\gamma^{\mu}(1-\gamma_5)\boldsymbol{N}^c W_{\mu}$$

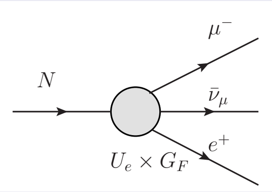
Neutral current-like: $$\tilde{\mathcal{L}}_{NC} = \frac{g\, U}{\cos\theta_W} \bar{\nu}\gamma^{\mu}(1-\gamma_5)\boldsymbol{N}^c Z_{\mu}$$

Typical values of parameters

Yukawa coupling $$\sim \left(\frac{M_N m_\nu}{\langle\Phi\rangle^2}\right)^{1/2} \approx 4\times 10^{-8}\left(\frac{M_N}{1\text{ GeV}}\right)^{1/2}$$

Mixing angles $$U^2 = \frac{m_\nu}{M_N} \approx 5\times 10^{-11}\left(\frac{1\text{ GeV}}{M_N}\right)$$

$$G_F \longrightarrow U \times G_F$$



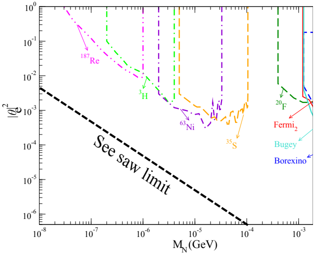
How to search for HNLs

Shrock+'80s; Gronau+'84; Gorbunov & Shaposhnikov'07; Atre et al.'09
Review: SHiP Physics Case'15

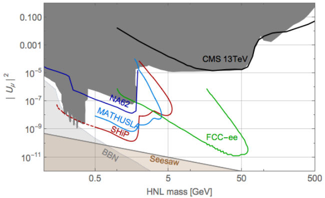
- $M_N <$ *few* MeV – only U_e mixing can be probed (kink searches)
- $\mathcal{O}(10)\mathrm{MeV} \lesssim M_N \lesssim M_K$ – intensity frontier experiments (peak searches)
- $\mathcal{O}(100)\mathrm{MeV} \lesssim M_N \lesssim M_B$ – intensity frontier experiments (fixed target experiments)
- $M_N \gtrsim$ *few* GeV – LHC searches (displaced vertices; multilepton final states; same sign same flavour leptons, ...)

  Helo+'15-'16; Izaguirre & Shuve'15; Ng+'15; Antush+'15-'16; Dib & Kim'15; Gado+'15; Dev+'15; Cvetic+'15-'16
- Z-factories (FCC-ee)

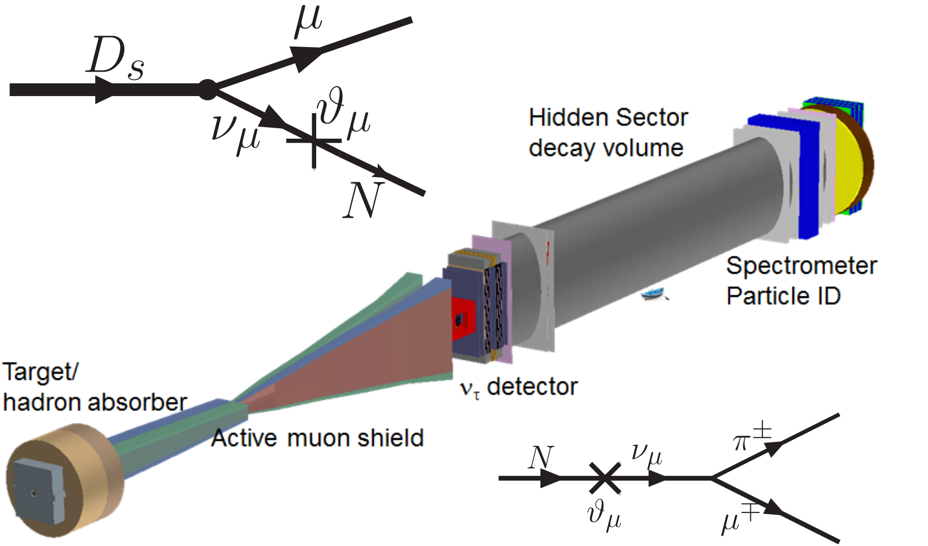
  Blondel+'14



[0901.3589]

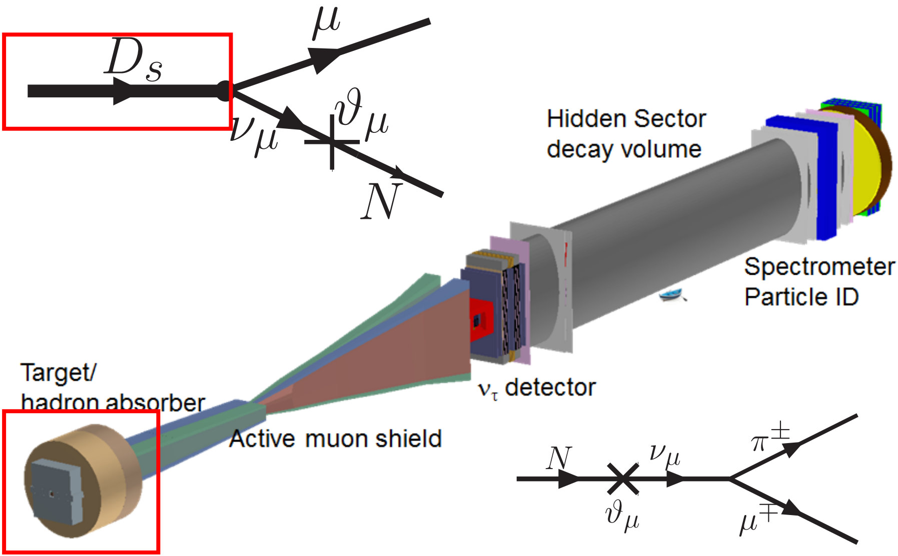


[1601.01658]


D_s
μ
ν_μ
ϑ_μ
N
Hidden Sector
decay volume
Spectrometer
Particle ID
ν_τ detector
Target/
hadron absorber
Active muon shield
N
ν_μ
ϑ_μ
$\pi^\pm$
$\mu^\mp$

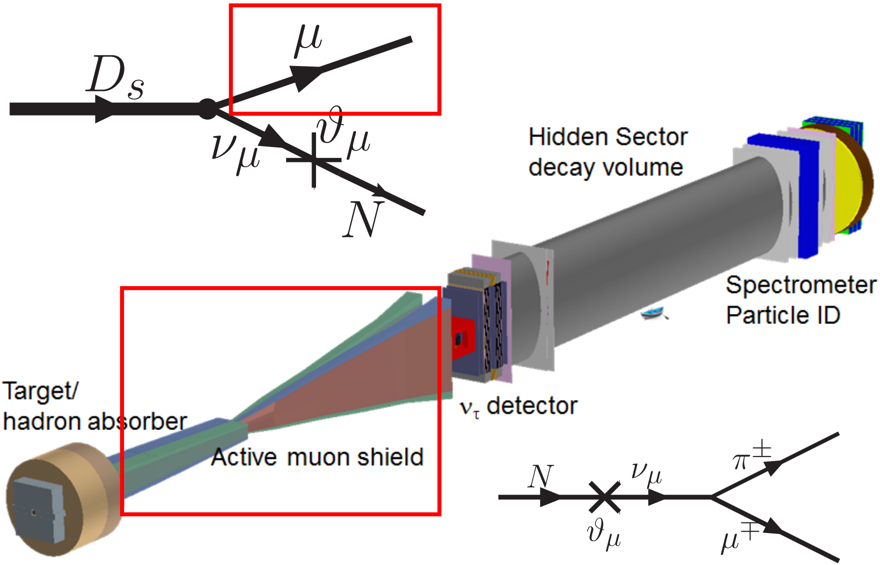
SHiP (*Search for Hidden Particles*) experiment

Step by step overview



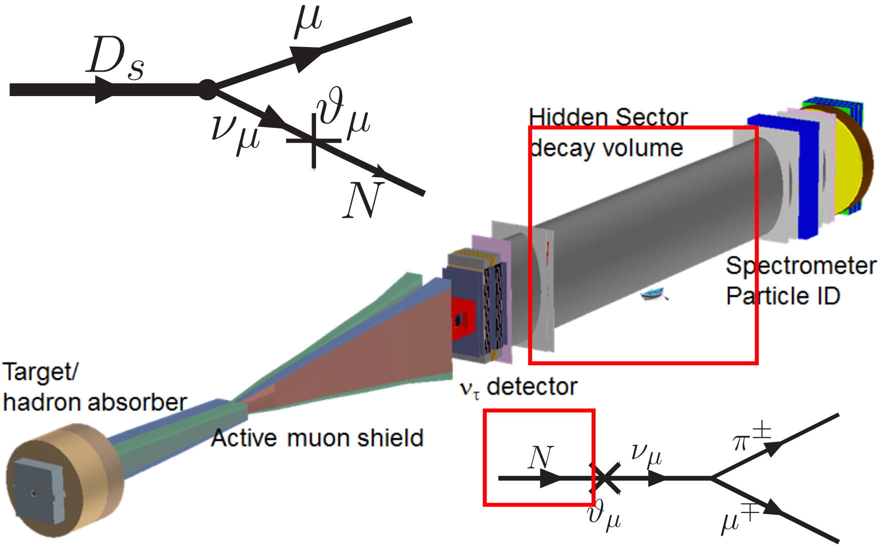
SHiP (*Search for Hidden Particles*) experiment

Step by step overview

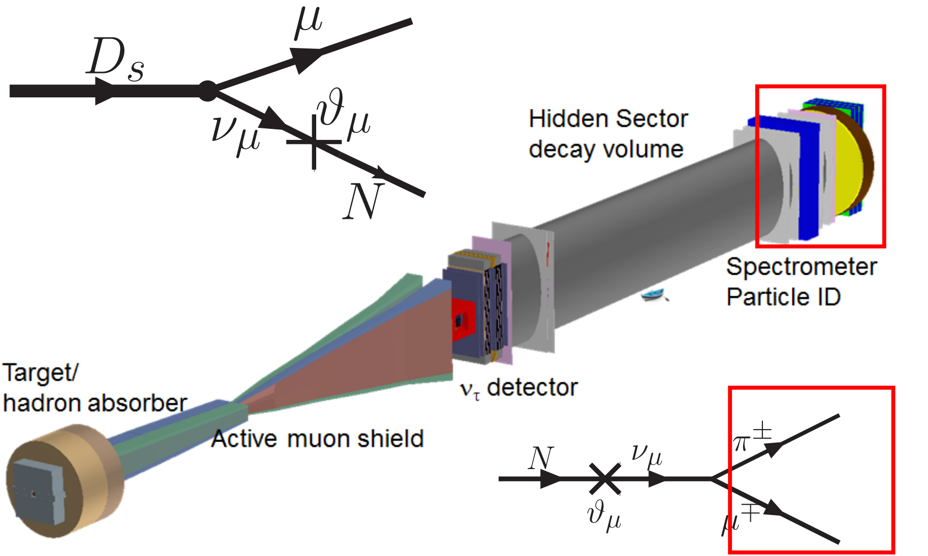


SHiP (*Search for Hidden Particles*) experiment

Step by step overview

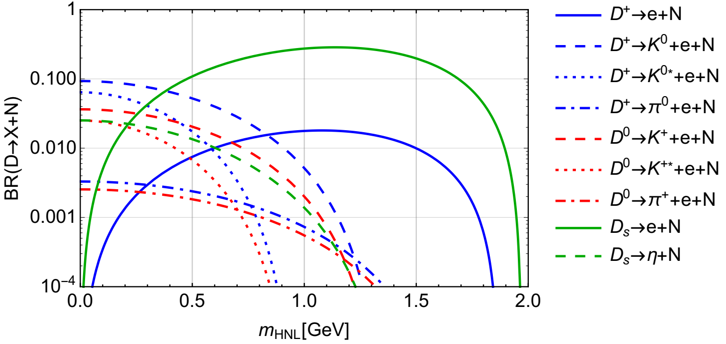


SHiP (*Search for Hidden Particles*) experiment
Step by step overview



HNL phenomenology I

- There is a great amount of production and decay channels
- HNL phenomenology was recently reviewed in [1805.08567]
- The main production channel is meson decays



HNL phenomenology II

Table 5: (continued)

Channel	Open, MeV	Rel. from, MeV	Rel. to, MeV	Max BR, %	Formula
$N \to \nu_\alpha e^+ e^-$	1.02	1.29	—	21.8	(3.4)
$N \to \nu_\alpha \pi^0$	135	136	3630	57.3	(3.7)
$N \to e^- \pi^+$	140	141	3000	33.5	(3.6)
$N \to \mu^- \pi^+$	245	246	3000	19.7	(3.6)
$N \to e^- \nu_\mu \mu^+$	106	315	—	5.15	(3.1)
$N \to \mu^- \nu_e e^+$	106	315	—	5.15	(3.1)
$N \to \nu_\alpha \mu^+ \mu^-$	211	441	—	4.21	(3.4)
$N \to \nu_\alpha \eta$	548	641	2330	3.50	(3.7)
$N \to e^- \pi^+ \pi^0$	275	666	4550	10.4	(B.42)
$N \to \nu_\alpha \pi^+ \pi^-$	279	750	3300	4.81	(B.43)
$N \to \nu_\alpha \omega$	783	997	1730	1.40	(3.9)
$N \to \nu_\alpha (3\pi)^0$	$\gtrsim 405$	$\gtrsim 1000$	?	?	No
$N \to e^- (3\pi)^+$	$\gtrsim 410$	$\gtrsim 1000$	?	?	No
$N \to \nu_\alpha \eta'$	958	1290	2400	1.86	(3.7)
$N \to \nu_\alpha \phi$	1019	1100	4270	5.90	(3.9)
$N \to \mu^- (3\pi)^+$	$\gtrsim 515$	$\gtrsim 1100$	?	?	No
$N \to \nu_\alpha K^+ K^-$	987	$\gtrsim 1100$	?	?	No

Sensitivity

- Number of detected events

$$N_{\text{events}} = N_{\text{prod}} \times P_{\text{decay}} \tag{1}$$

- Number of produced HNLs

$$N_{\text{prod}} \approx \sum_{q,\text{meson}} \overbrace{2N_{q\bar{q}} \times f_{q\to\text{meson}}}^{N_{\text{meson}}} \text{BR}_{\text{meson}\to N} \times \epsilon_{\text{decay}} \tag{2}$$

- Decay probability

$$P_{\text{decay}} = \left[\exp\left(-\frac{l_{\text{target-det}}}{l_{\text{decay}}}\right) - \exp\left(-\frac{l_{\text{target-det}} + l_{\text{det}}}{l_{\text{decay}}}\right)\right] \times \epsilon_{\text{det}} \times \text{BR}_{\text{vis}}, \tag{3}$$

where $l_{\text{decay}} = c\gamma\tau_N$

Main features

- If $l_{\text{decay}} \gg l_{\text{target-det}} + l_{\text{det}}$ (small U^2) then

$$P_{\text{decay}} \approx \frac{l_{\text{det}}\Gamma_N}{c\gamma} \times \epsilon_{\text{det}} \times \text{BR}_{\text{vis}} \tag{4}$$

  and $N_{\text{events}} \propto U^4$ for the given M_N. This gives a lower bound of the sensitivity

- If $l_{\text{decay}} \lesssim l_{\text{target-det}}$ (large U^2) then

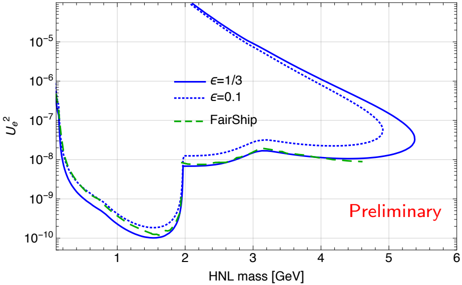
$$P_{\text{decay}} \approx \exp\left(-\frac{l_{\text{target-det}}\Gamma_N}{c\gamma}\right) \times \epsilon_{\text{det}} \times \text{BR}_{\text{vis}} \tag{5}$$

  and $N_{\text{events}} \propto U^2 \exp(-CU^2)$ for the given M_N. This gives an upper bound of the sensitivity

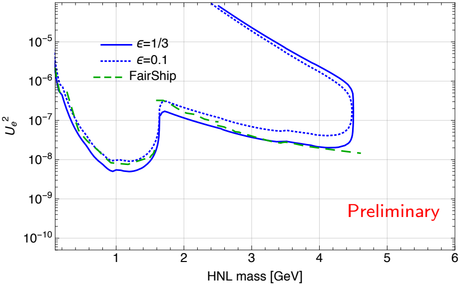
- Intersection of lower and upper bound determining the maximal probed mass

New sensitivity for HNLs

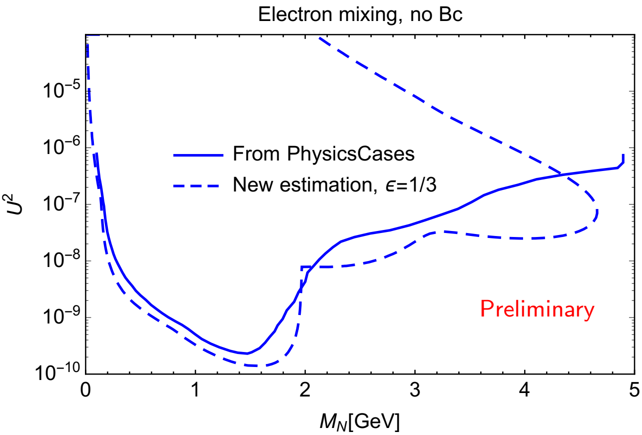
- Result for the pure electron and tau mixings from the SHiP collaboration paper [in preparation]



Electron mixing

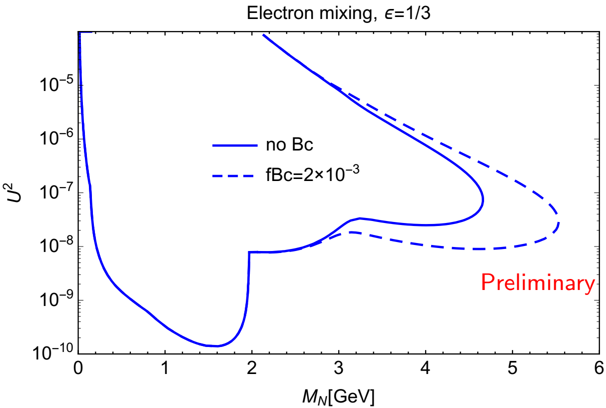


Tau mixing



SHiP physics cases paper [1504.04855]

Effect of B_c



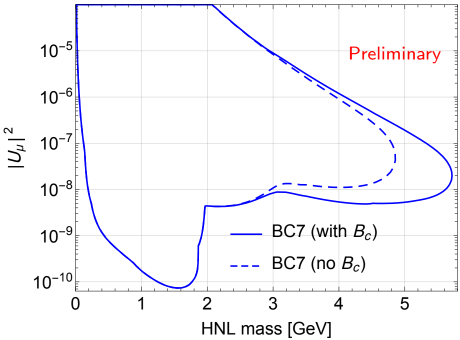
- Production from B_c mesons can be dominant for masses $M_N > 3$ GeV **if** the production fraction $b \to B_c \sim 10^{-3}$
- B_c production fraction at SHiP is unknown, but it could as high as 2.6×10^{-3} LHCb measurements

Sensitivity matrix

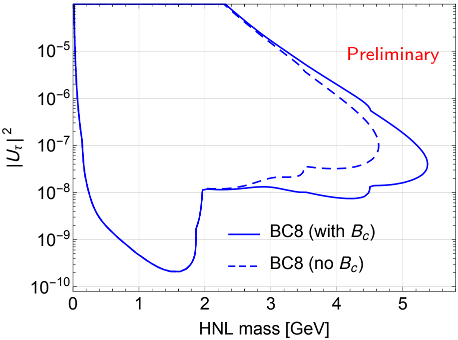
- Sensitivity of the experiment depends on the particular HNL model, with is usually fixed by choosing $U_e^2 : U_\mu^2 : U_\tau^2$ ratio
- The lower bound of the sensitivity curve has a simple analytic dependence on the set of mixing angles,

$$N_{\text{events}} = \sum_{\alpha,\beta\in(e,\mu,\tau)} U_\alpha^2 \mathcal{M}_{\alpha\beta}(M_N) U_\beta^2 \qquad (6)$$

  where the matrix $\mathcal{M}_{\alpha\beta}(M_N)$ gives a number of HNL produced through α flavour and decayed through β
- Using this matrix one can give a prediction for sensitivity in a model-independent way



BC7: $U_e^2 : U_\mu^2 : U_\tau^2 = 1 : 16 : 3.8$

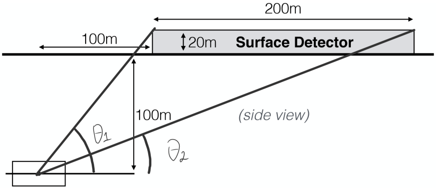


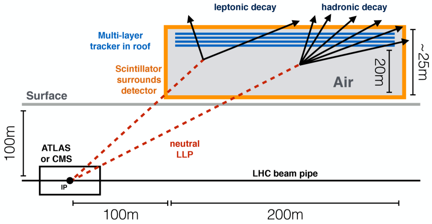
BC8: $U_e^2 : U_\mu^2 : U_\tau^2 = 0.061 : 1 : 4.3$

Conclusions

- New feebly interacting particles lighter than $W^{\pm}$ can exist
- Intensity frontier is an underexplored possibility to discover new particles, complimentary to LHC-like experiments
- Such experiments may turn out to be the future of particle physics for some time
- Experiments like SHiP are capable to discover new particles expected from various phenomenological and theoretical directions
- SHiP has capability not only to constrain many interesting models, but also directly experimentally resolve three major BSM phenomena: neutrino masses, dark matter, origin of matter-antimatter asymmetry

MATHUSLA





Parameter	θ_1	θ_2	η_1	η_2	$\bar{l}_{\text{target-det}}$, m	$\bar{l}_{\text{det}}$, m	$\Delta\phi$
Value	$44.3°$	$22.9°$	0.9	1.6	192.5	38.5	$\pi/2$

- MATHUSLA detectors is too big to generate magnetic fiels. Therefore one cannot restore momentum of particles

Lower bound

Experiment	N_D	$\langle\gamma\rangle_D$	N_B	$\langle\gamma\rangle_B$	$\langle l_{\rm det}\rangle$, m
MATHUSLA	3.6×10^{14}	2.6	2.6×10^{13}	2.3	38
SHiP	7.8×10^{17}	19.2	5.4×10^{13}	16.6	50

- If $l_{\rm decay} \gg l_{\rm det}$

$$\frac{N^{\rm SHiP}_{\rm decay}}{N^{\rm MATHUSLA}_{\rm decay}} \simeq \frac{N^{\rm SHiP}_{\rm meson}}{N^{\rm mat}_{\rm meson}} \times \frac{l^{\rm SHiP}_{\rm det}}{l^{\rm mat}_{\rm det}} \times \frac{\langle\gamma^{\rm mat}_{\rm meson}\rangle}{\langle\gamma^{\rm SHiP}_{\rm meson}\rangle} \times \frac{\epsilon_{\rm SHiP}}{\epsilon_{\rm mat}} \quad (7)$$

- Using these numbers

$$\left.\frac{N^{\rm SHiP}_{\rm decay}}{N^{\rm MATHUSLA}_{\rm decay}}\right|_{M_N<M_D} \simeq 55, \qquad \left.\frac{N^{\rm SHiP}_{\rm decay}}{N^{\rm MATHUSLA}_{\rm decay}}\right|_{M_N>M_D} \simeq 1/13 \quad (8)$$

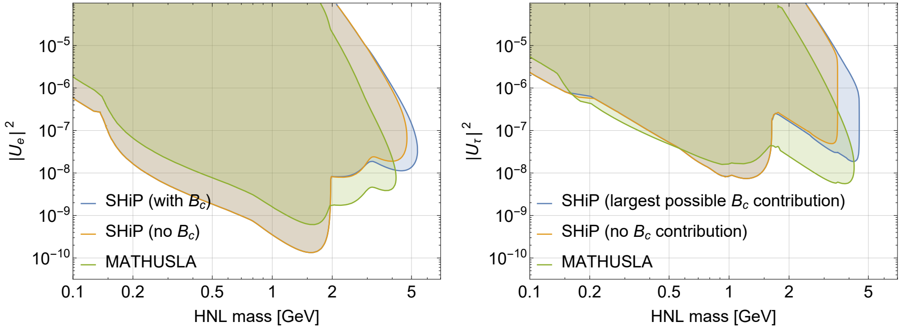
Maximal probed mass

- Maximal probed mass can be estimated at lower bound with additional condition
$$l_{\text{target-det}} \lesssim l_{\text{decay}} \tag{9}$$

- Decay length can be estimated as
$$l_{\text{decay}} \simeq \frac{\langle E\rangle}{M_X} \times \begin{cases} 170\,\text{cm}\left(\frac{10^{-5}}{U^2}\right)\left(\frac{2\,\text{GeV}}{M_X}\right)^5, & \text{HNL. Mixing with } U_{e/\mu} \text{ only} \\ 454\,\text{cm}\left(\frac{10^{-5}}{U_\tau^2}\right)\left(\frac{2\,\text{GeV}}{M_X}\right)^5, & \text{HNL. Mixing with } U_\tau \text{ only} \end{cases} \tag{10}$$

- Which gives $\frac{M^{\text{SHiP}}_{\text{decay,max}}}{M^{\text{MATHUSLA}}_{\text{decay,max}}} \simeq 1.3$

Sensitivity curve



- SHiP and MATHUSLA have similar sensitivity. MATHUSLA is YES/NO experiment, while SHiP could reconstruct mass of decaying particle
- SHiP and MATHUSLA are supplementary experiments, it would be nice to have them both