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Detecting Heavy Neutral Leptons with DUNE

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January 17, 2023

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Outline

- Heavy Neutral Leptons
- Deep Underground Neutrino Experiment
- Detector Sensitivity

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Heavy Neutral Leptons

Heavy Neutral Leptons

- Heavy Neutral Leptons (HNLs), also called Sterile Neutrinos, are new particles that are added to the Standard Model (SM) to solve three Beyond the Standard Model problems (Abazajian et al. [1204.5379]).
  - Neutrino masses and oscillations,
  - Dark Matter,
  - Baryon asymmetry in the Universe.

- HNLs are massive Majorana particles with interactions similar to the SM neutrino, but suppressed by a mixing angle U_α, with $\alpha \in \{e, \mu, \tau\}$.

- This mixing angle describes with which lepton flavour the HNL can interact and with what strength.

HNLs Parameter Space

- In constraining the HNL properties, some regions in $U_\alpha^2 - m_N$ parameter space of HNLs are excluded by;
  - previous experiments that were sensitive to specific regions of parameter space but did not detect any HNLs,
  - constraints from Big Bang Nucleosynthesis (BBN) and the observed neutrino masses.
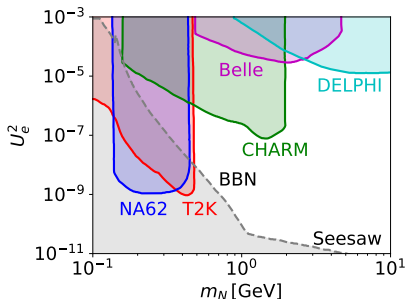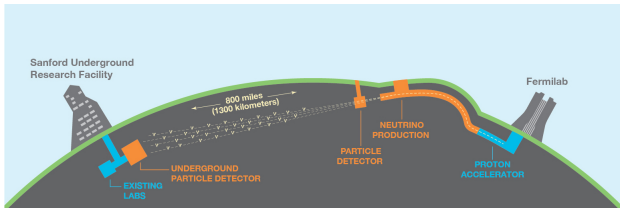

Credit: Data from Boiarska et al. [2107.14685]

Exploring HNL Parameter Space

- Most of unexplored parameter space is at $m_N > 0.5\,\mathrm{GeV}$
- Unconstrained regions of parameter space are probed by future accelerator experiments.
- In these experiments mesons are produced that could then decay into HNLs.
- HNLs can then decay inside detectors and the decay products leave behind tracks that can be observed and characterised as HNL decay events.

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DUNE

- One of these experiments is the Deep Underground Neutrino Experiment (DUNE).
- DUNE is an experiment under construction at the Long-Baseline Neutrino Fascility (LBNF) at Fermilab and the Sanford Underground Research Facility (SURF), separated by $1300\,\mathrm{km}$.
- The main goal of my thesis is to explore if the number of observed HNLs increases if the currently planned detector would be positioned elsewhere.
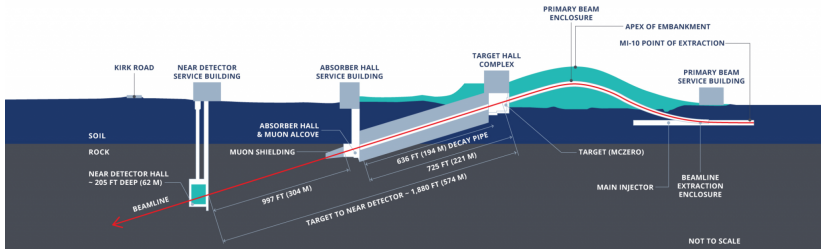

Credit: dunescience.org

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DUNE

- DUNE's primary science program is the study of (SM) neutrino physics.
- This is done by shooting $1.1 \cdot 10^{21} \, \mathrm{PoT/yr}$ protons of $120 \, \mathrm{GeV}$ at a target producing a large quantity of secondary mesons.
- These mesons decay and produce neutrinos, which are then observed at a Near Detector (Fermilab) and a Far Detector (SURF).
- Amongst other objectives, a secondary science program consists of the search for new particles, including HNLs, which the Near Detector can observe.

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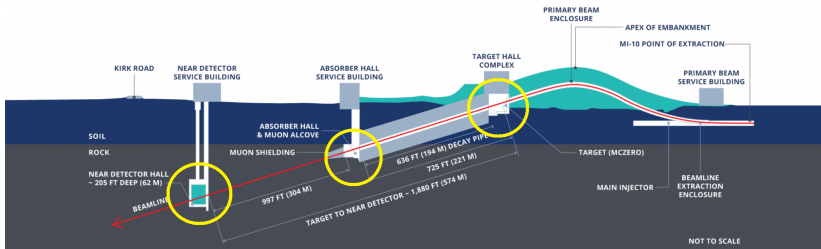
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Near Site Overview

- The Near Site at Fermilab consists of the proton beam, the Target Hall which houses the target, a Decay Pipe, an Absorber Hall and the Near Detector.

Credit: `lbnf-dune.fnal.gov`

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HNL Detector

- Beyond the Near Detector, other locations may be suitable for HNL detection, with possibly better sensitivity.
 - Target Hall (off-axis)
  - Absorber Hall (on-axis)

Credit: `lbnf-dune.fnal.gov`

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# HNL Distributions

- The most important production channel for $m_N > 0.5\,\mathrm{GeV}$ HNLs is $D_s^+ \to l^+ N$.

- I use Monte Carlo simulations to draw the distribution of HNL momentum produced by $D_s^+ \to l^+ N$.

- Because of the high centre of mass energy of the initial proton-target reaction, the D_s mesons and high mass HNLs are strongly confined to the beam axis.

- Low mass HNLs have more freedom to deviate.

- Off- (on)-axis detectors are more sensitive to low (high) mass HNLs.
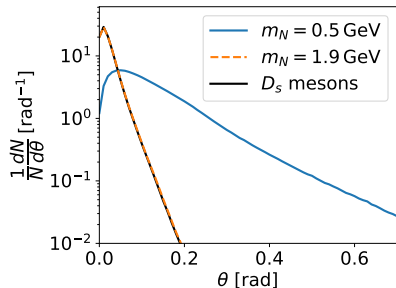
Iso-Contours

- Confidence intervals for 90% probability of detecting a single HNL without any background.
- We take a $5\,\mathrm{m} \times 5\,\mathrm{m} \times 5\,\mathrm{m}$ detector for reference.
- We consider pure electron mixing, i.e. $U_e^2 \neq 0$, $U_{\mu,\tau}^2 = 0$.
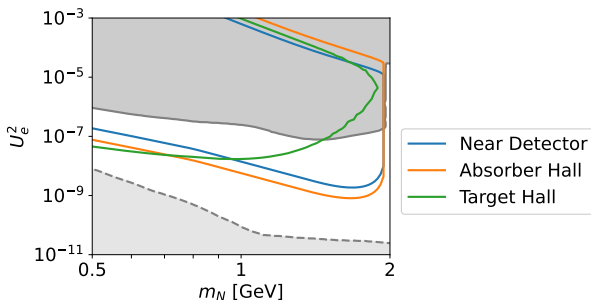
Conclusion

- The Target Hall proves to be a very poor choice for a detector, losing a lot of sensitivity to high mass HNLs.

- The Absorber Hall leads to more HNL events than the Near Detector due to its location closer to the target.

- On the other hand, the Absorber Hall does have a much higher amount of background than the Near Detector.

- However, a more detailed analysis of the effect of muon background is recommended to fully compare the Absorber Hall and the Near Detector.

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HNL Production (Electron- and Muon-Mixing)

- HNLs are most commonly produced by meson decay.
- D mesons are heavy enough to produce $m_N > 0.5\,\mathrm{GeV}$ HNLs, but not too heavy s.t. they are difficult to produce.
- The most important HNL production channel for electron- and muon-mixing is $D_s^- \to Nl^-$, with $l \in \{e, \mu\}$ (Bondarenko et al. [1805.08567]).
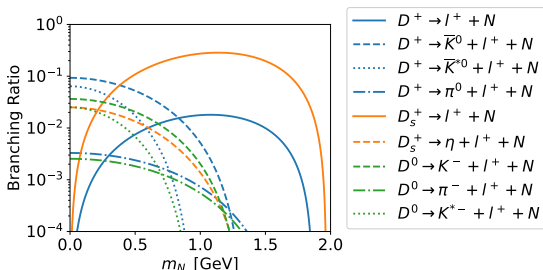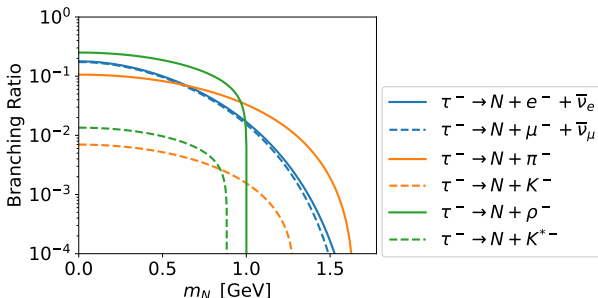

Figure for electron-mixing.

HNL Production (Tau-Mixing)

- Since $m_\tau \approx m_D$, production from D meson decay through tau-mixing only leads to $\mathcal{O}(\mathrm{MeV})$ HNLs.

- For tau-mixing, HNLs are most efficiently produced through $D_s^- \to \tau^- \nu_\tau$ and subsequent $\tau \to N$ (Boiarska et al. [2107.14685]).

- Relevant channels are $\tau^- \to N l_\alpha^- \overline{\nu}_\alpha, N\pi^-, N\rho^-$
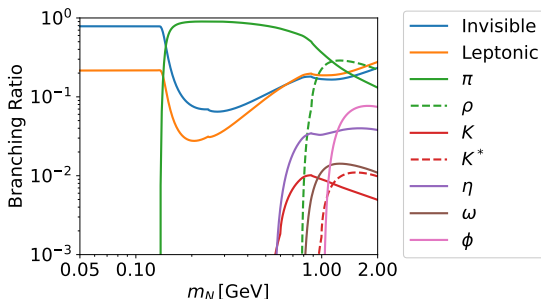
HNL decay

- HNLs can decay through the charged current (CC) and the neutral current (NC).
- CC decay leads to a charged lepton, plus a U fermion and $\overline{D}$ antifermion pair ($U = \nu_e, \nu_\mu, \nu_\tau, \{u, c, t\}$ and $D = e, \mu, \tau, \{d, s, b\}$).
- NC leads to a neutrino and any fermion-antifermion pair.
- Charged conjugate channels are also allowed due to the HNL Majorana nature.
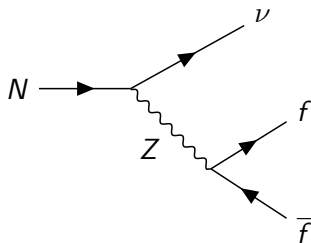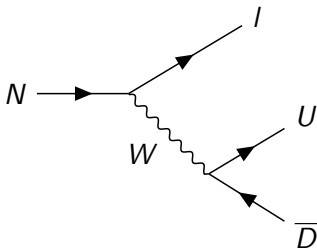
HNL Decay

- All decay channels are visible, except for $N \to 3\nu$.

Assuming mixing with $U_e^2 = U_\mu^2 = U_\tau^2$.

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Geometrical Acceptance

$$\frac{\mathrm{d}^2 N}{\mathrm{d}x_{\mathrm{F}}\mathrm{d}p_{\mathrm{T}}^2} \propto (1 - |x_{\mathrm{F}}|)^{6.1} e^{-1.08 p_{\mathrm{T}}^2 \,\mathrm{GeV}^{-2}}. \qquad (1)$$
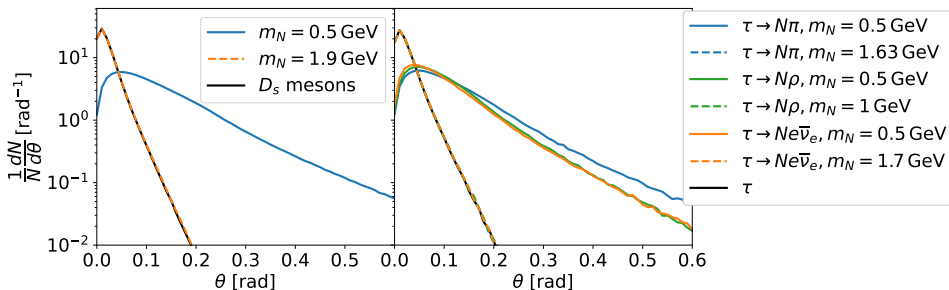
HNL Events

- The number of HNL events depends on the number of HNLs produced N_{prod} and the probability that a single HNL is detected P_{det}

$$N_{\mathrm{events}} = N_{\mathrm{prod}} P_{\mathrm{det}}. \qquad (2)$$

- The probability of detection depends on the probability that an HNL decays inside the detector, i.e. at a point between entry (l_{ent}) and exit (l_{exi}) of the detector

$$P_{\mathrm{det}} \propto \left[\exp\left(-\frac{l_{\mathrm{ent}}}{l_{\mathrm{dec}}} \right) - \exp\left(-\frac{l_{\mathrm{exi}}}{l_{\mathrm{dec}}} \right) \right]. \qquad (3)$$

- Iso-contours of regions in $U_{\alpha}^2 - m_N$ parameter space are found by taking two limits;
  - a lower bound is given by $l_{\mathrm{dec}} \gg l_{\mathrm{ent}}, l_{\mathrm{exi}}$; long living HNLs
  - an upper bound is given by $l_{\mathrm{dec}} \ll l_{\mathrm{det}}, l_{\mathrm{ent}}$; short living HNLs.

Target Hall

- The Target Chase is a tunnel inside the Target Hall, containing the target and horns that help focus charged particles.
- A detector could be placed in the Target Hall, but outside the Target Chase to minimise background.
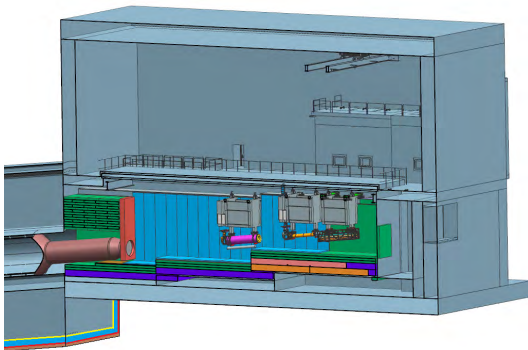
Credit: Strait et al. [1601.05823]

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Absorber Hall

- The Absorber Hall at the end of the Decay Pipe consists of a hadron absorber upstream, a muon monitor and muon shielding downstream.
- A detector could be placed between the hadron absorber and the muon monitor.

Absorber Pile

Muon Monitors

Muon Kern

Credit: https://indico.fnal.gov/event/22165/
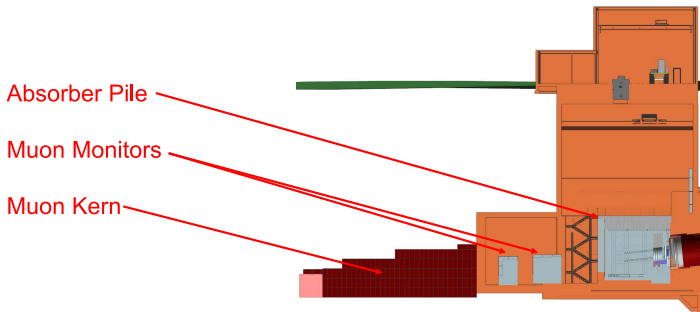
Sensitivity Bounds

- The number of events is

$$N_{\text{events}} = N_{\text{D}_\text{s}} \text{BR}_{\text{D}_\text{s} \rightsquigarrow \text{N}} \epsilon_{\text{geom}} \text{BR}_{\text{vis}} \tag{4}$$
$$\times \left[\exp\left(-\frac{l_{\text{ent}}}{l_{\text{dec}}} \right) - \exp\left(-\frac{l_{\text{exi}}}{l_{\text{dec}}} \right) \right]$$

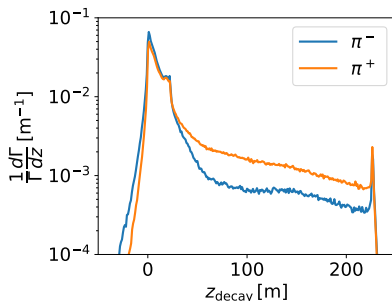- For $l_{\text{dec}} \gg l_{\text{det}}, l_{\text{ent}}$

$$N_{\text{events}} = N_{\text{D}_\text{s}} \widetilde{\text{BR}}_{\text{D}_\text{s} \rightsquigarrow \text{N}} \text{BR}_{\text{vis}} \epsilon_{\text{geom}} \frac{\langle l_{\text{det}} \rangle}{\langle v\gamma\tilde{\tau} \rangle} U^4 \tag{5}$$

- For $l_{\text{dec}} \ll l_{\text{det}}, l_{\text{ent}}$

$$N_{\text{events}} = N_{\text{D}_\text{s}} \widetilde{\text{BR}}_{\text{D}_\text{s} \rightsquigarrow \text{N}} \text{BR}_{\text{vis}} \epsilon_{\text{geom}} U^2 \exp\left(-U^2 \frac{\langle l_{\text{ent}} \rangle}{\langle v\gamma\tilde{\tau} \rangle} \right) \tag{6}$$

Combinatorial Muon Background

- The channels that suffer from this background are $N \to \nu\mu^+\mu^-$, and $N \to \mu^\pm\pi^\mp$, because $m_\pi \approx m_\mu$.
- Muons are produced from pion decay $\pi^+ \to \mu^+ + \nu_\mu$.
- Pions are (relatively) long lived, and so are effected by the horn focussing system.

Horn in neutrino mode; focussing positive particles and deflecting negative particles. Data from DUNE Collaboration.

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Muon Background

- A pair of muons can form background if they are closer than the detector resolution ($\sim 1\,\mathrm{cm}$, DUNE Collaboration [2103.13910]) to each other as they enter the detector.

- The number of muon pairs in the experiment is

$$N_{\mu\mu,\mathrm{exp}} = N_{\mu\mu,\mathrm{sim}} \left(\frac{N_{\mu,\mathrm{exp}}}{N_{\mu,\mathrm{sim}}} \right)^2 \frac{\Delta t_{\mathrm{det}}}{T_{\mathrm{exp}}} \tag{7}$$

- With the detector time resolution $\Delta t = 20\,\mathrm{ns}$ (DUNE Collaboration [2103.13910]) this leads to $\mathcal{O}(10^{18})$ events and $\mathcal{O}(10^{19})$ for the Near Detector and Absorber Hall respectively.

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Ray-AABB Algorithm

- The ray-AABB algorithm is used to determine the number of HNLs that move towards the detector.
- It determines if a ray (HNL) passes through a box (detector), and also returns the time at which it enters and exits the box.