Simulating Heavy Neutral Leptons with General Couplings at Collider/Fixed Target Experiments

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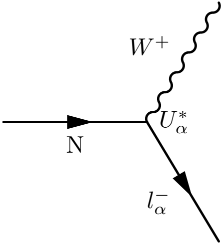
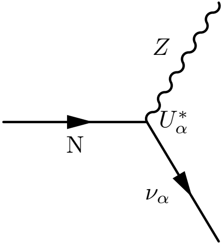
DPF-PHENO 2024
May 14, 2024

Arxiv: 2405.07330

Intro to HNL's

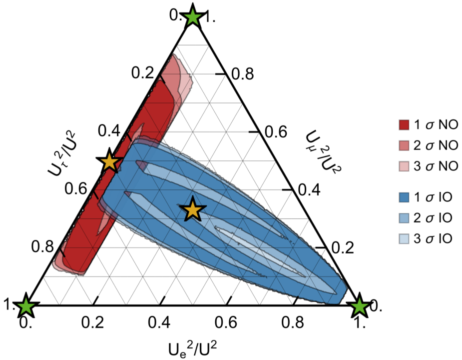
- A simple extension of the SM is a Heavy Neutral Lepton (HNL)
- HNL's can explain neutrino oscillations/masses, baryogenesis and dark matter
- Lagrangian comes with many mass terms, diagonalization leads to mixing
  - $\nu_\alpha = \sum_{i=1}^{3} V_{\alpha i}\,\nu_i + U_\alpha N^c$
- The HNL picks up charged current (CC) and neutral current (NC) interactions
  - $\mathcal{L} = -\frac{g}{\sqrt{2}} \sum_\alpha U_\alpha^* W_\mu^+ \overline{N^c}\,\gamma^\mu l_\alpha - \frac{g}{2\cos\theta_W} \sum_\alpha U_\alpha^* Z_\mu \overline{N^c}\,\gamma^\mu \nu_\alpha + \text{h.c.}$





- We discuss their signal in the 100 MeV to 10 GeV mass range at FASER using a COM pp energy of 14 TeV
  - Results simulated with FORESEE (FORward Experiment SEnsitivity Estimator)
  - Requires the extension HNLCalc which we have created for HNL pheno

Simple vs. Motivated Benchmarks

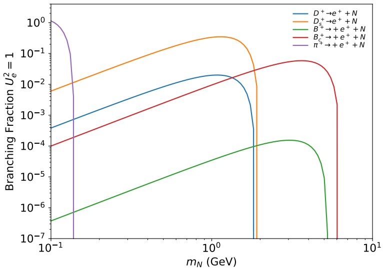


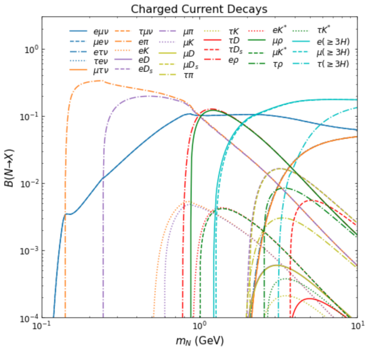
Drewes, Klaric, Pavon (2022)

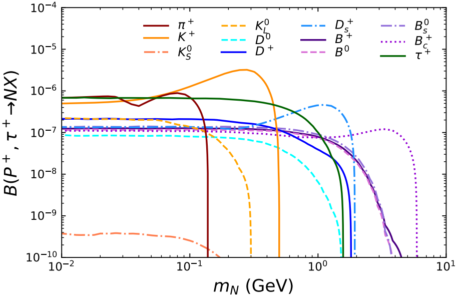
- Notation: $U_e^2 : U_\mu^2 : U_\tau^2$ denotes a benchmark (e.g. 0:1:1)
- Previous benchmarks 1:0:0, 0:1:0, 0:0:1 (Physics Beyond Colliders study group (2019))
- More motivated benchmarks are 0:1:1 and 1:1:1
- Benchmark motivations:
  - Neutrino Oscillations
  - Explain Leptogenesis
  - Simplicity
- This work builds off of previous works of others:
  - Gribonov, Kovalenko, Schmidt (2001)
  - Atre, Han, Pascoli, Zhang (2009)
  - Helo, Kovalenko, Schmidt (2011)
  - Coloma, Fernández-Martínez, González-López(2021)
  - Ballett, Boschi, Pascoli (2020)
  - Gorbunov, Shaposhnikov (2013)

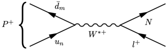
HNLCalc

- HNLCalc is a standalone package for HNL phenomenology that we have developed
- Can be used in conjunction with LLP event generators such as FORESEE
- HNLCalc supports arbitrary mixings U_e^2, U_μ^2, U_τ^2 and masses
- This tool calculates or contains:
  - LLP branching fractions for production and decay
  - Calculates τ_N
  - Plotting tools for visualization
  - More features to come soon...
  - HNLCalc available on Git: [laroccod/HNLCalc]()

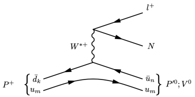




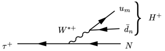




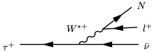
(a) 2-body decay $P \to lN$



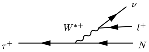
(b) 3-body decay $P \to P'lN$ and $P \to VlN$



(c) 2-body decay $\tau \to HN$



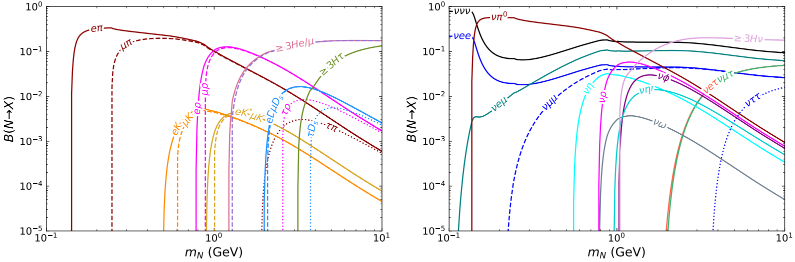
(d) 3-body decay $\tau^+ \to l^+\bar{\nu}N$

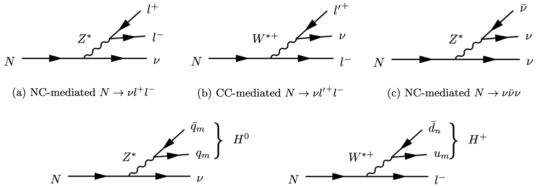


(e) 3-body decay $\tau^+ \to l^+\nu N$

- HNL’s could be produced from decaying SM particles
- These productions are modeled by generators (e.g. Pythia)
- HNLCalc implements dominant production mechanisms within the mass range 100 MeV to 10 GeV
- The production of HNL’s depends on (m_N, U_α^2)

- HNLCalc includes dominant HNL Decay mechanisms
  - Decays into hadrons and leptonic final states through: Left CC, Right: NC (1:1:1)





(a) NC-mediated $N \to \nu l^+ l^-$ (b) CC-mediated $N \to \nu l'^+ l^-$ (c) NC-mediated $N \to \nu\bar{\nu}\nu$

(d) NC-mediated $N \to \nu H^0$ (e) CC-mediated $N \to l^- H^+$

Decays of HNL's

- HNLCalc implements over 150 production modes of HNL's and over 100 decay modes!

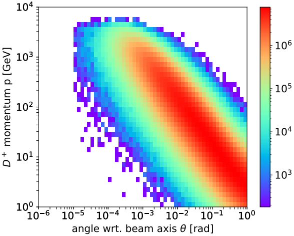
HNL Production Processes							
$P \to lN$	Fig. 1 (a)	$\pi^+ \to l^+ N$	$K^+ \to l^+ N$	$D^+ \to l^+ N$	$D_s^+ \to l^+ N$	$B^+ \to l^+ N$	$B_c^+ \to l^+ N$
$P \to P' l N$	Fig. 1 (b)	$K^+ \to \pi^0 l^+ N$	$K_S \to \pi^+ l^- N$	$K_L \to \pi^+ l^- N$	$D^0 \to K^- l^+ N$	$\bar{D}^0 \to \pi^+ l^- N$	$D^+ \to \pi^0 l^+ N$
		$D^+ \to \eta l^+ N$	$D^+ \to \eta' l^+ N$	$D^+ \to \bar{K}^0 l^+ N$	$D_s^+ \to \bar{K}^0 l^+ N$	$D_s^+ \to \eta l^+ N$	$D_s^+ \to \eta' l^+ N$
		$B^+ \to \pi^0 l^+ N$	$B^+ \to \eta l^+ N$	$B^+ \to \eta' l^+ N$	$B^+ \to \bar{D}^0 l^+ N$	$B^0 \to \pi^- l^+ N$	$B^0 \to D^- l^+ N$
		$B_s^0 \to K^- l^+ N$	$B_s^0 \to D_s^- l^+ N$	$B_c^+ \to D^0 l^+ N$	$B_c^+ \to \eta_c l^+ N$	$B_c^+ \to B^0 l^+ N$	$B_c^+ \to B_s^0 l^+ N$
$P \to V l N$	Fig. 1 (b)	$D^0 \to \rho^- l^+ N$	$D^0 \to K^{*-} l^+ N$	$D^+ \to \rho^0 l^+ N$	$D^+ \to \omega l^+ N$	$D^+ \to \bar{K}^{*0} l^+ N$	$D_s^+ \to K^{*0} l^+ N$
		$D_s^+ \to \phi l^+ N$	$B^+ \to \rho^0 l^+ N$	$B^+ \to \omega l^+ N$	$B^+ \to \bar{D}^{*0} l^+ N$	$B^0 \to \rho^- l^+ N$	$B^0 \to D^{*-} l^+ N$
		$B_s^0 \to K^{*-} l^+ N$	$B_s^0 \to D_s^{*-} l^+ N$	$B_c^+ \to D^{*0} l^+ N$	$B_c^+ \to J/\psi\, l^+ N$	$B_c^+ \to B^{*0} l^+ N$	$B_c^+ \to B_s^{*0} l^+ N$
$\tau \to H N$	Fig. 1 (c)	$\tau^+ \to \pi^+ N$	$\tau^+ \to K^+ N$	$\tau^+ \to \rho^+ N$	$\tau^+ \to K^{*+} N$		
$\tau^+ \to l^+ \nu N$	Fig. 1 (d,e)	$\tau^+ \to l^+ \bar{\nu}_\tau N$	$\tau^+ \to l^+ \nu_l N$				

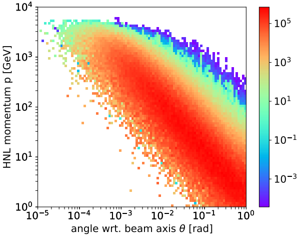
HNL Decay Modes							
$\nu\, l^+ l^-$	Fig. 3 (a)	$\nu_l e^+ e^-$	$\nu_l \mu^+ \mu^-$	$\nu_l \tau^+ \tau^-$			
$l^\pm\, \nu_{l'} l'^\mp$	Fig. 3 (b)	$l^\pm \nu_e e^\mp$	$l^\pm \nu_\mu \mu^\mp$	$l^\pm \nu_\tau \tau^\mp$			
$\nu_l\, \bar{\nu}\nu$	Fig. 3 (c)	$\nu_l \bar{\nu}_e \nu_e$	$\nu_l \bar{\nu}_\mu \nu_\mu$	$\nu_l \bar{\nu}_\tau \nu_\tau$			
$\nu_l\, H^0$	Fig. 3 (d)	$\nu_l \pi^0$	$\nu_l \eta$	$\nu_l \eta'$	$\nu_l \rho^0$	$\nu_l \omega$	$\nu_l \phi$
$l^\pm\, H^\mp$	Fig. 3 (e)	$l^\pm \pi^\mp$	$l^\pm K^\mp$	$l^\pm D^\mp$	$l^\pm D_s^\mp$	$l^\pm \rho^\mp$	$l^\pm K^{*\mp}$
$\nu_l\, q\bar{q}$	Fig. 3 (d)	$\nu_l u\bar{u}$	$\nu_l d\bar{d}$	$\nu_l s\bar{s}$	$\nu_l c\bar{c}$	$\nu_l b\bar{b}$	
$l^\pm\, u\bar{d}'$	Fig. 3 (e)	$l^- u\bar{d}$	$l^- u\bar{s}$	$l^- u\bar{b}$	$l^+ \bar{u}d$	$l^+ \bar{u}s$	$l^+ \bar{u}b$
		$l^- c\bar{d}$	$l^- c\bar{s}$	$l^- c\bar{b}$	$l^+ \bar{c}d$	$l^+ \bar{c}s$	$l^+ \bar{c}b$

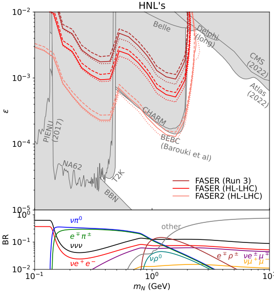
HNLCalc as an Extension to FORESEE

- FORESEE is a simulation package used for Long-Lived Particles (LLPs):
- This tool calculates or contains:
  - Hadronic spectra
  - HNL branching fractions for production/decay and lifetime from HNLCalc
  - Production rates
  - Event Analyses
  - Sensitivity/reach plots
- We apply this to the FASER and FASER2 experiments as an example

HNLCalc as an Extension to FORESEE

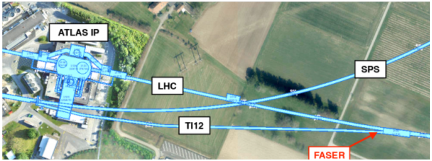




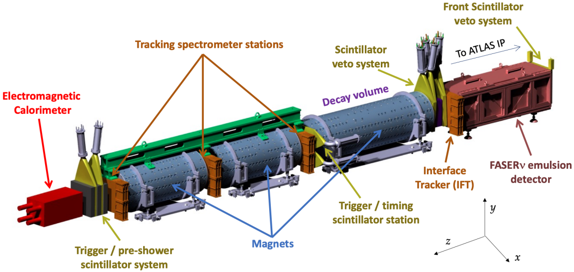


FASER and the Future of FPF

- FASER is in the far forward direction at LHC
- Positioned 480 m from ATLAS IP



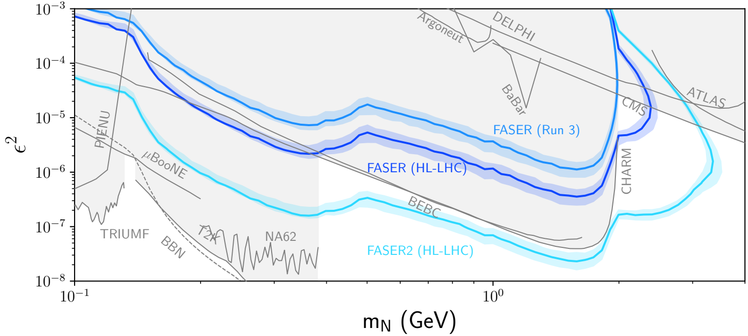
	L	Δ	Geometry	$\mathcal{L}$
FASER (Run 3)	480 m	1.5 m	Cyl. $R = 10\,\text{cm}$	$250\,\text{fb}^{-1}$
FASER (HL-LHC)	480 m	1.5 m	Cyl. $R = 10\,\text{cm}$	$3\,\text{ab}^{-1}$
FASER2 (HL-LHC)	650 m	10 m	Rect. $3\,\text{m} \times 1\,\text{m}$	$3\,\text{ab}^{-1}$



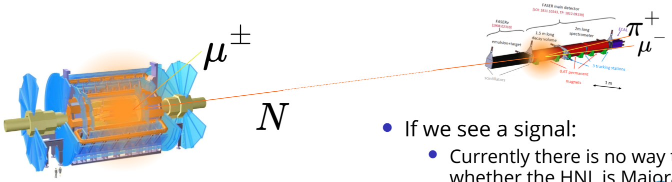
FASER Collaboration, 2207.11427

HNL Event Analysis

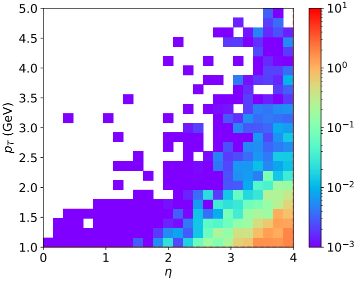
- We apply our new module to analyze 1:0:0, 0:1:0, 0:0:1, 0:1:1, 1:1:1 (here we show 1:1:1)
  - 1:1:1 initialized at $U_e^2 = U_\mu^2 = U_\tau^2 = \frac{1}{3}$ then scaled by ϵ^2
- Reach extends significantly in HL-LHC setup
- Reach is vastly improved upon the FASER2 upgrade
  - 1:1:1 grey experimental constraints are only approximate (also for 0:1:1)



Preliminary Analysis: Using FASER as a Trigger for ATLAS



- If we see a signal:
  - Currently there is no way to tell whether the HNL is Majorana or Dirac
  - Charge identification of prompt lepton could be determined at ATLAS (5.4 μs trigger time)
- A preliminary analysis assuming:
  - HL-LHC, Phase II at ATLAS, using FASER2 setup
  - $m_N = 1.8$ GeV, $U_\mu = 0.002$
- Current muon tagging $|\eta| < 2.5$ will not yield a good signal
  - An HNL event could help motivate a muon tagger $|\eta| < 4$
  - Pile-up could still be an issue



Summary and Conclusion

- HNL's can solve many problems, such as neutrino oscillations and baryogenesis
- HNLCalc is a general framework for HNL's in the mass range 100 MeV to 10 GeV
  - Incorporates arbitrary mixings to the *e*, μ, and τ neutrinos
  - Easy access to dominant production and decay branching fractions
  - Dominant productions come from 2-3 body decays of mesons and τ lepton
  - Over 150 production modes and 100 decay modes
- We use it as an extension to FORESEE to simulate FASER and FASER2 signals
- Competetive bounds in 2-3.5 GeV mass range for HL-LHC/FASER2 setup
- One could use FASER as a trigger for ATLAS to determine whether the HNL is Majorana or Dirac
- Our simulation package is available at: laroccod/HNLCalc

Thank You!

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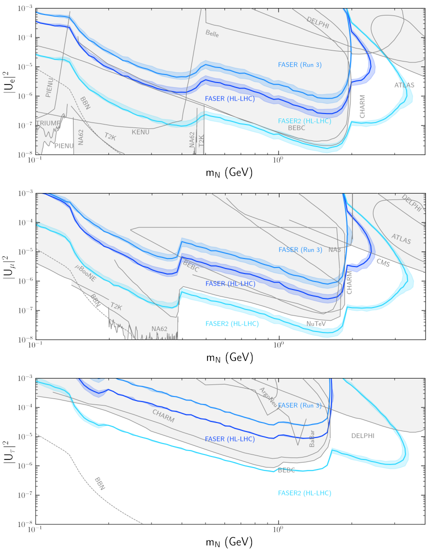
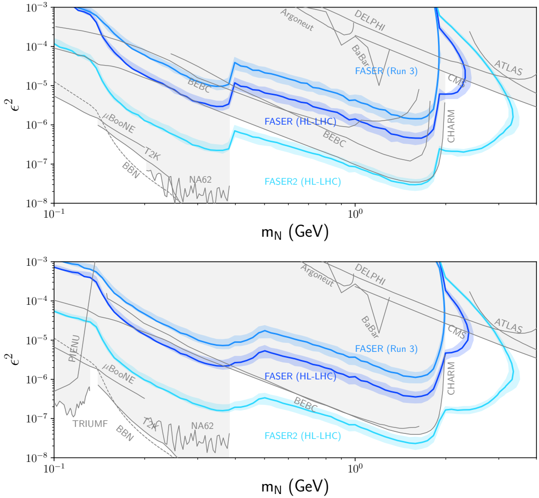
Sensitivity Plots

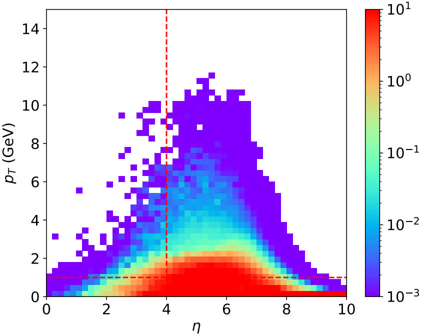


Top: 1:0:0, Middle: 0:1:0, Bottom: 0:0:1

Sensitivity Plots



Top: 0:1:1, Bottom: 1:1:1



14
12
10
8
6
4
2
0
p_T (GeV)
0
2
4
6
8
10
η
10^1
10^0
10^{-1}
10^{-2}
10^{-3}