Resonant HNL Production at Beam Dump Experiments

By: Francis Burk

[2601.18874]

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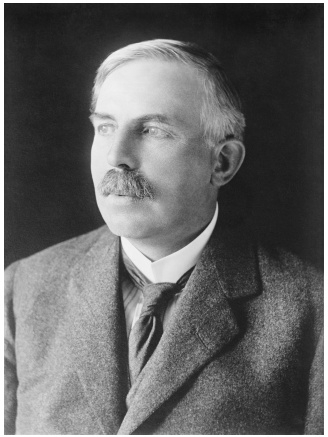
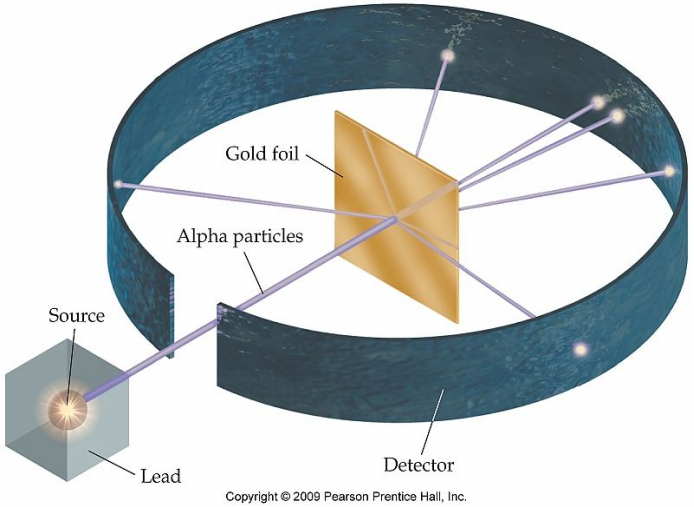
What is a Fixed Target Experiment?

1. Fixed Target



History Lesson:

- Rutherford's Gold Foil Experiment (1909)
- Beam of particles on gold
- Inferred gold nucleus from scattering

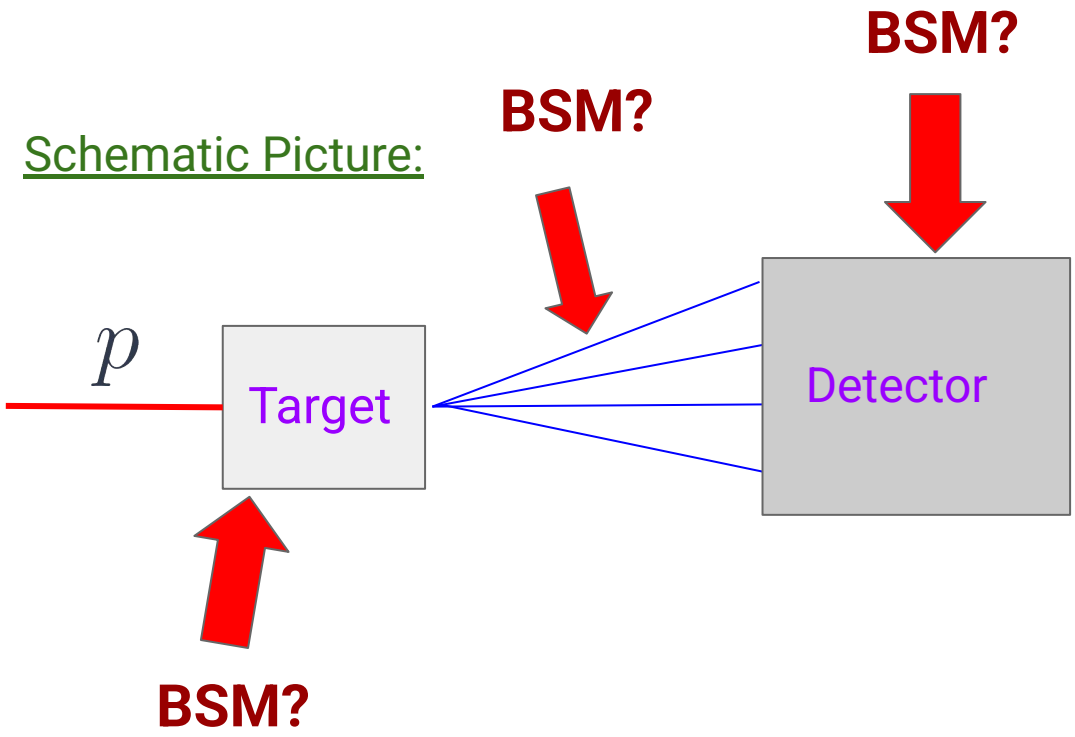


First fixed target experiment!

1. Fixed Target

Today:

- Many fixed target experiments
- Send a proton to a target
- Study final state products



1. Fixed Target

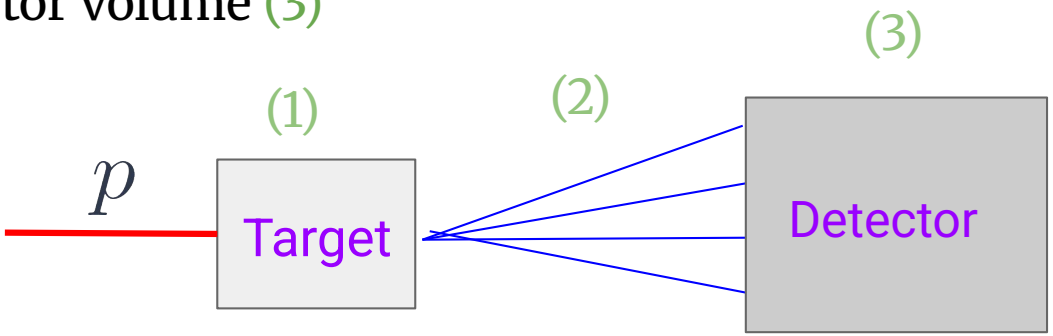
- Production for colliders:

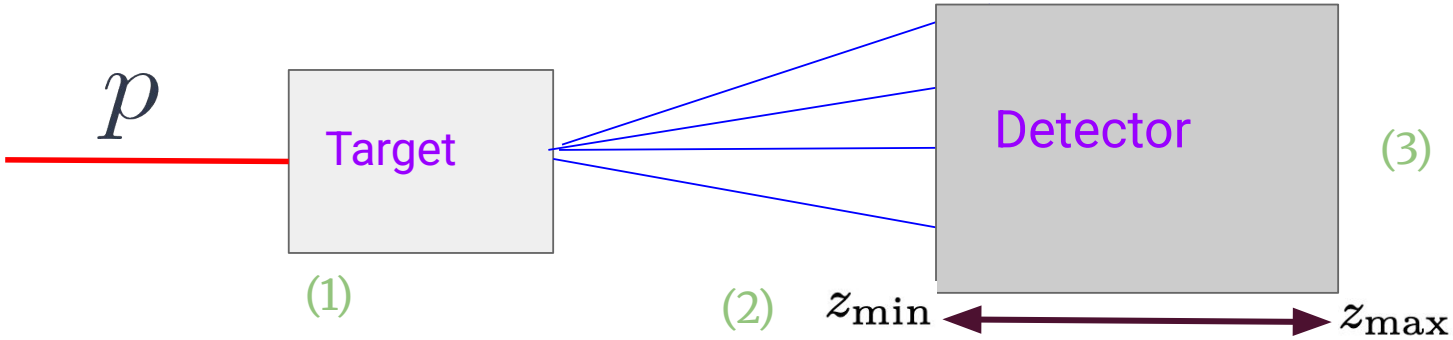
Process Cross Section

Integrated Luminosity

$$N = \sigma \mathcal{L}$$

- Important considerations:
  - Fixed Target (1)
  - Long-lived particles (2)
  - Decay within detector volume (3)





$$N_{\text{Produced}} = \text{POT} \times \left(1 - e^{-\frac{l_{\text{target}}}{\lambda_{\text{int}}}}\right) \times \frac{\sigma_{BSM}}{\sigma_{pN}} \qquad (1)$$

$$\text{eff} = m\Gamma \int_{z_{\min}}^{z_{\max}} dz \sum_{\text{events} \in \text{geom.}} \frac{e^{-z(m/p_z)\Gamma}}{N_{\text{MC}}\, p_z} \qquad (2)$$

$$N_{\text{Detected}} = N_{\text{Produced}} \times \text{BR}(N \to f) \times \text{eff}_f \qquad (3)$$

Enter: The Heavy Neutral Lepton (HNL) and The Z’

2. HNLs from a Z'

Interaction terms

$$\mathcal{L}_X \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu}+\frac{1}{2}m^2_{Z'}Z'_\mu Z'^\mu+g_X Z'_\mu\left(\sum_f \bar{f}\gamma^\mu(g_{V,f}+g_{A,f}\gamma_5)f+\bar{N}\gamma^\mu(g_{V,N}+g_{A,N}\gamma_5)N\right)$$

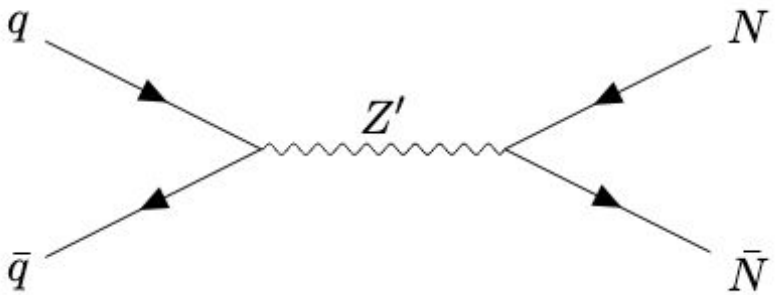
	$g_{V,q}$	$g_{A,q}$	$g_{V,l}$	$g_{A,l}$	$g_{V,N}$	$g_{A,N}$
$U(1)_{B-L}$	1/3	0	−1	0	0	−1
$U(1)_{B-3L_\tau}$	1/3	0	−3	0	0	−1
$U(1)_B$	1/3	0	0	0	0	−1

Rescale results for other similar U(1) models

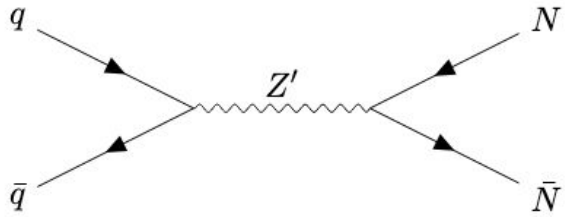
How far can we take an HNL and Z’ at a Fixed Target Exp?

3. Resonant HNL Production

- Focus on resonant production of HNLs
- Generate events using Madgraph



3. Resonant HNL Production



- s-channel production of HNLs
  - Such processes studied previously [1604.06099]
  - Scales as g^2_{B-L} during resonance

$$\sigma(pp \to Z' \to NN) = \frac{g^4_{B-L}}{1944\Gamma_{Z'}} \frac{\beta^3_N m_{Z'}}{s} \cdot \frac{1}{2} \sum_{q,\bar{q}} \int_{m^2_{Z'}/s}^{1} \frac{dx_2}{x_2} \left[f_q\left(\frac{m^2_{Z'}}{x_2 s}, m^2_{Z'}\right) f_{\bar{q}}(x_2, m^2_{Z'}) + (q \leftrightarrow \bar{q}) \right]$$

$$\equiv \mathcal{L}_{q\bar{q}}$$

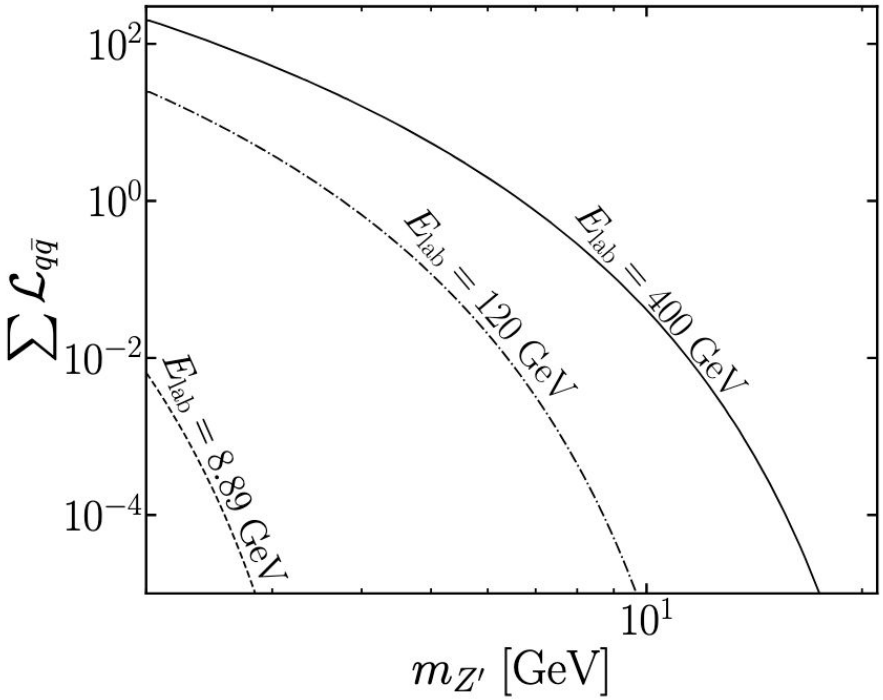
3. Production

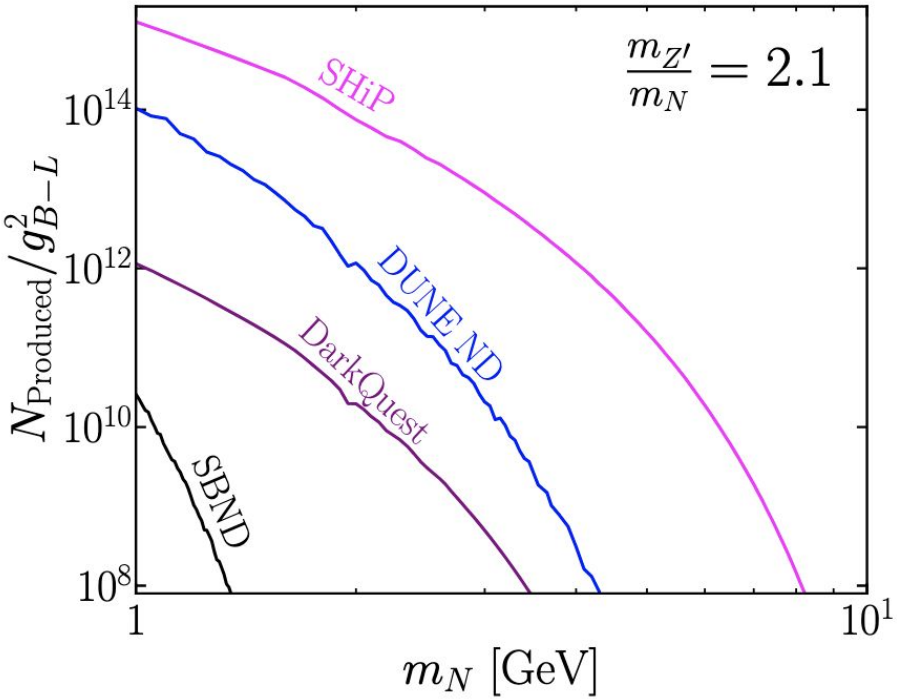
- Studied various fixed target scenarios
  - SBND
  - DUNE ND
  - DarkQuest
  - SHiP

[2601.18874]

Detectors (beam target)	Beam, E [GeV]	Baseline [m]	POT	l_{Target} [cm]	λ_{int} [cm]	ρ [g·cm^{-3}]	σ_{pN} [mb]
SBND (Be) [1, 65]	BNB, 8	110	1×10^{21}	71.1	42.10	1.848	21.37
DarkQuest (Fe) [8]	FMI, 120	5	1×10^{18}	500	16.77	7.87	12.55
DUNE ND (Graphite) [3, 66]	LBNF, 120	574	7×10^{21}	150	38.83	2.210	19.36
SHiP (Mo) [9]	SPS, 400	33	6×10^{20}	140	15.25	10.2	10.68

3. Production





4. Final States:

- Flavor alignment: $|U_\tau|$
- Studied two final states
  - $N \to e^+ e^- \nu_\tau$
  - $N \to \pi^0 (\to \gamma\gamma) \nu_\tau$

5. Background Considerations (1):

SBND: $E_{e^+e^-},\ E_{\pi^0} > 1.8\ \text{GeV}$ [1, 2]

DarkQuest: $E_{e^+e^-} > 500\ \text{MeV} \quad \text{and} \quad E_{\pi^0} > 2\ \text{GeV}$ [2203.08322, 2405.17651, 2410.07624]

SHiP: Negligible background due to vacuum in decay vessel [2112.01487]

$$S = 2.3$$

[1]: F.J.N. Arnaldos, “Neutrino Interaction Measurements with the SBND Experiment.”
[2]: R. Rajagopalan, “Searches for Physics Beyond the Standard Model with the Short-Baseline Near Detector.”

5. Background Considerations (3):

DUNE:

$$E_{e^+e^-} > 5 \text{ GeV}, \quad \theta_{\text{beam}} \leq 5^\circ \quad \text{and} \quad 1^\circ < \theta_{\text{ee}} < 20^\circ$$

[2410.07624, 2507.21228]

$$S = 2.3$$

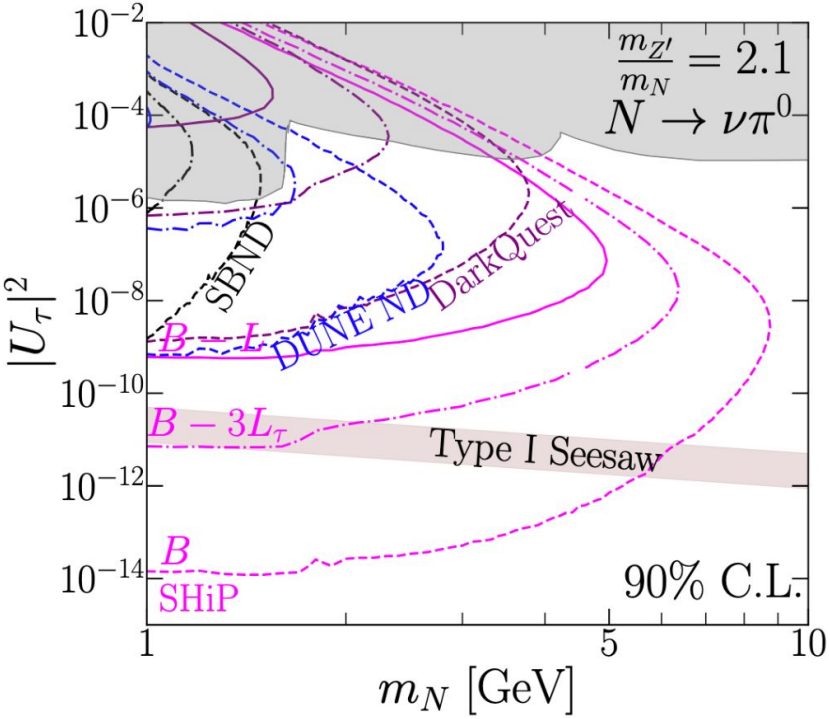
$$E_{\pi^0} > 20 \text{ GeV}, \quad \theta_{\text{beam}} < 2^\circ, \quad \text{and} \quad \theta_{\gamma\gamma} \geq 1^\circ$$

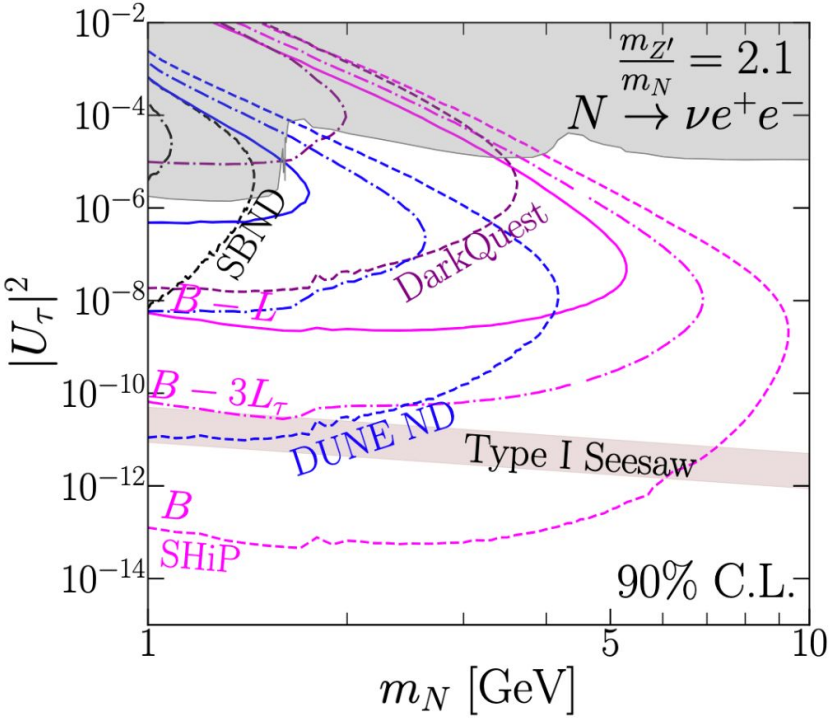
$$Z_0 = \sqrt{2\left[(S+B)\ln\left(1+\frac{S}{B}\right) - S\right]}$$

$$Z_0 = 1.64$$

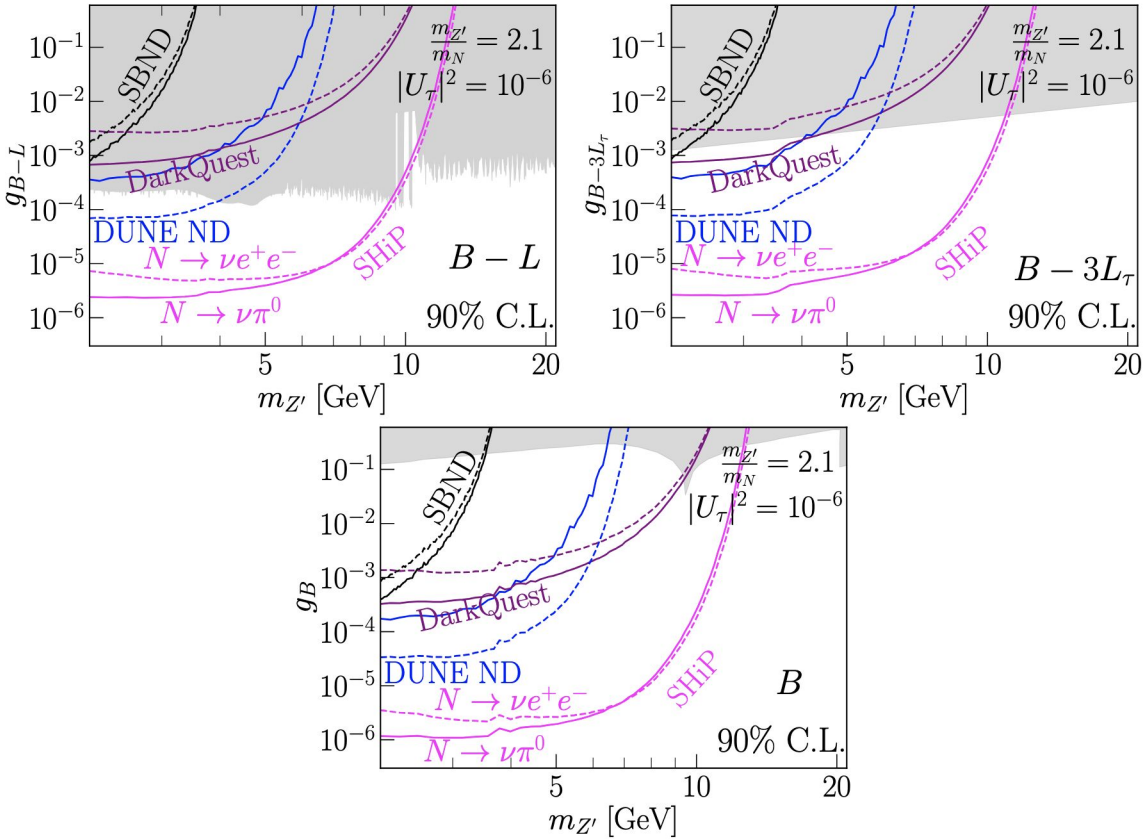
6. Sensitivities: HNL Mixing Angle:

	$B-L$	$B-3L_\tau$	B
gx	10^{-4}	10^{-3}	10^{-2}





6. Sensitivities: Gauge Coupling



Answer: HNL and Z’ can probe well outside of the excluded limits!

Conclusions/Outlook:

- Within our kinematically accessible region for some benchmarks, DUNE ND and SHiP may probe the Type I Seesaw band
- Drell Yan Resonance can be a powerful tool to search for BSM fields at a fixed target experiment.

Thanks for coming to my talk!

Decays: Z’ (1)

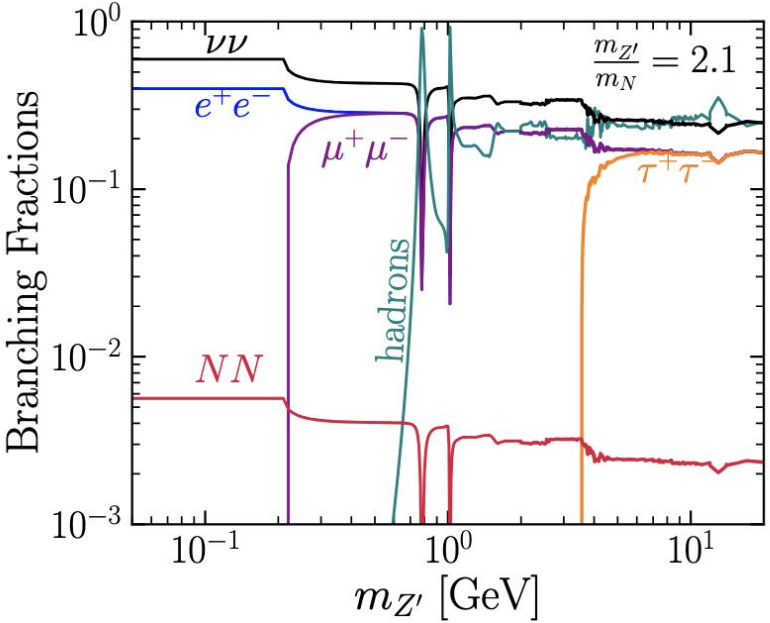
$$\Gamma(Z' \to f\bar{f}) = \frac{N_c}{S}\frac{g_X^2 m_{Z'}\beta_f}{12\pi}\left[(g_{V,f}^2 + g_{A,f}^2)\beta_f^2 + g_{V,f}^2\frac{6m_f^2}{m_{Z'}^2}\right]$$

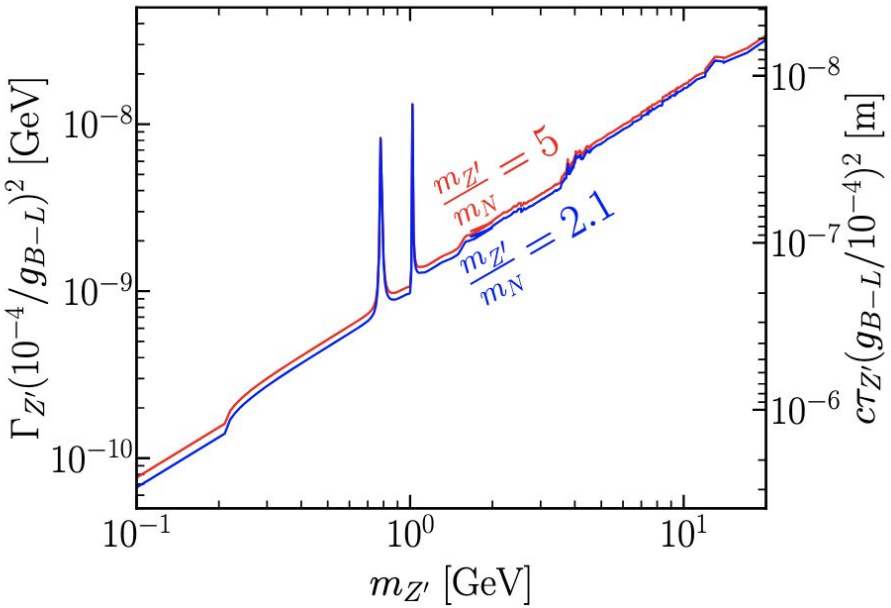
$$\Gamma(Z' \to NN) = \frac{g_{B-L}^2 m_{Z'}}{24\pi}\beta_N^3,$$

$$\Gamma(Z' \to \text{hadrons}) = \frac{\sum_q \Gamma(Z' \to q\bar{q})}{\sum_q Q_q^2 F_q} R(m_{Z'})$$

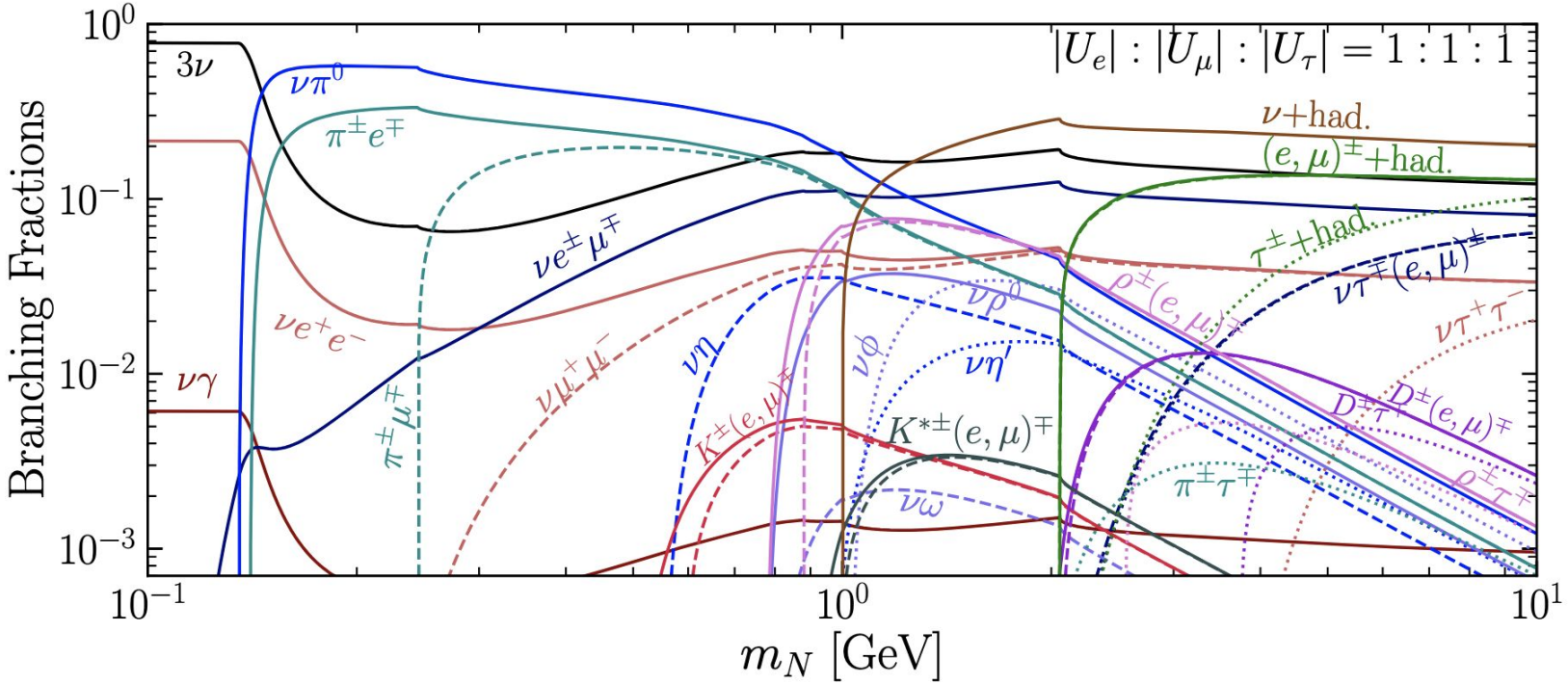
Decays: Z' (2)

$U(1)_{B-L}$

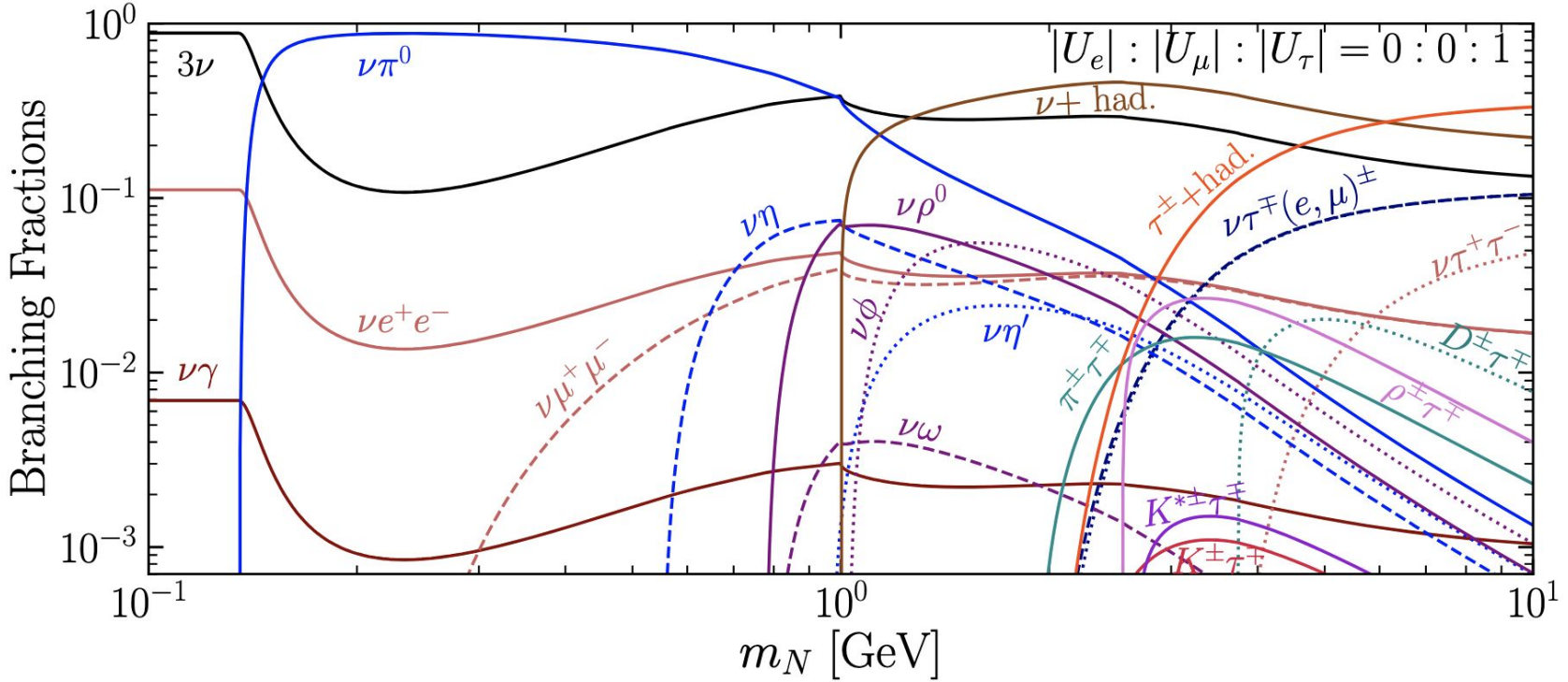




Decays: HNL (1)

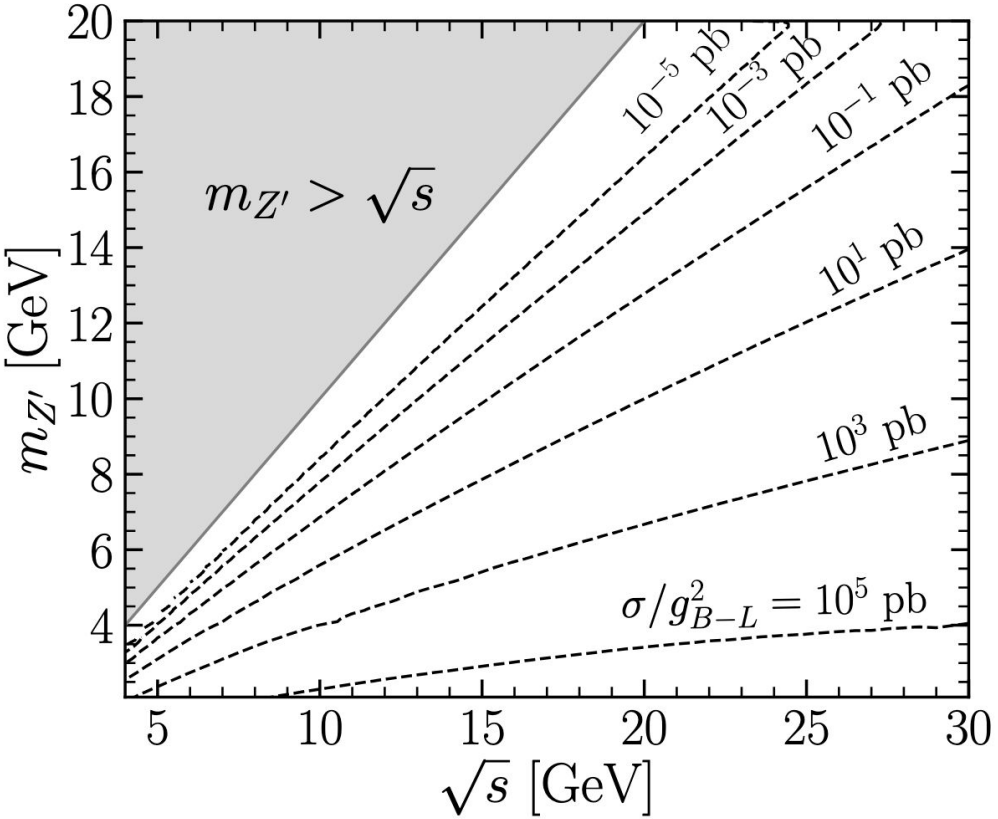

$|U_e| : |U_\mu| : |U_\tau| = 1 : 1 : 1$
Branching Fractions
m_N [GeV]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-1}
10^0
10^1
3ν
$\nu\pi^0$
$\pi^\pm e^\mp$
$\nu e^\pm \mu^\mp$
$\nu e^+ e^-$
$\nu\gamma$
$\pi^\pm \mu^\mp$
$\nu\mu^+\mu^-$
$\nu\eta$
$K^\pm(e,\mu)^\mp$
$\nu\phi$
$\nu\rho^0$
$\nu\eta'$
$K^{*\pm}(e,\mu)^\mp$
$\nu\omega$
ν+had.
$(e,\mu)^\pm$+had.
$\tau^\pm$+had.
$\rho^\pm(e,\mu)^\mp$
$\nu\tau^\mp(e,\mu)^\pm$
$\nu\tau^+\tau^-$
$D^\pm\tau^\mp$
$D^\pm(e,\mu)^\mp$
$\pi^\pm\tau^\mp$
$\rho^\pm\tau^\mp$

Decays: HNL (2)


Branching Fractions
m_N [GeV]
$|U_e| : |U_\mu| : |U_\tau| = 0 : 0 : 1$
3ν
$\nu\pi^0$
$\nu\gamma$
νe^+e^-
$\nu\mu^+\mu^-$
$\nu\eta$
$\nu\rho^0$
$\nu\phi$
$\nu\omega$
$\nu\eta'$
$\nu+$ had.
$\tau^\pm$+had.
$\nu\tau^\mp(e,\mu)^\pm$
$\nu\tau^+\tau^-$
$\pi^\pm\tau^\mp$
$D^\pm\tau^\mp$
$\rho^\pm\tau^\mp$
$K^{*\pm}\tau^\mp$
$K^\pm\tau^\mp$

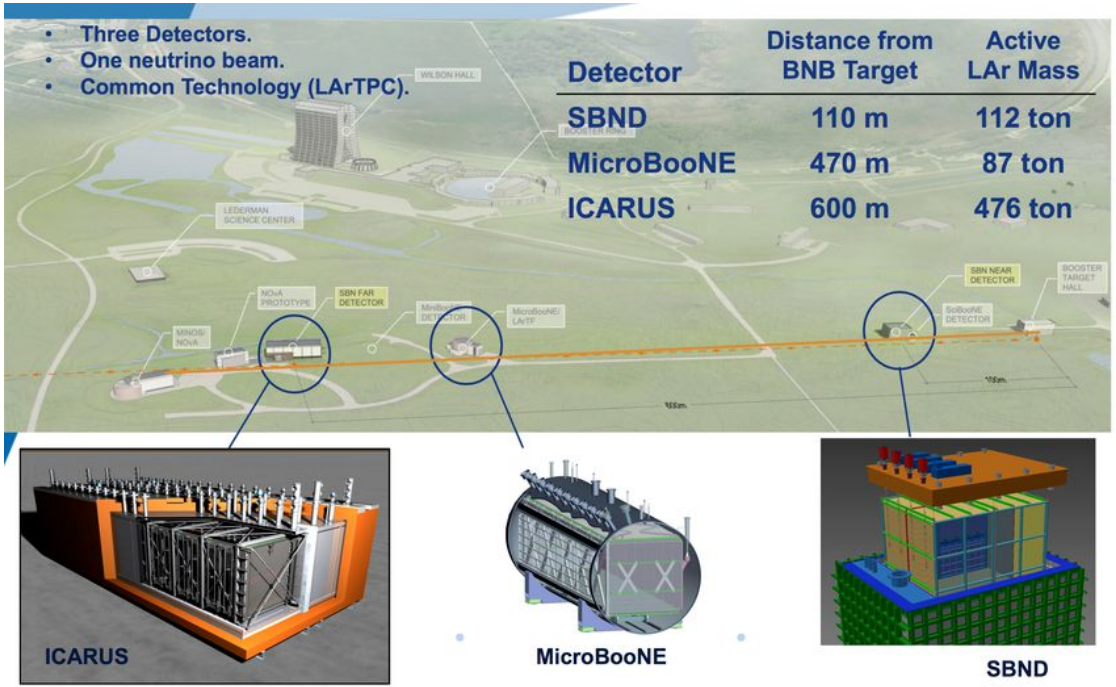
HNL Production:

$m_N \ll m_{Z'}$



Experimental Benchmarks Additional

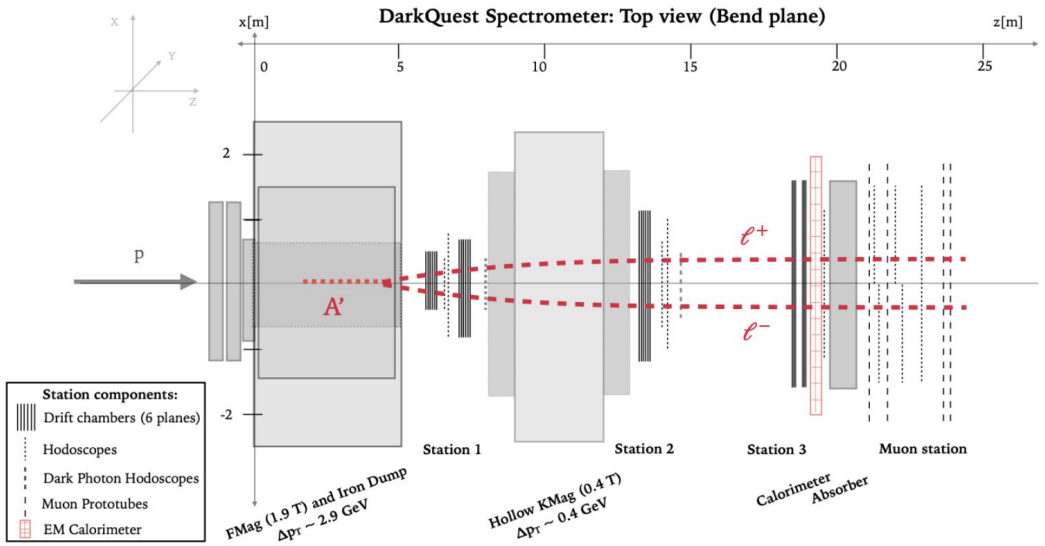
- SBND
  - Currently running Liquid Argon Time Projection Chamber (LArTPC) at Fermilab
  - HNL must decay within LArTPC



https://sbn-nd.fnal.gov/

Experimental Benchmarks Additional

- DarkQuest
  - Proposed upgrade to SpinQuest at Fermilab
  - HNL decay products must pass through three tracking stations
  - ECAL Detector

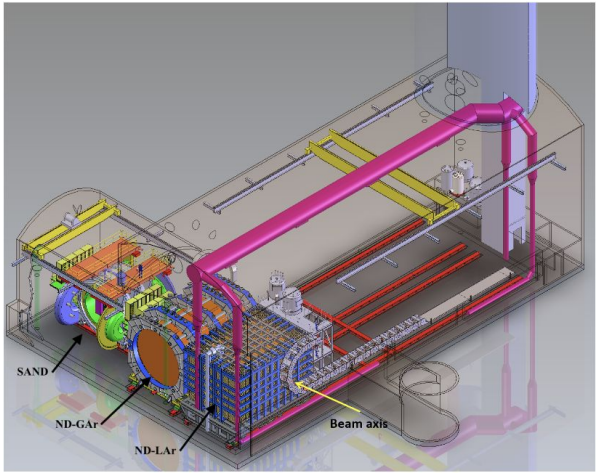


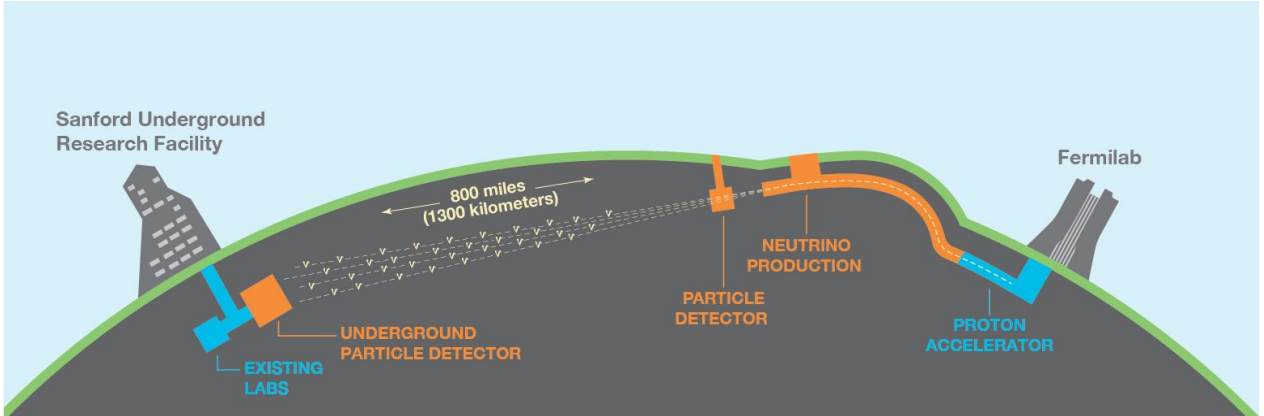
[2203.08322]

Experimental Benchmarks Additional

- DUNE ND
  - Proposed complex to be built on Long Baseline Neutrino Facility (LBNF)
  - HNL must decay in LArTPC detector

[2103.13910]



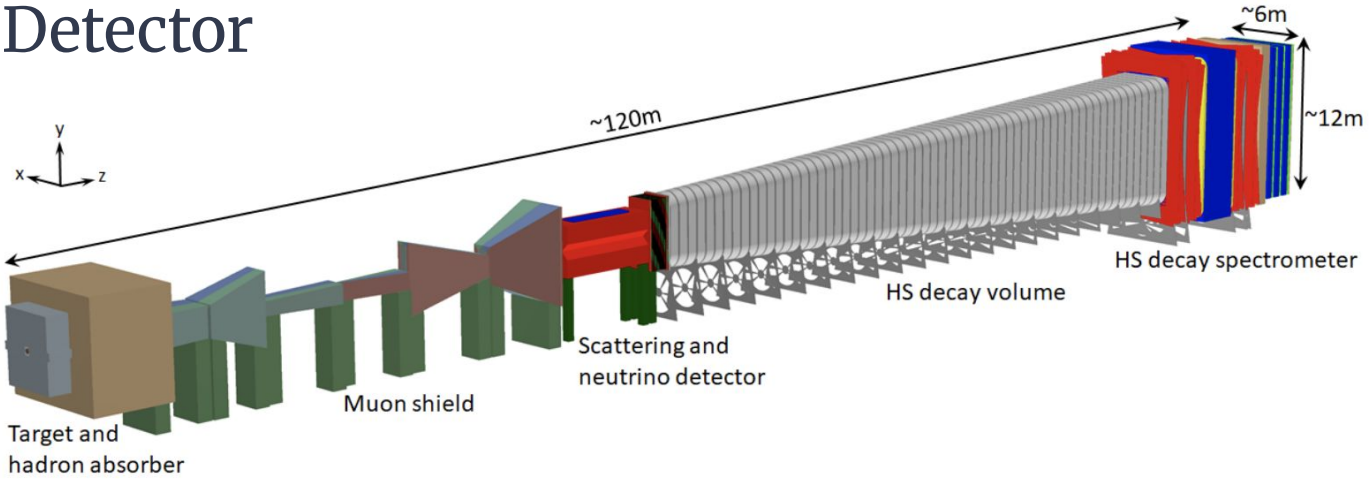


https://www.dunescience.org/

Experimental Benchmarks Additional

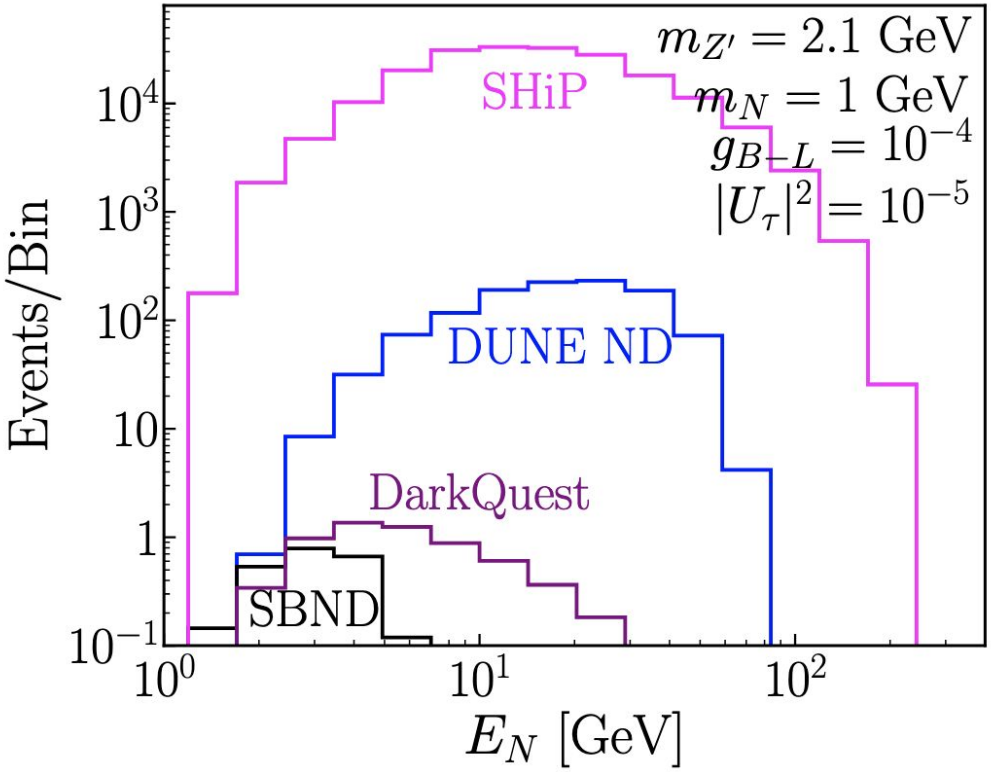
- SHiP
  - Proposed high intensity facility at CERN Super Proton Synchrotron
  - HNL decay products may decay in long vacuum decay chamber
  - ECAL Detector

SHiP
Search for Hidden Particles



[2112.01487]

HNL Energies:



DUNE ND HNL vs Background: