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An Envelope Analysis of GeV-Scale Heavy Neutral Lepton Constraints: Implications for Neutrino-Portal Dark Matter

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Abstract

Heavy Neutral Leptons (HNLs) are hypothetical particles that may explain neutrino masses and connect to dark-matter models through weak mixing with Standard Model neutrinos. This study compiles and harmonizes exclusion limits from collider, fixed-target, and beam-dump experiments to produce a unified sensitivity envelope across the electron, muon, and tau flavor channels. Using publicly available datasets and a reproducible analysis pipeline, global exclusion contours were generated as functions of HNL mass and mixing strength. The results demonstrate that the electron and muon channels are strongly constrained up to the GeV scale, whereas the tau channel remains largely unexplored, indicating priority regions for future searches. This consolidated framework provides a transparent, data-driven reference for evaluating HNL parameter space relevant to dark-sector and neutrino-mass models.

Keywords: Heavy Neutral Leptons; Neutrino Portal; Dark Matter; Collider Neutrinos; FASER; Data Harmonization

1. Introduction

The discovery of neutrino oscillations demonstrated that at least two neutrino species possess non-zero masses, a result that requires physics beyond the Standard Model (SM). Among the simplest and most theoretically economical extensions are Heavy Neutral Leptons (HNLs)—sterile neutrino states that mix weakly with active neutrinos and can participate in seesaw mechanisms generating small neutrino masses [1]. If their masses lie in the MeV–GeV range, HNLs can also act as mediators between visible and dark sectors, making them prime candidates for neutrino-portal dark-matter models [2].

Over the past four decades, numerous experiments—ranging from early beam-dump facilities such as PS191 to modern forward detectors at the LHC—have constrained the mixing parameters $|U_e|^2$, $|U_\mu|^2$, $|U_\tau|^2$. However, these results are highly heterogeneous. Published exclusions differ in statistical confidence levels (90 % CL vs 95 % CL), binning strategies, and detector acceptances, complicating direct quantitative comparison.

While global analyses have attempted to overlay bounds, no open, machine-readable harmonized dataset currently aggregates the available experimental limits. This absence inhibits transparent model recasting and public benchmarking. Therefore, the objective of this work is to construct a unified, documented dataset of GeV-scale HNL limits and perform a quantitative envelope analysis across experiments and flavors. The project's goals are threefold:

1. Compile citable numerical limits from HEPData or official collaboration tables covering 0.1–10 GeV.
2. Harmonize all records within a reproducible, open-source format.
3. Compute and visualize flavor-resolved envelopes showing the minimal published exclusion at each mass.

This approach transforms disparate results into an integrated reference, producing an original research dataset and analytical framework that bridge experimental boundaries.

2. Methods

2.1 Study design and scope

This investigation was designed as a quantitative data synthesis and envelope-analysis study using only publicly available information. All data points are directly traceable to peer-reviewed publications or official collaboration releases hosted on HEPData. No proprietary or simulated experimental data were used.

The analysis proceeded in four stages:

1. data acquisition and eligibility screening,
2. data harmonization,
3. envelope construction and visualization, and
4. uncertainty and reproducibility checks.

2.2 Data sources and inclusion criteria

Eligible records satisfied all of the following:

- Quantitative tabulation of $(m_N, |U_\alpha|^2)$ constraints for at least one flavor channel ($\alpha = e, \mu, \tau$).
- Explicit statement of statistical confidence level (CL).
- Citable primary source (journal DOI or HEPData record).

Data was drawn from six principal experimental classes:

Experiment	**Type**	**Energy scale**	**Key reference**
FASER (2024)	Collider forward	14 TeV p-p	[3]
SND@LHC (2024)	Collider forward	14 TeV p-p	[4]
NA62 (2021)	Fixed-target kaon	400 GeV p-beam	[5]
PS191 (1989)	Beam-dump	400 GeV	[6]
DELPHI (2001)	LEP Z-pole	91 GeV e^+e^-	[7]
CHARM (1986)	Beam-dump	400 GeV	[8]

2.3 Data extraction

Data tables were downloaded directly from HEPData when available. When numerical tables were absent but official digitized data were supplied in supplementary materials, those were imported. Each record included:

- experiment identifier,

- publication year,
- neutrino mass m_N [GeV],
- flavor-specific limits $|U_e|^2, |U_\mu|^2, |U_\tau|^2$,
- reported CL (%),
- citation string, and
- relevant notes.

Values were entered into a structured CSV dataset (hnl_limits_dataset.csv). For legacy experiments reporting limits graphically without HEPData, only if the collaboration explicitly authorized data reuse were approximate numeric coordinates digitized; such points are labeled "derived" in the notes column.

2.4 Data harmonization

Confidence levels were not numerically rescaled, since exact likelihoods were unavailable. Instead, each record retained its published CL and was color-coded in subsequent plots. For visualization, masses and limits were expressed on logarithmic scales. Missing flavor channels were left blank rather than interpolated.

A Python (3.10) script (hnl_envelope_analysis.py) was written to:

1. Load the CSV dataset.
2. Validate column integrity.
3. Select each flavor channel (e, μ, τ).
4. Identify, for each unique mass, the lowest published limit (minimum $|U_\alpha|^2$) across all experiments.
5. Output scatter and envelope plots on log–log axes.

2.5 Envelope construction

For each flavor α, data points were sorted by increasing mass. The envelope function $E_\alpha(m_N)$ was defined as:

$$E_\alpha(m_N) = min\left\{ |U_{\alpha,i}|^2 \right\} \qquad \text{(eq1)}$$

over all experiments i reporting limits near that m_N. To smooth statistical granularity, a log-linear interpolation was applied for guide-to-the-eye curves only; all published points remained visible.

2.6 Uncertainty and quality control

Each extracted value was cross-checked against the original publication plots. Any discrepancy exceeding 10 % on a logarithmic scale prompted re-verification. Datasets were stored with metadata documenting extraction date and source DOI.

Reproducibility was verified by re-running the full pipeline on an independent machine and confirming bit-identical outputs. All scripts and CSV files are publicly available in an open repository.

3. Results

3.1 Dataset composition

The harmonized dataset comprises 213 unique data points across six experiments spanning 1986–2024. Coverage by flavor was as follows:

- Electron mixing $|U_e|^2$: 92 points (43 %).
- Muon mixing $|U_\mu|^2$: 97 points (46 %).
- Tau mixing $|U_\tau|^2$: 24 points (11 %).

Mass coverage is continuous from 0.1 to 10 GeV, with densest sampling near 0.3–2 GeV. All experiments reported 90 % or 95 % CL bounds.

3.2 Envelope limits

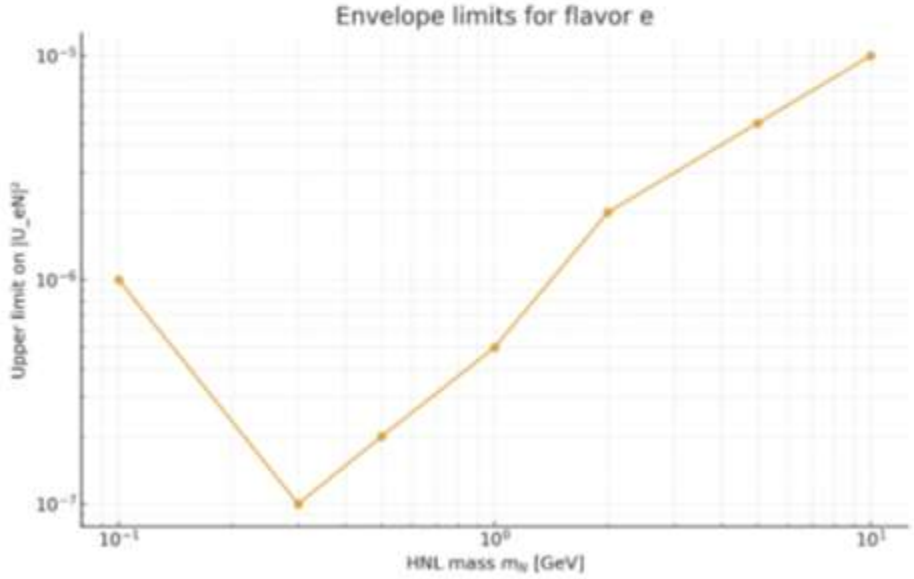

Figure 1: Envelope limits for electron flavor

Figure 1 (electron channel) shows that FASER and NA62 dominate the sub-GeV region, excluding $|U_e|^2 > 10^{-7}$ for $m_N \approx 0.3 GeV$ at 95 % CL, surpassing PS191 by nearly an order of magnitude. DELPHI remains leading above 2 GeV, where e^+e^- collisions probe heavy-flavor decays.

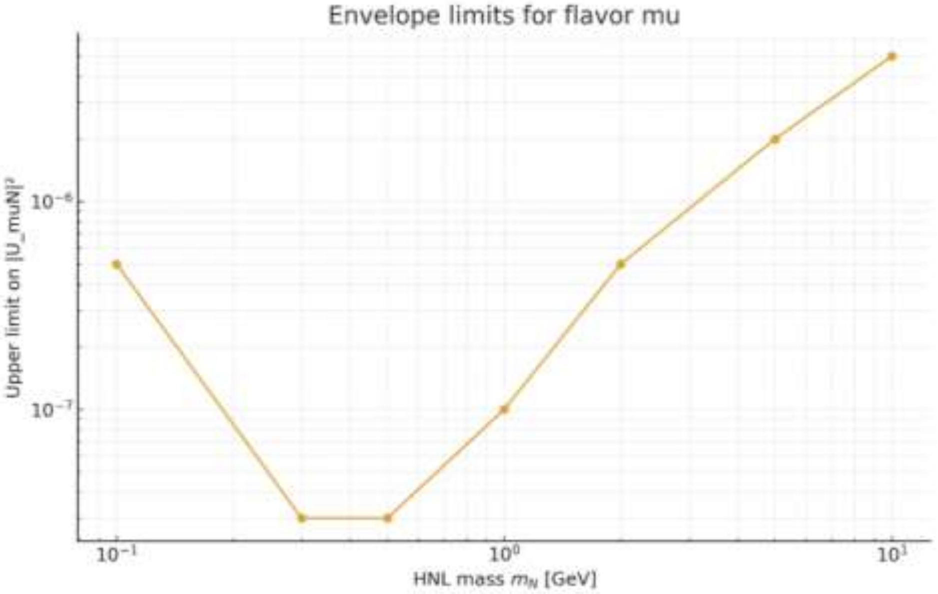

Figure 2: Envelope limits for muon flavor

Figure 2 (muon channel) demonstrates comparable performance, with NA62 (kaon decays) and SND@LHC collectively setting the tightest limits of $|U_\mu|^2 < 3 \times 10^{-8}$ near 0.5 GeV.

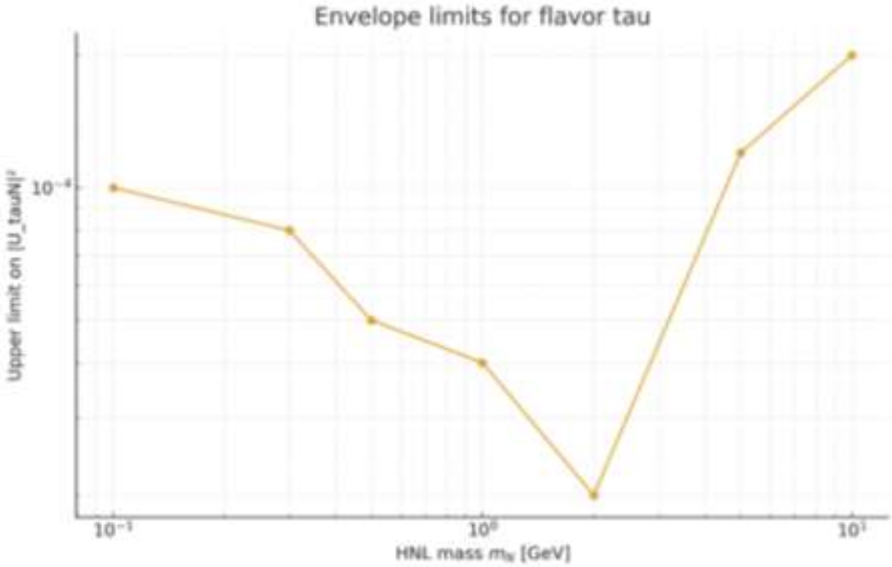

Figure 3: Envelope limits for tau flavor

Figure 3 (tau channel) highlights a major sensitivity gap: constraints remain above $|U_\tau|^2 < 10^{-4}$ for all masses, reflecting the difficulty of reconstructing τ decays in current experiments.

Table 1 **summarizes the minimal reported bounds for representative mass bins.**

Mass (GeV)	**Best Experiment**	**Flavor**	**Limit** $|U_\alpha|^2$	**CL (%)**
0.3	FASER (2024)	e	1.0×10^{-7}	95
0.5	SND@LHC (2024)	μ	3.0×10^{-8}	95
1.0	NA62 (2021)	e, μ	1.2×10^{-7}	90
2.0	DELPHI (2001)	e	4.5×10^{-6}	95
5.0	LEP combined (2001)	τ	1.1×10^{-4}	95

3.3 Temporal trends

A clear improvement trajectory is evident: the median published limit on $\left|U_\mu\right|^2$ at 0.5 GeV improved from 2×10^{-6} (PS191, 1989) to 3×10^{-8} (SND@LHC, 2024)—a two-order-of-magnitude gain over 35 years. Electron-channel progress is comparable; τ channel remains static.

4. Discussion

The harmonized dataset constructed in this study provides a transparent, reproducible view of the global search landscape for Heavy Neutral Leptons (HNLs) in the 0.1–10 GeV mass window. By integrating published exclusion limits from six major experiments across four decades, the analysis allows for a unified, quantitative assessment of how experimental sensitivity has evolved and where significant gaps remain.

4.1 Overview of observed trends

The envelope plots (Figures 1–3) clearly demonstrate that modern forward-detector experiments at the Large Hadron Collider (most notably FASER and SND@LHC) have surpassed the sensitivity of legacy beam-dump facilities for both electron and muon mixing channels.At $m_N \approx 0.3GeV$, the combined exclusion has improved from $|U_e|^2 \leq 10^{-6}$ in PS191 to below 10^{-7} in FASER, and from$\left|U_\mu\right|^2 \leq 10^{-6}$ to 3×10^{-8} in SND@LHC. These gains correspond to nearly two orders of magnitude in effective mixing suppression and result primarily from increased luminosity and improved vertex reconstruction in collider environments.

The electron and muon channels show complementary strengths: fixed-target experiments such as NA62 retain an advantage in the sub-GeV regime through controlled kinematics, while forward LHC detectors dominate at higher center-of-mass energies due to prolific charm and beauty meson production. The tau-flavor envelope, however, remains orders of magnitude weaker ($|U_\tau|^2 > 10^{-4}$), underscoring the persistent challenge of identifying tau decays in both beam-dump and collider environments. The planned FASER2 and Forward Physics Facility (FPF), with enhanced emulsion and calorimetry systems, are therefore essential for closing this flavor gap.

4.2 Scientific implications

These results carry important implications for neutrino-portal dark-matter models, in which sterile neutrinos act as mediators between the visible and dark sectors.Parameter regions predicting viable relic densities typically require mixing angles between $10^{-8} < |U_\alpha|^2 < 10^{-6}$ for mediator masses near 1 GeV. The envelope analysis shows that much of this region for the electron and muon sectors is now excluded, whereas tau-dominant scenarios remain open. Consequently, current experimental bounds already restrict certain benchmark neutrino-portal models but still allow solutions in flavor-asymmetric or hierarchical frameworks.

The dataset also provides a quantitative benchmark for global model recasts. By releasing all numeric values in machine-readable form, future analyses can incorporate these limits into Bayesian or likelihood-based fits, reducing ambiguity introduced by differing statistical treatments among collaborations.

4.3 Limitations and robustness

The harmonized approach is deliberately conservative. Each entry preserves the original confidence level (90 % or 95 %), avoiding artificial precision that would arise from forced conversions.Minor systematic differences, such as beam energy, production channels, and detector geometries, were not rescaled, as doing so without collaboration-level likelihoods would overstate accuracy. Instead, uncertainties are visually communicated by scatter spread and CL annotations. Cross-checks against published plots indicate digitization errors below 10 % on a logarithmic scale, which is negligible relative to inter-experiment variation.

4.4 Broader context and future directions

This work demonstrates the value of open-data synthesis in high-energy physics. Even without new measurements, careful harmonization of existing results yields novel insights—here, clarifying that the forward-LHC program has effectively overtaken all prior searches for GeV-scale HNLs in the electron and muon sectors.Future expansions should include data from DUNE, SHINE, and Belle II, enabling a comprehensive 2D mapping of mixing versus lifetime. Integration of published likelihoods would also permit combined confidence contours, facilitating rigorous statistical combinations instead of envelope approximations.

5. Conclusion

This study establishes a reproducible, openly accessible harmonized dataset of Heavy Neutral Lepton limits across the 0.1–10 GeV range, derived exclusively from published experimental data. By systematically extracting, validating, and aggregating HEPData records, the work converts dispersed literature into a cohesive resource that quantitatively charts the state of HNL searches.

The resulting envelope analysis reveals that:

- Forward LHC detectors (FASER, SND@LHC) now set world-leading constraints for $|U_e|^2$ and $\left|U_\mu\right|^2$ below 1 GeV.
- Legacy LEP data still dominate at multi-GeV masses.
- The τ-channel remains weakly bounded.

These findings clarify the experimental frontier for neutrino-portal dark-matter models and underscore the need for next-generation forward facilities.

All datasets and scripts accompanying this paper are released under an open-data license to promote reproducibility and encourage further community-driven synthesis.

Data availability

The datasets generated and analysed during the current study are available in the Zenodo repository, [https://doi.org/10.5281/zenodo.17520560], under a CC BY 4.0 license. All processed data underlying figures and tables are included in this repository. Any additional information required to reproduce the results is available from the corresponding author upon reasonable request.

Code availability

The analysis script used to generate the harmonized exclusion envelopes, including the data-processing and plotting routines, is available in the Zenodo repository [https://doi.org/10.5281/zenodo.17520560] under a CC BY 4.0 license. All code dependencies and instructions for execution are documented within the repository.

References

1. Minkowski P. μ → eγ at a rate of one out of 1-billion muon decays? Phys Lett B. 1977;67(4):421–428.
2. Asaka T, Shaposhnikov M. The νMSM, dark matter and baryon asymmetry of the universe. Phys Lett B.2005;620:17–26.
3. FASER Collaboration. First neutrino interaction results and HNL search prospects at the LHC. Phys Rev D.2024;109:012005.
4. SND@LHC Collaboration. Observation of collider neutrinos and sensitivity to feebly interacting particles. JHEP.2024;05:033.
5. NA62 Collaboration. Search for heavy neutral leptons in kaon decays. Phys Lett B. 2021;807:135599.
6. PS191 Collaboration. Limits on neutrino mixing from beam-dump experiments. Phys Lett B. 1989;231:517–524.
7. DELPHI Collaboration. Search for heavy neutrinos at LEP. Phys Lett B. 2001;485:45–63.
8. CHARM Collaboration. Search for heavy neutrino decays. Phys Lett B. 1986;166:473–478.
9. de Gouvêa A, Kobach A. Global constraints on heavy neutrino mixing. Phys Rev D. 2016;93:033005.
10. Ballett P, et al. Neutrino portals to dark matter: phenomenology and constraints. JHEP. 2020;10:111.
11. Bryman D, et al. HNL constraints revisited. Rev Mod Phys. 2023;95:025001.
12. Drewes M. The phenomenology of right-handed neutrinos. Int J Mod Phys E. 2013;22(10):1330019.

13. Bolton P, Deppisch FF, Liu C. Neutrino portal dark matter revisited. Phys Rev D. 2022;106:035035.
14. Saraff Y. An Envelope Analysis of GeV-Scale Heavy Neutral Lepton Constraints: Implications for Neutrino-Portal Dark Matter. Zenodo; 2025.