Snowmass2021 - Letter of Interest

Topical Groups:
- ■ (NF2) Sterile neutrinos
- ■ (NF3) Beyond the Standard Model
- ■ (TF11) Theory of neutrino physics
- ■ (RF4) Baryon and Lepton Number Violating Processes

Neutrino mass models at colliders in a post-ESU era

Richard Ruiz,

Centre for Cosmology, Particle Physics and Phenomenology (CP3),
Université Catholique de Louvain, Chemin du Cyclotron, Louvain la Neuve, B-1348, Belgium

E-mail: richard.ruiz@uclouvain.be

Abstract: In the lead up to the 2020 European Strategy Update, immense community efforts were undertaken to elucidate the discovery potential of neutrino mass models at energy-frontier experiments throughout the world. This includes the Large Hadron Collider (LHC), its high luminosity upgrade and proposed successors, as well as beam dump and deeply inelastic scattering facilities. In the time since, however, the development of novel search techniques and the multiplicity of investigations have continued, as has the analysis of collected LHC data at $\sqrt{s} = 13$ TeV. As a part of the Snowmass 2021 efforts, we provide an updated outlook for the sensitivity to neutrino mass models at collider experiments. We focus particularly on state-of-the-art production rates for competing production mechanisms, new detection techniques, newly available Monte Carlo tools, and the cumulative impact on sensitivity at current and proposed experiments.

Contents

1 Introduction and Scope

Uncovering the origin of neutrinos' tiny, degenerate masses and their large mixing angles are among the major, open challenges in high energy physics today [1, 2]. To reconcile phenomena such as neutrino oscillations with the Standard Model (SM) paradigm, it is necessary [3] to extend the SM by new particles and new interactions. Models that achieve such feats, known collectively as Seesaw models, do so by hypothesizing a variety of particles at qualitatively new mass scales. These range from postulating gauge-singlet fermions [4–10], to extended fermion [11] and scalar [10, 12–15] sectors with exotic SM gauge quantum numbers, to new force carries [16–20]. If such states are accessible at laboratory-based experiments, then their production and decay, which have been and continue to be extensively explored [21–23], give rise to rich phenomenology, including the violation of lepton number and/or charged lepton flavor number symmetries.

As a part of the Snowmass 2021 exercises, we aim to provide an updated outlook for the sensitivity to benchmark neutrino mass models at collider experiments, focusing particularly on developments and progress since the 2020 European Strategy Update [1, 2]. The scope of this work is directed specifically at state-of-the-art predictions for production rates of Seesaw particles [24–26], new detection strategies [27–29], newly available Monte Carlo tools [26, 28, 30, 31], and the cumulative impact on sensitivity at current and proposed experiments [23, 25].

A sample of this is summarized in Fig. 1. There state-of-the-art cross section predictions at various accuracies in perturbation theory for producing Seesaw particles at *pp* collider of various energies and mechanisms are shown for the (a) Phenomenological Type I Seesaw, (b) Left-Right Symmetric Model, (c) Type II Seesaw, and (d) Type I+III Seesaw. Due to an interplay between scatting matrix elements, which can become relatively enhanced or suppressed at increasing mass scales, and parton density functions a nontrivial dependence on collider energy and mass scale can be seen in scattering rates. This is particularly relevant for gluon-initiated states, which can arise at leading order or next-to-leading order in QCD, and which can contribute sizably to inclusive cross sections. For example: for heavy neutrinos in Fig. 1(a), one sees a dominance of gluon fusion and electroweak boson fusion as leading production mechanisms for multi-TeV masses.

By performing this update we hope to provide the community a standard resource for predicted rates, anticipated sensitivity, and simulation tools of standard-bearer Seesaw models at current and future colliders. In doing so, we hope to help guide discussions to achieving the goal of uncovering the origin of neutrinos' masses and mixing angles.

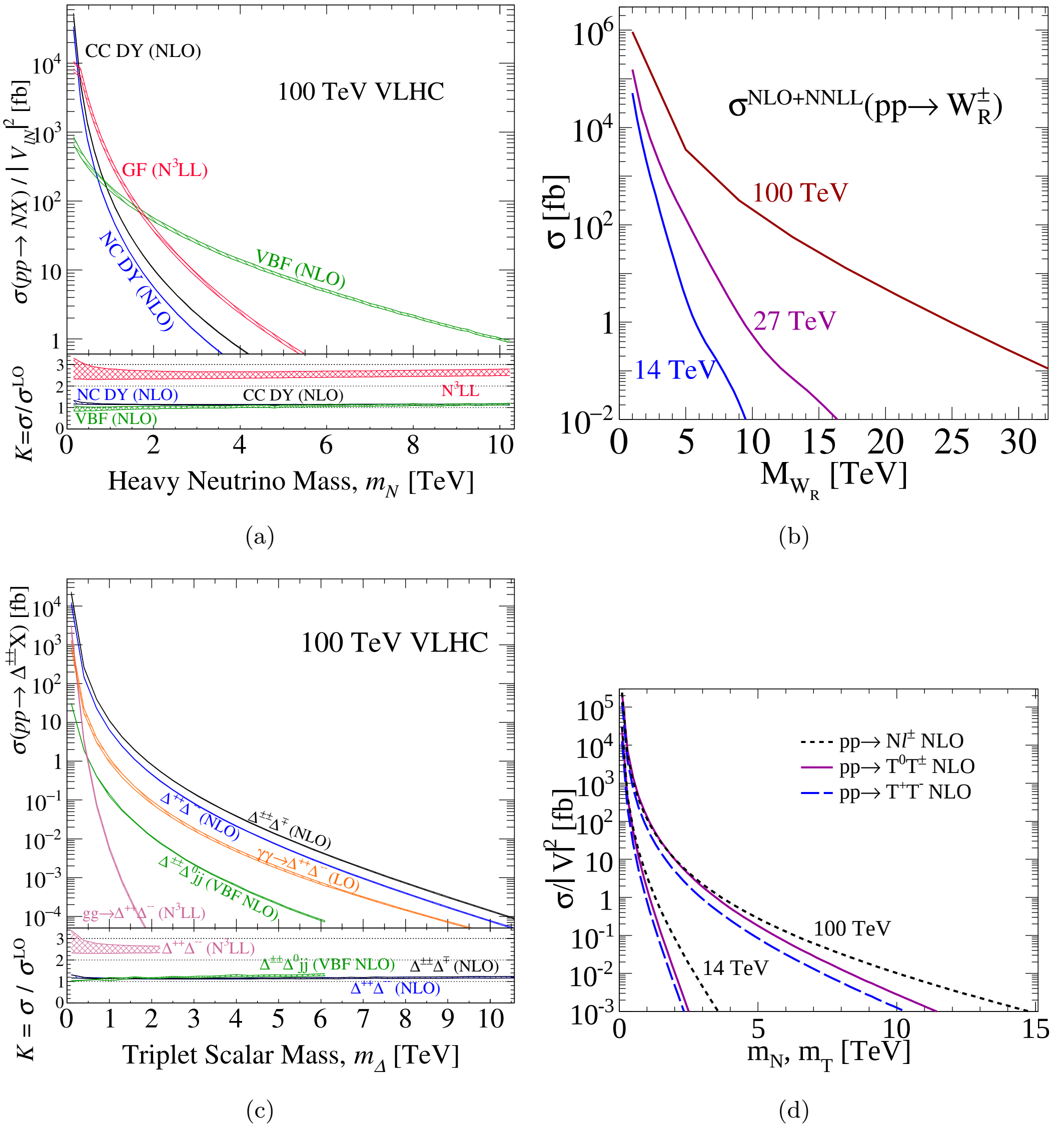

Figure 1. State-of-the-art cross section predictions at various accuracies for producing Seesaw particles at *pp* collider of various energies and mechanisms are shown for the (a) Phenomenological Type I Seesaw, (b) Left-Right Symmetric Model, (c) Type II Seesaw, and (d) Type I+III Seesaw.

References

[1] R. K. Ellis et al., Physics Briefing Book: Input for the European Strategy for Particle Physics Update 2020, 1910.11775.

[2] European Strategy Group collaboration, 2020 Update of the European Strategy for Particle Physics. CERN Council, Geneva, 2020, 10.17181/ESU2020.

[3] E. Ma, Pathways to naturally small neutrino masses, Phys. Rev. Lett. 81 (1998) 1171–1174, [hep-ph/9805219].

[4] P. Minkowski, $\mu \to e\gamma$ at a Rate of One Out of 10^9 Muon Decays?, Phys. Lett. B 67 (1977) 421–428.

[5] T. Yanagida, Horizontal gauge symmetry and masses of neutrinos, Conf. Proc. C 7902131 (1979) 95–99.

[6] M. Gell-Mann, P. Ramond and R. Slansky, Complex Spinors and Unified Theories, Conf. Proc. C 790927 (1979) 315–321, [1306.4669].

[7] S. Glashow, The Future of Elementary Particle Physics, NATO Sci. Ser. B 61 (1980) 687.

[8] R. N. Mohapatra and G. Senjanovic, Neutrino Mass and Spontaneous Parity Nonconservation, Phys. Rev. Lett. 44 (1980) 912.

[9] R. E. Shrock, General Theory of Weak Leptonic and Semileptonic Decays. 1. Leptonic Pseudoscalar Meson Decays, with Associated Tests For, and Bounds on, Neutrino Masses and Lepton Mixing, Phys. Rev. D 24 (1981) 1232.

[10] J. Schechter and J. Valle, Neutrino Masses in SU(2) x U(1) Theories, Phys. Rev. D 22 (1980) 2227.

[11] R. Foot, H. Lew, X. He and G. C. Joshi, Seesaw Neutrino Masses Induced by a Triplet of Leptons, Z. Phys. C 44 (1989) 441.

[12] W. Konetschny and W. Kummer, Nonconservation of Total Lepton Number with Scalar Bosons, Phys. Lett. B 70 (1977) 433–435.

[13] T. Cheng and L.-F. Li, Neutrino Masses, Mixings and Oscillations in SU(2) x U(1) Models of Electroweak Interactions, Phys. Rev. D 22 (1980) 2860.

[14] G. Lazarides, Q. Shafi and C. Wetterich, Proton Lifetime and Fermion Masses in an SO(10) Model, Nucl. Phys. B 181 (1981) 287–300.

[15] R. N. Mohapatra and G. Senjanovic, Neutrino Masses and Mixings in Gauge Models with Spontaneous Parity Violation, Phys. Rev. D 23 (1981) 165.

[16] J. C. Pati and A. Salam, Lepton Number as the Fourth Color, Phys. Rev. D 10 (1974) 275–289.

[17] R. N. Mohapatra and J. C. Pati, Left-Right Gauge Symmetry and an Isoconjugate Model of CP Violation, Phys. Rev. D 11 (1975) 566–571.

[18] R. Mohapatra and J. C. Pati, A Natural Left-Right Symmetry, Phys. Rev. D 11 (1975) 2558.

[19] G. Senjanovic and R. N. Mohapatra, Exact Left-Right Symmetry and Spontaneous Violation of Parity, Phys. Rev. D 12 (1975) 1502.

[20] G. Senjanovic, Spontaneous Breakdown of Parity in a Class of Gauge Theories, other thesis, 1979. 10.1016/0550-3213(79)90604-7.

[21] A. Atre, T. Han, S. Pascoli and B. Zhang, The Search for Heavy Majorana Neutrinos, JHEP 05 (2009) 030, [0901.3589].

[22] Y. Cai, J. Herrero-García, M. A. Schmidt, A. Vicente and R. R. Volkas, From the trees to the forest: a review of radiative neutrino mass models, Front. in Phys. 5 (2017) 63, [1706.08524].

[23] Y. Cai, T. Han, T. Li and R. Ruiz, Lepton Number Violation: Seesaw Models and Their Collider Tests, Front. in Phys. 6 (2018) 40, [1711.02180].

[24] R. Ruiz, QCD Corrections to Pair Production of Type III Seesaw Leptons at Hadron Colliders, JHEP 12 (2015) 165, [1509.05416].

[25] S. Pascoli, R. Ruiz and C. Weiland, Heavy neutrinos with dynamic jet vetoes: multilepton searches at $\sqrt{s} = 14$, 27, and 100 TeV, JHEP 06 (2019) 049, [1812.08750].

[26] B. Fuks, M. Nemevˇsek and R. Ruiz, Doubly Charged Higgs Boson Production at Hadron Colliders, Phys. Rev. D 101 (2020) 075022, [1912.08975].

[27] M. Mitra, R. Ruiz, D. J. Scott and M. Spannowsky, Neutrino Jets from High-Mass W_R Gauge Bosons in TeV-Scale Left-Right Symmetric Models, Phys. Rev. D 94 (2016) 095016, [1607.03504].

[28] O. Mattelaer, M. Mitra and R. Ruiz, Automated Neutrino Jet and Top Jet Predictions at Next-to-Leading-Order with Parton Shower Matching in Effective Left-Right Symmetric Models, 1610.08985.

[29] R. Ruiz, Lepton Number Violation at Colliders from Kinematically Inaccessible Gauge Bosons, Eur. Phys. J. C 77 (2017) 375, [1703.04669].

[30] C. Degrande, O. Mattelaer, R. Ruiz and J. Turner, Fully-Automated Precision Predictions for Heavy Neutrino Production Mechanisms at Hadron Colliders, Phys. Rev. D 94 (2016) 053002, [1602.06957].

[31] B. Fuks and R. Ruiz, A comprehensive framework for studying W' and Z' bosons at hadron colliders with automated jet veto resummation, JHEP 05 (2017) 032, [1701.05263].