1 Title

Probing Beyond Standard Model Physics: Left-Right Scenarios at the Large Hadron Collider (LHC) and Beyond

2 Introduction and Background

In the realm of particle physics, the celebrated Standard Model (SM) offers an elegant explanation of the fundamental components of visible matter and their interactions, based on the local gauge symmetry $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$. The predictions made by this model correspond remarkably well with experimental observations. Nevertheless, despite its considerable success, this model faces various limitations and challenges. It is structured within a chiral framework, demonstrating maximal parity violation in interactions governed by the weak force, while both the strong and electromagnetic forces maintain parity conservation. Additionally, the Standard Model doesn't incorporate neutrinos with right-handed chirality or other spin 1/2 states, which restricts its ability to explain results from neutrino experiments that have conclusively determined the mass of neutrinos and their mixing behavior.

For addressing the limitations of the Standard Model (SM) and tackle these issues various theoretical models have been proposed. Among these extensions, the left-right symmetric models (LRSMs) [1–4] emerge as a notable alternative. These frameworks are based on the gauge symmetry $SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$, which links the significant violation of parity to the exceedingly small masses of neutrinos. This left-right gauge symmetry can be viewed as stemming from a grand unified framework that is founded on the exceptional group E_6 [5–7], which is subsequently decomposed into its largest subgroup $SU(3)_C \otimes SU(3)_L \otimes SU(3)_H$. The primary $SU(3)$ component remains unchanged and is associated with the strong interaction symmetry of the Standard Model, whereas the other two components are further simplified to $SU(2)_L \times SU(2)_H \times U(1)_X$, ultimately resulting in the electroweak symmetry group. In this arrangement, the fermions of the theory are organized as triplets within $SU(3)_H$. There exist three distinct methods to obtain an $SU(2)_H$ doublet from the three elements of an $SU(3)_H$ triplet. Standard LRSM models link $SU(2)_H$ with $SU(2)_R$, necessitating that the first two elements of the $SU(3)_H$ triplets be combined into doublets of $SU(2)_R$, which consist of the right-handed Standard Model fermions and neutrinos u_R (which are singlets under the Standard Model gauge symmetry). The pattern of symmetry breaking requires an enlarged Higgs sector that encompasses various scalar fields, which may interact with the doublets of $SU(2)_L$ and $SU(2)_R$, potentially resulting in excessively large tree-level flavor-changing neutral interactions. Therefore, to prevent inconsistencies with empirical observations, the breaking of the $SU(2)_R$ symmetry must occur at an extremely high scale. Consequently, the spectrum of new particles is shifted beyond the detection capabilities of existing collider experiments, and the influence of these new states can only be indirectly observed through the study of rare phenomena.

Alternatively, the internal symmetry $SU(2)_H$ may be associated with a different symmetry gauge group, $SU(2)_{R'}$, where the first and third components of the triplets in $SU(3)_H$ are combined into doublets. Unlike traditional left-right symmetric models (LRSM), alternative left-right models (ALRM) [8–12] assert that the down-type quark field d_R and the neutrino field ν_R function as singlets under $SU(2)_{R'}$, while the up-type quark field u_R and the charged lepton field e_R are organized into doublets of $SU(2)_{R'}$, along with an exotic quark field d'_R and a scotino field n_R, respectively. To satisfy the requirement for parity invariance within this framework, the matter sector of the theory also includes exotic singlets of $SU(2)_L \times SU(2)_{R'}$, specifically the states d'_L and n_L [13]. These exotic matter states additionally enable the incorporation of a phenomenologically viable dark matter candidate [14, 15], and they inherently inhibit the emergence of significant flavour-changing neutral currents, even when the left-right symmetry breaking scale reaches several

TeV. As a result, the W_R boson cannot be generated from, nor decay into, a pair of ordinary quarks (or leptons), indicating that its mass remains unconstrained by any limits that could be inferred from direct searches for additional gauge bosons at the LHC. Moreover, this boson does not engage with the Standard Model (SM) W gauge boson. As a result, the W_R boson may be considerably lighter than what is generally anticipated in traditional Left-Right Symmetric Model (LRSM) frameworks. However, there exist indirect limitations on the mass of W_R, which arise from the relationship between its mass correlation with the exotic neutral gauge boson $Z^{'}$ [16, 17]. This new $Z^{'}$ boson can be generated and decay in the normal manner, and it can also mix with the SM Z boson. Consequently, the most tight limitations on the W_R mass comes out from these factors. Therefore, these scenarios can yield intriguing phenomenological signatures at colliders and thus studied at great length in literature. Earlier investigations in this direction have established the criteria for the vaccum state stability [18], underscored the possible implications on the model parameter space coming from the constraints of successful leptogenesis and neutrinoless double beta decay amplitude [19], the implications of tighter lepton violating muon (μ) decay rates [20], and the impact on top decays with flavour violation [21]. Importantly, this framework presents an opportunity for considerable enhancements in the associated branching ratios relative to the predictions of the Standard Model [21] and thus requires a very detailed investigation.

Moreover, various extensions of the minimal left-right symmetric model have been explored in the literature, providing potential phenomenological signatures and addressing the limitations of the minimal scenario. We would like to highlight a few of these here. In the dark matter sector, a vector-like singlet [22] and a vector-like fermion pair [23] were introduced in the minimal left-right scenario, which are linked to the visible sector through the gauged $U(1)$ portal. In another investigation pertaining to dark matter, the left-right symmetric model is expanded with a gauge-singlet scalar field [24], which serves as a dark-matter candidate. These scenarios, by incorporating various existing constraints, define the viable parameter space of the model, which can have potential implications for both LHC and dark-matter detection experiments. In addition to these dark-matter studies, a left-right symmetric model was also examined [25] as a potential explanation for the mass hierarchy of charged fermions. Here tiny neutrino masses are generated through radiative inverse seesaw at 3-loop level.

Motivated by these research explorations, this PhD proposal is formulated to investigate the phenomenology of TeV-scale Left-Right Symmetry (LR) scenarios that originate from E_6 grand unification and some extensions of the minimal left-right model. The primary focus will be on their experimental signatures, the prospects for new physics, and the implications for both collider and low-energy experiments. We aim to explore the structure of these models, their possible realization at the TeV scale, and the approaches through which they might be evaluated in current and upcoming particle physics experiments.

3 Research Gaps:

- The various versions of the left-right symmetric scenarios derived from the unified group E_6, along with potential extensions of the minimal left-right models, require further investigation.
- A comprehensive investigation of the implications of these frameworks, particularly focusing on specific collider signatures, has not yet been fully explored. This gap needs to be addressed to assess the viability of these models.
- Despite exploration of the RG evolution in left-right symmetric models, its effects on particle spectra and dark matter sector has not been thoroughly investigated.

- The influence of these left-right scenarios on the gravitational wave spectrum must be examined. An extensive study of the potential sources, frequency spectra, and amplitude predictions for gravitational wave observatories is necessary, as it may yield important new restrictions on the parameter space of these models.

4 Research Objectives

The primary aim of this research proposal is to explore the phenomenology of LR Scenarios within the framework of extensions to the Standard Model. The specific objectives are as follows:

4.1 Collider Signatures:

- Examine the experimental signatures associated with existing models at the Large Hadron Collider (LHC) and future high-energy colliders, assessing constraints from existing data to ascertain the most promising experimental detection strategies.

4.2 Theoretical Framework Development:

- Examine the established left-right theoretical frameworks and explore the possibility of formulating the new ones for TeV-scale physics, which can provide interesting phenomenological signatures and address the shortcomings of current scenarios.

4.3 Phenomenological Analysis:

- Analyze the restrictions on the parameter space of existing and new scenarios as inferred from cosmological phenomena and renormalization group (RG) analysis.

5 Research Methodology:

5.1 Collider Analysis:

- Use particle physics simulation tool, MadGraph5 to model possible experimental signatures and compare them with current data from particle physics experiments using MadAnalysis5.
- Evaluate the potential for discovering new particles stemming from these scenarios at the LHC and future colliders. Focus on the decay signatures of these new particles, which might yield unique signatures like dilepton pairs, jet-lepton resonances, or processes that violate lepton flavor.

5.2 Theoretical Framework of TeV-Scale Left-Right Symmetry:

- Model Construction: Explore existing and formulate new TeV-scale LRSMs, incorporating both the gauge sector and the Higgs sector. Examine the breaking of the left-right symmetry at high scales and study how the masses of the new exotic states depend on model parameters.

5.3 Phenomenology of TeV-Scale LR Models:

- New Particles and Interactions: Study the mass spectrum of the model, including the right-handed gauge bosons (W_R, Z_R), the additional Higgs particles, and their interactions with the SM particles.
- RG Analysis: Investigate the renormalization group analysis and examine the related implications for the particle spectra of these models.
- Low-Energy Observables: Explore the implications of LR models on low-energy processes such as lepton-flavor violation, rare decays, and muon anomalous magnetic moment.

5.4 Dark Matter and Gravitational Wave Analysis:

- Dark Matter: Focus on the dark-matter constraints from direct detection, indirect detection, and collider experiments (e.g., LHC), with the goal of proposing new avenues for future experiments to test these models.

- Gravitational Wave: Explore the potential sources of gravitational waves within these frameworks and constrain the model parameters by comparing predicted waveforms with observational data, identifying any unique signatures that could differentiate left-right models from other cosmological scenarios.

6 Resources Required

- **Model-building:** Use theoretical tools such as group theory, effective field theory, and model construction techniques to formulate viable TeV-scale LR models.

- **Software:** We will use following tools for simulations and phenomenological analysis.

  a) Mathematica: For general computations purpose.

  b) Fortran/Python: For writing the computational codes for numerical evaluation of physical observables and plotting.

  c) FeynRules: For implementing the model, generating feynrules, and and construct an interface for several other computational tools in the field of particle physics.

  d) Madgraph5: For performing cross-sectional computations across various processes, generating events, and event analysis.

  e) MadAnalysis5: For the reinterpretation of existing LHC data.

  f) GoSam: For the calculation of 1-loop amplitudes for multi-particle processes.

  g) LaTeX: For writing technical reports and research papers.

- **Access to Data:** Experimental data from the LHC, neutrino experiments, dark matter detection experiments, etc.

- **Computational Resources:** High-performance computing resources for simulations and numerical calculations.

- **Collaborations:** Collaboration with experimental physicists and theorists, particularly in the areas of collider physics and dark matter detection.

7 Expected Outcomes:

- Identification of clear signatures for TeV-scale LR models, including possible collider signatures and rare decays.

- Constraint determination for the mass spectrum and coupling strengths of new particles predicted by LR models based on current and future experimental data.

- Predictions for new physics that could be observed at the LHC or future colliders, including unique signatures of right-handed gauge bosons, Higgs particles, and right-handed neutrinos.

- Guidance for experimental searches at future high-energy and precision experiments, including suggestions for new observables that could indicate the presence of LR symmetry at the TeV scale.

8 Timeline:

9 Impact and Significance:

This research aims to advance our understanding of left-right symmetric models at the TeV scale, providing detailed predictions that can be tested at high-energy colliders and low-energy experiments. The outcomes could lead to a deeper understanding of neutrino physics, dark matter, gravitational waves, and potential signals of new physics beyond the Standard Model.

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