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Final Report

- DOE Award Number, name, and address of the institution: DE-SC0024160

Case Western Reserve University, 10900 Euclid Avenue, Cleveland, OH 44106-7015

- Project Title and name of the Principal Investigator:

Research in Theoretical Particle Physics: Neutrino Masses and The Origin of CP-Violation

Pavel Fileviez Perez

- Date of the report and award period covered by the report with approved budget amount.

06/01/2023 - 05/31/2024, $59.000.00 USD

- **Abstract**

The main goal of this project is to investigate the theories of neutrino masses at the low scale and the origin of CP-violation in physics beyond the Standard Model. The origin of neutrino masses is one of the most pressing issues in particle physics. In this proposal, we will investigate the theories for neutrino masses based on local total lepton number. In these theories anomaly cancellation predicts the existence of extra fermions with lepton number, and one of them is a good dark matter (DM) candidate. The cosmological constraints on the DM relic density implies that the lepton number symmetry breaking scale must be below the multi-TeV scale. Therefore, one can hope to test the origin of neutrino masses in current or future experiments. We will investigate in great detail the anomaly cancellation in these gauge theories, study the different mechanisms for neutrino masses, study the predictions for direct and indirect dark matter experiments. Since these theories predict new sources of CP violation, we will investigate the predictions for the electric dipole moments (EDM). The Higgs decays and the different signatures at the Large Hadron Collider will be investigated in great detail. Finally, we will study the possible baryogenesis mechanisms in these theories in agreement with the EDM, DM and collider constraints.

The origin of CP violation in the Standard Model is unknown. In this proposal, we will investigate the simplest mechanisms for spontaneous CP-violation to explain the CP-violation in the CKM matrix and the value of the QCD vacuum angle. We will discuss the Nelson-Barr mechanism in gauge theories predicting vector-like quarks from anomaly cancellation such as theories for local baryon number. We will discuss the Bento-Branco-Parada mechanism in gauge theories to explain the CP-Violation in the CKM matrix. We will investigate models with two Higgs doublets in the context of the minimal theory for quark-lepton unification. We will show the non-decoupling effects in the Higgs sector, the main constraints coming from flavour

violating processes when the Yukawa couplings are related by the gauge symmetry in theories for quark-lepton unification. We will investigate the predictions for electric dipole moments in these theories. The possibility to have successful baryogenesis will be investigated. Finally, we will investigate the relation between CP-violation in the quark and leptonic sectors. The future results from these studies could help us to understand two main issues in physics beyond the Standard Model: The Origin of Neutrino Masses and CP-violation.

- **Results:**

In *Lepton and Baryon Numbers as Local Gauge Symmetries*
Pavel Fileviez Pérez, Physical Review D 110, 035018 (2024) , a simple theory where the total lepton number is a local gauge symmetry is proposed. In this context, the gauge anomalies are cancelled with the minimal number of extra fermionic fields and one predicts that the neutrinos are Majorana fermions. The properties of the neutrino sector are discussed showing that this theory predicts a 3 + 2 light neutrino sector. We showed that using the same fermionic fields one can gauge the baryon number and define a simple theory where the lepton and baryon numbers can be spontaneously broken at the low scale in agreement with experiments.

In *Dark Matter from Anomaly Cancellation at the LHC,*
Jon Butterworth, Hridoy Debnath, Pavel Fileviez Pérez, Yoran Yeh
Physical Review D110, 075001(2024) we discussed a class of theories that predict a fermionic dark matter candidate from gauge anomaly cancellation. As an explicit example, we study the predictions in theories where the global symmetry associated with baryon number is promoted to a local gauge symmetry. In this context the symmetry-breaking scale has to be below the multi-TeV scale in order to be in agreement with the cosmological constraints on the dark matter relic density. The new physical "Cucuyo" Higgs boson in the theory has very interesting properties, decaying mainly into two photons in the low mass region, and mainly into dark matter in the intermediate mass region. We study the most important signatures at the Large Hadron Collider, evaluating the experimental bounds. We discuss the correlation between the dark matter relic density, direct detection and collider constraints. We find that these theories are still viable, and are susceptible to being probed in current, and future high-luminosity, running.

In *Majorana Neutrinos and Dark Matter from Anomaly Cancellation*
Hridoy Debnath, Pavel Fileviez Perez, Kevin Gonzalez-Quesada, Physical Review D 109, 115030 (2024), we discuss a simple theory for neutrino masses where the total lepton number is a local gauge symmetry spontaneously broken below the multi-TeV scale. In this context, the neutrino masses are generated through the canonical seesaw mechanism and a Majorana dark matter candidate is predicted from anomaly cancellation. We discuss in great detail the dark matter annihilation channels and find out the upper bound on the symmetry breaking scale using the cosmological bounds on the relic density. Since in this context the dark matter candidate has suppressed couplings to the Standard Model quarks, one can satisfy the direct detection bounds

even if the dark matter mass is close to the electroweak scale. This theory predicts a light pseudo-Nambu-Goldstone boson (the Majoron) associated to the mechanism of neutrino mass. We discuss briefly the properties of the Majoron and the impact of the Big Bang Nucleosynthesis bounds.

In *Custodial Symmetry Breaking and Higgs Signatures at the LHC*, Jon Butterworth, Hridoy Debnath, Pavel Fileviez Pérez, Francis Mitchell, Physical Review D 109, 095014 (2024), we discuss the simplest model that predicts a tree level modification of the ρ parameter from a shift in the W-mass without changing the prediction for the Z mass. This model predicts a new neutral Higgs and two charged Higgses, with very similar masses and sup- pressed couplings to the Standard Model fermions. We discuss the decay properties of these new scalar bosons, and the main signatures at the Large Hadron Collider. Comparing these signatures for the first time to the latest measurements, we show that while masses around 200 GeV are excluded for some scenarios, over a wide range of model parameter space the new bosons can have a mass close to the electroweak scale without violating existing limits from experimental searches or destroying the agreement with measurements. We investigate the scenario where the new neutral Higgs is fermiophobic and has a large branching ratio into W gauge bosons and/or photons, and show that this could lead to a signal in the diphoton mass spectrum at low Higgs masses. We discuss the different signatures that can motivate new measurements and searches at the Large Hadron Collider.

In *Finite Naturalness and Quark-Lepton Unification*
Pavel Fileviez Perez, Clara Murgui, Samuel Patrone, Adriano Testa, Mark B. Wise,
Physical Review D 109, 015011 (2024), we study the implications of finite naturalness in Pati-Salam models where SU(3)C is embedded in SU(4). For the minimal realization at low-scale of quark-lepton unification, which employs the inverse seesaw for neutrino masses, we find that the radiative corrections to the Higgs boson mass.The one-loop contributions to the Higgs mass are suppressed by four powers of the hypercharge gauge coupling. We find that for the vector leptoquarks the naively leading part of the two-loop corrections cancel. We assume the Dirac Yukawa couplings for neutrinos are equal to the up-type quark Yukawa couplings as predicted in the minimal theory for quark-lepton unification. Despite these findings, the two-loop corrections still dominate the finite naturalness bound. We mention a way to relax the lower bound on the vector leptoquark mass.

In *Low* Scale Seesaw with Local Lepton Number
Hridoy Debnath, Pavel Fileviez Perez, Physical Review D 108, 075009 (2023), we discuss a class of theories for Majorana neutrinos where the total lepton number is a local gauge symmetry. These theories predict a dark matter candidate from anomaly cancellation. We discuss the properties of the dark matter candidate and using the cosmological bounds, we obtain the upper bound on the lepton number symmetry breaking scale. The dark matter candidate has unique annihilation channels due to the fact that the theory predicts a light pseudo-Goldstone boson, the Majoron, and one can obtain the correct relic density in a large fraction of

the parameter space. In this context, the seesaw scale is below the 100 TeV scale and one can hope to test the origin of neutrino masses at current or future colliders. We discuss the lepton number violating Higgs decays and the possibility to observe lepton number violation at the Large Hadron Collider.

In *Automatic Nelson-Barr Solutions to the Strong CP Puzzle*
Pavel Fileviez Perez, Clara Murgui, Mark B. Wise, 2302.06620
Physical Review D 108, 015010 (2023), We discuss a simple model, based on the gauge group SU(3)C⊗SU(2)L⊗U(1)Y⊗U(1)R, where the Nelson-Barr solution to the strong CP problem is implemented. This model automatically provides a high quality solution to the strong CP puzzle. Weak CP violation in the lepton sector arises in the same fashion as in the quark sector. We derive explicit expressions for the flavor changing couplings of the electroweak and Higgs bosons. These expressions are more general than the particular model considered. Constraints from finite naturalness are briefly discussed. We briefly also discuss related models based on the gauge group B-L.

- **List of papers:**

Lepton and Baryon Numbers as Local Gauge Symmetries
Pavel Fileviez Pérez,
Physical Review D 110, 035018 (2024)

Dark Matter from Anomaly Cancellation at the LHC,
Jon Butterworth, Hridoy Debnath, Pavel Fileviez Pérez, Yoran Yeh
Physical Review D110, 075001(2024)

Majorana Neutrinos and Dark Matter from Anomaly Cancellation
Hridoy Debnath, Pavel Fileviez Perez, Kevin Gonzalez-Quesada,
Physical Review D 109, 115030 (2024)

Custodial Symmetry Breaking and Higgs Signatures at the LHC,
Jon Butterworth, Hridoy Debnath, Pavel Fileviez Pérez, Francis Mitchell,
Physical Review D 109, 095014 (2024)

Finite Naturalness and Quark-Lepton Unification
Pavel Fileviez Perez, Clara Murgui, Samuel Patrone, Adriano Testa, Mark B. Wise,
Physical Review D 109, 015011 (2024)

Low Scale Seesaw with Local Lepton Number
Hridoy Debnath, Pavel Fileviez Perez, Physical Review D 108, 075009 (2023)

Automatic Nelson-Barr Solutions to the Strong CP Puzzle
Pavel Fileviez Perez, Clara Murgui, Mark B. Wise, 2302.06620
Physical Review D 108, 015010 (2023)

- **List of people who worked in the project:**

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- **Cost Status**
  The 59.000.00 USD has been used to support the research of the PI and the graduate students during the summer.