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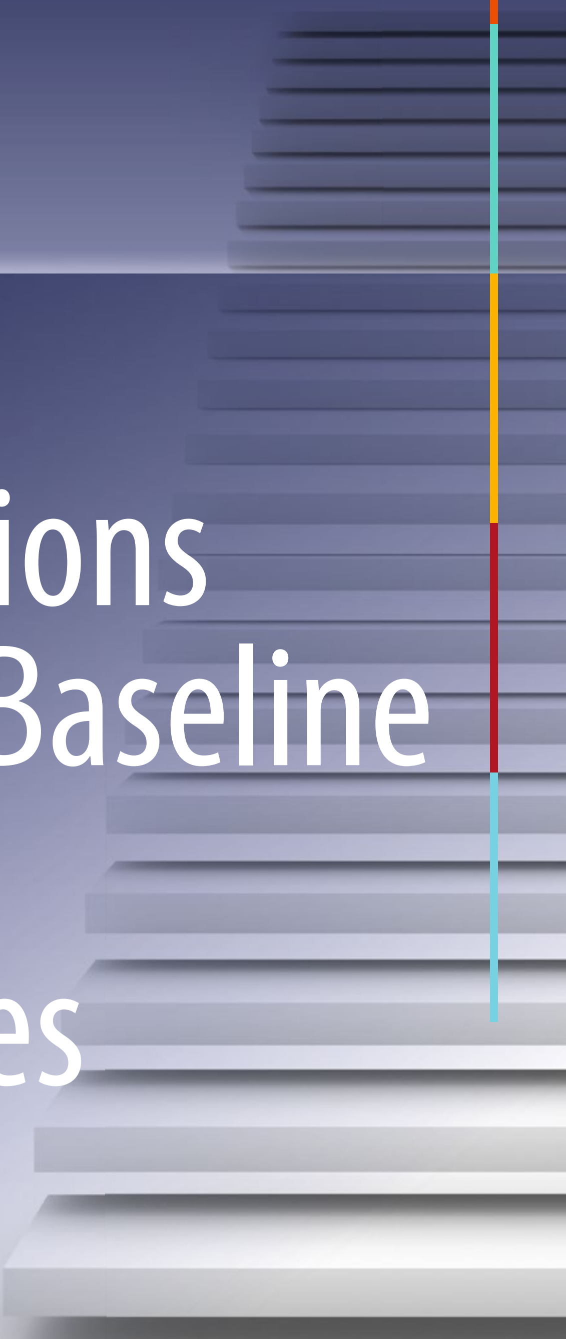
Nicolò Foppiani

Testing Explanations of Short Baseline Neutrino Anomalies



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Nicolò Foppiani

Testing Explanations of Short Baseline Neutrino Anomalies

Doctoral Thesis accepted by Harvard University,
Cambridge, MA, USA

Springer

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ISSN 2190-5053 ISSN 2190-5061 (electronic)
Springer Theses
ISBN 978-3-031-40832-8 ISBN 978-3-031-40833-5 (eBook)
https://doi.org/10.1007/978-3-031-40833-5

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To my family,
who shared with me
every emotion
of this journey.

Supervisor’s Foreword

It is a pleasure to introduce the work of my former student, Nicolò Foppiani, who was co-advised by Professor Roxanne Guenette and myself. This thesis is unique as it runs along two parallel paths, joined by their aim to resolve one of the most significant mysteries in neutrino physics.

The observation of non-zero neutrino masses implies that the Standard Model (SM) of particle physics is incomplete. How to include neutrino masses within the SM has a variety of solutions. The “simplest” would be to add a new, sterile particle—known for technical reasons as a right-handed neutrino—to the model and follow the same recipe as the other particles in the SM. Though this solution seems dull, it is, in fact, quite striking: a new particle must exist in nature, and its mass and other properties are unknown and unmeasured. On the other hand, this solution is unsatisfactory to many neutrino physicists as it does not explain why neutrino masses are so small compared to the other particles. The heaviest of neutrinos’ mass is no larger than one in a millionth of the electron mass, leaving a gap of many orders of magnitude in the mass spectrum between the other particles and the neutrinos. This observation strongly suggests that another distinct mechanism is responsible for generating the masses of neutrinos. Paraphrasing Borges from *La Muerte y la Brújula*: Nature has no obligation to be interesting, but hypotheses must be. Dr. Foppiani’s thesis follows this path and explores new models that imply neutrino masses are generated by several additional sterile neutrinos coupled with secret interactions.

The existence of more complex neutrino-mass generating scenarios is not only motivated by theoretical reasons. As Dr. Foppiani reminds us in Part I, a series of anomalies have been observed in experiments searching for flavor conversion of muon-neutrino to electron-neutrino. The most significant of these observations are the LSND and MiniBooNE experiments, which observed an excess of electro-antineutrino and electron-like events, respectively. These excesses are statistically beyond doubt, and when interpreted in a neutrino oscillation model that adds an additional light, sterile neutrino, they have a significance above five sigma (a p-value smaller than three in ten billion). Unfortunately, this interpretation is under severe tension with experiments searching for correlated signatures in muon-neutrino disappearance and electron-neutrino disappearance. Seeking to resolve this tension has led to the introduction of alternative explanations of the MiniBooNE anomaly that involve heavy sterile neutrinos, which Dr. Foppiani reviews in Part II.

Two results are presented in this thesis. The first one, discussed in Part II, reports new constraints on heavy neutrinos obtained by recasting searches performed in the T2K near detector, ND280. The relevant heavy neutrino models can be organized into two categories, the minimal and non-minimal scenarios. These two categories differ because, in the latter case, an additional "dark" force is added to the heavy neutrino model. The latter model is phenomenologically more interesting and also avoids strong constraints from cosmology. However, it also involves a larger parameter space, with six free parameters. Prior attempts to study this model have used simplified assumptions to obtain constraints or preferred regions by fixing one or more model parameters. This thesis introduces a new method that allows the exploration of the model parameter space in a continuous fashion, as discussed in Sect. 6.4. Both constraints for the minimal and non-minimal scenarios are world-leading, and the technique used to probe the multi-dimensional space has broad applicability.

The second result is a search for electron-neutrino appearance in the MicroBooNE experiment, discussed in detail in Part III. The MicroBooNE experiment operated on the same neutrino beamline as MiniBooNE, allowing for a close check of the MiniBooNE anomaly. One of the main disadvantages of MiniBooNE was that it could not differentiate between electrons and photons. Though the MiniBooNE Collaboration has auxiliary measurements to control their backgrounds, an independent analysis with a different technology is of crucial importance. MicroBooNE was built for this task: its Liquid-Argon Time Projection Chamber can reconstruct and identify the individual particles produced in a neutrino interaction. Importantly for this discussion, MicroBooNE can distinguish between electrons and photons. The analysis reported in this thesis did not find an excess of events analogous to that of MiniBooNE. Still, it did not entirely rule out the anomaly, leaving space for further exploration, which Dr. Foppiani discusses in his conclusions.

In summary, Dr. Foppiani's thesis constitutes a significant piece of work in resolving the MiniBooNE anomaly. The results and techniques introduced here will have a long-lasting impact on our field.

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Carlos A. Argüelles-Delgado

Parts of This Thesis Have Been Published in the Following Journal Articles

- C. A. Argüelles, N. Foppiani, and M. Hostert, “Heavy neutral leptons below the kaon mass at hodoscopic neutrino detectors,” *Phys. Rev. D, vol. 105, no. 9, p. 095006, 2022.*
- C. A. Argüelles, N. Foppiani, and M. Hostert, “Efficiently exploring multidimensional parameter spaces beyond the Standard Model,” *Phys. Rev. D, vol. 107, no. 3, p. 035027, 2023.*
- P. Abratenko et al., “Calorimetric classification of track-like signatures in liquid argon TPCs using MicroBooNE data,” *JHEP, vol. 12, p. 153, 2021.*
- P. Abratenko et al., “Search for an Excess of Electron Neutrino Interactions in Mi- croBooNE Using Multiple Final-State Topologies,” *Phys. Rev. Lett., vol. 128, no. 24, p. 241801, 2022.*
- P. Abratenko et al., “Search for an anomalous excess of charged-current νe interac- tions without pions in the final state with the MicroBooNE experiment,” *Phys. Rev. D, vol. 105, no. 11, p. 112004, 2022.*

Acknowledgments

This Ph.D. was a turbulent journey, which could not be possible without the support of the many friends, colleagues, and mentors I found along the way. Ph.D. advisors are fundamental pillars during graduate studies.

I would like to thank Roxanne Guenette for welcoming me into her group during my first year and always supporting my exploratory mindset and ideas, often off the beaten path. She made me realize that scientific endeavors can be very complex not simply because of the science but because of the many human interactions behind them. She created a humane environment where students are respected as individuals, acknowledging our needs, spare time, and lives outside of physics.

I would like to acknowledge Carlos Argüelles-Delgado for being first a friend, then a respected colleague and collaborator, and eventually a thesis advisor. He always encouraged me to think broadly, outside the box, and constantly innovate in every aspect of my scientific research. I will genuinely miss our physics chats, always full of enthusiasm, passion, and room for unconventional ideas. At the same time, I also appreciated all our deep conversations about the other aspects of life, always putting our well-being first, recognizing that, without it doing good science is challenging.

I also would like to acknowledge Melissa Franklin and Matt Reece for serving on my committee. Melissa convinced me to join Harvard in the first place, and she has always been a reference point for me. She often challenged my ideas, pushing me to think broadly about options and opportunities, both science- and career-wise. I always appreciated Matt's humility and thoughtfulness in our physics discussions. Since my first year, when I was just a QFT student, he never dismissed my questions, always finding some exciting and nontrivial aspects.

I thank all my collaborators in Guenette's group, especially Wouter, Marco, Roberto, Justo, and Lars. We shared many aspects of the MicroBooNE experience and many trips to Fermilab. Wouter has also been a special friend, sharing many outdoor adventures and trips during these past years. I thank the MicroBooNE collaboration for allowing me to work on the flagship analysis, and the Pandora eLEE team for sharing the endeavor of the electron neutrino searches. I especially thank David and Giuseppe for collaborating, following me closely, and mentoring me during this time. I thank the *Neutrino Penguins'* group (Argüelles' group) for being a new home after the pandemic. It also broadened my horizons to the edge of the universe, where astrophysical neutrinos originate. Within this group, I would like to especially thank Matheus for the fun projects we developed in the last two years. Although mainly working remotely, our meetings always brought joy, thanks to the friendly and enjoyable atmosphere we created.

If I am here writing this thesis, it is because my journey started some time ago when Gigi Rolandi caught me with his enthusiasm and passion during the first particle physics class at Scuola Normale in Pisa. He supervised me at CERN for both my Bachelor's and Master's theses, where the collaborative environment of the CMS experiment made my interest in particle physics grow further. It is thanks to his mentorship and all the time he dedicated to me that I decided to embark on the journey of a physics Ph.D.

Even if science was the main ingredient of this journey, it was definitely not the only one. I am grateful that I could be part of many *families* during these few years. The Harvard physics department has been a homy environment, where I found friends among the other students, especially within my cohort. I especially would like to thank Sepehr, Qianshu, Cari, Brendon, Nick, Zoe, Grace, Ruihua, Tim, Paloma, and Rashmish for the many fun and celebratory moments we shared in these few years. I would also like to acknowledge Lisa, Jacob, and Carol for always supporting and helping me navigate the troubles of the Ph.D.

Harvard also gave me opportunities to challenge myself in different subjects. The class in Human-Computer Interaction was an exciting experience that allowed me to apply my knowledge of statistics in a different field. The mentorship of Professor Elena Glassman and the great teamwork with Sana, Sophie, and Ziv culminated in a publication that I feel very proud of because it is outside of my primary field. How to Make Almost Anything was an extraordinary class. For a semester, the fabrication lab and the MIT Media Lab have been my second home. I had a chance to dive into digital fabrication and meet fantastic classmates and mentors. I would like to acknowledge Nathan for running the lab and ensuring everyone could complete their final projects, and Ibrahim, Gabby, Rosalie, Alfonso, Ian, and Camron for sharing many nights fighting with CAD and Arduino. The challenges I encountered in my scientific collaborations made me appreciate the importance of human relationships and led me to the Negotiation Workshop at Harvard Law School. Since the class is about human interactions, I could grow significantly thanks to the people I negotiated, debriefed, and argued with. I would like to thank the fantastic "group blue": especially Vi, for helping us students be always ready for the following case, and Professor Michael Chaffers for leading us through all the challenges posed during the class. After all our conversations reconciling my analytical skills with his negotiation experience, I am very grateful that I can consider him a mentor.

Challenges do not appear only in academia: the Harvard Mountaineering Club was a place for embarking on new challenges every week. I learned new mountaineering skills, improved my rock climbing, and even started ice climbing, thanks to the cold New England winters. Still, most importantly, I learned how to tackle mental challenges when finding myself in difficult and uncomfortable situations.

Among my fantastic climbing partners and friends, I would like to acknowledge Enrico, Larissa, Dom, and Walter for the many adventures we shared across multiple continents. I especially would like to thank Carlo for being not just a climbing partner or a friend but also a mentor: our conversations when returning from a long climbing trip always gave me perspective and clarity on my future steps during my Ph.D.

I am genuinely grateful to have had the privilege to join the Harvard Horizons program. The fantastic team at the Bok Center, Pamela, Erika, Marlon, Jordan, and Casey, helped me develop better outreach skills that, I am sure, improved both this manuscript and my thesis defense. My fellow scholars, Vanessa, Harry, Hannah, Karina, Chika, and Juliana, have been an essential element of this journey. All the time we spent together, from the very first meeting to the final day of the Symposium in Sanders Theater, made me not just better at communicating my research but made me also understand it more deeply.

I am also thankful to the Harvard Italian Student Society for reminding me of home whenever I felt nostalgic of Italy, between joyful glasses of Aperol Spritz and pasta competitions. I would like to acknowledge the many friends I met within this family: Alberto, Davide, Greta, Giuseppe, Gabriele, Benedetta, Elena, Eleonora, Gaia, and the many others I cannot name. Our shared experience in Boston is a bond we will keep in the future.

Meeting new friends from entirely different backgrounds is always a great opportunity to learn, and my friends from the Master in Public Administration and International Development (MPA/ID) at the Harvard Kennedy School were definitely not an exception. I found myself being caught in conversations about economics, thinking about introspective leadership, and reflecting on global poverty. This group definitely made me a little more humble. I especially acknowledge Alex, Jossie, Bia, Christian, Beto, Mechi, Nicole, and Nico, and all the other people I met during many trips, events, and parties.

Within this family, I am immensely grateful to Ruth for being my partner and supporting me throughout the last two years. We did not simply share the many pleasant moments of our journeys at Harvard. She truly supported me over all the difficult patches of my Ph.D., always showing empathy, compassion, and care.

You cannot say you moved to a new place until you find a new home, which I found in a cozy and quiet house in Somerville, at 19A Harvard Street. What made it home were my roommates, especially Sepehr, with whom we shared the house from the very beginning, and Sean, Mark, Diego, Ali, Brendon, Barton, and all the other roommates who have spent part of the journey at Harvard St. I will conserve all the lovely memories from the parties and meals we had during these few years. All the challenges we faced living together, from finding compromises between different cultures and habits to sharing the space during the pandemic, forged our friendships and made us grow as people.

Not all the people who supported me were around Cambridge: many of them were actually across the ocean, back in Europe. I am grateful to have been part of Officine Italia, a group of friends that gave me hope and energy at the beginning of the pandemic when we felt there was no way for us to help the world: I am looking forward to many more projects to come.

It always feels special to walk through the streets of Pisa, stop by the University, and meet my former classmates Marco, Federica, Olmo, Tommaso, Francesca, Marianna, and Agnese, either in person during our reunions or for a phone call now that we live far away. I feel thankful that I can always rely on this special group of friends with whom I shared one of the most meaningful experiences of my life.

And, going back to Chiavari, my hometown, always gives me pleasant feelings, evoking many lovely memories from the past. I am always happy to share new moments with my more historical friends, Giacomo, Sara, Luca, Erik, Riccardo, Emanuele, Serena, Gaia, and Francesco. I am thankful Chiavari will always be the place to come back to our roots and share our stories and experiences.

And eventually, my family is what I will always call home, always waiting for me throughout my adventures: my parents, Adriana and Luciano, and my grandmother, Nonna Lidia. Despite not fully grasping what a Ph.D. is about and what living in the USA looks like, they lived this adventure with me, sharing all the joyful moments and all the difficult patches. Although this time has been challenging for them, I am grateful that they have and always will support me.

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Part II Heavy Sterile Neutrino Explanations

Part III Light Sterile Neutrino Explanations

About the Author

Nicolò Foppiani is currently working as a fusion researcher at Proxima Fusion, where he applies numerical optimization techniques to the design of the first stellarator fusion power plant, aiming to produce abundant, clean, and safe energy, shaping the post-fossil-fuels world.

Before transitioning to fusion R&D, he worked on particle physics research on neutrino experiments and hadron colliders.

He graduated with a physics PhD at Harvard in 2022. His thesis work focused on neutrino physics and the search for sterile neutrinos.

While a Ph.D. student, he was awarded the prestigious Goldhaber Prize by the Harvard Physics Department, recognizing outstanding and promising graduate students.

While at Harvard, he cultivated his passion for public speaking as a Harvard Horizons Scholar, delivering a presentation about his thesis work in front of a multidisciplinary audience and winning the graduate student SLAM in 2020, a competition among graduate students to give the best three-minute presentation at the APS April Meeting.

He also cultivated a strong interest in building community. He served as the graduate student liaison in the Harvard Mountaineering Club between 2019 and 2021 and vice-president for the Harvard Italian Student Society in 2019.

He holds a Bachelor's and a Master's in physics from the University of Pisa and a Diploma in Physics from the prestigious Scuola Normale Superiore, where he complemented and deepened his physics education.

His interest in particle physics started in 2015 when we worked on simulations for the Future Circular Collider for his Bachelor's thesis. He was selected as a Summer Student at CERN in 2016. He continued his research with his Master's thesis on the "Measurement of the mass of the W boson with the CMS experiment," which was later awarded the Tito Maiani prize in 2018.

Parallel to science and research, he also worked for the NGO Officine Italia, which he co-founded in 2020 at the beginning of the COVID-19 pandemic, to increase youth participation in public policy and agenda-setting, with a strong focus on Italy.

Chapter 1
Prologue

Abstract It is astonishing that all the complex structures we observe in nature, from stars and galaxies to living organisms and molecules, emerge from the same underlying elementary pieces: the quarks up and down and the electron. It is through their fundamental interactions that these three particles can combine together, giving rise to an exponentially large amount of combinations and possibilities. This is what particle physics is about: understanding nature at its fundamental level. Particle physics is often referred to as high-energy physics because large energies correspond to small scales, which, in turn, require experiments at high energy to be investigated. Among the elementary particles, there is one more type: the elusive neutrino. Since neutrinos undergo only weak interaction, neutrinos cannot bind with other particles, and their probability of interacting with matter is very small for the typical energies of neutrinos around the Earth. In turn, this fact made neutrinos challenging to discover and makes them both hard to study and unknown to most people.

1.1 Surprising Neutrinos

However, neutrinos have brought many surprises over the past few decades. For example, we know they come in three distinct types, or *flavors*, and their interaction violates symmetries under parity and charge conjugations, which are instead respected by other forces. More importantly, neutrinos were first theorized as massless particles because of the lack of experimental evidence. We now know neutrinos are massive because the three flavors mix with each other. This discovery represents a crack into the standard model of particle physics, which requires the existence of new physics and other particles to be explained. Moreover, in a moment where most measurements performed in the lab agree with the theoretical predictions, several neutrino experiments report disagreements. These discrepant experimental results are often referred to as *short baseline anomalies* and form a genuinely unclear puzzle, which might hide new physics discoveries.

N. Foppiani, *Testing Explanations of Short Baseline Neutrino Anomalies*,
Springer Theses, https://doi.org/10.1007/978-3-031-40833-5_1

Such motivations pushed me to pursue research in neutrino physics as a Ph.D. student. This thesis represents the summary and the completion of my work between 2017 and 2022. All the original work in this thesis has been published in peer-reviewed journals. The work is not organized in chronological order but rather in a logical order, hoping that the reader would agree with the rationale behind this scheme.

1.2 A Tale in Three Parts

Part I sets the background for the thesis work, introducing the current understanding of neutrinos and the theoretical and experimental motivations that justify the search for new particles. While it does not contain any original work, I explained the physics in my preferred way and included all the insights I find effective in understanding neutrinos. Although I started working on short baseline anomalies five years ago, I described the theoretical and experimental status at the time of writing the thesis. I want to acknowledge, however, that several things have changed, and new insights were brought in by both the experimental and theoretical communities.

Part II contains some more *phenomenological* work I performed, considering possible solutions to the short baseline anomalies in terms of heavy sterile neutrino models and looking for datasets and experiments that could test them. Chapter 5 is adapted from [1], which was published in Physical Review D. Chapter 6 is adapted from [2], also published in Physical Review D. Both works have been performed with Matheus Hostert and Carlos Argüelles-Delgado. Together with testing physical models, we also developed a new statistical approach to test models in ample parameter spaces. Although it started a year before the first paper, the second was made public only recently.

Part III summarizes most of my contribution in the MicroBooNE collaboration. I joined MicroBooNE in 2018 and have been an active member until the electron neutrino search was finalized and published. Chapter 7 introduces the MicroBooNE experiment, describing the most important features relevant to this thesis. Chapter 8 describes how particles are measured and identified in MicroBooNE. A large chunk of the chapter is adapted from [3], published in the Journal of High Energy Physics, which describes a new method to improve the identification of track-like particles in MicroBooNE substantially. This new methodology was not only essential for the electron neutrino searches I was directly involved in, but it is also the basis of many detailed cross-section measurements published by MicroBooNE. The rest of the chapter complements the paper and describes other unpublished work. Chapters 9 and 10 are adapted from and expand the electron neutrino search published in [4, 5], in Physical Review Letters and Physical Review D, respectively.

References

1. C. A. Argüelles, N. Foppiani, and M. Hostert, “Heavy neutral leptons below the kaon mass at hodoscopic neutrino detectors,” *Phys. Rev. D*, vol. 105, no. 9, p. 095006, 2022.
2. C. A. Argüelles, N. Foppiani, and M. Hostert, “Efficiently exploring multidimensional parameter spaces beyond the Standard Model,” *Phys. Rev. D*, vol. 107, no. 3, p. 035027, 2023.
3. P. Abratenko *et al.*, “Calorimetric classification of track-like signatures in liquid argon TPCs using MicroBooNE data,” *JHEP*, vol. 12, p. 153, 2021.
4. P. Abratenko *et al.*, “Search for an Excess of Electron Neutrino Interactions in MicroBooNE Using Multiple Final-State Topologies,” *Phys. Rev. Lett.*, vol. 128, no. 24, p. 241801, 2022.
5. P. Abratenko *et al.*, “Search for an anomalous excess of charged-current νe interactions without pions in the final state with the MicroBooNE experiment,” *Phys. Rev. D*, vol. 105, no. 11, p. 112004, 2022.