Research Statement

Rebekah Pestes

As a nearly massless neutral particle associated with multiple unsolved anomalies, neutrinos provide an excellent probe to explore the edges of the standard model. So far, my research in theoretical particle physics has primarily focused on simulating neutrino oscillation experiments. Specifically, I have looked at the experiments' sensitivities to various parameters and properties of (or affecting) neutrino oscillation, systematic uncertainties that could affect these sensitivities, and possibilities for counteracting the effects of these uncertainties. My research has also included the effects of scenarios beyond the standard model on neutrino oscillation experiments and what neutrino oscillation experiements can tell us about the inside of the Earth.

Regarding JUNO

The Jiangmen Underground Neutrino Observatory (JUNO) collaboration is scaling up liquid scintillator technology to unprecedented extremes in order to build a neutrino detector that detects electron antineutrinos coming from two nuclear reactors with a low enough energy resolution to resolve the difference between the two large mass-squared-differences Δm^2_{31} and Δm^2_{32}, enabling JUNO to measure the mass ordering of neutrinos. However, the reactor antineutrino anomaly with a bump at 5 MeV shows us that we do not know the energy spectrum of neutrinos coming from a nuclear reactor as well as we thought. There is a possibility of significant "fine structure" in the reactor neutrino energy spectrum at a small enough scale that the Daya Bay experiment could not measure it, and it has the potential to interfer with JUNO's ability to measure the neutrino mass ordering. My first project addressed how this problem could affect JUNO's goals if they do not use a reference spectrum with comparable energy resolution [1]. Using GLoBES to simulate JUNO with added code I wrote to make it possible for the minimizer to work well with so many parameters to marginalize over, we found that their sensitivity to the mass ordering could drop to merely a hint if they used Daya Bay's measured spectrum, instead of having a near detector with comparable energy resolution. As a result, the JUNO collaboration has decided to build the Taiman Antineutrino Observatory (JUNO-TAO) to provide a reference spectrum for JUNO. Another project I did, using a modified oscillation probability function in GLoBES, found that JUNO (with JUNO-TAO) is also a great detector to observe the interference between the two mass-squared-differences in neutrino oscillation, which is a quantum-mechanical effect of having three flavors of neutrinos that mix with each other [2]. This result can also be extended to looking for Sorkin's Triple Interference in neutrino oscillations. By testing various forms of the triple interference term, we found that JUNO's sensitivity to Sorkin's Triple Interference could be comparable to photon experiments designed to look for this form of interference [3]. A search is underway looking for theories that produce a triple interference term so we can have a particular form of the term to test with JUNO. It is exciting to see neutrinos being able to be used to test the foundations of quantum mechanics.

CP Violation in Neutrino Oscillations

Other than the neutrino mass ordering, there are two unknowns in standard neutrino oscillations that future precision neutrino experiments are striving to discover: the octant of the mixing angle θ_{23} and the value of the "CP-violating phase" ($\delta_{\rm CP}$). These are parameters in the most common parameterization of the neutrino mixing matrix ($U_{\rm PDG}$). In this parameterization, $\delta_{\rm CP}$ is the only source of complex numbers, which are needed for the existance of CP violation in neutrino oscillations. However, it is not exactly accurate to say that $\delta_{\rm CP}$ tells us how large CP violation is in neutrino oscillations, since the terms that violate CP in the oscillation probability also contain all of the mixing angles in such a way that if any of the mixing angles are 0 or $\pi/2$, those terms vanish. Thus, the values of the mixing angles also restrict how much CP violation exists in neutrino oscillations. Not only that, but $\delta_{\rm CP}$ (as well as the mixing angles) can have a different value if you change the parameterization scheme, even though the amount of CP violation does not change. I worked on a project in which we found that these differences can be quite substantial, turning a 15% measurement of $\delta_{\rm CP}$ into a $\sim 1\%$ measurement (and vice versa) [4]. We also noticed that the smallness of θ_{13} in U_{PDG} is what drove this effect, and I developed some approximate formulas to characterize how δ_{CP} in other parameterizations was restricted. Unlike δ_{CP}, the Jarlskog invariant, which is invariant with regard to parameterizations of the neutrino mixing matrix, is directly related to the amount of CP violation in neutrino oscillations. Therefore, we concluded that discussion and plots should be of the Jarlskog invariant when talking about allowed amounts of CP violation in neutrino oscillations. Some people from both the Deep Underground Neutrino Experiment (DUNE) and Tokai to KamiokaNDE (T2K) collaborations have responded to this work by stating that they plan to do analyses in terms of the Jarlskog invariant in the future.

There are two long-baseline accelerator experiments, which detect (anti)neutrinos coming from a beam of muon (anti)neutrinos, that are currently giving the most precise measurements of δ_{CP} and the mass ordering: T2K and NuMI Off-axis ν_e Appearance (NOνA). However, we found that they are in tension with each other. They both prefer the normal mass ordering, but the areas of parameter space they prefer for θ_{23} vs δ_{CP} are different enough that when doing a joint fit, they prefer the inverted mass ordering, and it is not a very good fit. The two most notable differences between these experiments are the mean neutrino energy and the distance from the start of the beam to the detector: T2K's baseline is 295 km with a mean energy of 0.6 GeV, but for NOνA, they are 810 km and 1.9 GeV, respectively. Due to a larger mean neutrino energy, NOνA has a larger matter effect than T2K, which means that a neutrino non-standard interaction (NSI) would have a larger effect in NOνA than in T2K. I participated in a project, extracting and fitting data from plots presented by both collaborations, in which it was revealed that CP-violating NSIs do a much better job at alleviating this tension than changing the neutrino mass ordering to the inverted ordering [5].

There is a persistantly troublesome source of systematic uncertainty in neutrino oscillation experiments regarding the interaction cross-section of neutrinos with the detector. Event generators predict substantially different results, and it is hard to quantify our uncertainty in the cross-sections. I am currently working on a project that explores this uncertainty in DUNE and whether CP-violating NSIs could be degenerate with this uncertainty. We also look at combining data from DUNE with T2HK (Tokai to Hyper-KamiokaNDE) to see if this possible degeneracy can be alleviated and if changing one of the DUNE far detector modules to a different type of detector could further constrain the degeneracy.

Neutrino Earth Tomography

It is really exciting when something you study can be used to help another discipline or society in general, so I like looking into possible uses for neutrino oscillations outside of particle physics. Neutrinos are known for being hard to detect, but the same underlying condition that causes this also allows them to travel all the way through the earth unhindered. However, travelling through the earth, or any other matter, changes the neutrino's oscillation pattern, due to the matter effect. This change depends on the density of the matter being travelled through and can be measured by looking at the spectra for various flavors of neutrinos coming from different directions on or near the surface of the earth. Since the mass of the Earth is better measured than the density and size of the Earth's core, I did a project that looked into the sensitivity of DUNE's far detector, when used as an atmospheric neutrino experiment, to the size of the Earth's core, varying the density of the core in such a way as to keep the mass of the Earth constant. When I simulated this experiment using nuSQuIDS, we found that DUNE could detect the existance of the Earth's core quite strongly and measure the size of the Earth's core with $\sim 9\%$ precision [6]. There are some indications of the Earth's core being spherically asymmetric, and I would like to see how sensitive various combinations of atmospheric neutrino experiements would be to these asymmetries. I would also like to investigate using neutrinos to explore some other open questions in geoscience, such as the nature of Large Low-Sheer-Velocity Provinces (LLSVPs) and the composition of the Earth's core. These measurements could be effected by new physics scenarios, such as NSIs or dark matter accumulation in the Earth with neutrino dark matter interactions, and I would like to investigate how to disentangle neutrino tomography measurements from new physics cases.

More Possiblities for Future Work

There are also many other topics I am interested in exploring in future research projects, including reasons behind the various unsolved neutrino anomalies, the nature of dark matter, and the possiblity of the existance of other physics beyond the standard model, such as sterile neutrinos and neutrino non-standard interactions. I am excited to apply what I learned while doing simulations of neutrino oscillation experiments and complicated numerical and analytical calculations to advance our understanding of the workings of the universe.

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