Probing the pseudo-Dirac neutrino scenario with Galactic plane neutrino flux: Summer 2023 Final Report

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1. Background

In the early 21st century, the Super Kamiokande collaboration found neutrino flavor oscillations [6], thus indicating that neutrinos have non-zero mass, a property not predicted by the Standard Model. Extensive theoretical and experimental work has been done since then on determining the exact mechanism by which neutrinos get their mass. One such theory is that neutrinos are pseudo-Dirac. In such a theory, very small Majorana mass terms are added to the neutrino mass matrix, resulting in near-degenerate active-sterile mass states.

Over short baselines, the effect of oscillations between these active and sterile states is negligible, and neutrino flavor oscillation is dominated by the (much larger) differences between active mass states. However, over very long baselines (O(kpc) in this analysis), these much shorter oscillations average out and the overall oscillation behavior is dominated by the active-sterile mass splitting term δm^2:

$$P_{\alpha\beta} = \sum_j |U_{\alpha j}|^2 |U_{\beta j}|^2 \cos^2\left(\frac{\delta m^2 L_{\text{eff}}}{4E_\nu}\right), \tag{1}$$

where α and β are the initial and final flavor states, U is the PMNS matrix, L_{eff} is the effective distance traveled, and E_ν is the true neutrino energy.

Obtaining sensitivity to particular values of δm^2 is thus determined by the value of $L_{\text{eff}}/4E_\nu$, and obtaining sensitivity to smaller mass-splitting values requires larger values of this term. Astrophysical neutrinos have thus become the go-to targets for pseudo-Dirac parameter searches, due to their extremely long baselines.

Past studies probing the pseudo-Dirac nature of neutrinos have examined solar [1] and extragalactic [3, 7] neutrino flux, exploring values in ranges of $\delta m^2 \gtrsim 10^{-13}$ eV^2 and $\delta m^2 \lesssim 10^{-16}$ eV^2 respectively. However, notwithstanding poor bounds within these regions, there remains a lack of understanding in the parameter space between these ranges.

The IcecCube collaboration has recently published an analysis that identifies Galactic plane neutrino flux at 4.5σ significance [5]. This new source of astrophysical neutrinos provides an exciting laboratory for testing neutrino physics beyond the Standard Model (BSM).

In particular, the kpc-scale baselines and TeV energy scales provide the possibility of gaining sensitivity to δm^2 values of $\sim 10^{-15}$ eV^2, a previously unexplored region of the parameter space. I have been working this summer in the Carlos Argüelles-Delgado lab on determining exactly how sensitive IceCube is to a pseudo-Dirac scenario.

2. Modified Goals

Going into the summer, I was anticipating doing more work on developing the actual Galactic neutrino distribution models. However, we changed plans at the beginning of the summer, and my graduate student advisor Kiara Carloni was instead going to use the software CRPropa [2] to generate neutrino distribution models at point of creation in the galaxy. My task was to take this model, calculate the angle- and energy-dependent event distributions we would expect at IceCube, and use these results to compute sensitivities to different values of δm^2.

3. Process

I began the summer by reproducing a previous pseudo-Dirac study done by my advisors, Kiara Carloni and Ivan Martinez-Soler [3], where they used the galaxy NGC 1068, confirmed as an astrophysical neutrino point source by IceCube last year [4], to calculate binned sensitivities to mass splittings in the range 10^{-21} eV^2 $< \delta m^2 < 10^{-16}$ eV^2. Because many of the analysis procedures, including much of the binned sensitivity calculations, were similar to the Galactic plane analysis, I was able to gain familiarity with the analysis process. I did all of my coding in Python and spent around two weeks reproducing plots and sensitivity calculations.

I then moved on to working with preliminary Galactic neutrino distribution models Kiara had made. Due to the draft nature of the models, we assumed spatial and energy independence in the flux calculation. I used the model to derive a 3D spatial probability density ditribution P_ν. I then injected a constant spectral index of $\gamma = 2.7$ and a flux normalization factor of 21.8×10^{-16} TeV^{-1} cm^{-2} s^{-1}, both numbers taken from the IceCube Galactic plane analysis [5]. We can thus model the Galactic neutrino flux as the following:

$$\Phi(E, r, \vec{\Theta}) = \Phi_0 \left(\frac{E}{E_0}\right)^{-\gamma} P_\nu(r, \vec{\Theta}), \tag{2}$$

where $E_0 = 100$ TeV is the reference energy.

Taking into account the energy resolution (which is modeled by a skewed Gaussian N), angular resolution, which I implemented using the healpy Python package [8], and detector effective area A_{eff}, I calculated the binned angle-dependent energy distributions with the following formula:

$$N_\nu \in [E_i, E_{i+1}] \times A = \int_{E_i}^{E_{i+1}} dE_r \int_A d\vec{\Theta} \int_0^\infty dE_t \; N(E_t|E_r) A_{\text{eff}}(E_t, \vec{\Theta}) \int_0^\infty dr \; O(E_t, r) \Phi(E_t, r, \vec{\Theta}) \tag{3}$$

where A is the given angular bin, E_r, E_t are reconstructed and true neutrino energies, and O is the oscillation probability in (1).

During this process, I learned Julia 1.9 and switched over to using Julia for all of my computations. Julia's speed and specialization for scientific computing allowed me to obtain results from these computationally expensive calculations much faster than (say) Python.

Once I had a working simulation of IceCube event distributions, I moved on to performing a binned sensitivity analysis using a Poisson likelihood ratio test. For each spatial bin, I calculated the Poisson likelihood of getting Standard Model (SM) data under a given pseudo-Dirac scenario. Due to our lack of knowledge about the flux parameters Φ_0 and γ, these were left free to obtain a maximum likelihood of observing the SM data. I assumed a χ^2 distribution of the resulting test statistic to obtain sensitivity values.

In addition to my main analysis, I looked at how changing energy and angular resolution would affect IceCube's sensitivity—these factors might be relevant for future searches, as better energy and angle reconstruction algorithms are developed. I also explored the possibility of gaining sensitivity to scenarios where the different mass states had distinct active-sterile splitting values.

4. Results

While the analysis process is still ongoing, I have made significant progress in calculating event distributions and have obtained tentative binned IceCube sensitivities to ranges of pseudo-Dirac parameter space. These sensitivities are dependent on IceCube's energy and angular resolution, which we've approximated using the plots they provide in the paper at around 50% and 7%, respectively.

Initial results indicate that IceCube could be sensitive to a δm^2 range of $10^{-14.5}$ eV$^2 \lesssim \delta m^2 \lesssim 10^{-13.5}$ eV^2 at a 5σ confidence level or above. It is additionally sensitive at a 3σ confidence level to mass splitting values as large as $\delta m^2 \approx 10^{-12.6}$ eV^2. These initial results, though still rough, strongly motivate a full unbinned sensitivity analysis with real IceCube data, considering astrophysical background flux.

5. Plan for Future Research

I plan on continuing work at the lab this fall, continuing this pseudo-Dirac sensitivity analysis. Future goals include improving the implementation of energy and angular smearing to better match with true IceCube efficiency; optimizing the Julia serial code and parallelizing it on the cluster to improve computational speed; and further exploring the physical and phenomenological impacts of a hypothetical pseudo-Dirac reality.

I have also begun leveraging the L_{eff} information gained from a non-zero mass splitting value (see (1)) to probe the possibility of constructing a 3D spatial galactic neutrino distribution model in the case that neutrinos are indeed pseudo-Dirac. I look forward to continuing work on this project in the fall.

References

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