Pion Scattering Data-Model Comparisons in Geant4.

Background

Neutrino oscillations are of high interest to the scientific community, and were the subject of the 2015 Nobel Prize in Physics. Oscillation is the process by which neutrinos produced as one flavor can be detected as a different flavor after traveling some distance. The upcoming Deep Underground Neutrino Experiment (DUNE) – an international collaboration – seeks to probe new physics in neutrino oscillations, such as the potential presence of charge-parity (CP) symmetry violation in oscillations. CP symmetry would require that neutrinos and antineutrinos behave identically, so breaking this symmetry would mean neutrinos and antineutrinos have a different oscillation probability. If present, this difference could provide an explanation to the matter-antimatter asymmetry we observe in the universe. Thus, the presence of CP violation in neutrino oscillations is one of the most important open questions in High Energy Physics.

In the oscillation probability, CP violation is represented by the parameter δ_{CP}. It enters into the probability at a point that is dependent on the neutrino energy. Therefore, any bias in estimating the energy will result in a biased measurement of δ_{CP}. Due to this, neutrino energy reconstruction is one of the largest sources of systematic uncertainty in DUNE. It has been shown that in an experiment similar to DUNE, an underestimation of neutrino energy by 20% can lead to a bias to the measurement of δ_{CP} on the order of one standard deviation[1].

The effect of CP violation on the oscillation probability is coupled to the neutrino energy. Therefore, any bias in estimating the energy could result in a false signal – or lack thereof – for CP violation. Due to this, neutrino energy reconstruction is one of the largest sources of systematic uncertainty in DUNE. It has been shown that in an experiment similar to DUNE, an underestimation of neutrino energy by 20% can lead to a bias of the CP effect on the order of one standard deviation[1].

Neutrino energy is estimated from the reconstructed energy of final state particles that are produced in neutrino-nucleus interactions. The neutrino energy can be incorrectly estimated if particles interact inelastically or are unable to be reconstructed because of scattering in the detector medium. This is referred to as Secondary Interactions (SI) of these particles. These processes will be a significant problem for DUNE and must be studied.

For DUNE – which will use Liquid Argon technology to detect neutrinos – knowledge of pion-argon SI, in particular, will require a large improvement. Data from previous pion scattering experiments is used to inform pion SI models, and, until recently, pion-argon data existed only up to a pion kinetic energy of 240 MeV. This leaves a lack of constraints for pion-argon SI at energies relevant to DUNE. The recent Liquid Argon in a Testbeam (LArIAT) experiment has provided pion-argon scattering data up to 1.2 GeV, and my upcoming measurement on DUNE's prototype detector, ProtoDUNE, will provide data at even higher energies. I will use this data to constrain SI models used in DUNE's experimental simulations.

Geant4[2] is a software package that is used to simulate particles as they travel through a detector, and will be used by DUNE to simulate SI. One part of the overall SI simulation is the modeling of pion-nucleus scattering rates. It is important to quantify pion SI model uncertainties by comparing Geant4's pion scattering predictions to external data sets. This ability is absent in Geant4, and it must be implemented in order to utilize LArIAT and ProtoDUNE data. My project will consist of providing this implementation and then comparing Geant4's pion scattering model to the recent LArIAT data. This project will be an extension of work done by the T2K collaboration to use recent pion-carbon scattering data[3] to constrain models for a similar process. This work will then allow me to complete another comparison to ProtoDUNE data once my measurement has been made.

At Fermi National Accelerator Laboratory (FNAL), I will work with Dr. Laura Fields to implement and produce these data-model comparisons in Geant4. Dr. Fields is the co-spokesperson for the MINERvA experiment, which performs neutrino-nucleus cross section measurements, and uses Geant4 to simulate final state particles in its detector. Additionally, she is a convener of the DUNE Beam Simulation and Systematics Working Group. This group uses Geant4 to provide predictions of the neutrino flux produced at FNAL. Both of these projects require a quantification of Geant4's model uncertainties, thus motivating Dr. Fields' interest in this project. Her expertise in using and developing Geant4 makes her an excellent supervisor of this project.

Research Objectives and Goals

The overall plan of this project is contained within three major steps: 1) Implement model-data comparisons into Geant4 and distribute. 2) Use historical data to quantify the current uncertainties associated with pion-argon SI in Geant4. 3) Update these uncertainties with a fit to LAriAT data.

This work will be an extension of work first performed by the T2K collaboration. In this work, the nominal pion-carbon scattering model in Geant4 was replaced by the model used by the NEUT neutrino interaction simulation. This model was then parameterized by factors that scale the rate of individual pion-nucleus interaction modes, allowing for new predictions of the total rate of pion-carbon scattering to be produced. These parameters were then varied, and a fit to external data was performed. A constrained prediction and its associated uncertainties were produced from the fit results.

As this work was entirely contained within the T2K experiment, it must be updated and implemented into an official Geant4 release to be more widely available to the general neutrino physics community. The first step of my project will be to again implement the NEUT pion scattering model into the latest Geant4 release. I will then develop the software package that will provide the data-model comparisons and uncertainty quantification. At minimum, this software will have the following functionality:

- Loading in external data sets
- Reading in previously computed nominal prediction
- Performing the fit and finding the best-fit prediction
- Producing error bands from the fit results

After this, I will validate the software by reproducing the results to the original T2K work, and finalize it to be included in a later, official Geant4 release.

In order to understand the current status of the nominal Geant4 and NUET pion scattering models, an important step will be to determine their current predictions for the pion-argon interaction cross section. This will be shown in comparison to the available LArIAT data, and will be used to highlight any discrepancies between prediction and data.

The next step will be to perform a fit to previous data sets in order to understand the uncertainties associated with Geant4 and NEUT's models. These data sets will come from experiments of pions scattering off of various nuclear targets, including the one data set for pion-argon scattering up to 240 MeV. After this, a final fit will be performed with the LArIAT data set included. The original and updated predictions and error bands will be presented along with the LArIAT data for comparison.

This research will be critical to my thesis work, as I will have to develop this functionality in Geant4 in order to transfer information from my ProtoDUNE measurement to the detector simulation. Additionally, performing the fits to the LArIAT data will provide an understanding of the uncertainties for a measurement and detector similar to my ProtoDUNE measurement.

R&D Approach, and Expected Scientific and Technical Results

This technique of parameterizing and tuning simulations in order to quantify model uncertainties is commonly utilized within the particle physics community in general, and is well practiced within T2K. The previous work introduced a framework that enabled the experiment to easily determine where their SI models failed, and it reduced their associated pion SI uncertainties on the order of 50%. In general, implementing the ability to quantify these uncertainties in broader releases of Geant4 would allow for other neutrino experiments to conduct similar work for their models and simulations. Specifically for DUNE, it is necessary to be able to update predictions of SI models and reliably estimate the associated uncertainties. This work would provide this ability, and would allow for a reduction of uncertainties by including future data sets such as that from ProtoDUNE.

FNAL hosts a High Performance and Parallel Computing (HPC) department that I will use for performing the simulations and fits necessary for the model uncertainty quantification. These processes are computationally intensive, so having a stable and powerful computing resource such as the HPC will be crucial for this work.

Additionally, FNAL is the site of the LArIAT experiment, as well as many of the scientists who work on the experiment. Performing this work at FNAL will put me in close proximity with those scientists, and will give me the chance to learn firsthand about the experimental setup and uncertainties associated with LArIAT's measurements. This will not only benefit this work, but will inform my decisions in assigning uncertainties in my measurement at ProtoDUNE.

Finally, FNAL is one of the main centers of Geant4 expertise in the United States. Similar to the availability of LArIAT expertise, this would grant me the benefit of having access to experienced Geant4 users and developers. It would support this work by providing me with technical support and guidance in my development of Geant4. Dr. Fields' own group is one set of these experts in the larger community at FNAL. They have a large amount of experience with building releases for Geant4, and I would bring modeling expertise to this group by performing this project.

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References

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