Particle Physics Kalman Filter Implementation

Abigail Hatcher[1, 2], Mark Boady[1], Michelle Dolinski[2], and Jonathan Paley[3]

[1]College of Computing and Informatics, Drexel University [2]College of Arts and Sciences, Drexel University [3]Neutrino Physics Division, Fermi National Accelerator Laboratory

Background

Neutrinos

Neutrinos are small, neutrally charged particles. The neutrino is the most abundant particle with mass in the universe. [1] Neutrinos oscillate between three "flavors" (electron, muon, and tau) with probabilities corresponding to the mass of the neutrino [2].

Motivations for neutrino research

Matter and antimatter likely existed in equal parts at the origin of the universe. However, most particles interacting with their antimatter counterparts cancel into pure energy. This implies that there should be no matter in the universe, which is obviously not true. Neutrinos are a candidate for explaining this "charge-parity violation" since they are extremely abundant, and we do not yet know to what extent they break the matter/anti-matter symmetry. [2]

Deep Underground Neutrino Experiment (DUNE)

A future experiment will involve observing a beam of neutrinos before and after travelling a long distance. A major goal is to compare the oscillation rates of neutrinos and antineutrinos in order to determine whether the neutrino and antineutrino behave differently, breaking charge-parity symmetry. [3]

EMPHATIC

Part of the production of neutrino beams includes smashing beams of protons into a target. There is a moderate amount of uncertainty associated with the production and scattering that occurs on impact with the target. This approximately 10% "flux uncertainty" can make it difficult to determine whether observed anomalous behavior is an instance of a rare and interesting phenomenon or whether it is simply a product of this uncertainty. EMPHATIC is a project aiming to reduce neutrino flux uncertainty by measuring this behavior to better account for it in DUNE and other, similar experiments. [4]

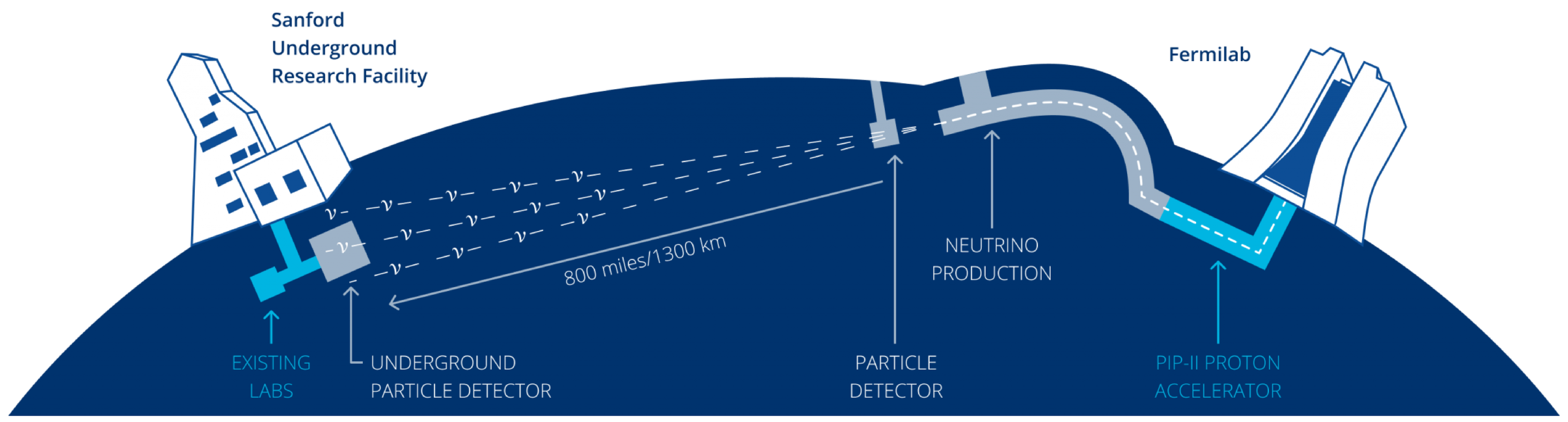

Figure 1: Deep Underground Neutrino Experiment layout. [3]

EMPHATIC Setup

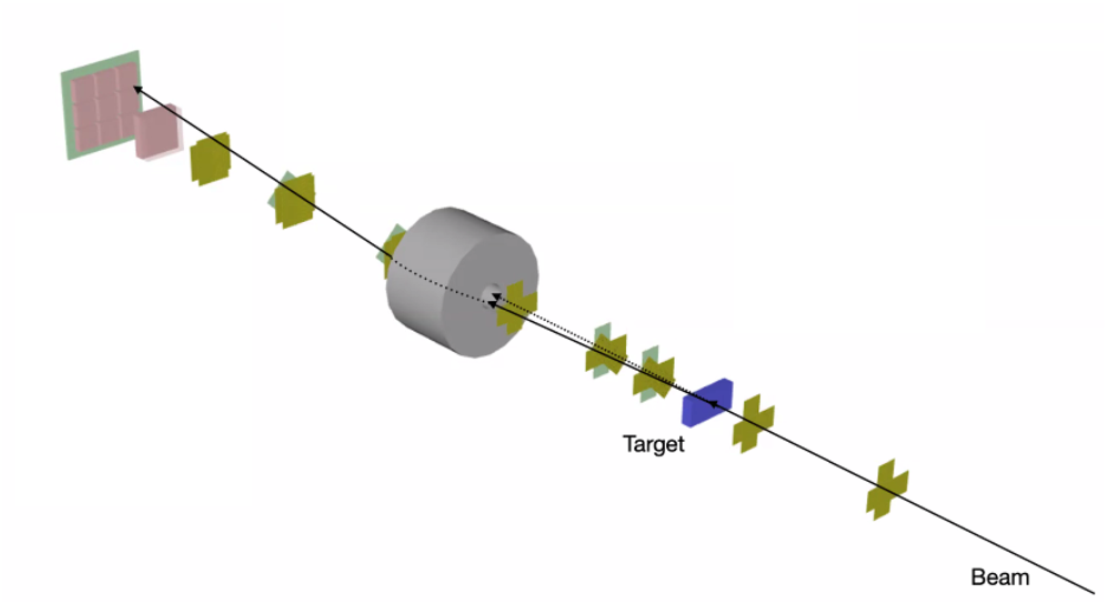

Figure 2: EMPHATIC layout. [4]

During the EMPHATIC experiment, particles collide with a target in a beam, enter a magnetic chamber where their angles are adjusted according to their momenta, and eventually arrive at a particle identification sensor. Along the way, their (x, y) positions are detected at several sensors. The Kalman filter will be used to estimate particle momenta at these sensors. It will also be used to associate sensor hits with specific particles. [4]

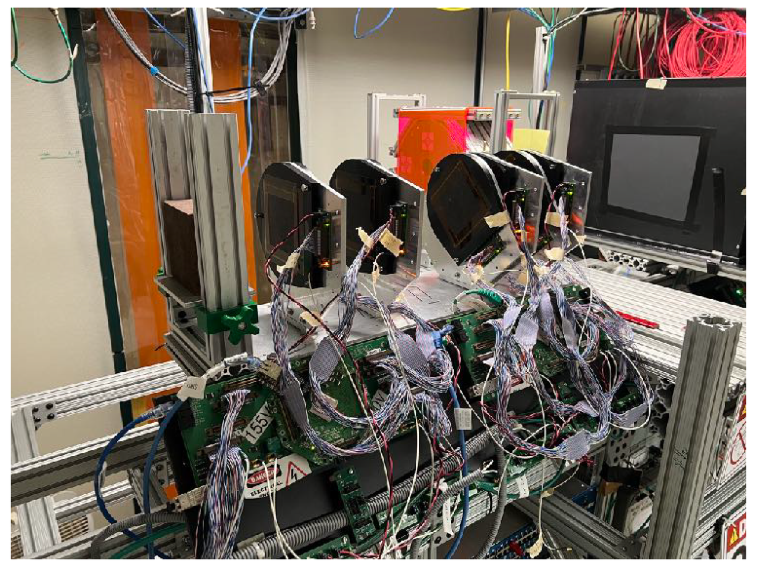

Figure 3: EMPHATIC image. [5]

Kalman Filter Application

The Kalman filter is an algorithm which takes noisy data recorded at discrete time-points, and uses it to predict the full trajectory of the data (or related data). At each algorithm step, prior knowledge of experiment geometry is utilized to generate a prediction for the next recording and its covariance. The prediction is then combined with true measurements in a weighted average informed by prediction covariance and recording noise. This weighting factor is called "Kalman Gain". The result of each step in the algorithm is an updated estimate for true data at that recording point, accounting for noise in the recording and variability in the predictions. [6]

The Kalman filter relies on stepping through a series of sensors front-to-back, using information recorded up to a point in time at each step. In order to equally incorporate information from later recordings, it is often useful to also walk through sensors back-to-front, smoothing these estimates with those from the front-to-back traversal. In preparing for this geometry reversal, special attention must be paid to vector directions. [7]

The Kalman filter with smoothing will be used during EMPHATIC to estimate the true (x, y) positions of particles at each sensor point. Since there are multiple particles travelling at the same time in this experiment, the Kalman filter estimate also allows us to associate specific particles with sensor hits by observing where particles were most likely headed.

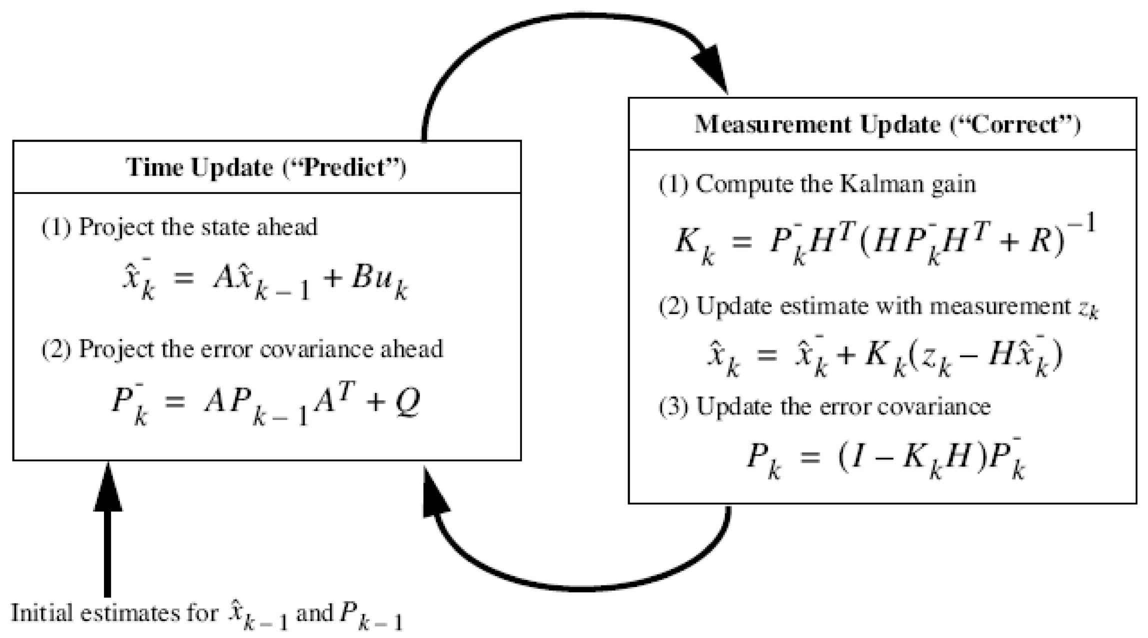

Figure 4: A graphic visualizing the Kalman filter algorithm. [8]

Debugging and Testing

At the start of the project, a Kalman filter implementation existed but was not working properly. This was determined through logging messages. The code lacked documentation and crucially, data visualization. This made it difficult to identify, track, and resolve issues. Without resolving these issues, experiment data could not be properly analyzed. An overview of corrections performed is provided here.

- The initial procedure repeated many processes with slight changes, sometimes incorrectly. These patterns were generalized and refactored. Multiple issues were found in this process, where code that was working in some cases was not generalized for others.
- The entire codebase was documented and refactored. This code is engineered to be turned over to the research team for continued use on future experiments.
- A procedure was designed to log data of interest and capture it for analysis. Output was originally presented only as text logs, which was challenging to analyze. Data visualization was added to allow for both debugging and data analysis once all issues were repaired.

Several issues were resolved throughout this process, notably including accidental magnetic field sign flips and inconsistencies in loop variable updates on backwards/smoothing passes.

Analysis and Visualization

The initial code only provided text output, which made analysis slow and error-prone. A data visualization tool was added, providing a quick visual gauge of reconstruction effectiveness. Prior to this tool, it was difficult to determine if suspected bugs were resolved. Researchers relied on their intuition and expectations alone. With the new visualization tool, researchers can easily grasp reconstruction results. It allows for quick analysis and bug resolution. These visualizations can be be used in future experiments to help researchers understand the effectiveness of reconstruction techniques.

Simulations previously existed which logged, among other parameters, expected measured particle momentum at each sensor hit. These "truth" values were aggregated and plotted against particle momenta predicted by the Kalman filter. The following plots show the momenta of particles at two sensors. Particles are affected by a magnetic region between the sensors. There is significant noise in the plot, but the reconstruction centers around the expected momenta. In this test data, a ground truth was provided.

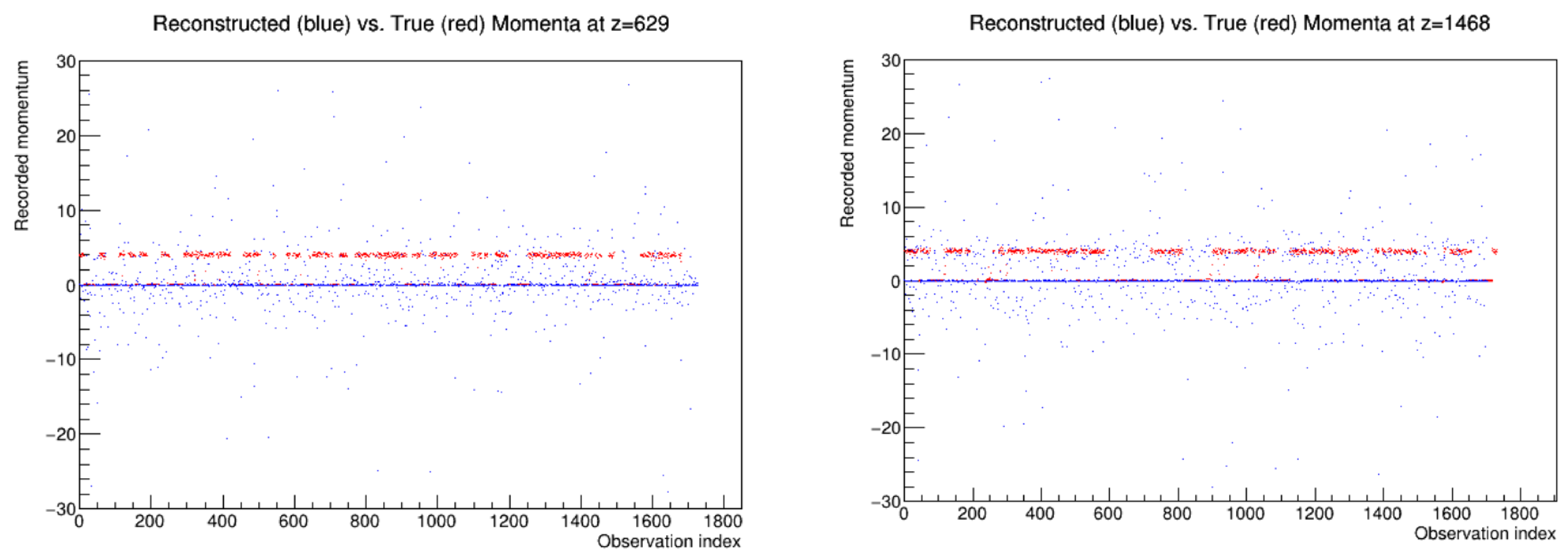

Figure 5: Plots recorded at z-positions corresponding to particular sensors before ($z = 629$) and after ($z = 1468$) particles travel through the magnetic region.

Conclusions

The completed code revisions resolved issues inherited from previous researchers. The code was re-engineered to allow for better long-term upkeep. It correctly reconstructs data estimates from discrete measurements. The data produced is visualized for analysis by researchers. The final product will be turned over to the research team for use in future experiments.

Citations

[1] Harris, Debbie. "DOE Explains. . . Neutrinos". U.S. Department of Energy, accessed 10 Dec. 2025, https://www.energy.gov/science/doe-explainsneutrinos.

[2] "Which neutrino is the lightest?". All Things Neutrino, accessed 10 Dec. 2025, https://neutrinos.fnal.gov/mysteries/mass-ordering/.

[3] "DUNE at LBNF Science Goals". Fermilab, https://lbnf-dune.fnal.gov/about/science-goals/.

[4] Akaishi, T. et al. (2019). "EMPHATIC: A proposed experiment to measure hadron scattering and production cross sections for improved neutrino flux predictions." arXiv, *1912.08841*.

[5] Paley, Jonathan. (2025). Fermilab.

[6] Kalman, R. E. (1960). "A New Approach to Linear Filtering and Prediction Problems". Journal of Basic Engineering, *82*.

[7] Rauch, H. et. al. (1965). "Maximum likelihood estimates of linear dynamic systems". AIAA Journal, *3*.

[8] Boeing, Adrian. (2010). "Kalman Filters". Adrian Boeing: Blog, accessed 20 May 2026, https://adrianboeing.blogspot.com/2010/05/kalman-filters.html.