SULI Internship Report

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The EMPHATIC experiment aims to make new measurements of hadron scattering and production in a variety of nuclei and beam energies. Measuring these processes to precision would greatly improve the efficacy of current and future neutrino experiments, which are currently limited by large uncertainties in the neutrino flux stemming from uncertainties in hadron production in the beam-target collision. This experiment will also aid the nuclear/particle physics community at large, as hadron production simulations rely on interpolation and extrapolation of previous experiments, which do not adequately cover the energy scale to high precision. This summer I developed the EMPHATIC code base to record GEANT4 simulation information about the production of secondary particles into the collaboration's Common Analysis Format (CAF). I also tested Silicon Strip Detector (SSD) readout electronics, establishing a procedure to configure them using the data acquisition software.

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I. INTRODUCTION

With the development of large experiments designed to detect and measure neutrino oscillations underway, one of the leading physics problems that must be addressed is the large uncertainty of the neutrino beam flux.

Measuring and predicting neutrino flux is a very difficult endeavor, with several obstacles. To begin with, neutrinos, while abundant, are notoriously difficult to detect. Secondly, the most common method to produce neutrinos, hadron production and subsequent decay, is difficult to predict using theoretical methods, and current measurements of hadron production do not adequately cover the full range needed for precise flux predictions.

Currently, neutrino oscillation experiments such as NOvA[1], T2K[2], DUNE[3] and Hyper-K[4] get around the difficult measurement of neutrino flux by using two detectors. However, experiments that use one detector (eg. measurements of neutrino-nucleus cross sections) are limited by the uncertainties in the neutrino flux[5], and two-detector experiments are still limited in the types of physics searches they can do without precise flux measurements.

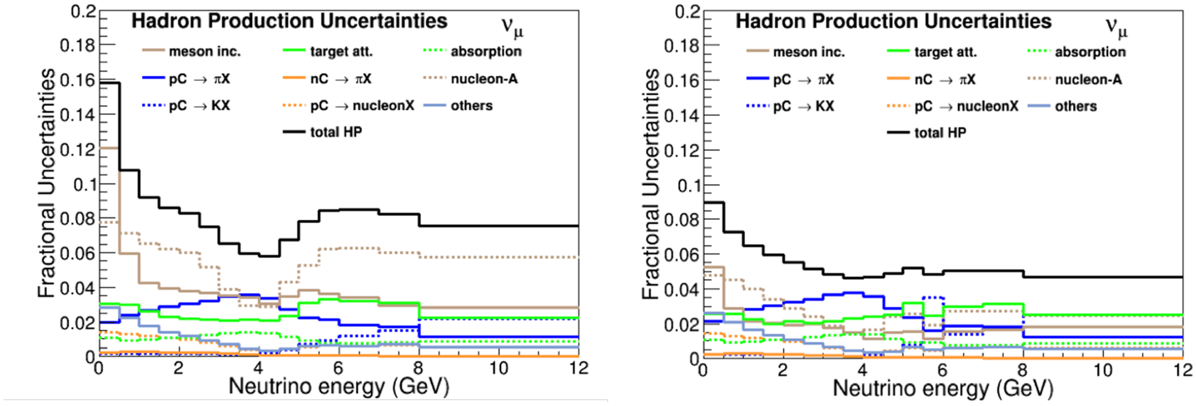


FIG. 1. *Figure from*[6]*. Left: Current hadron production uncertainties. Right: Reduced uncertainties with modest improvements in hadron production uncertainties, from 40% to 10%.*

The dominant uncertainty in the neutrino flux measurement is hadron production in the process of making the neutrino beam. Measuring hadron production is extremely important for neutrino experiments, as it reduces one of the largest uncertainties, as well as the nuclear/particle physics community at large, who would benefit from improved hadron production models.

The Experiment to Measure the Production of Hadrons At a Test beam In Chicagoland[7], or EMPHATIC, is exactly what it's name suggests: an experiment to measure hadron production. The experiment aims to measure hadron production in the energy range of 1-120 GeV. It has a simple table-top design with an ultimate acceptance of 350 mrad. It has a compact permanent magnet and silicon strip detectors for momentum measurement, and ring-imaging Cherenkov and time of flight detectors for particle identification. This work uses a Phase 1 version of the experiment with a 150 mrad acceptance spectrometer.

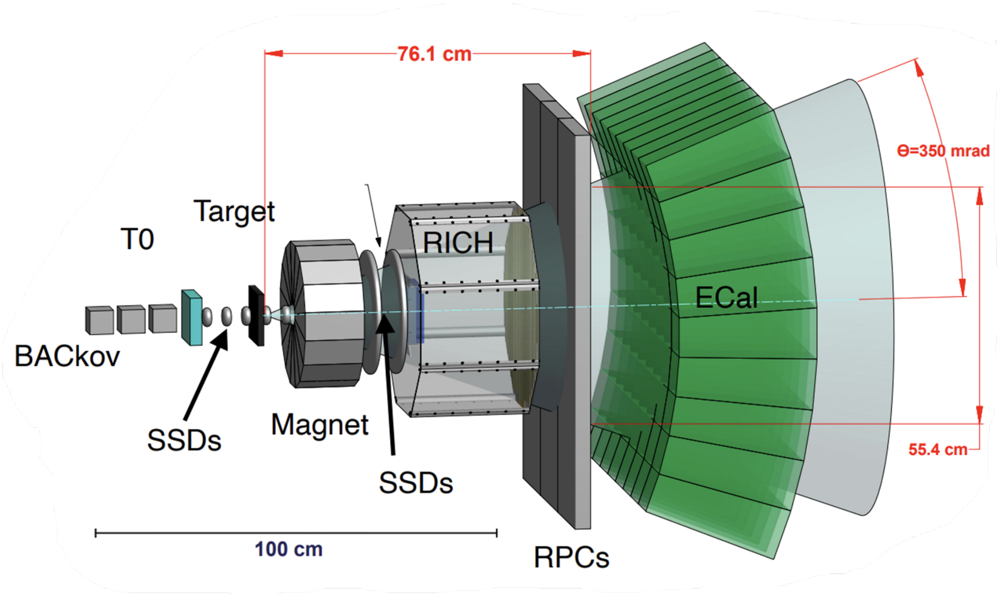


FIG. 2. *EMPHATIC spectrometer design.*

EMPHATIC plans to improve their use of simulation to understand the spectrometer performance and other physics potentials. After running in 2022, the experiment is undergoing some upgrades heading into Phase 2. One of these changes is upgrading the tracking detectors (SSDs).

My summer work focused on these two initiatives. I developed the EMPHATIC code base to record the simulation truth information about the production of hadrons in the spectrometer, and I established a procedure to set up and test SSD readout electronics using an off-the-shelf data acquisition system.

II. SIMULATION

Monte-Carlo simulation is a technique used by physicists to numerically simulate their experiments, providing an *a priori* prediction of the performance and capabilities of each part of the experiment. A Monte-Carlo simulator such as GEANT4 will randomly sample events, creating particles through random processes with random trajectories, following a predetermined probability distribution derived either through some theoretical model or by some experimental data, or both.

The EMPHATIC simulation begins by creating a ”beam” particle with user-defined particle type and momentum. The beam particle is then passed to GEANT4, which tracks it as it travels through the spectrometer. GEANT4 will ”step” the particle through the materials using equations of motion, and will randomly choose an interaction for it to have: ionization, Coulomb scattering, elastic/inelastic scattering, nothing, etc. When an interaction like in Figure 3 does occur, GEANT4 will create the resulting output of particles, called daughter particles, and continue tracking all particles until they either lose all their energy or exit the spectrometer.

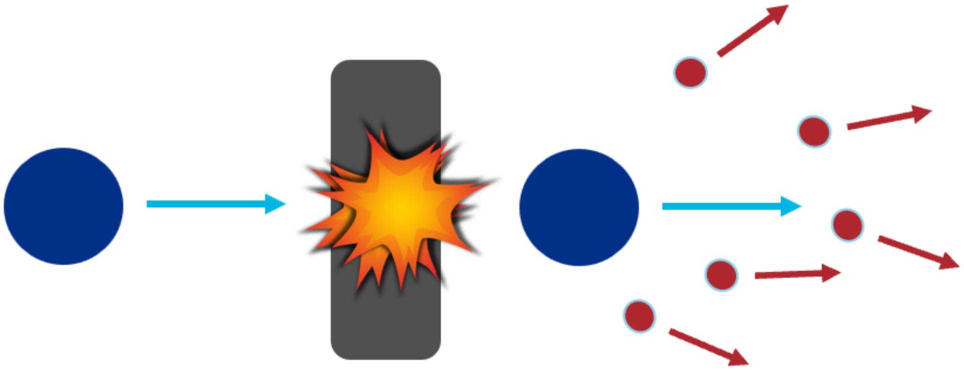


FIG. 3. *Visual example of a particle collision. Blue: beam particle. Red: daughter particles produced in the interaction. Grey: detector material.*

It was my goal to record all the ”truth” information about the simulation from GEANT4 to the analysis framework of EMPHATIC. EMPHATIC records data into a Common Analysis Format (CAF) of data structures called Trees for efficiency and ease of use (see figure 4). I added a branch to the Tree that would store the simulation truth information, and wrote code that would record data relevant for analysis into the branch. I also made a class in C++ that would represent a particle as a C++ object. This particle class would have all the kinematic information about a particle: position, momentum, particle type, mass, energy, ID of the parent particle, etc.

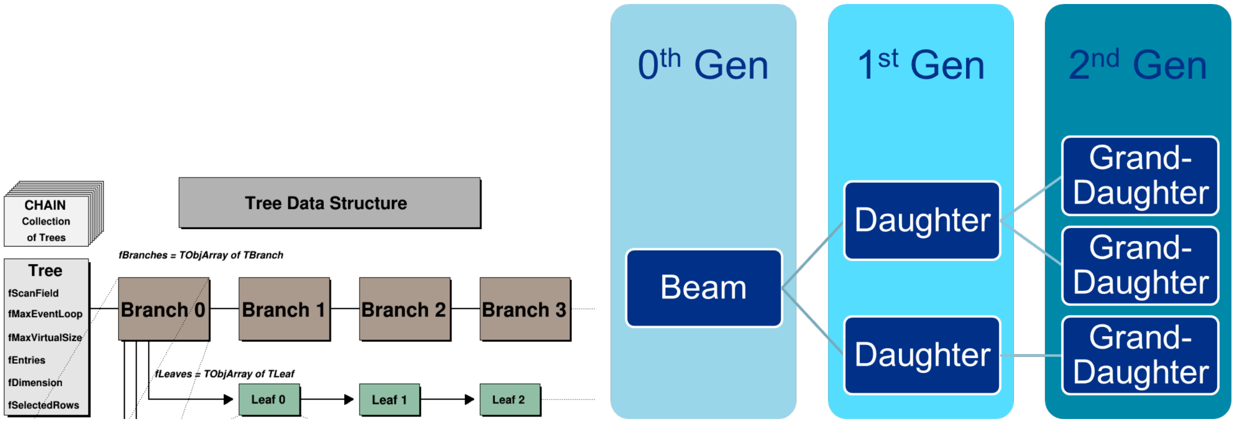
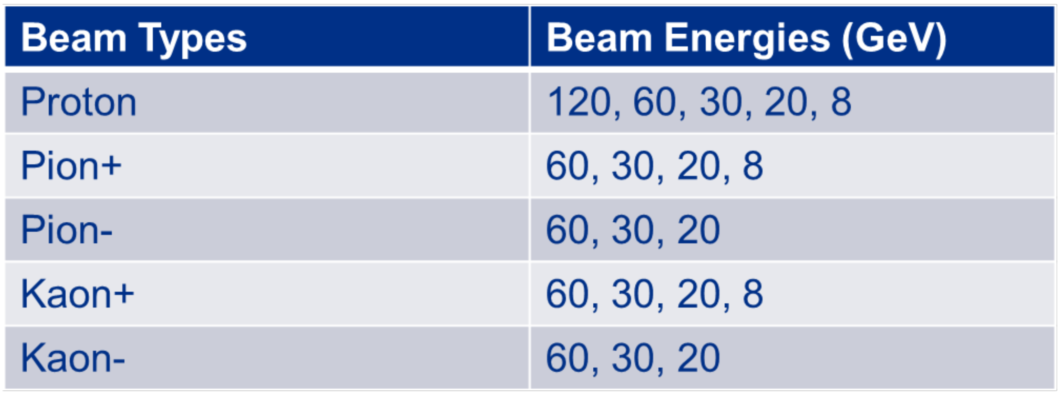


FIG. 4. *Left: structure of the ROOT Tree class. Figure from*[8]*. Right: hierarchy structure used in recording* Geant4 *events.*

Because the interactions we're interested in were ones where the beam particle interacts with the spectrometer and produces secondary particles, we record Geant4 events with a simple structure, as seen in Figure 4. The beam particle, in addition to all its kinematic information, contains a vector of daughter particles, which in turn can also own their daughters.

We were also able to place restrictions on the types of daughter particles we wanted to record. For example, we only wanted to record particles with enough energy to be seen by our detector, so we placed a minimum kinetic energy requirement in the Geant4 code. Additionally, we did not want to simulate the calorimeter portion of the detector, where copious amounts of uninteresting electrons would be produced, so we cut out that portion of the detector in our simulation.

With the ability to record information about particles produced during the experiment, I can now study some important features of the simulation. We started by running simulations of different beams that EMPHATIC can use in their runs. Because the beam that EMPHATIC gets can contain protons, pions, or kaons, we simulated cases where the beam was made of each of those particles.



Beam Types	Beam Energies (GeV)
Proton	120, 60, 30, 20, 8
Pion+	60, 30, 20, 8
Pion-	60, 30, 20
Kaon+	60, 30, 20, 8
Kaon-	60, 30, 20

FIG. 5. *Table of beam configurations studied.*

One of the first plots I made was a plot of where interactions occurred in the spectrometer. This plot served as a sanity check, and confirmed that all the parts of the experiment were being registered in the simulation.

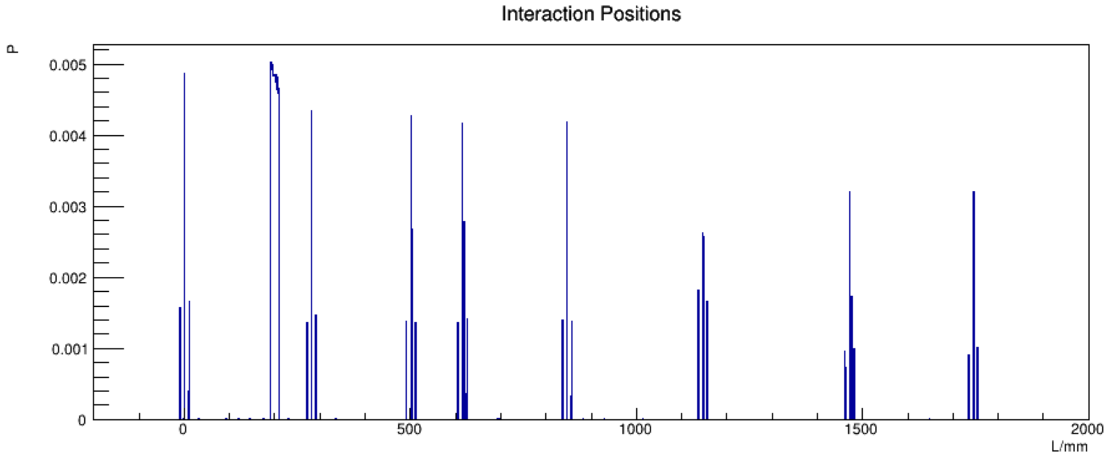


FIG. 6. *Probability of interaction positions of a 120 GeV proton beam.*

Each skinny peak of interactions is an SSD station, where the proton beam will interact with the detectors. The important feature is that we see a majority of interactions in one finite region around 200 mm in, which corresponds to our carbon target. An important feature of our target is that it is a 5% interaction length target, meaning that at 120 GeV, 5% of protons will interact with the material. If we integrate over that region, we find that it is a 10% interaction length target.

We also wanted to know what types of interactions were occurring in the spectrometer, and because we can record that information from GEANT4, we can make that plot also.

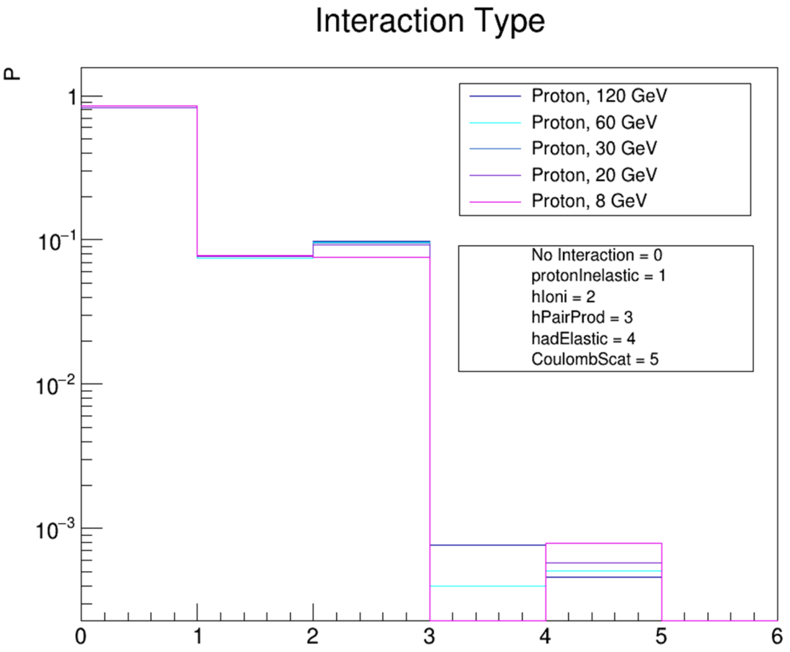


FIG. 7. *Histogram of interaction types for different proton beam energies.*

As we can see in Figure 7, a vast majority of the events result in no interaction at all, as the beam simply passes through the spectrometer without anything happening. Something interesting to note is that the amount of inelastic scattering events does not change significantly as the beam's energy falls.

Another important question arises from the experiment's design. The Phase 1 spectrometer has an acceptance of 150 mrad, with plans to upgrade to 350 mrad, so if there are secondary particles produced with too wide of an angle with respect to the beam axis, EMPHATIC cannot detect it. Therefore, something we want to look at is the angular distribution of secondary particles produced in the spectrometer.

Just by inspection, we can see that most of the secondary particles are produced within 350 mrad. The angular distribution of the secondary protons on the left of Figure 8 has an interesting shape, but is not surprising when we realize that most of the interactions the beam will have are low-momentum-transfer collisions where the beam particle will stay very close to its original trajectory. After closer inspection, we determined that both peaks are produced by an inelastic process, so we reason that the higher peak consists of

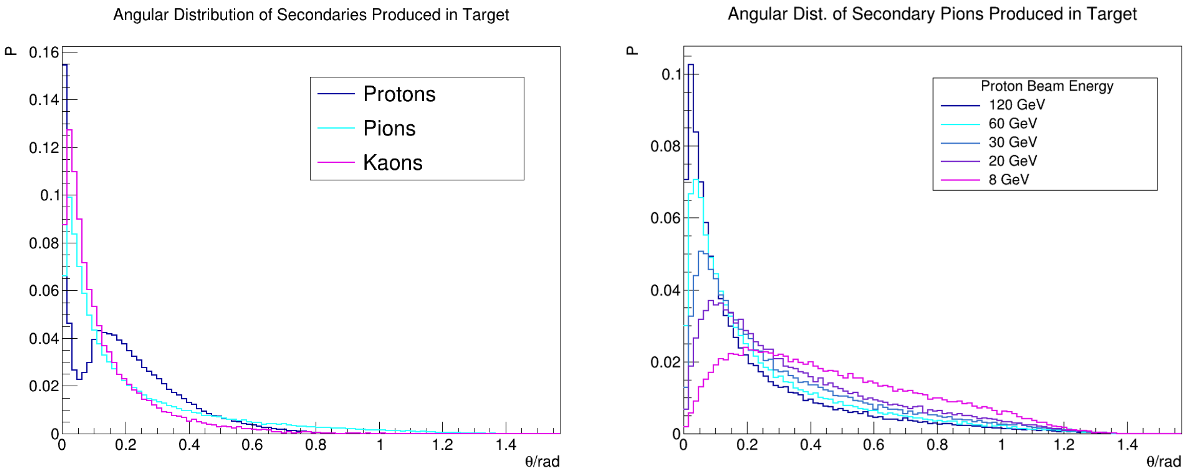


FIG. 8. *Probability distributions of particle trajectories. Left: angular distribution of secondary particles produced by a 120 GeV proton beam. Right: angular distribution of pions produced at different proton beam energies.*

the beam protons, while the smaller peak consists of protons that were actually produced from the inelastic scatter as a nucleus is blasted apart.

III. SILICON STRIP DETECTOR TESTING

The second part of my project focused on EMPHATIC's tracking detector upgrades. EMPHATIC uses a series of silicon strip detectors to track charged particle particles as they travel through the spectrometer. A diagram on the left of Figure 9 shows that as a charged particle passes through the silicon, it knocks out an electron from an atom, creating an electron-hole pair. By using an electric field in the silicon, the charge released by that pair is pulled towards a detector strip, which will record the position of the hit.

EMPHATIC plans to upgrade the electronics which read the outputs of the detector strips, convert them into a digital signal, and send them to the computer. Before they can do this, they need to test the electronic components to make sure they work and can operate at the level desired for the upgrade. It was my goal to use a commercial data acquisition program to test the SSD readout electronics by establishing a configuration procedure, measuring pedestals and noise, and performing a software test of the module's trigger system.

The configuration setup consists of 4 components: an AliVATA mother board, a

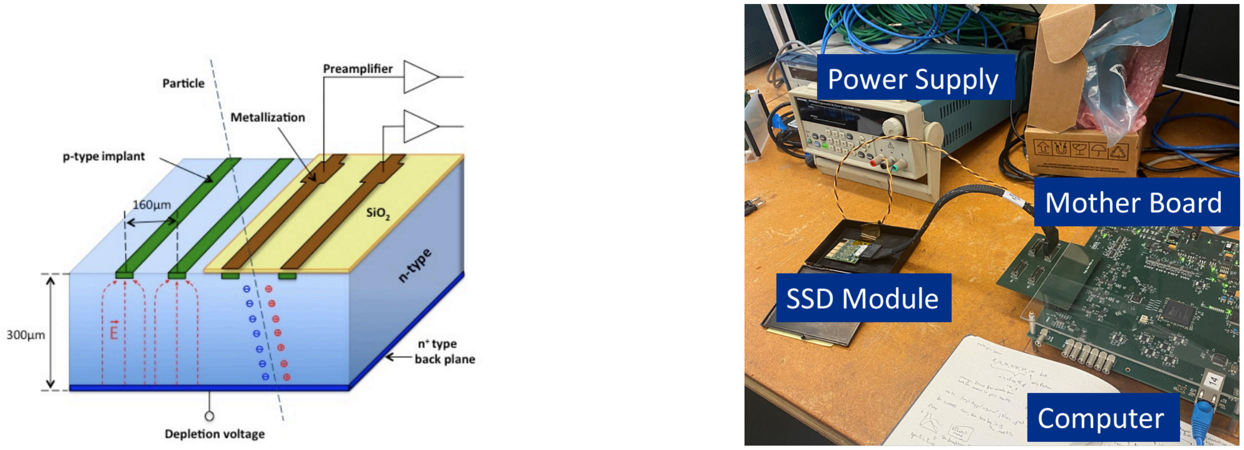


FIG. 9. *Left: diagram of a silicon strip detector. Figure from*[9]*. Right: experimental setup for hardware configuration and testing.*

daughter board (the SSD readout module), a power supply for the mother board, and a computer to communicate the system from (see right side of Figure 9).

Once the mother board is powered up and the SSD module is connected, we can start up the AliVATA VDaq data acquisition software are configure the modules. First, we have to create a ”plugin” for the module, which lets the software know what type of electronic it’s connected to. Next, we have to tell the software how many of these electronics we’ve connected, how many chips they have, and where we connected it. Once the VDaq software recognizes the module, it is straightforward to do a pedestal and software trigger runs (Figure 10).

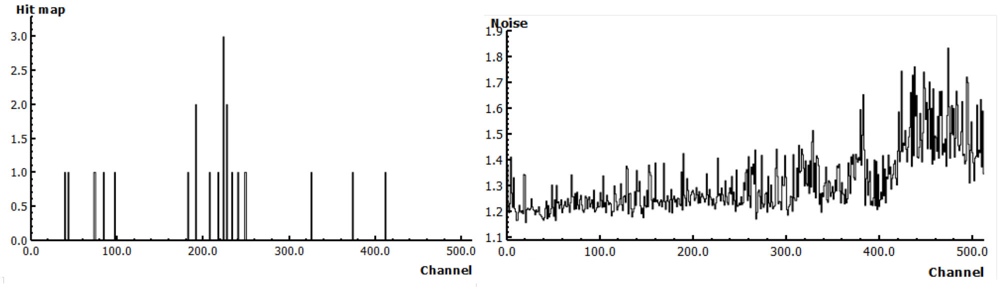


FIG. 10. *Software test of the AliVATA SSD module. Left: histogram of hits recorded by channel. Right: noise measured by channel in Analog-to-Digital Conversion (ADC) counts.*

IV. CONCLUSION & FUTURE WORK

In conclusion, this project was able to greatly improve the efficacy of EMPHATIC's simulation tools, and push forward progress on the SSD readout chip upgrades. The collaboration can now record data about the secondary particles produced in the spectrometer, and ask detailed questions about the physics potential of the experiment. Future work will go into doing geometric acceptance studies to see whether the detector can see enough of the particles that are produced to make a meaningful measurement. It will also go into using the simulation truth information to do reconstruction efficiency tests to see if the reconstruction algorithms and techniques are effective enough. On the hardware side, future work can now be made in performing tests on the custom SSD readout chips, so that the upgrades to the tracking system can move forward.

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