HEPCAT Progress Report
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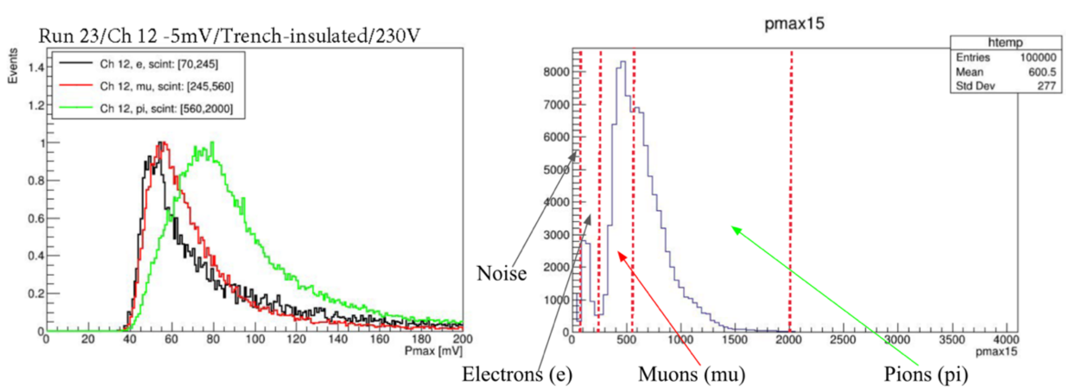
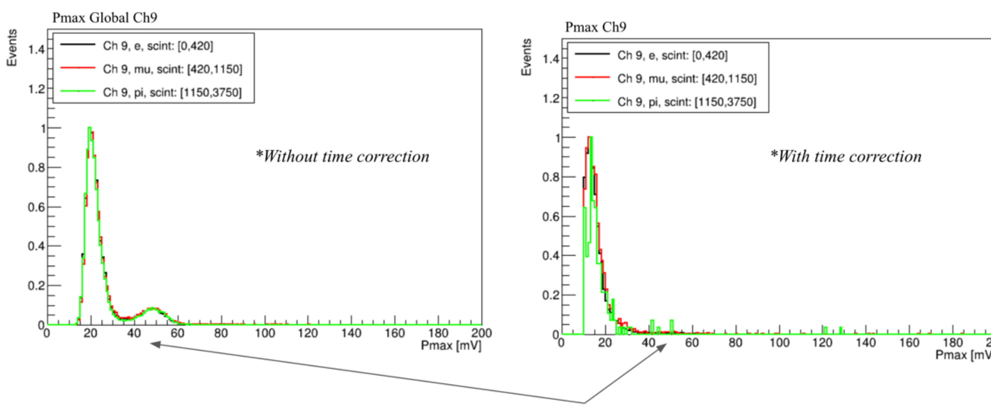
This progress report will detail the work that I have accomplished towards the research and development of a Low Gain Avalanche Detector (LGAD) based Active Target (ATAR) for the Rare Pion Decay Experiment known as PIONEER. Since receiving the award, the PIONEER group has continued to grow and evolve into a true collaboration. In October 2022 the Santa Cruz Institute for Particle Physics (SCIPP) held a Rare Pion Decay workshop where the burgeoning collaboration held a three-day conference on the best way to achieve the desired sensitivity for the ratio of the ($\pi \rightarrow e\nu$) signal over the ($\pi \rightarrow \mu\nu \rightarrow e\nu\nu\nu$) background. As a member of SCIPP, I helped organize and run the conference. Furthermore, PIONEER has continued preparations at PSI including a test beam in 2022 and PIONEER was even mentioned a couple times in the 2021 Snowmass report (which was postponed until the summer of 2022)[1]. In terms of my own academic progress, I passed my written qualifiers in early 2023 and finished all of my mandatory courses, significantly increasing my available research time for the upcoming funding period. While working through these mandatory courses, I was also able to make significant progress on ATAR research and development.

Over the course of the last project period, my work on PIONEER has been categorized into two distinct projects: an analysis of data taken at a beam line at PSI in 2022 and the simulation effort from SCIPP on the ATAR. For the PSI analysis portion, the SCIPP PIONEER group performed our first ever test beam at PSI in 2022. During this test beam, the group tested several different kinds of LGADs, looked at how different particle species interacted with the LGADs (pion, electrons, and muons), and got familiarized with the beam line. I have been leading the analysis of this data and mentoring two undergraduate students who are assisting on the project. Firstly, I created the software that creates a statistics file for each run of the test beam data. The stats file was intended to create certain helpful statistics about each trigger event. For example, Pmax and Tmax are the amplitude and time of the largest peak of the waveform. Although SCIPP already uses an existing framework for our betascope, I created a new branch of the framework that would work for the PSI data as the two experimental set ups are vastly different. Using the creation of my branch as a driving force, I also implemented version control for the framework by moving the entire code base onto GitHub.

Once we had created preliminary versions of the stats files, we started the data analysis in earnest. The first facet we examined was the different energy deposits in the scintillator in relation to how they correlate to deposits in the LGADs.



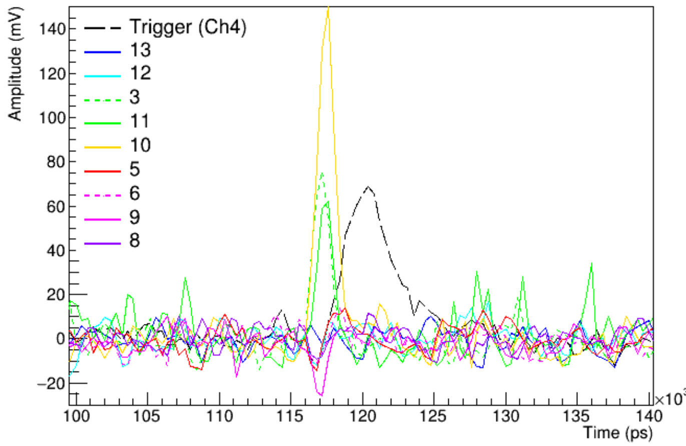
The diagram on the right shows the scintillator channel where the different species cuts were made by eye. The left shows the distribution of Pmaxes in a Trench Isolated LGAD that correspond to the cuts made in the scintillator channel. As expected, the pion on average left the most energy, followed by the muon, and lastly the electron. These preliminary results looked promising, but large noise spikes plagued the data set. In order to avoid these spikes, I implemented time windows for the Pmax and Tmax statistics to prevent large noise spikes from muddling the data. This is an important issue to resolve for the AC-LGAD sensors due to their charge sharing. We expect a small response several neighbors away from the primary hit electrode, but the noise was swamping the signal. Below is an example of how the time cuts were able to remove the periodic noise.



Time window constraint on pmax effectively eliminates high-amplitude noise

Following this study, we noticed that there were multiple instances of double-peaked events in the data set. This is very exciting, as the ATAR project will need to examine pileup and differentiate two events that happen in quick succession. In addition, some of these double peaked events could potentially represent decays. At the time of writing, we have more questions than answers on this front, but we've put significant effort towards implementing certain statistics to allow us to investigate these double peaks and determine what they are.

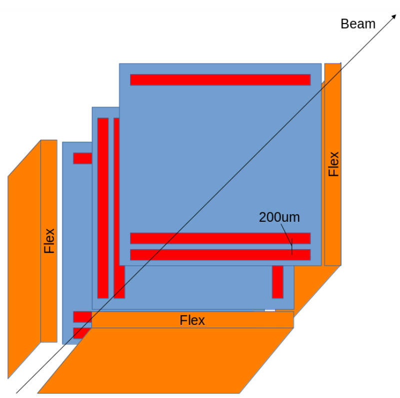
Our group is also actively studying this data set for evidence of cross talk. Due to device physics, when one channel of an AC-LGAD has a very large signal, the surrounding strips have a small but significant negative pulse. There are concerns that this mechanism could be convolved into the charge sharing signal, thus this small but significant effect is key to our understanding of these devices.

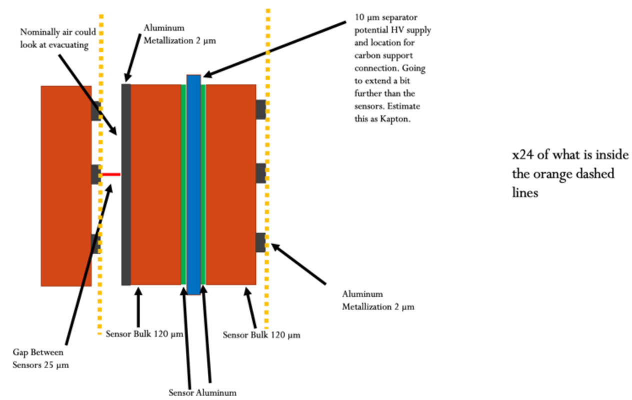


The diagram above shows the negative signal in pink occurring at the same time as the large signals in multiple other channels.

My other project focused on the PIONEER simulation. Many questions have emerged in the past year on the best way to instrument the PIONEER experiment, especially in regards to the ATAR. As a member of the institute with predominant expertise on silicon detectors, I have been leading the ATAR simulation effort to investigate these questions. In the past year of discussion, we have narrowed down a list of questions that need to be answered before we can make final design choices on that ATAR. Unresolved areas of discussion for the ATAR include energy resolution, time separation resolution, position resolution, the ideal amount of charge sharing, with regards to AC-LGADs and whether or not cross talk in general can be tolerated, what amount of dead material can be tolerated, and what kind of sensor type and distribution would be optimal for the ATAR. These lingering questions necessitate further investigation, and the collaboration aims to answer as many as possible over the next year. I will personally be leading these efforts.

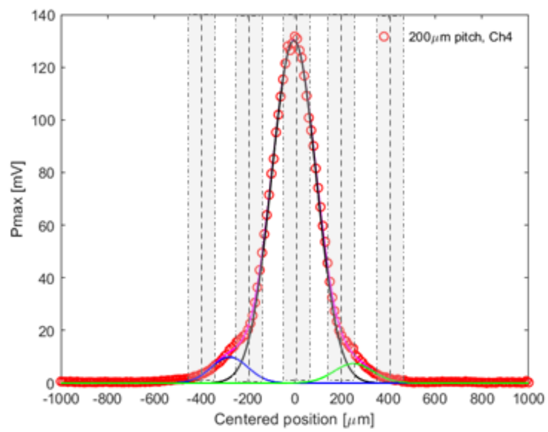
In order to find concrete answers to these questions, the collaboration and I have focused our efforts on developing a full-blown simulation framework. My personal efforts have been focused on creating and inserting the nominal ATAR model seen below into the framework:





The image on the left showcases how the nominal ATAR design has the layers of sensors staggered in order to allow for wire bonds to reach into the active sensors. The right image is a horizontal view of the ATAR, which represents a more realistic representation of what the ATAR, with all of its dead material, will look like.

The second simulation task that I have been working on is implementing detector response. As described above, AC-LGADs utilize charge sharing, but to fully understand the ramifications this has for the experiment and for particles that are not minimum ionizing particles, we need to implement a robust simulation effort. To facilitate this, we have created a triple gaussian model that will emulate actual test beam data as seen in the below picture:



Current efforts are focused on writing this model, along with other kinds of LGAD models, into the simulation.

In the past year, I have made excellent progress towards achieving the goal of my HEPCAT research proposal, which was to discover the optimal silicon sensor for instrumenting PIONEER's ATAR. I have made great strides in both simulation, which will give in-depth information about how different potential ATAR designs would interact with the full experiment, and data analysis, which feeds the models that enter the simulation. Moving forward, I will continue to set up the necessary framework for these experiments, but will also work on more substantive simulation efforts to tackle specific questions and determine their effect on signal uncertainty. I will also be traveling to CENPA this summer to perform a test beam at their tandem accelerator facility to further test LGADs in a high energy deposition environment. Lastly, I will soon be starting work on an LGAD testing platform that will be used in annual PIONEER test beams at PSI.

[1] Butler, Joel N., Chivukula, R. Sekhar, de Gouvea, Andre, Han, Tao, Kim, Young-Kee, Cushman, Priscilla, Farrar, Glennys R., Kolomensky, Yury G., Nagaitsev, Sergei, Yunes, Nicolás, Gourlay, Stephen, & Raubenheimer, Tor. *Report of the 2021 U.S. Community Study on the Future of Particle Physics (Snowmass 2021)*. United States. https://doi.org/10.2172/1922503