An Analysis of the Extinction Mu2e Experiment

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The Mu2e Experiment is a search for the conversion on low momentum muons into electrons. In order to see this conversion, the fractional level of out of time beam delivered by the Fermilab Recycler must be no more than 10^{-5} . We did not the observe the 53MHz structure of the Booster Beam on the batches sent to the Recycler Ring in our analysis of the data, although previous analyses did reveal this structure. We concluded that there is an issue with the trigger or the algorithm in the current data set. The next steps will be to check the trigger at Fermilab, and to compare the algorithm to the code used to analyzed previous data.

The Mu2e Experiment

Particle physics currently works on indirect studies that are trying to maximize the chances of discovering new physics, and to inform of the direction of major research initiatives in the future for the physics fields. A good example would be the study of rare particle decays or conversions. The study of rare processes provide a way to search for new physics that is complementary to direct searches at colliders.

The Mu2e experiment studies one of these rare conversions. It is an experiment based on the rate of conversion of muons into electrons related to the ordinary muon capture by the weak force. If a low momentum muon is captured on a nucleus, it could convert to an electron via an exchange of a particle with this nucleus. The electron produced is monoenergetic which carries most of the muon rest energy, which is equal to 105Mev.

This conversion is effectively forbidden in the Standard Model, but we know that the Standard Model is incomplete. Moreover, this conversion is a virtually universal feature of extensions to it. The probability to see this conversion is really low, $2.85 \cdot 10^{-17}$. It is the same probability as the probability of your house getting hit by a meteorite, and you being struck by a lighting both in the next three months. However, right now we have the resources to measure this rate with a precision 10^4 times better than previous experiments.

The Mu2e experiment measures the rate of muon to electron [1], relative to ordinary muon capture[2]. Defined as

$$R_{\mu e} \equiv \frac{\Gamma\left(\mu^- N(A,Z) \to e^- + \mathrm{N(A,Z)}\right)}{\Gamma\left(\mu^- \mathrm{N(A,Z)} \to \nu_\mu + \mathrm{N'(A,Z\text{-}1)}\right)}$$

The goal is to achieve a single event sensitivity of R Goal: single event sensitivity of Rme = $3 \cdot 10^{-17}$

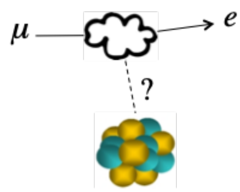

FIG. 1: Diagram of the muon conversion into an electron by the exchange of a particle with a nucleus.

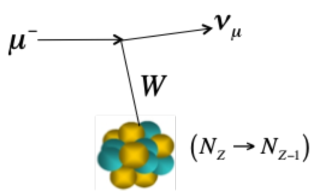

FIG. 2: Diagram of the ordinary muon captured by protons in nuclei through the weak force.

Extinction Experiment

Muons are produced by protons hitting a *Tungsten* target, then the muons are captured on an Aluminum target. From those muons the Transport Solenoid selects the low momentum muons, which are captured on target to then convert into electrons by the exchange of a virtual particle with a nucleus[3].

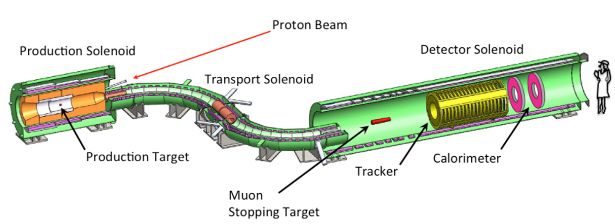

FIG. 3: Diagram of the solenoid used by the Mu2e Experiment.

The timing of the Mu2e experiment is one of the keys to see the conversion from muons to electrons. The proton beam has to hit the target on periods of 1.7 μs in order to achieve a beam extinction level sufficient to detect the electrons converted from the low momentum muons[4]. This period is needed to allow the pions to decay into muons, and then the muons convert into the electrons; and also to get rid of backgrounds that could cause noise as protons, muonic Al, or other particle decays. Finally the electrons are detected in the last 925 ns after the beam hits the target, and the main goal of the extinction experiment is to get a beam extinction of a level of 10^{-10} or better.

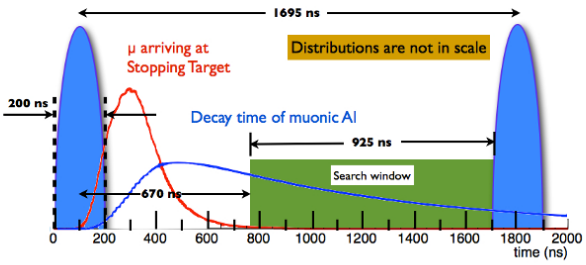

FIG. 4: Longitudinal micro-structure of the proton beam delivered to the Mu2e production target. The blue peaks represent the beam at the target on periods of 1.7 μs. The search green window is located in the last 925 ns, where the goal is to have a level of extinction of the beam of 10^{-10} or better.

The Mu2e experiments uses a 8 Gev proton beam that is generated at the Fermilab Booster. It is injected into the Recycler Ring as 2 batches of $4 \cdot 10^{12}$ protons each with a structure of 53MHz. Then, a 2.5 MHz RF system re-bunches both batches into 8 bunches of 10^{12} protons each. They are transferred one a time to the Delivery Ring. From the Delivery Ring, the beam is resonantly extracted with a 1.7 μs period from the Delivery Ring, which is the required Mu2e time structure[5].

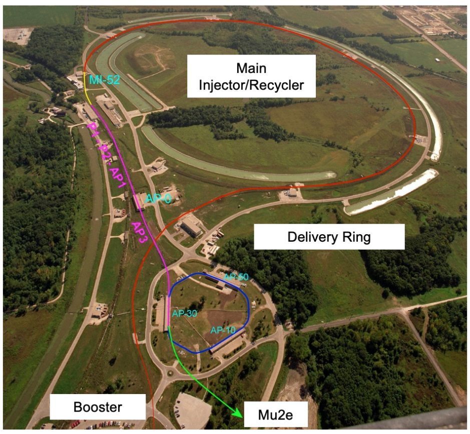

FIG. 5: Fermilab Accelerator Complex. 2 batches of $4 \cdot 10^{12}$ protons are injected into the Recycler Ring and they are re-bunched into 8 bunches of 10^{12} protons each. Those 8 bunches are extracted with a 1.7 μs period to the Mu2e Experiment.

The structure of the beam used for the Mu2e Experiment is the same one from the Fermilab Booster, the Recycler Ring receives batches of 8 GeV protons at a rate of 15Hz (one proton batch every 67 msec). The 67 msec cycle is fundamental in the beam generation process. This time interval is typically called a "Booster tick", which is the time required to reset the Booster, accelerate another proton batch, and send it to the Recycler. The batch contains 4e12 protons in bunches of 53 MHz. This structure can be seen at Figure 6. In the first 200 traces one can see how the 2 batches of 53MHz are injected from the Fermilab Booster for 1.6us, and then they are re-bunched into the 8 2.5MHz bunches that are transferred to the delivery ring. The protons that are part of the 2.5MHz are considered protons in time, and then the protons that are in between the 2.5MHz bunches are consider the out of time protons that could interfere in the detection of the conversion of low momentum muons into electrons. Therefore, the goal of the extinction experiment is to achieve a level of e-5 protons out of time(in between bunches).

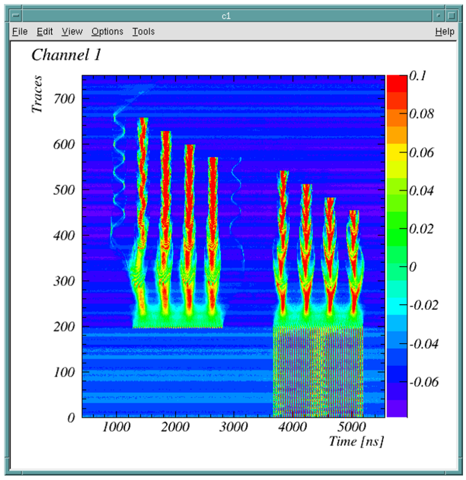

FIG. 6: Plot of the 2 batches injected into the Recycler Ring. At 200 traces we can see how the 2 batches of 53MHz are re-bunched into the 8 bunches of 2.5MHz. The red and green traces represent the in-time protons(2.5MHz bunches) and the gaps in between the traces represent the out-of-time protons.The goal is to achieve a level of 10^{-5} protons in between the red and green traces(out-of-time.

All the data is collected by 4 photoelectric sensors. During the last years, all the analysis has been done on data extracted directly from the monitor that reads the data collected by the sensors. In order to improve the efficiency of the data analysis, the process was modified. The data recorded by the sensors now is sent to a digitizer where there is an algorithm that finds the information that is useful for the analysis of the extinction of the beam, for example, the peaks of protons, the peak times, or the areas of those peaks. An external beam line system will provide additional extinction to achieve the e-10 level required by the experiment.

My contribution

The main goal of my work was to understand the data that we were collecting with the algorithm and see if it was accurate. Professor Eric Prebys had collected data reading it directly from the oscilloscope, and then he had processed the data after with a code. However, that process was not the most efficient one because it was too slow. Postdoc Truong Minh Nguyen has developed an algorithm that finds the proton peaks and areas at the same time we are triggering the beam, therefore we wanted to understand this new data and compare it to the data that Professor Prebys was getting which we know showed the right structure of the beam.

The first step was to plot the peak areas in terms of the event number and the peak time from the first 600 msec [5]. One is able to clearly see the 2 batches of $4 \cdot 10^{12}$ protons separated by a tick of 67ms(Booster cycle), and then the 8 re-bunched bunches of 10^{12} protons that are extracted to the Delivery Ring.

Zooming into one of the batches[8], one was able to see an approximated period of the protons at the Recycler Ring (time required to complete one full lap), which was equal to approximately 11.13 μs.

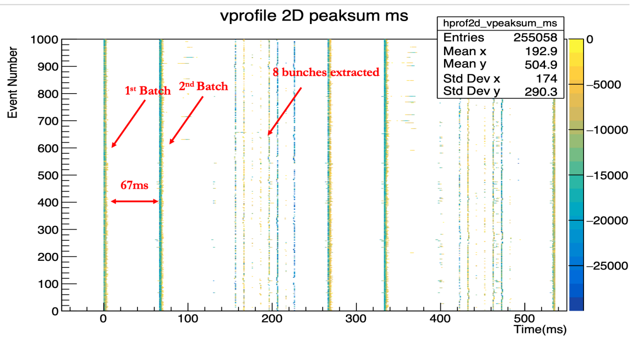

FIG. 7: Plot of the peak sum in terms of the event number and the frequency. In it one can see the 2 batches of 53 MHz injected in the Recycler Ring separated by a Booster Tick of 67 ms. One can also see the 8 bunches of 2.5 MHz extracted to the Delivery Ring.

The period of the protons at the recycle ring should be the same no matter the batch being analyzed.Therefore, looking at the first batch, first 10,000 μs, we were able to calculate a period. In order to find it, a Fourier Transform can be used in order to decompose a function depending on time, into a function depending on frequency (See Figure 8 for a visual representation). Then, scaling that function that depends on frequency, we got a frequency of f = 0.089800 MHz, which was a result that made sense for us. Having the frequency, the period can be easily calculated using the equation T = 1/f, what gave us a period of 11.135857 μs for the first batch injected.

Having the period, one can see the structure of the beam.

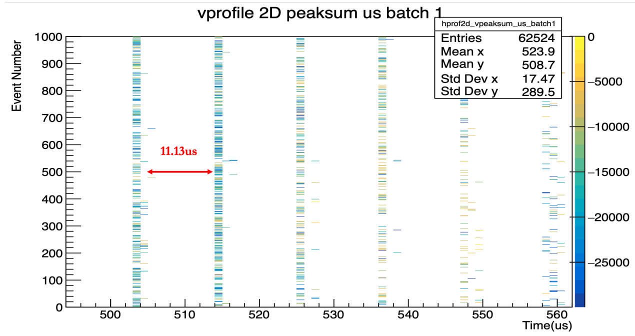

FIG. 8: Plot that shows a zoom into the first batch of Figure 7. The distance in between the traces is equal to 11.13 μs, the period of the protons at the Recycler Ring.

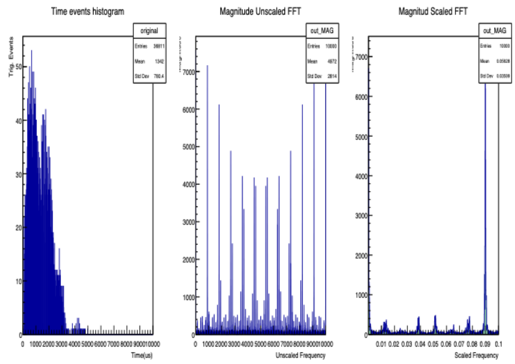

FIG. 9: Histogram of the peak times in terms of the event number of the most recent data collected with an algorithm. Also, one can see the unscaled and scaled Fast Fourier Transform used to calculate the Recycler Period seen in Figure 8. The frequency obtained was f = 0.089800 MHz, giving a period of T = 11.135857 μs.

If the data is accurate the structure should be equal to the 53 MHz from the Fermilab Booster. In order to see this frequency, one can modulate the peak times by the period calculated, 11.135857 μs[10]. A frequency of 53 MHz gives us a period of 18.86 ns, by using the equation T = 1/f again. Then dividing a time frame by the period is the same as modulating the time. Therefore, if we modulate 150 ns by 18.86ns, one should be able to see something close to 8 peaks (150ns / 18.86ns = 7.95). However, the new data modulated by T = 11.135857 μs did not show these 8 peaks, the 53 MHz structure.

Not being able to see the beam structure in our data, we decided to compare our plots to the ones Professor Prebys´ got years ago, where he was able to see the 53MHz analyzing the raw data from the monitor. One can see in Figure 11 Professor Prebys' plot, in it one can see 8 clear peaks between 200-350ns (150ns). However, zooming into Figure 10, it was impossible to see that structure[12]. There are many more peaks and they are not as clean as in Professor Prebys' plot.

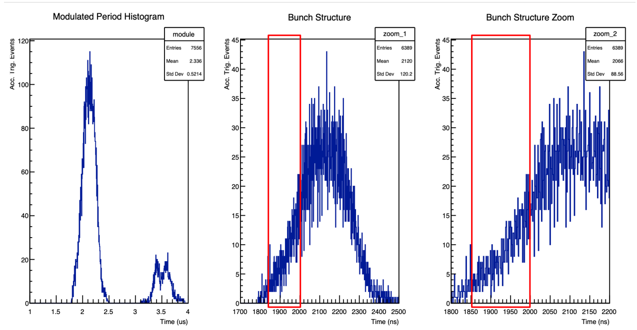

FIG. 10: Histogram of modulated period. The center histogram shows a zoom into the first peak of the modulated period. The right histogram is a zoom of the center histogram. The main goal was to see the 53MHz structure of the beam in the right histogram. This was not achieved as one cannot see 8 clear peaks in between 150ns.

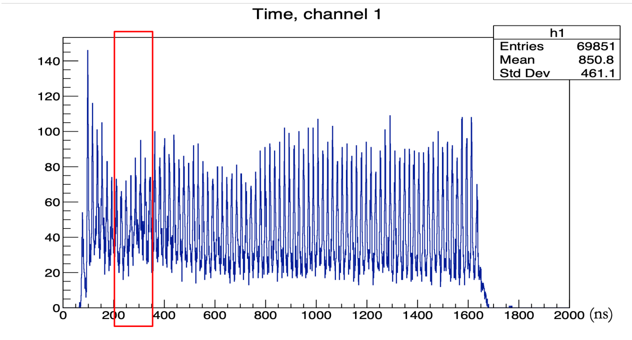

FIG. 11: Eric Prebys' histogram. It shows the 53MHz beam structure. One can clearly see the 8 peaks every 150ns. The main difference from the data that we were analyzing, Figure 12, is that Eric used a code to analyze the raw data from the monitor, and the new data we are analyzing was being collected and then analyzed by an algorithm.

Conclusion

After analyzing the data we were not able to see the beam structure of 53MHz from the Fermilab Booster. Also, it did not make a lot of sense that after the Fourier Transform, we saw two peaks instead of only one as Professor Prebys was able to see using the raw data from the monitor. The next steps will be to try to see the 2.5MHz of the 8 bunches that are extracted in case the problem is just detecting the first batch. The fact that we cannot see that structure, means that there must be something wrong with the data we are currently using, maybe the trigger or the algorithm. Therefore, the best thing would be to check the trigger at Fermilab when the experiment is back running, and compare the code used by Professor Prebys, to what the algorithm is currently doing for us, and see if there is something wrong with it. The beam is not currently running at Fermilab, so we won't be able to short this out until it comes back later in the fall.

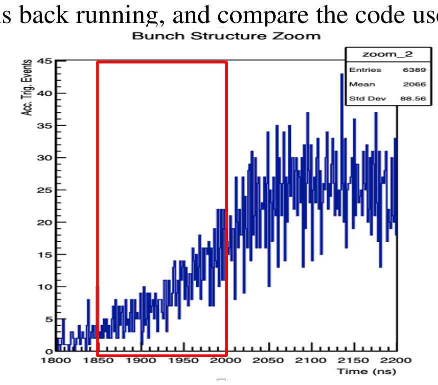

FIG. 12: Zoom of Figure10. One cannot see the 8 clear peaks every 150ms that we can see at Figure11, this means we cannot see the 53MHz beam structure.

Acknowledgements

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[5] Eric Prebys, "Simulation of Extinction Channel," 8 September 2016.