Counting Calories: Light Yield Studies with ADRIANO2 Calorimeter Prototype

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Precision in measuring particle energies is crucial to understand the intricacies of high-energy physics beyond the standard model. For the REDTOP experiment to detect $\eta/\acute{\eta}$ mesons potentially decaying into dark-matter particles not yet discovered, it is essential to have accurate measurements through sophisticated and innovative detector technology built with special properties. The ADRIANO2 (A Dual Readout Integrally Active Non-segmented Option) Calorimeter Prototype plays a pivotal role in advancing detection capabilities, offering the potential to enhance the particle identification procedure. This study delves into the characterization of the ADRIANO2 prototype's light yield with the ultimate goal of contributing to broader high-energy physics objectives. To estimate the light yield for the ADRIANO2 prototype, we must calibrate the light sensors as well as collect data from beams of known properties. Several prototypes of the ADRIANO2 detector have been tested at the Mtest Facility at Fermi National Accelerator Laboratory in the last few years. This paper attempts to summarize the calibration of one such ADRIANO2 prototype to estimate its experimental performance.

I. Introduction:

Part 1- REDTOP:

The REDTOP Experiment proposes that laboratories with high intensity proton accelerators have the opportunity to uncover new physics beyond the standard model "through the production and study of extremely large $\eta/\acute{\eta}$ samples". However, an equally crucial note to consider along with the production of $\eta/\acute{\eta}$ mesons is proper detection of these particles as the statistics and background may limit sensitivity related to REDTOP. The most efficient production of $\eta/\acute{\eta}$ mesons is from nuclear scattering of protons onto a nuclear target, with the largest background component consisting of events with only baryons or single pions. To successfully proceed with this experiment, it is critical for REDTOP to be paired with excellent particle identification techniques and detectors. ADRIANO2 is one such calorimetric technique. (Gatto, 2023)

Part 2- ADRIANO2:

ADRIANO2 is built with a pair of optically isolated, small sized tiles made of scintillating plastic and lead glass. The Čerenkov light produced from lead glass is used to perform high resolution timing measurements, and the "high granularity provides good resolution of the spatial components of the shower". The dual readout from the plastic and the glass provides excellent energy resolution for particle identification. The light generated in each tile from the plastic and the glass would be individually read out with silicon photomultipliers (SiPM) coupled to the tiles. The Čerenkov signal can be exploited for fast-triggering the data acquisition. Three distinct measurements of the energy deposition in every scintillator-radiator tile pair can be made: the amplitude of the charge deposited, the component of the charge that is from electrons, and its precise time of arrival. (Gatto, 2022)

The light yield for ADRIANO2 plays an indispensable role in this project as we attempt to explore the calorimeter's proficiency and streamline its calibration for future data analysis. Our objective extends beyond the confines of this project, as we seek to fundamentally enhance the particle detection process for this calorimetric technique. Thus, my research delves into its light yield and efficiency studies and plays a key role to optimize its performance, ensuring full exploitation of the detector's capabilities to study new physics with unprecedented precision.

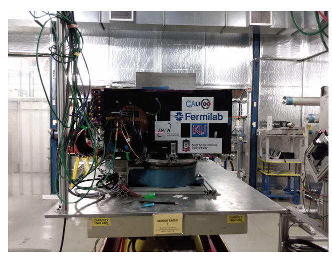

FIG. 1. ADRIANO Prototype at Mtest Facility at Fermi National Accelerator Laboratory

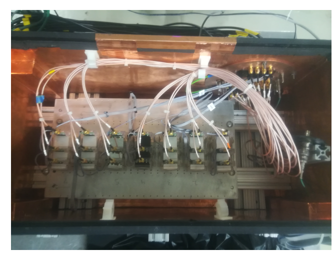

FIG. 2. Setup of a test beam at FTBF of seven triplets of ADRIANO2 tile.

II. Method:

My primary task was to systematically gather light yield data across a spectrum of particle energies. My contribution to this research can be categorized in these 3 points below:

A) Calibrate SiPM (Silicon Photo-multiplier) sensors to detect "single" photoelectrons amid noise.

B) Analyze data taken on ADRIANO2 calorimeter prototypes to estimate key parameters such as light yield and efficiency.

C) Develop and improve detector prototypes based on the experimental needs of REDTOP.

Data acquisition was meticulously executed through a highly sensitive system, designed to detect subtle variations in light emissions. ADRIANO2 front-end electronics initially captured signals produced by test beams subsequently sent to DAQ which records them as waveforms. Digitizers, such as Sampic, capture these signals and convert them into analog waveforms. The latter allows for precise analysis. Once digitized, the data and their corresponding histograms are systematically saved into specific file formats: ROOT for general storage and AIDA for analysis.

Following data acquisition, the analysis phase involved processing the collected data using sophisticated algorithms. Emphasis is placed on eliminating any data distortions caused by anomalies from electronic noise or from physical characteristics of tiles.

The histograms, which graphically represent the frequency of the data, are retrieved from AIDA repositories. Calibrating this system demanded regular adjustments to individual energy boundaries and parameters of each tile-triplet to maintain measurement accuracy. Rigorous record keeping was implemented to ensure the reliability of the data collected. Specialized software tools were employed through Java and JAS3 (Java Studio Analysis 3, freeHEP), offering advanced data handling and analytical capabilities. These tools were instrumental in streamlining the analysis process, facilitating a more accurate interpretation of the calorimeter's performance. Various mathematical functions are applied to fit the shape of these histograms to understand the patterns and properties of the signals from the detector.

III. The Fitting Procedure

The functions used to fit the signal histograms for ADRIANO2 is a combination of Moyal and Gaussian used below:

$$\text{Moyal}(x) = \text{normalization} \times \frac{1}{\sqrt{2\pi} \times \text{width}} \times e^{-\frac{1}{2}\left(e^{-\frac{(x-\text{mpv})}{\text{width}}} - \frac{x-\text{mpv}}{\text{width}}\right)} \quad (1)$$

$$\text{Gaussian}(x) = \text{normalization} \times \frac{1}{\sqrt{2\pi} \times \text{width}} \times e^{-\frac{1}{2}\left(\frac{x-\text{mpv}}{\text{width}}\right)^2} \quad (2)$$

The calibration runs analyzed were fitted with one Moyal (for the pedestal) and a summation of multiple Gaussians (for the signal generated by photoelectrons), where regular runs were fitted with a summation of multiple Moyals (for pedestal and signal). Calibration runs are produced by setting the tiles at an angle to generate very few photoelectrons from test beams of known properties. This allows us to clearly observe an early pedestal in the signals as electronic noise is picked up by the detector which can be fitted with a Moyal distribution for electronic noise. The remaining signals are picked up well using Gaussian distributions to show the amplitude of the signals generated by photoelectrons reaching the light sensors. Regular runs are fitted with a sum of multiple Moyal's because they capture a wider range of asymmetric (uncontrolled) responses. An example of this fitting procedure in its preliminary stage for the calibration is shown in FIG. 3, and FIG. 4. As they can be seen, when the figure is fitted with 1 Moyal there are many signals that are missed by the function. However, once the Moyal is summed with a Gaussian distribution, the summation encompasses the missed signals. It is crucial to note however, that this fitting is not relevant and without further context, can be contradictory to our previous statement on how the pedestal is the first set of signals picked up by the detector because in FIG. 4 the Gaussian distribution is fitted first. This phenomenon is not a product of faulty hypothesis but rather because the signals picked up during this particular run were primarily electronic noise from the pedestal, making it much more challenging to locate the proper parameters and bounds for when the pedestal ends and the signals begin. In this paper, FIG. 3 and FIG. 4, simply serves as a visual for how the summation of the fitting functions are plotted and these runs will be revisited in the coming weeks to be studied in greater detail.

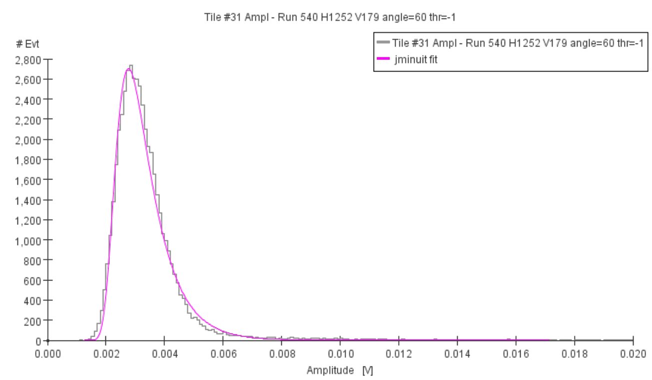

FIG. 3. Runs with very few photoelectrons fitted with single Moyal

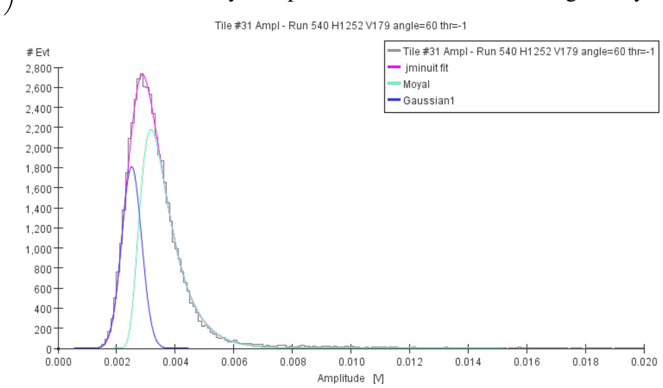

FIG. 4. The signals missed by the single Moyal fit are now incorporated when summed with Gaussian.

IV. Figures and Results:

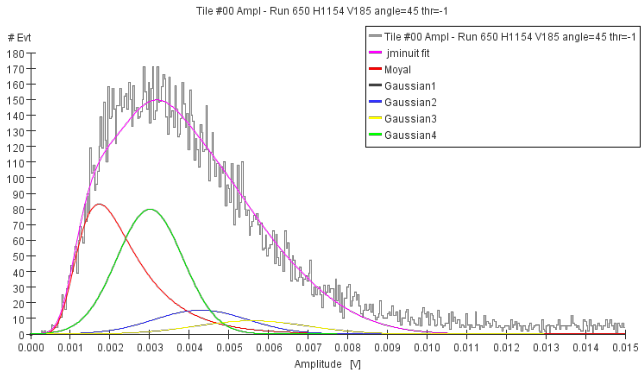

FIG. 5. Run 650- Tile 0- Angle 45°

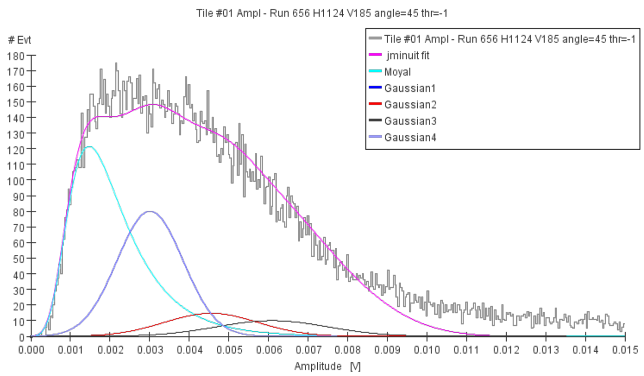

FIG. 6. Run 656- Tile 0- Angle 45°

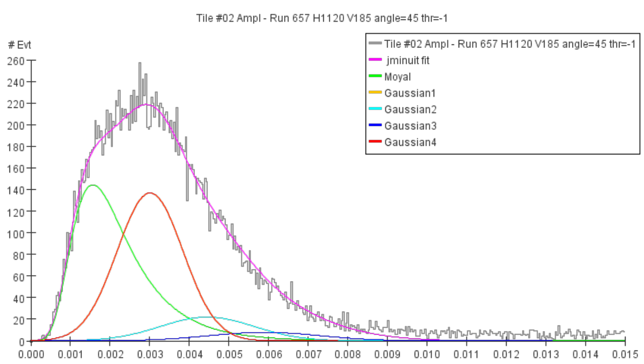

FIG. 7. Run 657- Tile 0- Angle 45°

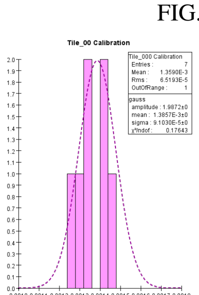

FIG. 8. Mean efficiency for Tile-0 1.36 mV

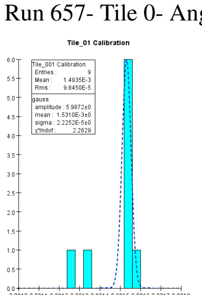

FIG. 9. Mean efficiency for Tile-1 1.50 mV

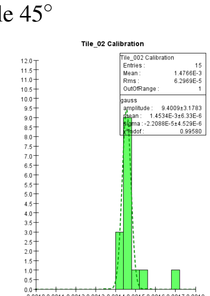

FIG. 10. Mean efficiency for Tile-2 1.45 mV

FIG. 5, 6, and 7 show the pedestal, or the electronic noise, through the peak of the first Moyal and the most probable values (MPV) for the number of photoelectrons passing the detector through the peaks of each Gaussian. The Gaussian's peak represent the energy for the number of photoelectrons passing directly correlating the the numbers of Gaussians fitted. The efficiency of the detector can be found by subtracting the Pedestal from the first MPV. The distribution of efficiency from the calibration runs in FIG. 8, 9, and 10 show the expected values from the detector's performance. Using the parameters from this calibration, we can now fit regular runs with the similar tile configurations such as the one shown in FIG. 11. The analyses of these regular runs are currently still in progress.

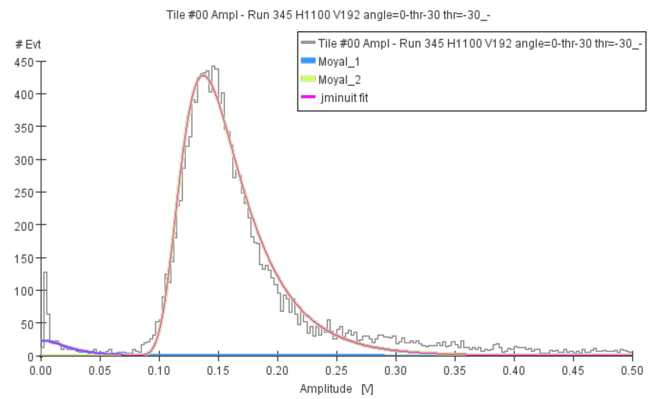

FIG. 11. Run 345- Tile 0- Angle 0°

V. Challenges:

During the course of this experiment, I encountered certain challenges that stem from variations in the behavior of tiles within each triplet, primarily influenced by differences in their width. Notably, the parameters and constraints established for Tile-0 often exhibit a poor fit when applied to Tile-2 due to a different shape of the histograms. While such discrepancies may seem inconsequential in calibration runs involving a limited number of photoelectrons, they pose significant challenges in the context of regular runs featuring more extensive particle showers within the detector. In order to address these issues effectively, I've been compelled to categorize tiles into groups with similar angular configurations and minor structural distinctions. This approach entails fitting each histogram individually rather than employing universal parameters for all. Although these methods currently demand considerable time and resources, I am actively engaged in the development of additional procedures and algorithms aimed at streamlining this process, which will ultimately enhance the efficiency of future analyses.

VI. Conclusion:

For REDTOP to successfully uncover elusive processes, the ADRIANO2 detector necessitates the incorporation of unique and tailored properties. Over the past two months, we have diligently crafted advanced software programs, specifically designed for the calibration and comprehensive analysis of ADRIANO2 calorimeter data. Our meticulous approach has resulted in well-fitted histograms, accurately representing both background and signal characteristics. We are well-prepared to implement this enhanced procedure on the dataset obtained from the most recent series of test beams. We anticipate publishing our results at the end of my second term in Spring 2024 as Science Undergraduate Laboratory Intern at Fermilab.

VII. Acknowledgements:

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VIII. References:

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