Frascati Physics Series Vol. 76 (2024)
8TH YOUNG RESEARCHERS' WORKSHOP 'PHYSICS CHALLENGES IN THE LHC ERA'
May 13 and 16, 2024

Mu2e calorimeter: in situ calibration of energy and time with selected Cosmic Ray samples

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Abstract

The Mu2e electromagnetic crystal calorimeter is a state-of-art detector that will play a crucial role in detecting the signal of a neutrino-less muon to electron conversion that the Mu2e experiment will explore. The calibration in time and energy of the calorimeter is necessary to match the requirements and will serve as monitoring during the operations. In this article, we present the results of our calibration study in energy and time for the Mu2e crystal calorimeter as well as the time-scale inter-calibration between the tracker and the calorimeter using simulated cosmic rays in the configuration where both the detectors are placed outside the detector solenoid, named extracted position.

1 Introduction

The Mu2e experiment 1) is under construction at the Fermilab National Accelerator Laboratory and will explore physics beyond the Standard Model (BSM) through the search for the charged lepton flavor violation (CLFV) process of a neutrino-less conversion of a muon into an electron in the field of an aluminum nucleus. The Mu2e experiment plans to improve the current best limit by four orders of magnitude 2) reaching an upper limit value $< 6.2 \times 10^{-16}$ at 90% C.L.

The final state of the conversion process is a monoenergetic electron with an energy of approximately 105 MeV which will be detected by a high-resolution straw tracker and an undoped CsI crystal calorimeter. Both the detectors are inserted in a solenoid which provides a 1T magnetic field and the whole detector region is surrounded by the highly-efficient Cosmic Ray Veto which will suppress the cosmic ray (CR) background.

A pulsed beam of 8 GeV protons will strike a tungsten target; the produced pions will be sign-selected and guided through an S-shape system of solenoids where they will decay and be captured by the aluminum atoms in the Muon Stopping Target (MST). The normalization of the CLFV events is calculated with the

Stopping Target Monitor (STM) composed of the High Purity Germanium Detector and the Lanthanum Bromide crystal detector which observe the X-rays emitted from the muonic atoms formed in the MST.

2 The electromagnetic crystal calorimeter

The electromagnetic calorimeter 3) must have a large acceptance for the conversion electron and a strong particle identification capability with a muon-electron rejection factor of 200. This results in requiring an energy resolution of $\mathcal{O}(10\%)$ and a time resolution of 500 ps for 100 MeV electrons. In addition, the calorimeter must have the capability to withstand a high-radiation environment up to 100 krad and 10^{12} $\mathrm{n}_{1\mathrm{MeVeq}}/\mathrm{cm}^2$ within a 10^{-4} torr vacuum.

The Mu2e calorimeter is arranged in two annular disks, each one composed of 674 undoped CsI scintillating crystals 3.4cm × 3.4cm × 20cm. Each crystal is read out by two custom UV-extended Silicon Photo-Multipliers (SiPMs) and each SiPM is connected to a Front-End Electronics board (FEE). Groups of 20 FEE are managed by the Mezzanine Board (MZB) which is the interface between the FEE, the voltage source, and a custom DIgitizer and ReAdout Controller (DIRAC) module.

The performance of the calorimeter and the technological choices were evaluated using a large-scale prototype composed of 51 crystals, named Module-0, which was assembled at Laboratori Nazionali di Frascati. At the Beam Test Facility in Frascati, Module-0 was tested with a 100 MeV electron beam, obtaining an energy resolution of 7% and a time resolution of 200 ps 4).

3 Calibration with simulated cosmic ray sample

In the official Mu2e simulation campaign, simulating the whole detector, two Monte Carlo generators, CRY 5) and CORSIKA 6) are used to generate cosmic ray data. Subsequently, the interaction processes are simulated using the Geant4 toolkit. 7) 8) 9)

For the calorimeter, the simulation considers a nominal Longitudinal Response Uniformity (LRU) of a few percent for the crystals, as derived from quality control assessments. The energy deposited within the calorimeter is translated into optical photons, and the signal is digitized using experimentally-acquired pulse shapes. This process includes a nominal Light Yield (LY) of 30 photoelectron/MeV, Poisson-distributed photostatistics fluctuations, SiPM response, and electronic noise levels equivalent to 150 keV. Crystal hits are organized into clusters by starting with the crystal that has the highest reconstructed energy and adding hits from adjacent crystals with similar relative timing.

3.1 Energy calibration

For the presented analysis, a dataset simulating 10 hours of cosmic ray flux incident on the two calorimeter disks is used. To select clean cosmic ray (CR) events, we require a candidate to have a minimum of 6 crystals hit with energy deposited of at least 15 MeV. The track of a cosmic ray event is then identified as the linear fit to the positions of the crystals above the energy threshold. CR candidates must have a $\chi^2/\mathrm{NDF} \leq 2.5$ for the linear fit. From the fit to the deposited-energy distribution (Fig. 1) we extract the most probable value (MPV) which is the corresponding calibration scale parameter for each crystal.

To simulate a real experimental environment, we apply a random offset of up to ±10% to each crystal. The calibrated energy response of readout channels is defined as:

$$E_{\text{calibrated}} = \frac{E_{\text{smeared}}}{\text{MPV}} \cdot 20\ \text{MeV} \tag{1}$$

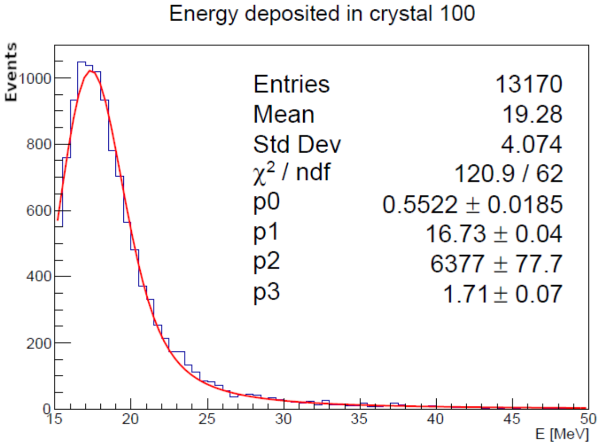

Figure 1: The deposited-energy distribution in one of the 1348 crystals of the Mu2e calorimeter. The fit is performed with a Landau function convoluted with a Gaussian. In this crystal, the extracted MPV value corresponds to 16.73 MeV.

since the energy deposit of a cosmic ray event is equivalent to 20 MeV electrons. The energy calibration reaches 0.2% accuracy with 2 simulated hours (Fig 2).

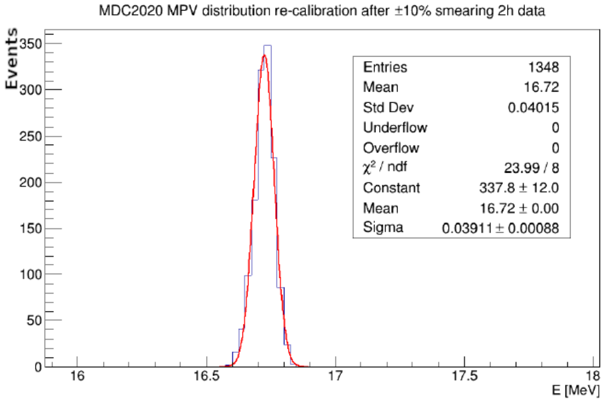

Figure 2: The MPV distribution after calibration shows a resolution σ/μ=0.2%.

3.2 Light Yield and Noise study with cosmic rays

The consistency of the SiPMs double readout is studied through the asymmetry variable:

$$\mathrm{Asymm} = \frac{E_L - E_R}{E_L + E_R} \tag{2}$$

Where E_L and E_R indicate respectively the energy readout by the left SiPM and the right SiPM.
The sigma of the asymmetry variable can be parameterized using the Light Yield (LY) and the noise (SigNoise) value of the crystals:

$$\sigma(\mathrm{Asymm}) = \sqrt{\frac{1}{2}\left(\left(\frac{1}{\mathrm{LY}\cdot\mathrm{E}}\right) + \left(\frac{\mathrm{SigNoise}}{\mathrm{E}}\right)^2\right)} \tag{3}$$

where E is the mean value of E_L and E_R.
For every 5 MeV slice, we extract the σ from the Gaussian fit to the asymmetry variable. As a function of the mean energy of the left and right readout (E), the extracted σ's distribution is fitted with Eq. 3 (Fig 3 - Left). The LY and the SigNoise values are extracted for every crystal.
As a confirming result, Fig. 3 - Right shows the asymmetry variable as a function of energy which is well

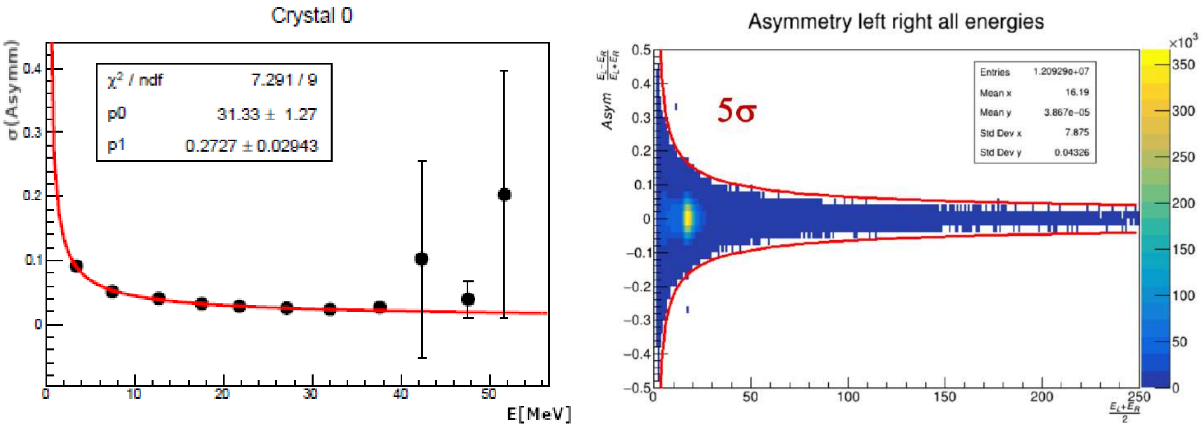

Figure 3: Left: σ(Asymm) distribution of the asymmetry variable for every 5 MeV slice fitted with Eq. 3. Right: The asymmetry variable as a function of the mean energy readout by the two SiPMs. The red lines identified 5σ's described by Eq. 3 for a LY value of 30 photoelectrons/MeV and a SigNoise value of 0.3 MeV.

confined in 5σ's described in Eq. 3 where we set a LY value of 30 Photoelectrons/MeV and a SigNoise value of 300 KeV.

3.3 Time Calibration

A time calibration is needed to remove the time offset and align the time response of crystals. An event selection is applied by requiring cosmic ray events belonging to one disk hitting at least four cells with a deposit of energy between 10 MeV and 30 MeV. The slope of the CR track is evaluated using a linear fit with the least-square method.
The time calibration method is organized in a two-step procedure: the first calibration step aligns the timing offsets at the ns level by using laser signals. In the second step, imposing that cosmic rays with minimum ionization travel at the speed of light, we correct the linear fit evaluation with its residual values iteratively. The process gets stable after few iterations and reaches a time resolution of 500 ps for a single readout unit (Fig. 4) and a time resolution of 350 ps at crystal level.

3.4 Time scale inter-calibration

The last step of calorimeter time calibration provides a global offset, which aligns crystal times with respect to the tracker. To perform this analysis, The CR track is reconstructed in the tracker, extrapolated to one of the two calorimeter disks, and associated to the nearest cluster. A subsequent selection for the tracker-calorimeter time calibration requires that the CR tracks cross at least a whole disk in the beam direction and is contained in the annulus defined by the radius R $\in$ [400, 600]mm. A further cut on the 2D distance between the cluster centroid and track extrapolation on the disk surface is applied along with a cut on the energy of the cluster. The timing of the calorimeter and tracker are calibrated independently.

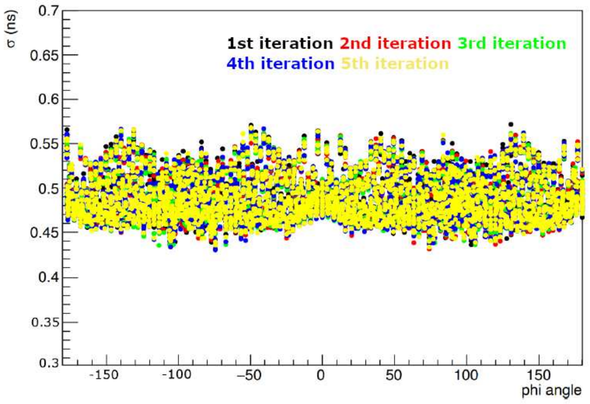

Figure 4: Time resolution of the time calibration method as a function of the azimuthal angle of the calorimeter for the iterative correction steps to the linear CR track fit.

Given the known relative positions of the two detectors and assuming that cosmic rays travel at the speed of light, the expected time-of-flight (TOF) can be computed and compared to the measured TOF.
To reach an agreement between the two TOF's, we parametrize their difference in terms of the polar angle of the CR track (Fig. 5) and we correct the calorimeter time response accordingly.
Fig 6 shows the tracker-calorimeter time difference before and after inter-calibration. The measured and expected TOF's are aligned after applying the correction.

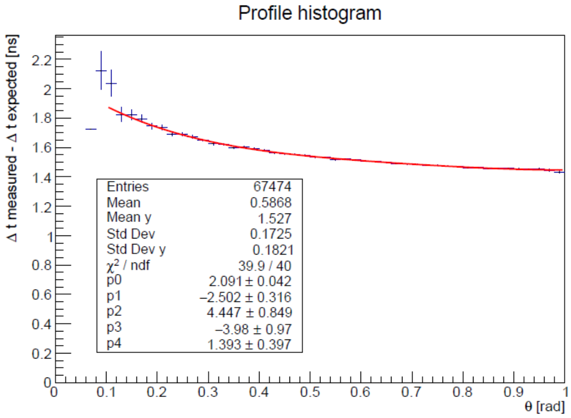

Figure 5: Parametrization of the difference between the TOF measured and the TOF expected in terms of the polar angle of the cosmic ray tracks

4 Acknowledgements

We are grateful for the vital contributions of the Fermilab staff and the technical staff of the participating institutions. This work was supported by the US Department of Energy; the Istituto Nazionale di Fisica Nucleare, Italy; the Science and Technology Facilities Council, UK; the Ministry of Education and Science, Russian Federation; the National Science Foundation, USA; the National Science Foundation, China; the Helmholtz Association, Germany; and the EU Horizon 2020 Research and Innovation Program under

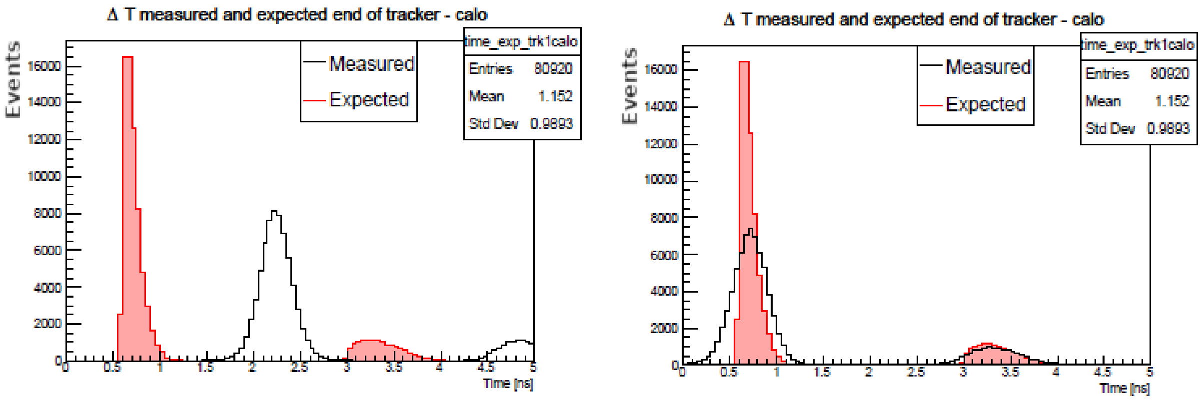

Figure 6: Left: TOF expected and TOF measured before the time scale inter-calibration show a relative offset of 1.5 ns. The two populations correspond to the TOFs with respect to the position of the two calorimeter disks. Right: TOF expected and TOF measured after the time scale inter-calibration.

the Marie Sklodowska-Curie Grant Agreement Nos. 734303, 822185, 858199, 101003460, and 101006726. This document was prepared by members of the Mu2e Collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359.

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