PMu2e/LNF 2024

S. Bini, C. Bloise, S. Carsi (Associato), F. Colao (Associato), G. Delle Monache, E. Diociaiuti (Art. 36), P. Fedeli (Laureando), M. Garattini (Assegnista), S. Giovannella, D. Hampai, F. Happacher, M. Martini (Associato), S. Miscetti, L. Montalto (Associato), D. Rinaldi (Associato), I. Sarra (Responsabile Locale)

in collaboration with "LNF-SEA": S. Ceravolo (Tecnico), M. Gatta (Tecnico)
the Detectors Development and Construction unit: A. Russo (Tecnico), D. Pierluigi (Tecnico)
and the Experimental Activities Support unit: B. Ponzio (Tecnico), E. Capitolo (Tecnico).

The assembly of the Mu2e calorimeter at SiDet, Fermilab, is in its final stage, with all mechanical components, crystals, SiPMs, front-end electronics (FEE), cabling, and digital electronics installed. This report summarizes the commissioning activities carried out over the past year. A pilot commissioning run in July 2024 successfully collected data from six DIRAC boards (120 channels), covering three calorimeter sectors. This marked two key milestones: (i) data acquisition based on the final optical fiber distribution and first functional firmware for DTC-DIRAC communication, and (ii) completion of final cabling, ensuring a consistent mapping of crystals, SiPMs, and electronics. This first complete *Vertical Slice Test* validated the entire system, confirming consistency between cabling, electronics, and readout firmware. Over the following six months, the cooling system was made operational, enabling data collection from half a disk at a time. Additional power supplies, DTCs, and PC servers increased the readout capacity to 674 channels and 34 MZB/DIRAC boards per run. This allowed extended detector testing and efficient debugging of connectivity and readout issues. We now conduct noise, laser, and cosmic ray (CR) data-taking runs for several hours uninterrupted, maintaining stable operating conditions. While further data analysis is ongoing to refine reconstruction, initial results confirm excellent data quality and detector performance. In the coming months, we will finalize minor adjustments, improve calibration and reconstruction, and prepare for the detector's transport to its final location. The following sections describe the calorimeter system, the commissioning strategy, and the data collection and analysis performed for noise, laser, and cosmic ray events.

1 Calorimeter System and Readout Overview

The Mu2e calorimeter consists of two disks, each hosting 674 pure CsI crystals read by SiPMs and FEE units [1]. Details on its technical requirements are in Refs. [2, 3]. This note focuses on the Vertical Slice Tests for detector commissioning.

1.1 Assembly and Readout Organization

The calorimeter disks were assembled at Fermilab SiDet over the past 2.5 years. The process included:

- Mechanical assembly: FEE Peek plates, aluminum supports, custom crates for digital electronics.
- Cooling system: Separate circuits for SiPMs and digital electronics, tested with helium leak detection.
- Crystal stacking: 674 undoped CsI crystals per disk, surveyed post-installation.

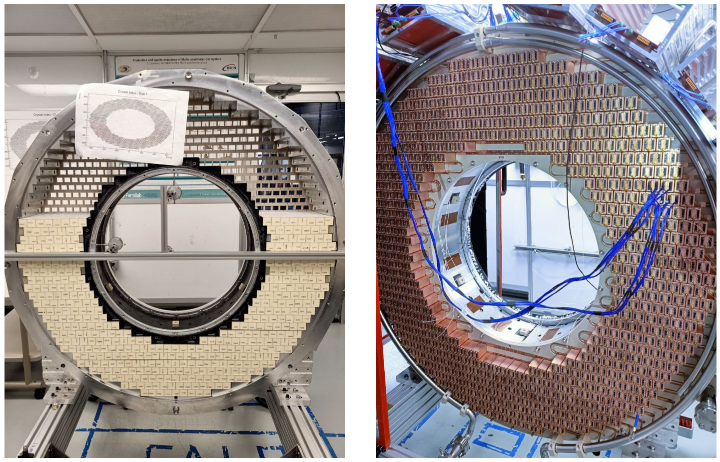

Figure 1: Assembling of a calorimeter disk: crystal stacking (left), ROUs on the FEE back plate (right).

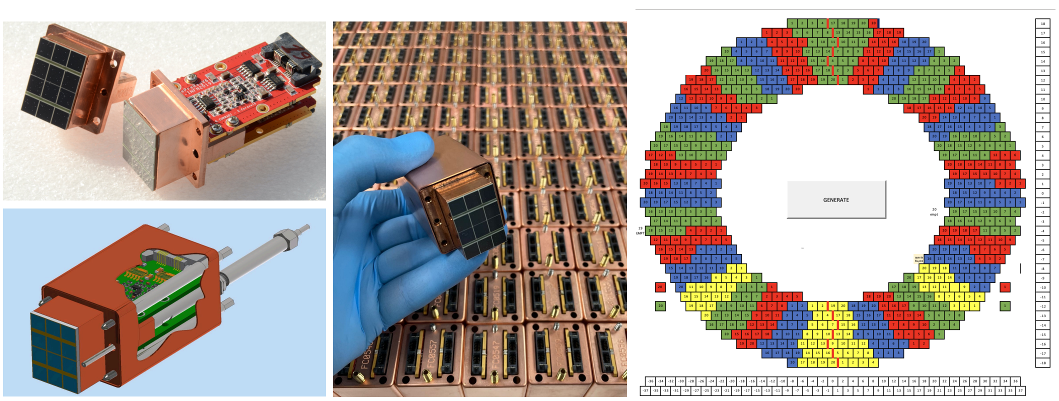

Figure 2: ROU details (left): SiPMs on a copper holder (top), final ROU design (bottom); readout mapping (right).

- Readout Unit (ROU) insertion: Each ROU (Fig. 2.left) consists of two SiPMs on a copper holder, two FEE boards, and a protective copper Faraday cage.

Each disk is divided into 34 azimuthal sectors, each covering 20 crystals (Fig. 2.right). This subdivision accounts for space constraints, cooling pipes, and radiation exposure [7]. Readout includes:

1. Mezzanine Boards (MZB): Manage SiPM/FEE configuration via SPI, control HV distribution, and regulate power using LTM8033 converters.

2. Digital Boards (DIRAC): Handle fast data readout with a MicroSemi SmartFusion2 M2S150T FPGA, interfacing with 12-bit ADS4229 ADCs at 200 Msps [8].

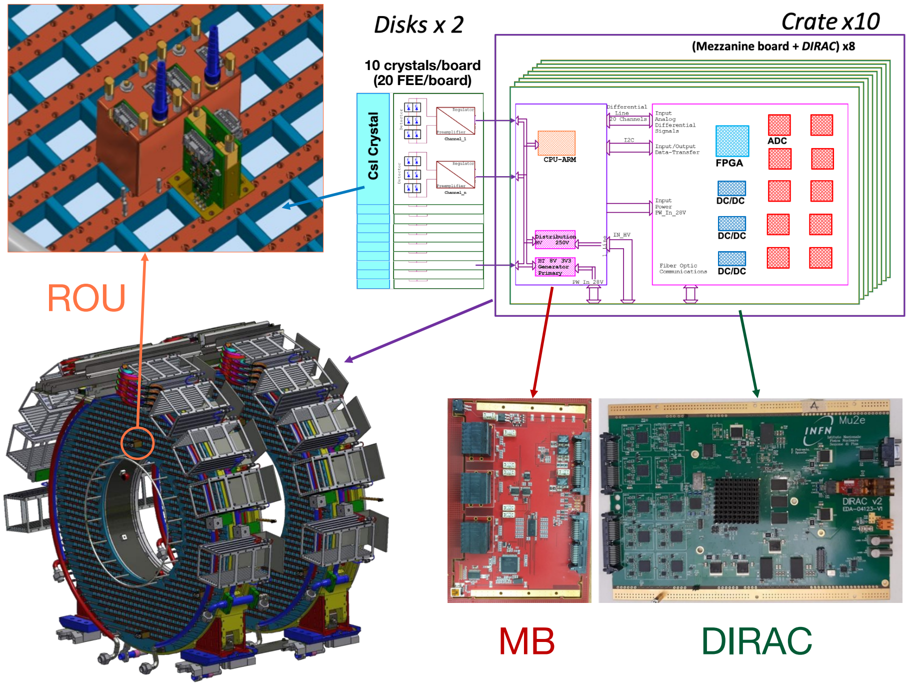

Figure 3: FEE, MZB, and DIRAC architecture (left) and DIRAC block scheme (right).

1.2 DAQ and Electronics Integration

The DAQ digitizes 2696 analog signals, processing SiPM pulses (150 ns width, 40 ns rise time, 2 V range). The system includes 140 DIRAC boards across 10 crates per disk, performing:

- Zero suppression, baseline calculation, amplitude extraction, and time-stamping.
- Data compression and transmission via dual-fiber optical links to the event builder.
- Control of MZBs and monitoring via I2C interfacing with the Detector Control System (DCS).

The MZB and DIRAC production, performed in Italy, included full QA/QC testing at INFN before shipment to Fermilab. Boards were integrated with copper cooling plates and degassed under vacuum before installation. Final integration included LV, HV, and TDAQ fiber connections (Fig. 4). The fully assembled calorimeter (Fig. 5) is now undergoing final commissioning.

2 Pilot Run and Disk Commissioning

After completing the FEE-MZB cabling and LV services distribution, we tested ROU functionality by connecting L and R board cables to a test bench with an MZB and a simplified DIRAC for signal translation. Malfunctioning cables and two faulty ROU units were replaced. Calorimeter commissioning was performed reading half a disk at a time (34 MZB and 34 DIRAC boards), enabling a fast cosmic ray data acquisition. Simulations [9] suggest that six hours of data suffice for calibration within 1% energy precision and 30 ps time resolution. The following services were set up near the disks:

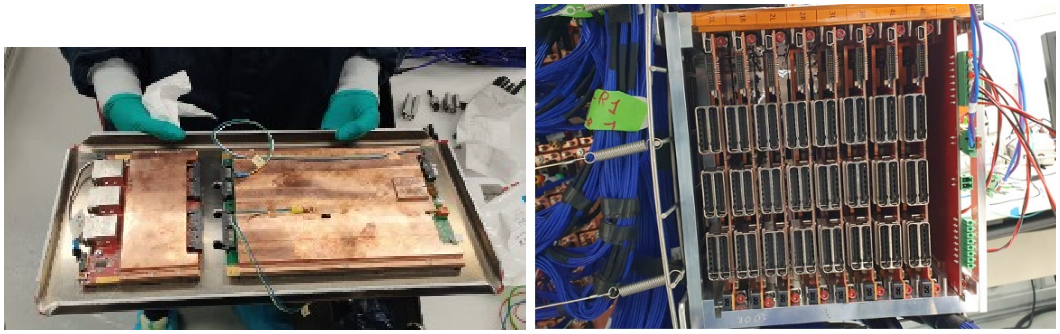

Figure 4: MZB and DIRAC boards with copper plates (left); digital boards in a crate (right).

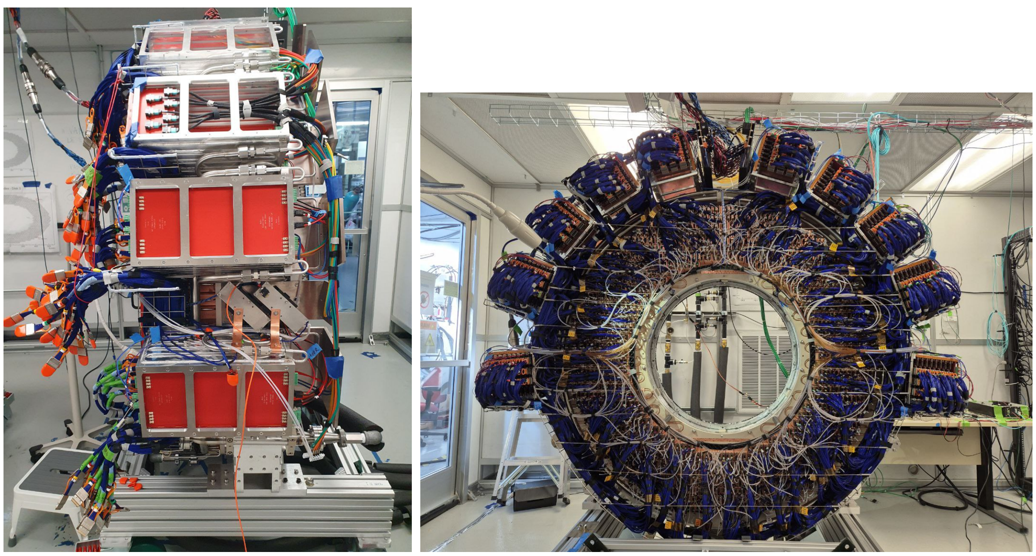

Figure 5: Lateral (left) and front (right) view of fully cabled Disk1.

1. 10 LV and 10 HV power supplies (TTI-PLH250-P for HV, TTI-CPX400SP for LV) were installed in a rack and connected to an Ethernet hub for remote control via DCS, developed with EPICS and PHOEBUS (Fig. 7).
2. Four PC servers, configured with TDAQ software, host 6 DTCs and 1 CFO for DIRAC board readout. A dedicated DAQ PC (mu2ecalo01) controls the system via a local network.
3. Optical link distribution was completed using MTP cables, breakout fibers, and tested prototypes for half-disk operation (Fig. 5).

For the Pilot Run, data collection time and active boards were minimized due to DIRAC power dissipation (28 W/board). Six DIRACs (120 channels) were readout in selected calorimeter sectors (Fig. 8).

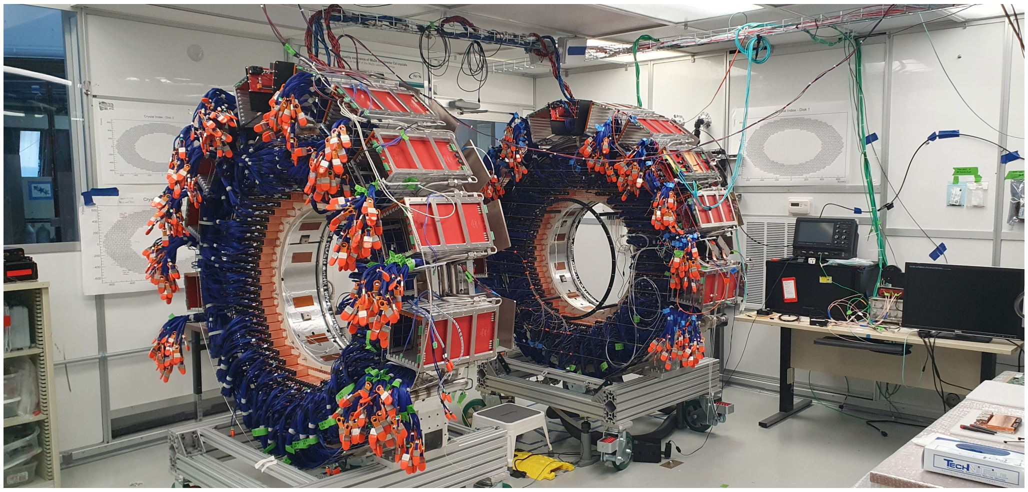

Figure 6: Both calorimeter disks in the assembly hall.

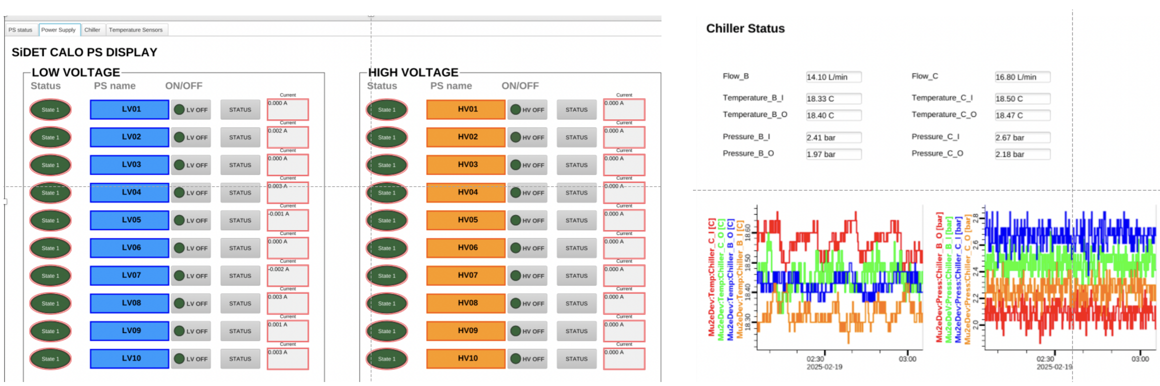

Figure 7: Phoebus control monitor for LV/HV supplies (left) and chiller monitoring (right).

2.1 Pilot Run Results

The July 2024 run used six selected sectors to optimize cosmic ray track reconstruction (Fig. 9).

Energy deposition was fitted with a Landau-Gaussian function to extract MPV values, yielding an average response of 450 ADC counts/MIP, corresponding to 22 ADC counts/MeV. DIRAC's 11-bit dynamic range supports up to 120 MeV, requiring a 30% SiPM gain reduction. Future adjustments will refine HV settings for optimal performance. Timing resolution was evaluated using $T_L - T_R$ differences for each crystal, yielding values between 250-350 ps, in line with expectations (Fig. 9).

3 Commissioning Data Taking

Half-disk commissioning started in November 2024, with dedicated runs for different analysis types.

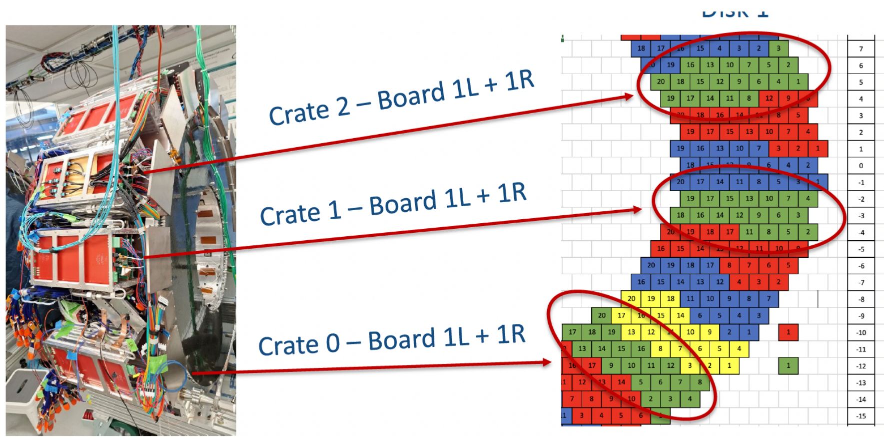

Figure 8: Pilot Run: TDAQ fiber distribution and selected calorimeter sectors (green).

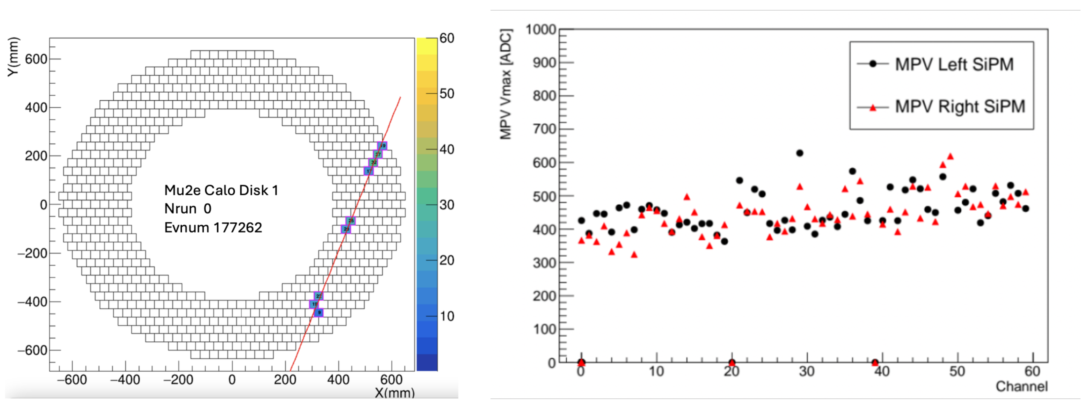

Figure 9: Pilot Run: event display (left) and MIP peak distribution (right).

3.1 Noise Runs

Noise runs characterized waveform baselines, identifying nominal, noisy, and hot channels. Baseline RMS was typically 1-2 ADC counts, decreasing when SiPMs were powered off. These studies helped optimize noise filtering in the DAQ system and refine the triggering configuration.

3.2 Laser Runs

Laser runs were conducted to measure the timing response and gain calibration of the SiPMs. The pulsed laser system provided fast signals with precise timing, allowing the evaluation of time synchronization across the detector. Results confirmed the expected behavior, with measured transit time spreads in the range of 100-150 ps, demonstrating the uniformity of the optical links and readout electronics.

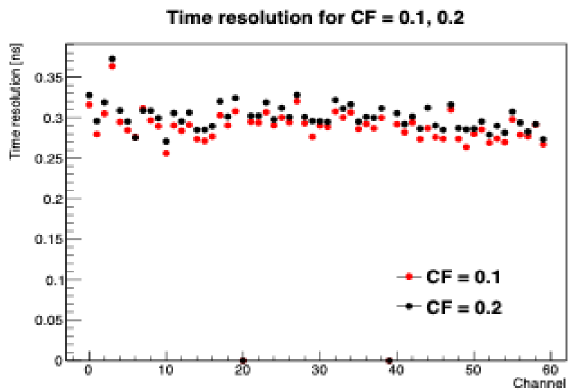

Figure 10: Timing resolution distribution for the calibrated channels.

3.3 Cosmic Ray Runs and Performance

Cosmic ray runs validated energy and time response stability over extended periods. The data confirmed a consistent ADC response across all channels, with variations within 5%. Time resolution remained stable, see figure 10, with inter-channel calibration refinements planned for the final setup. Overall, the commissioning phase confirmed expected detector performance, with ongoing refinements planned for final calibration and full system integration in upcoming data-taking campaigns.

4 Services and Transportation

A dedicated section is warranted for the calorimeter services and the extensive work carried out for transportation. These aspects fall under the exclusive responsibility of the National Laboratories of Frascati, and significant progress was made throughout 2024 to finalize these systems. The installation of cables and optical fibers from the TDAQ room was completed. This room hosts the servers, low-voltage (LV) and high-voltage (HV) power supplies for the calorimeter, the laser system, and the CAN bus control system. The interlock system was also finalized, ensuring proper safety and operational protocols.

Regarding transportation, the procedural framework was completed, and the dedicated transport tool was designed and sent into production. This tool, scheduled for deployment in mid-2025, will be used to safely transfer the two calorimeter disks to the experimental hall.

Figure 11: Layout of the TDAQ room connections, including cabling and fiber routing.

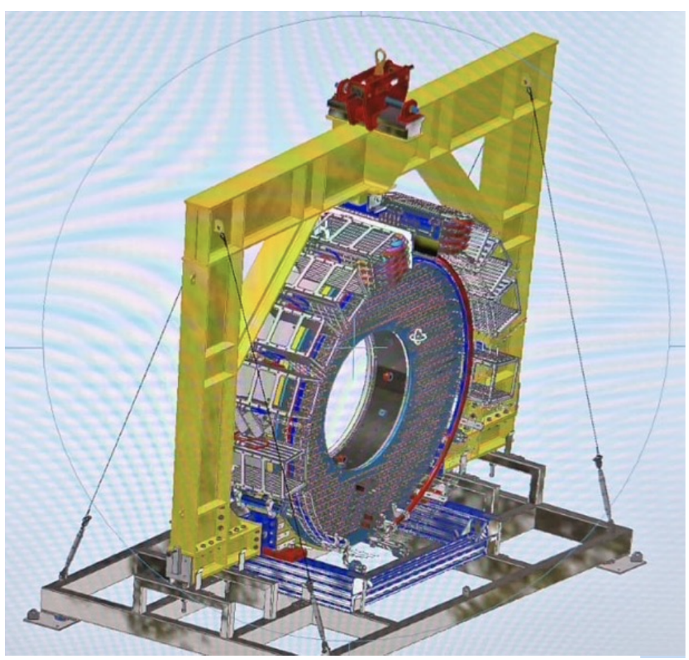

Figure 12: Designed transport tool for the calorimeter disks, scheduled for use in 2025.

5 Thesis

- P. Fedeli, “Commissioning and calibration of the Mu2e calorimeter in extracted position”, master thesis at the Università degli Studi La Sapienza.

6 List of Conference Talks/Posters by LNF Authors in the Year 2024

1. S. Miscetti, Status of the Mu2e experiment, Channeling 2024, Riccione, IT.
2. S. Giovannella, The Mu2e crystal and SiPM calorimeter, 16th Pisa Meeting on Advanced Detectors, Elba, IT.
3. P. Fedeli, Mu2e calorimeter: in situ calibration of energy and time with selected cosmic ray samples, XXI LNF Spring School “Bruno Touschek” in Nuclear, Subnuclear and Astroparticle Physics, Frascati, IT.
4. P. Fedeli, Construction and qualification tests of the Mu2e crystal calorimeter, APS2024, USA.
5. I. Sarra, Crystal calorimetry for cLFV, WIFAI2024, Bologna, IT.
6. F. Happacher, The Mu2e Calorimeter, ICHEP2024, Prague, CZ.

7 Publications

- N. Atanov et al., Design and assembly status overview of the Mu2e electromagnetic calorimeter mechanical structures, Nucl.Instrum.Meth.A 1070 (2025) 170040. DOI: https://doi.org/10.1016/j.nima.2024.1700
- N. Atanov et al., The Mu2e crystal and SiPM calorimeter, Nucl.Instrum.Meth.A 1069 (2024) 169959. DOI: https://doi.org/10.1016/j.nima.2024.169959.
- N. Atanov et al., The Mu2e Digitizer ReAdout Controller (DiRAC): characterization and radiation hardness, Nucl.Instrum.Meth.A 1068 (2024) 169688. DOI: https://doi.org/10.1016/j.nima.2024.169688.

References

1. N. Atanov *et al.*, ”The Calorimeter Final Technical Design Report”, arXiv:1802.06341 (2018).
2. N. Atanov *et al.*, ”The Mu2e Crystal Calorimeter: An Overview”, Instruments 6 (2022) 60.
3. N. Atanov *et al.*, ”The Mu2e crystal and SiPM calorimeter”, Nucl. Inst. Meth. A 1069 (2024) 169959.
4. N. Atanov *et al.*, ”Design and assembly status overview of the Mu2e electromagnetic calorimeter mechanical structures”, Nucl. Inst. Meth. A 1070 (2025) 170040.
5. C. Bloise *et al.*, ”An automated QC station for the calibration of the Mu2e calorimeter readout units”, Nucl. Inst. Meth. A 1046 (2023) 167811.
6. N. Atanov *et al.*, ”Summary of the radiation hardness tests for the Calorimeter Front End Electronics”, Mu2e-doc-37046, February 2021.
7. S. Giovannella *et al.*, ”Updates on calorimeter dose estimate”, Mu2e-doc-23833, January 2019

8. N. Atanov et al., "Mu2e Crystal Calorimeter Readout Electronics: Design and Characterisation", Instruments 6 (2022) 68.

9. S. Giovannella and S. Miscetti, "In-situ time calibration of the Mu2e calorimeter", Mu2e-doc-38991, July 2021.