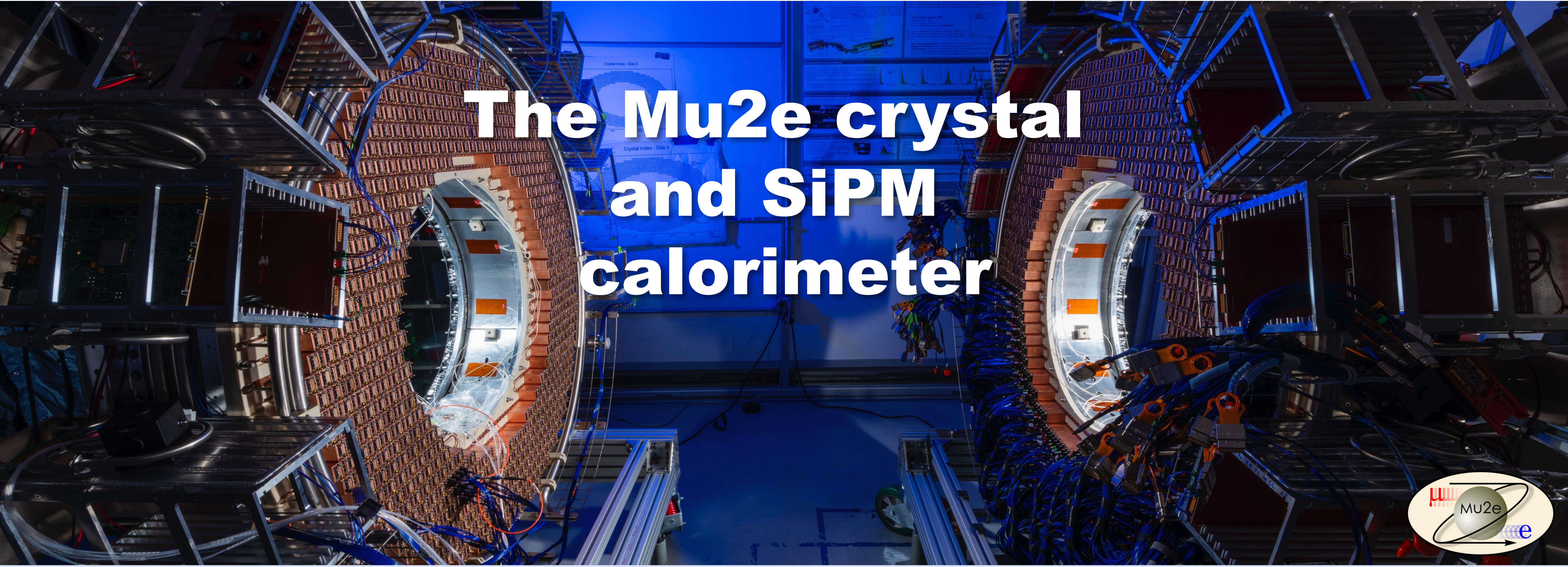


The Mu2e crystal and SiPM calorimeter

S. Giovannella (INFN LNF)

on behalf of the Mu2e Calorimeter Group

INFN

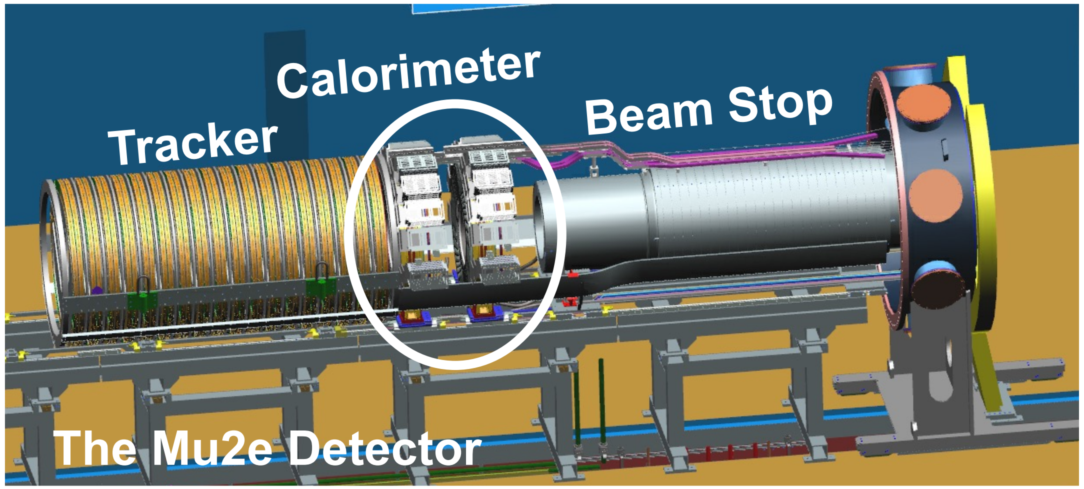
Fermilab

16th Pisa Meeting on Advanced Detectors

26 May – 1 June 2024

Outline

- Charged Lepton Flavor Violation and the Mu2e experimental technique
- Calorimeter requirements, technological choices and design
- Calorimeter performance
- Quality Control of production components
- Assembly status
- Commissioning
- Conclusions



Charged Lepton Flavour Violation @ Mu2e

CLFV strongly suppressed in Standard Model: BR ≤10^{-50} ➪ **Its observation indicates New Physics**

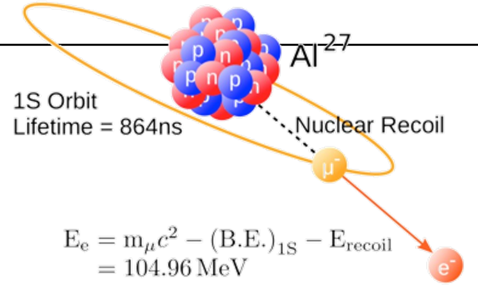
- CLFV@Mu2e: coherent neutrinoless conversion of a muon to an electron in the field of a nucleus
- Goal: **10^4 improvement w.r.t. current sensitivity experiment** (SINDRUM II at PSI)

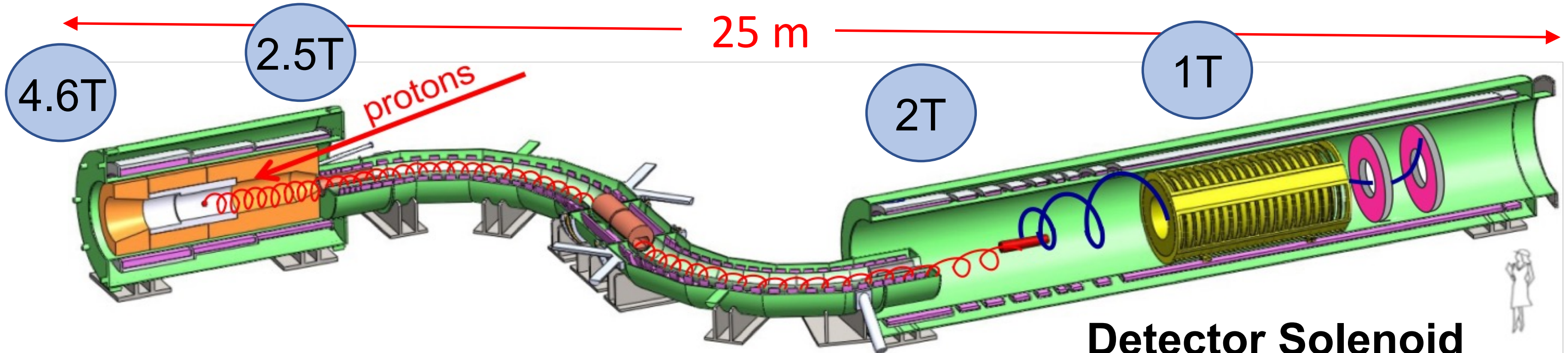
With 10^{18} μ stops:

$$R_{\mu e} = \frac{\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)}{\mu^- + N(A,Z) \rightarrow \nu_\mu + N(A,Z-1)} < 8.4 \times 10^{-17}$$

Experimental technique:

- Pulsed beam of low momentum muons
- 10 GHz of μ stopped in Al target trapped in nuclear orbit
- Normalization: nuclear captures
- $\mu^- N \rightarrow e^- N$ signature: **mono-energetic e^-** with E ~ M_μ produced with **τ_μ^{Al} = 864 ns**





Production and Transport Solenoids

Production, selection and transport of low momentum muon beam

Detector Solenoid

- Muon stop on Al target
- Tracker, EM Calorimeter

+

Cosmic Ray Veto

- Covers entire DS and half TS
- Reduces cosmic rays mimicking CLFV signal

Stopping Target Monitor

- Provides normalization factor
- Detects x-rays from muon atomic and nuclear capture procs

The Electromagnetic Calorimeter

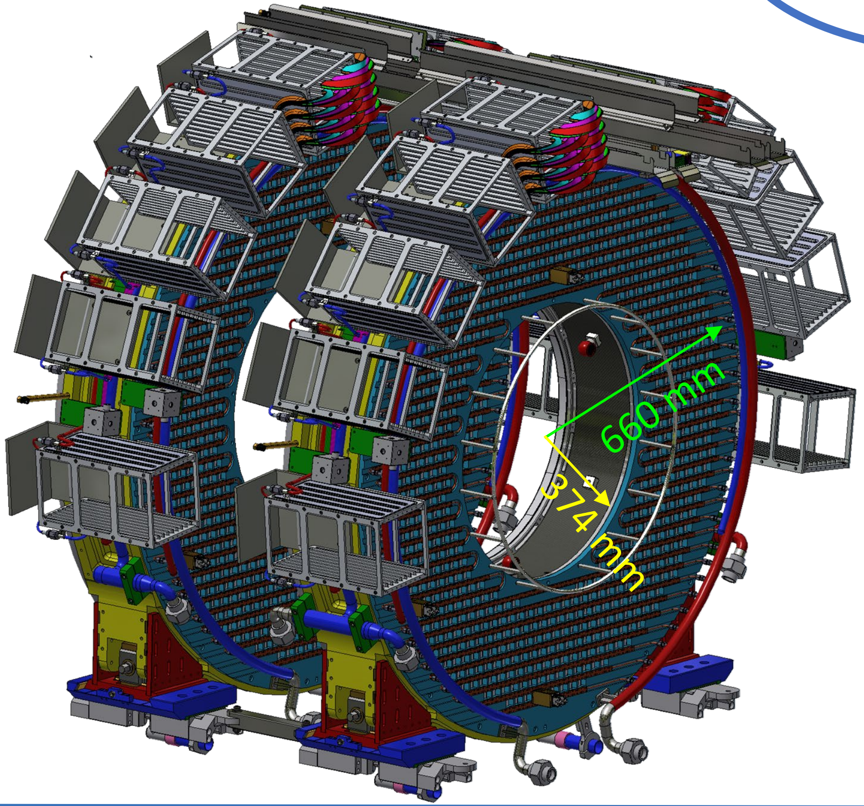
Calorimeter adds redundancy and complementarity w.r.t. the high precision tracking system:

- Large acceptance for mono-energetic conversion electron candidates (~100 MeV)
- PID with μ/e rejection of 200
- EMC seeded track finder
- Standalone trigger

For 100 MeV electrons @ 50 degrees impact angle

Requirements:

- $\sigma_E/E = \mathcal{O}(10\%)$ for CE
- σ_T < 500 ps for CE
- $\sigma_{X,Y} \leq 1$ cm
- Operate in 1T and 10^{-4} Torr
- Operate in harsh radiation environment

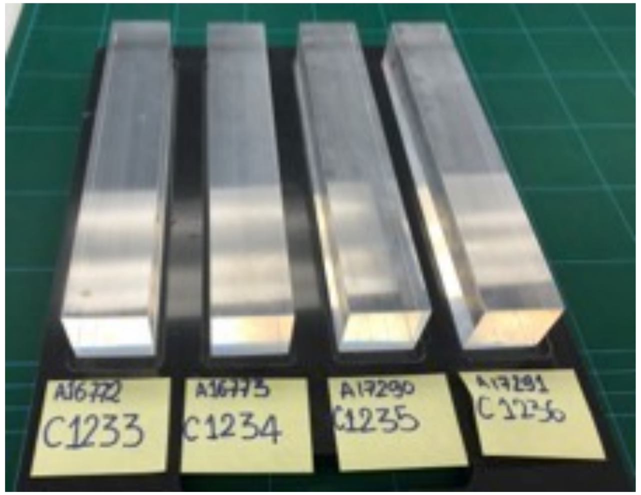


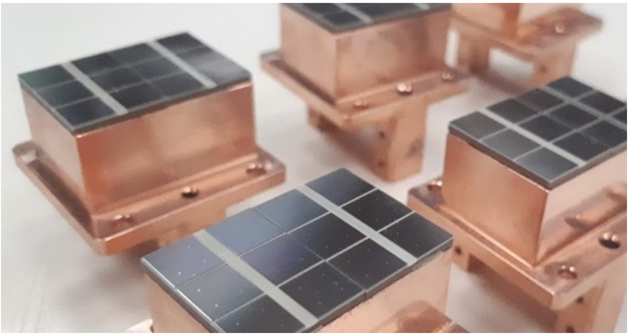
EMC design:

- Two annular disks, R_{in}=374 mm, R_{out}=660 mm, $10X_0$ length, ~ 70 cm separation
- 674+674 square x-sec **pure CsI crystals**, (34×34×200) mm^3, Tyvek + Tedlar wrapping
- Redundant readout: For each crystal, two custom arrays (2×3 of 6×6 mm^2) **large area UV-extended SiPMs**
- Analog FEE directly mounted on SiPM + digital electronics in on-board custom crates
- Calibration/Monitoring with 6 MeV radioactive source and a laser system

Technological choice

- Crystals with high Light Yield for timing/energy resolution
  - **LY(photosensors) > 20 pe/MeV**
- Fast signal for Pileup and Timing:
  - **τ of emission < 40 ns**
  - Fast readout chain
- Redundancy in the readout chain
  - **Two full independent readout chains per crystal**
- Radiation Hardness (5 years of running with a safety factor 3):
  - Crystals should survive a TID of **90 krad** and a fluence of **3×10^{12} n/cm^2**
  - Photo-sensors should survive **45 krad** and a fluence of **1.2×10^{12} n_{1MeV}/cm^2**
- **1 T magnetic field** operation





Undoped CsI + **UV-extended SiPMs** + **Fast electronics**

Undoped CsI	UV-extended SiPMs	Fast electronics
Radiation hard	New silicon optical window	FEE: amplifier + shaper
Fast emission time	30 % PDE @ 310 nm	Digitizer @ 200 Msps
310 nm emission	TSV readout, Gain = 10^6	Rad-hard components

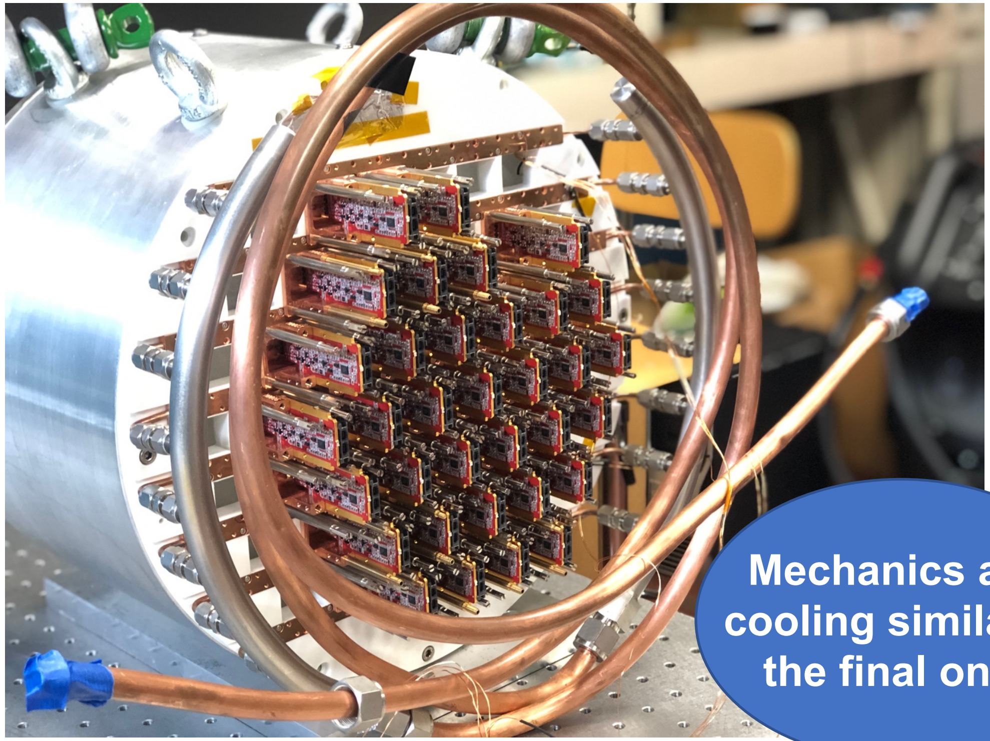
To reduce/handle the neutron induced leakage current SiPMs should be cooled down (x2 Idark reduction/10 °C)

SiPM running temperature at –10 °C

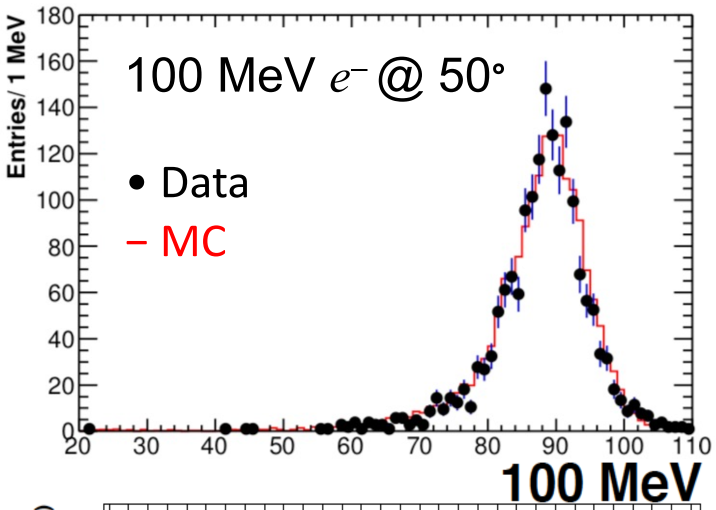
Module 0

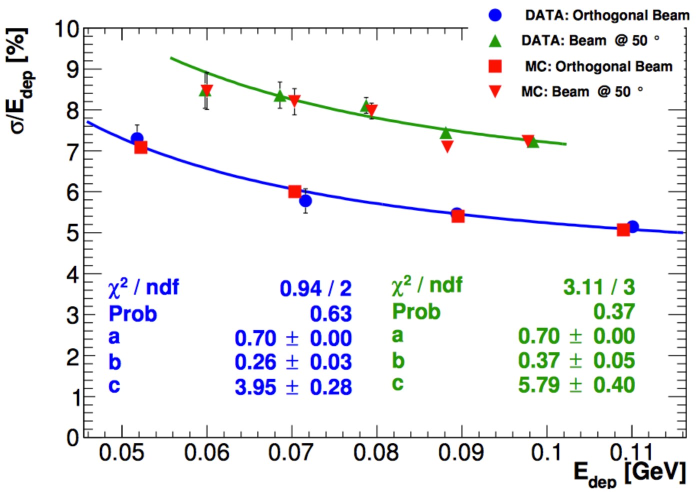
Calorimeter performance validated with Module 0, a large-scale calorimeter prototype (51 crystals, 102 SiPMs/FEE, commercial digitizer) equipped with pre-prod components and tested with e^- beam

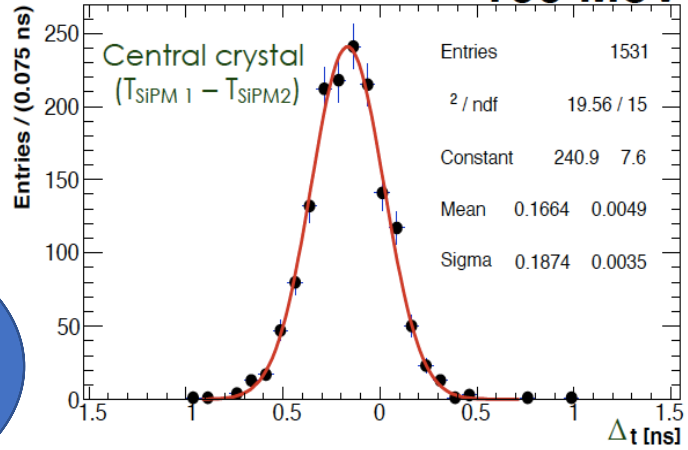
- Mu2e requirements well satisfied
- Green light for production components

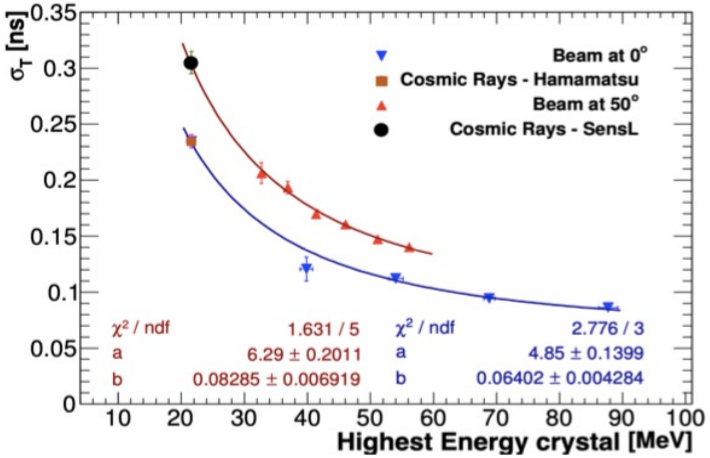


Mechanics and cooling similar to the final ones



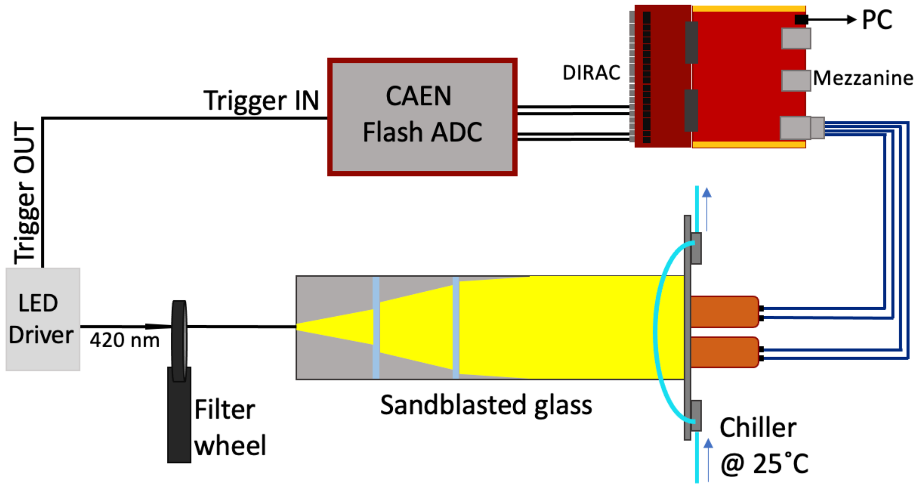


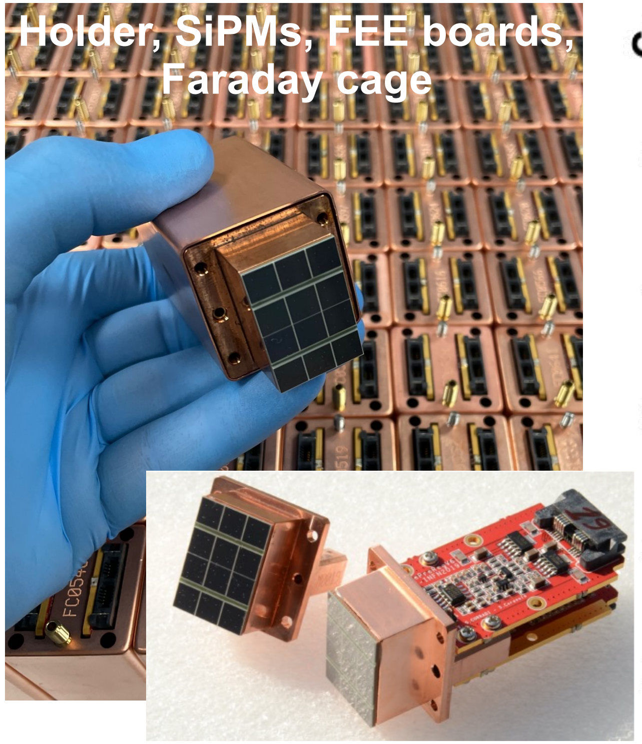


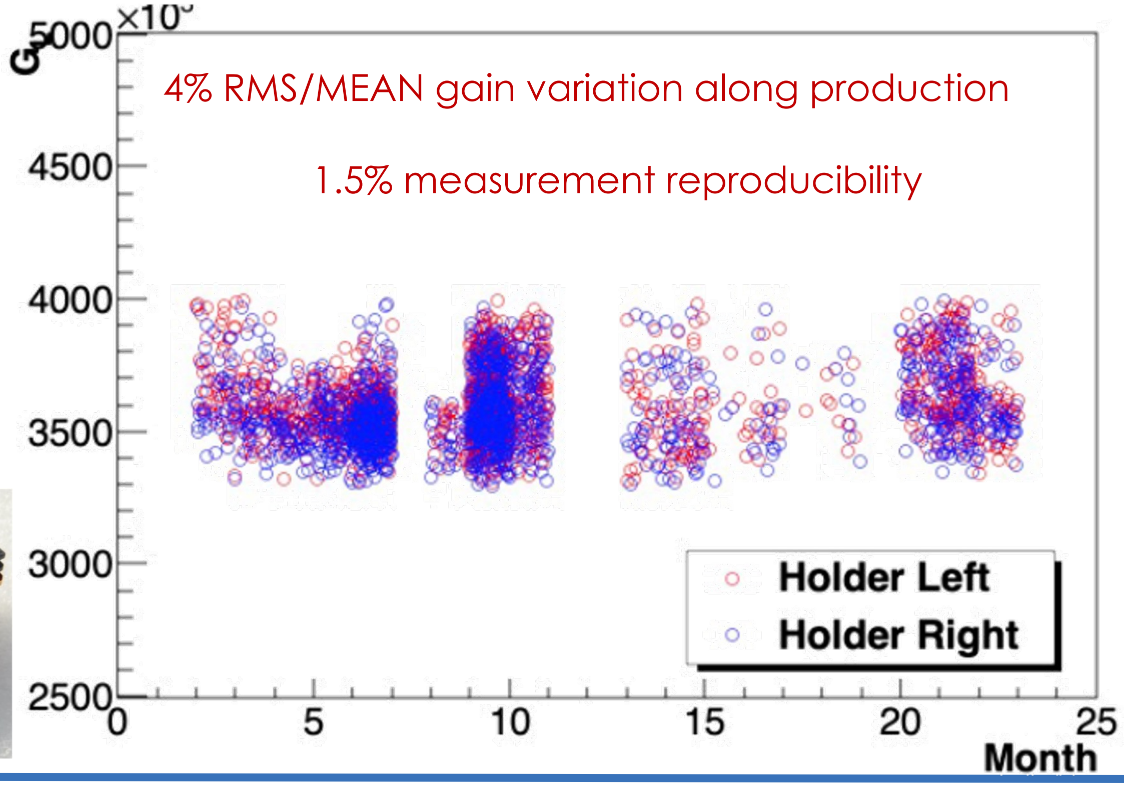


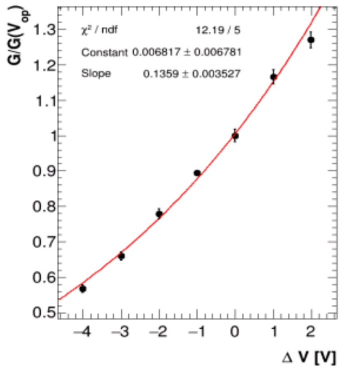
QC of production components

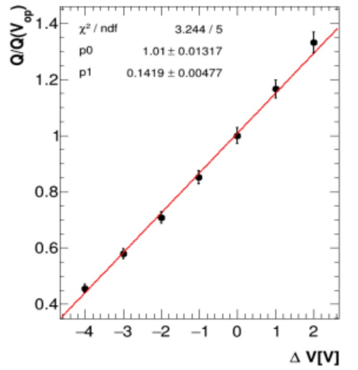
- Crystals/SiPM production tests successfully completed in 2020
- All ~ 1500 Read-Out Units assembled and tested:
  - 7 HV settings in the V_{op}-4V ÷ V_{op}+2V interval
  - 9 position filter wheel scan per HV value
  - ➤ **Calibration of Gain, response and PDE + dependency on Vbias**

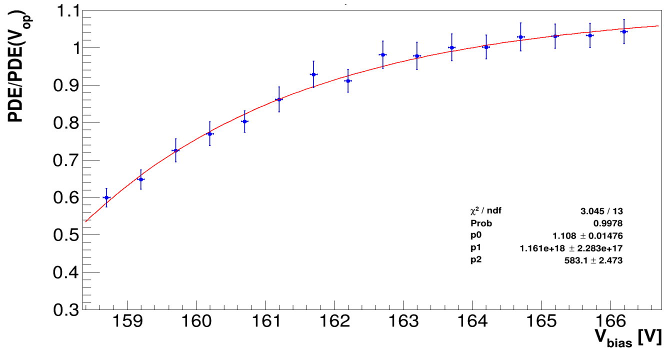








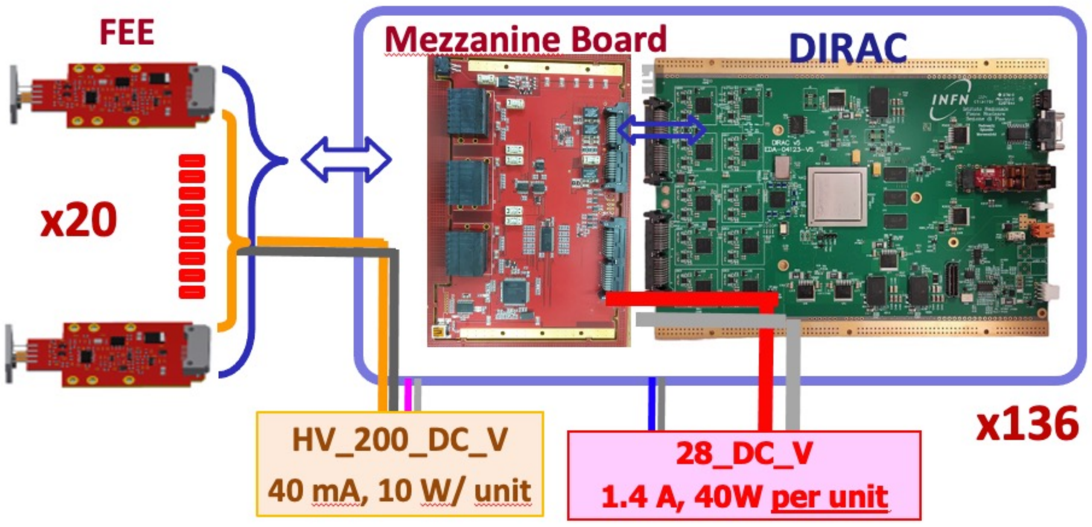


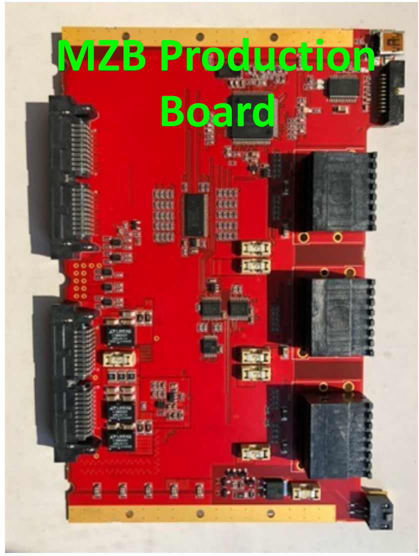


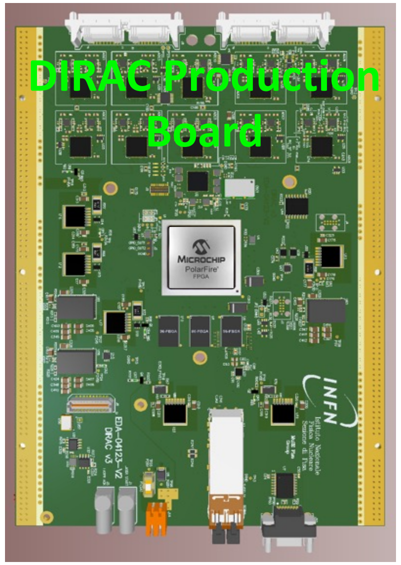
Digital electronics

More info in Poster Session:
Electronics and On-Detector Processing (E.Pedreschi/F.Spinella)

- Two digital boards:
  - MZB for SiPM/FEE HV settings & readout (HV, I, T)
  - DIRAC for digitization @ 200 Msps, 12 bit ADC
- 2019-2021 B-field test + irradiation tests (TID, neutrons) with single components/boards
- End of 2022: **SEL problem discovered on ARM processor (MZB) and Flash Memory (DIRAC)** when irradiating boards with charged particle (proton, 60–200 MeV/c, 10^{10} p/cm^2)
- 2023: proton irradiation campaigns + engineering effort to understand and solve the problem
  - **new ARM, new Flash memory** production
  - **new layout with recovery circuits**





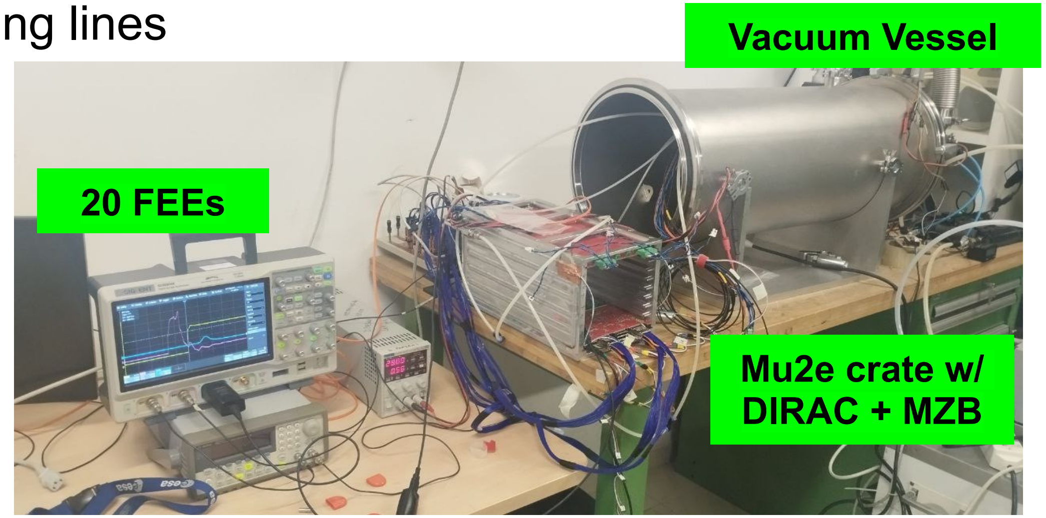


MZB production (140 units) completed
+ Burn-IN + QC tested. **First 80 shipped to FNAL**

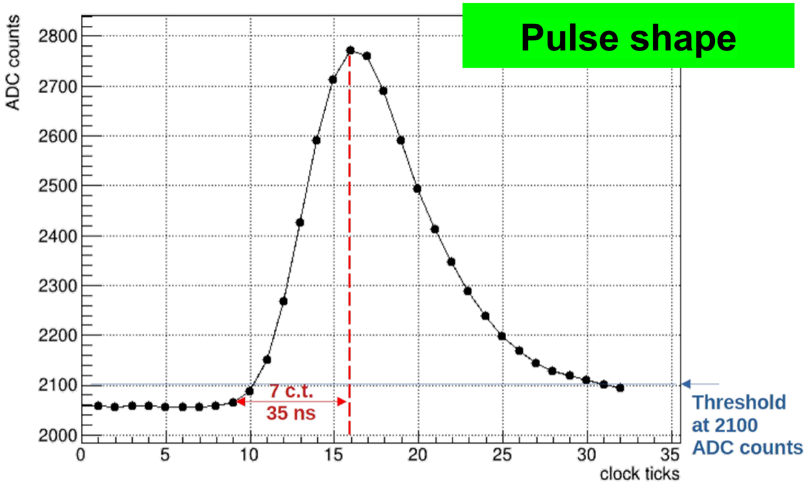
1/2 DIRAC production (70 units) completed
Burn-IN + QC test in progress. **Ship to Fermilab in June**

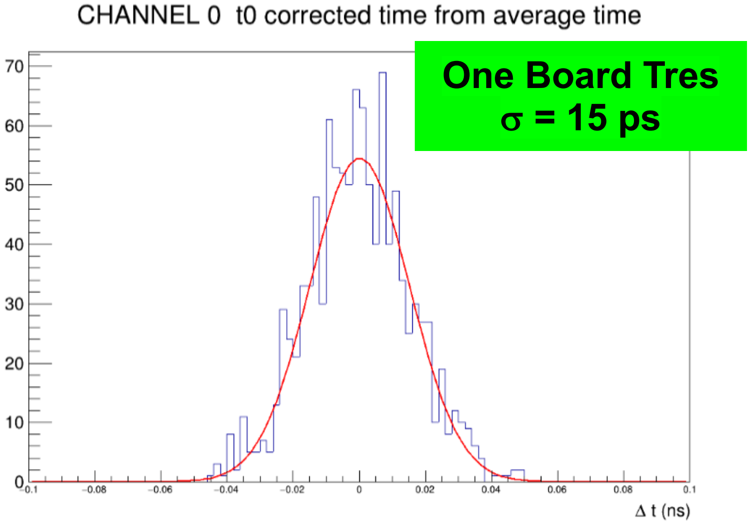
Thermal vacuum test and VST

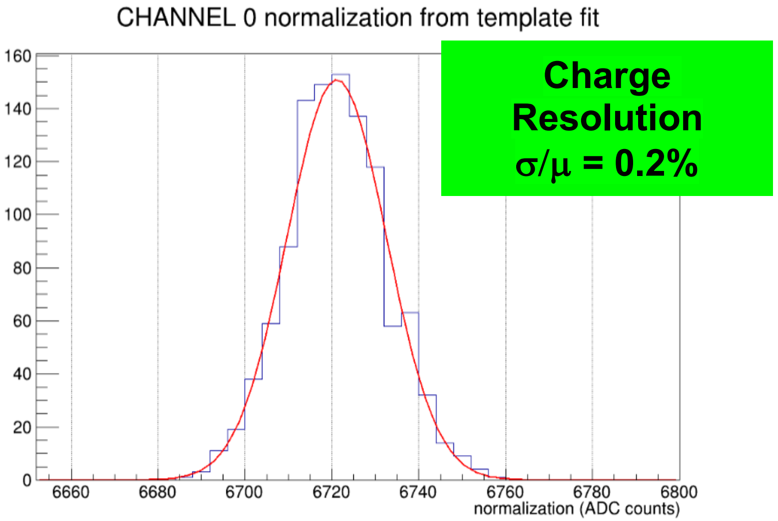
- Setup ready in Pisa for thermal vacuum test to complete temperature measurements in vacuum
- Missing MZB copper plates to dissipate heat through crates' cooling lines
  - 8 DIRACs and 8 MZBs in a final crate
  - More than 20 thermal sensors monitored
  - 20 FEEs modified to provide signals from pulse injection
  - 1 DIRAC is connected to a DTC through an optical flange
  - Mu2e slow control and data acquisition
  - Template fit of signal to evaluate performance



- Preliminary test @ room temperature:

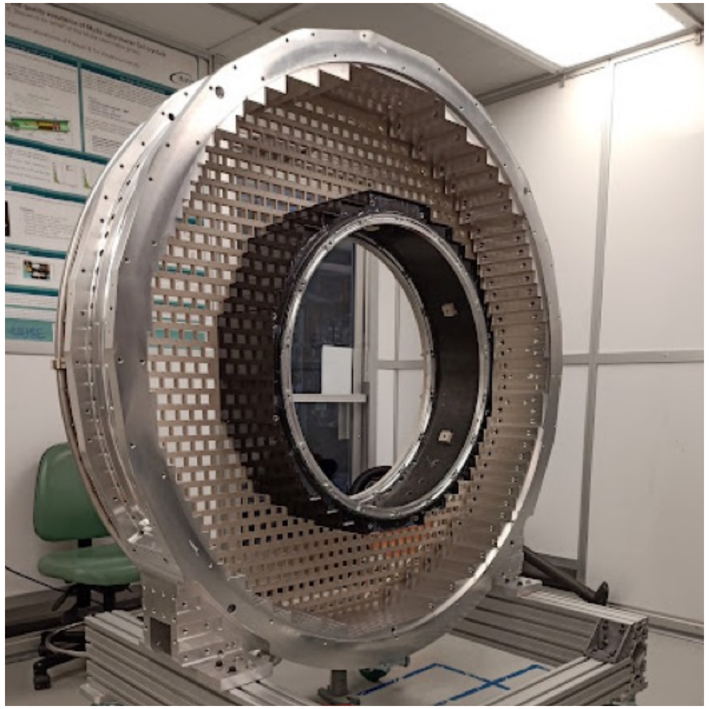
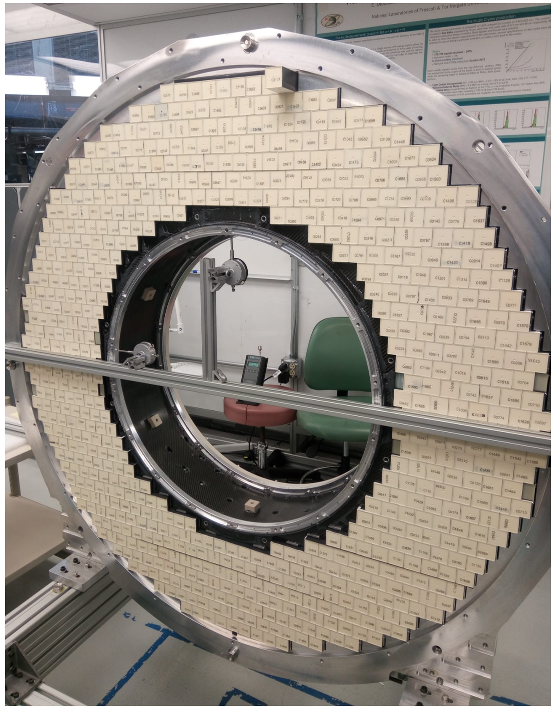
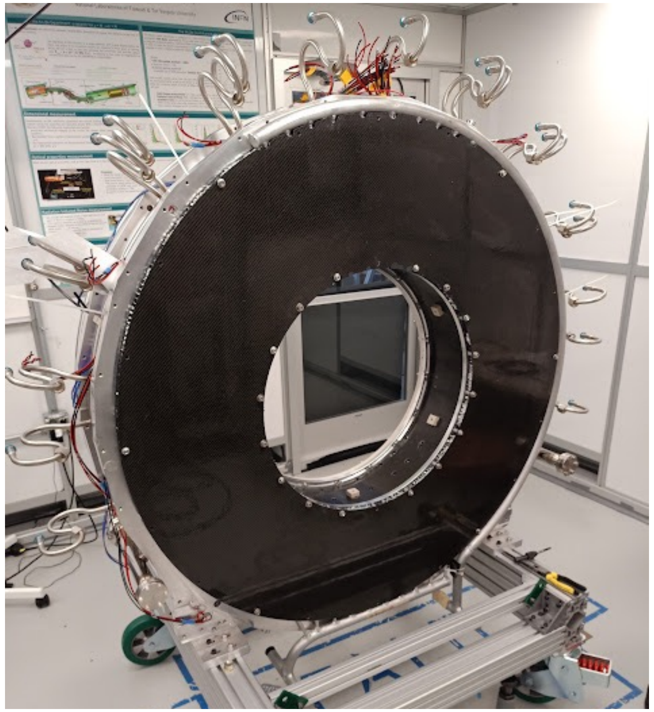
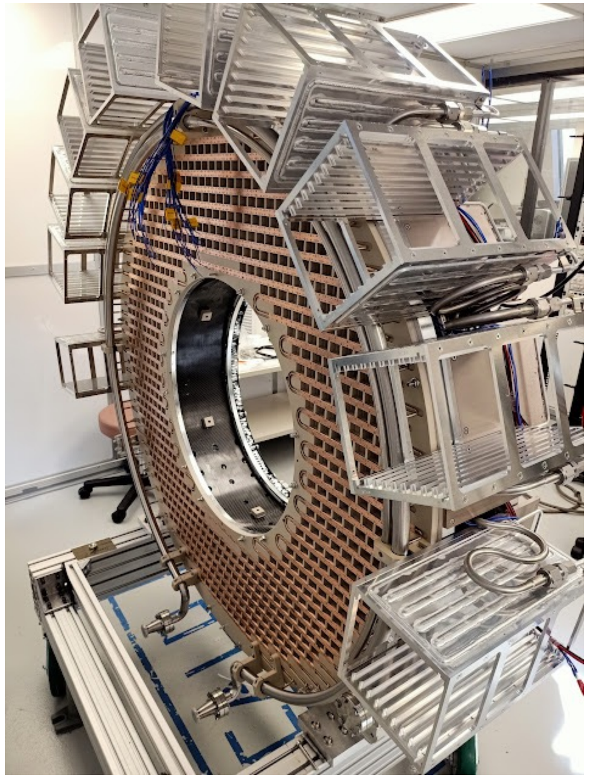






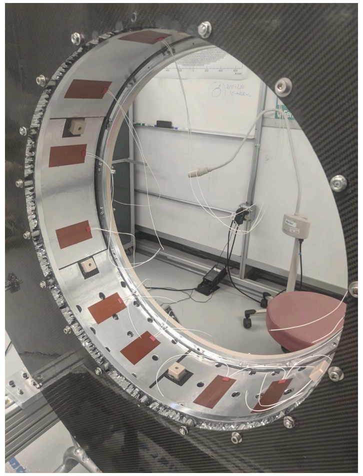
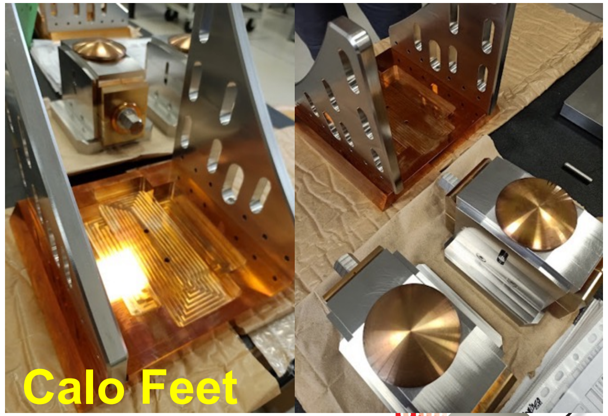
Assembly status: mechanics

More info in Poster Session:
Calorimetry (D. Pasciuto)

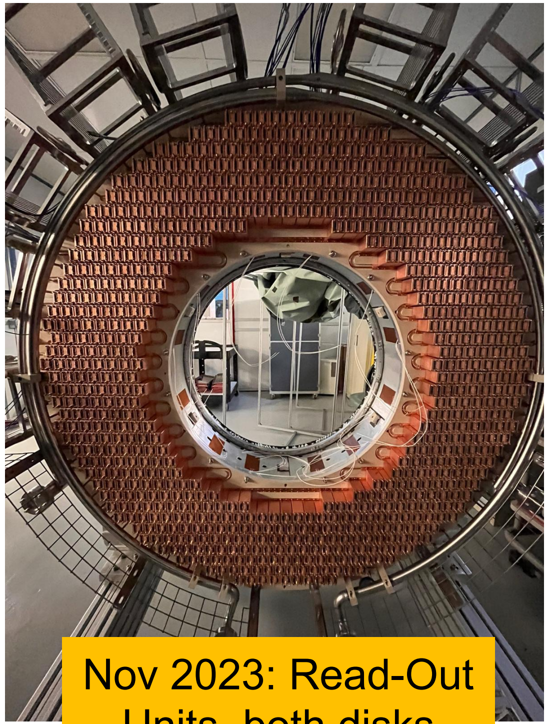





All calorimeter mechanical parts built

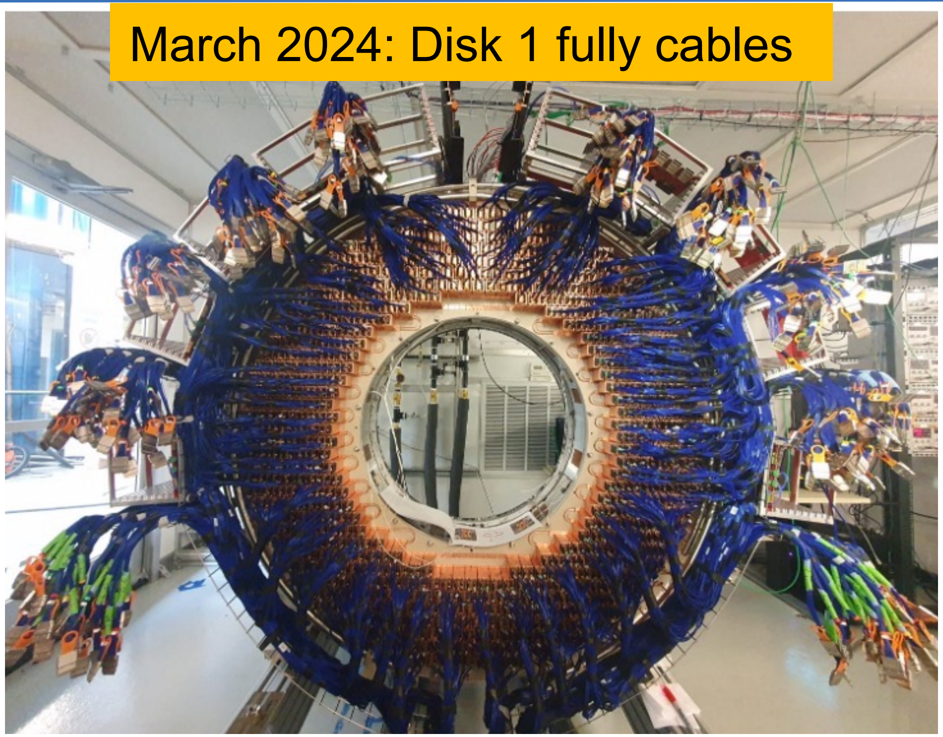
- Disk-1 (Disk-0) mech structure assembled in June 22 (March 23)
- All crystals stacked on both disks
- CF plates with source tubing, Inner Rings installed
- Crates+FEE plates installed and leak checked
- Calorimeter feet for rails at Fermilab (March 2023)

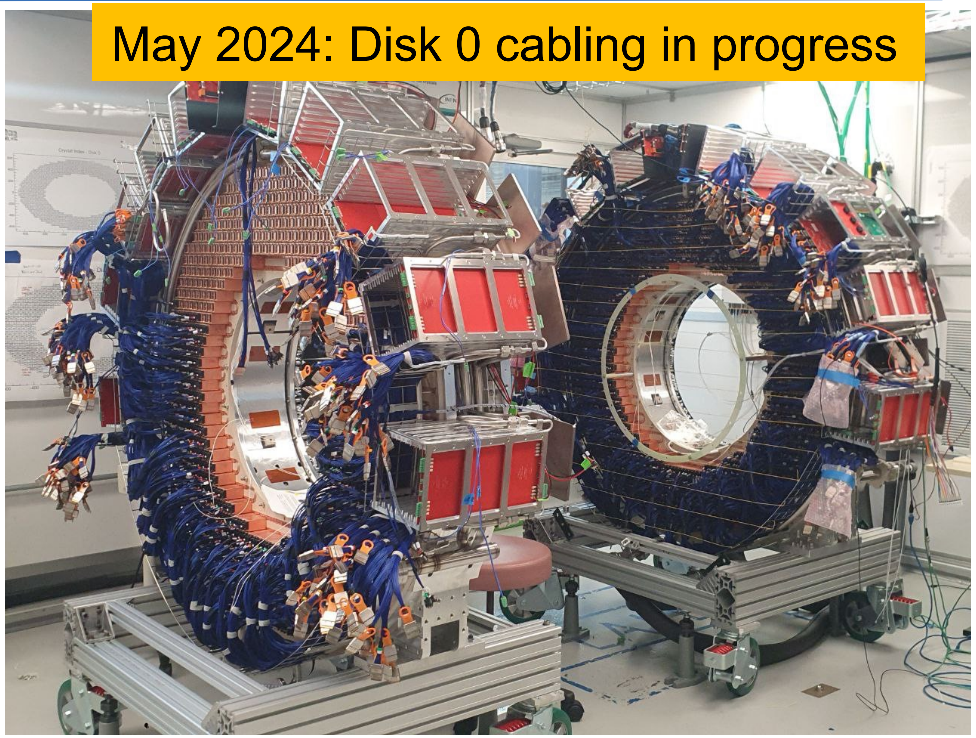
Assembly status: readout



Nov 2023: Read-Out Units, both disks

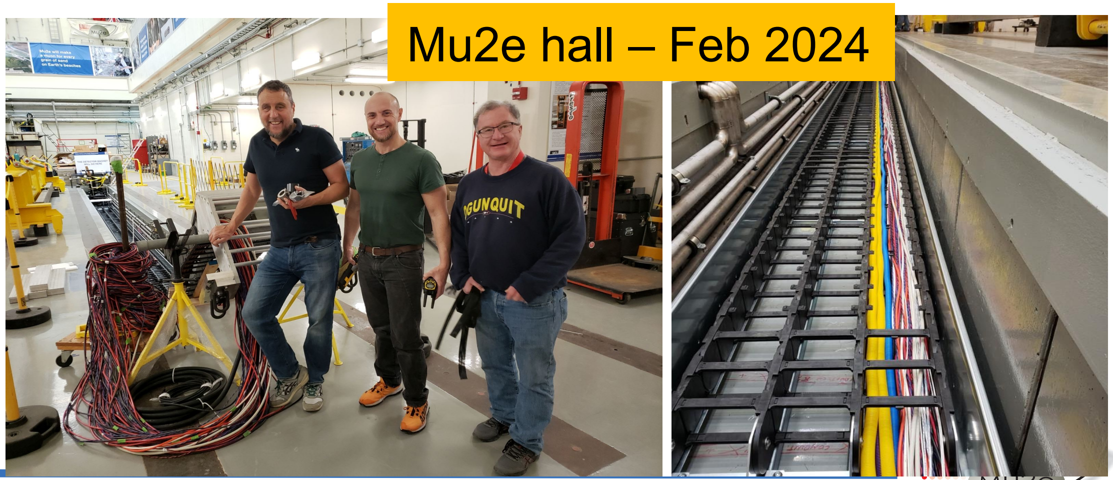


March 2024: Disk 1 fully cables



May 2024: Disk 0 cabling in progress

- For both disks, assembly of analog electronics and power distribution is completed
- Cable routing completed for Disk-1 and 2/3 for Disk-0
- At Mu2e Hall:
  - LV/HV power supplies installed
  - Half DAQ cables and optical fibers installed



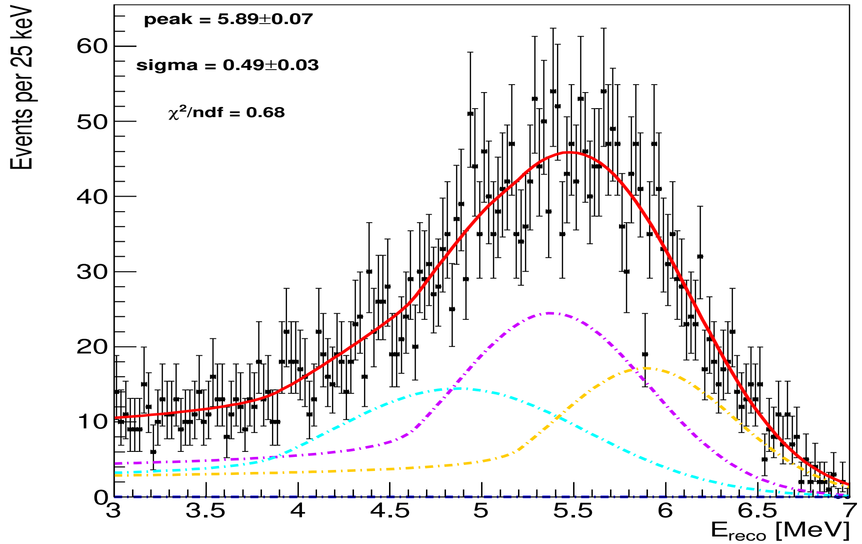
Mu2e hall – Feb 2024

Source calibration system

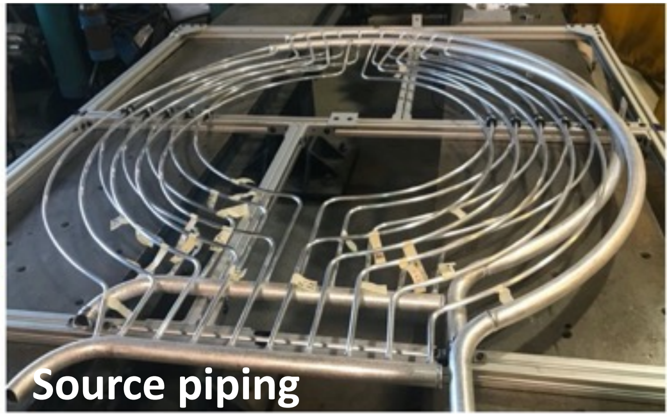
- Neutrons from a DT generator irradiate a fluorine rich fluid (Fluorinert) that is piped to the front face of the disks
- The following reaction chain grants photons at 6.13 MeV

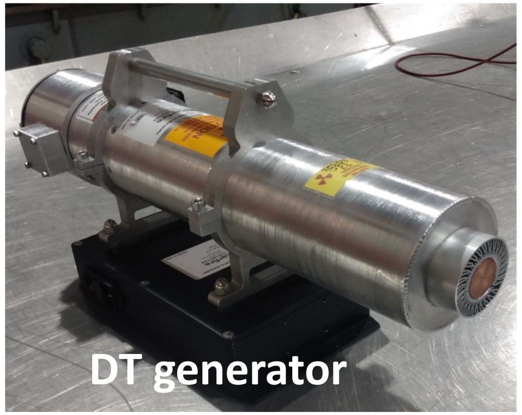
$$^{19}F + n \rightarrow \; ^{16}N + \alpha$$
$$^{16}N \rightarrow \; ^{16}O^{*} + \beta \quad t_{1/2} = 7\ \mathrm{s}$$
$$^{16}O^{*} \rightarrow \; ^{16}O + \gamma(6.13\ \mathrm{MeV})$$

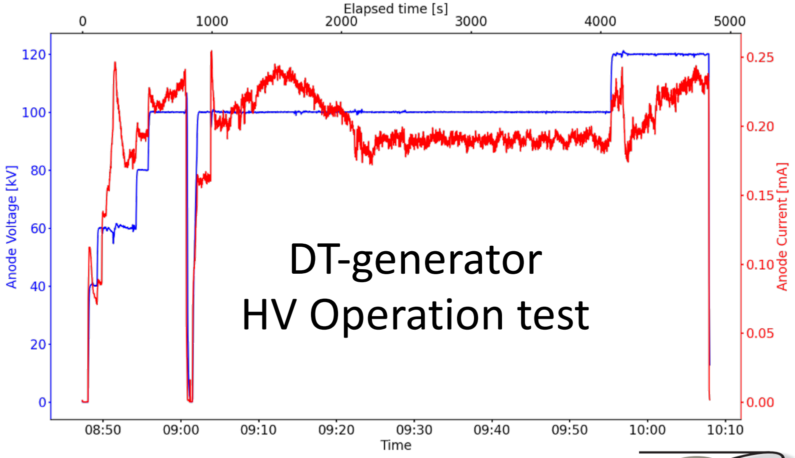
- The produced gamma's illuminate uniformly the crystals
- Few minutes of data taking calibrate each crystal at O(%)



- Source DT generator installed in Mu2e hall in its "cave" in 2022, final shielding completed in 2023
- DT-generator HV operated up to 120 kV. ESH radiation survey performed in 2023 /2024 well within limits

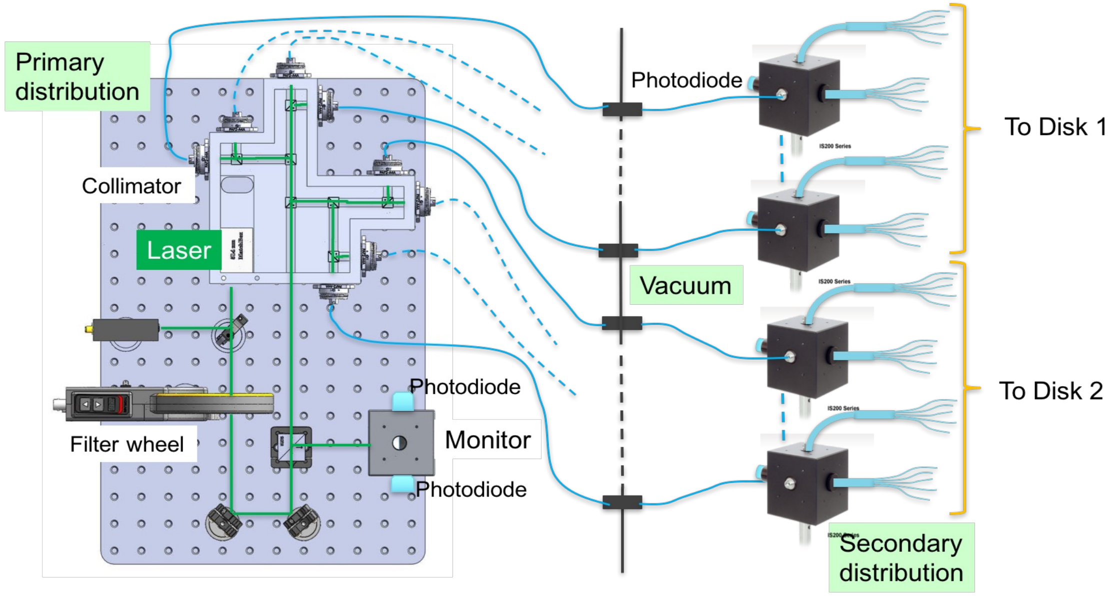


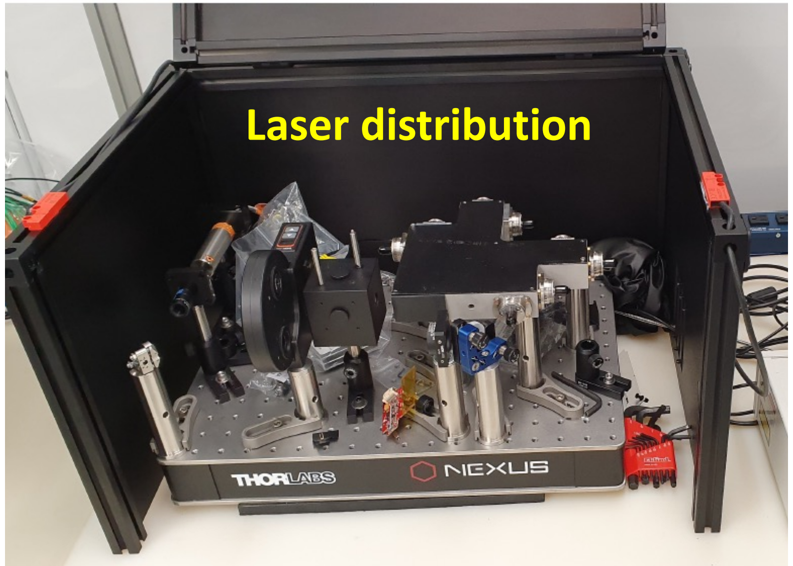


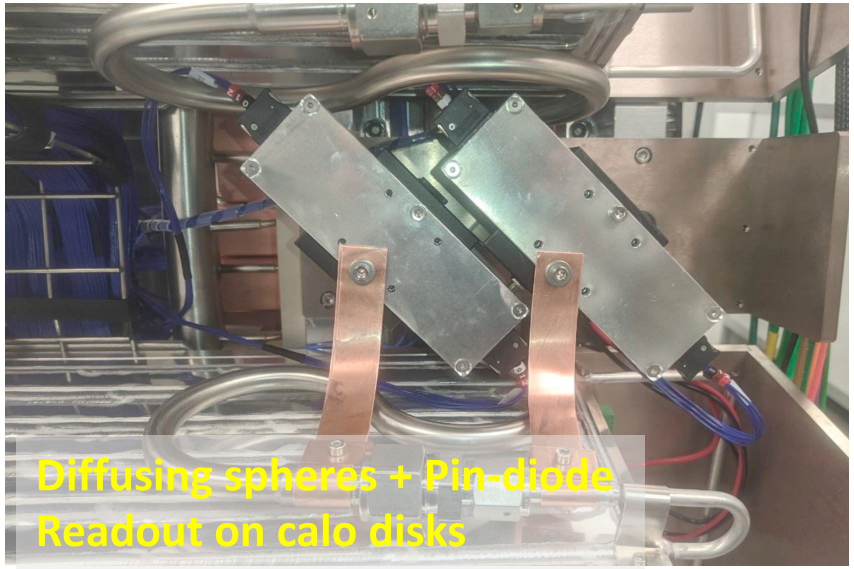


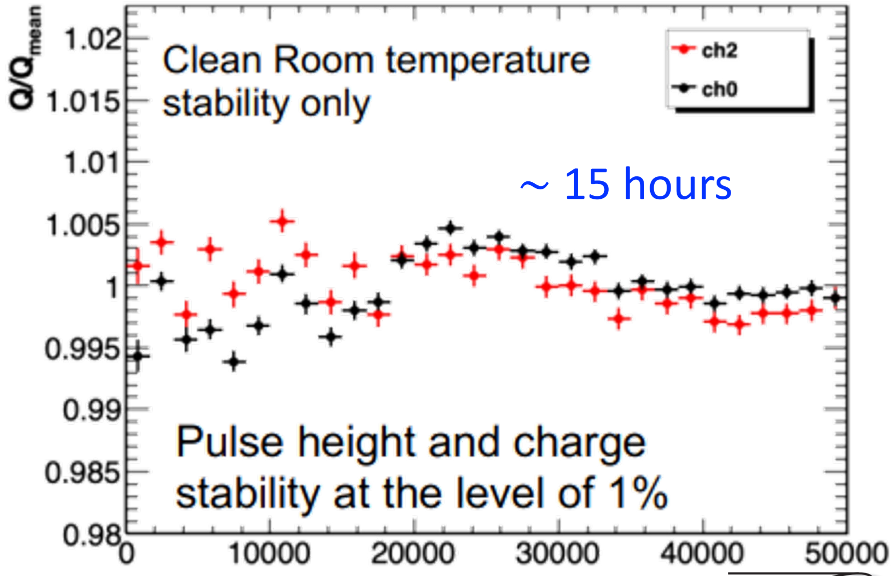
Laser calibration system

- A pulsed green laser illuminates all crystals through a distribution system based on optical fibers and integration spheres
- Monitor gain variation at level of 0.5%
- Determine T0's at level of 100 ps
- Stability at a level of few %, monitored with PIN Diodes at laser source. Used at low rate in off-spill gates





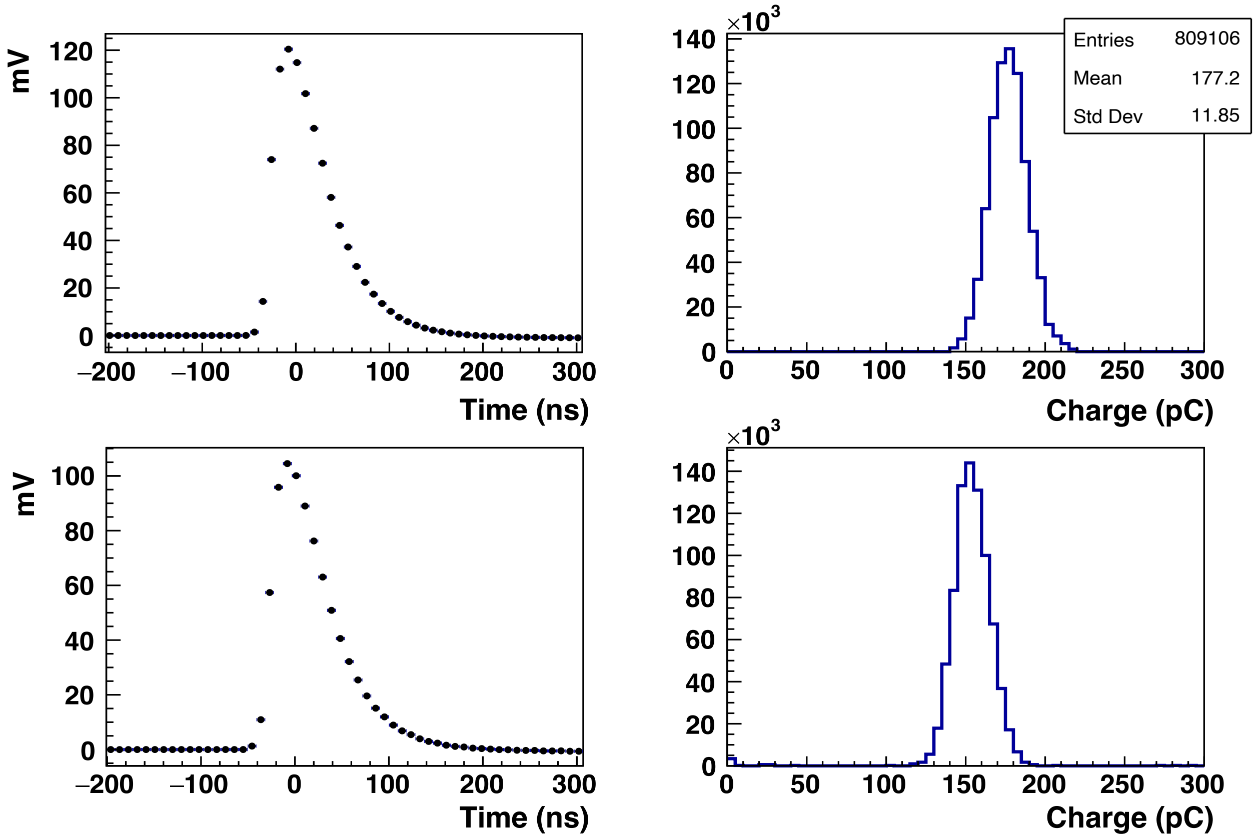


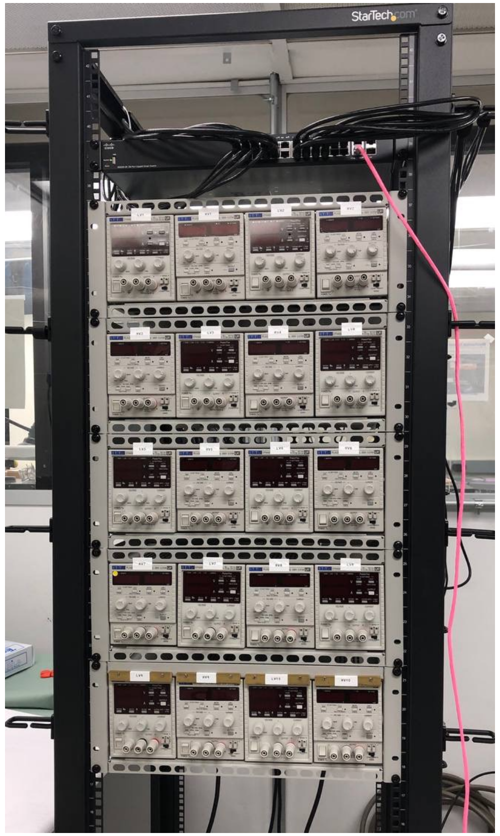


Calorimeter commissioning

Assembly room @ FNAL, commissioning of ½ disk at a time:

- 4 PC servers, 6 Data Transfer Controllers, TDAQ fibers
- Readout of 36 boards, Event Builder + CR trigger selection
- Calibration/Commissioning with laser + Cosmic Ray events



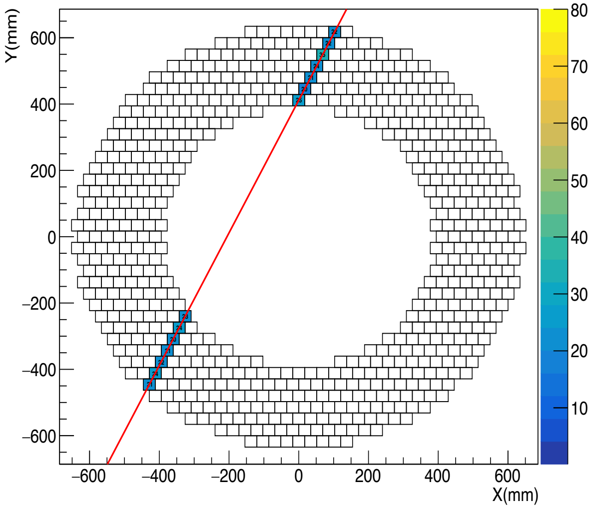


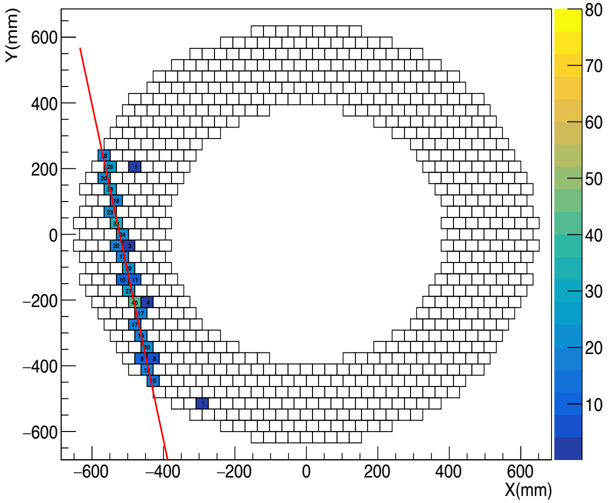
- First laser data from the fully cabled calo disk in one calorimeter sector
- After this final test, the calorimeter will be moved in the Mu2e hall (fall 2024)

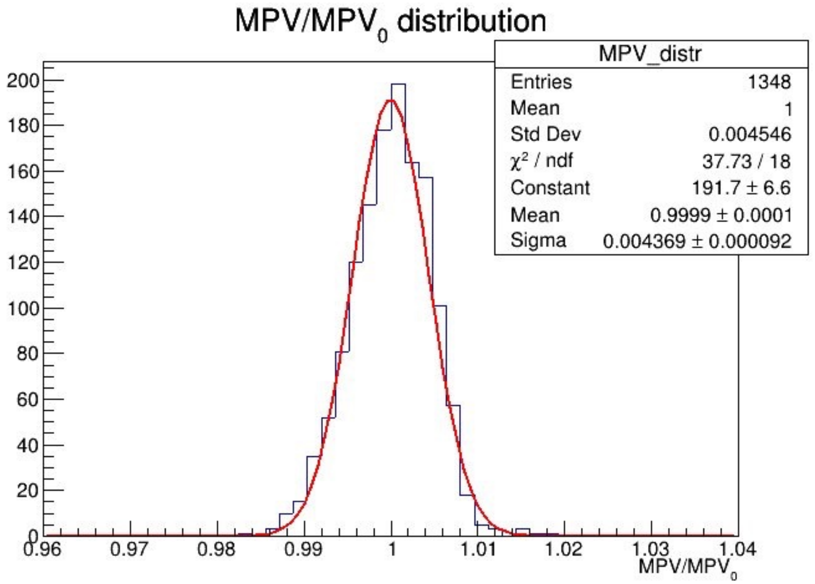
Monte Carlo studies for in-situ calibration

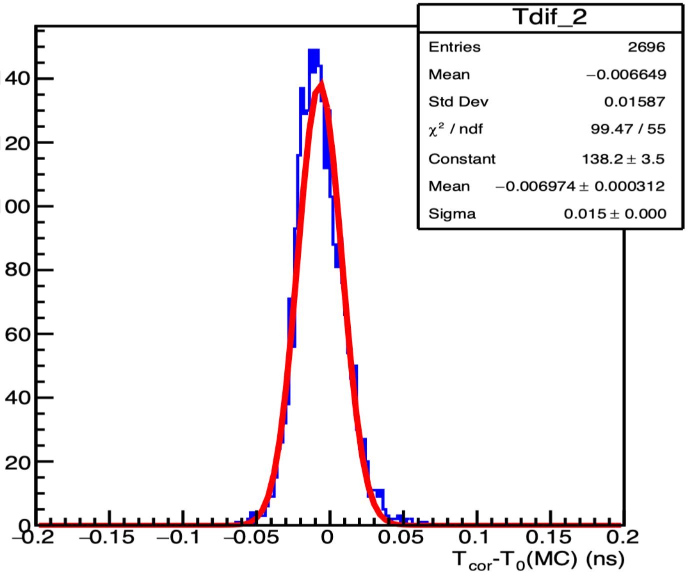
Calibration algorithms developed for in-situ energy and time calibration with 10h cosmic ray MC events:

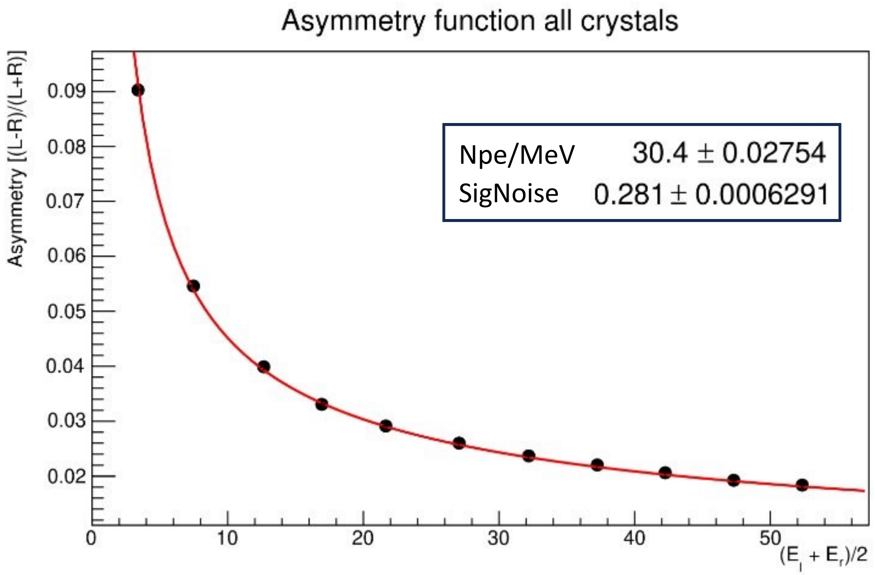
- Fast calorimeter-based trigger selecting CRs crossing calo disks
- ~ 0.5% spread on energy calibration
- T_0 calibration at 15 ps level
- Npe/MeV evaluated from the response of the two SiPMs connected to the same crystal





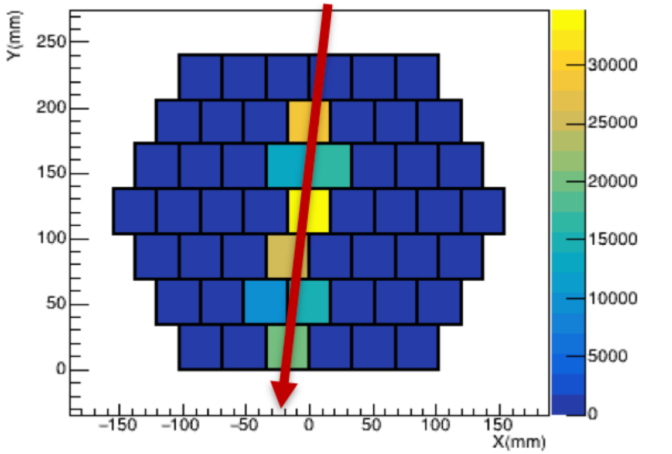


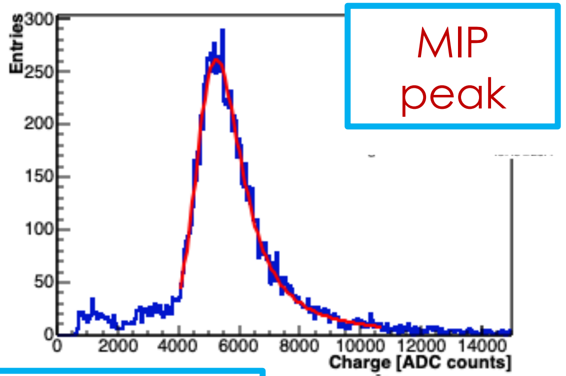


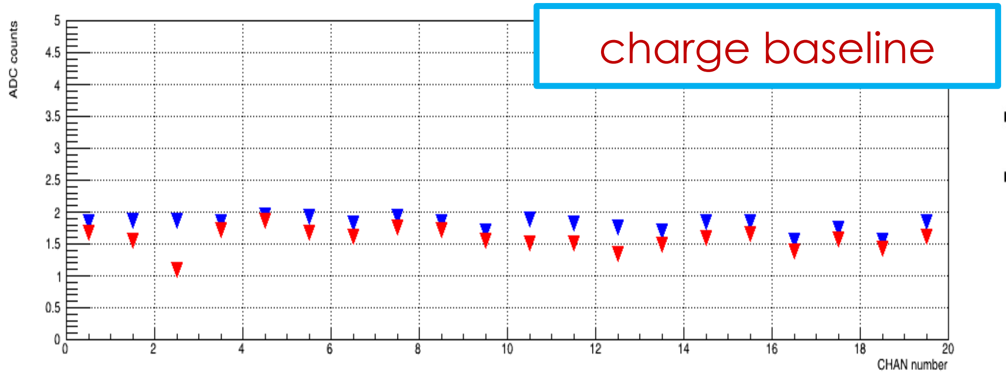


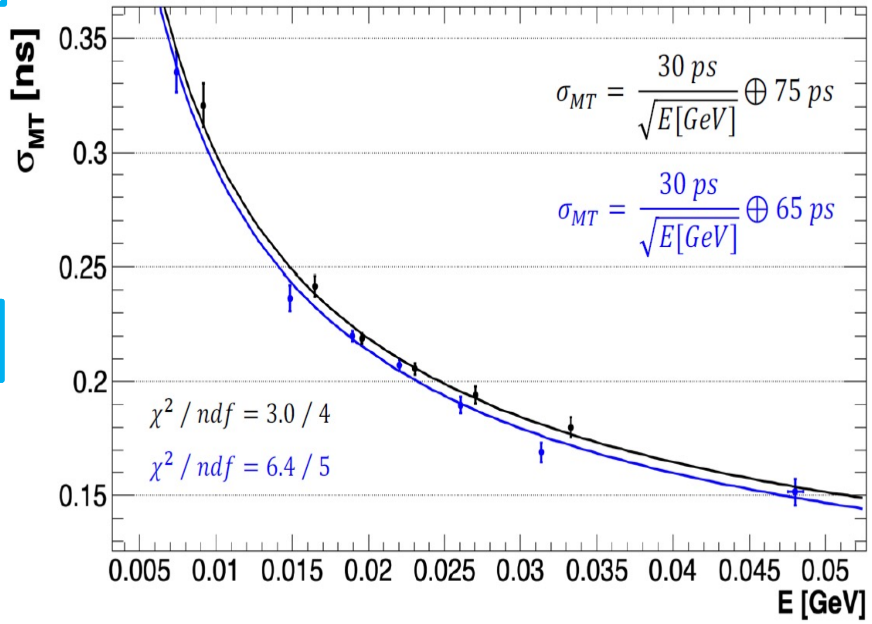
Vertical Slice Test: cosmic ray events

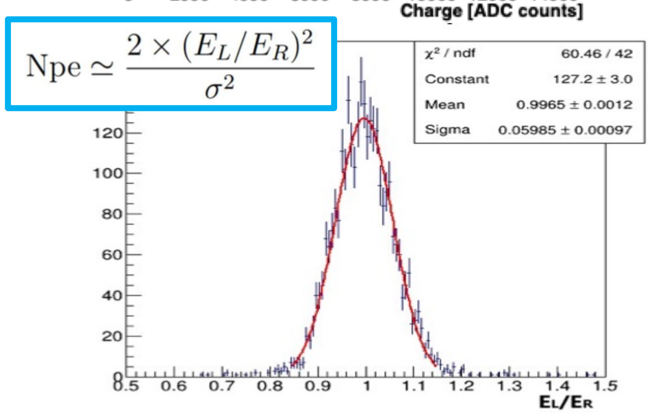
- Module-0 equipped with MZB + DIRAC v2 boards, data collected in vacuum and at low T
- CR events triggered with external scintillators, XY MIP track reconstruction
- Calo calibration & monitoring algorithms finalized with simulation and Module-0 data:
  - Energy equalisation on 21 MeV MIP peak
  - Equivalent noise ≈ 200 KeV
  - Npe and SiPM gain stability check (+1.6 % /°C for SiPM gain)
  - Improved time evaluation + timing alignment @ 15 ps level

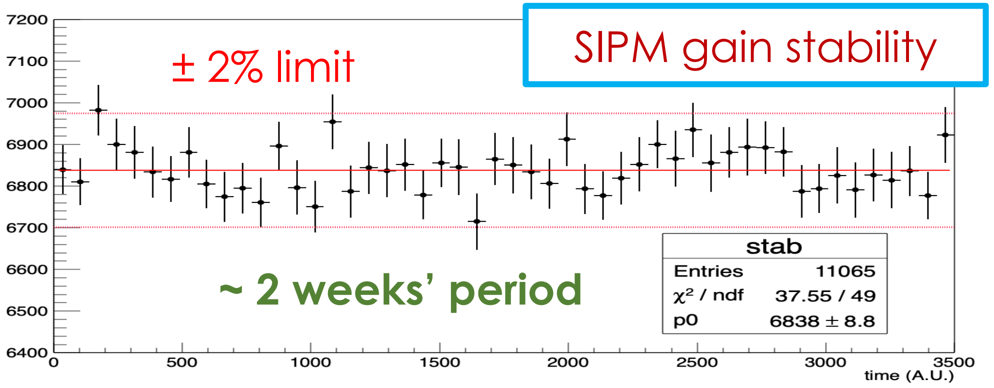






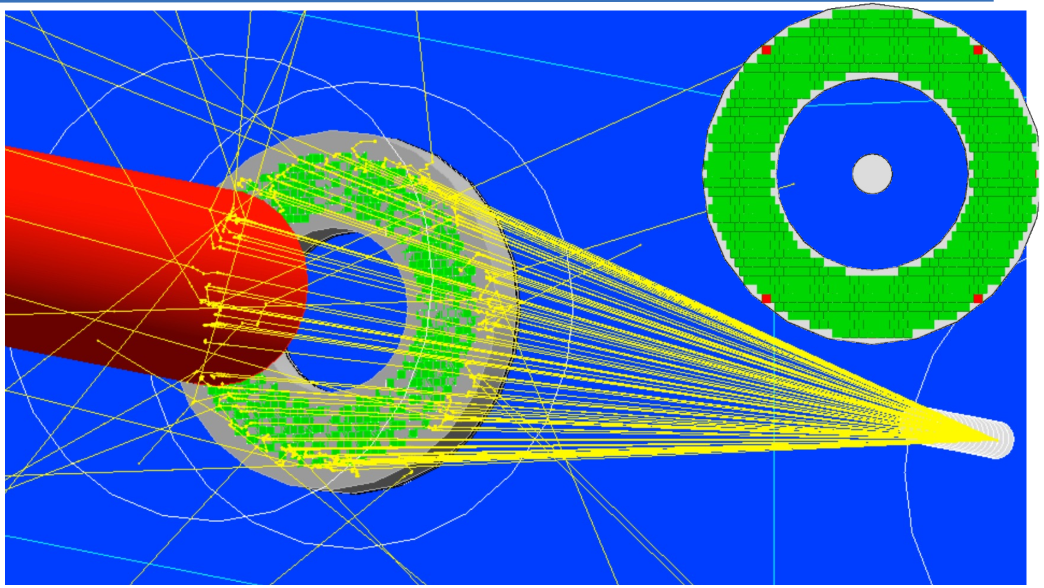


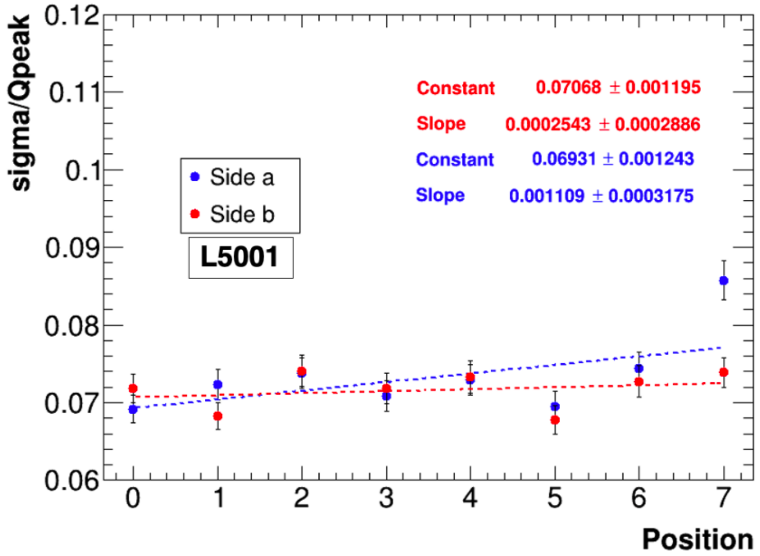




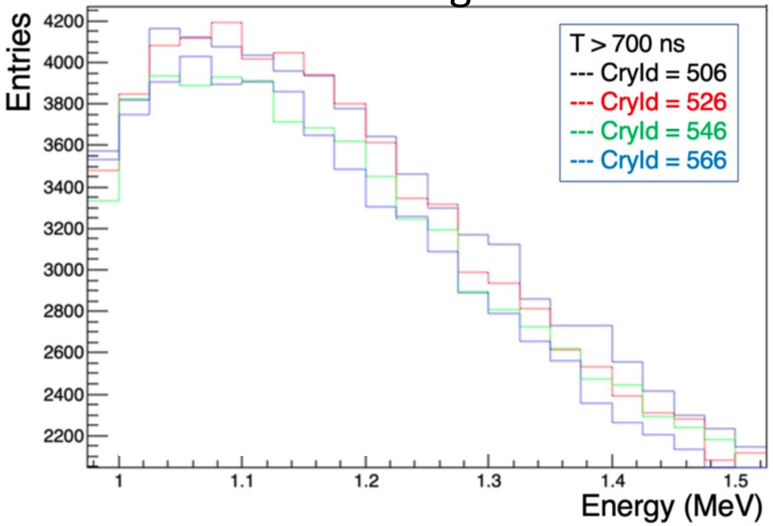
CAPHRI: calo beam normalization & monitor

- Calorimeter Precision Hi-Resolution Intensity Detector (CAPHRI)
- 4 LYSO counters (ESR wrapped) replacing CsI to measure the 1.8 MeV ”golden” line from muon capture in Al nuclei
- Same size of CsI crystals with Mu2e SiPM readout
  - 7-8% E resol., LY ~ 2000 Npe/MeV measured at 511 keV
  - $<\sigma/\mu>$ ~ 3% @ 1.8 MeV
- Faster measurement than STM to follow PBI variations
- **3%** counting error per Injection Cycle (**1.4 sec**) expected from simulation, dominated by sqrt(Bckg)

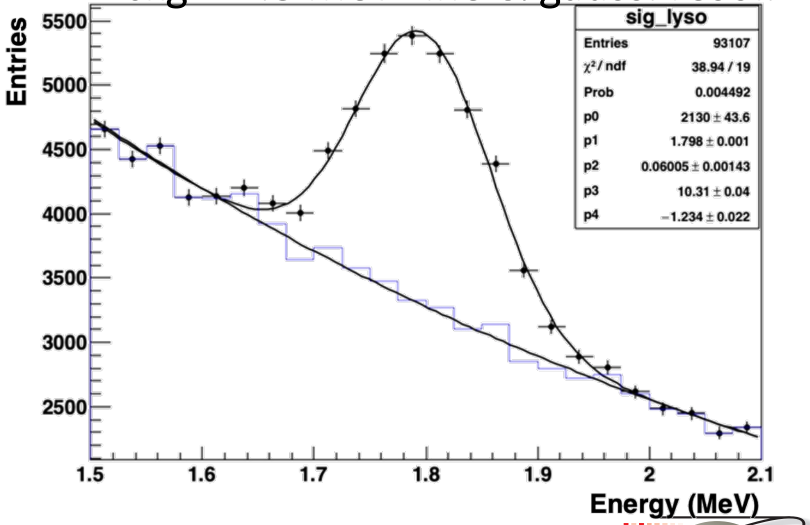




Full simulated bckg



Bckg + 1.8 Mev Line & gauss. resol.



Conclusions

- The Mu2e calorimeter demonstrated excellent energy (<10%) and time (< 500 ps) resolution for 100 MeV electrons for PID, triggering and track seeding purposes
- Production of detector components completed, digital electronics under completion
- Successful VST proved reliable operations and performance in vacuum and at low temperature
- Calibration procedures finalized on Monte Carlo events and verified on prototype
- Calorimeter assembly in an advanced stage, including calibration system
- Final integration of the detector with the TDAQ system is underway
  - Calorimeter commissioning with cosmic ray events with 1/2 disk at a time planned
- Installation and transportation plans are progressing well
  - We expect to move the disks in the Mu2e hall in fall 2024