

Mu2e calorimeter readout electronics

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1. Mu2e: Search for $\mu + N \rightarrow e + N$

Mu2e will search for the coherent, neutrinoless muon-to-electron conversion in the field of a nucleus. This charged lepton flavor-violating process allows to probe energy scales up to thousands TeV, far above the existing colliders. If no conversion events are observed in 3 years of running, Mu2e will set a limit on the ratio between the muon conversion and the muon capture rate: $R_{\mu e} < 6 \times 10^{-17}$ (@ 90% C.L.).

Production Solenoid (PS)

An 8 GeV proton beam hits a tungsten target
A graded magnetic field reflects muons to the TS

Cosmic Ray Veto (CRV)

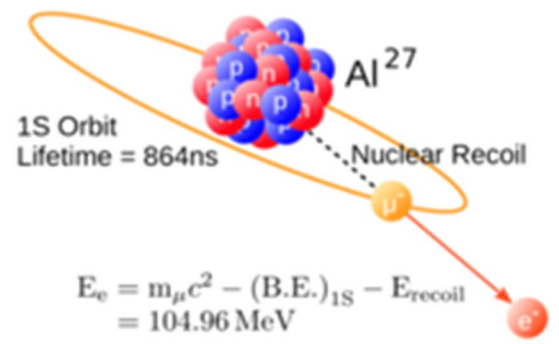
4 layers of plastic scintillator bars
Covers the entire DS and half of the TS

Straw Tracker (TRK)

20,000 low mass straw drift tubes
Momentum resolution **180 keV/c**
@100MeV/c

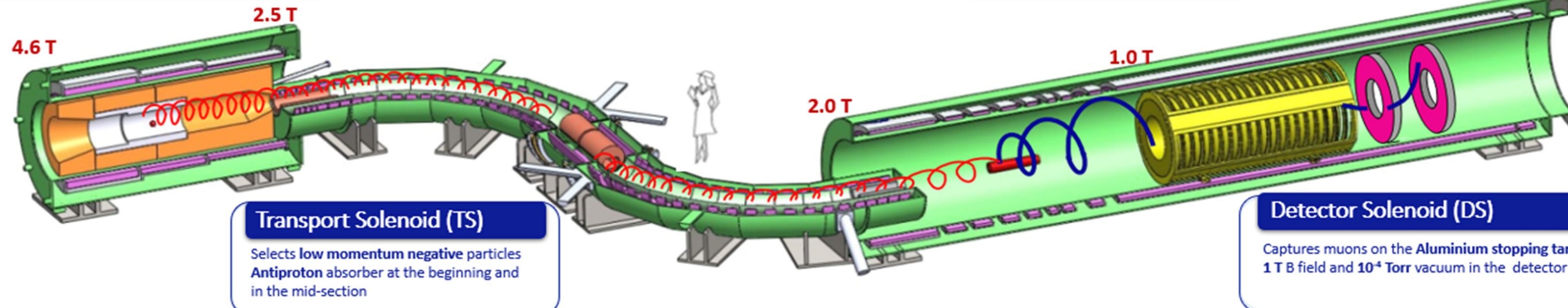
Electromagnetic Calorimeter (ECAL)

1348 undoped CsI crystals
Energy, Time and Position measurements



Experimental Technique

Stop muons in Aluminium target
Muons quickly get to 1S orbit
Lifetime of muonic atom is 864 ns
Look for the 105 MeV conversion electron



Transport Solenoid (TS)

Selects low momentum negative particles
Antiproton absorber at the beginning and in the mid-section

Detector Solenoid (DS)

Captures muons on the Aluminium stopping target
1 T B field and 10^{-4} Torr vacuum in the detector zone

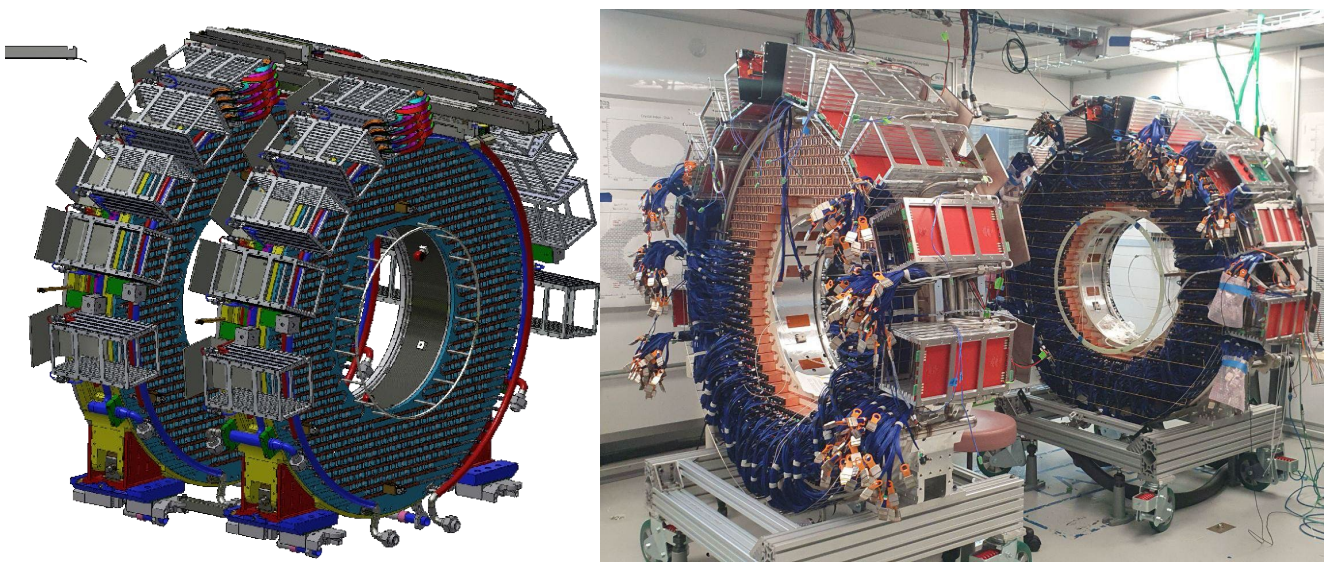
2. The electromagnetic calorimeter

Calorimeter provides:

- Particle identification μ/e
- Seed for track pattern recognition
- Independent trigger

- $\Delta E/E < 10\%$ and $\Delta t/t < 500$ ps
- Position resolution of $O(1$ cm)

- High granularity -> made of 1348 undoped CsI crystals
- Crystals arranged in **two disks** (inner/outer radius 37.4 cm / 66 cm)
- 1 crystal coupled to 2 **large** (14x 20 mm) area **UV-extended SiPM** -> 2696 electronic channels
- DAQ crates located **inside the cryostat** to limit the number of pass-through connectors
- 10 crates/disk with 6/8 boards/crate



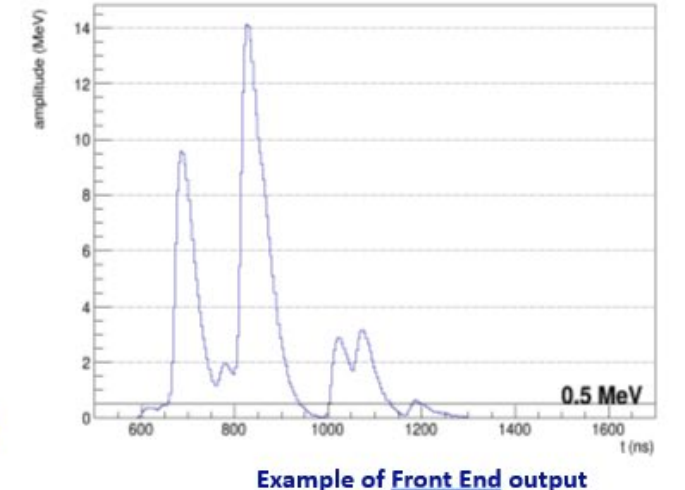
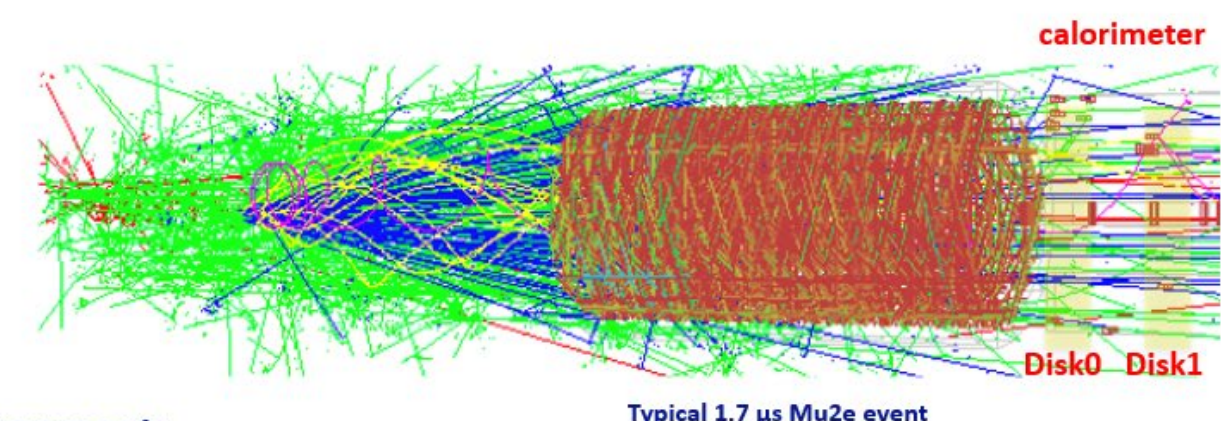
3. Why a digitizer? What requirements?

Requirements:

- Very intense particle flux** expected in the calorimeter -> High Sampling Rate digitizer crucial to resolve pile-up
- Sample SiPM signal at the frequency of **200 Msamples** with **12 bits ADC**

System located inside the cryostat -> Harsh Environment:

- Magnetic field** of 1 T and 10^{-4} Torr vacuum
- Total Ionizing Dose (TID):**
 - 0.5 krad/yr X 12 SF X 5 years
 - TID requirements of 30 krad
- Neutron flux** 5×10^{11} 1 MeV (Si)/yr (from simulation)
- Mechanical constraints:**
 - Limited space -> 20 ADC channels/board
 - Limited access for maintenance -> **Highly Reliable Design** mandatory

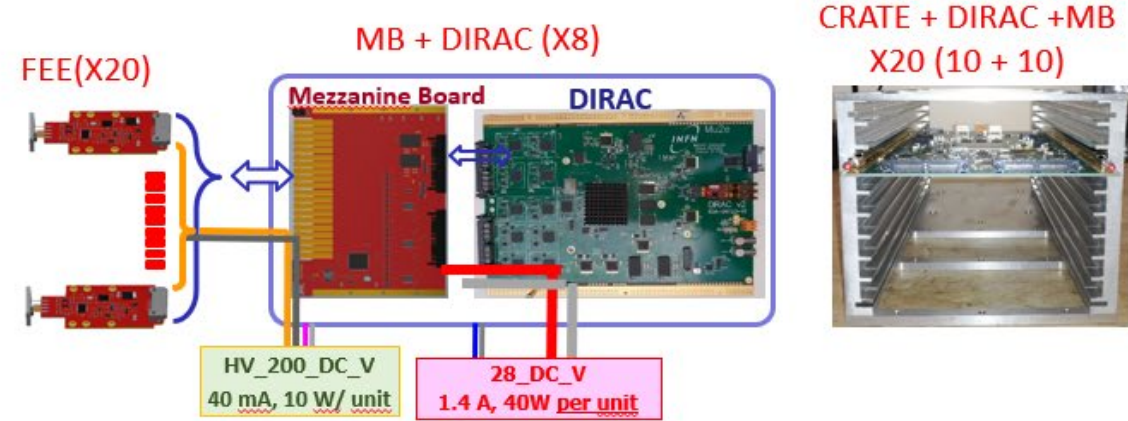


4. Front End Electronics and readout flow

- FE Boards (FEB) connected to SiPM provide:
 - Amplification
 - Local linear regulation of the bias voltage
 - Monitoring of current and temperature
- 2696 FE boards produced + 800 spares
- 20 FEB controlled by 1 Mezzanine Board (MB)
- Differential signals from 20 FEB sent to MB and then to 1 DIRAC
- DIRAC -> sampling, processing and transmission to the Mu2e DAQ

FE requirements:

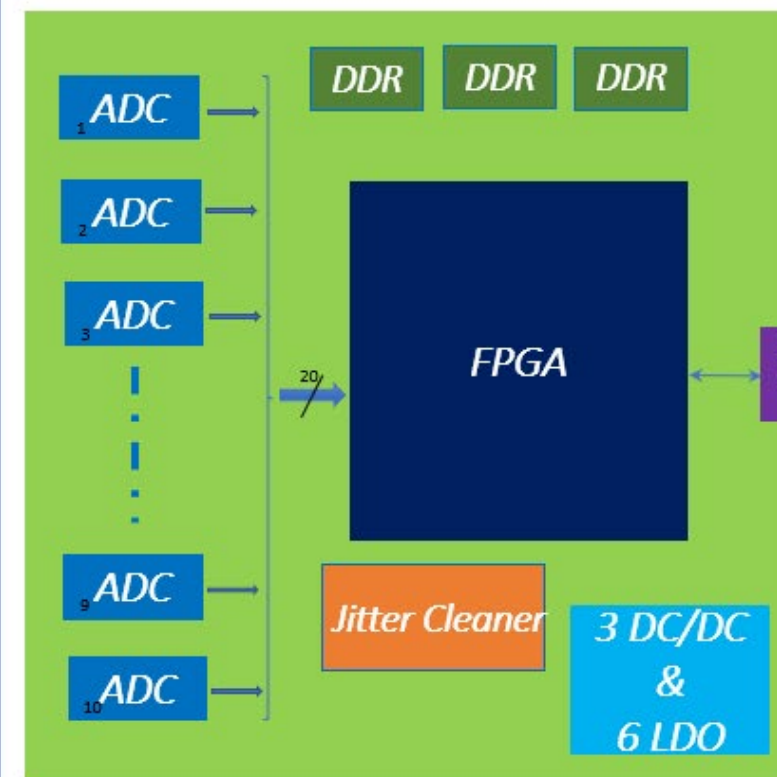
- Magnetic field of 1 T and 10^{-4} Torr vacuum
- Total Ionizing Dose (TID):
 - 1,8 krad/yr x 12 SF x 5 years
 - TID requirement of 100 krad
- Neutron flux 5×10^{11} 1 MeV (Si)



5. Digitizer architecture and design

After an intense campaign of tests:

- ADC:** ADS4229 (Texas Instruments®)
- FPGA:** Polarfire MPF300 (Microsemi®)
- DC-DC:** LMZM33606
- LDO:** MIC69502 (Micrel®)
- Jitter Cleaner:** LMK04828 (Texas Instruments®)
- Optical Transceiver:** CERN VTRX

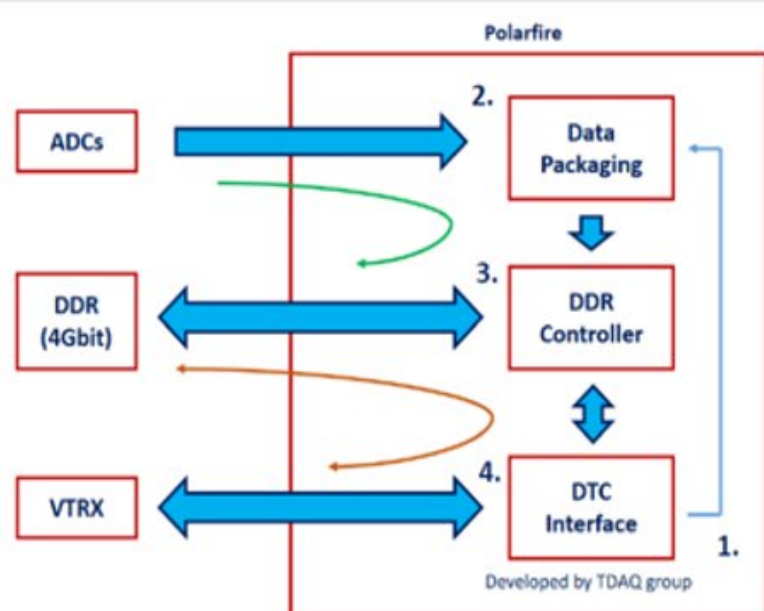


DIRAC PCB specs:

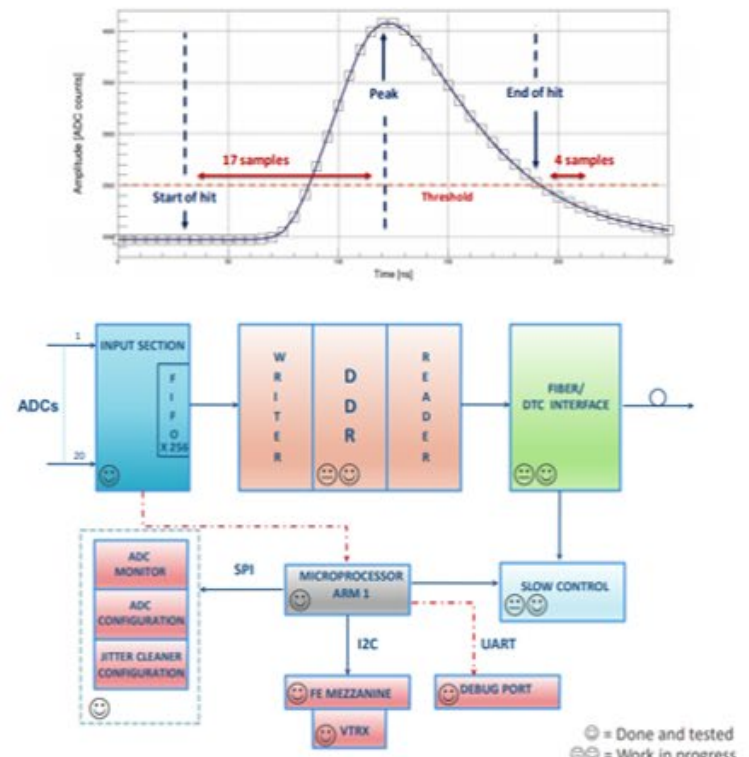
- Material:** FR408-HR
- Layers:** 16
- Dimensions:** 233x165 mm
- Thickness:** 2.127 mm
- Differential lines:** 100 Ω
- Single ended lines:** 50 Ω



6. Digitizer architecture and design



- TDAQ sends an **Heartbeat packet** that contains **EVENT TAG** and **EVENT WINDOWS**
- DIRAC builds the calo hit **applying a zero suppression** and **pre-processing data**
- Data stored in **DDR**
- Tdaq sends a **specific EVENT TAG**, and DIRAC retrieve requested Data Packet from DDR and sends it out to DTC



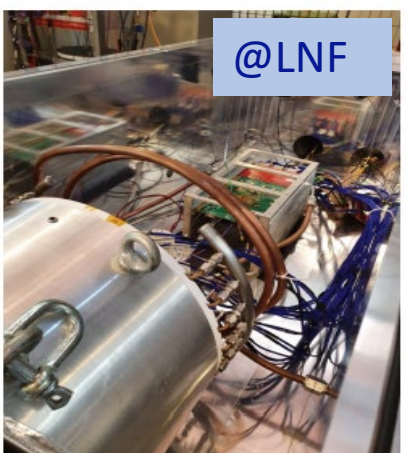
7. DIRAC Qualification Campaign

Final QA/QC tests performed:

- Dose Test of components and boards OK
- B-Field test of DC-DC converters and boards OK
- Neutrons test for DD OK
- Proton test for SEL OK
- Thermal tests in vacuum with copper plate OK

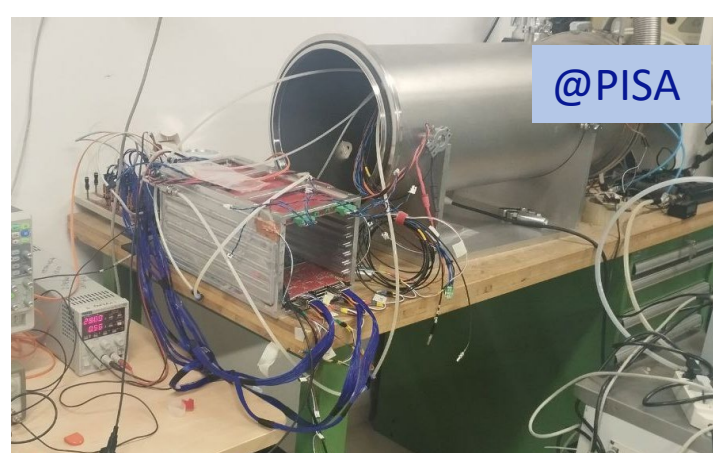


8. Vertical Slice test



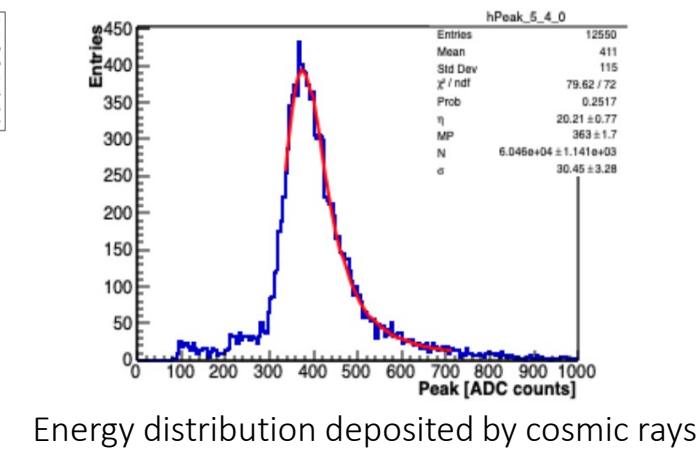
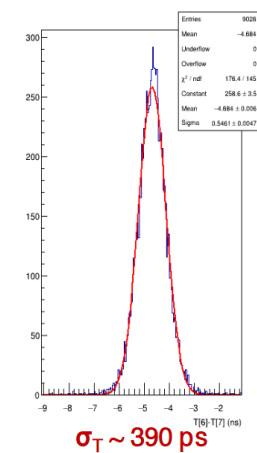
Large scale EMC prototype:

- 51 CsI crystals
- 102 Mu2e SiPMs
- 102 FEE boards
- 2 DIRAC
- Vacuum & Cooling



Final crate, fully equipped

- 8 DIRAC V5 (final)
- 8 Mezzanine board
- 20 Front end (ext. pulse)
- Vacuum & Cooling



- Comparison with commercial digitizer showed no differences in performances
- Obtained time resolution in accordance with expectations
- Noise level and dynamic scale as expected