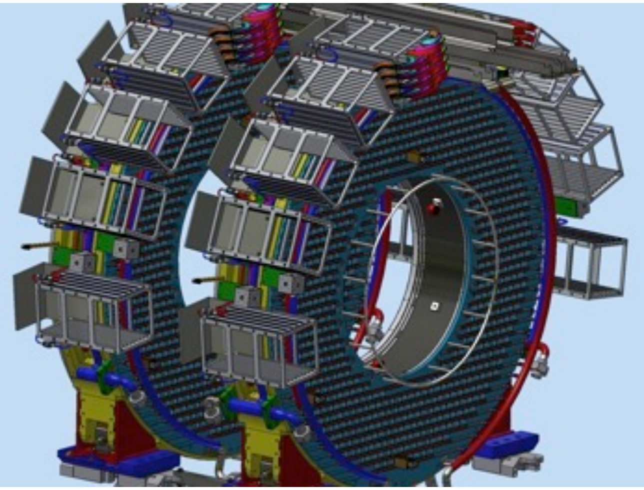
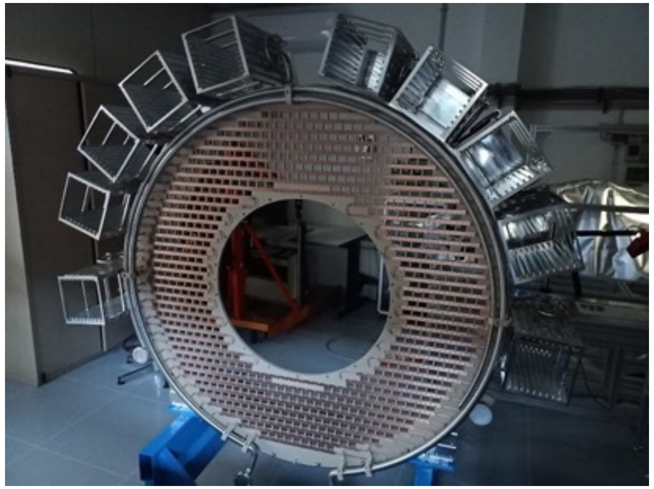
The Calorimeter of the Mu2e experiment

Fabio Happacher – Laboratori Nazionali di Frascati dell'INFN
on behalf of the Mu2e Collaboration

15th Pisa Meeting on Advanced Detectors, May 22-28 28, 2022.



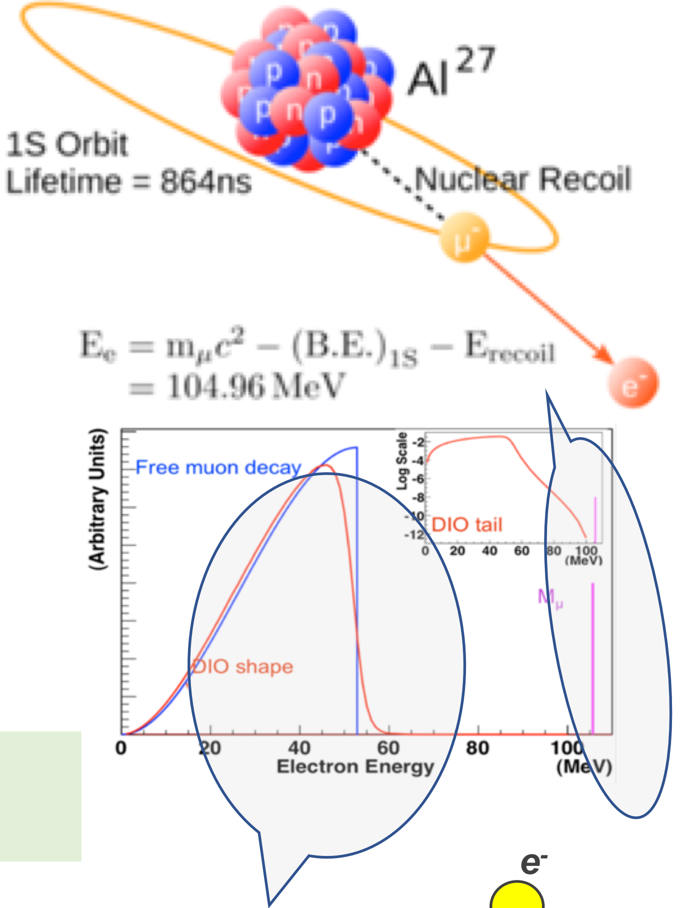


Fermilab

Talk outline

- Measurement overview and experimental technique of Mu2e
- Calorimeter requirements, technical choices and design
- Calorimeter Engineering Design and Integration
- Calorimeter expected performance from Beam Test and prototypes
- Production of crystals , SiPMs, FEE and digital electronics
- Calorimeter Mechanics status
- Assembly plans and conclusions

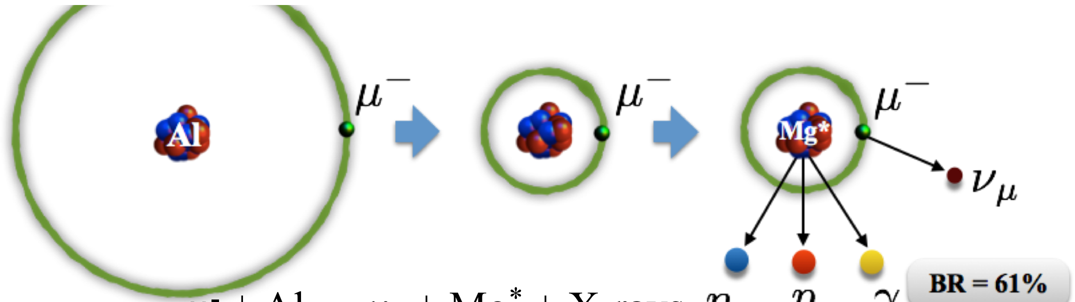
The Mu2e Experiment



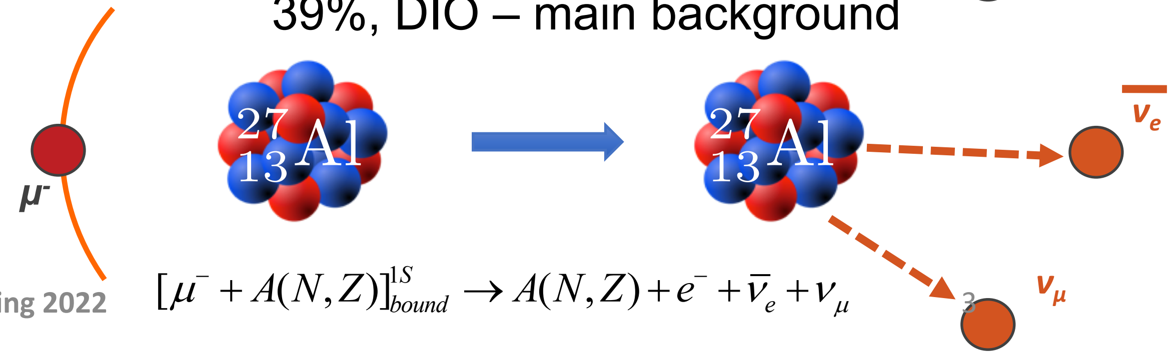
- ❑ **Mu2e will search for the CLFV conversion of the muon into an electron** after stopping it on **Al nucleus** $\mu^- Al \rightarrow e^- Al$
- ❑ Clear signature provided by the **mono-energetic conversion e⁻ with E ~ M_μ**
- ❑ The proton beam of the Fermilab accelerator complex and the Mu2e solenoidal system produce **a high intensity "pulsed" muon beam - 10 GHz of stopped μ**
- ❑ Goal is to reach a **single event sensitivity of ~3 x10^{-17} i.e. 10^4 better than Sindrum II** → This requires 10^{20} protons on target , 10^{18} stopped muons
- ❑ Mu2e will detect and count the conversion electrons with respect to the standard muon capture.
- ❑ **Main background is SM μ^- decay in orbit (DIO) – softer p_T spectrum**

$$R_{\mu e} = \frac{\Gamma\left(\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)\right)}{\Gamma\left(\mu^- + N(A,Z) \rightarrow all\ muon\ captures\right)}$$

61%, Muon capture - normalization



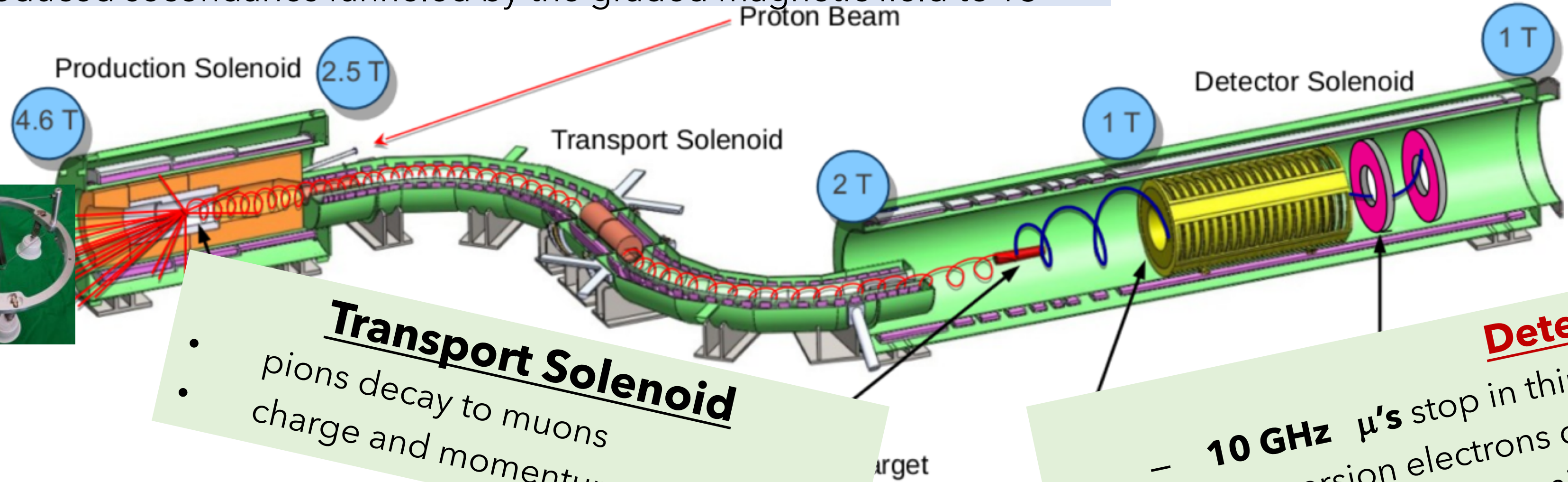
39%, DIO – main background

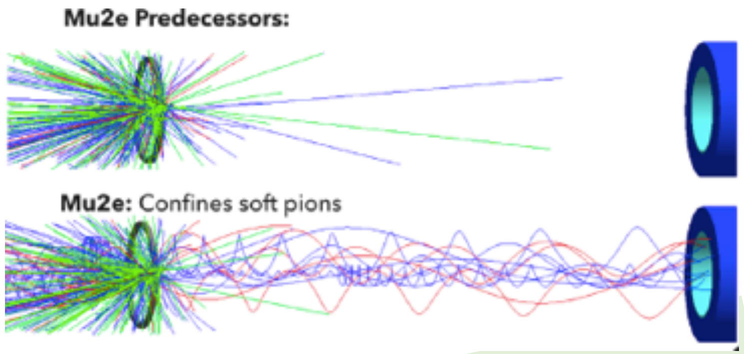


Mu2e experiment: from cartoons to reality

Production Solenoid

- 10^{12}/s 8 GeV protons on Tungsten target (POT)
- Produced secondaries funneled by the graded magnetic field to TS



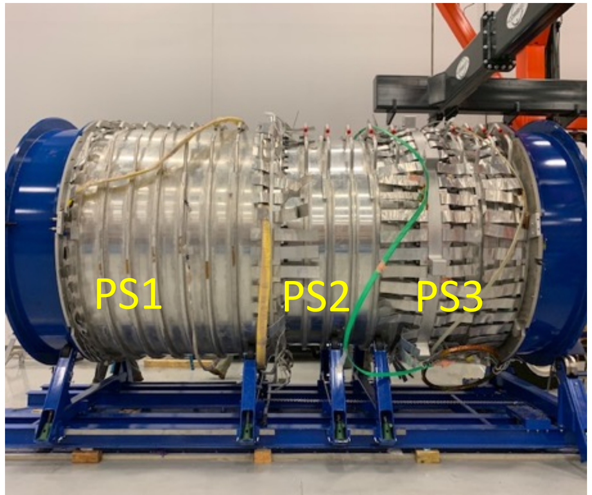


Transport Solenoid

- pions decay to muons
- charge and momentum selection

Detector Solenoid

- **10 GHz μ's** stop in thin Al foils of stopping target
- Conversion electrons detected by a tracker and a calorimeter
- A sourrounding cosmic ray veto detector tags Cosmic Rays



Calorimeter scope and requirements

For the μ → e conversion search, the calorimeter adds redundancy and complementary qualities with respect to the high precision tracking system

- Large acceptance for the mono-energetic electron candidate events
- Particle Identification capabilities with μ/e rejection of 200
- Additional "Seeds" to improve track finding at high occupancy
- A tracking independent trigger

For 100 MeV electrons @ 50 degrees impact angle

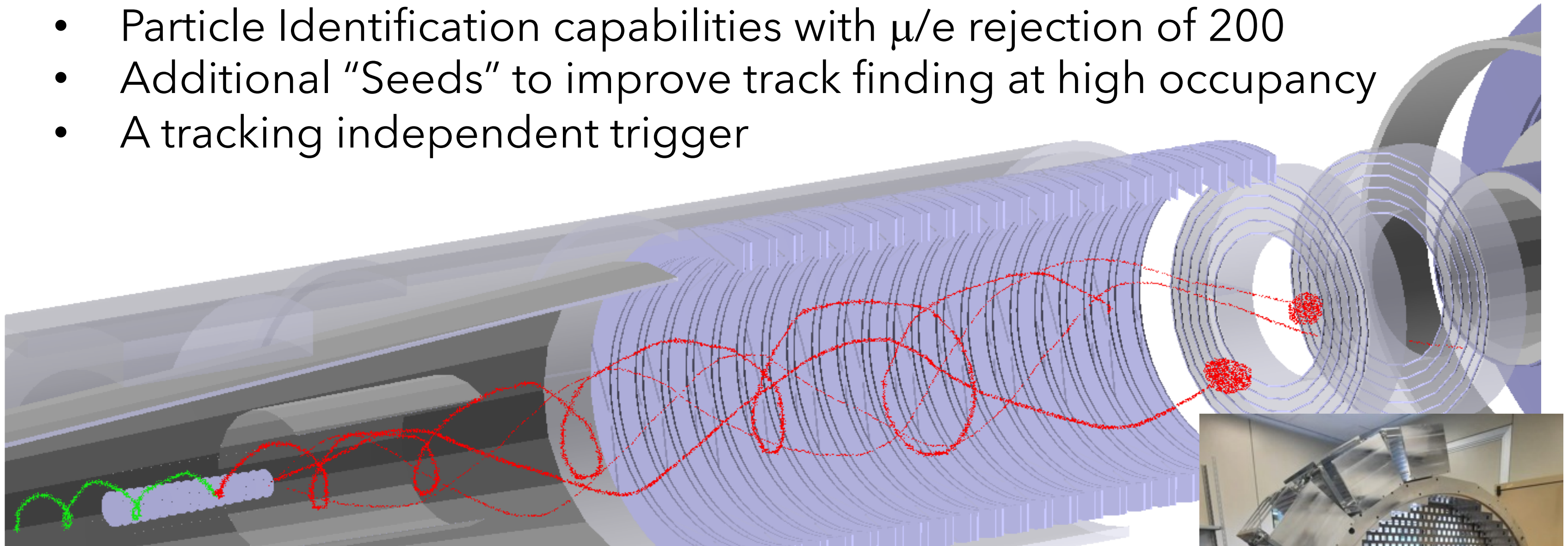
→ Provide energy resolution σ_E/E of O(< 10 %)

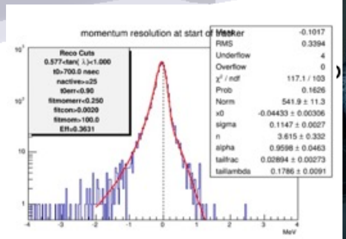
→ Provide timing resolution σ(t) < 500 ps

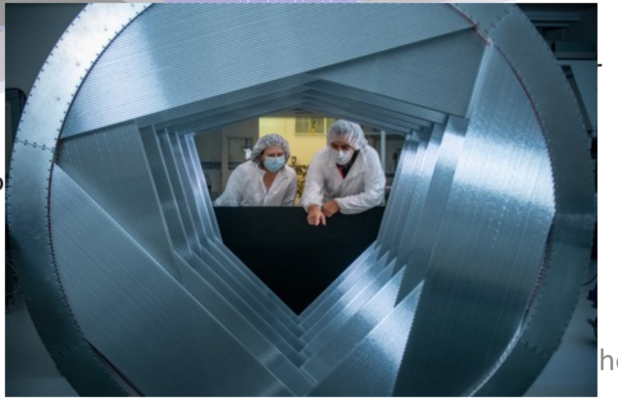
→ Provide position resolution < 1 cm

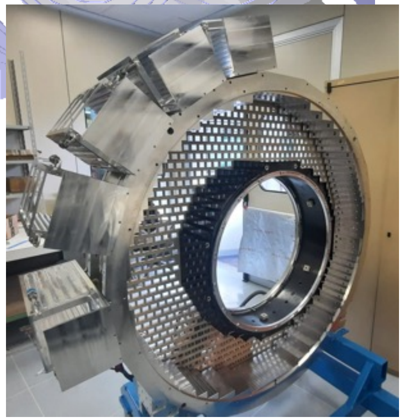
→ Work in vacuum @ 10-4 Torr and 1 T B-Field

→ stand harsh radiation









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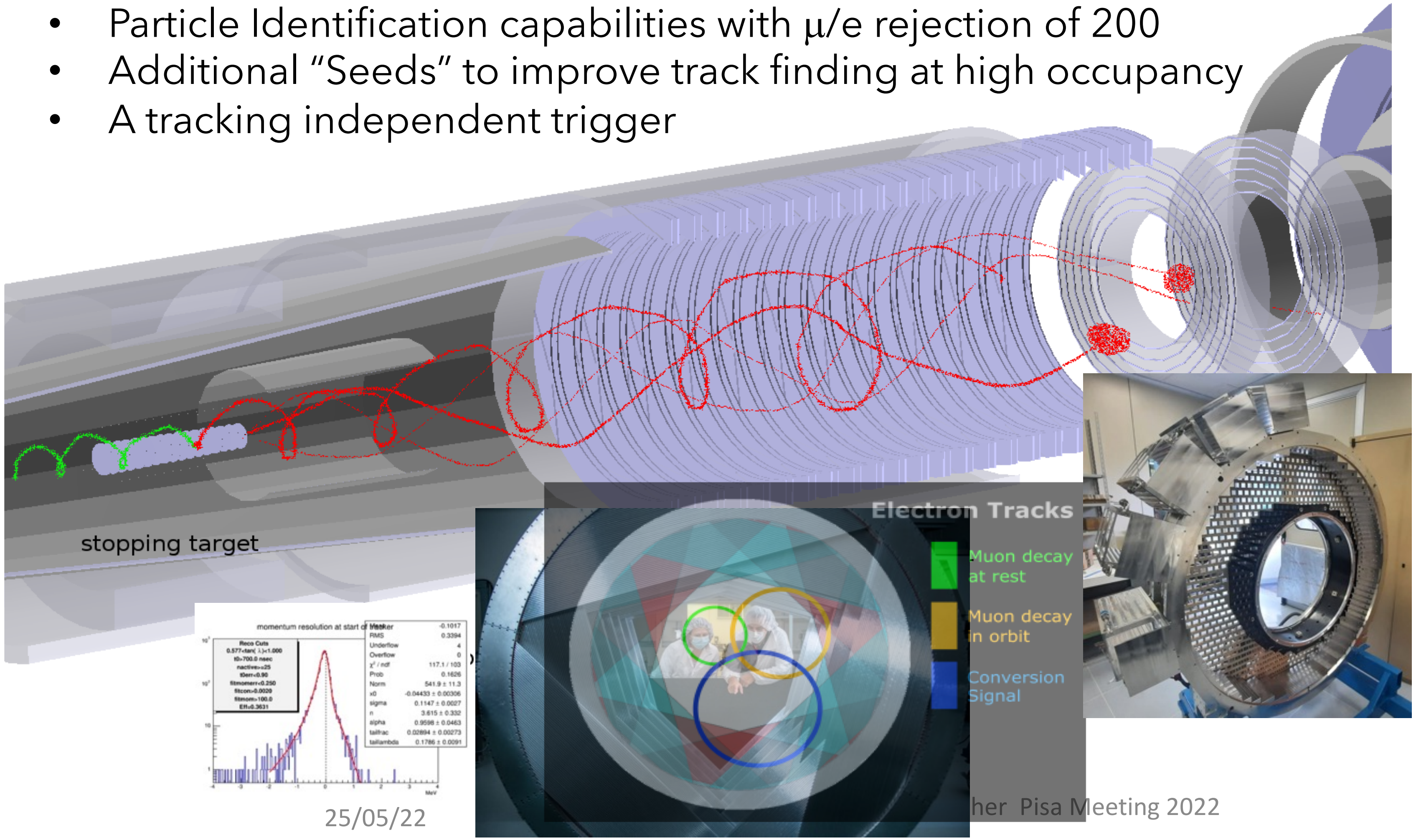

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Technical specifications

- Chosen Technical Solution: **High Granularity Crystal calorimeter with SiPMs readout**

- 2 Disks (Annuli) geometry to improve acceptance

- Crystals with high Light Yield for time/energy resolution → **LY(SiPM) > 20 pe/MeV**

- **2 SiPMs/preamps per crystal** for redundancy and MTTF requirement → **1 million hours/SIPM**

- **SiPM thermally controlled down to -10**°C **to reduce radiation induced leakage current**
  (factor of ~ *3* every 10 °C : 30mA → 3mA, 25 → -5 °C)

- Fast signal and Digitization for Pileup and Timing → **τ of emission < 40 ns + Fast preamps**

- **Crystals should withstand a TID** of 90 krad and a fluence of $3\times \frac{10^{12}\ n_{1\mathrm{MeV}}}{cm^2}$

- **SiPM/FEE should withstand** 45 krad and a fluence of $1.5\times \frac{10^{12}\ n_{1\mathrm{MeV}}}{cm^2}$

- **Digital electronics should withstand :**
  - → a TID of 15 krad
  - → a neutron fluence of 3×10^{11} n/cm^2.
  - → Charged Hadron (>20MeV) 10^{10}/cm^2

Mu2e calorimeter design

✓ Two annular disks, each one with 674 un-doped CsI parallelepiped crystals with square faces:

➔ Crystal dimensions (34 x 34 x 200 mm^3) ~ 10 X_0

➔ Inner/Outer Radius = 374/660 mm

✓ Each crystal is read out by two large area UV extended (silicone resin window) SiPM's (14x20 mm^2) coupled in air with 2mm gap

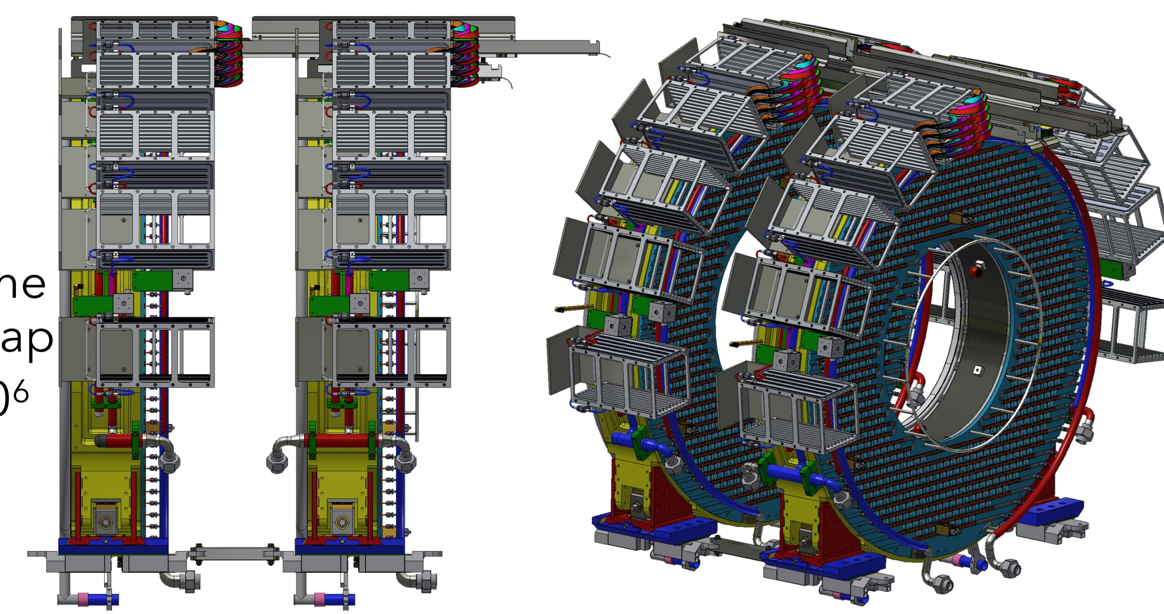
➔ PDE=30% @ CsI emission peak =315 nm. Gain ~1.7×10^6

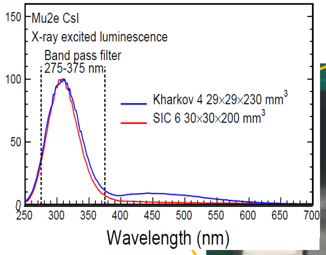
➔ Tyvek+Tedlar wrapping (LY↗ and cross talk↘)

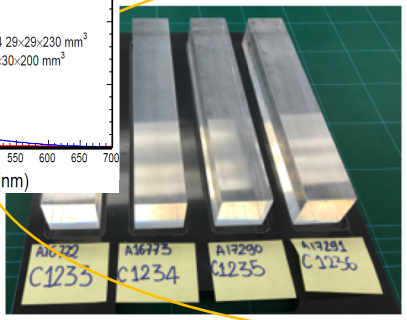
✓ SiPM glued on copper holders for heat dissipation/cooling and connected to FEE

✓ Digital electronics at 200 Msps on-board custom crates

✓ Radioactive source (a la Babar) and green laser systems provide absolute calibration and monitoring capability





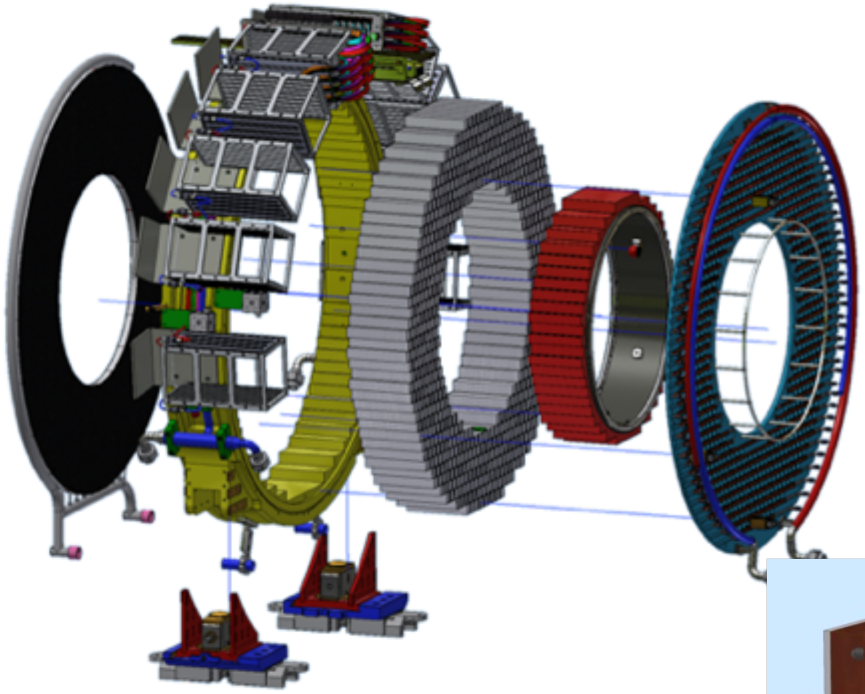


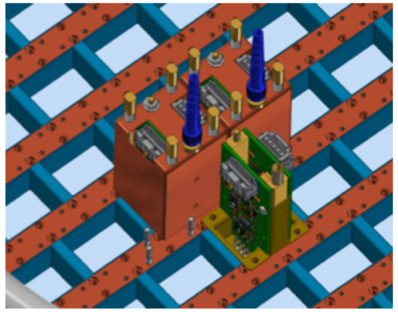
Operate with very high reliability in vacuum, magnetic field and be resilient to radiation harsh environment

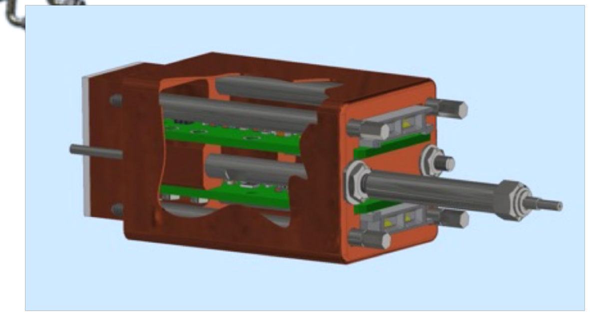
Exploded view of components

See A. Saputi's poster for Mech. Engineering details

- Outer monolithic stepped Al supporting cylinder with integrated cradle and stands
- Inner carbon fiber stepped cylinder
- PEEK back plate, housing Read Out Units
  - Embedded copper cooling lines
- Read Out Units, ROU's, composed of
  - Copper holders
  - Glued SiPm
  - FEE cards
  - Faraday cages
  - Fibers needle
- Carbon fiber front plate integrating the source calibration pipes
- Array of 674 Tyvek wrapped crystals
- 10 Read out/service electronics crates (6-8 boards each)
- Cabling and pipes



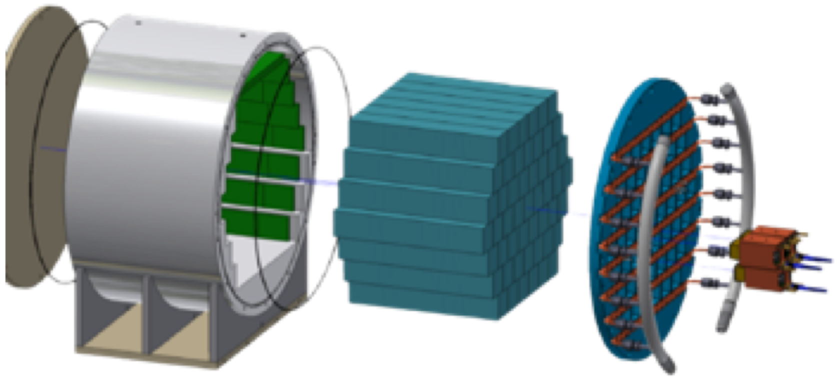


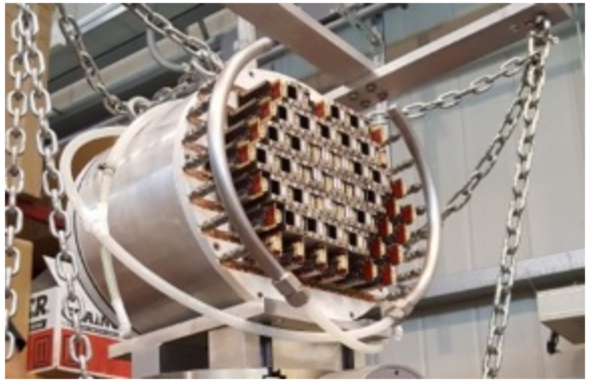


ROU's

Module-0 test beam

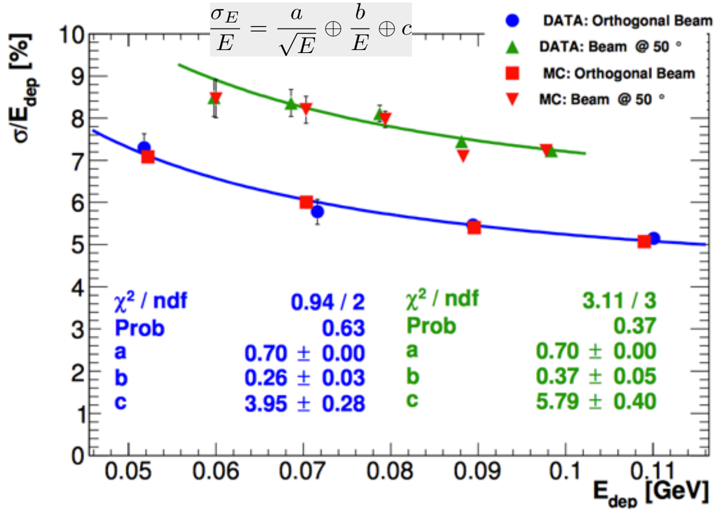
A Module-0 (51 crystals + 102 SiPMs + 102 FEE) was built to resemble the final design. Calorimeter performances fulfillment have been checked testing it with e-beams in Frascati. The energy and timing resolution obtained for 100 MeV electron is well in agreement with the Mu2e requirements.

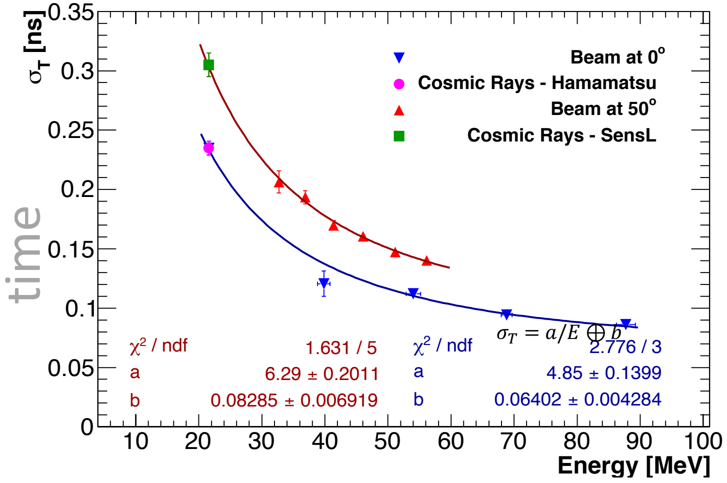




- Single particle selection
- Mips equalization and time scale
- LightYield/SiPM =30 pe/MeV
- Excellent Data-Mc agreement
- 5.4% (7.3%) resolution @100 MeV for 0° (50°)
- σ_T ~ 100 ps

✓Results fully comply with our requirements
✓Green light for Production of components





Procurement of Crystals and SiPMs

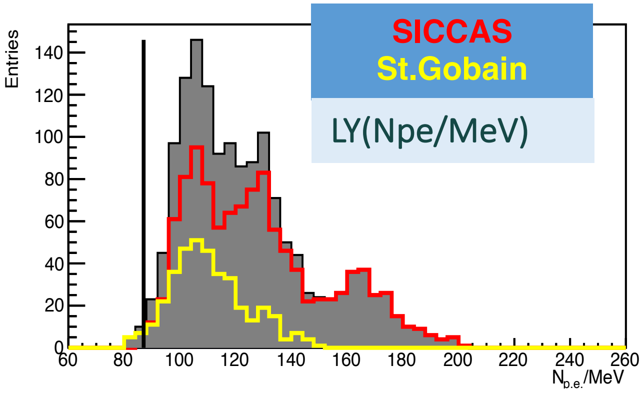
Production Completed

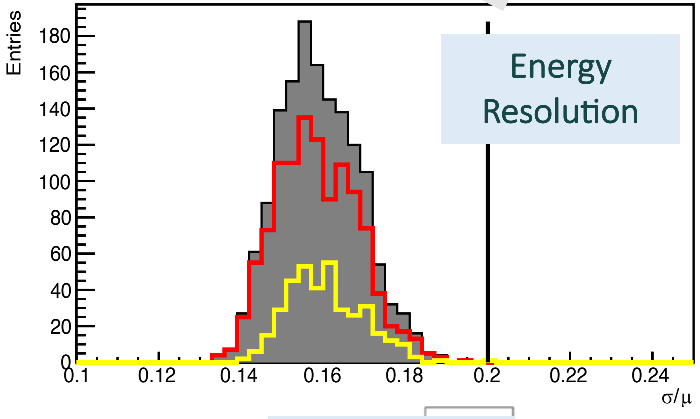
- ❑ Production of 1500 CsI crystals and 4000 Mu2e SiPMs started in 2018
- ❑ ^{22}Na QA test at SIDET (FNAL) + irradiation tests at Caltech, HZDR, FNG, Calliope

Crystals

- ❑ Two producers **(SICCAS, St. Gobain)**
- ❑ QA of optical (**LY, LRU, F/T, RIN)** and mechanical dimensions
  - ✓ St.Gobain failed to match our specs.
  - ✓ Final production back to SICCAS
- ❑ OK with irradiation tests
- ❑ ~8 % had specification failure

Completed end of 2020

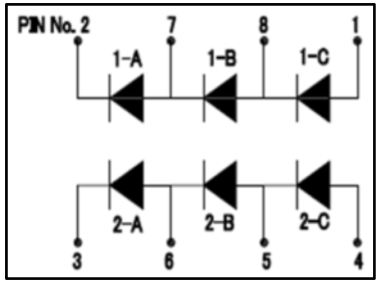


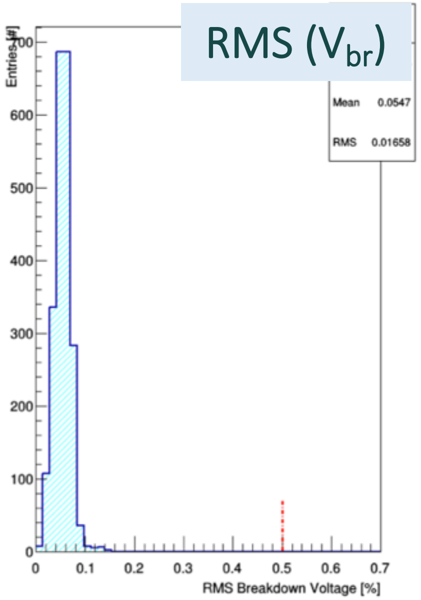


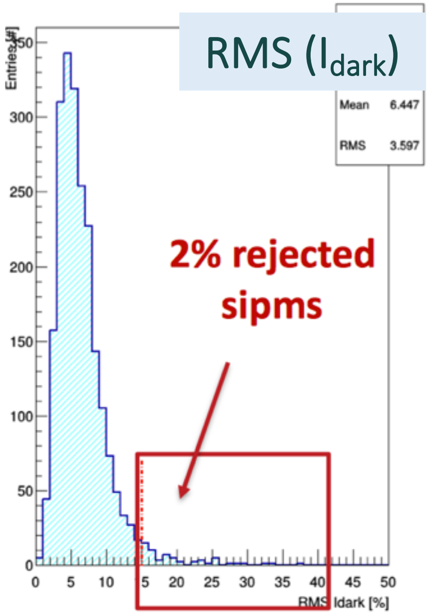
SiPMs

- ❑ Producer: **HAMAMATSU**
- ❑ **6 individual 6x6 mm² 50 μm px MPPCs** (Hamamatsu) paralleled series (2/3 C_i)
- ❑ All 6 cells/SiPM tested, measuring
  V_{br}, I_{dark}, Gain x PDE
- ❑ **Irradiation with ~1x10¹² neutrons/cm² and (MTTF)** test on 5 SiPMs/batch

Completed in 2019





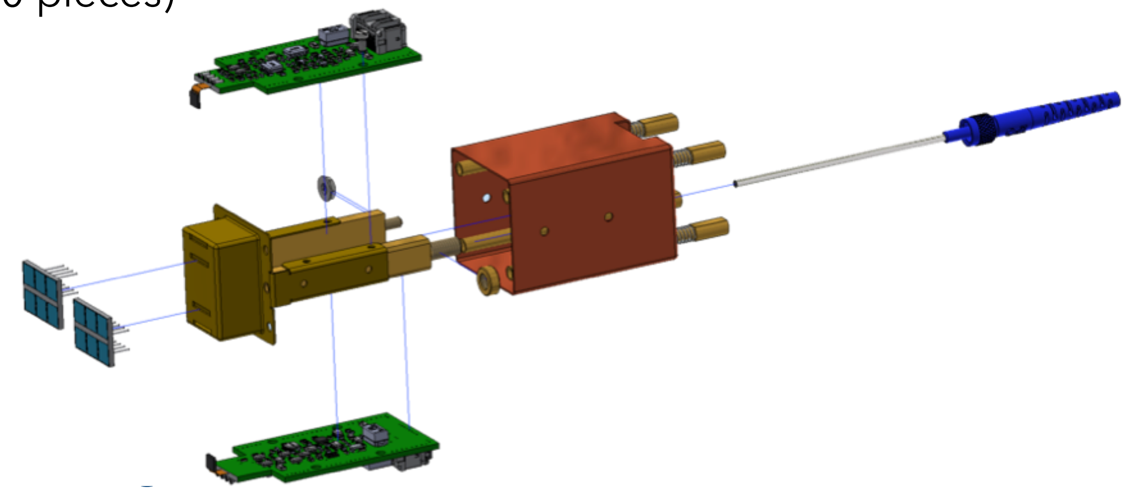


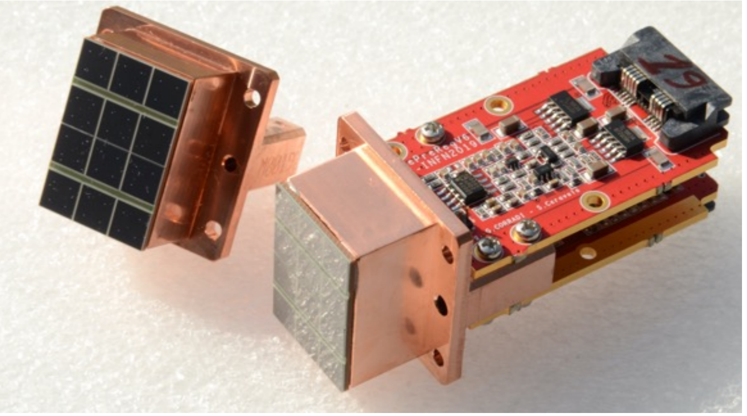
Read Out units

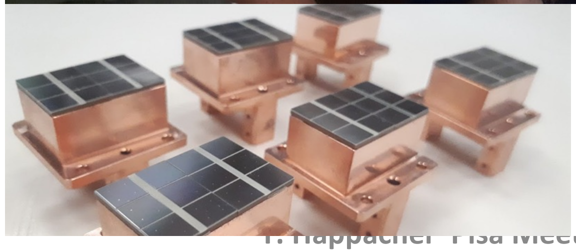
see E. Sanzani's poster for details on ROU's assembly and tests

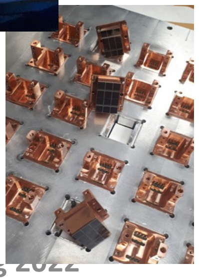
Due to the pandemics, we moved the gluing operation from FNAL to INFN (+ 1 year delay)

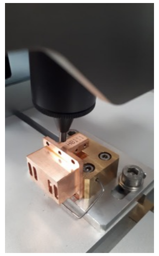
- ❑ All copper holders produced (1500 pieces)
- ❑ Faraday cages produced
- ❑ All SiPM's glued
- ❑ FEE produced, 2500/3500 tested
- ❑ Readout units under assembly 500/1500 done

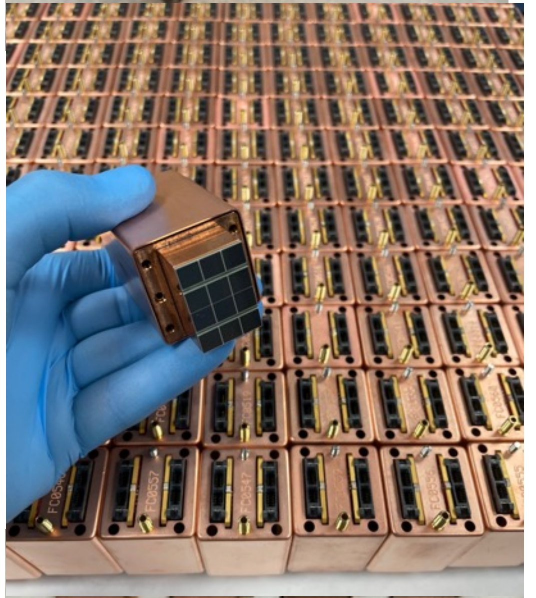


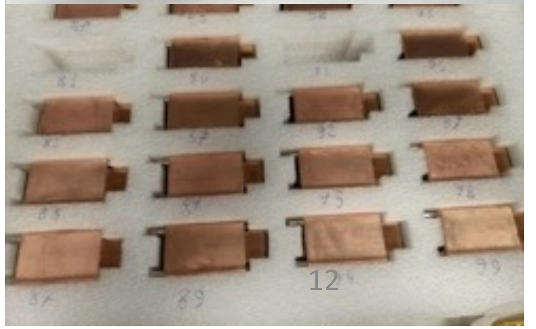






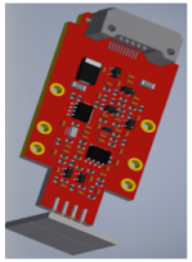


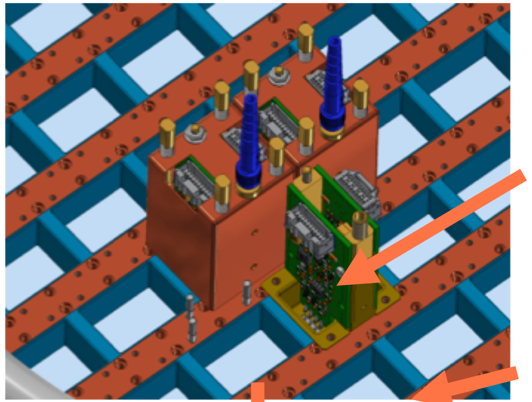


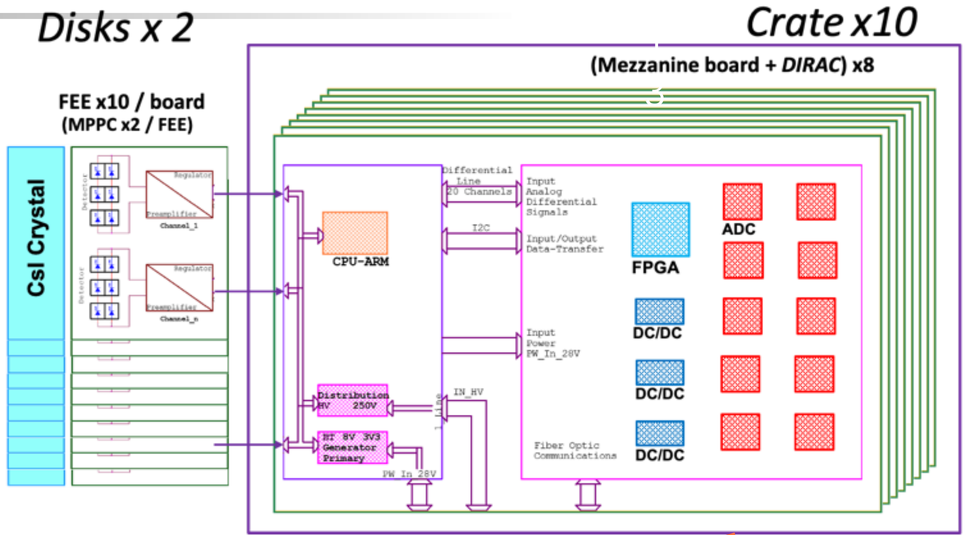


Signal processing chain overview

- 2700 readout channels
- Fully custom readout chain (from SiPM to DAQ)



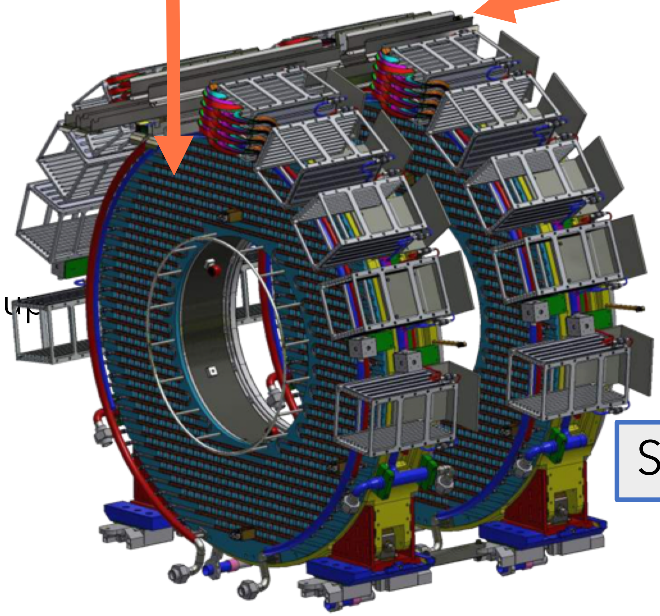


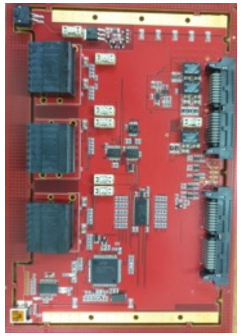


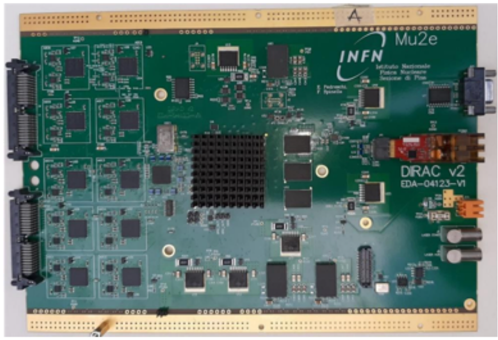
- **2700 Read-Out Units**
  - FEE consists in trans-impedance preamp. shaper and HV regulator

10 DAQ crates/disk housing:

- 140 custom **Mezzanine Boards**
  - Slow-control distribution for HV/LV setting
- 140 custom **DIRAC digitizer board**
  - Signal digitization @ 200 Msps w/ 12-bit flash ADC
  - Sampling optimized for signal reconstruction and pileup handling
  - *PolarFire* rad-hard FPGA
  - VTRX 10 Gbps optical link to Detector Control System

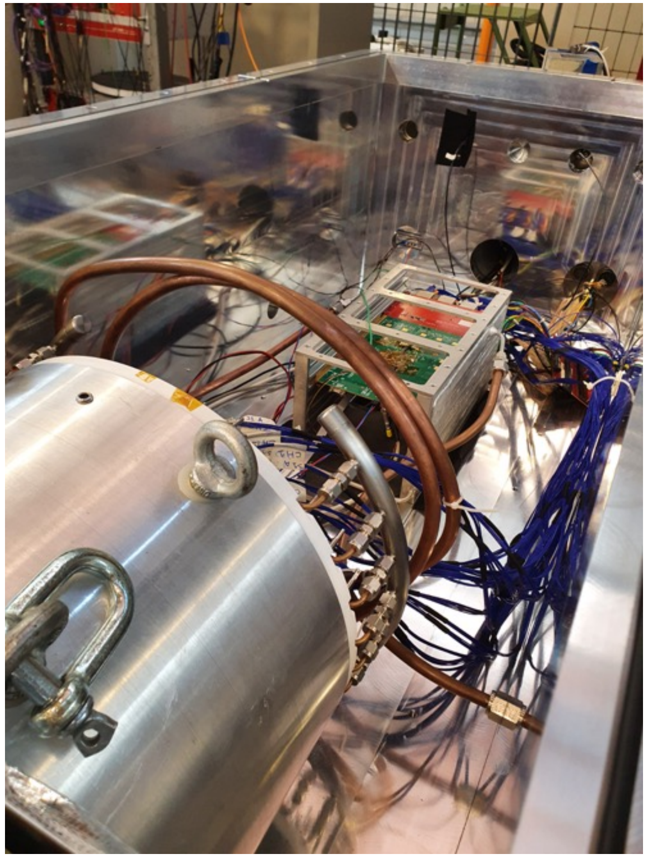


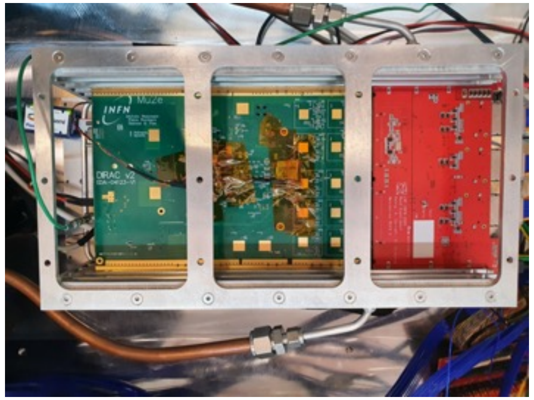


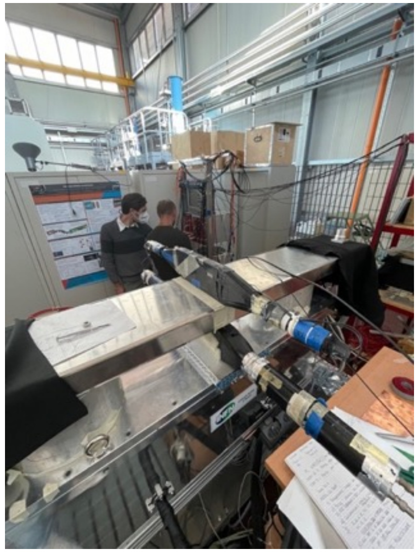


See F. Spinella's poster on electronics

Calorimeter Vertical Slice Test (VST) with cosmics

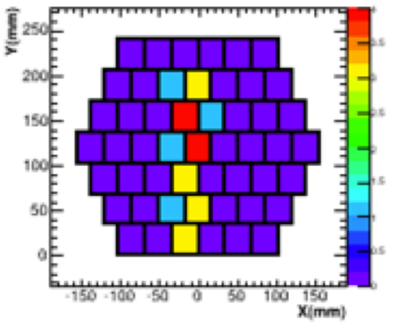


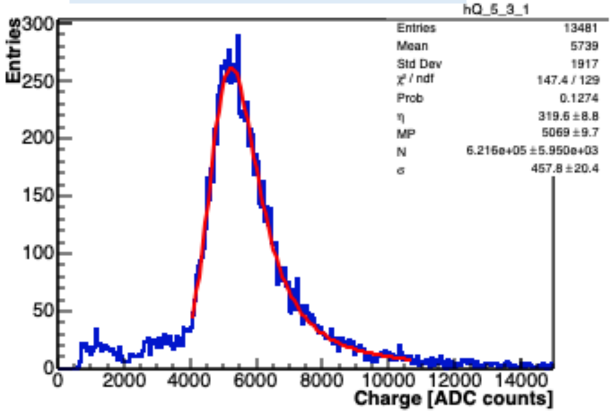




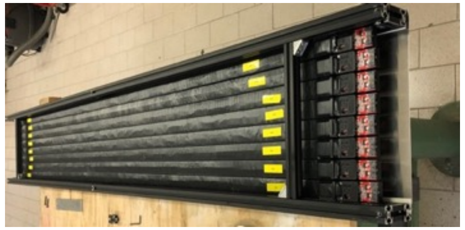
- 20 ch MB+ DIRAC V2 boards used for full Vertical Slice Test
- **Data collected in vacuum, at low T**
- **Test of cooling system**
- Stable operation and reconstruction
- Data taking of CR events triggered with external scintillators

MIP charge distributions





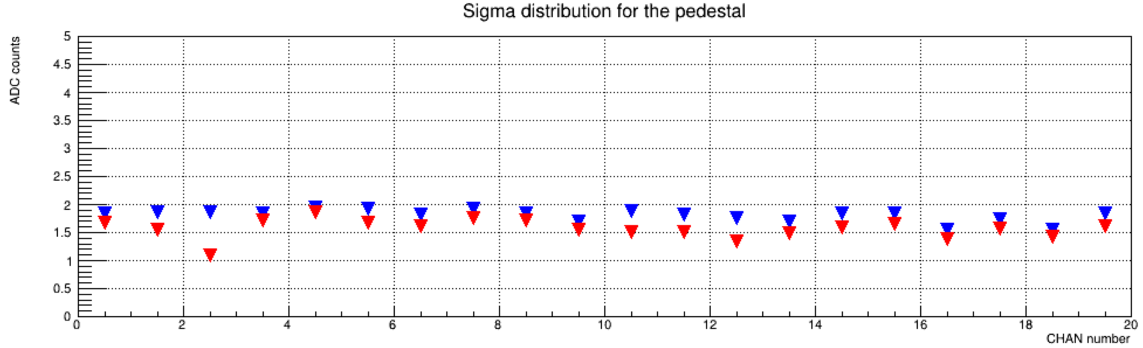
Cosmic Ray Tagger
(See R. Gargiulo's poster)

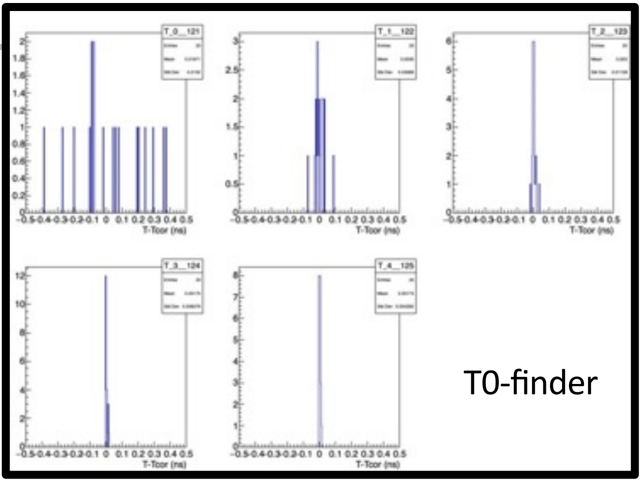


- Two sets of 8 (1.6 m long) Scint Counters with SiPM readouts integrated with FEE readout + mech support
- The CRT allows to test the depedence of response and resolution along the crystal axis for Module-0 and will provide an external trigger during calorimeter assembly and commissioning at SIDET (FNAL)

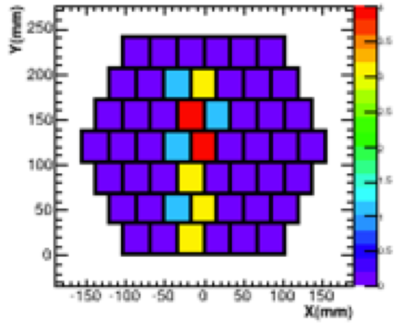
VST: summary of results

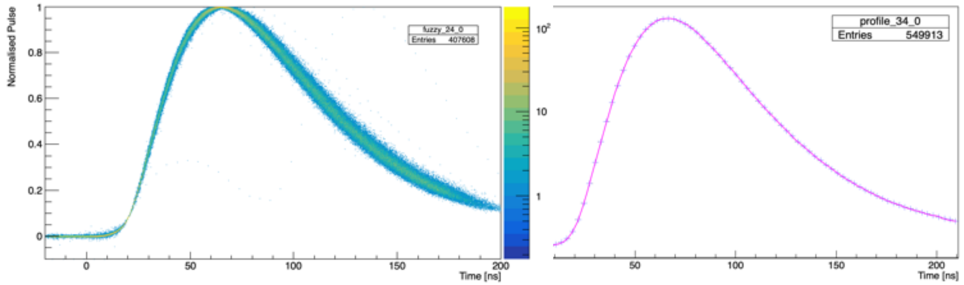
200 keV Noise



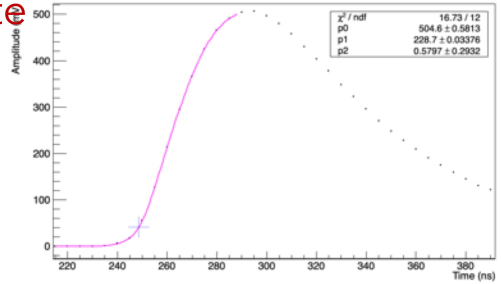


T0-finder



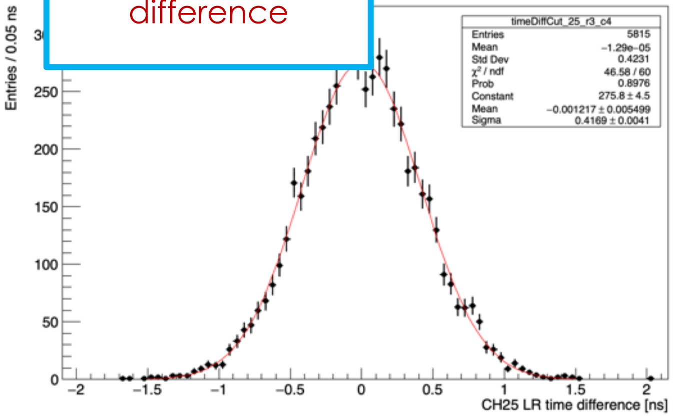


3 parameters template generated from data to fit time and charge

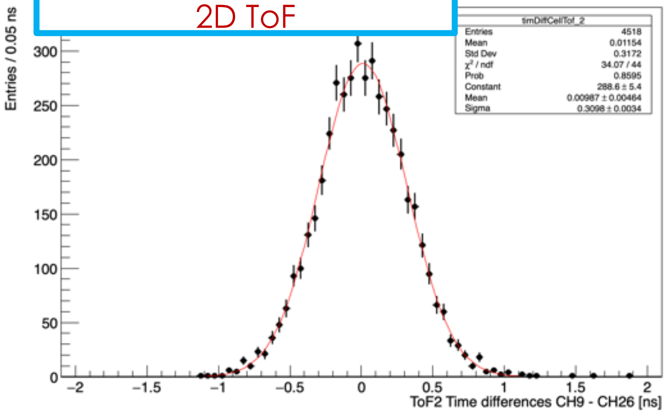


400 mV/MIP

left-right time difference



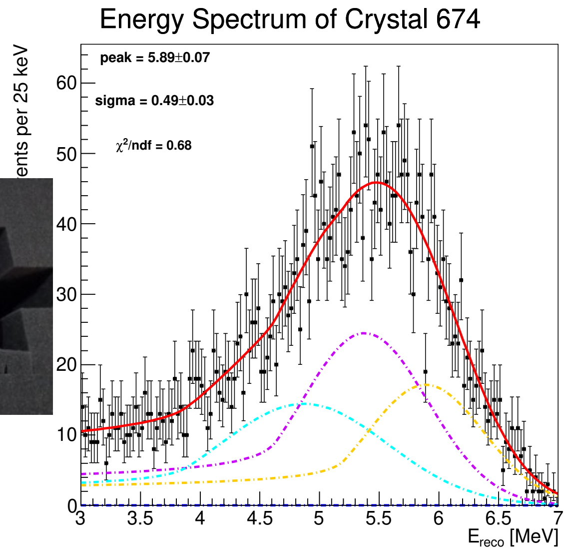
mean time difference between 2 crystals w/ 2D ToF



- T0-calibration done with iterative "alignment" method (residual better than 10 ps)
- Cell mean **time resolution** w/ MIPs ≈ 210 ps

Calibration Tools – Source and laser

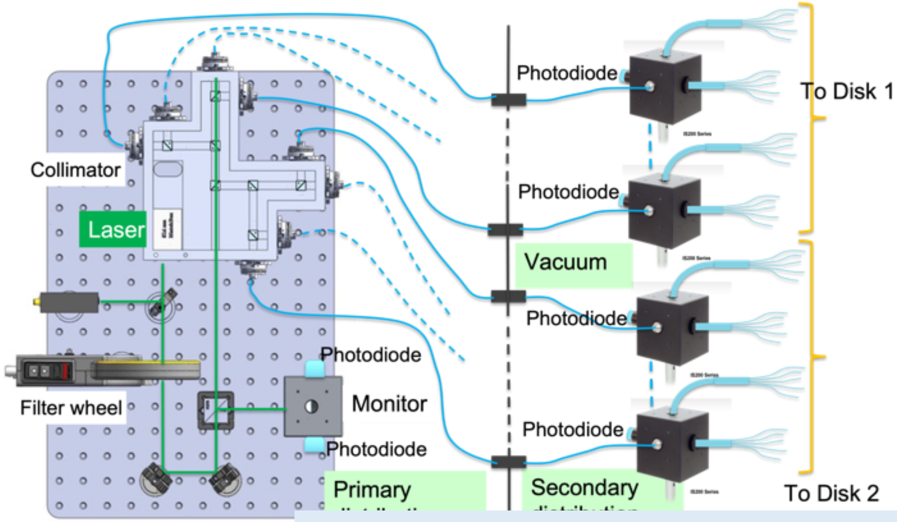
- ✓ Neutrons from a DT generator irradiate a fluorine rich fluid (Fluorinert) that is then piped to the front face of the disks



- ✓ The following reaction gives rise to 6.13 MeV photons

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

- ✓ The produced γ's uniformly shines the crystals
- ✓ Few minutes of data taking to calibrate each crystal at O(1%)

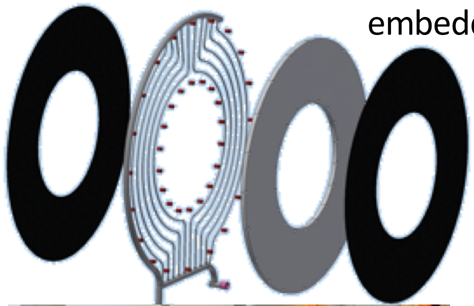


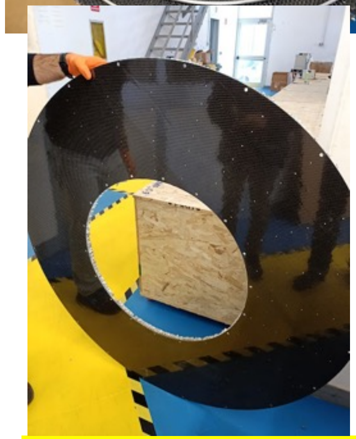
- ✓ A pulsed, 530 nm, green laser illuminates all crystals through a distribution system based on optical fibers and integration spheres
- ✓ Monitor gain variation at level of 0.5%
- ✓ Determine T0's at level of 100 ps
- ✓ Stability at level of few %, monitored with PIN Diodes at laser source. Used at low rate in off-spill gates

In-situ calibration with crossing MIPs, DIO's and other physics processes

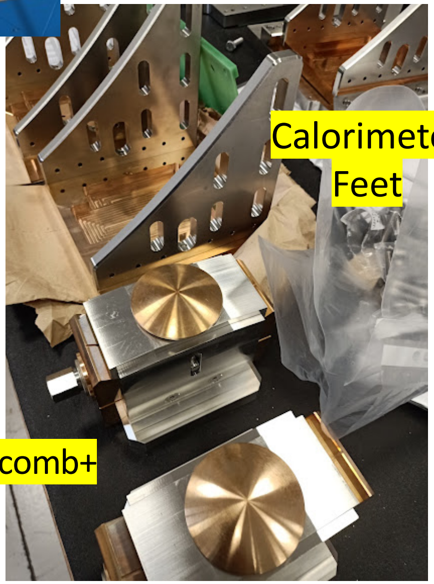
mechanical parts procurement

Front Panel CF with embedded source pipe

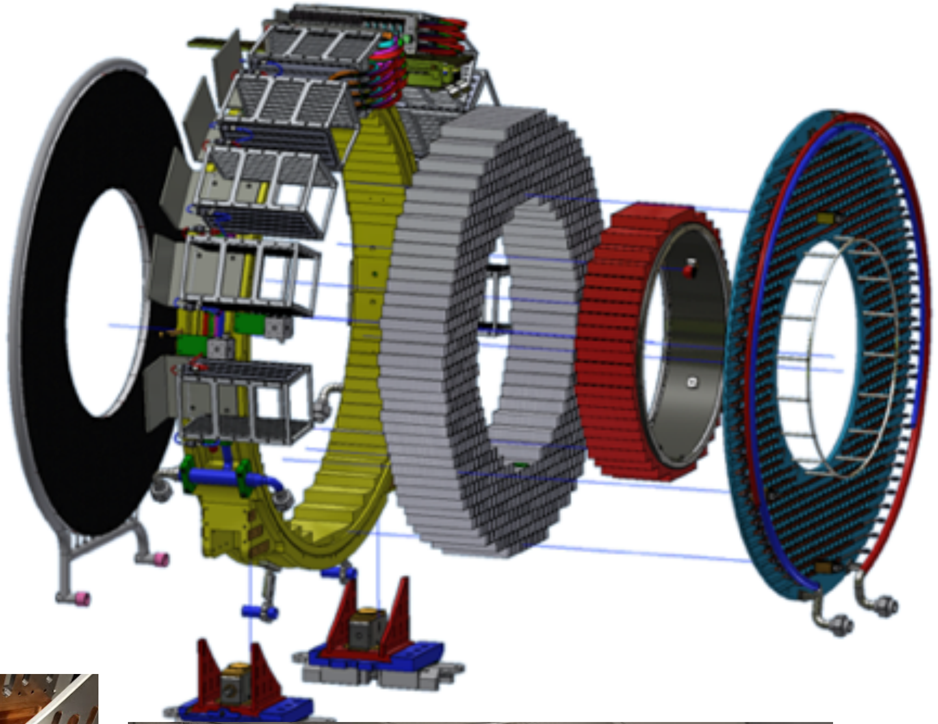


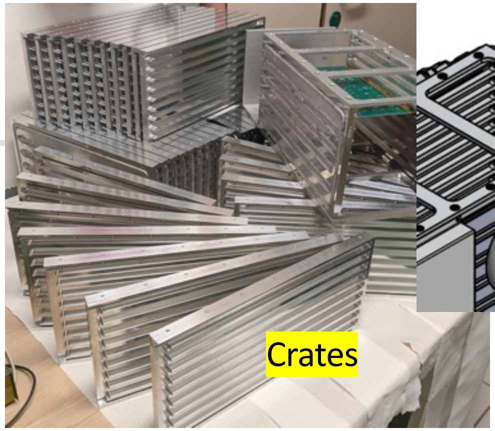


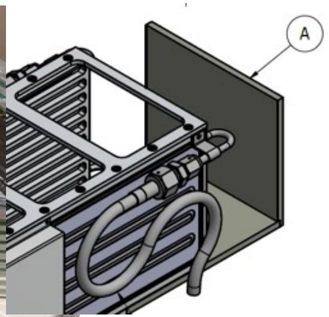
Front Plate: CF+Al Honeycomb+ Source Al Tubing



Calorimeter Feet

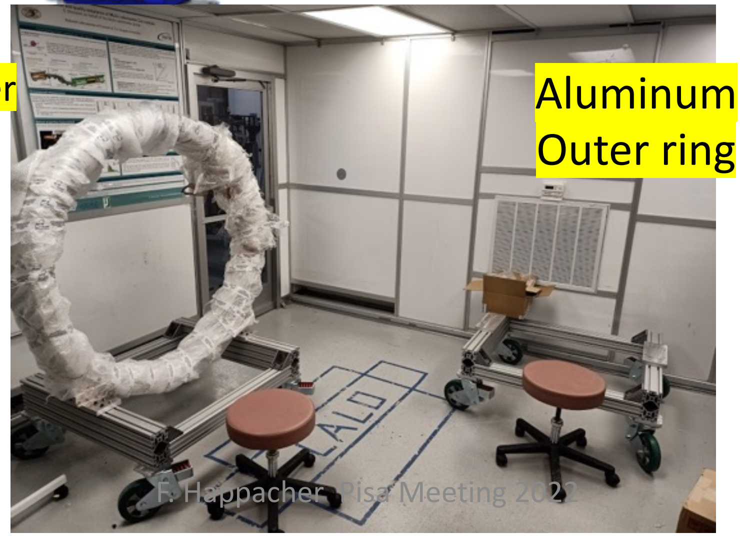




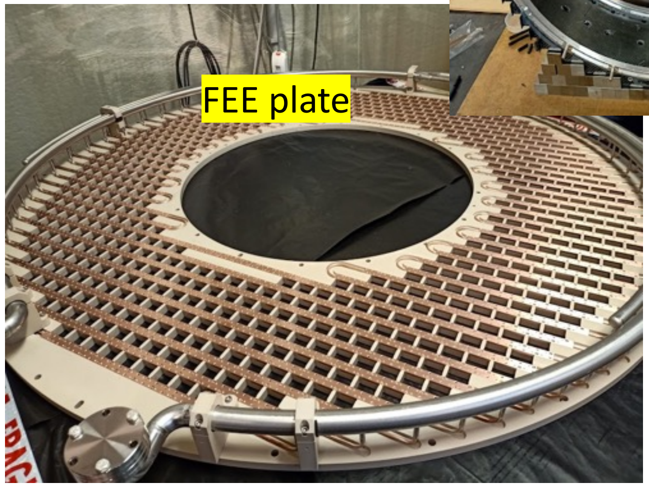


Crates

Carbon Fiber Inner Ring

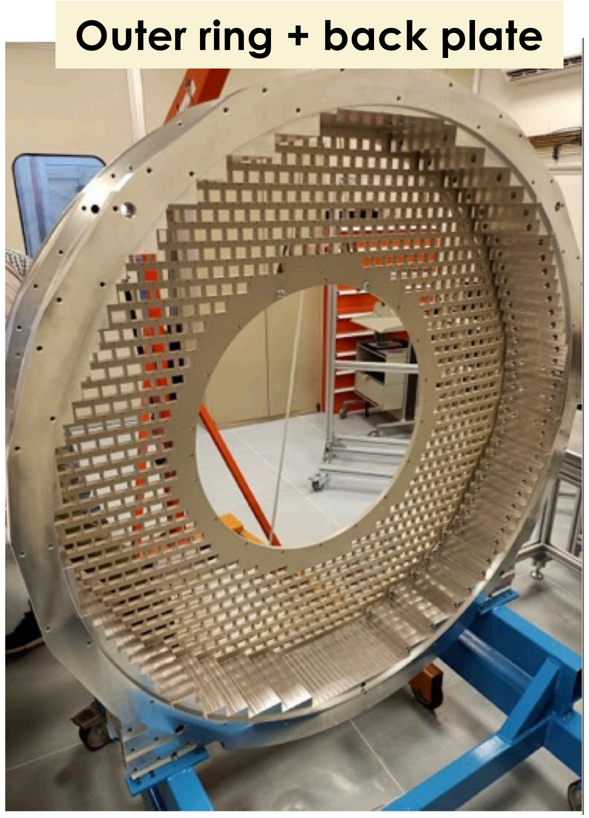


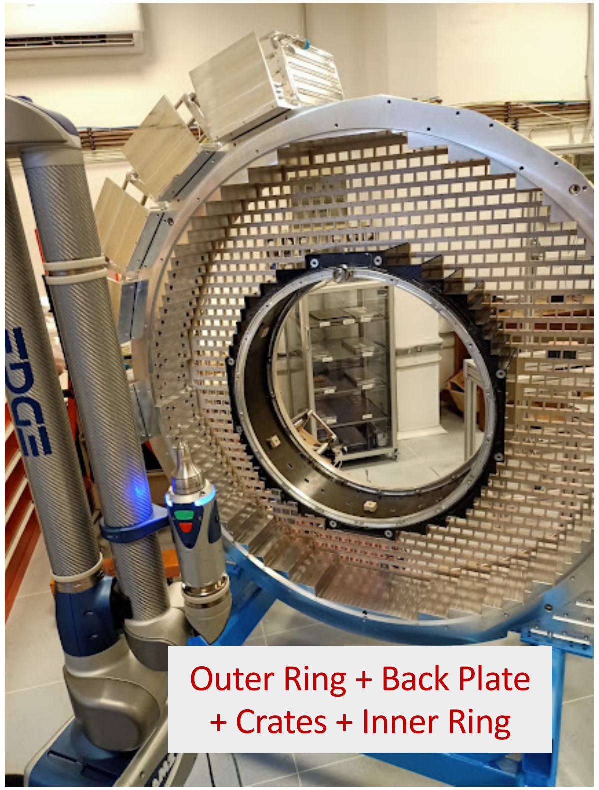
Aluminum Outer ring



FEE plate

Dry fit at INFN





- Apart from the source tubing integration on the front plate **all calorimeter mechanical parts have been produced**
- In progress: routing test of FEE-MB cables from FEE plate to the crates
- Shipment to FNAL of all large mechanical parts in progress for the downstream disk

Conclusions

- The Mu2e CsI+SiPM Calorimeter shows excellent energy (< 7 %) and timing (< 200 ps) resolution @100 MeV as tested with electrons beams

- *The most demanding requirements are to operate in a 1 T field, in vacuum and in a rad-hard environment:*
  - → SiPM's work under neutron irradiation but eventually need to be cooled down to -10 °C
  - → Engineering of cooling and calorimeter mechanics has been challenging

- **Production of crystals, SiPMs and FEE completed**

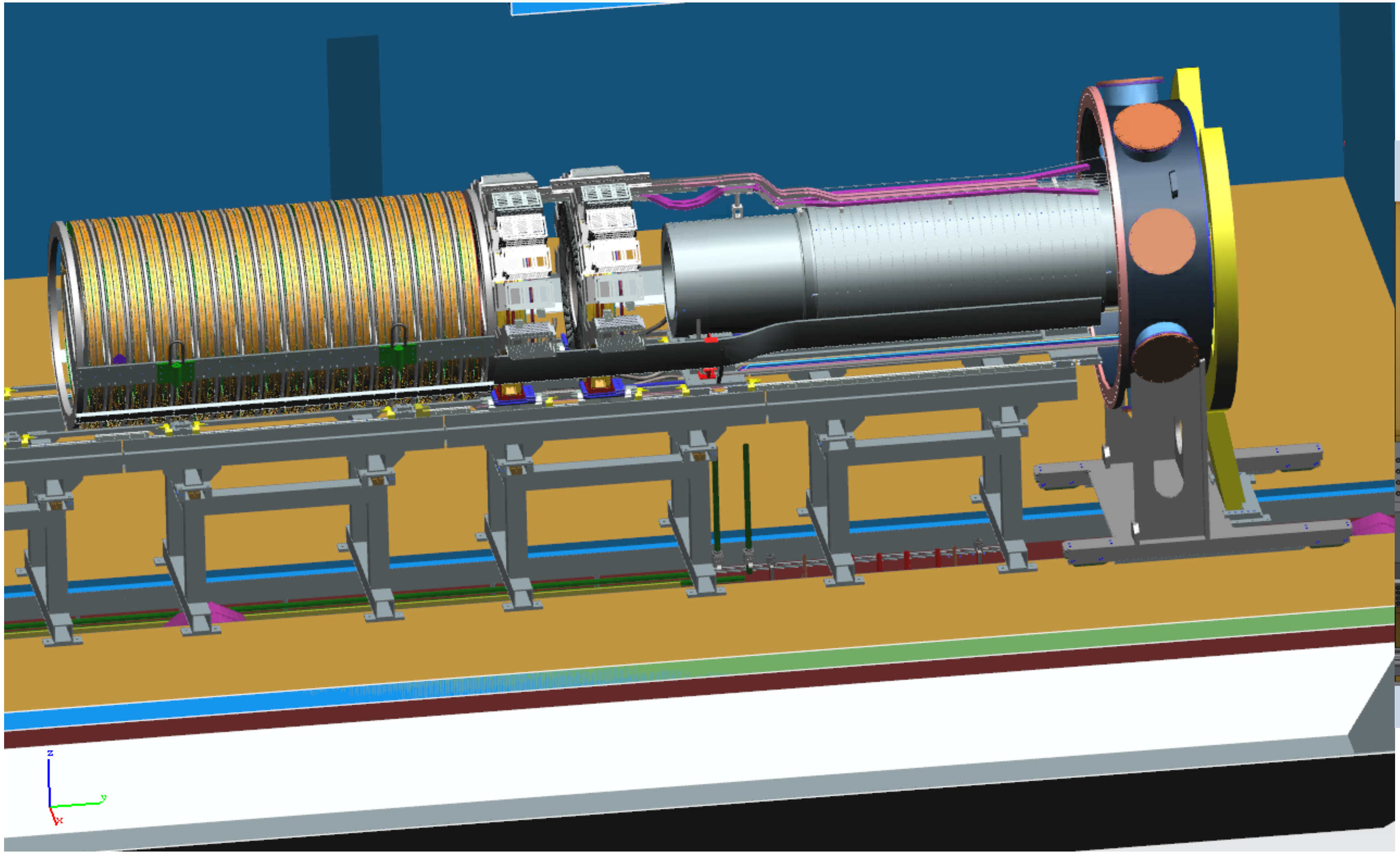
- **Production of mechanical parts almost completed+ dry FIT ongoing**

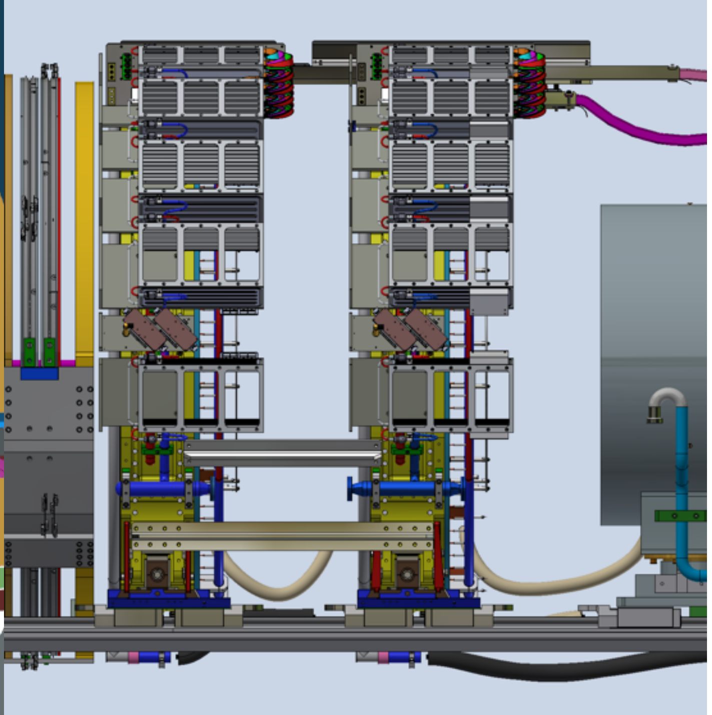
- **Successful VST carried out** with excellent results on timing and energy calibration
  - → Production of Digital electronics underway as planned

- Shipments of material from INFN to FNAL is in ongoing as we talk

- **Assembly room at FNAL being completed**
  - We plan to start outgassing components in June
  - We plan to begin crystal stacking this summer
  - to be ready to move in the Mu2e building by the end of 2023

Calorimeter Integration in the Muon Beam line





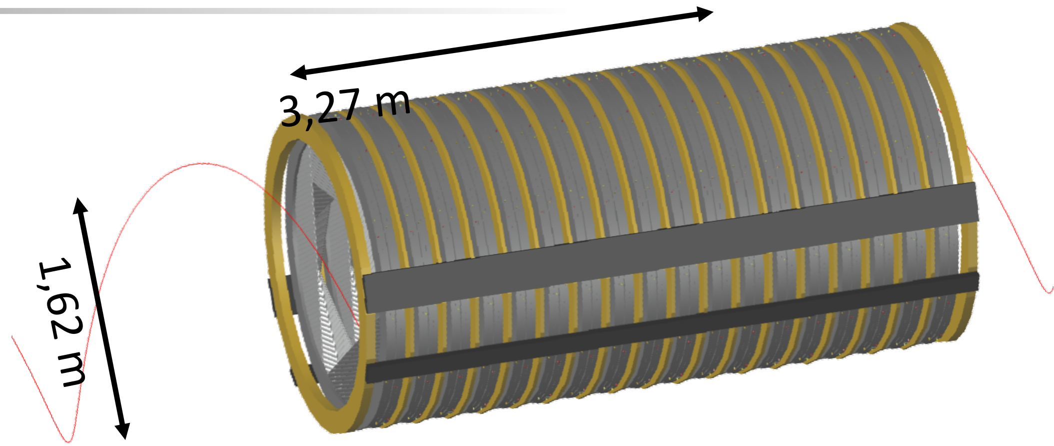
Disks can move apart for servicing

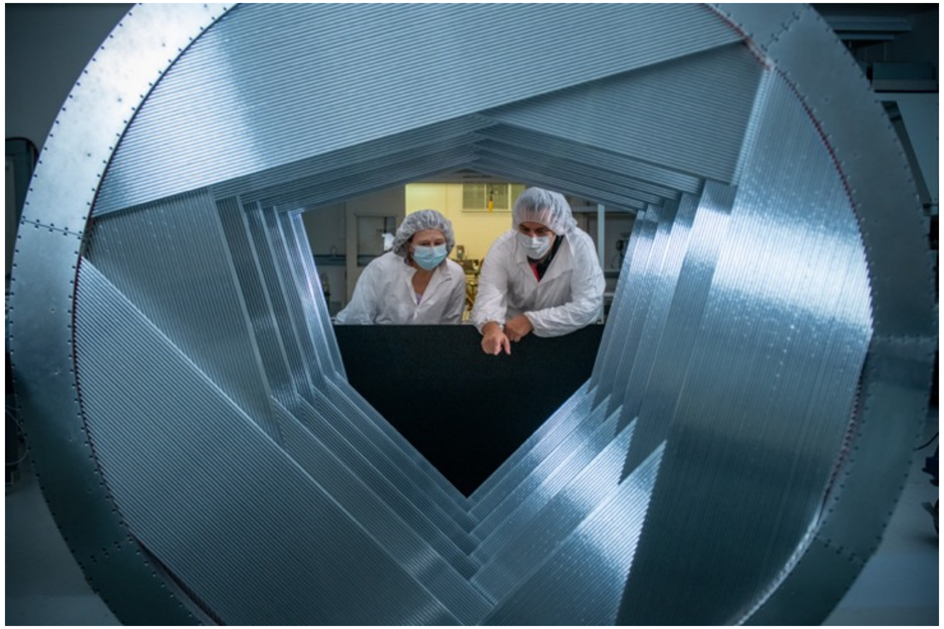
The Calorimeter design is already fully integrated in the Mu2e detector train

The straw tube tracker

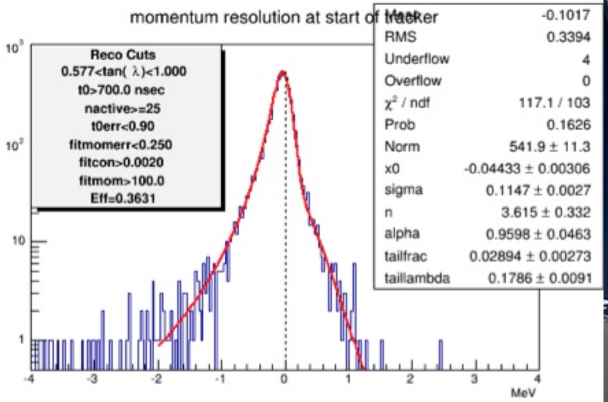
18 stations of 12 panels covering 120 degree each (stereo view)

- dual ended TDC/ADC readout large Radii
- ~21000 straw tubes, 5 mm diameter
- Spiral wound
- Walls: 12 μm Mylar + 3 μm epoxy + 200 Å Au + 500 Å Al
- 25 μm Au-plated W sense wire
- 33 – 117 cm in length
- 80/20 Ar/CO_2 with HV < 1500 V





σ_p < 115 keV @ 105 MeV



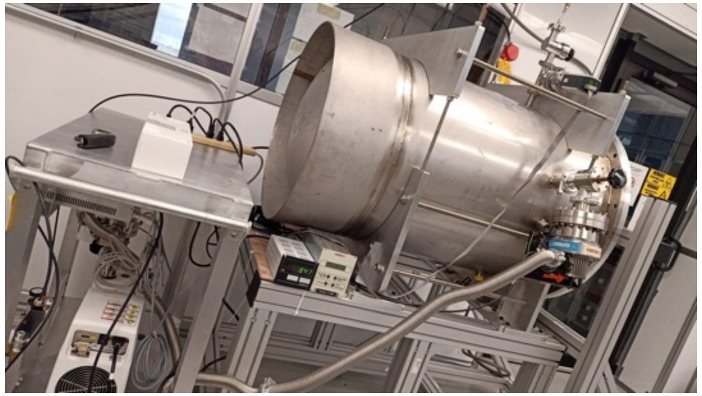
Tracker not sensitive to particles with p_T<80 MeV/c (beam flash and most of DIOs)

Parts procurement status

- Pure CsI Crystals all procured, LY response and dimensionally tested and Tyvek wrapped
- Hamamatsu SiPM's all procured and tested for gain, MTTF and irradiation
- FEE boards being produced and calibrated + integrated to SiPM
- ROU's being assembled
- Mezzanine boards being produced
- Digitizer boards prototypes received, production planned

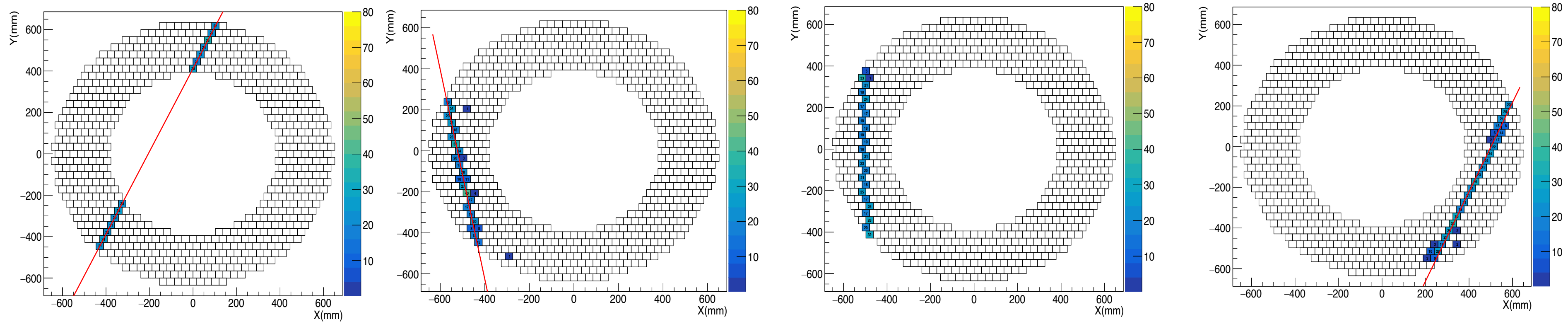
Mechanical parts

- Outer Al support rings ready, one at FNAL, one at LNF for Dry run
- FEE plates ready, being shipped
- Feet ready
- Carbon Fiber Inner Ring ready and being shipped, Source plate under construction
- SiPM+FEE copper holder and Faraday cages in our hands
- HV/LV+ Digitizer crates are ready, being shipped
- Outgassing station assembled and ready



In Situ Cosmic Ray calibration

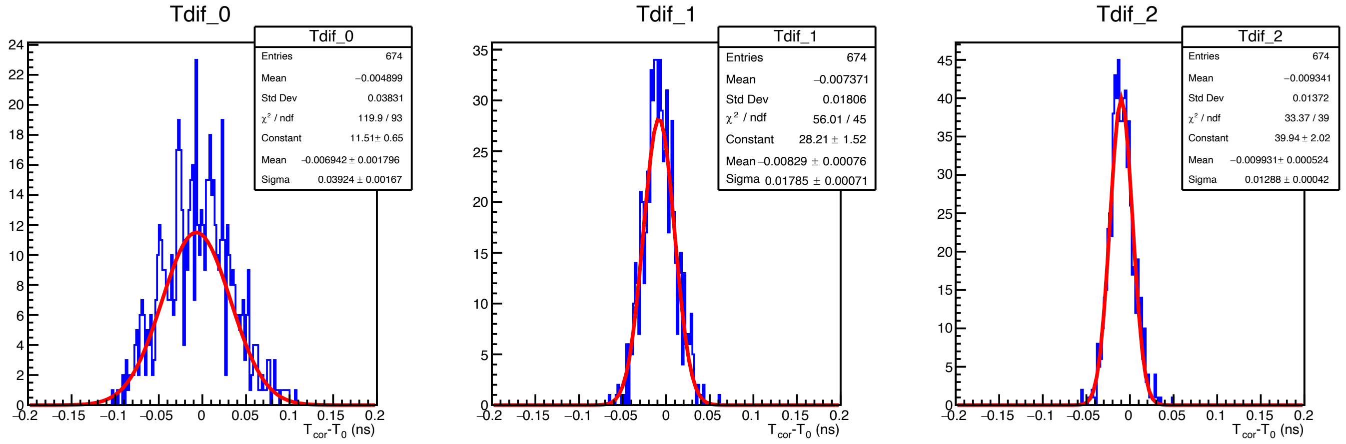
IN-OUT/OUT-IN **OUT-OUT** **Vertical -- Diagonal**



Calibration trigger for commissioning, 20Hz. (Docdb # 36767)

Procedure for Energy calibration based on MIPs

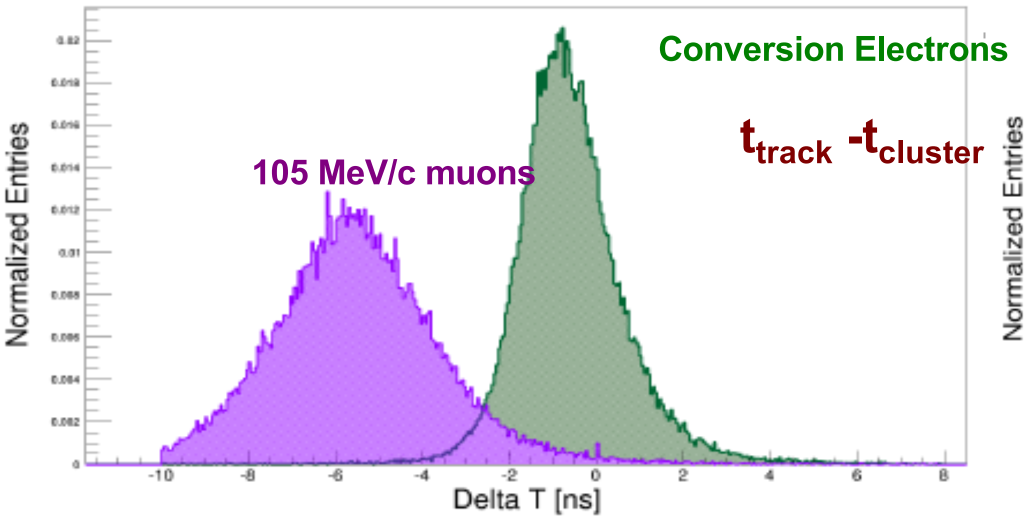
Procedure for Timing Calibration based on crossing time alignment

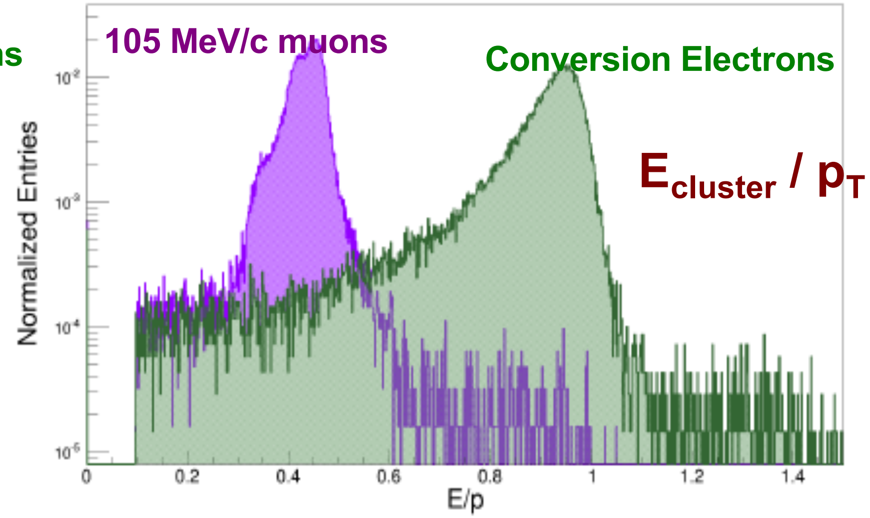


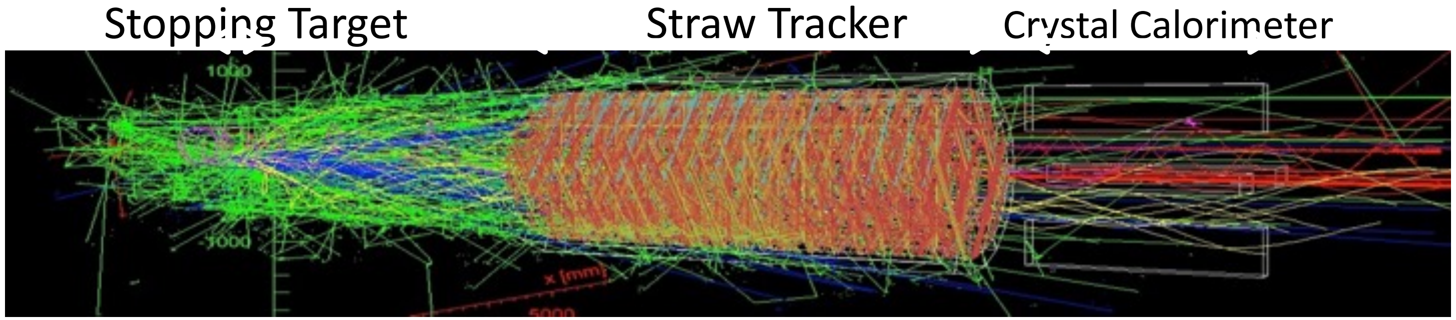
With few iterations from ns to O(10 ps) T0's corrections

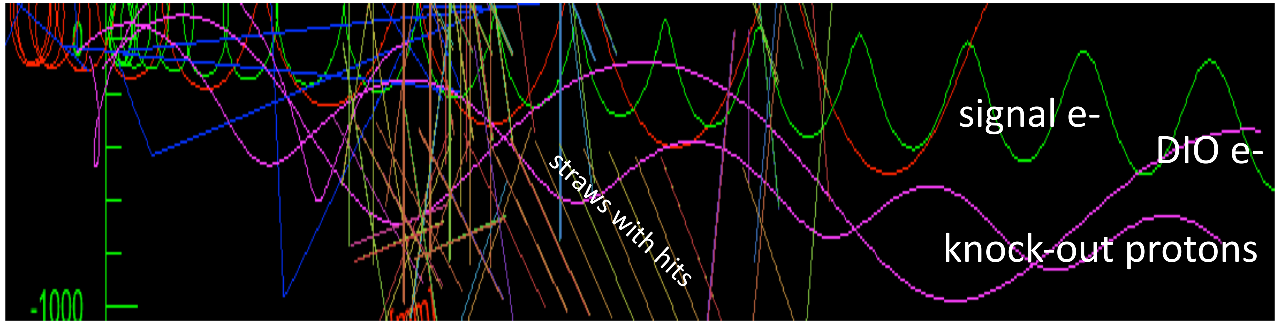
Resolution at 250ps/MIP

Particle identification and Pattern Recognition









particles with hits within +/-50 ns of signal electron t_{mean}