Status of the Mu2e crystal calorimeter

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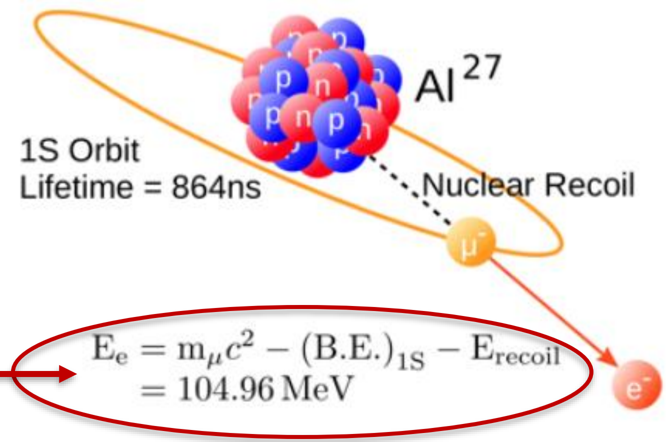
The Mu2e Experiment

- Mu2e searches for Charged Lepton Flavor Violation (CLFV) via the coherent conversion:

$$\mu^- \mathbf{N} \rightarrow e^- \mathbf{N}$$

at Fermilab muon campus..



Clear experimental signature!

- Since the Standard Model prediction is ~ $(\Delta m_\nu^2 / M_W^2)^2 < 10^{-54}$, far beyond experimental reach, any observation will be clear evidence for New Physics.

- In case of no observations, Mu2e will improve by a factor 10^4 the current world best limit from Sindrum II experiment:

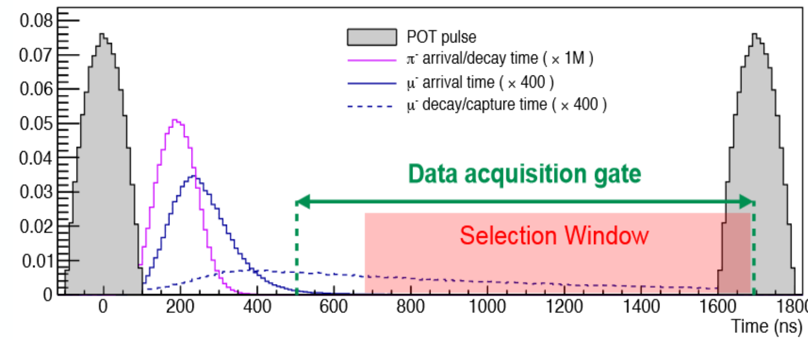
$$R_{\mu e} = \frac{\Gamma\left(\mu^- + \mathrm{N(A,Z)}\right) \rightarrow e^- + \mathrm{N(A,Z)}}{\Gamma\left(\mu^- + \mathrm{N(A,Z)}\right) \rightarrow \text{all muon captures}} \leq 8 \times 10^{-17} \text{ @ } 90\% \text{ C.L.}$$

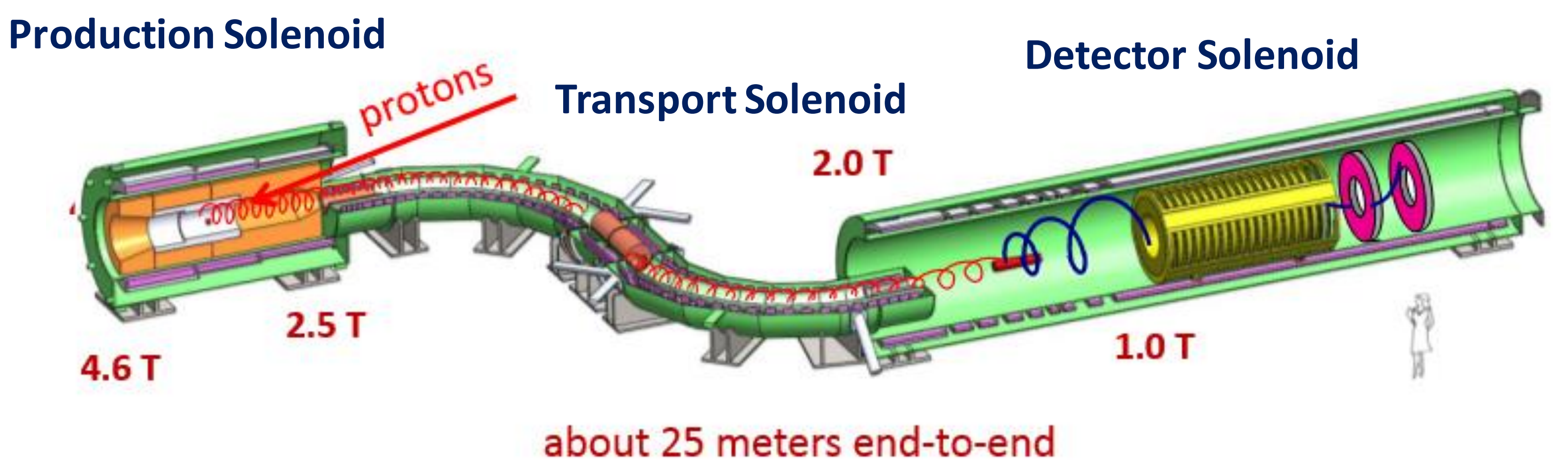
Mu2e Technique

1. Generate a beam of low momentum muons
   - High intensity, high purity, pulsed
2. Transport and stop the muons in aluminum target
   - Muonic Atom mean life: **τ_{μ}^{A} = 864 ns**
3. Look for events consistent with a conversion electron:
   - In case of aluminum: **E_{CE} = 104.96 MeV**
   - Signal windows of few hundreds of keV below E_{CE}

Pulsed beam and a delayed live gate:

Beam Period: 1700 ns ~ 2 x τ_{μ}^{Al}
Beam Intensity: 40 Mp/bunch

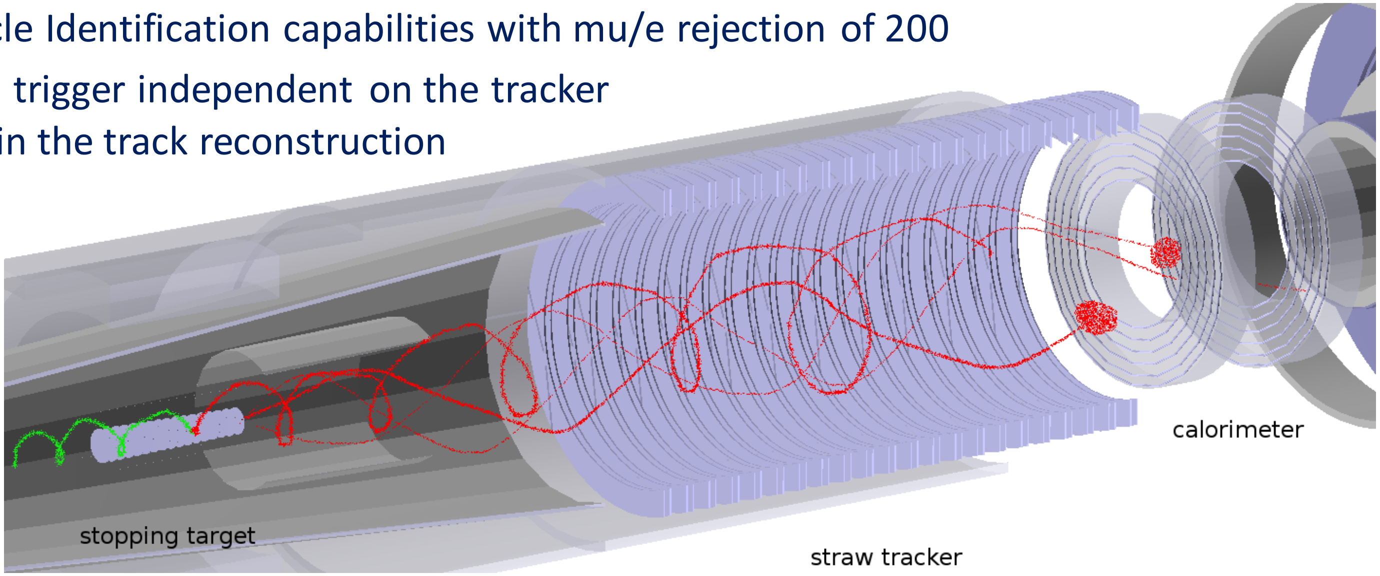


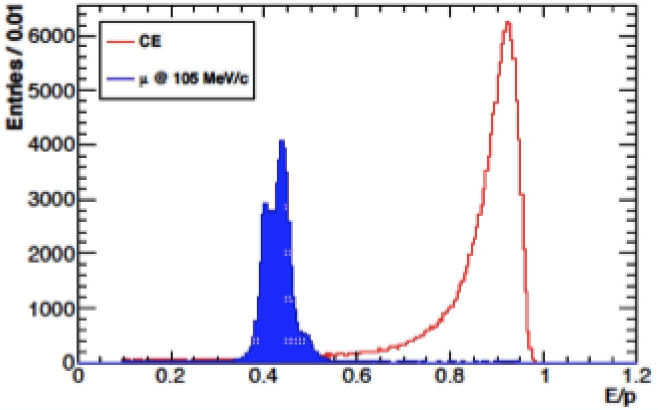


Calorimeter Requirements

The calorimeter has to add redundancy and complementary qualities with respect to the tracker (that has a 160 keV/c resolution on the momentum):

- Particle Identification capabilities with mu/e rejection of 200
- A fast trigger independent on the tracker
- Help in the track reconstruction

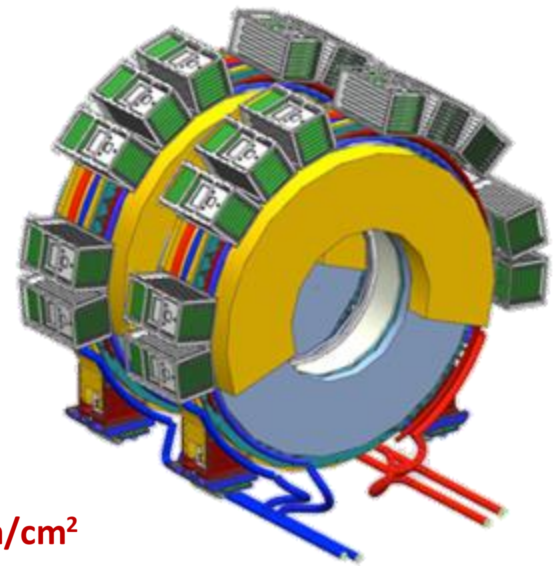




→ Provide energy resolution σ_E/E of O(10 %)
→ Provide timing resolution $\sigma(t) < 500$ ps
→ Provide position resolution < 1 cm
→ Work in vacuum @ 10^{-4} Torr and 1 T B-Field
→ Survive the harsh radiation environment

Technical Specifications

- Fast signal for Pileup and Timing:
  - **τ of emission < 40 ns**
  - Fast Digitization (WD) to disentangle signals in pileup
- Crystals with high Light Yield for timing/energy:
  - resolution → **LY(photosensors) > 20 pe/MeV**
- 2 photo-sensors/preamps/crystal for redundancy:
  - reduce MTTF requirement → **1 million hours/SIPM**
- Radiation Hardness (5 years of running with a safety factor 3):
  - Crystals should survive a TID of **90 krad** and a fluence of **$3x10^{12}$ n/cm²**
  - Photo-sensors should survive **45 krad** and a fluence of **$1.2x10^{12}$ n_1MeV/cm²**
- The 1 T magnetic field + the very small available space suggests the use of SiPMs



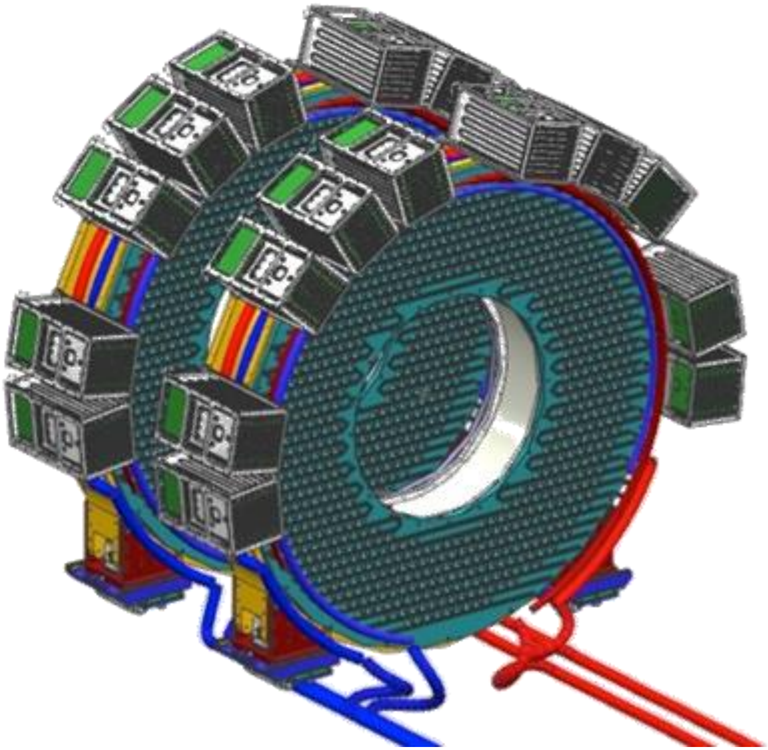
Viable solution

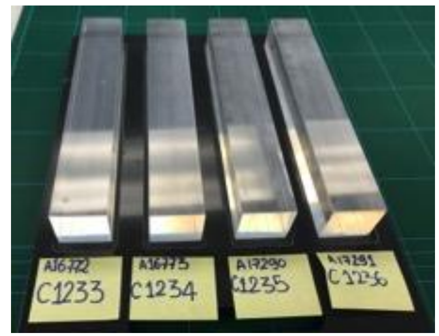
Undoped CsI + UV-extended SiPMs

→ It is radiation hard
→ It has a fast emission time
→ Emits at 310 nm

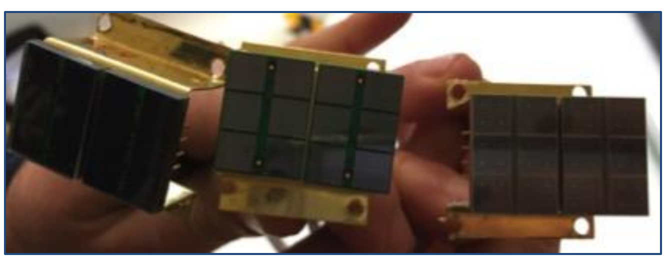
→ 30 % PDE @ 310 nm
→ New silicon resin window
→ TSV readout, Gain = 10^6

Calorimeter Design





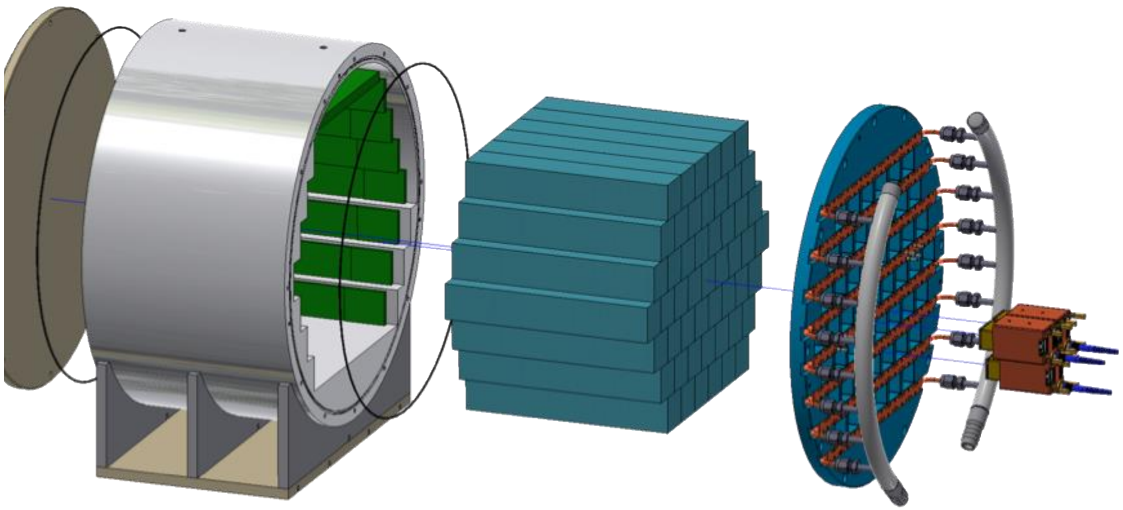
- Two disks, R_{in}=374 mm, R_{out}=660 mm, $10X_0$ length, ~ 75 cm separation
- 674+674 square x-sec **pure CsI crystals**, (34×34×200) mm^3
- For each crystal, two custom array (2×3 of 6×6 mm^2) **large area UV-extended SiPMs**
- Analog FEE directly mounted on SiPM
- Calibration/Monitoring with 6 MeV radioactive source and a laser system

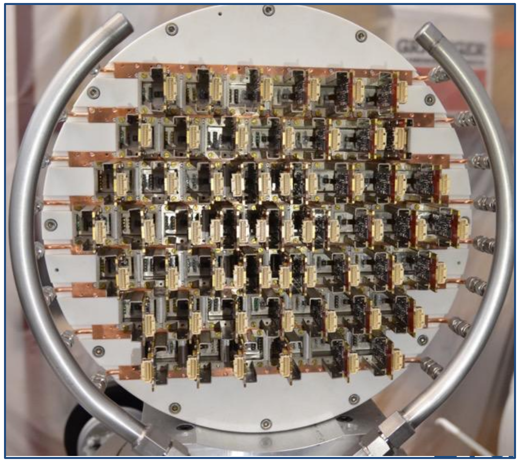


The Module-0

Large EMC prototype: 51 crystals, 102 SiPMs, 102 FEE boards

Readout: 1 GHz CAEN digitizers (DRS4 chip), 2 boards x 32 channels





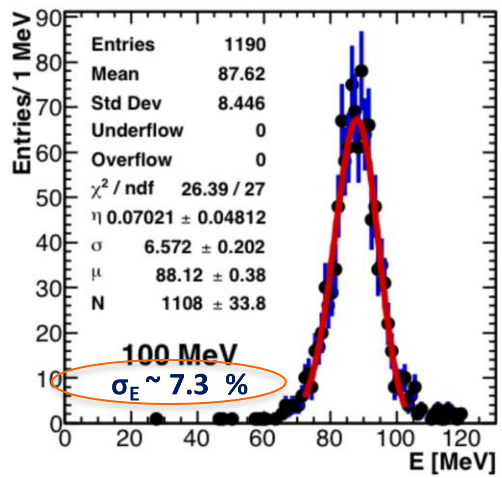
Mechanics and cooling system similar to the final ones but smaller scale → Main goals:

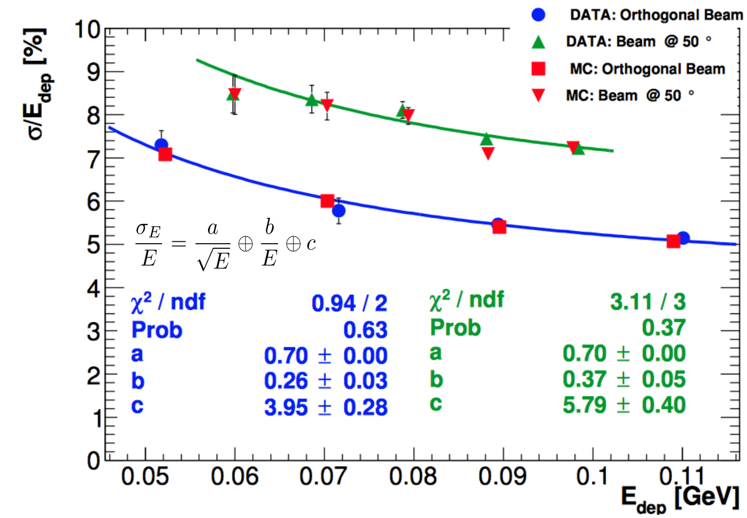
- Integration and assembly procedures
- Test beam May 2017, **60-120 MeV** e^- **(@ 0° and @ 50°)**
- Work under vacuum, low temperature, irradiation test

Module-0 – Performances

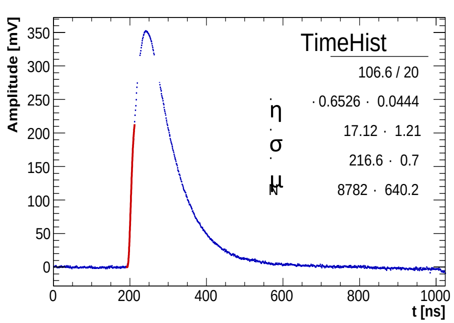
- Energy response
  - Single particle selection
  - MIPs Equalization & E-scale
  - LY/SiPM = 30 pe/MeV
  - **Great Data-MC agreement**

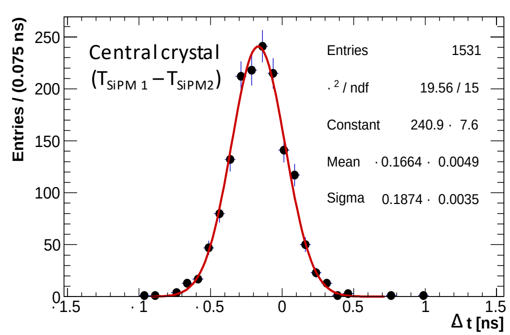
Beam @ 50°

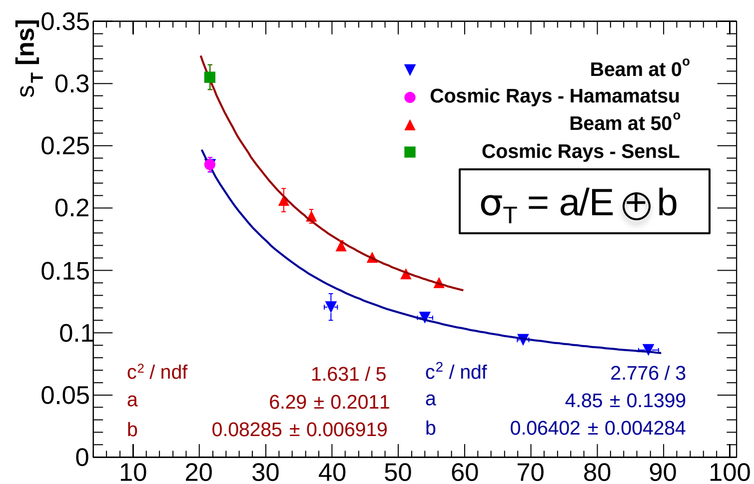




- Time response
  - Log-normal fit on leading edge
  - Constant Fraction method used → CF = 5%



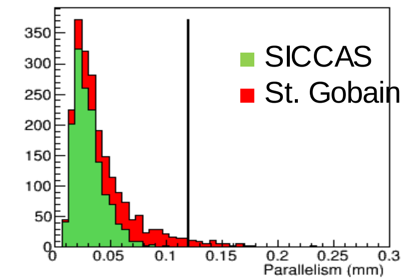


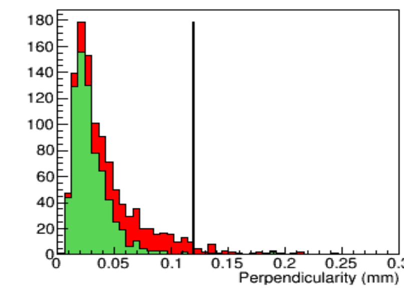


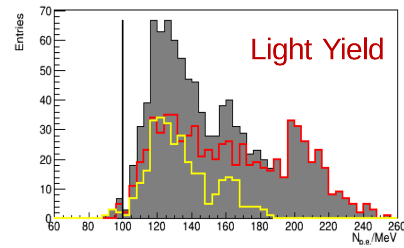
Crystals and SiPMs Production

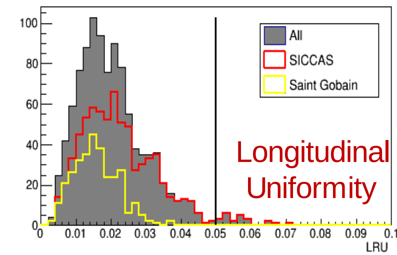
CsI crystals (SICCAS, St.Gobain)

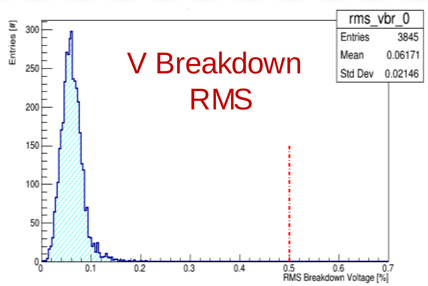
- 1225/1450 delivered and tested
- Dimensional problems with StG
- Good optical properties (4% rejection)
- Irradiation test up to 100 krad on random samples

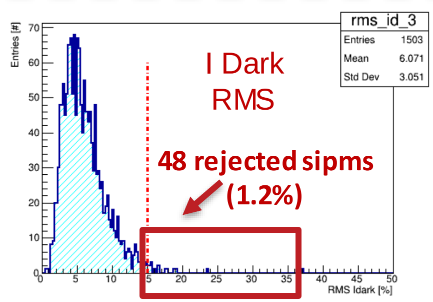


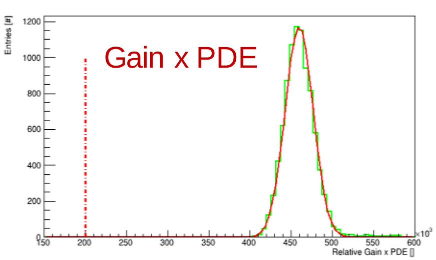


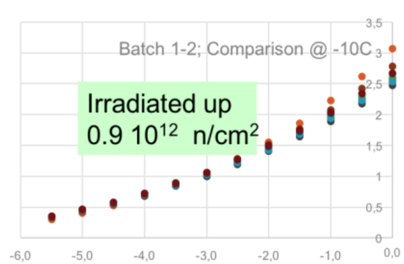








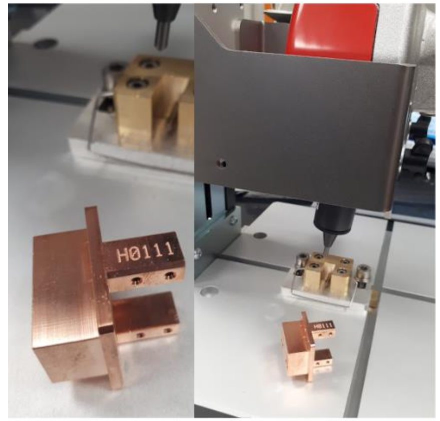


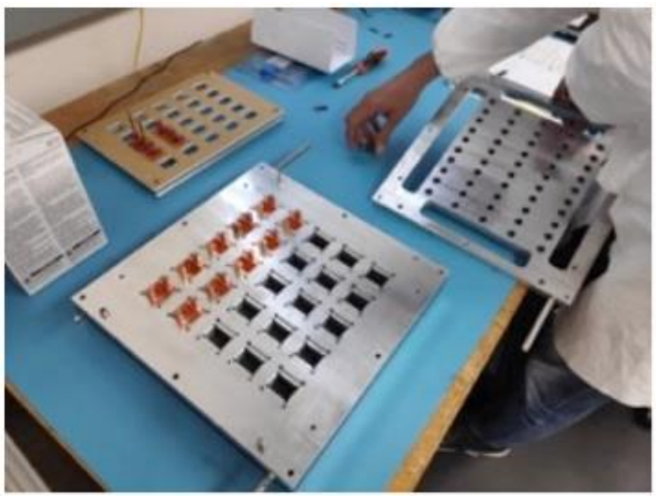


Custom SiPMs (Hamamatsu)

- 4000/4000 delivered and tested
- 1.2% overall rejection factor
- Passive neutron irradiation @ HZDR
- MTTF > 10 million hours

Status of the assembling



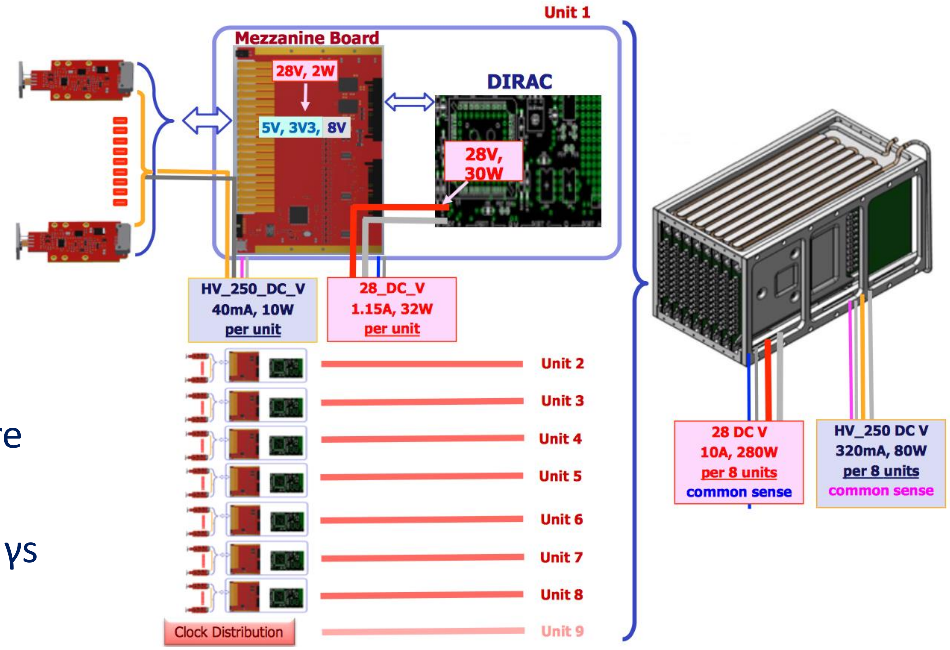


Logistic problem of working at FNAL due to the outbreak of the COVID-19

Status of Electronics

Front End Electronics board.

- 2 amplification stages (x 3, x6)
- Linear regulation of bias voltage
- Shaping:
  → Rise time 25 ns
  → Full width 150 ns
- 2 V dynamic range
- Monitoring of SiPM currents/temperature
- V3 version rad-hard up to 100 krad
- Tested at Calliope (ENEA-Italy) with Co^{60} γs and with 14 MeV neutrons @ FNG



Waveform Digitizer board:

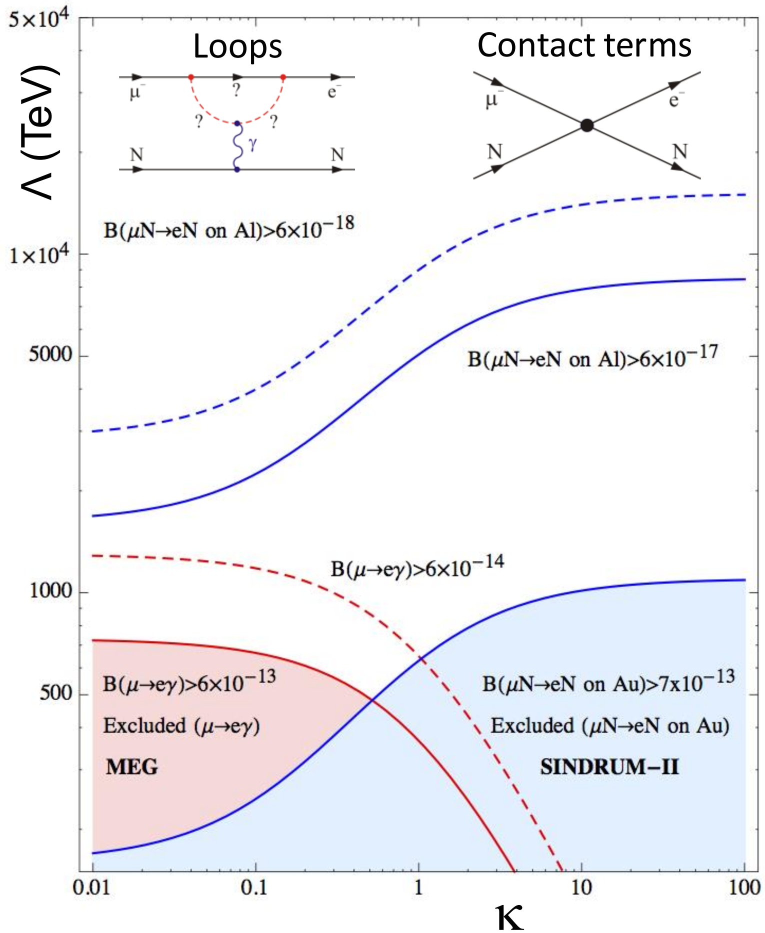
- 20 SiPM+FEE channels per board
- Mezzanine: input FEE signals, HV to SiPMs
- DIRAC board provides digitization at 200 Msps, with 12 bit ADC
- VTRX optical readout
- Final Rad-Hard FPGA PF300T
- V2 version rad-hard up to 20 krad

Conclusions

- The Mu2e calorimeter has concluded its prototyping phase satisfying the Mu2e requirements:
  - **Un-doped CsI crystals perform well**
    - **Excellent LRU and LY** 100 pe/MeV (PMT+Tyvek wrapping)
    - τ of 30 ns with negligible slow component
    - **Radiation hardness OK** for our purposes: 40% LY loss at 100 krad
  - **Mu2e SiPMs quality OK,** high gain, high PDE, small I_{dark}, small spread inside array
    - SiPM performance after **irradiation OK**
    - SiPM **MTTF > 10 million hours**
  - **Calorimeter prototypes** tested with e^- beam
    - **Good time and energy resolution achieved @ 100 MeV**
- **Calorimeter production phase started in March 2018**
- Active component production ended, Electronics production is ongoing
- Calorimeter assembly started but with logistic problem of working at FNAL
- **Calorimeter installation in Mu2e experimental hall delayed for COVID-19**

Additional Slides

Probing New Physics with CLFV

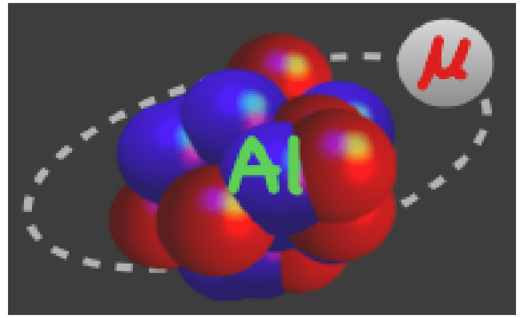


- Contact κ, mass scale Λ
- 'Loops', electromagnetic operator, κ<<1, can be probed by *μ→eγ* and *μN→eN*
- 'Contact terms', direct coupling between quarks and leptons, κ>>1, accessible by *μN→eN*
- **Mu2e will have sensitivity to Λ (mass scale) up to hundreds TeV beyond any existing accelerator!**

$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}R\sigma_{\mu\nu}e_L F_{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L \sum_{q=u,d}\bar{q}_L\gamma^\mu q_L$$

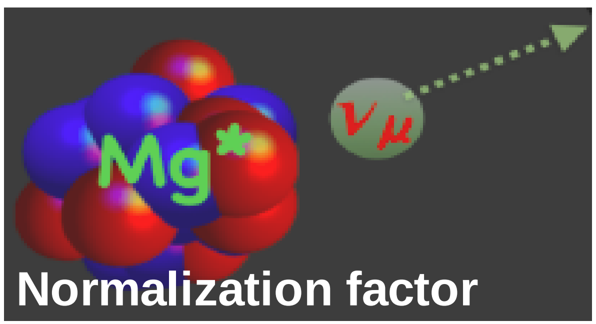
Mu2e Background

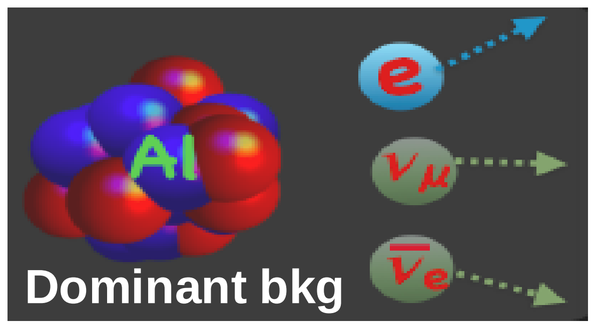
1. Background from muon capture:

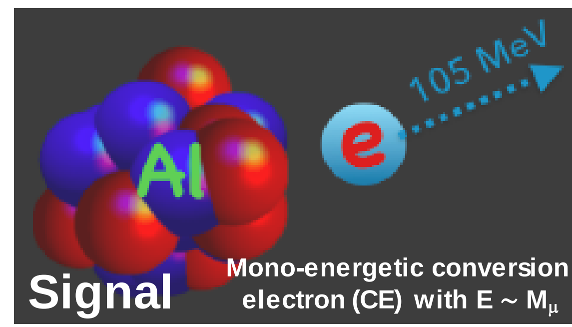


τ_{μ}^{Al} = 864 ns

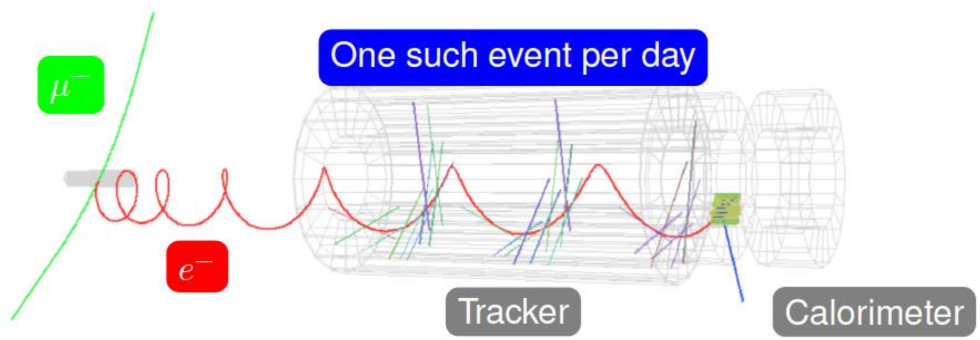
Nuclear capture ~ 61% | Decay In Orbit (DIO) ~ 39% | Conversion < 10^{-12}





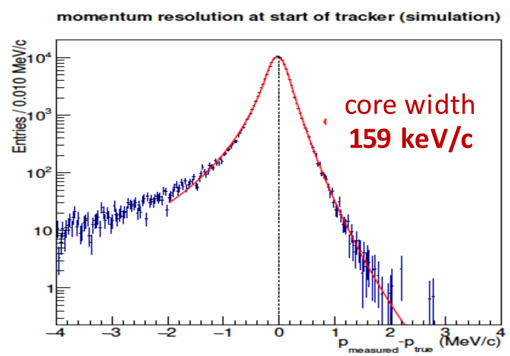


2. Background from cosmic rays:
   - CR muon decays
   - CR muons identified as e^-
   - e^- from CR muon interactions



The Mu2e Detector

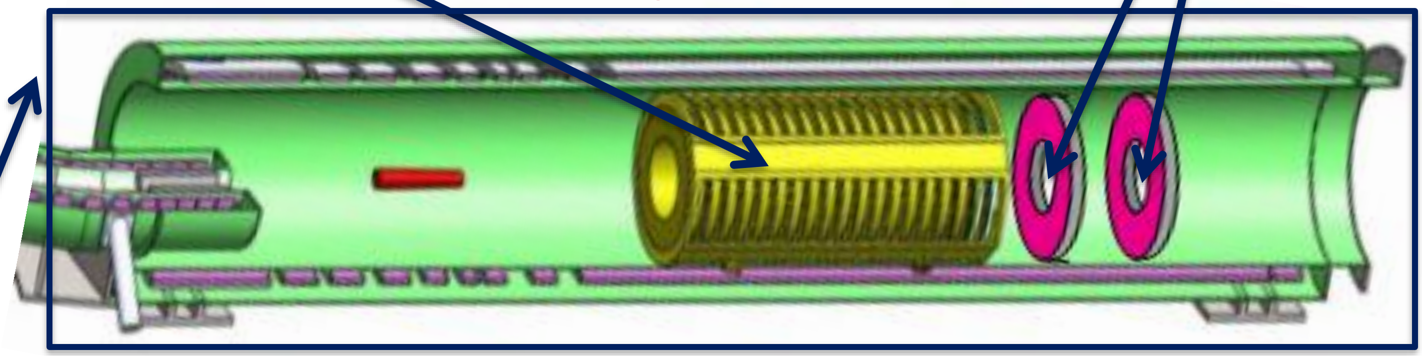
Straw Tracker:
- High precision momentum measurement
- 20000 low mass straw drift tubes



Crystal Calorimeter:
- Energy, time and position measurements

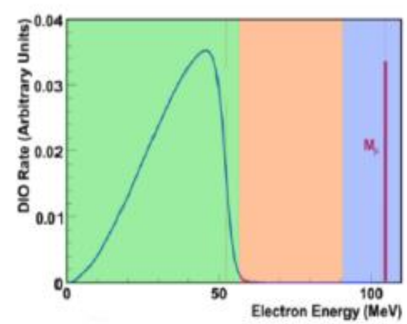
2.0 T

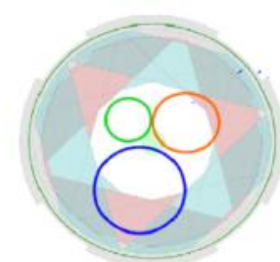
1.0 T



- A **Cosmic Ray Veto System** surrounds the detector solenoid:
  - **veto inefficiency < 10^{-4}**

The detectors have an annular geometry, in order to be blind to low momentum particles coming from muon decays

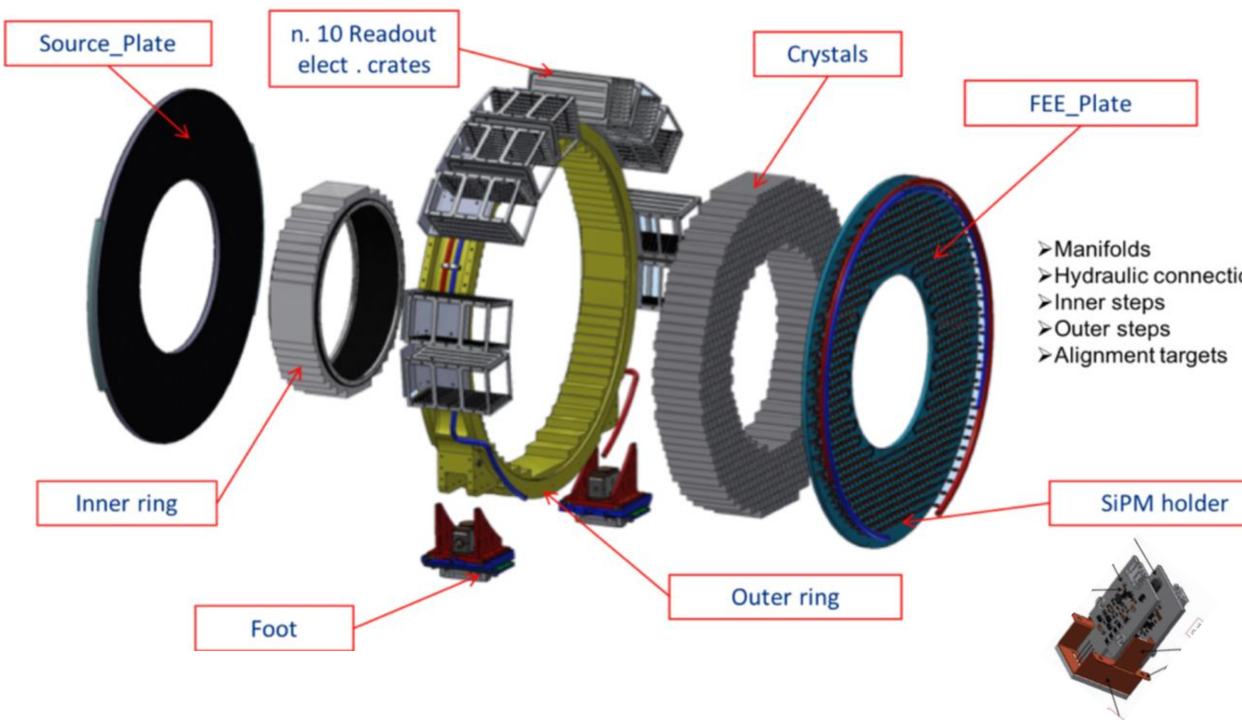




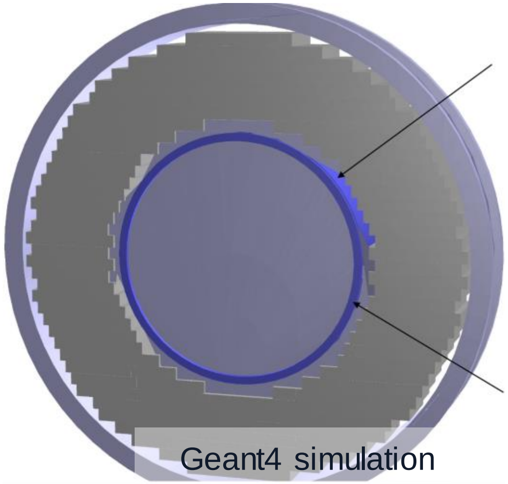
Final Mechanical Design

Crystals stacked from the bottom to the top inside an external stainless steel cylindrical support

- FEA completed: good stability, small stress on legs
- Inner cylinder: composite material
- FEE plate: PEEK
- CF front face with source tubing integrated
- FEE crates mounted on the external cylinder

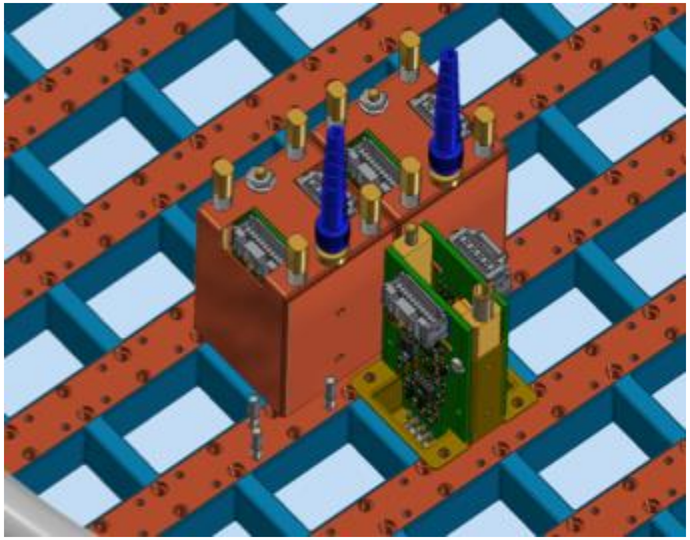


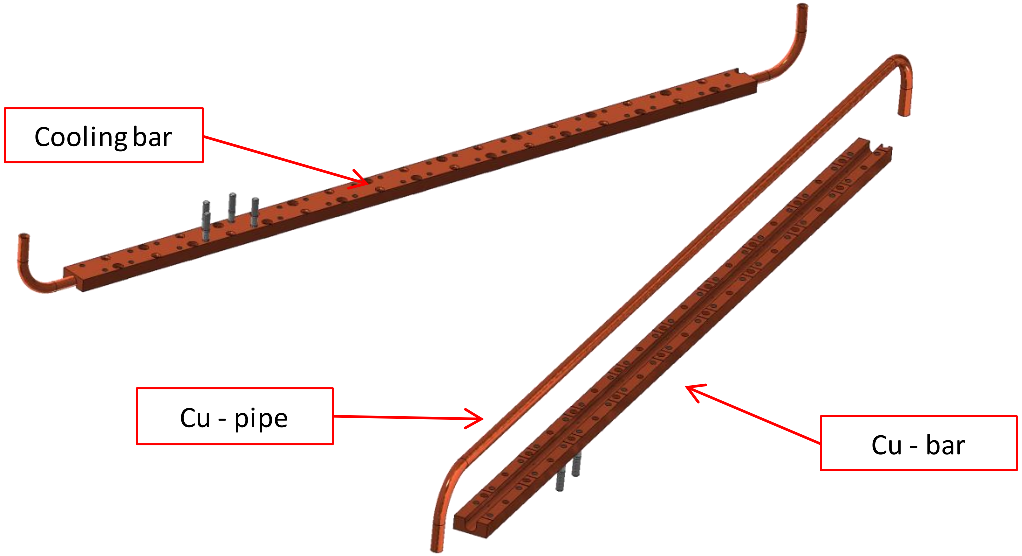

mockup with fake iron crystals

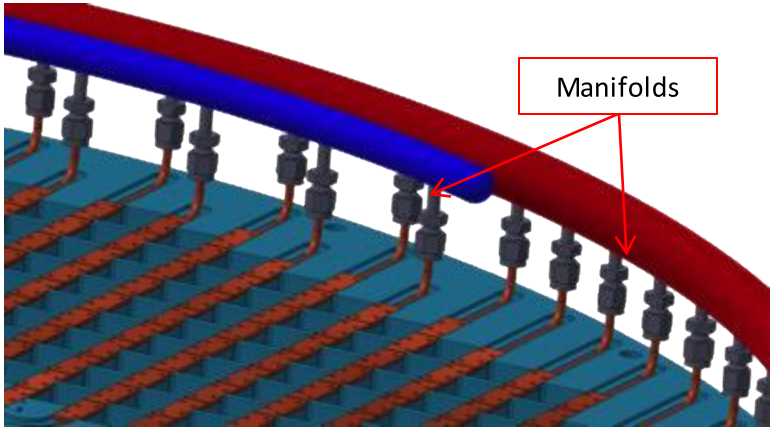

Geant4 simulation

Calorimeter Cooling

- The FEE plate houses the Front End electronics and photosensors holders and provides cooling.
- The manifolds are jointed to the cooling channels by means of tube fittings (Swagelok type).
- The SiPM holders are bolted to the cooling channels by means four stud screws. It is in thermal contact with the cooling channels.
- The plate is thermally isolated from the outer ring and from the crystals.







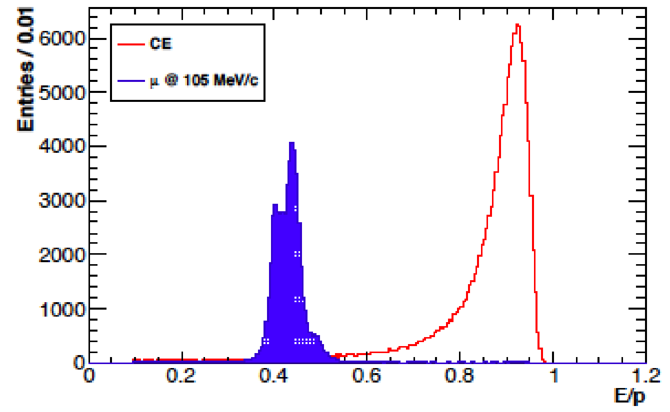
Calorimeter PID

- With a CRV inefficiency of 10^{-4} an additional rejection factor of ~ 200 is needed to have < 0.1 fake events from cosmics in the signal window

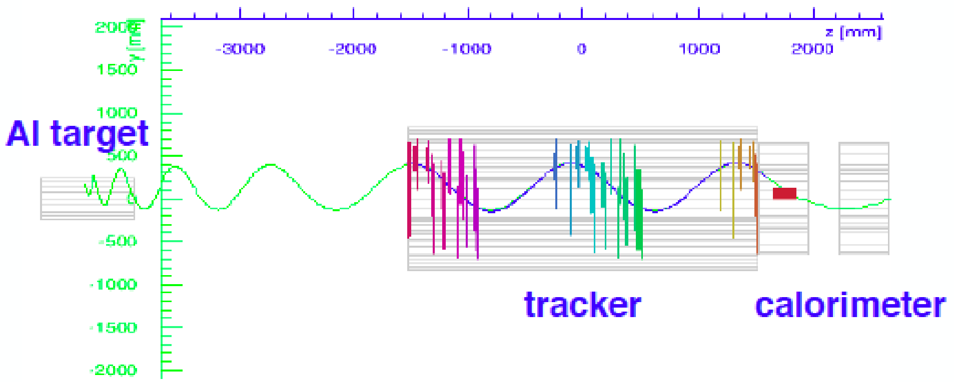
- 105 MeV/c e^- are ultra-relativistic, while 105 MeV/c μ have β~ 0.7 and a kinetic energy of ~ 40 MeV
- Likelihood rejection combines

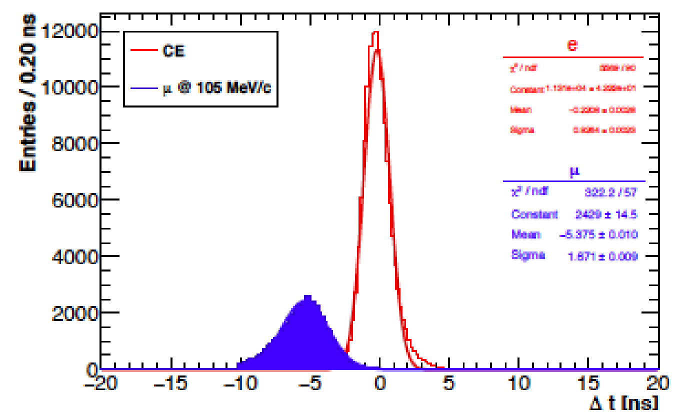
  $\Delta t = t_{track} - t_{cluster}$ and E/p:

$$\ln L_{e,\mu} = \ln P_{e,\mu}(\Delta \mathrm{t}) + \ln P_{e,\mu}(\mathrm{E/p})$$



μ mimicking the CE

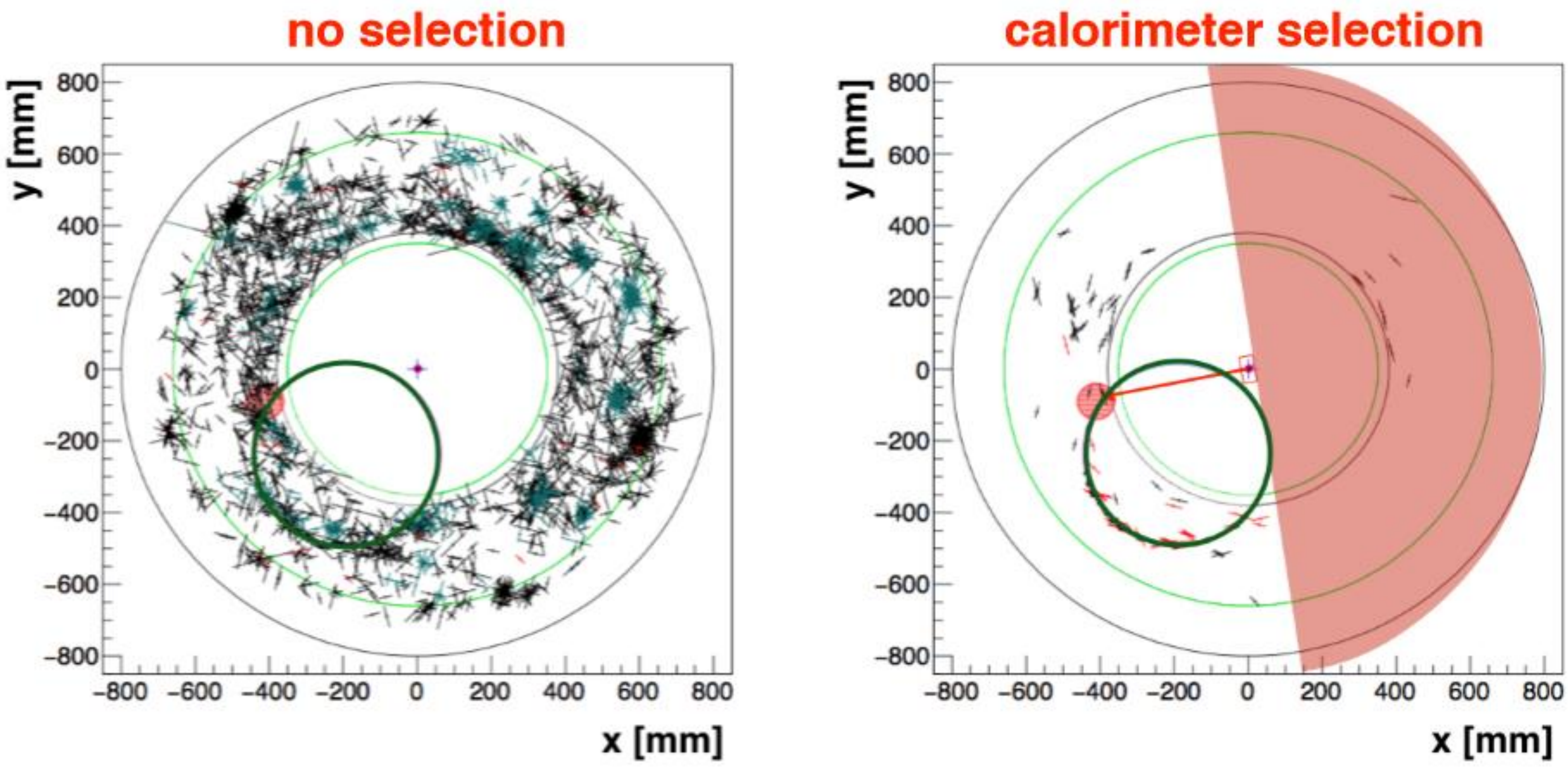




A rejection factor of 200 can be achieved with ~ 95% efficiency for CE

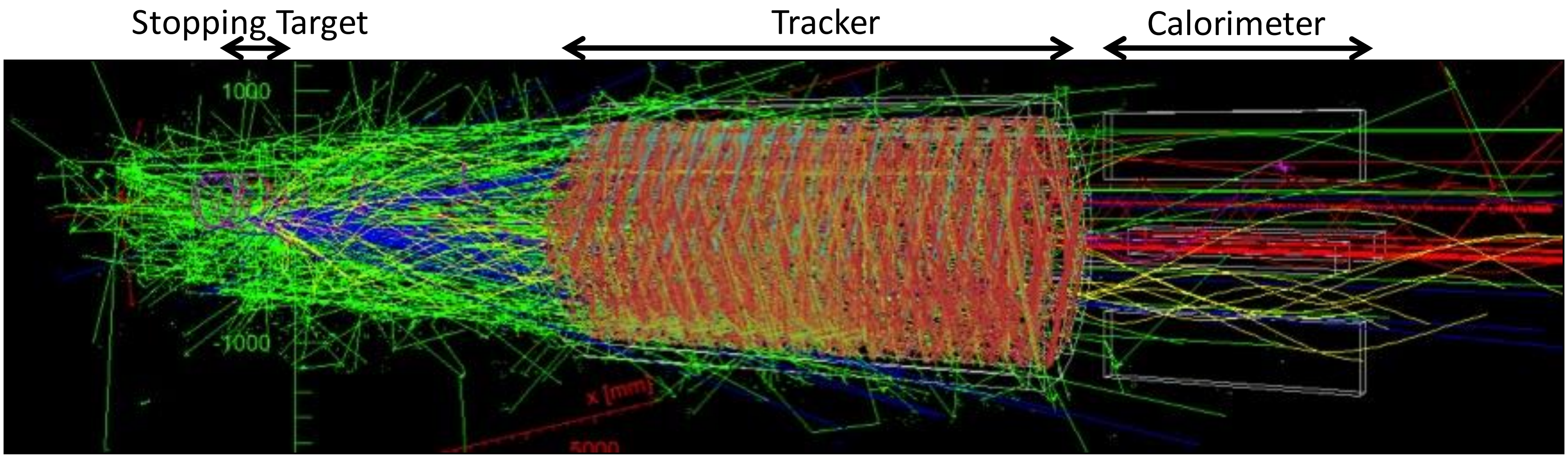
Pattern Recognition

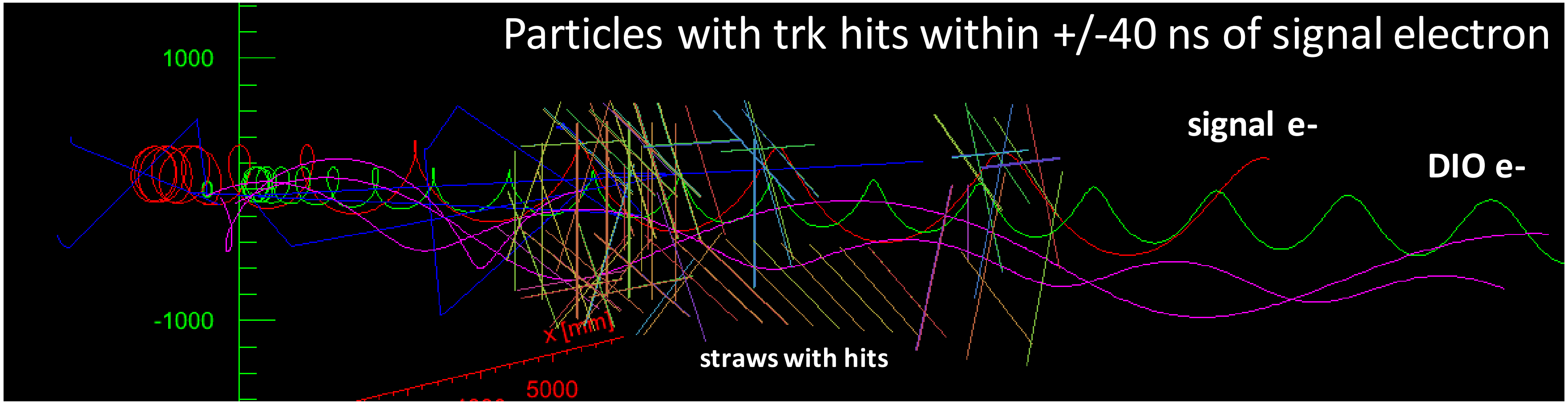
- The speed and efficiency of tracker reconstruction is improved by using calorimeter clusters as seed for the pattern recognition:
  - Time windows of 80 ns around cluster time
  - Spatial correlation



A typical Mu2e signal event

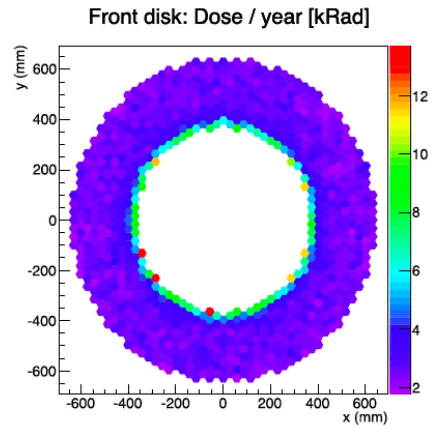
- Signal electron, together with all the other hits/tracks occurring simultaneously, integrated over 500-1695 ns window

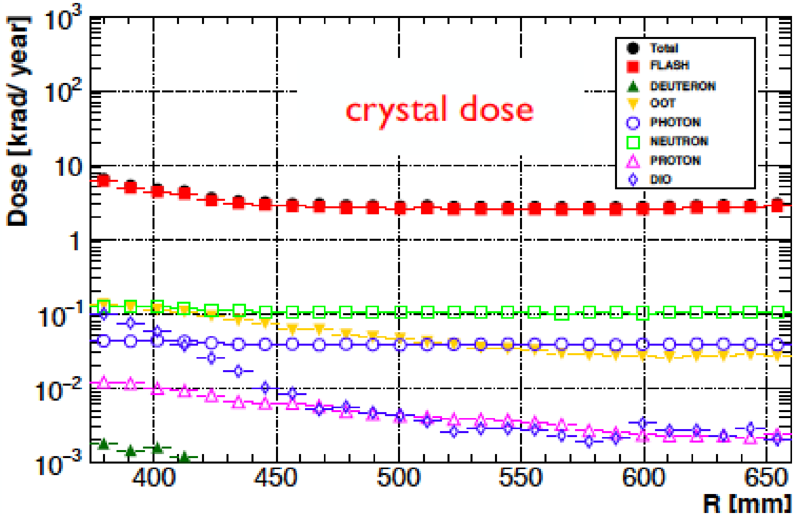


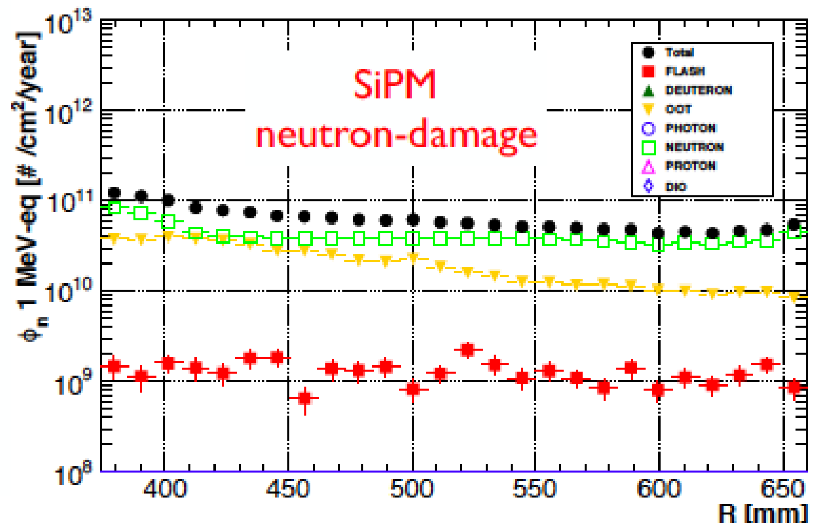


Radiation Damage

- Calorimeter radiation dose driven by beam flash (interaction of proton beam on target)
- Dose from muon capture is x10 smaller
- Dose is mainly in the inner radius
- Highest dose ~10 krad/year
- Highest n flux on crystals ~ 2×10^{11} n/cm^2/year
- Highest n flux on SiPM ~ 10^{11} n_{1MeVeq}/cm^2/year





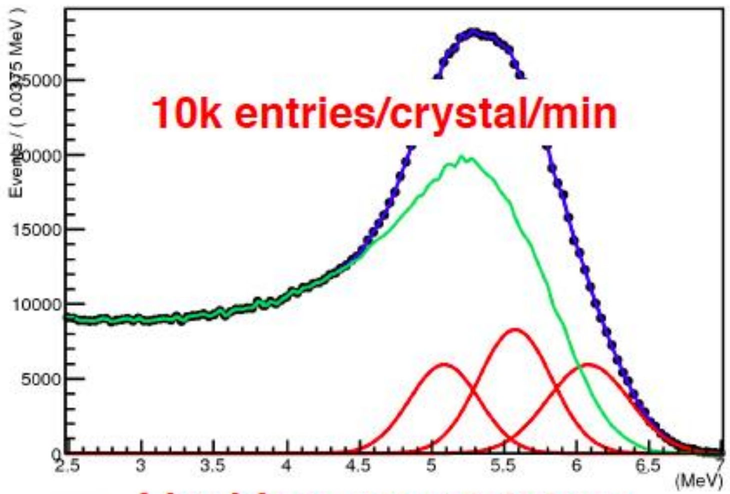


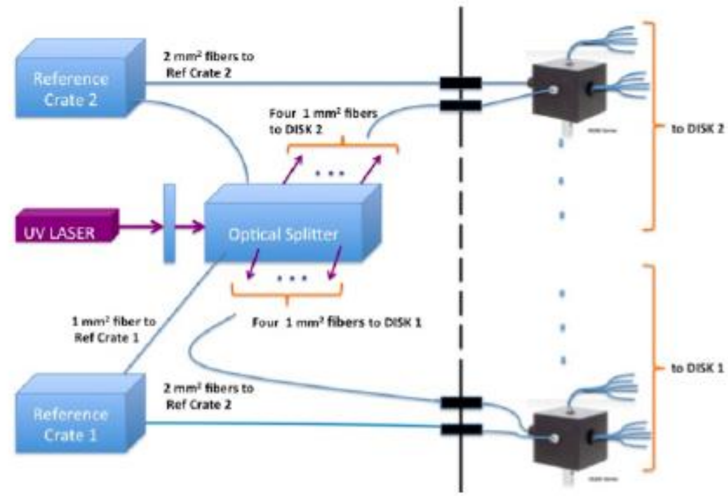
Qualify crystals up to ~ 100 krad, 10^{12} n/cm^2
Qualify SiPM up to ~ 10^{12} n_{1MeVeq}/cm^2

This includes a safety factor of 3 for a 3 year run

Calorimeter Calibration

- Liquid source FC 770 + DT generator: 6 MeV + 2 escape peaks
- Laser system to monitor SiPM performance





Liquid source prototype

Laser system - test station

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

QA of CsI Crystals

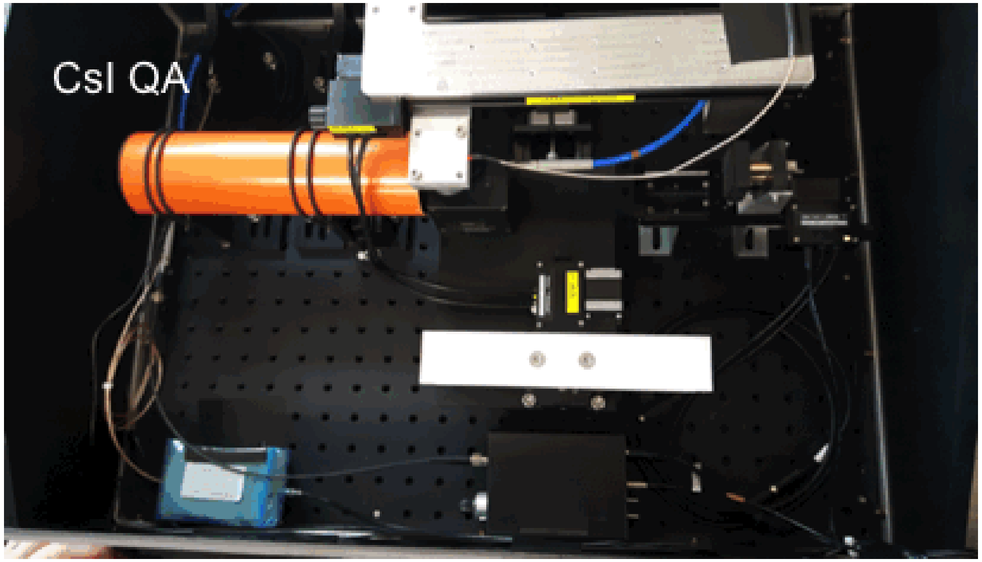
Mechanical test:

Visual inspection: check if crystal presents chips, halos or inclusion

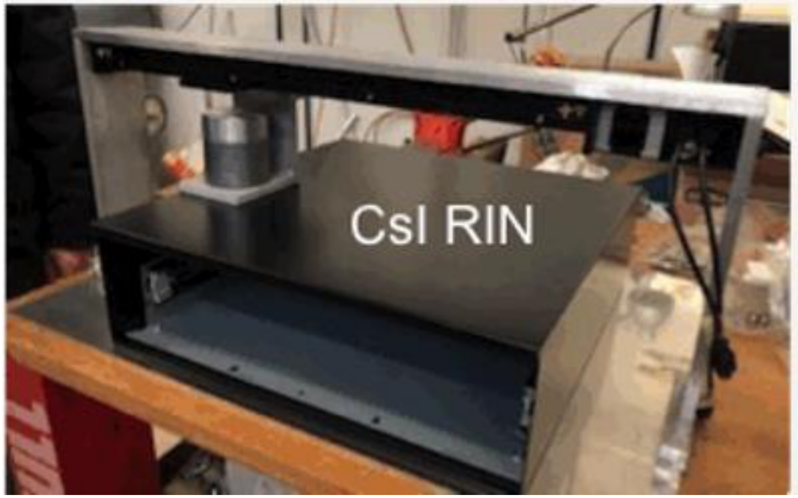
CMM measurements: x ,y ,z, flatness, perpendicularity, parallelism

Optical properties test:

Light yield, Longitudinal Response Uniformity, E_{res}, Fast/Total ratio



Test box designed and produced @ LNF



Radiation Induced Noise:

Radiation Induced Noise with ^{127}Cs and neutron

Radiation Damage:

irradiation @ HZDR, Dresden, up to 100 kRad only for 2 crystals/batch

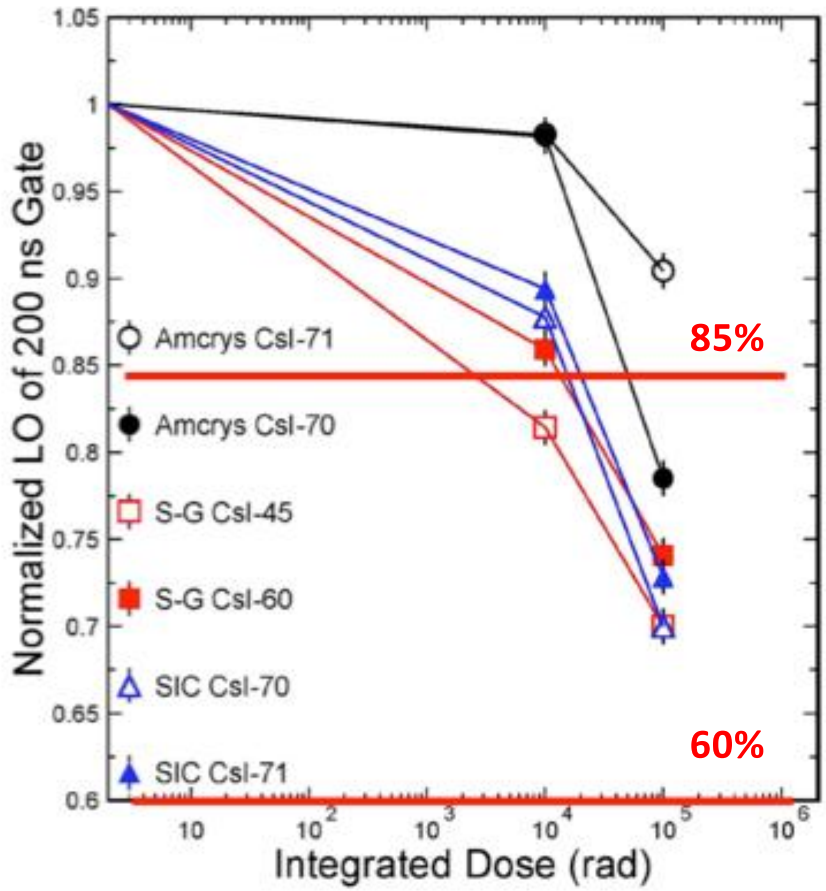
- All crystals tested satisfy the specification concerning the optical properties
- some problems with the dimensional test

Radiation Hardness of Crystals

Few samples per vendor have been exposed both to **ionizing dose** and **neutrons**

- Irradiation test up to 100 krad
- Requirement:
  normalized LY **after 10/100 krad > 85/60%**

Most crystals have LY larger than 100 p.e./MeV after 100 krad (40% max. loss), promising a robust CsI calorimeter



- **Radiation Induced Noise** (RIN) @ 1.8 rad/h required is **< 0.6 MeV**
  - All 72 samples tested. All OK apart some Amcrys crystals that
    do not satisfy the required limit

- Negligible LY and LRU variation after **1.6 x 10^{12} n_{1MeV}/cm^2 integrared flux**
- Neutron RIN is also smaller than the one from dose

QA of SiPMs

Dimensional test:

Laser Chinese Shadow technique, 100 μm tolerance

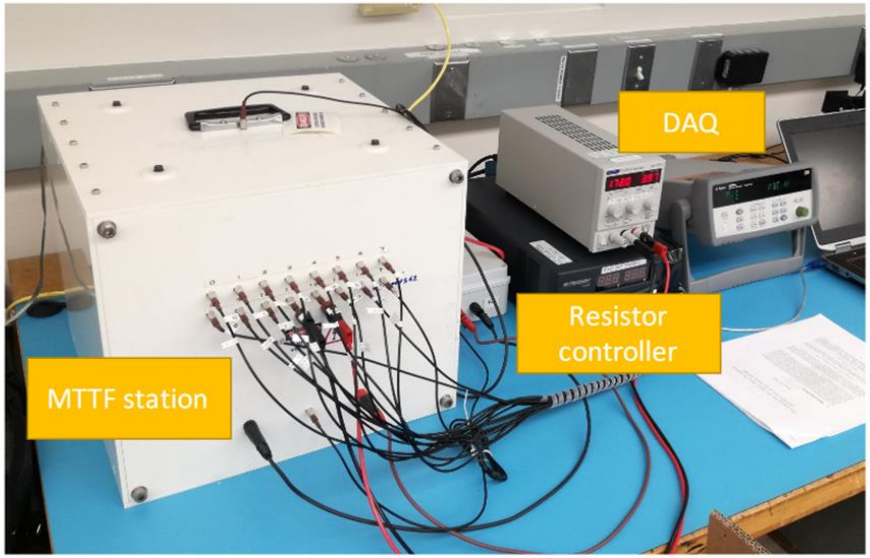
SiPMs Characterization:

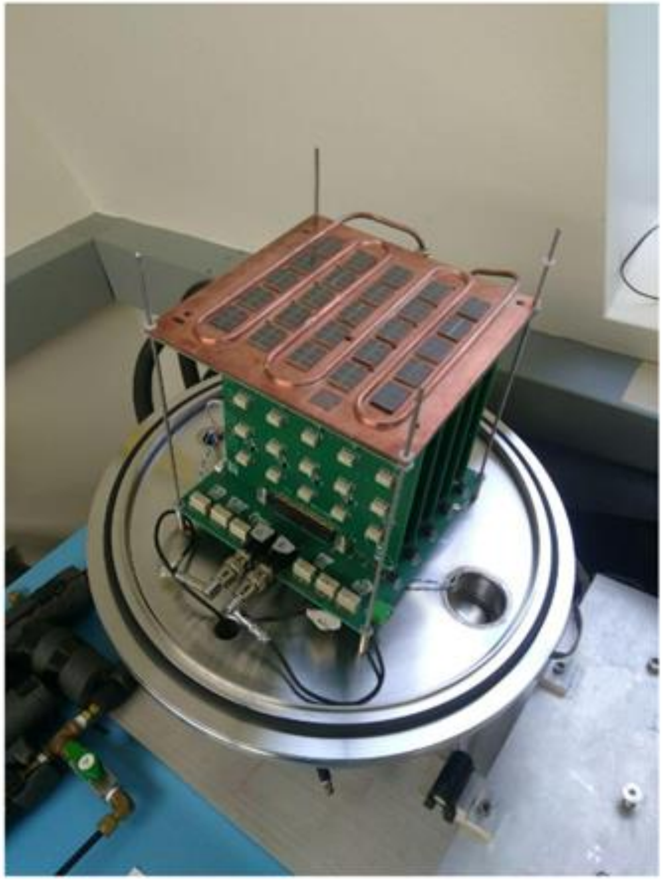
Breakdown Voltage
Dark Current
Gain x PDE

} performed for each cell at three temperatures 20° C, 0° C and -10° C

Mean Time To Failure:

18 days of test for 15 SiPMs/batch (65 C)
If no failures, batch MTTF > 10^6 hours





Radiation Hardness:

irradiation @ HZDR, Dresden,
5 SiPMs/batch
up to 1.7 x 10^{12} n1MeV (Si) / cm^2

Waveform Digitizer

10 crates per disk with 8 digital boards/crate

- 20 SiPM+FEE channels per board
- Mezzanine: input FEE signals, HV to SiPMs
- DIRAC board provides digitization at 200 Msps, with 12 bit ADC
- DC-DC converter
- VTRX optical readout
- Final Rad-Hard FPGA PF300T

- 5 **V1-prototypes** tested with commercial optical readout and FPGA SmartFusion-2
- **V2 prototype with rad-hard components**, FPGA PF300T

➔ Rad-hard up to **15 krad**

➔ FPGA PF300T test OK

➔ ADC tested OK