Design and test of the Mu2e undoped CsI crystal calorimeter

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on behalf of the Mu2e Calorimeter Group

INFN – Sezione di Pisa

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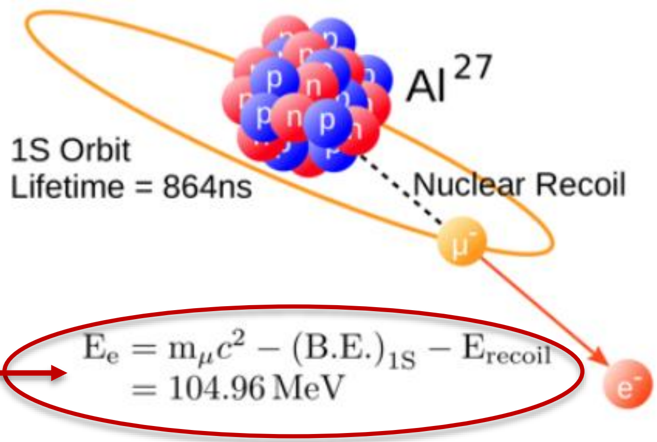
The Mu2e Experiment

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

$$\mu^- N \rightarrow e^- N$$

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:

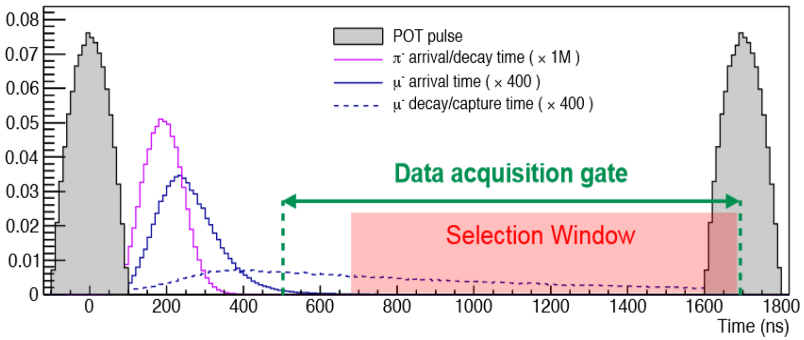
$$R_{\mu e} = \frac{\Gamma\left(\mu^- + N(A,Z)\right) \rightarrow e^- + N(A,Z)}{\Gamma\left(\mu^- + N(A,Z)\right) \rightarrow \text{all muon captures}} \leq 8\times 10^{-17} \text{ @ } 90\% \text{ C.L.}$$

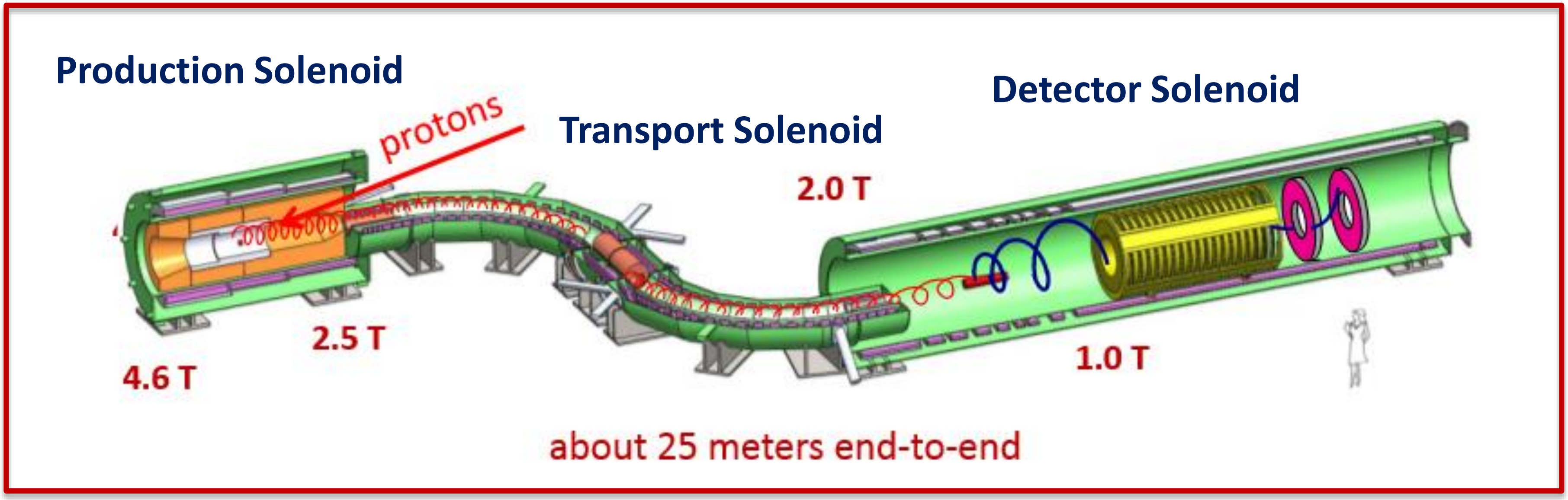
Mu2e Technique

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

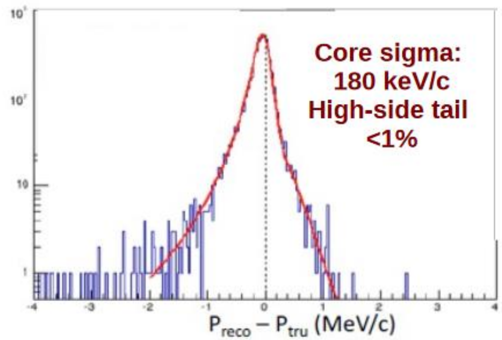




The Mu2e Detector

Straw Tracker:

- High precision momentum measurement
- 20000 low mass straw drift tubes

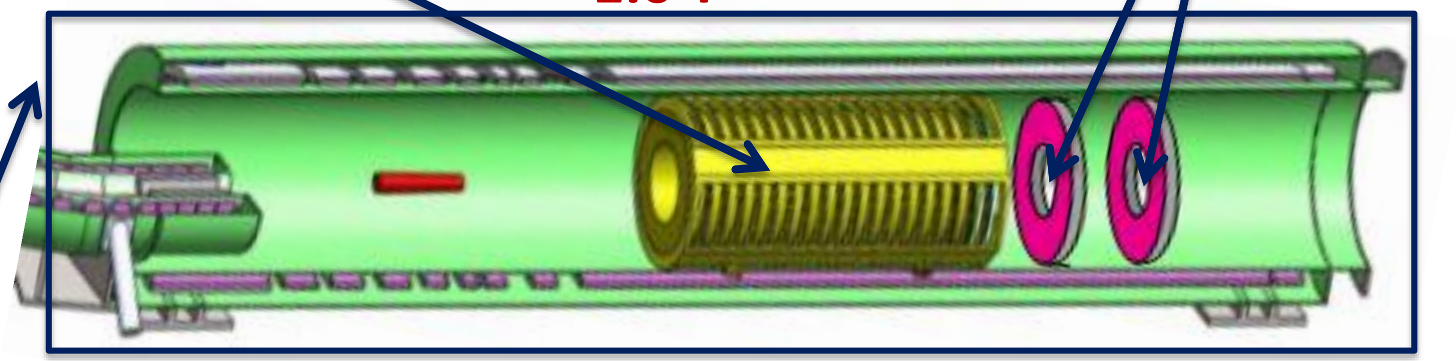


Crystal Calorimeter:

- Energy, time and position measurements

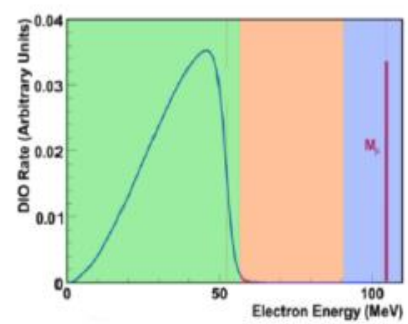
2.0 T

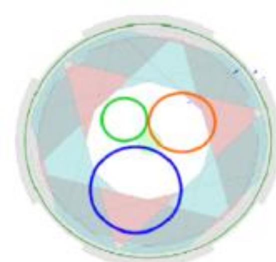
1.0 T



- 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

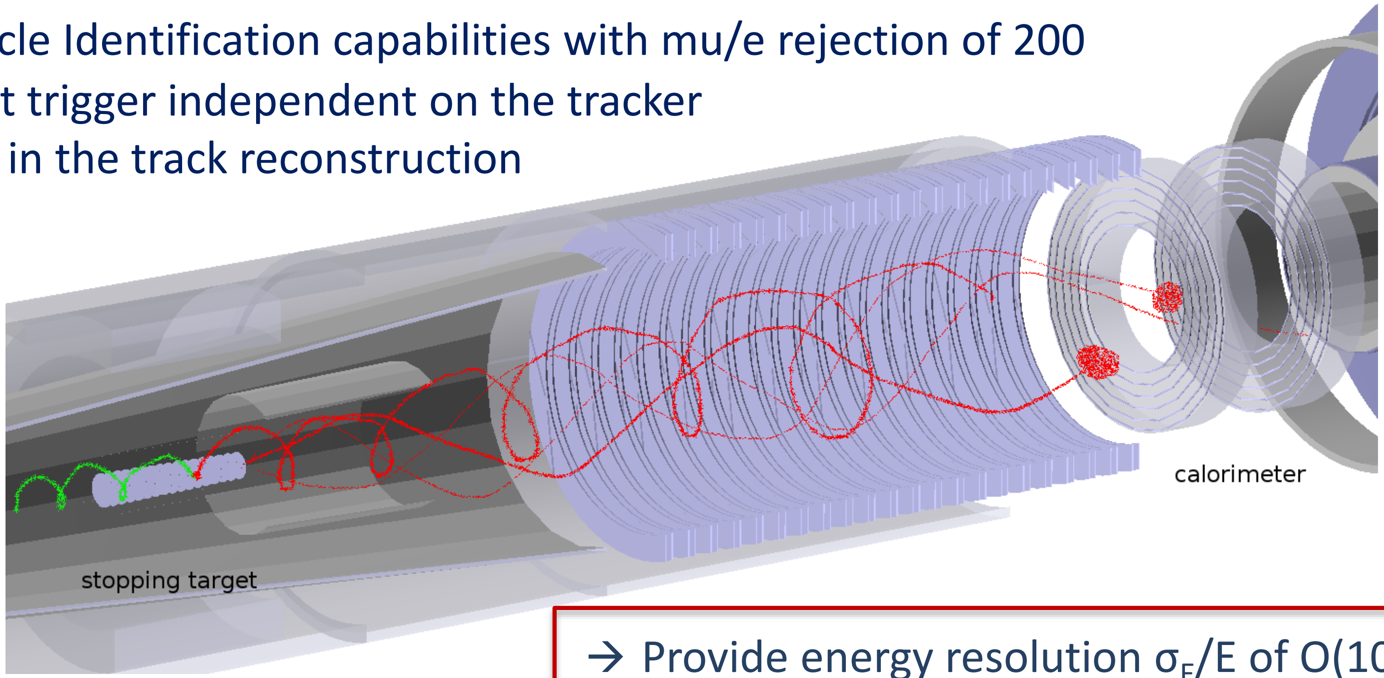




Calorimeter Requirements

For the muon to electron conversion search, the calorimeter has to add redundancy and complementary qualities with respect to the tracker:

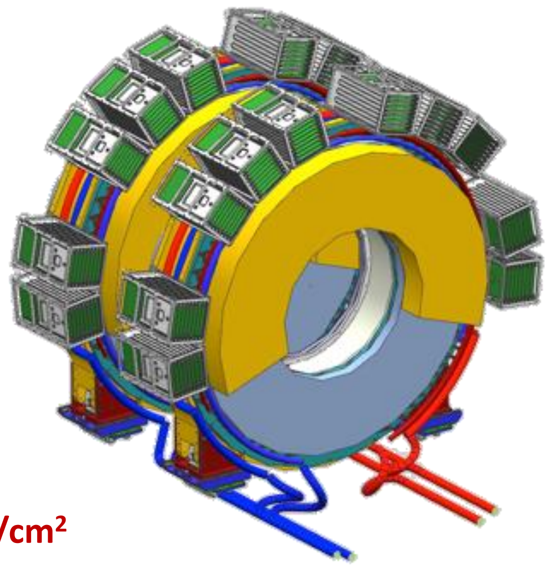
- Particle Identification capabilities with mu/e rejection of 200
- A fast trigger independent on the tracker
- Help in the track reconstruction



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

<u>Good reliability: one scheduled access per year!</u>

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 **3×10^{12} n/cm^2**
  - Photo-sensors should survive **45 krad** and a fluence of **1.2×10^{12} n_1MeV/cm^2**
- The 1 T magnetic field + the very small available space suggests the use of SiPMs

Viable solution →

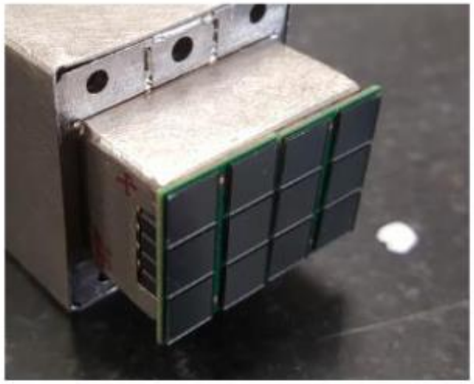
Undoped CsI + UV-extended SiPMs

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

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

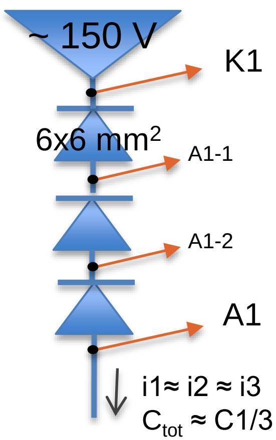
Mu2e Custom SiPM

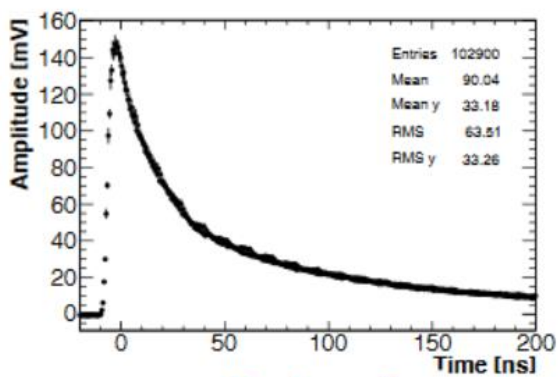
- A modular and custom SiPM layout consisting of **2 arrays of 3 6 x 6 mm^2 UV-extended** monolithic SiPMs has been developed



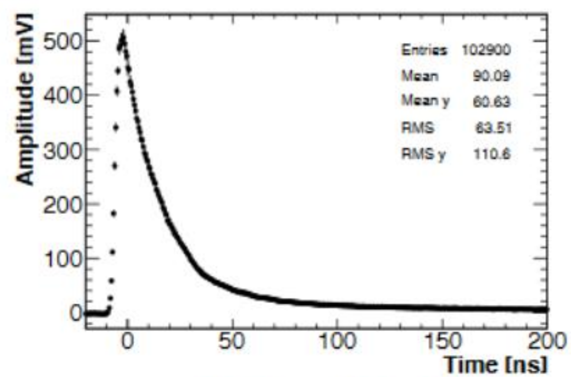
Pixel pitch [μm]	50
Effective photosensitive area [mm]	6.0×6.0
Number of pixel	14400
Window material	Silicon resin
Gain (at 25° C)	2.4×10^6
PDE @ 310 nm	28%

- The readout series configuration reduces the overall capacitance and allows to generate faster signals





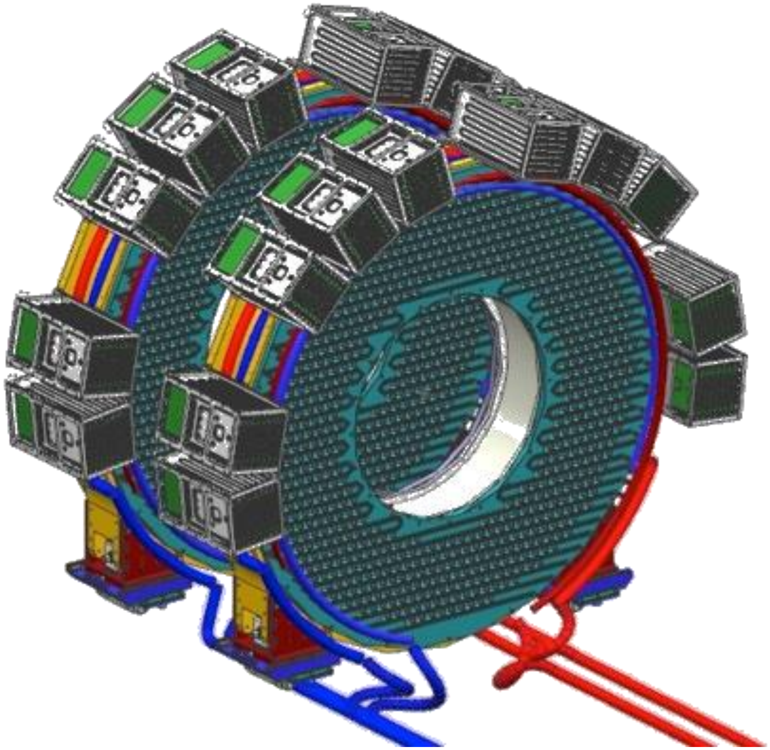
Single cell

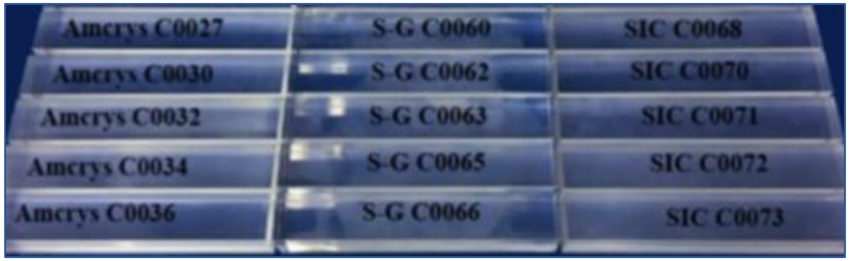


Series of 3 cells

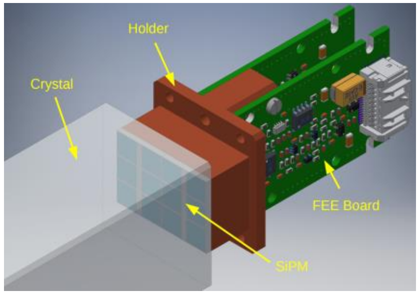
Calorimeter Design

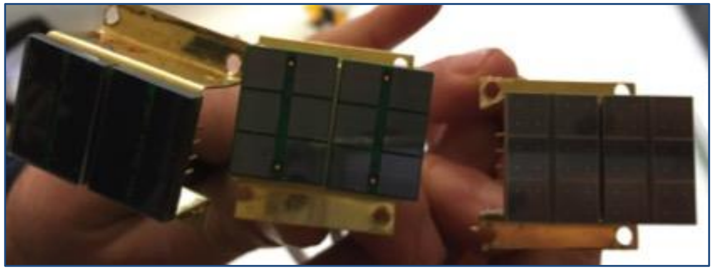
The Mu2e Calorimeter consists of two disks of 674 un-doped CsI 34 x 34 x 200 mm^3 crystals





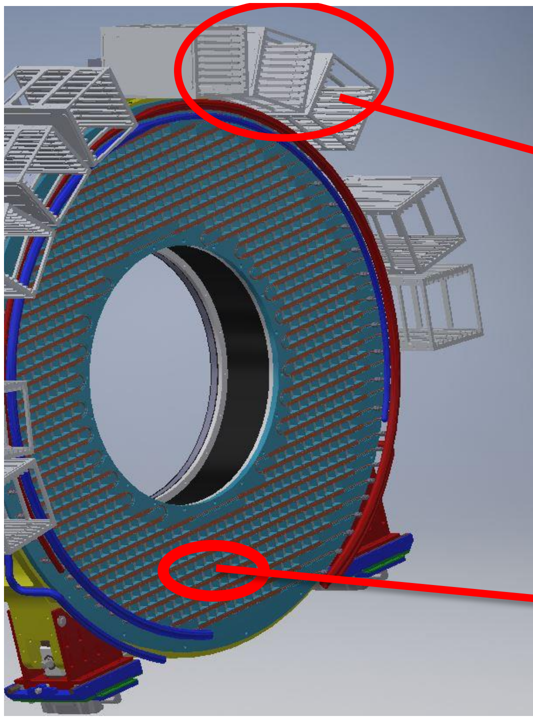
- Each crystal is read out by two large area UV extended Mu2e SiPM's (14x20 mm^2)

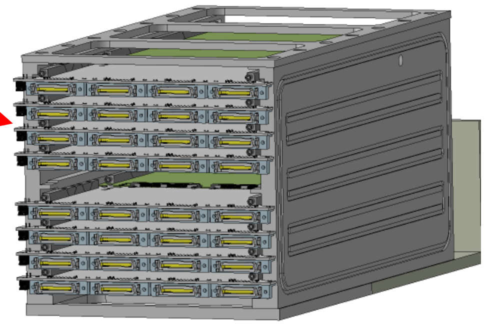


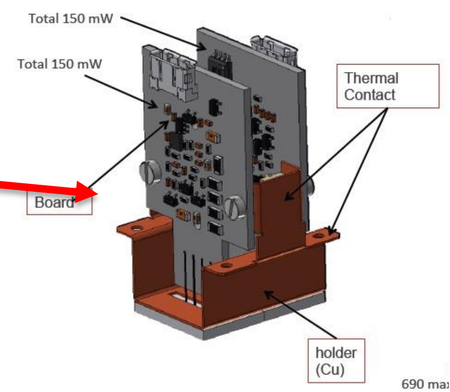


- Fast analog FEE is on the SiPM while digital electronics at 200 Msps is located in near-by electronics crates
  - Radiation hard electronics!
- Radioactive source and laser system provide absolute calibration and monitoring capability

Calorimeter Electronics





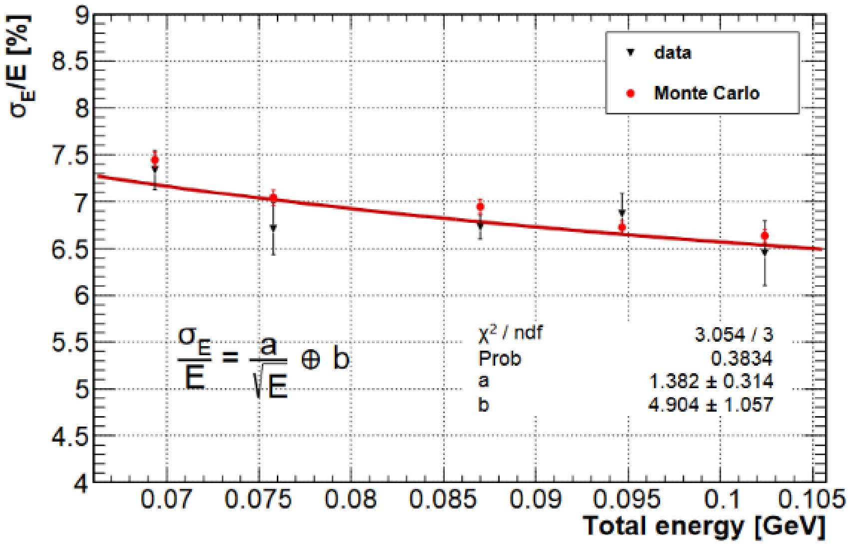


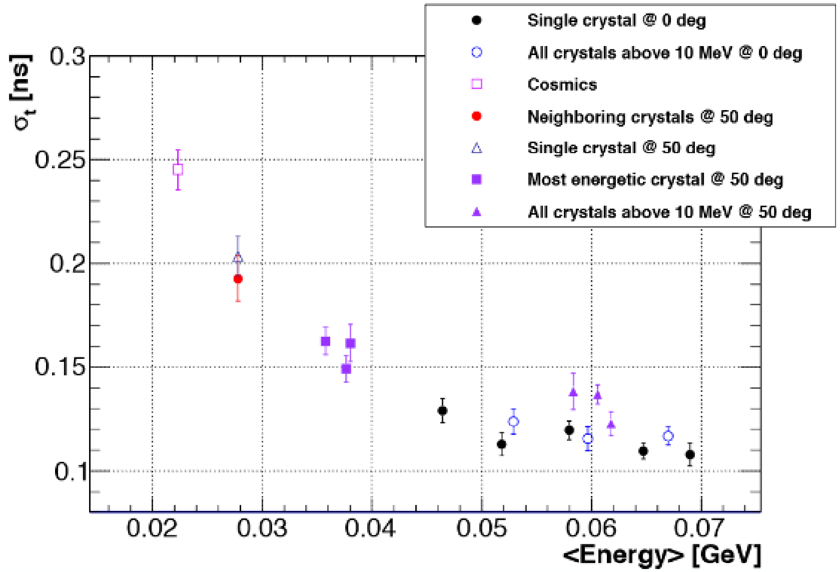
WD 20 ch Prototype

- **1 FEE chip (amplification and HV regulation) locally on the SiPM pins** +
  - Independent amplification, HV & readout for Left/Right SiPMs
- **8 (Digitizer + Mezzanine) boards in 10 crates → 20 chs format.**
  - Digitizer @ 200 Msps (5 ns binning), Mezzanine to set/read HV of each SiPM.
  - Alternate Left and Right boards in crate.

Small Prototype

- 3×3 array of 30×30×200 mm² undoped CsI crystals, about 10 X_0, coupled to one Hamamatsu MPPC (12x12) mm² with Silicon optical grease
- Small prototype tested @ BTF (Frascati) in April 2015, 80-120 MeV e^-
- DAQ readout: 250 Msps CAEN V1720 WF Digitizer





σ_E ~ 6.7% at 100 MeV

σ_T ~ 110 ps at 100 MeV

Good Data-MC agreement..

Performances satisfies requirements..

Crystals and SiPMs Pre-Production

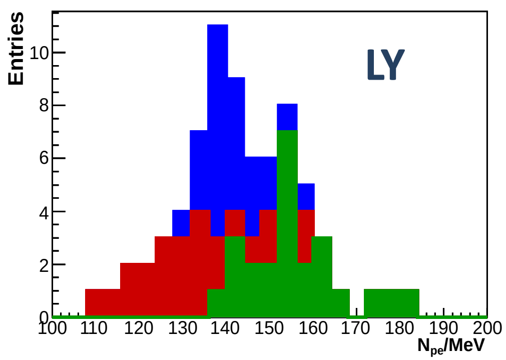
- 24 **crystals** from three different vendors: **SICCAS**, **Amcrys**, **Saint Gobain**
- Optical properties tested with 511 keV γ's along the crystal axis
- Crystals wrapped with 150 μm of Tyvek and coupled to an UV-extended PMT

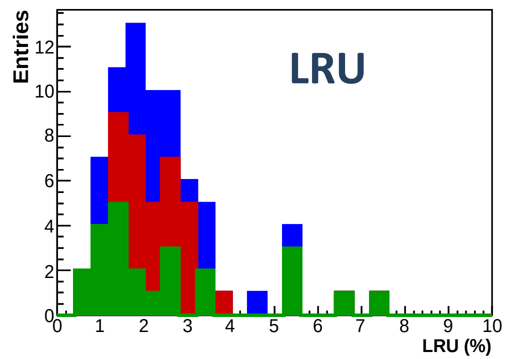
Requirements on optical properties:

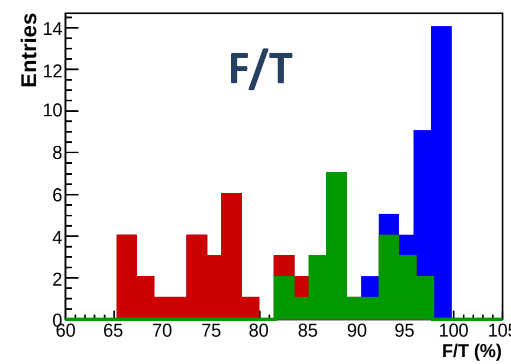
→ Light Yield > 100 p.e/MeV
→ Longitudinal Response Uniformity (LRU) < 5%
→ Fast to Slow Component Ratio > 70%

Requirements on radiation hardness:

→ Radiation Induced Noise < 0.6 MeV (phosphorescence)
→ Degradation of LY < 60% @ 100 krad







- 50 pre-production **SiPMs** from three different vendors: **Hamamatsu**, **SenSl** and **AdvanSiD**
- 3x35x6 = 630 cells were fully characterized: Breakdown Voltage, Dark Current, Gain, PDE..

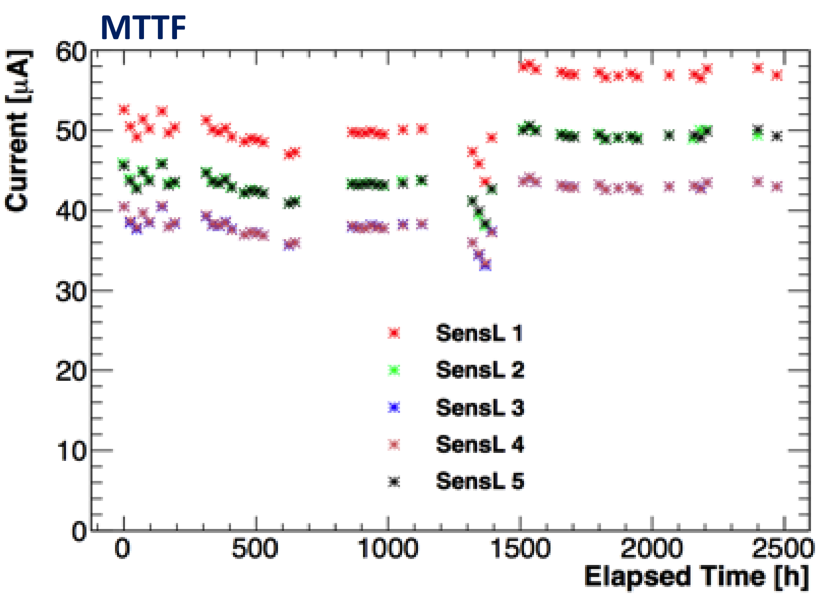
Required performances:

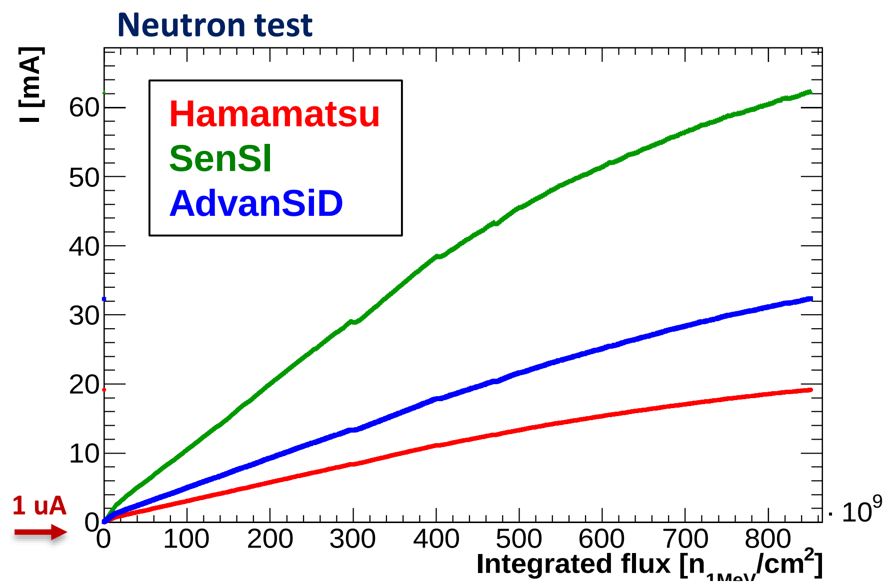
→ Breakdown voltage spread in sensor < 0.5%
→ Dark current spread in sensor < 15%

→ Gain > 10^6 for each cell
→ PDE > 20% for each cell

SiPMs Radiation Hardness and Reliability

- 5 sipm/vendor have been used to estimate the mean time to failure value
- 1 sipm/vendor has been exposed to neutron fluence up to 8.5×10^{11} n_{1MeV}(Si) /cm^2 (@ 20 °C)





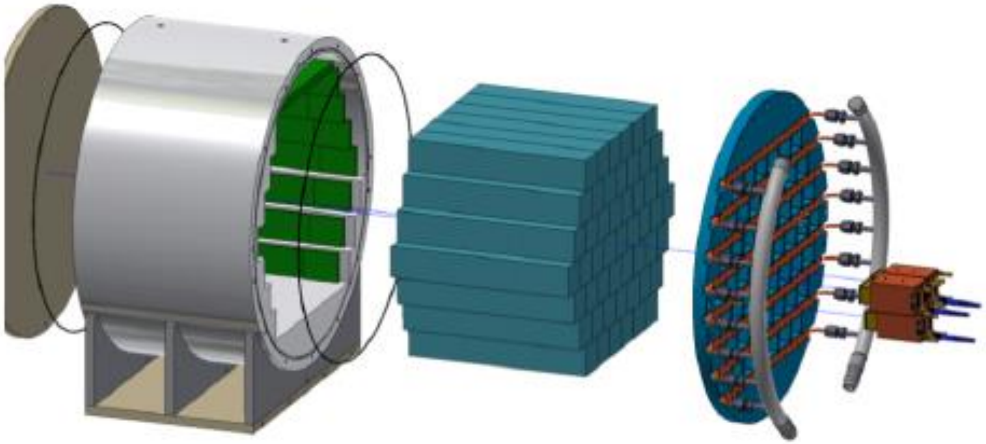
- MTTF evaluated operating SiPMs @ 50 °C for 3.5 months
- No failures observed

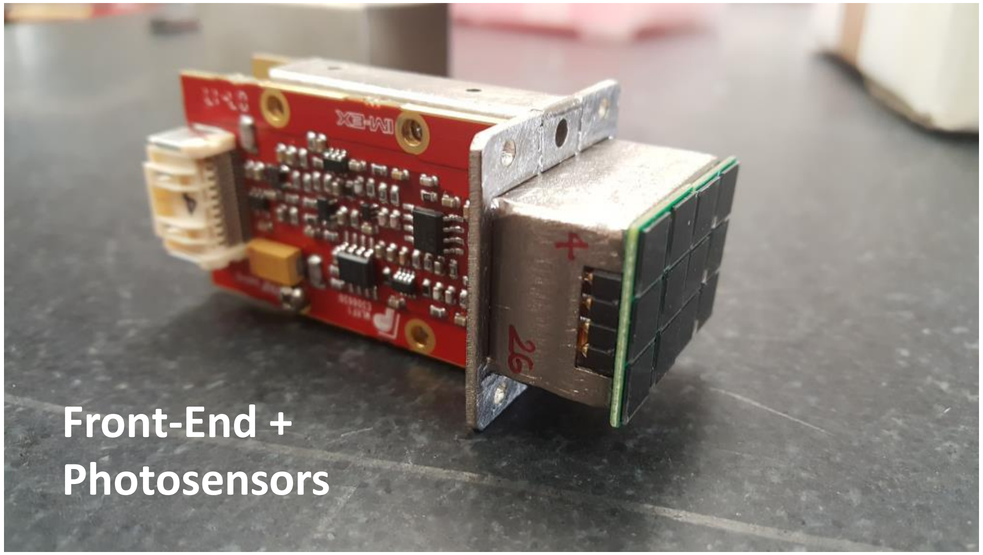
MTTF ≥ 6×10^5 hours

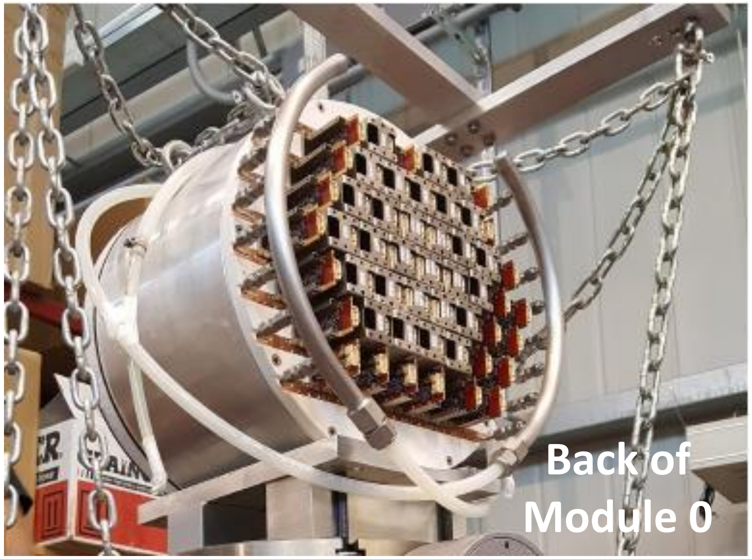
- SiPMs will operate @ 0 °C: a decrease of 10 °C in SiPMs temperature corresponds to a I_d decrease of 50%
- Lower V_{op} also helps to decrease the I_d

The Module-0

- **Large size prototype** in April 2017:
  - -> 51 crystals, 102 sensors
  - -> 102 FEE prototype chips
  - -> 5 MB boards prototype
- Assembled with crystals and SiPMs passed the selection tests
- Cooling system prototype
- WD board prototypes under construction

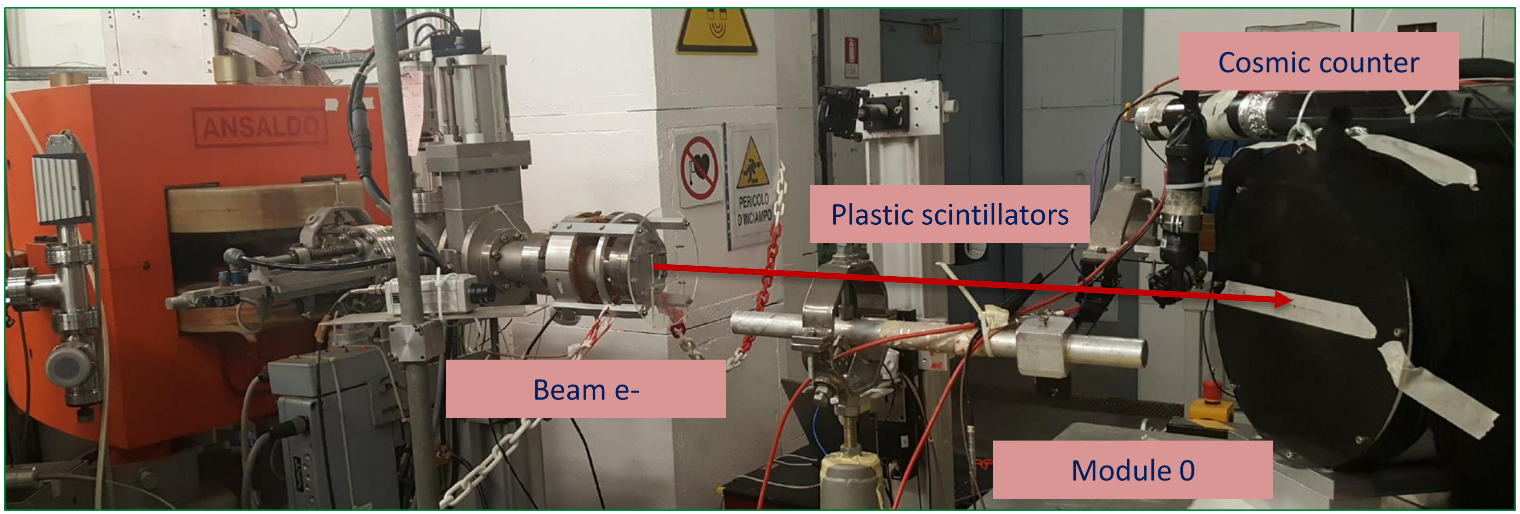






Module-0 Test Beam

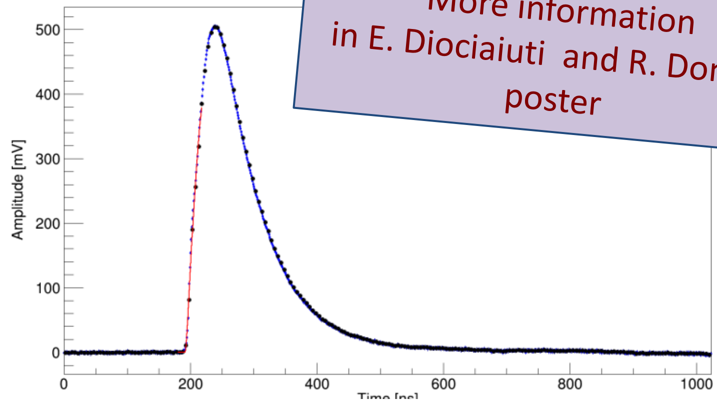
- Module Zero tested in May 2017 at the BTF Facility (LNF) with a 60-120 MeV electrons beam
- 1 GHz CAEN high-speed digitizers (DRS4 chip) used as read out (2 boards x 32 channels)
- Waveforms re-sampled at 200 MHz with software algorithm
- Temperature stable at 20 deg
- Laser calibration for the central crystal



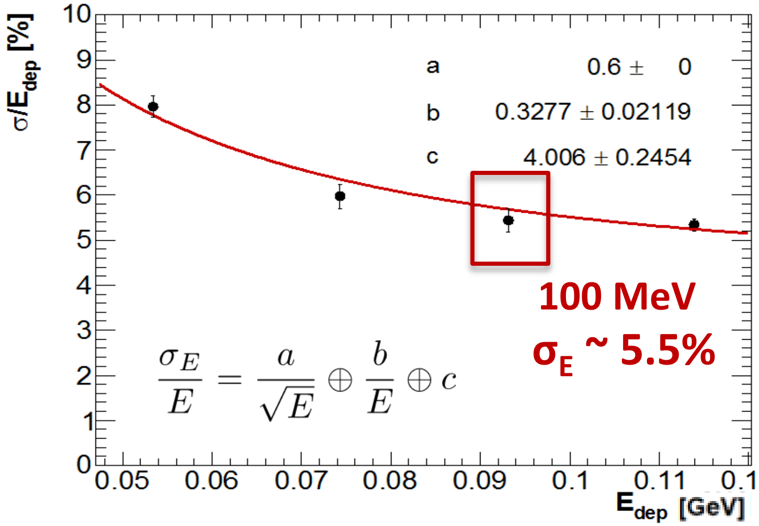
- Beam orthogonal @ 0 deg, fired on the center of each crystal to equalize channels
- Beam @ 50 deg, the most probable incidence angle for Conversion Electrons

Module-0 Performances

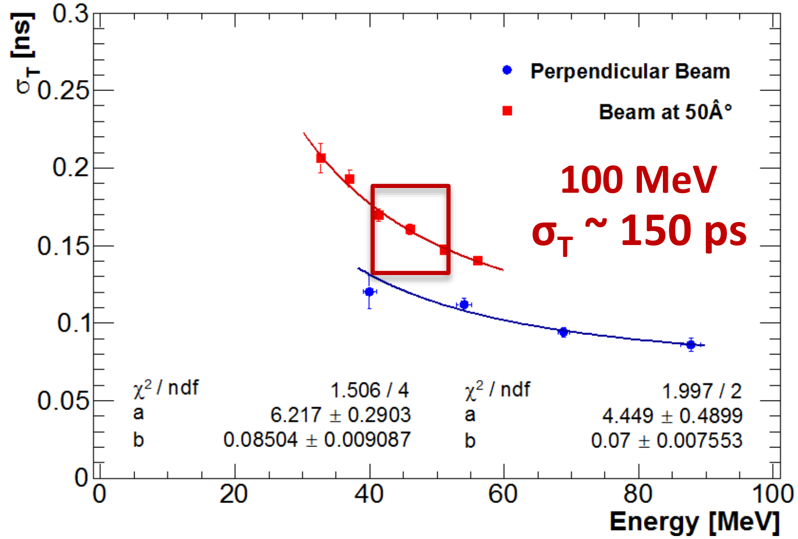
- Single particle selection with cuts on scintillators
- Charge and time reconstruction:
  - **Charge**: Numerical integration of digitized samples in a 250 ns gate after pedestal subtraction
  - **Time** : Log-normal fit on leading edge, optimized constant fraction method used



More information in E. Diociaiuti and R. Donghia poster



$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$



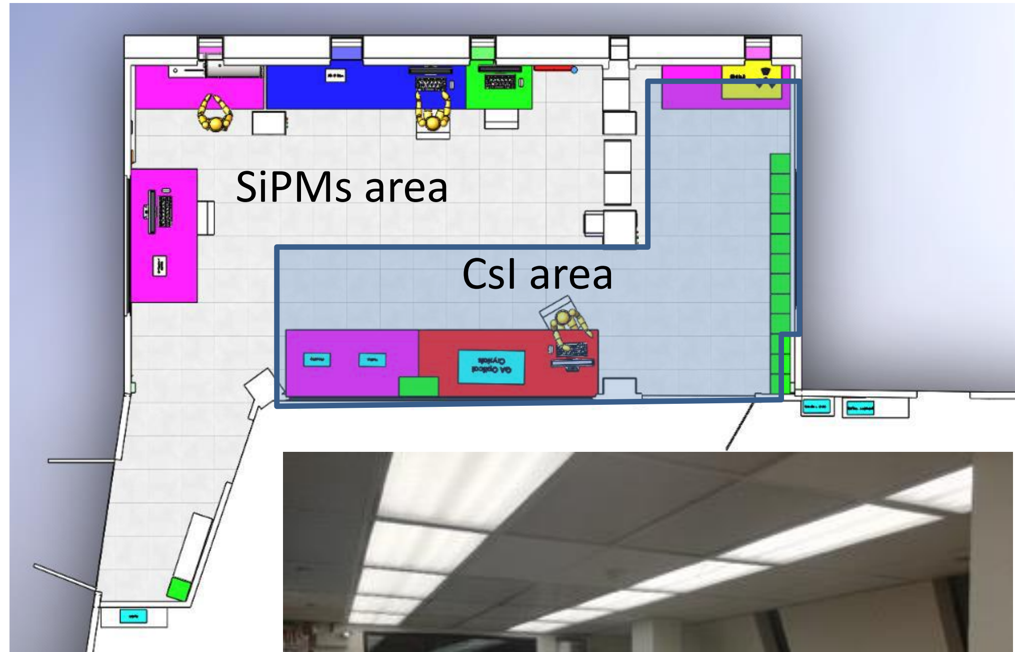
Calorimeter has time and energy resolutions that satisfy the requirements

Status of Crystals and SiPMs Production

- Production phase for SiPMs and crystals started in February 2018 (Z. Ren-Yuan talk)

- The core of the Quality Assurance (QA) process is in the SiDet department @ FNAL

  - Soft clean room with controlled environment: 40HR and 20 °C



- Vendors are delivering 100 crystals and 300 SiPMs per month

- Half of the crystals are sent to Caltech after the wrapping procedure

- QA measurements are performed by means of automatized stations and will last up to March 2019..

QA of CsI Crystals

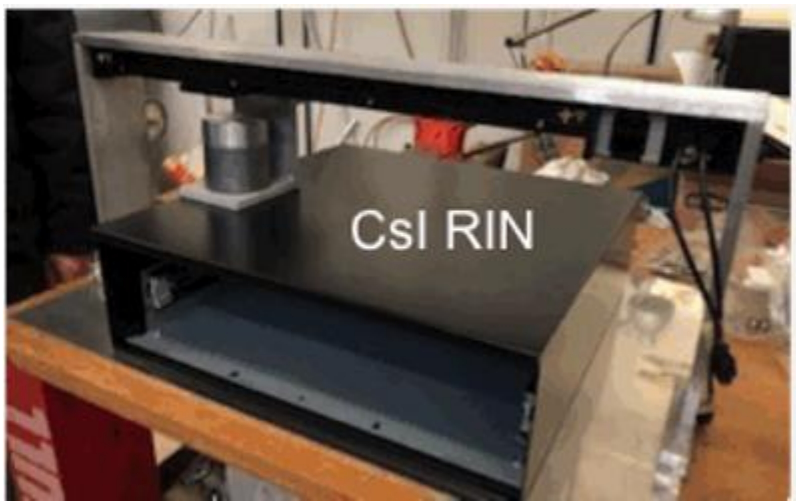
More information in Z. Ren-Yuan talk

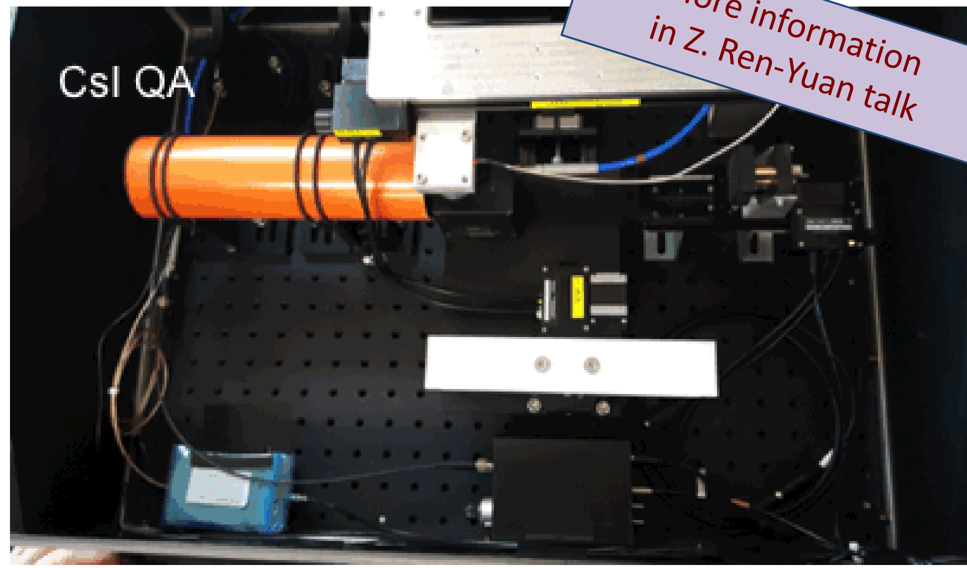
Mechanical test:

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

QA of SiPMs

More information in L. Morescalchi poster

Dimensional test:

Laser Chinese Shadow technique, 100 μm tolerance

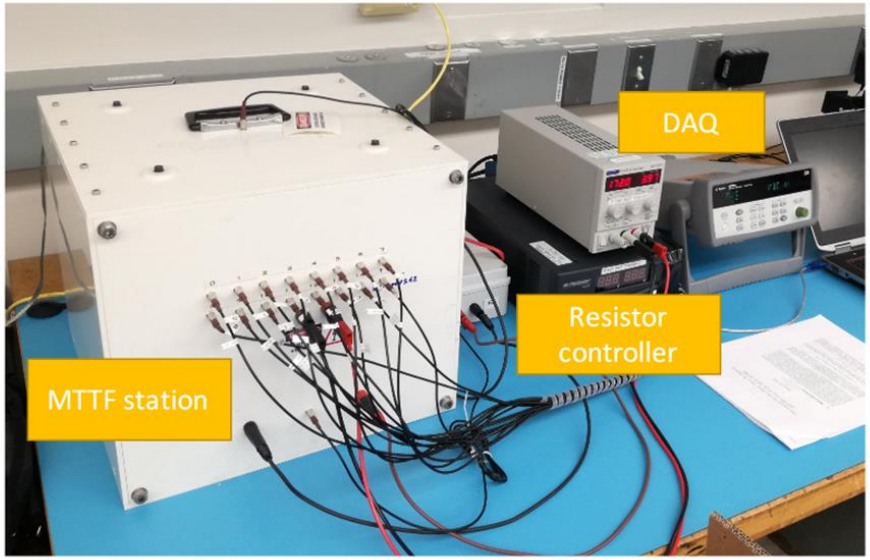
SiPMs Characterization:

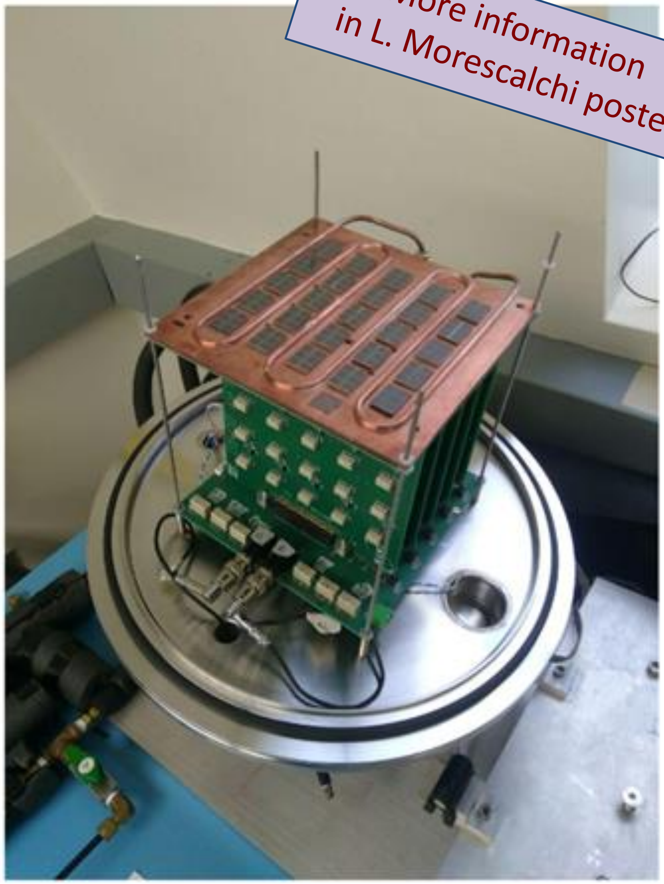
Breakdown Voltage
Dark Current
Gain x PDE

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:

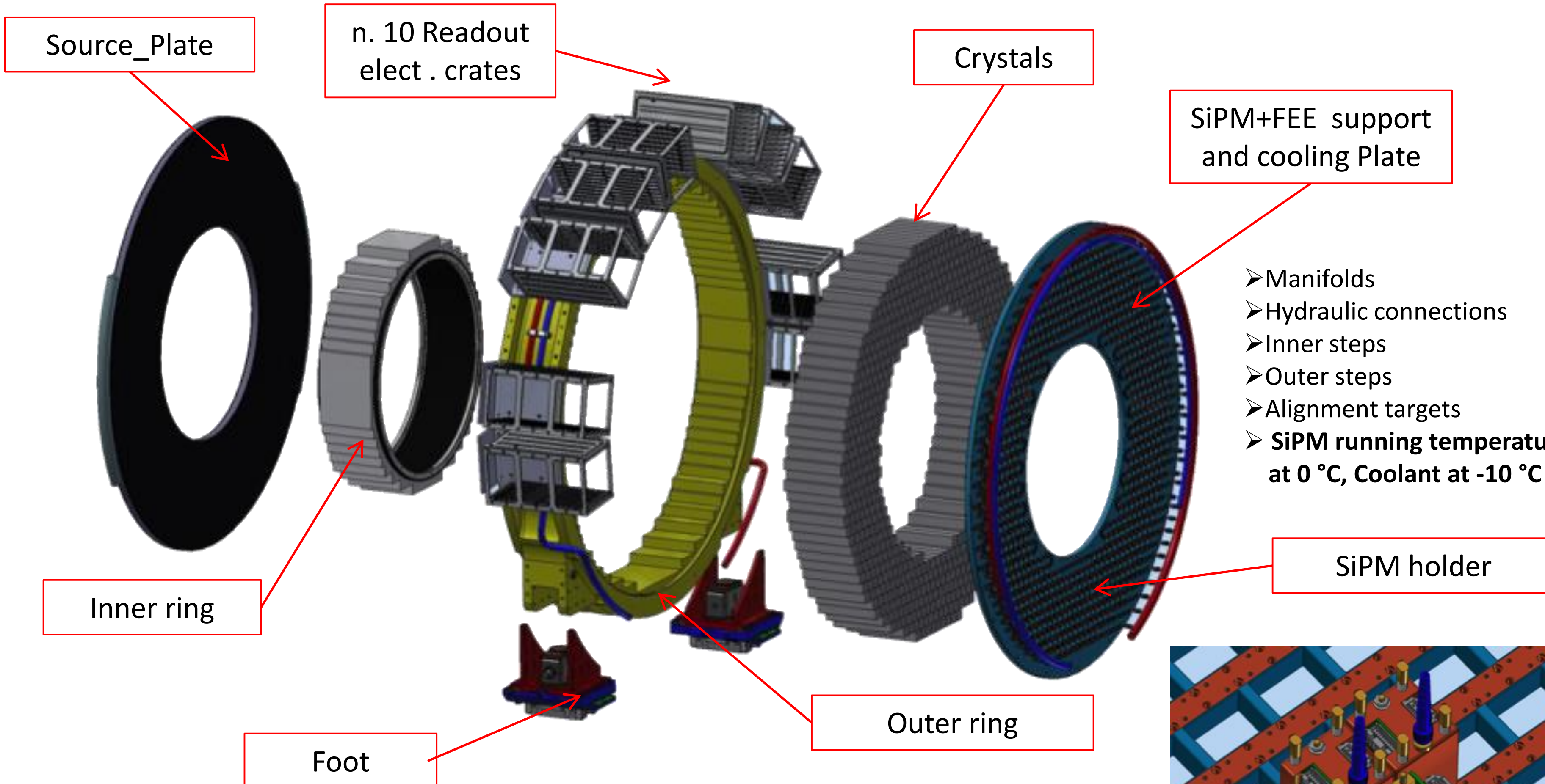
irradiation @ HZDR, Dresden,
5 SiPMs/batch
up to 1.7 x 10^{12} n1MeV (Si) / cm^2

Conclusions

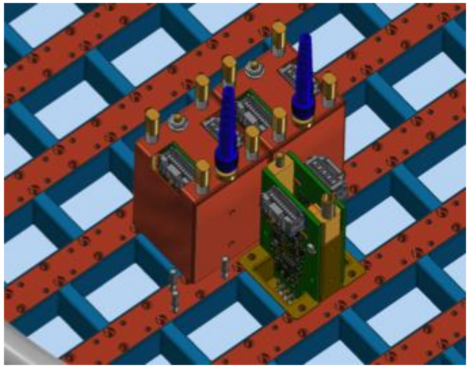
- The Mu2e calorimeter has concluded its prototyping phase satisfying the Mu2e requirements:
  - **Un-doped CsI crystals perform well**
    - **Excellent LRU and LY** 100 pe/MeV (PMT+Tyvek wrapping)
    - τ of 30 ns with negligible slow component
    - **Radiation hardness OK** for our purposes: 40% 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 > 2.2 million hours**
  - **Small prototype** tested with e^- beam
    - **Good time and energy resolution achieved @ 100 MeV**
  - **Module 0 built and first tests done.**
    - **TB** data analysis results satisfies the requirements
    - **Good time and energy resolution achieved @ 100 MeV, in agreement with the small prototype**
- **Calorimeter production phase started**
- In 2020 installation of the calorimeter in the Mu2e experimental hall begins

Additional Slides

Calorimeter Engineering

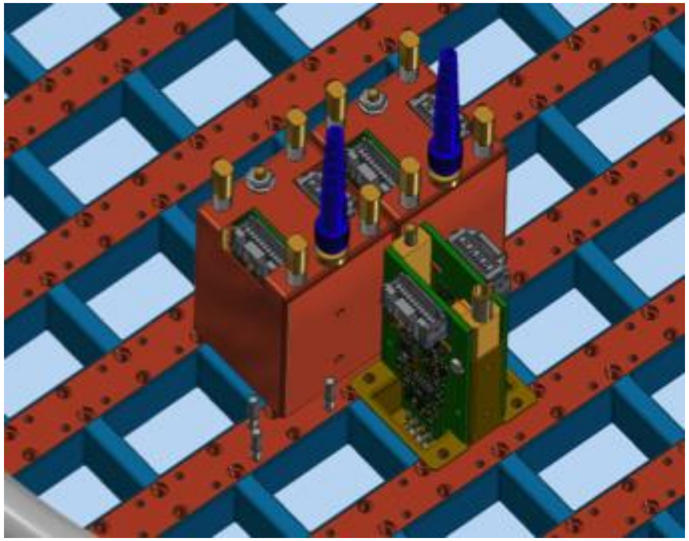


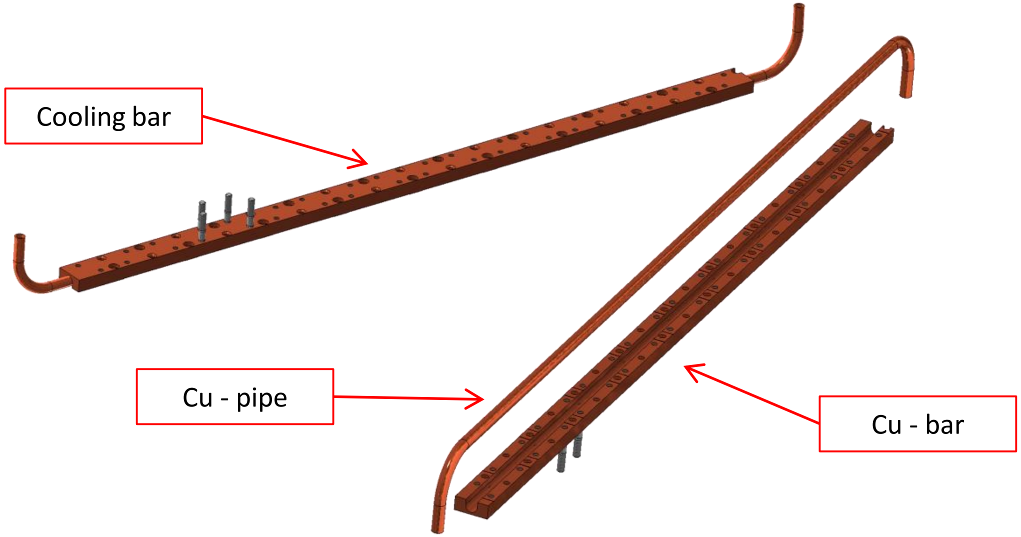
- Manifolds
- Hydraulic connections
- Inner steps
- Outer steps
- Alignment targets
- **SiPM running temperature at 0 °C, Coolant at -10 °C**

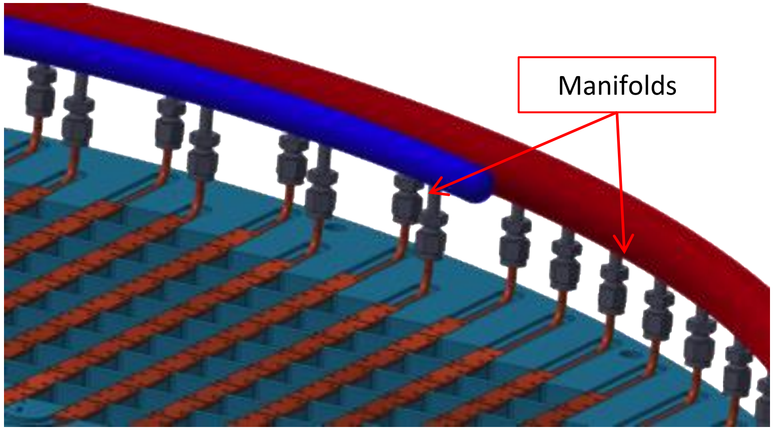


Calorimeter Cooling

- The FEE plate houses the Front End electronics and photosensors holders and provides cooling.
- The coolant runs inside the cooling channels, at ~ -10ºC.
- 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.

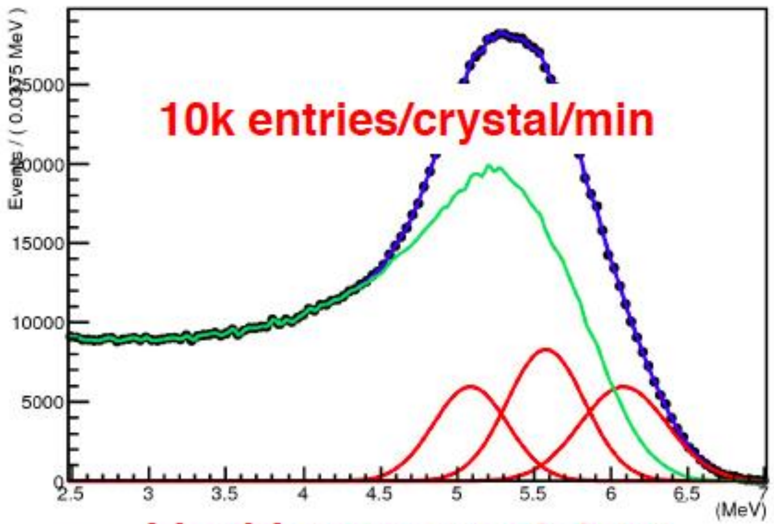


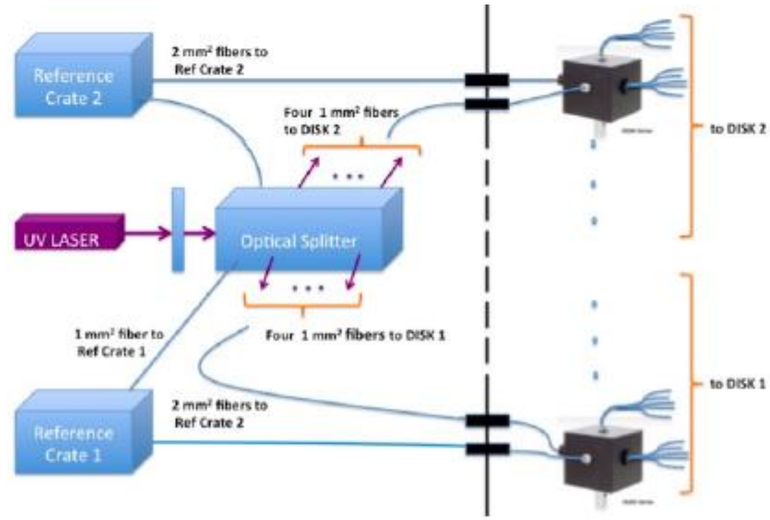




Calorimeter Calibration

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





Liquid source prototype

Laser system - test station

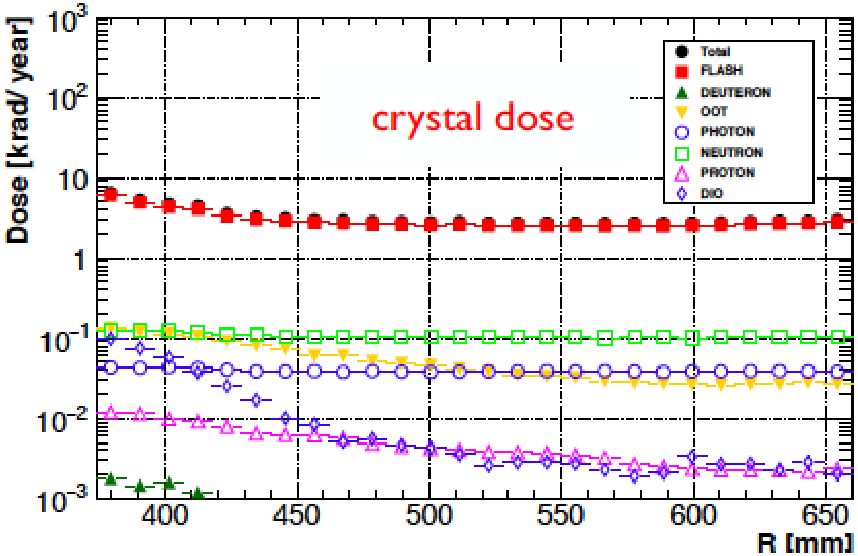
$$^{19}F + n \rightarrow \; ^{16}N \; + \alpha$$
$$^{16}N \rightarrow \; ^{16}O^{*} + \beta \quad t_{1/2} = 7 \text{ s}$$
$$^{16}O^{*} \rightarrow \; ^{16}O + \gamma (6.13 \text{ MeV})$$

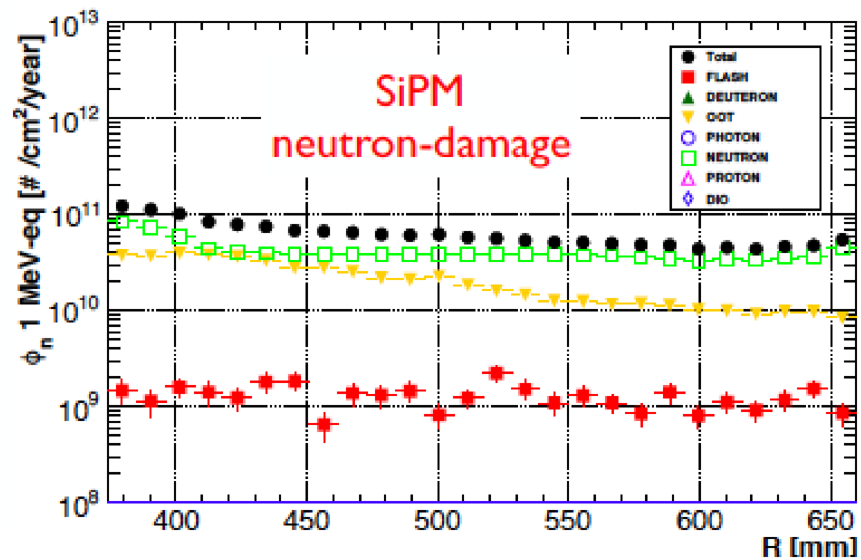
Radiation Damage

- 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

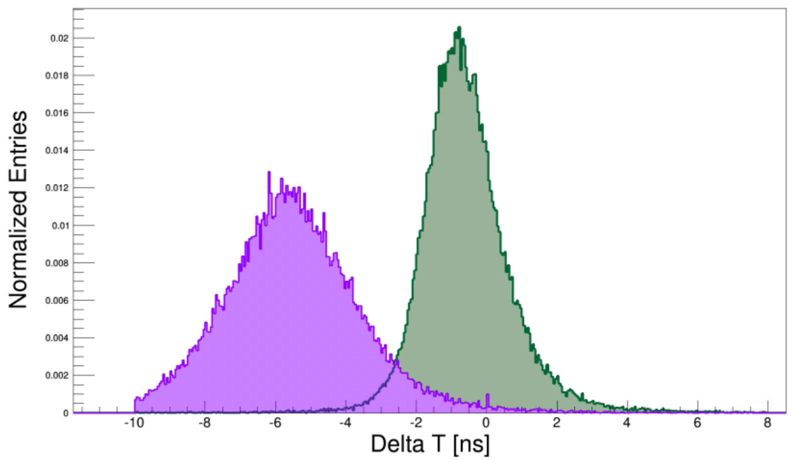


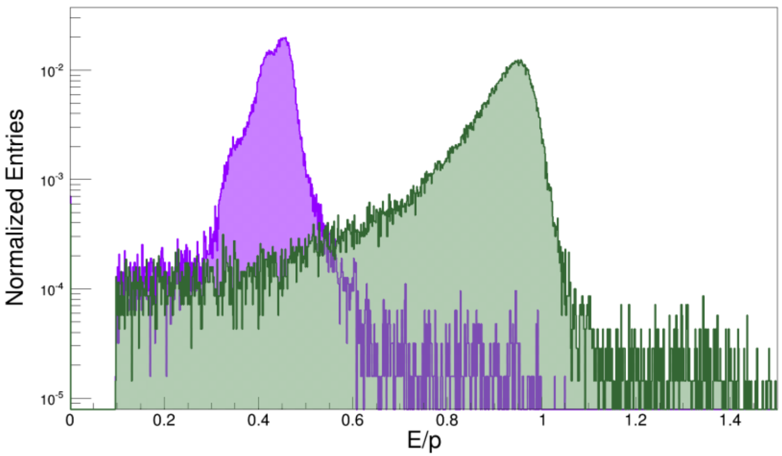


Particle Identification

- **Muons with 105 MeV momentum are not relativistic particles:**

$\beta \sim 0.7$ $E_k \sim 40$ MeV





- **Compare the reconstructed track and calorimeter information:**
  - $E_{cluster}/p_{track}$ & $\Delta t = t_{track} - t_{cluster}$,
  - Build a likelihood for e- and mu- using distribution on E/p and Δt

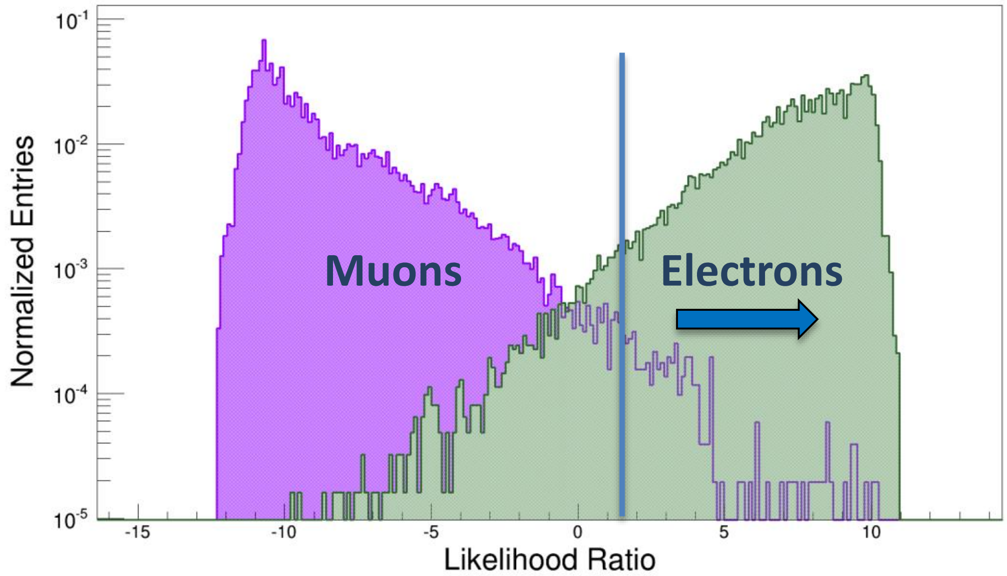
PID performances

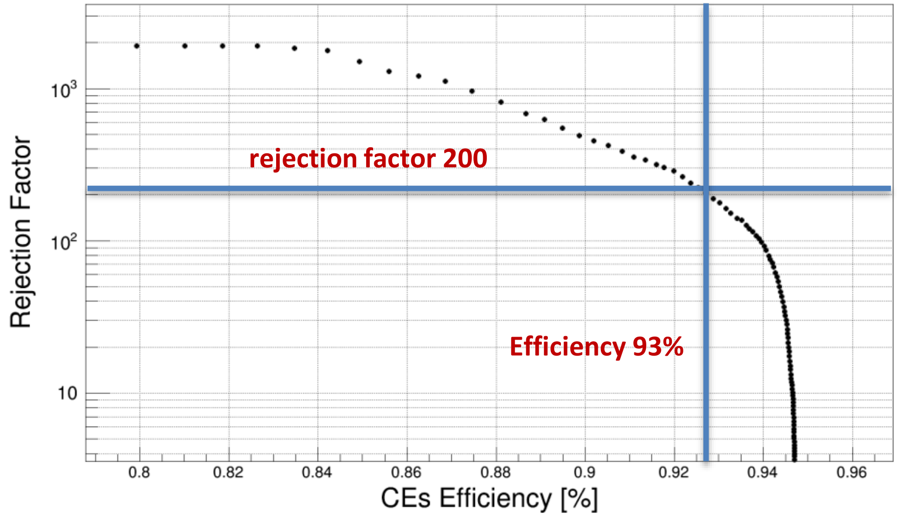
- Final classifier is the ratio between electron and muon likelihood:

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

$$\ln(L_e) = \ln(P_e(\Delta t)) + \ln(P_e(\mathrm{E/p}))$$

$$\ln(L_{e/\mu}) = \frac{\ln(L_e)}{\ln(L_\mu)} = \ln(L_e) - \ln(L_\mu)$$

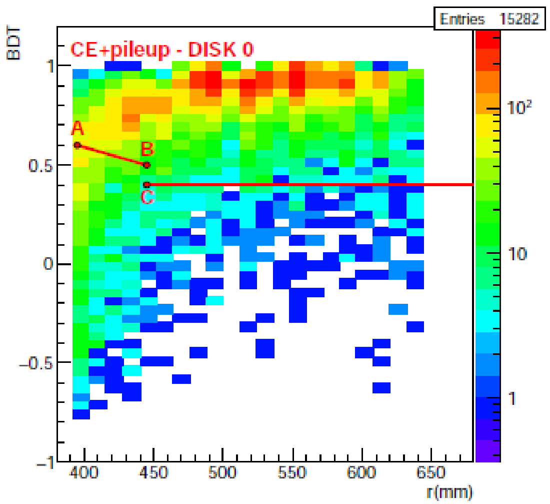




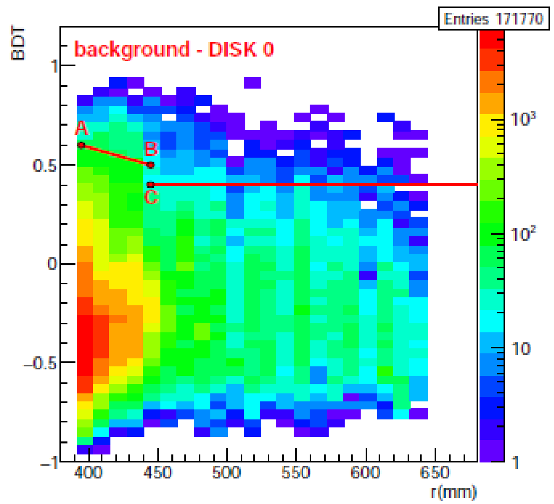
- A cut at $L_{e/\mu} > 1.5$ corresponds to:
  - **Muon rejection factor 200**
  - **Efficiency on CEs of 93%**
- Efficiency evaluated with respect to standard preselection cuts

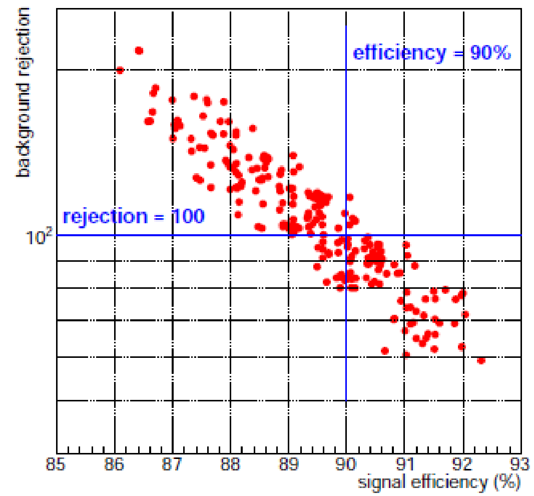
Trigger Performances

CE



Background





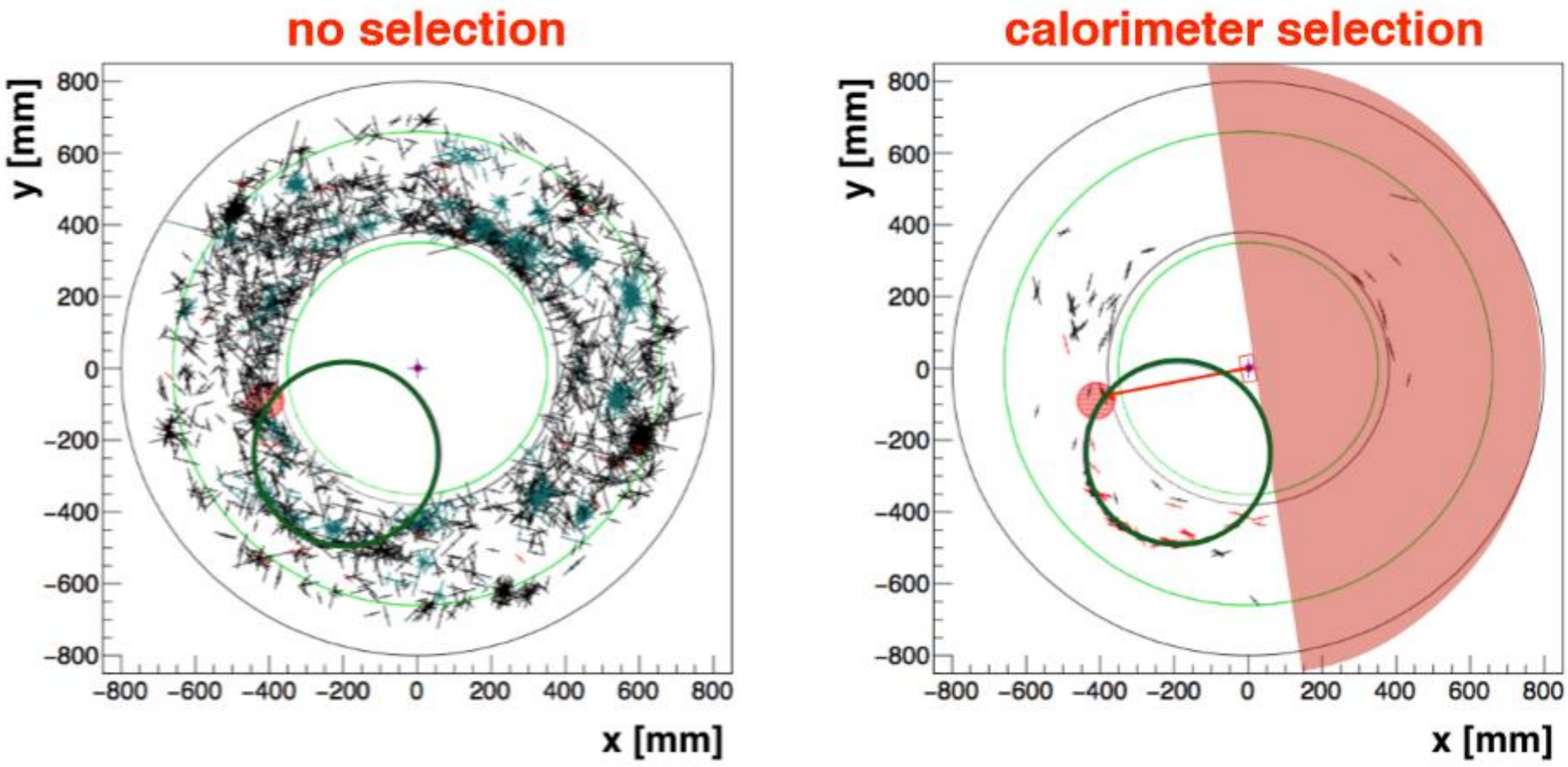
- Cut on classifier as a function of the radius of the cluster peak, parametrized with points A, B and C

✓ **Processing time of 0.9 ms**

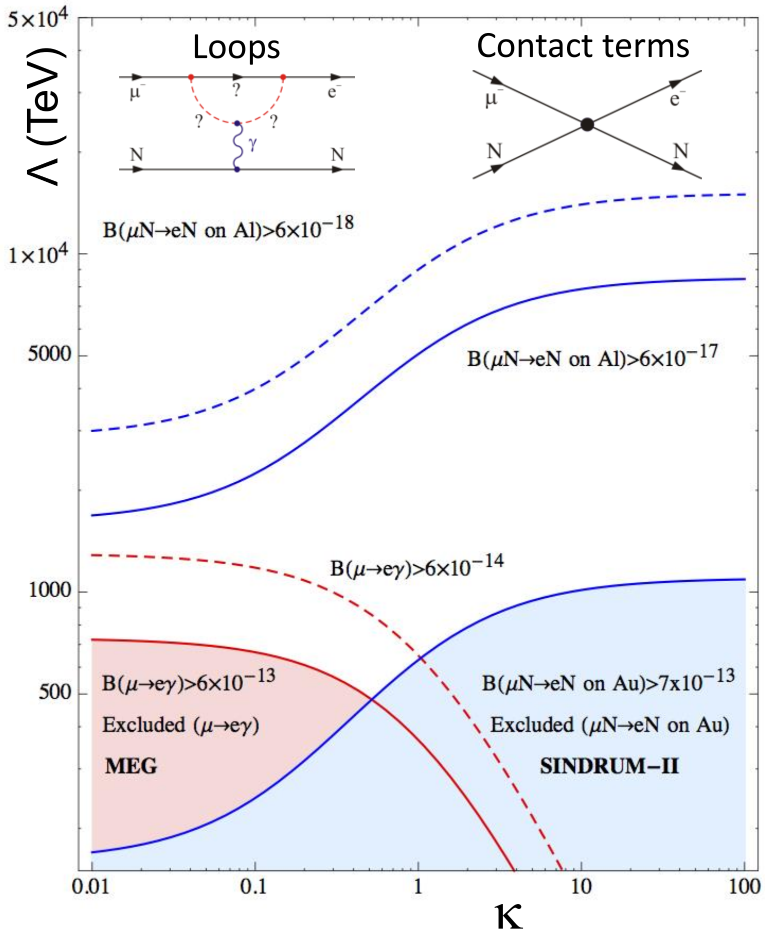
- Fast calorimetric trigger satisfies global trigger requirements..

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



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!**

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