The Mu2e crystal calorimeter

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Fermilab

INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Talk overview

- **The Mu2e experiment**
  - CLFV introduction
  - Experiment layout

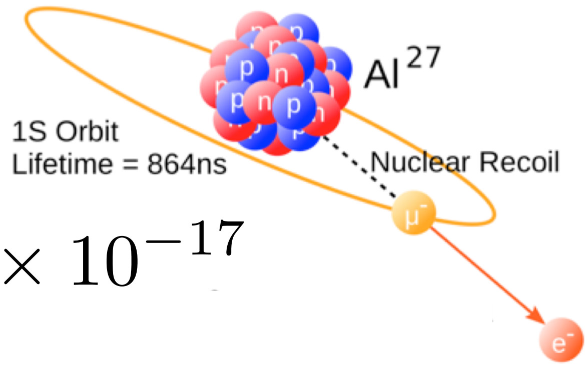
- **Mu2e Electromagnetic Calorimeter**
  - Components
  - Performance
  - Production status

Charged Lepton Flavor Violation

More info in G. Pezzullo talk

- CLFV processes are forbidden in SM
  - Even allowing neutrino oscillation BR ~ 10^{-54}
- **Observation of a CLFV process: clear evidence of New Physics**
- Mu2e : Coherent muon conversion in the electric field of a nucleus
  - Broad sensitivity across different models
  - Very clear signature: **monoenergetic electron**

$$E_e = m_\mu c^2 - (B.E.)_{1S} - E_{recoil} = 104.96 MeV$$



μ-e conversion in the field of a nucleus

$$R_{\mu e} = \frac{\mu^- + N(A,Z) \to e^- + N(A,Z)}{\mu^- + N(A,Z) \to \nu_\mu + N(A,Z-1)} < 8 \times 10^{-17}$$

Nuclear capture of muonic Al atom

- Improve of **4 orders of magnitude** the previous limit set by the SINDRUM II experiment (6.1×10^{-13})

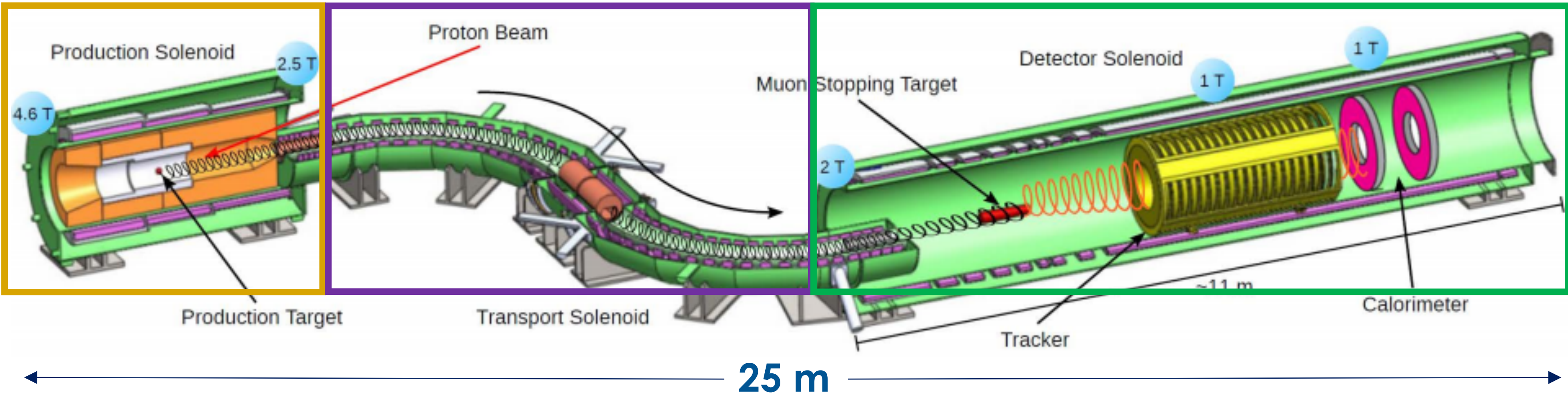
The Mu2e experiment

PRODUCTION SOLENOID

- Protons hitting the target and producing mostly π
- Graded magnetic field reflects slow forward π

TRANSPORT SOLENOID

- π decay to μ
- Selection and transportation of low momentum μ^-



DETECTOR SOLENOID

- Capture μ on the Al target
- Momentum measurement in the tracker and energy reconstruction with calorimeter
- CRV to veto cosmic ray events

Calorimeter requiremens

High acceptance for reconstructing energy, time and position of signals for:

- **Particle Identification: e/μ separation → reject μ background**
- **Improve the track pattern recognition**
- **Standalone trigger**

@ 105 MeV

Calorimeter requirements

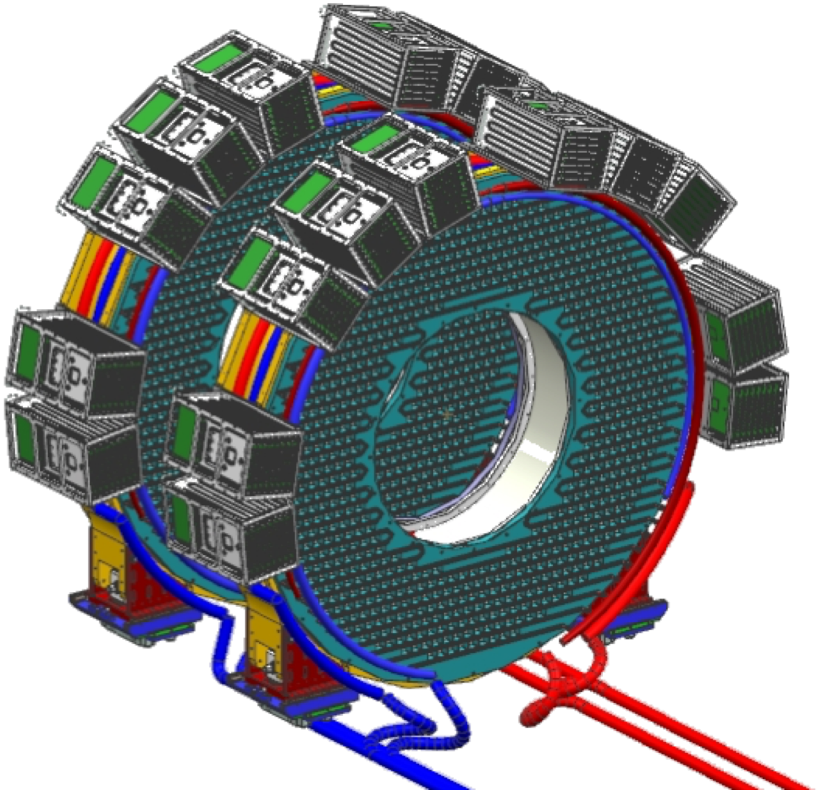
- energy resolution $\sigma_E/E < 10\%$
- timing resolution $\sigma(t) < 500$ ps
- position resolution < 1 cm
- Work in vacuum @ 10^{-4} Torr
- 1 T Magnetic Field

Crystals coupled with Silicon PhotoMultipliers(SiPM)

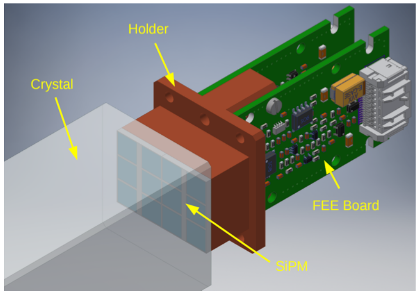
- Light Yield(photosensor)>20 pe/MeV
- Fast signal for pileup and timing
- **Survive an high radiation environment**
  - Total Ionizing Dose (TID) of 90 krad/5 year for crystal
  - TID of 75 krad/5 year for sensor
  - 3×10^{12} n/cm^2 for crystal
  - 1.2×10^{12} n/cm^2 for sensor

Calorimeter Design

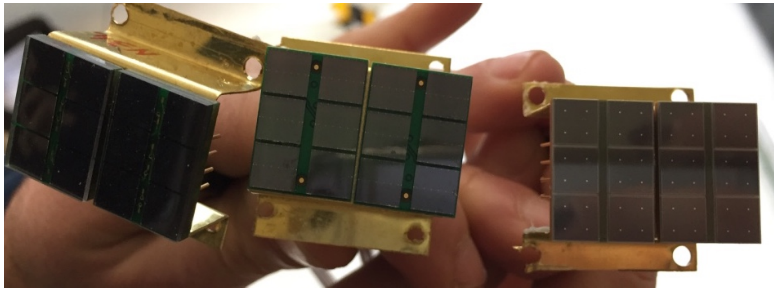
2 disks each with 674 undoped $(34x34x200)mm^3$ square pure CsI crystals



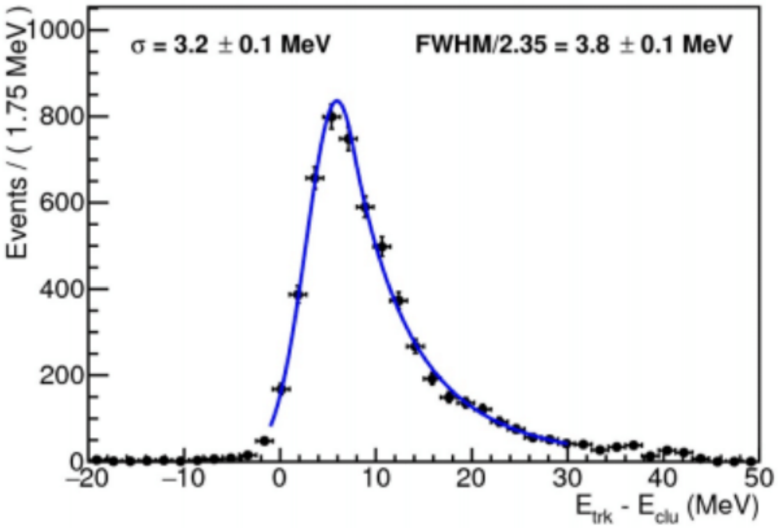
- Readout: 2 UV-extended SiPMs/crystal



- Analog FEE and digital electronics located in near-by electronics crates
- Source for energy calibration
- Laser system for monitoring gain stability



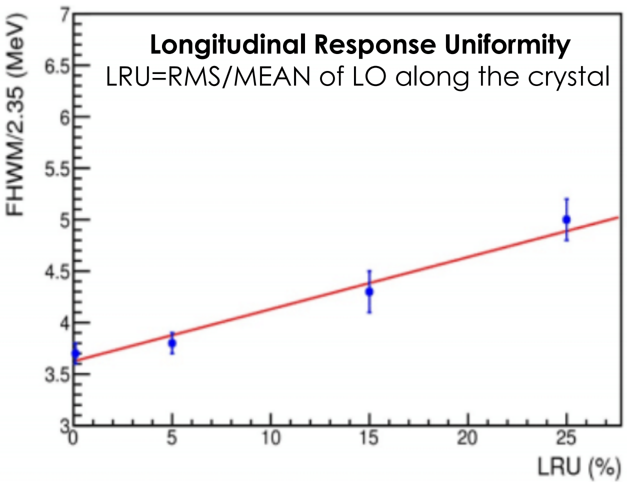
Mu2e EMC: MC performance

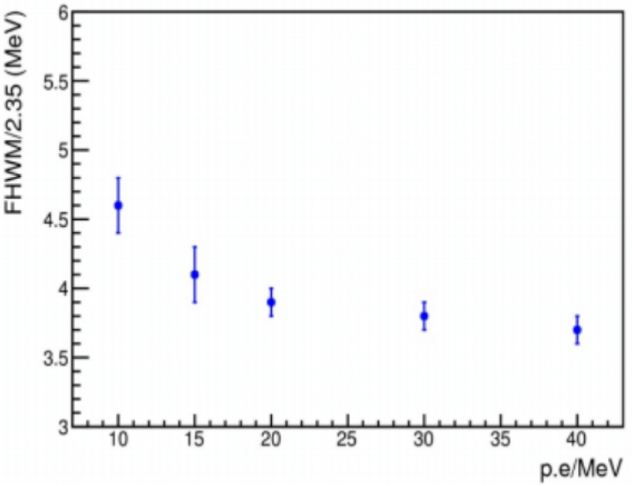


The calorimeter energy resolution is estimated taking into account signal and predominant background, as the difference of the conversion electron energy and the cluster energy.

FWHM/2,35 = 3.8 ± 0.1 MeV

The overall resolution depends on the crystal features



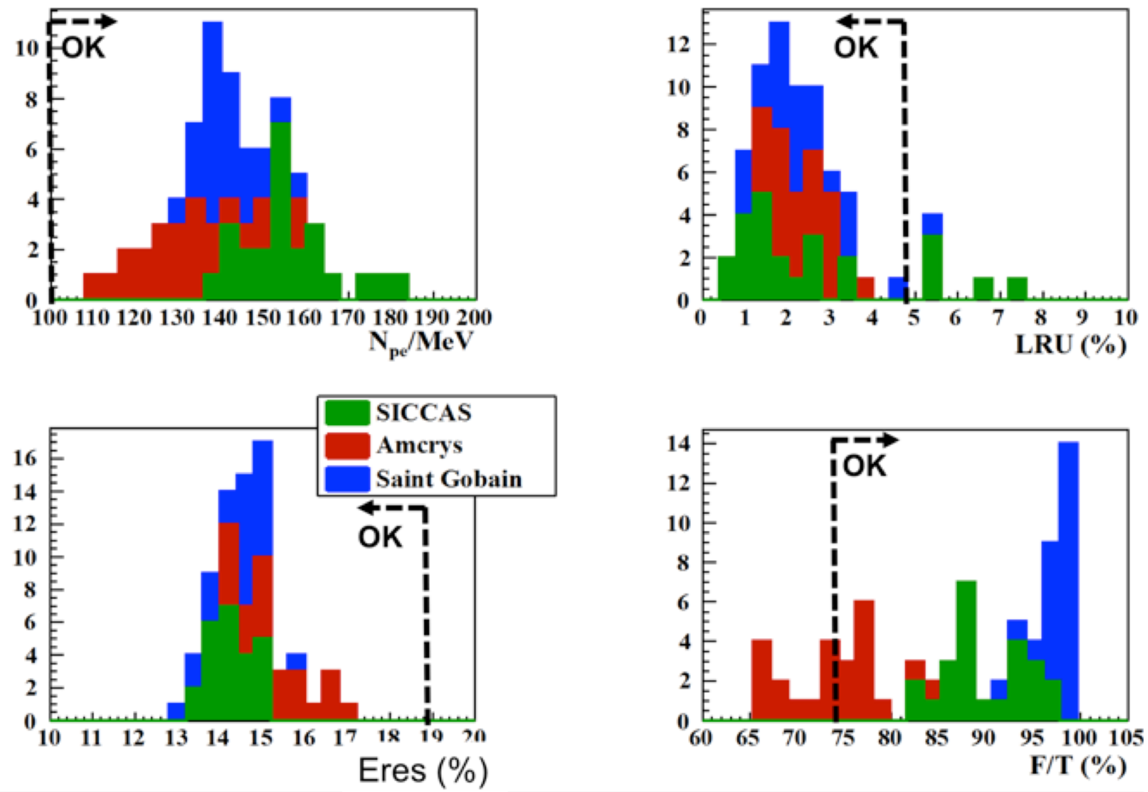


Crystal preproduction

- 24 crystals from three different vendors: **SICCAS**, **Amcrys**, **Saint Gobain**
- ^{22}Na source to test crystal properties along the crystal axis
- Crystals coupled in air to an UV-extended PMT

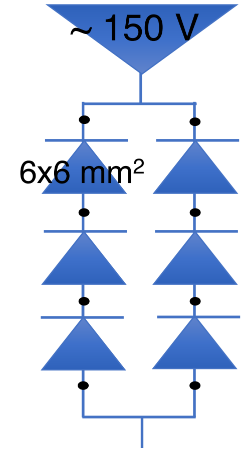
- **Optical properties:**
  - 100 pe/MeV with PMT readout
  - LRU < 5%
  - Fast/Total>75%
- **Radiation hardness**
  - Smaller than 40% LY loss @ 100 krad
  - Radiation Induced Noise <0.6 MeV

Selected vendors: SICCAS and Saint Gobain

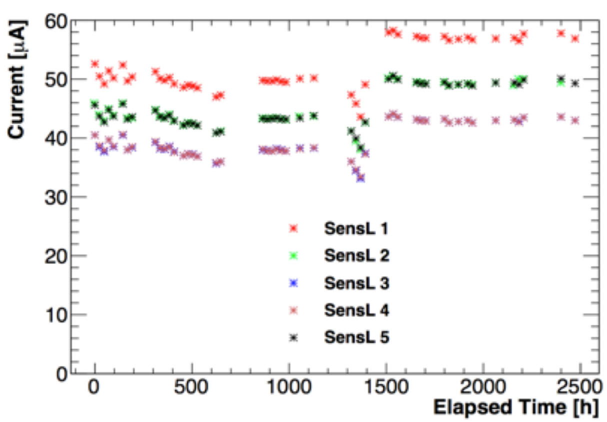


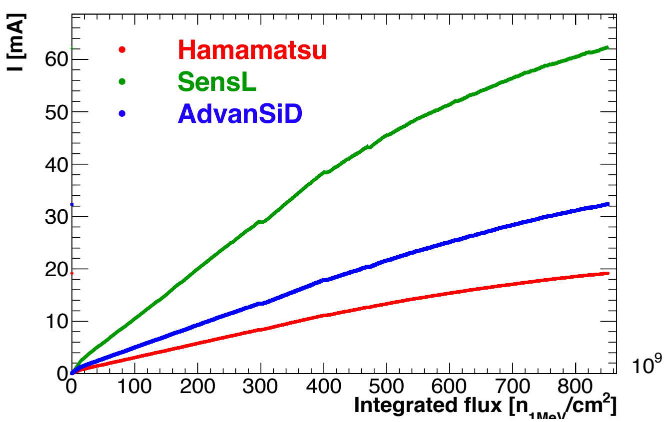
SiPM preproduction

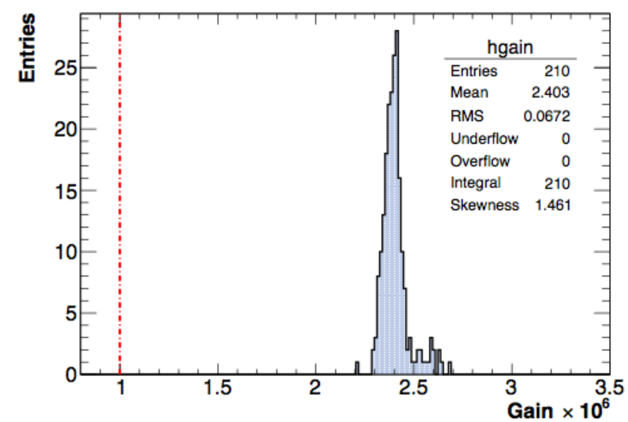
- 2 arrays of three 6x6 mm^2 SiPMs
  - total active area of (12x18) mm^2
  - 50 µm pitch
- Photon Detection Efficiency (@ 315 nm)>20%
- The series configuration → narrower signals
- **150 Pre-production SiPMs** (3×50 Mu2e SiPMs from **Hamamatsu**, **SensL** and **AdvanSiD**):
  - 3×35x6 cells fully characterized **(V_{op}, G, I_{dark}, PDE)**
  - 1 sample/vendor exposed up to a fluence of 8.5×10^{11} n_{1MeVeq}/cm^2 (@ 20 °C)
  - Mean Time To Failure estimated by operating 15 SiPM at 50 °C for 3.5 months → MTTF > 0.6×10^6 h



Selected vendor: Hamamatsu

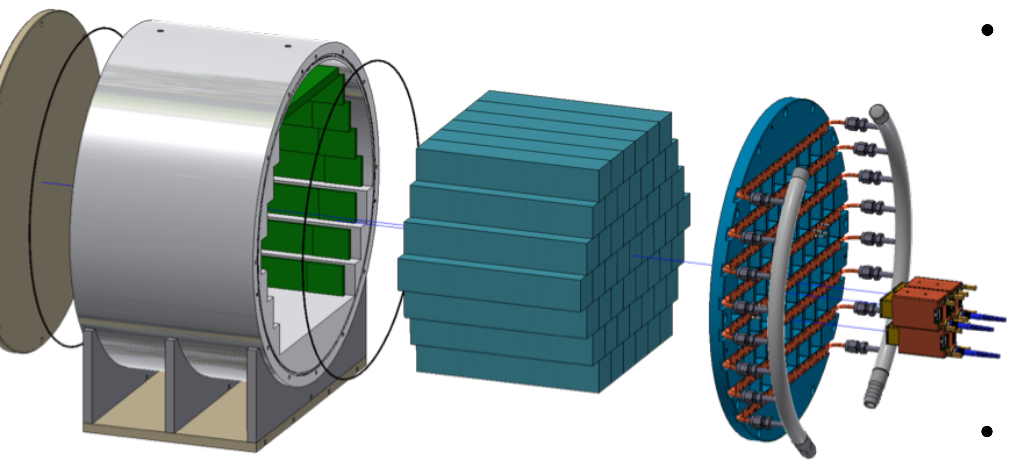




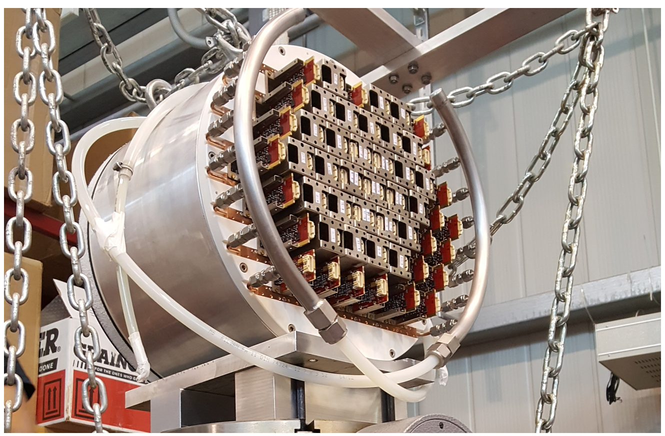


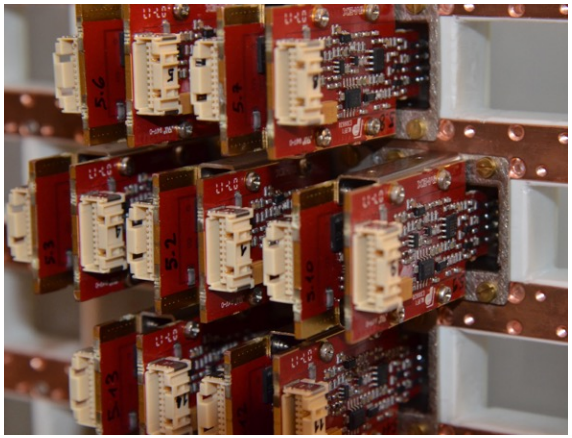
Module-0

Large size prototype: 51 crystals coupled to 102 sensors



- Goals:
  - Test the performances
  - Test integration and assembly procedures
  - e^- beam (60-120 MeV), May 2017
    - **Orthogonal and 50° incidence (CE)**
  - Operate under vacuum, low temperature and irradiation tests
- Readout: 1 GHz CAEN digitizers (DRS4 chip), 2 boards x 32 channels

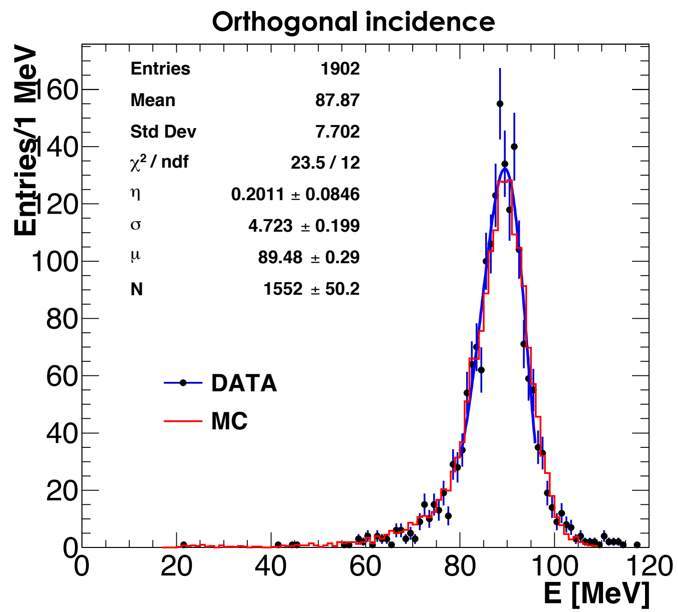


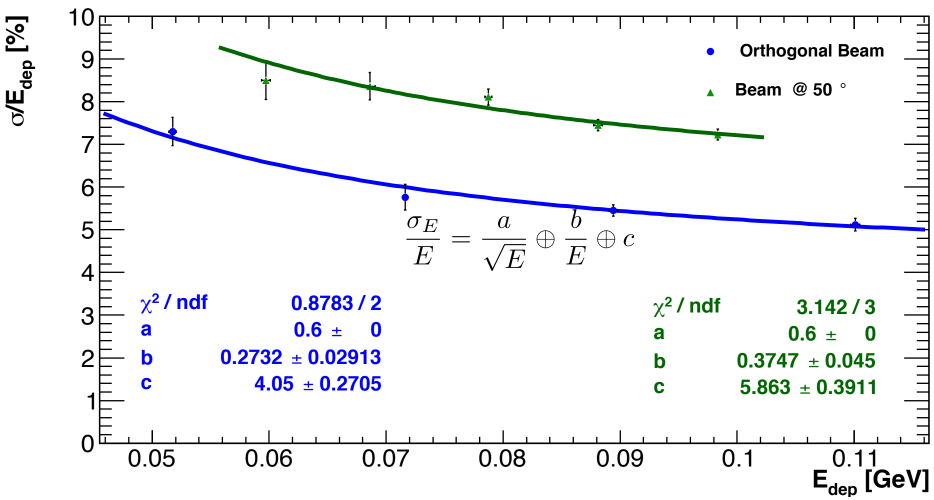


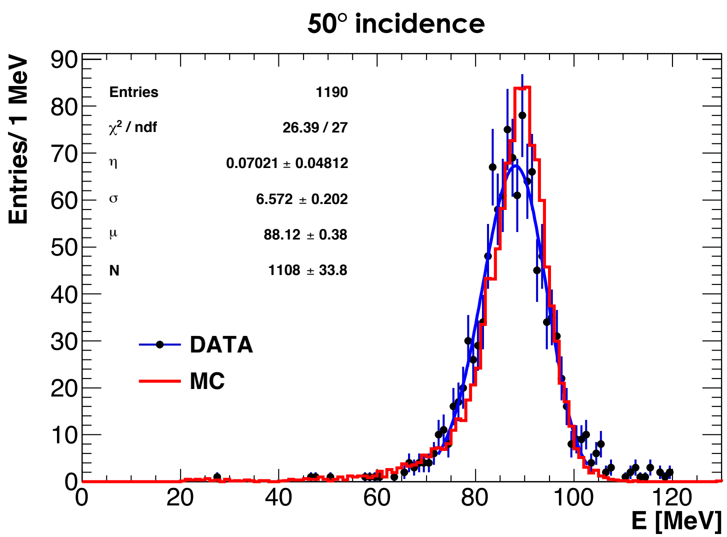
Module-0: Energy resolution

- Single particle selection
- Calibration:
  - Cosmic
  - Beam

Orthogonal Run:
$\sigma_E \sim 5\%$
Tilted Run :
$\sigma_E \sim 7.5\%$
@ E_{beam} = 100 MeV

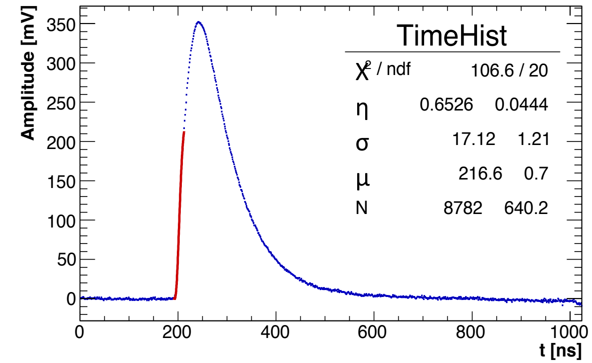


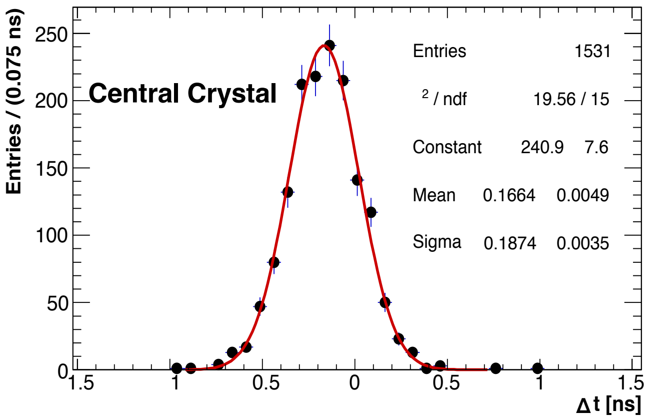




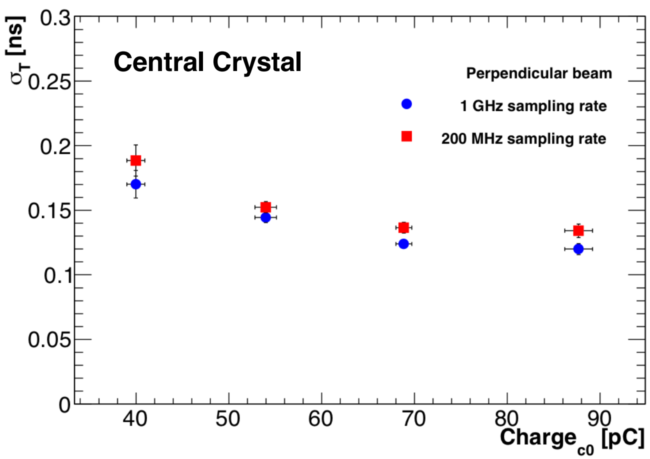
Module-0: Single Sensor Time resolution

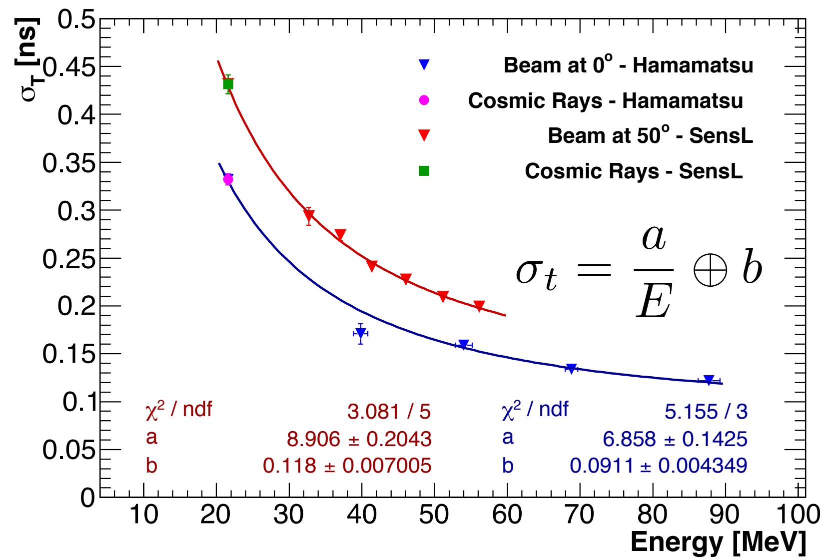
- Log Normal fit on leading edge
- Constant Fraction method used CF = 5%
- Comparison between 1GHz (TB sampling) and 200 MHz (Mu2e sampling) shows no deterioration in the resolution





σ (T1+T2)/$\sqrt{2}$ ~ 132 ps @ E_{beam} = 100 MeV



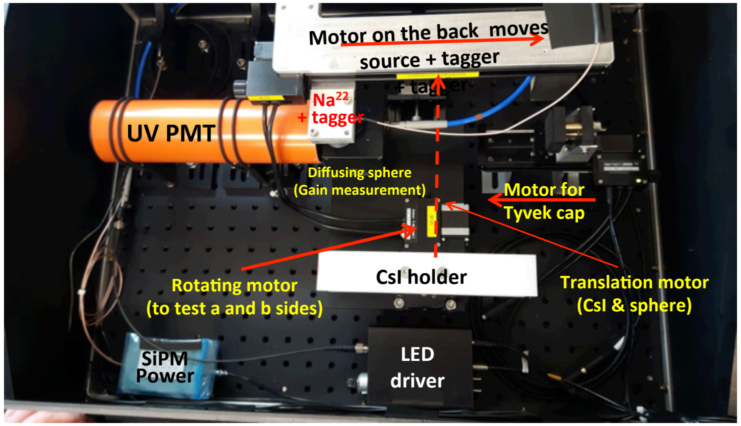


QA room @ FNAL for production

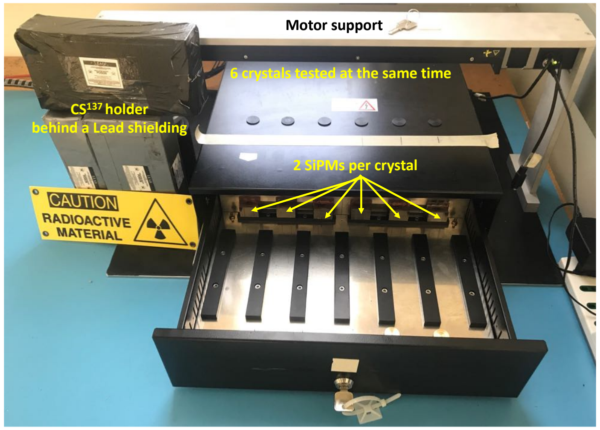
- QA tests started on March 2018
  - ~1000 SiPMs tested (25% of the total number)
  - ~300 crystals (23% of the total number)

CsI dimensional test

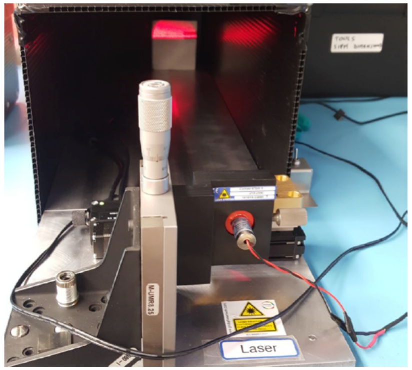
CsI QA



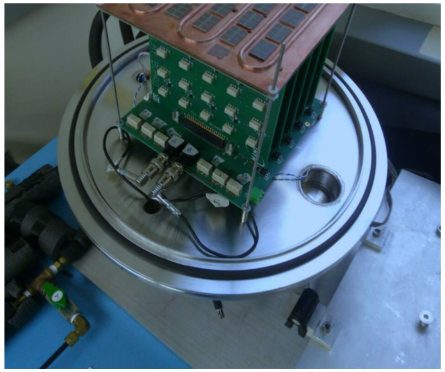
CsI RIN



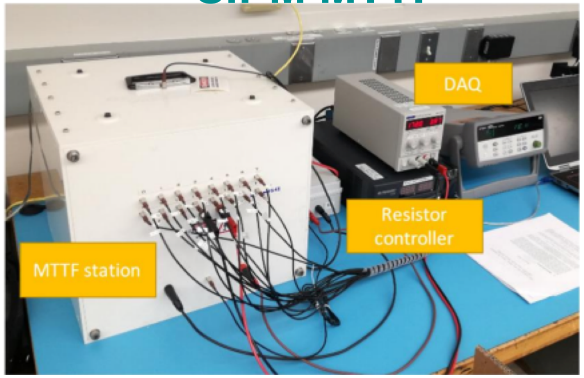
SIPM dimensional test



SiPM QA

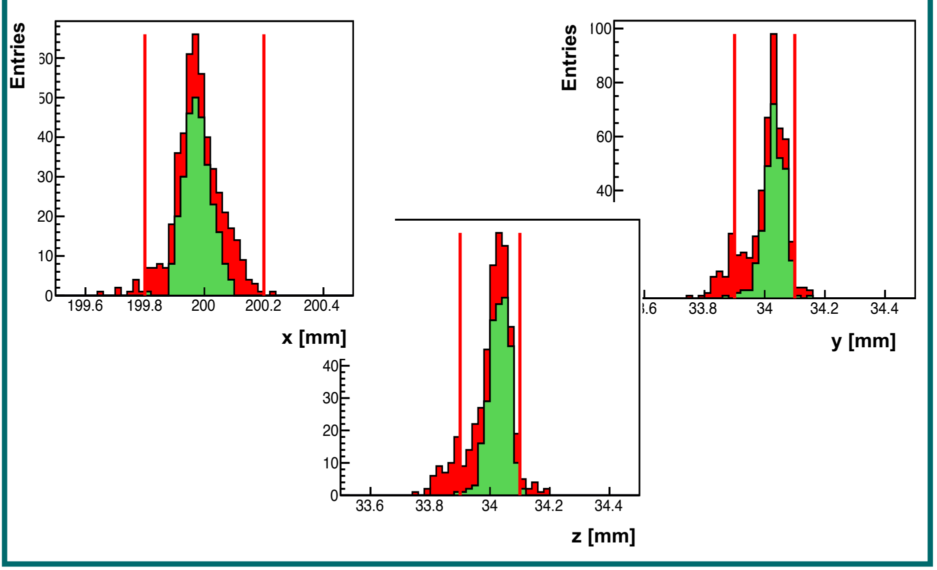


SiPM MTTF

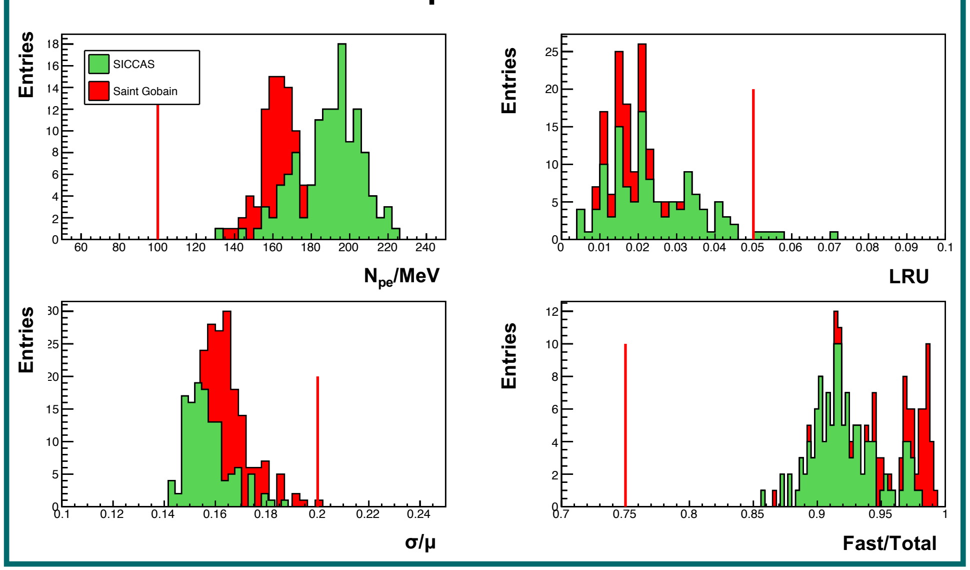


First QA results - Crystal

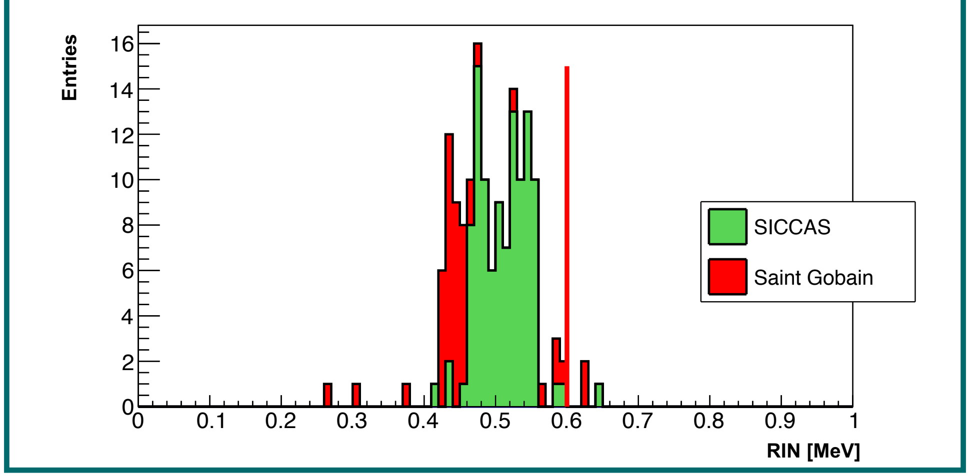
Dimensional test



Optical test

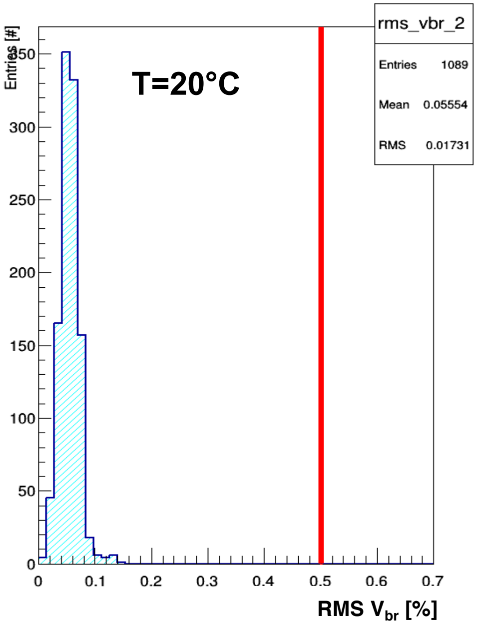


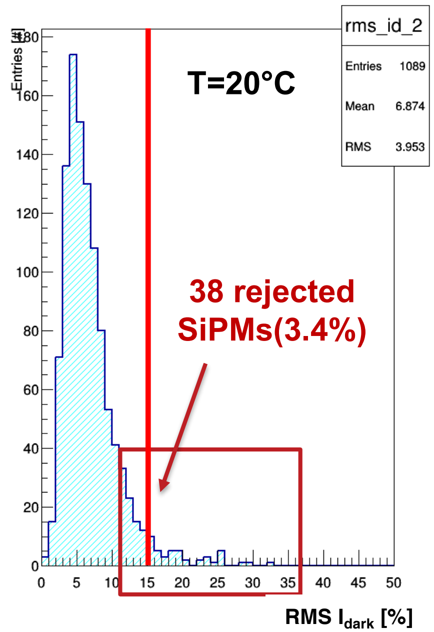
RIN test

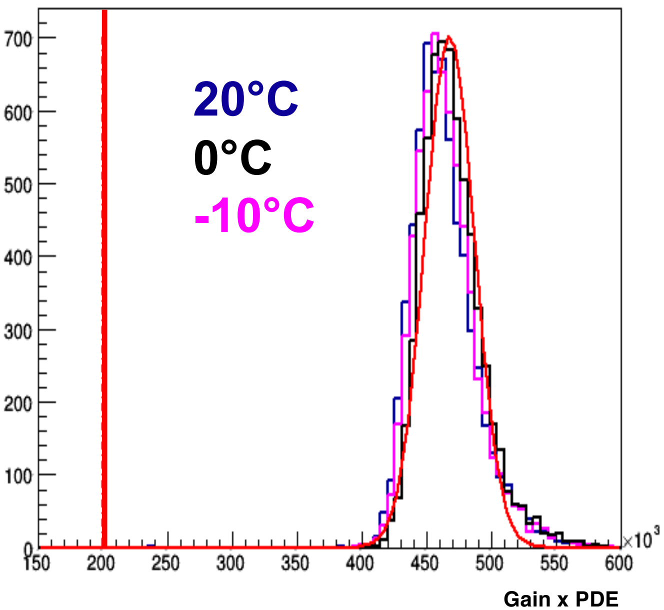


- ❑ 99% of crystals satisfy the specifications concerning optical properties
- ❑ Some problems to satisfy the mechanical specs

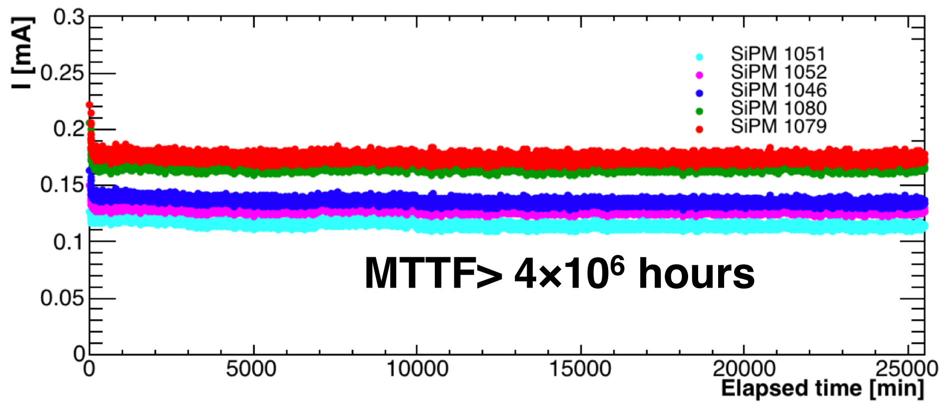
First QA results -SiPMs



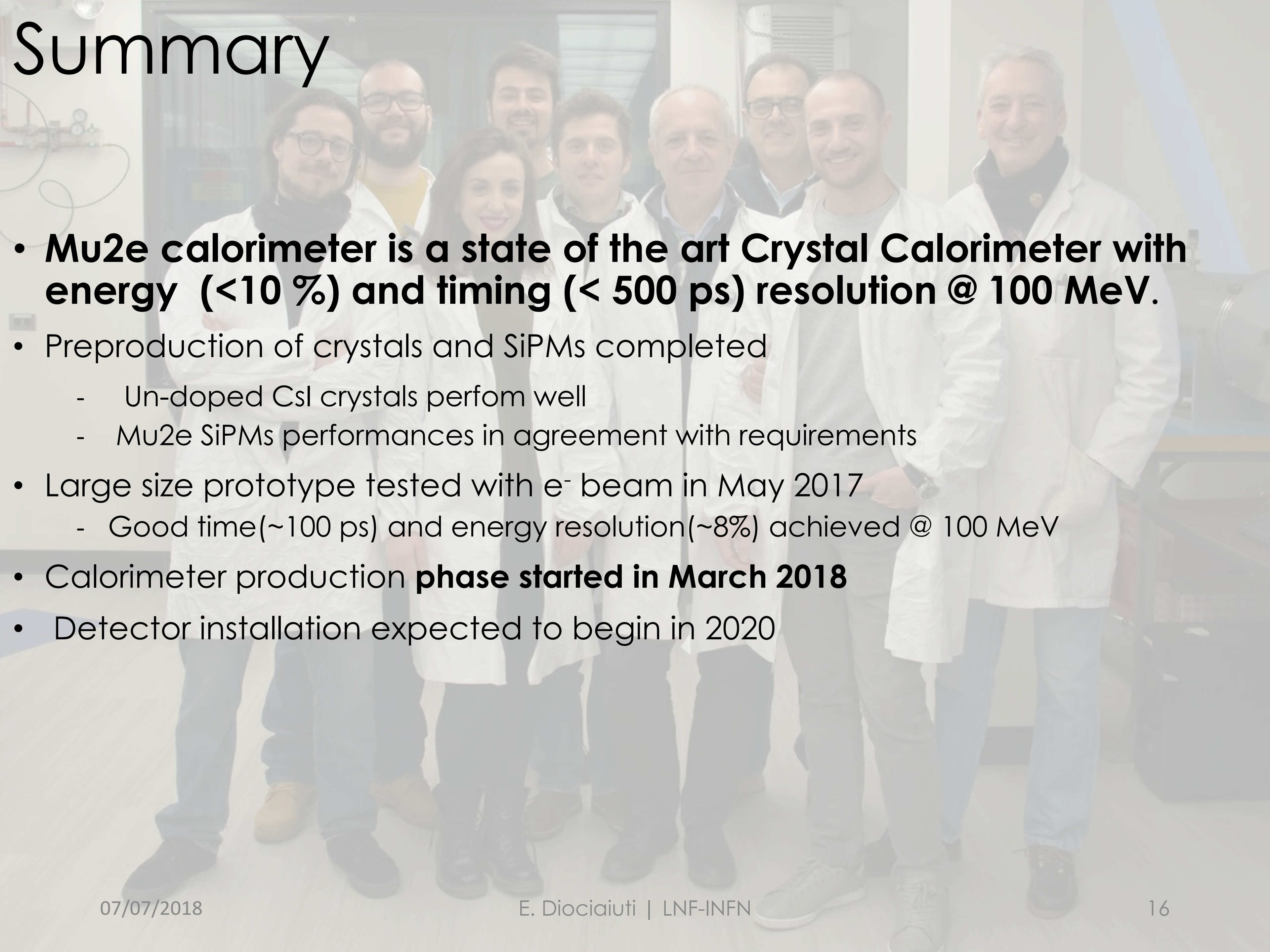




- ❑ 96% of SiPMs satisfy the Mu2e requirements
- ❑ Performances after the irradiation OK



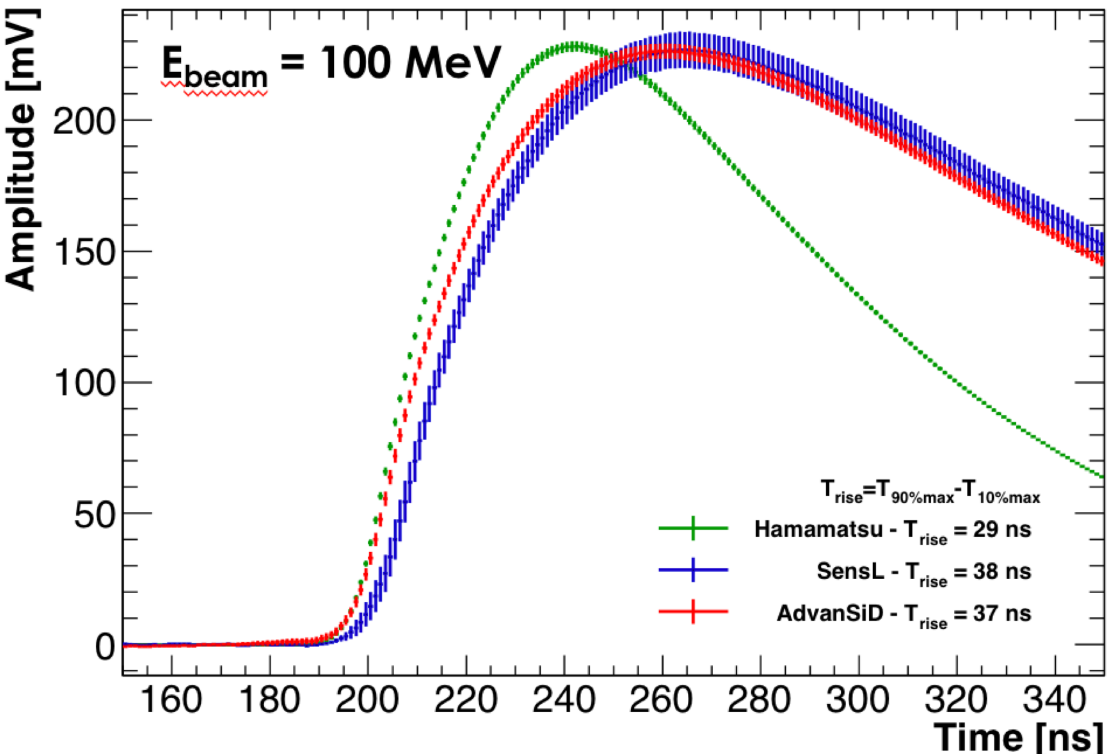
Summary

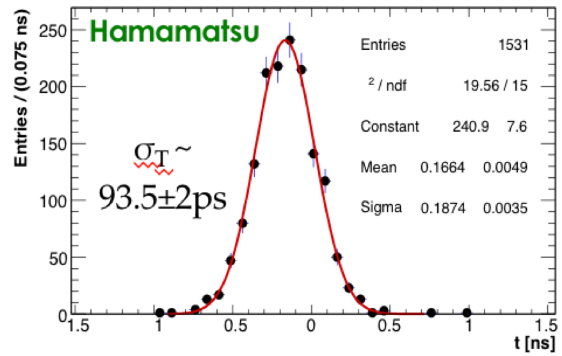


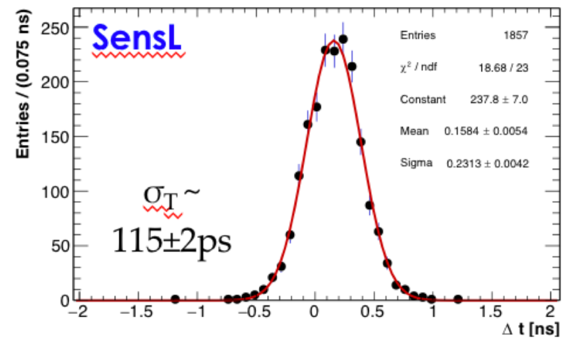
- **Mu2e calorimeter is a state of the art Crystal Calorimeter with energy (<10 %) and timing (< 500 ps) resolution @ 100 MeV**.
- Preproduction of crystals and SiPMs completed
  - Un-doped CsI crystals perfom well
  - Mu2e SiPMs performances in agreement with requirements
- Large size prototype tested with e^- beam in May 2017
  - Good time(~100 ps) and energy resolution(~8%) achieved @ 100 MeV
- Calorimeter production **phase started in March 2018**
- Detector installation expected to begin in 2020

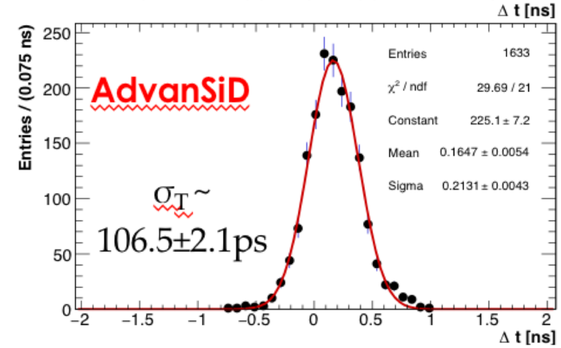
spares

Vendor Comparison -time









$$\sigma_{tot}^2 = \sigma_{Landau}^2 + \left(\frac{t_{rise}}{S/N}\right)^2 + \left(\left[\frac{V_{thr}}{S/t_{rise}}\right]_{RMS}\right)^2$$

Energy fluctuation

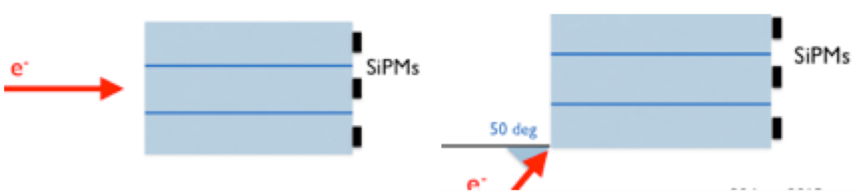
CF discriminator

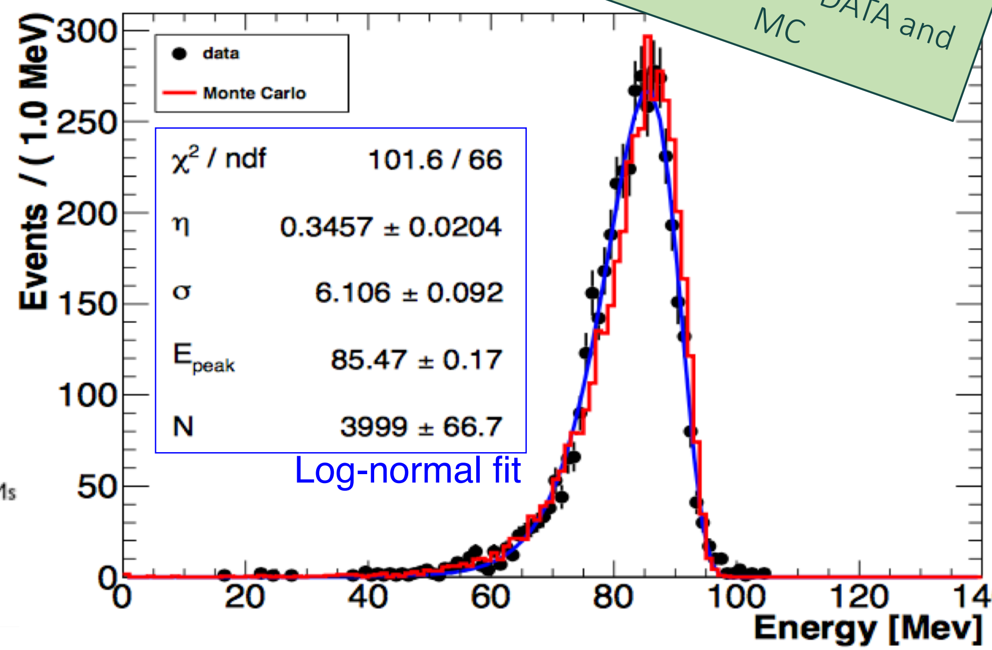
Small prototype TB

JINST 12 (2017) P05007

- Small prototype tested @ BTF (Frascati) in April 2015, 80-120 MeV e^-
- 3×3 array of 30×30×200 mm^2 undoped CsI crystals coupled to one Hamamatsu SiPM array (12x12) mm^2 with Silicon optical grease
- DAQ readout: 250 Msps CAEN V1720 WF Digitizer

Good agreement between the DATA and MC

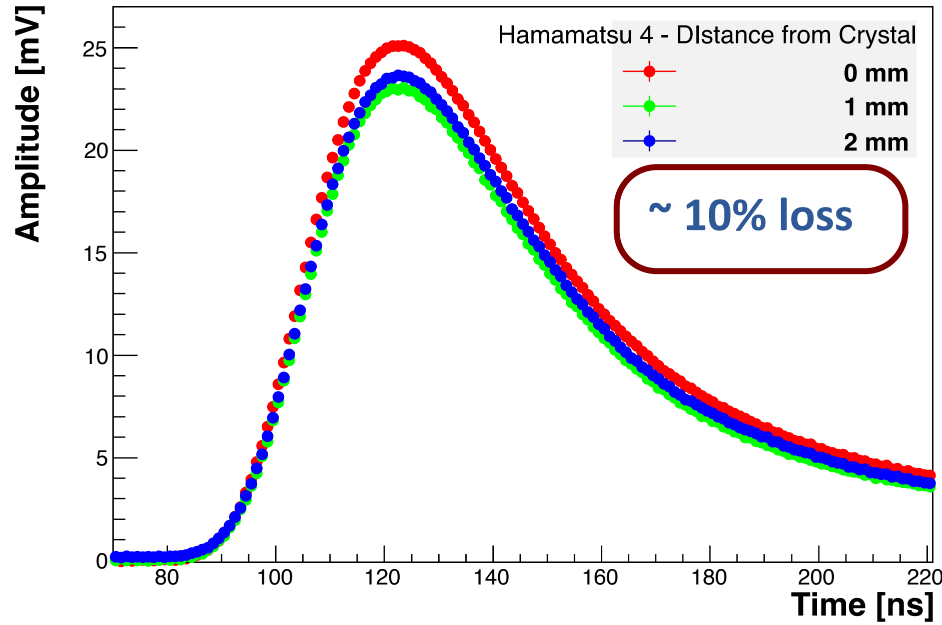




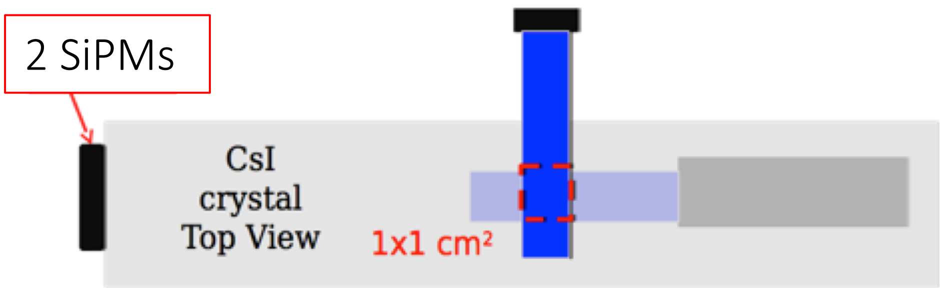
Single channel slice test

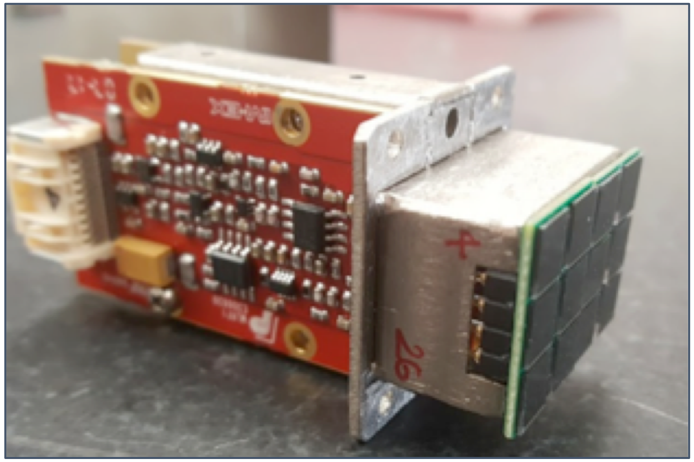
SG crystal + Hamamatsu SiPM + FEE
Optical coupling in air.

- ^{22}Na source
  - TRG: small scintillator readout by a PMT
  - Study distance effect for air-coupling



- Cosmic ray test → 2 SiPMs readout
  - TRG: crystal between 2 small scintillators





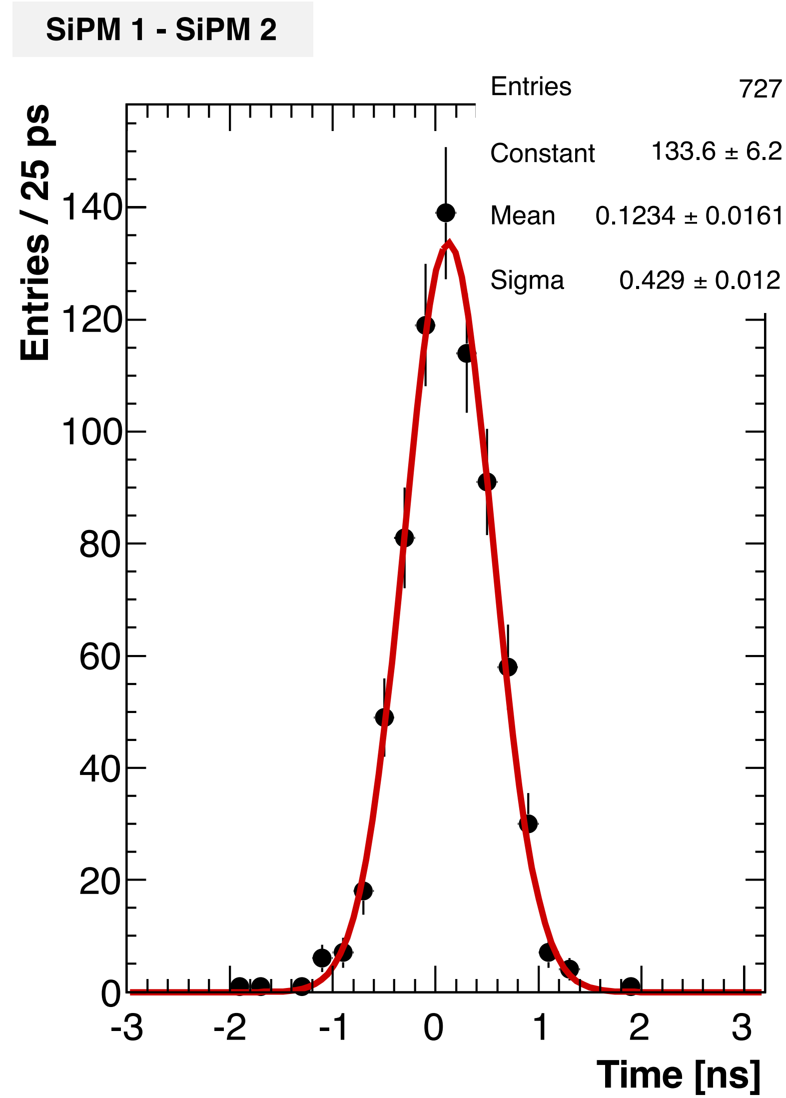
Single channel – CR test

- TRG time resolution ~ 170 ps
- Constant fraction method used
- Pulse height correction applied (slewing)

After jitter subtraction:
SiPM 1 – σ_T ~ 330 ps
SiPM 2 – σ_T ~ 340 ps

T(SiPM1 - SiPM2)/2 → ~ 215 ps
@ ~ 23 MeV energy deposition
(MIP energy scale from Na^{22} source peak)

Timing result well compares with old tests:
→ Reduced light output/SiPM (22 vs 30 pe/MeV)
→ 2 SiPMs/crystal
→ LY of 44 vs 30 → 215 ps (now) vs 250 ps (old).



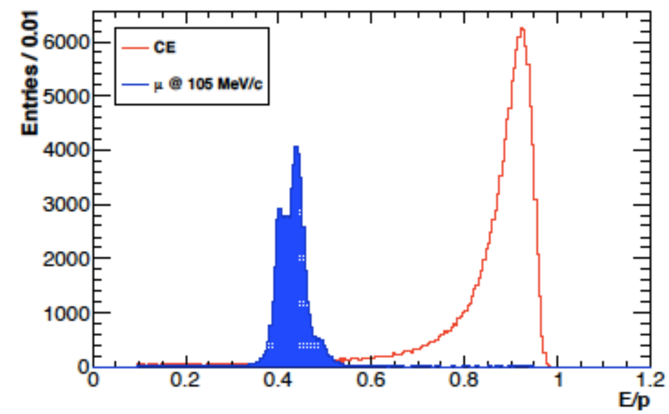
Particle Identification

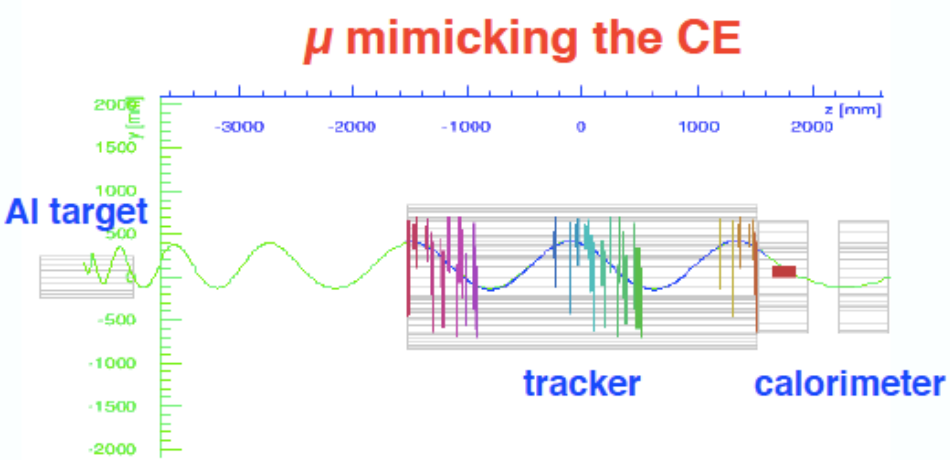
With a CRV inefficiency of 10^{-4} an additional rejection factor of ~ 200 is needed to have < 0.1 fake events from cosmic in the signal window

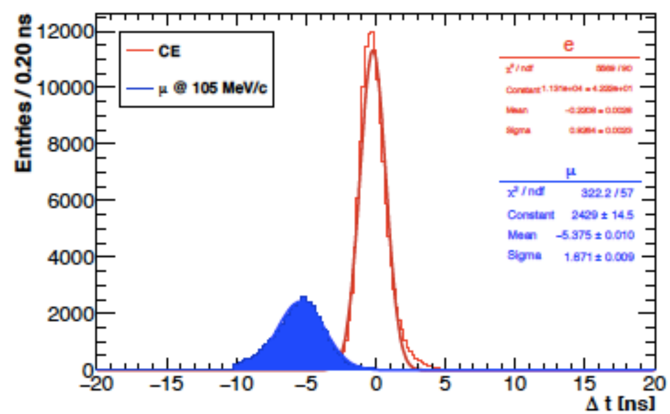
- 105 MeV/c e^- are ultra-relativistic, while 105 MeV/c μ have β~ 0.7 and a kinetic energy of ~ 40 MeV
- Likelihood rejection combines

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

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



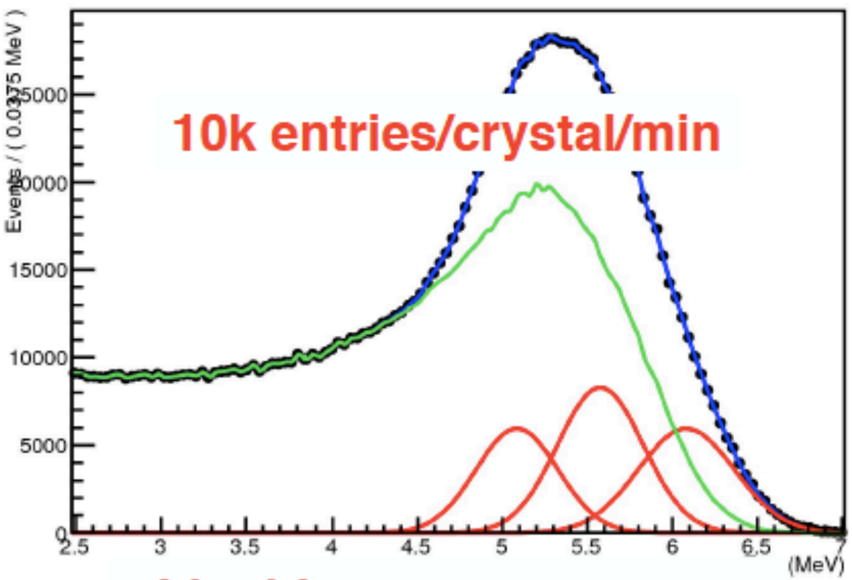


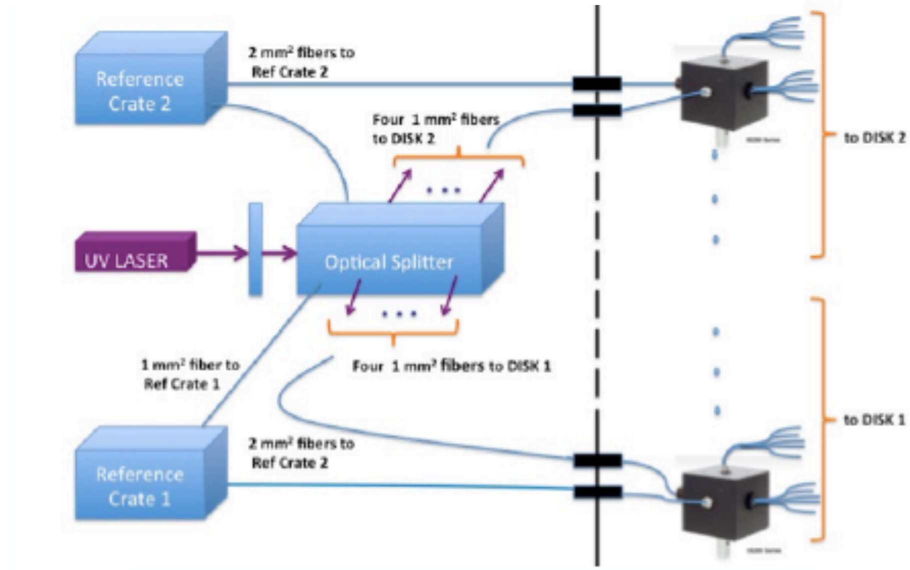


A rejection factor of 200 can be achieved with ~ 95% efficiency for CE

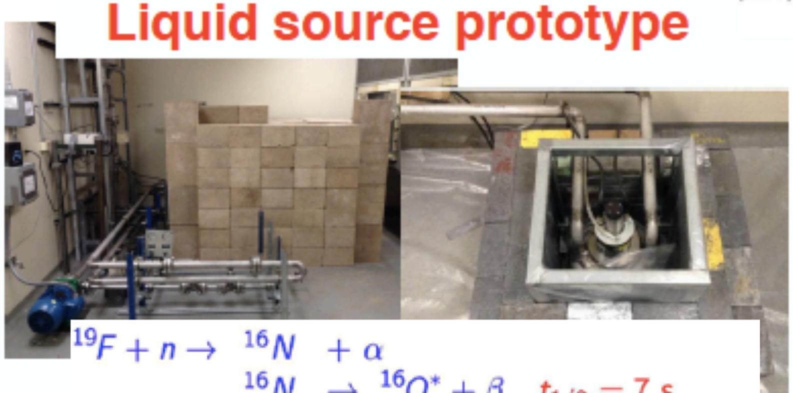
Calorimeter Calibration

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



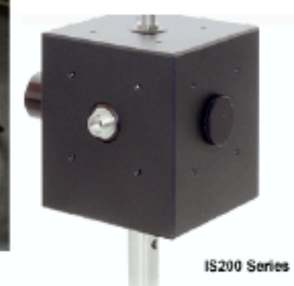


Liquid source prototype



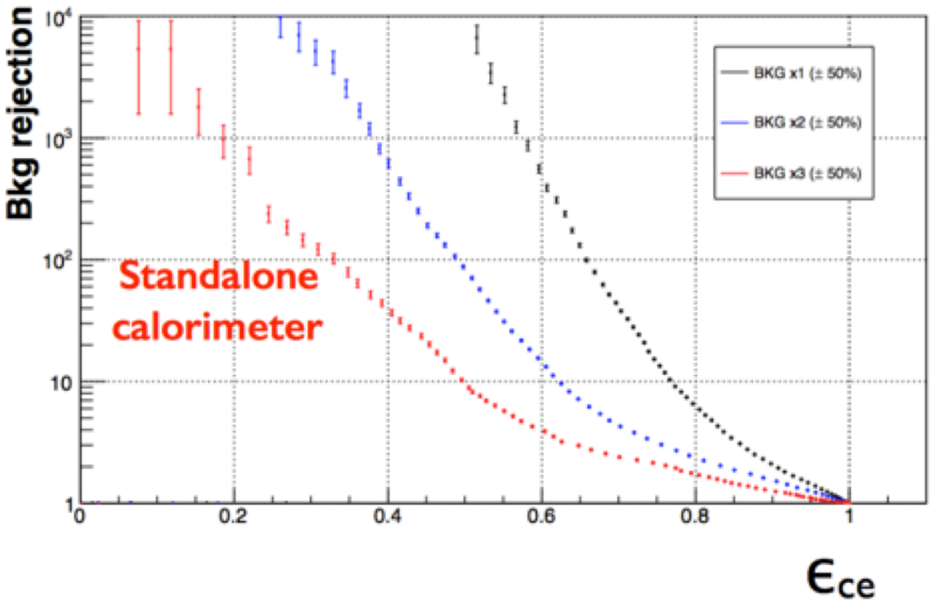
$$^{19}F + n \rightarrow \; ^{16}N \; + \alpha$$
$$^{16}N \; \rightarrow \; ^{16}O^* + \beta \quad t_{1/2} = 7\ \mathrm{s}$$
$$^{16}O^* \rightarrow {}^{16}O + \gamma(6.13\ \mathrm{MeV})$$

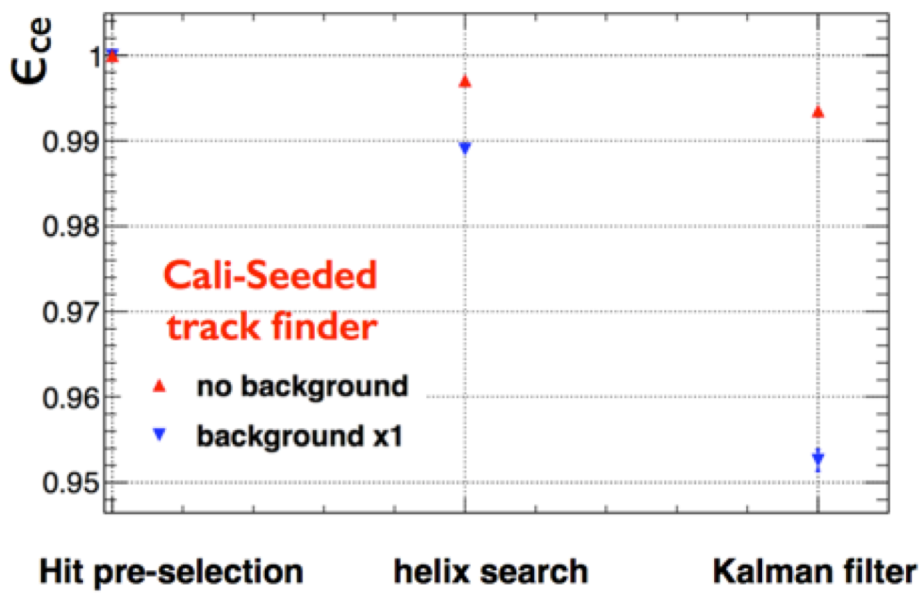
Laser system - test station



Calorimeter trigger

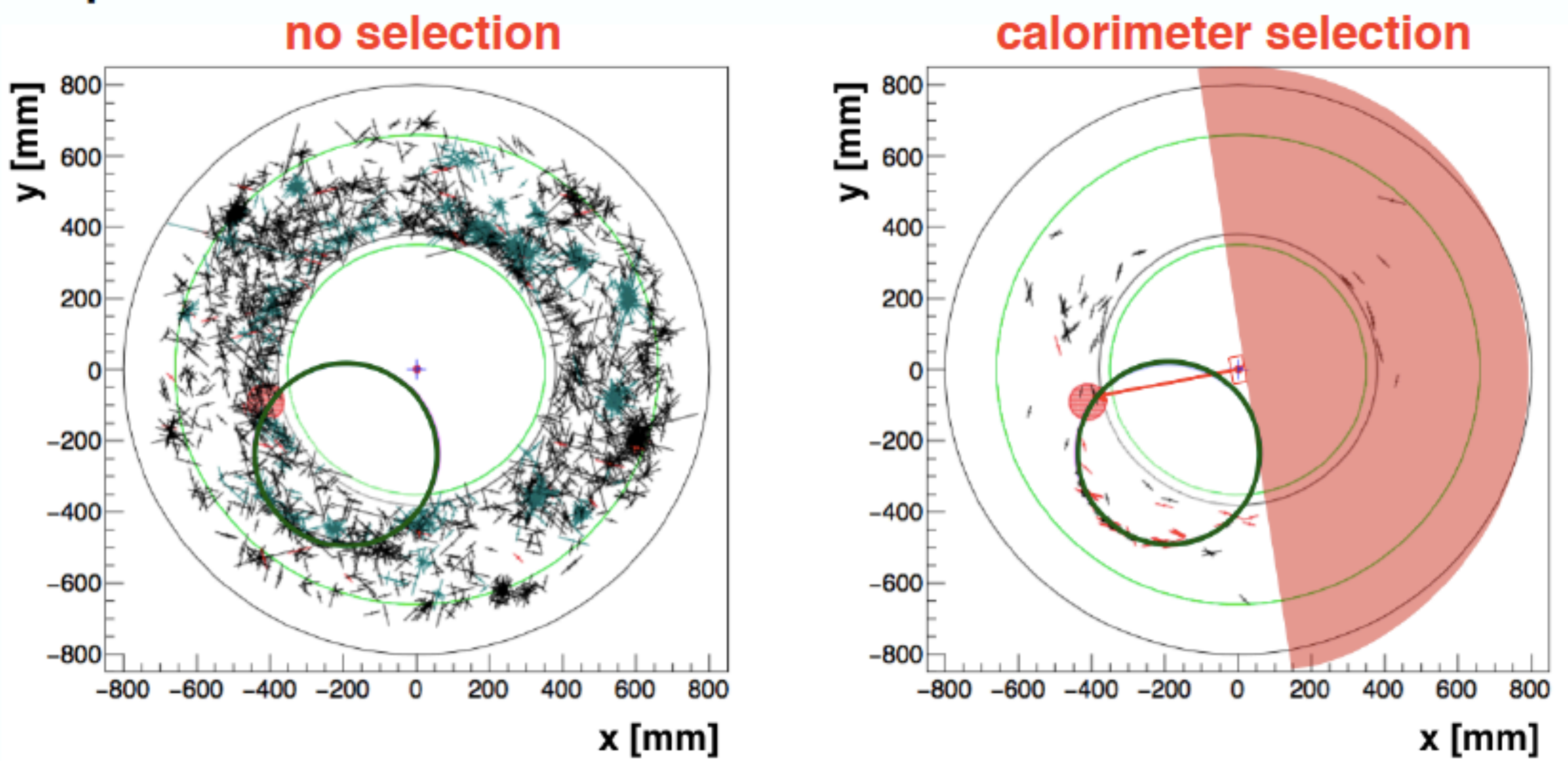
- Calo info can provide additional trigger capabilities in Mu2e:
- Calorimeter seeded track finder
  - Factorized into 3 steps: hit pre-selection, helix search and track fit
  - ε ~ 95% for background rejection of 200
- Standalone calorimeter trigger that uses only calo info
  - E ~ 65% for background rejection 200





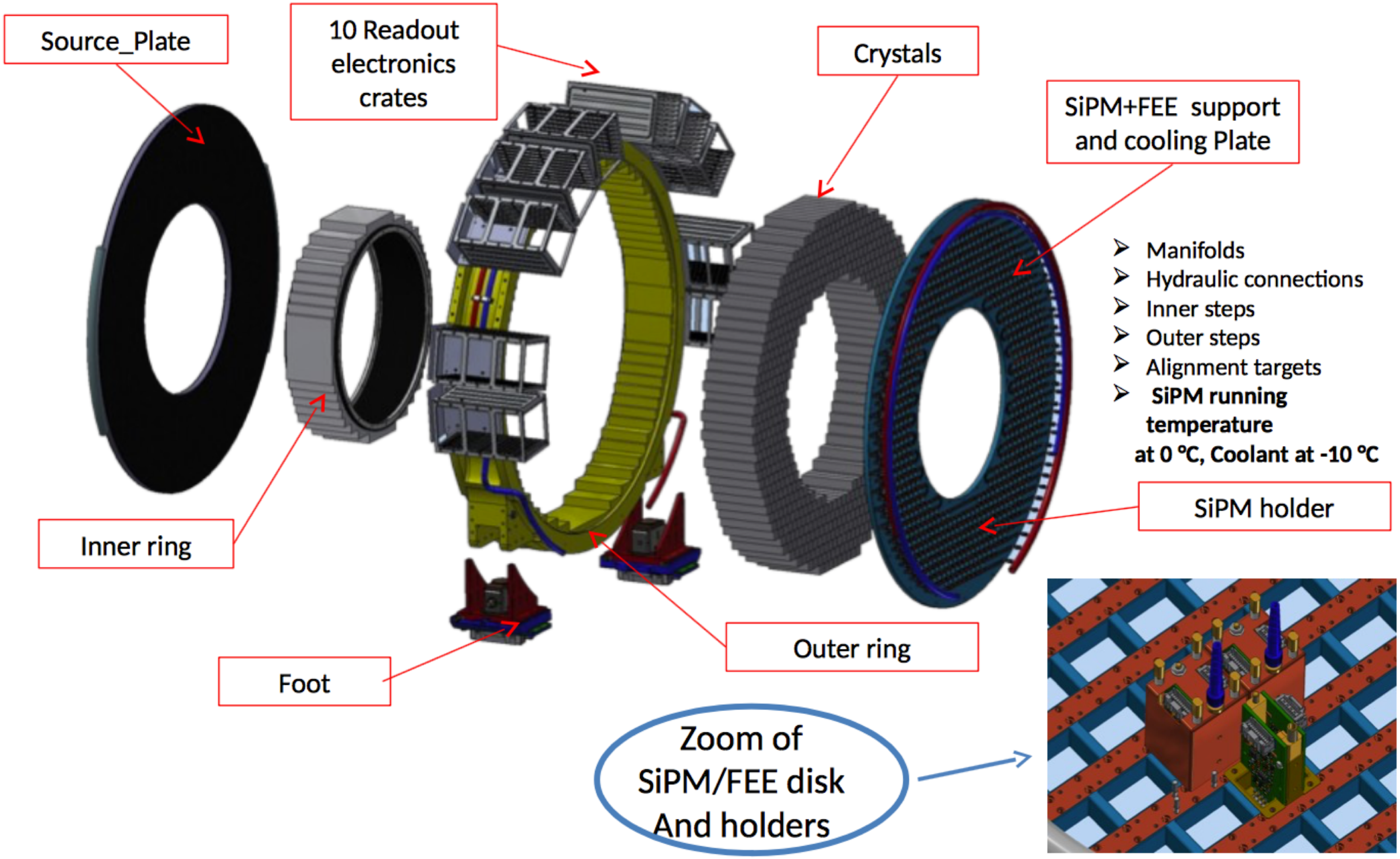
Calorimeter seeded track finder

- Cluster time and position are used for filtering the straw hits:
  - ✓ **time window of ~ 80 ns**
  - ✓ **spatial correlation**



- **black crosses** = straw hits, **red circle** = calorimeter cluster, **green line** = CE track

Calorimeter Mechanics



SiPM = Silicon PhotoMultiplier
FEE = Front End Electronics

Background for Mu2e

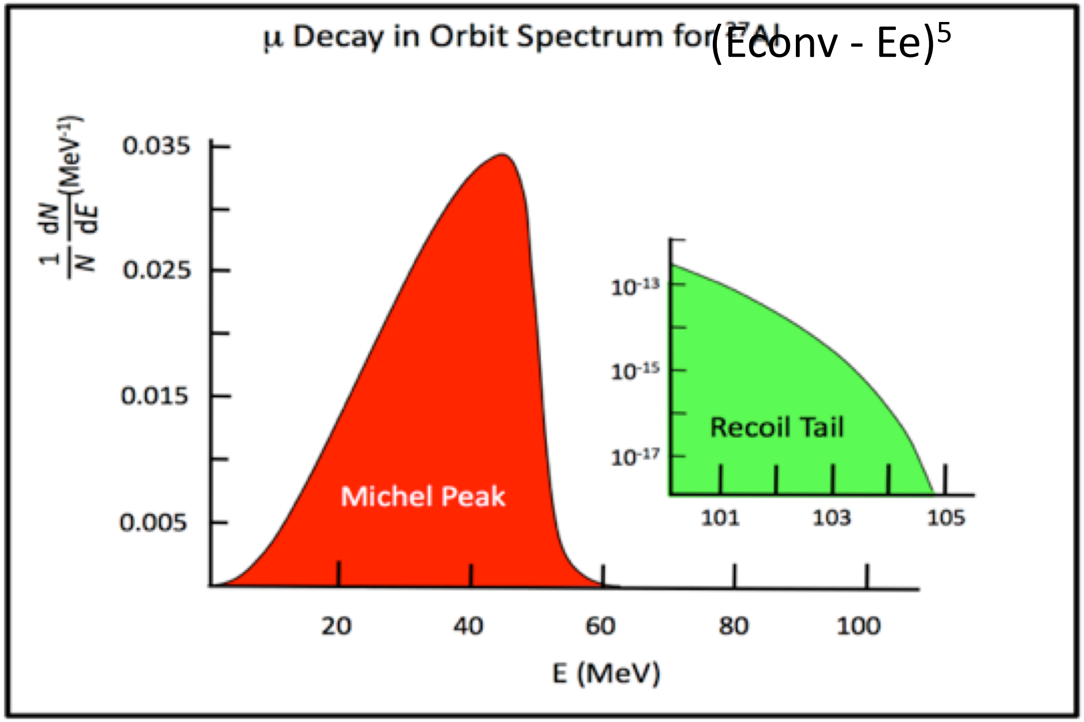
- **Intrinsic physics background:**
  - Muon Decay in Orbit (DIO)→ end point @ signal energy
  - Radiative Muon Capture →πN → $\gamma N'$; $\gamma \rightarrow e^+e^-$
  - Neutron from muon nuclear capture
  - Proton from muon nuclear capture
- **Beam related backgrounds:**
  - Radiative Pion Capture (RPC)
  - Beam electron
  - Muon decay in flight
  - Neutron
  - Antiprotons producing pions when annihilating in the target
- **Cosmic rays**

DIO background

- Electron energy distribution from the decay of bound muons follows a modified-Michel spectrum:

○ The Michel spectrum is distorted by the presence of the nucleus and the electron can have an energy similar to the one of CE if neutrino are almost at rest

→**To separate DIO endpoint from CE line Mu2e needs an high Resolution Spectrometer**



Minimizing prompt background

- Prompt backgrounds arise from the interaction occurring at the stopping target
  - Radiative Pion Capture (τ_π^{Al} = 26 ns) $\pi^- N \to \gamma N^* \to e^+ e^- N^*$
  - π/μ decay in flight
- **Muonic atomic life>> prompt background**
- Narrow pulsed proton beam
- Delayed signal window starting 700 ns after the initial proton pulse
- Out-of-time proton suppressed by O(10^{10})