# Design and status of the Mu2e calorimeter

**E. Diociaiuti**
LNF-INFN and Tor Vergata University
On behalf of the Mu2e calorimeter group

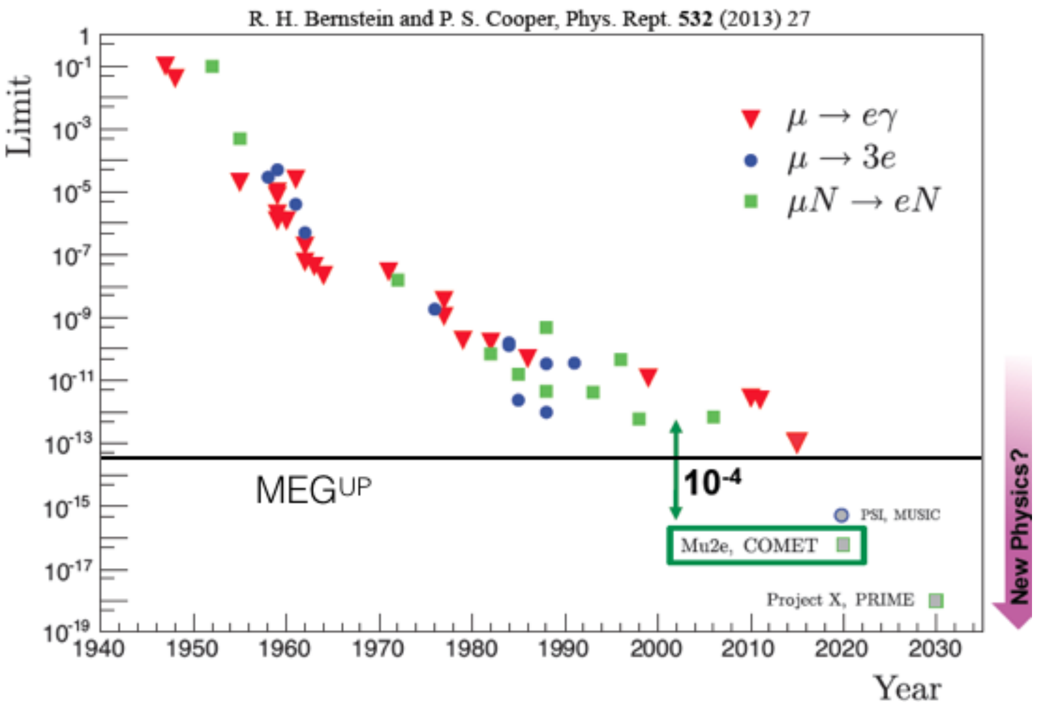
2017 IEEE Nuclear Science Symposium & Medical Imaging Conference

# Outline

- **Charged Lepton Flavour Violation (CLFV):** muon conversion in the electric field of a nucleus
- **The Mu2e experiment**: Requirements and design considerations
- **The Mu2e electromagnetic calorimeter**
  - Pre-production of crystals and photosensors
  - Module-0 performances
  - Future plans

# CLFV processes

- Processes as μ-e conversion, μ→eγ, μ→3e represent examples of CLFV.
- These processes are forbidden in the SM. Even assuming neutrino oscillations, their rate is negligible(BR~ $\Delta m_\nu^2/M_W^2$ ~10$^{-52}$)
- Several models BSM expect these processes to be detectable with current/ next future experiment




**The observation of a CLFV event represents a clear evidence of New Physics**

# The Mu2e experiment

Mu2e searches for the muon to electron coherent conversion in the field of an aluminium nucleus

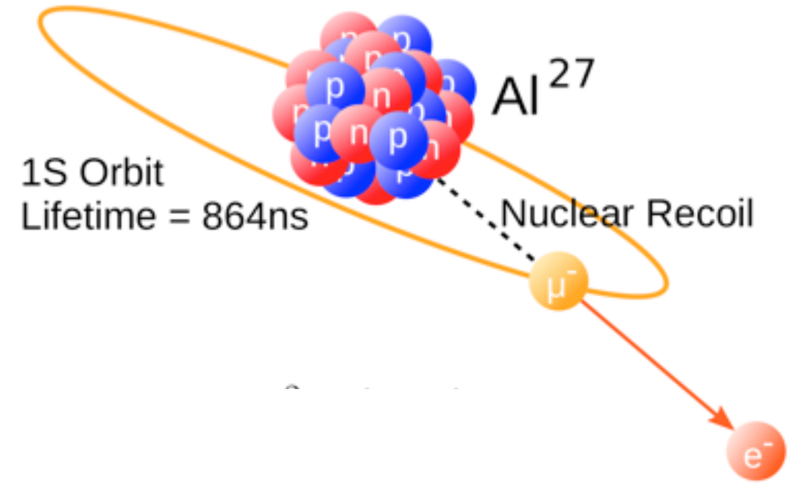
- Intense (10 GHz) negative low momentum muon beam stopped in an aluminium target
- Muon trapped in the orbit around the nucleus → muonic atom
- Muon conversion with a **clear signature**: single mono-energetic electron

**Goal**: $10^4$ improvement w.r.t. the current limit (set by Sindrum II)

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \rightarrow e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \rightarrow \nu_\mu + N(A,Z-1))}$$

$<8.4\times10^{-17}$ limit @ 90% CL

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

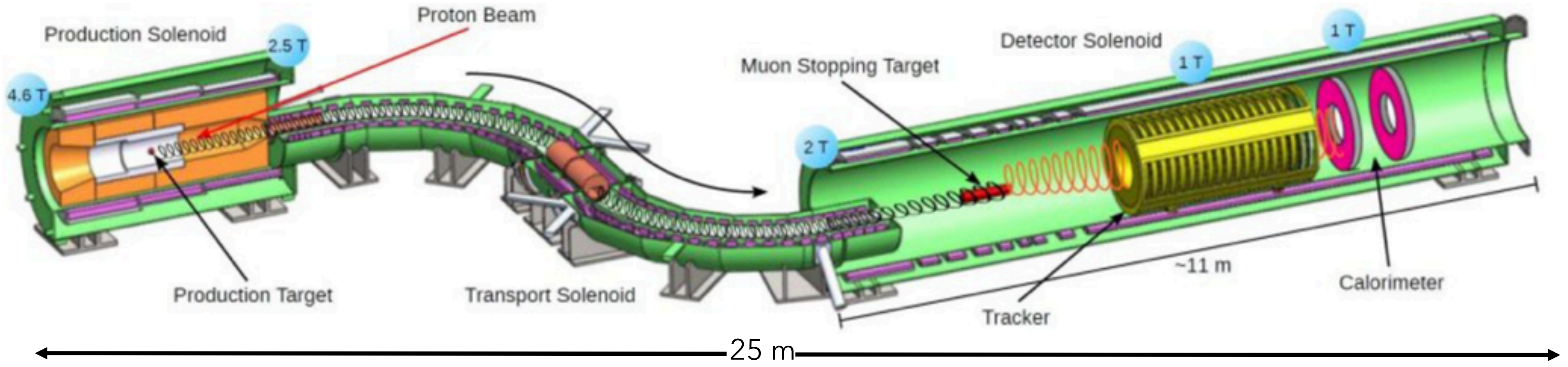


# Mu2e design

**Production Solenoid (PS):**

•8 GeV proton beam strikes target, producing mostly pions.

•Graded magnetic field contains backwards pions/muons and reflects slow forward pions/muons




**Transport Solenoid (TS):**

•Selects low momentum, negative muons

– Antiproton absorbers and collimators

**Detector Solenoid (DS):**

•Capture muons on Al target

•Tracker: high precision p measurement ($\sigma_p$= 180 keV/c)

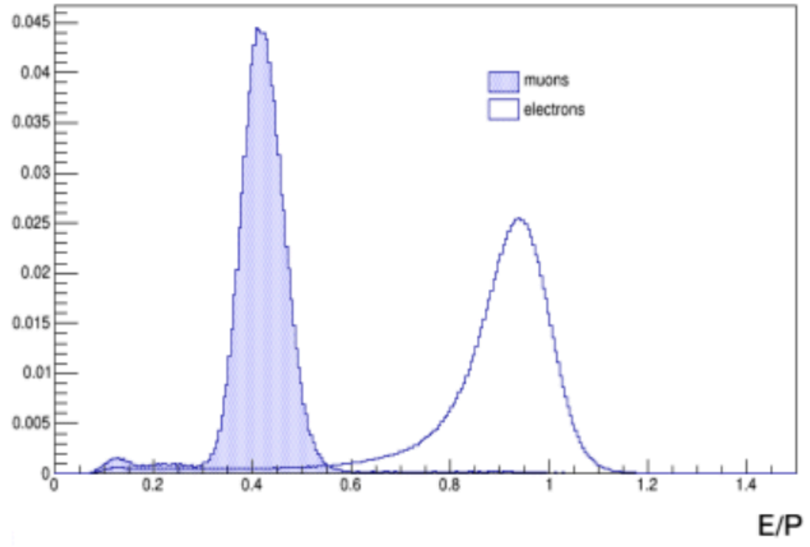
•Calorimeter energy/ time measurements

•Cosmic Ray Veto surrounds the solenoid

# Calorimeter requirements

The electromagnetic calorimeter (EMC) should provide high acceptance for reconstructing energy, time and position of signals for:

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




**Calorimeter requirements**

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

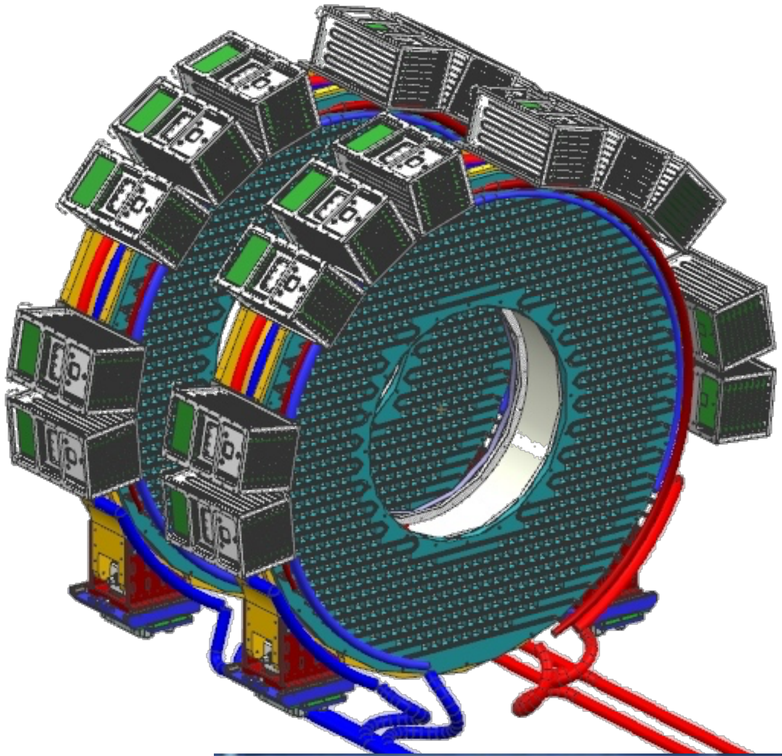
**Crystals coupled with Silicon PhotoMultipliers(SiPM)**

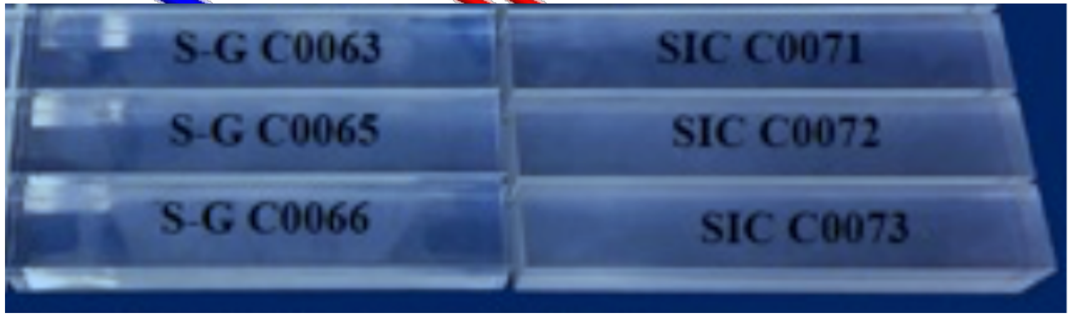
- 2 disks to enhance the geometrical acceptance
- LY(photosensor)>20 pe/MeV
- Fast signal for pileup and timing
- Survive an high radiation environment
  - TID of 90 (45) krad and a fluence of $1.2\times10^{12}$ ($3\times10^{12}$) n/cm$^2$ per crystal (sensor)

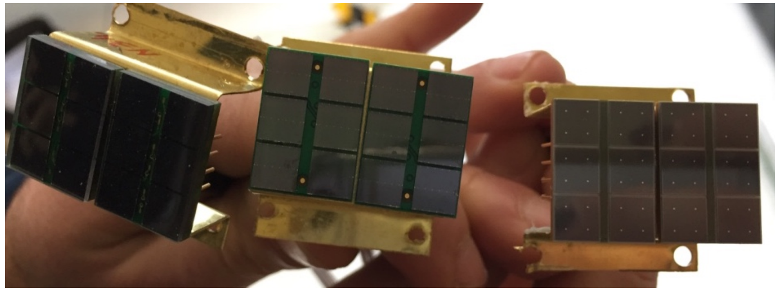
# Electromagnetic calorimeter

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

- $R_{IN}$ = 374 mm, $R_{OUT}$ = 660 mm
- Depth = 10 $X_0$ (200 mm), Disk separation 70 cm
- 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



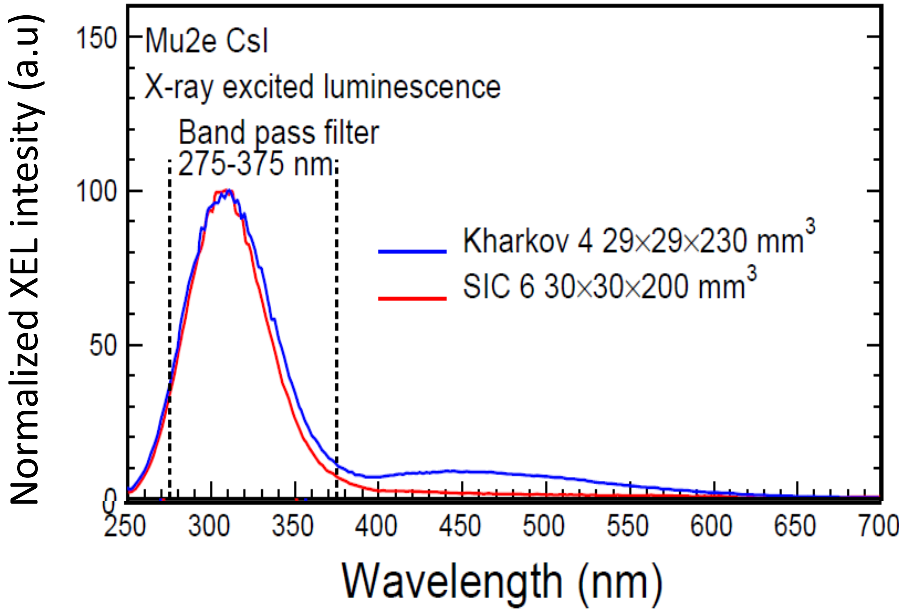


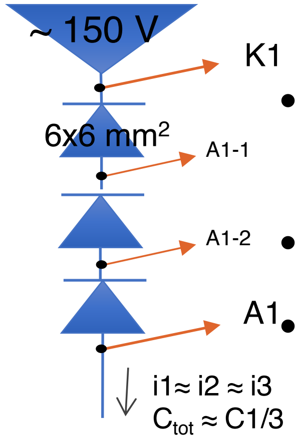



# Undoped CsI+ UV-extended SiPM

## Undoped CsI Crystal

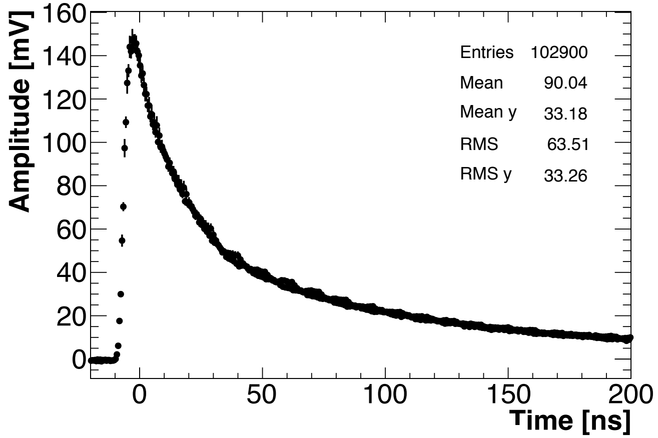
- τ < 30 ns
- No significant loss in LY up to 100 krad
- Emission peak at 310 nm



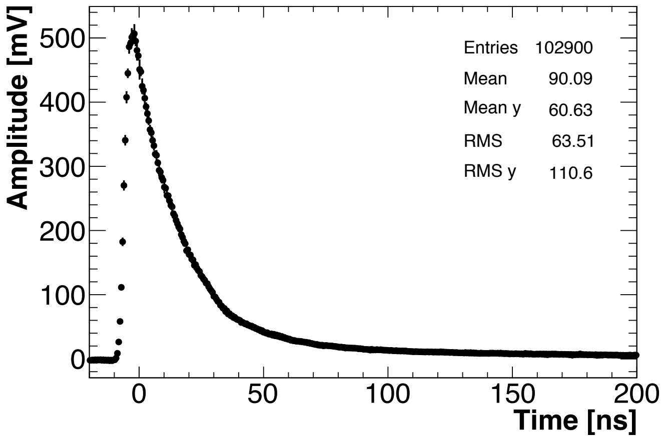




## Mu2e SiPM

- 2 arrays of three 6x6 mm$^2$ SiPMs for a total active area of (12x18) mm$^2$
- UV-extended to increase the PDE @ 310 nm
- The series configuration reduces the overall capacitance →narrower signals

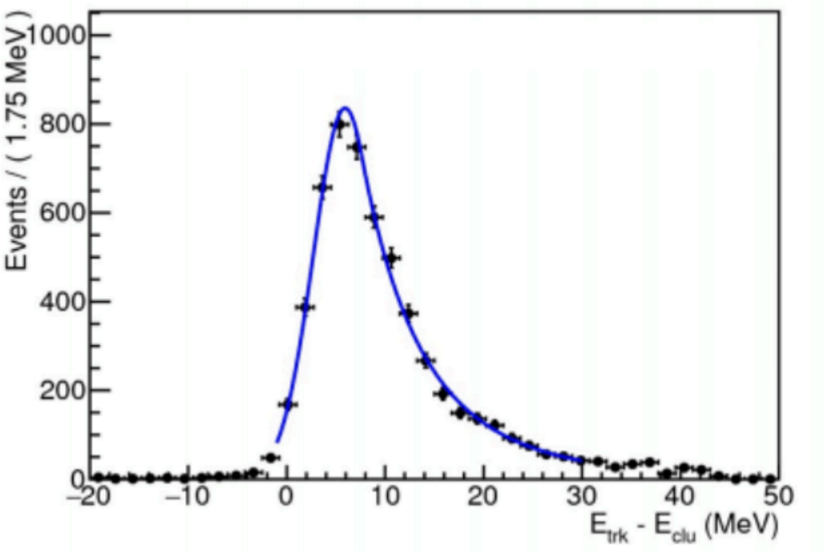



**Single cell**




**Series of 3 cells**

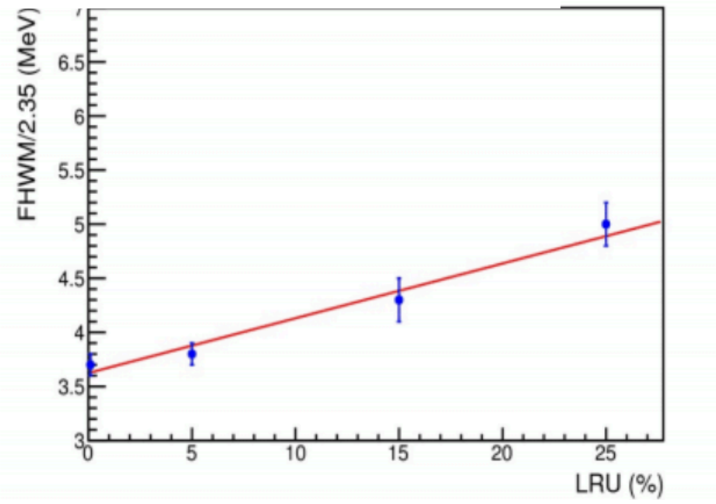
# Mu2e EMC: MC performances

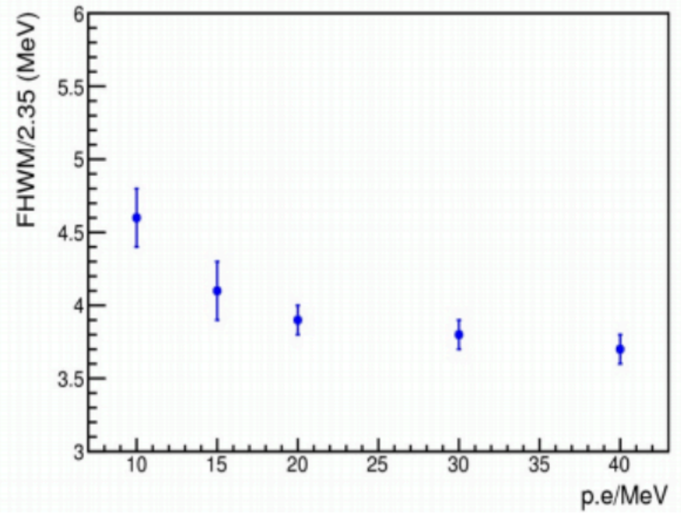



The calorimeter energy resolution is estimated from MC, taking into account signal and predominant background, as the difference of the conversion electron energy and the cluster energy.

**FWHM/2,35 = 3.8 ± 0.1 MeV**

**Energy resolution dependency on Uniformity Longitudinal response**



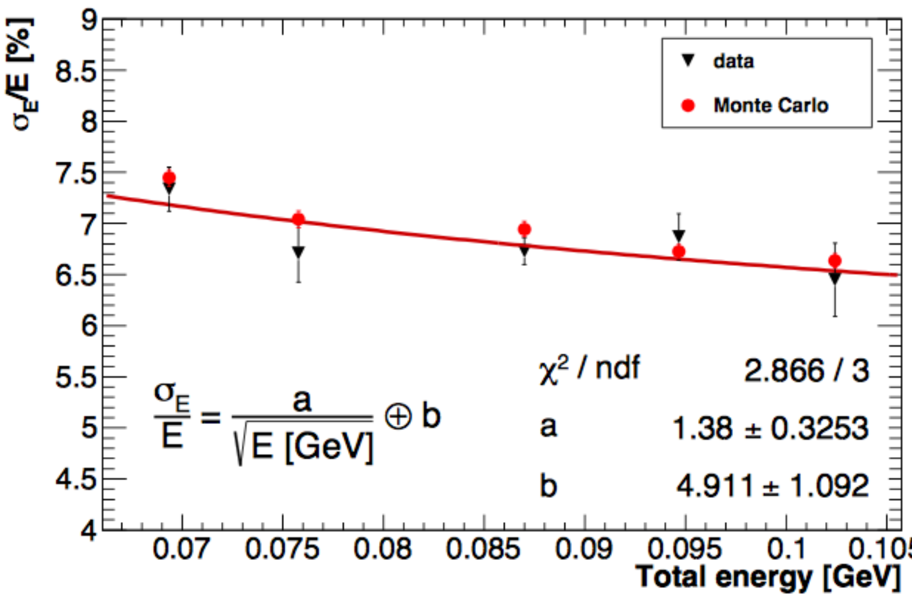




**Energy resolution dependency on Light Yield**

# Small size prototype

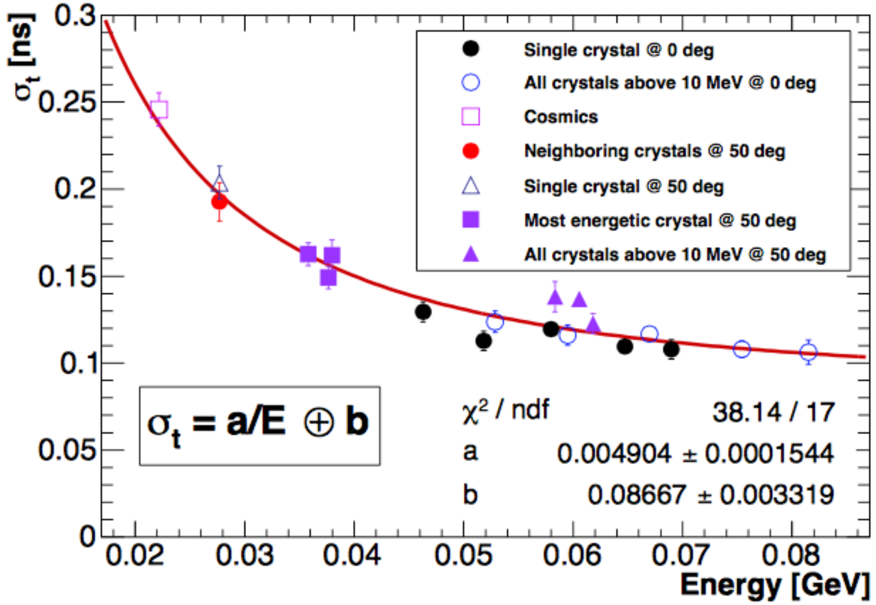
- Small prototype tested @ Beam Test Facility (LNF,Frascati) in April 2015, 80-120 MeV $e^-$
- 3×3 array of 30×30×200 $mm^3$ un-doped CsI crystals coupled to UV-extended Hamamatsu SiPM array (12x12) $mm^2$
- DAQ readout: 250 Msps CAEN V1720 Waveform Digitizer

**JINST 12 (2017) P05007**




**$\sigma_E$ ~ 6.5% at 100 MeV**

**Significant leakage contribution due to the matrix dimensions**




**$\sigma_T$ ~ 110 ps at 100 MeV**

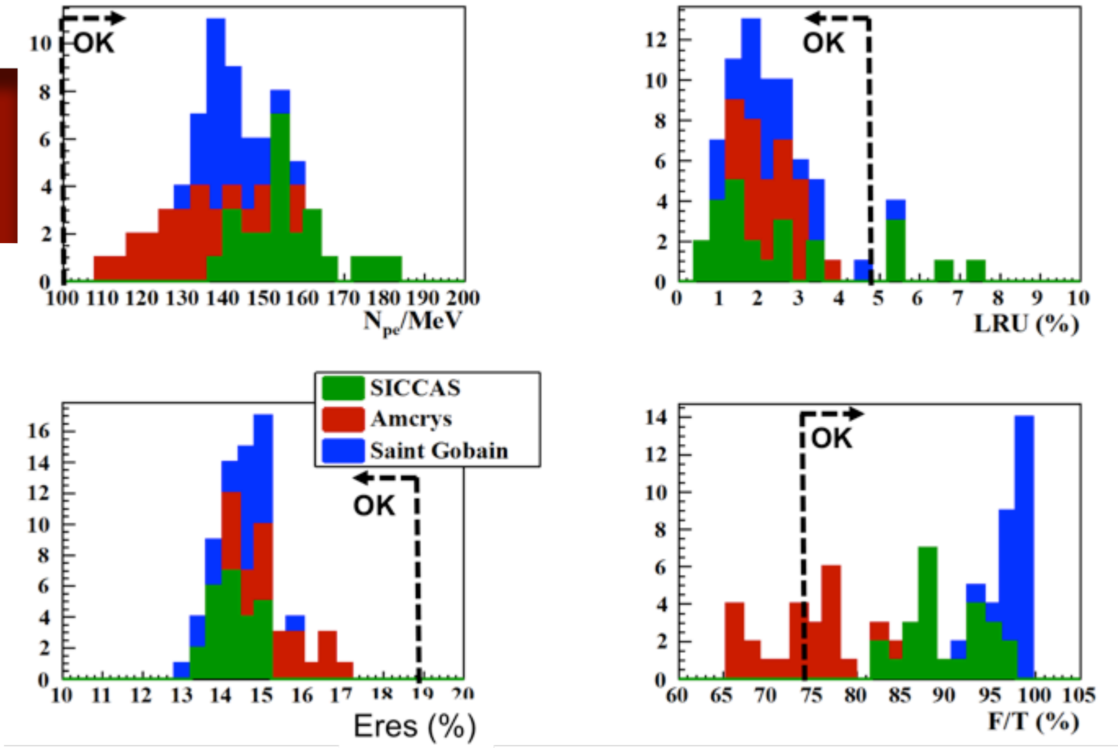
# Crystal pre-production

- 24 crystals from three different vendors: **SICCAS**, **Amcrys**, **Saint Gobain**
- Crystal 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

**Un-doped CsI crystals perform well**

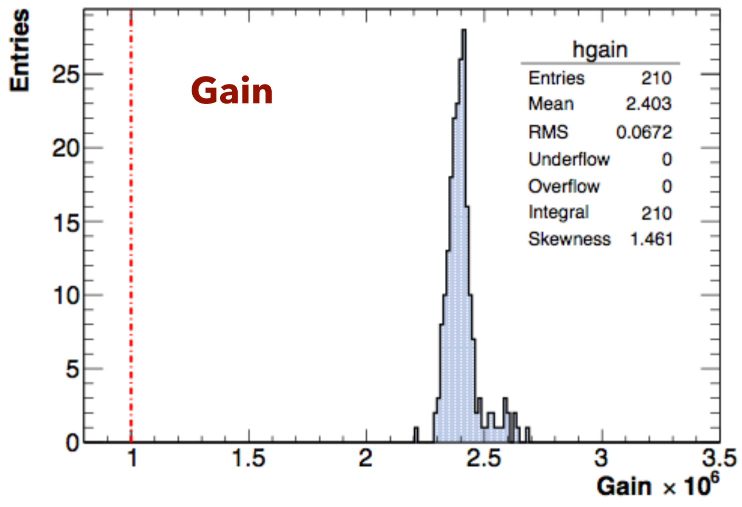
More information on C. Hu poster

- **Excellent LRU and LY:**
  - 100 pe/MeV with PMT readout
  - LRU < 5%
- **Radiation hardness OK for Mu2e**
  - Smaller than 40% LY loss @ 100 krad
  - Radiation Induced Noise <0.6 MeV

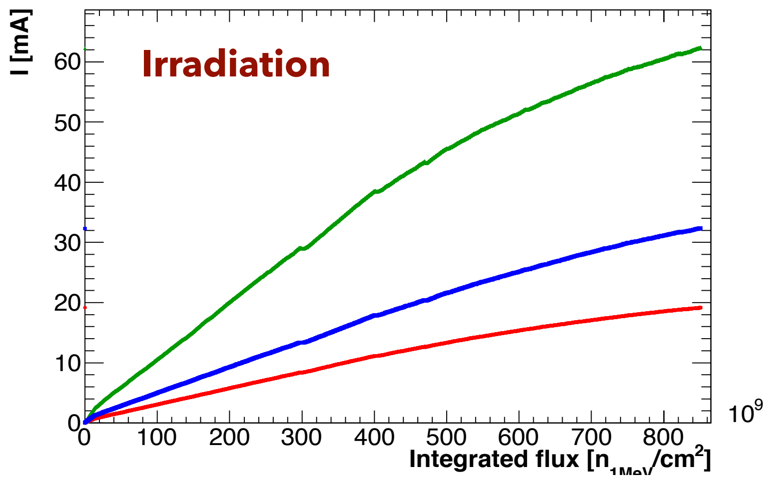


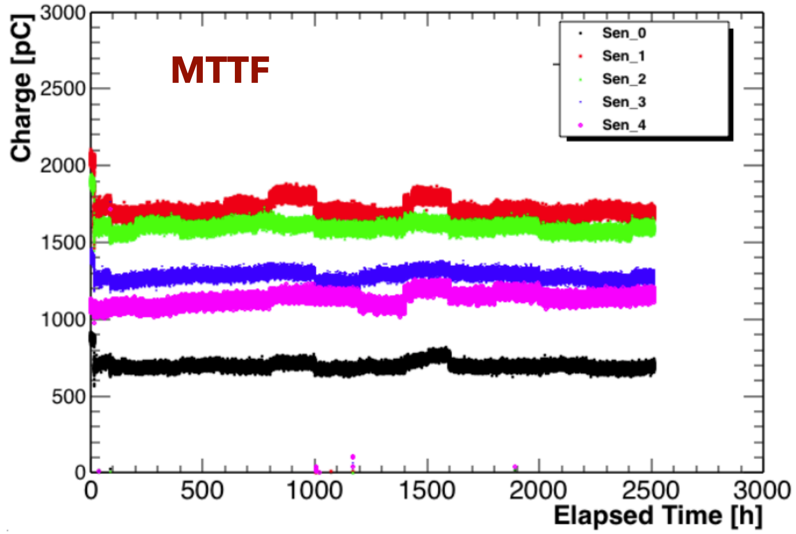
# Mu2e SiPM pre-production

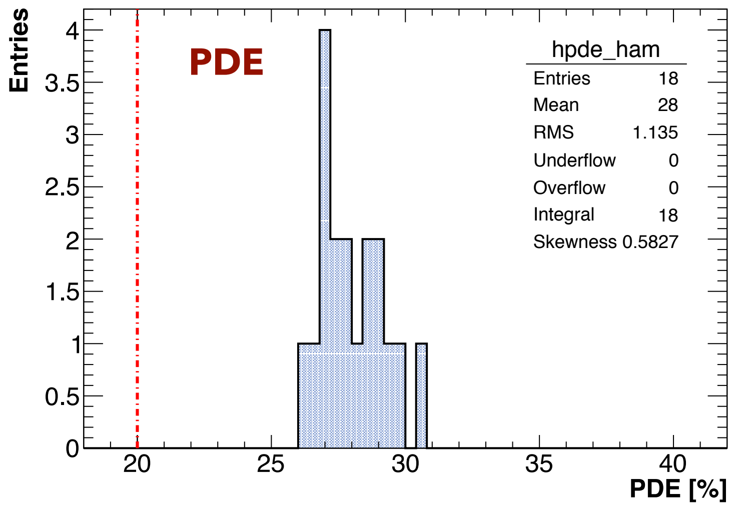
**150 Pre-production SiPMs**
**(**3×50 Mu2e SiPMs from **Hamamatsu**, **SensL** and **AdvansiD**):
- 3×35 were fully characterized for all six cells in the array **($V_{op}$, G, $I_{dark}$, PDE)**
- 1 sample/vendor exposed up to a fluence of $8.5\times10^{11}$ $n_{1MeVeq}/cm^2$ (@ 20 °C)
- MTTF estimated by operating 15 SiPM at 50 °C for 3.5 months → MTTF > $0.6\times10^6$ h




More information on G. Pezzullo poster

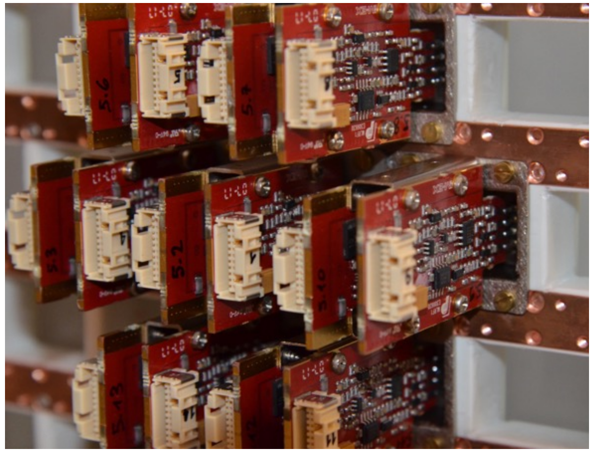


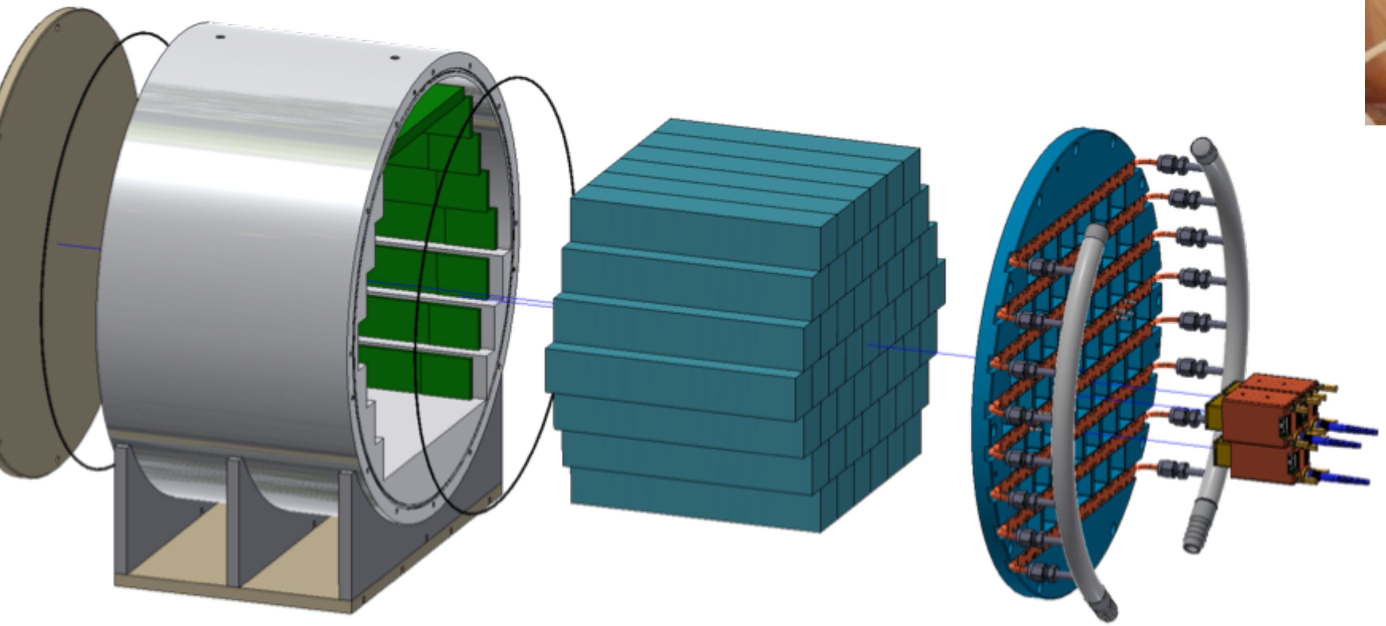



# Module - 0

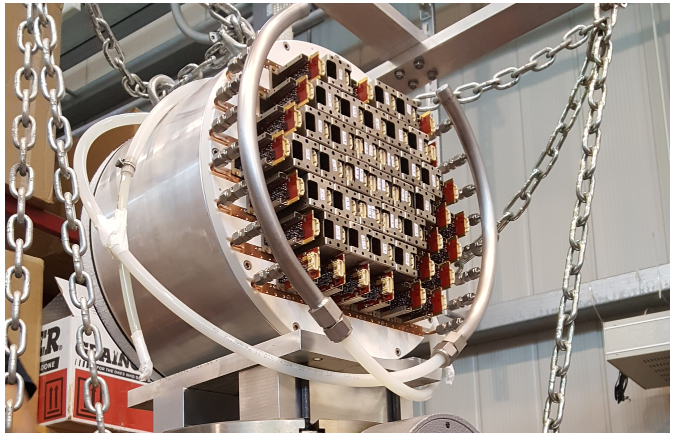
- Large size prototype of the disk assembled  in April 2017
  - 51 crystals coupled with 102 sensors
  - 102 FEE chips
  - Cooling lines



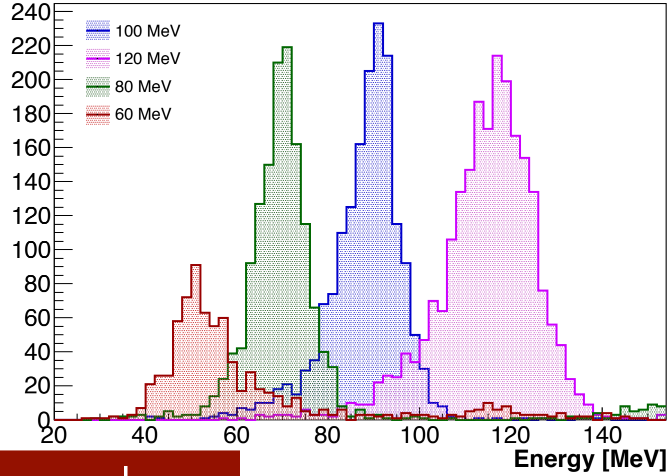


- Goals:
  - Test the performances
  - Test integration and assembly procedures
  - Test of temperature stability at RT
  - Next: Operate under vacuum, low temperature and irradiation tests

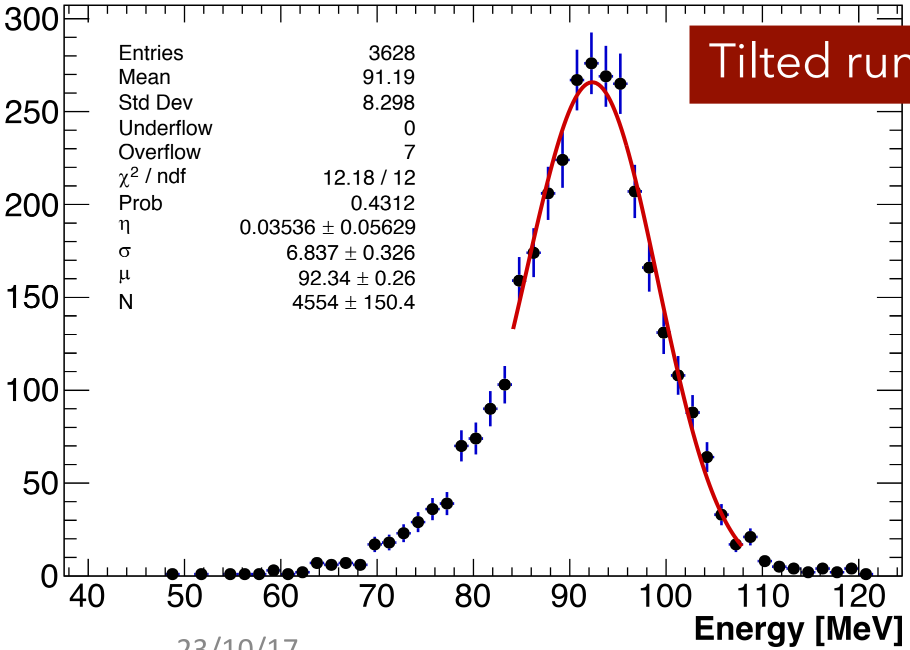
# Module-0: Energy resolution



- Module -0 tested with with e- beam (60-120 MeV)
- Orthogonal incidence
  - Beam calibration
  - Test the resolution behaviour
- 50 degree beam
  - Evaluate the performances
  - Understand the reconstruction @ 100 MeV
- Temperature kept stable @ 20° using a chiller



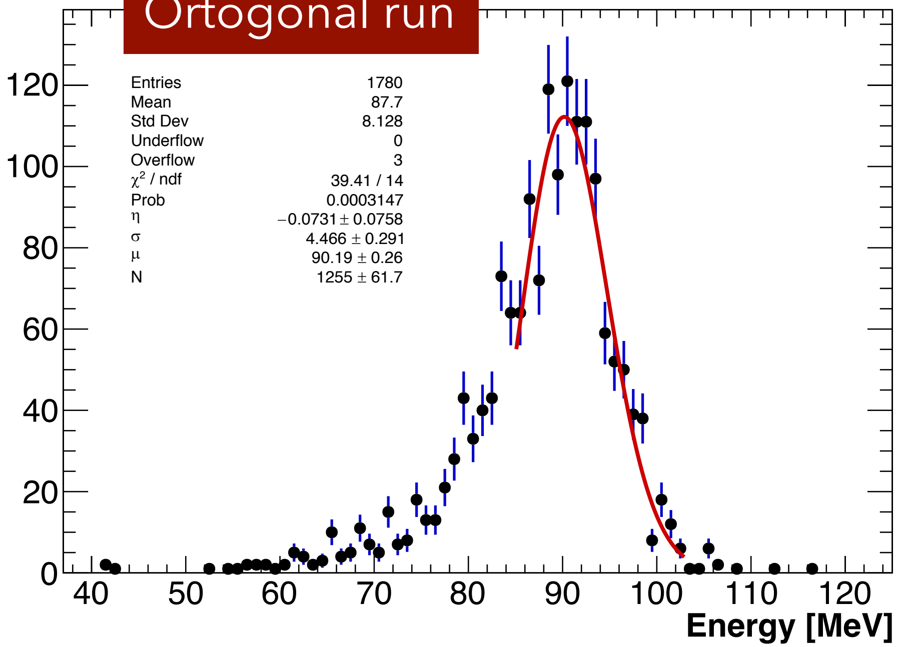

Tilted run




**ORTHOGONAL CONFIGURATION:**
**$\sigma_E$ ~ 5% all the Module -0 @ $E_{beam}$= 100 MeV**

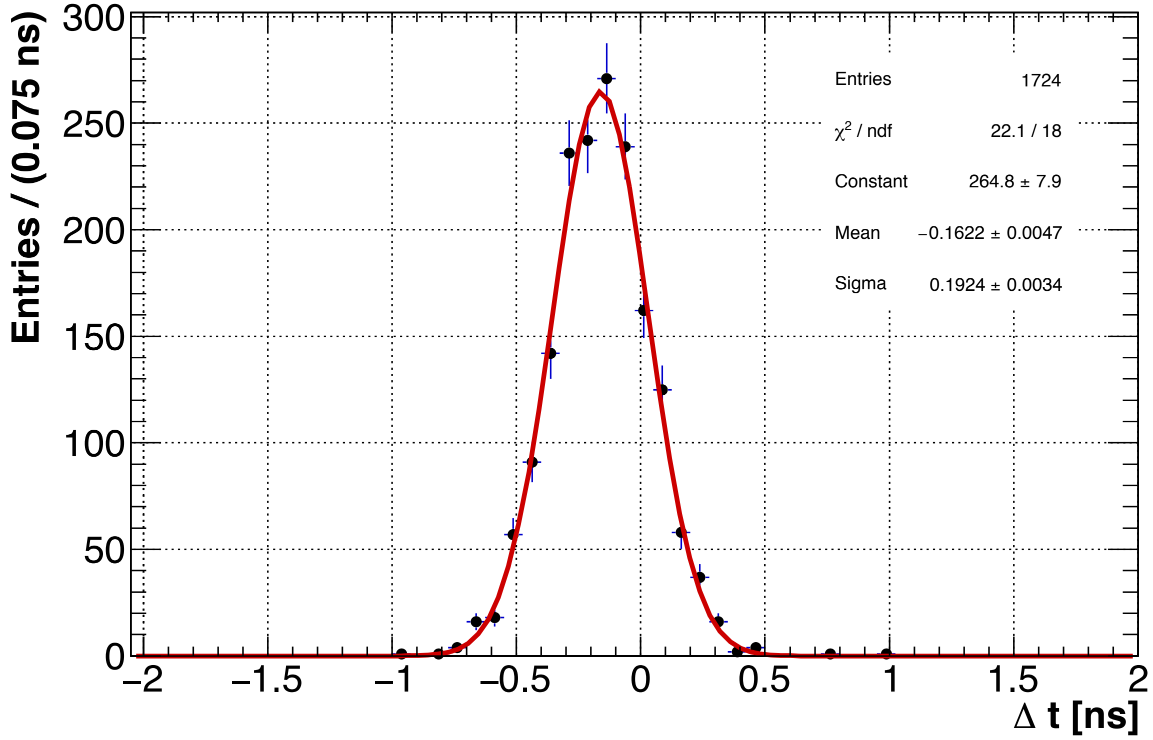
**TILTED CONFIGURATION:**
**$\sigma_E$ ~ 7% all the Module -0 @ $E_{beam}$= 100 MeV**

Ortogonal run

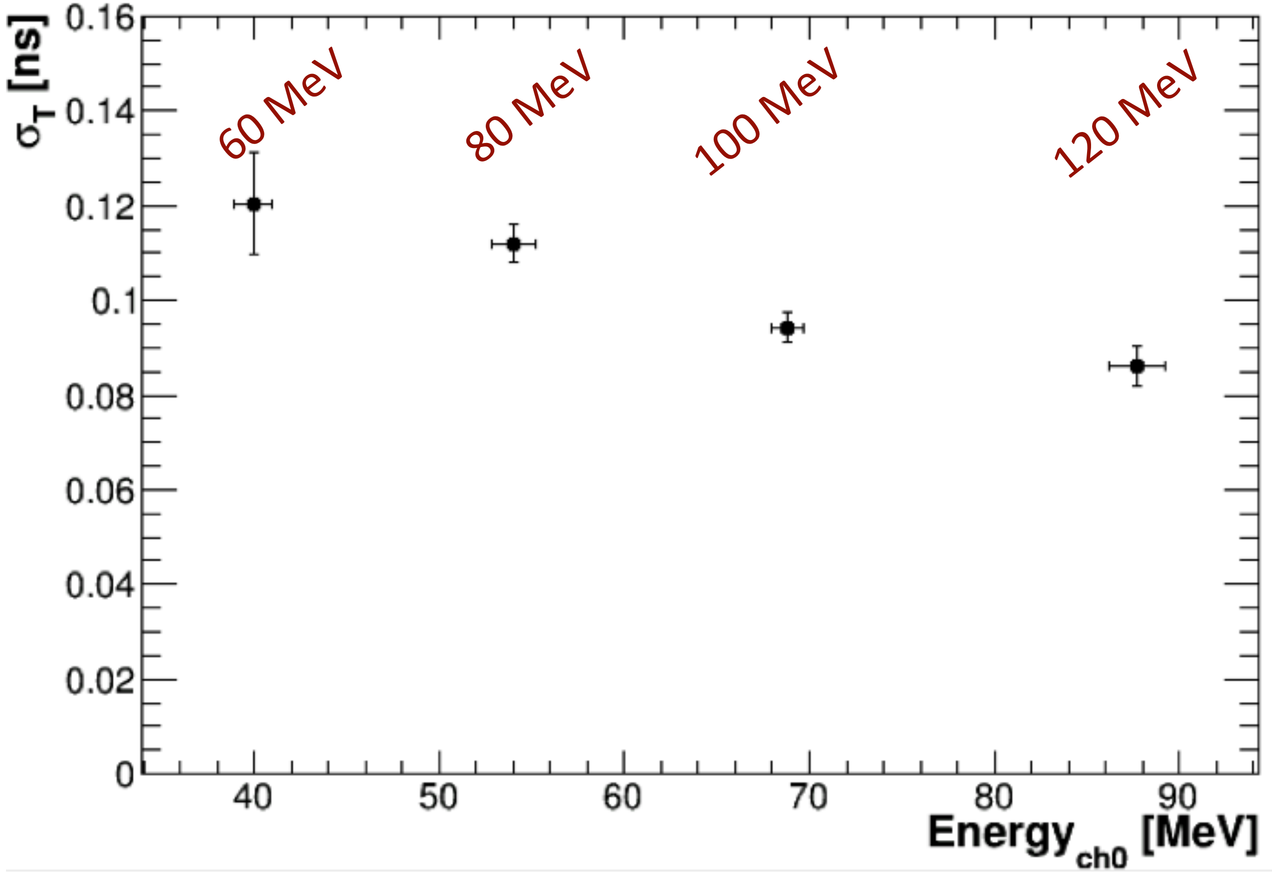


# Module-0: Time Resolution

- Time reconstructed using a fit of the leading edge




Nominal beam energy



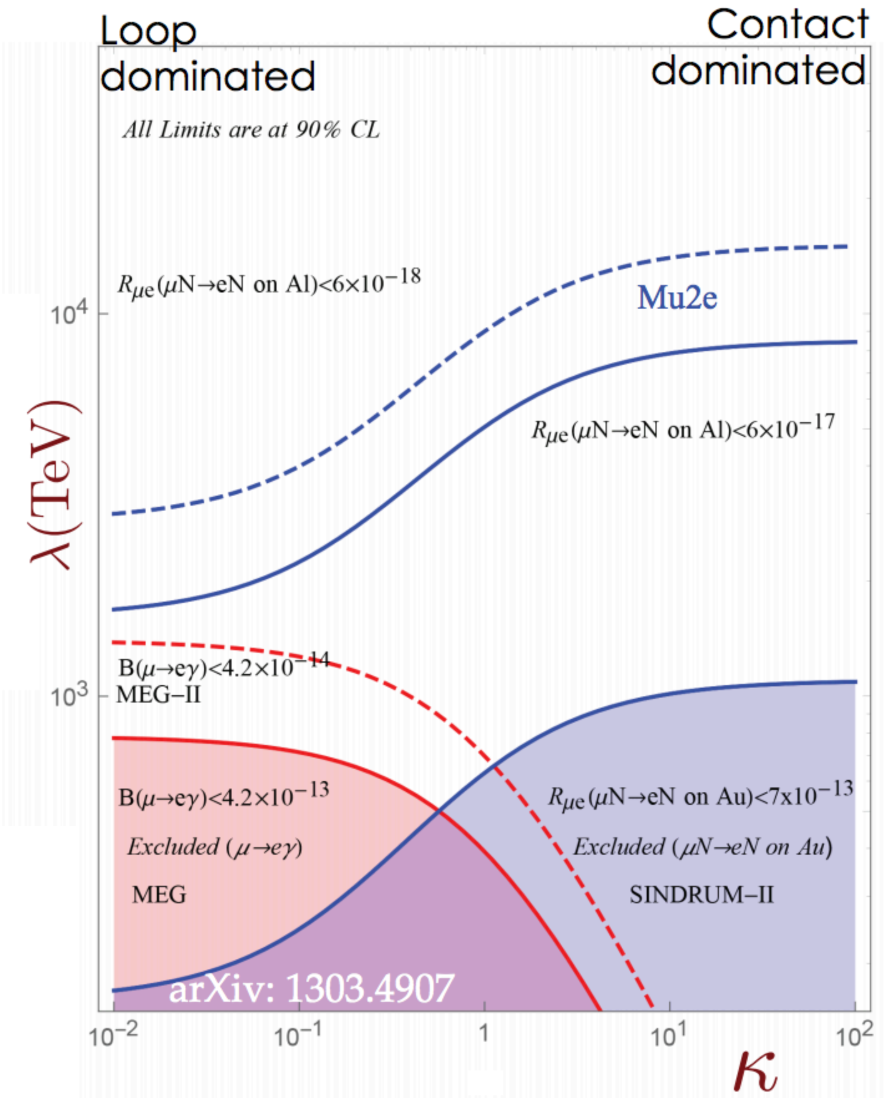

$\Delta T = t_{SiPM1} - t_{SiPM2}$
$\sigma_T \sim 192/2$ ps $\sim 96 \pm 2$ ps
@$E_{beam}$= 100 MeV

# Summary and Conclusions

- **Mu2e calorimeter is a state of the art Crystal Calorimeter with excellent 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(~7%) achieved @ 100 MeV
- Calorimeter production phase will start by the end of 2017
- Detector installation expected for beginning of 2020

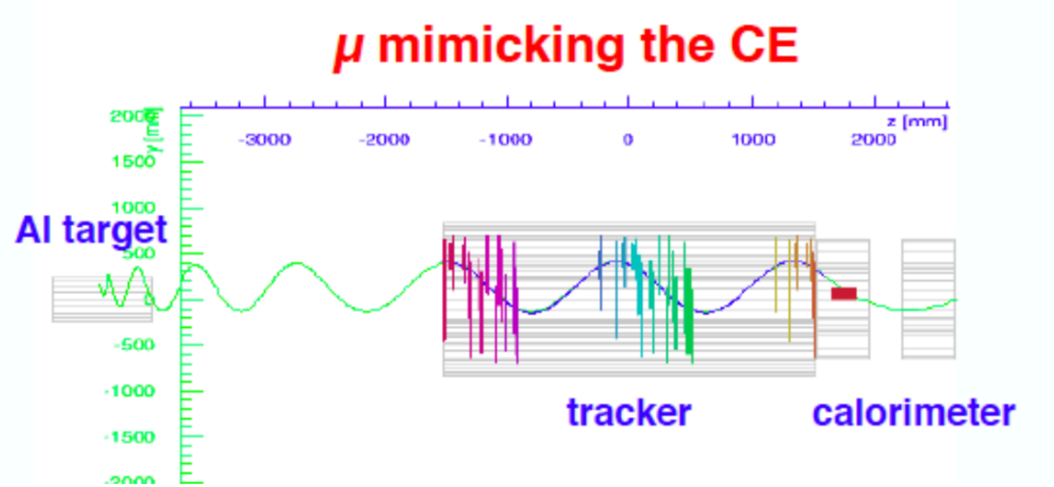
# Charged Lepton Flavor Violation

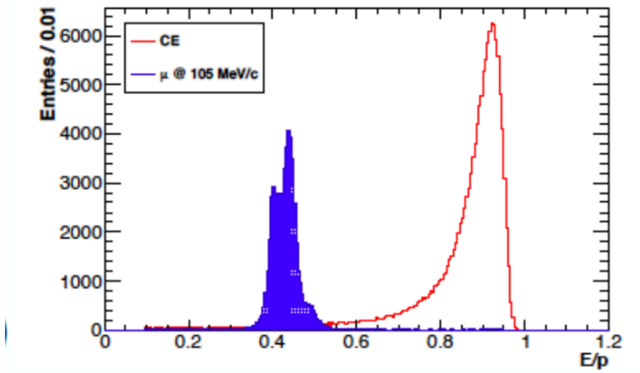
- CLFV strongly suppressed in SM: BR ≤10-54
  - Observation indicates New Physics
- CLFV@Mu2e:μ- e conversion in a nucleus field
  - discovery sensitivity on many NP models

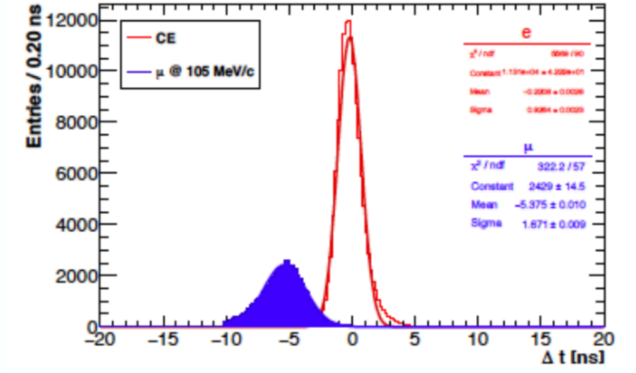


# Particle Identification

- With a CRV inefficiency of $10^{-4}$ an addition 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 muons have $\beta$~0.7 and a kinetic energy of 40 MeV
- Likelihood rejection combines:
  - $\Delta t = t_{track} - t_{cluster}$
  - E/p



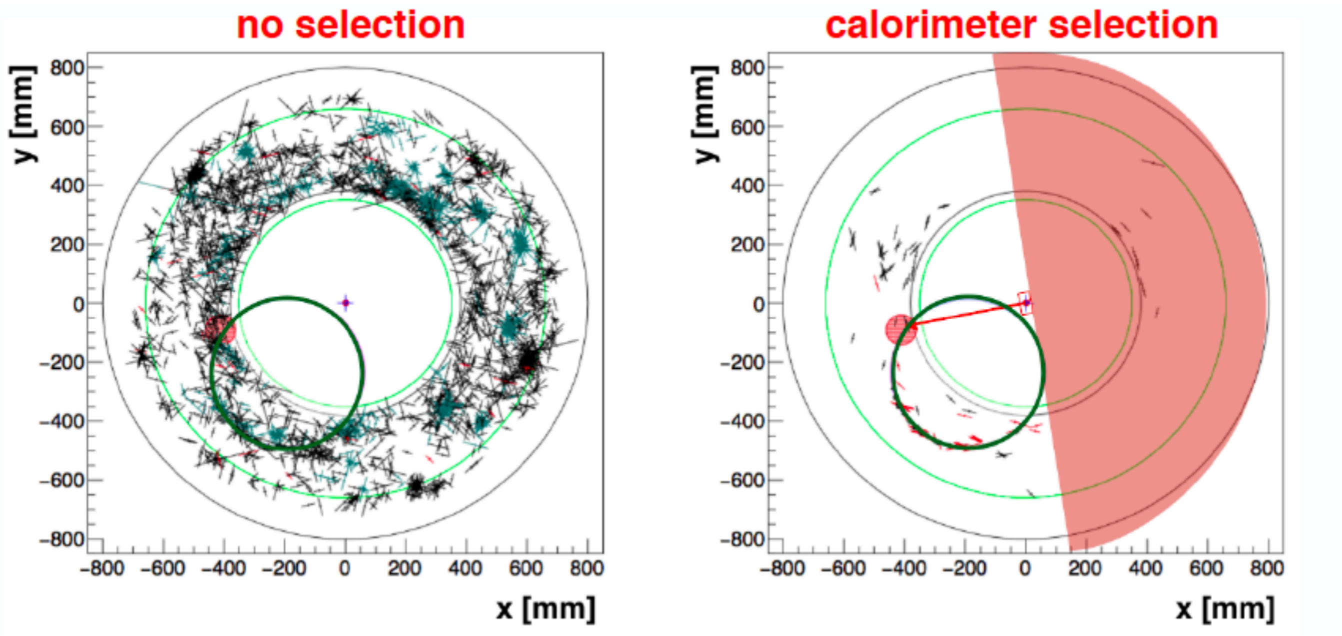




**A rejection factor of 200 cam be achieved with ~95% efficiency for CE**

# Calorimeter seeded track finder

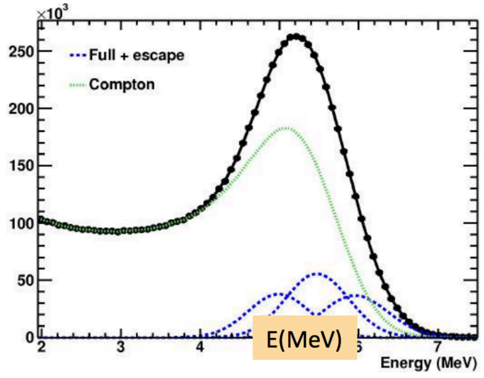
- Cluster time and position are used for filtering the straws hits:
  - Time window of ~80 ns
  - Spatial correlation




- **Black crosses**: straw hits, **red circle**: calorimeter cluster, **green line**: CE track

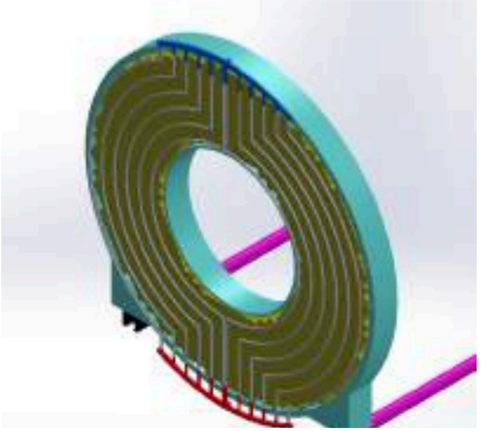
# Calibration and monitoring system

- Neutrons from a DT generator adjacent to the Detector irradiate a fluorine rich fluid (Fluorinert).
- The activated liquid is piped to the front face of the disks.
- Few per mil energy scale in a few minutes.
- Final experiment scale (E/P) is set using DIO's.




Based on BABAR scheme & salvage of their components

→ Salvage of BABAR DT generator done @ Caltech
→ Integration of pump, mechanics and controls done
→ **First tests done in summer 2015**



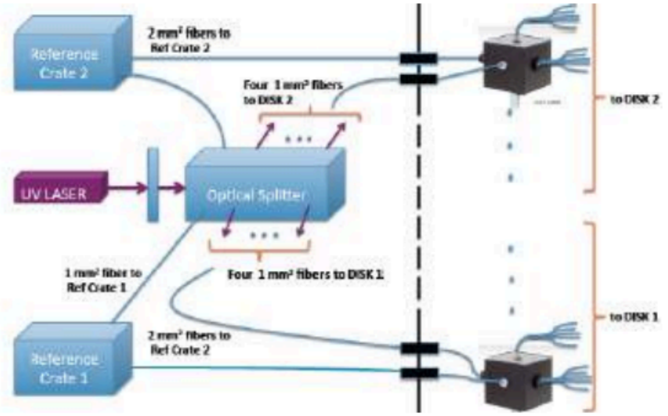
Laser system adapted from CMS calibration system.
UV light to monitor continuously the variation of the APD gain and as the first tool for calibrating the timing offsets

→ Green laser prototype used for LYSO test.

→ Distribution system with Silica optical fibers developed

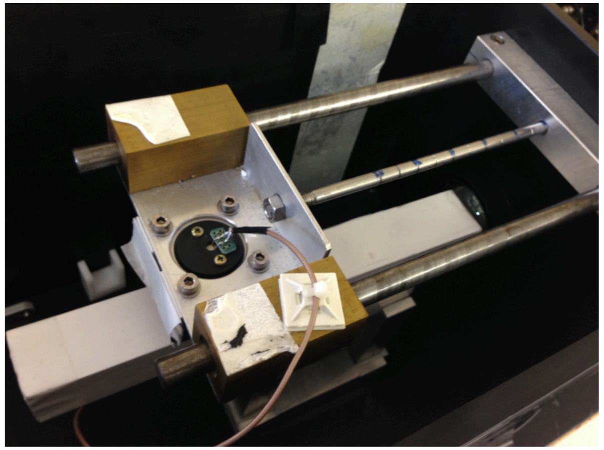
→ Successful

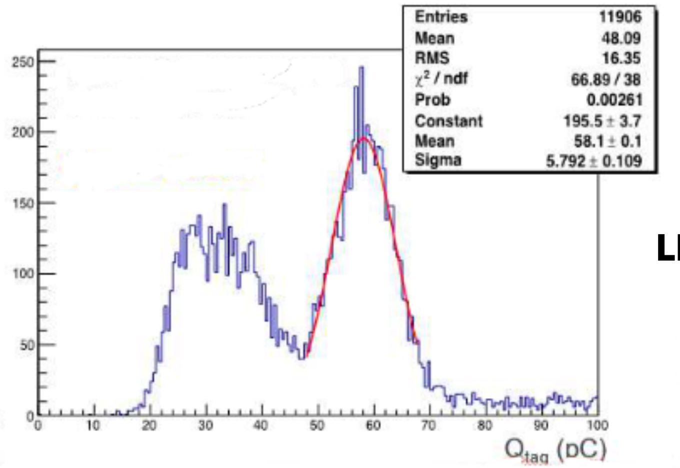
→ **UV laser and monitoring system still to be optimized.**



# Crystal properties : Setup & data clean up

- Low intensity collimated $^{22}$**Na source** emitting back-to-back **511 keV gamma**
- **Tag**: (3×3×10) mm$^3$ LYSO crystal coupled to (3×3) mm$^2$ MPPC
- 2″ UV extended **PMT**
- Crystals wrapped with 150 μm Tyvek (4173D)
- **8 scan points** along the crystal, with 2 cm step

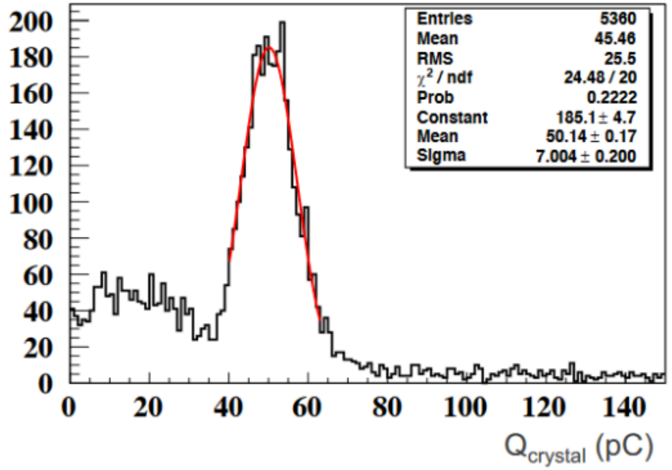





**400 ns gate**

$$LY = \frac{N_{p.e.}}{MeV} = \frac{\mu_Q}{G_{PMT} \times E_\gamma \times q_e}$$

**LRU= RMS value of the eight light output point**

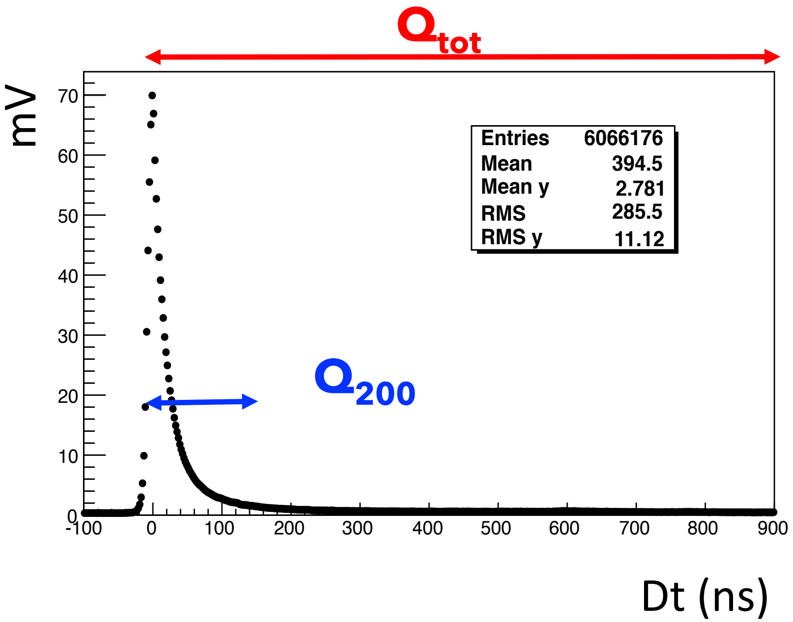


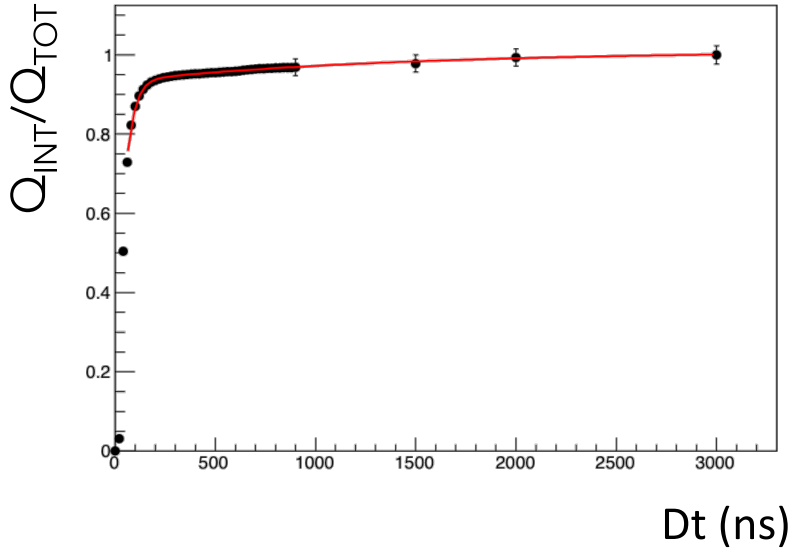

**200 ns gate**

# F/T evaluation

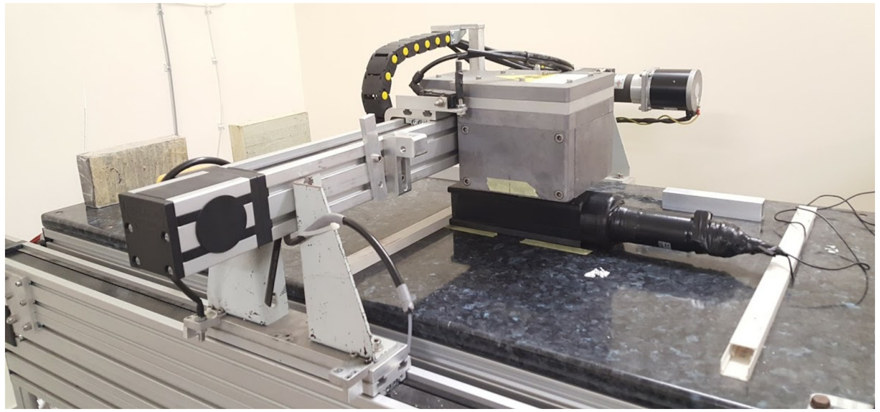
- Study the relative contribution of the CsI fast component
- Plot $Q_{INT}/Q_{TOT}$ vs $DT=T-T_{mean}$, with 20 ns bin width, where:
  - $Q_{INT}$ is the charge integrated from the start of the signal
  - $Q_{TOT}$ is the total integrated charge up to 3000 ns

$$\frac{Q_{INT}}{Q_{TOT}} = P_0 \cdot (1 - e^{-\Delta_t/\tau_1}) + P_2 \cdot (1 - e^{-\Delta_t/\tau_2})$$



# Radiation Induced Noise Measurement



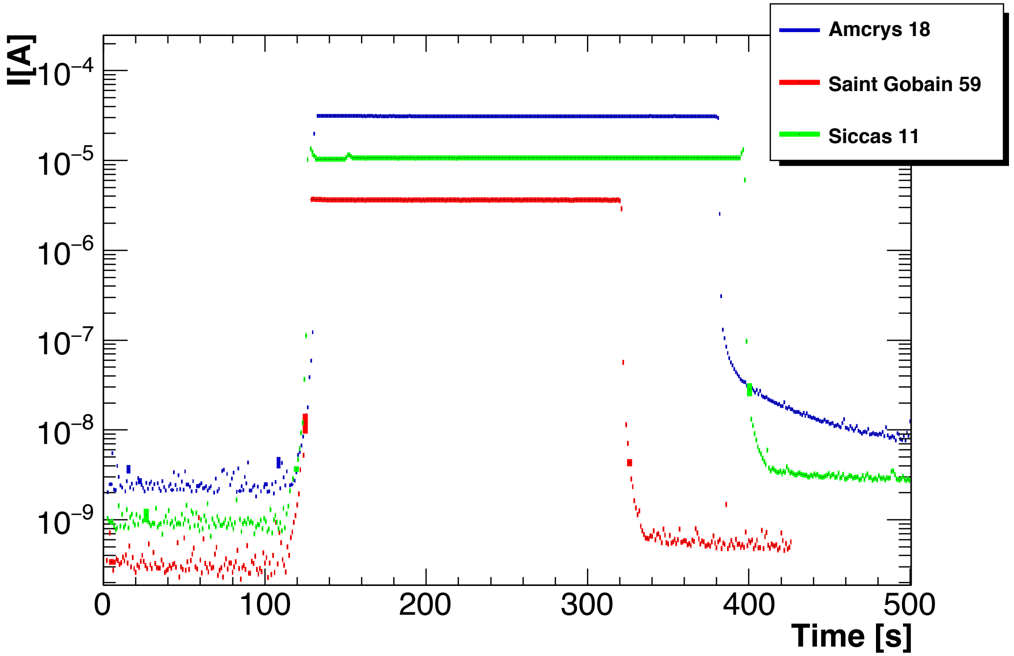
- $^{137}$Cs source→ 0.67 MeV Gamma rays
- Dose rate: $Rate_{g\text{-}ray}$ = 0.24 rad/h
- Mu2e dose rate~1.8rad/h
- Integration range: 200 ns

$$F = \frac{\frac{I_{PMT}}{e \times G_{PMT}}}{\Phi_n}$$

$$N_{p.e.} = F \times \Phi_{Mu2e} \times \Delta t$$

$$RIN = \frac{\sqrt{N_{pe}}}{LY}$$

| Vendor | RIN mean value |
|---|---|
| Amcrys | 0.60 |
| Saint Gobain | 0.21 |
| Siccas | 0.27 |



# Target material choise

- Determining Z dependence is very important
- Lifetime is *shorter*  for high Z -> Decrease useful time window
- Avoid bg from radiative muon capture

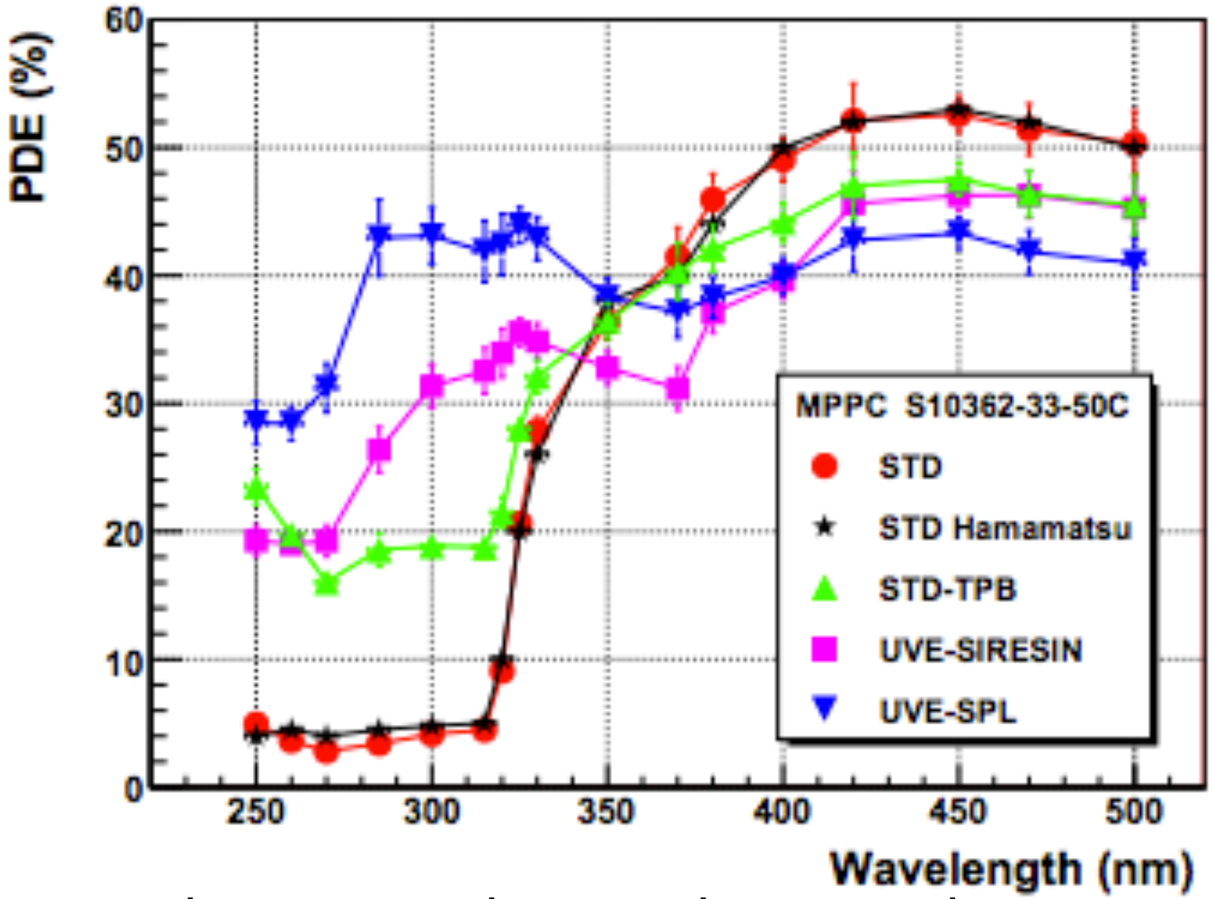
⇒Aluminum is nominal choice for Mu2e

| Nucleus | $R_{\mu e}(Z)$ / $R_{\mu e}(Al)$ | Bound lifetime | Atomic Bind. Energy(1s) | Conversion Electron Energy | Prob decay >700 ns |
|---|---|---|---|---|---|
| Al(13,27) | 1.0 | .88 μs | 0.47 MeV | 104.97 MeV | 0.45 |
| Ti(22,~48) | 1.7 | .328 μs | 1.36 MeV | 104.18 MeV | 0.16 |
| Au(79,~197) | ~0.8-1.5 | .0726 μs | 10.08 MeV | 95.56  MeV | negligible |

# Crystal choise

| Crystal | $BaF_2$ | LYSO | CsI | $PbWO_4$ |
|---|---|---|---|---|
| Density ($g/cm^3$) | 4.89 | 7.28 | 4.51 | 8.28 |
| Radiation length (cm) $X_0$ | 2.03 | 1.14 | 1.86 | 0.9 |
| Molière radius (cm) Rm | 3.10 | 2.07 | 3.57 | 2.0 |
| Interaction length (cm) | 30.7 | 20.9 | 39.3 | 20.7 |
| $dE/dx$ (MeV/cm) | 6.5 | 10.0 | 5.56 | 13.0 |
| Refractive Index at $\lambda_{max}$ | 1.50 | 1.82 | 1.95 | 2.20 |
| Peak luminescence (nm) | 220, 300 | 402 | 310 | 420 |
| Decay time $\tau$ (ns) | 0.9, 650 | 40 | 26 | 30, 10 |
| Light yield (compared to NaI(Tl)) (%) | 4.1, 36 | 85 | 3.6 | 0.3, 0.1 |
| Light yield variation with temperature (% / °C) | 0.1, -1.9 | -0.2 | -1.4 | -2.5 |
| Hygroscopicity | None | None | Slight | None |

# UV-extended SiPMs




Particular coating deposited to enhance the PDE in the UV region