

The Mu2e crystal calorimeter

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on behalf of the Mu2e calorimeter group



July 7, 2018
XXXIX INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS



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

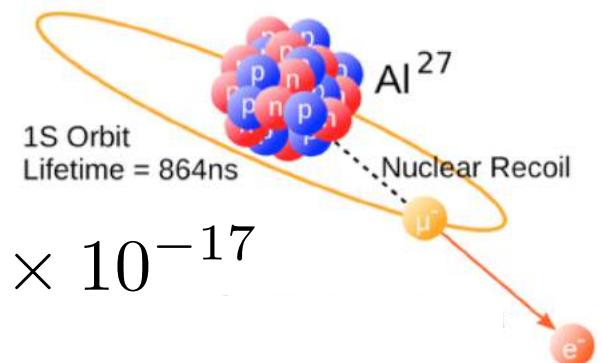
- CLFV processes are forbidden in SM
 - Even allowing neutrino oscillation BR $\sim 10^{-54}$
- **Observation of a CLFV process: clear evidence of New Physics**
- Mu2e : Coherent muon conversion in the electric field of a nucleus
 - Broad sensitivity across different models
 - Very clear signature: **monoenergetic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

μ -e conversion in the field of a nucleus

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

Nuclear capture of muonic Al atom

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



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

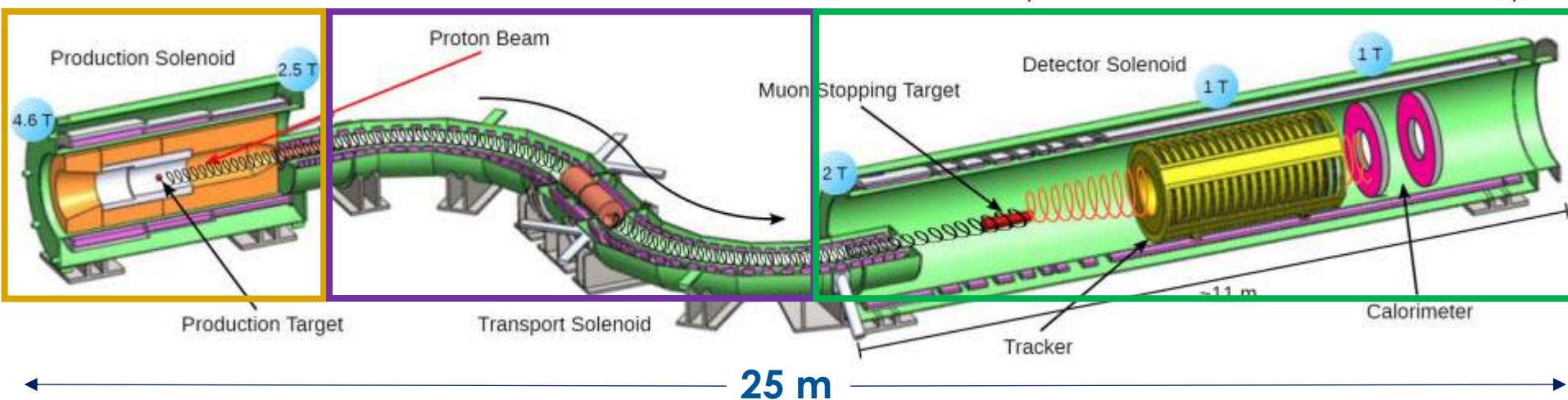
The Mu2e experiment

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 requirements

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

- **Particle Identification: e/ μ separation \rightarrow 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

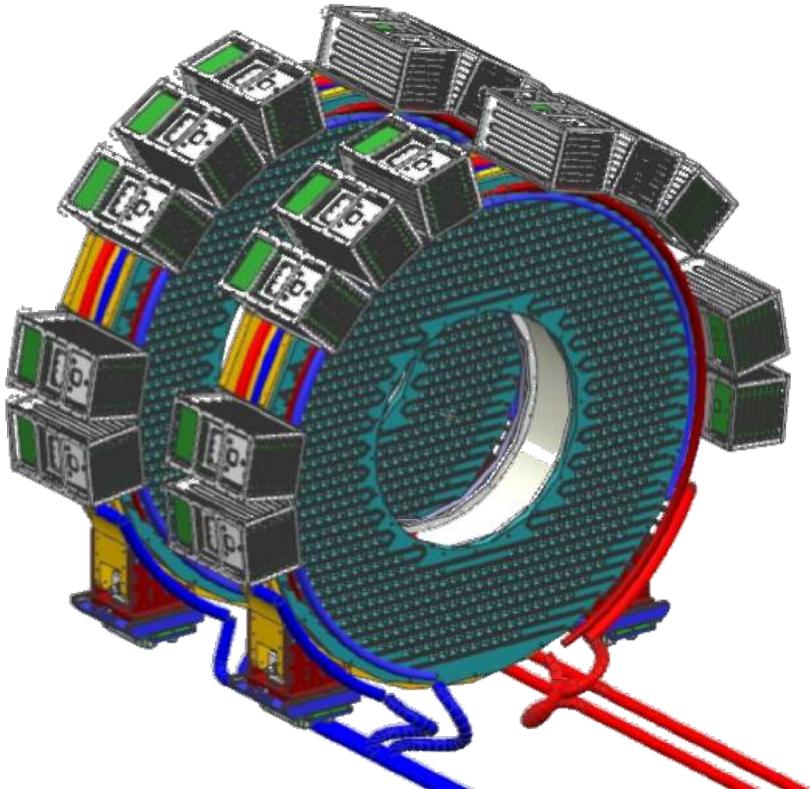


Crystals coupled with Silicon Photomultipliers(SiPM)

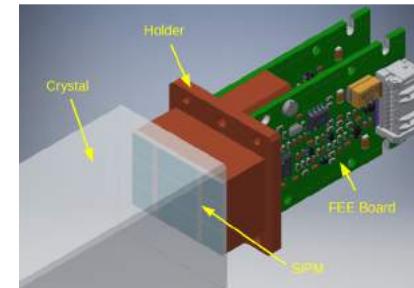
- Light Yield(photosensor)>20 pe/MeV
- Fast signal for pileup and timing
- **Survive an high radiation environment**
 - Total Ionizing Dose (TID) of 90 krad/5 year for crystal
 - TID of 75 krad/5 year for sensor
 - 3×10^{12} n/cm² for crystal
 - 1.2×10^{12} n/cm² for sensor

Calorimeter Design

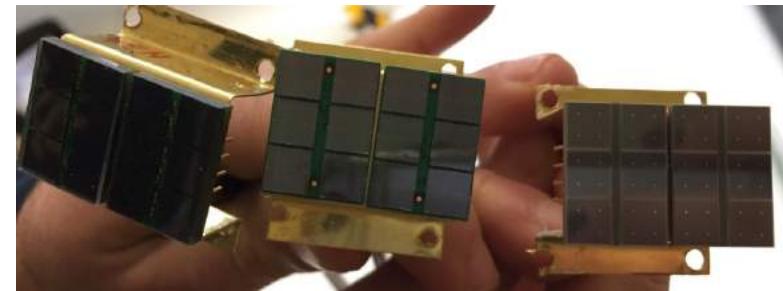
2 disks each with 674 undoped (34x34x200)mm³ square pure CsI crystals



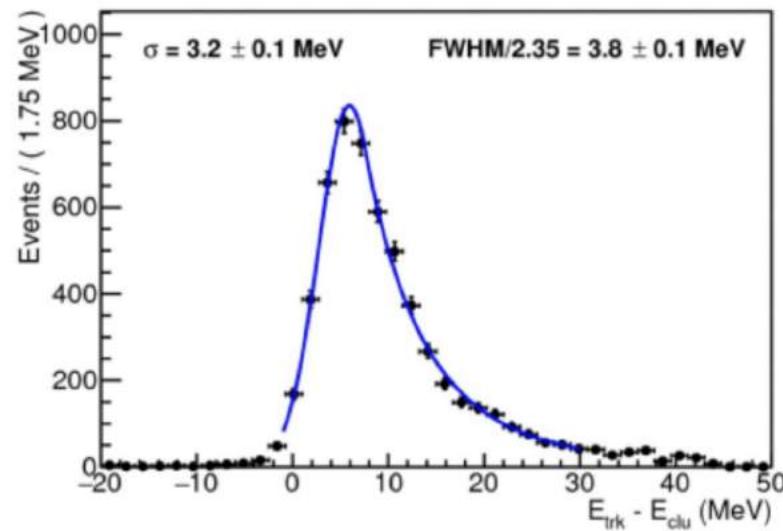
- Readout: 2 UV-extended SiPMs/crystal



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



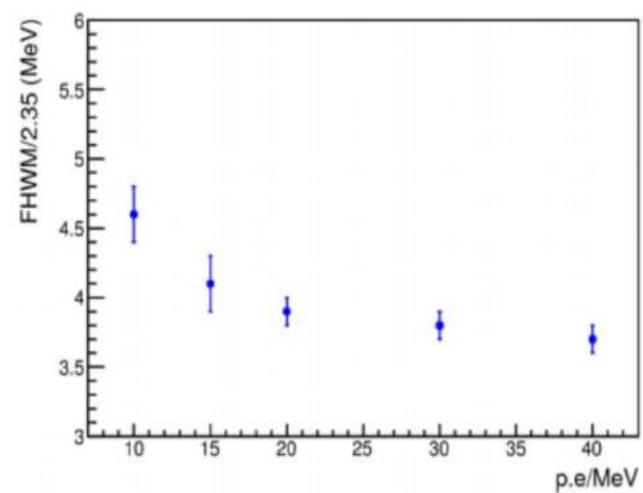
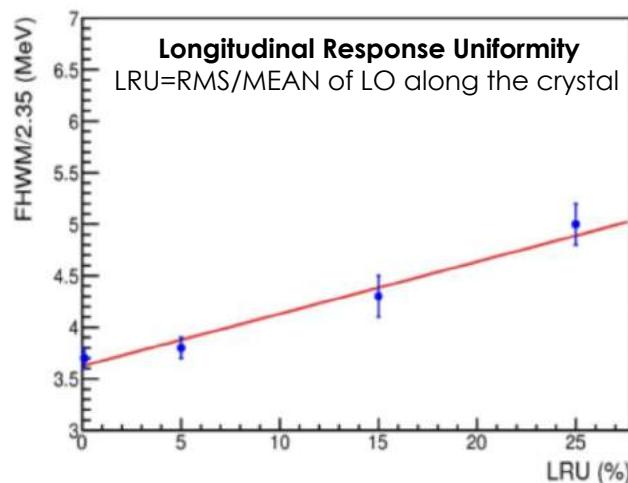
Mu2e EMC: MC performance



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.

$$\text{FWHM}/2.35 = 3.8 \pm 0.1 \text{ MeV}$$

The overall resolution depends on the crystal features

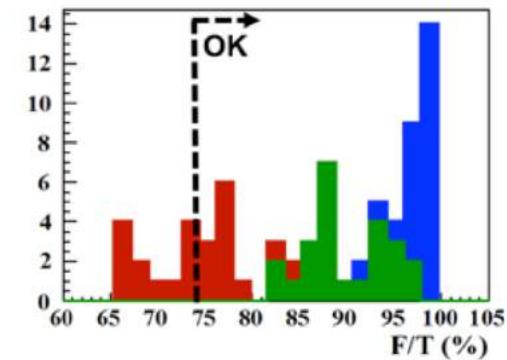
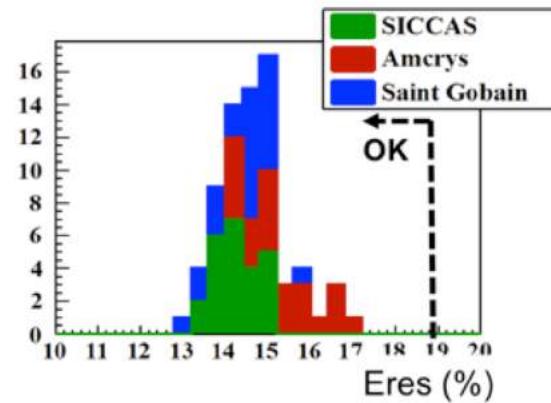
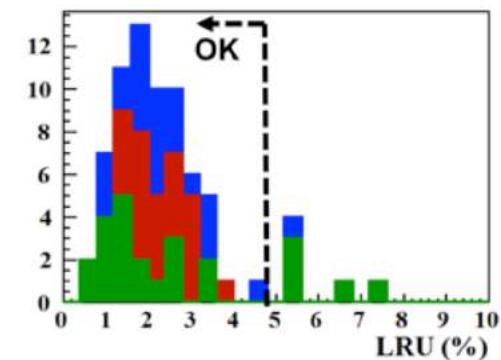
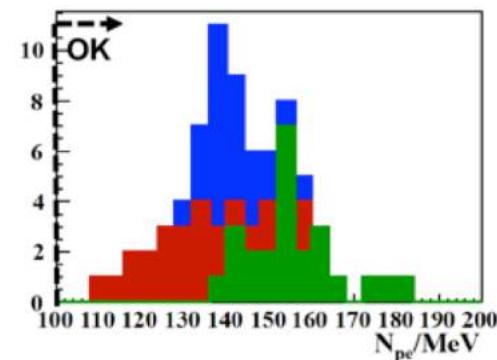


Crystal preproduction

- 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:**

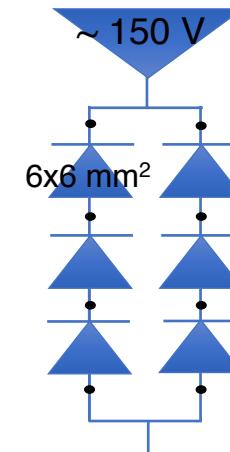
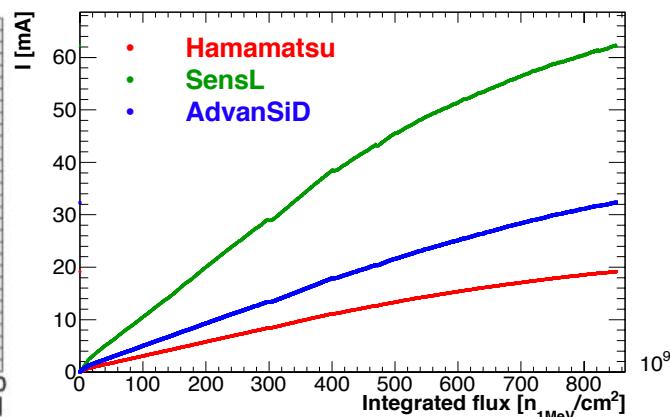
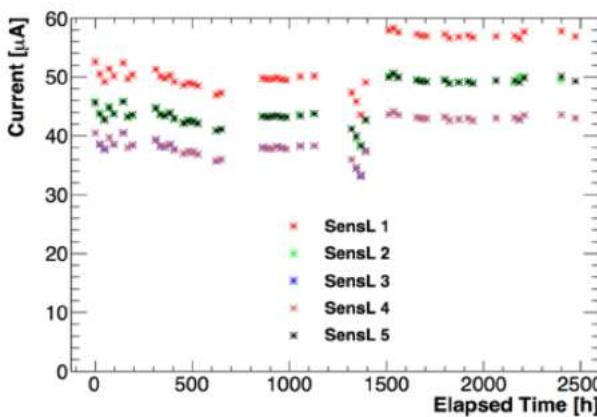
- 100 pe/MeV with PMT readout
- LRU < 5%
- Fast/Total>75%



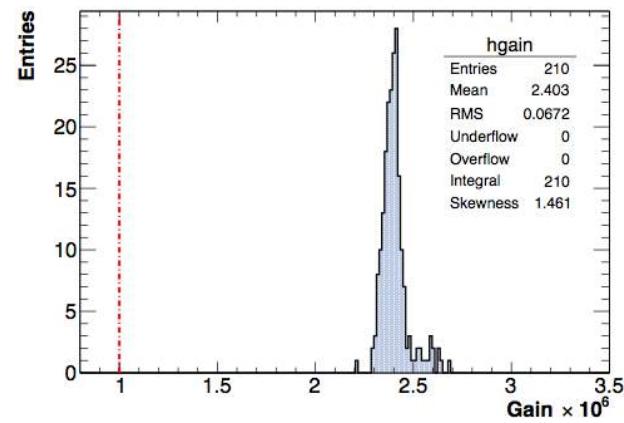
Selected vendors:
SICCAS and Saint Gobain

SiPM preproduction

- 2 arrays of three $6 \times 6 \text{ mm}^2$ SiPMs
 - total active area of $(12 \times 18) \text{ mm}^2$
 - $50 \mu\text{m}$ pitch
- Photon Detection Efficiency (@ 315 nm) $> 20\%$
- The series configuration \rightarrow narrower signals
- **150 Pre-production SiPMs** (3×50 Mu2e SiPMs from **Hamamatsu**, **SensL** and **AdvanSiD**):
 - $3 \times 35 \times 6$ cells fully characterized (V_{op} , G , I_{dark} , PDE)
 - 1 sample/vendor exposed up to a fluence of $8.5 \times 10^{11} \text{ n}_{1\text{MeVeq}}/\text{cm}^2$ (@ 20 °C)
 - Mean Time To Failure estimated by operating 15 SiPM at 50 °C for 3.5 months \rightarrow MTTF $> 0.6 \times 10^6 \text{ h}$

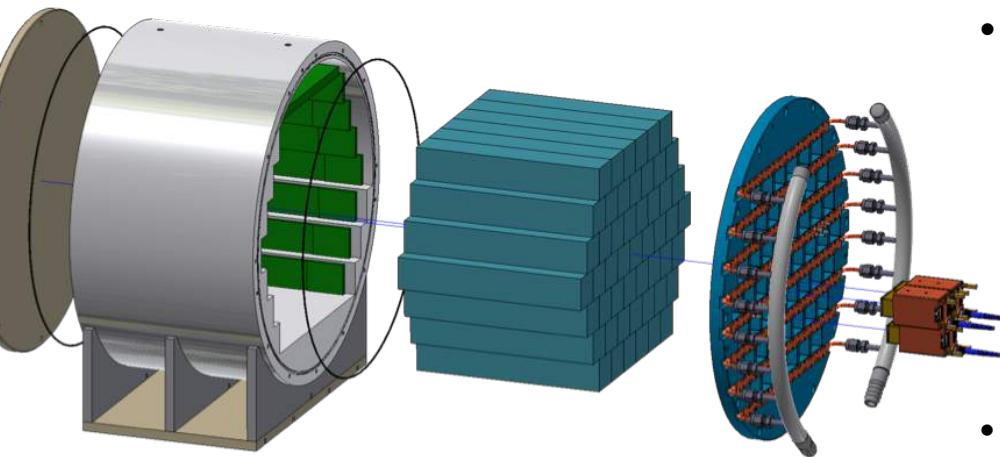


Selected vendor:
Hamamatsu

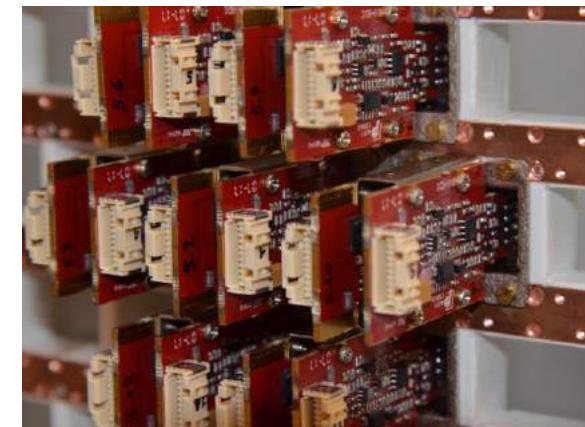


Module-0

Large size prototype: 51 crystals coupled to 102 sensors



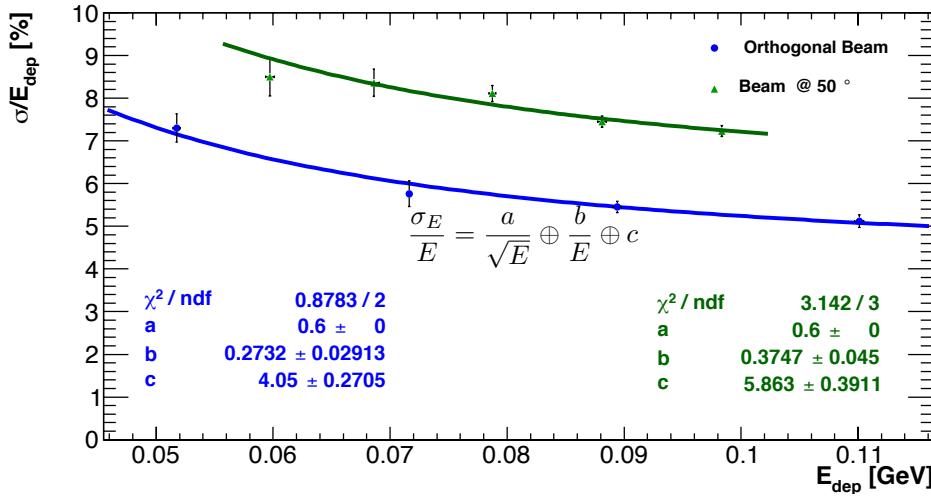
- Goals:
 - Test the performances
 - Test integration and assembly procedures
 - e^- beam (60-120 MeV), May 2017
 - **Orthogonal and 50° incidence (CE)**
 - Operate under vacuum, low temperature and irradiation tests
- Readout: 1 GHz CAEN digitizers (DRS4 chip), 2 boards x 32 channels



Module-0: Energy resolution

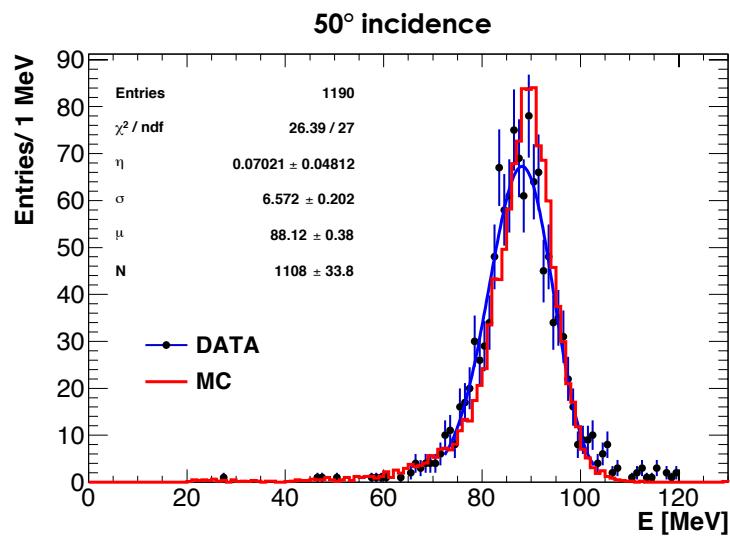
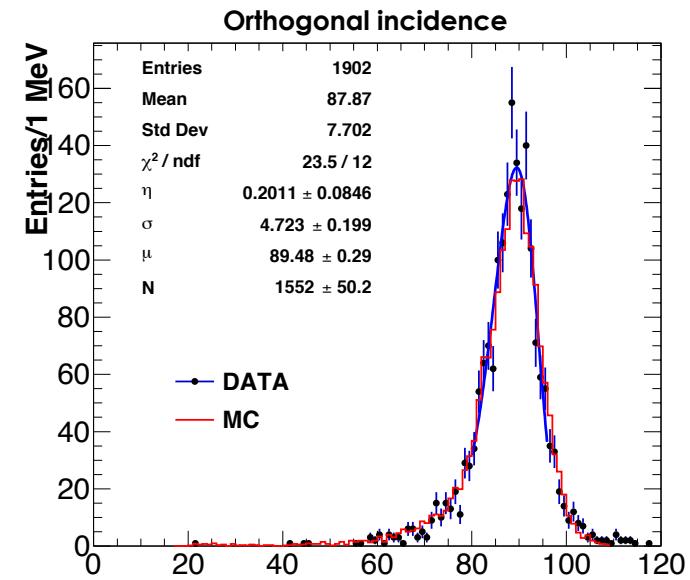
- Single particle selection
- Calibration:
 - Cosmic
 - Beam

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



07/07/2018

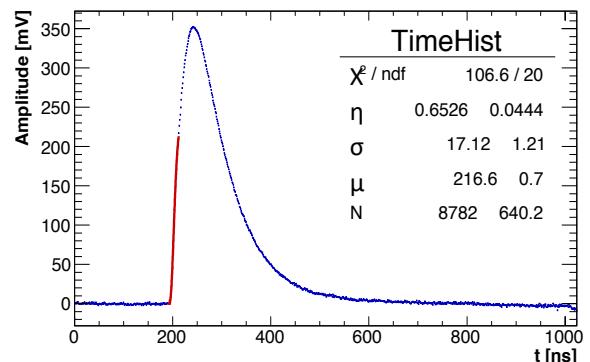
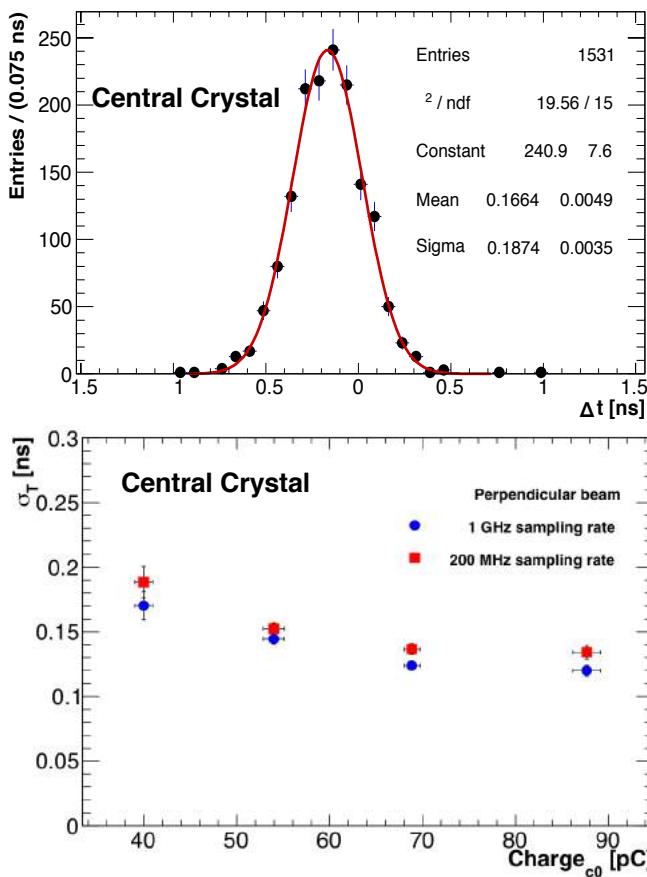
E. Diociaiuti | LNF-INFN



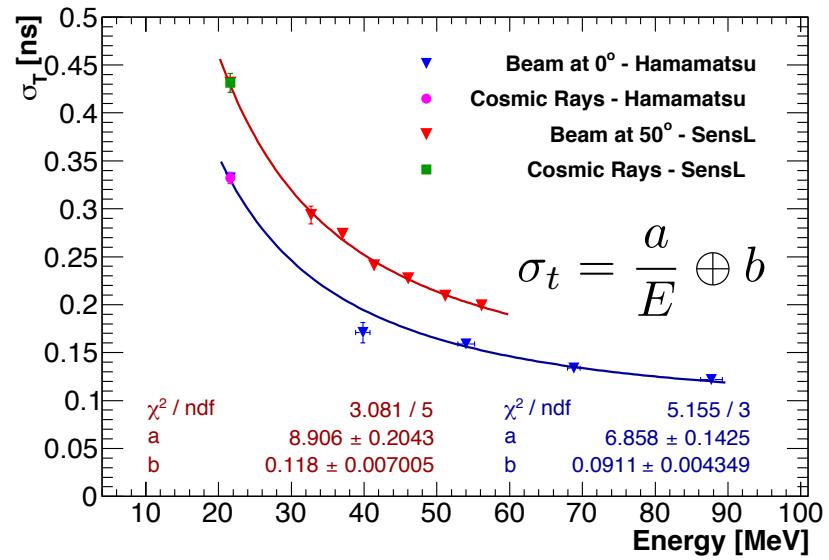
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Module-0: Single Sensor Time resolution

- 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



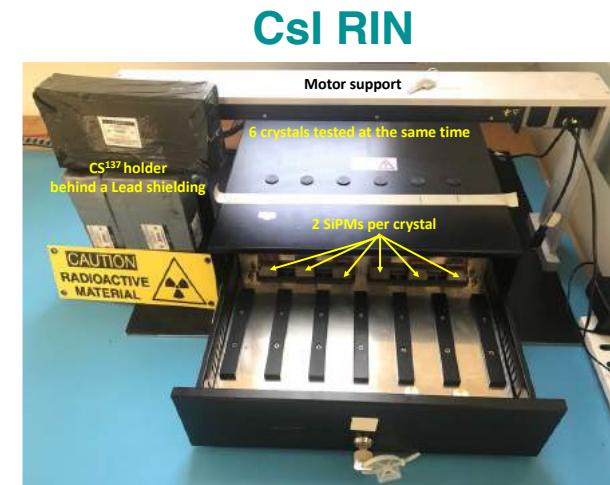
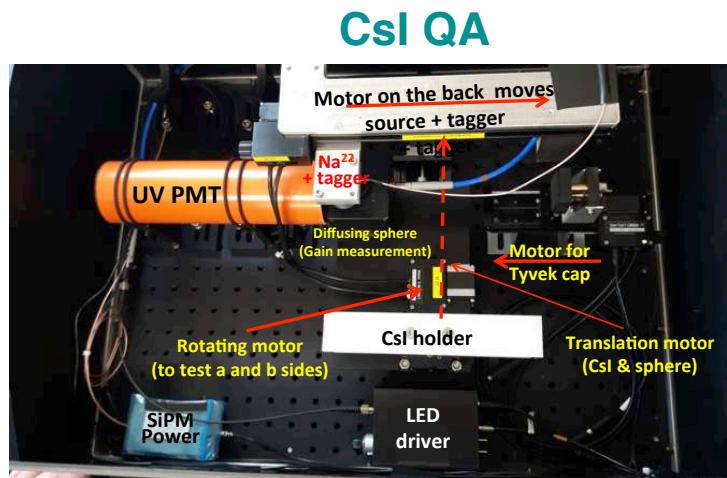
$\sigma (T_1 + T_2)/\sqrt{2} \sim 132 \text{ ps}$
@ $E_{\text{beam}} = 100 \text{ MeV}$



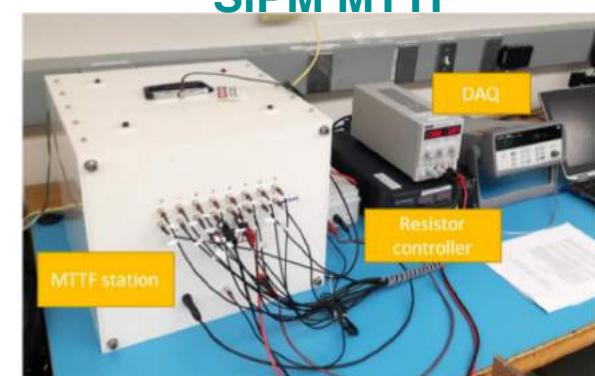
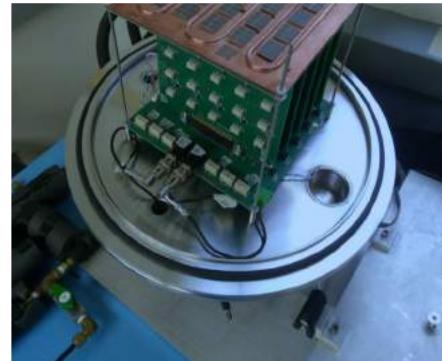
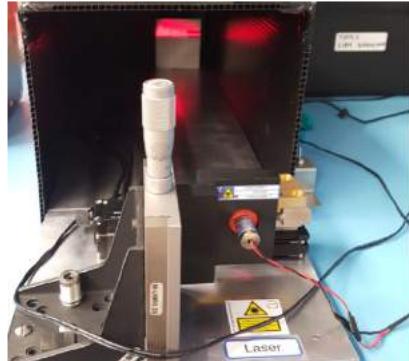
QA room @ FNAL for production

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

CsI dimensional test

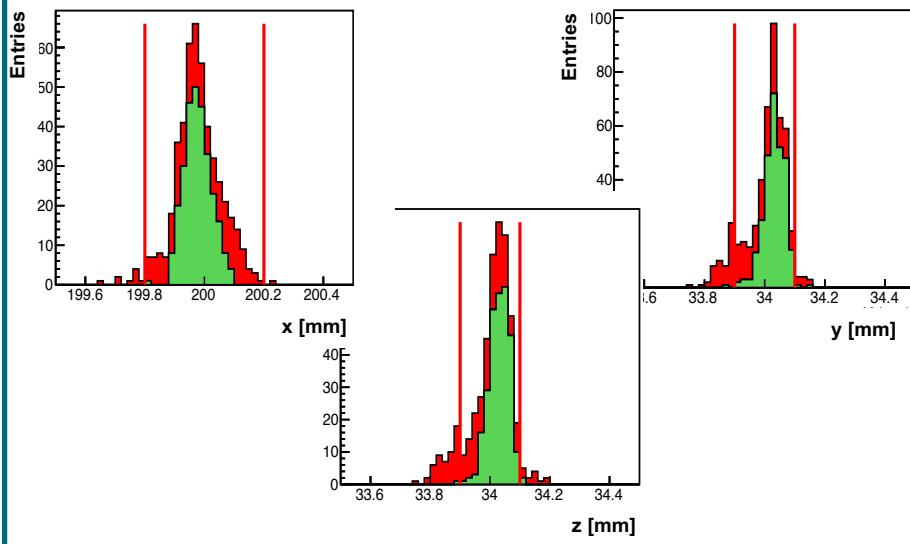


SiPM dimensional test

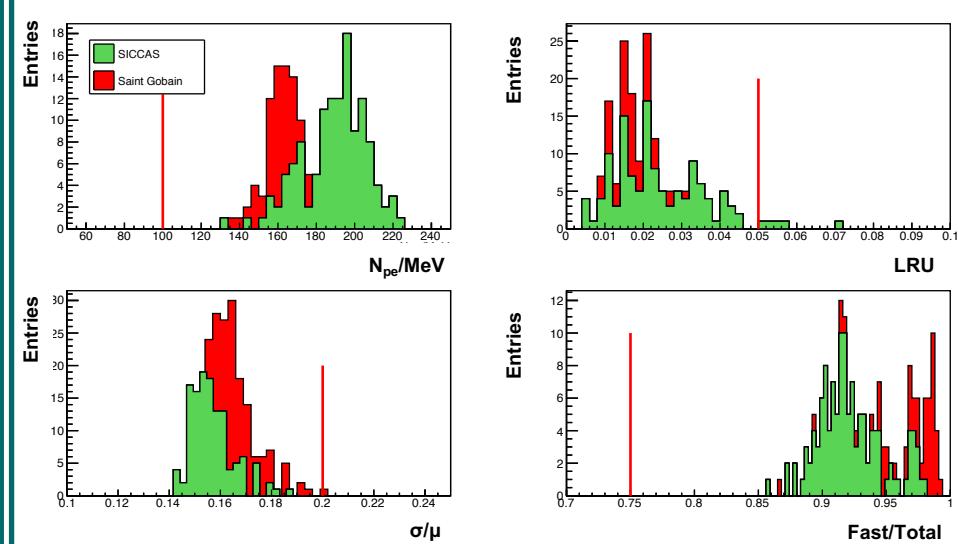


First QA results - Crystal

Dimensional test

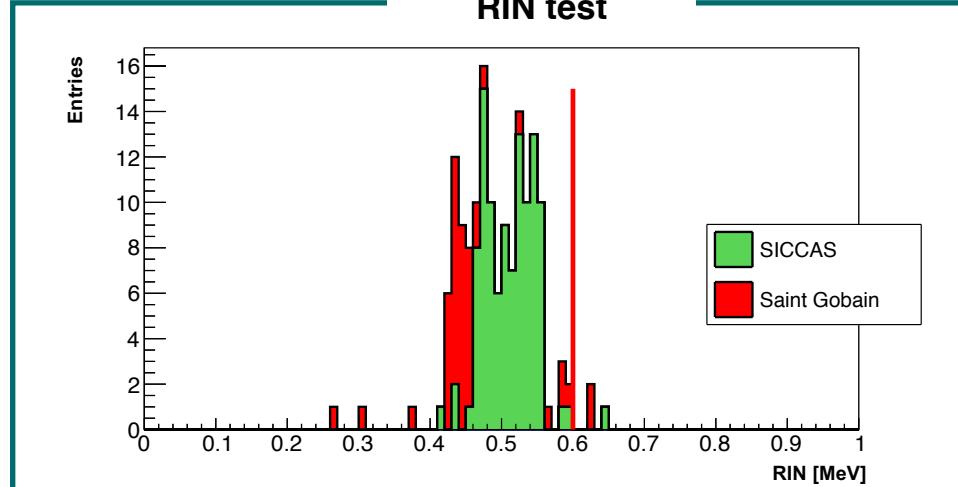


Optical test

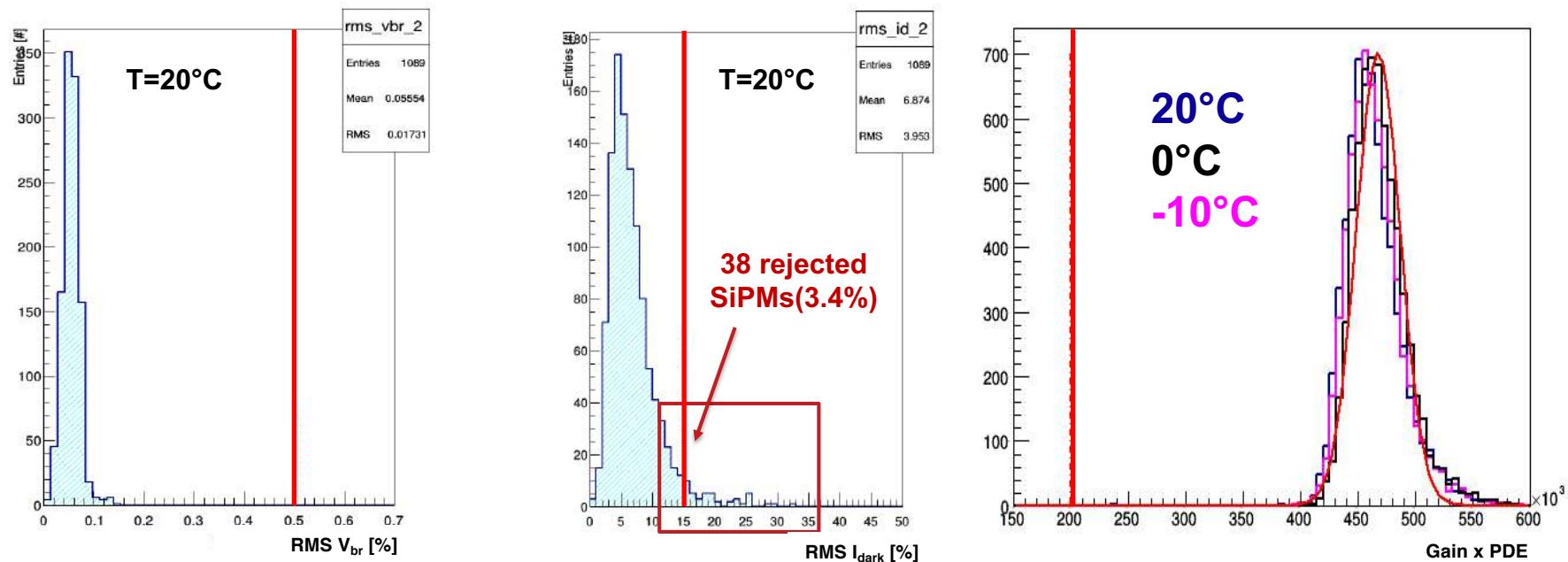


- 99% of crystals satisfy the specifications concerning optical properties
- Some problems to satisfy the mechanical specs

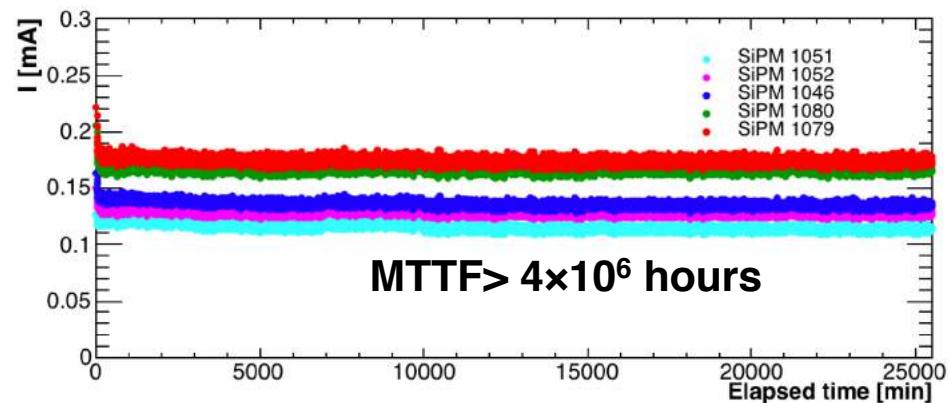
RIN test



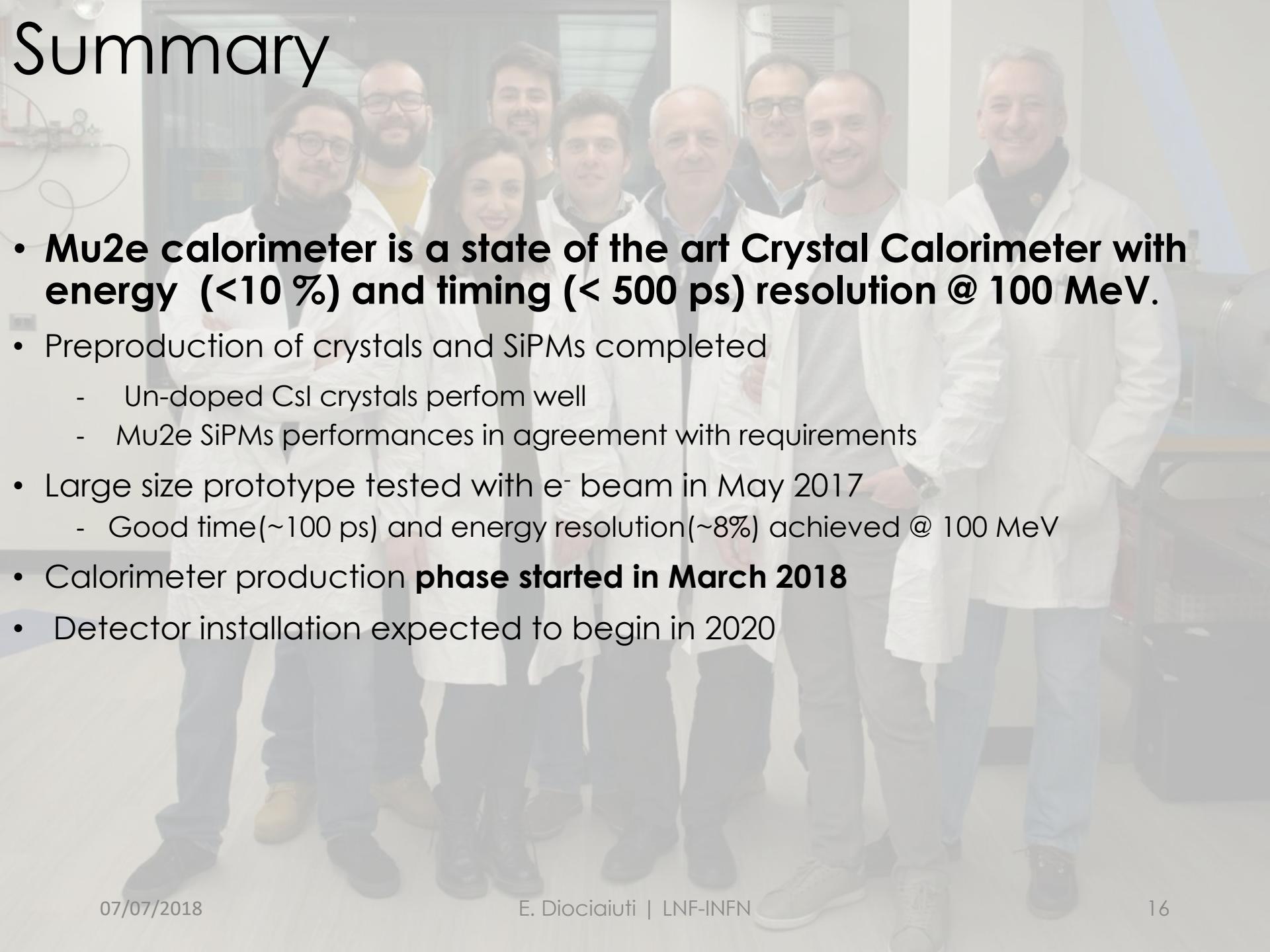
First QA results -SiPMs



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

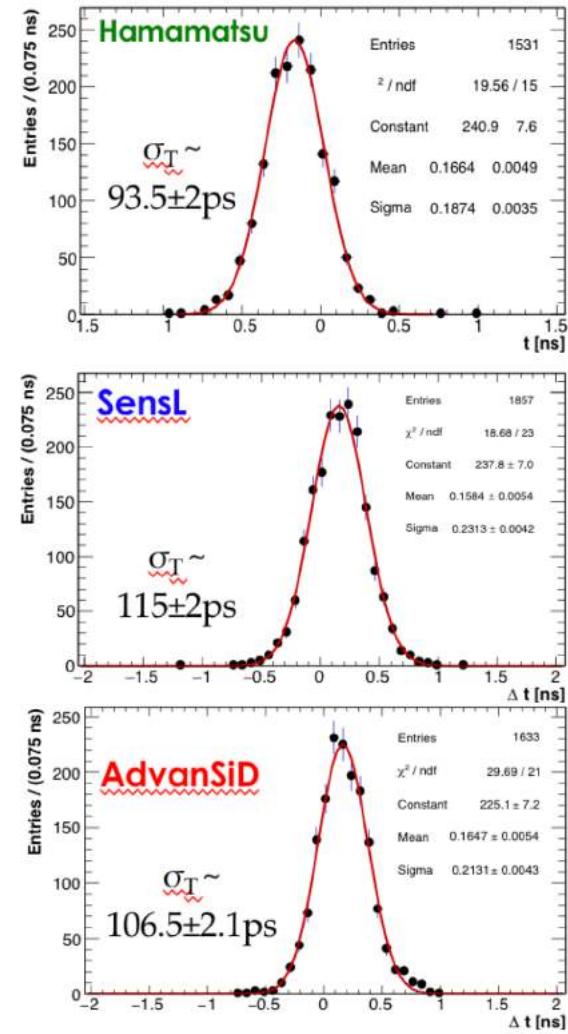
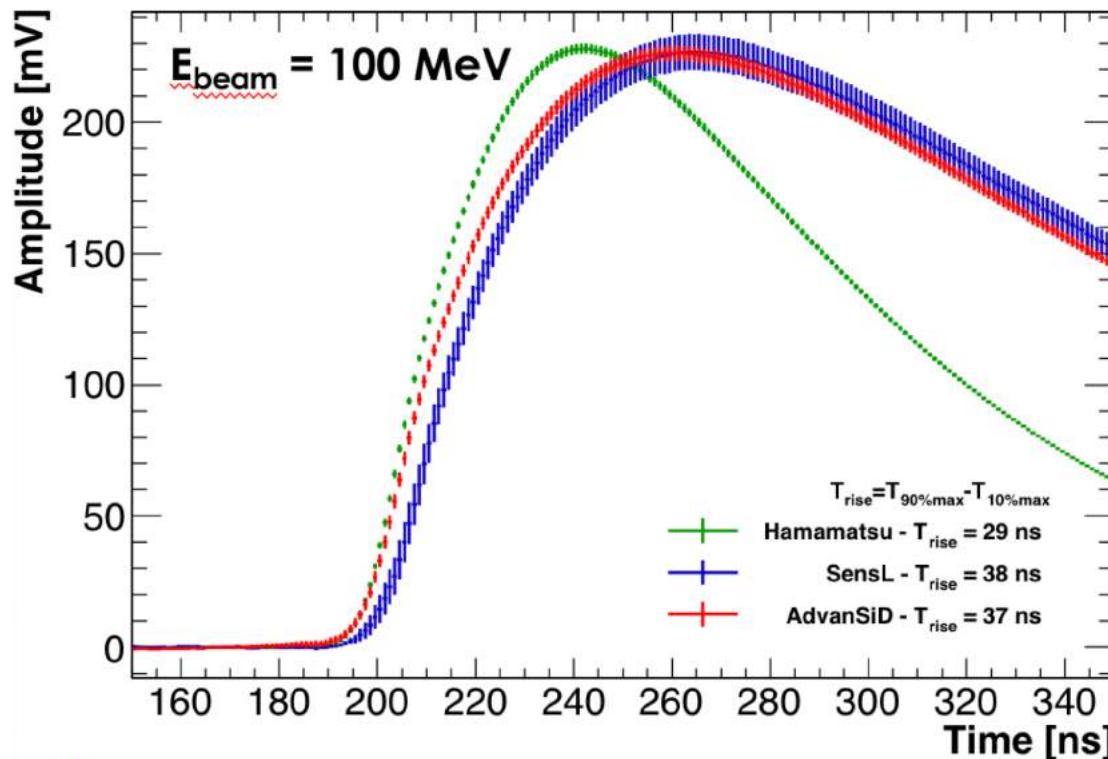


Summary

- 
- A group of nine people in white lab coats are standing together in a laboratory setting. They are all smiling and appear to be scientists or engineers. The background shows various pieces of scientific equipment and piping.
- **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 perform 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

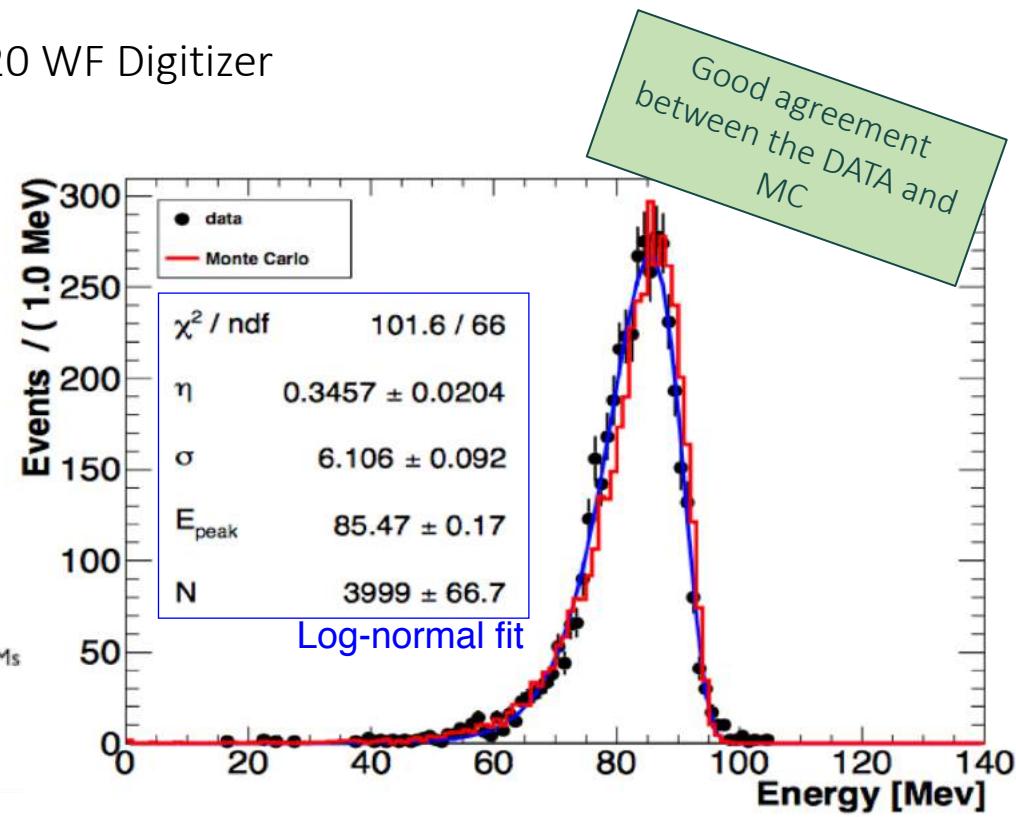
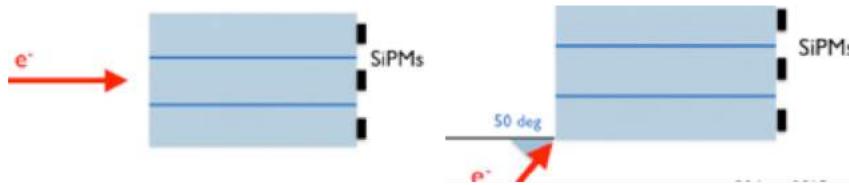
Vendor Comparison -time



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 mm² undoped CsI crystals coupled to one Hamamatsu SiPM array (12x12) mm² with Silicon optical grease
- DAQ readout: 250 Msps CAEN V1720 WF Digitizer

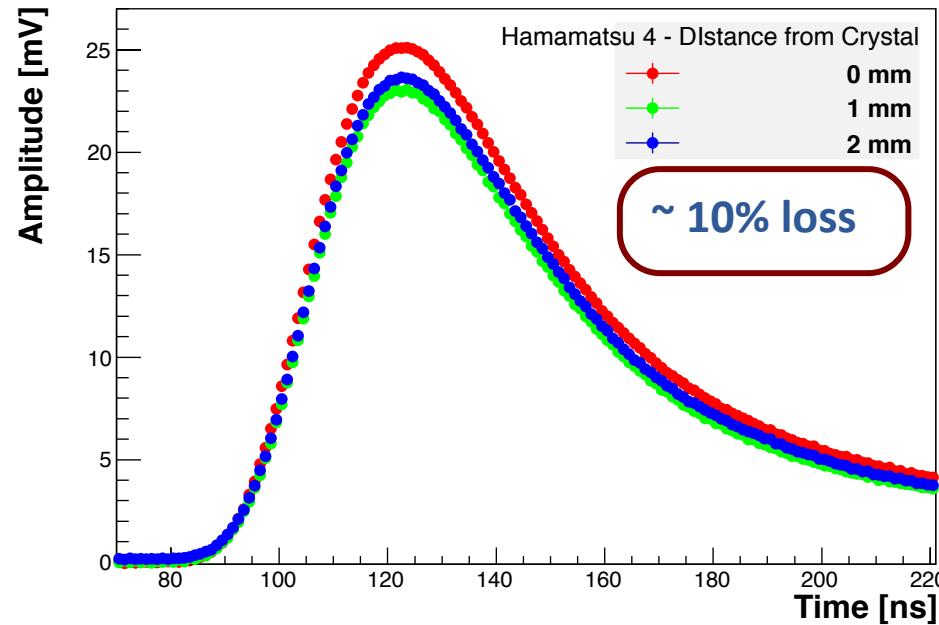


Single channel slice test

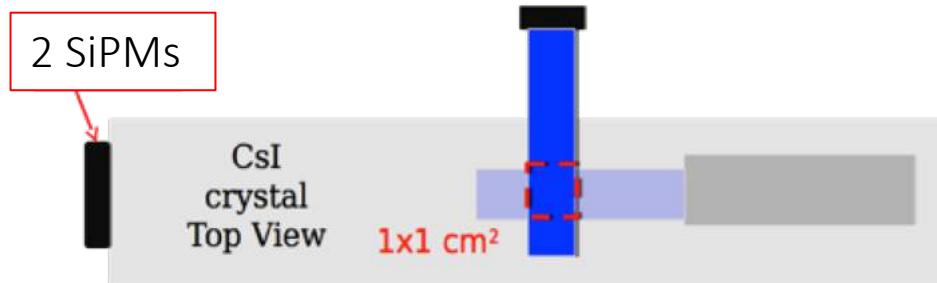
SG crystal + Hamamatsu SiPM + FEE

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:

$$\text{SiPM 1} - \sigma_T \sim 330 \text{ ps}$$

$$\text{SiPM 2} - \sigma_T \sim 340 \text{ ps}$$

$$T(\text{SiPM1} - \text{SiPM2})/2 \rightarrow \sim 215 \text{ ps}$$

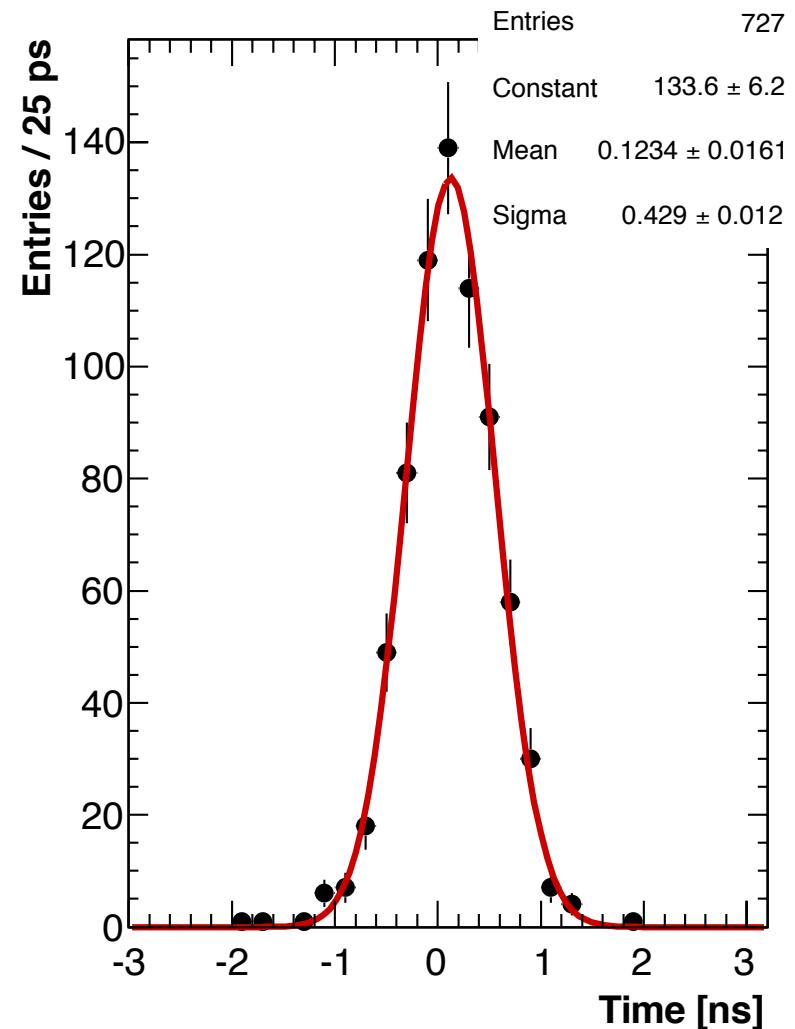
@ ~ 23 MeV energy deposition

(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).

SiPM 1 - SiPM 2

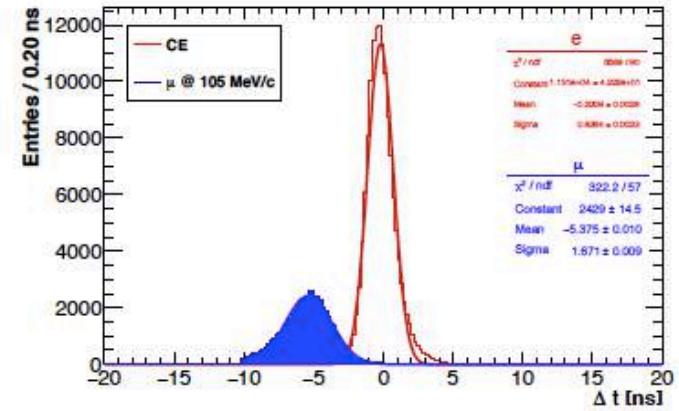
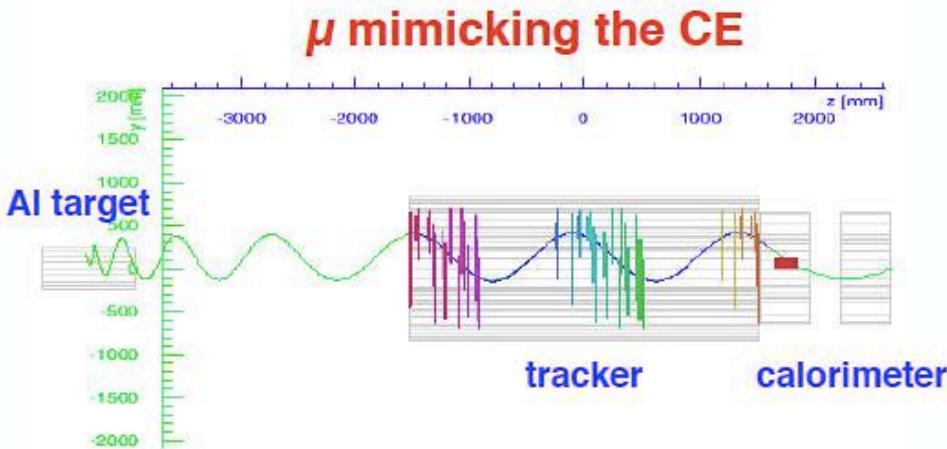
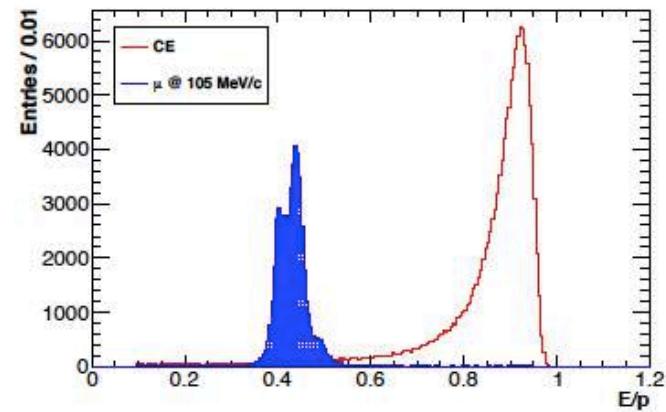


Particle Identification

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 $\beta \sim 0.7$ and a kinetic energy of ~ 40 MeV
- Likelihood rejection combines $\Delta t = t_{\text{track}} - t_{\text{cluster}}$ and E/p :

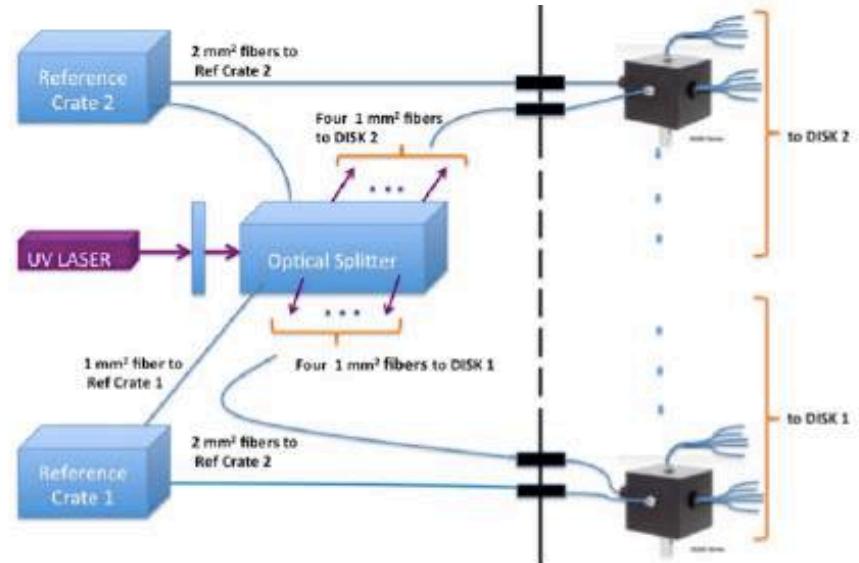
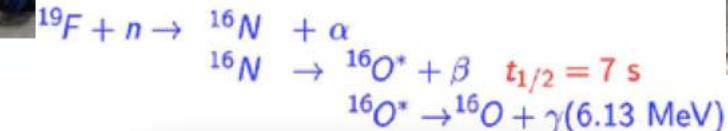
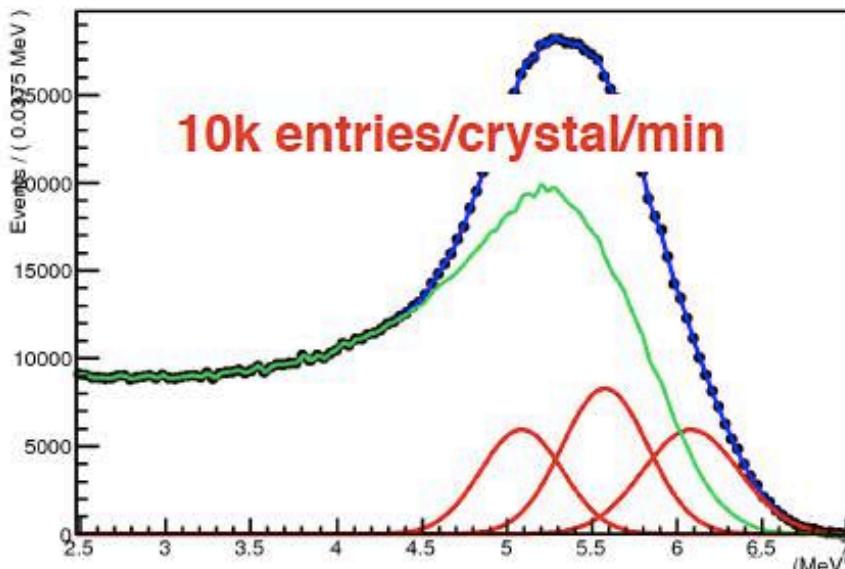
$$\ln L_{e,\mu} = \ln P_{e,\mu}(\Delta t) + \ln P_{e,\mu}(E/p)$$



A rejection factor of 200 can be achieved with $\sim 95\%$ efficiency for CE

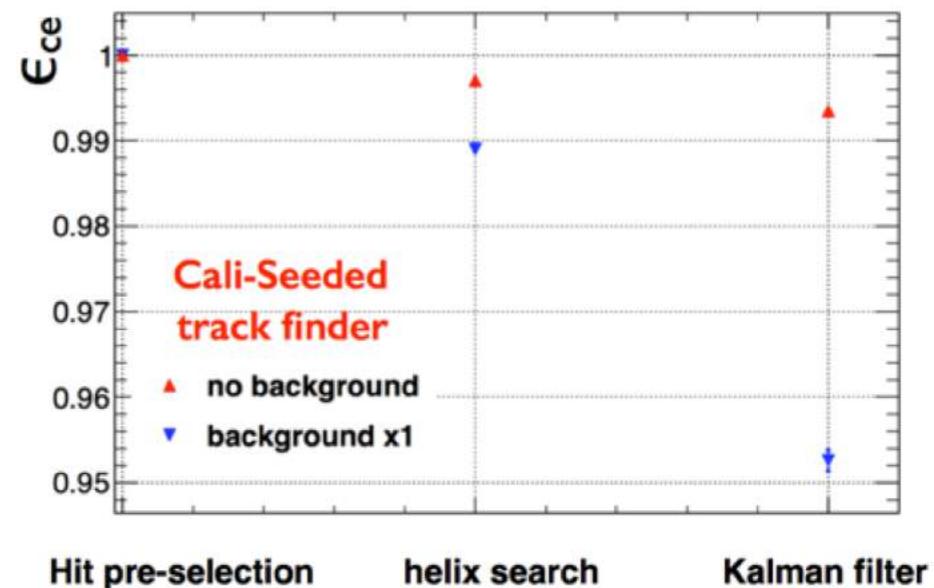
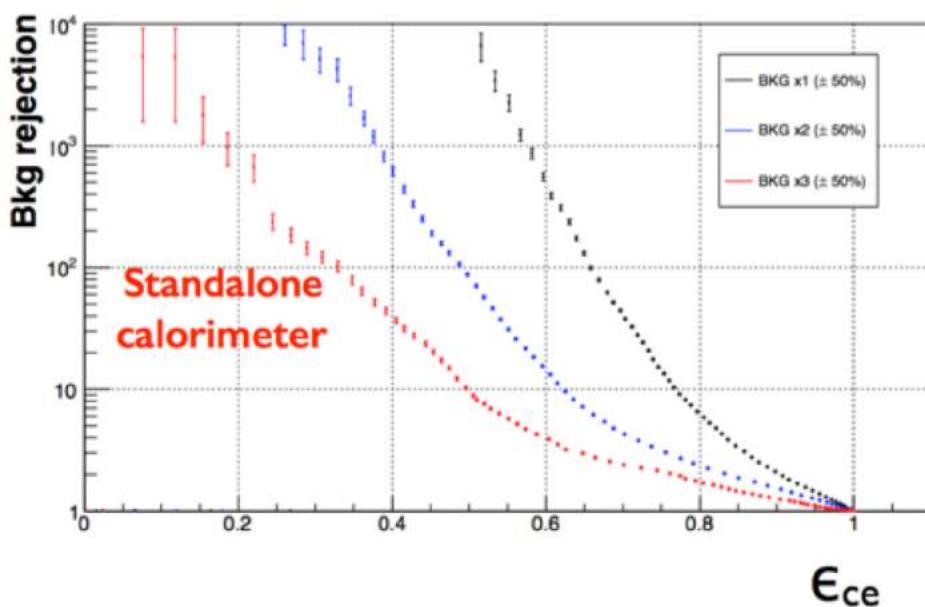
Calorimeter Calibration

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



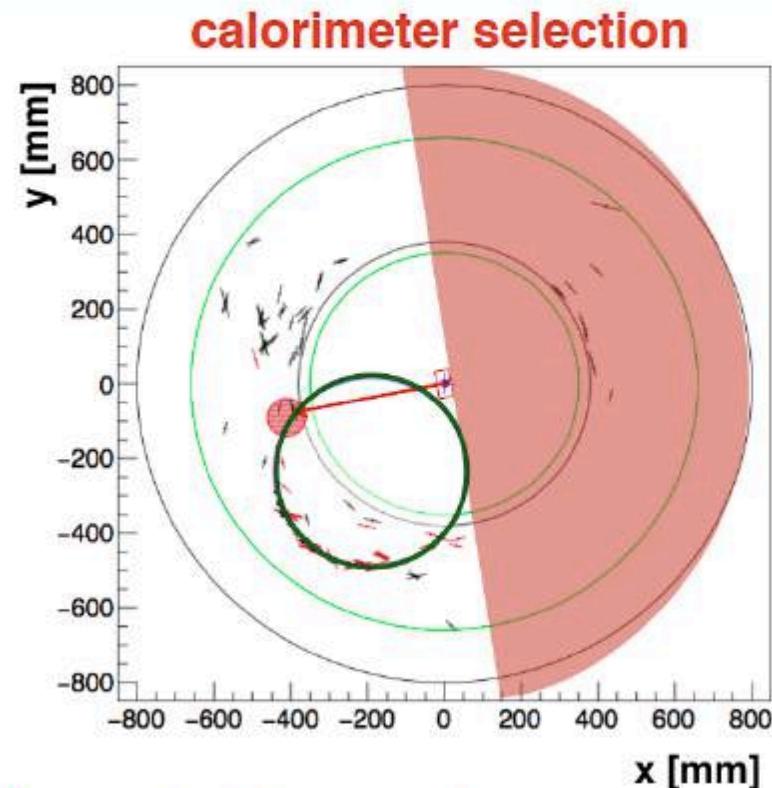
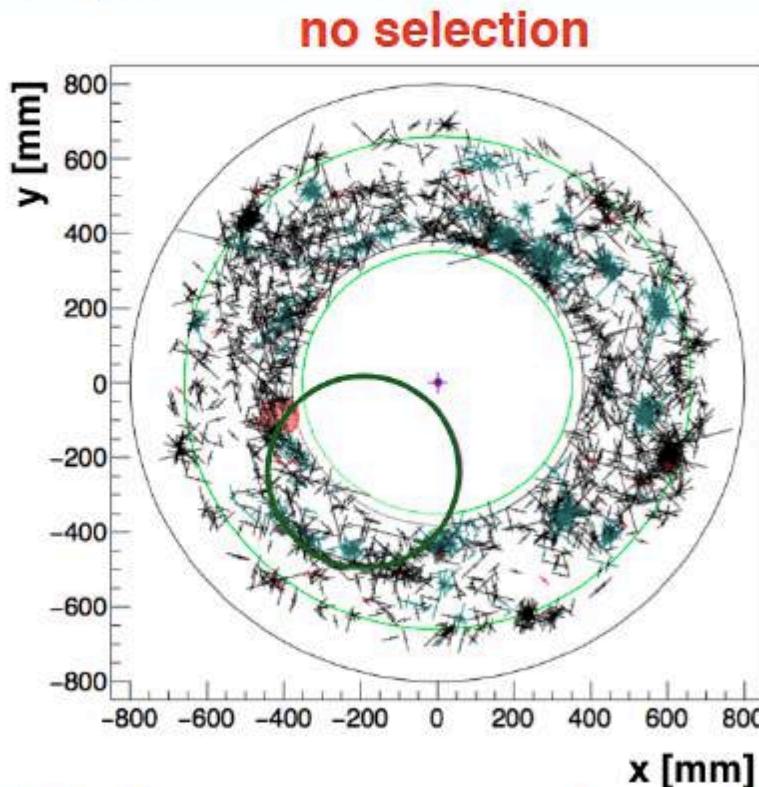
Calorimeter trigger

- 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
 - $\epsilon \sim 95\%$ for background rejection of 200
- Standalone calorimeter trigger that uses only calo info
 - $E \sim 65\%$ for background rejection 200



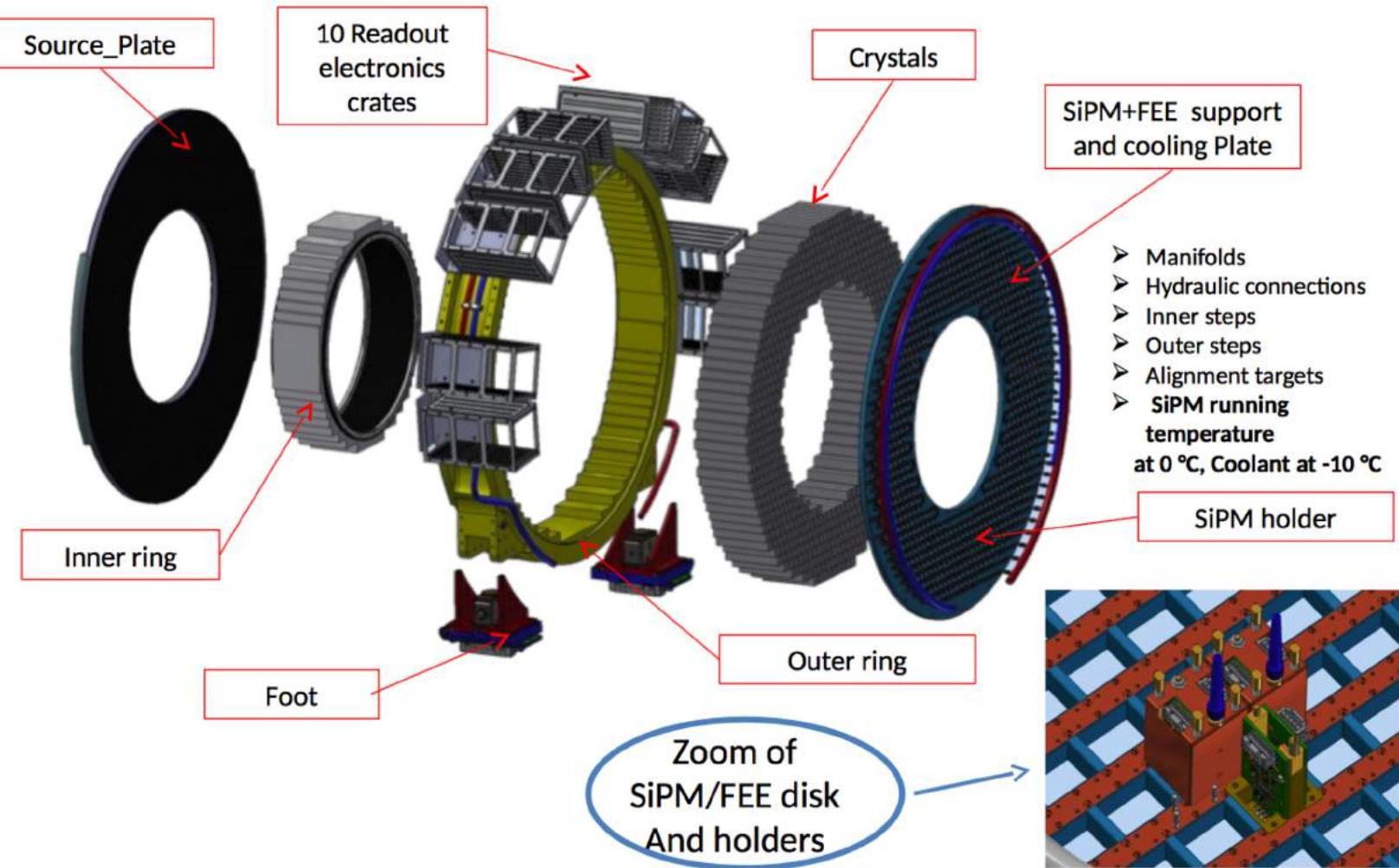
Calorimeter seeded track finder

- 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 → $\pi N \rightarrow \gamma N'$; $\gamma \rightarrow e^+ e^-$
- Neutron from muon nuclear capture
- Proton from muon nuclear capture

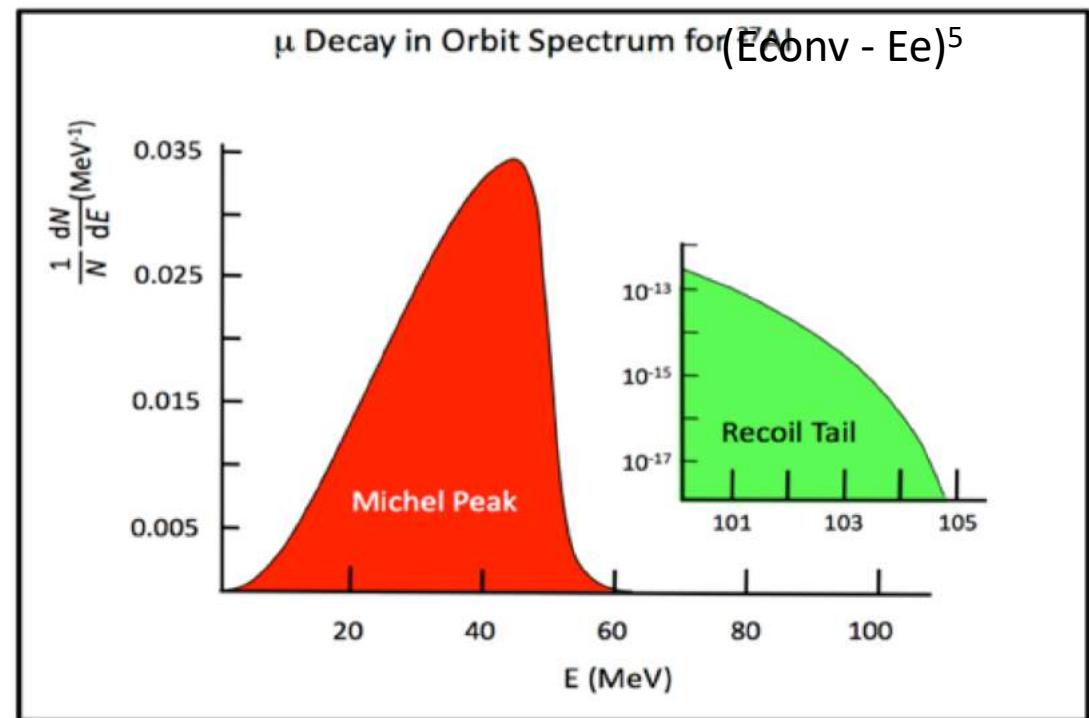
- **Beam related backgrounds:**

- 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 ($\tau_{\pi}^{\text{Al}} = 26 \text{ ns}$) $\pi^- N \rightarrow \gamma N^* \rightarrow e^+ e^- N^*$
 - 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 $O(10^{10})$

