The Mu2e e.m. calorimeter: crystals and SiPMs production status

Ivano Sarra
LNF-INFN and Guglielmo Marconi University
on behalf of the Mu2e calorimeter group

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Fermilab

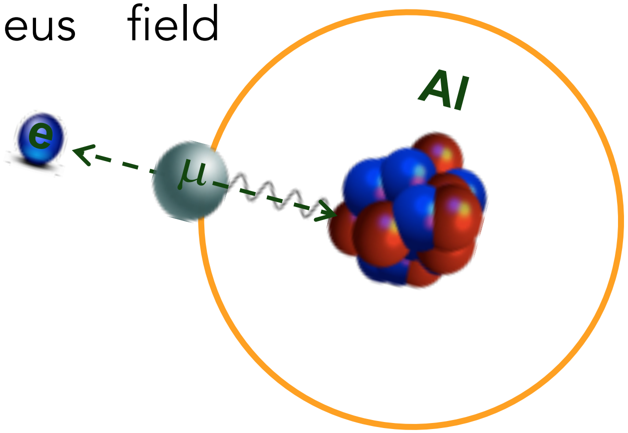
INFN
Istituto Nazionale di Fisica Nucleare

Charged Lepton Flavor Violation

- CLFV strongly suppressed in SM: Branching Ratio $\leq 10^{-54}$
  → Observation would indicate New Physics

$E_{CE} = m_\mu c^2 - E_b - E_{recoil} =$
$= 104.97$ MeV

- CLFV @ Mu2e: μ- e conversion in a nucleus field
  → discovery sensitivity to many NP models



- Goal:

10^4 improvement w.r.t. current limit (SINDRUM II)

μ-e conversion in the presence of a nucleus

$$R_{\mu e} = \frac{\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)}{\mu^- + N(A,Z) \rightarrow \nu_\mu + N(A,Z-1)} < 8.4 \times 10^{-17}$$

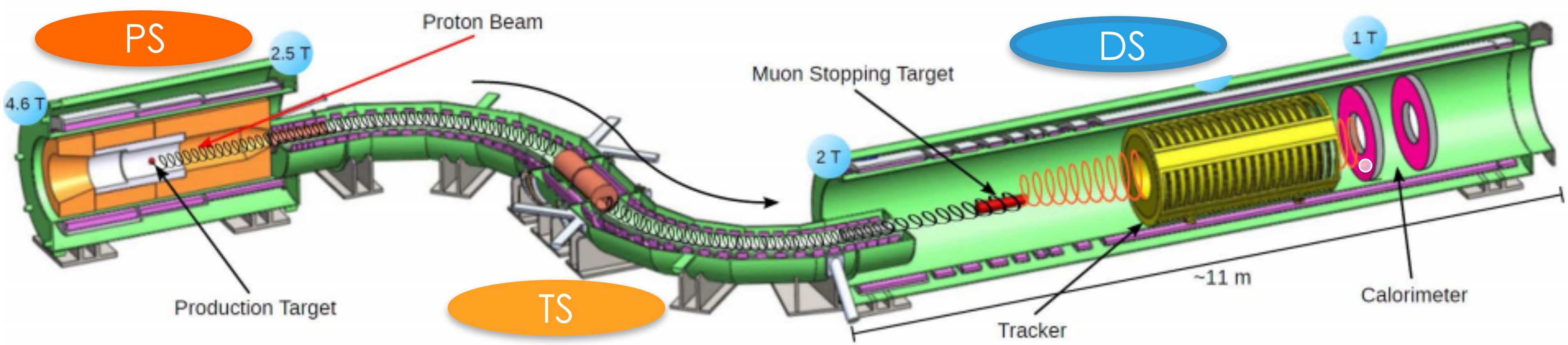
Nuclear captures of muonic Al atoms

(@ 90% CL, with ~ 10^{18} stopped muons in 3 years of running)

More information at mu2e.fnal.gov

Mu2e experiment design

1. Generate **high intensity pulsed** low momentum μ^- beam
2. **Stop muons in an Al target** → trapped in orbit around the nucleus
3. Look for a **mono-energetic-excess (105 MeV/c)** in the electron momentum spectrum



← 25 m →

Production Solenoid / Target

- Protons hitting target and producing mostly π

Transport Solenoid

- Selects and transports low momentum μ^-
- Filter out neutral particles

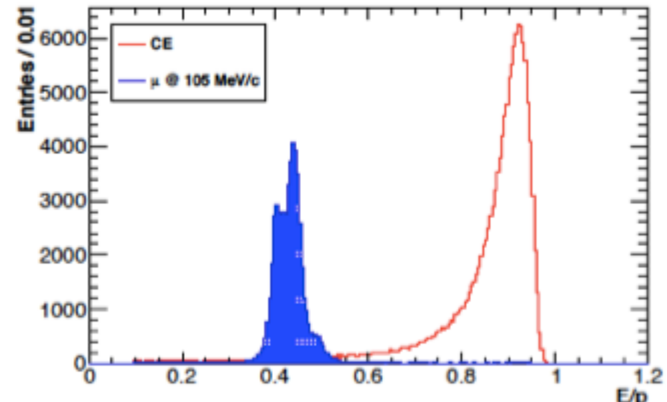
Detector Solenoid: stopping target & detectors

- Stops μ^- on Al foils
- Events reconstructed by detectors optimized for 105 MeV/c momentum
- Fully surrounded by veto for cosmic rays

Calorimeter requirements

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

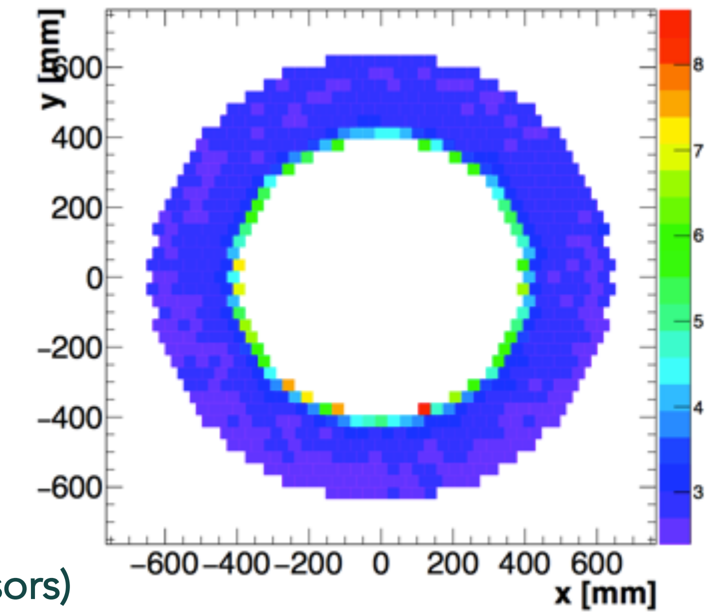
1) PID: *e*/μ separation
2) EMC seeded track finder
3) Fast and track-independent trigger



Requirements @ 105 MeV/c

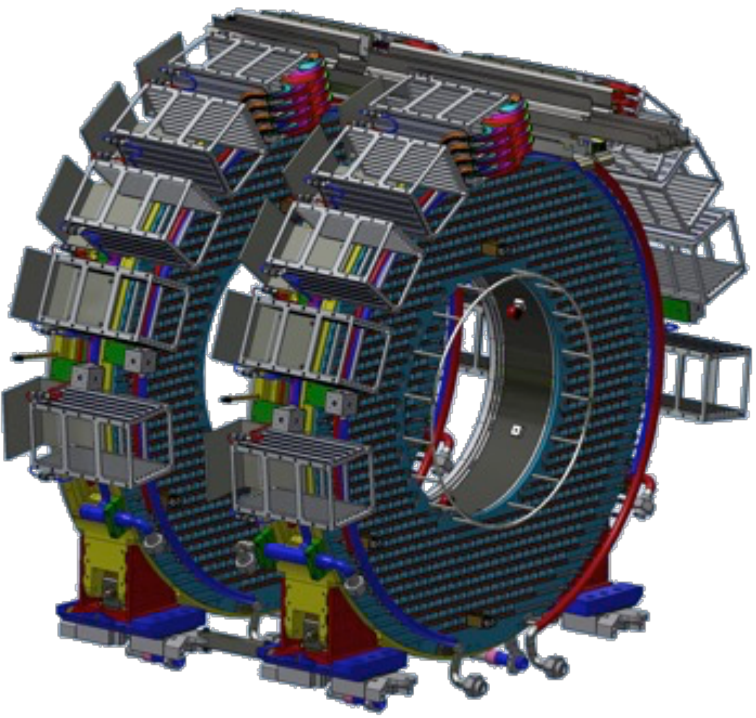
- **$\sigma_E/E = \mathcal{O}(10\%)$ for CE**
- **σ_T < 500 ps for CE**
- **$\sigma_{X,Y} \leq 1$ cm**

- Fast signals, τ<40 ns
- Operate in 1 T and in vacuum at 10^{-4} Torr
- Redundancy in readout (2 sensors+FEE /crystal)
- Radiation hardness (safety factor of 3):
  - 100 krad (45 krad) dose for crystals (sensors)
  - 3×10^{12} n_{1MeV}/cm^2 (6×10^{11} n_{1MeV}/cm^2) for crystals (sensors)
- Low radiation induced readout noise < 0.6 MeV



Front Disk Dose – 1 year [krad]

Calorimeter Design



Two annular disks with 674 undoped CsI (34 x 34 x 200) mm^3 square crystals each

→ ½ from SICCAS and ½ from St. Gobain

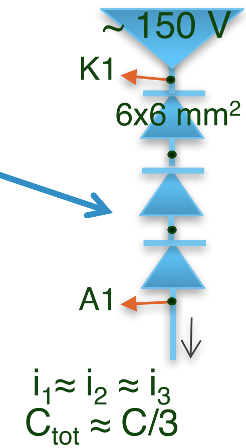
- R_{IN} = 374 mm, R_{OUT} = 660 mm
- Depth = 10 X_0 (200 mm); Distance = 70 cm
- Redundant readout:

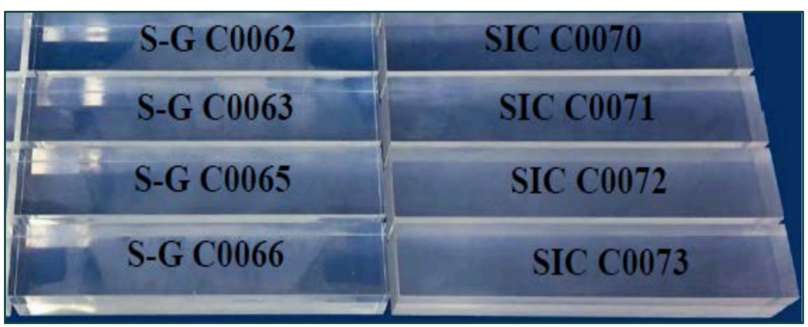
2 UV-extended SiPMs/crystal (Mu2e SiPMs)

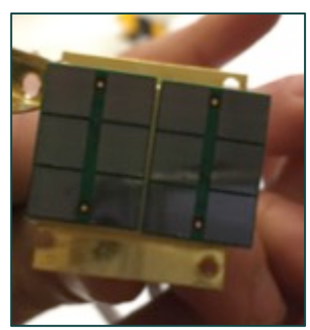
50 um pixel, 12x18 mm^2 active area

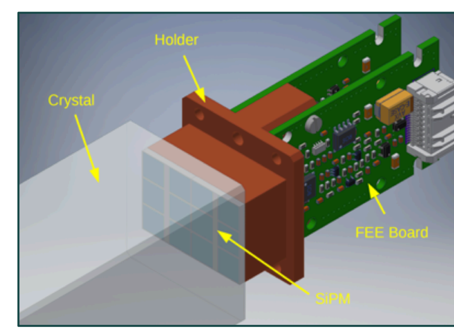
→ from Hamamatsu

- 1 FEE / SiPM, digital readout on crates
- Long R&D phase to select final producer



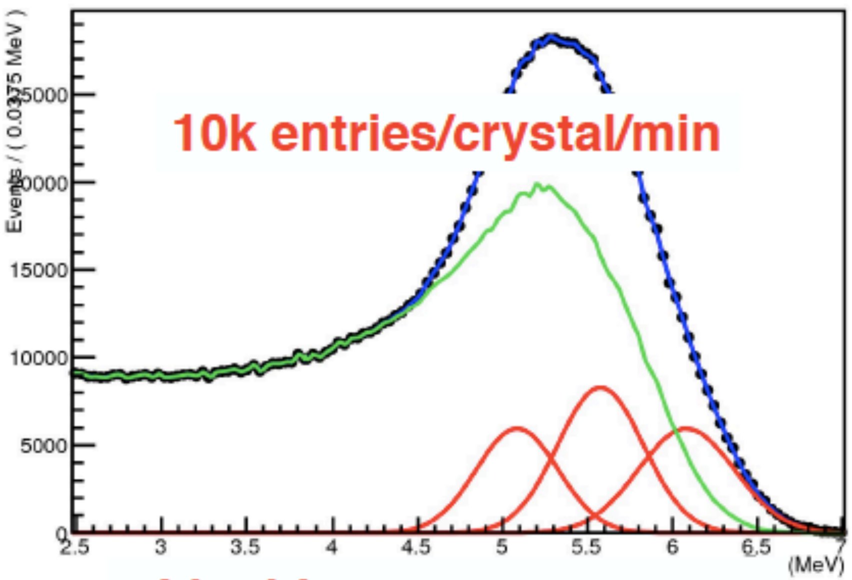




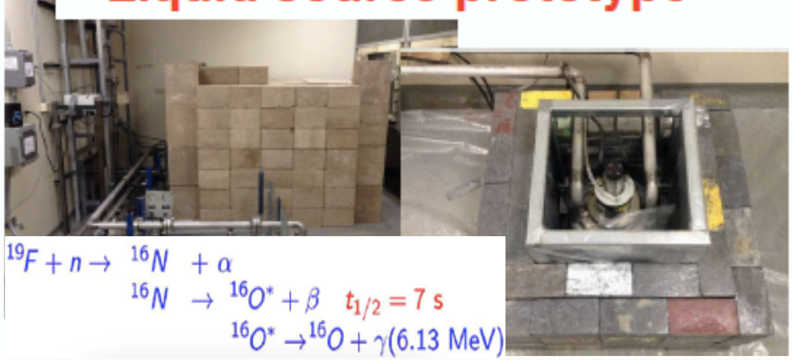


Calibration source and laser

Liquid source FC 770 + DT generator: 6 MeV + 2 escape peaks → **E-scale**



Liquid source prototype

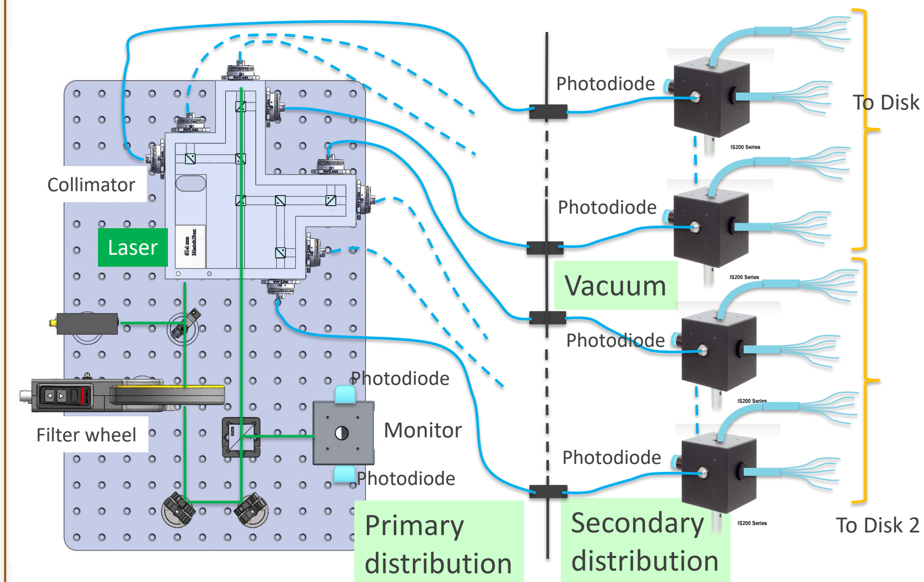


$^{19}F + n \rightarrow {}^{16}N + \alpha$

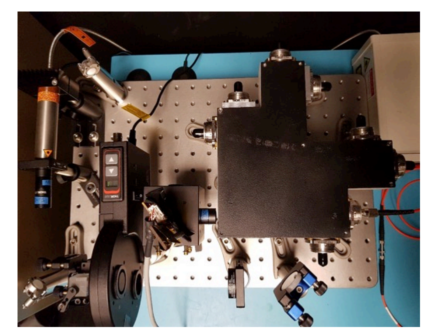
$^{16}N \rightarrow {}^{16}O^{*} + \beta \quad t_{1/2} = 7\ s$

$^{16}O^{*} \rightarrow {}^{16}O + \gamma(6.13\ MeV)$

Laser system to **monitor SiPMs gain** and timing performance



- New lens
- New cube splitter
- Room for a spare laser

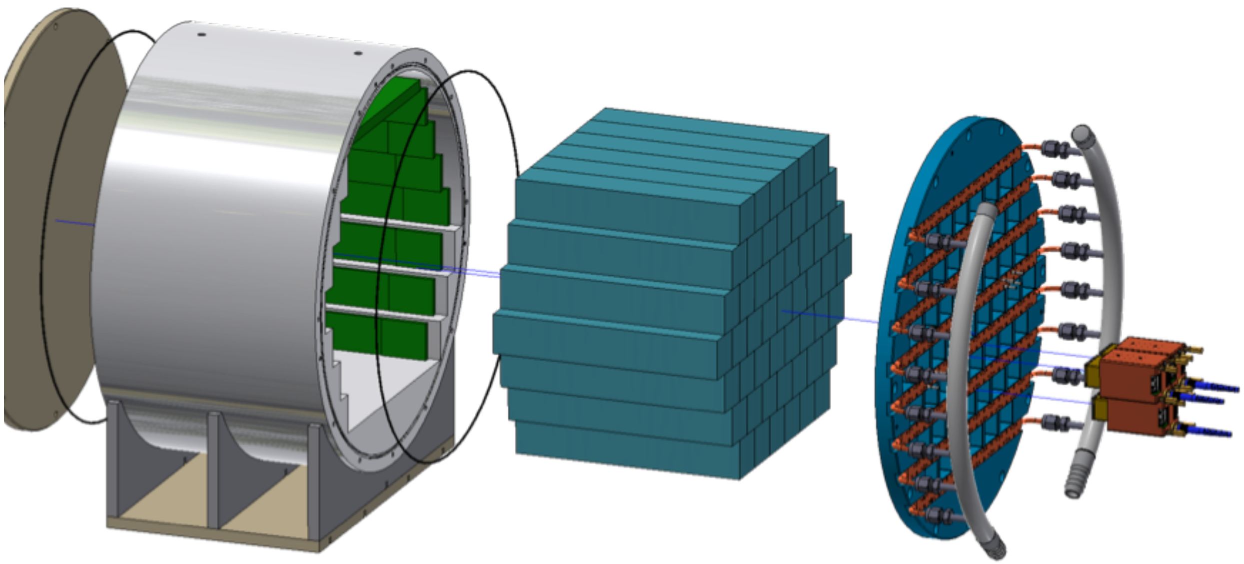


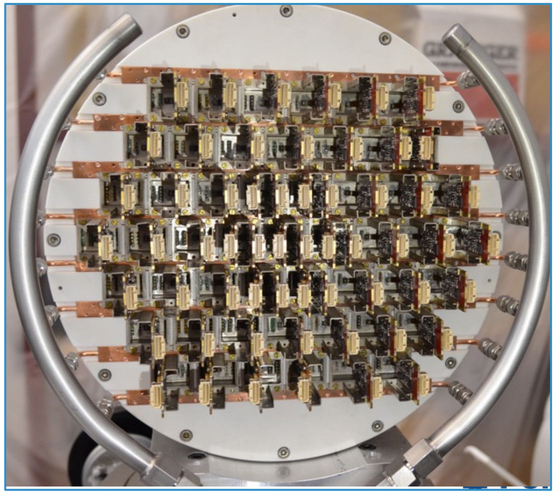
Module 0

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

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

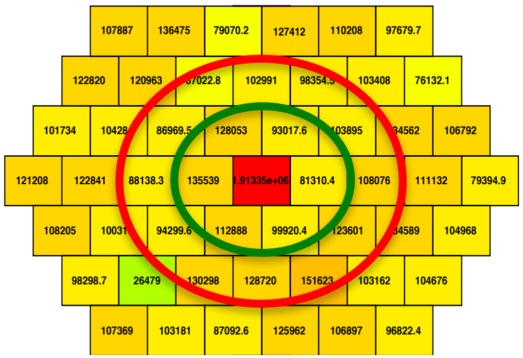
- Integration and assembly procedures
- Test beam May 2017, **60-120 MeV e⁻** (**@ 0° and @ 50°**)
- Work under vacuum, low temperature, irradiation test

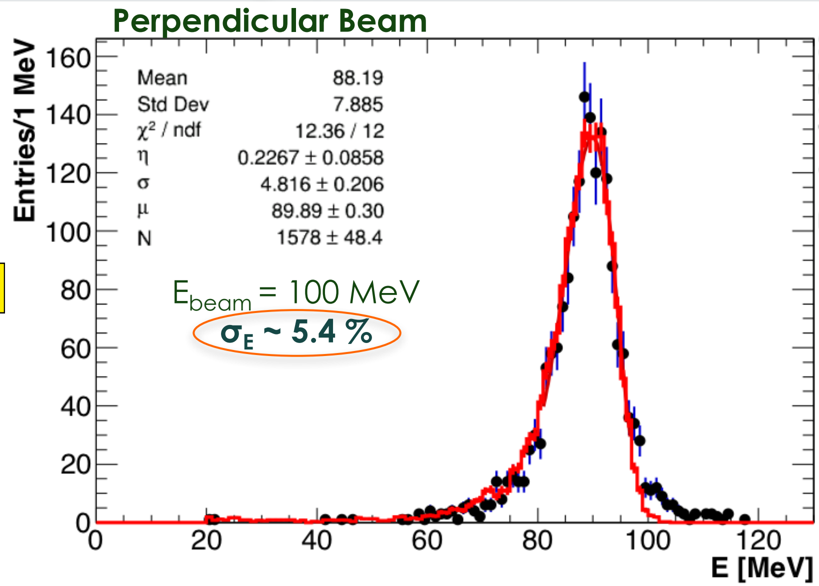


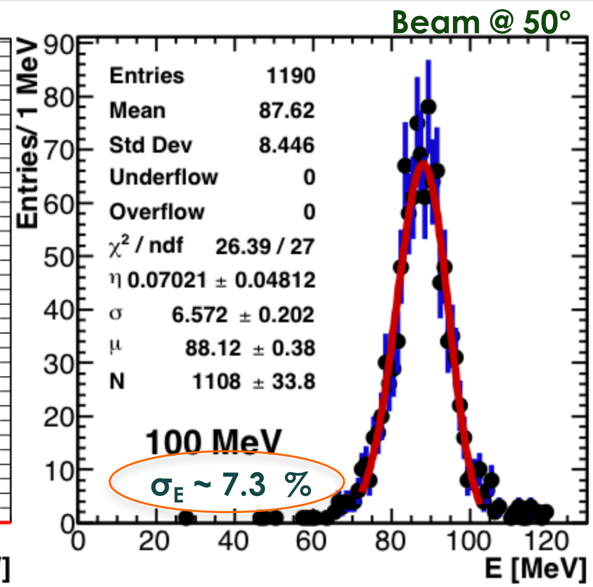


Readout: 1 GHz CAEN digitizers (DRS4 chip), 2 boards x 32 channels

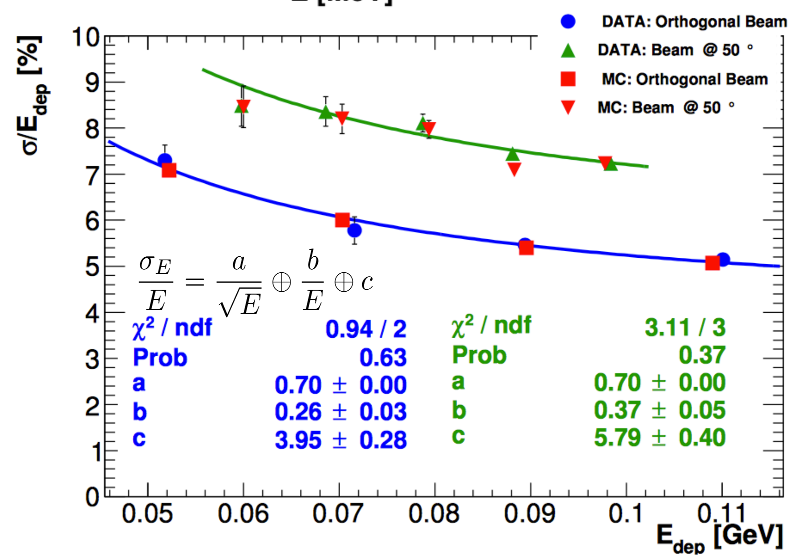
Module 0
Energy resolution



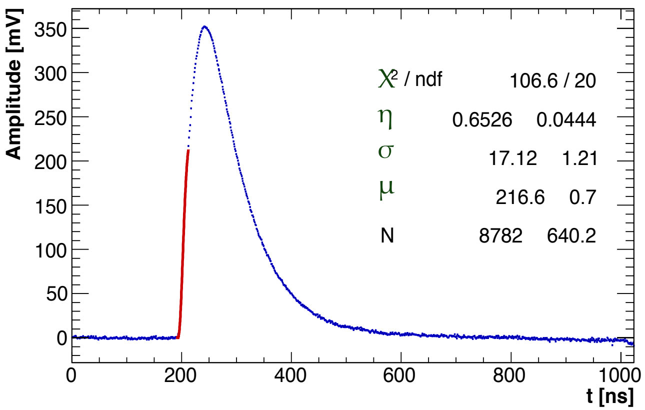


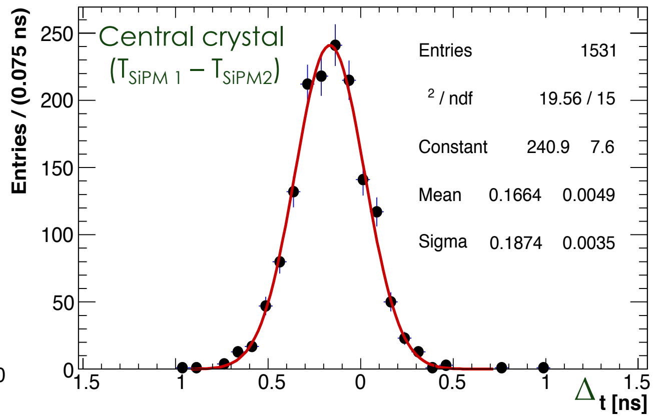


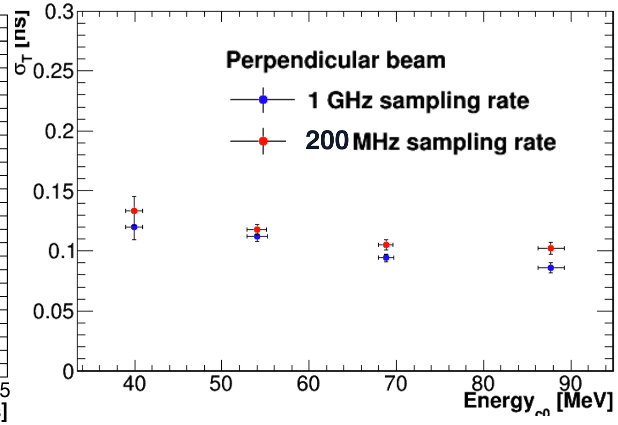
- Single particle selection
- Equalization and E-scale
  - MIPs
  - 100 MeV e^- beam, up to ring **2**
- Threshold applied @ 3 σ (Noise)
- LY/SiPM = 30 pe/MeV
- **Great Data-MC agreement**



Module 0
Time resolution

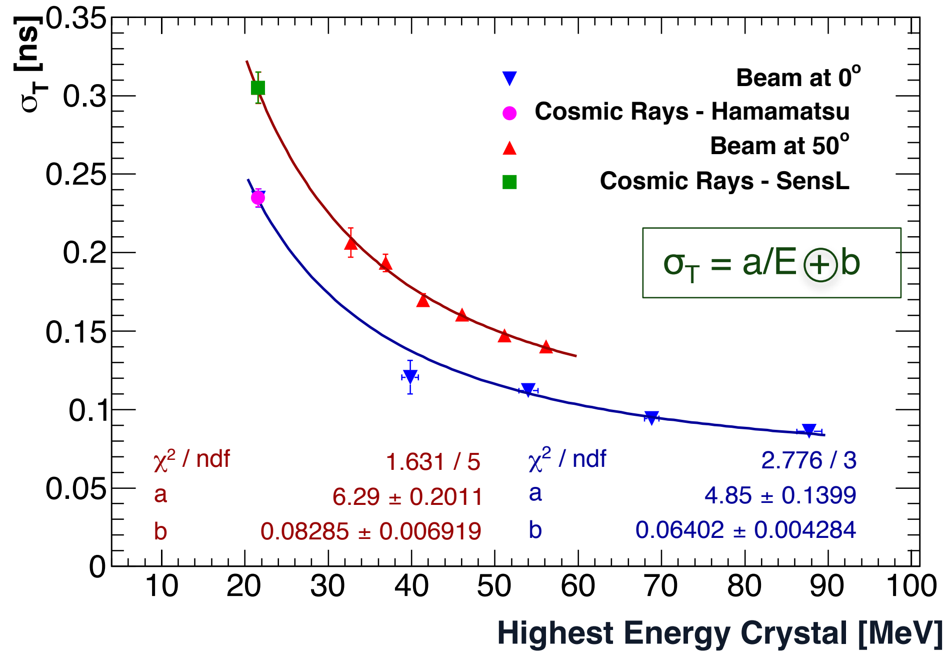






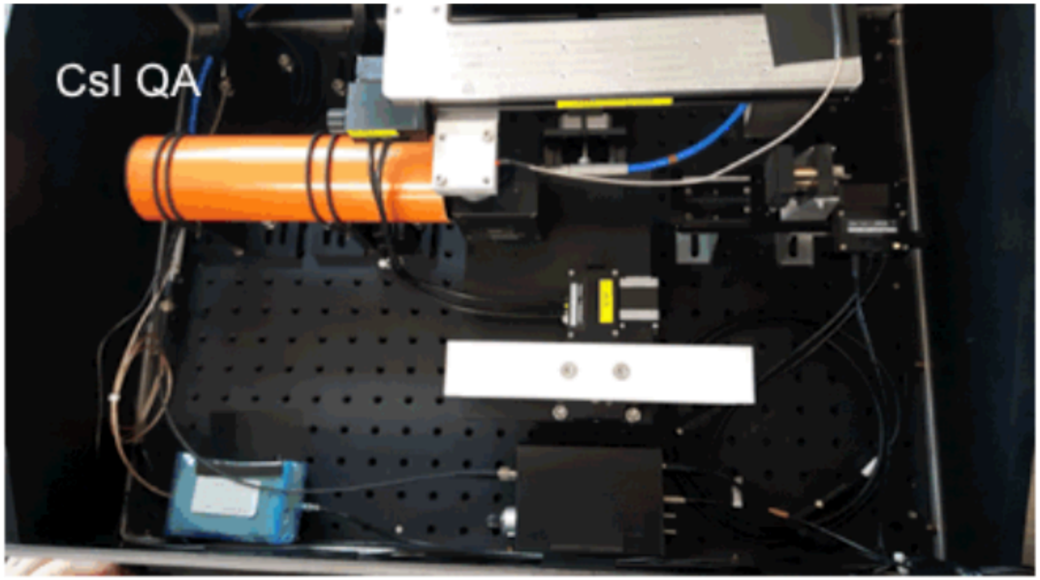
- Single particle selection
- Log-normal fit on leading edge
- Constant Fraction method used
  → CF = 5%

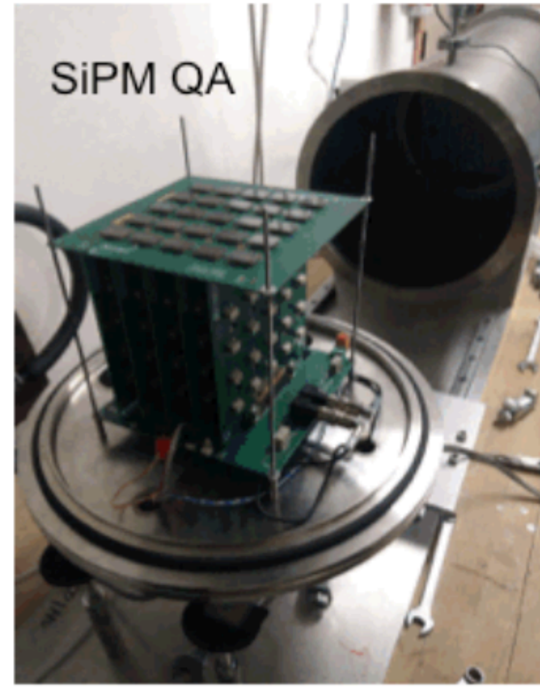
σ (T1) ~ 130 ps
@ E_{beam} = 100 MeV

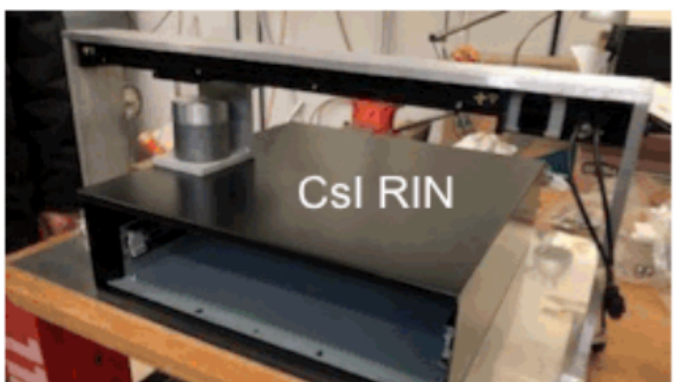


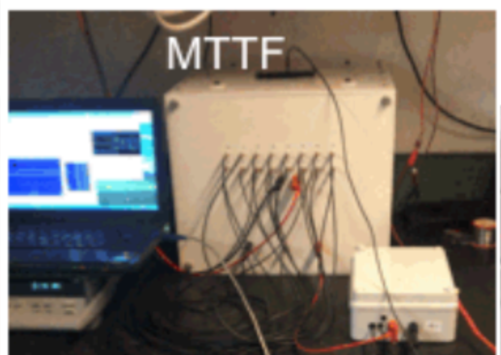
QA of components for production (2018-2019)

Dedicated QA laboratory at SiDet (FNAL) ➔ production started on March 2018
Additional laboratories for crystals and irradiation testing at Caltech and HZDR









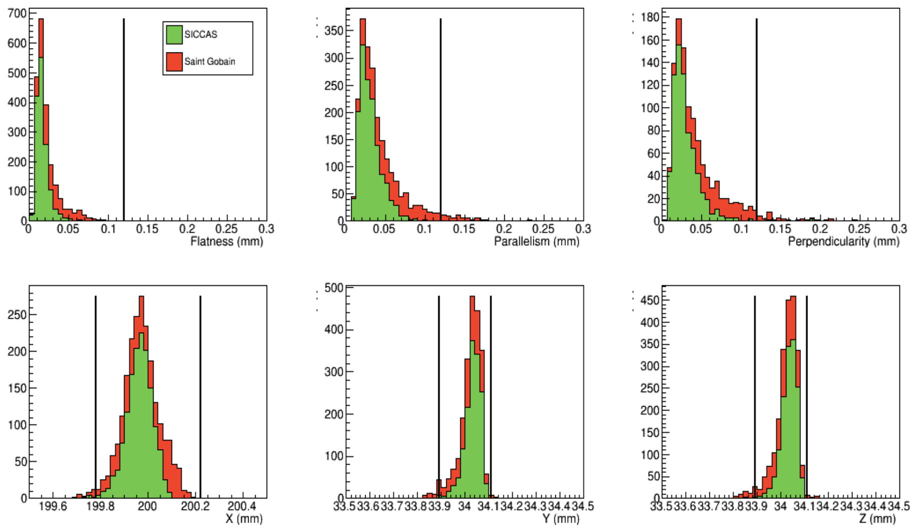
Crystals QA status

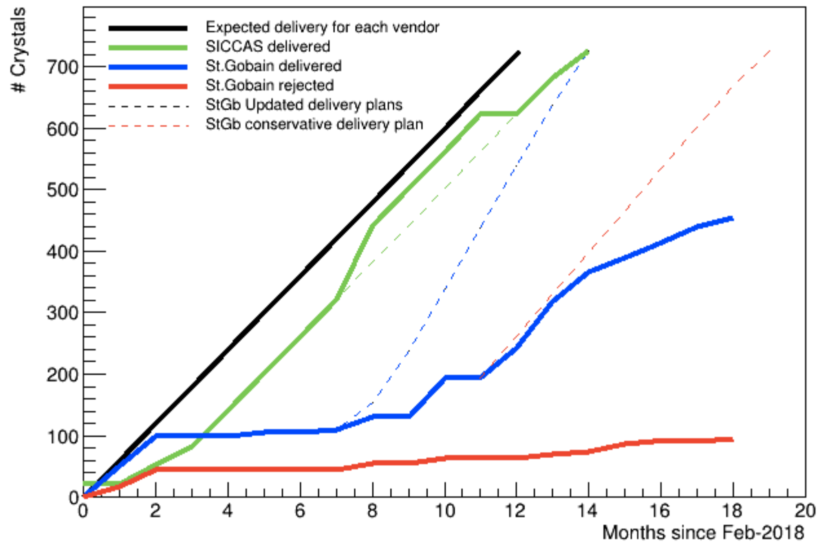
SICCAS

- **725/725 crystals received**
- **# out-of-specs crystals: 30**

  → 4% of the production

St. Gobain problems persisting on the mechanical tolerance



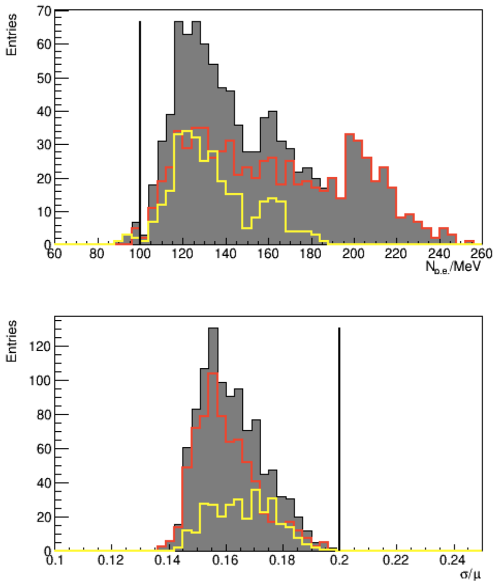


Proposal of closing the contract & swapping to SICCAS for the rest of production in progress

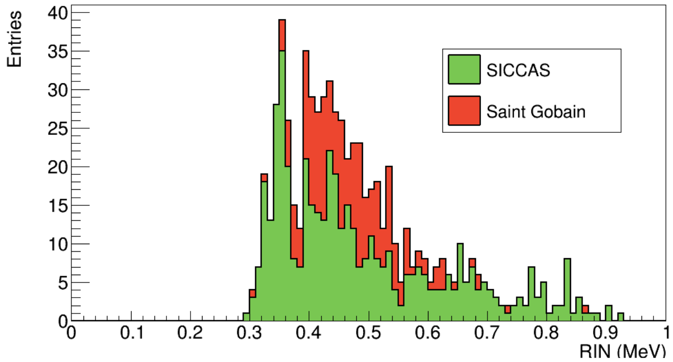
Plan is to re-start production with SICCAS in 1 month from now ..

Crystals QA status

QA of crystal optical properties



Radiation Induced Noise extrapolated @ 1.8 rad/h, 200 ns gate

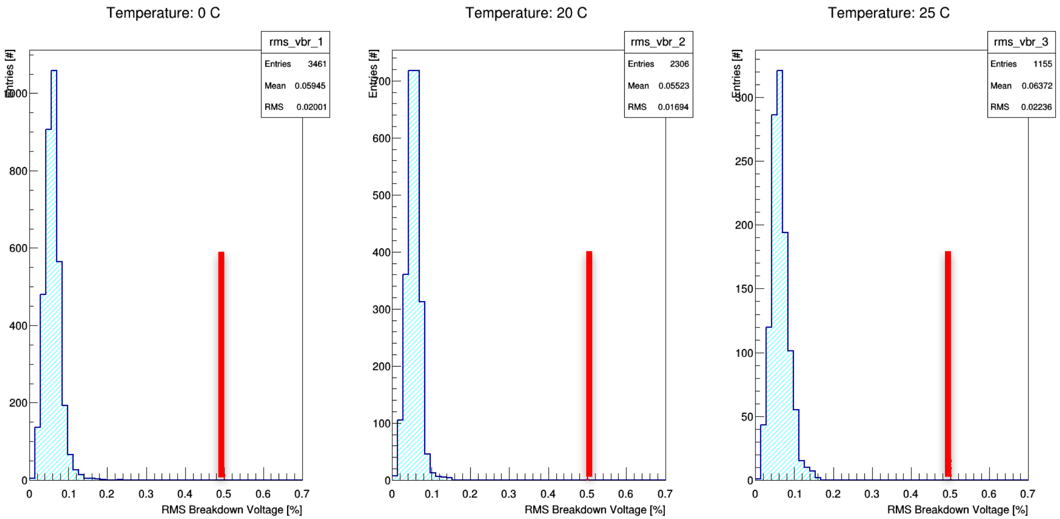


- ✗ Optical cross-talk between adiacent crystals of ~ 2% observed in Module 0 test beam data (Mu2e-doc-20862). Confirmed with laser measurements.
- ✗ **An extra wrapping of 50 mm Tedlar reduces the effect to a negligible level**
- ✗ Adopted solution for disk crystal assembly: single Tedlar foil between crystal planes + 1 Tedlar foil glued on Tyvek wrapping, on the aluminum taped side

SiPMs QA status

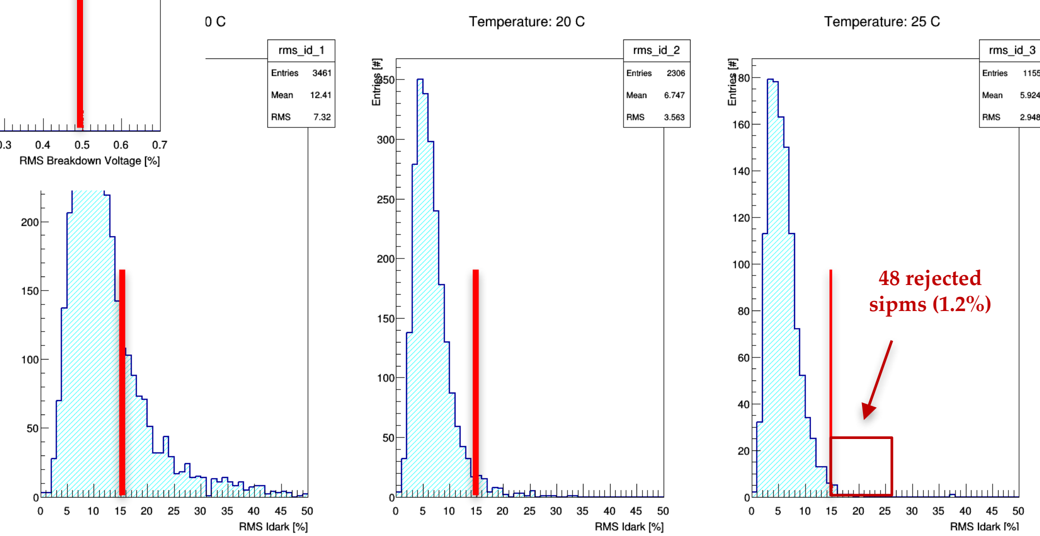
About 4000/4000 Mu2e SiPMs characterized → Producer: **HAMAMATSU**

- 280 pieces/month
- All 6 cells tested, measuring **V_{br}, I_{dark}, Gain x PDE**



RMS of Vbr: all the tested sensors still well below the 0.5% limit!

RMS of Idark of the 6 cells in the SiPM array @ VOP < 15% @ 25 ^{0}C:



SiPMs QA status

Radiation Hardness

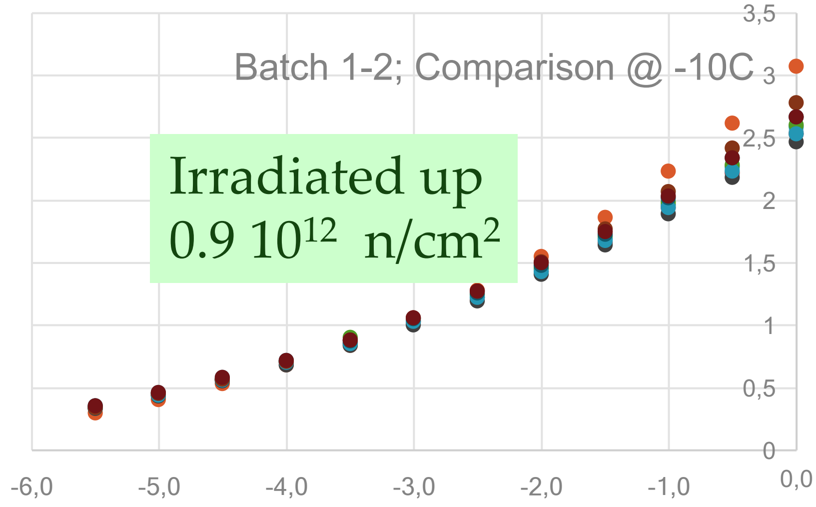
- 5 SiPMs/batch "passively" neutron irradiated @ Dresden

For Mu2e, the max n-flux in SiPM area is of around (4)x10^{10} n/cm^2

Safety Factor 3(MC)x5(Years) = **6 10^{11} n/cm^2**

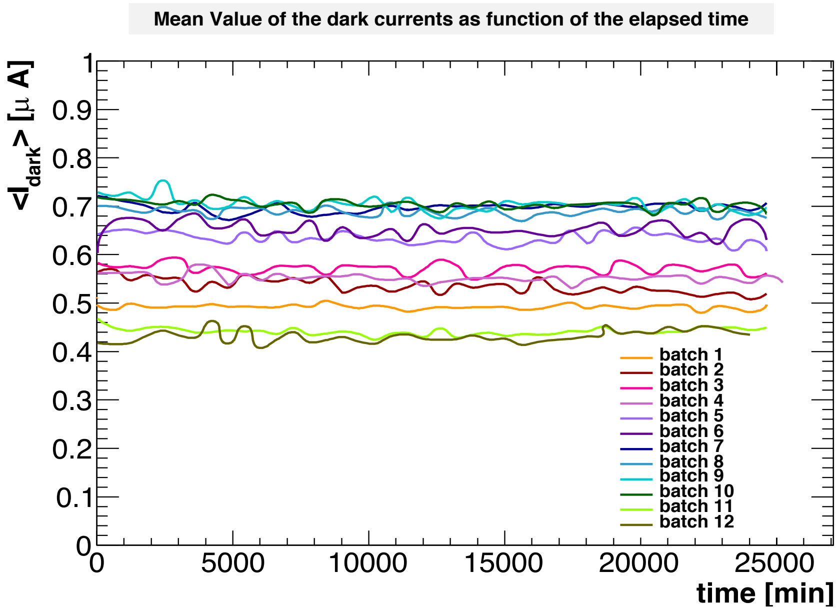
Max Idark current for operation of 2 mA

At the end of the run:
- requires cooling of -10 C,
- lower operation overvoltage to Vop-3V
- 20% of PDE relative loss



MTTF

- Requirement: grant an MTTF of 1 million hours at 0°
- sensors tested 18 days burn-in at 65°
- **SiPM $_{MTTF}$ > 10 million hours**



Summary and Conclusions

- The Mu2e calorimeter 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, negligible slow component
    - **Radiation hardness OK**: 40% LY loss at 100 krad
  - **Mu2e SiPMs quality OK**
    - High gain, high PDE, low I_{dark}, low RMS spread in array
    - SiPMs performance after **irradiation OK → require 0 ° C cooling**
    - SiPM **MTTF > 10 million hours**
  - **Calorimeter prototypes** tested with e^- beam
    - **Good time and energy resolution achieved @ 100 MeV**
- Calorimeter production phase started March 2018
- Calorimeter assembly at the end of 2019
- **Calorimeter installation in Mu2e experimental hall planned for 2021**