Design and status of the Mu2e crystal calorimeter

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On behalf of the Mu2e calorimeter group

May , 2016
XVII LNF Spring School "Bruno Touschek"

ROMA TRE UNIVERSITÀ DEGLI STUDI
Fermilab
INFN Istituto Nazionale di Fisica Nucleare

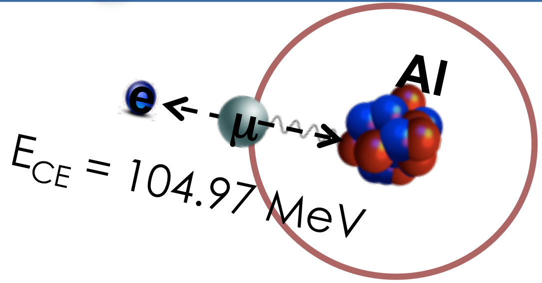
Talk overview

Mu2e Electromagnetic calorimeter

- Requirements
- Components
- Single Channel Tests
- “Module-0” performance
- Production phase

Mu2e experiment design

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



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

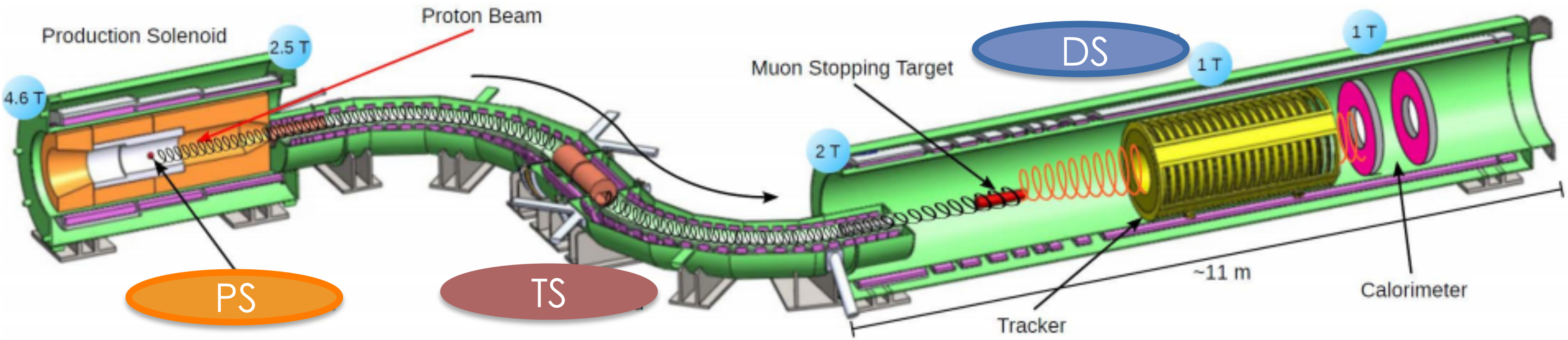
- **Goal:**

μ-e conversion in the presence of a nucleus

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

(@ 90% CL, with ~ 10^{18} stopped-μ)

Nuclear captures of muonic Al atoms



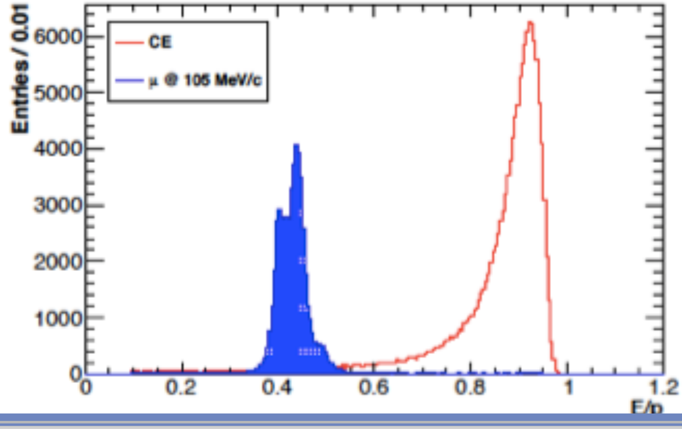
Detector Solenoid: stopping target and detectors

- Stops μ^- on Al foils
- Events reconstructed by detectors optimized for 105 MeV/c momentum

Calorimeter requirements

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

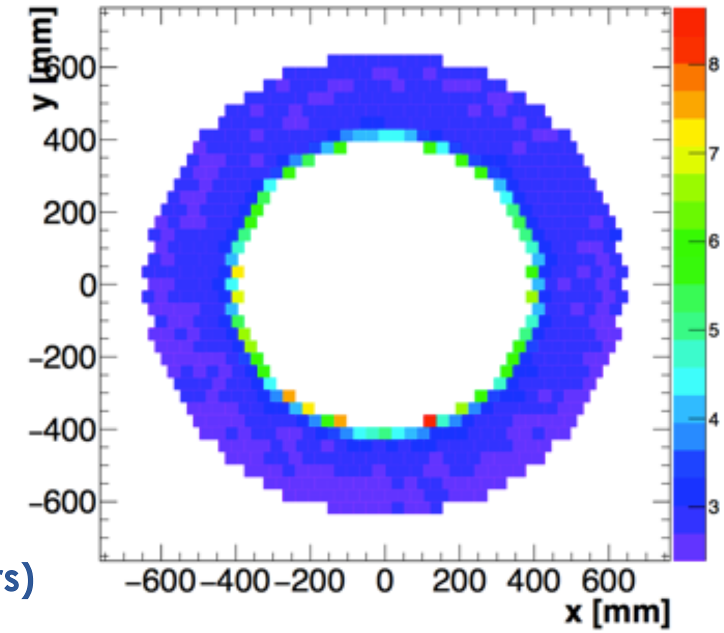
1) **PID: e/μ separation**
2) **EMC seeded track finder**
3) **Standalone trigger**



Requirements @ 105 MeV/c

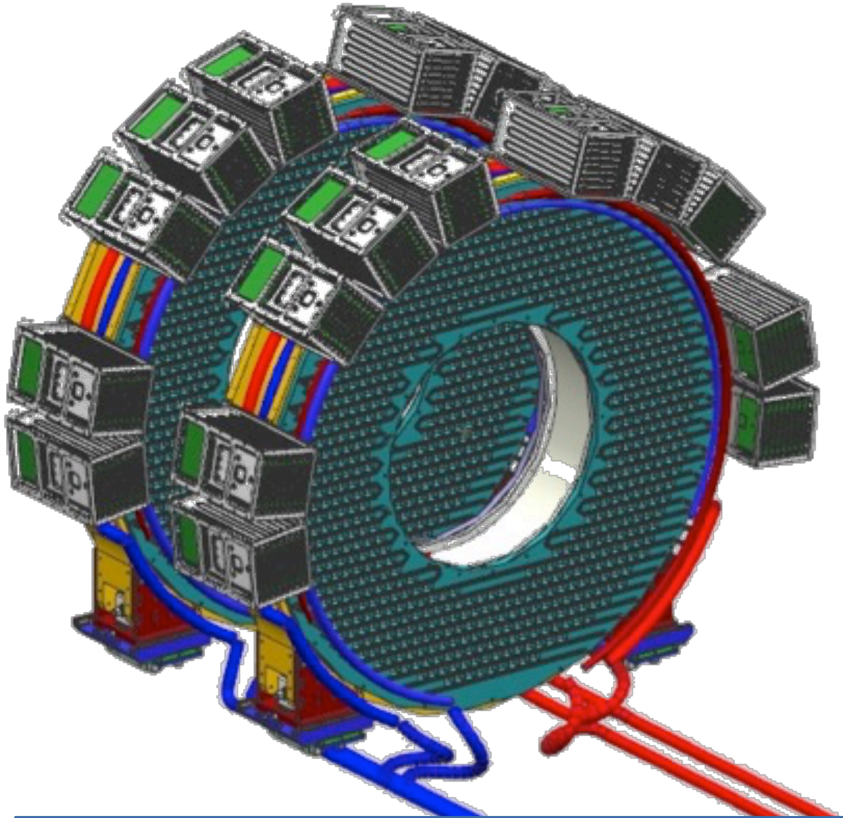
- **$\sigma_E/E = \mathcal{O}(5\%)$ for CE**
- **σ_T < 500 ps for CE**
- **$\sigma_{X,Y} \leq 1$ cm**

- Fast scintillation signals (τ <40 ns)
- Operate in 1 T and in vacuum at 10^{-4} Torr
- Redundancy in readout (2 sensors+FEE /crystal)
- **Radiation hardness (with a safety factor of 3):**
  - **100 krad (45 krad) dose for crystals (sensors)**
  - **3×10^{12} n_{1MeV}/cm^2 (1.2×10^{12} n_{1MeV}/cm^2) for crystals (sensors)**
- Low radiation induced readout noise < 0.6 MeV



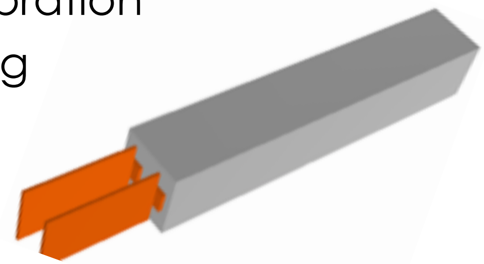
Front Disk Dose – 1 year [krad]

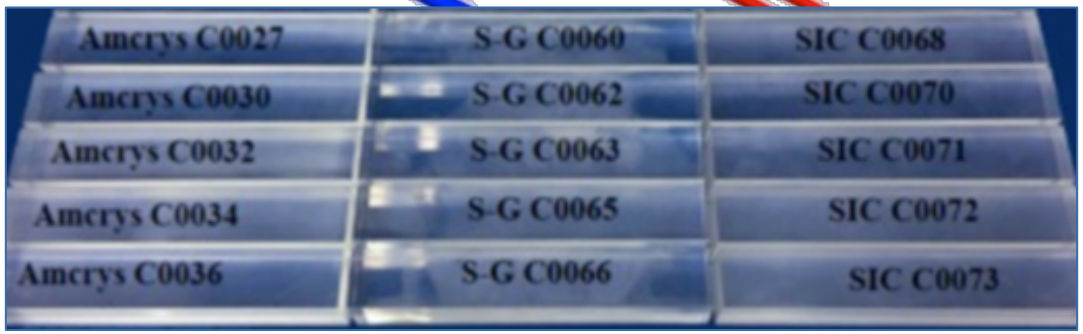
Calorimeter Design

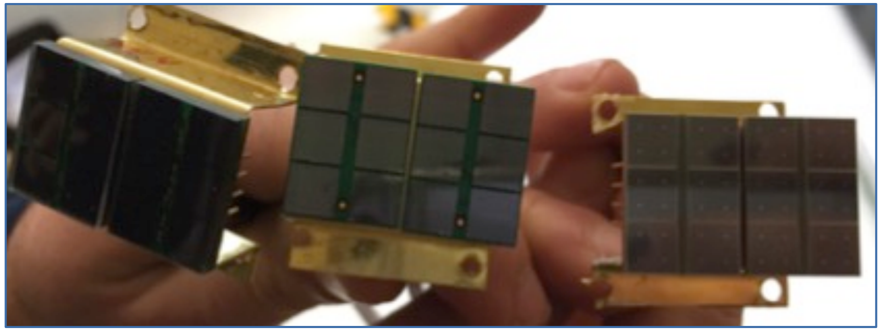


2 annular disks with 674 undoped CsI (34 x 34 x 200) mm^3 square crystals/each disk

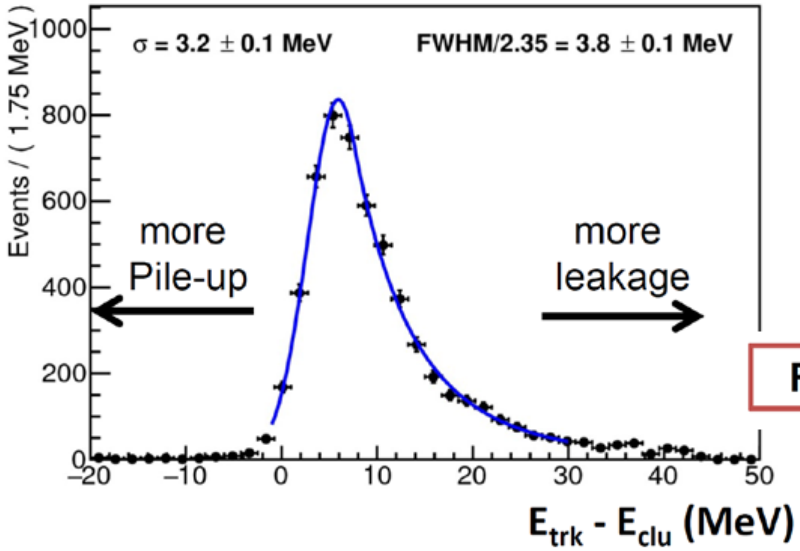
- R_{IN} = 374 mm, R_{OUT} = 660 mm
- Depth = 10 X_0 (200 mm), Distance 70 cm
- Readout: **2 UV-extended SiPMs/crystal**
- FEE on the SiPMs , Digital readout on crates
- RA source for energy calibration
- Laser system for monitoring





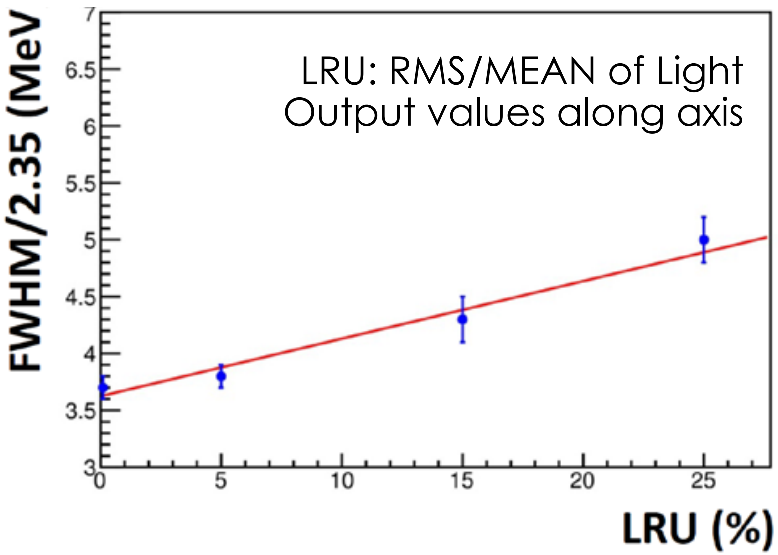


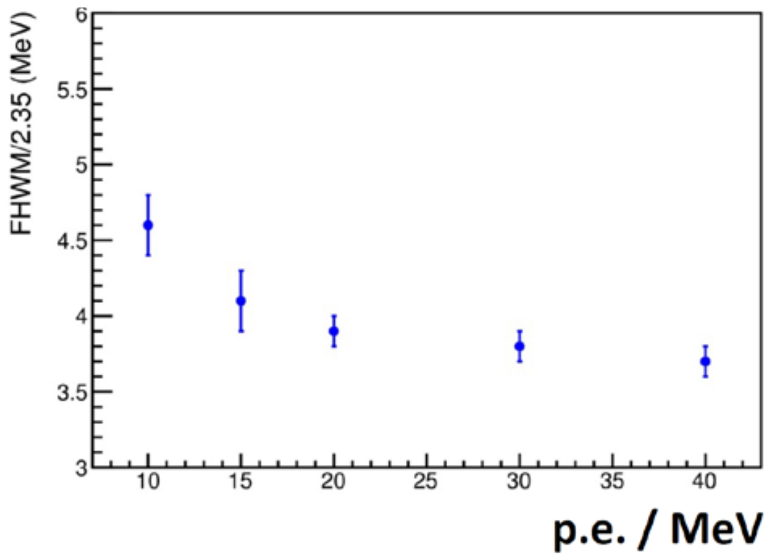
Simulated performance



Simulation includes full background and digitization and cluster-finding, with split-off and pileup recovery

FWHM / 2.35 = 3.8 ± 0.1 MeV



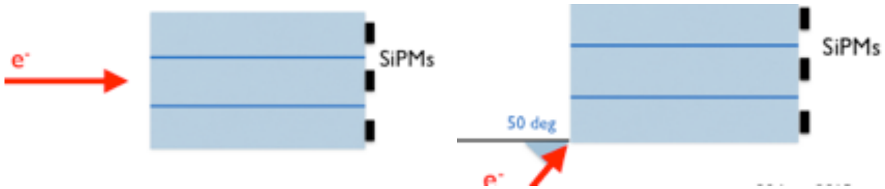


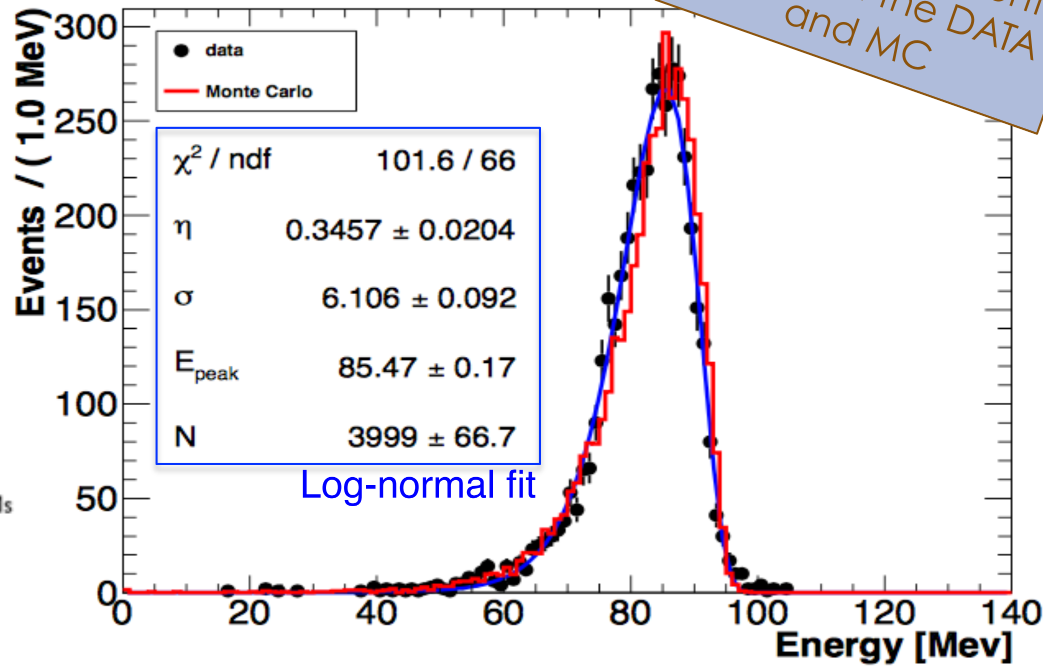
Small prototype: Test Beam

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





Small prototype: Time and Energy resolution

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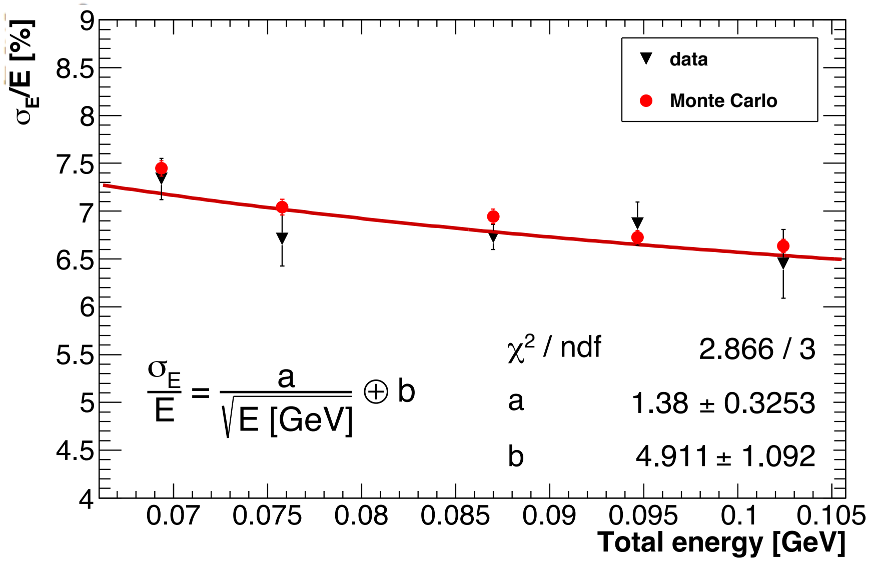
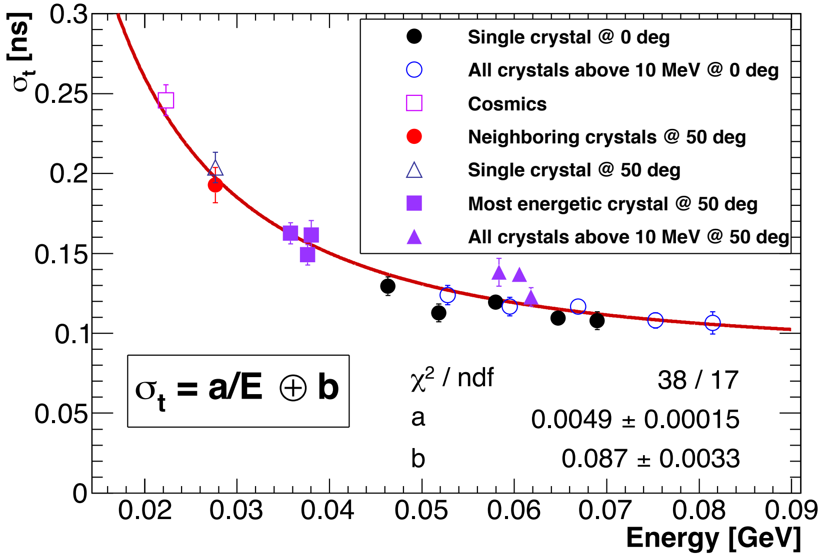




$\sigma_E \sim 6.5\%$ at 100 MeV

$\sigma_T \sim 110$ ps at 100 MeV

Significant leakage contribution due to block dimensions w.r.t. the shower

1 year long R&D phase for the final test of the option CsI + UV extended SiPM

PRE-PRODUCTION

72 crystals + 150 SiPM + 150 FEE chips completed in 2016

Pre-production Crystals

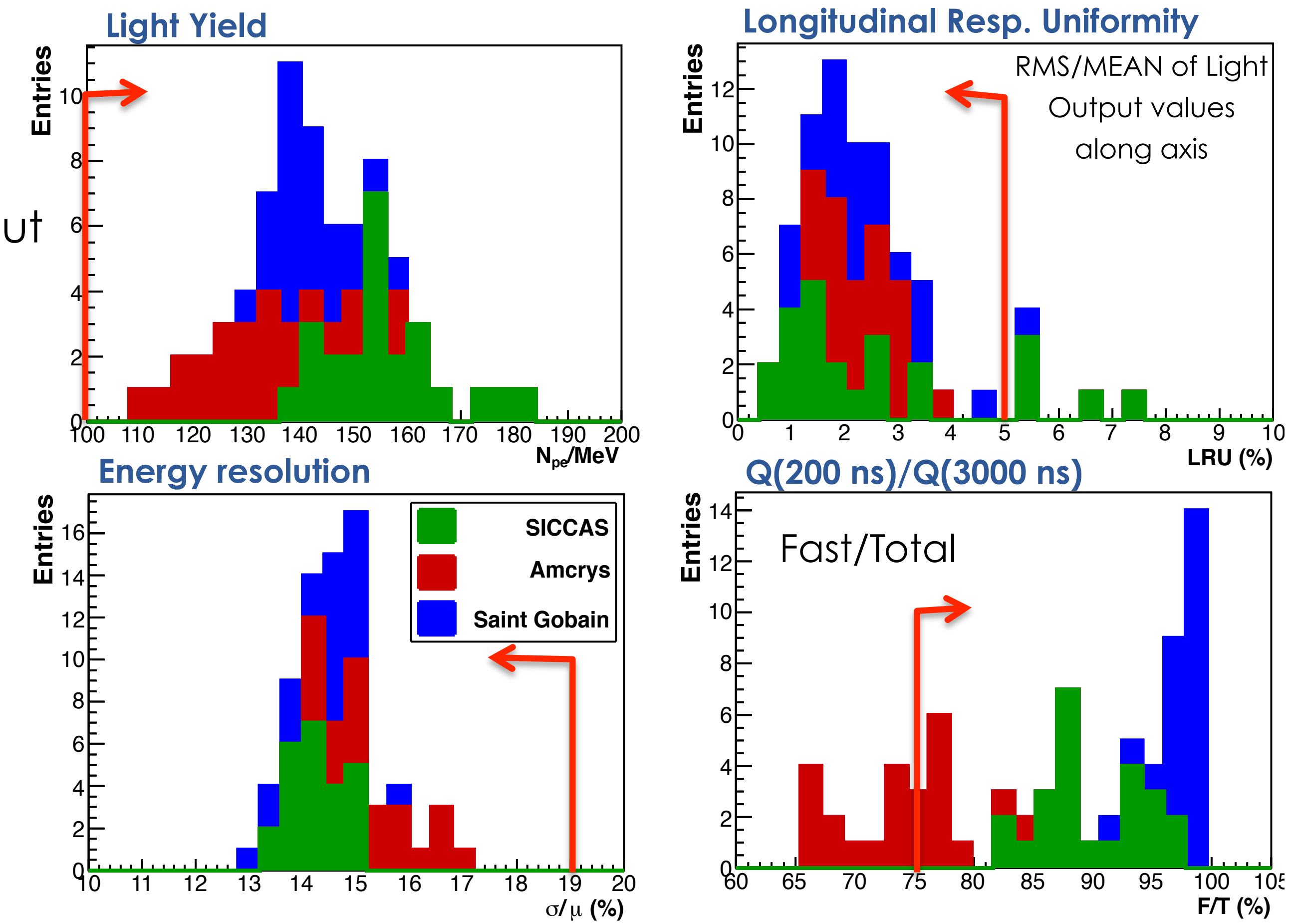
- 24 crystals from three different vendors: **SICCAS**, **Amcrys**, **Saint Gobain**
- Optical properties tested with 511 keV γ's along the crystal axis
- Crystals wrapped with 150 μm of Tyvek and coupled to an UV-extended PMT

Un-doped CsI crystals perform well

- **Excellent LRU and LY:**
  -100 pe/MeV with PMT readout
  -LRU < 5%

- τ of 30 ns with small slow component

- **Radiation hardness OK**
  Smaller than 40% LY loss @ 100 krad

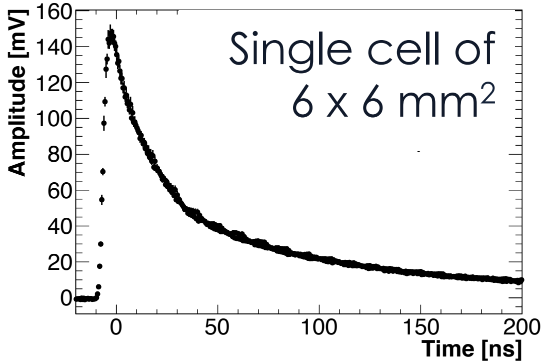


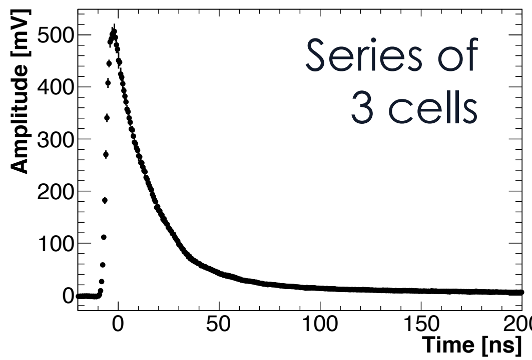
Pre-production test: SiPMs (1)

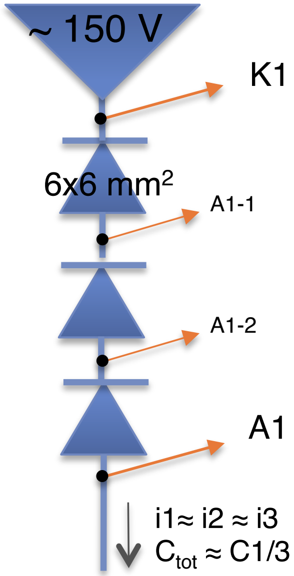
Mu2e custom silicon photosensors:

→ **2 arrays of 3 6 x 6 mm² UV-extended SiPMs: total area (12x18) mm²**

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

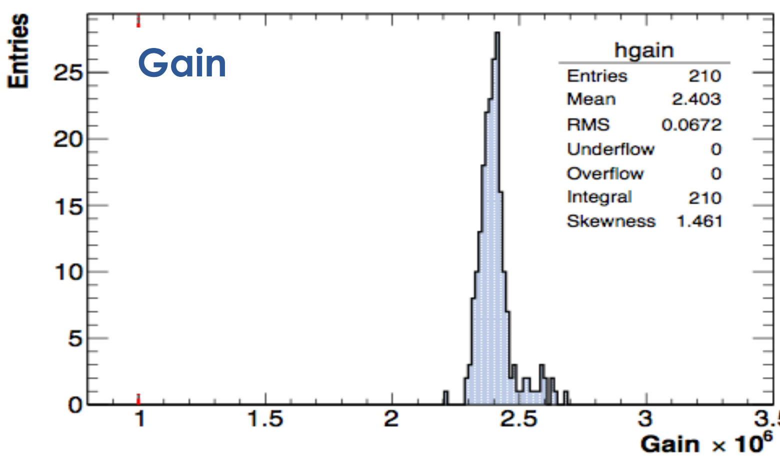


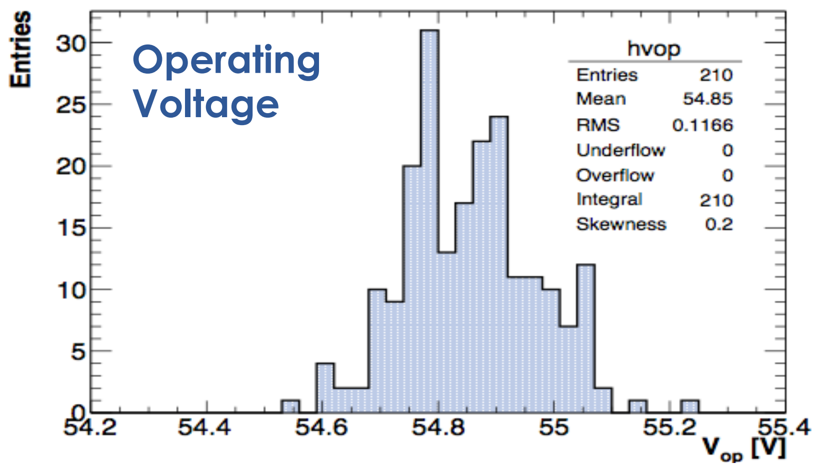




150 sensors: 3×50 Mu2e pre-production SiPMs from **Hamamatsu**, **SenSl** and **AdvanSiD**

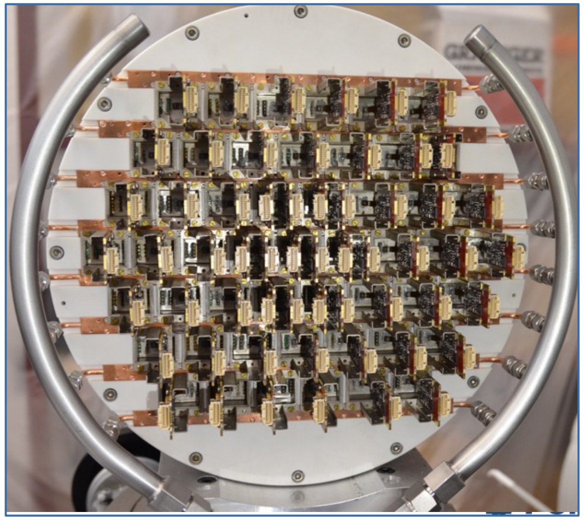
- 3×35 were fully characterized for all six cells in the array





Module 0

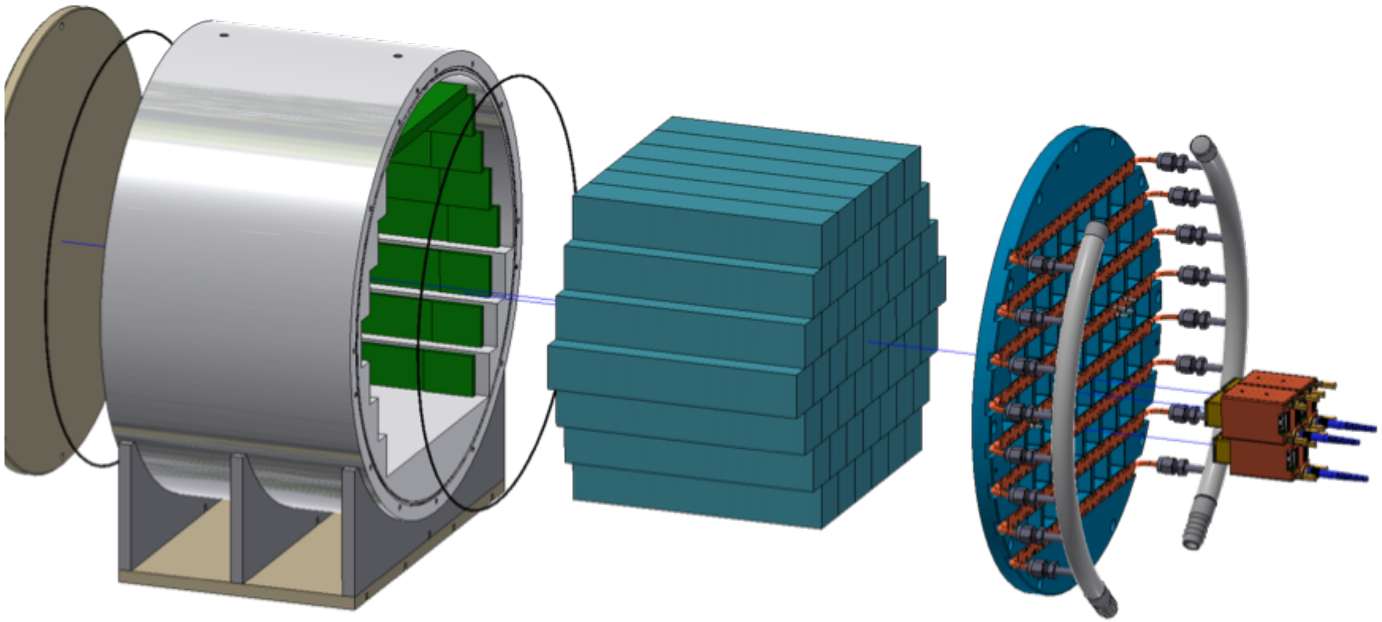
Large EMC prototype: **51 crystals, 102 SiPMs, 102 FEE boards**



Mechanics and cooling system similar to the final ones!

Goals:

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



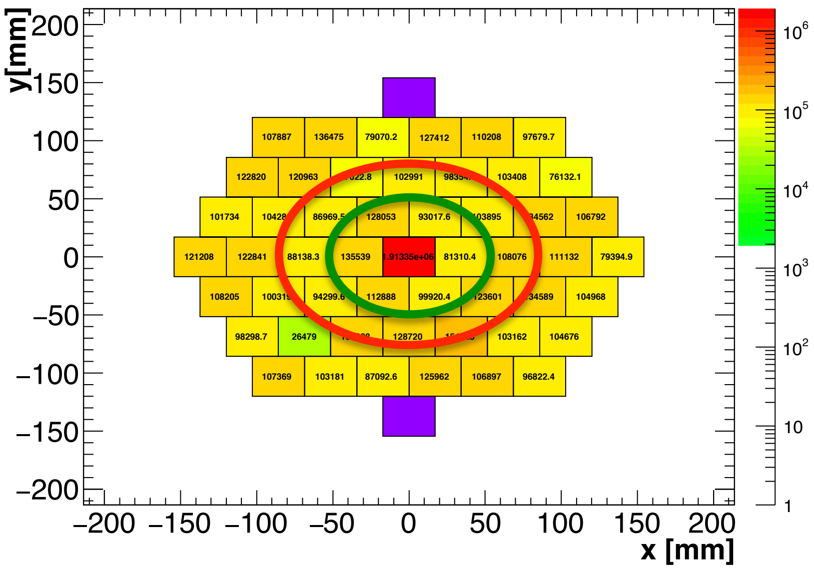
Module 0
Energy resolution

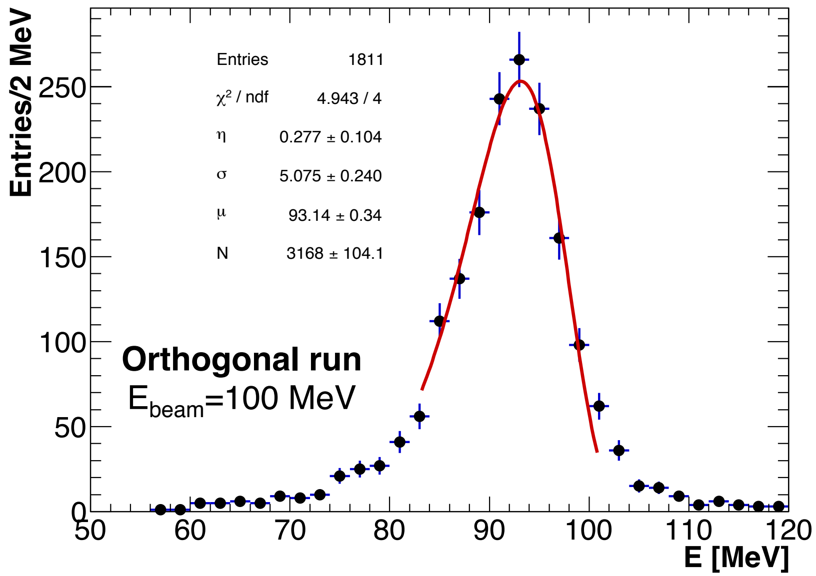
- Calibration
  - cosmic rays
  - beam→completed for second ring around central crystal

- Data quality good, resolution in agreement with 3x3 prototype

σ_E ~ 5.4 % (entire matrix)

@ E_{beam} = 100 MeV

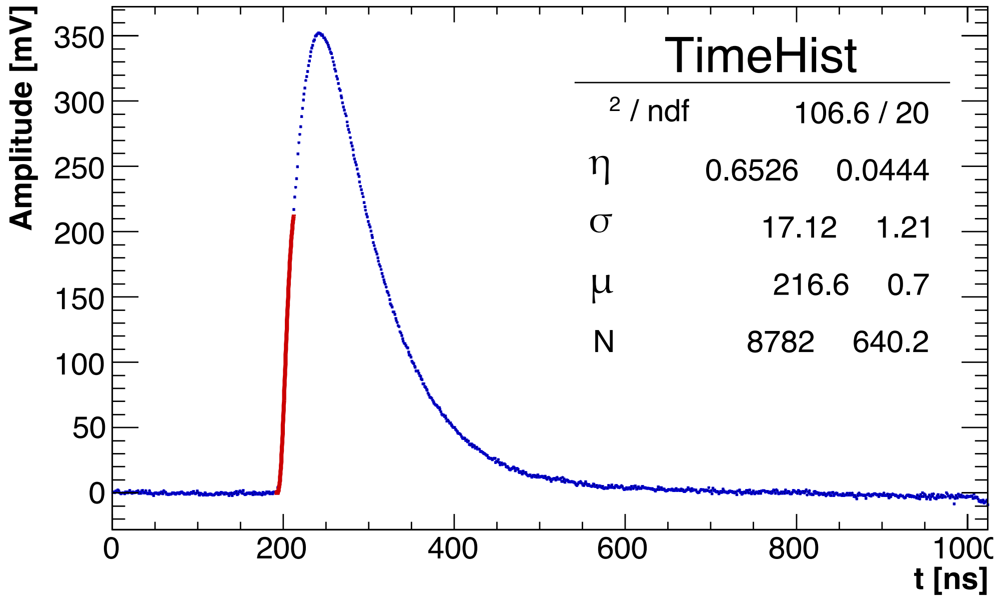




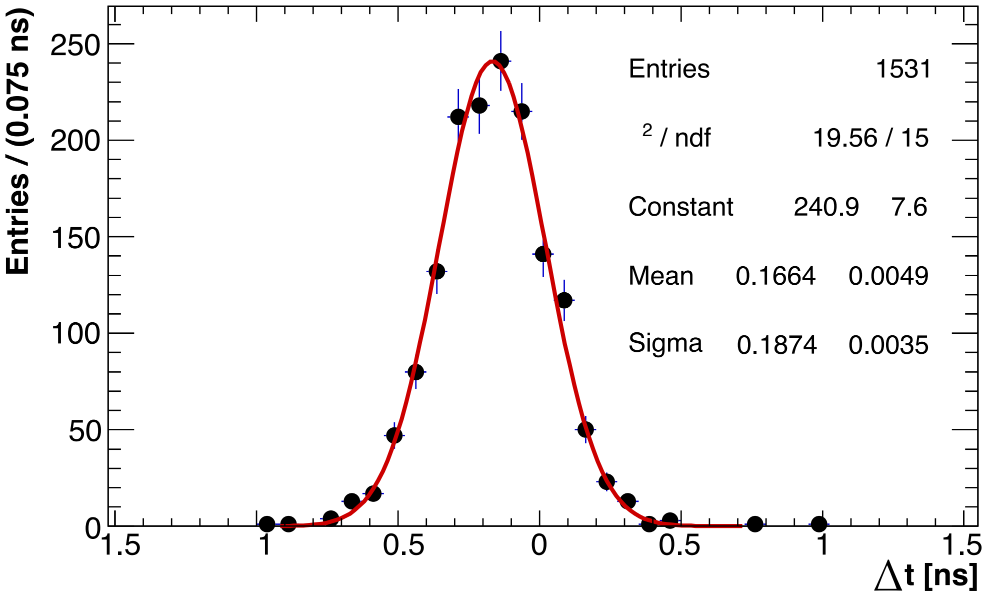
Module 0
Time resolution

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

Fit Example



Central crystal time distribution
($T_{SiPM\ 1} - T_{SiPM2}$)



σ (T1+T2)/2 ~ 94 ps
@ E_{beam} = 100 MeV

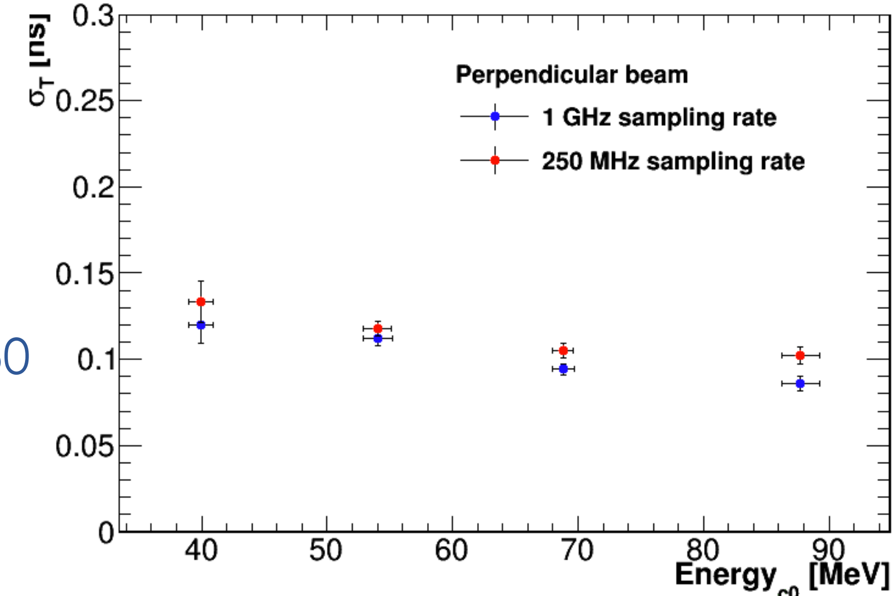
Module 0 Results

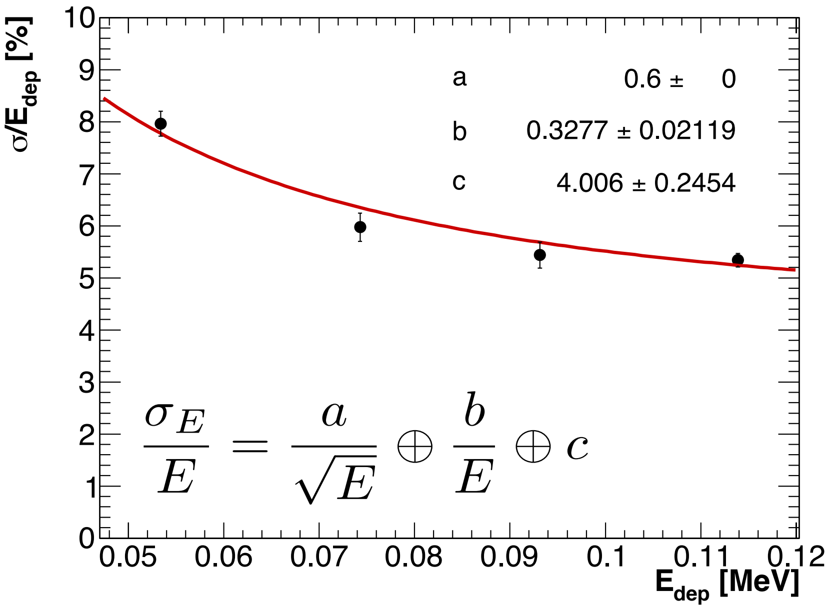
Test Beam data analysis results satisfy Mu2e requirements

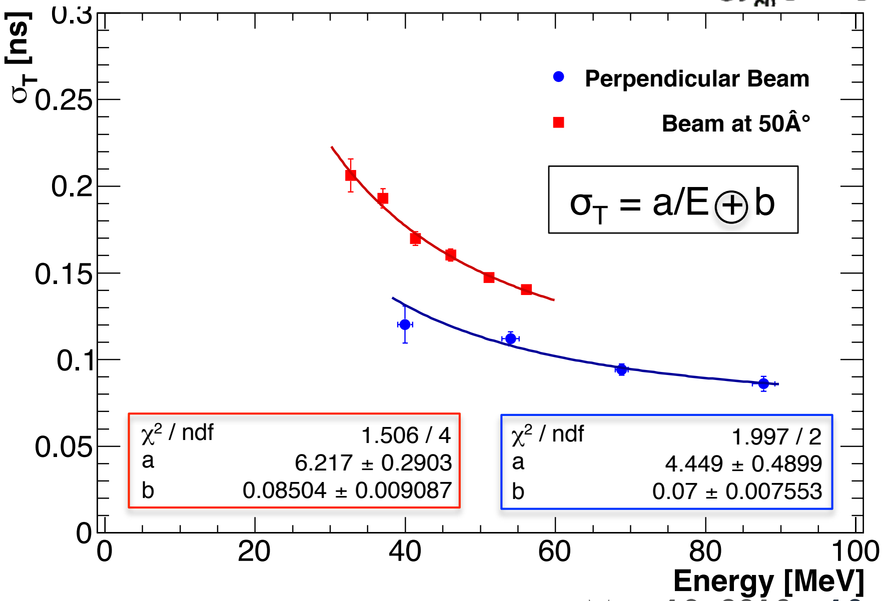
→ @ 100 MeV

- **σ_E ~ 5.44 ± 0.25 %**
- **σ_T < 100 ps**, both @ 1 GHz and 250 MHz sampling rate

→ MC simulation still on going

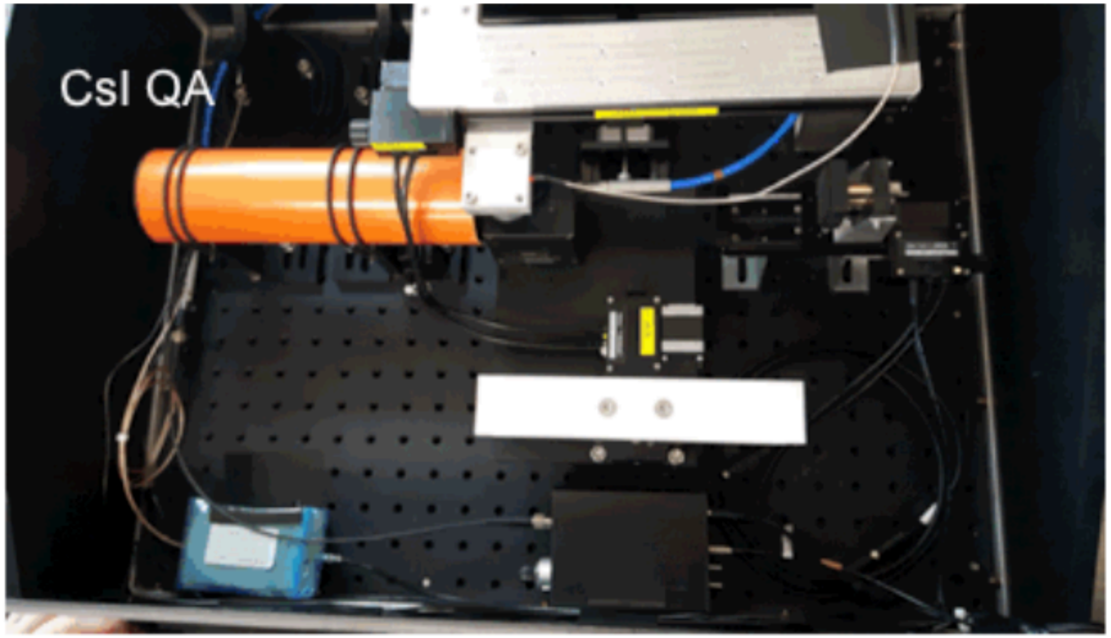


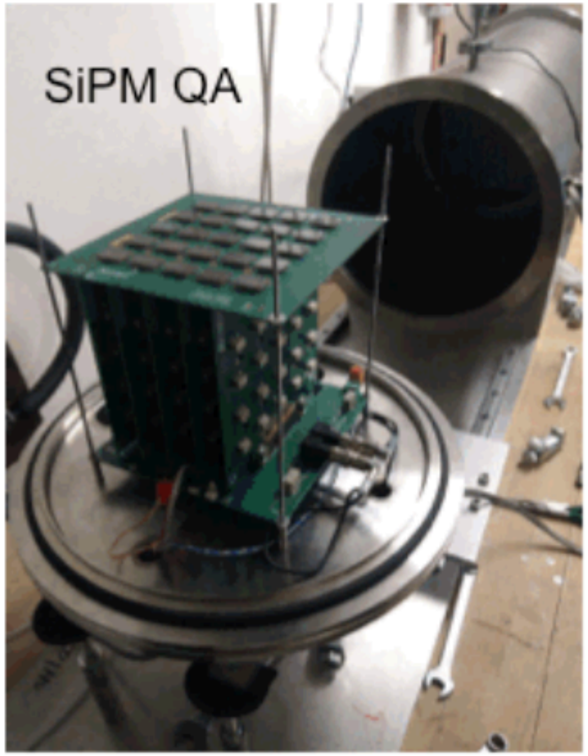


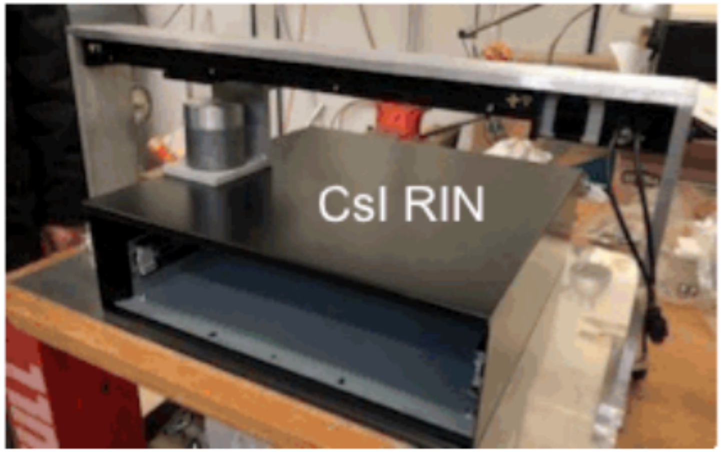


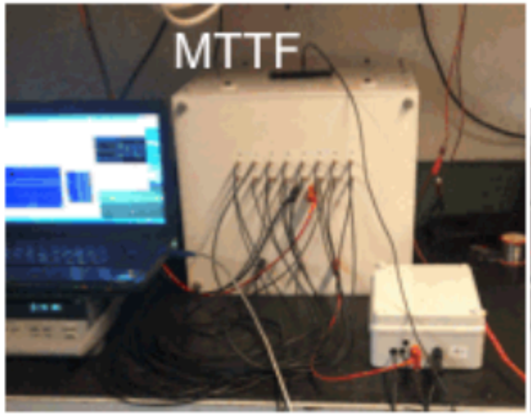
Calorimeter Assembly status

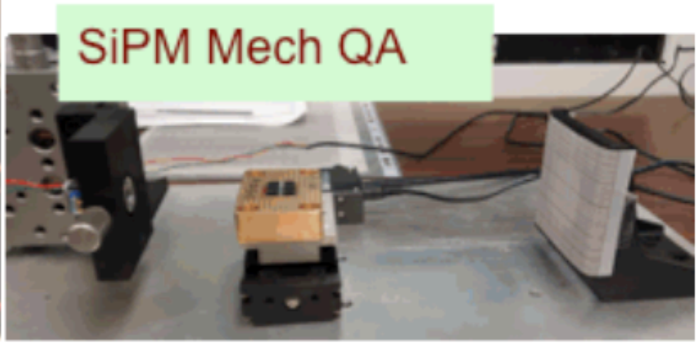
New laboratory built at FNAL. QA tests of all components started on march 2018











Summary and 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 > 0.6 million hours**
  - **Single calorimeter channel:** timing resolution of **215 ps /MIP**
  - **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
- Detector installation expected for beginning of 2020

Spares

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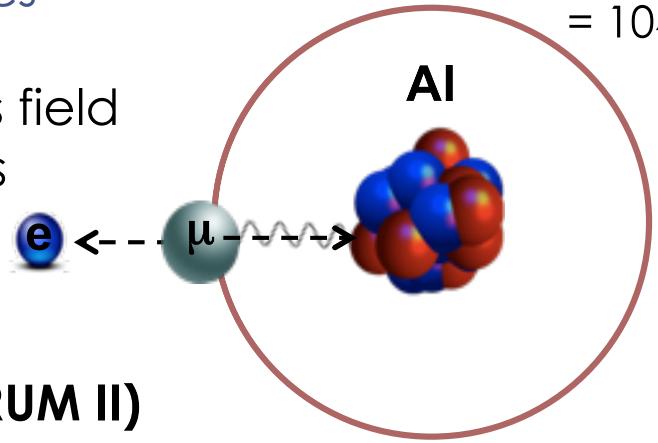
Charged Lepton Flavor Violation

- 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

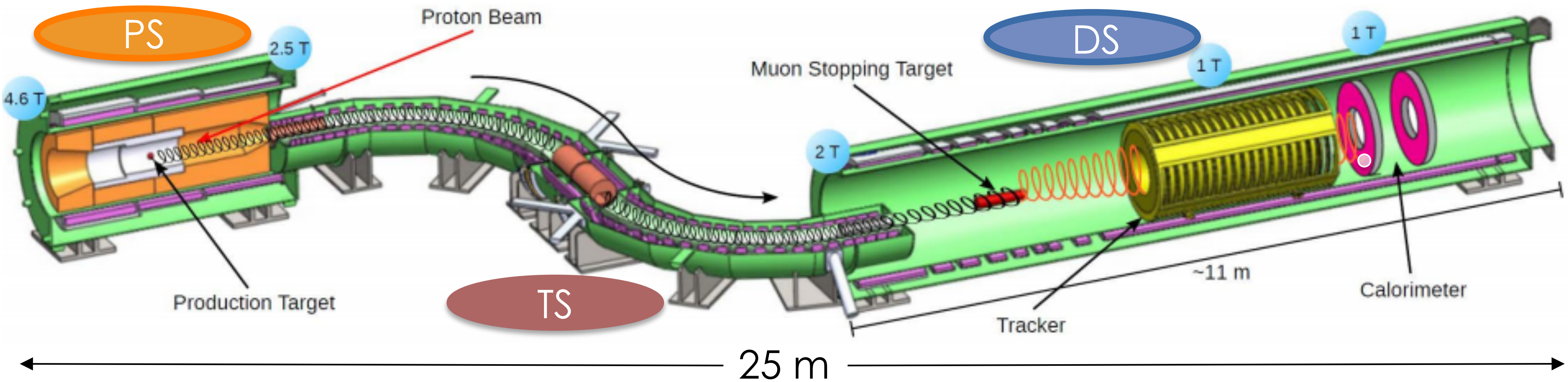
$$R_{\mu e} = \frac{\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)}{\mu^- + N(A,Z) \rightarrow \nu_\mu + N(A,Z-1)} < 8.4 \times 10^{-17}$$

Nuclear captures of muonic Al atoms

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

Mu2e experiment design

1. Generate low momentum μ^- beam
2. Stop the muons in an Al target → trapped in orbit around the nucleus
3. Look for an excess around 105 MeV/c in the electron spectrum



Production Solenoid / Target

- Protons hitting target and producing mostly π

Detector Solenoid: stopping target and detectors

- Stops μ^- on Al foils
- Events reconstructed by detectors optimized for 105 MeV/c momentum

Transport Solenoid

- Selects and transports low momentum μ^-

Charged Lepton Flavor Violation

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  → Observation indicates New Physics

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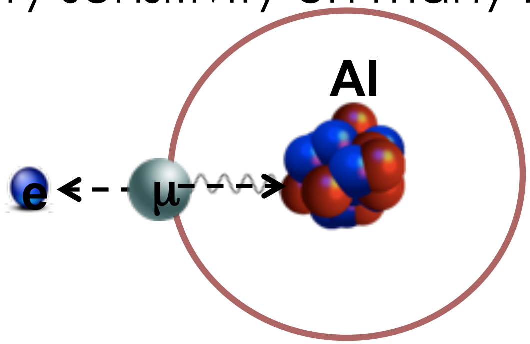

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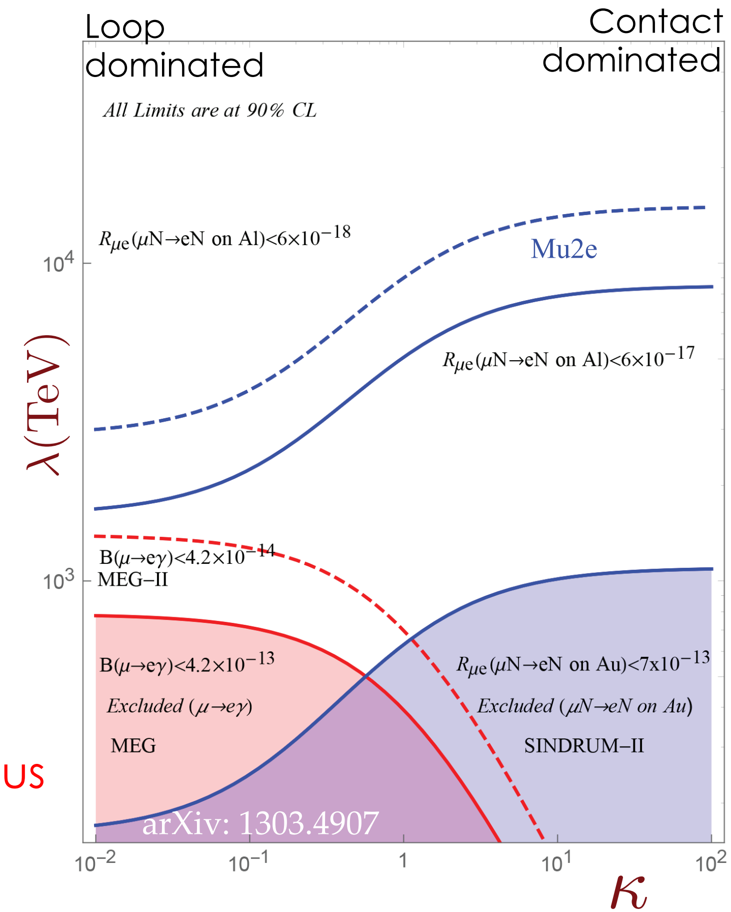
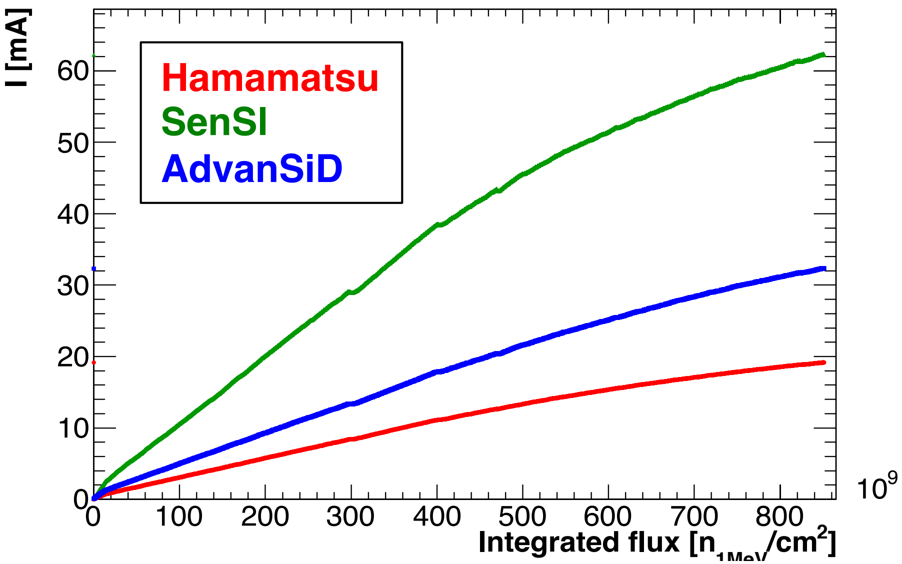


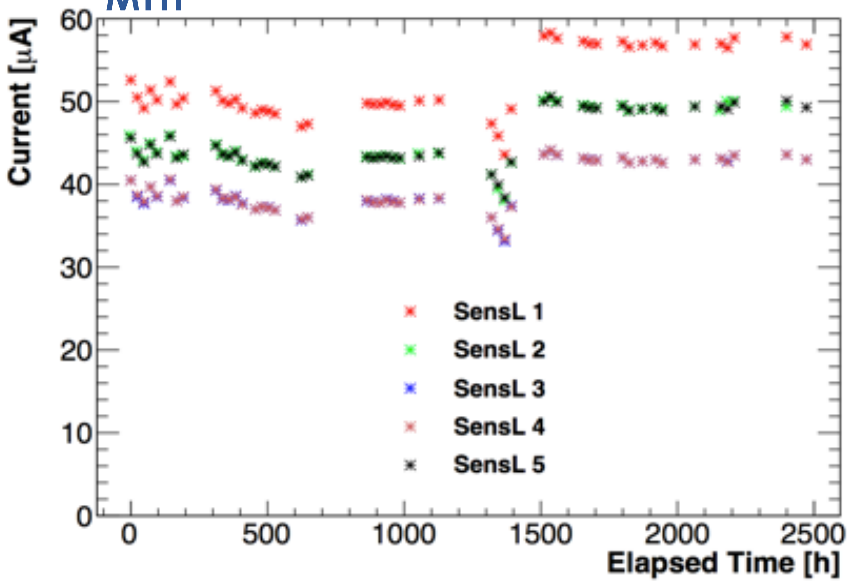
Pre-production test: SiPMs (2)

- 1 sample per vendor has been exposed to neutron flux up to 8.5×10^{11} n_{1MeVeq}/cm^2 (@ 20 °C)
- 5 samples per vendor have been used to estimate the mean time to failure value
  Requirement: obtain an MTTF of 1 million hours when operating at 0 °C

Neutron test



MTTF



- 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

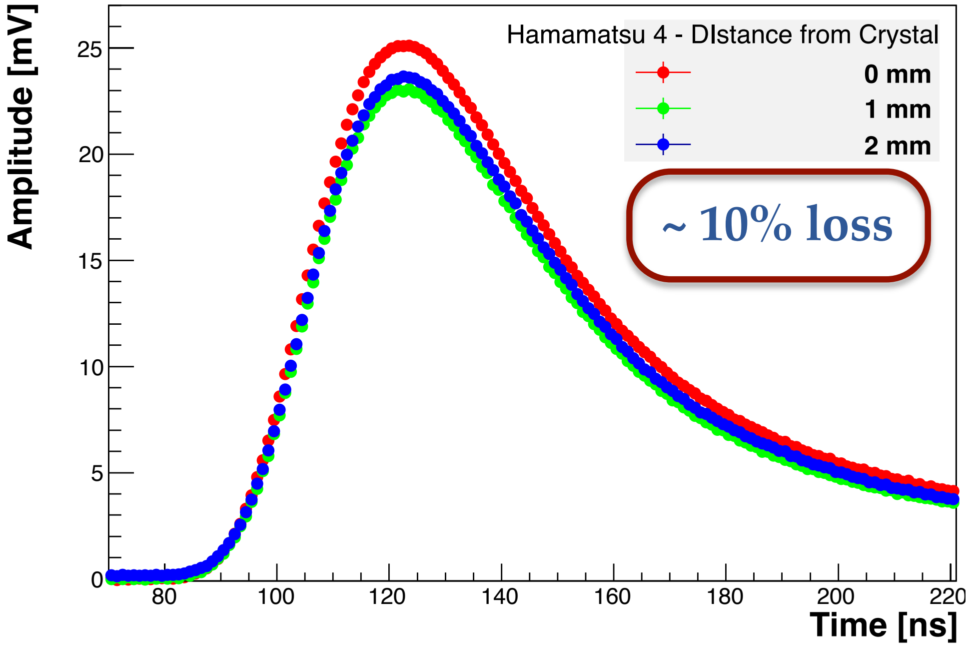
- MTTF evaluated operating SiPMs @ 50 °C for 3.5 months
- No dead channels observed

MTTF ≥ 6×10^5 hours

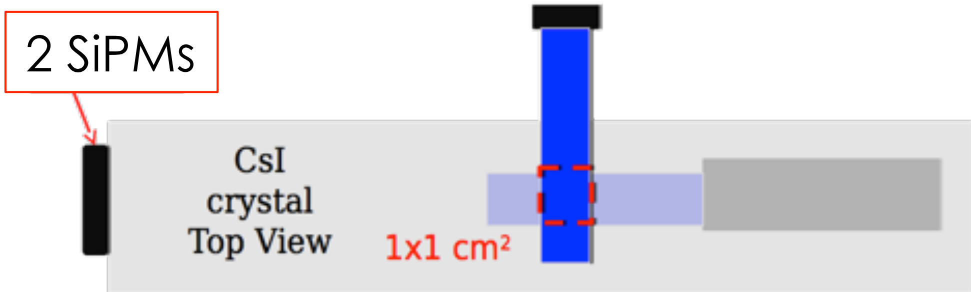
Single channel slice test

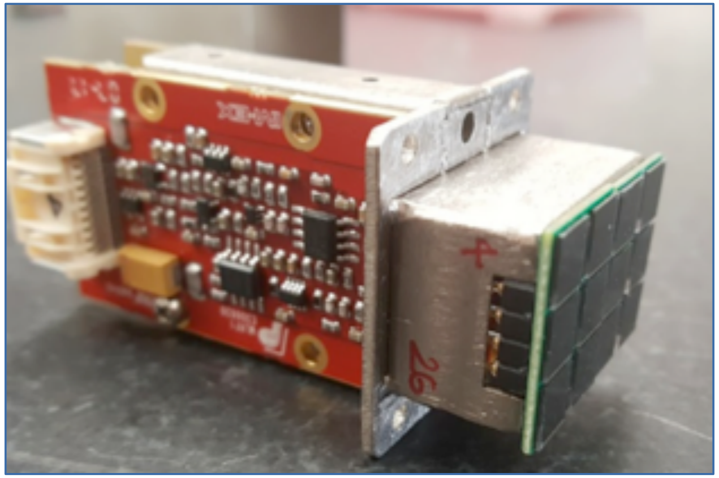
SG crystal + Hamamatsu SiPM + FEE
Optical coupling in air.

- **^{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





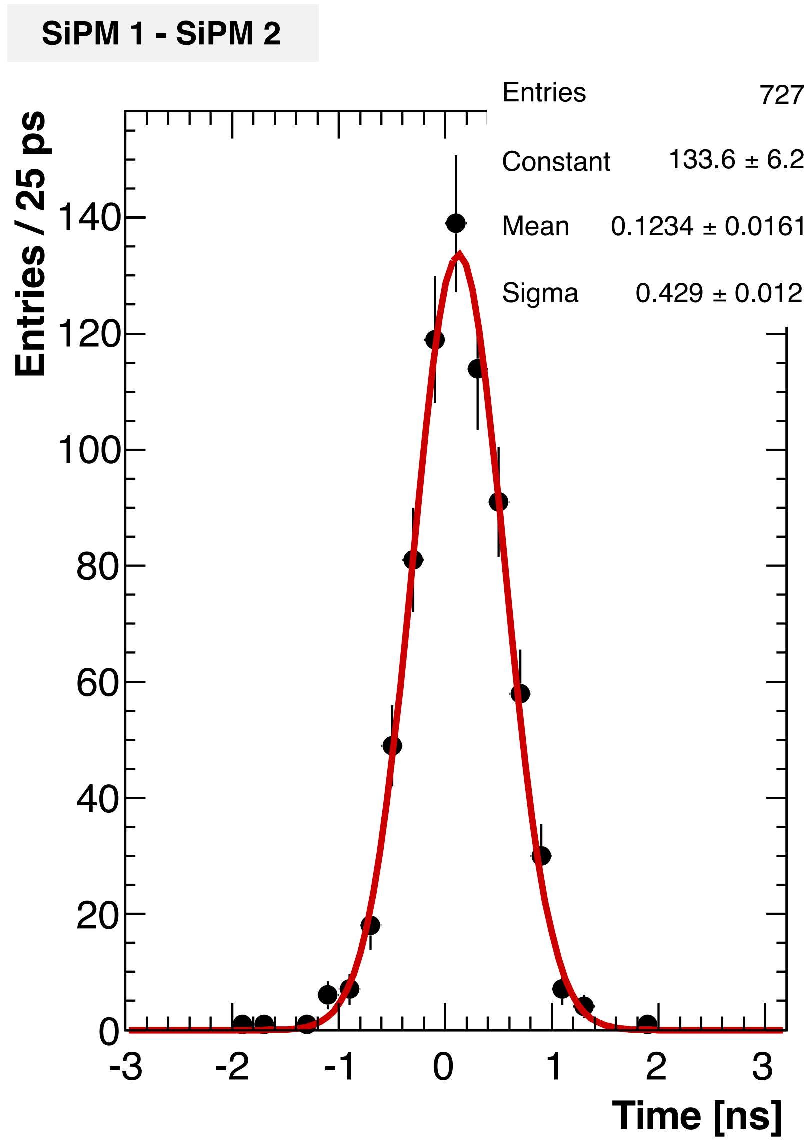
Single channel Cosmic Rays Test

- 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).

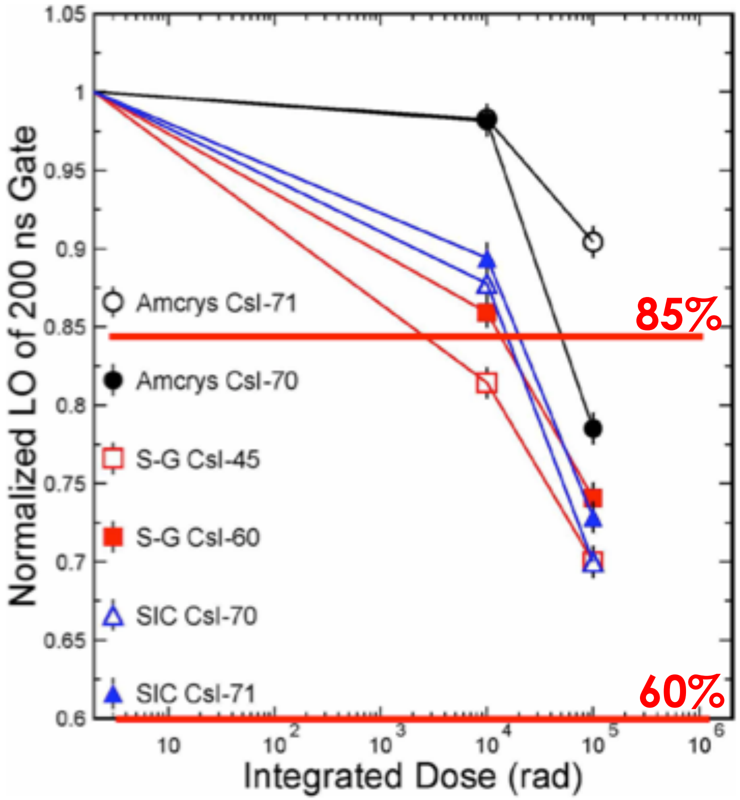


Pre-production test: Crystals (2)

Few samples per vendor have been exposed both to **ionizing dose** and **neutrons**

- Irradiation test up to 100 krad
- Requirement:
  normalized LY **after 10/100 krad > 85/60%**

Most crystals have LY larger than 100 p.e./MeV after 100 krad (40% max. loss), promising a robust CsI calorimeter



- **Radiation Induced Noise** (RIN) @ 1.8 rad/h required is **< 0.6 MeV**
  - All 72 samples tested. All OK apart some Amcrys crystals that do not satisfy the required limit
- Negligible LY and LRU variation after **1.6 x 10^{12} n_{1MeV}/cm^2 integrared flux**
- Neutron RIN is also smaller than the one from dose

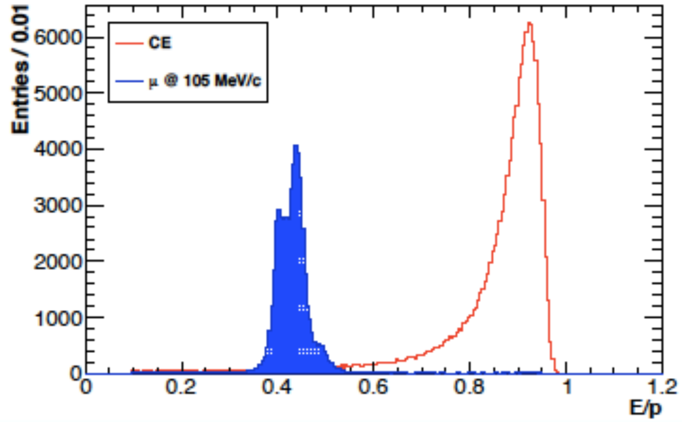
PId

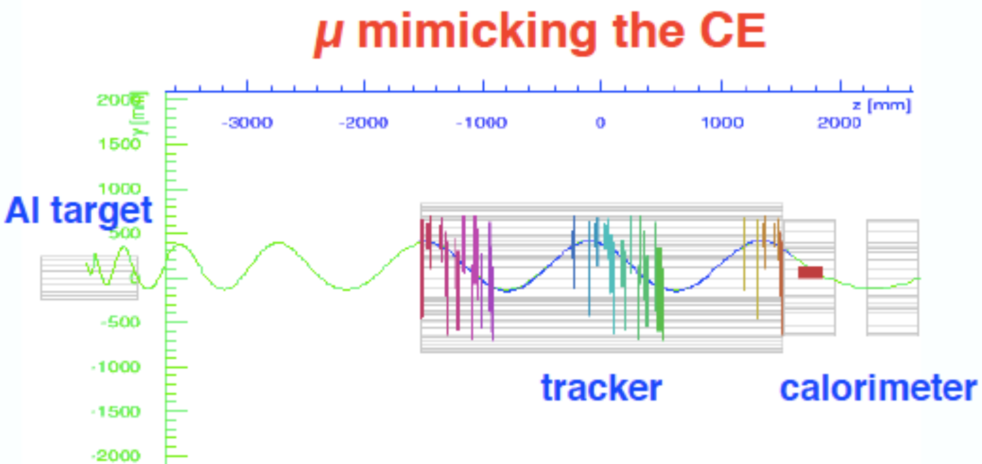
With a CRV inefficiency of 10^{-4} an additional rejection factor of ~ 200 is needed to have < 0.1 fake events from cosmics in the signal window

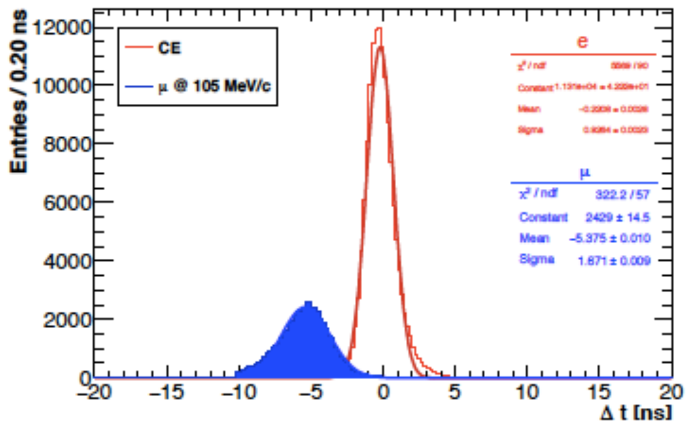
- 105 MeV/c e^- are ultra-relativistic, while 105 MeV/c μ have β~ 0.7 and a kinetic energy of ~ 40 MeV
- Likelihood rejection combines

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

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



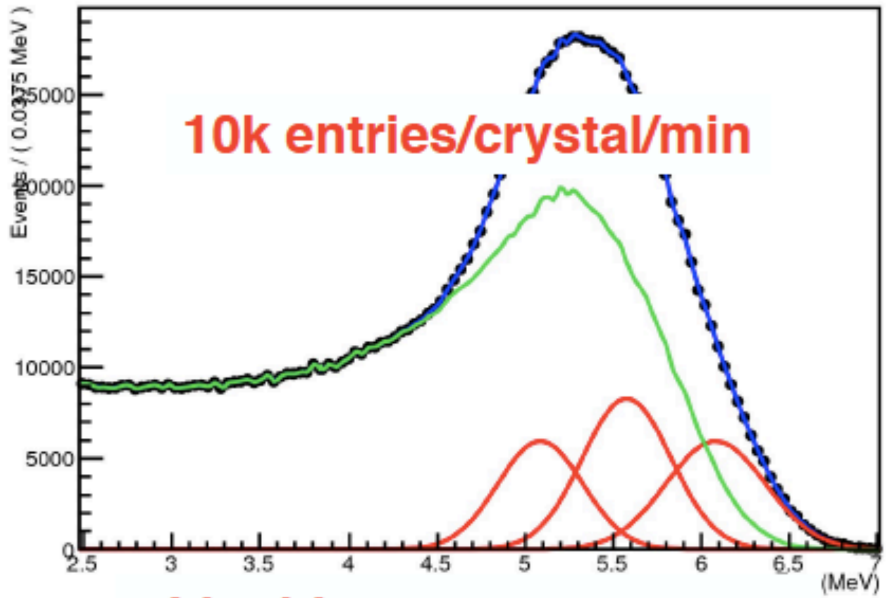


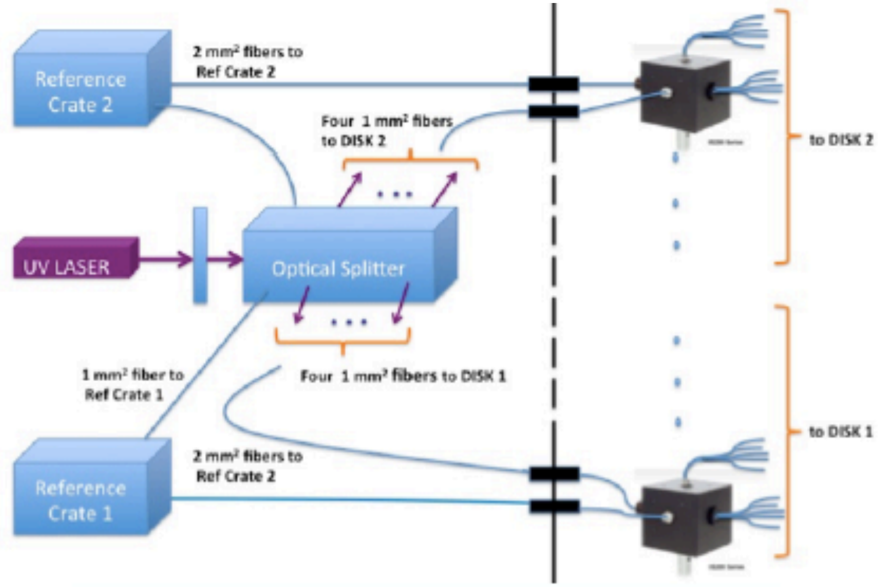


A rejection factor of 200 can be achieved with ~ 95% efficiency for CE

Calibration source and laser

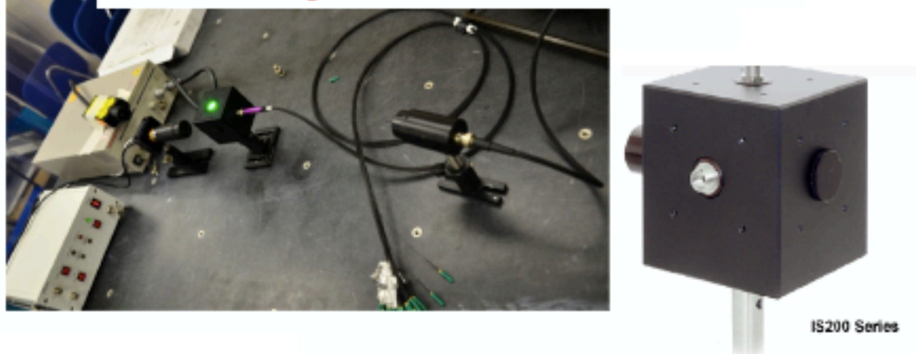
- Liquid source FC 770 + DT generator: 6 MeV + 2 escape peaks
- Laser system to monitor SiPM performance





Liquid source prototype

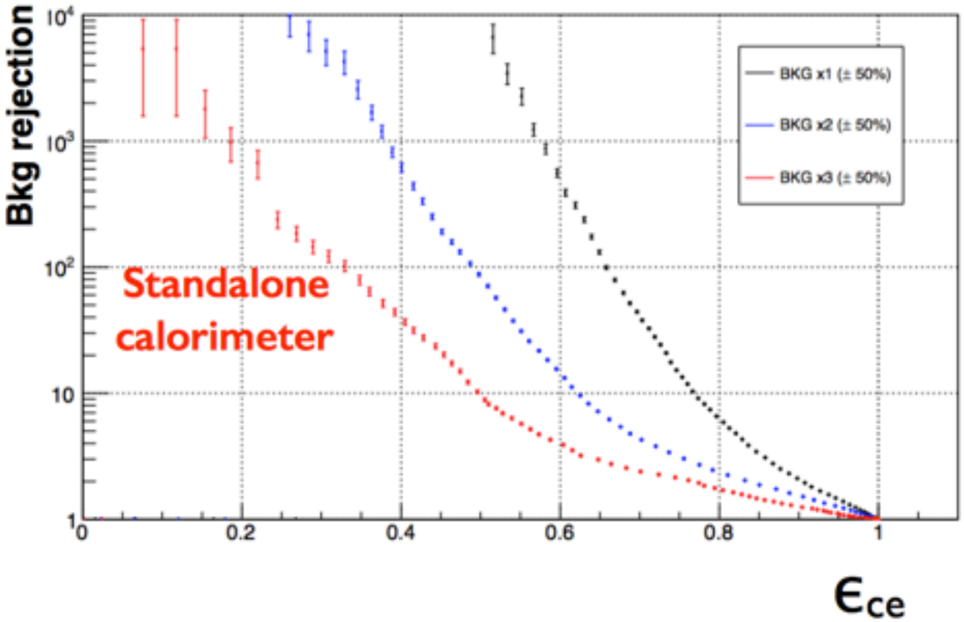
Laser system - test station

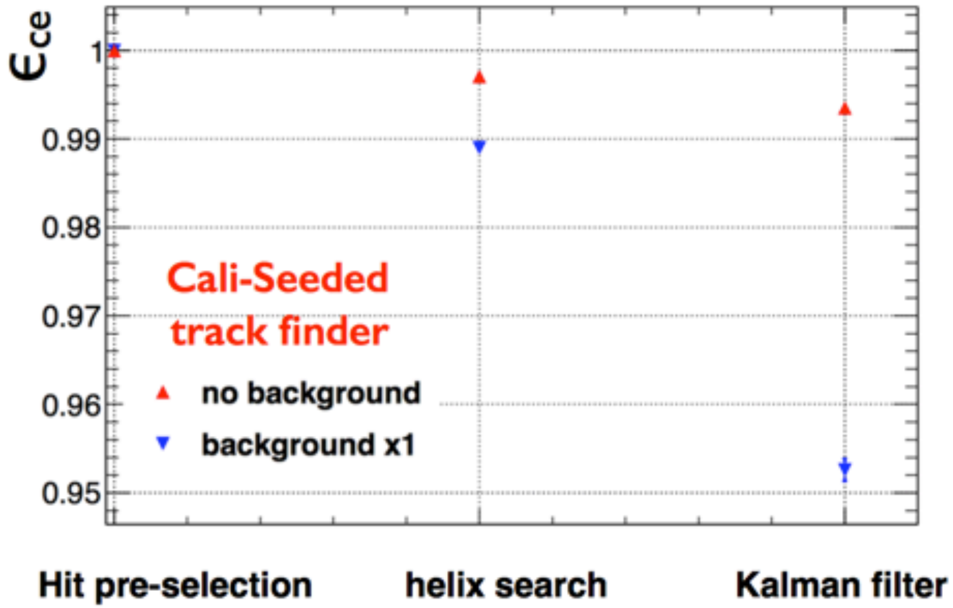


$$^{19}F + n \rightarrow \; ^{16}N + \alpha$$
$$^{16}N \rightarrow \; ^{16}O^{*} + \beta \quad t_{1/2} = 7 \text{ s}$$
$$^{16}O^{*} \rightarrow \; ^{16}O + \gamma (6.13 \text{ MeV})$$

Calorimeter Trigger

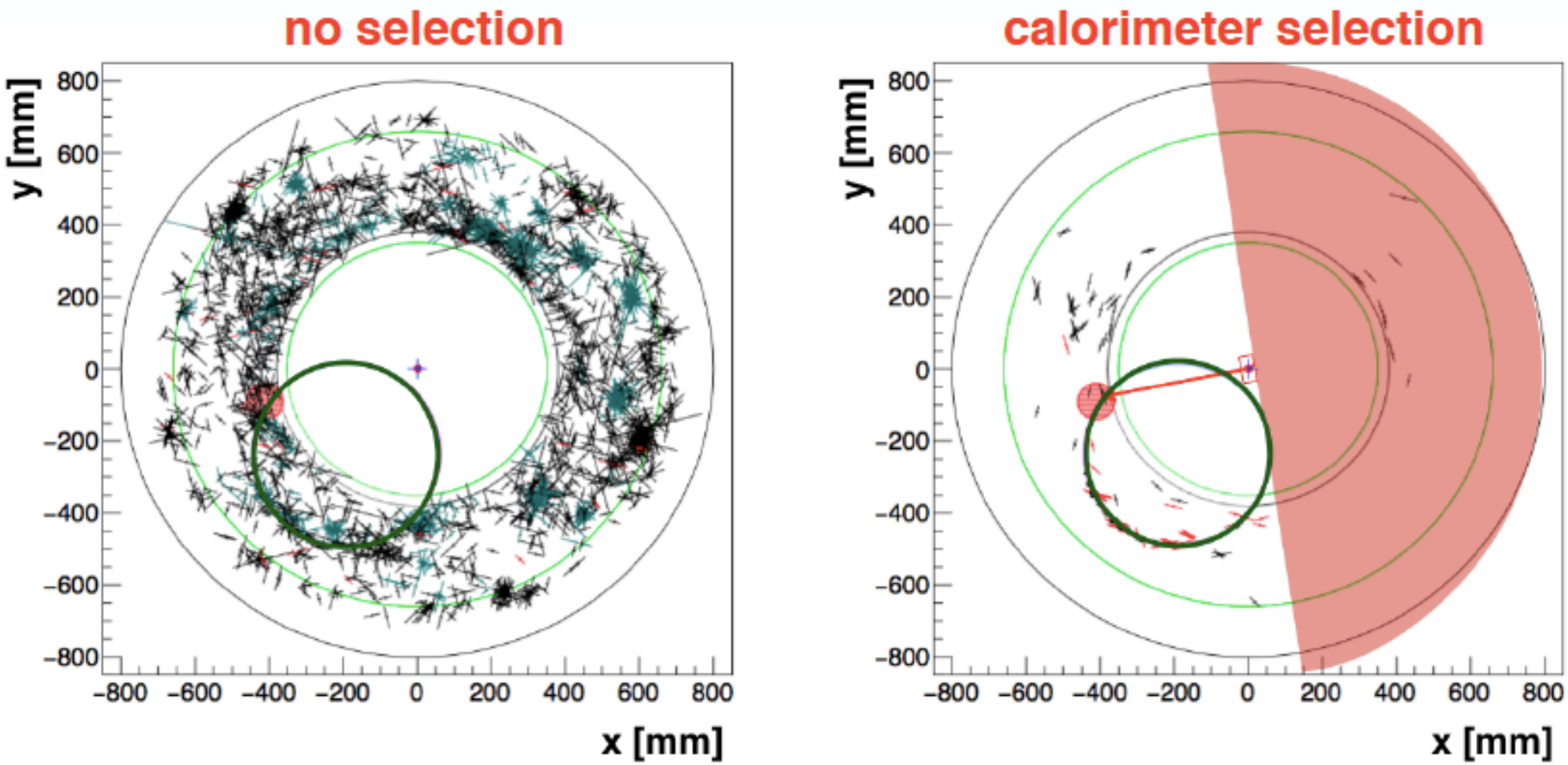
- Calo info can provide additional trigger capabilities in Mu2e:
- Calorimeter seeded track finder
  - Factorized into 3 steps: hit pre-selection, helix serach and track fit
  - ε ~ 95% for background rejection of 200
- Standalone calorimeter trigger that uses only calo info
  - E ~ 65% for background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

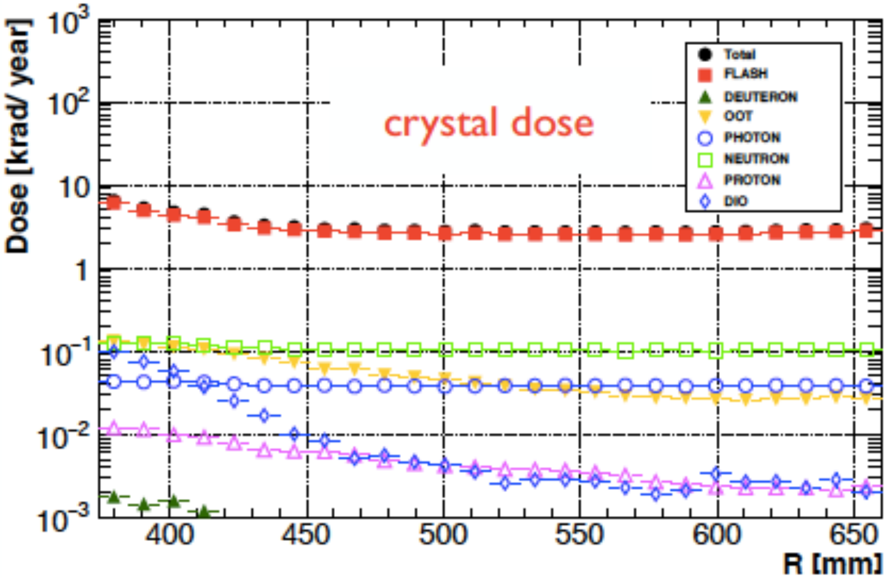
Calorimeter radiation damage

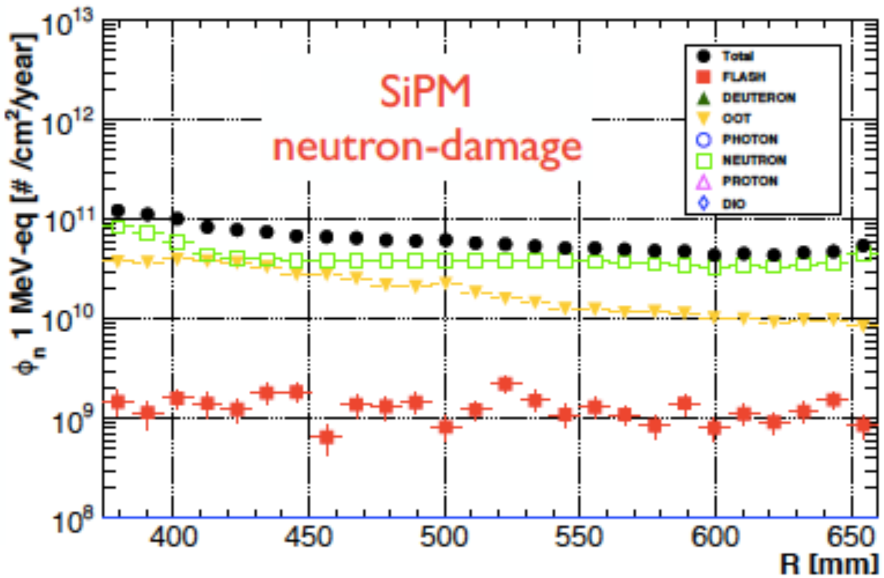
- Calorimeter radiation dose driven by beam flash (interaction of proton beam on target)
- Dose from muon capture is x10 smaller
- Dose is mainly in the inner radius
- Highest dose ~10 krad/year
- Highest n flux on crystals ~ 2×10^{11} n/cm^2/year
- Highest n flux on SiPM ~ 10^{11} n_{1MeVeq}/cm^2/year

• Qualify crystals up to ~ 100 krad, 10^{12} n/cm^2

• Qualify SiPM up to ~ 10^{12} n_{1MeVeq}/cm^2

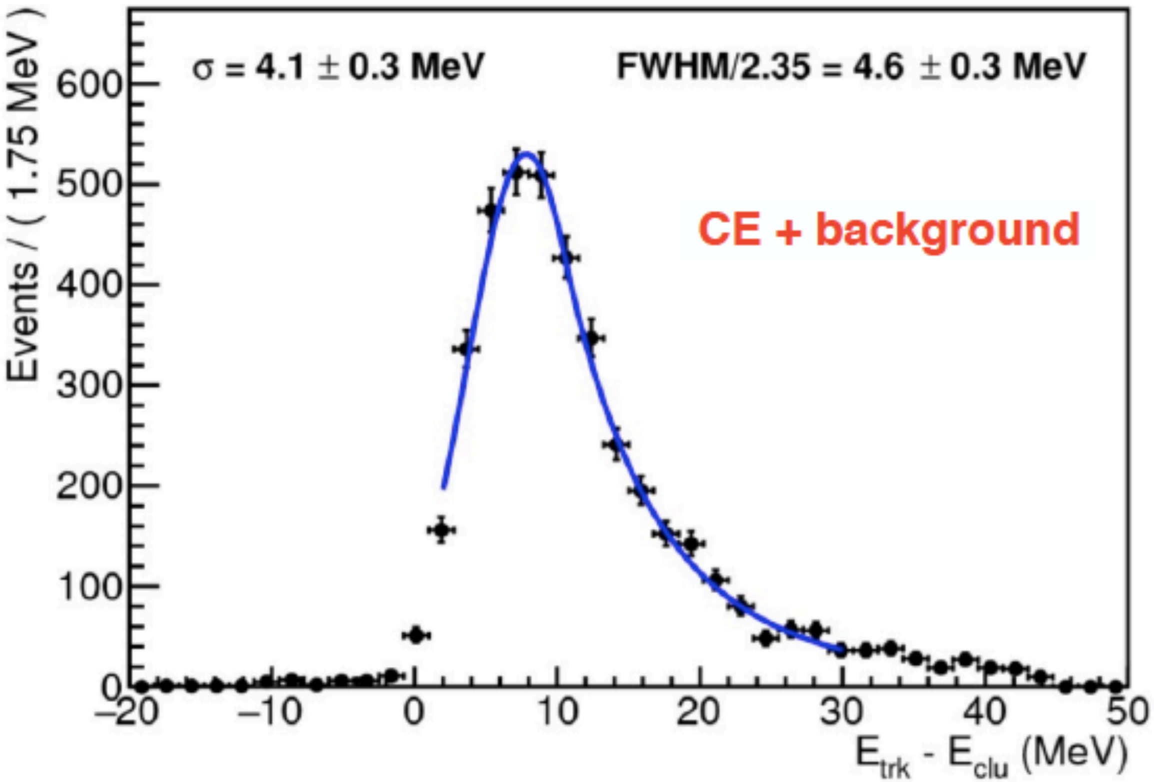
This includes a safety factor of 3 for a 3 year run



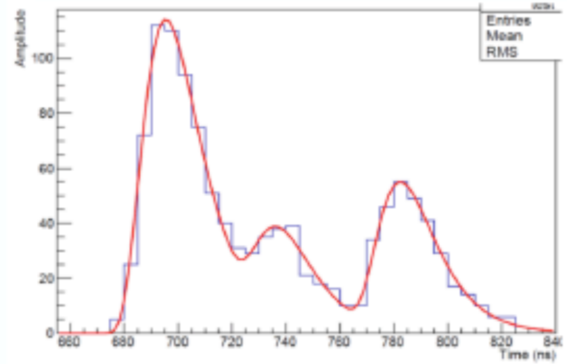


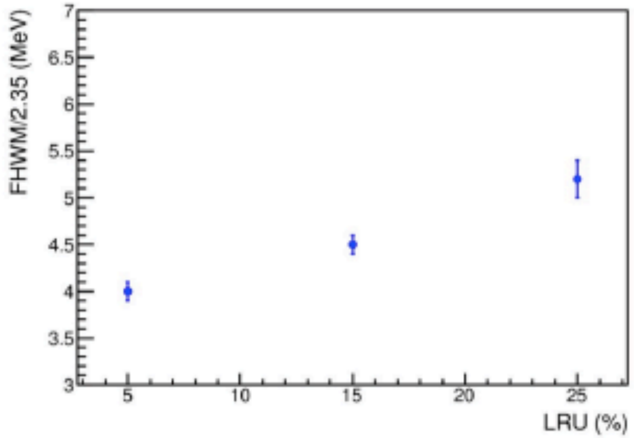
Calorimeter radiation damage

- Offline simulation including background hits
- Experimental effects included: longitudinal response uniformity (LRU), electronic noise, digitization, etc
- Waveform-based analysis to improve pileup separation

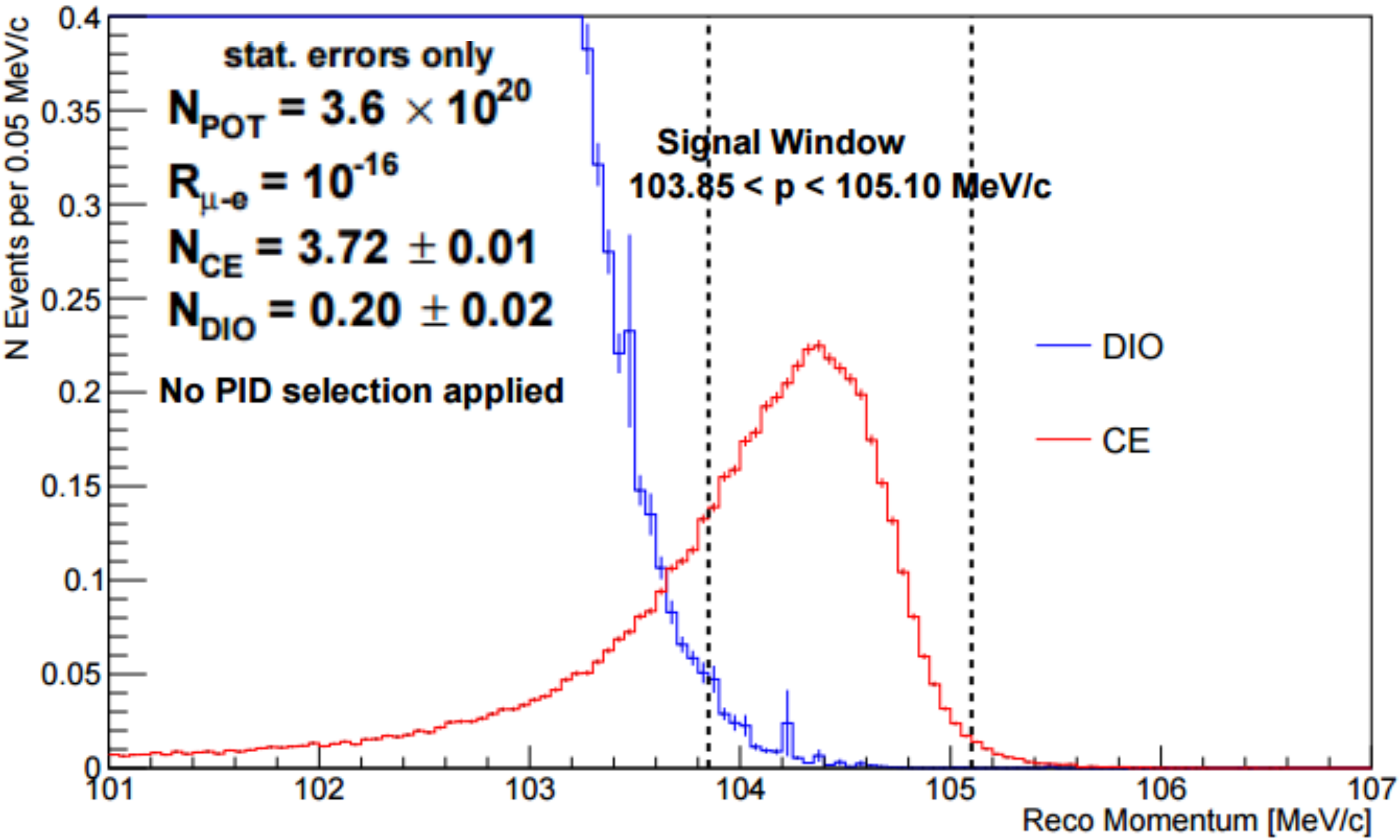


pile-up separation





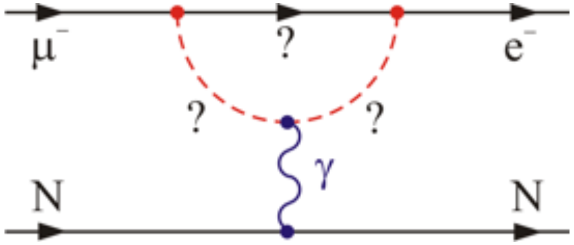
Three years run
Expectation by full Simulation



CLFV Lagrangian

$$L_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

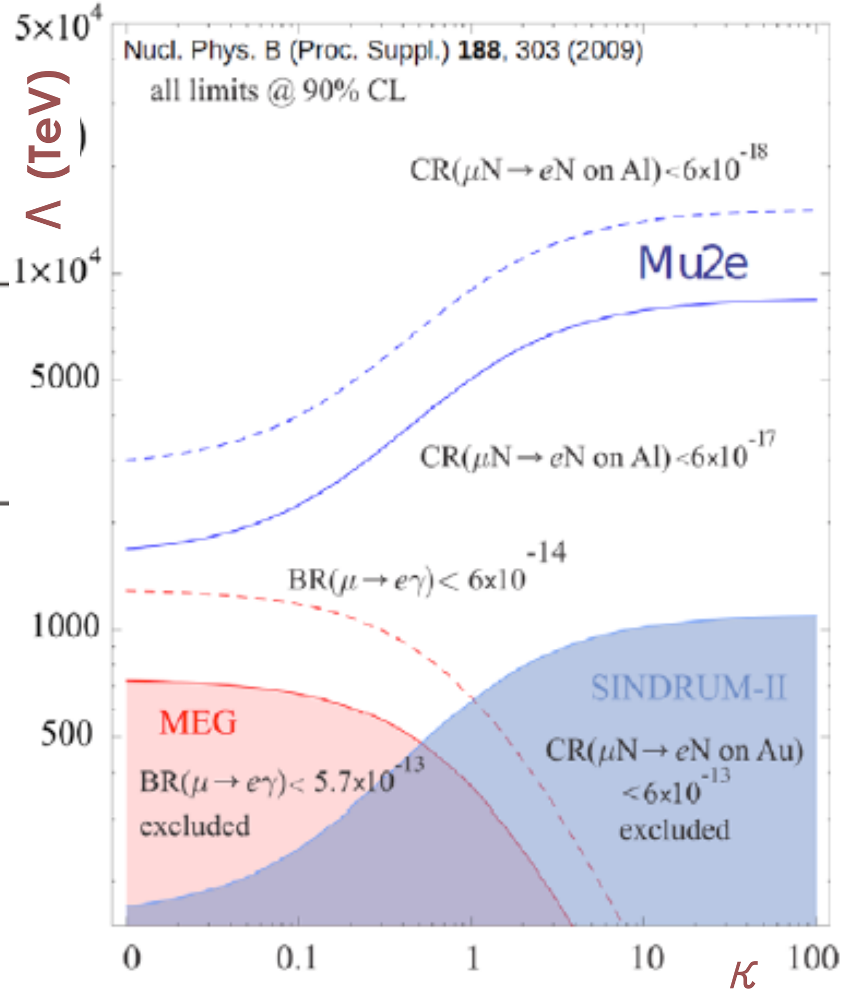
Loops dominate for
κ << 1



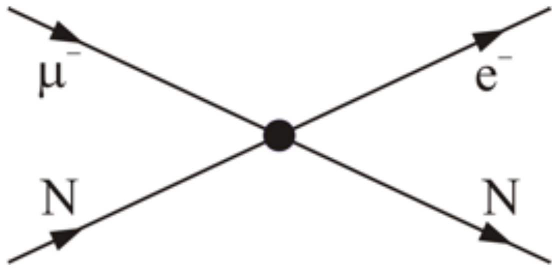
$\mu \to e\gamma$

$\mu N \to eN$

$\mu \to eee$



Contact terms
dominate for
κ >> 1



~~$\mu \to e\gamma$~~

$\mu N \to eN$

$\mu \to eee$