Design and test of the Mu2e undoped CsI + SiPM crystal calorimeter

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On behalf of the Mu2e calorimeter group

May 29, 2018
Frontier Detectors for Frontier Physics
14th Pisa Meeting on Advanced Detectors

ROMA TRE UNIVERSITÀ DEGLI STUDI

Fermilab

INFN Istituto Nazionale di Fisica Nucleare

Talk overview

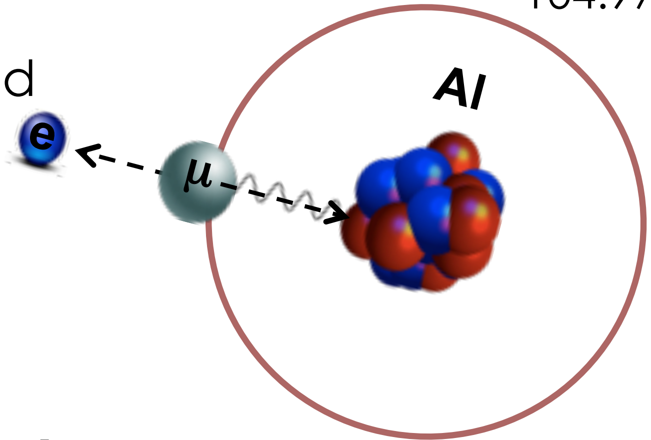
- Mu2e
  - CLFV Introduction
  - Experiment layout and detectors
- Calorimeter requirements
  - Components
  - Single Channel Tests
  - Prototypes' performance
  - Production phase

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

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

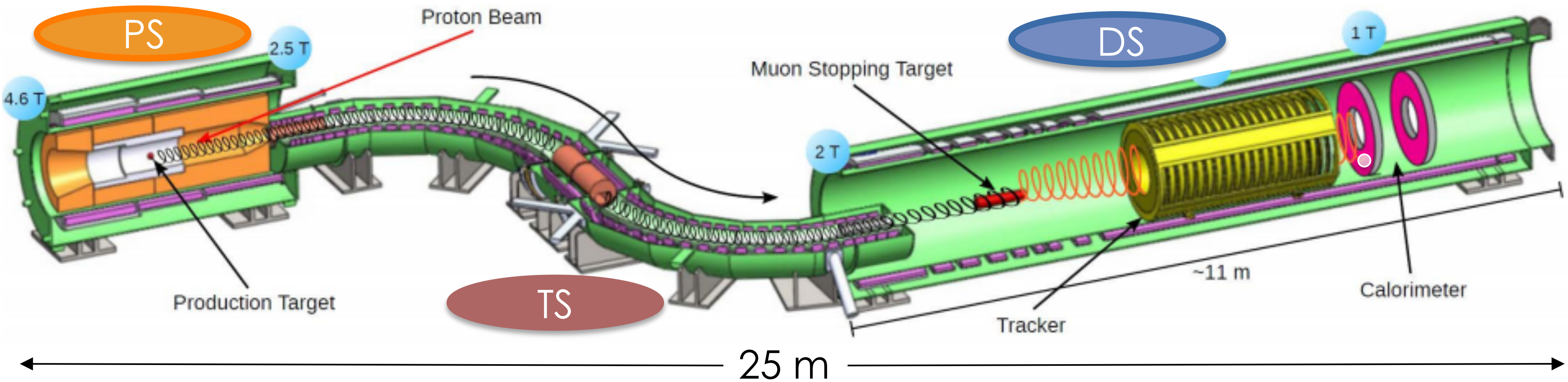
Nuclear captures of muonic Al atoms

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

More information at mu2e.fnal.gov

Mu2e experiment design

1. Generate 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

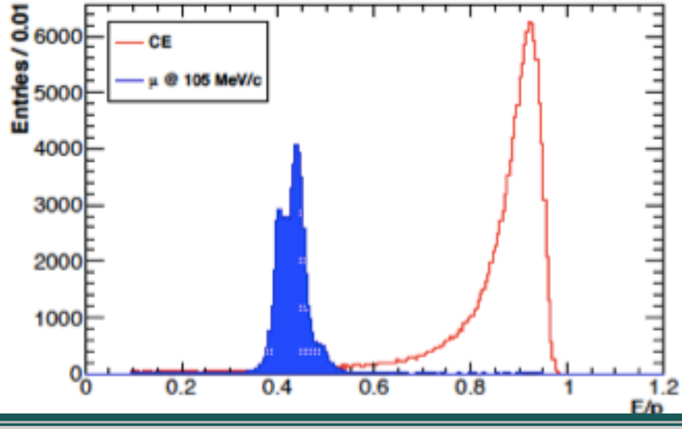
Transport Solenoid

- Selects and transports low momentum μ^-

Calorimeter requirements

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

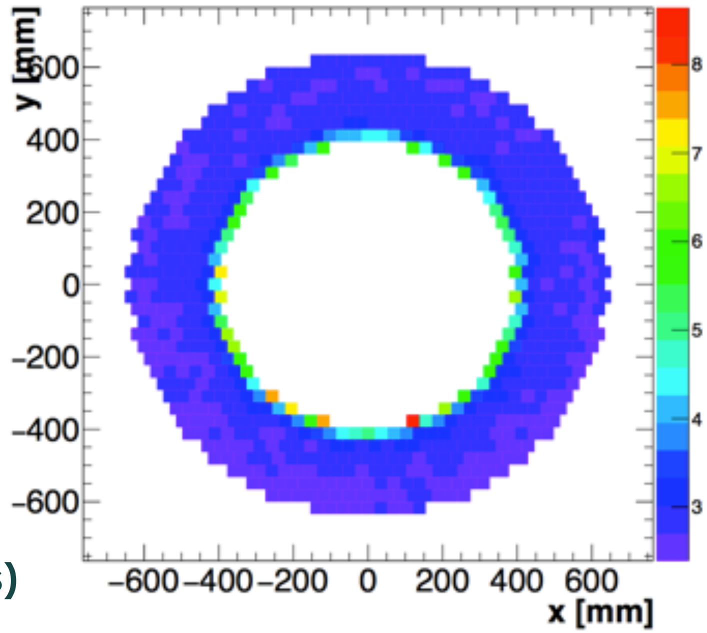
1) **PID: e/μ separation**
2) **EMC seeded track finder**
3) **Standalone trigger**



Requirements @ 105 MeV/c

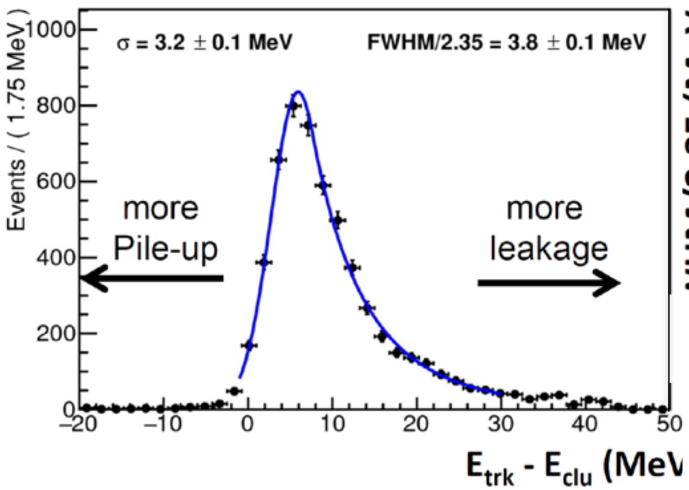
- **$\sigma_E/E = \mathcal{O}(10\%)$ for CE**
- **σ_T < 500 ps for CE**
- **$\sigma_{X,Y} \lesssim 1$ cm**

- 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

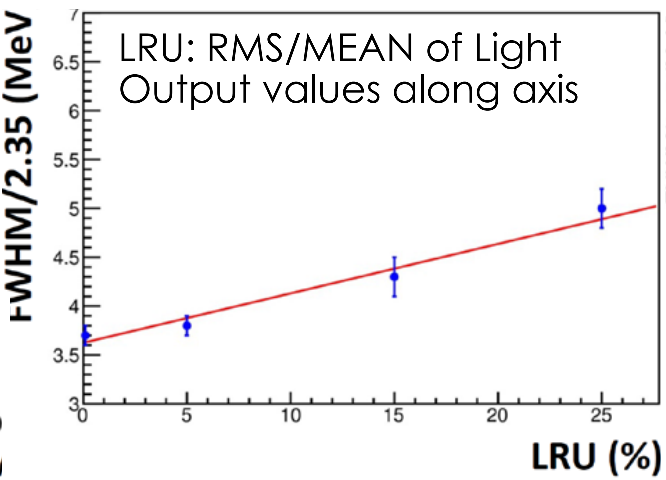


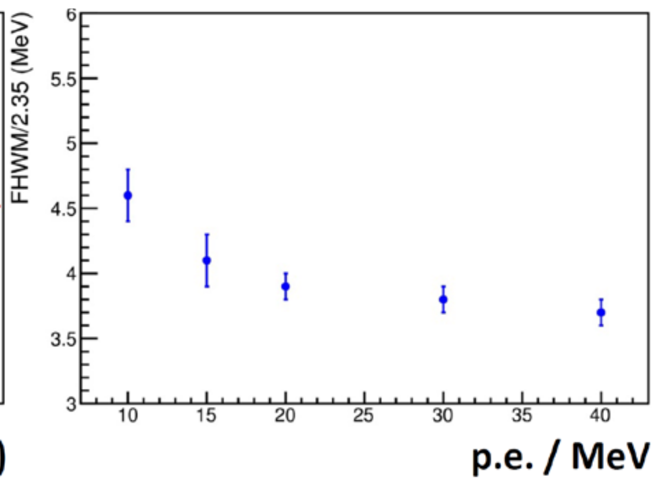
Front Disk Dose – 1 year [krad]

Simulated performance



FWHM / 2.35 = 3.8 ± 0.1 MeV



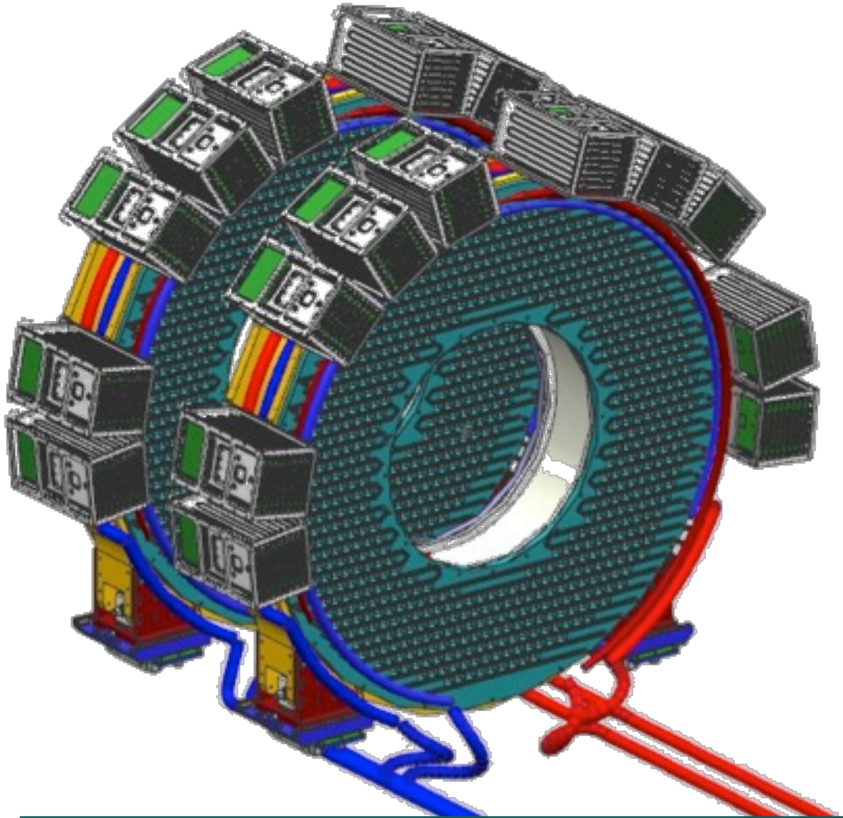


- **Simulation includes full background and digitization and cluster-finding, with split-off and pileup recovery**
- The overall resolution depends on crystals features
  - Several crystals considered

	LYSO	BaF_2	CsI
Radiation Length X_0 [cm]	1.14	2.03	1.86
Light Yield [% NaI(Tl)]	75	**4**/36	3.6
Decay Time[ns]	40	**0.9**/650	20
Photosensor	APD	**RMD APD**	SiPM
Wavelength [nm]	402	**220**/300	310

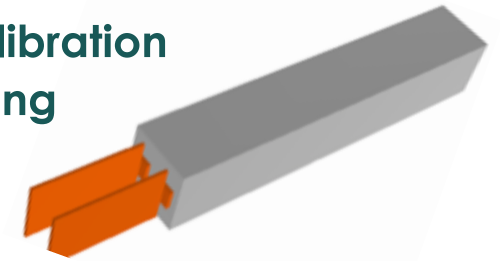
$

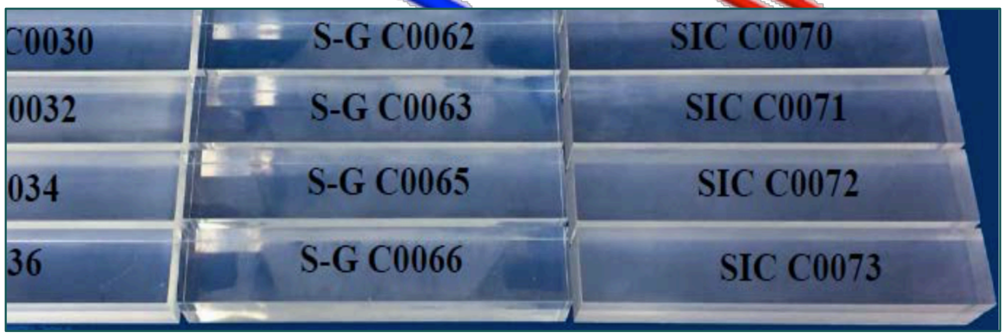
Calorimeter Design

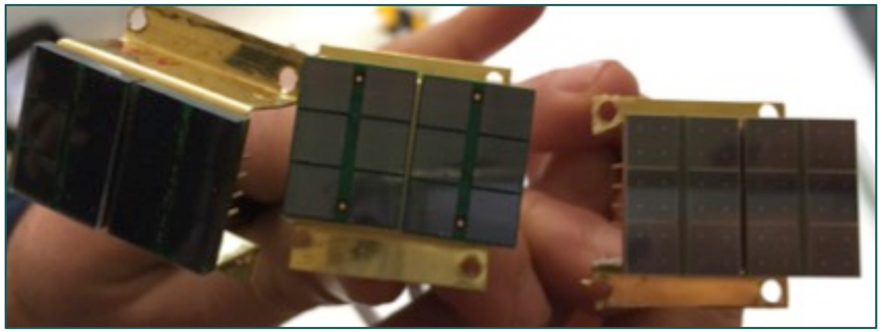


2 annular disks with 674 undoped CsI (34 x 34 x 200) mm^3 square crystals/each disk

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

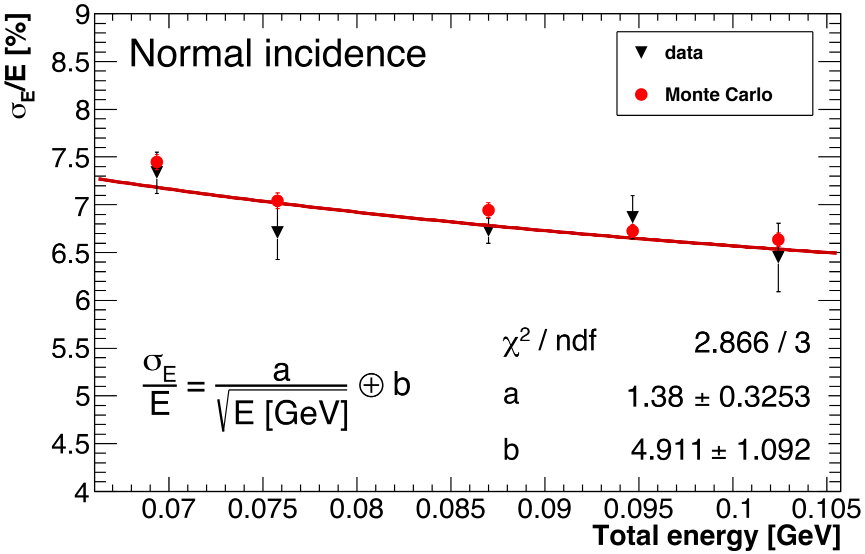


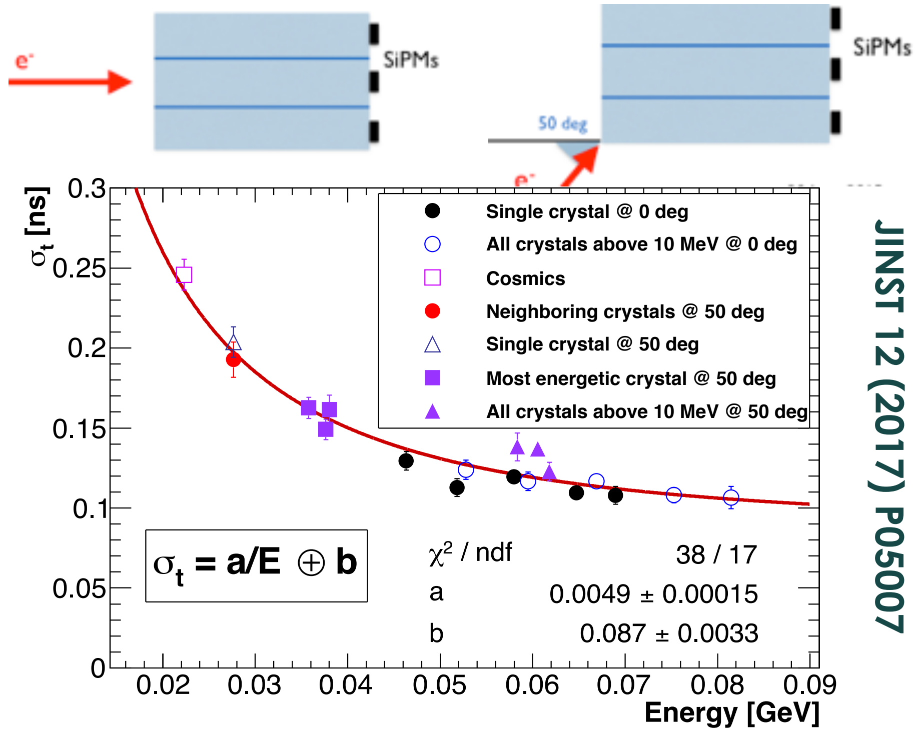




Small prototype: Time and Energy resolution

Small prototype 3x3 tested @ BTF (LNF) in 2015, **80-120 MeV e⁻**





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σ_E ~ 7 % at 100 MeV **σ_T ~ 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

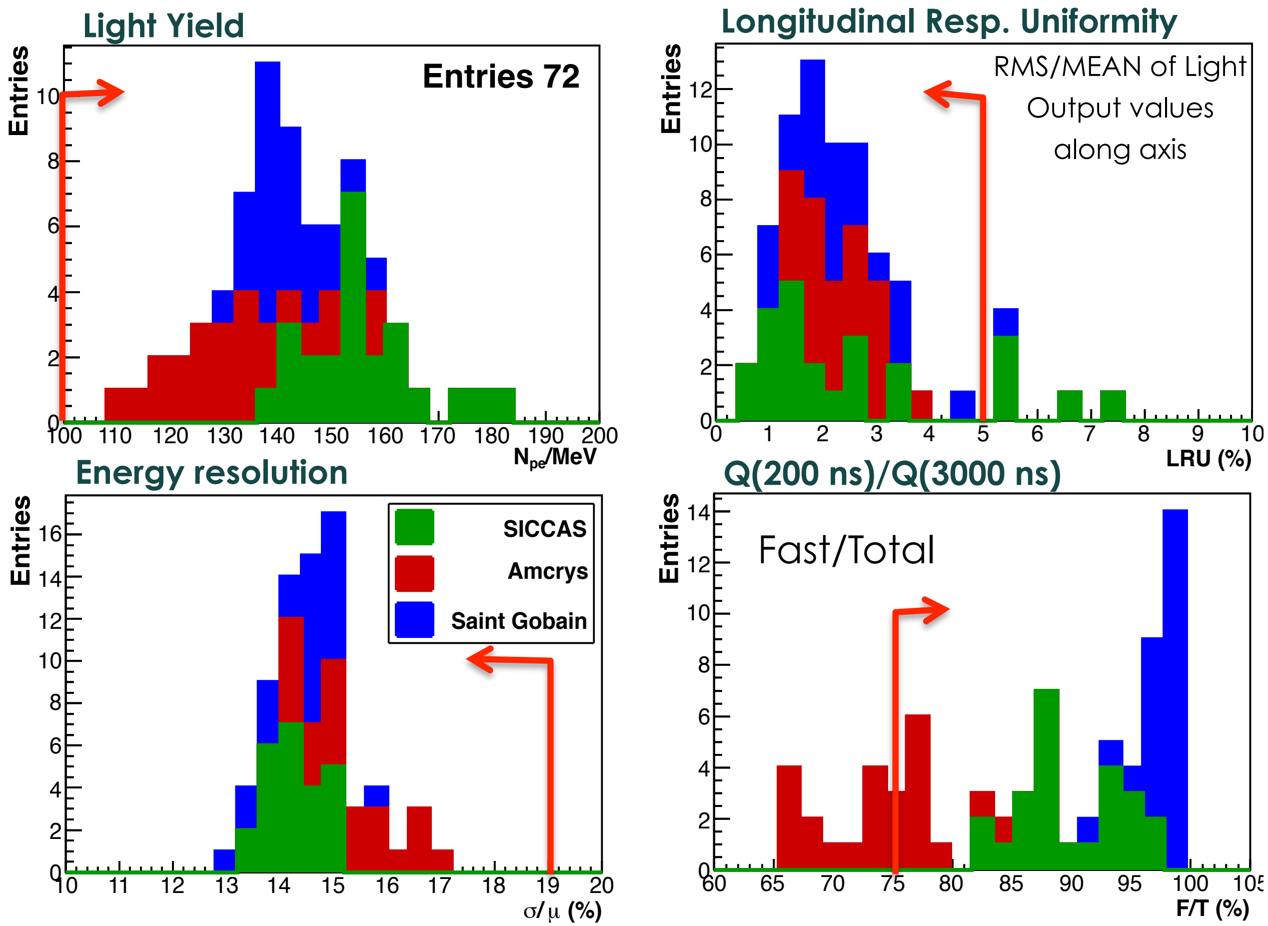
- 24 crystals from **SICCAS**, **Amcrys**, **Saint Gobain**
- Optical properties tested with **511 keV γ's** along the crystal axis
- 150 μm **Tyvek** wrapping and UV-extended **PMT** readout

Un-doped CsI crystals perform well:

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

- **τ of 30 ns** (small slow component)

- **Radiation hardness OK**
  LY loss < 40% (@ 100 krad)

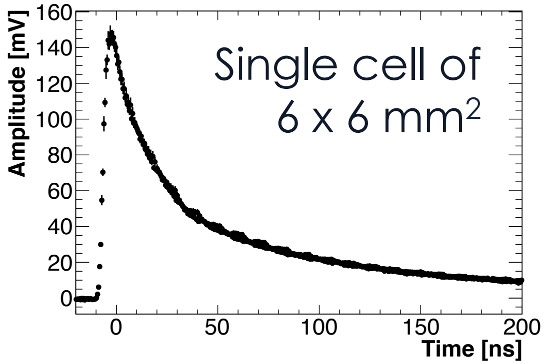


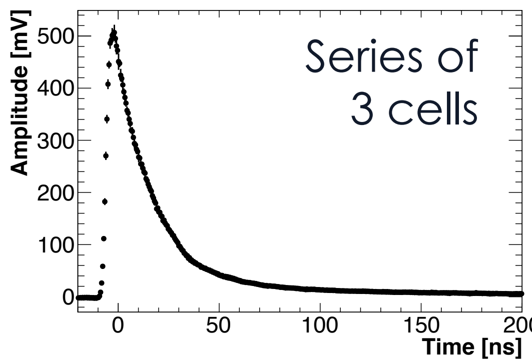
Pre-production SiPMs

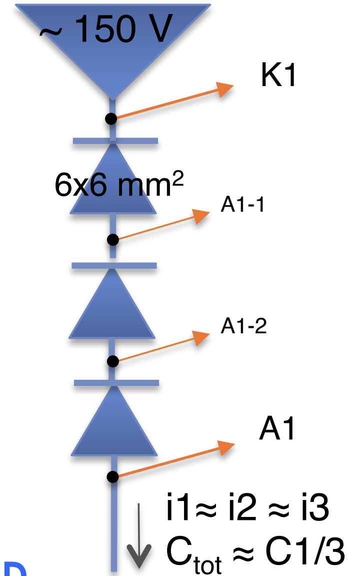
Mu2e custom silicon photosensors:

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

The readout series configuration reduces the overall capacitance→faster signals

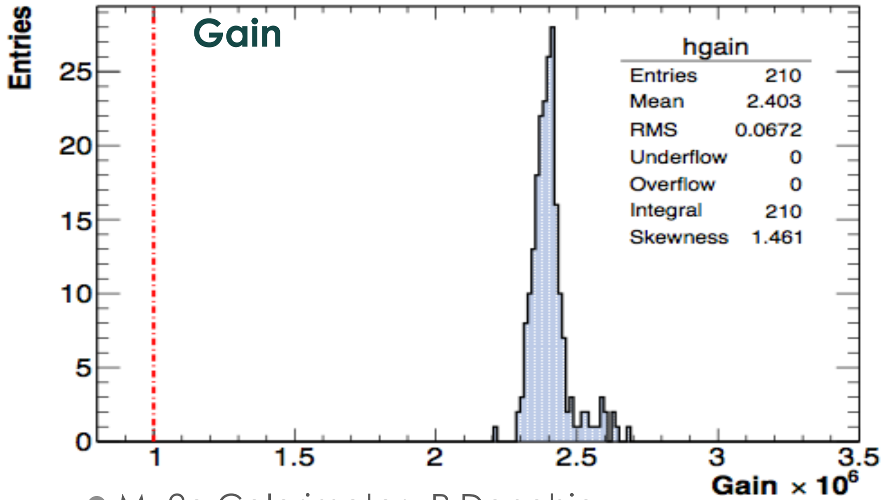


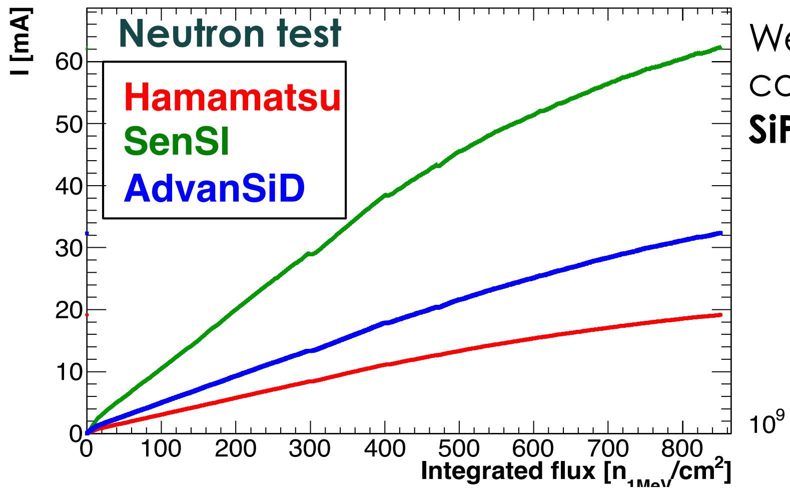




150 sensors: 3×50 Mu2e pre-production SiPMs from **Hamamatsu**, **SenSI** and **AdvanSiD**

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





We need to cool down **SiPMs at 0 °**

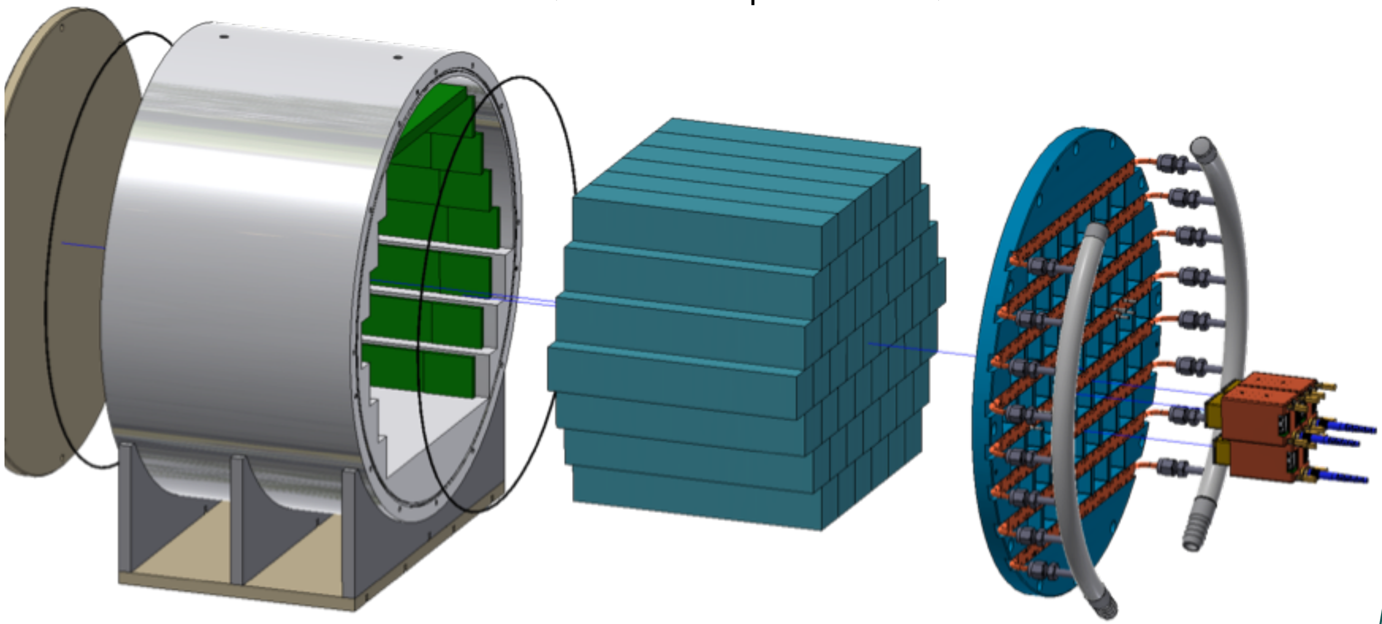
Module 0

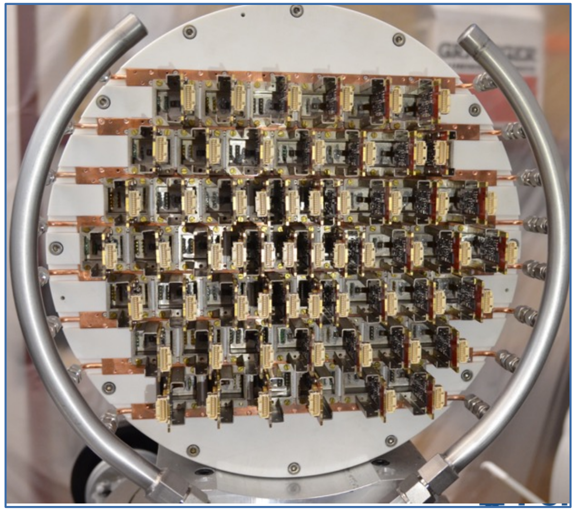
Large EMC prototype: **51 crystals, 102 SiPMs, 102 FEE boards**

Mechanics and cooling system similar to the final ones!

Goals:

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

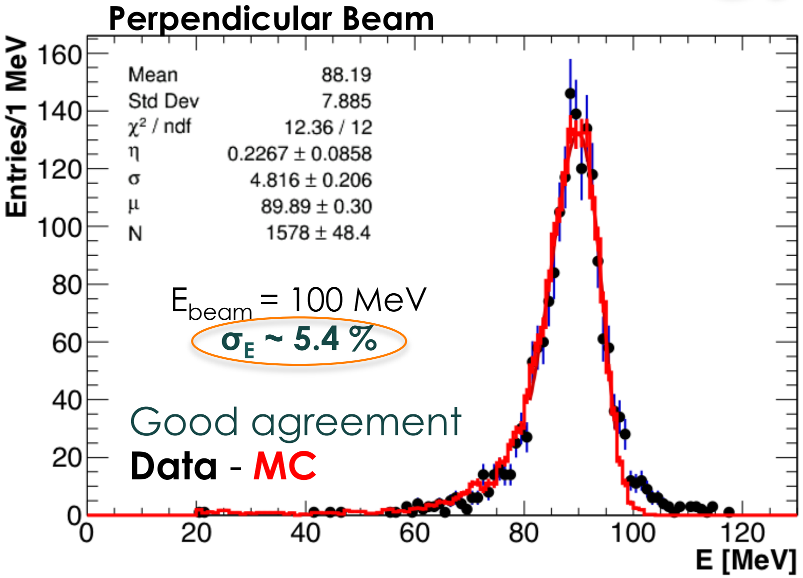


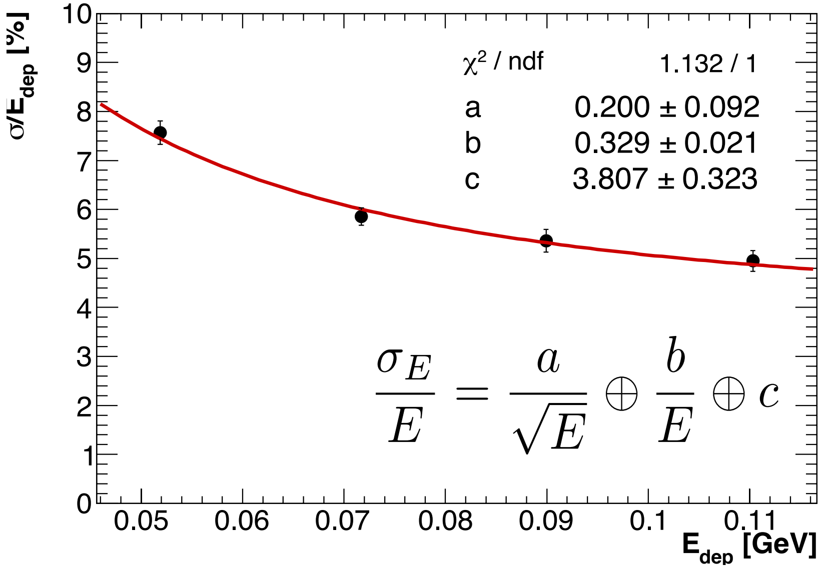


Readout: 1 GHz CAEN digitizers (DRS4 chip), 2 boards x 32 channels

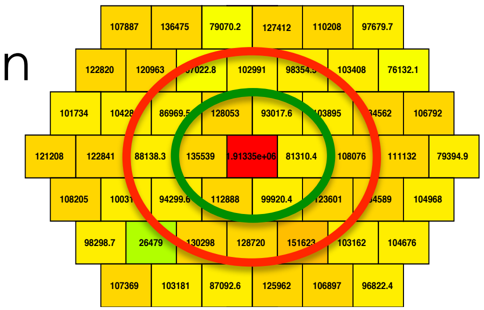
Final readout details in Caiulo's poster

Module 0 Energy resolution

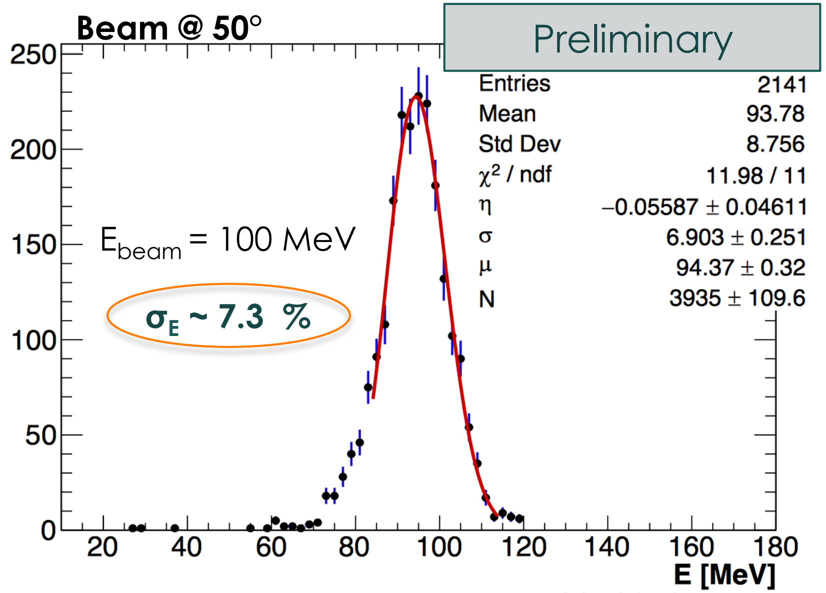




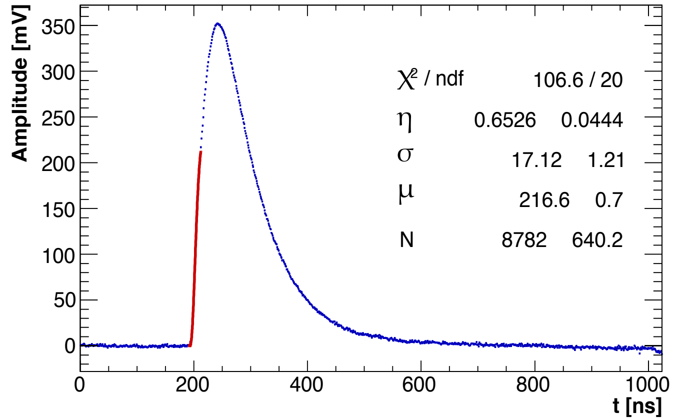
- Single particle selection

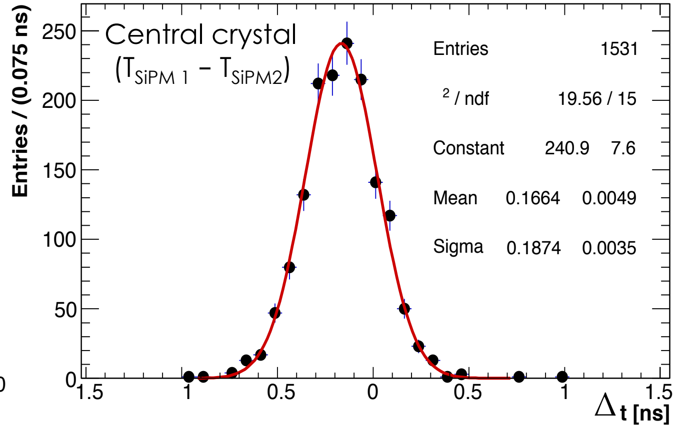


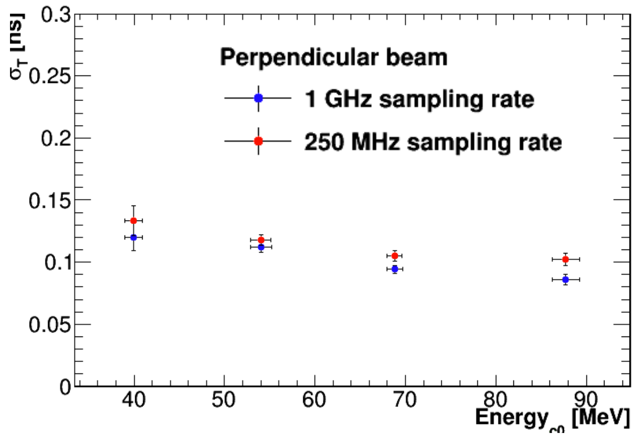
- Calibration
  - MIPs
  - 100 MeV e^- beam, up to ring **2**
- Threshold applied after noise run @ 3 σ



Module 0
Time resolution

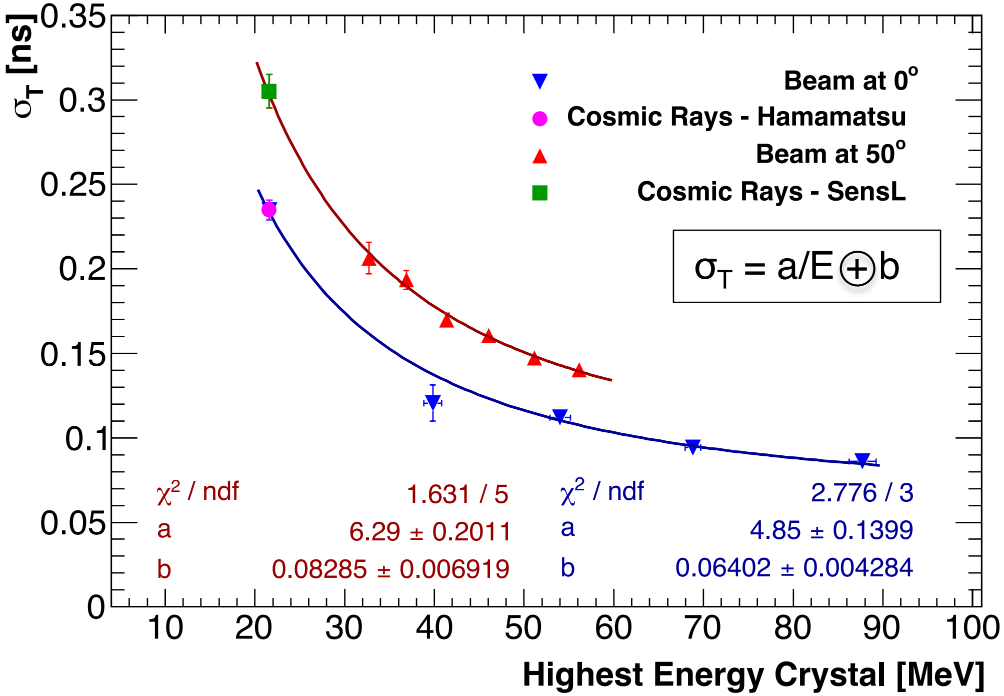






- Selection on single particle
- Log-normal fit on leading edge
- Constant Fraction method used
  → CF = 5%

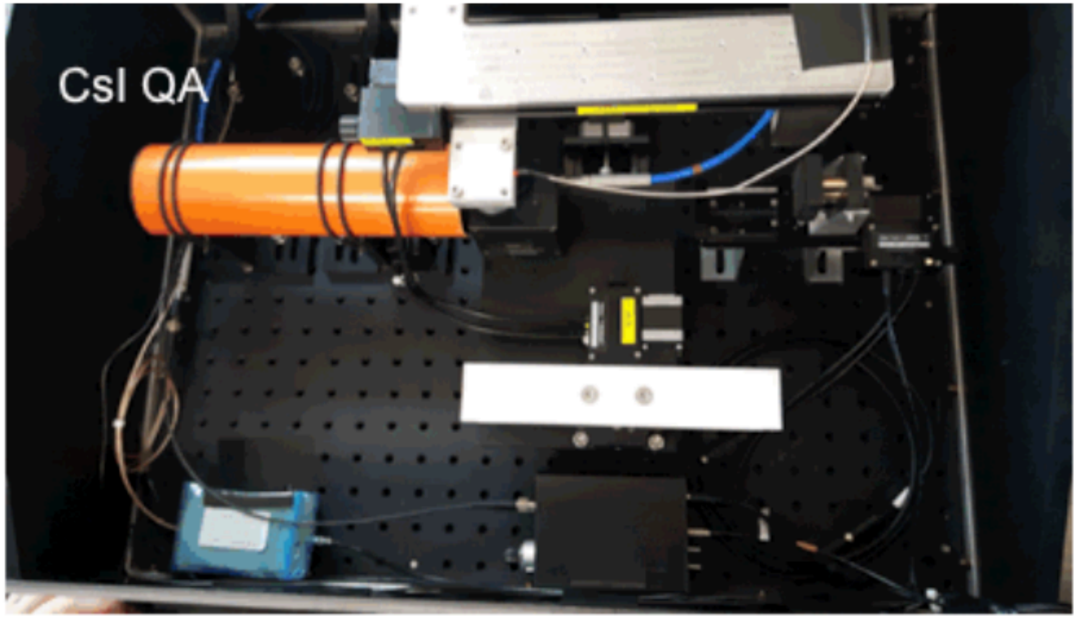
σ (T1+T2)/2 ~ 94 ps
@ E_{beam} = 100 MeV

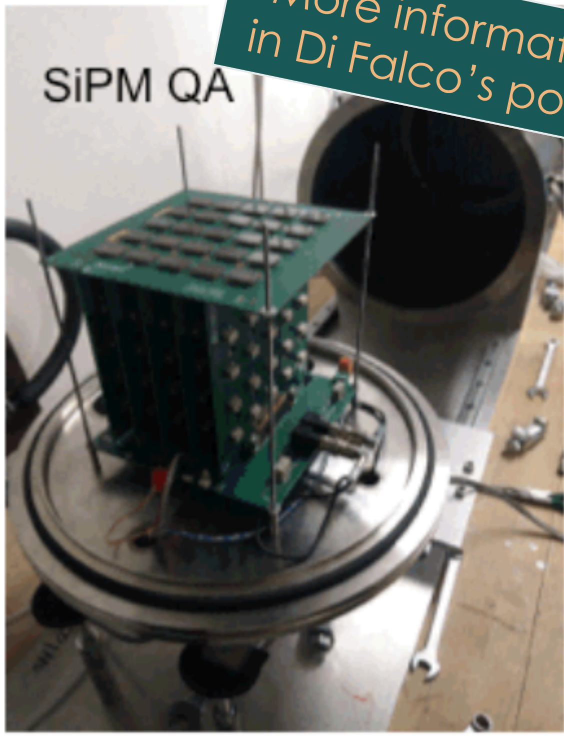


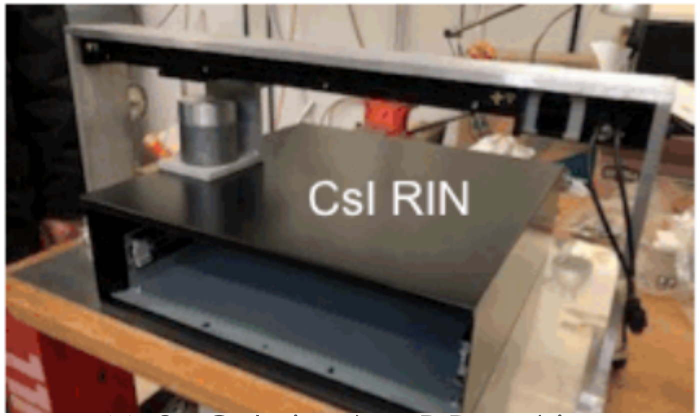
QA status of basic components

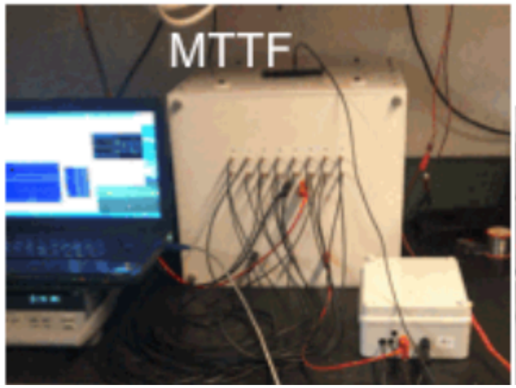
New laboratory built at FNAL. QA tests of all components started on march 2018

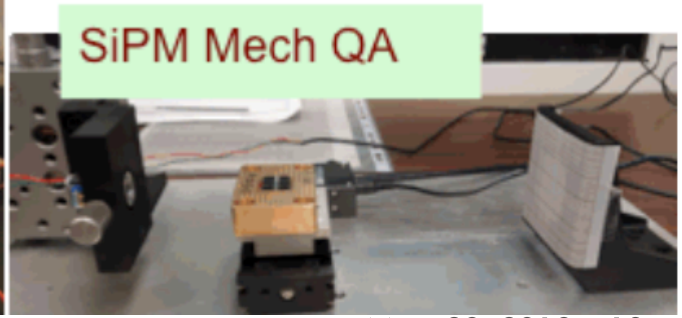
More information in Di Falco's poster









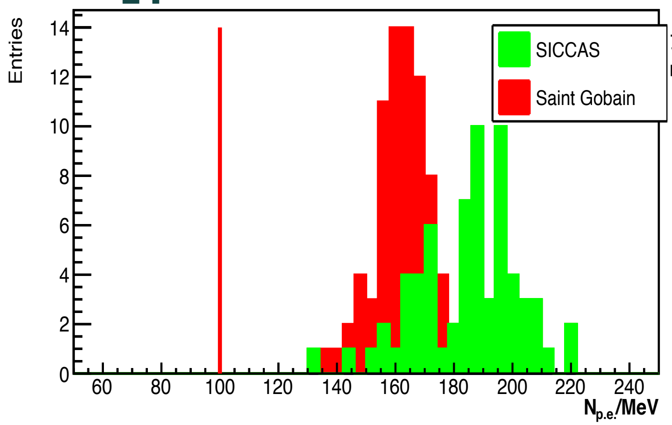


Crystals QA status

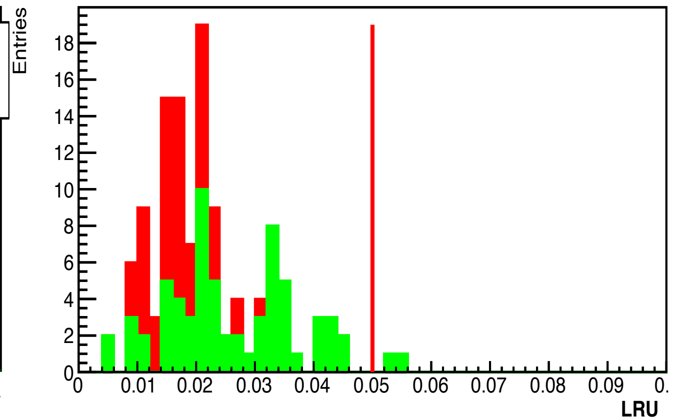
More than 100 crystals already tested

- SICCAS rate: 60 crystals / month
- SG almost same rate, mechanical problem not fixed yet

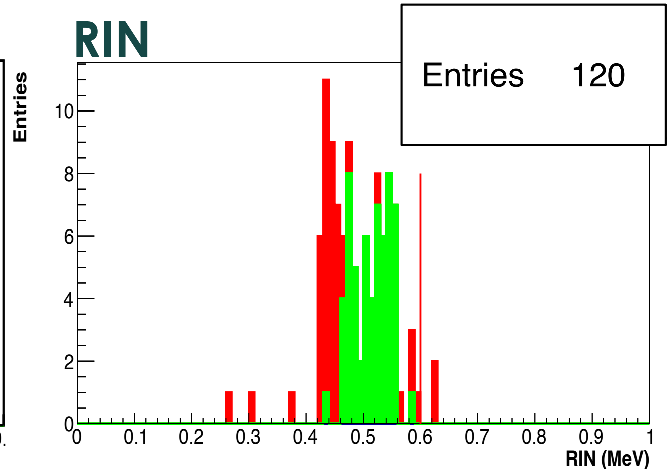
LY



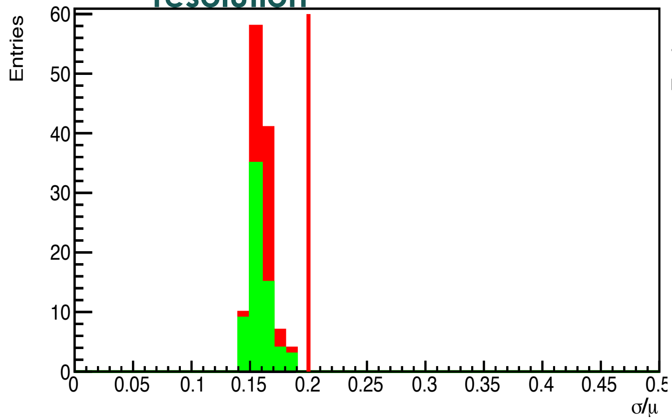
LRU



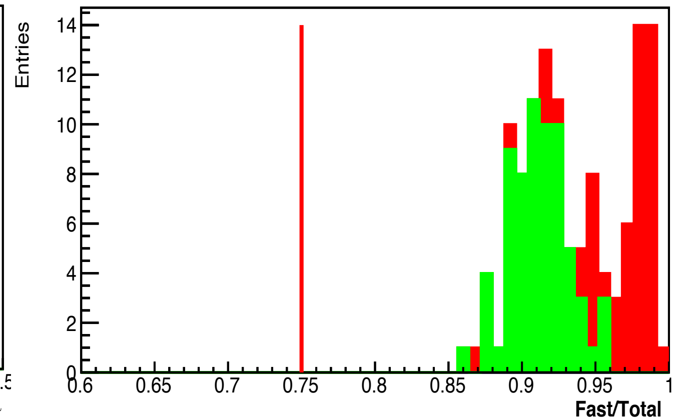
RIN



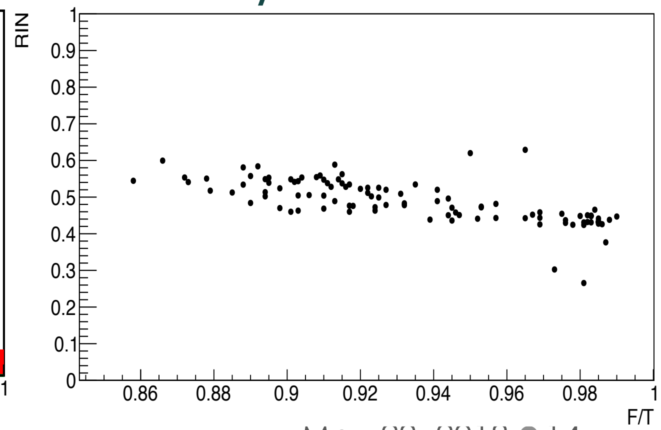
$E_{resolution}$



F/T



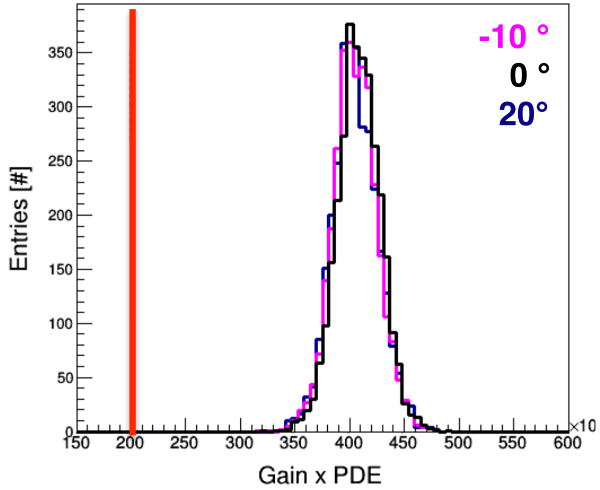
RIN vs F/T

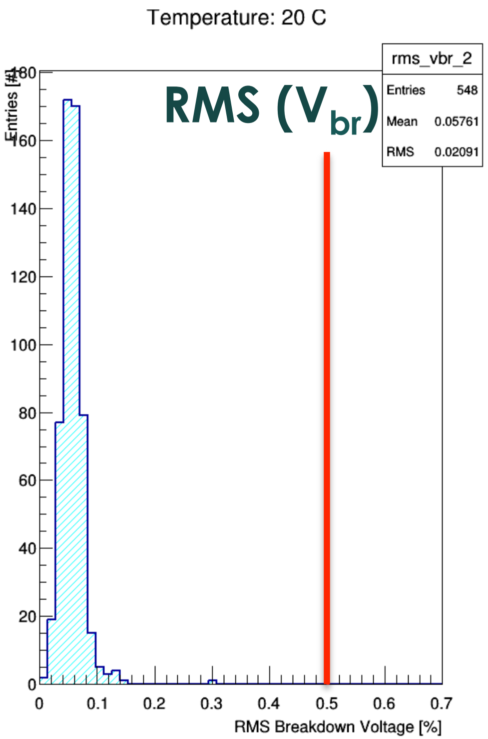


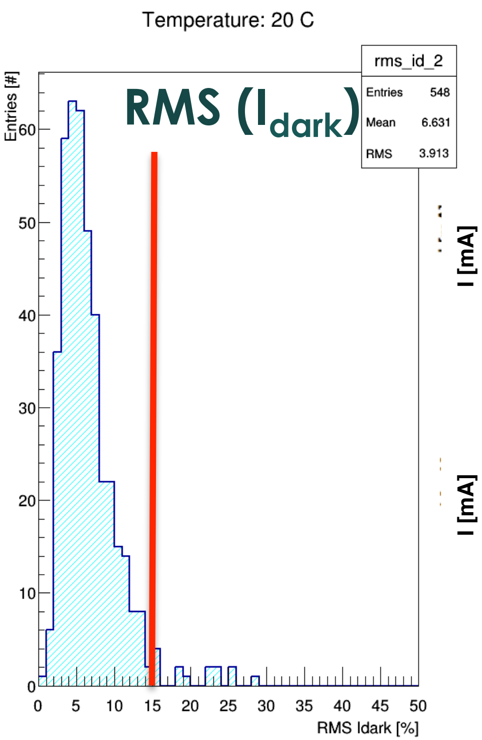
SiPMs QA status

About 550 Mu2e SiPMs already characterized

- 300 pieces/month from March 2018
- All the 6 cells tested, measuring **V_{br}, I_{dark}, Gain x PDE**
- 4 % of tested SiPMs rejected (defective or with high I_{dark} RMS)
- **Irradiation with ~1x10[12] neutrons/cm[2] (MTTF)** test on 5 (15) SiPMs/batch

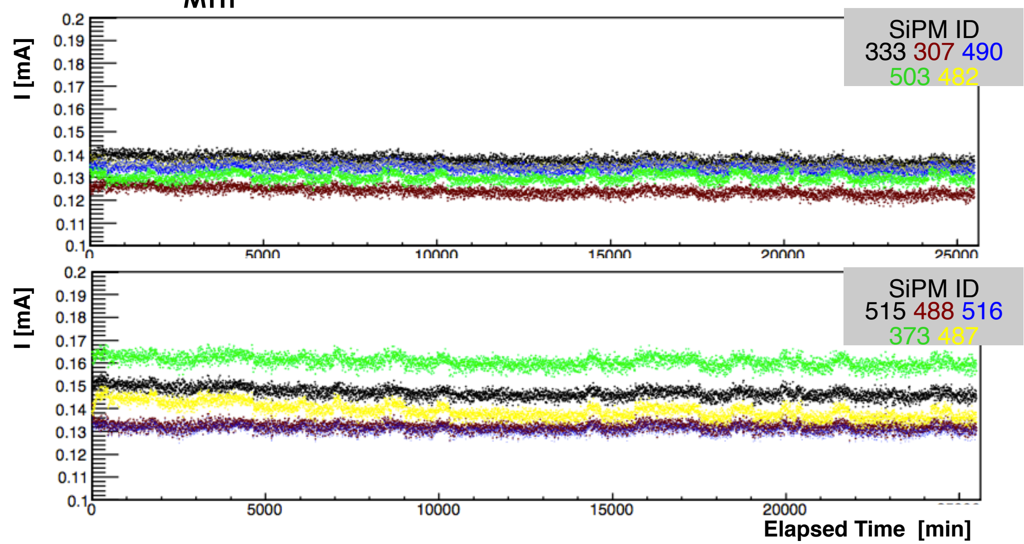






MTTF

- Requirement: grant an MTTF of 1 million hours at 0°
- sensors tested 18 days burn-in at 65°
- **$SiPM_{MTTF}$ > 3 million hours**



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 > 3 million hours**
  - **Calorimeter prototypes** tested with e^- beam
    - **Good time and energy resolution achieved @ 100 MeV**

- Calorimeter production phase started

In 2020 installation of the calorimeter in the Mu2e experimental all begins!

Spares

Raffaella Donghia
LNF-INFN and Roma Tre University
On behalf of the Mu2e calorimeter group

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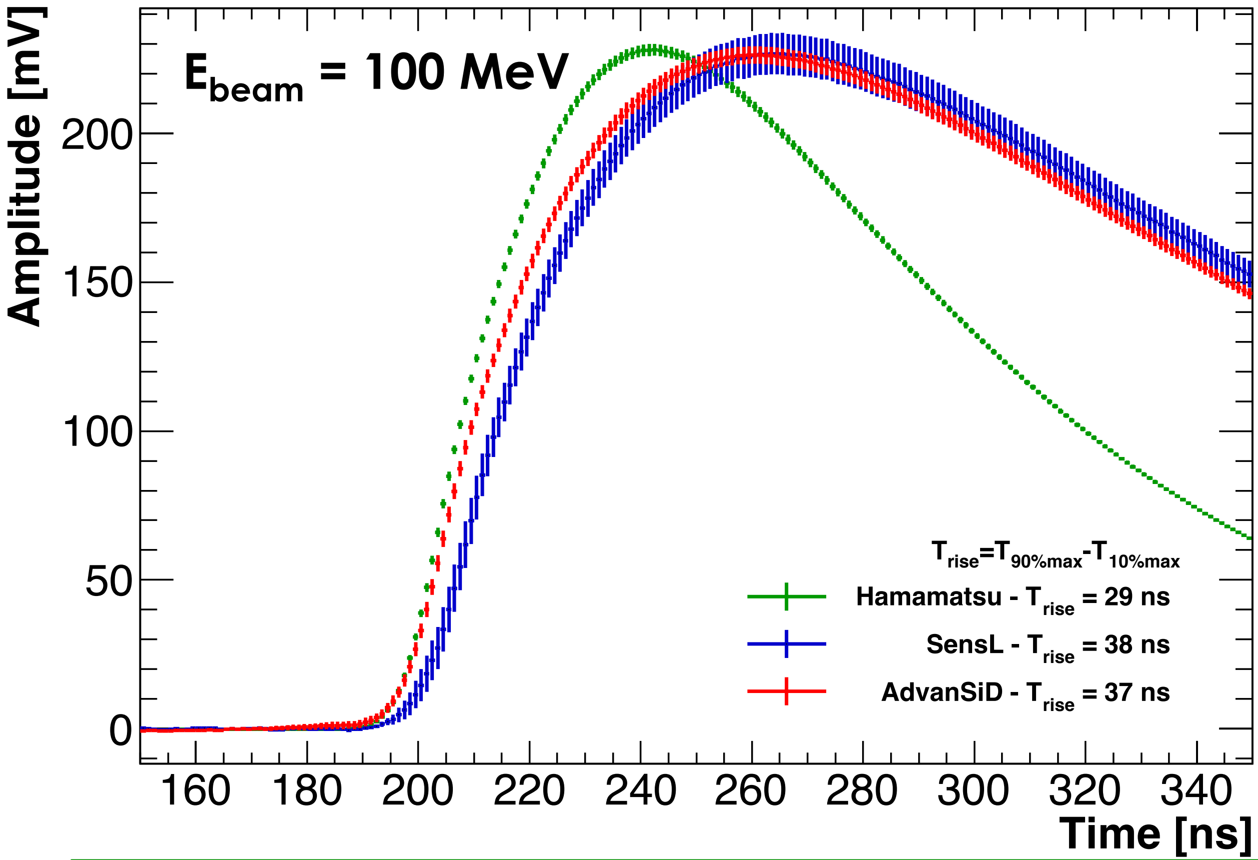
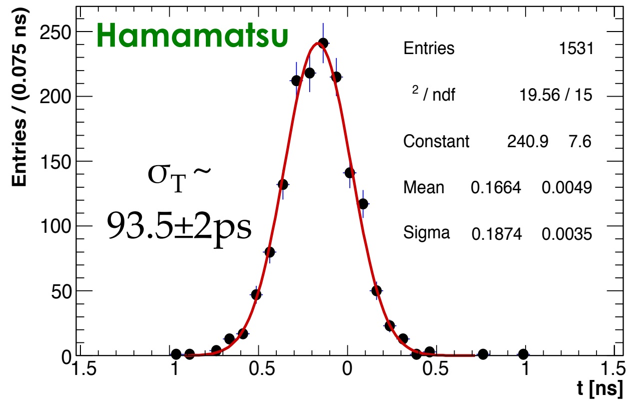
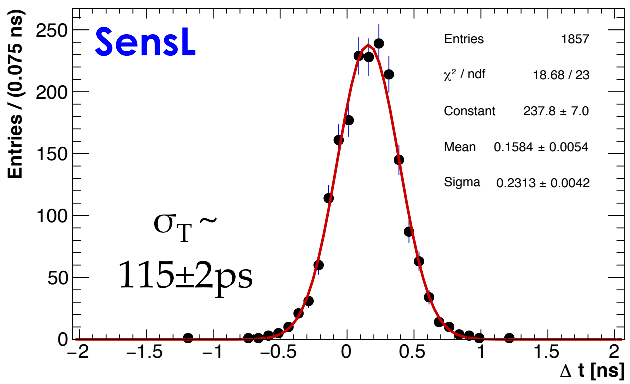
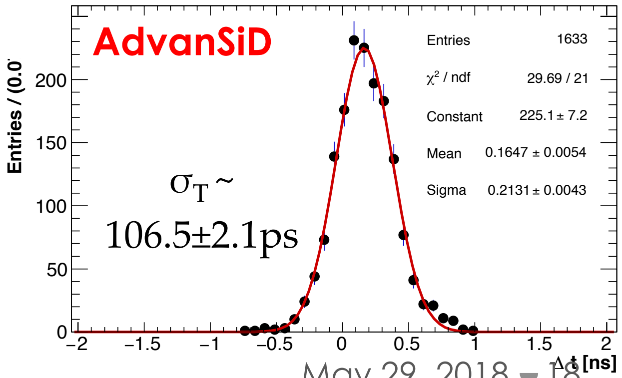
Module 0
SiPM-vendors comparison









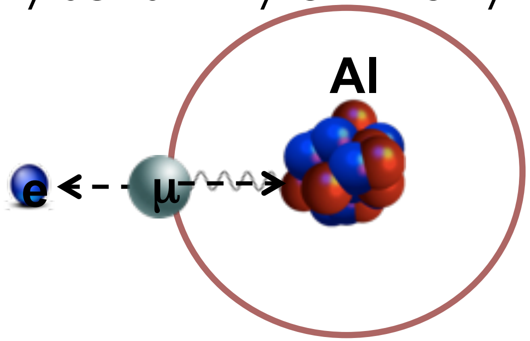
$$\sigma^2_{tot} = \sigma^2_{Landau} + \left(\frac{t_{rise}}{S/N}\right)^2 + \left(\left[\frac{V_{thr}}{S/t_{rise}}\right]_{RMS}\right)^2$$

Energy fluctuation

CF discriminator

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

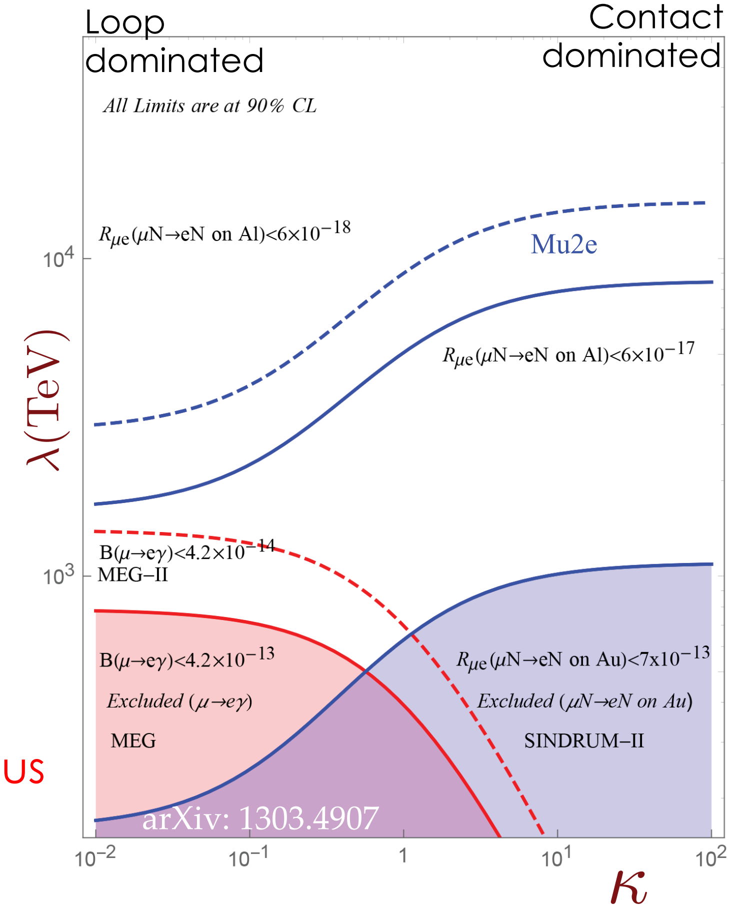


- **Goal:**
  10^4 improvement w.r.t. current limit (SINDRUM II)

μ-e conversion in the presence of a nucleus

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

Nuclear captures of muonic Al atoms



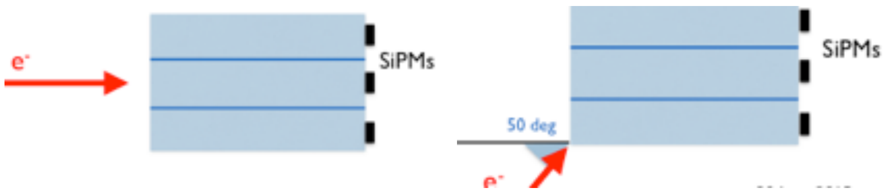
(@ 90% CL, with ~ 10^{18} stopped muons in 3 years of running)

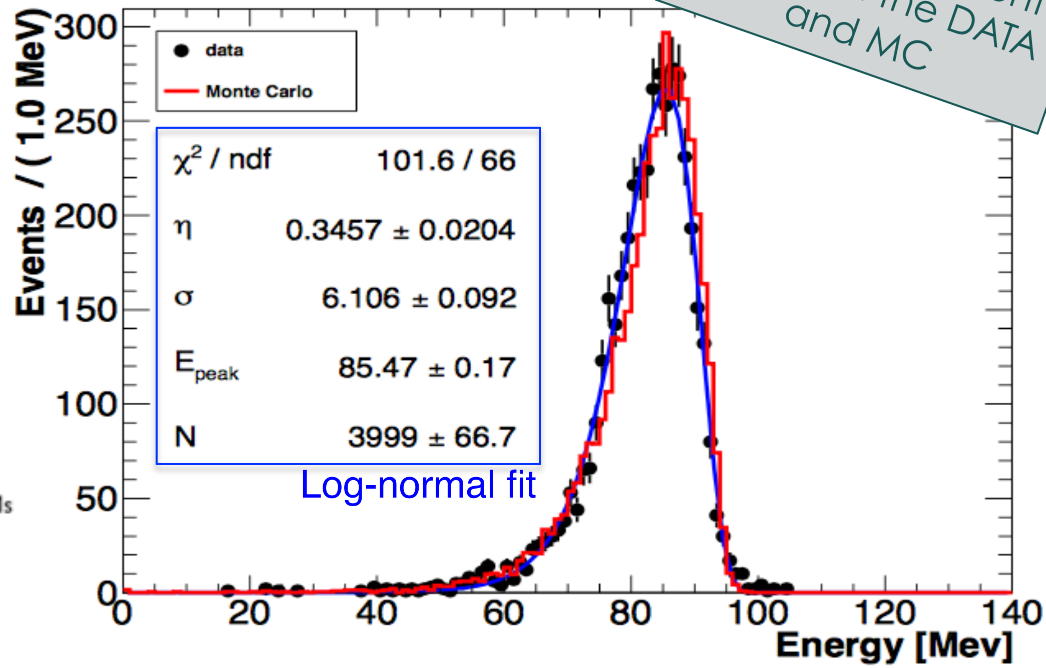
Small prototype: Test Beam

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

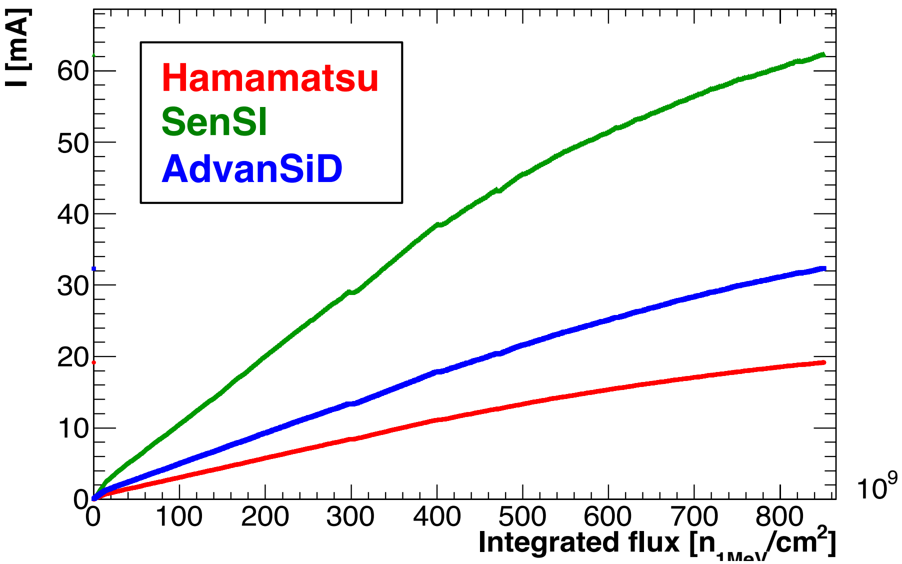




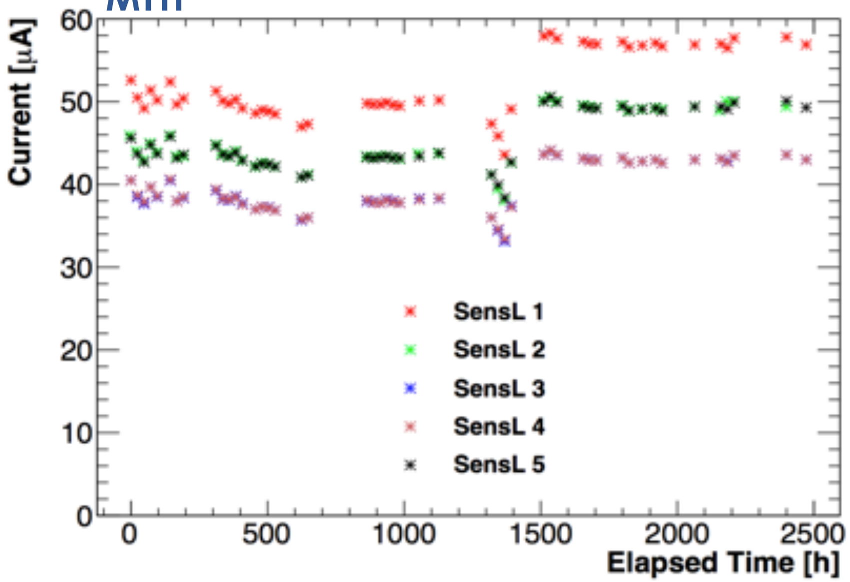
Pre-production test: SiPMs (2)

- 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

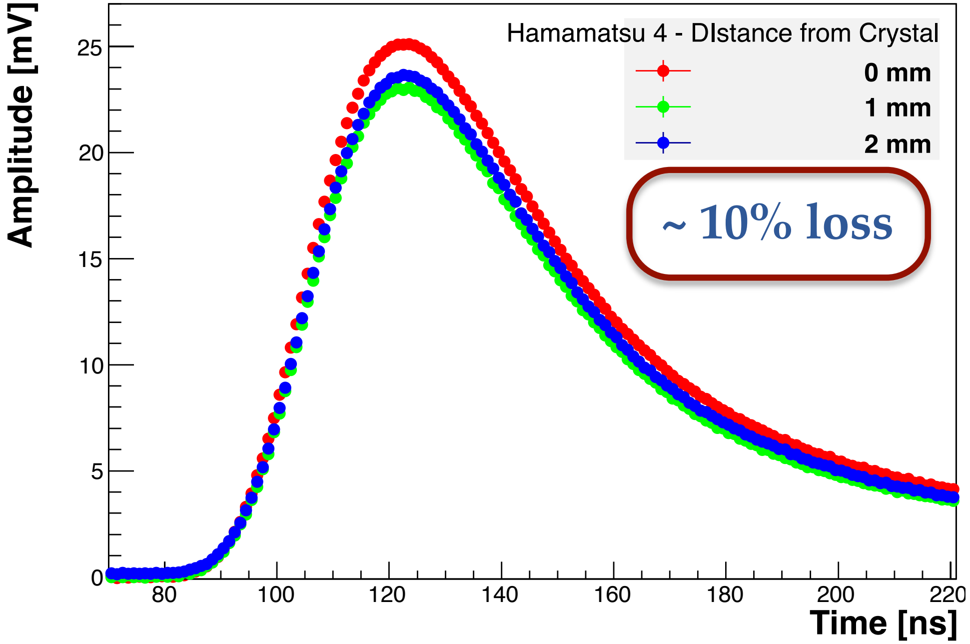
- MTTF evaluated operating SiPMs @ 50 °C for 3.5 months
- No dead channels observed

MTTF ≥ 6×10^5 hours

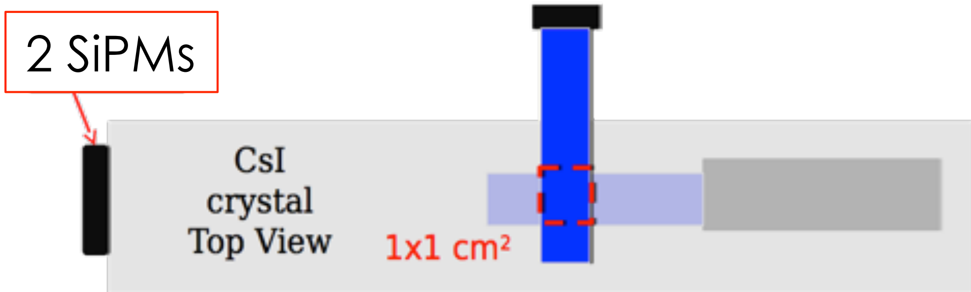
Single channel slice test

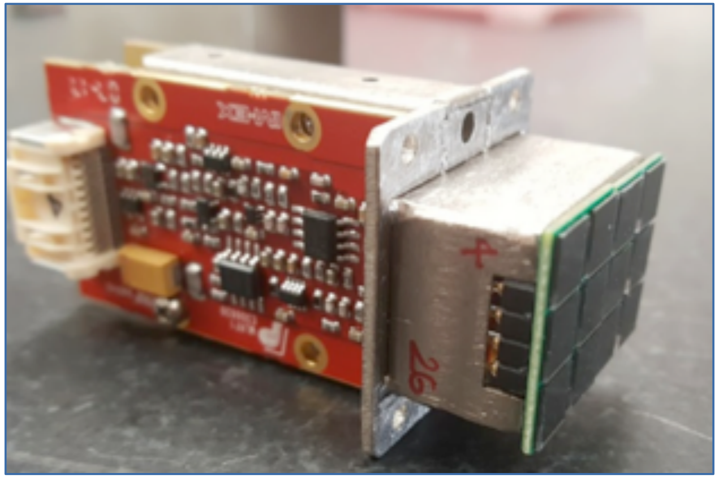
SG crystal + Hamamatsu SiPM + FEE
Optical coupling in air.

- **^{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





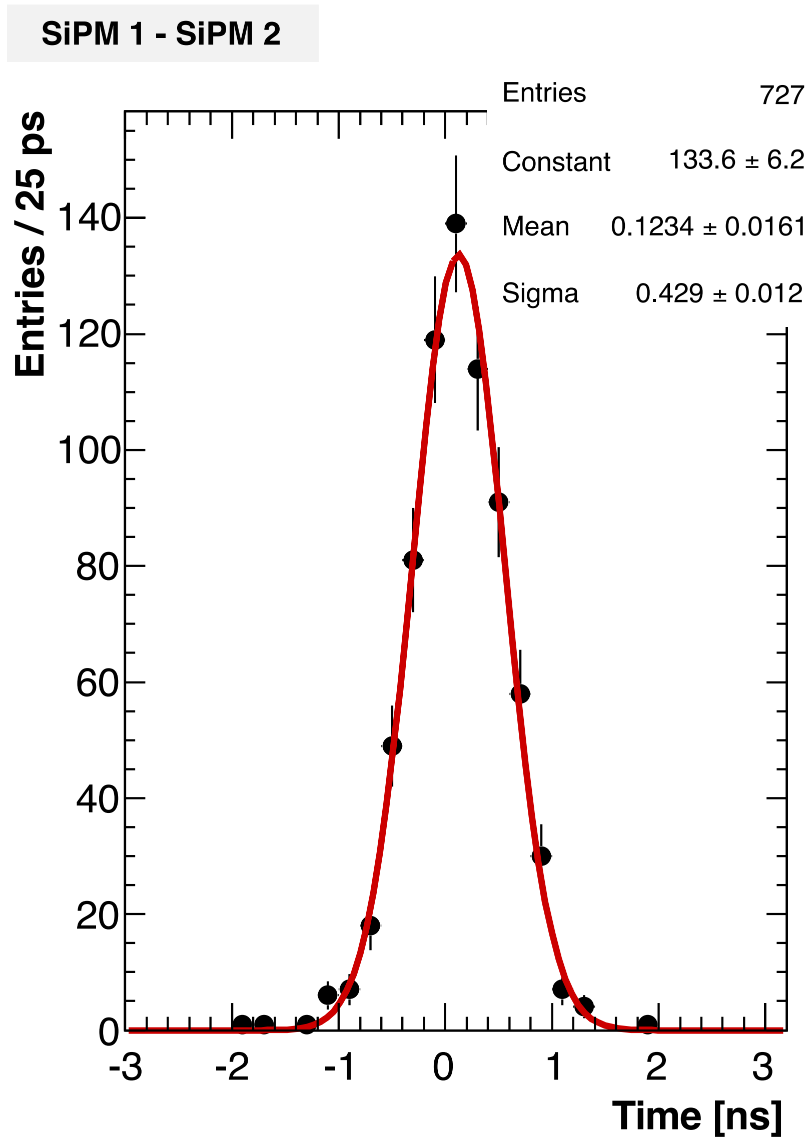
Single channel Cosmic Rays Test

- 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)

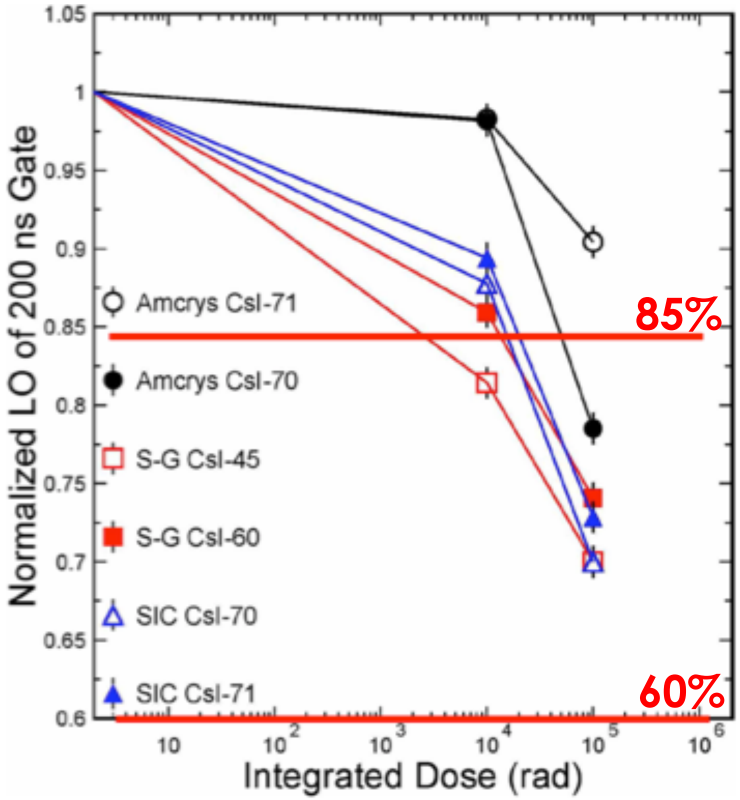
Timing result well compares with old tests:
→ Reduced light output/SiPM (22 vs 30 pe/MeV)
→ 2 SiPMs/crystal
→ LY of 44 vs 30 → 215 ps (now) vs 250 ps (old).



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

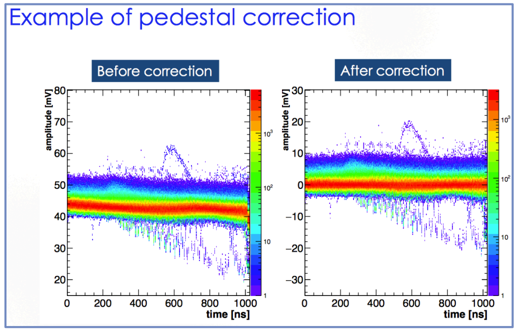
- **Radiation Induced Noise** (RIN) @ 1.8 rad/h required is **< 0.6 MeV**
  - All 72 samples tested. All OK apart some Amcrys crystals that do not satisfy the required limit
- Negligible LY and LRU variation after **1.6 x 10^{12} n_{1MeV}/cm^2 integrared flux**
- Neutron RIN is also smaller than the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

Module 0
Event selection

Pedestal correction: Results

- The integration range reduced to(150,400) ns
- Pedestal distribution reduction **better than a factor 2**

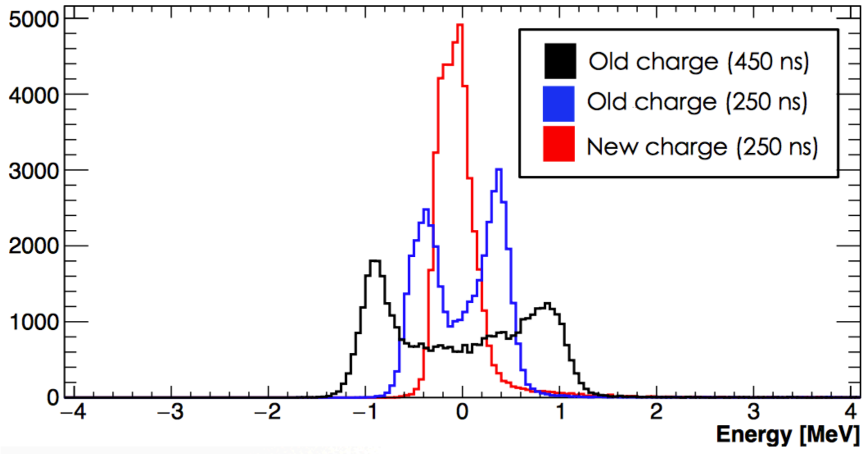
Example of pedestal correction



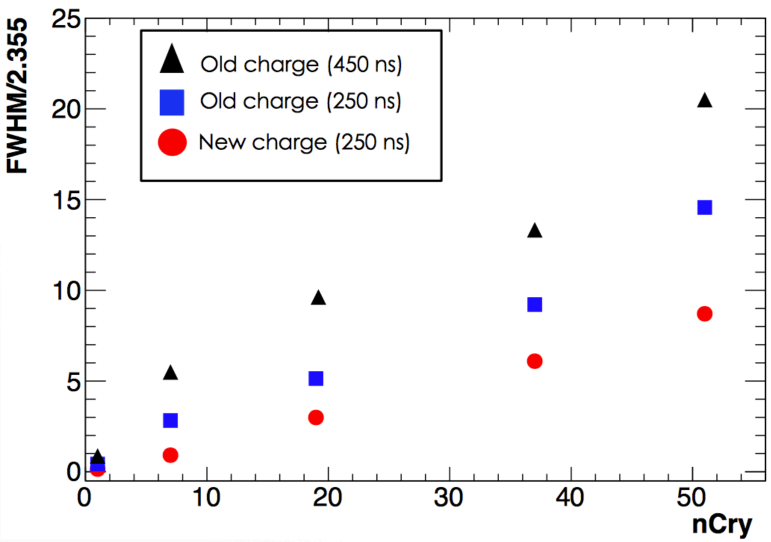
FWHM/2.355 = 0.870 MeV

FWHM/2.355 = 0.148 MeV

FWHM/2.355 = 0.424 MeV



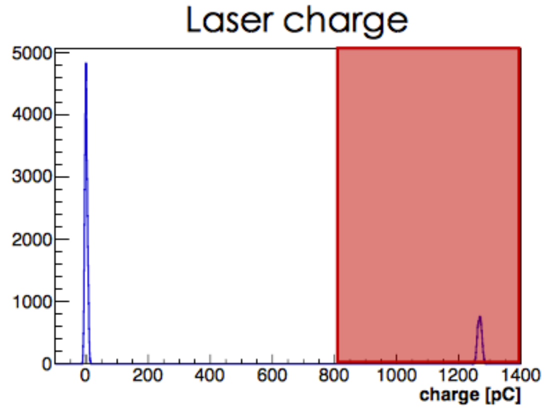
Pedestal energy vs Crystal number



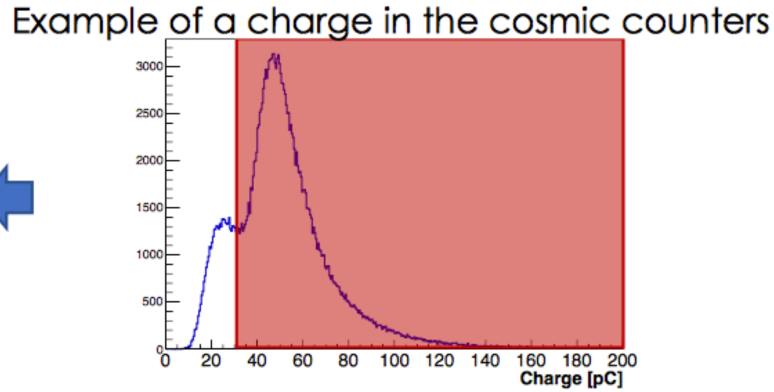
Noise width in the new charge increase linearly with the number of crystals added

Module 0
Event selection

1)We reject events with laser trigger

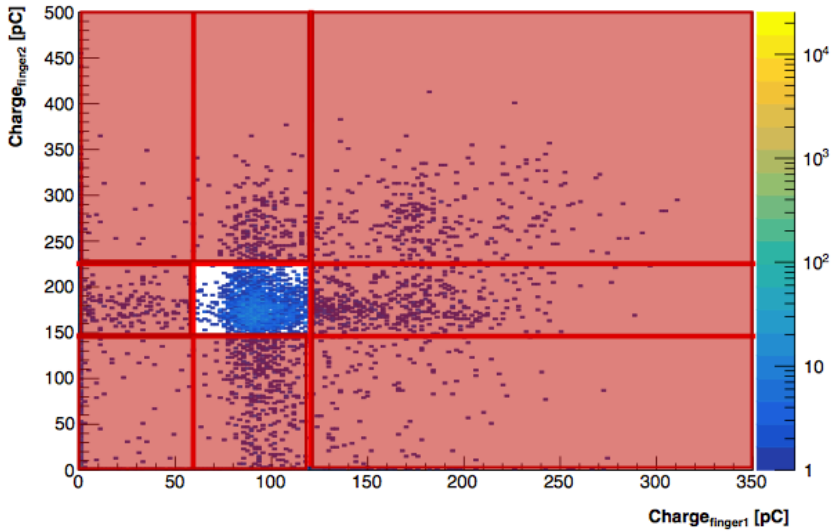


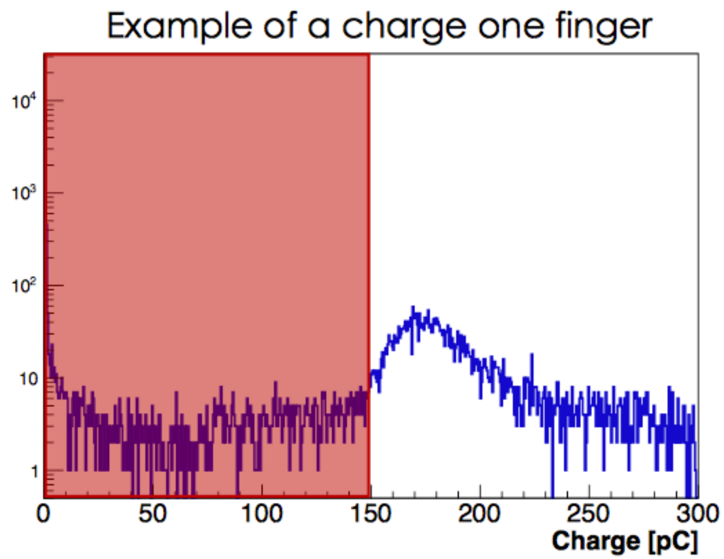
2)We reject events with cosmic trigger



Events~50000

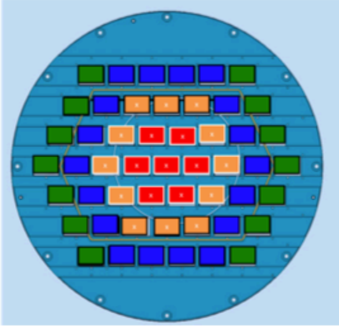
3)We ask for a single particle in the beam counters



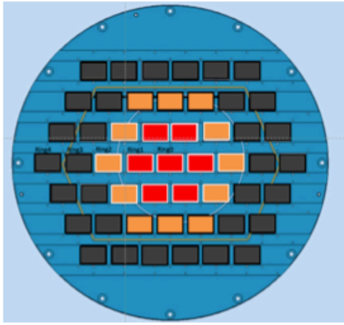


Events after selections~1600

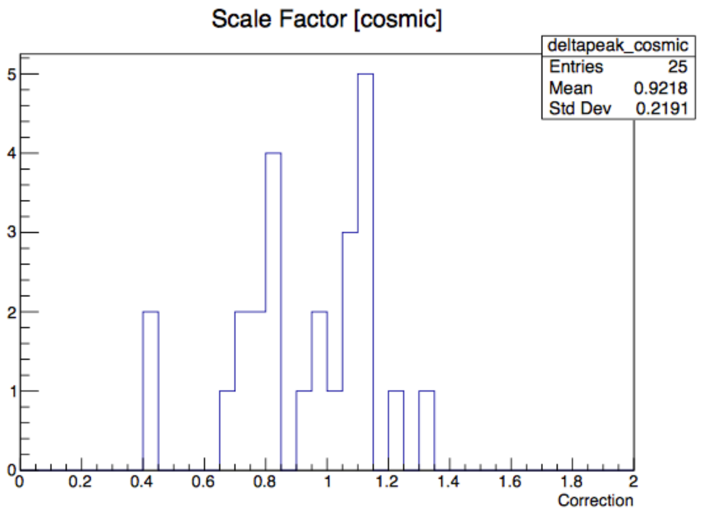
Module 0
Event selection

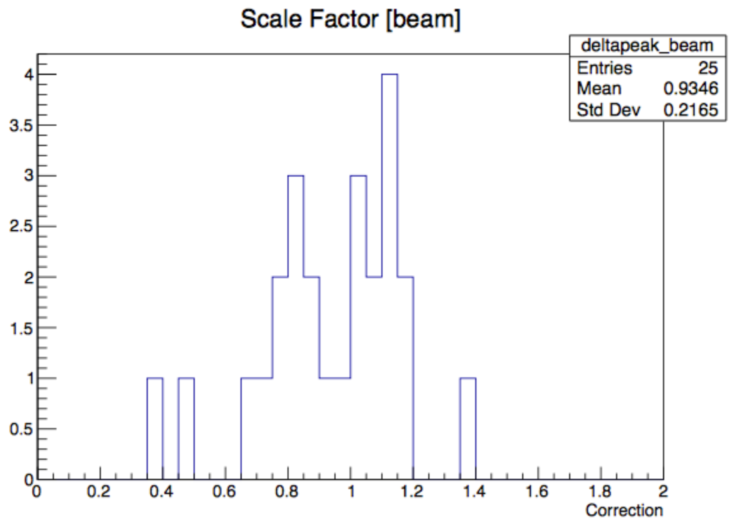


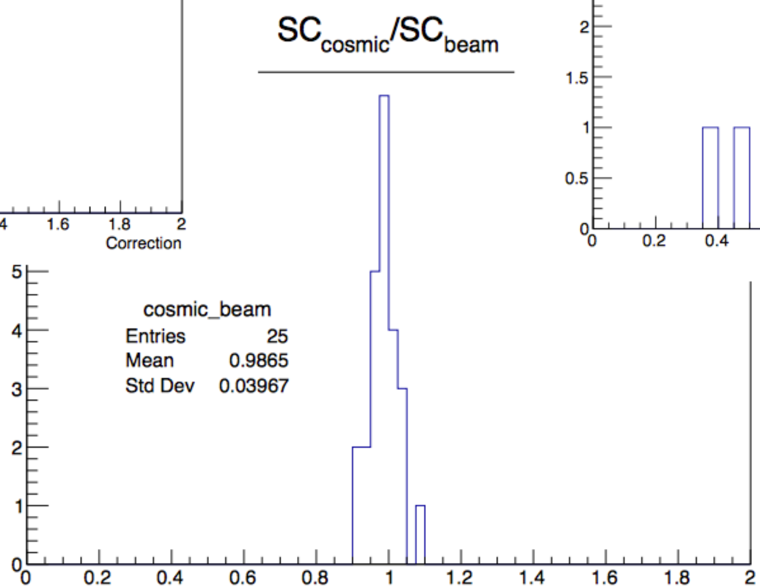
Cosmic trigger used to provide the equalization of all channels



Dedicated runs with beam centered on each crystal of the inner part of the matrix (up to second ring included)

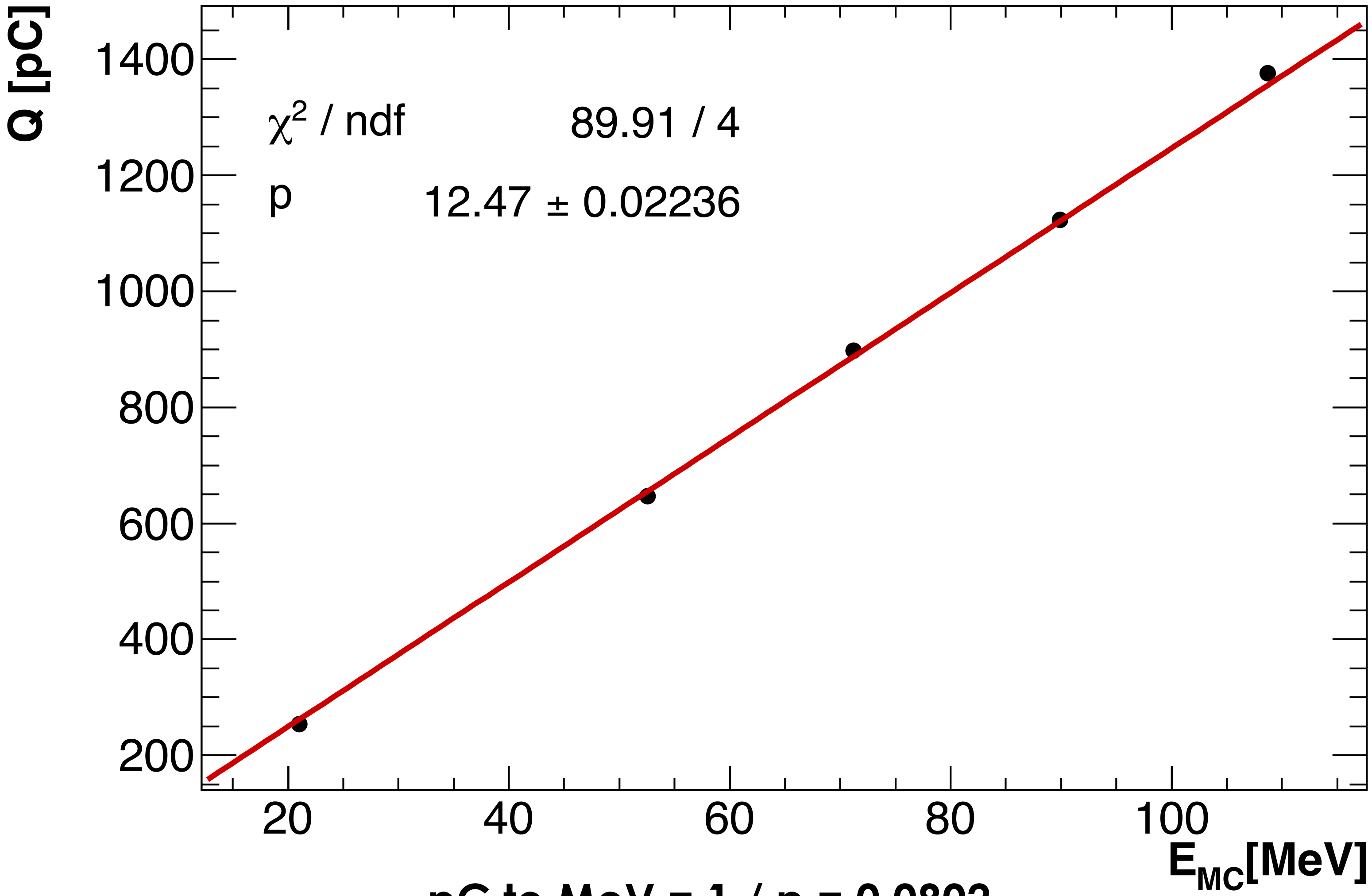






In all the analysis cosmic equalization is used

Module 0
Event selection



pC to MeV = 1 / p = 0.0802

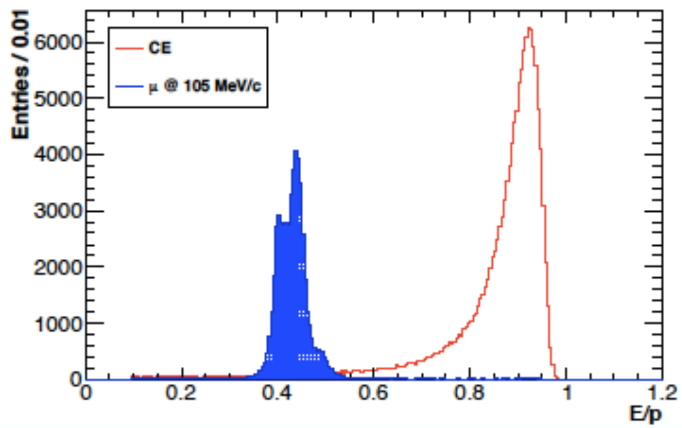
PId

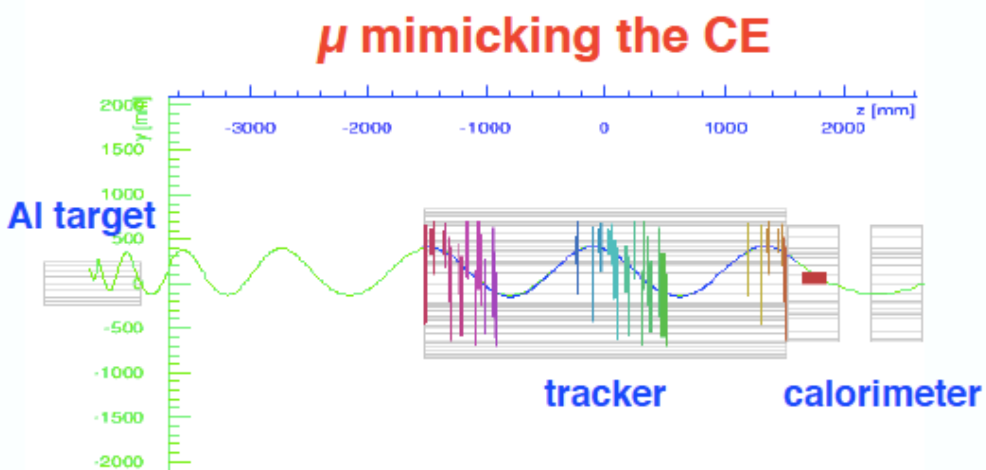
With a CRV inefficiency of 10^{-4} an additional rejection factor of ~ 200 is needed to have < 0.1 fake events from cosmics in the signal window

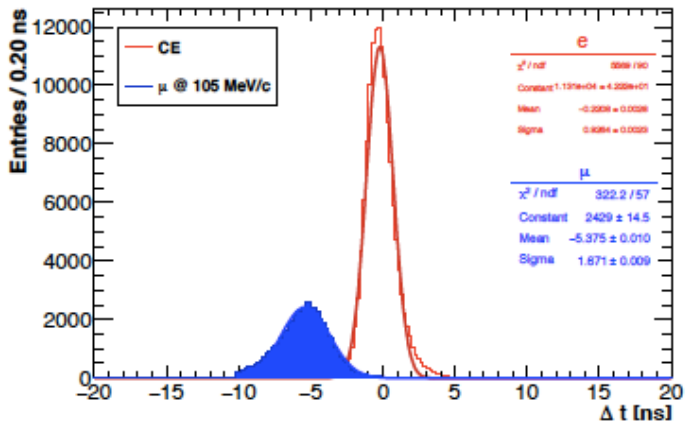
- 105 MeV/c e^- are ultra-relativistic, while 105 MeV/c μ have β~ 0.7 and a kinetic energy of ~ 40 MeV
- Likelihood rejection combines

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

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



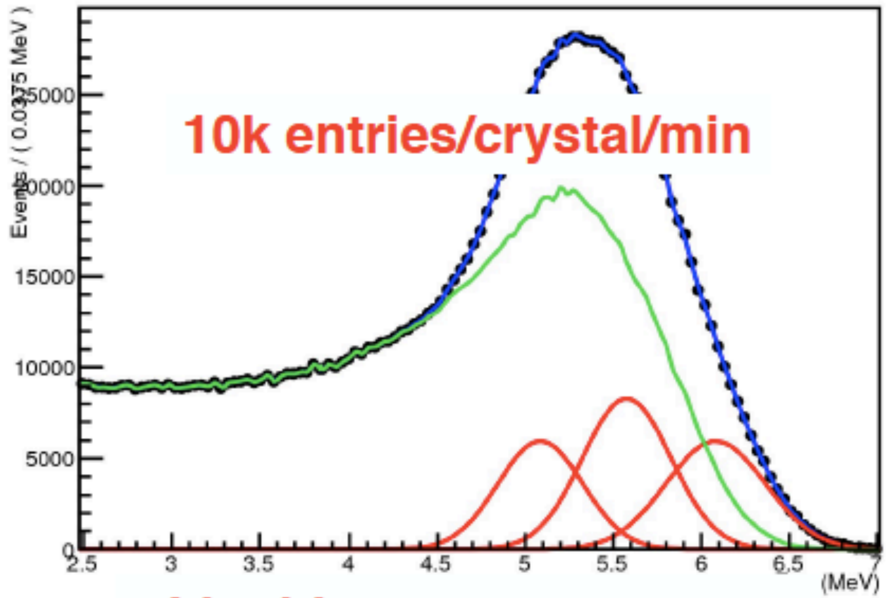


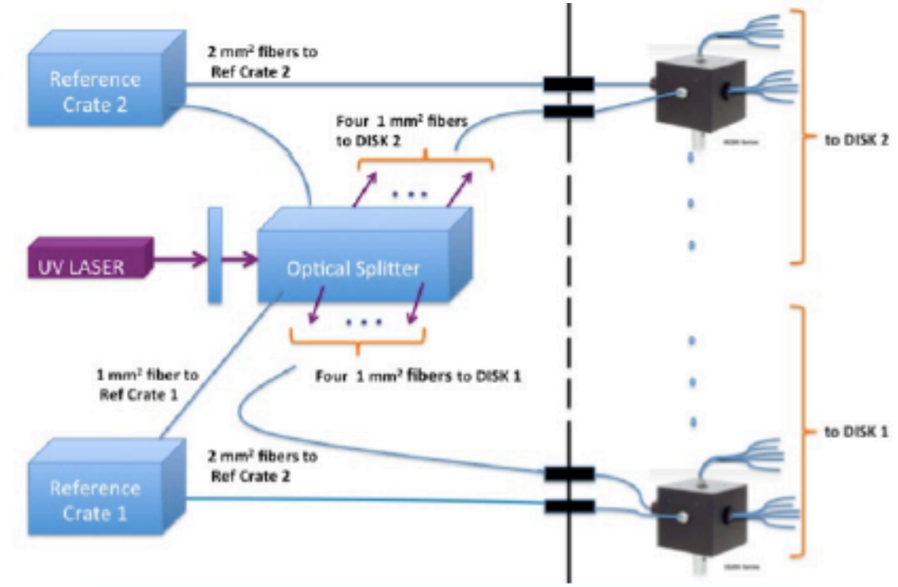


A rejection factor of 200 can be achieved with ~ 95% efficiency for CE

Calibration source and laser

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





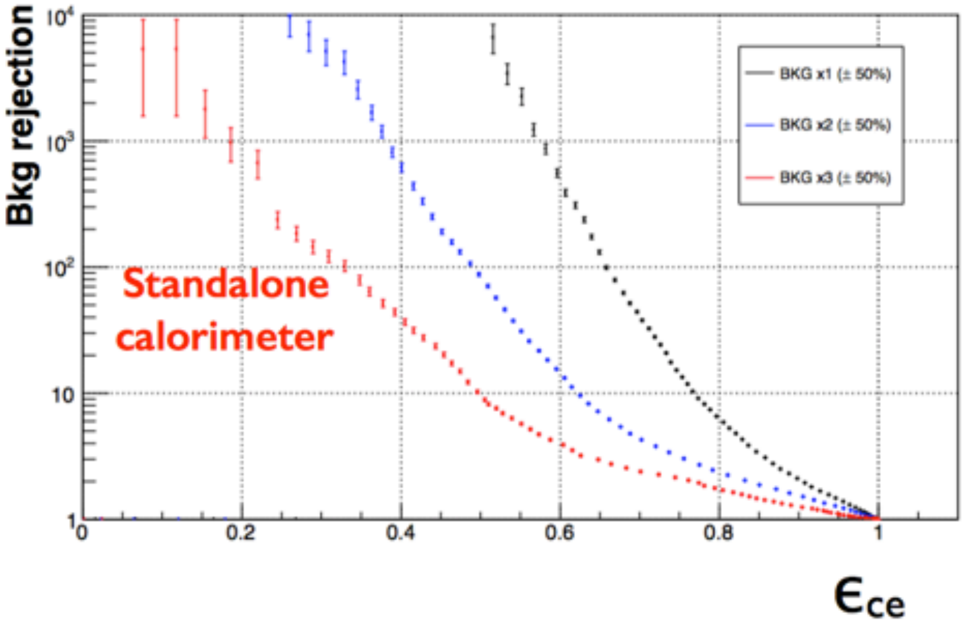
Liquid source prototype

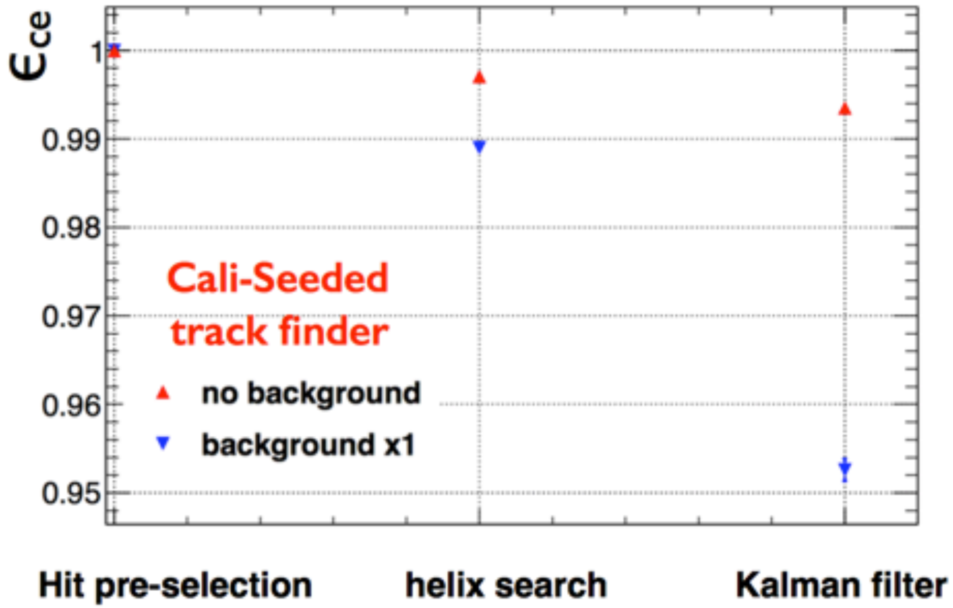
Laser system - test station

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

Calorimeter Trigger

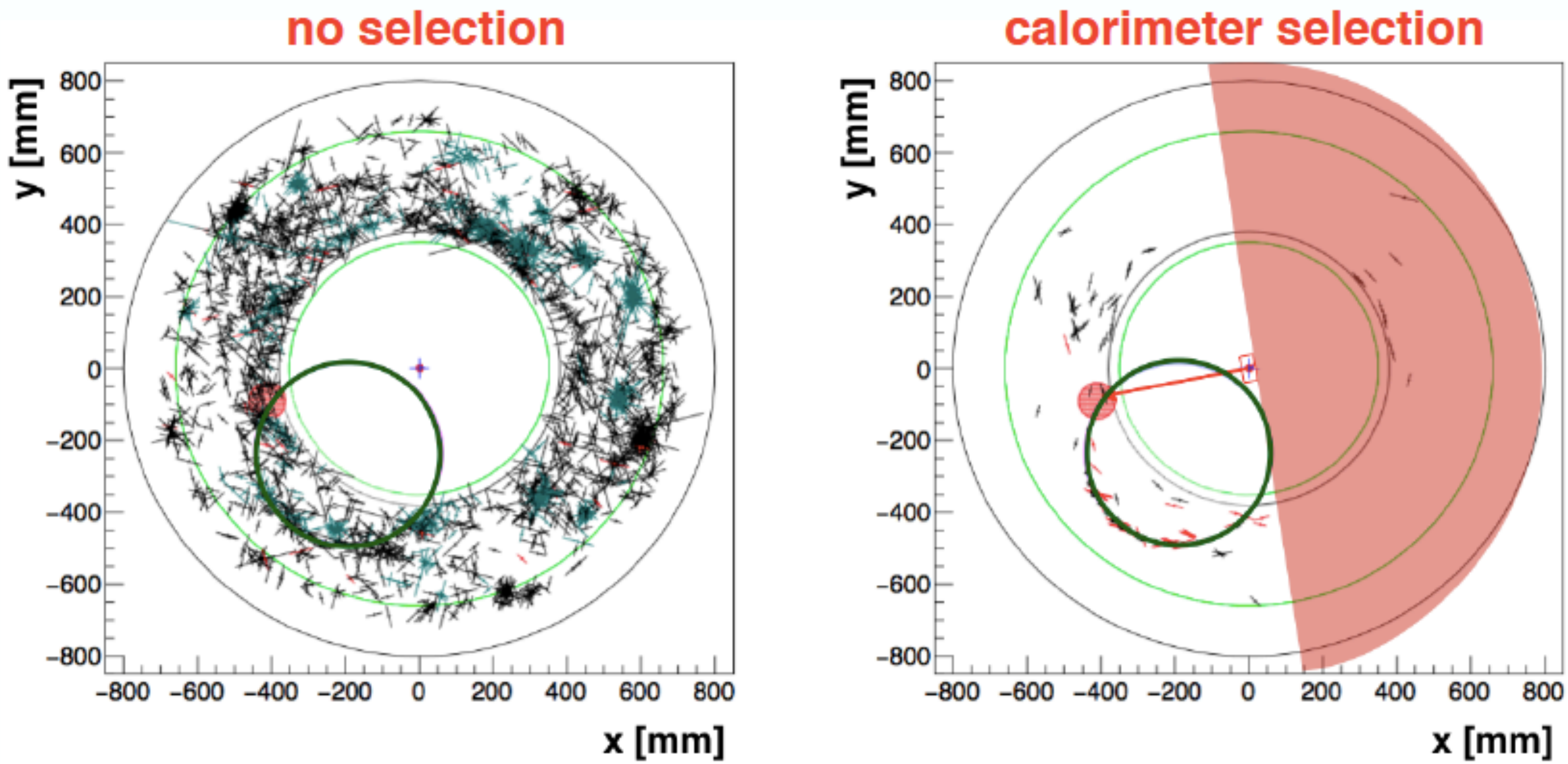
- Calo info can provide additional trigger capabilities in Mu2e:
- Calorimeter seeded track finder
  - Factorized into 3 steps: hit pre-selection, helix serach and track fit
  - ε ~ 95% for background rejection of 200
- Standalone calorimeter trigger that uses only calo info
  - E ~ 65% for background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





Calorimeter seeded track finder

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



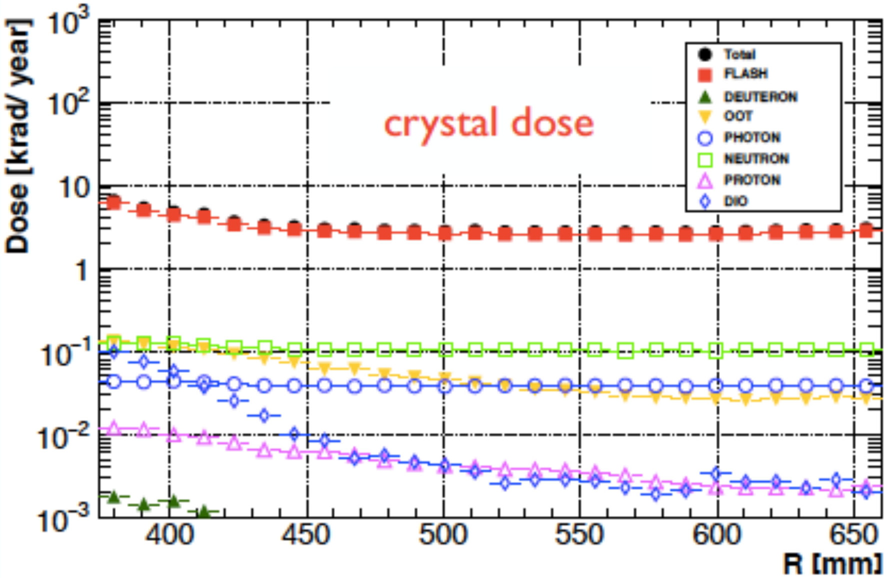
- **black crosses** = straw hits, **red circle** = calorimeter cluster, **green line** = CE track

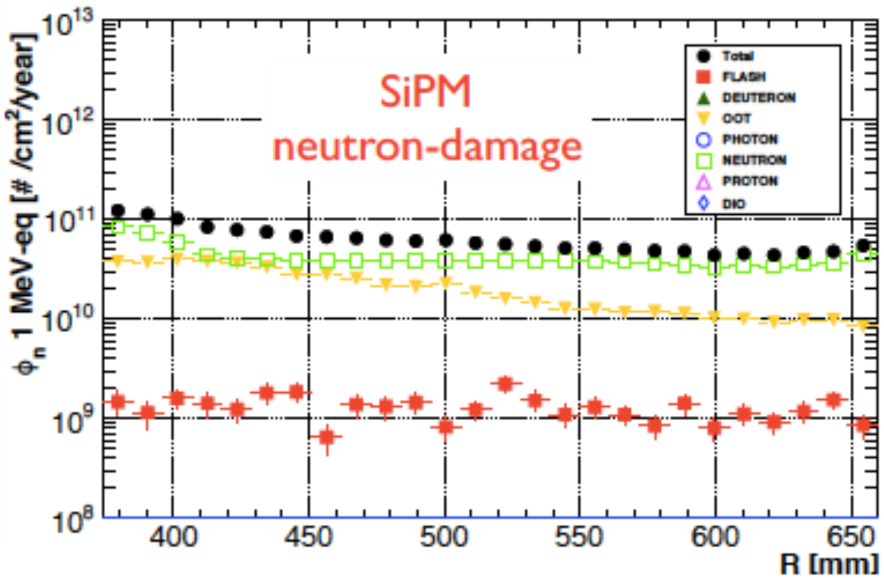
Calorimeter radiation damage

- 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**

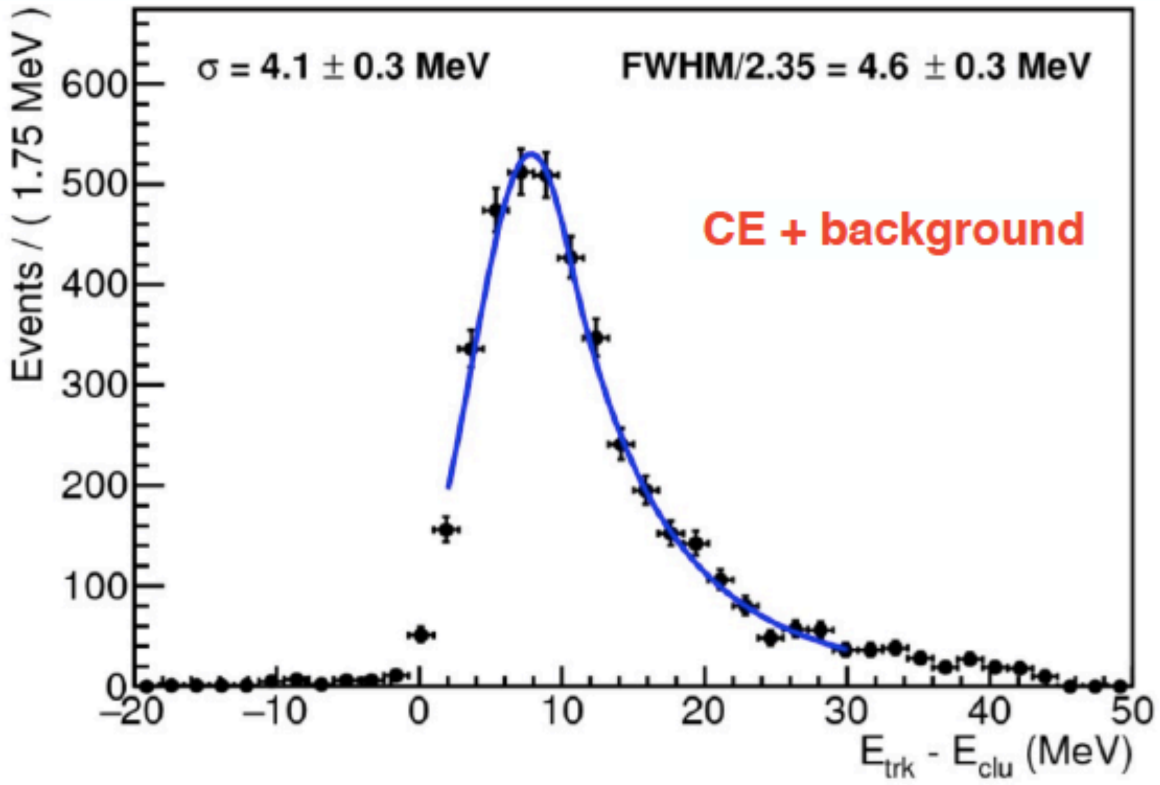
This includes a safety factor of 3 for a 3 year run



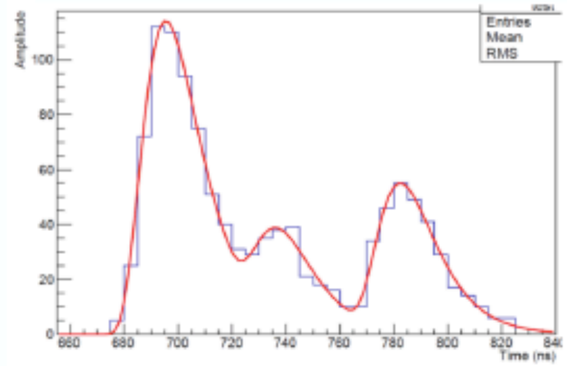


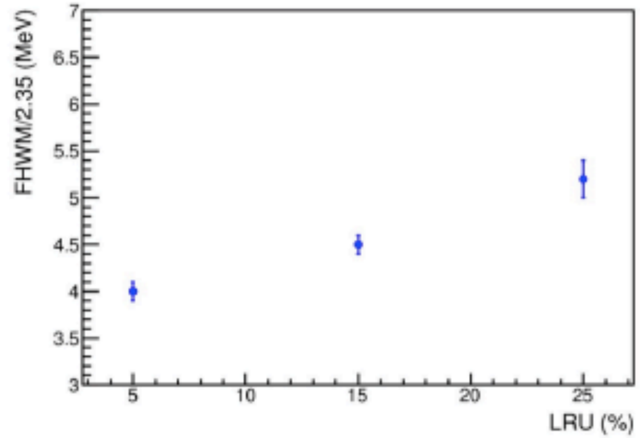
Calorimeter radiation damage

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

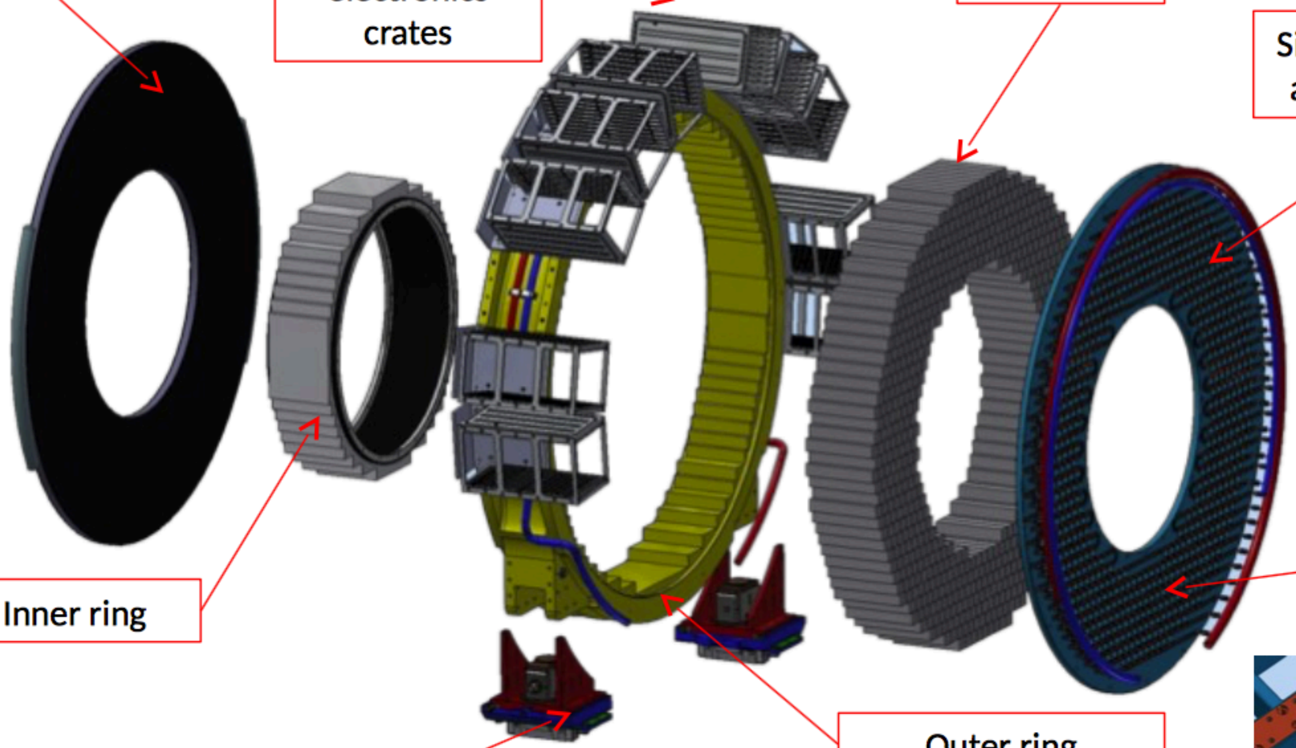


pile-up separation



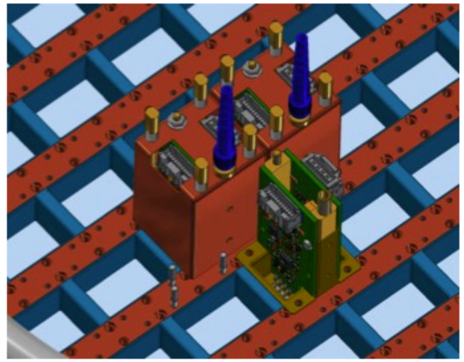


Calorimeter mechanics



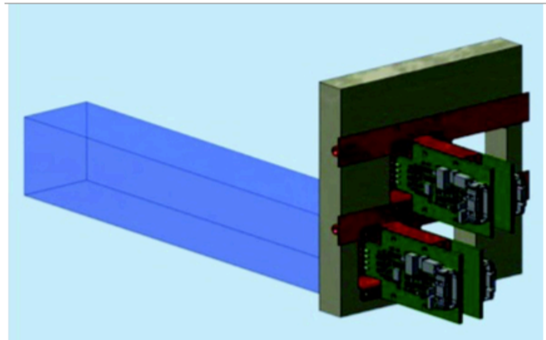
- Manifolds
- Hydraulic connections
- Inner steps
- Outer steps
- Alignment targets
- **SiPM running temperature at 0 °C, Coolant at -10 °C**

Zoom of SiPM/FEE disk And holders

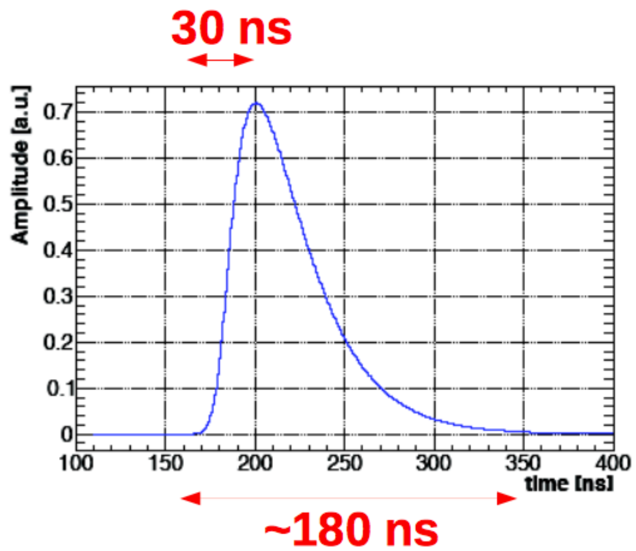


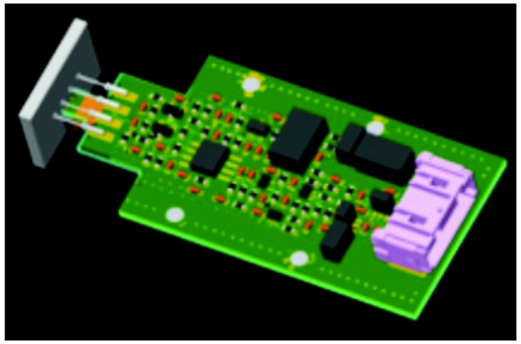
SiPM = Silicon PhotoMultiplier
FEE = Front End Electronics

Calorimeter
Readout electronics

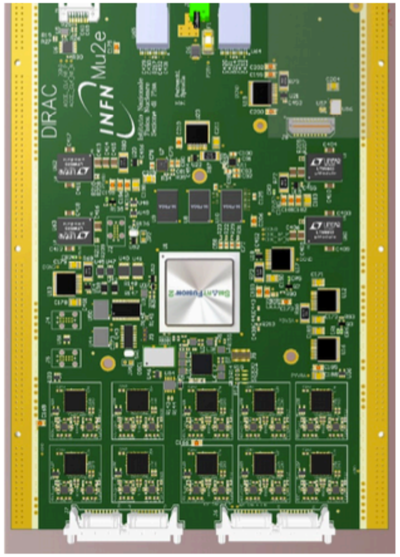


2 SiPM arrays/crystal
1 FEE board/array

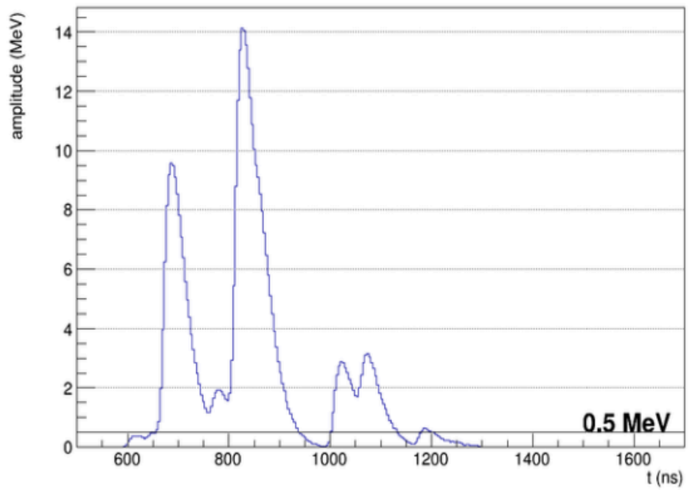




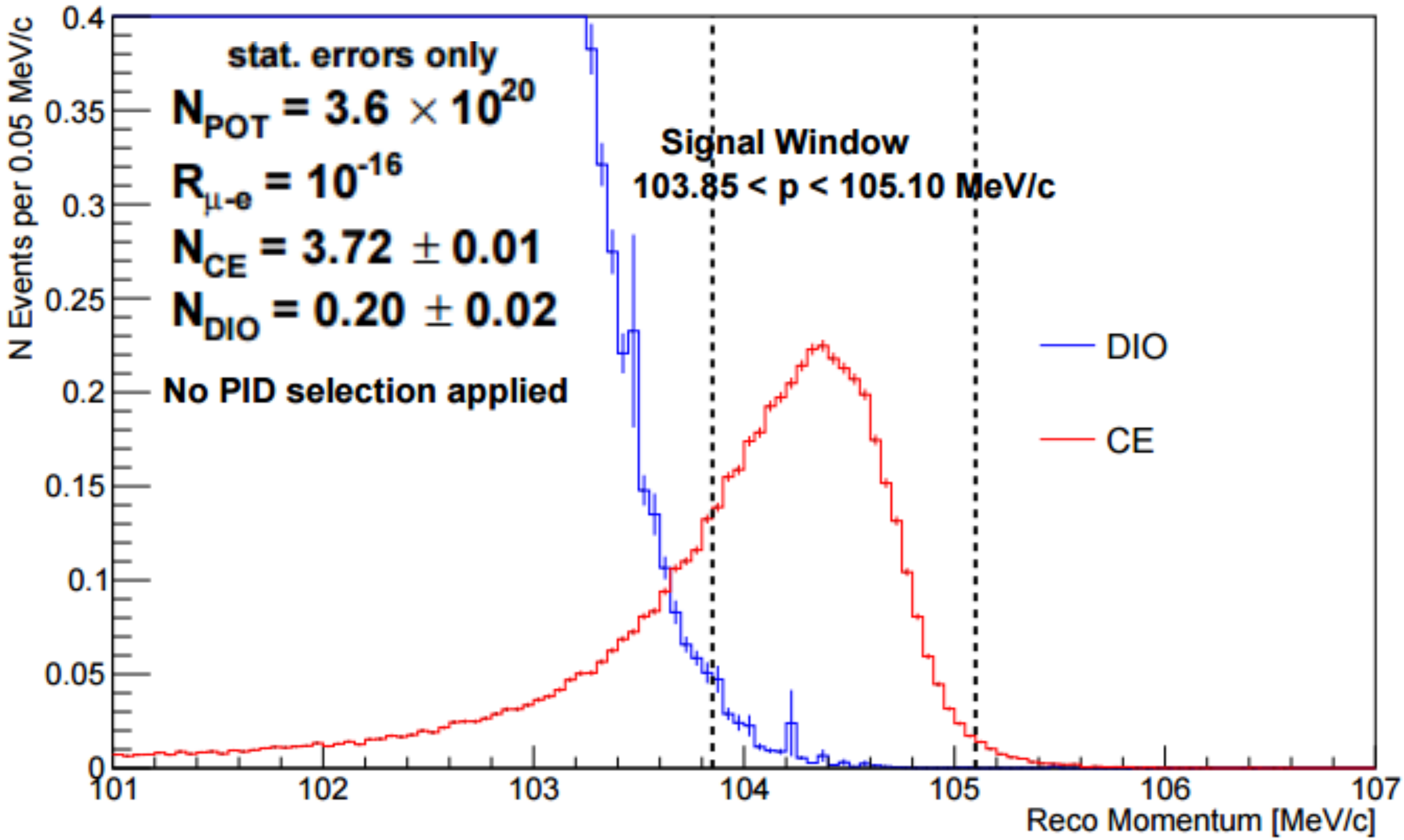
FEE board:
amplification, shaping
and voltage regulation



Waveform Digitizer:
Reads 20 channels
at 200 Mhz
(1 sample each 5 ns)



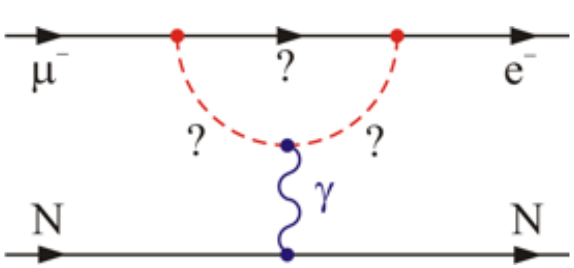
Three years run
Expectation by full Simulation



CLFV Lagrangian

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

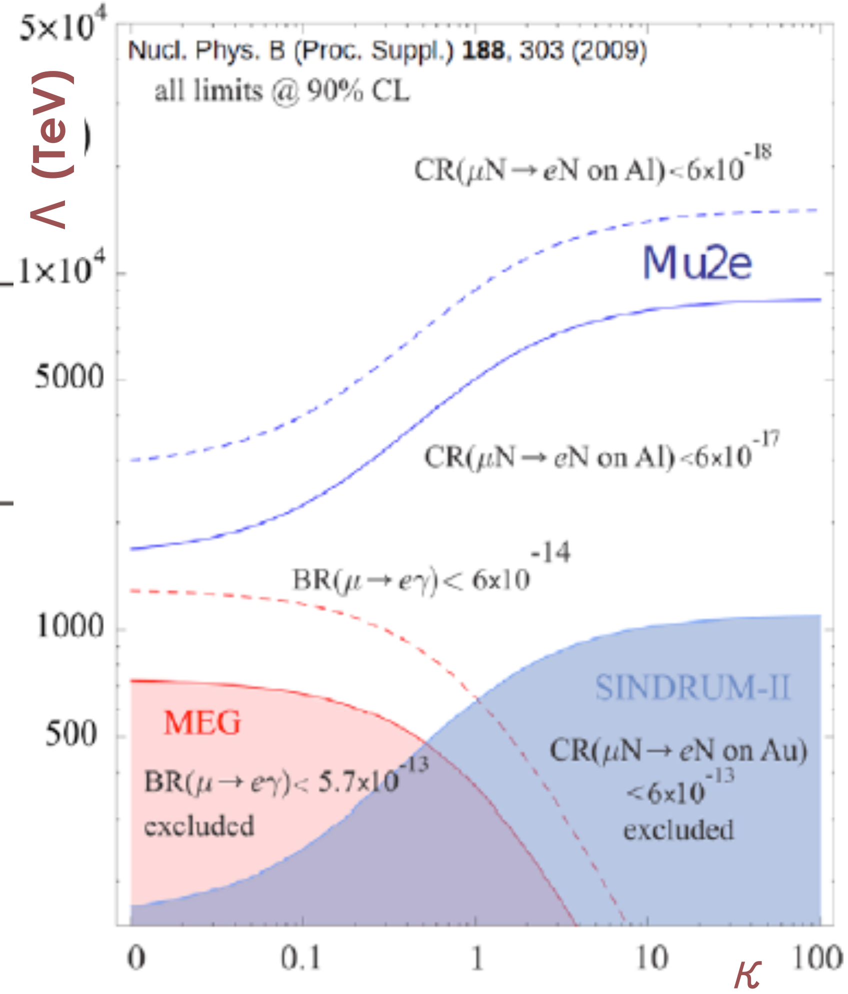
Loops dominate for
κ << 1



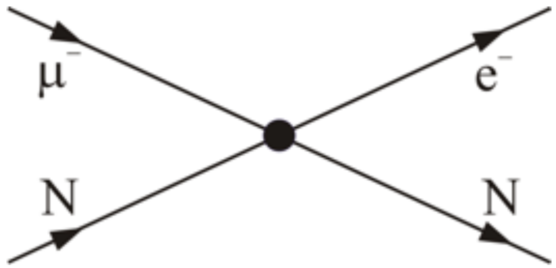
$\mu \to e\gamma$

$\mu N \to eN$

$\mu \to eee$



Contact terms
dominate for
κ >> 1



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

$\mu N \to eN$

$\mu \to eee$