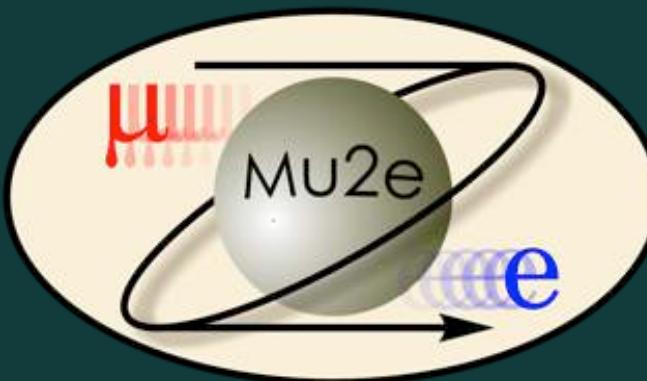


Design and test of the Mu2e undoped CsI + SiPM crystal calorimeter



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

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



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

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

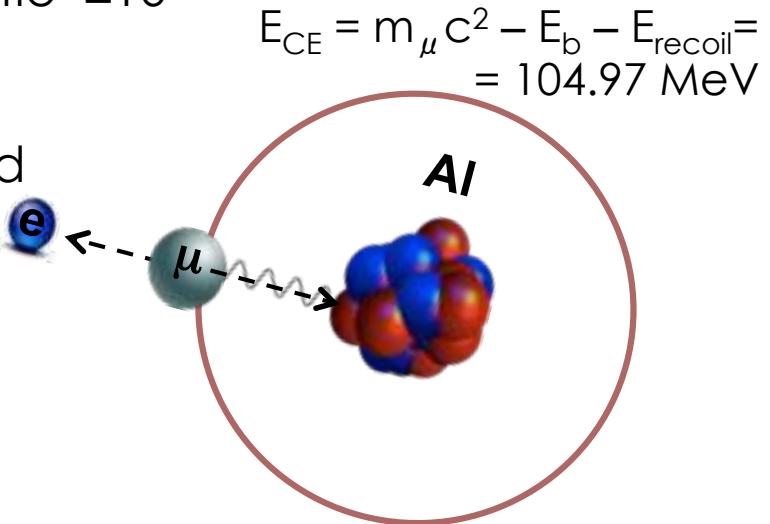
- Goal:
10⁴ improvement w.r.t. current limit (SINDRUM II)

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 $\sim 10^{18}$ stopped muons in 3 years of running)



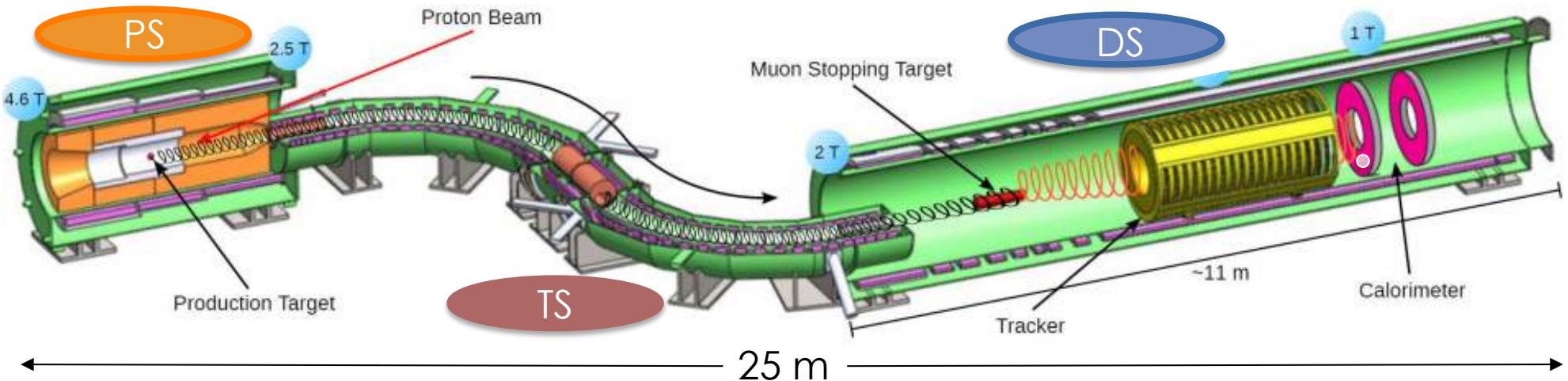
More information
at mu2e.fnal.gov



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

Transport Solenoid

- Selects and transports low momentum μ^-

Detector Solenoid: stopping target and detectors

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

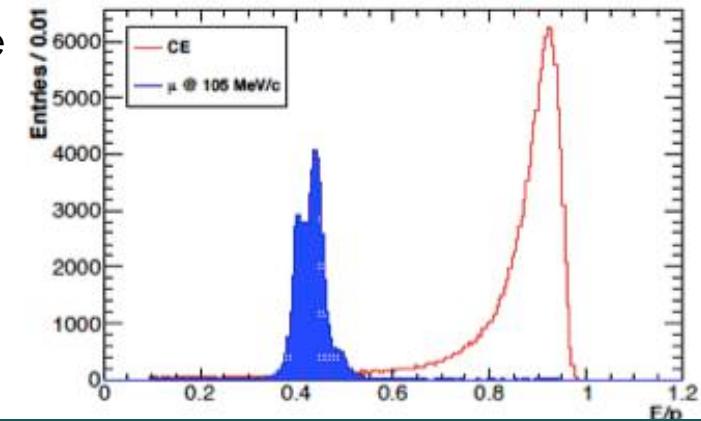


Calorimeter requirements



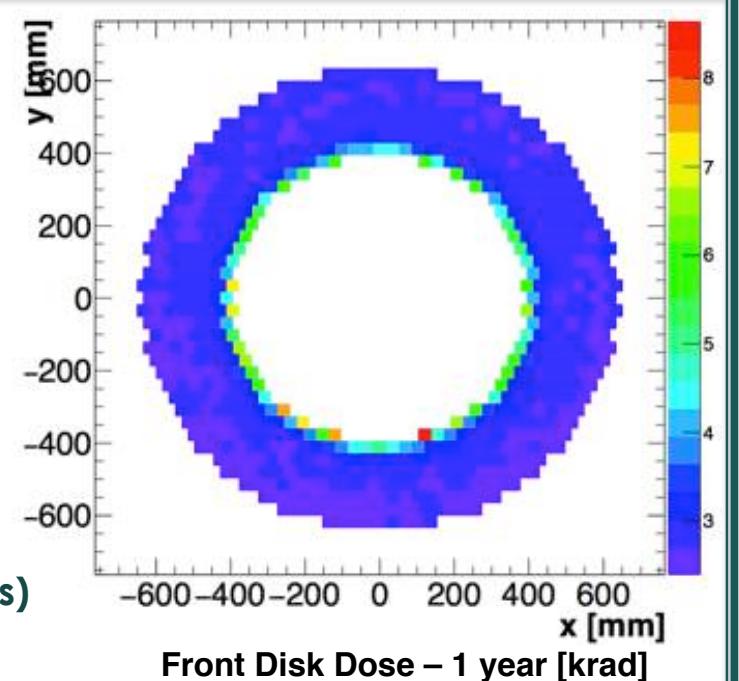
The electromagnetic calorimeter (EMC) should provide high acceptance for reconstructing energy, time and position of CEs for:

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



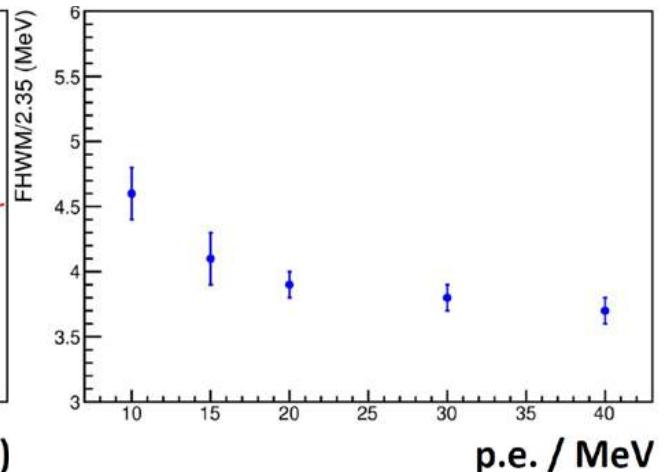
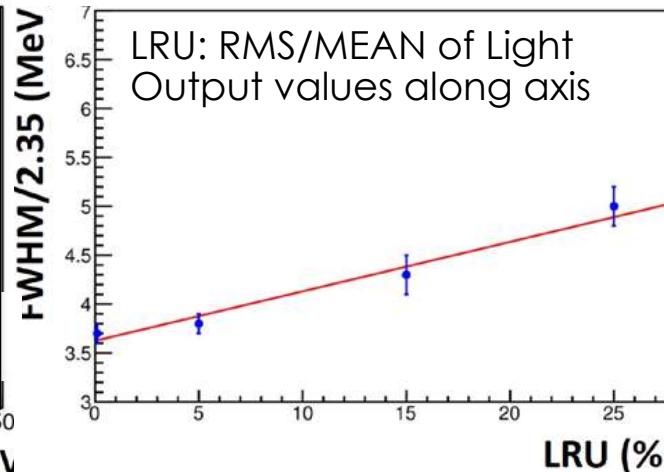
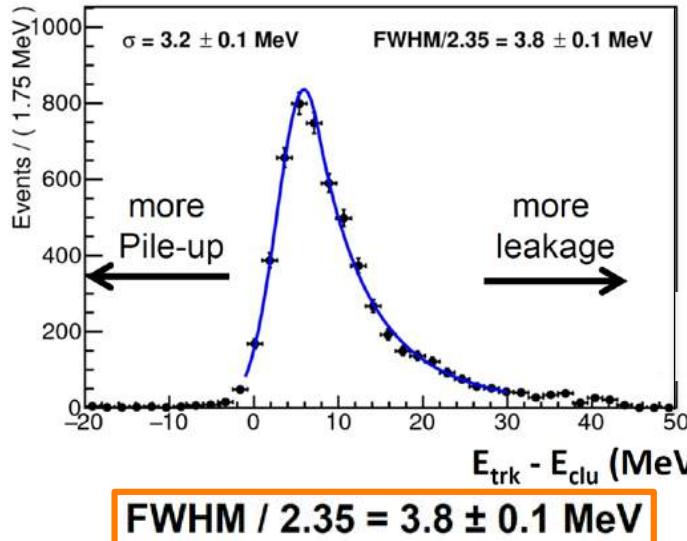
Requirements @ 105 MeV/c

- $\sigma_E/E = \mathcal{O}(10\%)$ for CE
- $\sigma_T < 500 \text{ ps}$ for CE
- $\sigma_{X,Y} \leq 1 \text{ cm}$
- Fast scintillation signals ($\tau < 40 \text{ ns}$)
- 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)
 - $3 \times 10^{12} n_{1\text{MeV}}/\text{cm}^2$ ($1.2 \times 10^{12} n_{1\text{MeV}}/\text{cm}^2$) for crystals (sensors)
- Low radiation induced readout noise $< 0.6 \text{ MeV}$





Simulated performance



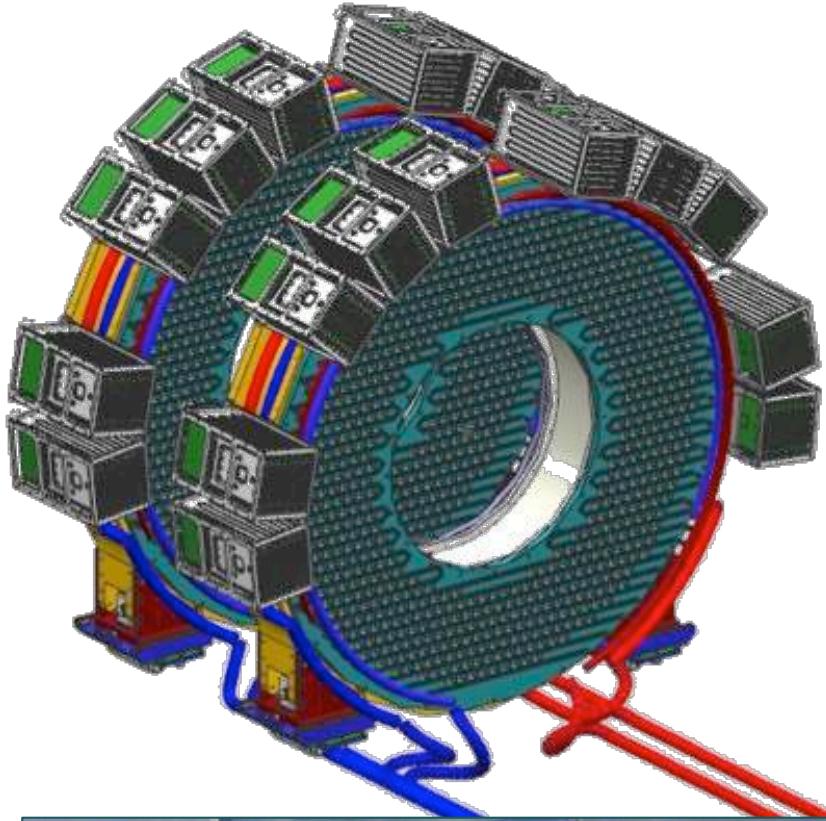
- Simulation includes full background and digitization and cluster-finding, with split-off and pileup recovery
- The overall resolution depends on crystals features
 - Several crystals considered

A table comparing the properties of different crystals: LYSO, BaF₂, and CsI. The table has five rows and four columns. The last column, CsI, is circled in red. Red lines cross over the LYSO and BaF₂ columns.

	LYSO	BaF ₂	CsI
Radiation Length X_0 [cm]	1.14	2.03	1.86
Light Yield [% NaI(Tl)]	75	<u>4/36</u>	3.6
Decay Time [ns]	40	<u>0.9/650</u>	20
Photosensor	APD	RMD APD	SiPM
Wavelength [nm]	402	220/300	310



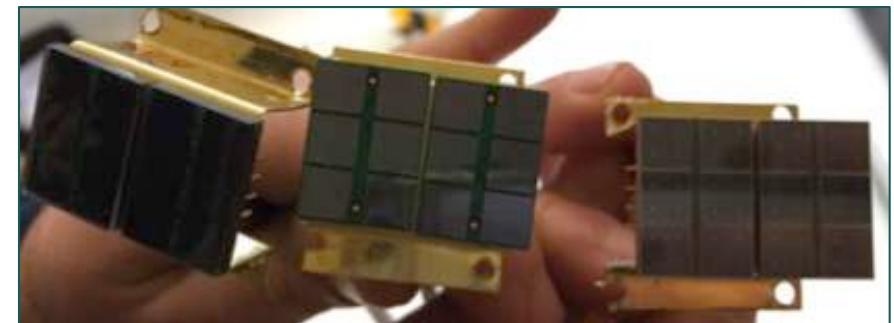
Calorimeter Design



2 annular disks with 674 undoped CsI ($34 \times 34 \times 200$) mm³ 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**

C0030	S-G C0062	SIC C0070
0032	S-G C0063	SIC C0071
034	S-G C0065	SIC C0072
36	S-G C0066	SIC C0073

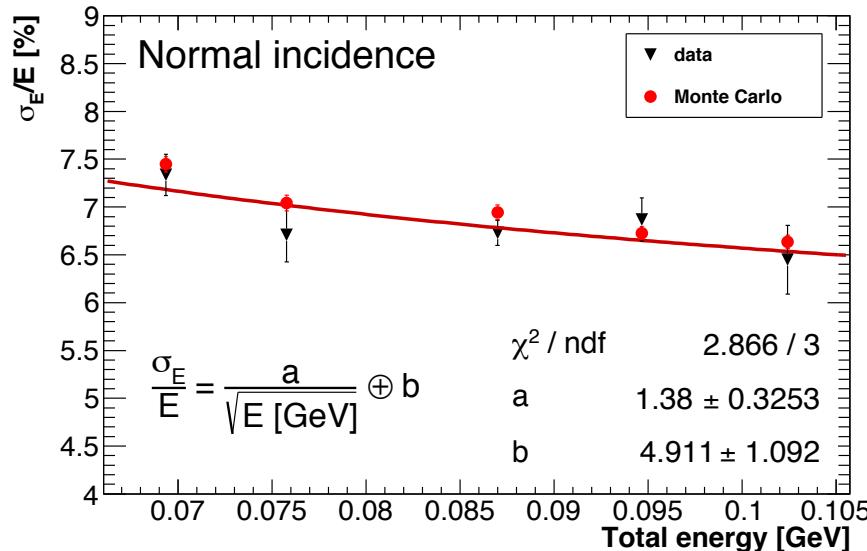




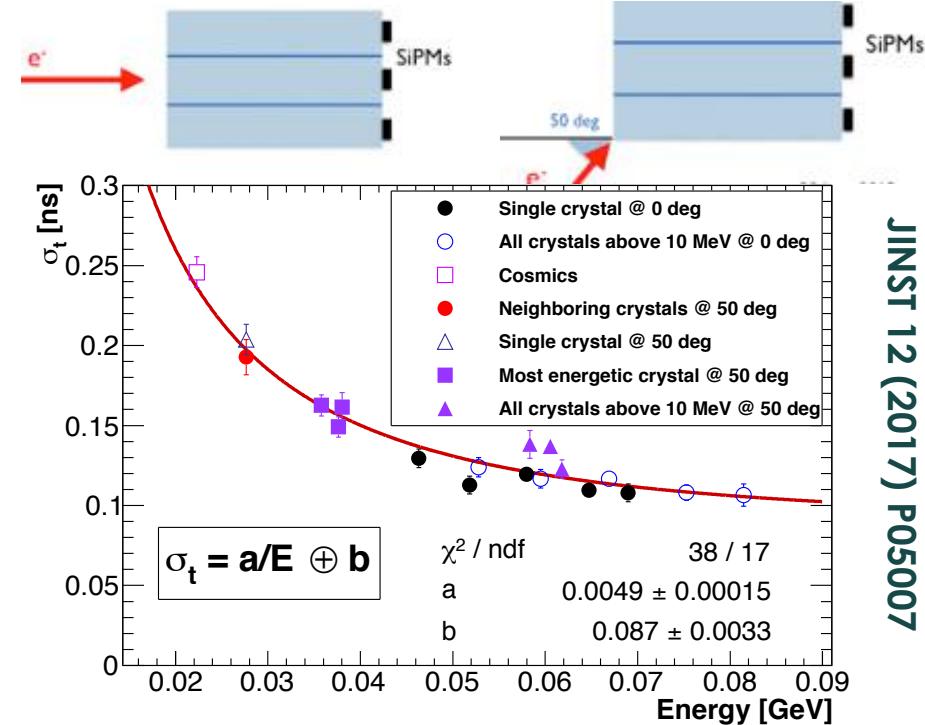
Small prototype: Time and Energy resolution



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



$\sigma_E \sim 7 \% \text{ at } 100 \text{ MeV}$



$\sigma_T \sim 110 \text{ ps at } 100 \text{ MeV}$

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

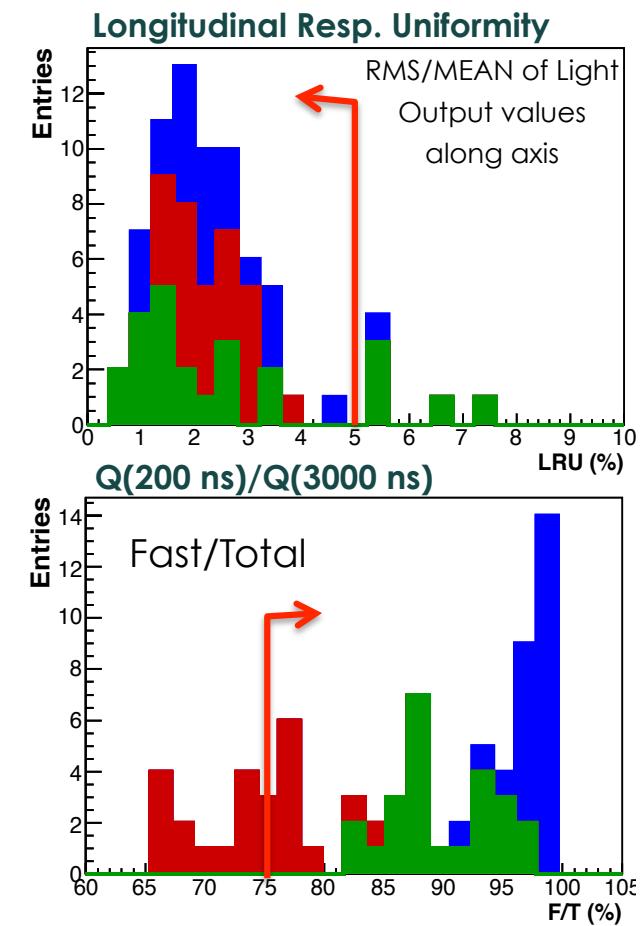
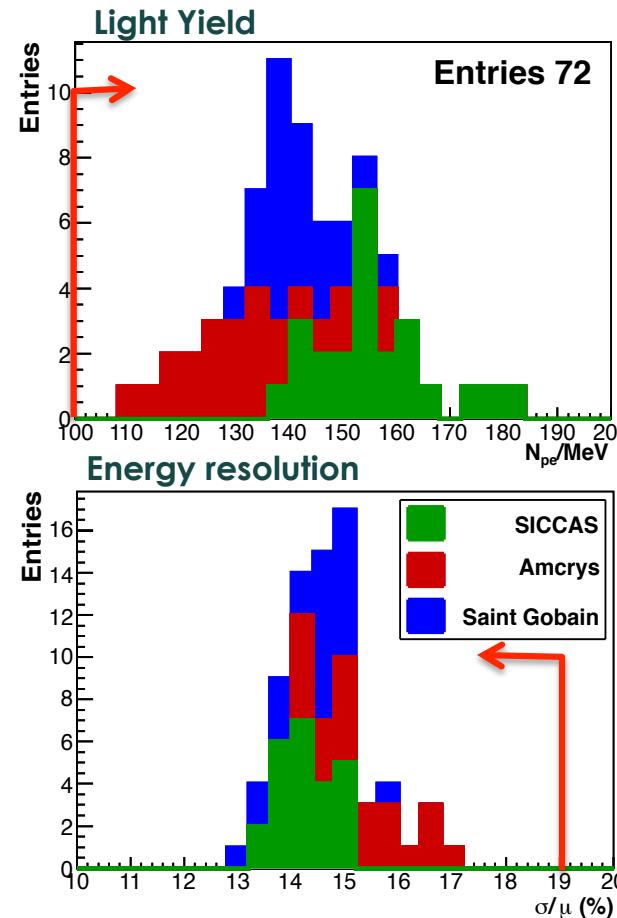
Pre-production Crystals

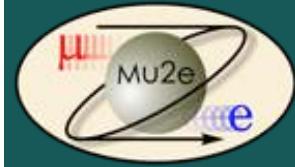


- 24 crystals from **SICCAS**, **Amcrys**, **Saint Gobain**
- Optical properties tested with **511 keV γ 's** along the crystal axis
- 150 μm **Tyvek** wrapping and UV-extended **PMT** readout

**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)





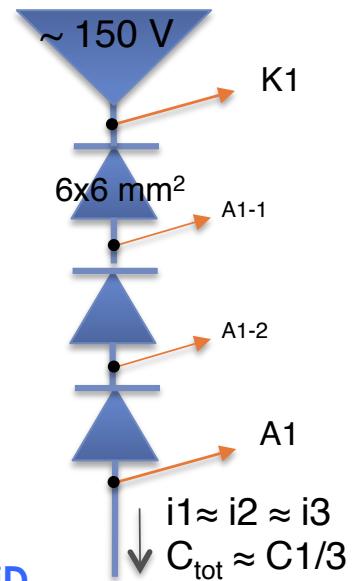
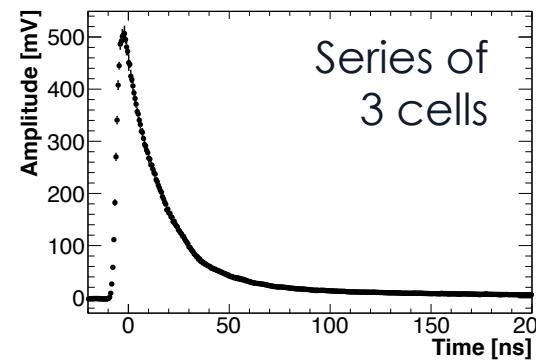
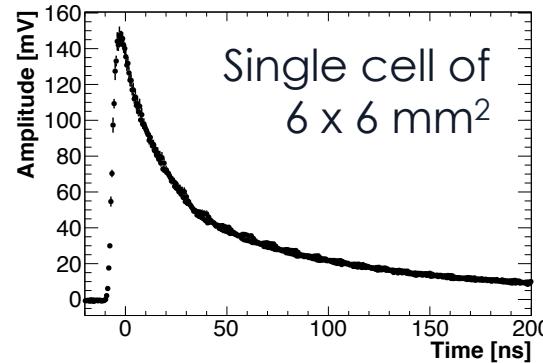
Pre-production SiPMs



Mu2e custom silicon photosensors:

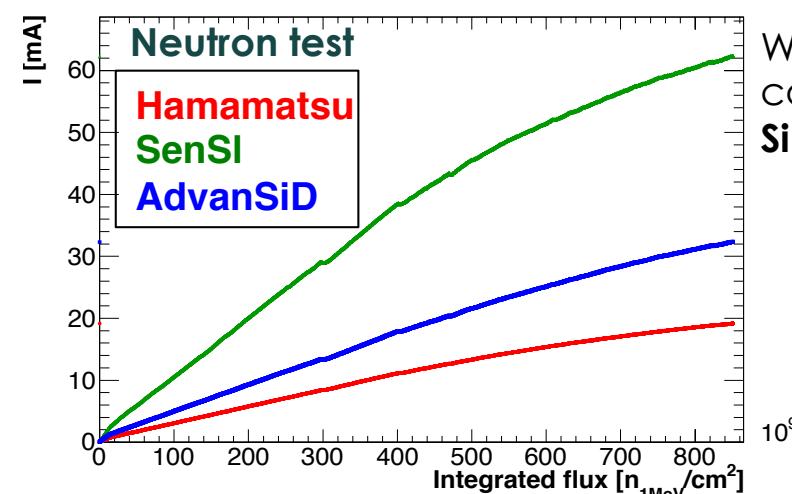
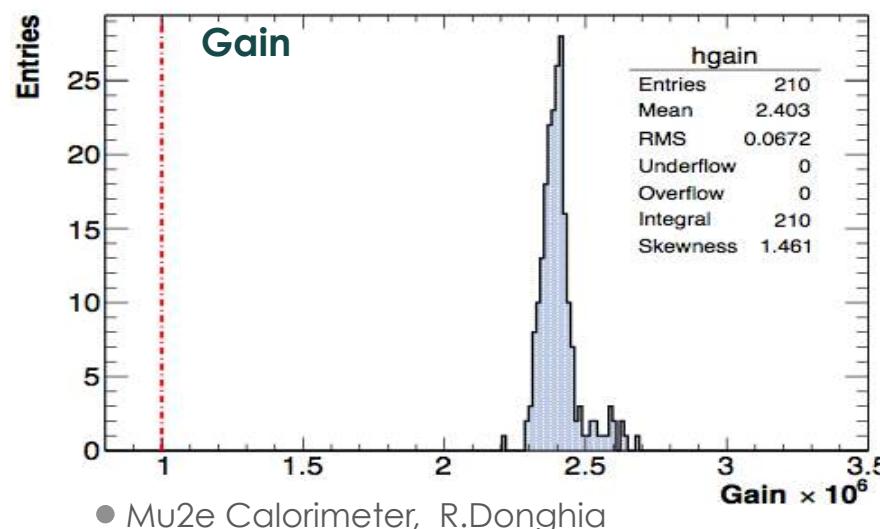
→ **2 arrays of 3 6 × 6 mm² UV-extended SiPMs: total area (12x18) mm²**

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





Module 0

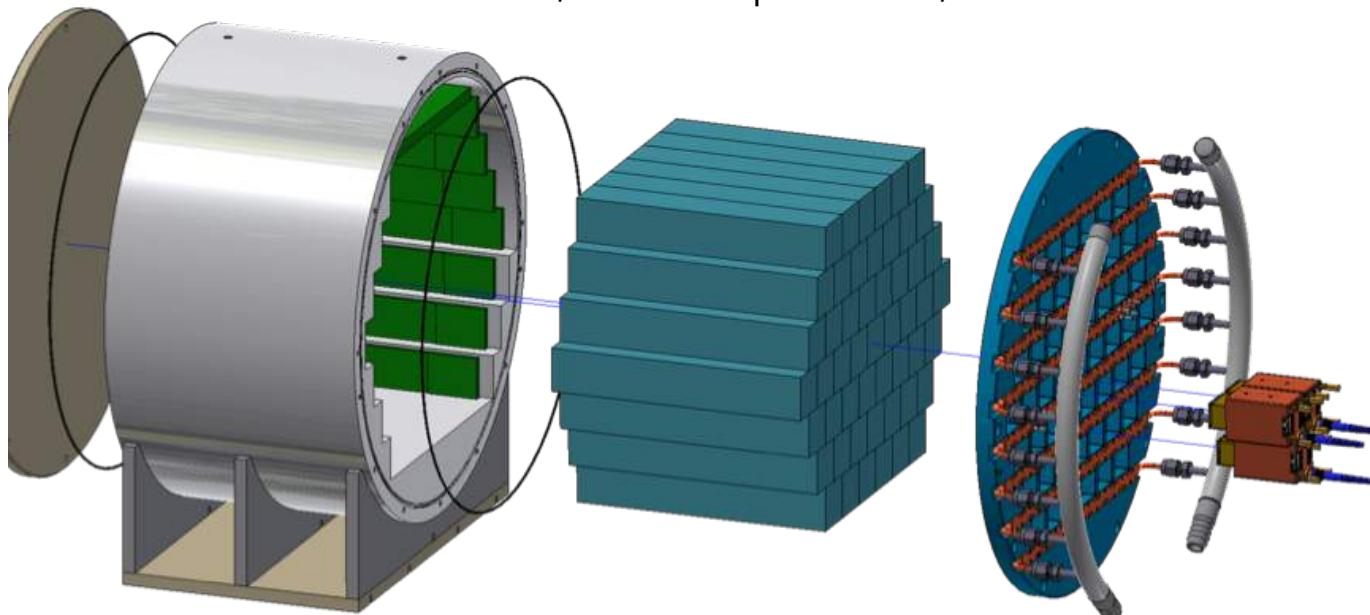


Large EMC prototype: **51 crystals, 102 SiPMs, 102 FEE boards**

Mechanics and cooling system similar to the final ones!

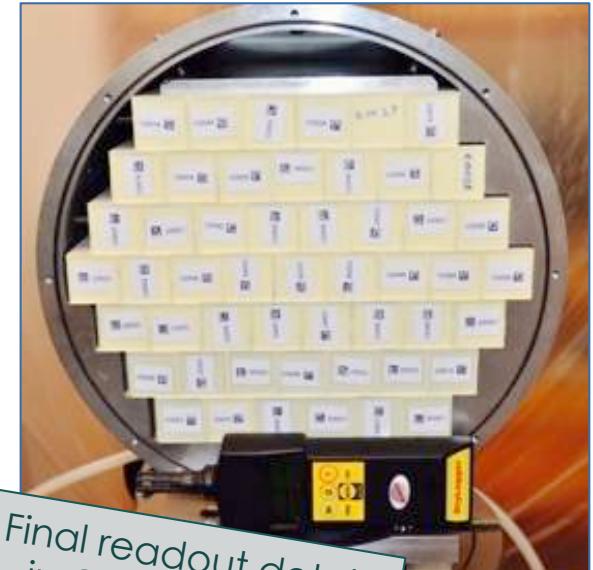
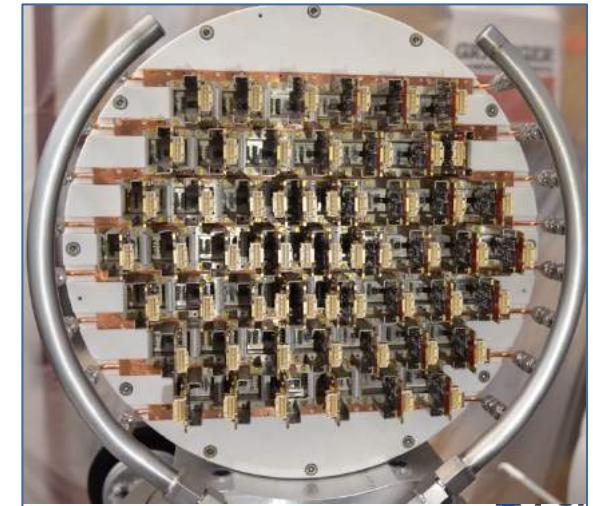
Goals:

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

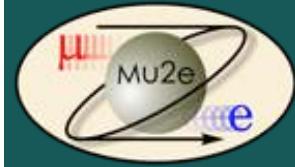


Readout: 1 GHz CAEN digitizers (DRS4 chip), 2 boards x 32 channels

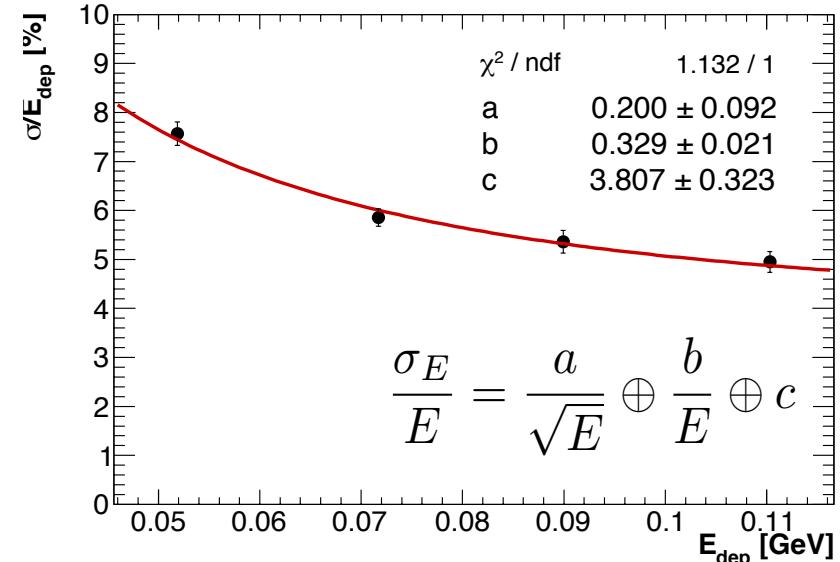
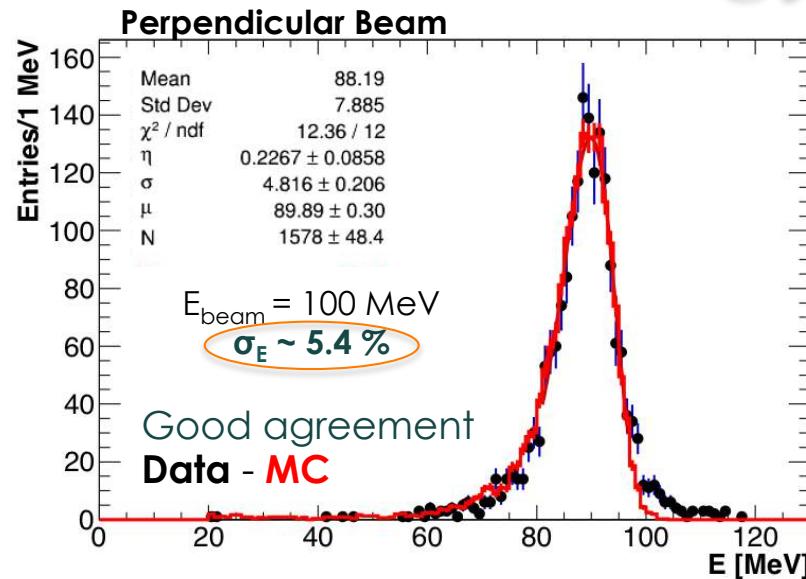
- Mu2e Calorimeter, R.Donghia



Final readout details
in Caiulo's poster

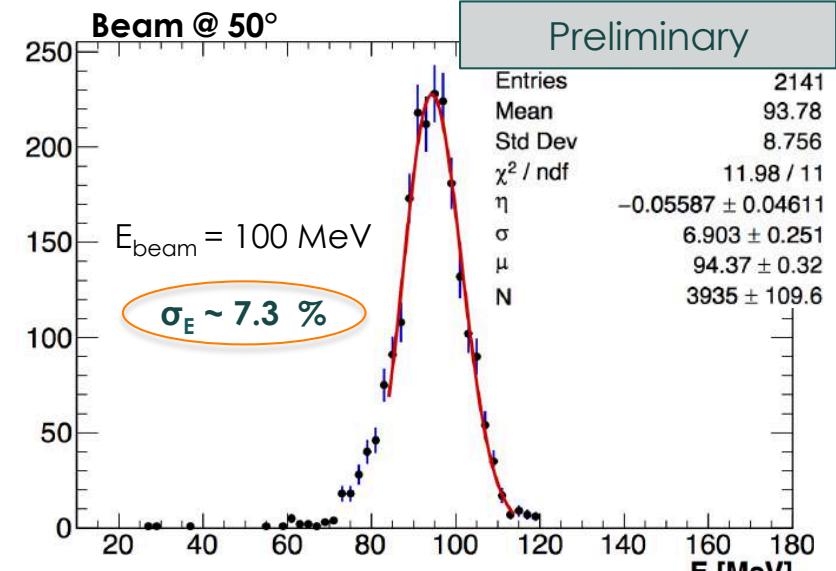
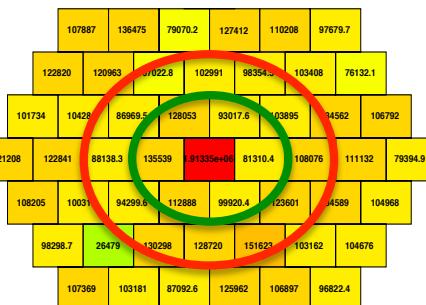


Module 0 Energy resolution

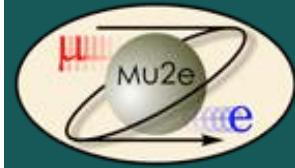


- Single particle selection
- Calibration
 - MIPs
 - 100 MeV e⁻ beam, up to ring 2
- Threshold applied after noise run @ 3 σ

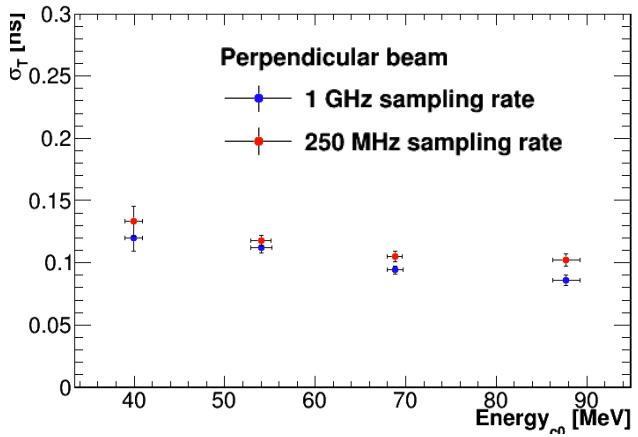
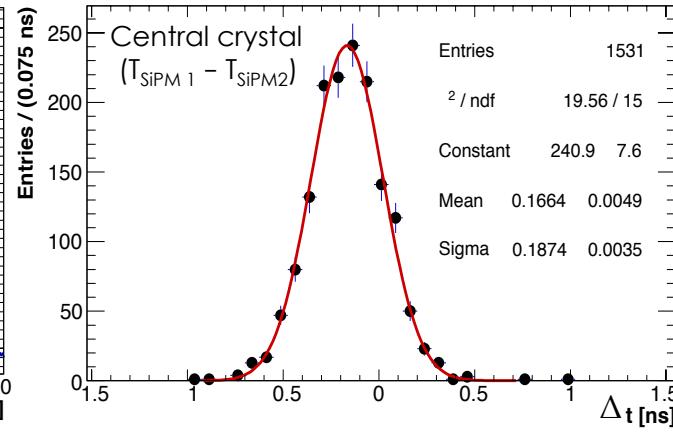
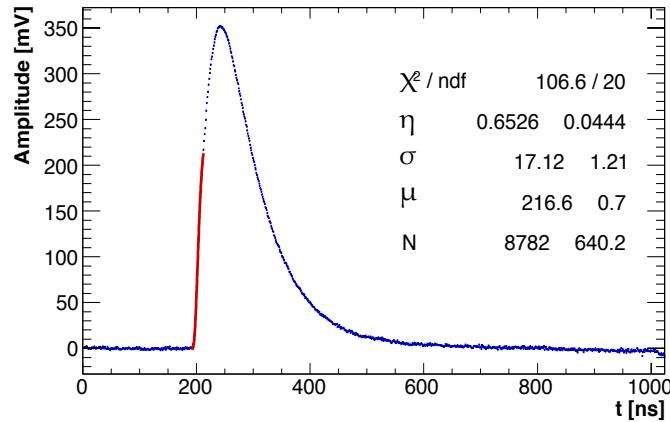
● Mu2e Calorimeter, R.Donghia



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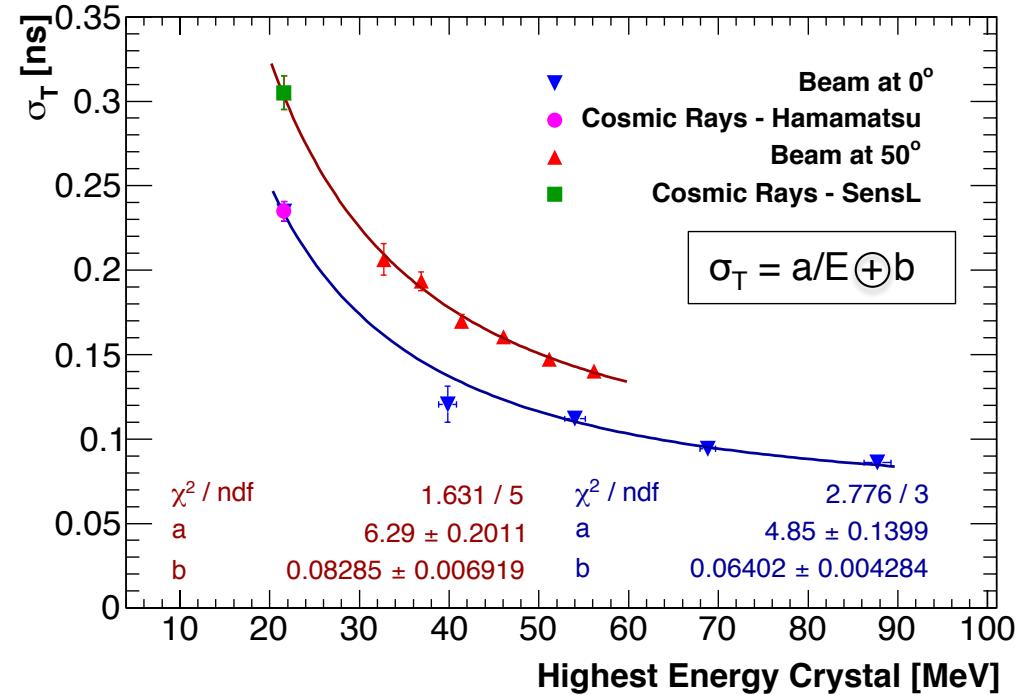


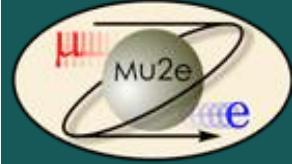
Module 0 Time resolution



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

$\sigma(T_1+T_2)/2 \sim 94 \text{ ps}$
@ $E_{\text{beam}} = 100 \text{ MeV}$

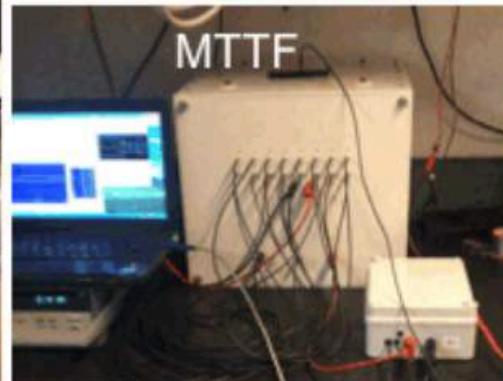
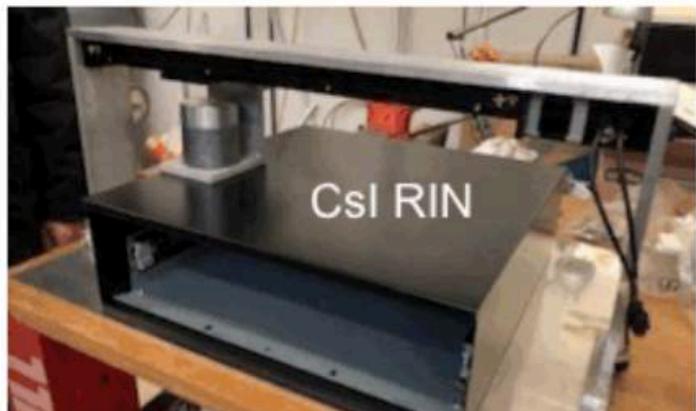
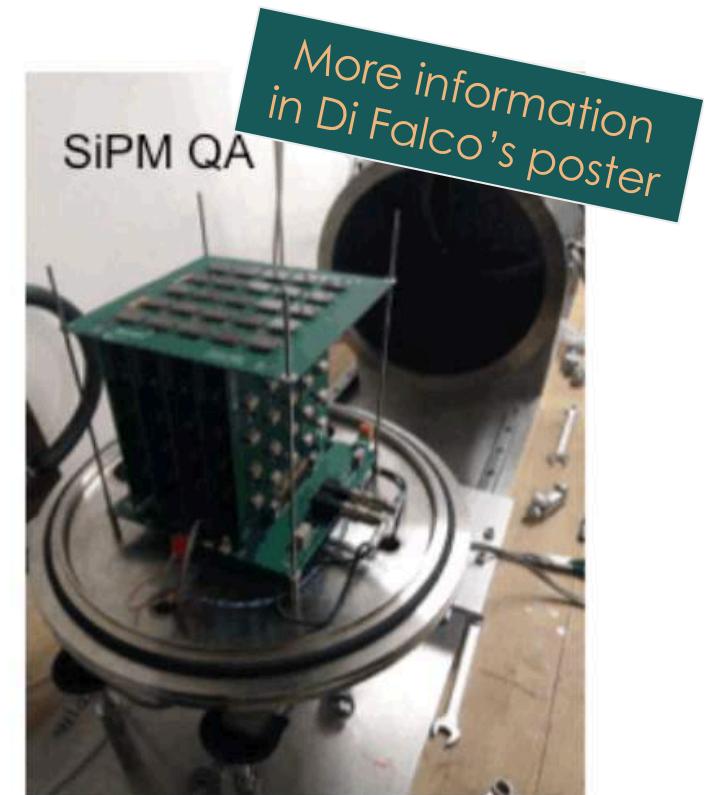
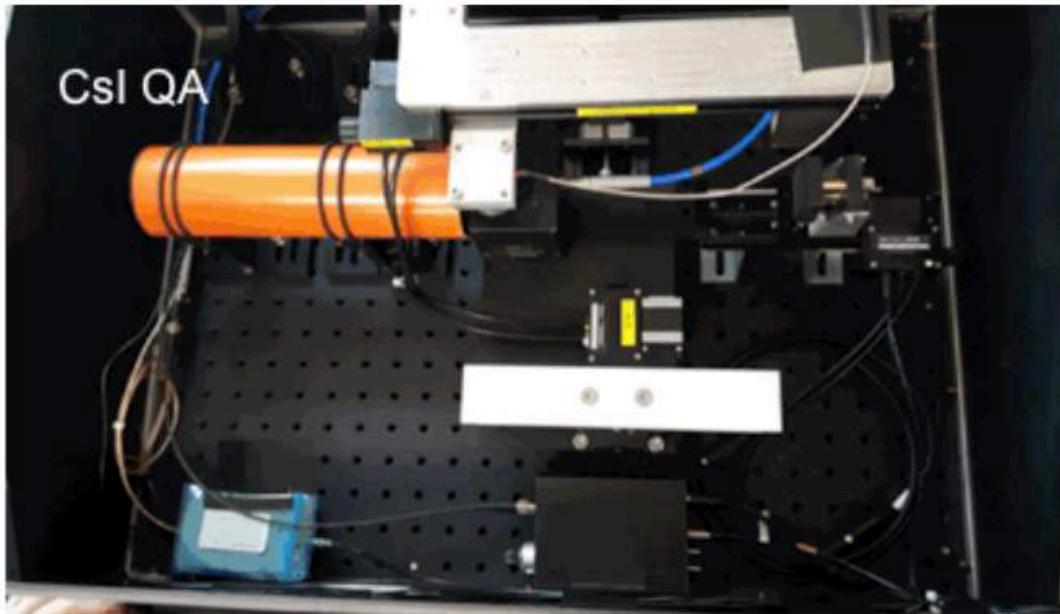




QA status of basic components

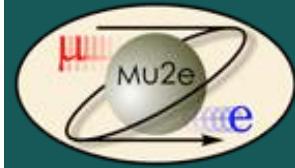


New laboratory built at FNAL. QA tests of all components started on march 2018



● Mu2e Calorimeter, R.Donghia

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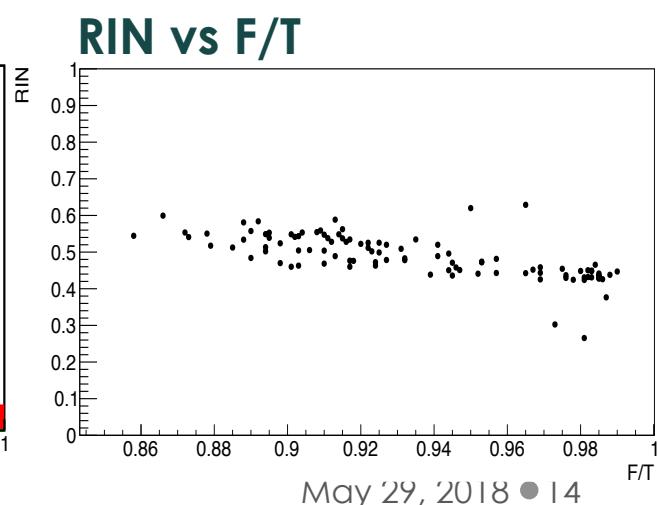
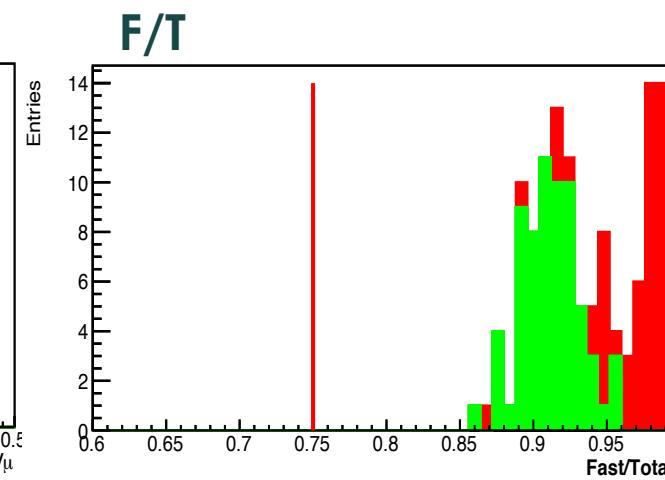
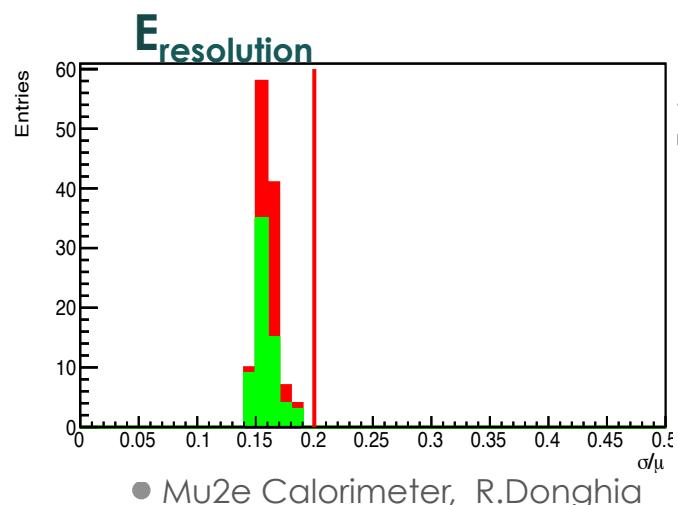
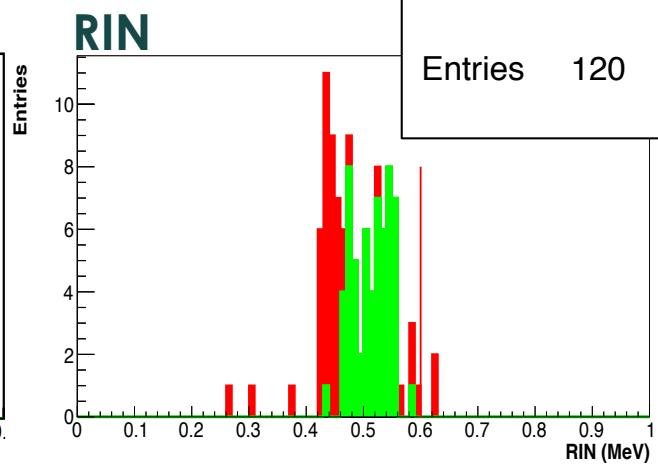
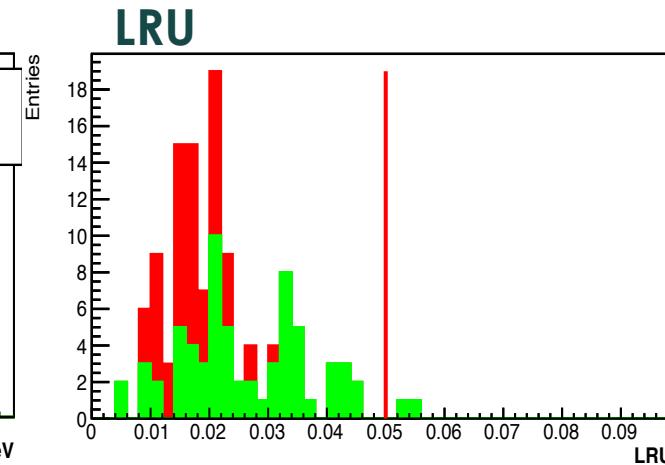
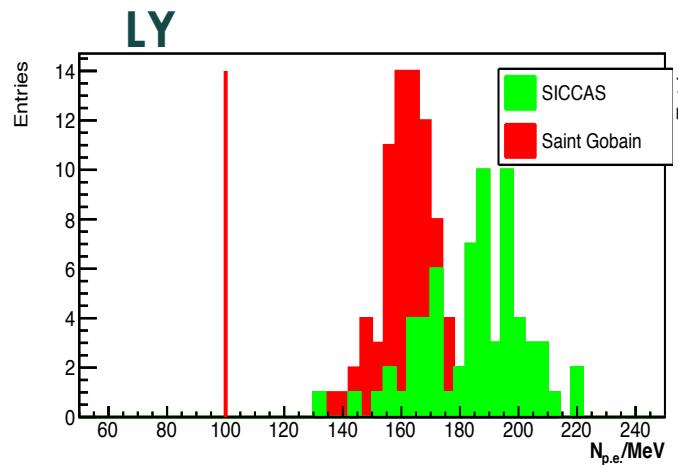


Crystals QA status



More than 100 crystals already tested

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



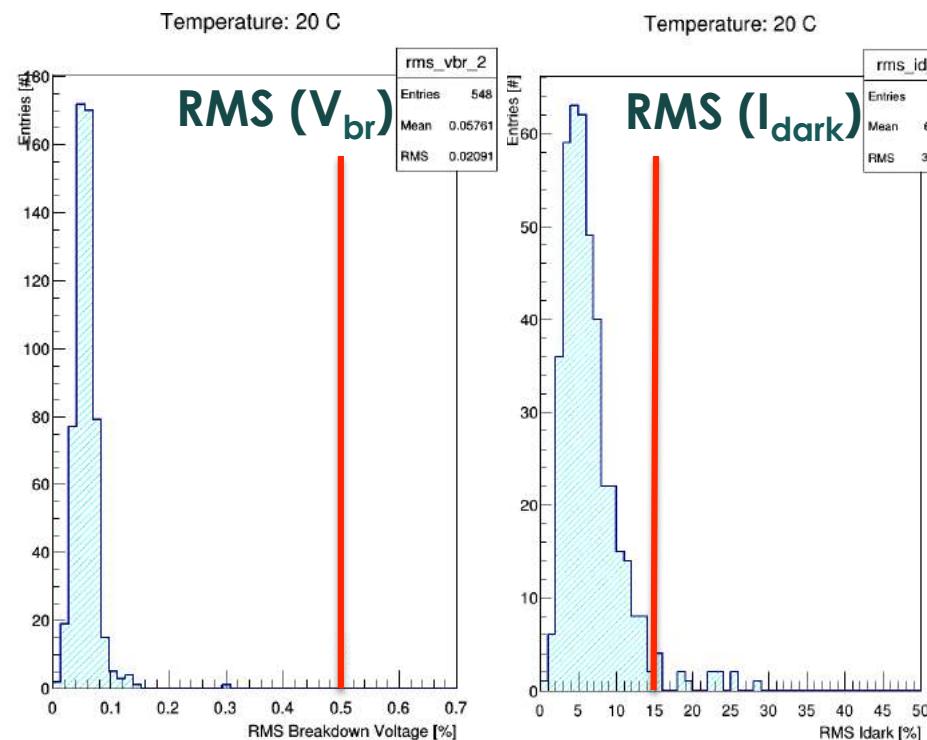


SiPMs QA status



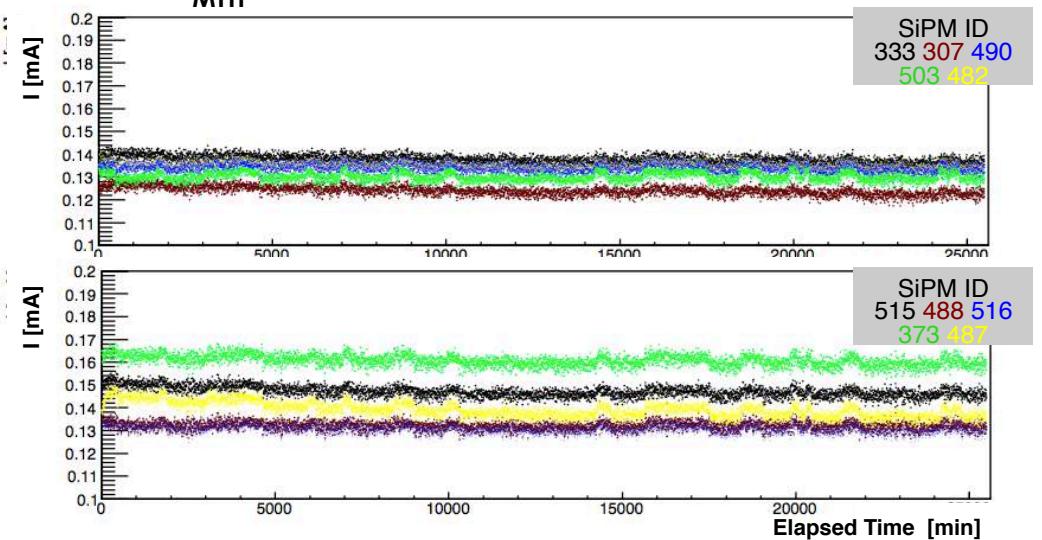
About 550 Mu2e SiPMs already characterized

- 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 $\sim 1 \times 10^{12}$ neutrons/cm² (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**





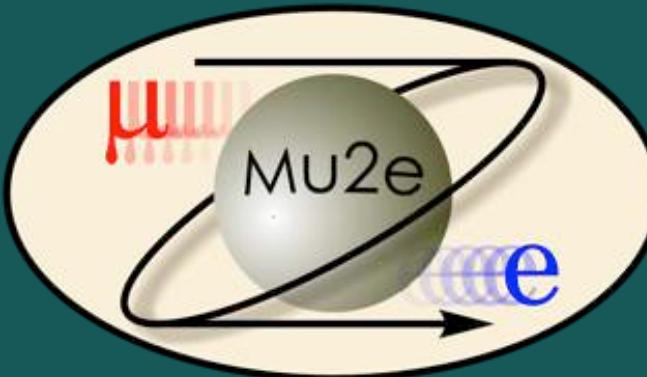
Summary and Conclusions



- 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

May 29, 2018

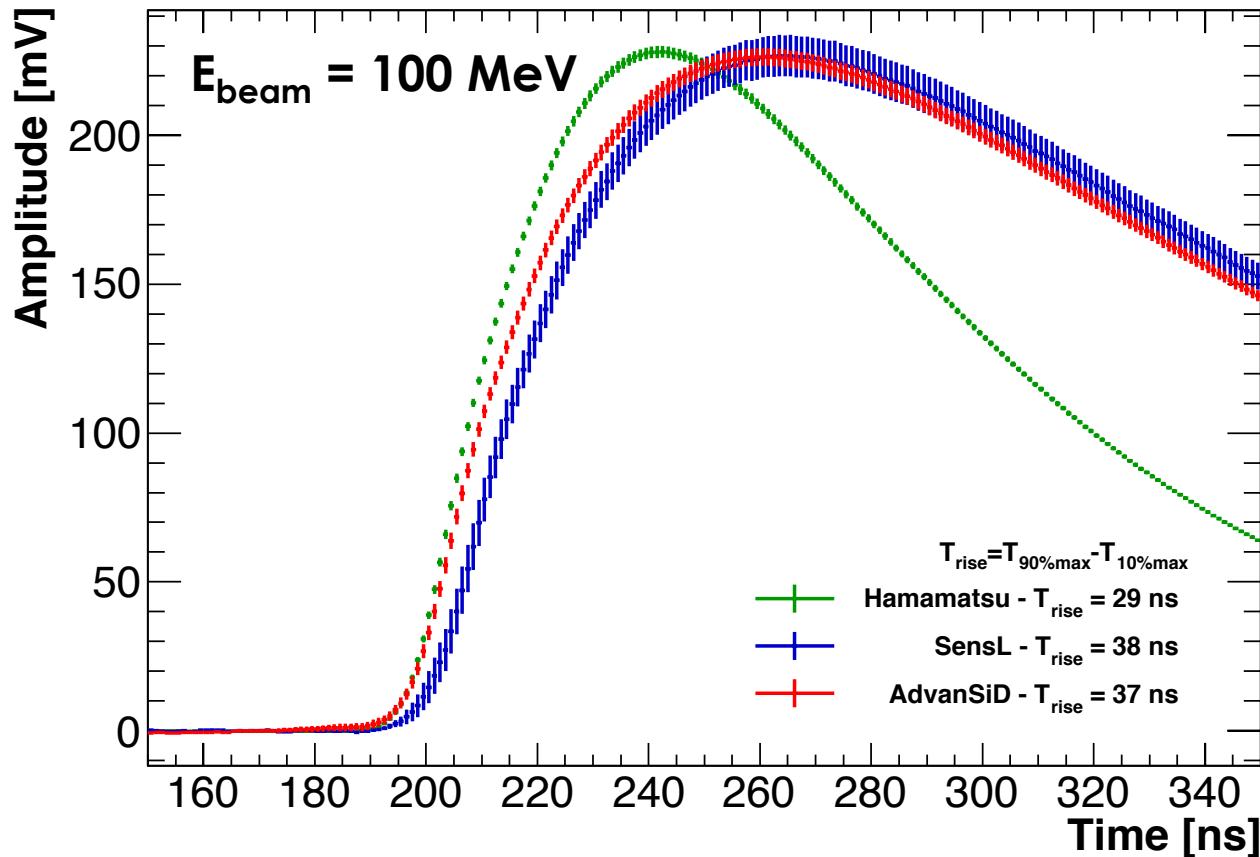
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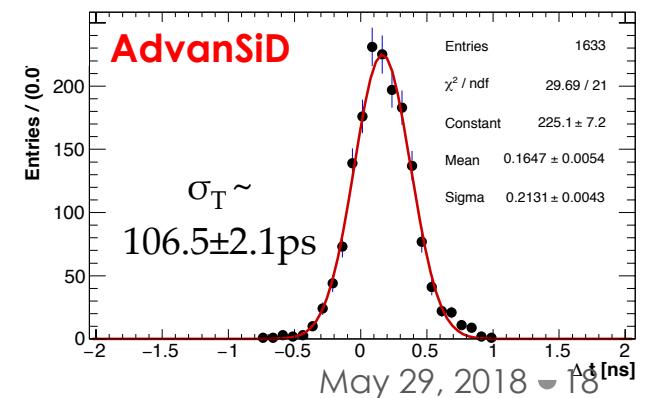
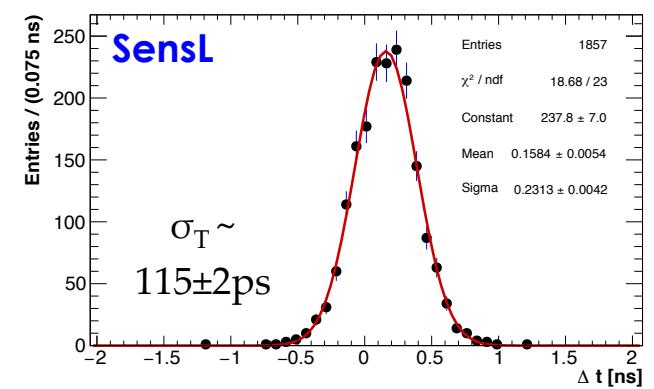
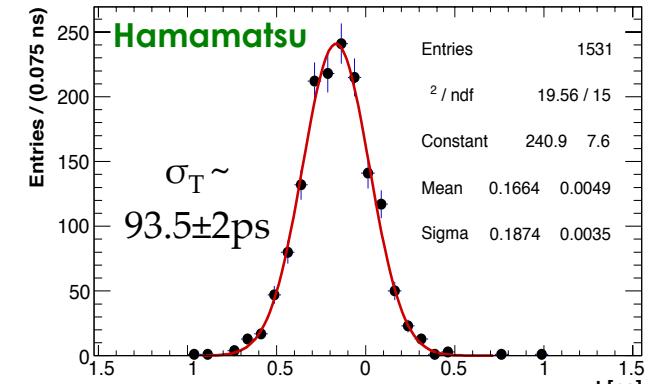
Module 0 SiPM-vendors comparison



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

Energy fluctuation
discriminator

● Mu2e Calorimeter, R.Donghia

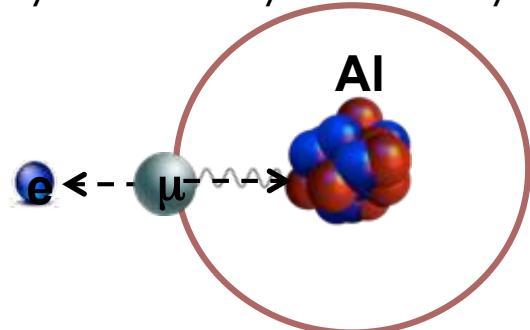




Charged Lepton Flavor Violation



- CLFV strongly suppressed in SM: $\text{BR} \leq 10^{-54}$
→ Observation indicates New Physics
- CLFV@Mu2e: $\mu - e$ conversion in a nucleus field
→ discovery sensitivity on many NP models



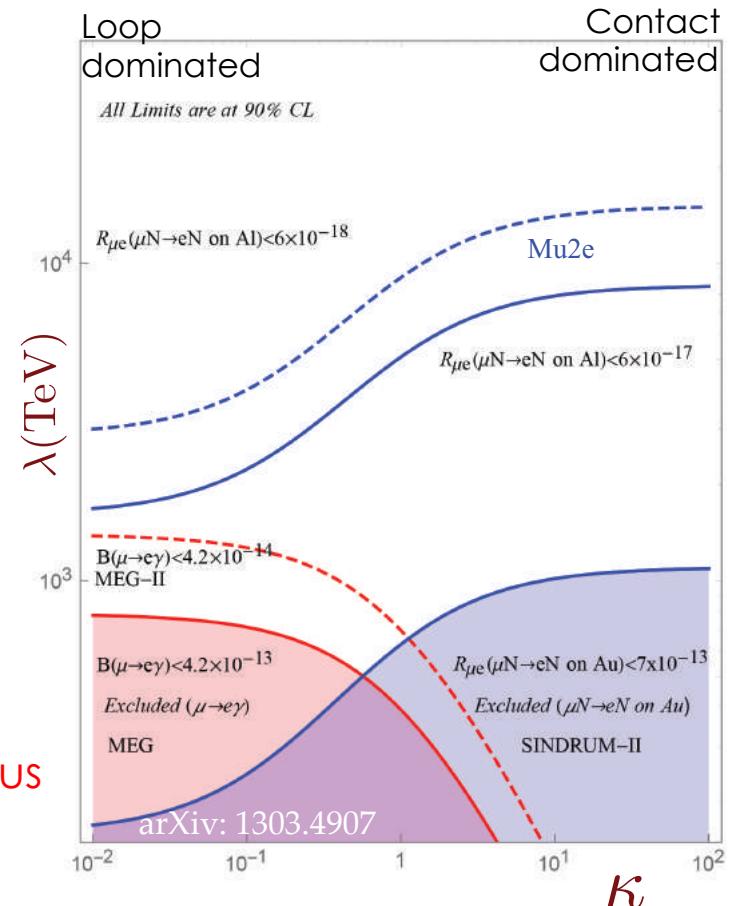
- **Goal:**
10⁴ improvement w.r.t. current limit (SINDRUM II)
 $\mu - e$ conversion in the presence of a nucleus

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

Nuclear captures of muonic Al atoms

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

- Mu2e Calorimeter, R.Donghia



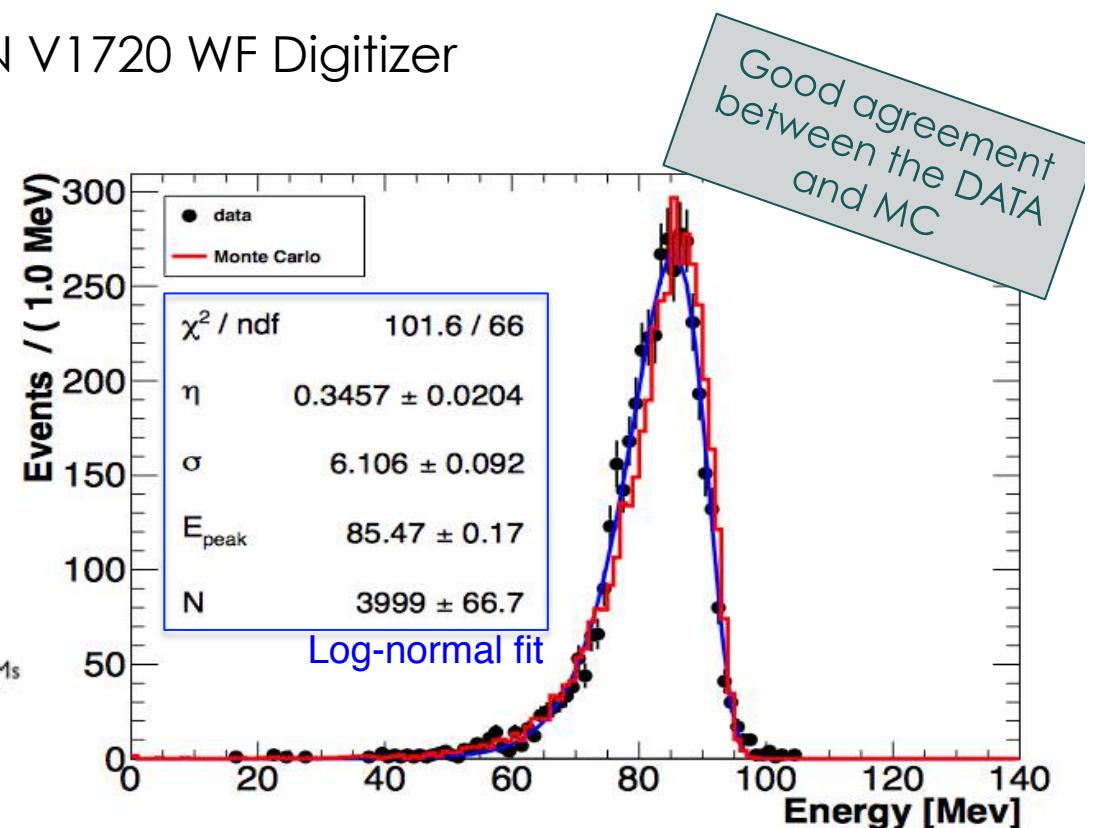
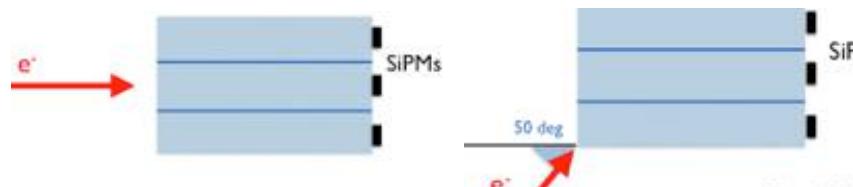


Small prototype: Test Beam



JINST 12 (2017) P05007

- Small prototype tested @ BTF (Frascati) in April 2015, 80-120 MeV e^-
- 3×3 array of 30×30×200 mm² undoped CsI crystals coupled to one Hamamatsu SiPM array (12x12) mm² with Silicon optical grease
- DAQ readout: 250 Msps CAEN V1720 WF Digitizer

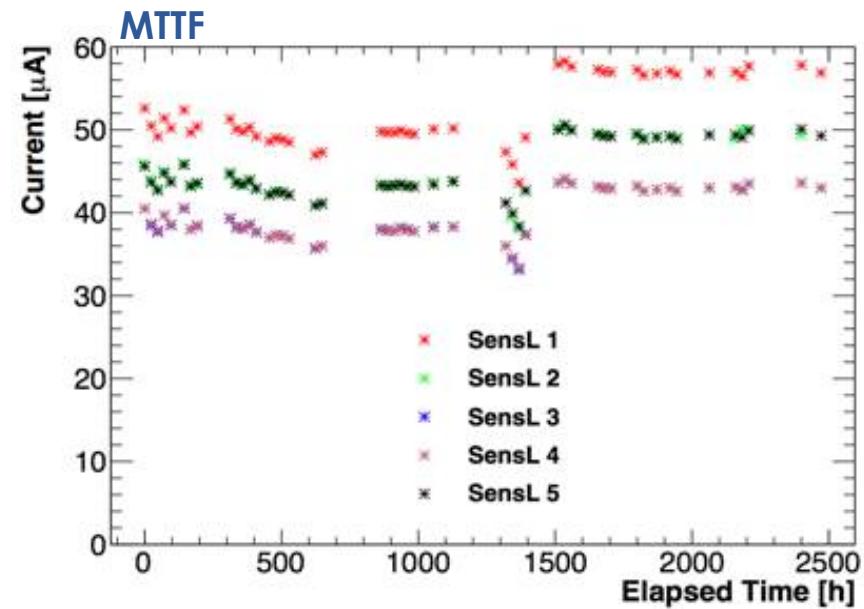
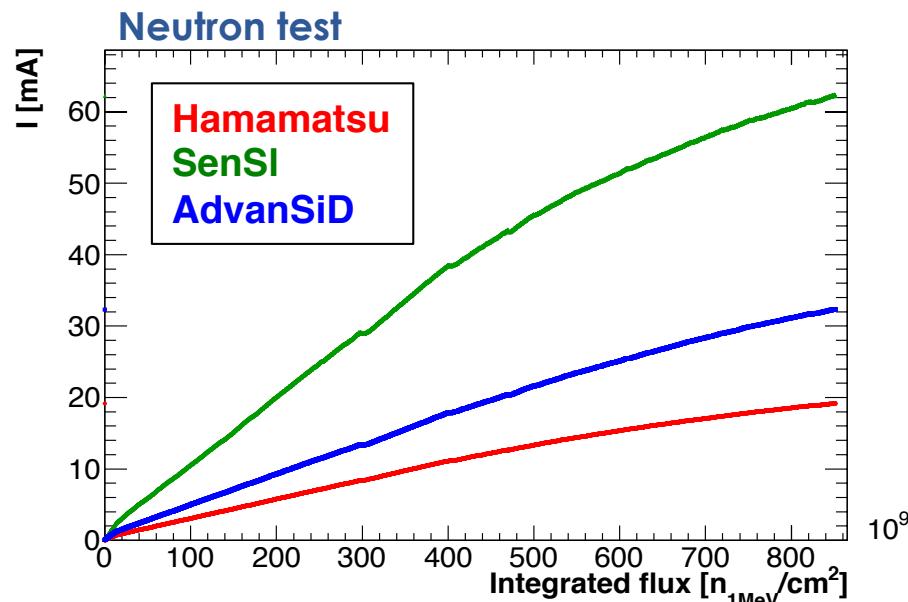




Pre-production test: SiPMs (2)



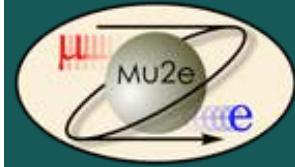
- 1 sample per vendor has been exposed to neutron flux up to $8.5 \times 10^{11} n_{1\text{MeV}_{\text{eq}}}/\text{cm}^2$ (@ 20 °C)
- 5 samples per vendor have been used to estimate the mean time to failure value
Requirement: obtain an MTTF of 1 million hours when operating at 0 °C



- 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 $\geq 6 \times 10^5$ hours



Single channel slice test

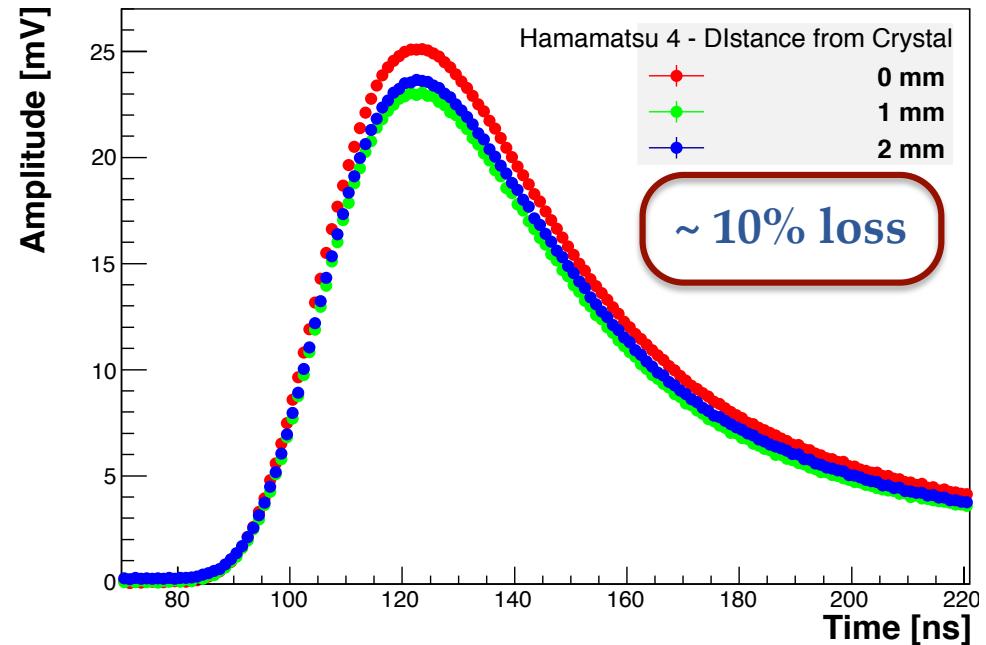


SG crystal + Hamamatsu SiPM + FEE

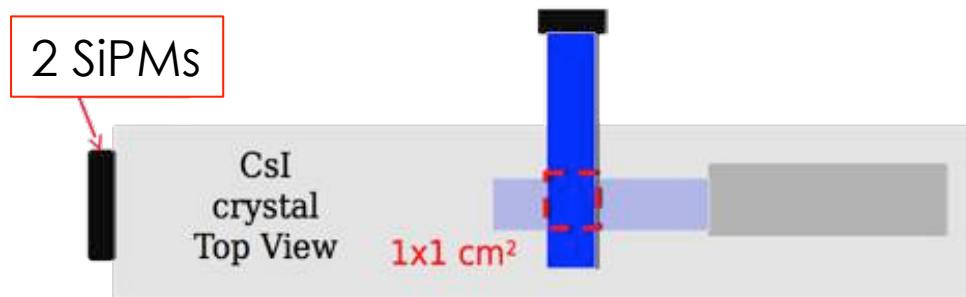
Optical coupling in air.

- **^{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



● Mu2e Calorimeter, R.Donghia





Single channel Cosmic Rays Test



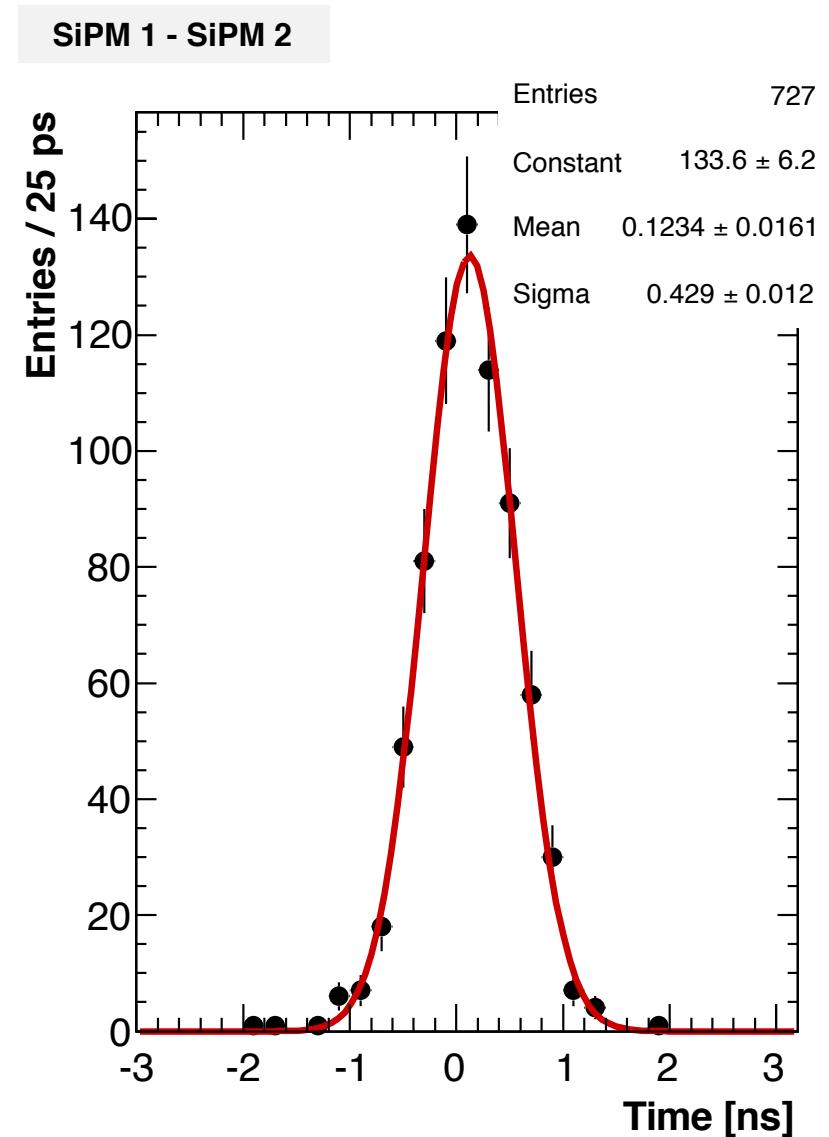
- TRG time resolution ~ 170 ps
- Constant fraction method used
- Pulse height correction applied (slewing)

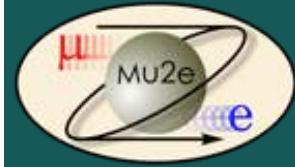
After jitter subtraction:
 $\text{SiPM 1} - \sigma_T \sim 330$ ps
 $\text{SiPM 2} - \sigma_T \sim 340$ ps

$T(\text{SiPM1} - \text{SiPM2})/2 \rightarrow \sim 215$ 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 $\rightarrow 215$ ps (now) vs 250 ps (old).





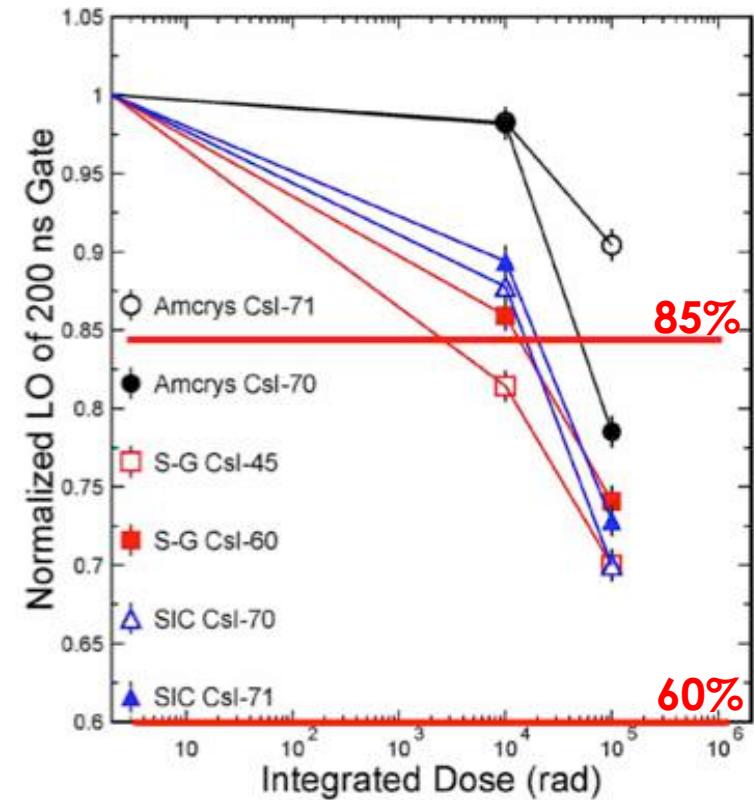
Pre-production test: Crystals (2)



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 **$1.6 \times 10^{12} n_{1\text{MeV}}/\text{cm}^2$ integrated flux**
- Neutron RIN is also smaller than the one from dose

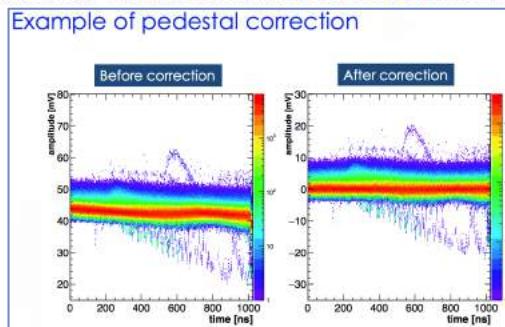


Module 0 Event selection



Pedestal correction: Results

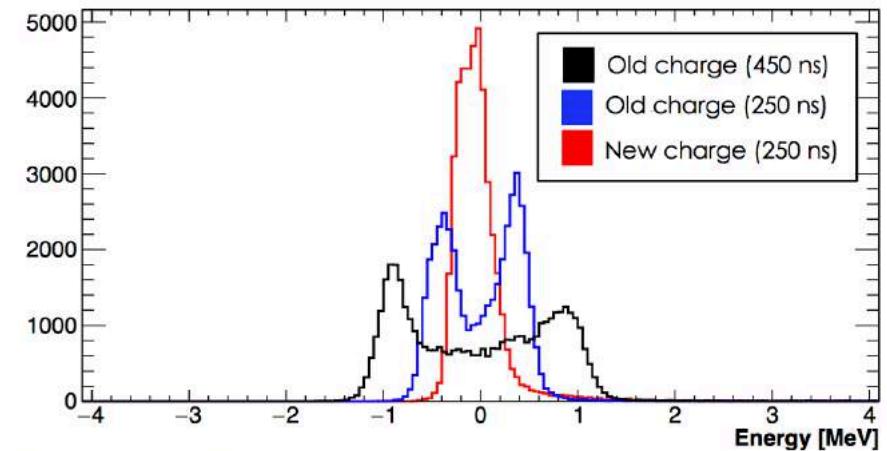
- The integration range reduced to (150,400) ns
- Pedestal distribution reduction **better than a factor 2**



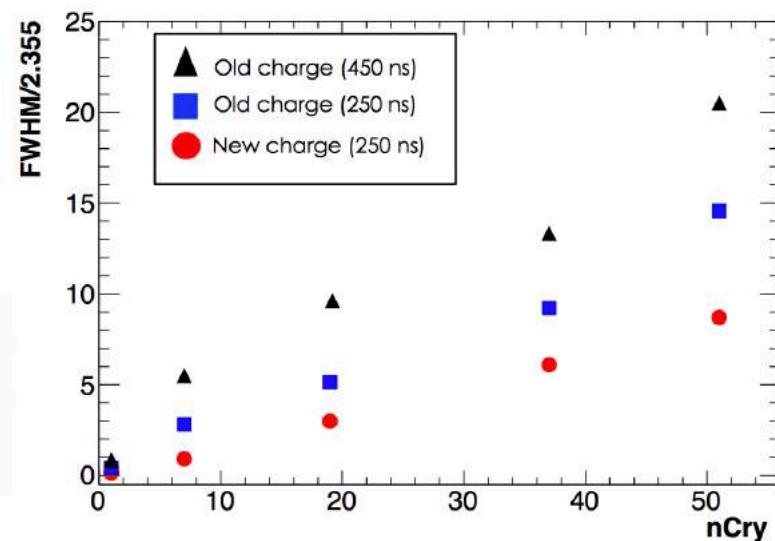
$\text{FWHM}/2.355 = 0.870 \text{ MeV}$

$\text{FWHM}/2.355 = 0.148 \text{ MeV}$

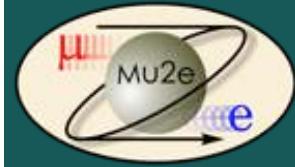
$\text{FWHM}/2.355 = 0.424 \text{ MeV}$



Pedestal energy vs Crystal number



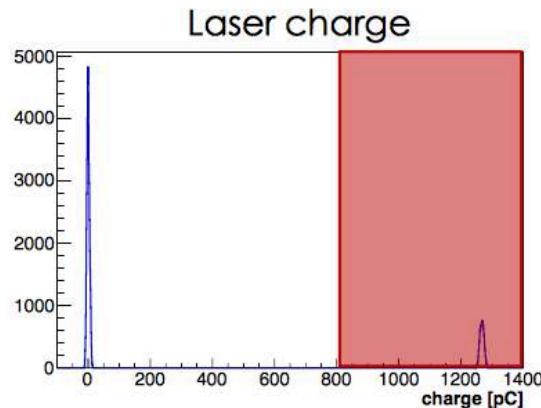
Noise width in the new charge increase linearly with the number of crystals added



Module 0 Event selection

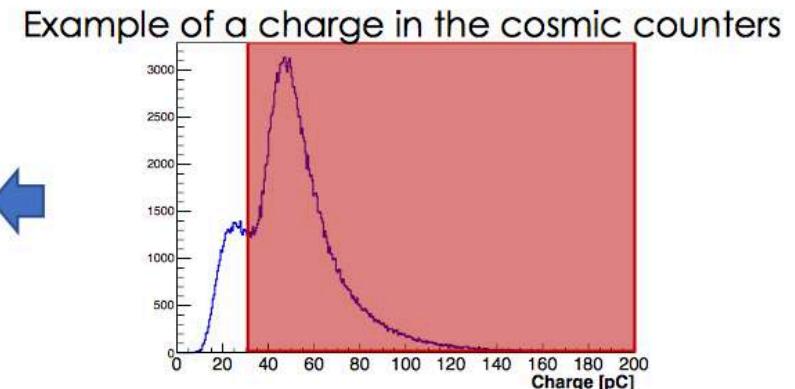


1) We reject events with laser trigger

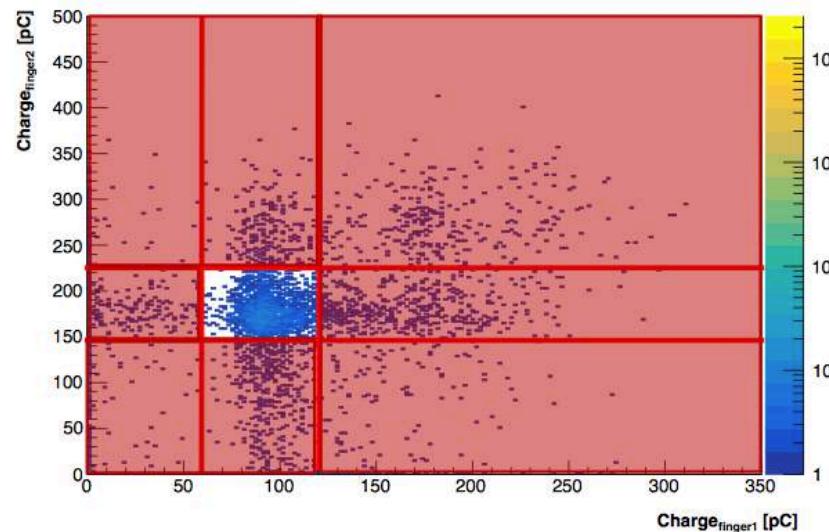


Events~50000

2) We reject events with cosmic trigger



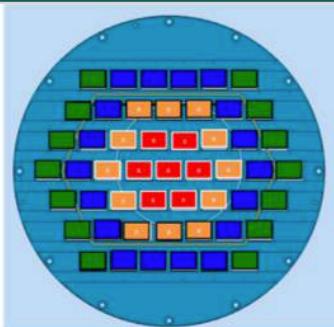
3) We ask for a single particle in the beam counters



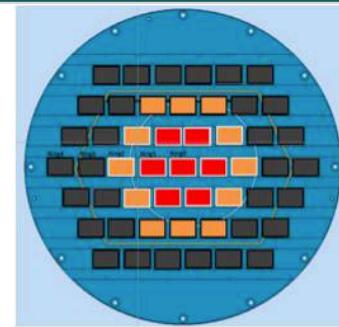
Events after selections~1600



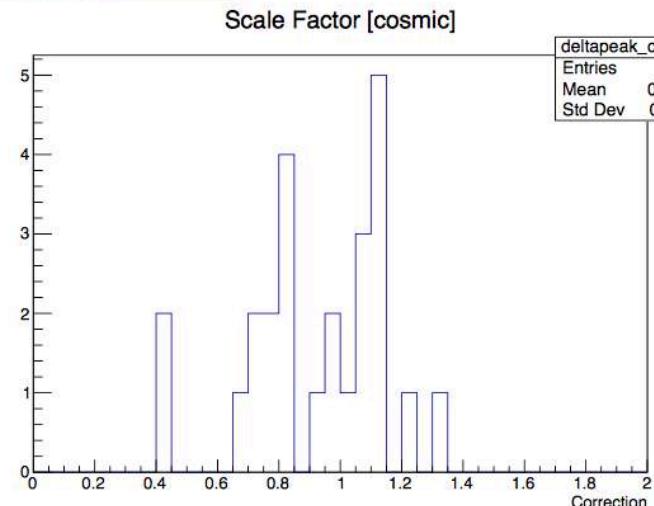
Module 0 Event selection



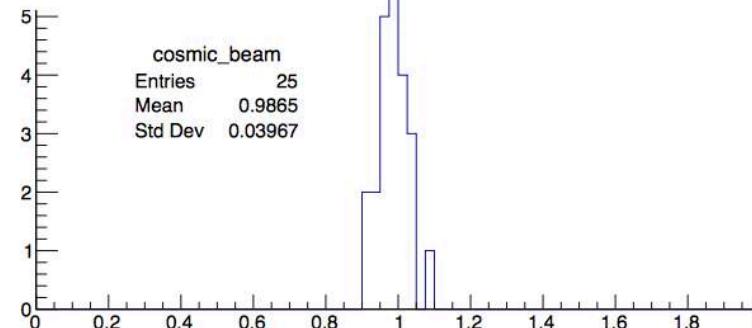
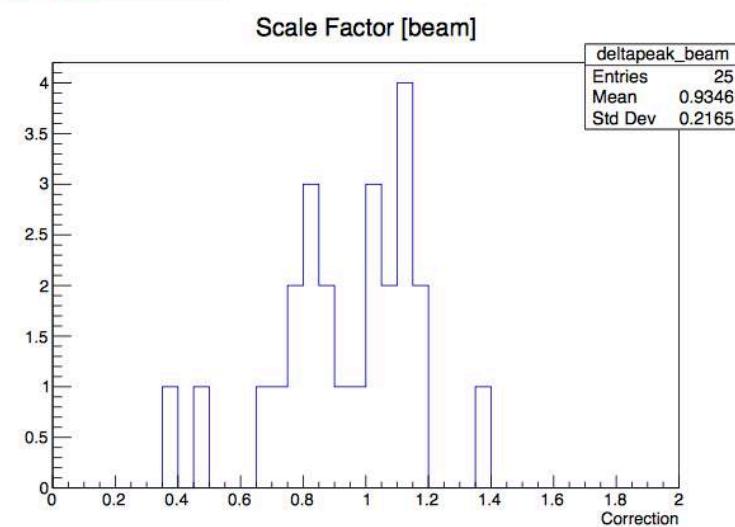
Cosmic trigger used to provide the equalization of all channels



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



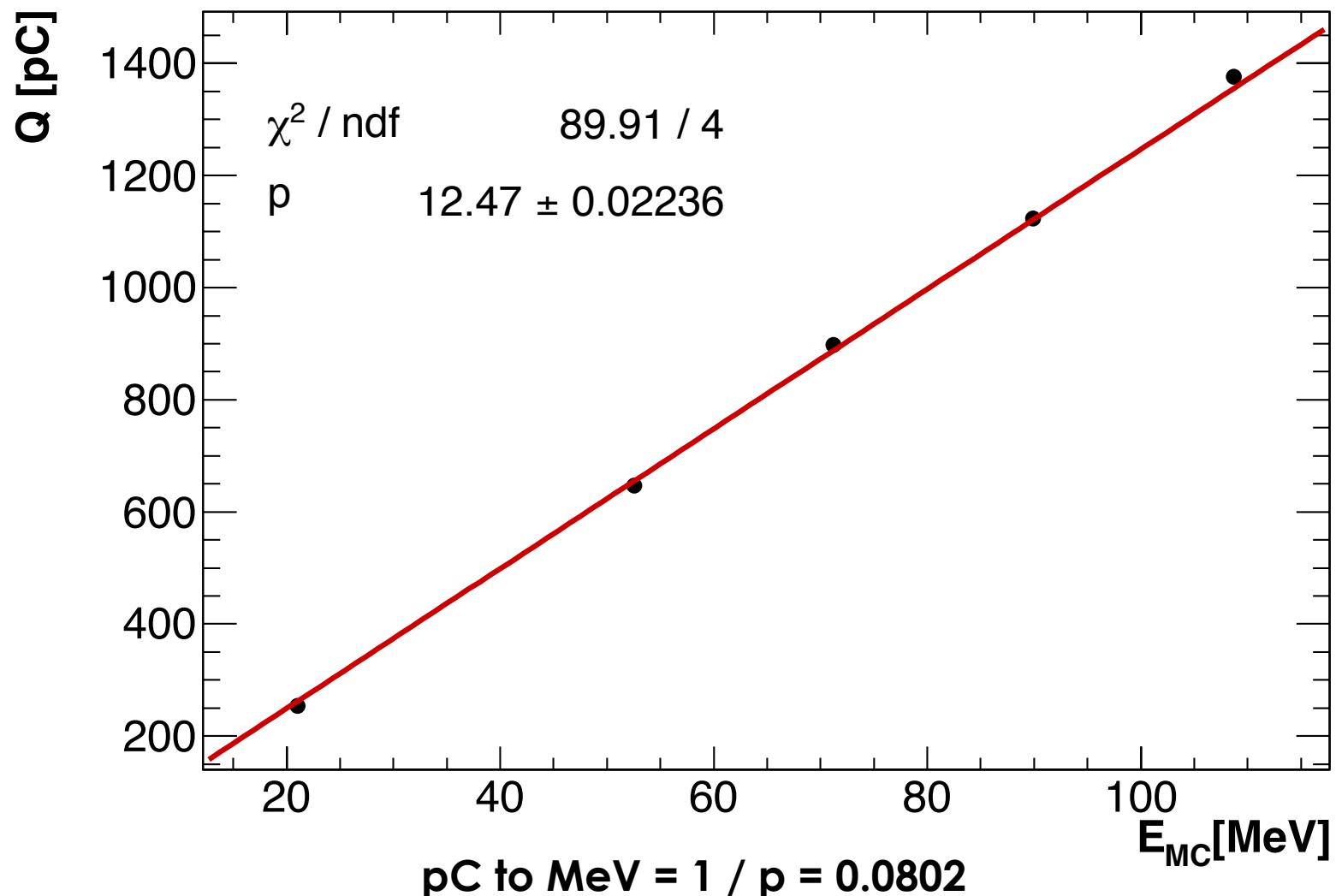
$SC_{\text{cosmic}} / SC_{\text{beam}}$



In all the analysis
cosmic equalization
is used



Module 0 Event selection





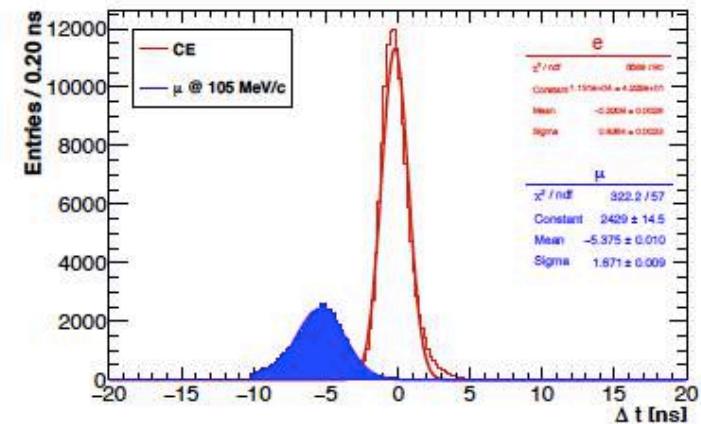
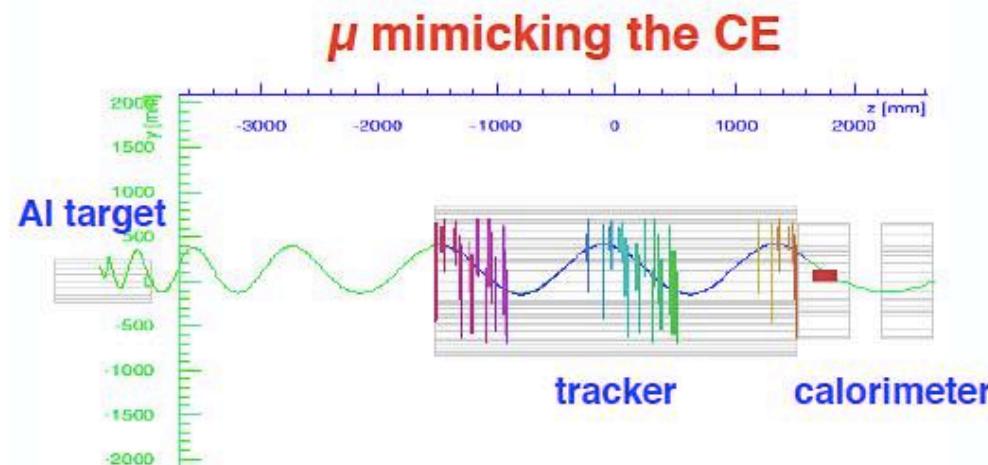
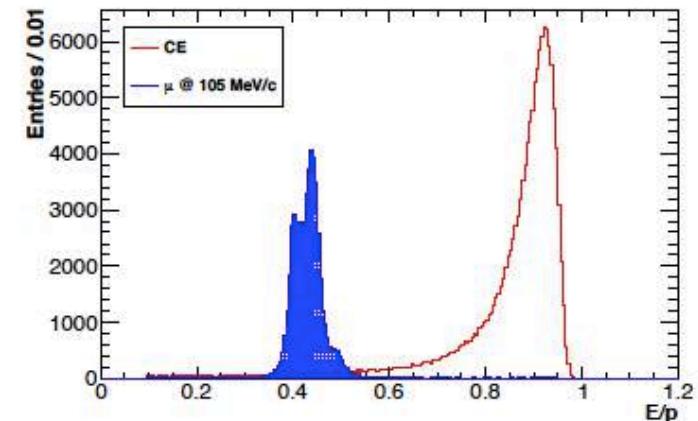
Pld



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 $\beta \sim 0.7$ 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

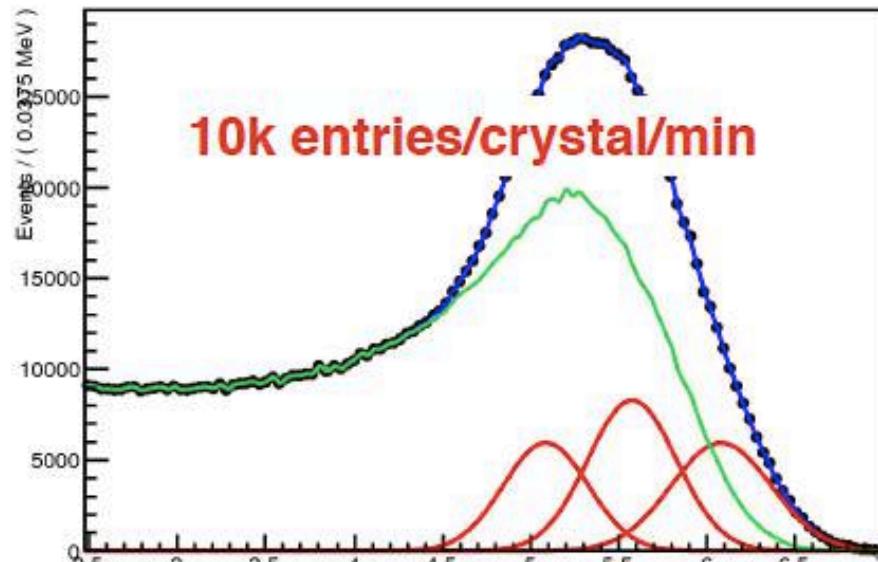
- Mu2e Calorimeter, R.Donghia



Calibration source and laser



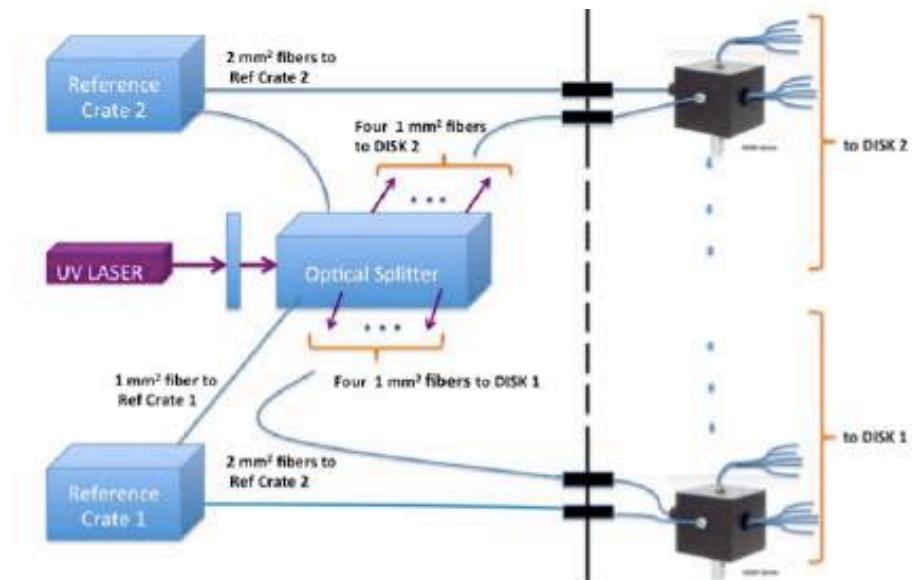
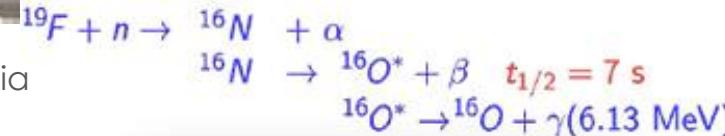
- Liquid source FC 770 + DT generator: 6 MeV + 2 escape peaks
- Laser system to monitor SiPM performance



Liquid source prototype

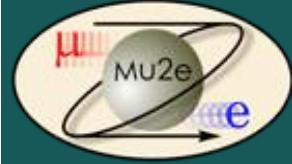


● Mu2e Calorimeter, R.Donghia



Laser system - test station

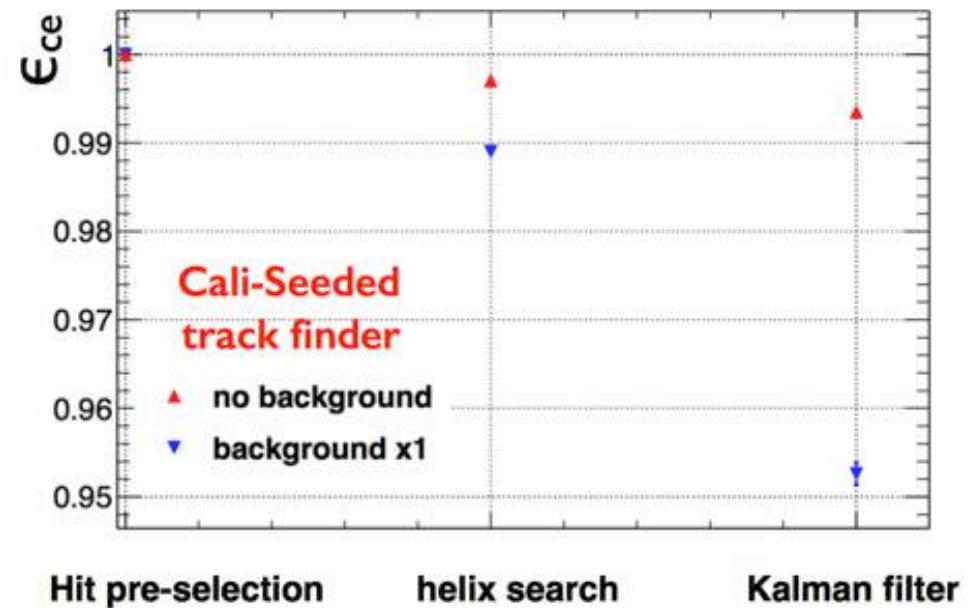
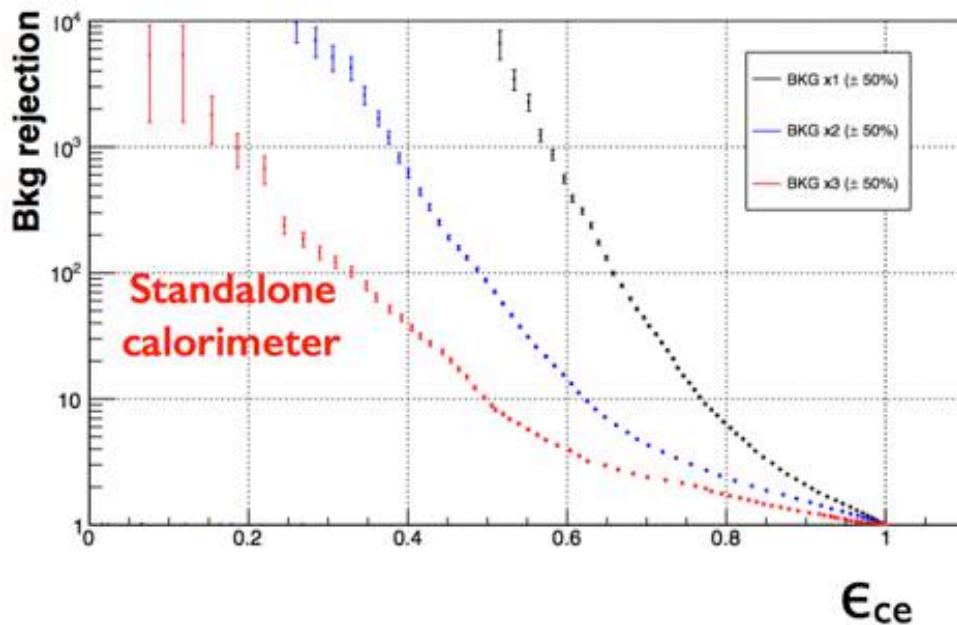




Calorimeter Trigger



- 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

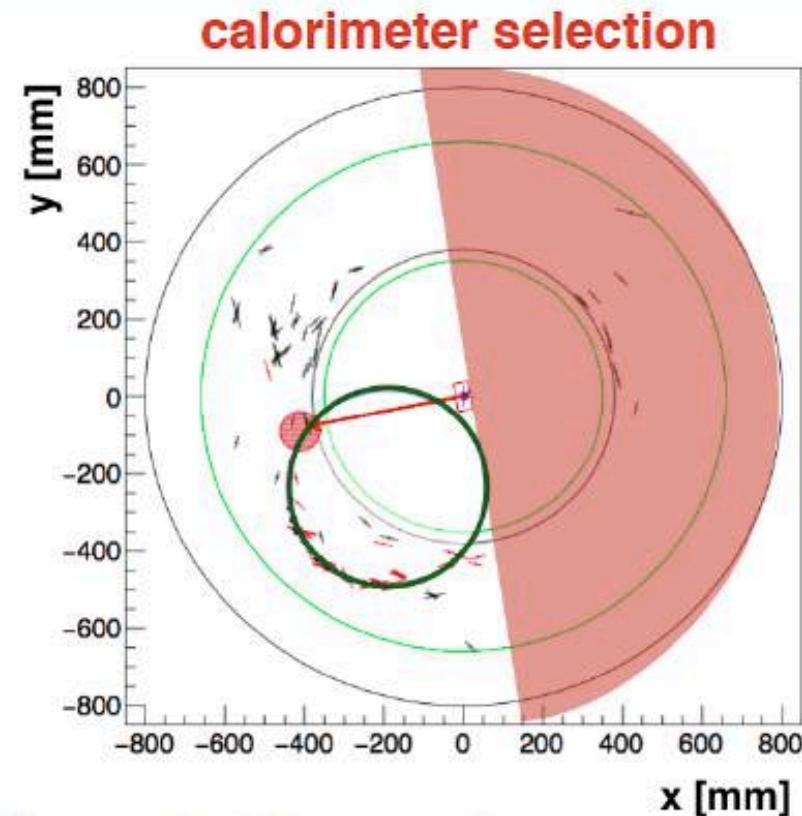
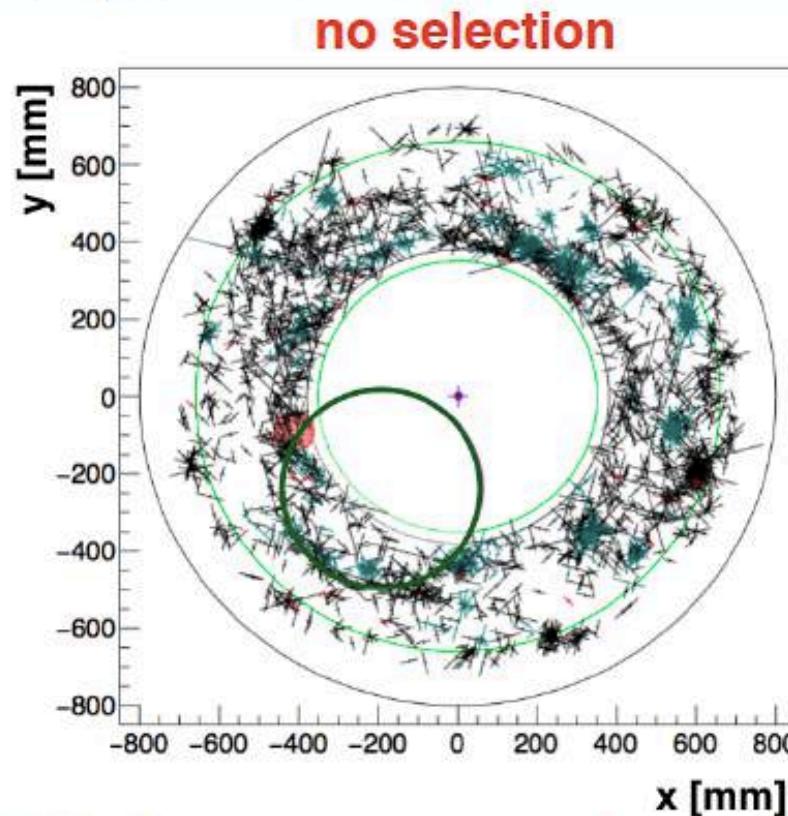




Calorimeter seeded track finder



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



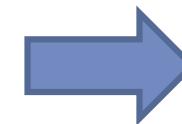
- **black crosses** = straw hits, **red circle** = calorimeter cluster,
green line = CE track



Calorimeter radiation damage

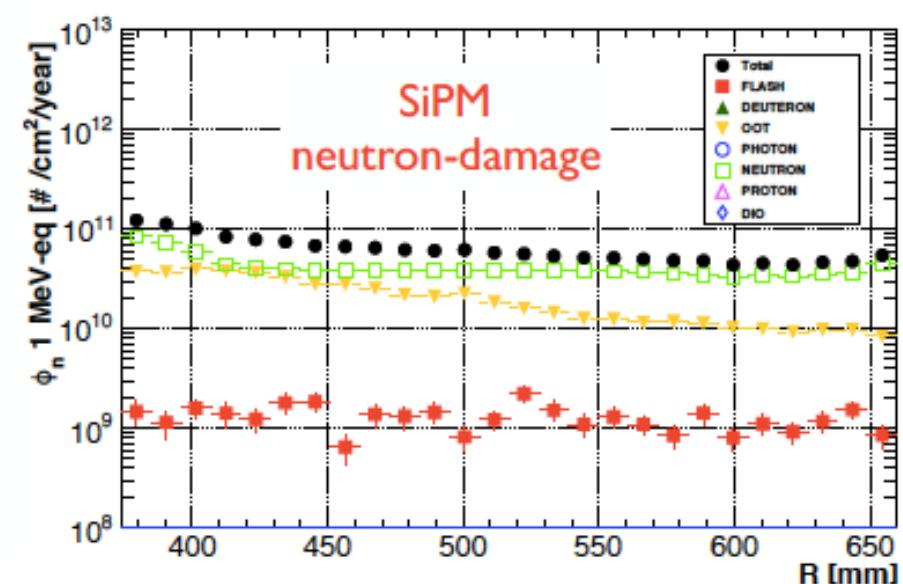
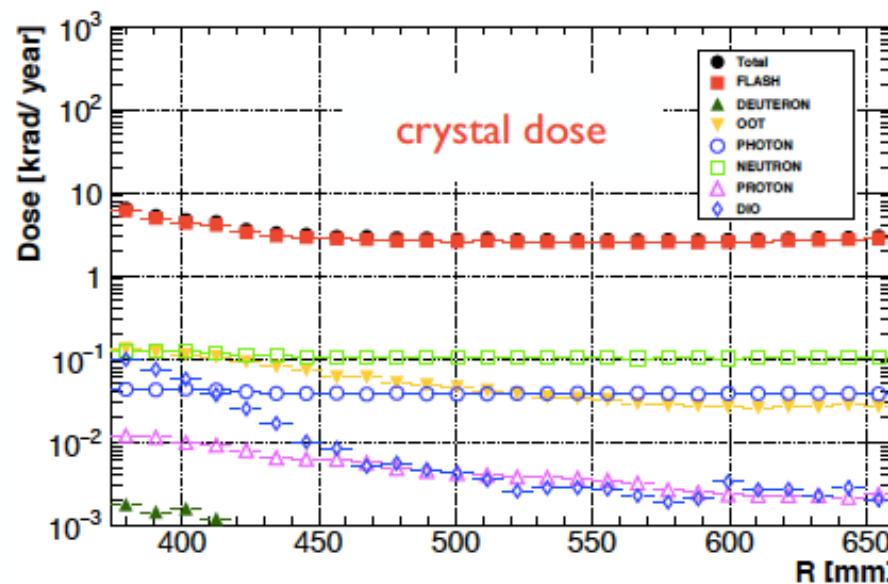


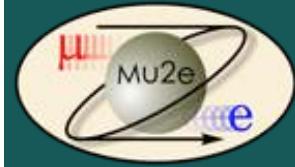
- Calorimeter radiation dose driven by beam flash (interaction of proton beam on target)
- Dose from muon capture is $\times 10$ smaller
- Dose is mainly in the inner radius
- Highest dose ~ 10 krad/year
- Highest n flux on crystals $\sim 2 \times 10^{11} \text{ n/cm}^2/\text{year}$
- Highest n flux on SiPM $\sim 10^{11} \text{ n}_{1\text{MeV eq}}/\text{cm}^2/\text{year}$
-



- **Qualify crystals up to ~ 100 krad, 10^{12} n/cm^2**
- **Qualify SiPM up to $\sim 10^{12} \text{ n}_{1\text{MeV eq}}/\text{cm}^2$**

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

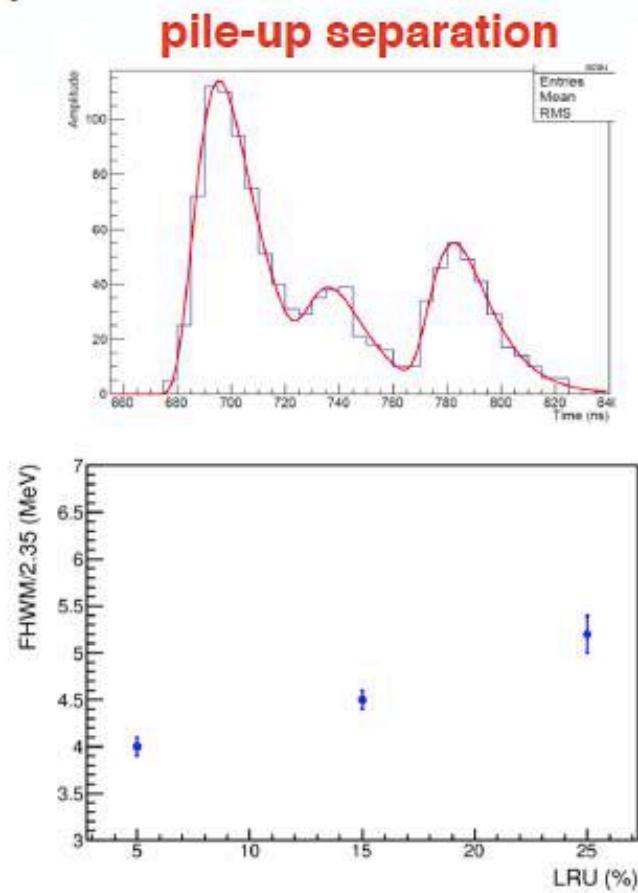
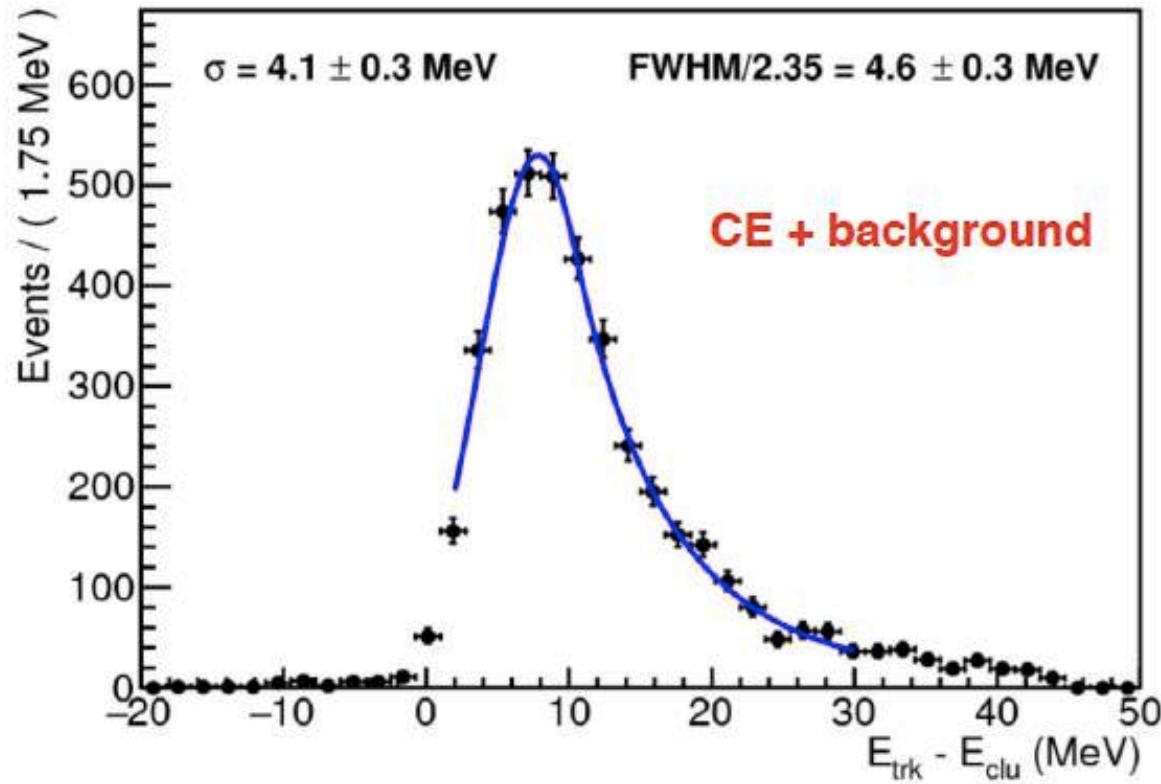


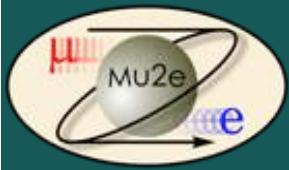


Calorimeter radiation damage

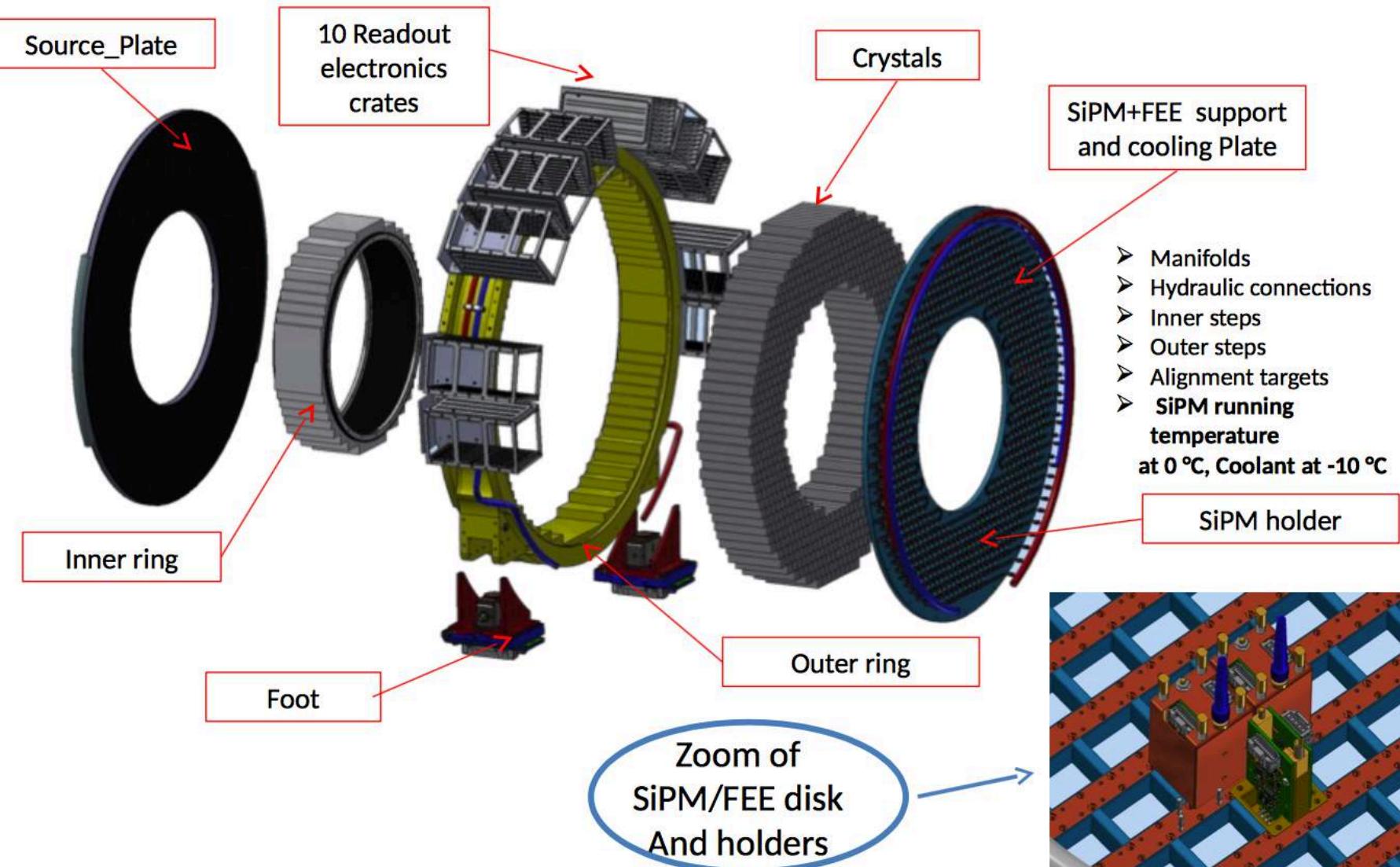


- Offline simulation including background hits
- Experimental effects included: longitudinal response uniformity (LRU), electronic noise, digitization, etc
- Waveform-based analysis to improve pileup separation





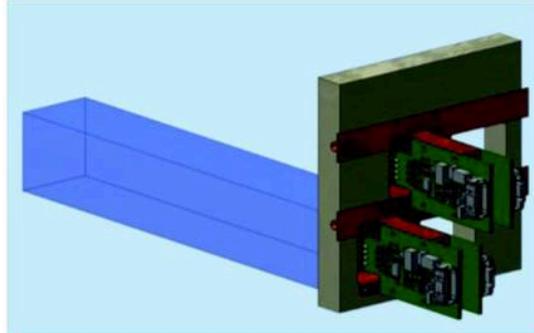
Calorimeter mechanics



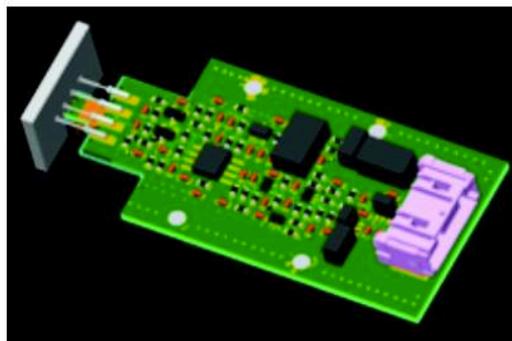
SiPM = Silicon PhotoMultiplier
FEE = Front End Electronics



Calorimeter Readout electronics



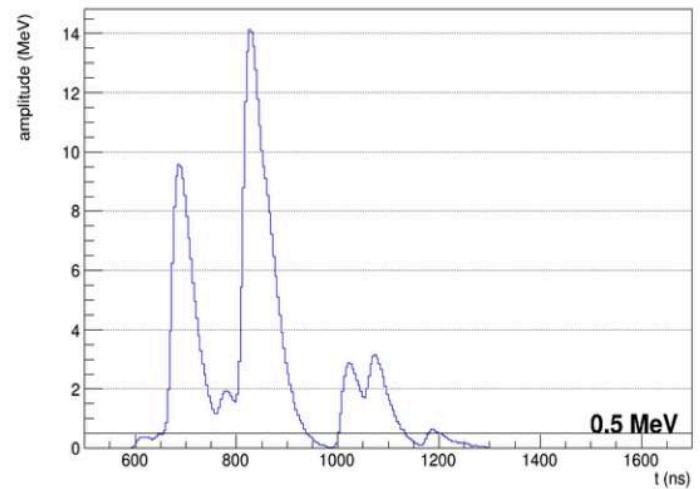
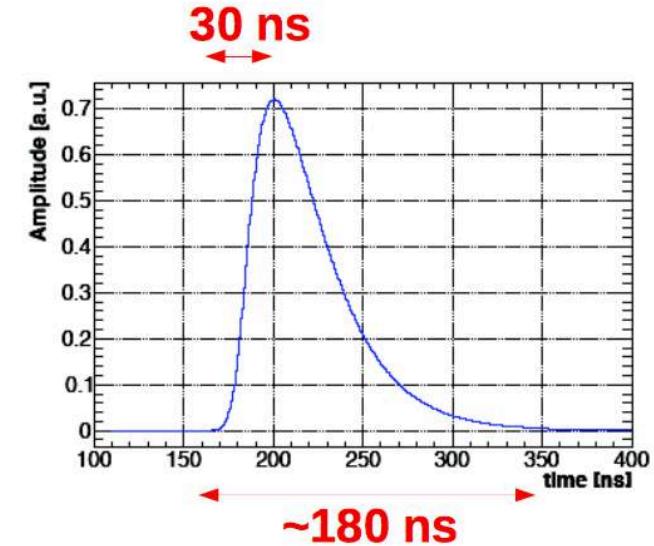
2 SiPM arrays/crystal
1 FEE board/array

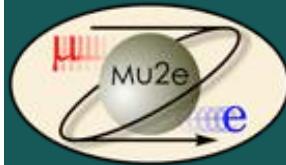


FEE board:
amplification, shaping
and voltage regulation

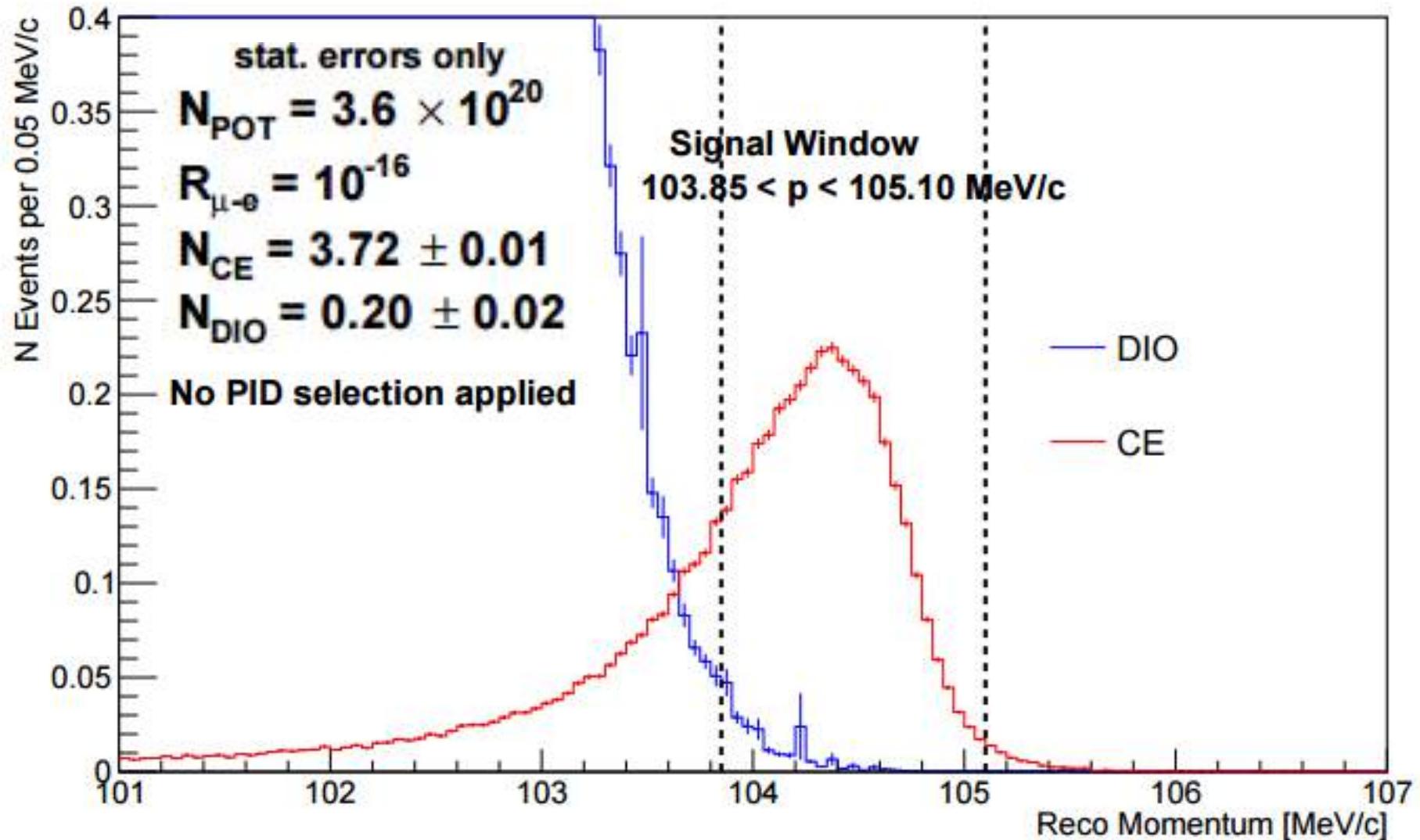


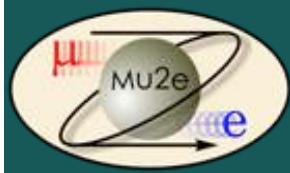
Waveform Digitizer:
Reads 20 channels
at 200 Mhz
(1 sample each 5 ns)





Three years run Expectation by full Simulation



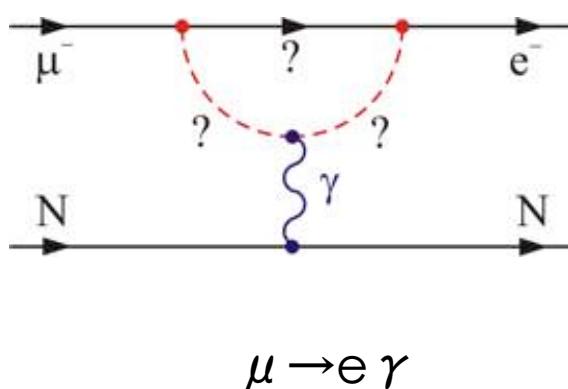


CLFV Lagrangian



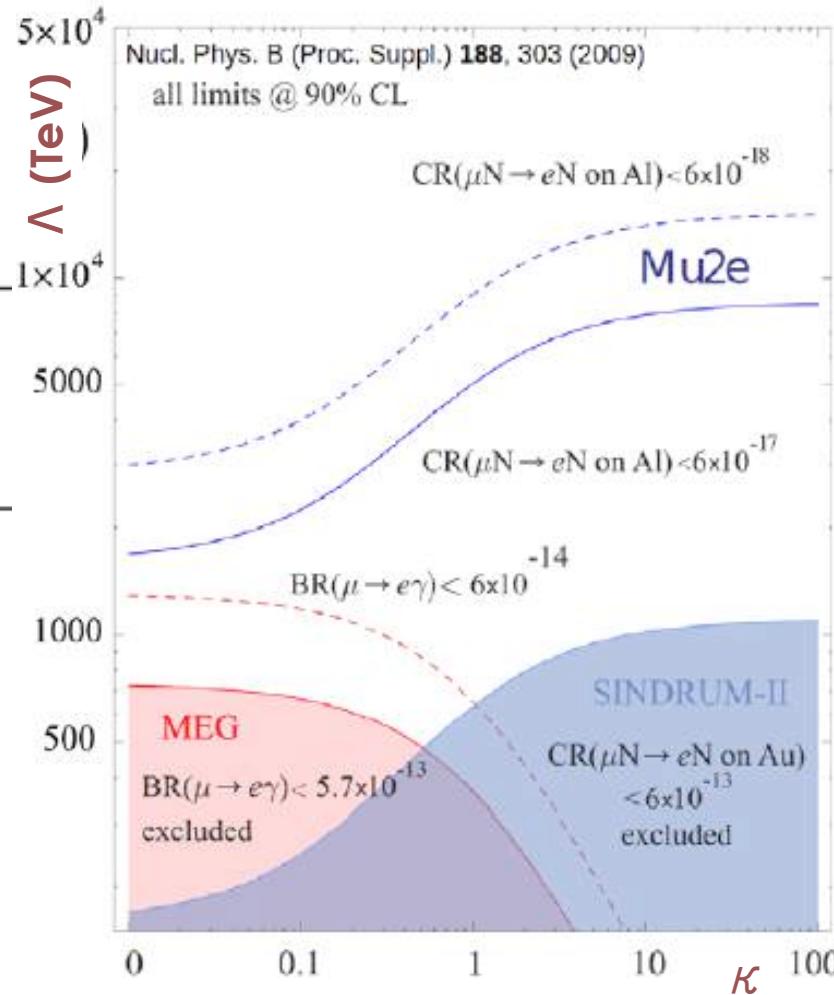
$$L_{\text{CLFV}} = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1 + \kappa)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L (\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L)$$

Loops dominate for
 $\kappa \ll 1$

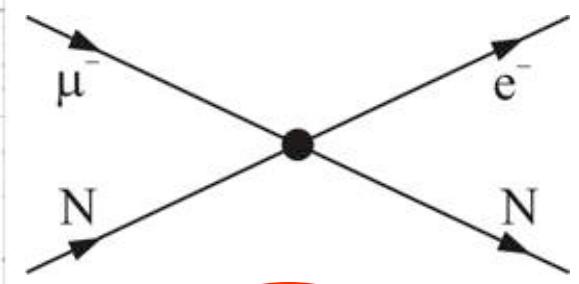


$\mu N \rightarrow e N$

$\mu \rightarrow eee$



Contact terms
dominate for
 $\kappa \gg 1$



$\mu \rightarrow e\gamma$

$\mu \rightarrow eee$