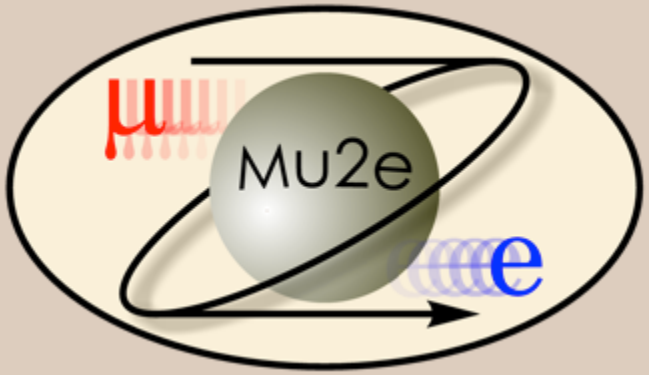
# Design and status of the Mu2e crystal calorimeter




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

Meeting of the American Physical Society Division of Particles and Fields
Fermilab, July 31 – August 4, 2017

ROMA TRE UNIVERSITÀ DEGLI STUDI

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INFN Istituto Nazionale di Fisica Nucleare

# Talk overview

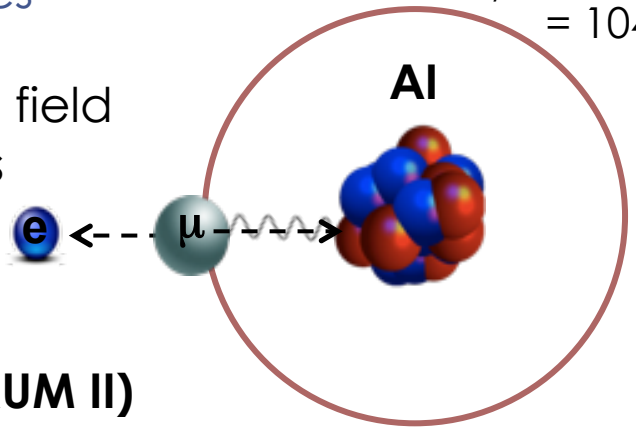
- Charged Lepton Flavor Violation (CLFV)
  - Introduction to Mu2e
  - Mu2e Detector

- **Electromagnetic calorimeter**
  - Requirements
  - Components
  - Single Channel Tests
  - "Module-0" performance

# Charged Lepton Flavor Violation

- CLFV strongly suppressed in SM: Branching Ratio $\leq 10^{-54}$
  → Observation would indicate New Physics
- CLFV@Mu2e: $\mu$ - e conversion in a nucleus field
  → discovery sensitivity to many NP models
- **Goal:**
  **$10^4$ improvement w.r.t. current limit (SINDRUM II)**

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




$\mu$-e conversion in the presence of a nucleus

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

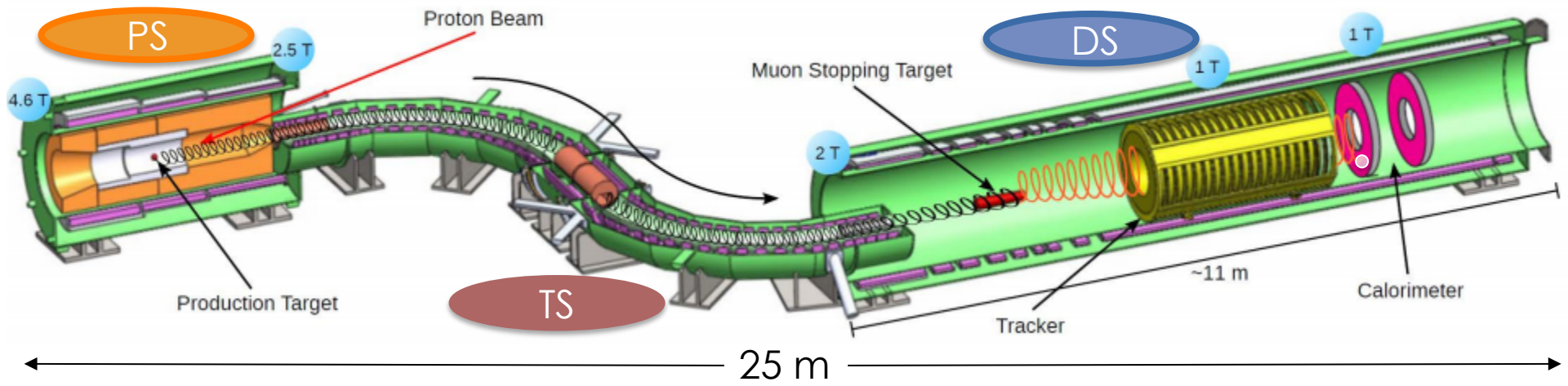
Nuclear captures of muonic Al atoms

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

More information in Y.Oksuzian talk and in mu2e.fnal.gov

# Mu2e experiment design

1. Generate low momentum $\mu^-$ 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 $\pi$

**Detector Solenoid: stopping target and detectors**

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

**Transport Solenoid**

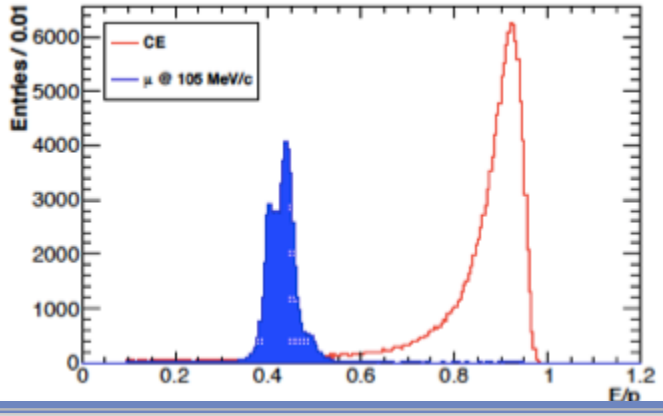
- Selects and transports low momentum $\mu^-$

More information in Y.Oksuzian talk and A.Lucà poster

# Calorimeter requirements

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

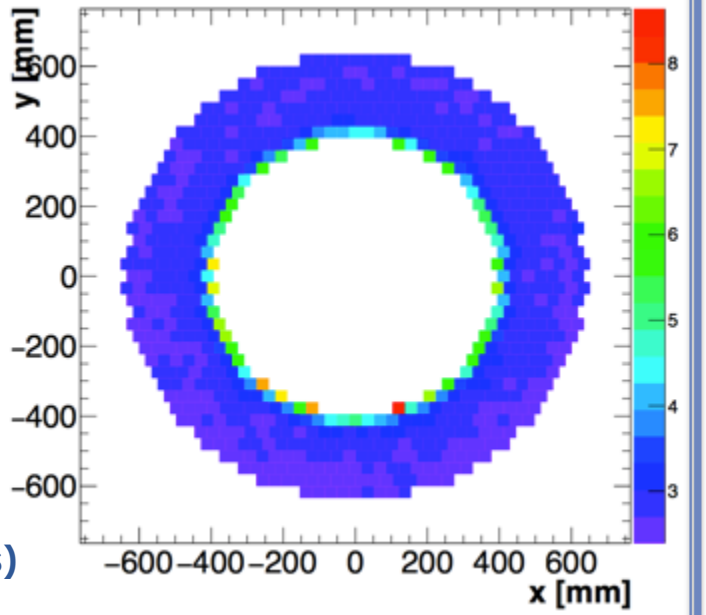
1) **PID: e/$\mu$ separation**
2) **EMC seeded track finder**
3) **Standalone trigger**




## Requirements @ 105 MeV/c

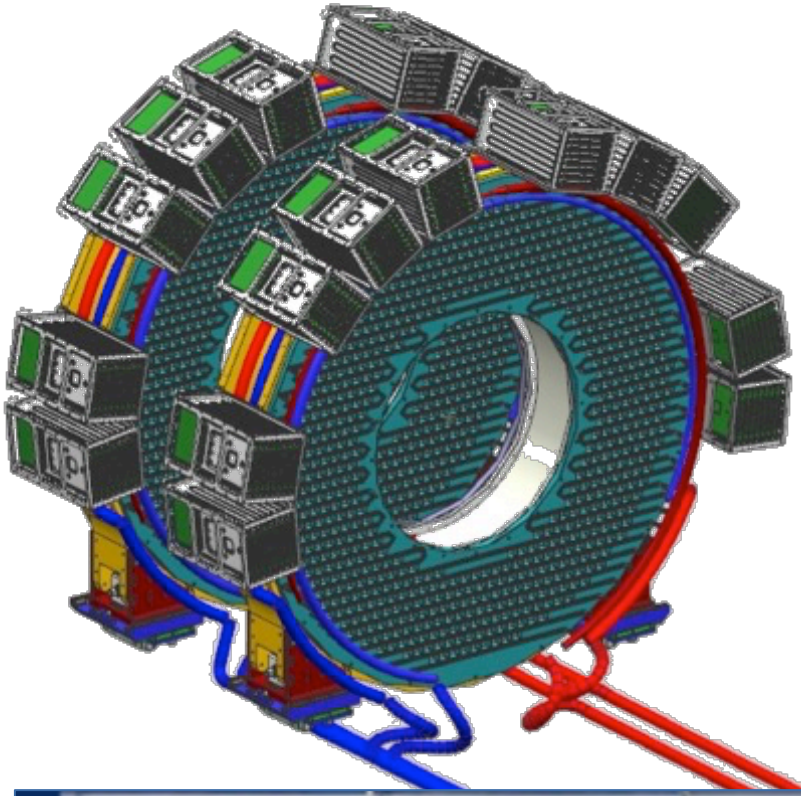
- $\sigma_E/E = \mathcal{O}(5\%)$ for CE
- $\sigma_T < 500$ ps for CE
- $\sigma_{X,Y} \leq 1$ cm

- Fast scintillation signals ( $\tau$ <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)**
  - **$3\times10^{12}$ $n_{1MeV}/cm^2$ ($1.2\times10^{12}$ $n_{1MeV}/cm^2$) for crystals (sensors)**
- Low radiation induced readout noise < 0.6 MeV



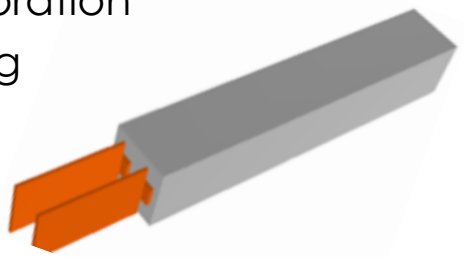

**Front Disk Dose – 1 year [krad]**

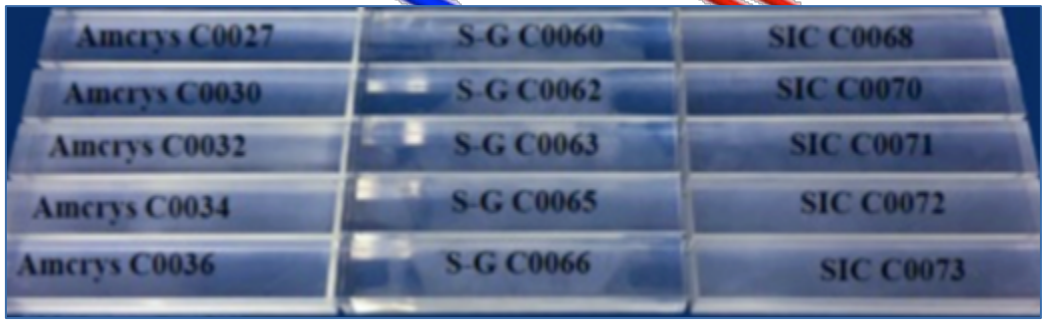
# Calorimeter Design

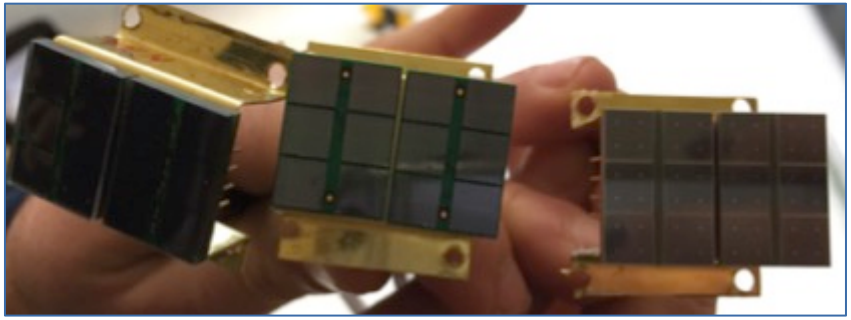


**2 annular disks with 674 undoped CsI (34 x 34 x 200) mm$^3$ square crystals/each disk**

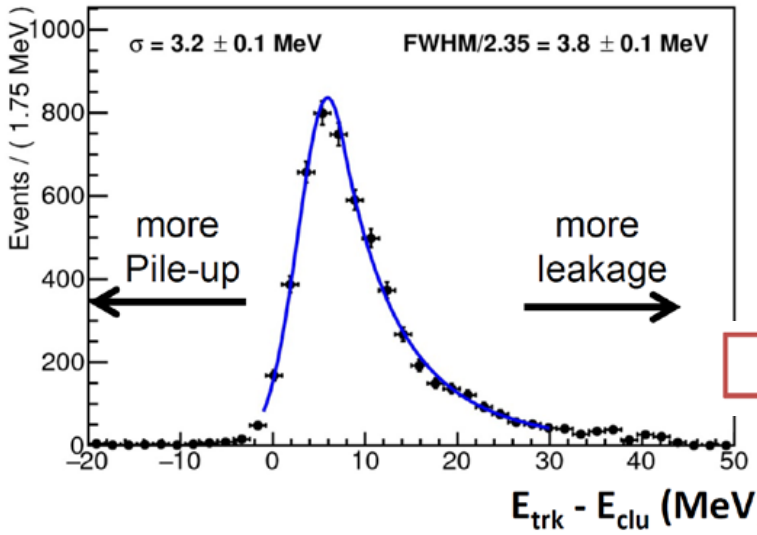
- $R_{IN}$ = 374 mm, $R_{OUT}$ = 660 mm
- Depth = 10 $X_0$ (200 mm), Distance 70 cm
- Readout: **2 UV-extended SiPMs/crystal**
- FEE on the SiPMs , Digital readout on crates
- RA source for energy calibration
- Laser system for monitoring





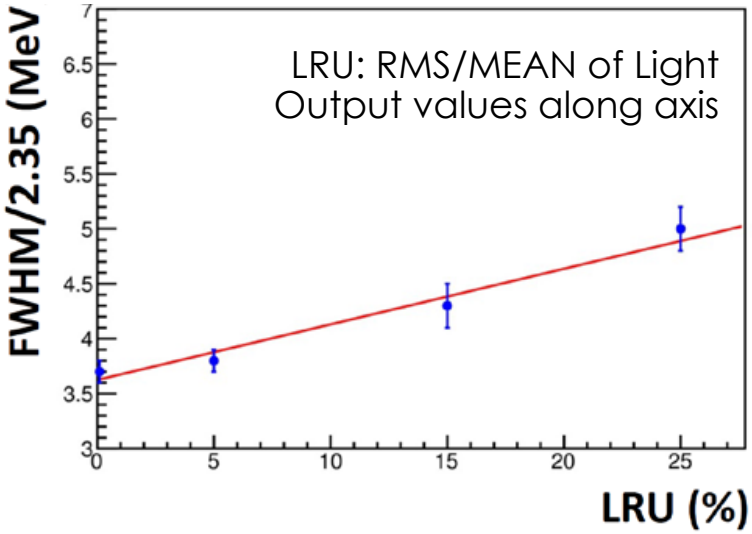



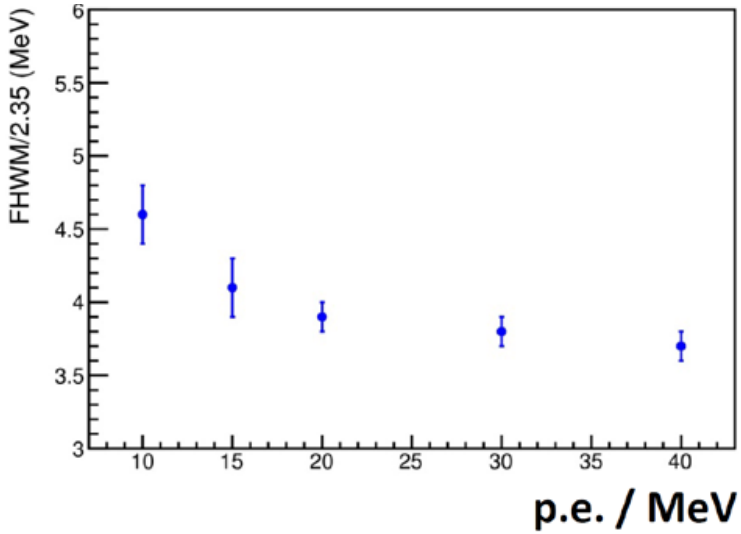
# Simulated performance




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

**FWHM / 2.35 = 3.8 ± 0.1 MeV**

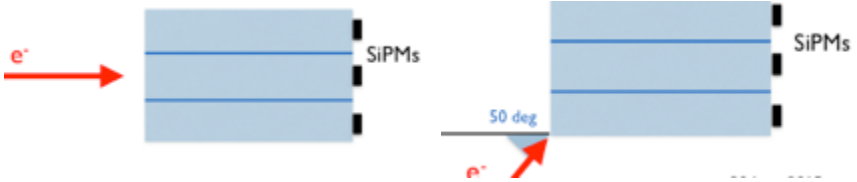


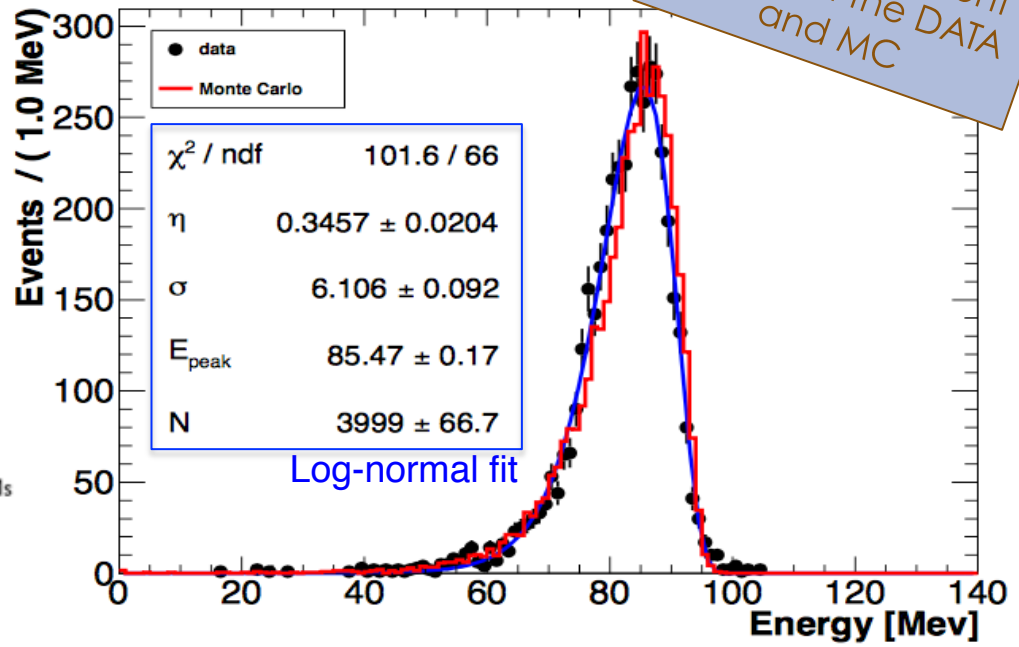



# Small prototype: Test Beam

JINST 12 (2017) P05007

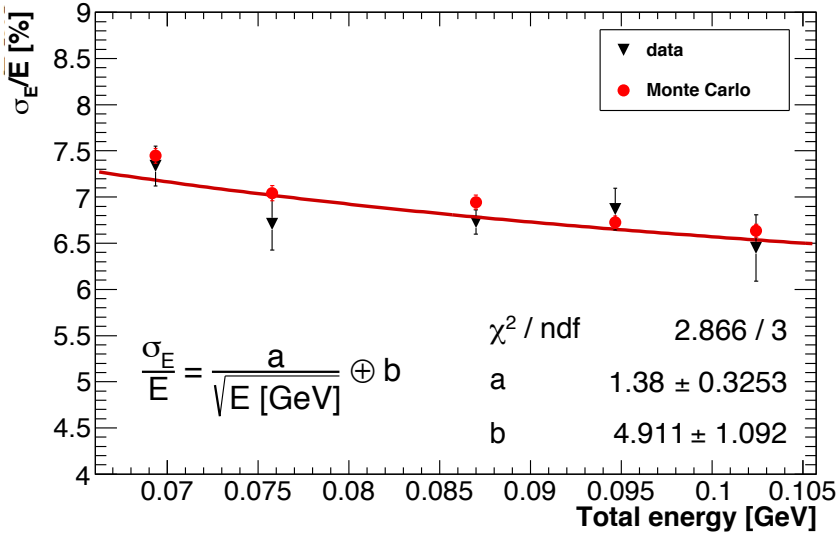
- Small prototype tested @ BTF (Frascati) in April 2015, 80-120 MeV $e^-$
- 3×3 array of 30×30×200 $mm^2$ undoped CsI crystals coupled to one Hamamatsu SiPM array (12x12) $mm^2$ with Silicon optical grease
- DAQ readout: 250 Msps CAEN V1720 WF Digitizer

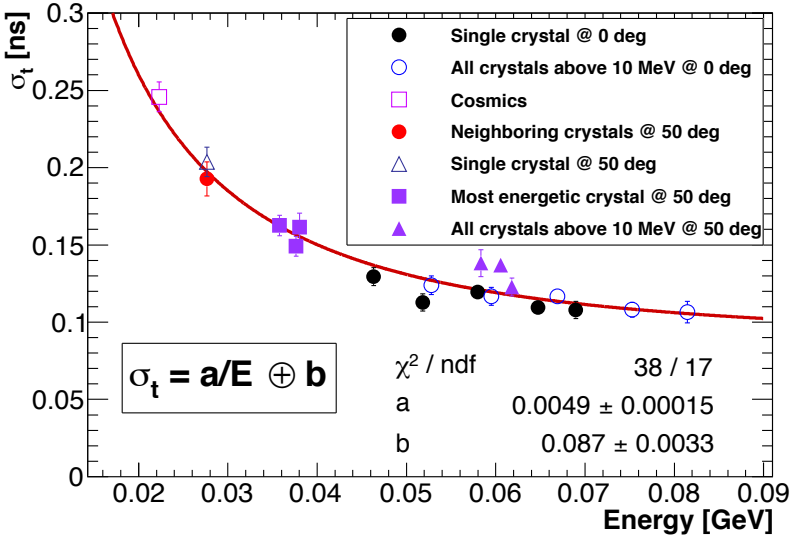


# Small prototype: Time and Energy resolution

JINST 12 (2017) P05007




**$\sigma_E$ ~ 6.5% at 100 MeV**

**$\sigma_T$ ~ 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**

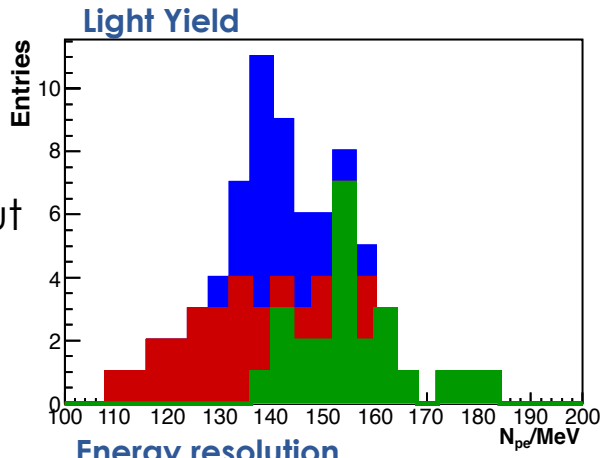
# Pre-production Crystals

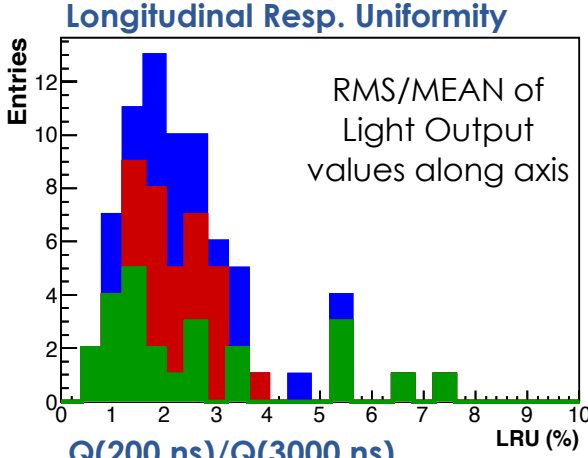
- 24 crystals from three different vendors: **SICCAS**, **Amcrys**, **Saint Gobain**
- Optical properties tested with 511 keV γ's along the crystal axis
- Crystals wrapped with 150 μm of Tyvek and coupled to an UV-extended PMT

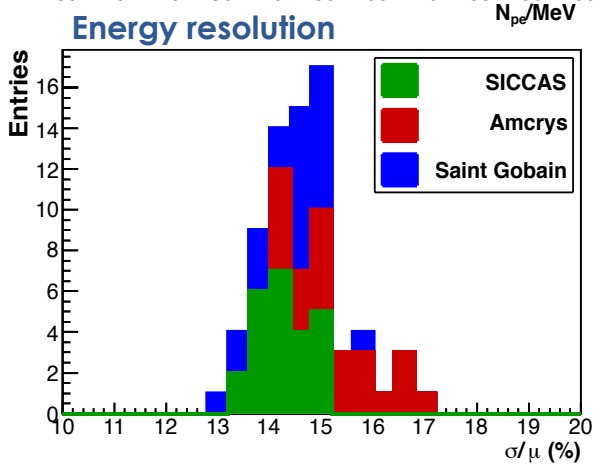
**Un-doped CsI crystals perform well**

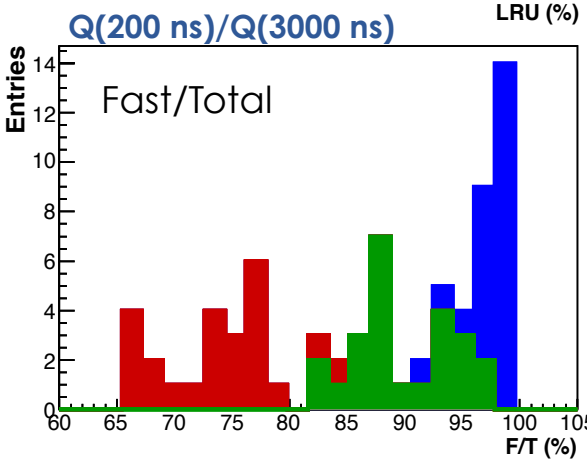
- **Excellent LRU and LY:**
  -100 pe/MeV with PMT readout
  -LRU < 5%
- $\tau$ of 30 ns with small slow component
- **Radiation hardness OK**
  Smaller than 40% LY loss @ 100 krad

More information in B.Echenard talk



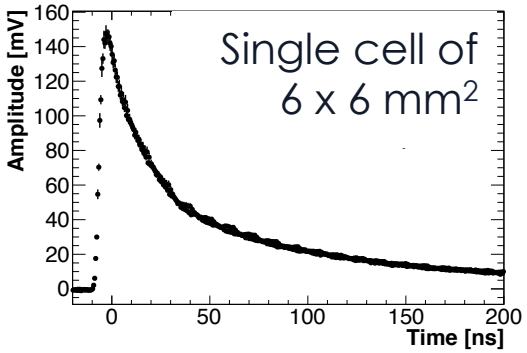



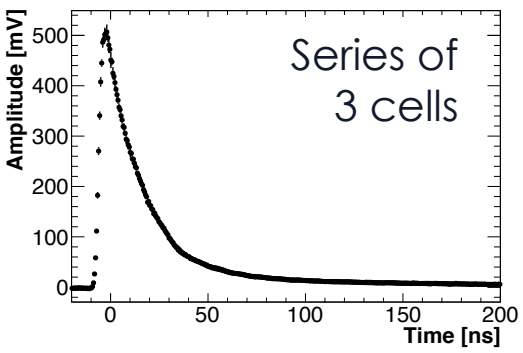



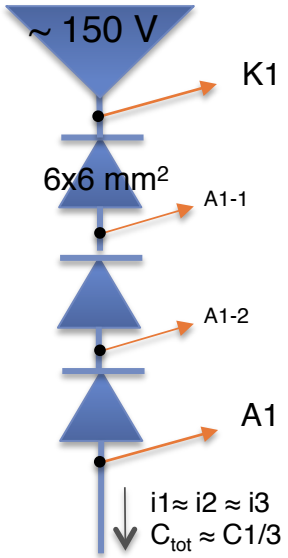
# Pre-production test: SiPMs (1)

More information in poster session

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

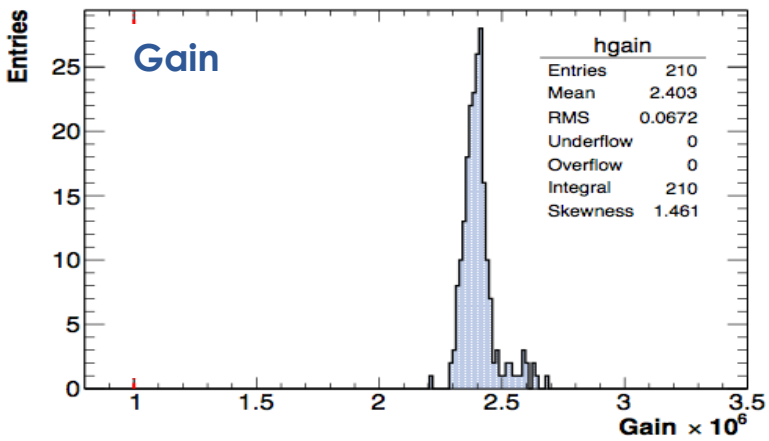


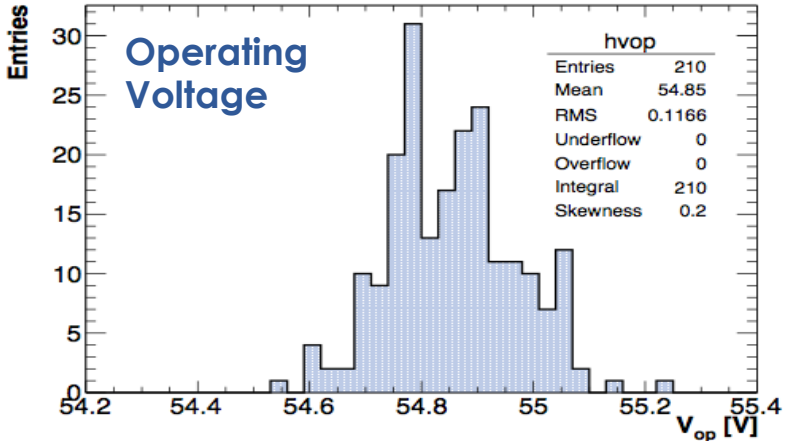




**150 sensors:** 3×50 Mu2e pre-production SiPMs from **Hamamatsu**, **SenSI** and **AdvanSiD**

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



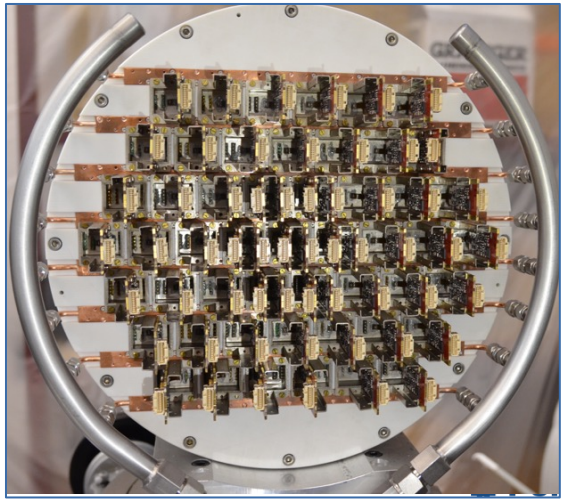
# Module 0

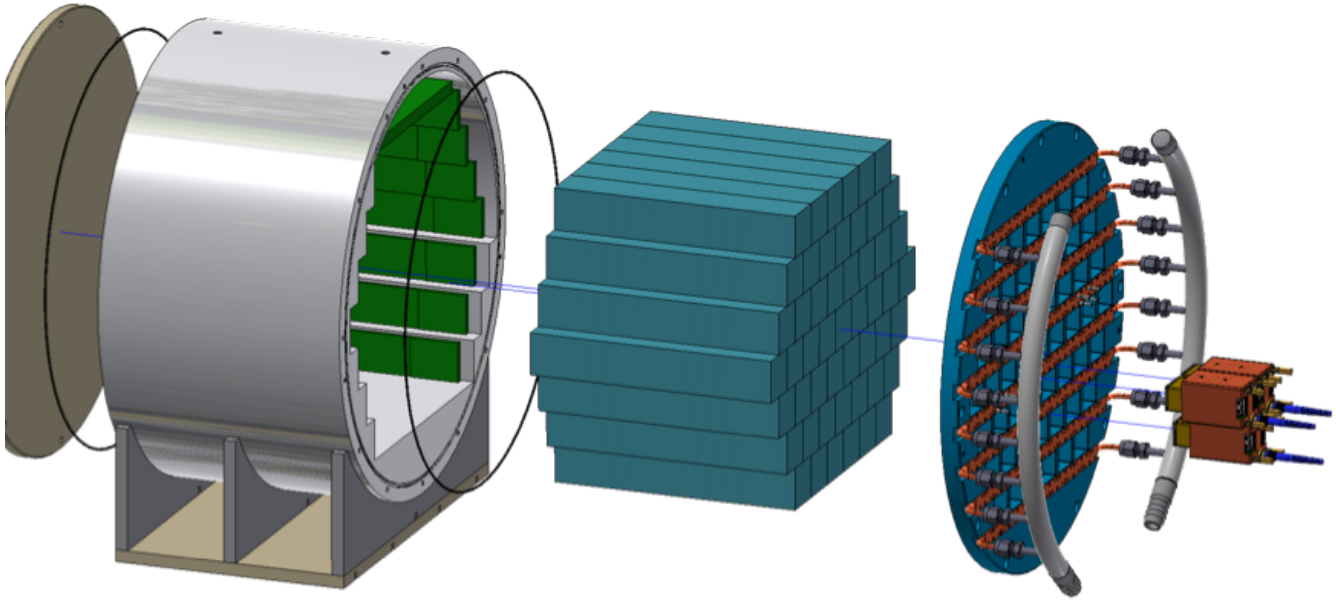
Large EMC prototype: **51 crystals, 102 SiPMs, 102 FEE boards**

**Mechanics and cooling system similar to the final ones!**

Goals:

- Integration and assembly procedures
- Test beam May 2017, 60-120 MeV $e^-$
  Analysis in progress
- Next: work under vacuum, low temperature, irradiation test



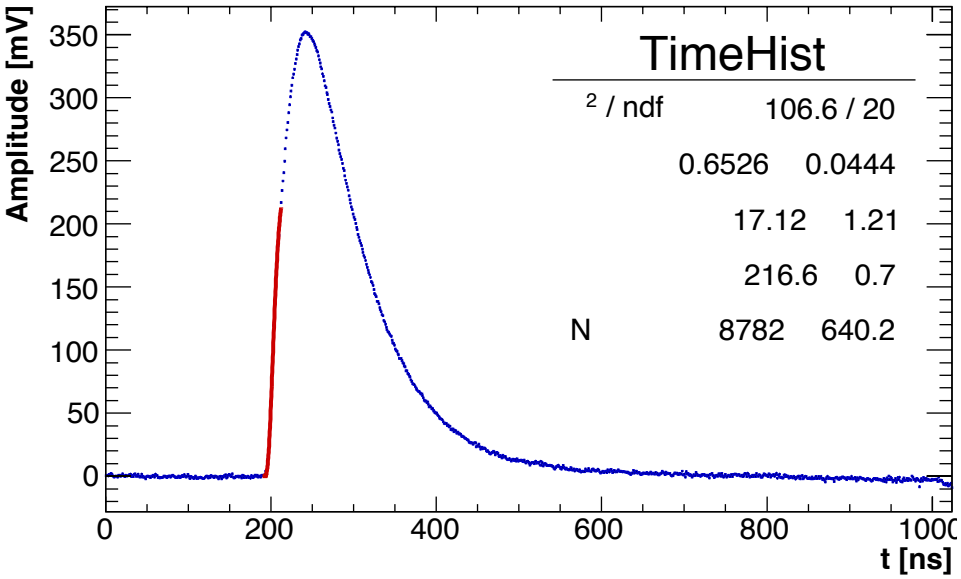


# Module 0 Time resolution

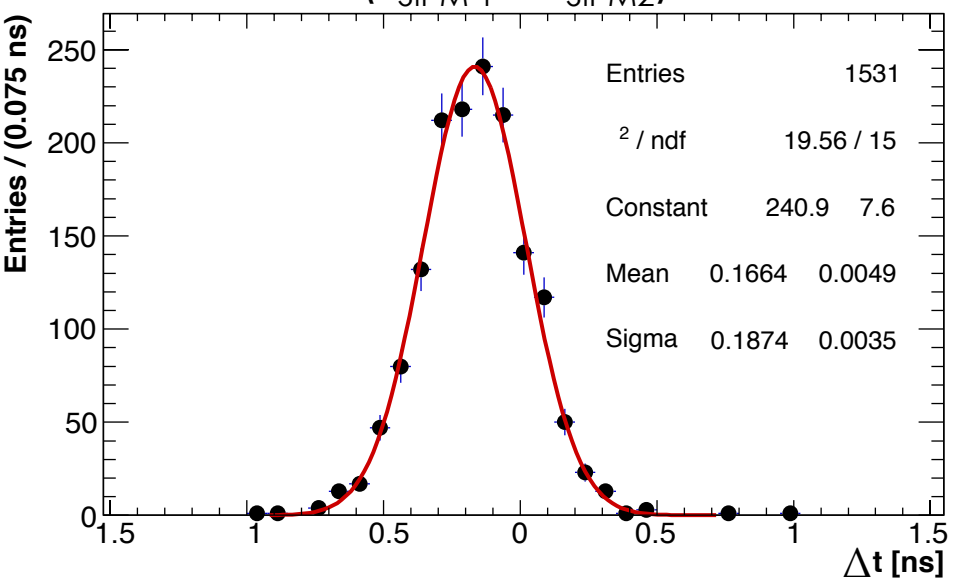
- Log-normal fit on leading edge
- Constant Fraction method used → CF = 5%
- Selection on single particle

PRELIMINARY

Fit Example




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

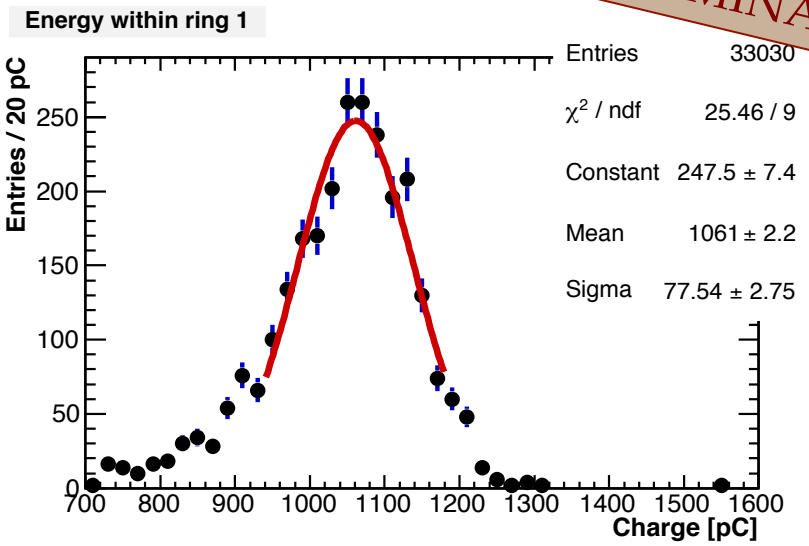


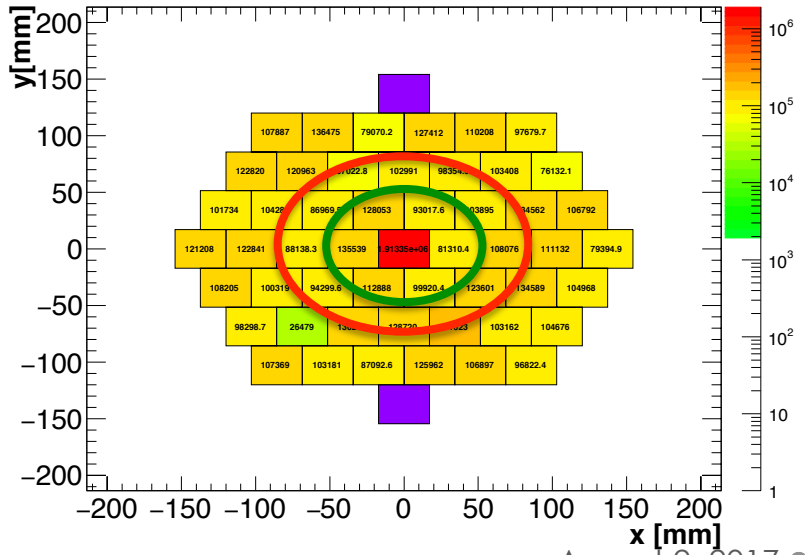

**σ (T1+T2)/2 ~ 94 ps**
**@ $E_{beam}$ = 100 MeV**

# Module 0 Energy resolution

PRELIMINARY

- Calibration completed for first ring around central crystal
- Noise observed in test beam too high to extend calorimeter clustering after first ring
- Data quality still good to extract preliminary resolution in agreement with 3x3 prototype



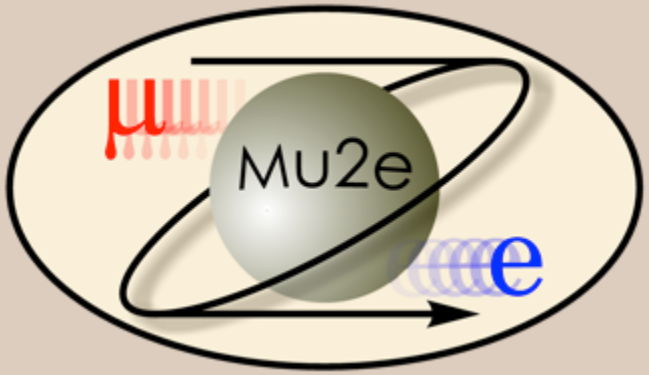

$\sigma_E$ ~ 7.3% within 1° ring

@ $E_{beam}$ = 100 MeV

# 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 )
    - $\tau$ 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.** Data analysis is still ongoing
    - Preliminary results satisfies the requirements
- Calorimeter production phase will start by the end of 2017
- Detector installation expected for beginning of 2020

# Spares

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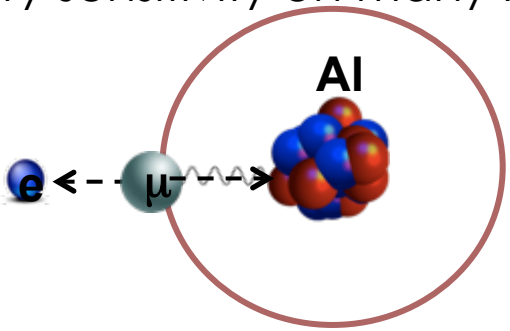
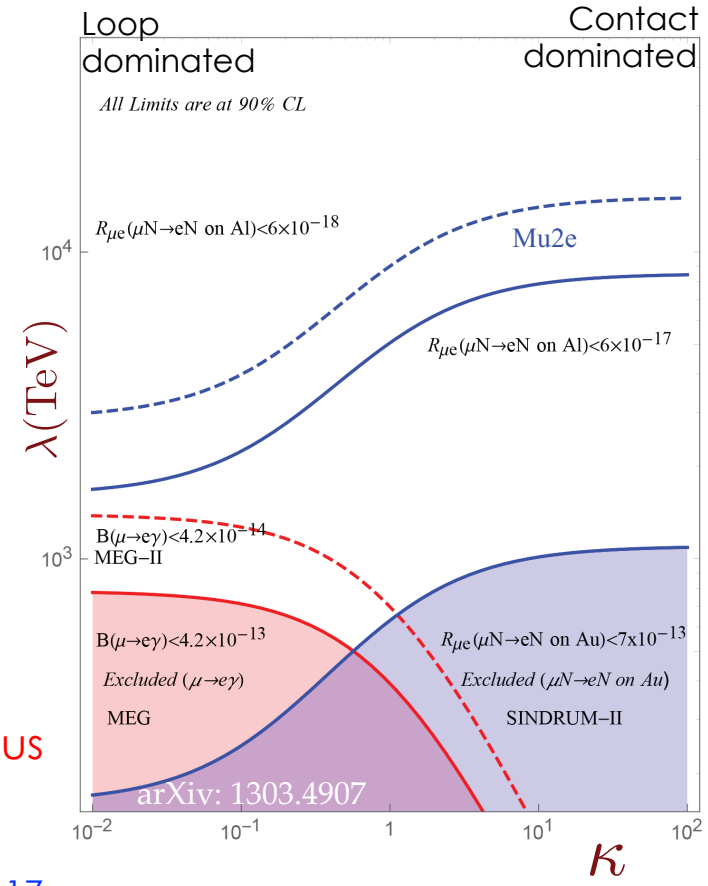
# Charged Lepton Flavor Violation

- CLFV strongly suppressed in SM: BR ≤$10^{-54}$
  → Observation indicates New Physics

- CLFV@Mu2e: $\mu$ - e conversion in a nucleus field
  → discovery sensitivity on many NP models




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




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

$\mu$-e conversion in the presence of a nucleus

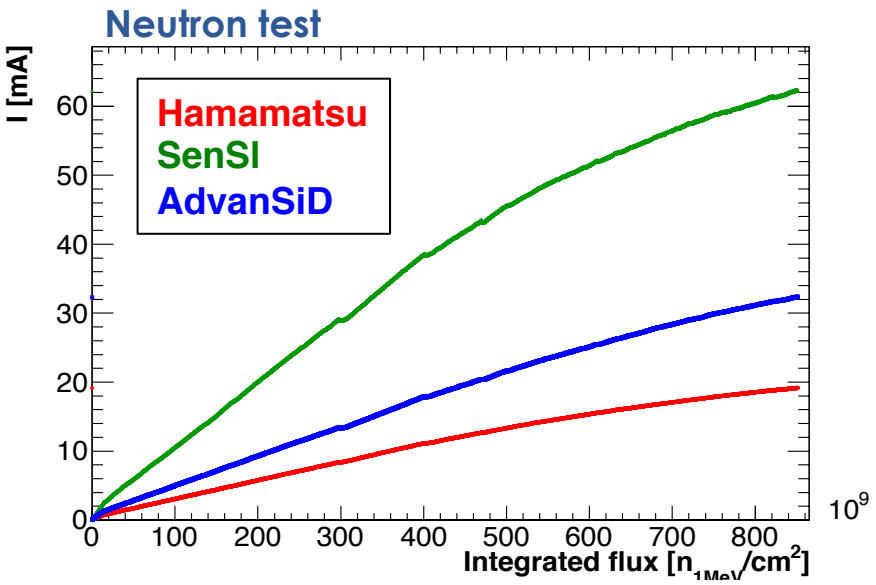
Nuclear captures of muonic Al atoms

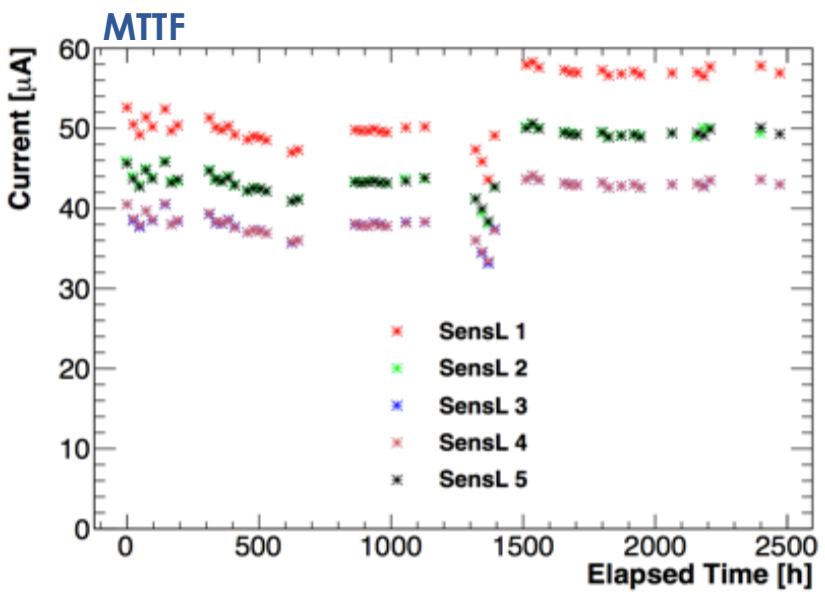
(@ 90% CL, with ~ $10^{18}$ stopped muons in 3 years of running)

More information in Y.Oksuzian talk

# Pre-production test: SiPMs (2)

- 1 sample per vendor has been exposed to neutron flux up to $8.5\times10^{11}$ $n_{1MeVeq}/cm^2$ (@ 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




- 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 $I_d$

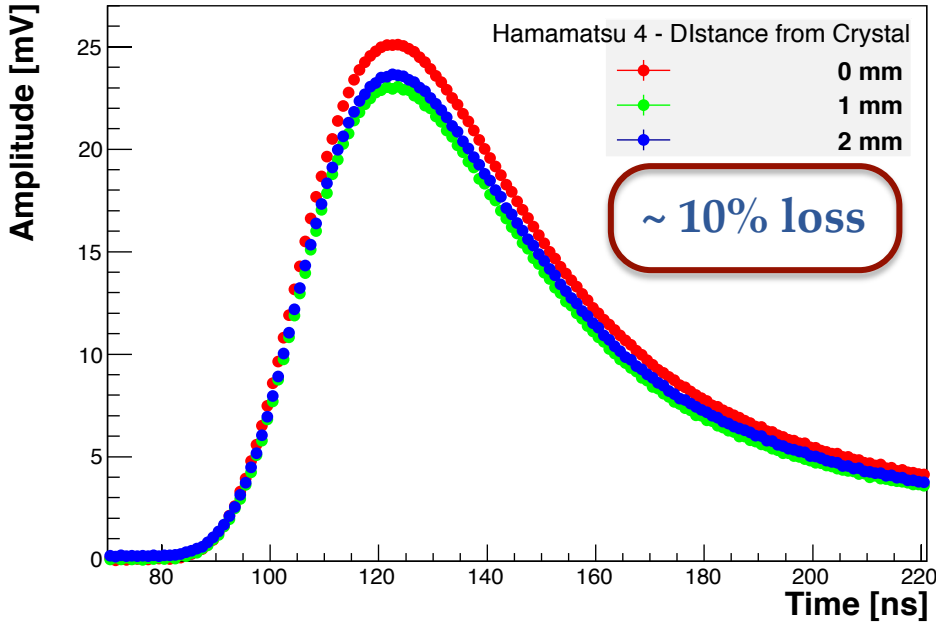
- MTTF evaluated operating SiPMs @ 50 °C for 3.5 months
- No dead channels observed

**MTTF ≥ $6\times10^5$ hours**

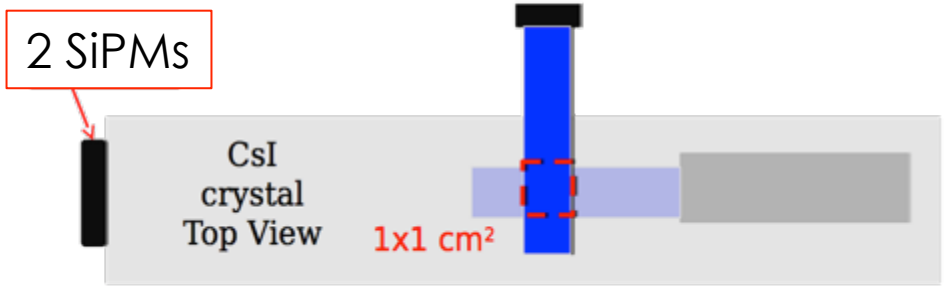
# Single channel slice test

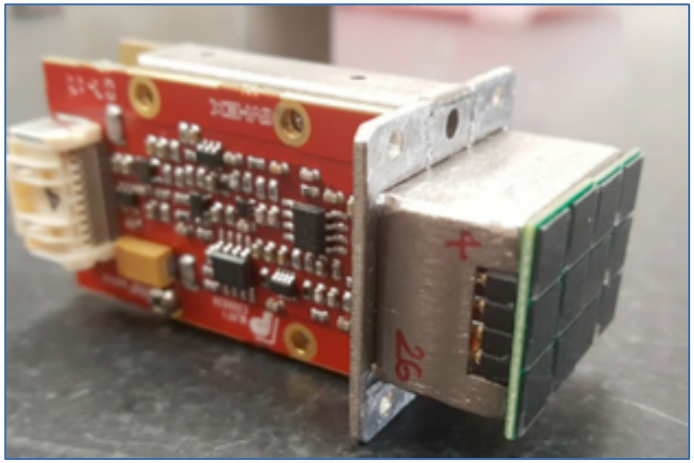
**SG crystal + Hamamatsu SiPM + FEE**
Optical coupling in air.

- **$^{22}$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



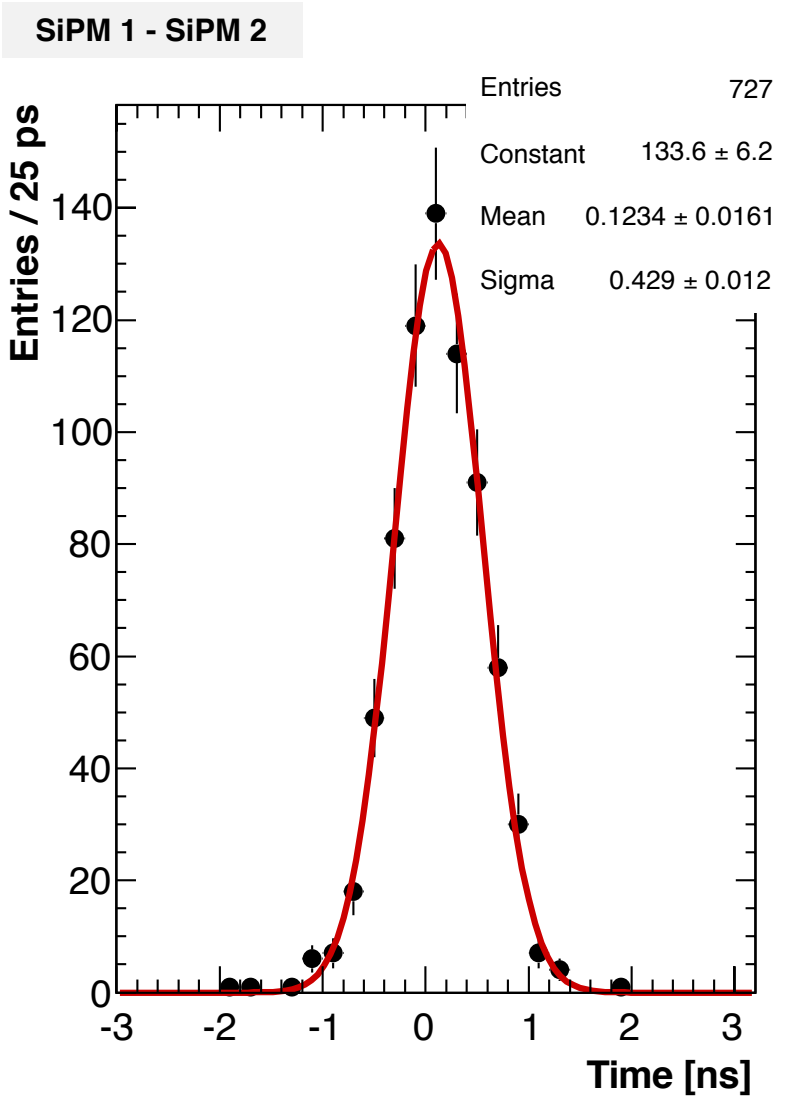
# Single channel Cosmic Rays Test

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

After jitter subtraction:
**SiPM 1 – $\sigma_T$ ~ 330 ps**
**SiPM 2 – $\sigma_T$ ~ 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).

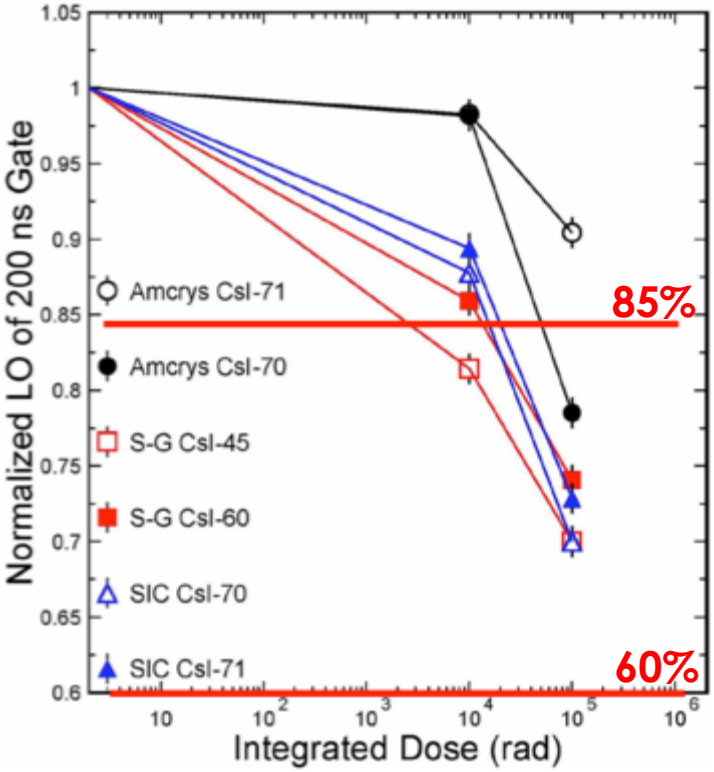


# Pre-production test: Crystals (2)

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

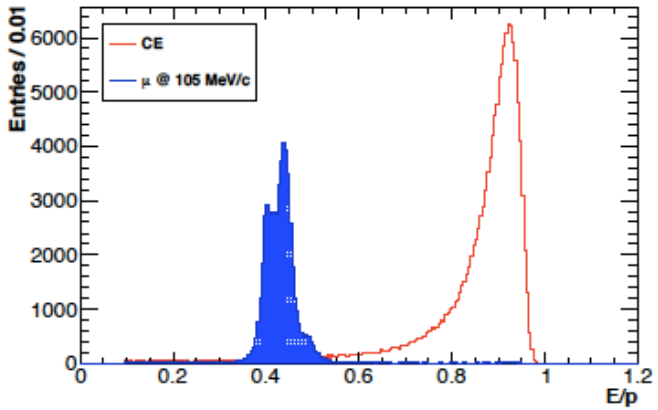
# PId

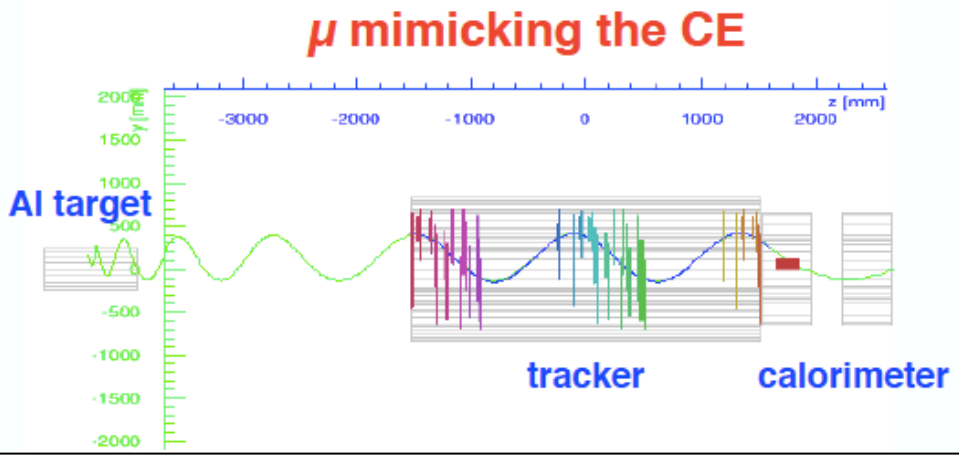
With a CRV inefficiency of $10^{-4}$ an additional rejection factor of ~ 200 is needed to have < 0.1 fake events from cosmics in the signal window

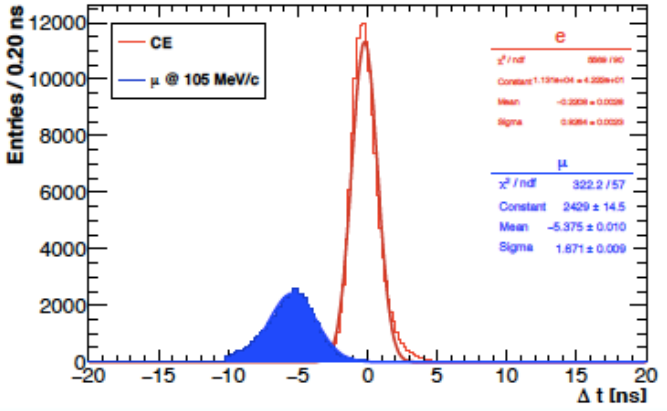
- 105 MeV/c $e^-$ are ultra-relativistic, while 105 MeV/c μ have β~ 0.7 and a kinetic energy of ~ 40 MeV
- Likelihood rejection combines

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

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



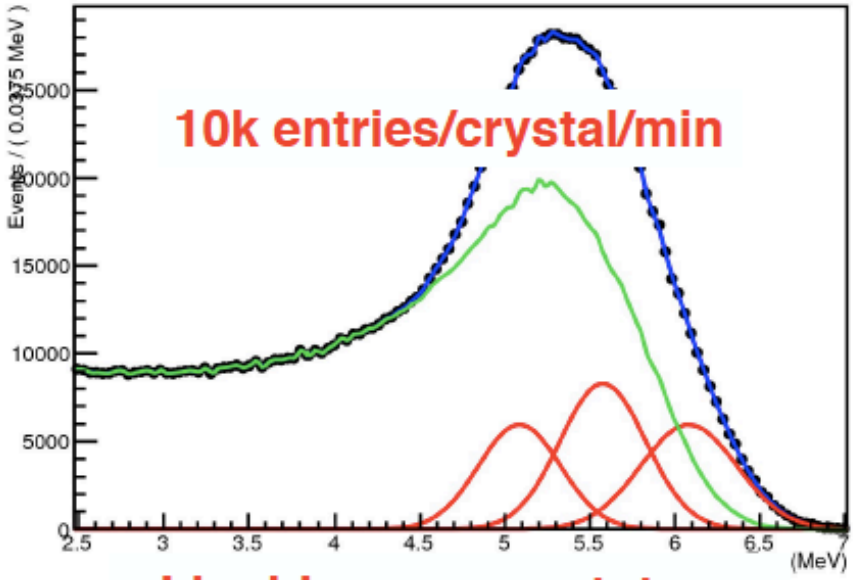



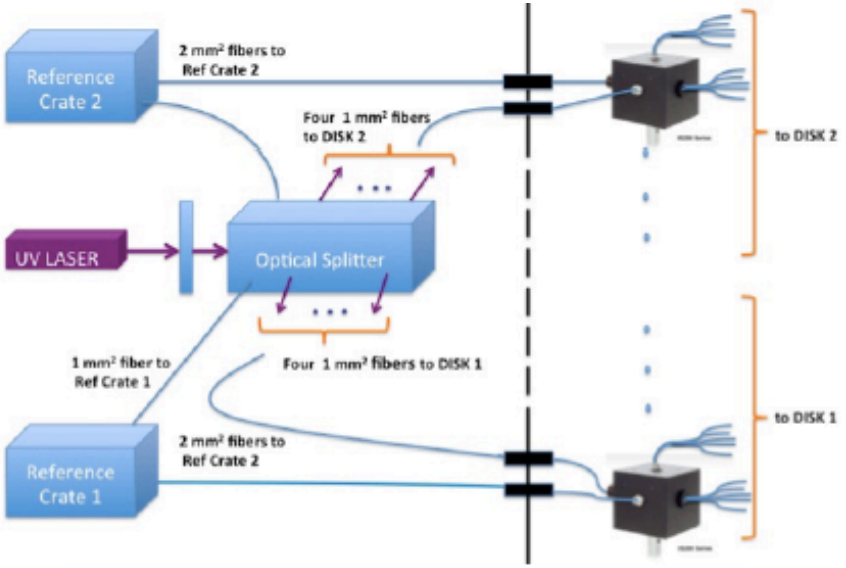




**A rejection factor of 200 can be achieved with ~ 95% efficiency for CE**

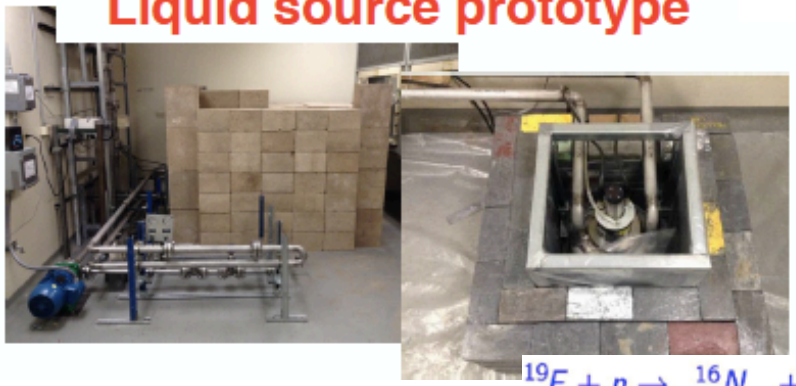
# Calibration source and laser

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




## Liquid source prototype

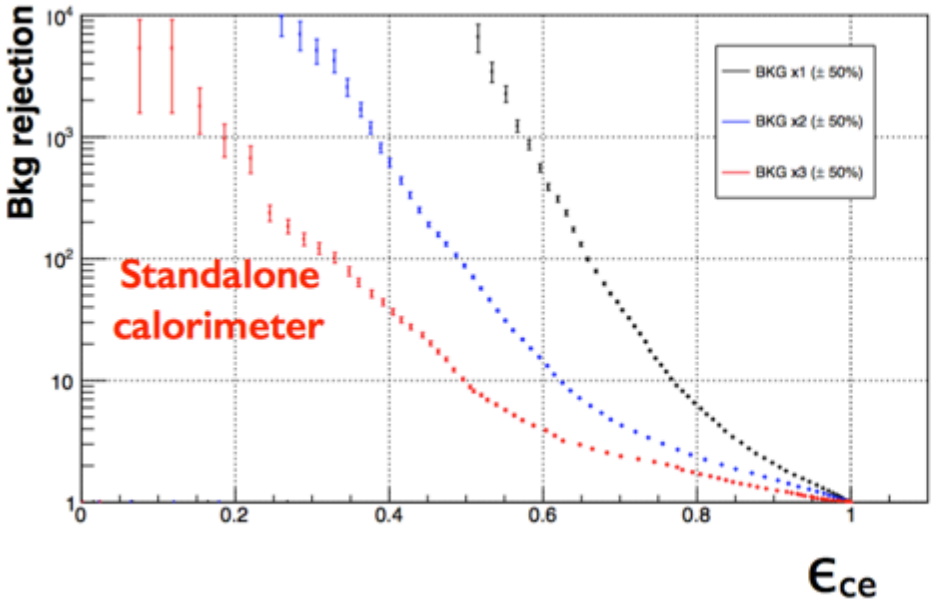


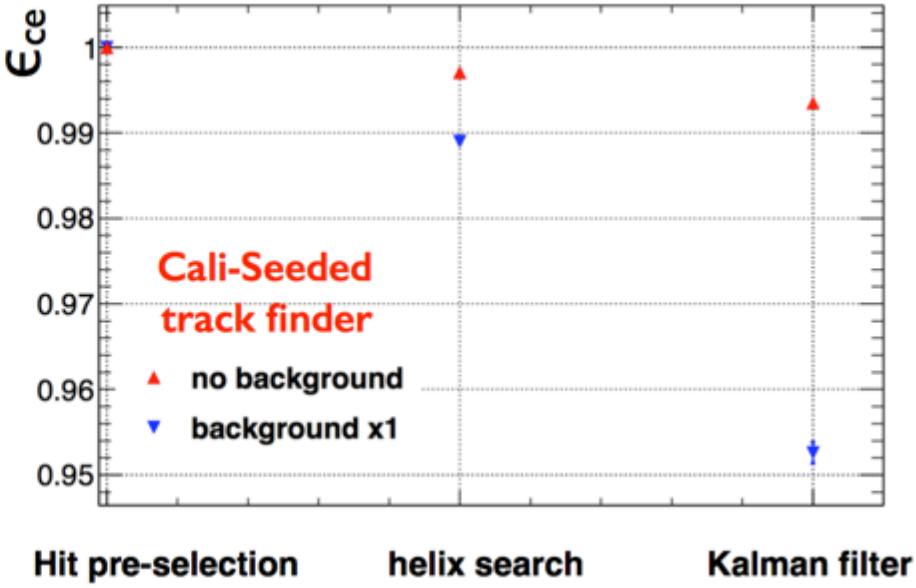
## Laser system - test station

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

# Calorimeter Trigger

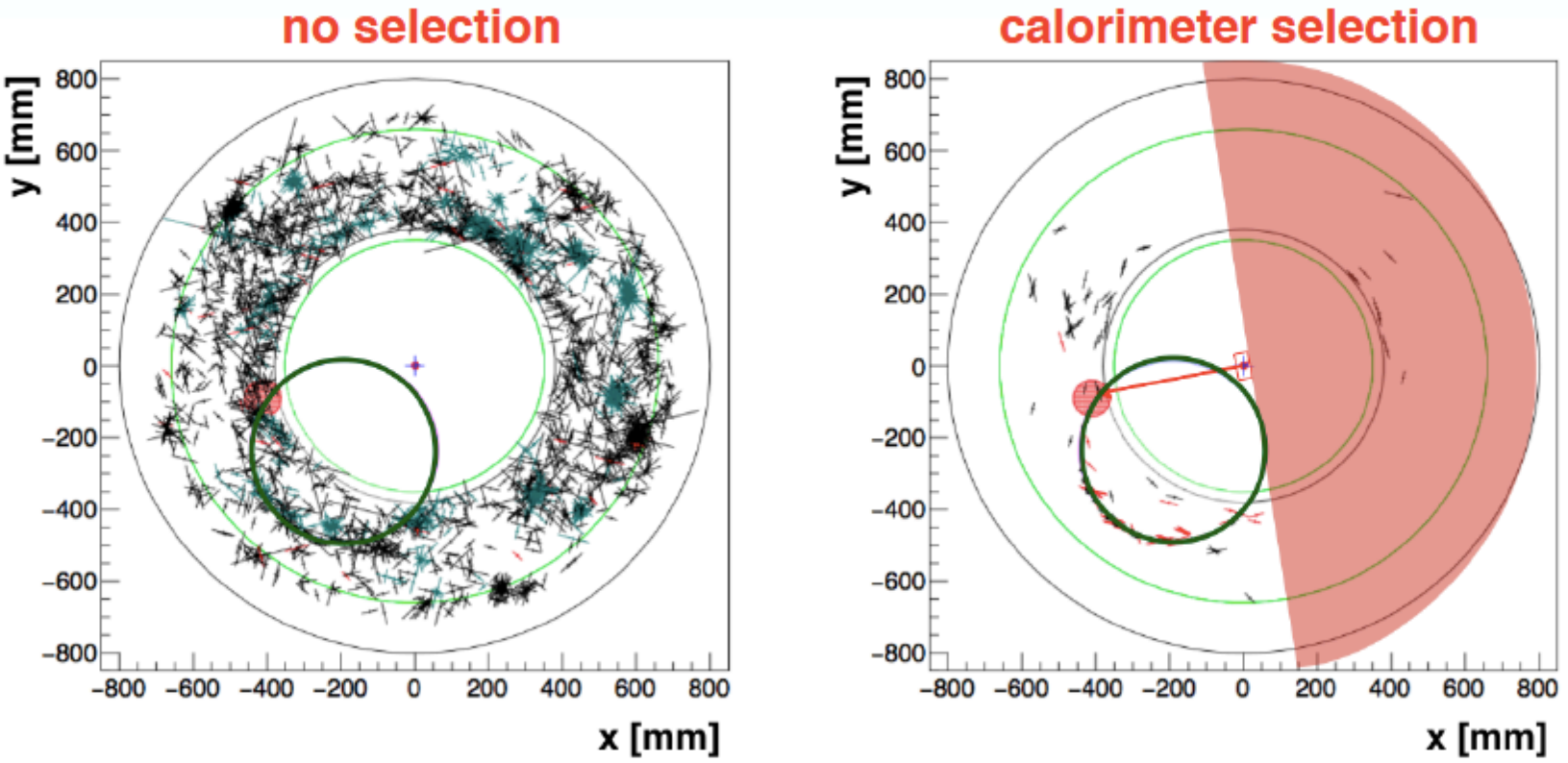
- Calo info can provide additional trigger capabilities in Mu2e:
- Calorimeter seeded track finder
  - Factorized into 3 steps: hit pre-selection, helix serach and track fit
  - $\varepsilon$ ~ 95% for background rejection of 200
- Standalone calorimeter trigger that uses only calo info
  - E ~ 65% for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



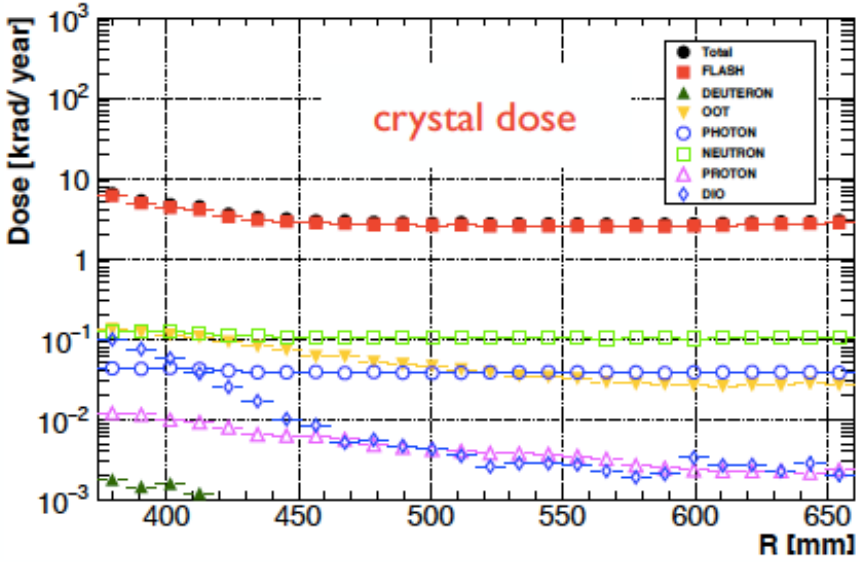

- black crosses = straw hits, red circle = calorimeter cluster, green line = CE track

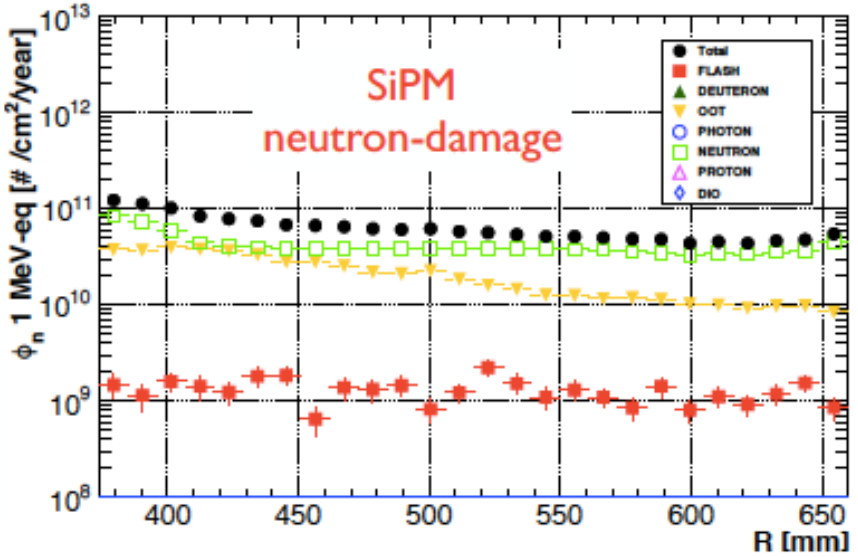
# Calorimeter radiation damage

- 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 ~ $2\times10^{11}$ 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$^2$**

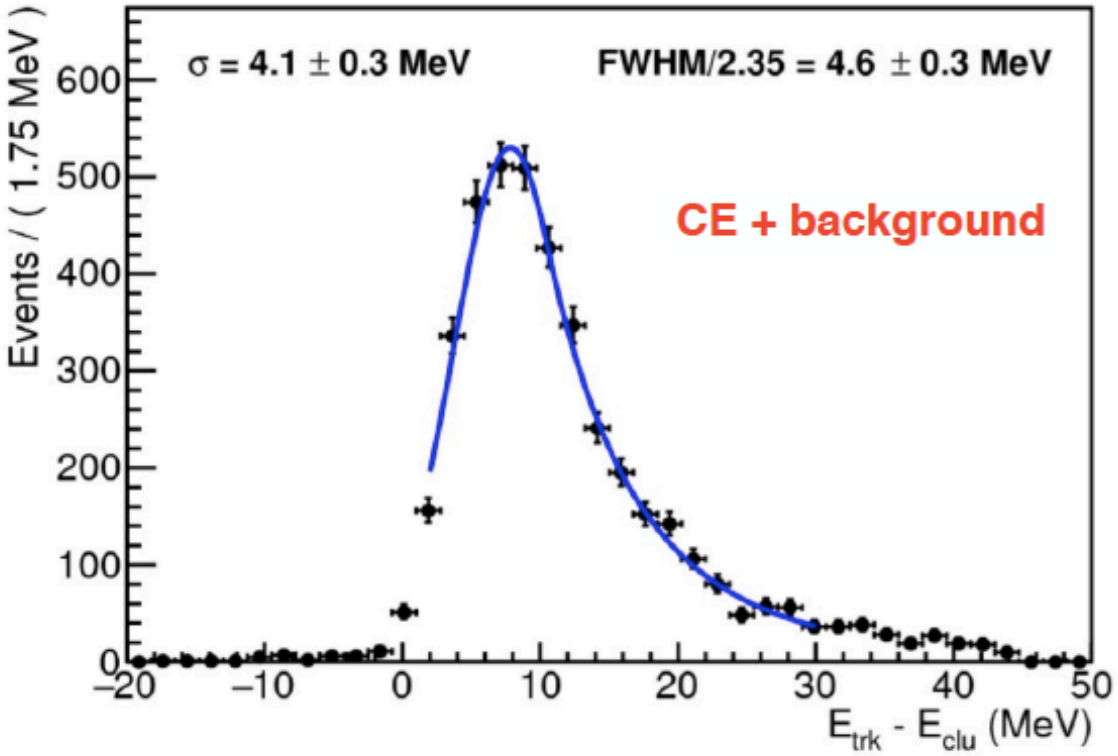
This includes a safety factor of 3 for a 3 year run



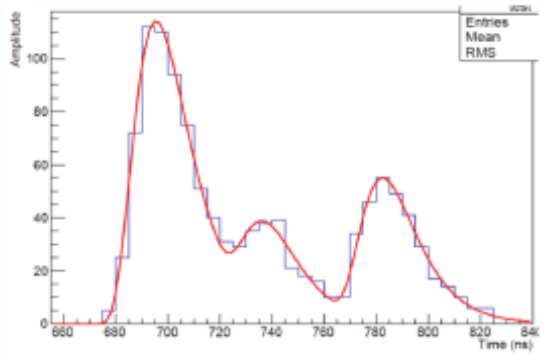



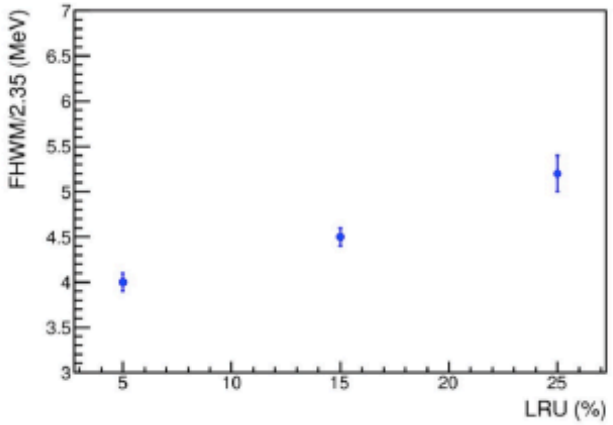
# Calorimeter radiation damage

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

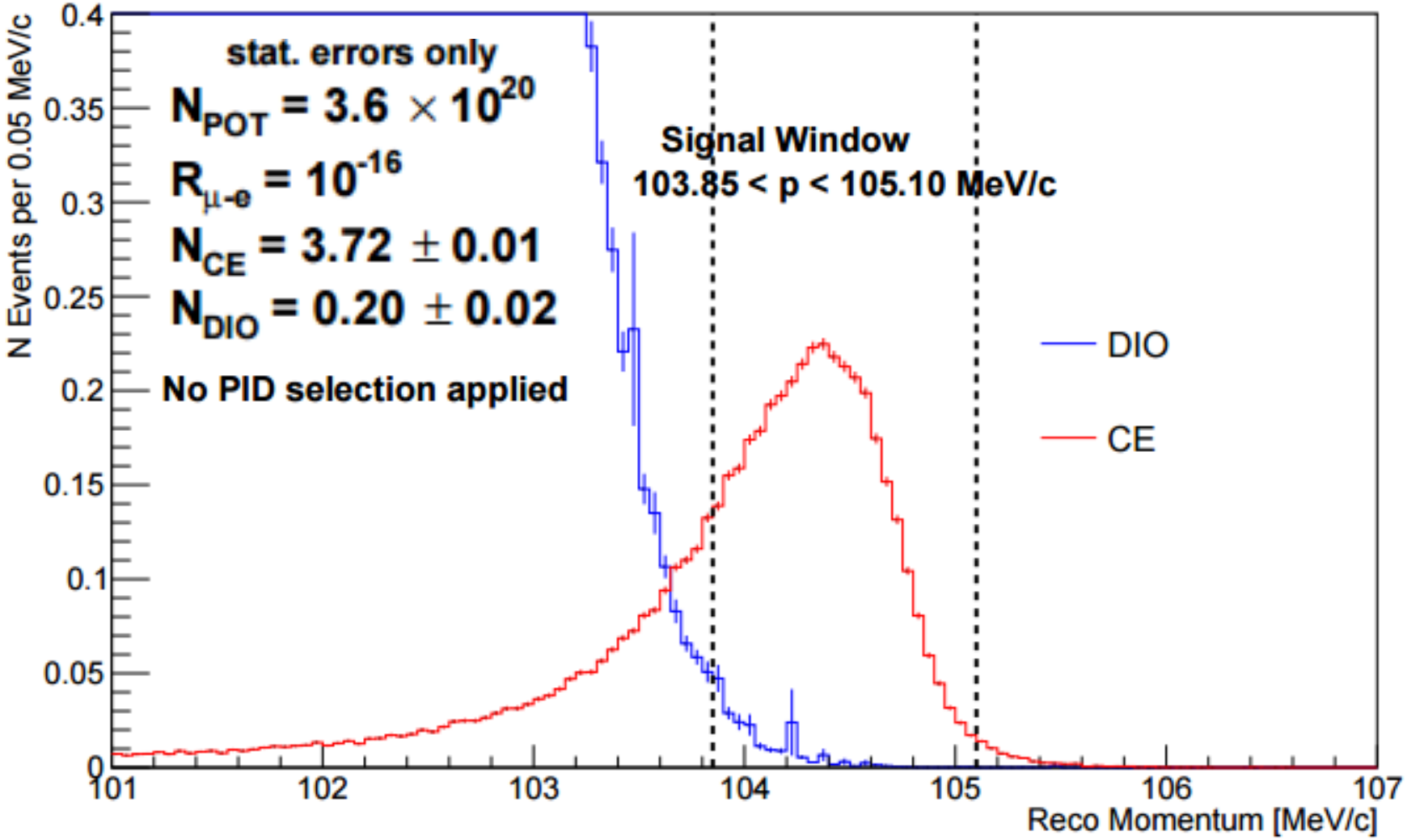



pile-up separation



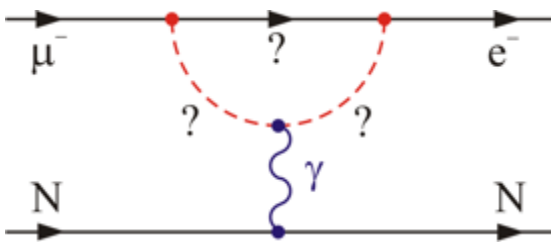
# Three years run Expectation by full Simulation



# CLFV Lagrangian

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

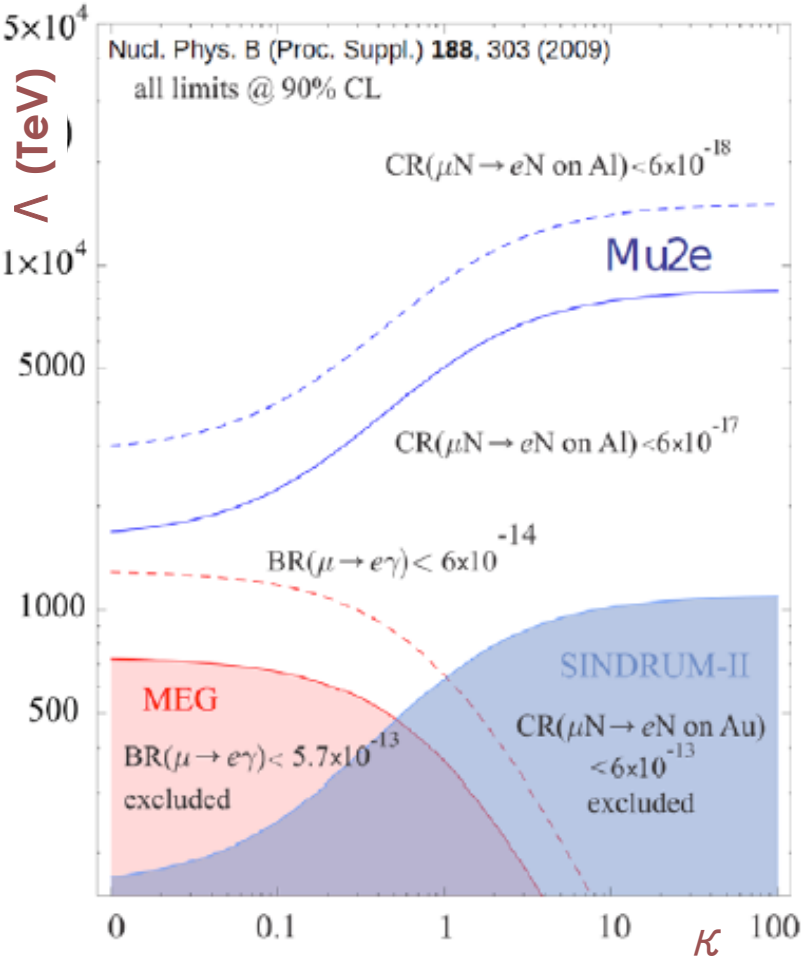
Loops dominate for
$\kappa$ << 1



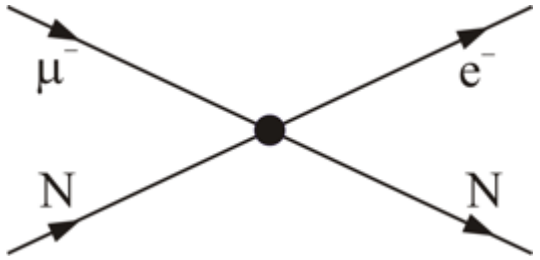

$\mu \rightarrow e\,\gamma$

$\mu$ N→eN

$\mu \rightarrow eee$




Contact terms
dominate for
$\kappa$ >> 1




$\mu \rightarrow e\,\gamma$

$\mu$ N→eN

$\mu \rightarrow eee$