# Design, status and perspective of the Mu2e crystal calorimeter


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*on behalf of the Mu2e calorimeter group*

# Outline

- The Mu2e experiment
- Calorimeter design
- The role of the calorimeter in Mu2e
- R&D
- Conclusion

# The Mu2e collaboration


Argonne National Laboratory, Boston University, Brookhaven National Laboratory
University of California, Berkeley, University of California, Irvine, California Institute of Technology, City University of New York, Joint Institute for Nuclear Research, Dubna, Duke University, Fermi National Accelerator Laboratory, Laboratori Nazionali di Frascati, Helmholtz-Zentrum Dresden-Rossendorf, University of Houston, University of Illinois, INFN Genova, Kansas State University, Lawrence Berkeley National Laboratory, INFN Lecce and Università del Salento, Lewis University, University of Louisville, Laboratori Nazionali di Frascati and Università Marconi Roma, University of Minnesota, Muons Inc., Northern Illinois University, Northwestern University, Novosibirsk State University/Budker Institute of Nuclear Physics, Institute for Nuclear Research, Moscow, INFN Pisa, Purdue University, Rice University, University of South Alabama, Sun Yat Sen University, University of Virginia, University of Washington, Yale University

# What is μ→e conversion

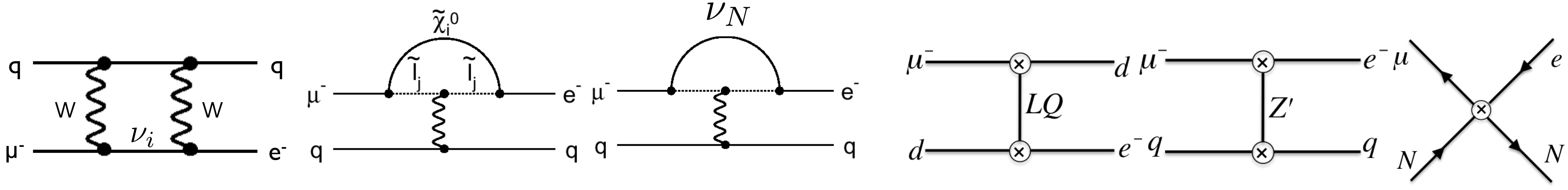
- μ converts to an electron in the presence of a nucleus $\mu^- N \rightarrow e^- N$

$$E_e = m_\mu\ c^2 - B_\mu(Z) - C(A) = 104.973\ \text{MeV}$$

- for Aluminum: $\begin{cases} B_\mu(Z) \text{ is the muon binding energy (0.48 MeV)} \\ C(A) \text{ is the nuclear recoil energy (0.21 MeV)} \end{cases}$

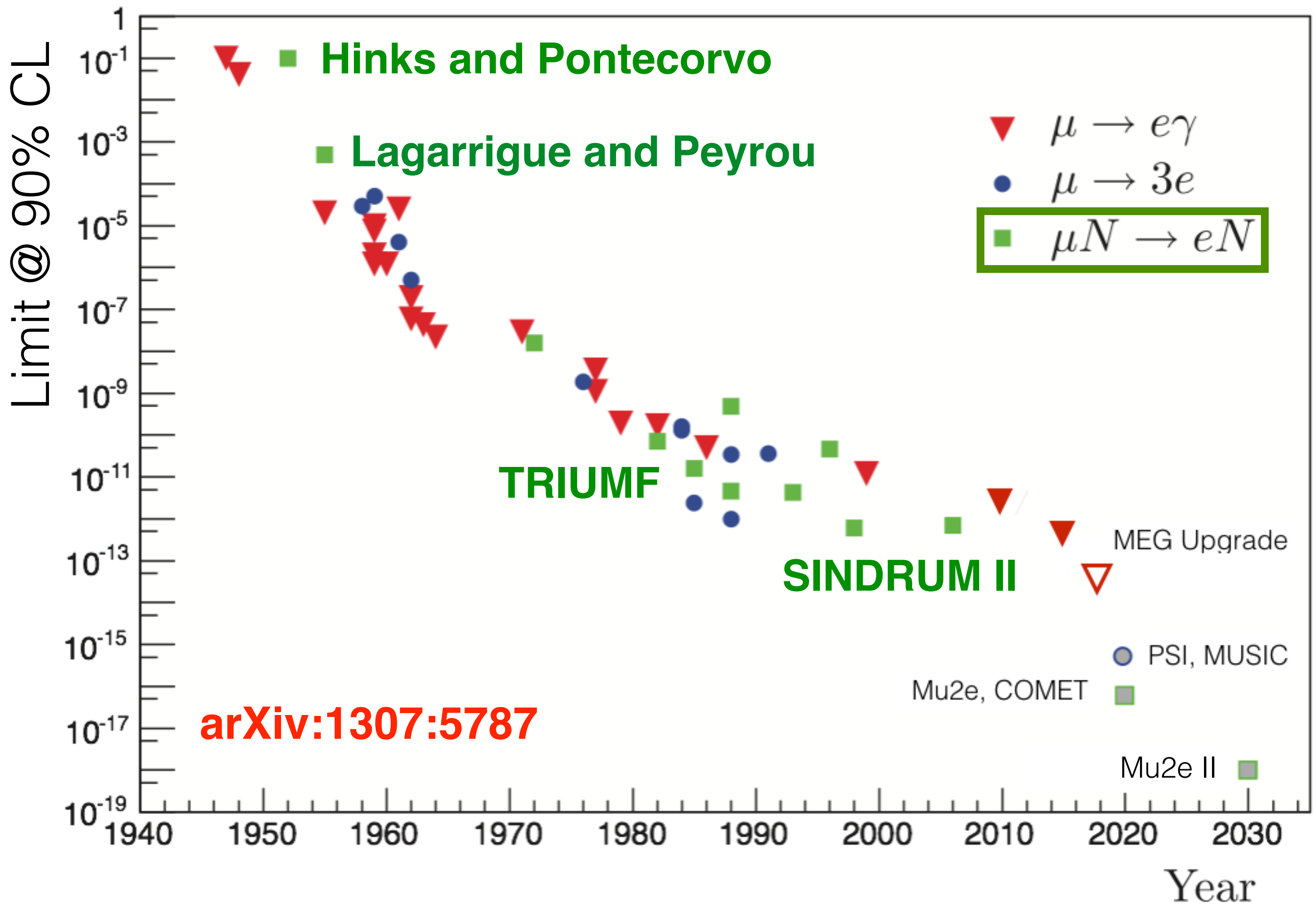
- μ conversion in the SM is induced by **neutrino masses and mixing** at a negligible level ~ $10^{-52}$

- Many **SM extensions enhance the rate** through mixing in the high energy sector of the theory (other particles in the loop…)




νMSM Muon conversion : R≈$10^{-52}$ | Supersymmetry : R ≤$10^{-13}$ | Heavy neutrino | Lepto-quark exchange | Z' exchange | Effective contact interaction

# Historical perspective




- Mu2e will improve by a factor $10^4$ the present best limit!

# Experimental setup

## (1) Production Solenoid:

➡ Proton beam strikes target, producing mostly pions

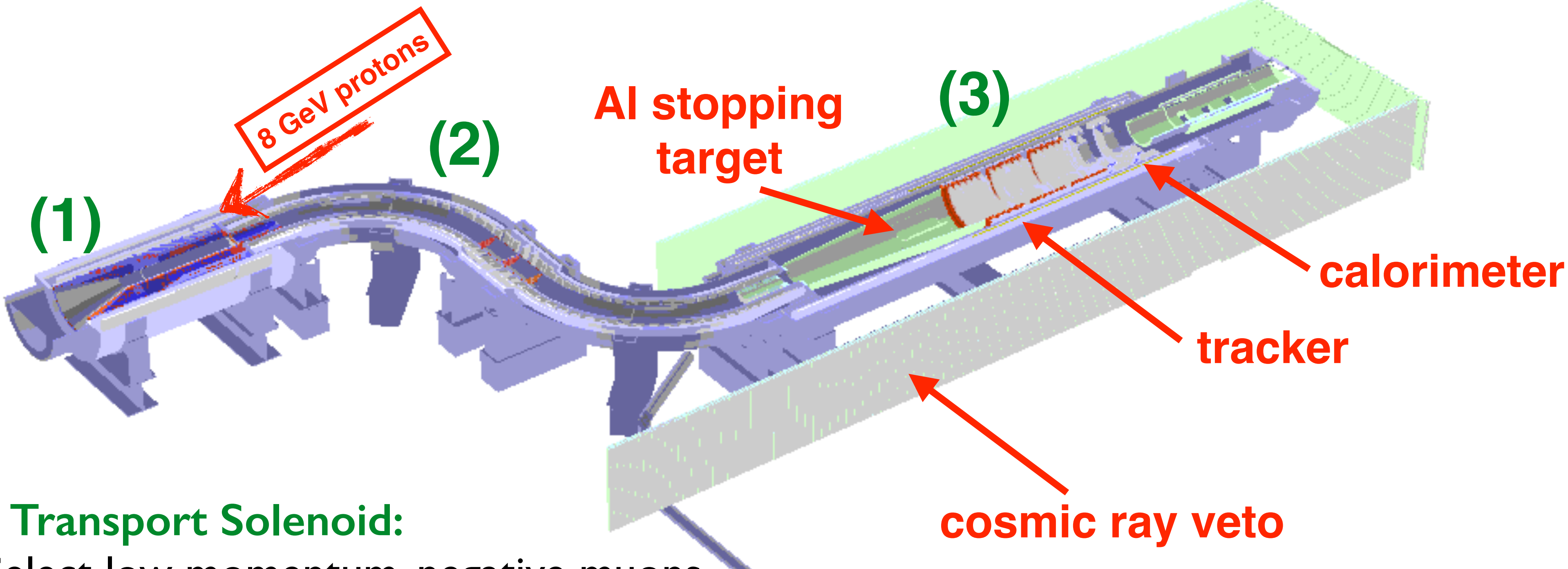
➡ Graded magnetic field contains backwards pions/muons and reflects slow forward pions/muons

## (3) Detector Solenoid:

➡ Capture muons on Al target

➡ Measure momentum in tracker and energy in calorimeter

➡ Graded field "reflects" downstream conversion electrons emitted upstream




## (2) Transport Solenoid:

➡ Select low momentum, negative muons

➡ Antiproton absorber in the mid-section

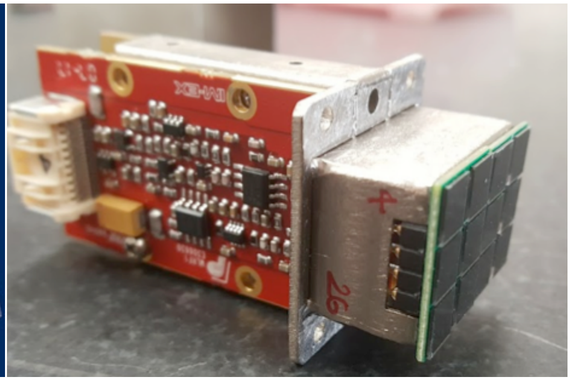
# Calorimeter design

- 2 disks; each disk contains 678 undoped CsI crystals 20 x 3.4 x 3.4 $cm^3$
- Disk separation ~ 75 cm
- Inner/outer radii: 37.4/66 cm
- **Crystal choice:** undoped CsI provides light yield (LY) > 100 pe/MeV, longitudinal response uniformity < 10%, emission decay time $\tau$ ~ 16 ns
- **Photosensor choice:** custom array 2x3 of 6x6 $mm^2$ UV-extended SiPM

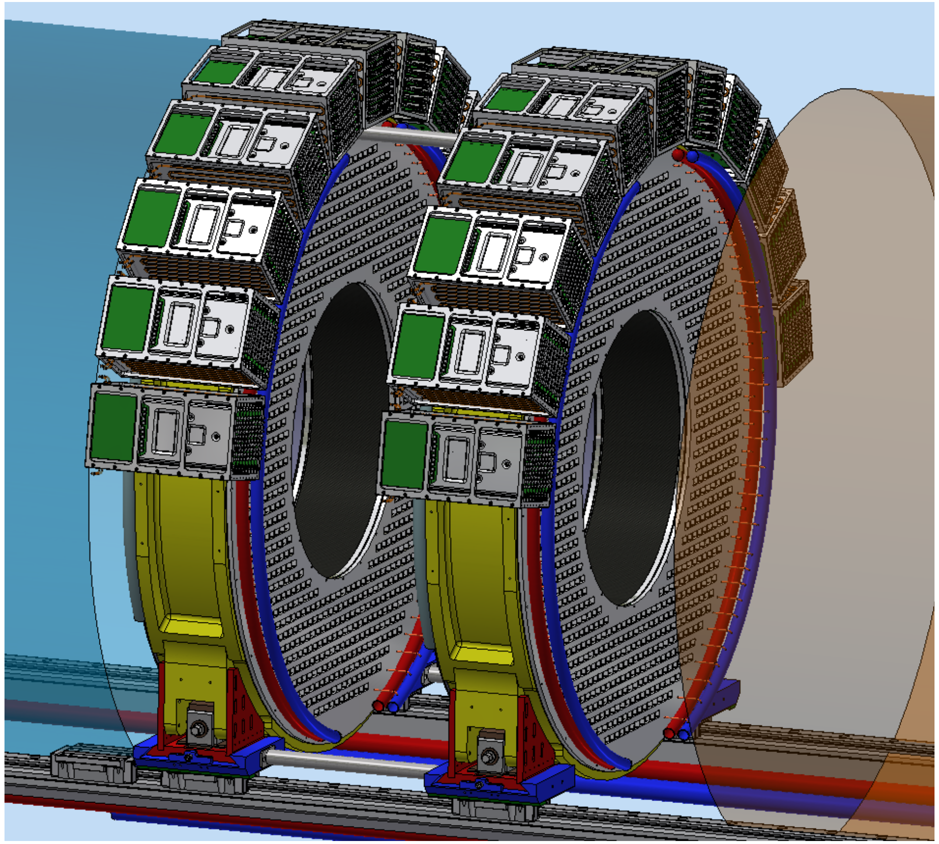
undoped CsI


(R. Y. Zhu talk)

SiPM array + FEE

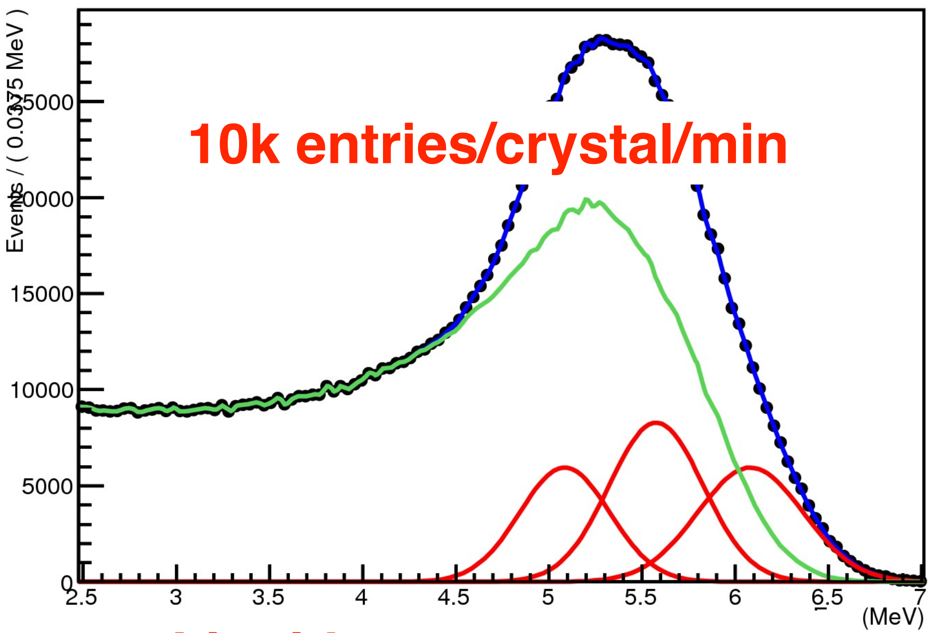


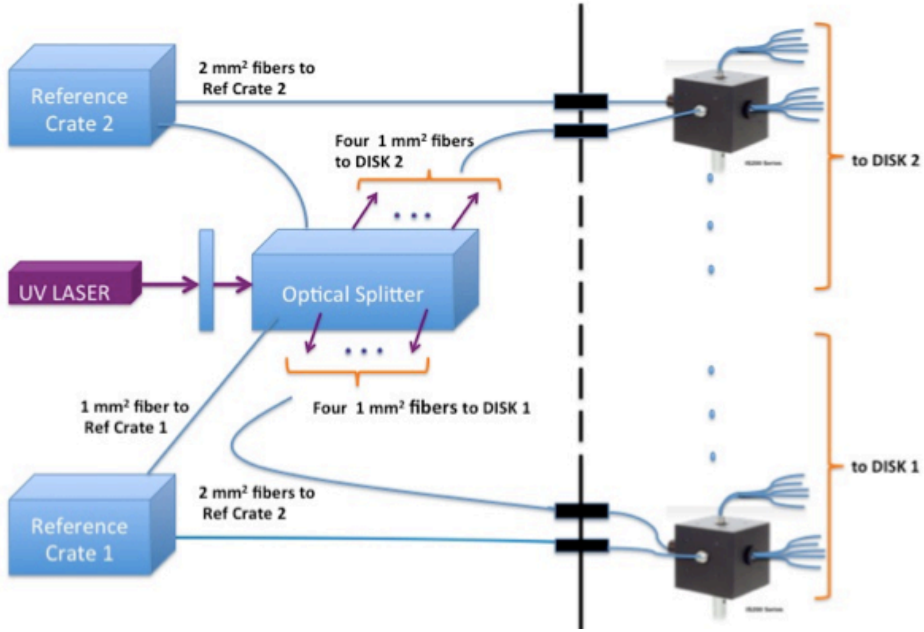
(I. Sarra talk)



# Calibration methods

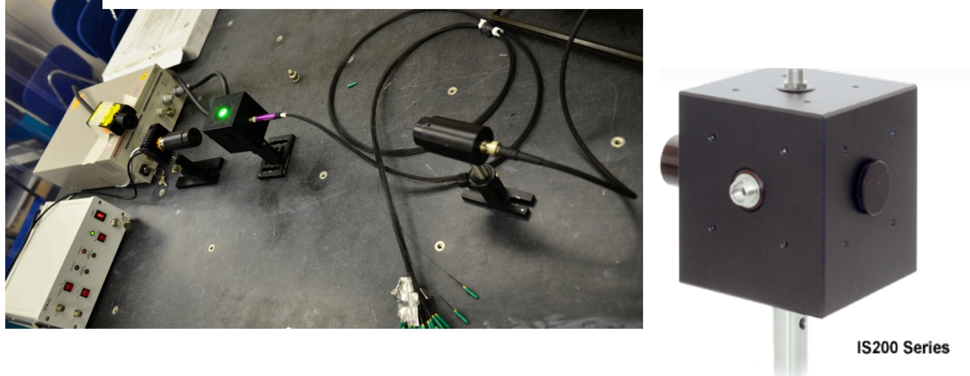
- Liquid source FC 770 + DT generator: 6 MeV + 2 escape peaks
- Laser system to monitor SiPM performance



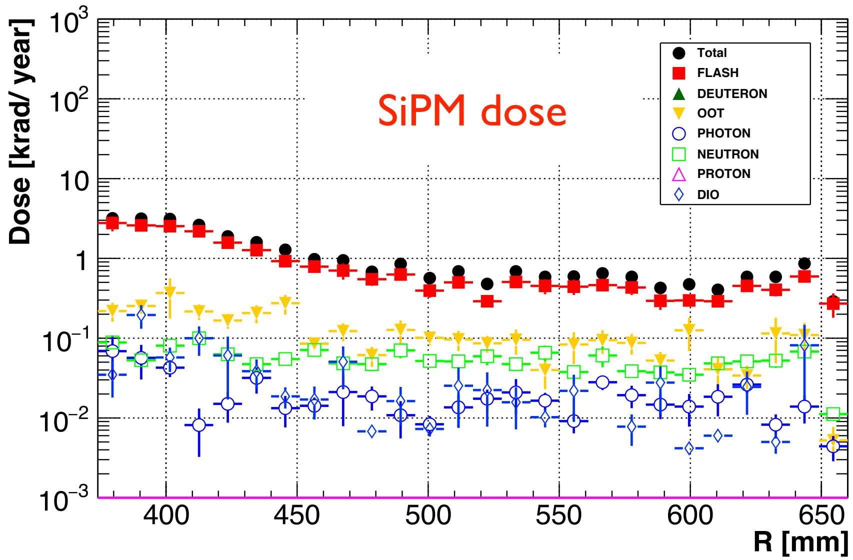

**Liquid source prototype**

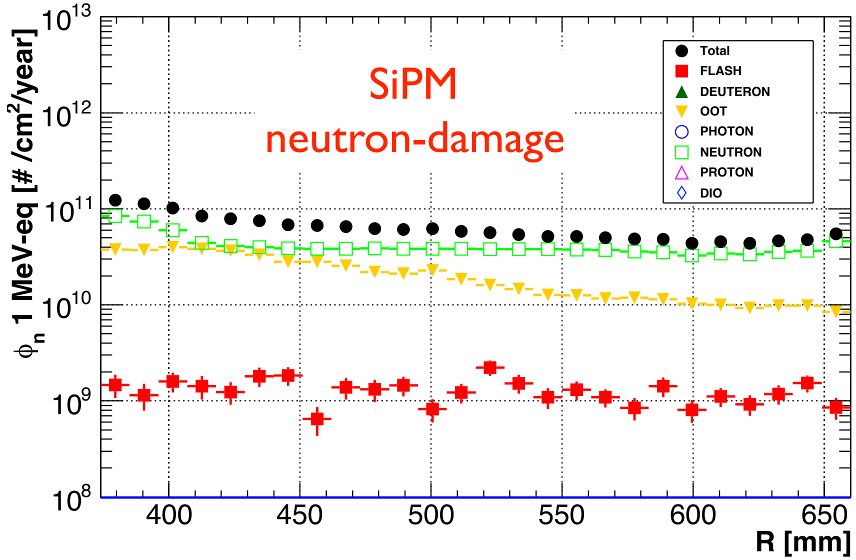
**Laser system - test station**

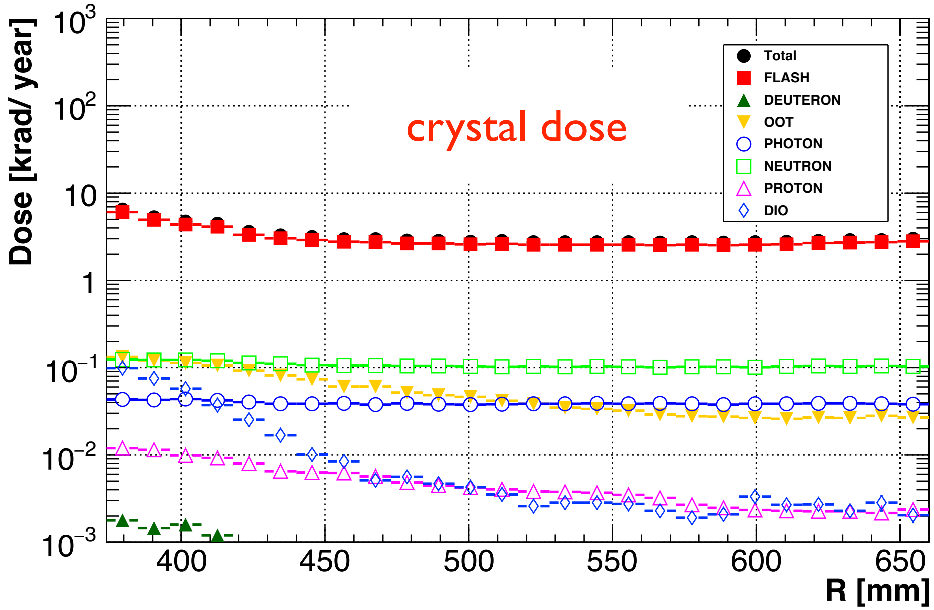


# Radiation Environment

- High level of dose impact on Si devices and crystals performance

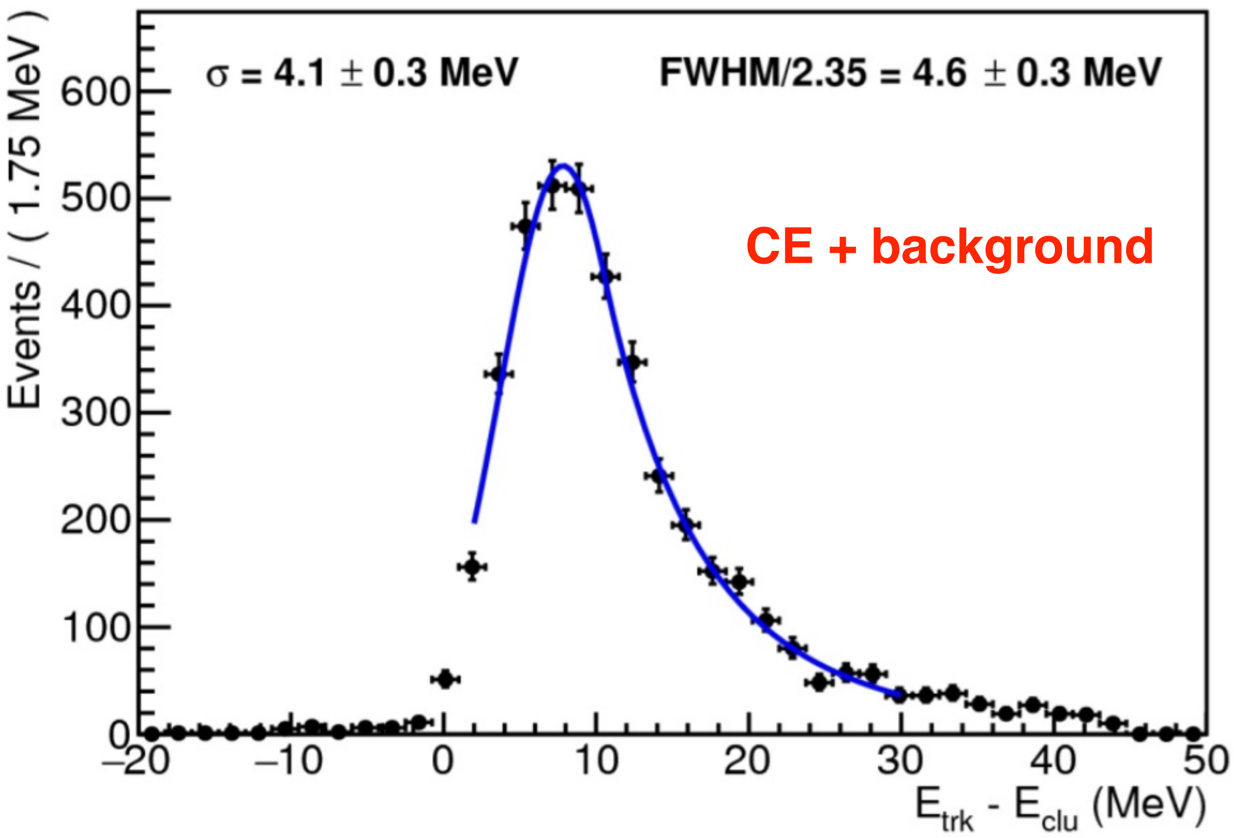


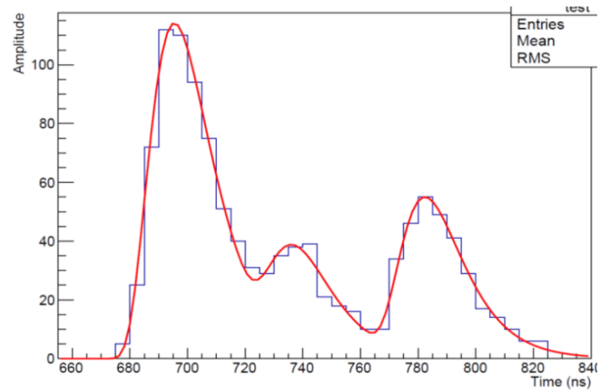



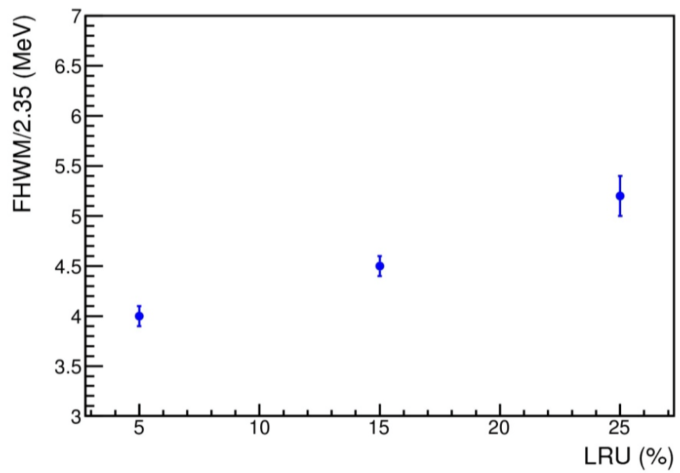
# Simulation results

- 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



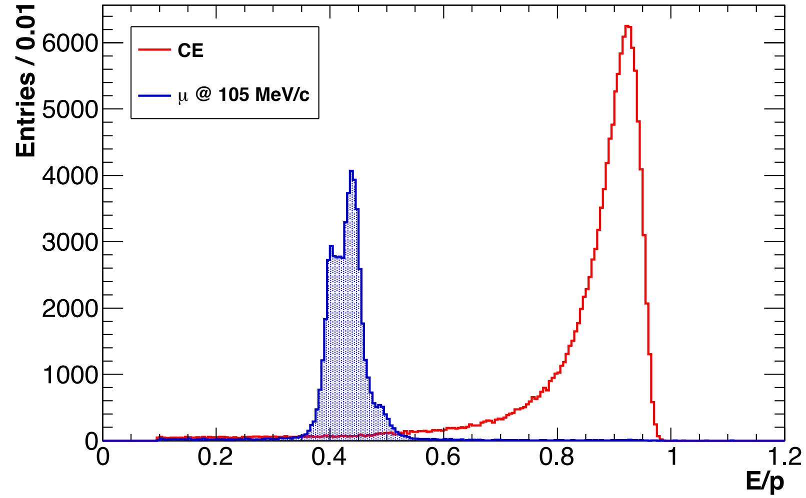



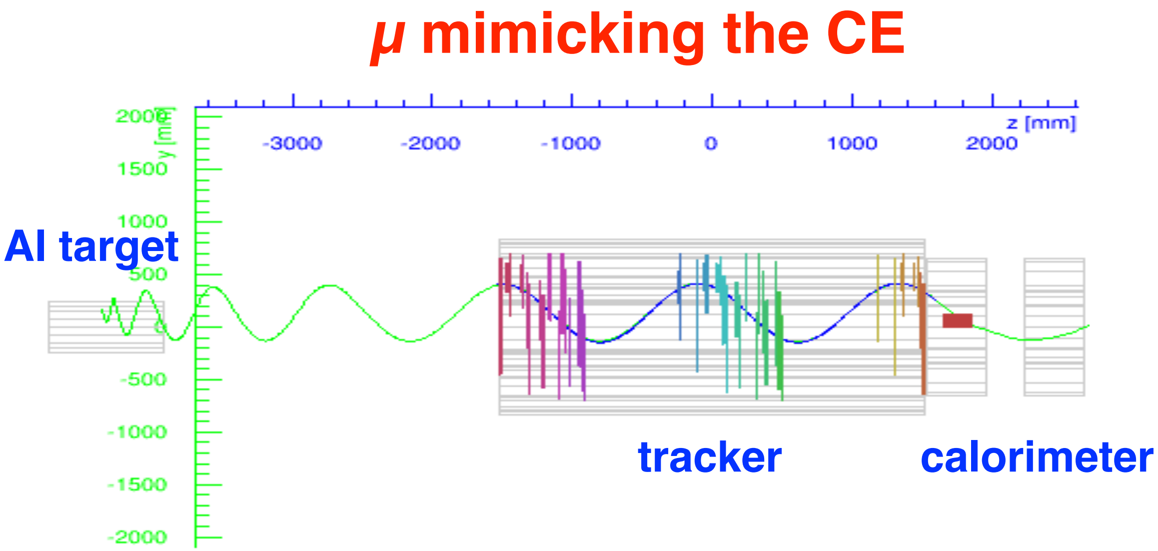
# PID: e/μ separation

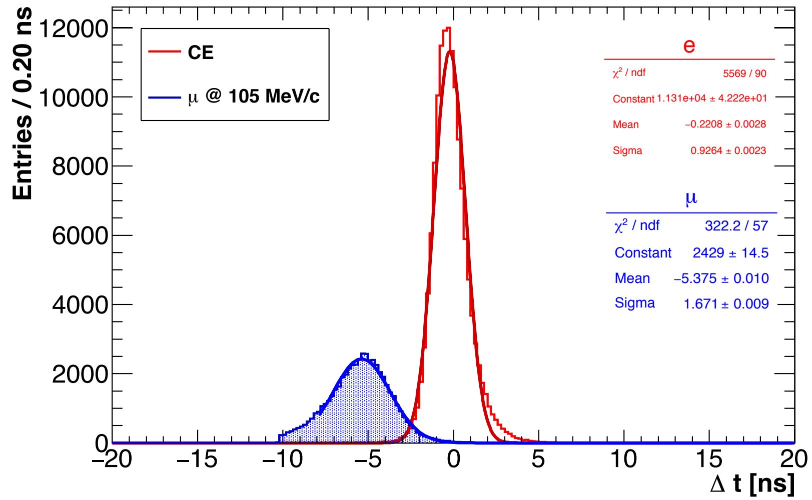
- 105 MeV/c $e^-$ are ultra-relativistic, while 105 MeV/c μ have β~ 0.7 and a kinetic energy of ~ 40 MeV
- Likelihood rejection combines

  **Δ**t = $t_{track}$ - $t_{cluster}$ and E/p:

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

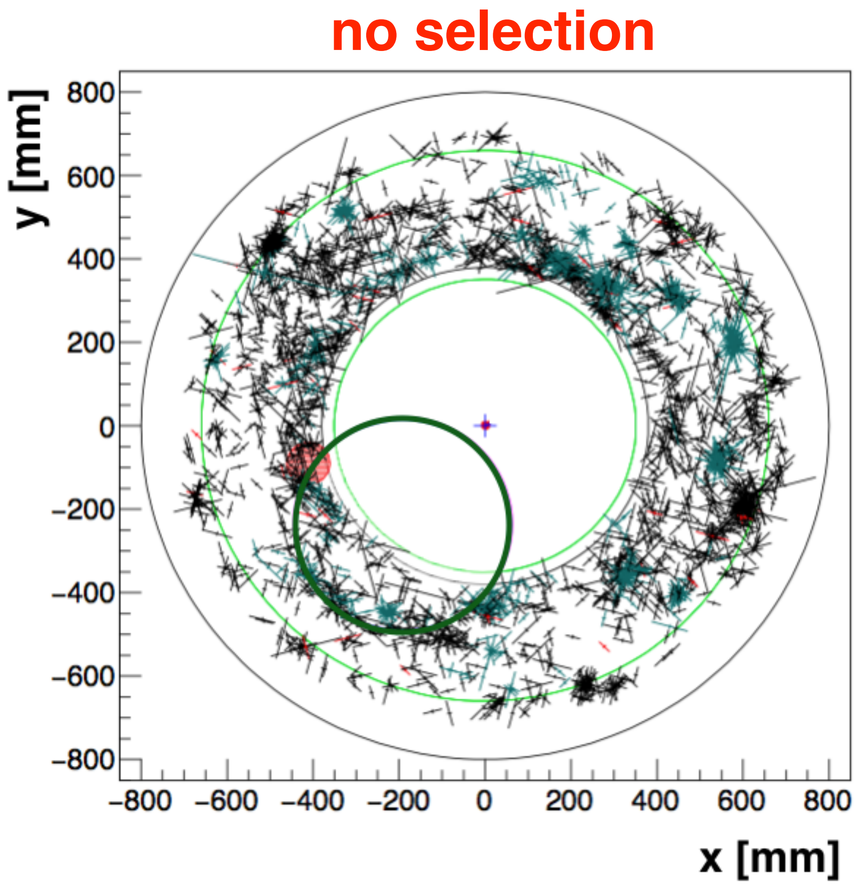


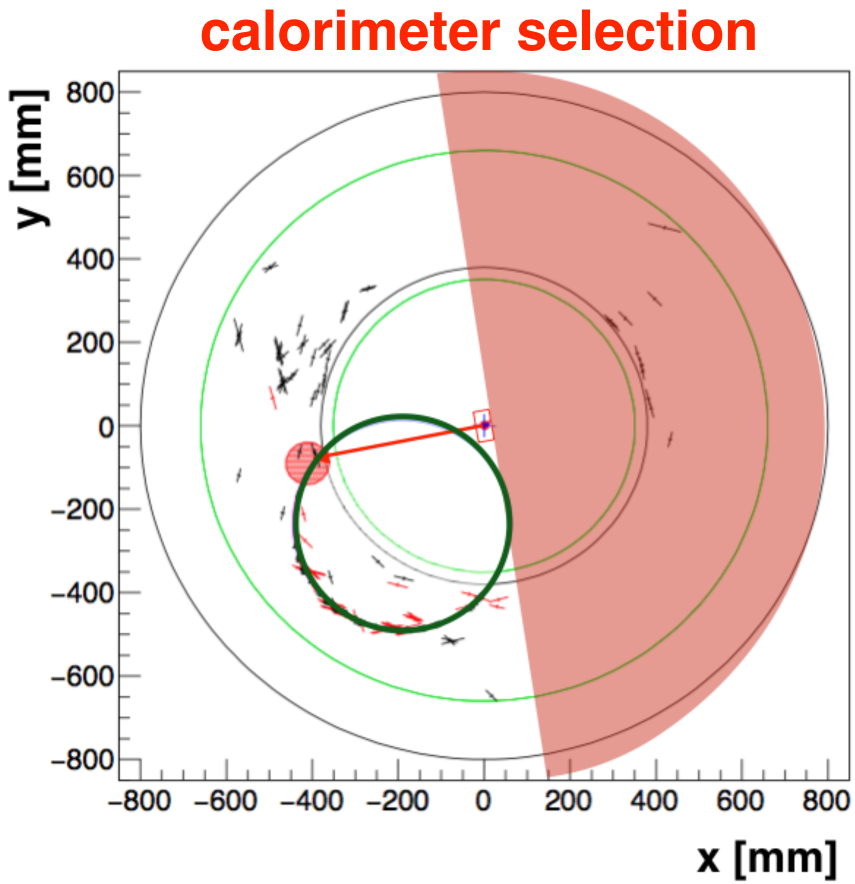



# Calo seeded track finder

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

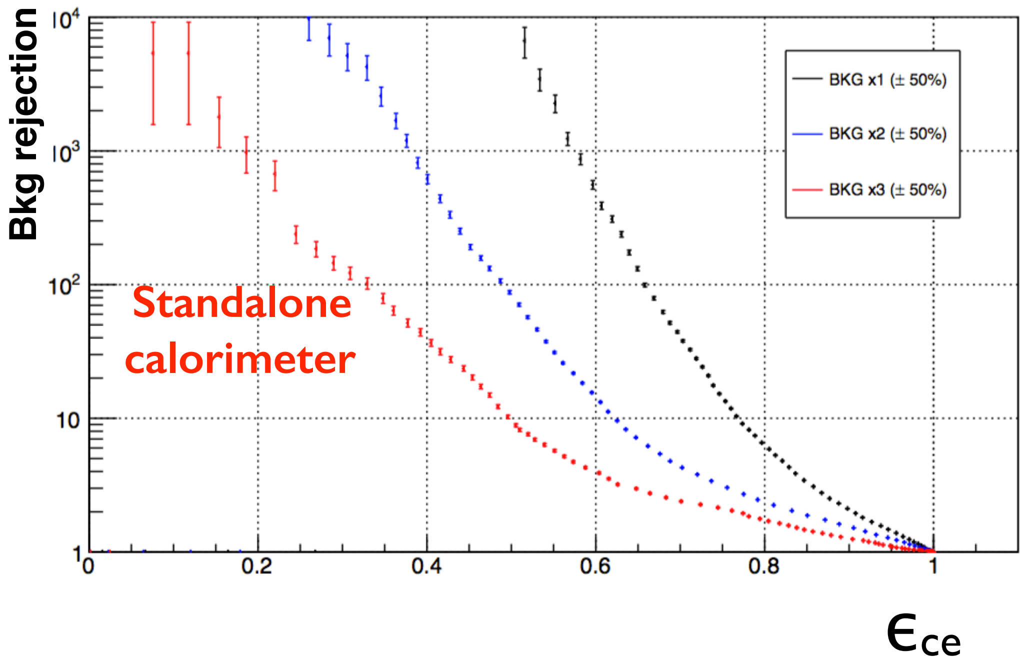


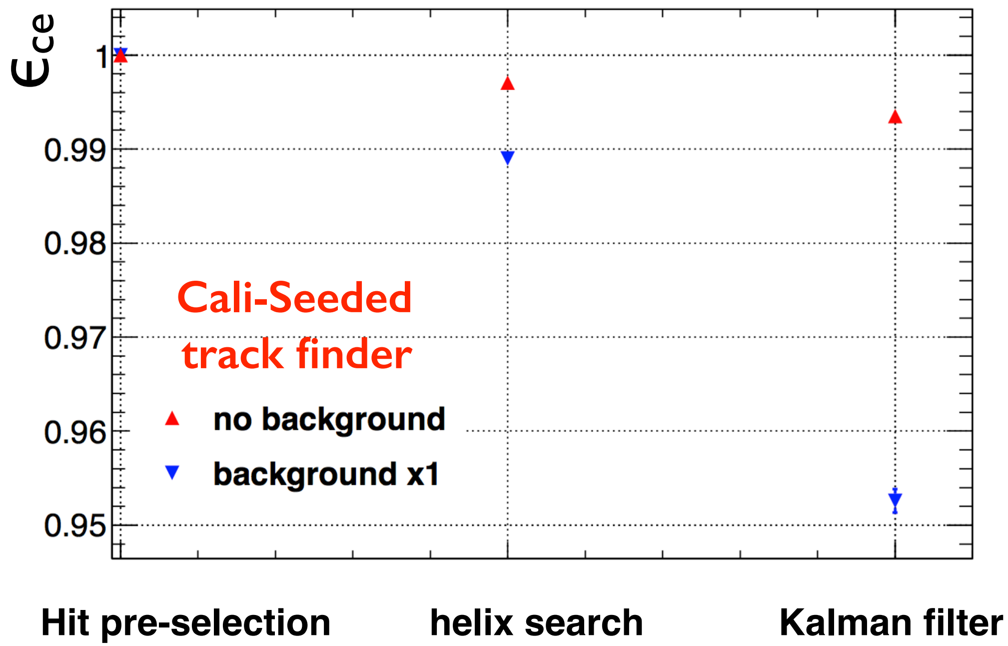




- **black crosses** = straw hits, **red circle** = calorimeter cluster, **green line** = CE track

# Calorimeter trigger

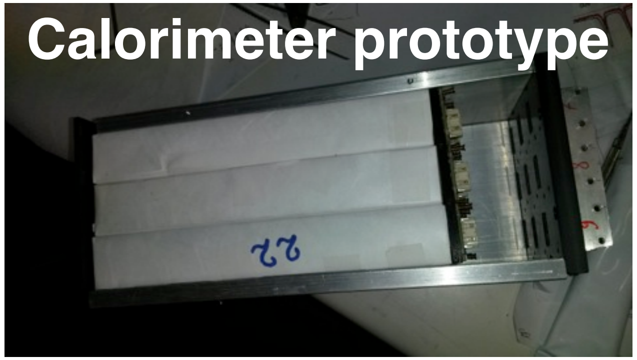
- Calo info can provide additional trigger capabilities in Mu2e:
- **Calorimeter seeded track finder**:
  - ✓ factorized into 3 steps: hit pre-selection, helix search and track fit
  - ✓ $\epsilon$~95% for a background rejection of 200
- **Standalone calorimeter** trigger that uses only calo info:
 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

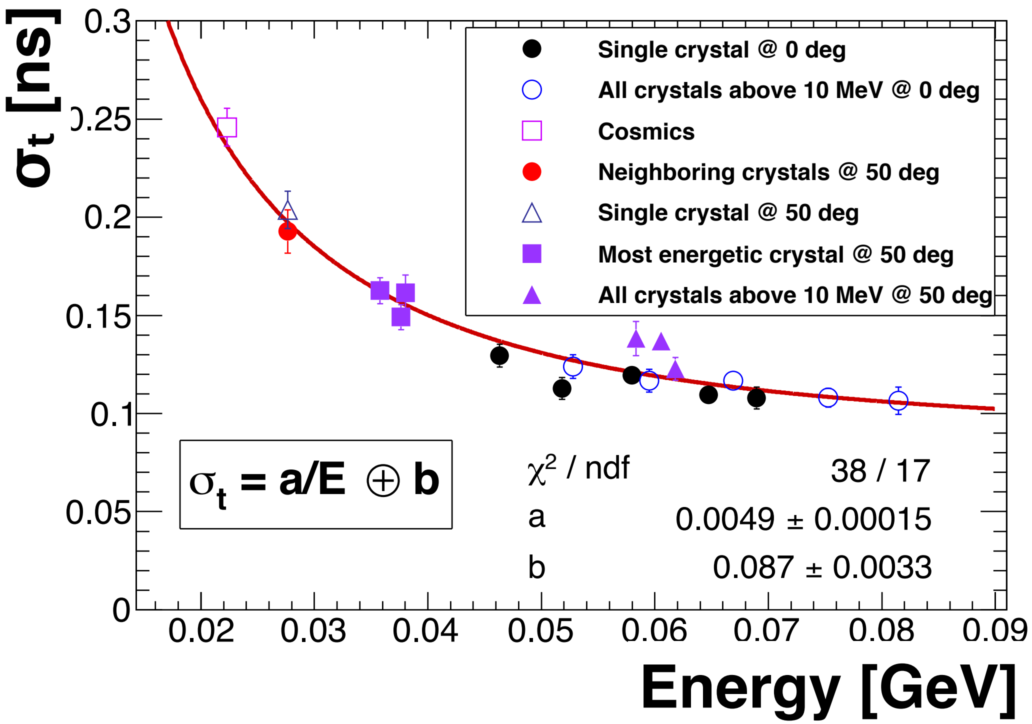


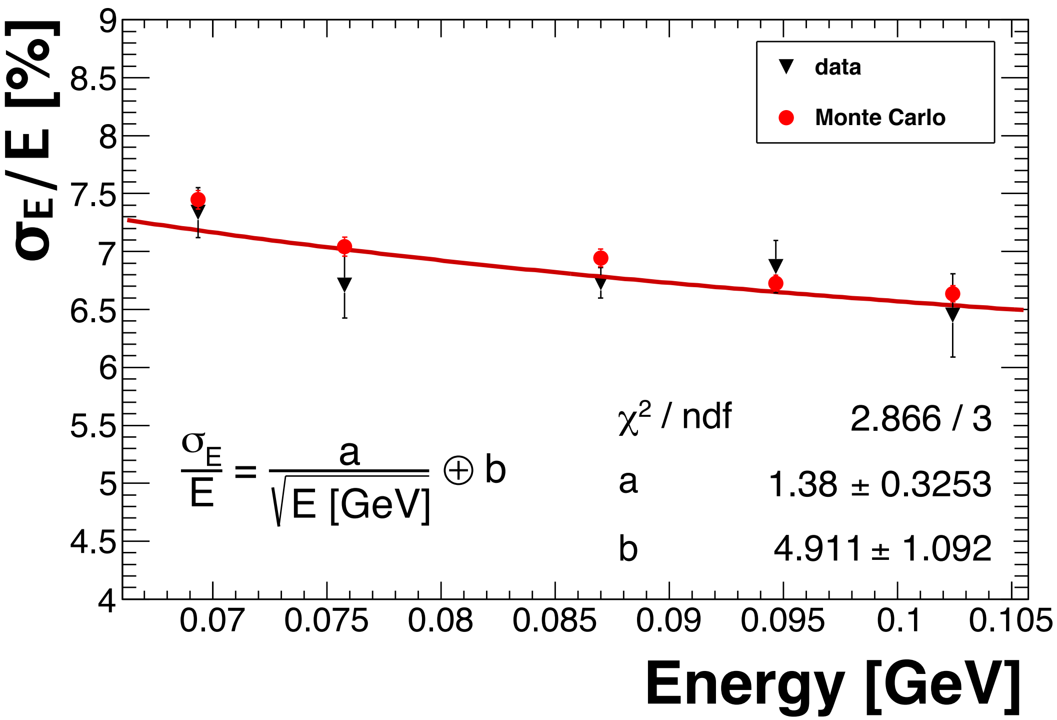



# Test with small prototype

- Small prototype tested @ the BTF in Frascati during April 2015
- Array 3 x 3 with undoped CsI 3 x 3 x 20 $cm^3$ coupled with Hamamatsu MPPC
- All channels were read out with the 12 bit 250 Msps waveform digitizer board V1720

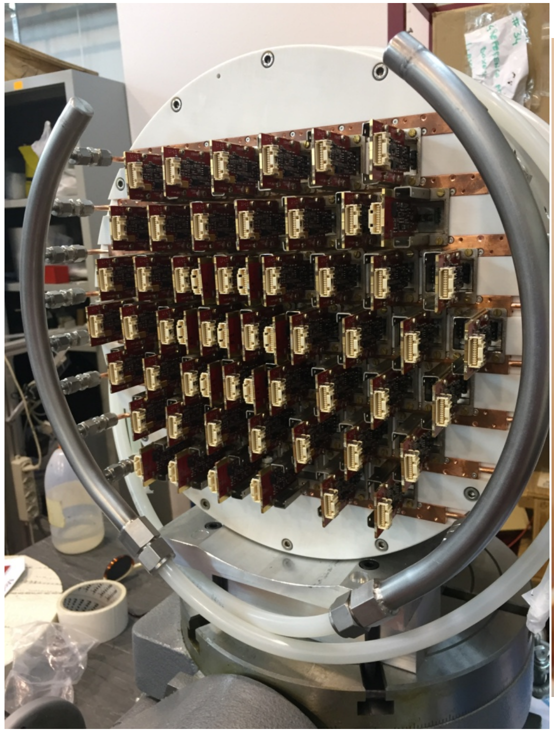


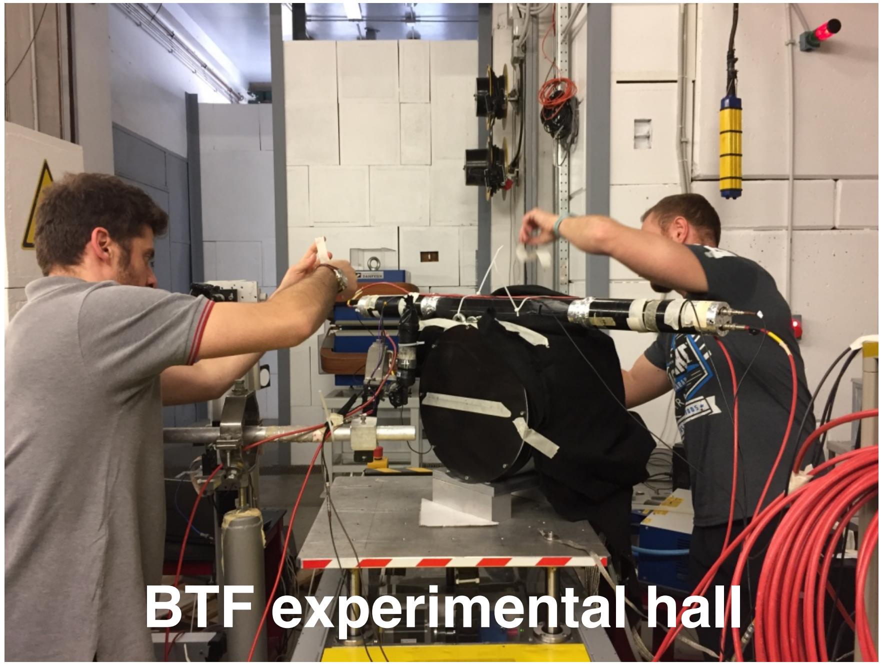



# New prototype

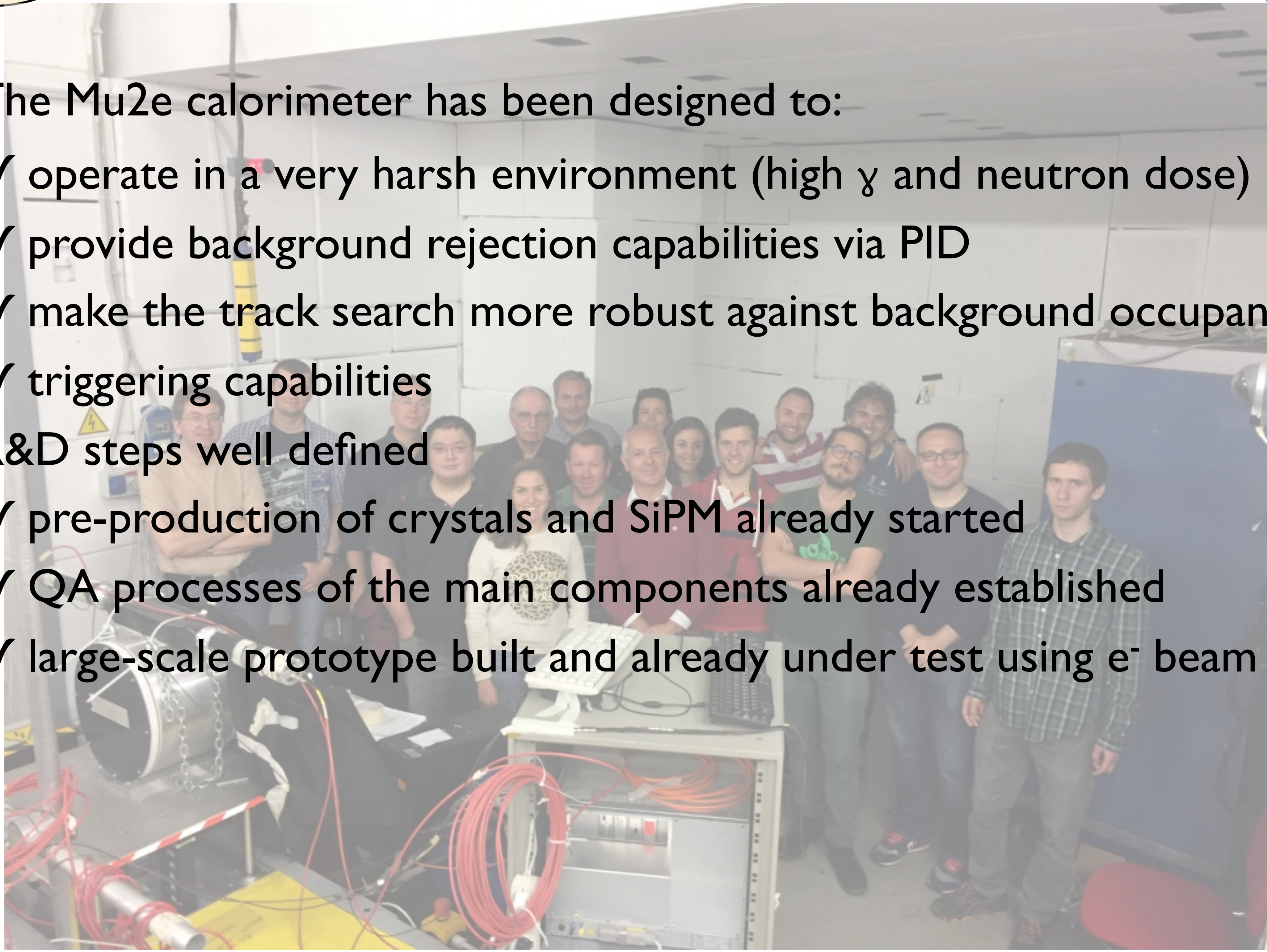
- Large prototype: 51crystals + 102 SiPM + 102 FEE boards
- Mechanics and cooling system similar to the final ones
- Beam test successfully performed on 4-14 May 2017 @ BTF in Frascati using $e^-$ beam in the range [60, 120] MeV
- Energy & timing resolution studied @ normal and 50 deg incidence
- Analysis is underway





# Conclusions

- The Mu2e calorimeter has been designed to:
  - ✓ operate in a very harsh environment (high $\gamma$ and neutron dose)
  - ✓ provide background rejection capabilities via PID
  - ✓ make the track search more robust against background occupancy
  - ✓ triggering capabilities
- R&D steps well defined
  - ✓ pre-production of crystals and SiPM already started
  - ✓ QA processes of the main components already established
  - ✓ large-scale prototype built and already under test using $e^-$ beam



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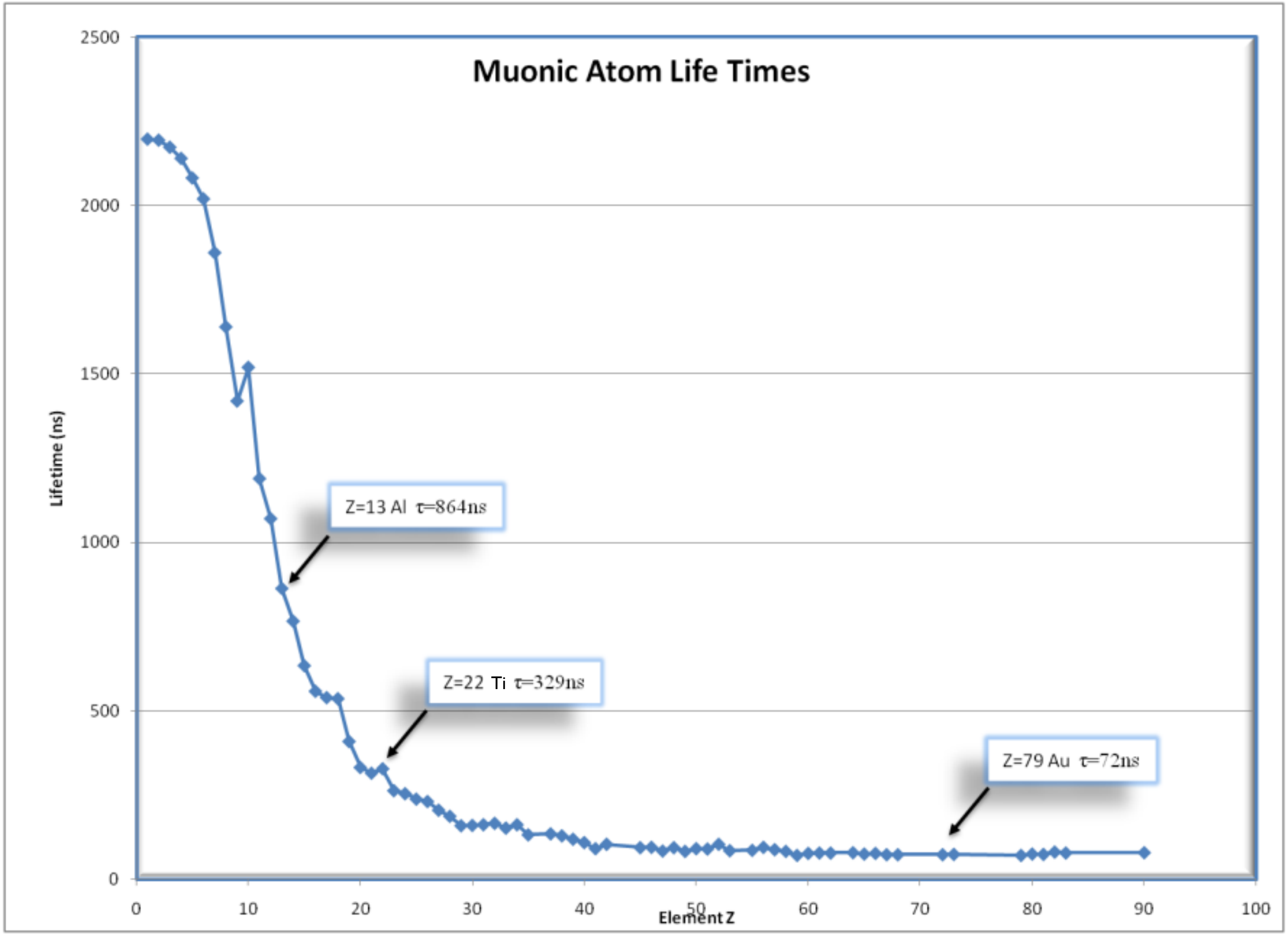
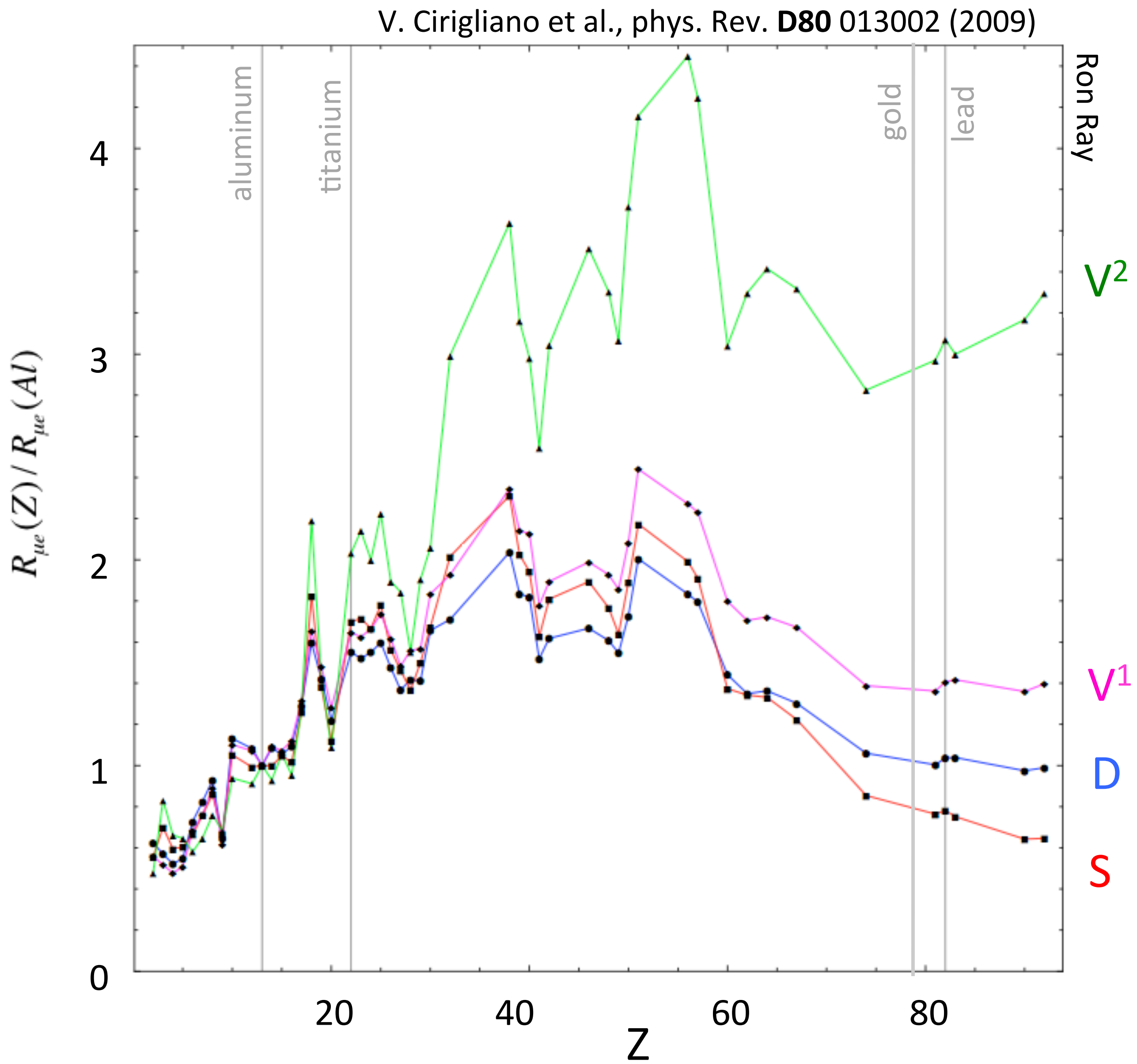
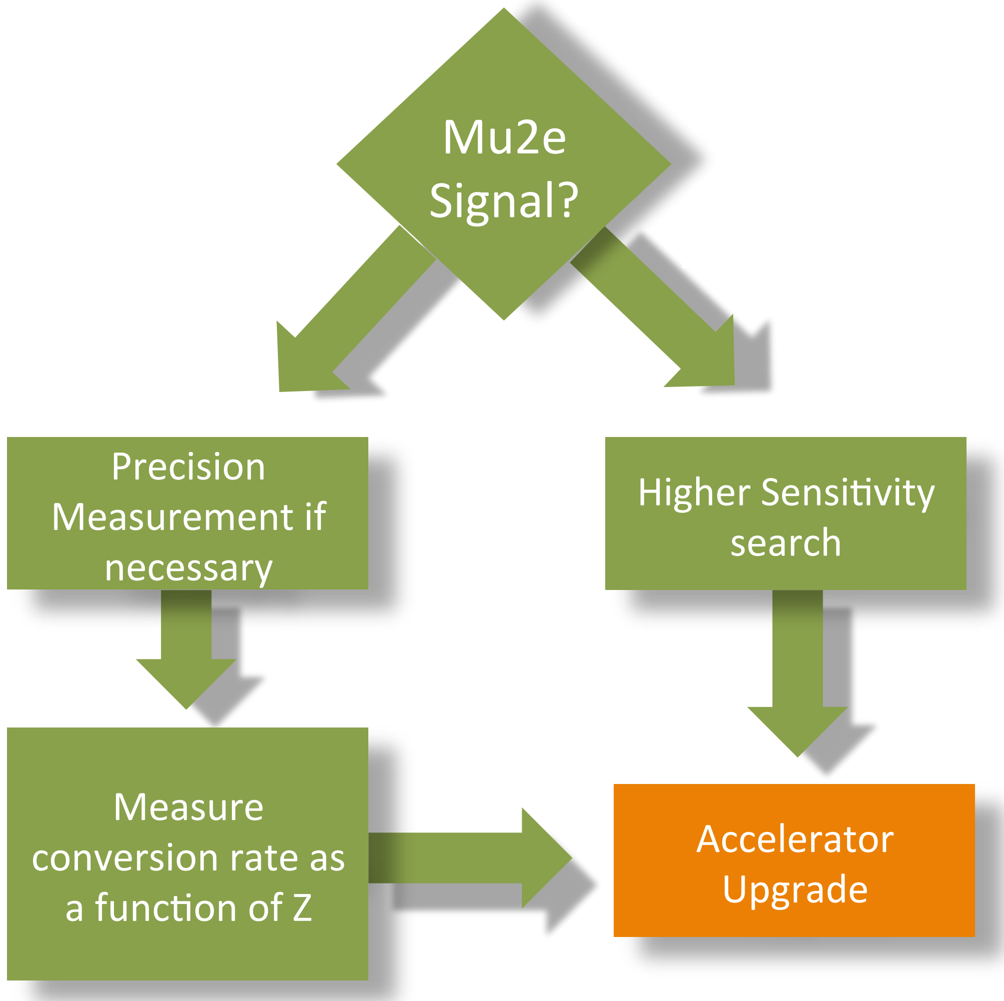
# Muonic atom life times



# $R_{\mu e}$ rate vs Z

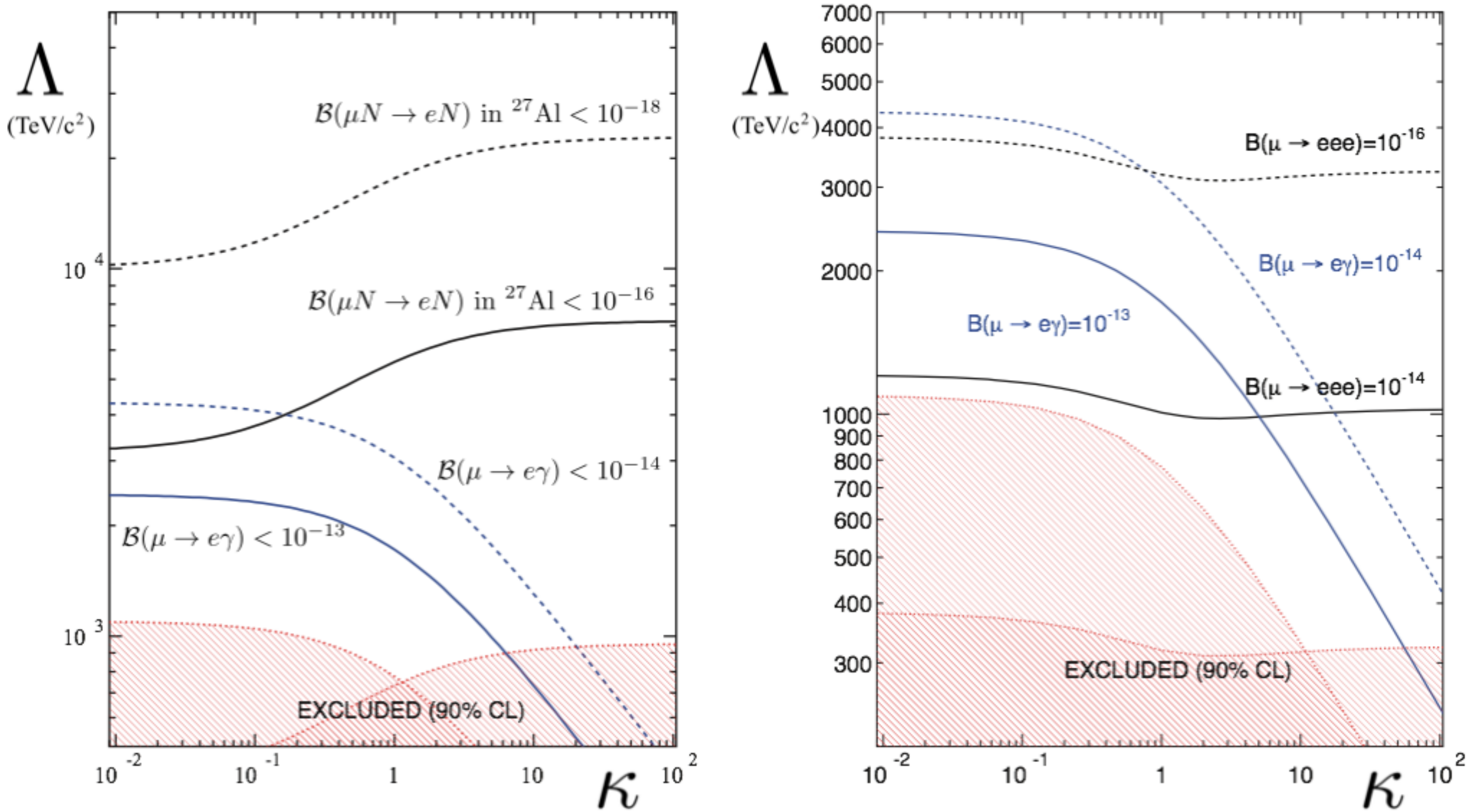


# Mu2e signal?




- A next-generation Mu2e experiment makes sense in all scenarios:
  - ✓ Push sensitivity or
  - ✓ Study underlying new physics
  - ✓ Will need more protons upgrade accelerator
  - ✓ **Snowmass** white paper, arXiv:1307.116

# Model independent Lagrangian




$$L_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{e}\gamma^\mu e\right)$$

**“dipole term”** **“contact term”**

# CLFV limits I

| Process | Upper limit |
|---|---|
| $\mu^+ \to e^+\gamma$ | $< 5.7 \times 10^{-13}$ |
| $\mu^+ \to e^+e^-e^+$ | $< 1.0 \times 10^{-12}$ |
| $\mu^-\mathrm{Ti} \to e^-\mathrm{Ti}$ | $< 1.7 \times 10^{-12}$ |
| $\mu^-\mathrm{Au} \to e^-\mathrm{Au}$ | $< 7 \times 10^{-13}$ |
| $\mu^+e^- \to \mu^-e^+$ | $< 3.0 \times 10^{-13}$ |
| $\tau \to e\gamma$ | $< 3.3 \times 10^{-8}$ |
| $\tau^- \to \mu\gamma$ | $< 4.4 \times 10^{-8}$ |
| $\tau^- \to e^-e^+e^-$ | $< 2.7 \times 10^{-8}$ |
| $\tau^- \to \mu^-\mu^+\mu^-$ | $< 2.1 \times 10^{-8}$ |
| $\tau^- \to e^-\mu^+\mu^-$ | $< 2.7 \times 10^{-8}$ |
| $\tau^- \to \mu^-e^+e^-$ | $< 1.8 \times 10^{-8}$ |
| $\tau^- \to e^+\mu^-\mu^-$ | $< 1.7 \times 10^{-8}$ |
| $\tau^- \to \mu^+e^-e^-$ | $< 1.5 \times 10^{-8}$ |

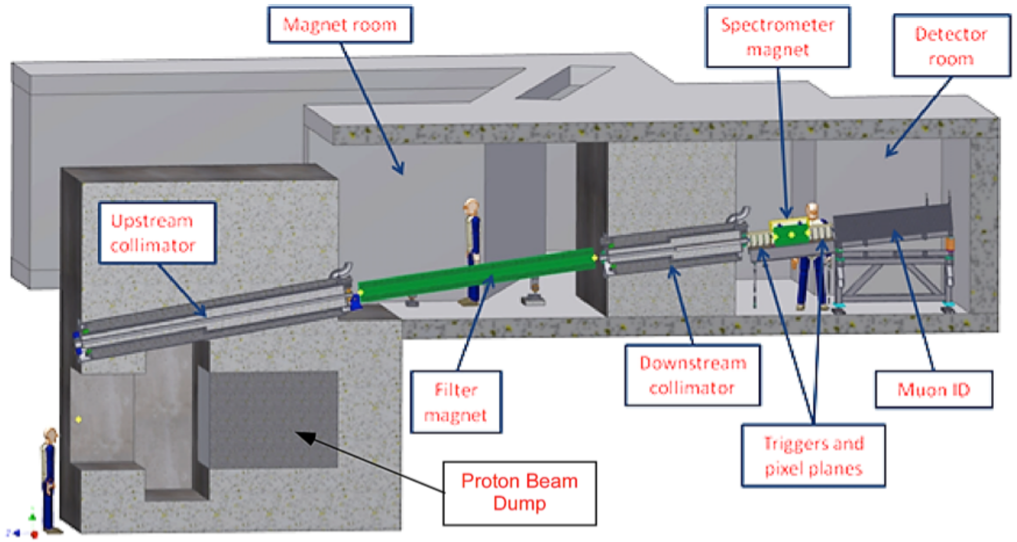
# CLFV limits 2

| **Process** | **Upper limit** |
| --- | --- |
| $\pi^0 \to \mu e$ | $< 8.6 \times 10^{-9}$ |
| $\mathrm{K_L^0} \to \mu e$ | $< 4.7 \times 10^{-12}$ |
| $\mathrm{K}^+ \to \pi^+ \mu^+ e^-$ | $< 2.1 \times 10^{-10}$ |
| $\mathrm{K_L^0} \to \pi^0 \mu^+ e^-$ | $< 4.4 \times 10^{-10}$ |
| $\mathrm{Z}^0 \to \mu e$ | $< 1.7 \times 10^{-6}$ |
| $\mathrm{Z}^0 \to \tau e$ | $< 9.8 \times 10^{-6}$ |
| $\mathrm{Z}^0 \to \tau \mu$ | $< 1.2 \times 10^{-6}$ |

# Out-of-time protons

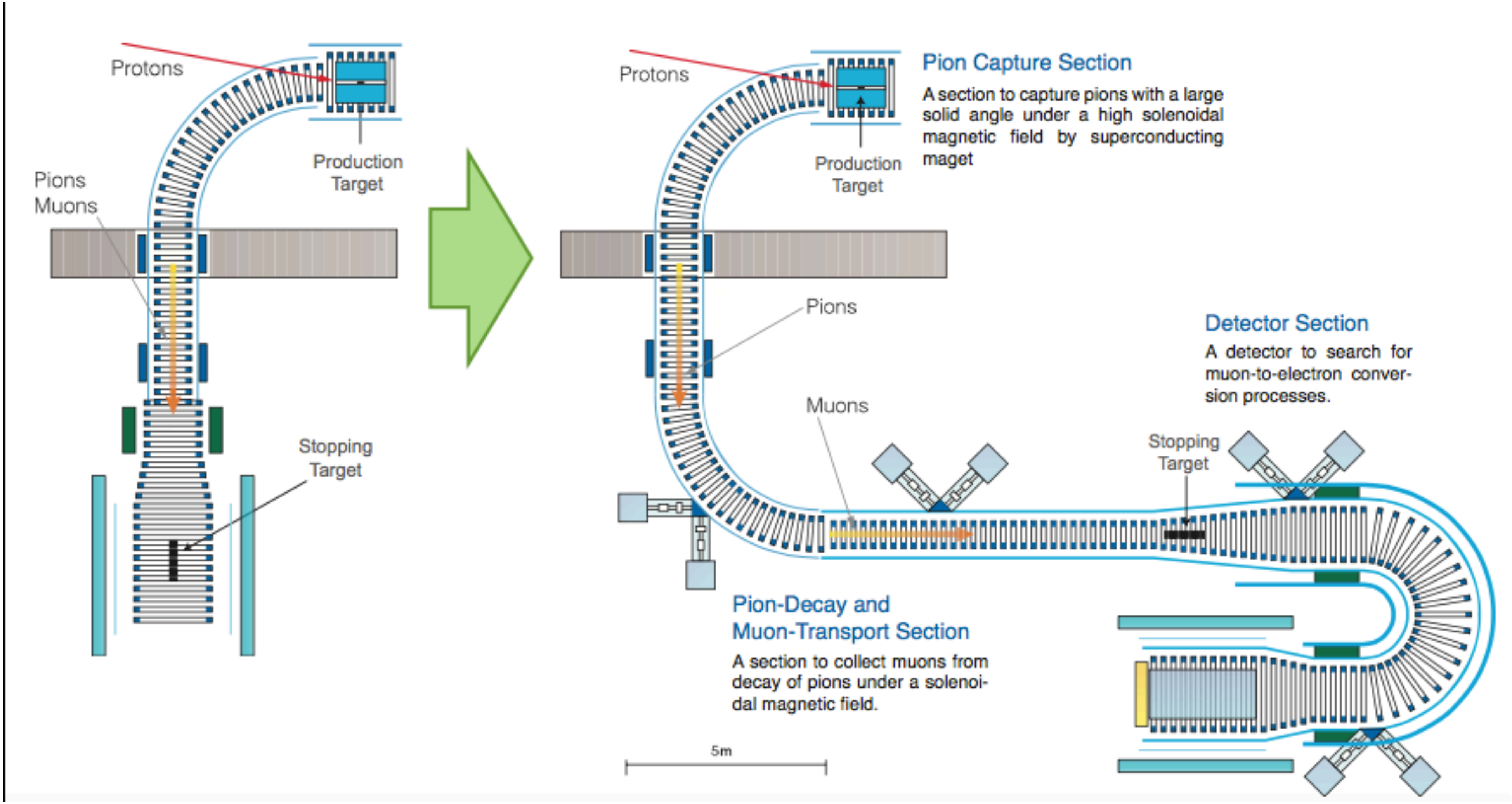
- The RF structure of the Recycler provides some "intrinsic" extinction:
  - ✓ **Intrinsic extinction ~$10^{-5}$**
- A custom-made AC dipole placed just upstream of the production solenoid provides additional extinction:
  - ✓ **AC dipole extinction ~ $10^{-6}$ - $10^{-7}$**
- Together they provide a total extinction:
  - ✓ **Total extinction ~ $10^{-11}$ - $10^{-12}$**

- Extinction measured using a detector system: Si-pixel + sampling EMC



# COMET experiment

**phase I** **phase II**



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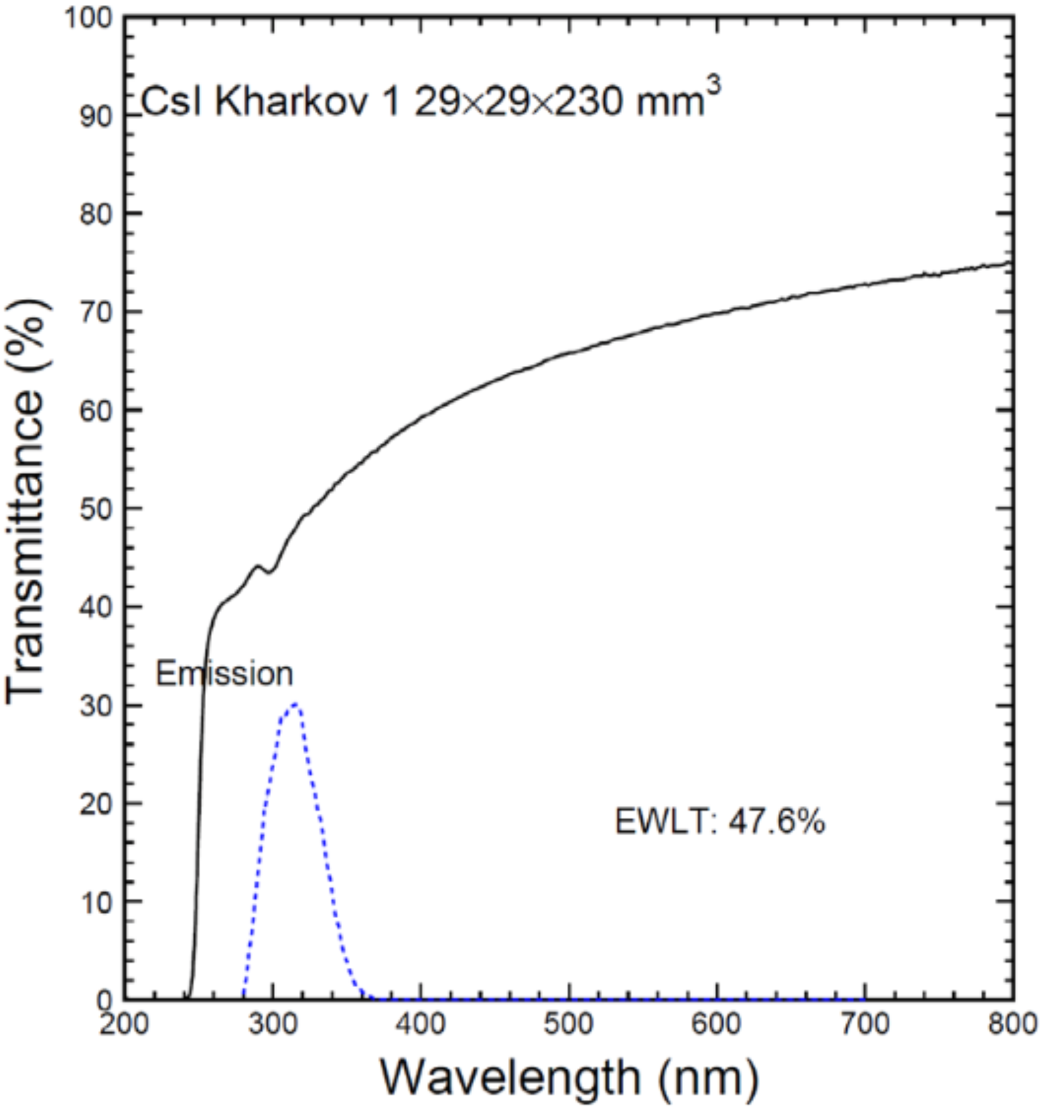
# calorimeter

# Crystals properties

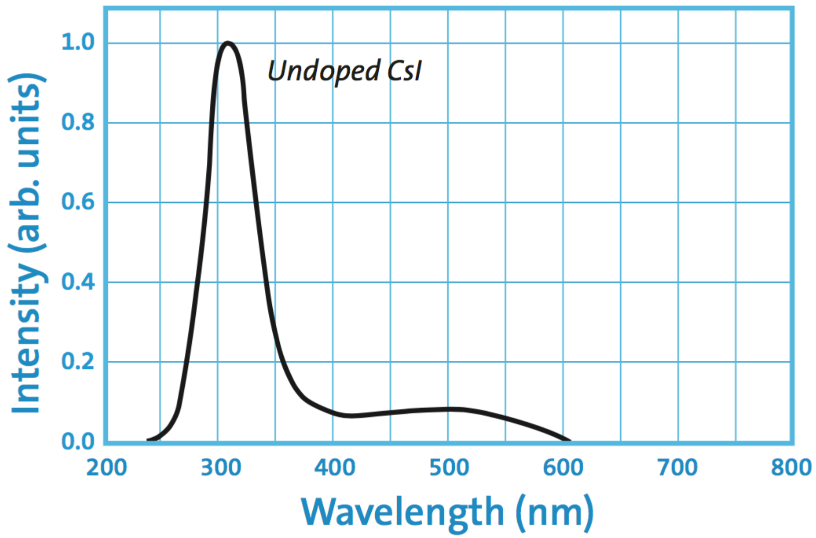
| **Crystal** | **$BaF_2$** | **LYSO** | **CsI** |
|---|---|---|---|
| Density [$g/cm^3$] | 4.89 | 7.28 | 4.51 |
| Radiation length [cm] $X_0$ | 2.03 | 1.14 | 1.86 |
| Molière radius [cm] $R_m$ | 3.10 | 2.07 | 3.57 |
| Interaction length [cm] | 30.7 | 20.9 | 39.3 |
| dE/dx [MeV/cm] | 6.5 | 10.0 | 5.56 |
| Refractive Index at $\lambda_{max}$ | 1.50 | 1.82 | 1.95 |
| Peak luminescence [nm] | 220, 300 | 402 | 310 |
| Decay time $\tau$ [ns] | 0.9, 650 | 40 | 16 |
| Light yield (compared to NaI(TI)) [%] | 4.1, 3.6 | 85 | 3.6 |
| Light yield variation with temperature [$\%/^\circ C$] | 0.1, -1.9 | -0.2 | -1.4 |
| Hygroscopicity | Slight | None | Slight |

# CsI properties

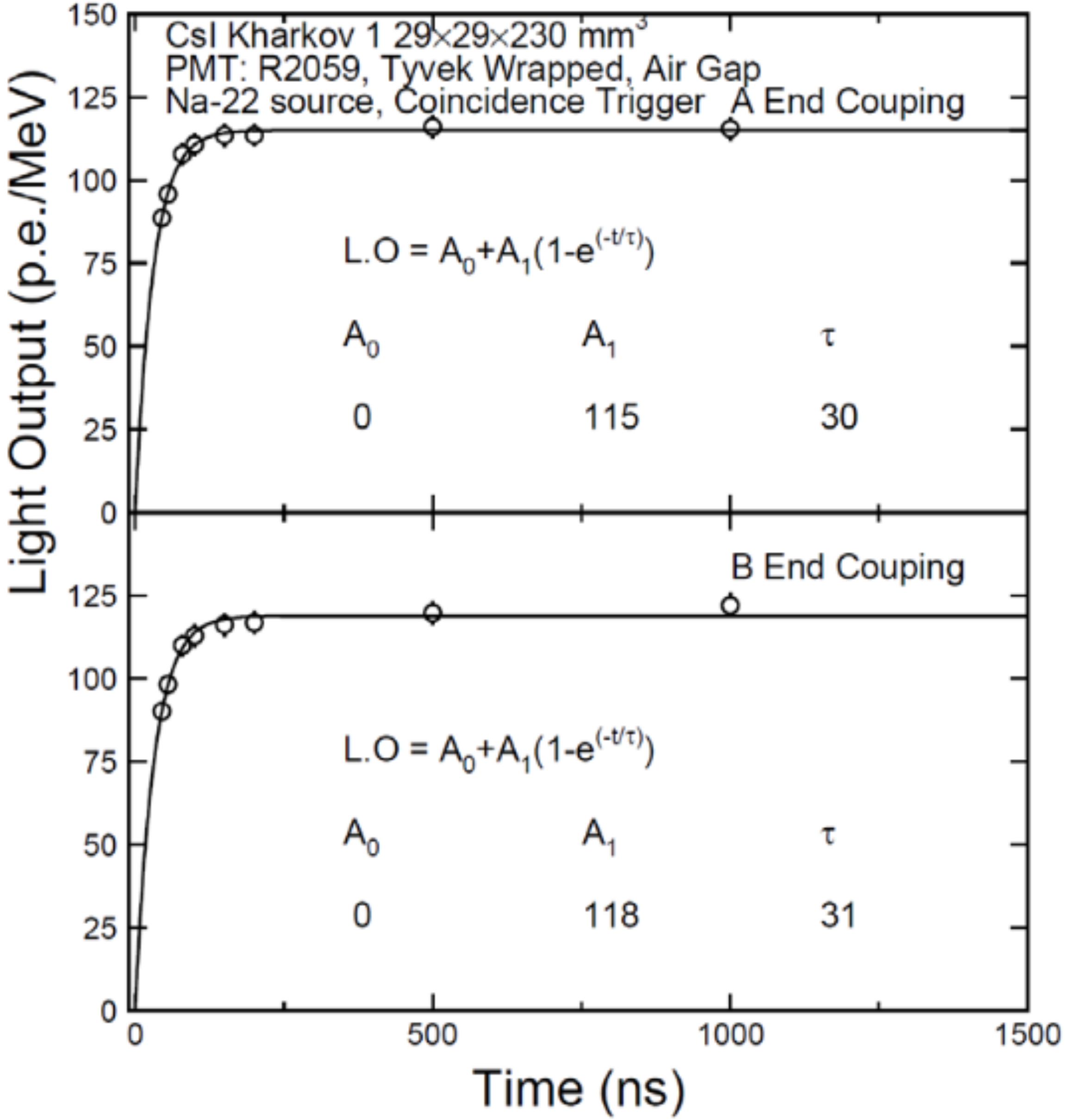



$$\mathrm{EWLT} = \frac{\int \mathrm{LT}(\lambda)\mathrm{Em}(\lambda)d\lambda}{\int \mathrm{Em}(\lambda)d\lambda}$$

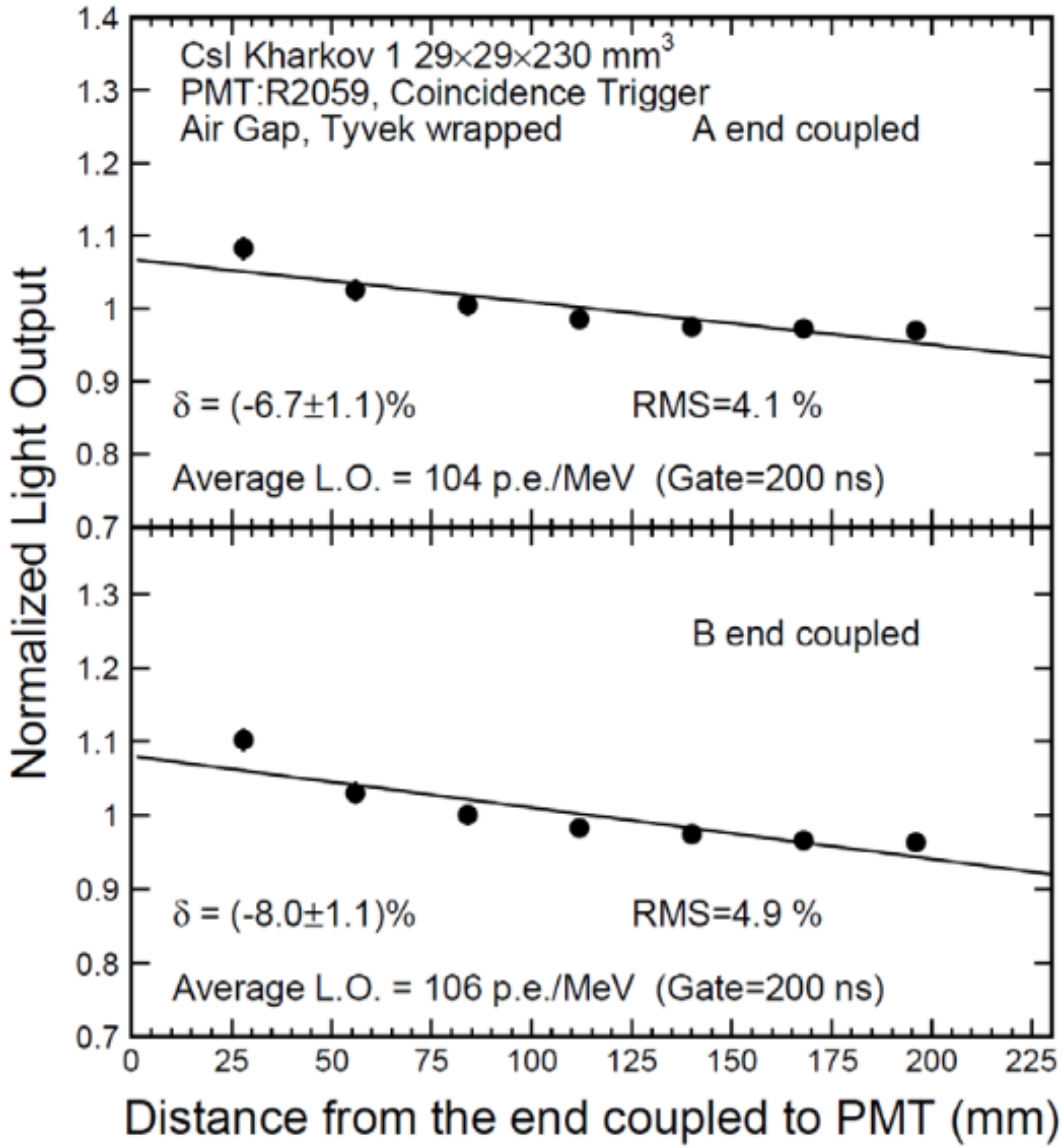
- where LT(λ) is the light transmittance and Em(λ) is the emission spectrum



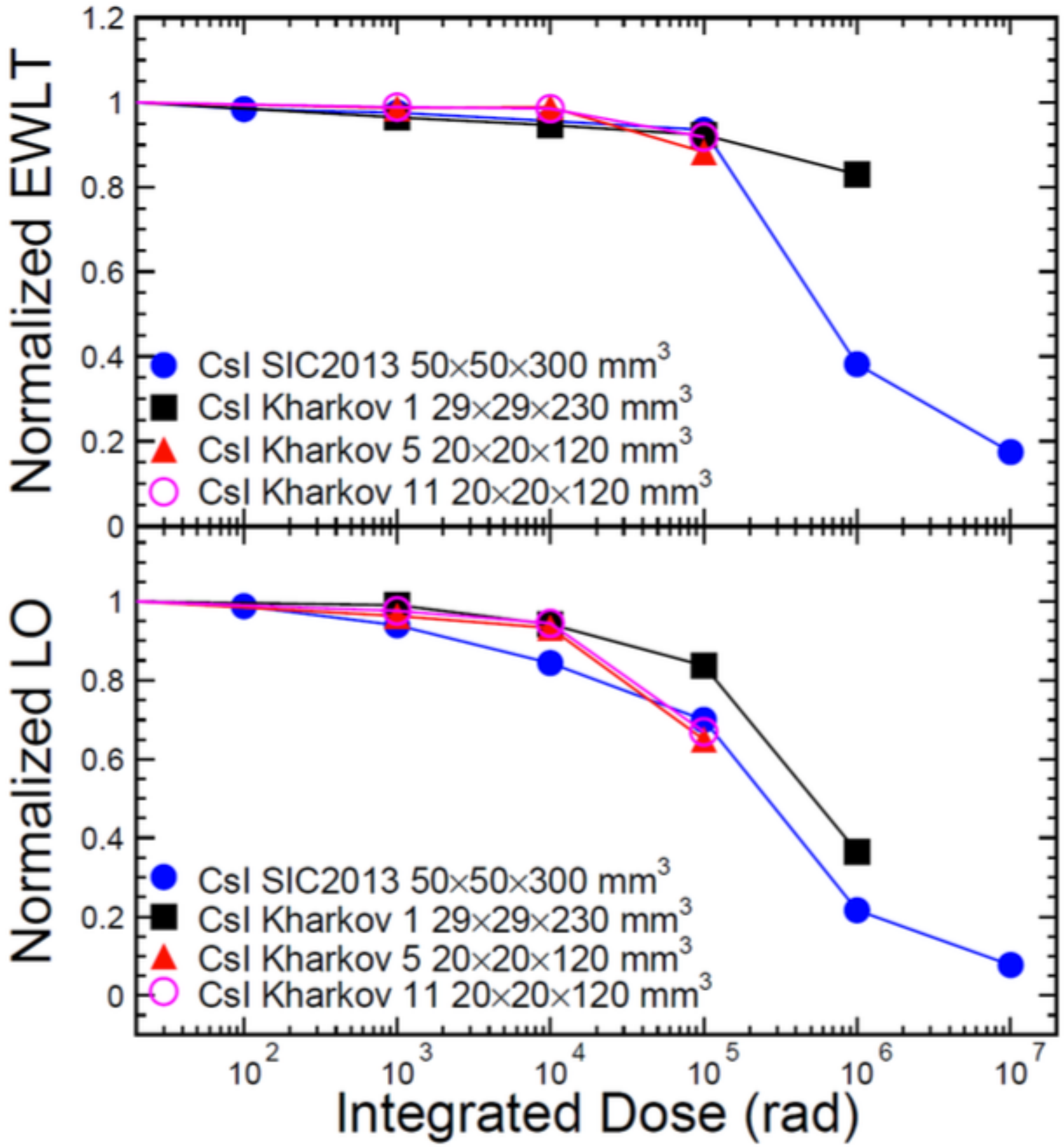
# CsI Light Output



# CsI LRU


CsI Kharkov 1 29×29×230 mm³
PMT:R2059, Coincidence Trigger
Air Gap, Tyvek wrapped
A end coupled
δ = (-6.7±1.1)%
RMS=4.1 %
Average L.O. = 104 p.e./MeV (Gate=200 ns)
B end coupled
δ = (-8.0±1.1)%
RMS=4.9 %
Average L.O. = 106 p.e./MeV (Gate=200 ns)
Normalized Light Output
Distance from the end coupled to PMT (mm)
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0
25
50
75
100
125
150
175
200
225

# CsI rad damage



# CsI neutron damage