Crystal calorimetry for cLFV

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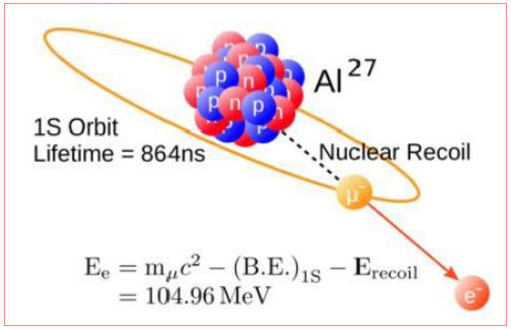
On behalf of the Mu2e Calorimeter group

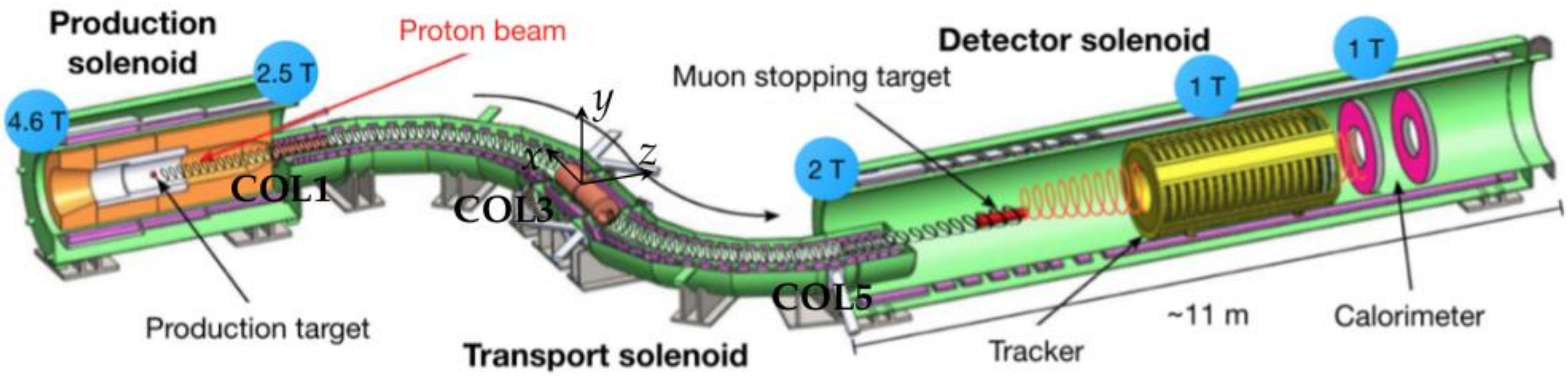
WIFAI 2024 – Bologna (Italy)
November 14, 2024

The Mu2e Experiment at Fermilab

Mu2e searches for **Charged Lepton Flavor Violation (CLFV)** via the coherent conversion:



$$\mu^- + Al \rightarrow e^- + Al$$



$$R_{\mu e} = \frac{\Gamma(\mu^- + N \rightarrow e^- + N)}{\Gamma(\mu^- + N \rightarrow \text{all captures})}$$

Current 90% CL limit:

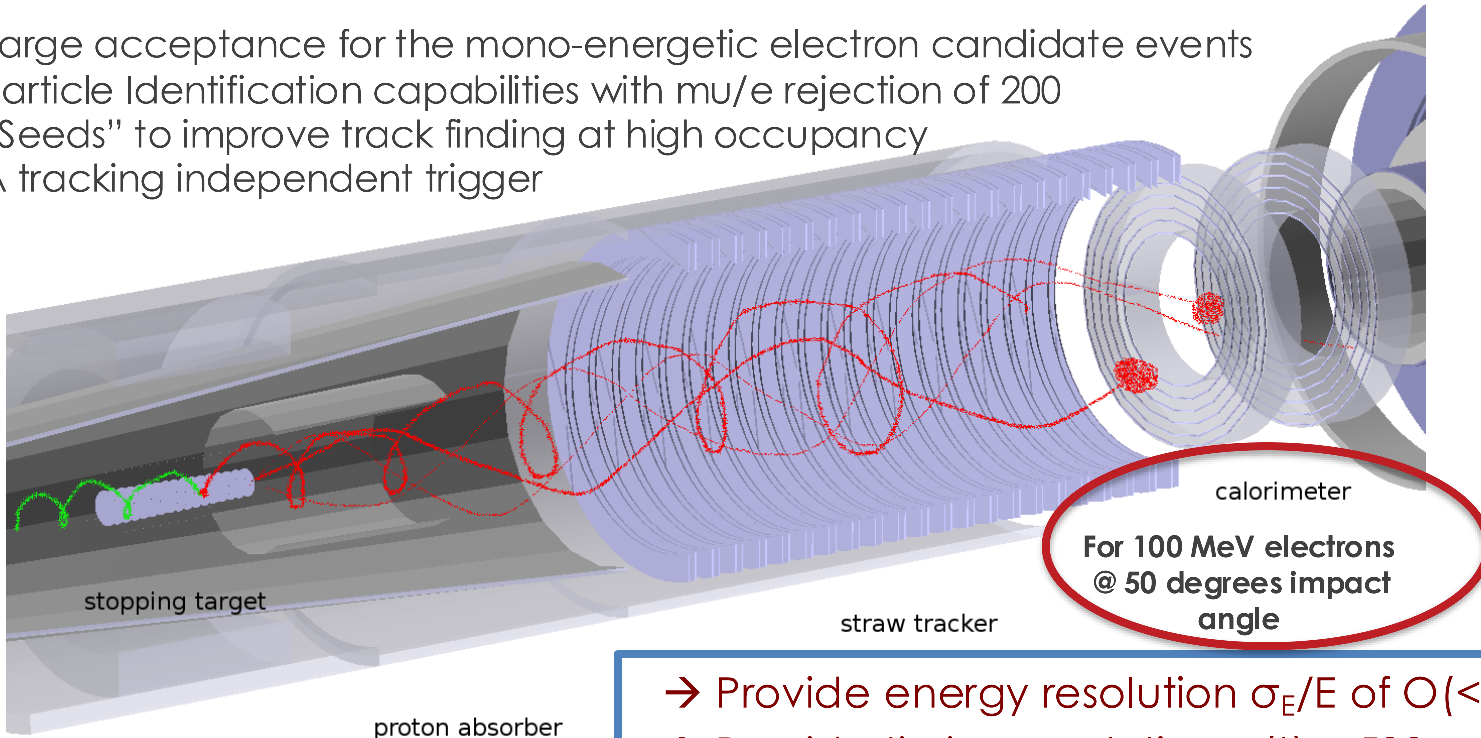
$R_{\mu e} < 7 \cdot 10^{-13}$ SINDRUM II (2006) Bertl et al. Eur.Phys.J.,C47,337

Mu2e goal: 5σ discovery or x10^4 limit improvement

Calorimeter Requirements

For the μ → e conversion search, the calorimeter adds redundancy and complementary qualities concerning the high-precision tracking system

- Large acceptance for the mono-energetic electron candidate events
- Particle Identification capabilities with mu/e rejection of 200
- “Seeds” to improve track finding at high occupancy
- A tracking independent trigger



- → Provide energy resolution σ_E/E of O(< 10 %)
- → Provide timing resolution σ(t) < 500 ps
- → Provide position resolution < 1 cm
- → **Work in vacuum @ 10^{-4} Torr and 1 T B-Field**
- → **Survive the harsh radiation environment**

Technological Choice

- Fast signal for Pileup and Timing:
  - **τ of emission < 40 ns**
  - Fast Digitization (WD) to disentangle signals in pileup
- Crystals with high Light Yield for timing/energy:
  - resolution → **LY(photosensors) > 20 pe/MeV**
- 2 photo-sensors/preamps/crystal for redundancy:
  - reduce MTTF requirement → **1 million hours/SIPM**

- Radiation Hardness (5 years of running with a safety factor 3):
  - Crystals should survive a TID of **90 krad** and a fluence of **$3\text{x}10^{12}$ n/cm²**
  - Photo-sensors should survive **45 krad** and a fluence of **$1.2\text{x}10^{12}$ n_1MeV/cm²**
- The 1 T magnetic field + the small space suggests → SiPMs

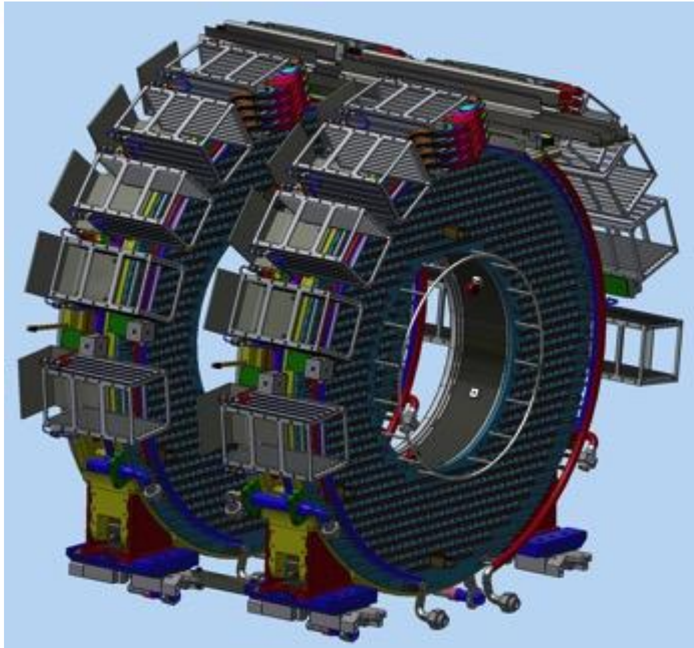
best compromise

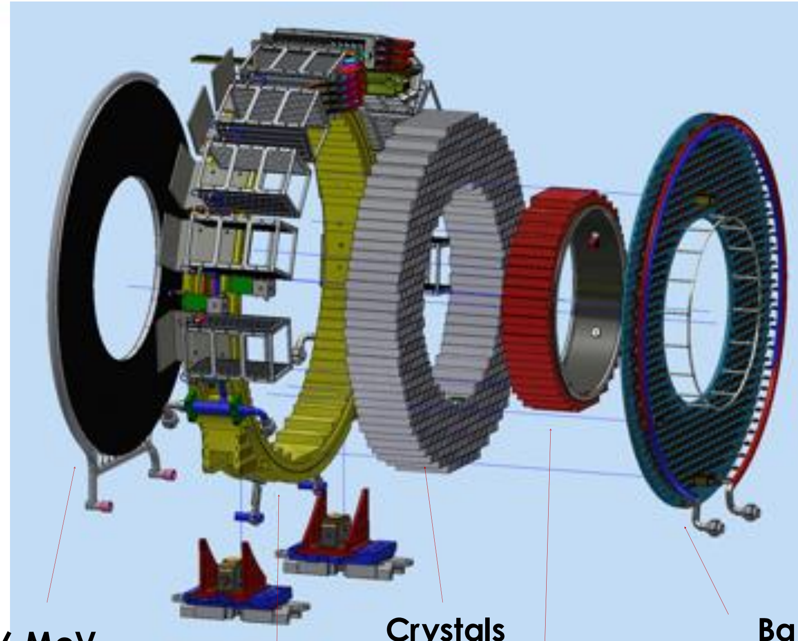
Undoped CsI + UV-extended SiPMs

Undoped CsI:
→ It is radiation hard
→ It has a fast emission time
→ Emits at 310 nm

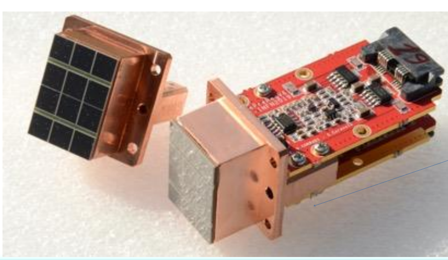
UV-extended SiPMs:
→ 30 % PDE @ 310 nm
→ New silicon resin window
→ TSV readout, Gain = 10^6

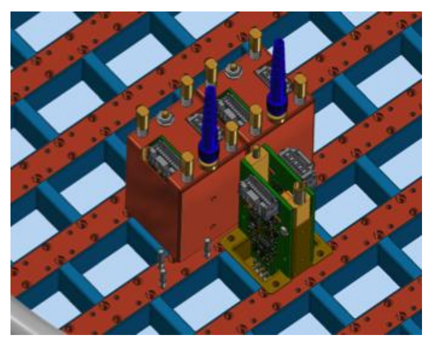
Mu2e e.m. Calorimeter

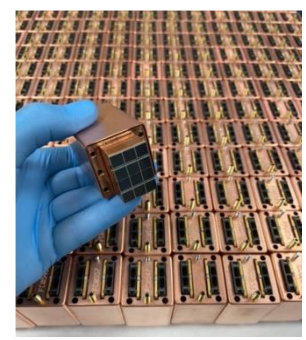




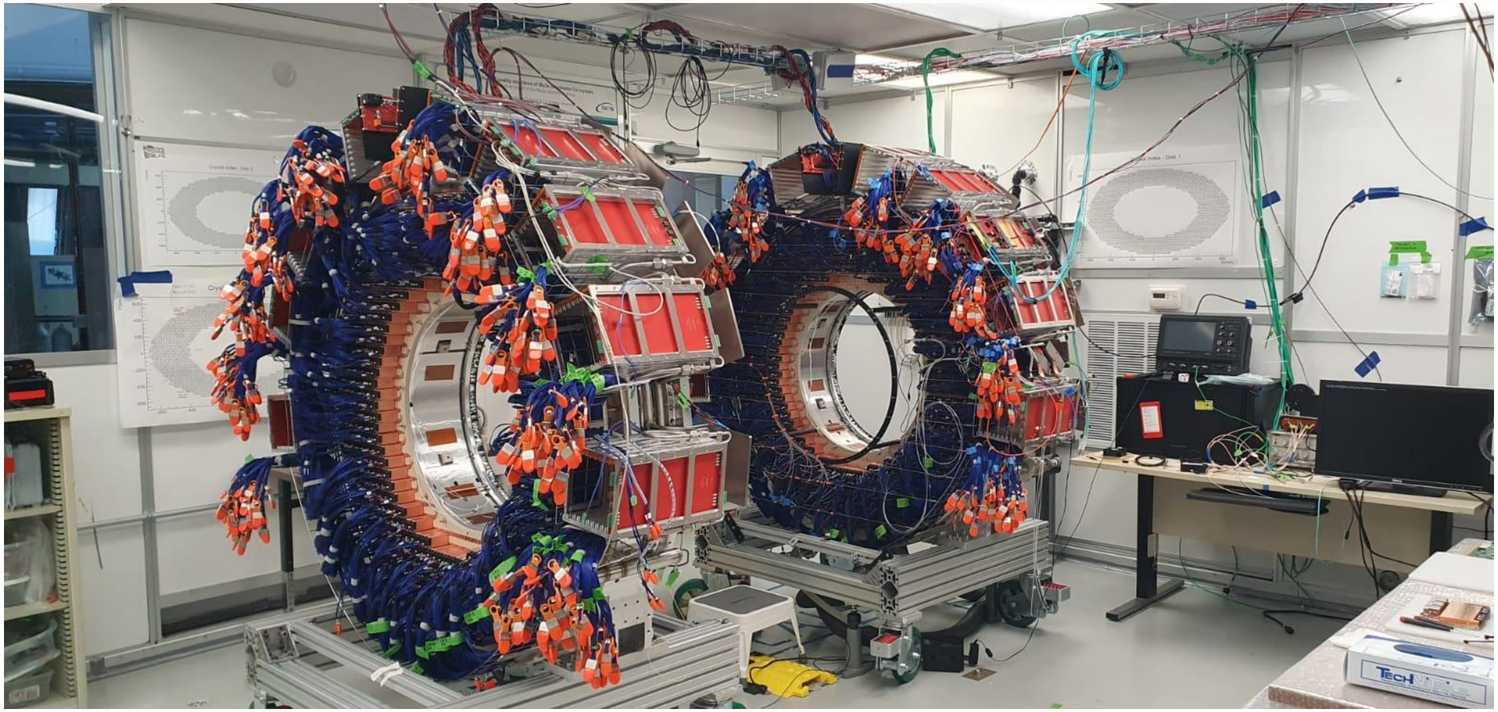
2 disks each consisting of
- 674 pure CsI crystals
- 1248 SiPMs+FEE boards







Calorimeter Disks status (91% complete)



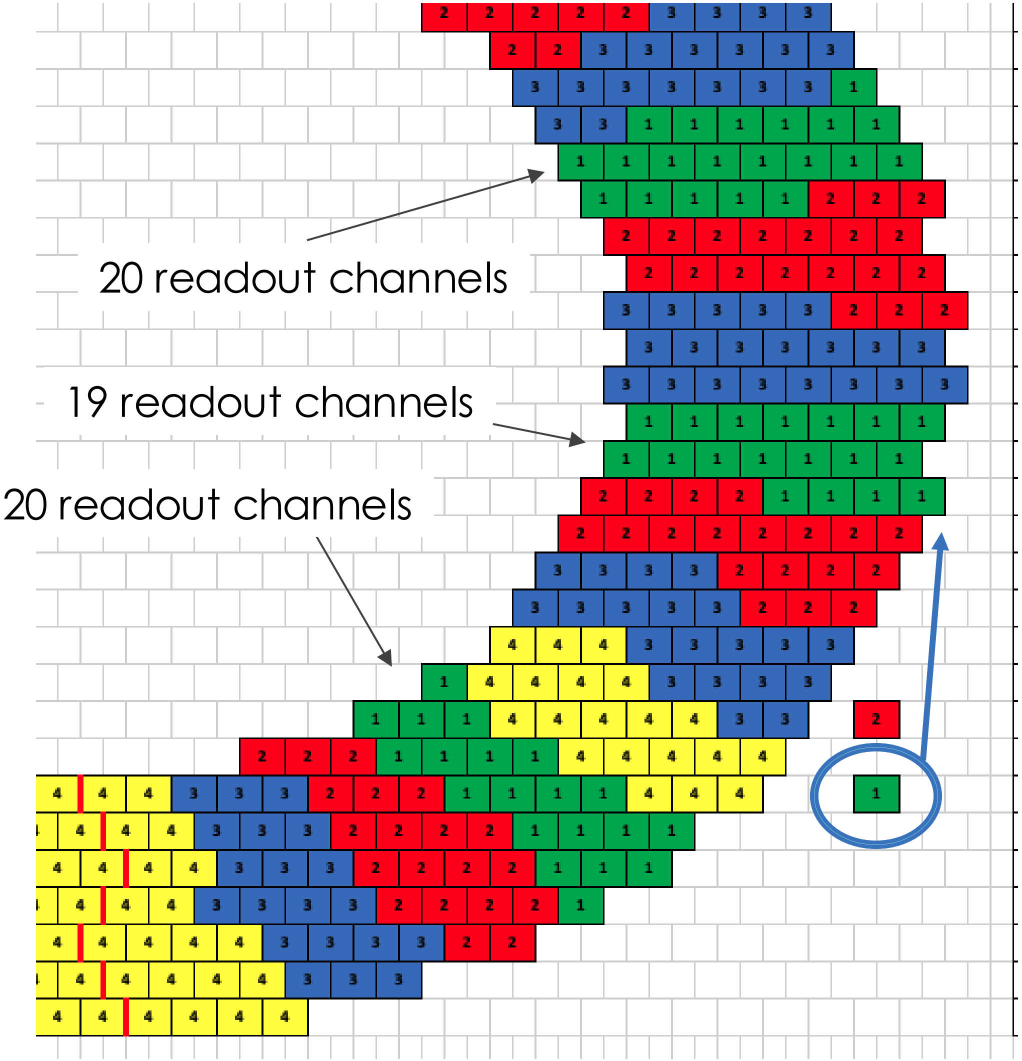
- Crystals and SiPMs+FEE readout units and electronics crates installed
- A quick leak test of the cooling system done
- Cable routing from FFE to crates completed
- All readout units tested with laser pulses

Next Activities in 2024/2025:

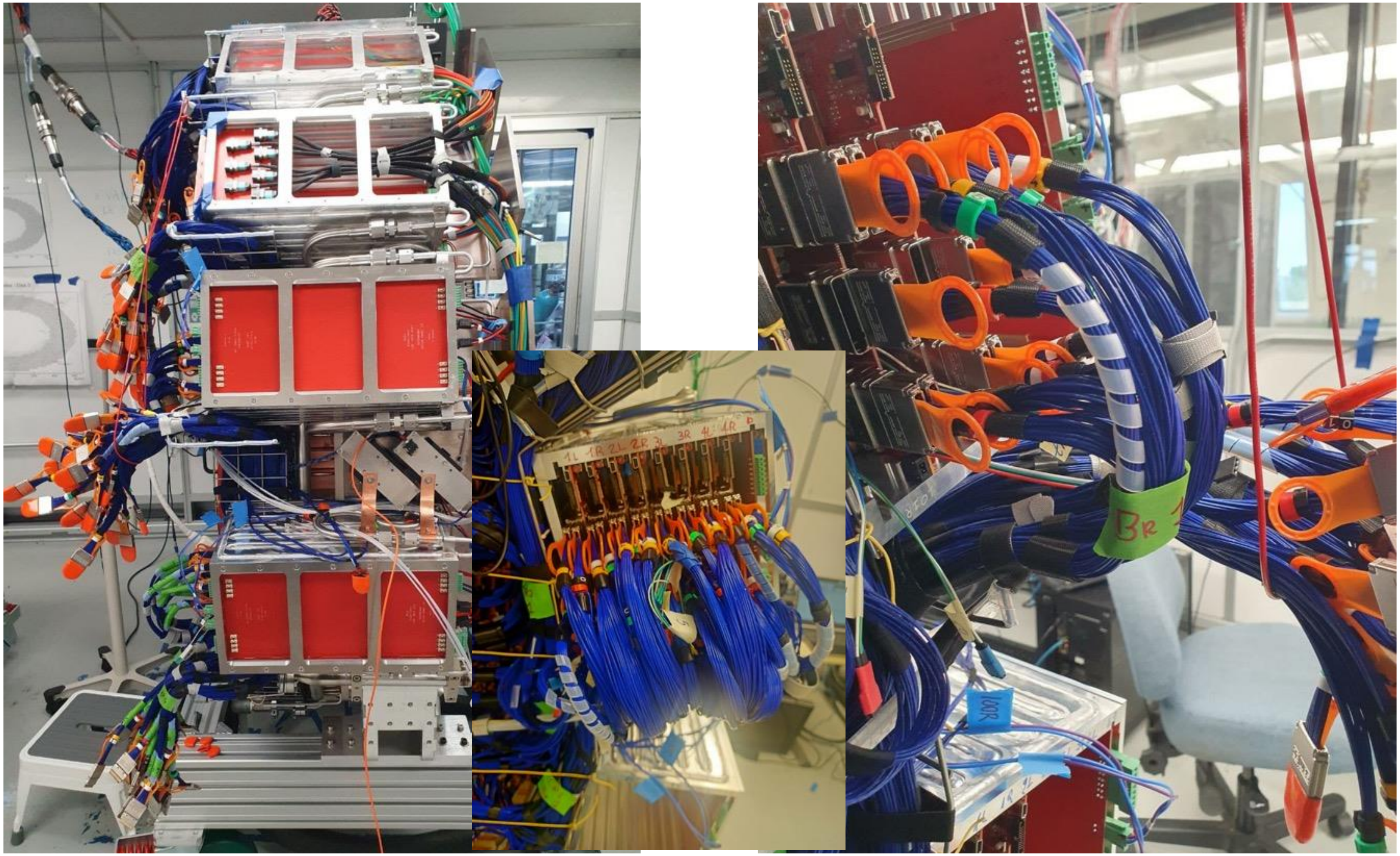
- Now: installing all electronics in crates
- Nov: run with cosmics (DAQ test)
- Dic: complete laser system
- Feb: move Disk 1 to Mu2e Hall

First calorimeter VST @ SiDet

- First data from six boards:
  - Disk 1, phi=1
  - Board 1 of Crates 0/1/2
  - Both SiPMs
- Few hours of running
- Nominal V_{op} setting loaded through configuration files
- Most of the data acquired with average FEE calibration
- Three V_{bias} configurations
- Cosmics, laser and noise runs

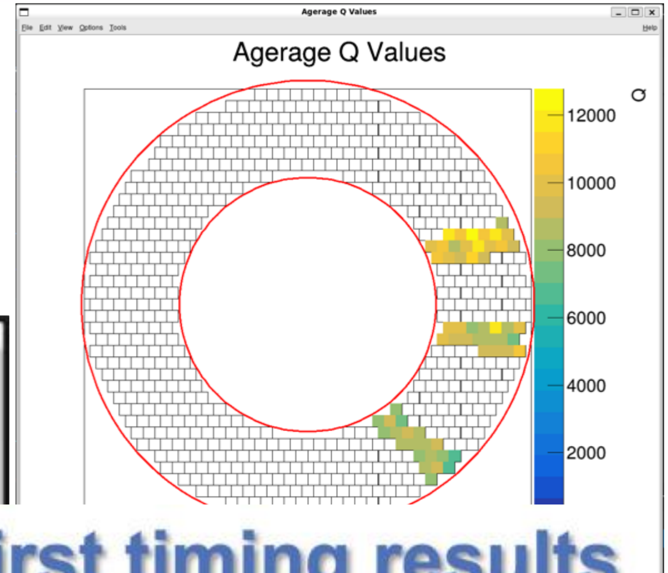


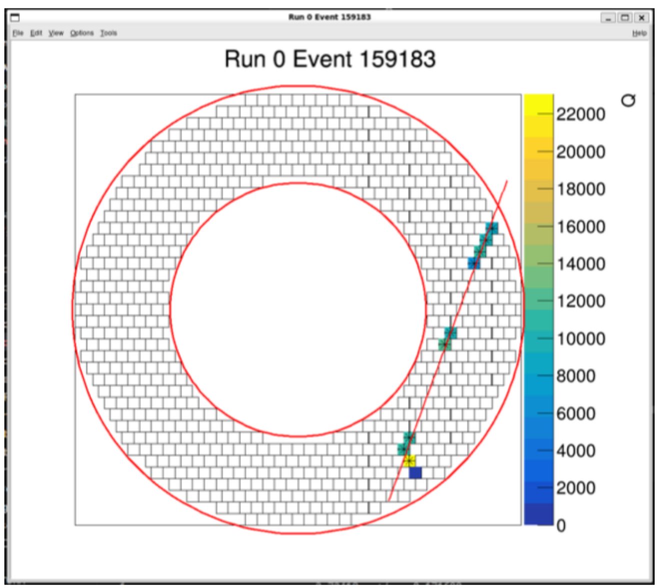
First boards insertion and connection

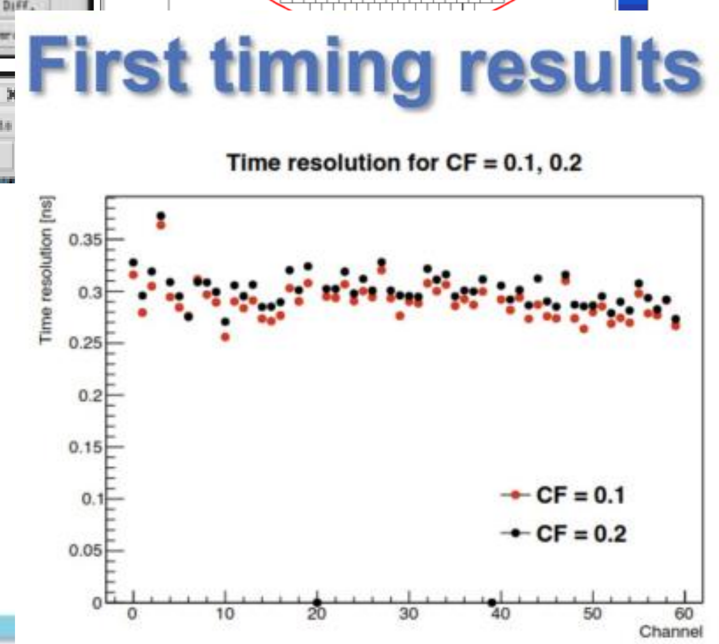


First Results

- PyROOT script working on reconstructed ntuples starting from SDF code
- Fitting hits above a threshold with a linear function
- Menus to select events, their topology and to display different quantities







A step in the future…

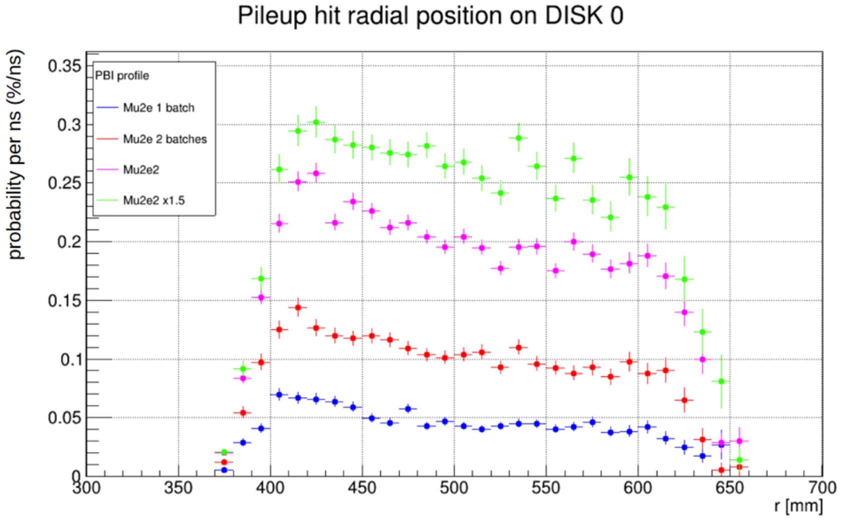
Mu2e → Mu2e-II
An order of magnitude improvement in the search sensitivity

Calorimeter Requirements (1/3)

Maintain the Mu2e-I requirement:

- We aim to same energy (< 10%) and time (< 500 ps) resolutions as in Mu2e.
- Aiming to provide standalone trigger, track seeding and PID as before.
- Work in vacuum @ 10^{-4} Torr, keep a low level of outgassing.

Face up to the higher rate, neutron flux and dose on Disks:



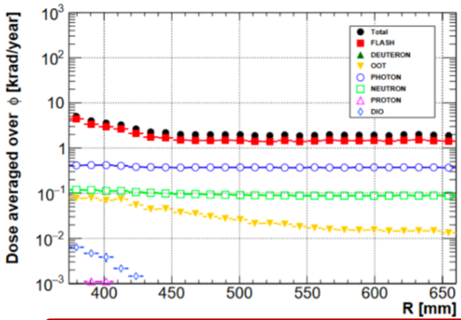
- **The pileup with respect to Conversion Electron seems to scale linearly with beam intensity**, so to keep the same level we have in Mu2e (15%) with 150 ns we need to rescale the new signals lenght:

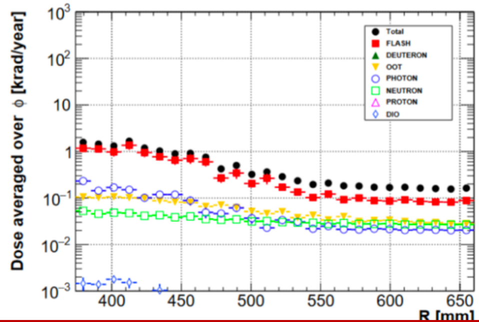
1. The length for Mu2e-II should be 75 ns (50 ns for 1.5 times Mu2e-II)

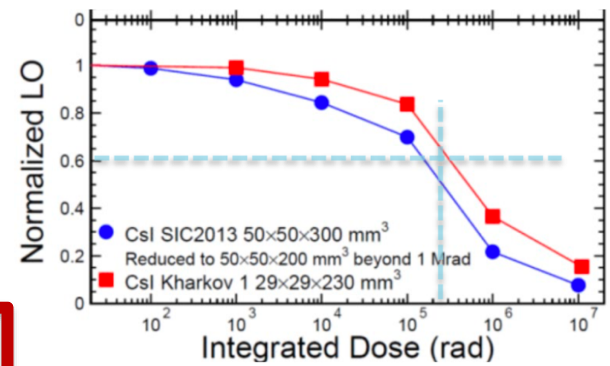
Pileup resolution in the waveform fit is still under study and can loose this requirement

Calorimeter Requirements (2/3)

- Under the **assumption** that the TID from the beam flash in the calorimeter from 800 MeV protons scales as the number of stopped muons wrt Mu2e 8 GeV beam, a **x10** is expected:



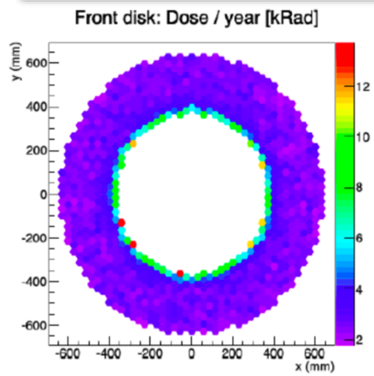




F. Yang, L. Zhang and R. -Y. Zhu, "Gamma-Ray Induced Radiation Damage Up to 340 Mrad in Various Scintillation Crystals," in *IEEE Transactions on Nuclear Science*, vol. 63, no. 2, pp. 612-619, April 2016, doi: 10.1109/TNS.2015.2505721.

TID req = simulated TID x3 Safety Factor, x3 yrs, x10 Mu2-II

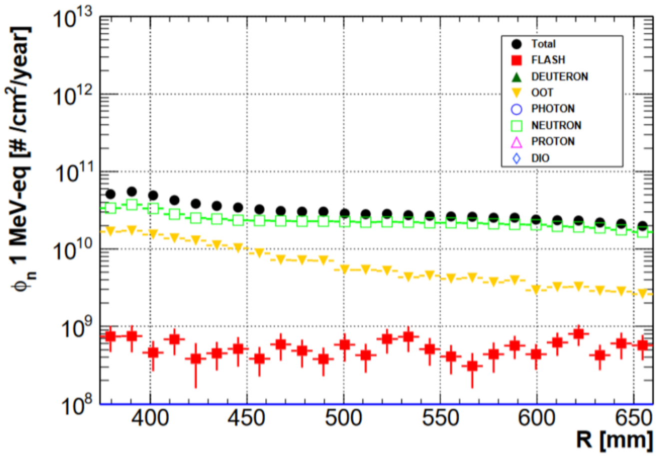
- R < 47 cm -> **600 krad**	- R < 55 cm -> **160 krad**
- R > 47 cm -> **180 krad**	- R > 52 cm -> **50 krad**

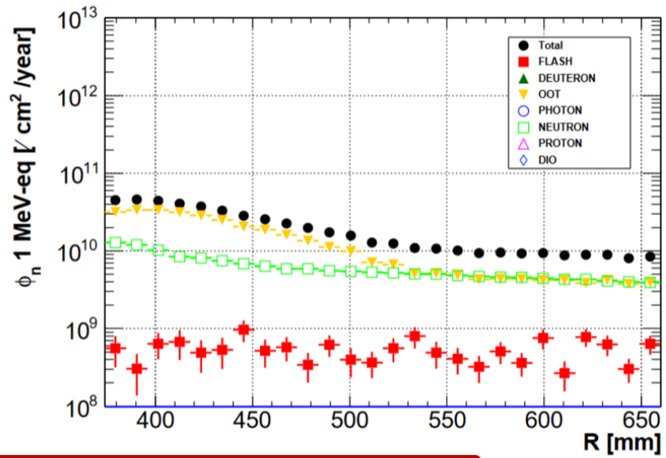


- Mu2e QA requirement for TID was a **LO after 100 krad > 60%**
  - The requirements on light collection was 30 p.e./MeV
- Dedicated simulation of the new beam flash and upgraded detectors materials are required to determine exact numbers, but so far wrt TID:
  - Disk 1 crystals should survive the new radiation level (??)
  - Disk 0 outer crystals should be in the same situation of disk 1 inner (??)
  - **Disk 0 inner crystals must be changed** -> BaF2, LYSO (??)

Calorimeter Requirements (3/3)

- Neutrons comes mainly from muonic atom decays, so a **x10 factor** wrt Mu2e is expected





1MeV-eq n Fluence = simulated Fluence x3 Safety Factor, x3 yrs, x10 Mu2-II

5.4 X 10^12 n/cm^2

- The **dark current value after the neutron damage** is expected to be of the order of tens of mA, mitigable (??) with decrease of breakdown voltage or lowering the operational temperature (-40 C?)
  - We need to substitute the majority (or all) the photosensors -> more rad hard sipm? solar blind?
- Other than the dark current increase related to neutrons we need also to consider the new Radiation Induced Noise (RIN) level

Mu2e-II ECAL:

- BaF2 Yttrium doped crystals
- Solar Blind delta-doped FBK SiPM

→ efforts to reduce the slow component working on

Crystals

Photo-sensors

Crystals (1/3)

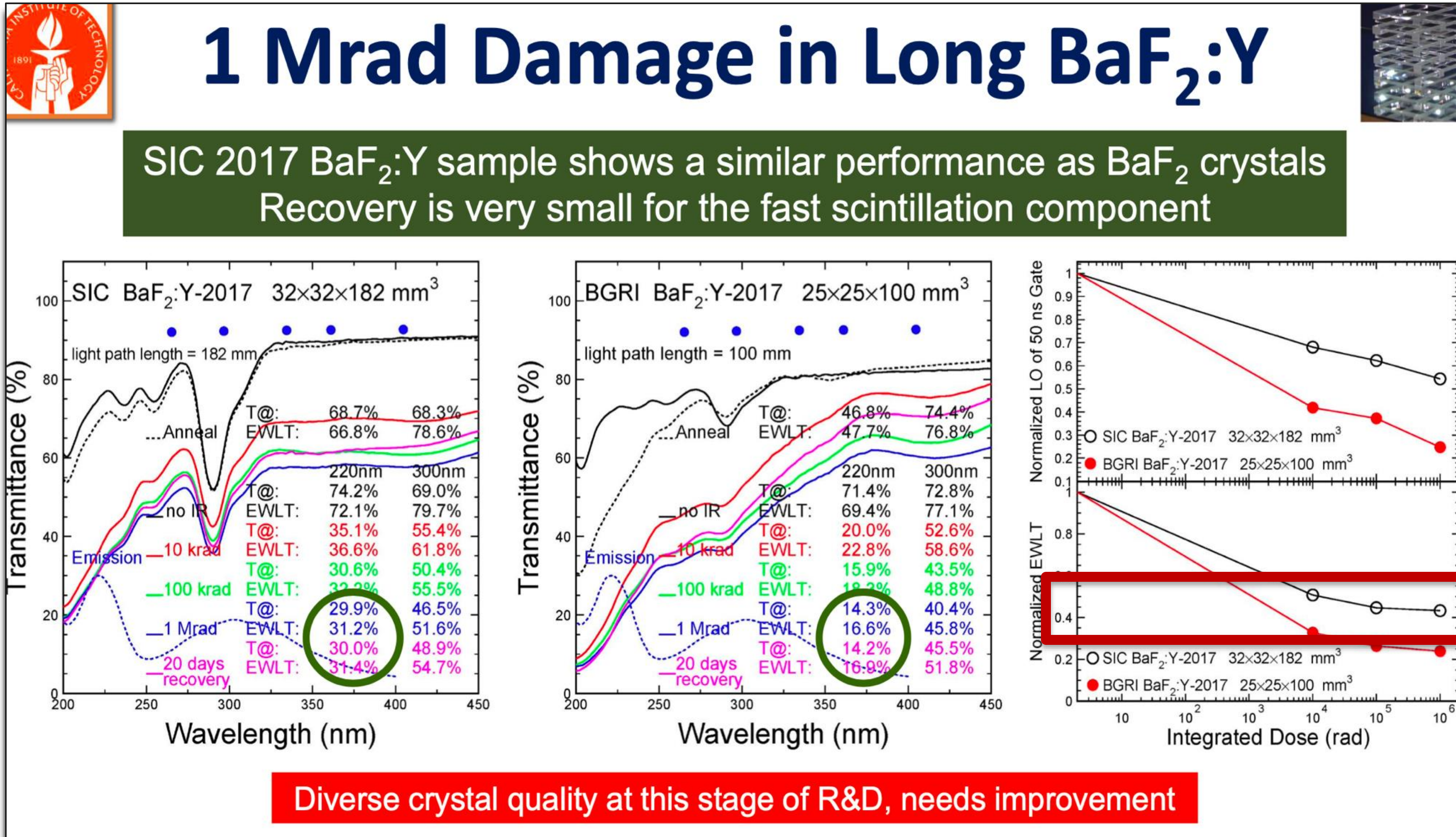
Fast/Ultrafast for HEP TOF & X-ray Imaging

arXiv: 2203.06788

	BaF_2	BaF_2:Y	Lu_2O_3:Yb	YAP:Yb	YAG:Yb	ZnO:Ga	β-Ga_2O_3	LYSO:Ce	LuAG:Ce	YAP:Ce	GAGG:Ce	LuYAP:Ce	YSO:Ce
Density (g/cm^3)	4.89	4.89	9.42	5.35	4.56	5.67	5.94	7.4	6.76	5.35	6.5	7.2[f]	4.44
Melting points (°C)	1280	1280	2490	1870	1940	1975	1725	2050	2060	1870	1850	1930	2070
X_0 (cm)	2.03	2.03	0.81	2.59	3.53	2.51	2.51	1.14	1.45	2.59	1.63	1.37	3.10
R_M (cm)	3.1	3.1	1.72	2.45	2.76	2.28	2.20	2.07	2.15	2.45	2.20	2.01	2.93
λ_I (cm)	30.7	30.7	18.1	23.1	25.2	22.2	20.9	20.9	20.6	23.1	21.5	19.5	27.8
Z_{eff}	51.0	51.0	67.3	32.8	29.3	27.7	27.8	63.7	58.7	32.8	50.6	57.1	32.8
dE/dX (MeV/cm)	6.52	6.52	11.6	7.91	7.01	8.34	8.82	9.55	9.22	7.91	8.96	9.82	6.57
λ_{peak} [a] (nm)	300 220	300 220	370	350	350	380	380	420	520	370	540	385	420
Refractive Index[b]	1.50	1.50	2.0	1.96	1.87	2.1	1.97	1.82	1.84	1.96	1.92	1.94	1.78
Normalized Light Yield[a,c]	42 4.8	1.7 4.8	0.95	0.19[d]	0.36[d]	2.6[d] 4.0[d]	6.5 0.5	100	35[e] 48[e]	9 32	190	16 15	80
Total Light yield (ph/MeV)	13,000	2,000	280	57[d]	110[d]	2,000[d]	2,100	30,000	25,000[e]	12,000	58,000	10,000	24,000
Decay time[a] (ns)	600 0.5	600 0.5	1.1[d]	1.1[d]	1.8[d]	3.0[d] 1.0[d]	110 5.3	40	820 50	191 25	570 130	1485 36	75
LY in 1st ns (photons/MeV)	1200	1200	170	34[d]	46[d]	980[d]	43	740	240	391	400	125	318
LY in 1st ns /Total LY (%)	9.0	64	60	60	43	49	2.0	2.5	1.2	3.3	0.7	1.4	1.3
40 keV Att. Leng. (1/e, mm)	0.106	0.106	0.127	0.314	0.439	0.407	0.394	0.185	0.251	0.314	0.319	0.214	0.334

[a] top/bottom row: slow/fast component; [b] at the emission peak; [c] normalized to LYSO:Ce; [d] excited by Alpha particles; [e] 0.3 Mg at% co-doping; [f] $Lu_{0.7}Y_{0.3}AlO_3$:Ce.

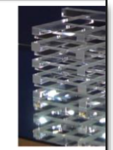
Crystals (2/3)



1 Mrad Damage in Long BaF2:Y
SIC 2017 BaF2:Y sample shows a similar performance as BaF2 crystals
Recovery is very small for the fast scintillation component
SIC BaF2:Y-2017 32×32×182 mm3
light path length = 182 mm
Anneal
no IR
10 krad
100 krad
1 Mrad
20 days recovery
Emission
T@: 68.7% 68.3%
EWLT: 66.8% 78.6%
220nm 300nm
T@: 74.2% 69.0%
EWLT: 72.1% 79.7%
T@: 35.1% 55.4%
EWLT: 36.6% 61.8%
T@: 30.6% 50.4%
EWLT: 55.5%
T@: 29.9% 46.5%
EWLT: 31.2% 51.6%
T@: 30.0% 48.9%
EWLT: 31.4% 54.7%
Transmittance (%)
Wavelength (nm)
BGRI BaF2:Y-2017 25×25×100 mm3
light path length = 100 mm
T@: 46.8% 74.4%
EWLT: 47.7% 76.8%
220nm 300nm
T@: 71.4% 72.8%
EWLT: 69.4% 77.1%
T@: 20.0% 52.6%
EWLT: 22.8% 58.6%
T@: 15.9% 43.5%
EWLT: 48.8%
T@: 14.3% 40.4%
EWLT: 16.6% 45.8%
T@: 14.2% 45.5%
EWLT: 16.9% 51.8%
Normalized LO of 50 ns Gate
Normalized EWLT
SIC BaF2:Y-2017 32×32×182 mm3
BGRI BaF2:Y-2017 25×25×100 mm3
Integrated Dose (rad)
Diverse crystal quality at this stage of R&D, needs improvement

Crystals (3/3)

SIC Mass-Produced Crystals (Mar 2019)



Scaling to X_0, order of crystal cost: PWO, BGO, CsI, BSO, BaF_2:Y, LYSO

Item	Size	1 m^3	10 m^3	100 m^3	Scaled to X_0
BGO	22.3×22.3×280 mm	$8/cc	$7/cc	$6/cc	1.23
BaF_2:Y	31.0×31.0×507.5 cm	$12/cc	$11/cc	$10/cc	2.28
LYSO:Ce	20.7x20.7x285 mm	$36/cc	$34/cc	$32/cc	1.28
PWO	20x20x223 mm	$9/cc	$8/cc	$7.5/cc	1.00
BSO	22x22x274 mm	$8.5/cc	$7.5/cc	$7.0/cc	1.29
CsI	35.7x35.7x465 mm	$4.6/cc	$4.3/cc	$4.0/cc	2.09

Photo-detectors

- A **large area SiPM**, with **delta-doping** (a super-lattice) for improved speed and QE, and an integrated ALD-applied **interference filter**
  → Caltech and JPL are working with FBK to incorporate a 220nm filter on a large area SiPM and to also incorporate a superlattice.

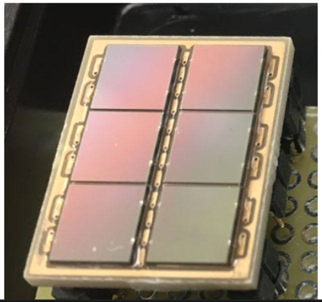
DONE
1. Build a three-layer ALD filter on a 6x6 mm NUV SiPM structure, exploring different SiNx passivation layers, guard ring structures, …
2. Fabricate 2x3 arrays of the 6x6 mm chips, biased in series parallel configuration à la MEG and Mu2e to read out larger crystals

Underway
3. Improve slow component rejection with more sophisticated five-layer filters – devices at Caltech, in queue for measurement/test
4. Use delta doping and backside illumination to improve PDE, the effectiveness of the filter, timing performance and UV tolerance

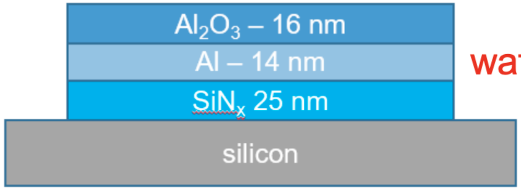
Underway
- First explore parameter space of MBE fab of delta-doping using diode structures of various sizes – wafers entering production

Not funded
- Fabricate back-illuminated SiPMs with a five-layer filter and delta-doping

Configuration is identical to that for Mu2e:

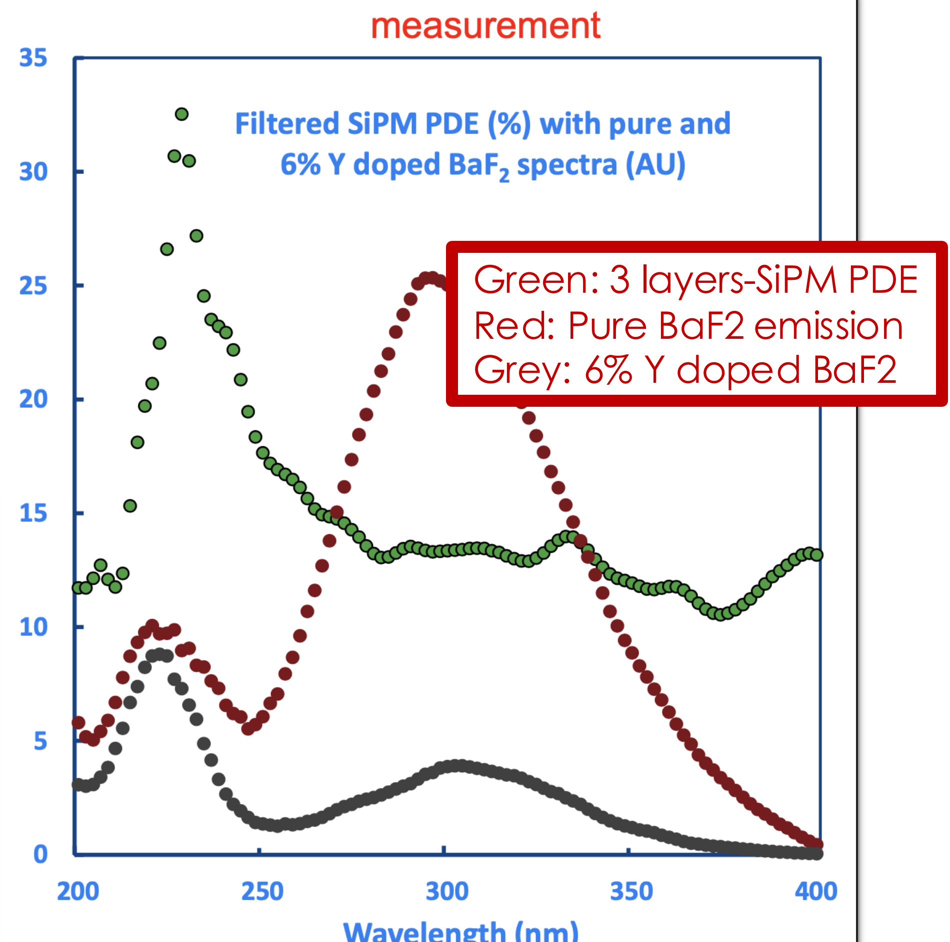


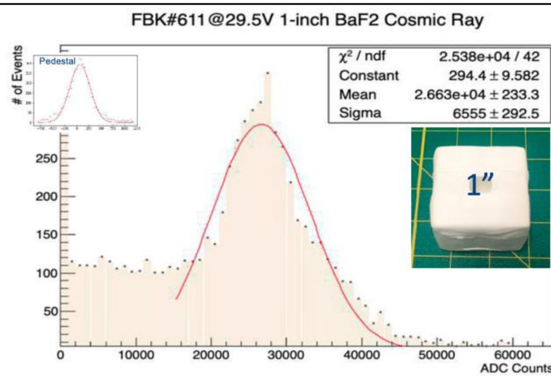
FBK SiPM with three-layer filter



wafer 11

PDE scanned *vs.* wavelength at several bias voltages, with gain measured

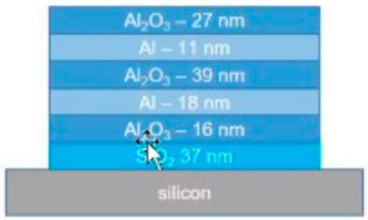




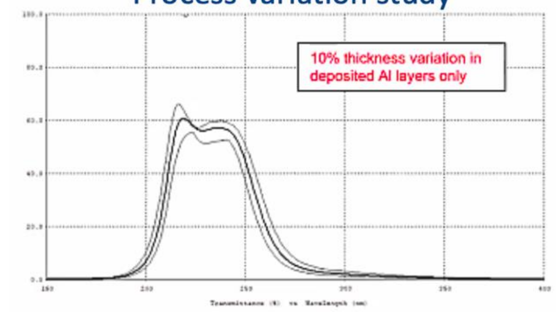
- FBK SiPM #611, dimension 6x6 mm, operated at 29.5V
- BaF_2 dimension 1” x 1” x 1”, wrapped with teflon with an opening of 6x6 (mm)
- Cosmic ray deposits 6.374 MeV/cm * 2.54 cm = 16.2 MeV
- (26631 - 68) adc / 148 pe/adc = 180 pe
- 180 pe / 16.2 MeV = 11 pe/MeV With 2x3 array, expect 60-70 pe/MeV

Next steps in the program

1) Optimization of the MBE superlattice layer parameters
2) More complex filters will be incorporated (5 layers filter)



Process variation study



3) Backside illuminated SiPM with optimized superlattice

Awaits funding ~ 400k$

Thoughts on Mu2e-II calo requirements - 1

Requirements
Crystals:
- Hardness to dose
- Moderate light yield for energy and timing resolution

Photosensors:
- Fast
- Good QE
- High radiation hardness

Are these two points compatible?

Short summary from Mu2e experience and Tech choices:
- pure CsI LY 4%(NaI),
- Ham UV-extended SiPMs 30% PDE(@310 nm, 50 μm pixel size)

  - LY~30 p.e./MeV (10% LY drop at 100 krad)
  - Cooling needs to reduce noise, -10 °C on SiPMs
  - 10^{12} neutrons/cm^2 total → ~ 1MeV noise level/crystal

Thoughts on Mu2e-II calo requirements - 2

Requirements

Crystals:

- Hardness to dose
- Moderate light yield for energy and timing resolution

Photosensors:

- Fast
- Good QE
- High radiation hardness

Are these two points compatible?

❑ In Mu2e-2, we expect x10 increase in n-flux up to 10^{13} n/cm^2 total

→ SiPM 50um pixel @ -30/-40 °C ???

→ *We must demonstrate that **Ham SiPMs with >15 μm pixel size can work at 10^{13} neutrons/cm^2***

→ ***We have to test as well FBK SiPMs*** (from Mu2e R&D: the FBK SiPMs radiation hardness is lower than Hamamatsu SiPMs)

Short LYso crystal calorimetER - SLYER -

ADVANTAGES

- **8 cm length LYSO** are enough to achieved O(5%) energy resolution
- Not problem of ENE and good LRU
- Great timing resolution still after 10^{13} neutrons/cm^2
- SiPMs already exist **NOT R&D needed**
- High LY → SiPM @ low over voltage → enhanced resistance → lower power dissipation
- Not Front-End Amplifier is needed → not problems with irradiation level

DISADVANTAGES

- LYSO ~30$/cc vs ~10$/cc BaF2
  (17$/cc vs **10$/cc for equal X0)**

IS the pile-up rate acceptable with LYSO?
We need simulation …

SLYER proposal:
Total cost of the LYSO crystals for the 2 disks = 3.8M$
(Mu2e: 20 cm CsI + FEE = 1.7M$ + 0.2M$)
(14 cm BaF2 + FEE = 2.2M$ + 0.2M$)

- *Emission time of 40 ns of LYSO vs <1 ns of BaF2*

SiPMs radiation hardness

15 μm

Temperature [°C]	V_{br} [V]	$I(V_{br}+4V)$ [mA]	$I(V_{br}+6V)$ [mA]	$I(V_{br}+8V)$ [mA]
-10 ± 1	75.29 ± 0.01	12.56 ± 0.01	30.45 ± 0.01	46.76 ± 0.01
-5 ± 1	75.81 ± 0.01	14.89 ± 0.01	32.12 ± 0.01	46.77 ± 0.01
0 ± 1	76.27 ± 0.01	17.38 ± 0.01	33.93 ± 0.01	47.47 ± 0.01

10 μm

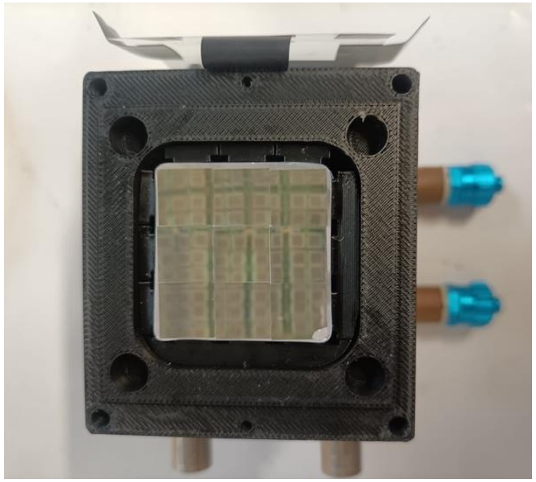
Temperature [°C]	V_{br} [V]	$I(V_{br}+4V)$ [mA]	$I(V_{br}+6V)$ [mA]	$I(V_{br}+8V)$ [mA]
-10 ± 1	76.76 ± 0.01	1.84 ± 0.01	6.82 ± 0.01	29.91 ± 0.01
-5 ± 1	77.23 ± 0.01	2.53 ± 0.01	9.66 ± 0.01	37.51 ± 0.01
0 ± 1	77.49 ± 0.01	2.99 ± 0.01	11.59 ± 0.01	38.48 ± 0.01

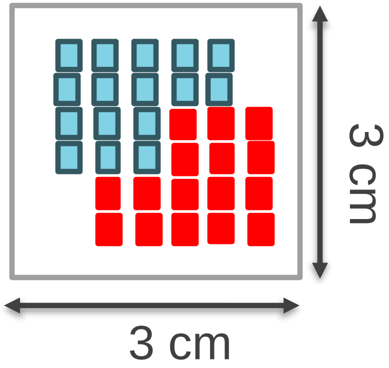
Neutrons irradiation: 14 MeV neutrons with a total fluence of 10^{14} n/cm^2 for 80 hours on a series of two SiPMs (10 and 15 μm)

At 10^{13} n_{1MeV}/cm^2:

- 10 μm pixel size OK, with Mu2e calorimeter cooling system
- 15 μm pixel size OK, probably with the Mu2e calorimeter cooling system → specific tests should be done

First tests of LYSO crystals with SiPM readout



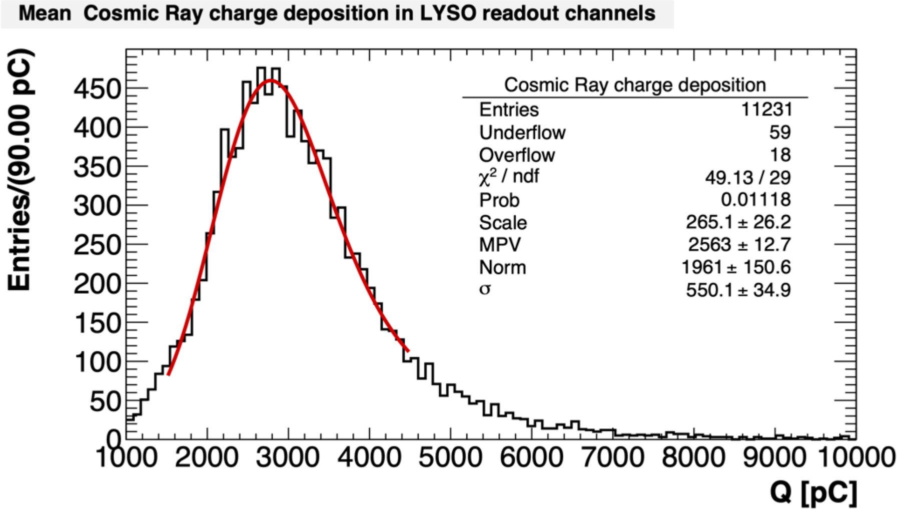


- **LYSO Crystals:**
  - Dimensions: 3x3x8 cm^3
  - Wrapped with ESR (Enhanced Specular Reflector)
  - No optical grease applied
- **Mu2e-II SIPMs:**
  - Configuration: Two new Mu2e SIPMs
  - Each SIPM comprises 16 SiPMs (3x3 mm^2) with a 10 μm pixel size
  - Equivalent to 4 SiPMs (6x6 mm^2) per channel
  - Area SiPM/Cry → 16% per SiPM
- **Readout and Acquisition:**
  - Individual readout of each SiPM
  - Acquired with Flash ADC CAEN V1742 at 2.5 Gs/s
- **Future Studies:**
  - Hamamatsu now offers 6x6 mm^2 SiPMs with a 10 μm pixel size
  - Future studies will utilize these new SiPMs directly

CR and Test Beam @ BTF

scale factor=0.0117 MeV/pC

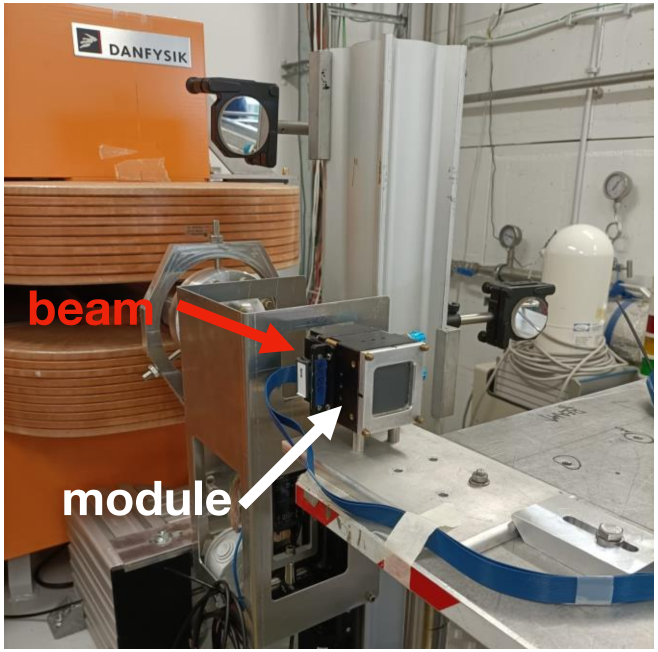
Npe/MeV ~ 300 p.e.



- TB carried out at LNF BTF using e^- beam with multiplicity 1

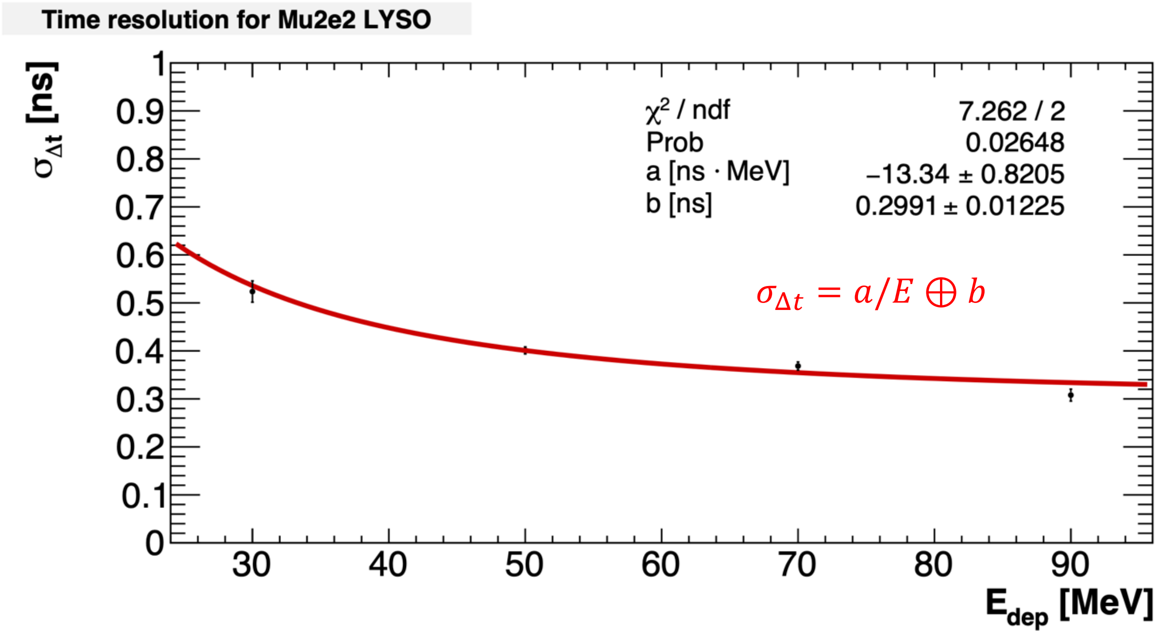
E = 100, 80, 60 MeV

- Beam impacted on the module's center



Timing Resolution

- **Waveform Summation:**
  - Difficulty in summing waveforms corresponding to each SiPM
- **Upcoming Test:**
  - Next test will be conducted directly in the Mu2e-like configuration
  - Configuration: Parallel of two series per channel



Summary

Even if the requirement about the energy [**σ_E/E of O(10 %)**] and time [**σ(t) < 500 ps**] resolution remain the same, a big part of the detector and all the electronics **can't survive** to the new radiation environment

- To run Mu2e-II a new technological solution (crystal + photosensor) for the calorimeter is needed
  - TID of about 600 krad and 1-MeV-eq n fluence of 5×10^{12}
  - Signals with an approximative length of 75 ns

Solar Blind SIPMs R&D should be concluded and tested the performances
- After neutron irradiation
- with BaF2:Y in a dedicated test beam

LYSO + 10 um pixels SiPMs is a reasonable possibility → but dedicated simulations are needed

SPARES

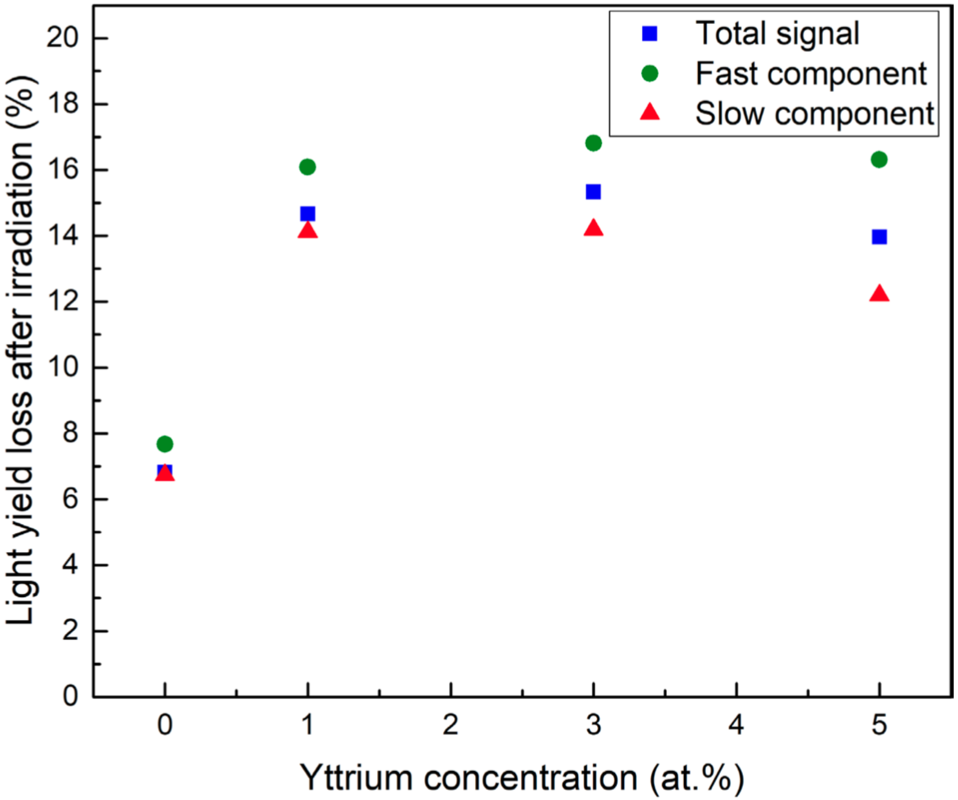
BaF2 Neutron Irradiation

For the first session of neutron irradiation, only four samples (1x1x1 cm^3) produced by SICCAS were selected: one pure BaF_2 crystal and three samples doped with yttrium in the proportion of 1 at.%Y, 3at.%Y and 5at.%Y

- All four samples were placed together about 5 m from the water moderator
- During the 14-day reactor cycle about 2.3×10^{14} n/cm^2 (E>1MeV) passed through the samples

  - All samples were measured before and after irradiation
  - Light outputs were measured using ^{22}Na source
  - Signals were digitized by CAEN NDT5751
  - The total signal from the BaF_2 samples was measured for 2 μs, the fast component during the first 20 ns, and the slow component after 20 ns

Light yield loss after irradiation



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- The light output loss of the pure BaF_2 crystal is about 7%.
- The light output loss of the yttrium doped samples is approximately two times higher than that of the pure BaF_2 sample.
- In all yttrium doped samples the light output loss of the fast emission component is 2-3% higher than that of the slow emission

Plan to irradiate samples in an electron beam at the Linac-200 accelerator at JINR in a few months

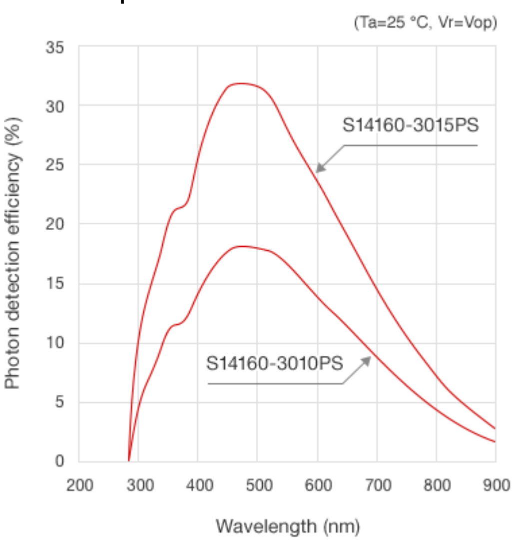
What we are doing for Muon Collider

Crilin: Fast and Rad. Hard. Semi-homogeneous calorimeter

https://iopscience.iop.org/article/10.1088/1748-0221/17/09/P09033
https://iopscience.iop.org/article/10.1088/1748-0221/17/05/T05015

What can be used/proposed also to Mu2e-II?
- Photosensors
- Electronics

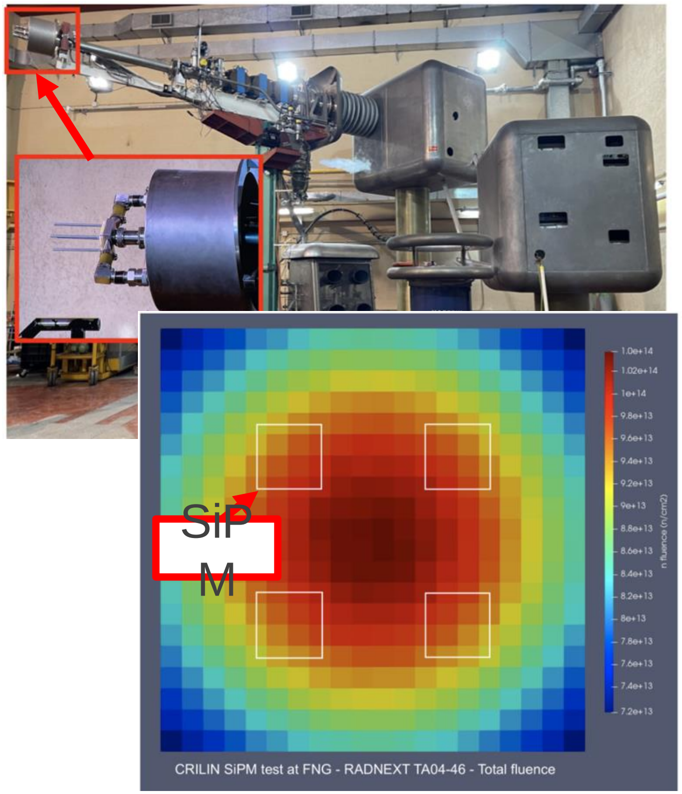
Crucial point is the radiation hardness. We tested SiPM of 10 and 15 um



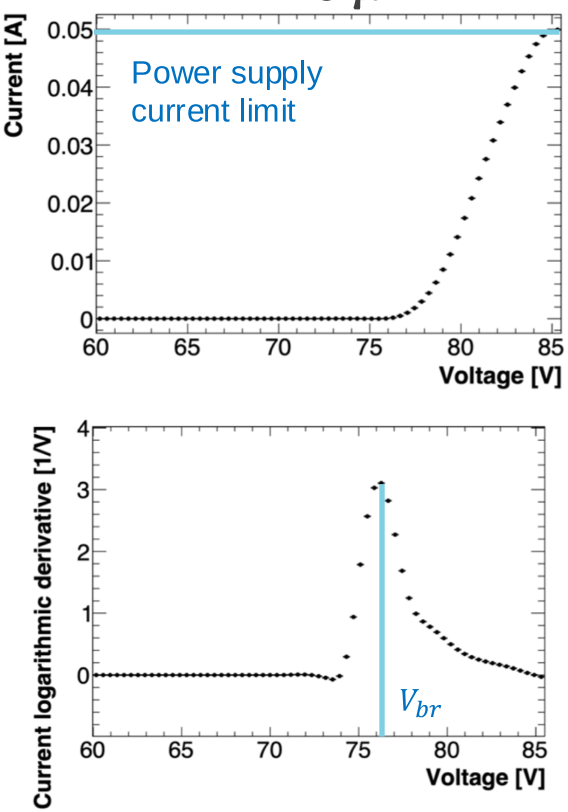
Crilin Picture/CAD ???

SiPMs Characterisation done: neutrons-1

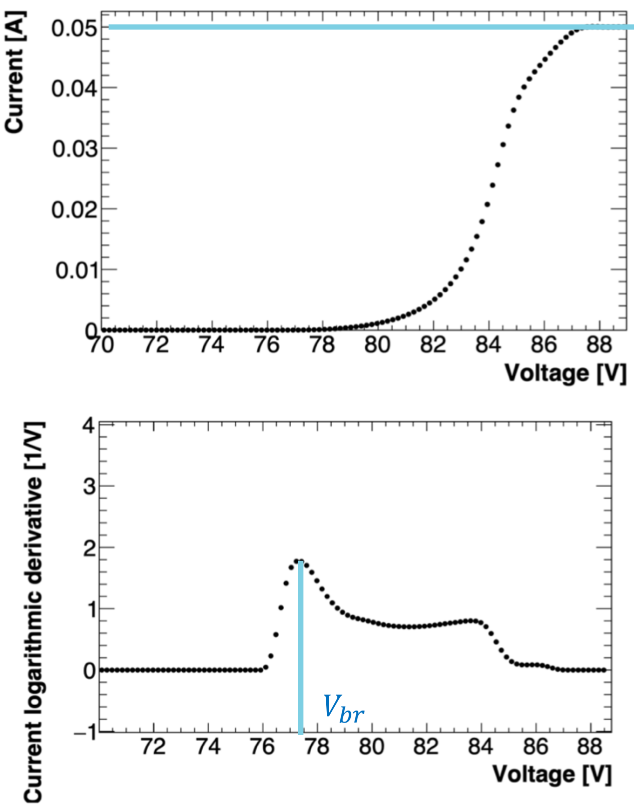
Neutrons irradiation: 14 MeV neutrons with a total fluence of 10^{14} n/cm^2 for 80 hours on a series of two SiPMs (10 and 15 μm)



15 μm



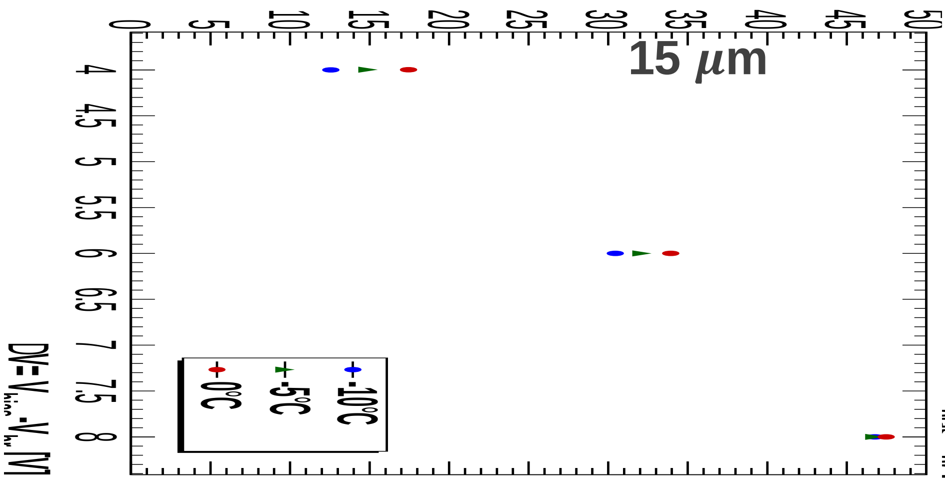
10 μm

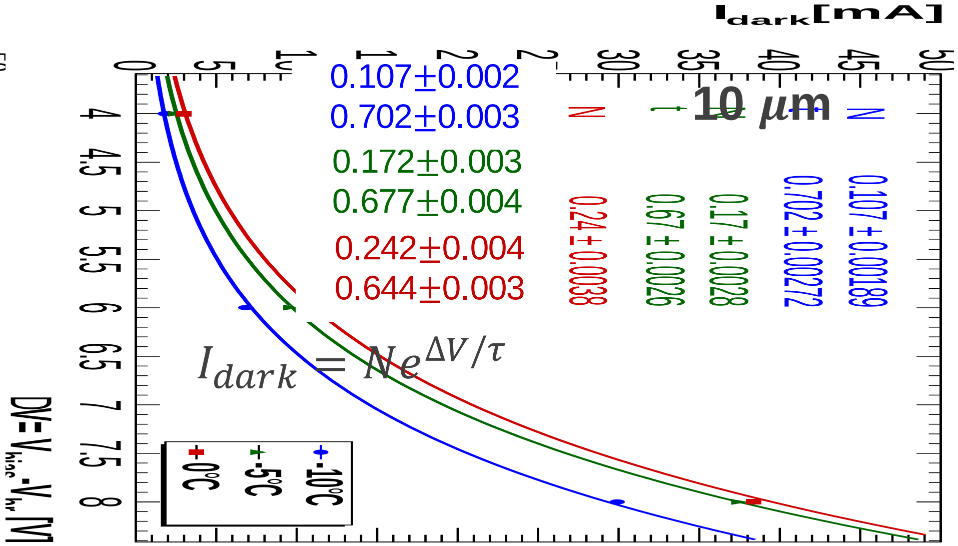


SiPMs Characterisation done: neutrons -2

Extrapolated from I-V curves at 3 different temperatures:

- Currents at different operational voltages.
- Breakdown voltages;





For the expected radiation level, **the best SiPMs choice is the 10 μm one** for its minor dark current contribution.

SiPMs Characterisation done: neutrons-3

15 μm

Temperature [°C]	V_{br} [V]	$I(V_{br}+4V)$ [mA]	$I(V_{br}+6V)$ [mA]	$I(V_{br}+8V)$ [mA]
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10 μm

Temperature [°C]	V_{br} [V]	$I(V_{br}+4V)$ [mA]	$I(V_{br}+6V)$ [mA]	$I(V_{br}+8V)$ [mA]
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0 ± 1	77.49 ± 0.01	2.99 ± 0.01	11.59 ± 0.01	38.48 ± 0.01

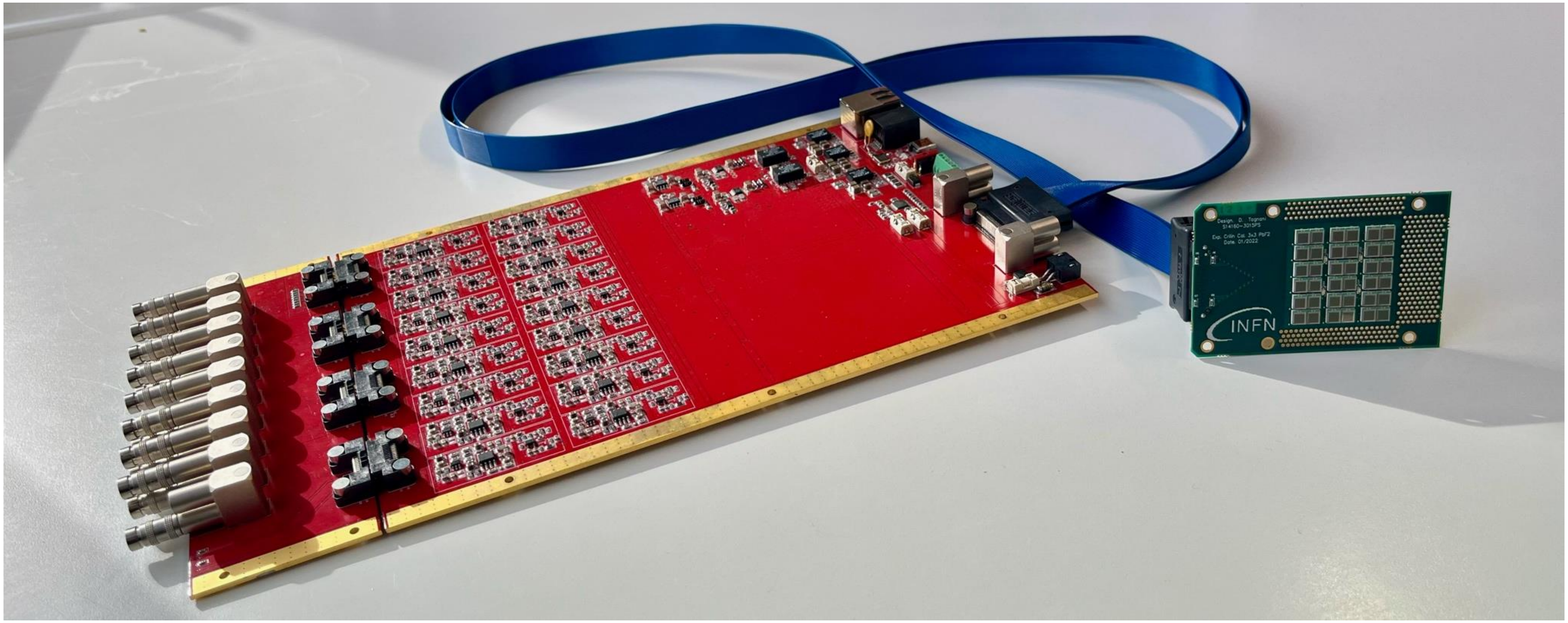
At 10^{13} n_{1MeV}/cm^2:

- **10 μm pixel size OK**, with current Mu2e calorimeter cooling system
- **15 μm pixel size probably OK** with the current Mu2e calorimeter cooling system → few specific tests should be still carried out

Electronics - developments

- SiPMs are connected via 50-ohm micro-coaxial transmission lines to a microprocessor-controlled Mezzanine Board which provides signal amplification and shaping, along with all slow control

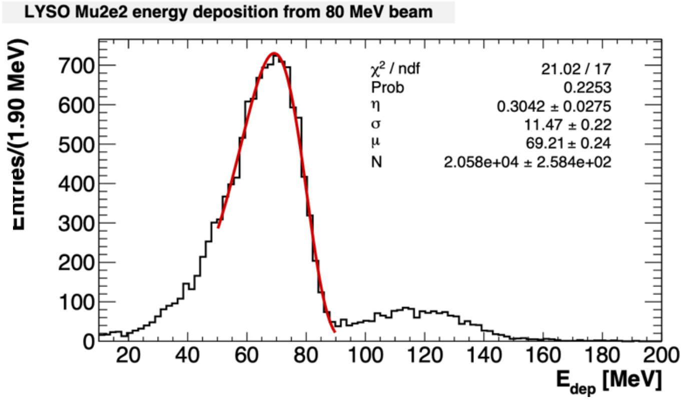
  1 ch → 2 micro-coax cables



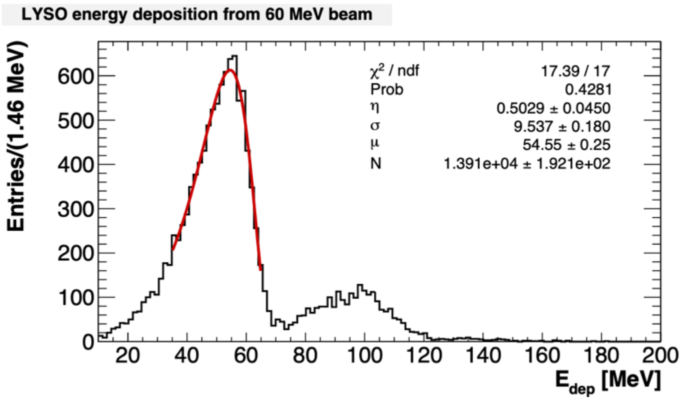
Huge advantages here: reduceTID requirement to FEE – easier cabling

Energy response for electron beam

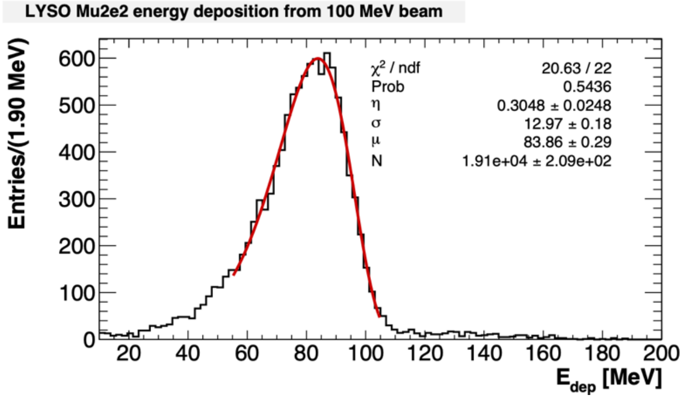
$Eres_{80MeV}$ = 16.5%



$Eres_{60MeV}$ = 17.4%

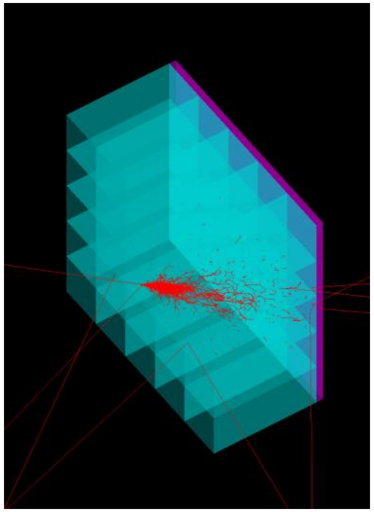


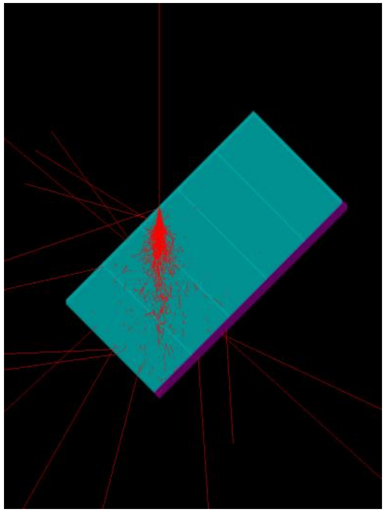
$Eres_{100MeV}$ = 15.4%



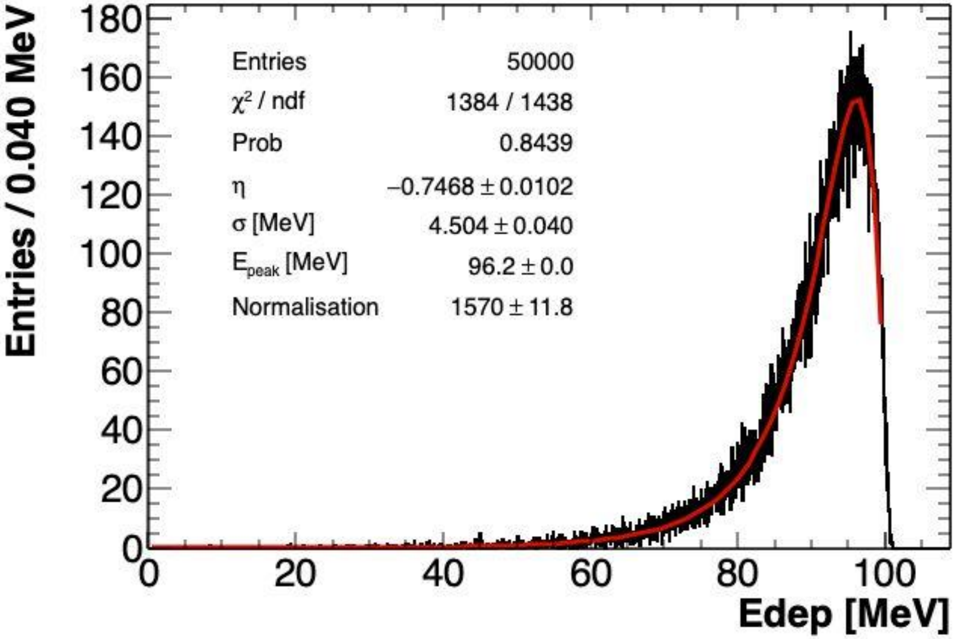
Future Prototype: Simulation

- 25 Crystals with dimension 34x34x80 mm^3
- 300 p.e./MeV as measured
- 100 keV ENE with threshold apply @ 3σ
- 100 MeV e^- at 45 degrees





4.6% @ 100 MeV



Short LYSO crystal calorimetER - SLYER -

- The Mu2e-II calo alternative design we propose is a compromise between the current Mu2e calo and Crilin.

- **What we can re-use of the Mu2e calo:**
  1) The Calibration Source
  2) The Laser System
  3) The Cooling distribution and cooling station
  4) All the support Mechanics
  5) **The digitizers??**

- **What we need to procure and do:**
  1) pure CsI 34x34x200 mm^3 → LYSO 34x34x80 mm^3
  2) 50 um SiPMs → 10 um SiPMs
  3) FEEs + cabling → only 2 cables per SiPM

SLYER - Advantages

- 8 cm length LYSO crystals are enough to achieve O(5%) energy resolution
- Not problem of Equivalent Noise Level nor probably RIN
- Reasonably small LRU
- Great timing resolution still after 10^{13} neutrons/cm^2
- SiPMs already exist – other **R&D not needed**
- High LY → SiPM @ low over voltage → enhanced resistance → lower power dissipation
- Not Front End Amplifier needed → no problems with TID

SLYER – Disadvantages

- **Buy expensive crystals**

  budgetary estimate:
  - LYSO ~30$/cc vs ~10$/cc BaF2
  - **(17$/cc** vs **10$/cc for equivalent X0**, X0-Lyso (1cm), X0-BaF2 (2cm)

- **Total cost of SLYER full proposal**
  - Slyer LYSO crystals for 2 disks = 3.8M$
  - Mu2e: (20 cm CsI + FEE = 1.7M$ + 0.2M$)
  - Mu2e-2-baseline: (14 cm BaF2 + FEE = 2.2M$ + 0.2M$)
  - Relaxed price for SiPMs:
    - 600 k$, no R&D needs
    - wrt 500 k$ R&D for SolarBlind SiPMs

- **SLYER reduced proposal:** 1 disk only, specific radial regions

- *Emission time of 40 ns of LYSO w.r.t. 0.9 ns of BaF2*