Design and construction status of the Mu2e crystal calorimeter and its future upgrade

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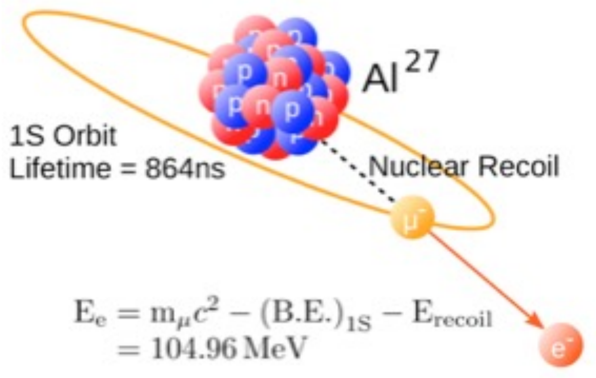
on behalf of the Mu2e calorimeter group
IDTM23 – September 14th 2023

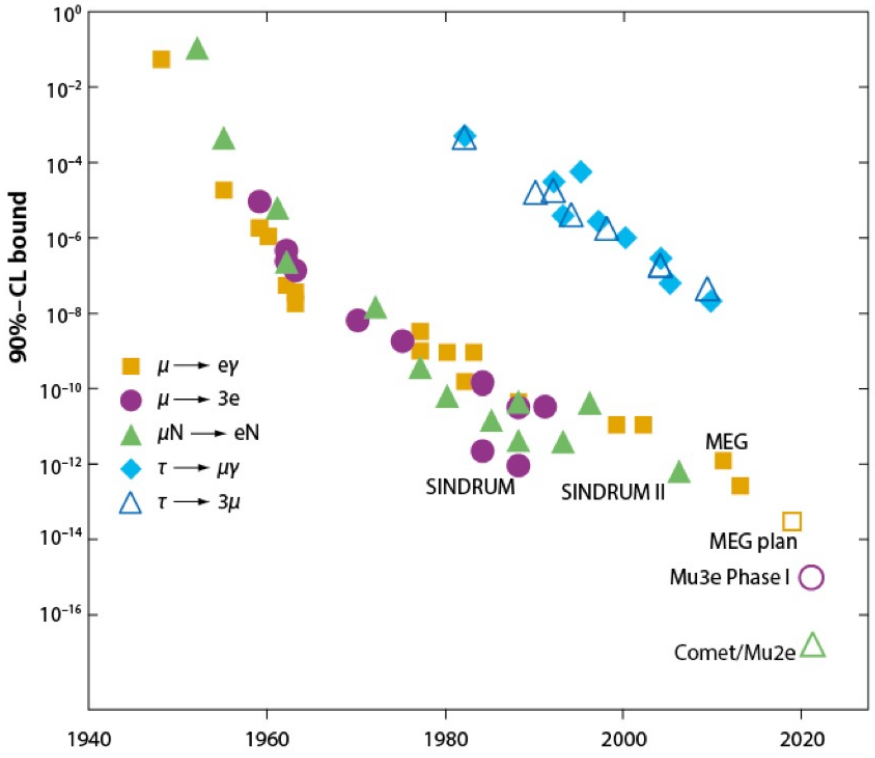
The Mu2e experiment: physics



- The Mu2e experiment is under construction at Fermilab;
- It searches the CLFV neutrinoless coherent conversion of muons into electrons in the electric field of Al nuclei $\mathbf{\mu^- N \rightarrow e^- N}$;

- **CLFV processes are forbidden in SM → any observation will be a clear hint of New Physics**
- BR according to Standard Model extension: $\sim 10^{-52}$
- Mu2e will improve the current best limit by a factor 10^4

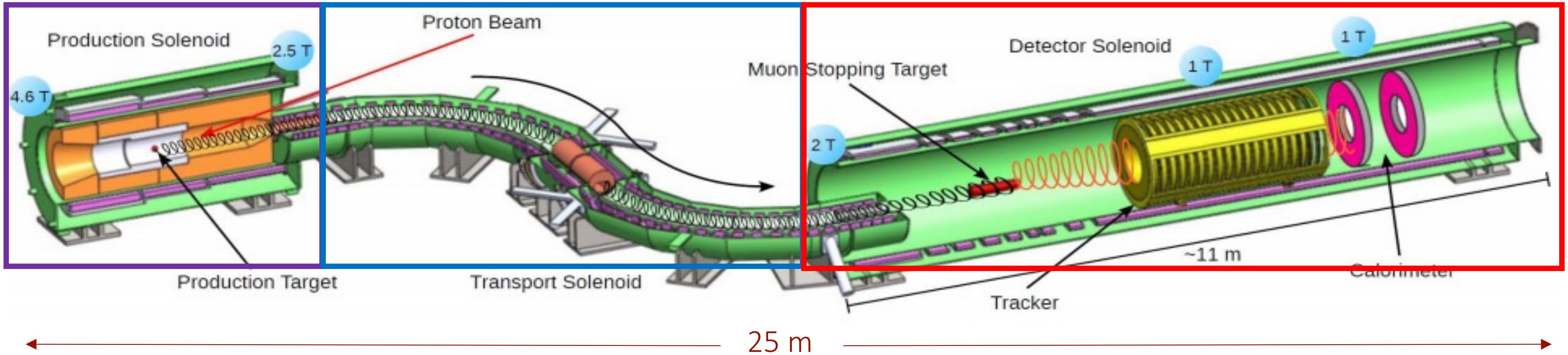
$$R_{\mu e} = \frac{\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)}{\mu^- + N(A,Z) \rightarrow \nu_\mu + N(A,Z-1)} < 8 \times 10^{-17} \ (@ \ 90\% \ CL)$$



The Mu2e experiment: setup

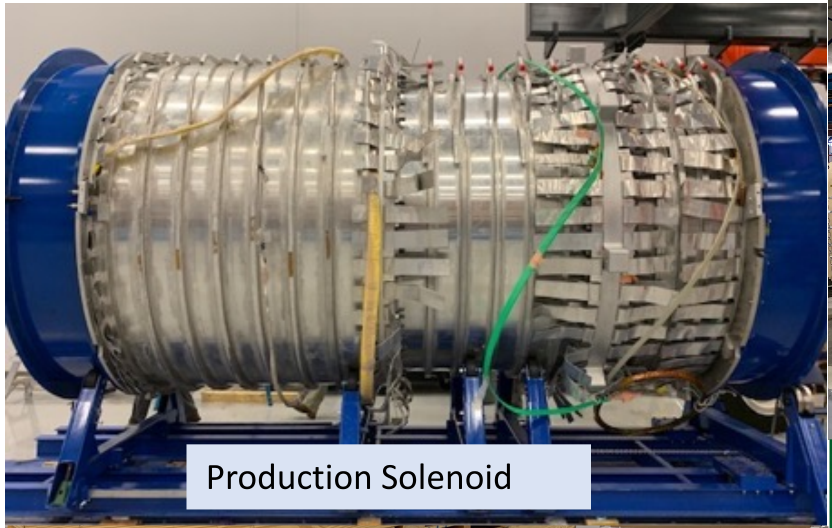
PRODUCTION SOLENOID
- Protons hitting the target and producing mostly π
- Graded magnetic field reflects slow forward π

TRANSPORT SOLENOID
- Selection and transportation of low momentum μ^-



DETECTOR SOLENOID
- Capture μ on the Al target
- High precision momentum measurement in the **tracker** ($<$ 180 keV/c) and energy and timing reconstruction with the **calorimeter**
- **CRV** to veto cosmic rays events

The Mu2e experiment: construction status


Production Solenoid


Transport Solenoid


Stopping Target


TDAQ station

CRV Module


Production Target


Tracker station

The Mu2e calorimeter

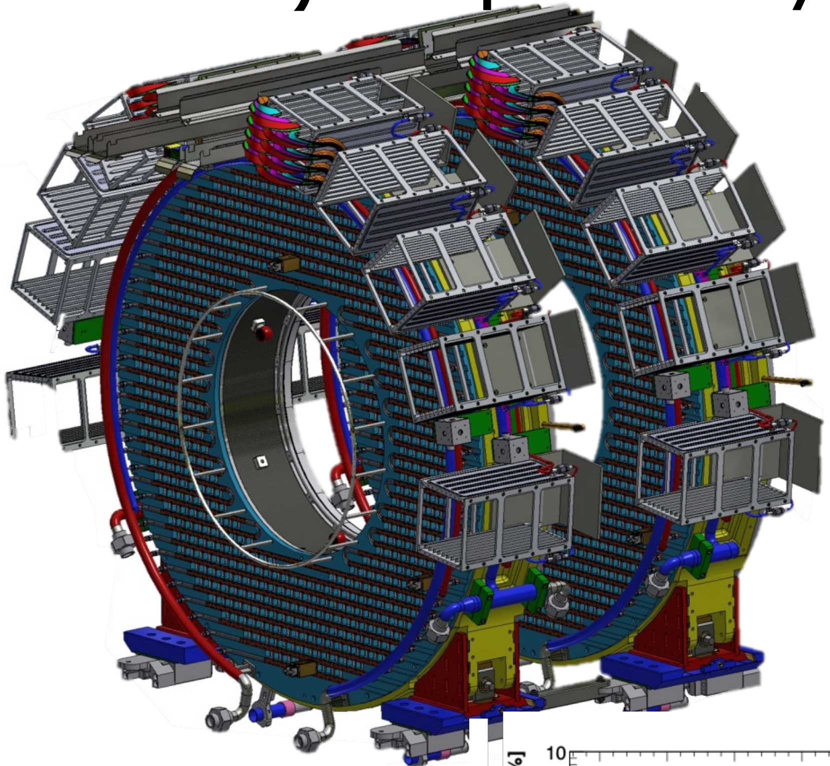
2 disks with 674 undoped (34x34x200) mm^3 pure CsI crystals + 2 UV extended SiPMs

Tasks

- Confirm 105 MeV CE observation,
- PID (e/μ separation)
- EMC seeded track finder
- standalone trigger

Technology

- 10 X_0 (200 mm) crystal depth
- RO/crystal = 2 UV SiPM array+2 FEE
  SiPM array = 6 x(6x6)mm^2, 50 um pixel
- Two annulus ring with 70 cm spacing
  30 cm (66 cm) inner (outer) radius,
- Fluid cooling down to –10° C



Design validation

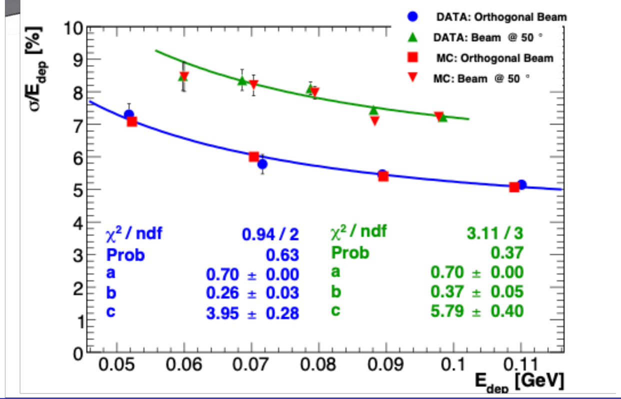
- Large size prototype (Module-0) with 102 crystals and 51 RO
- exposed to 60-120 MeV e- beam @ BTF
- Kept in operation for years at CR test stand w/wo vacuum
- Excellent results in agreement with the required performance and operation environment

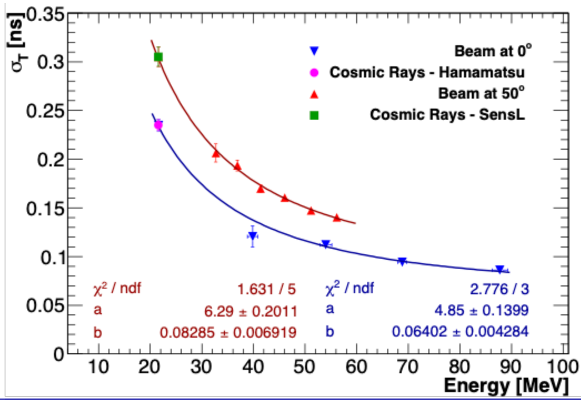
Performance

- $\sigma_E/E < 10\%$,
- σ_T<500 ps,
- $\sigma_{X,Y}$< 1 cm,
- High acceptance

Operation

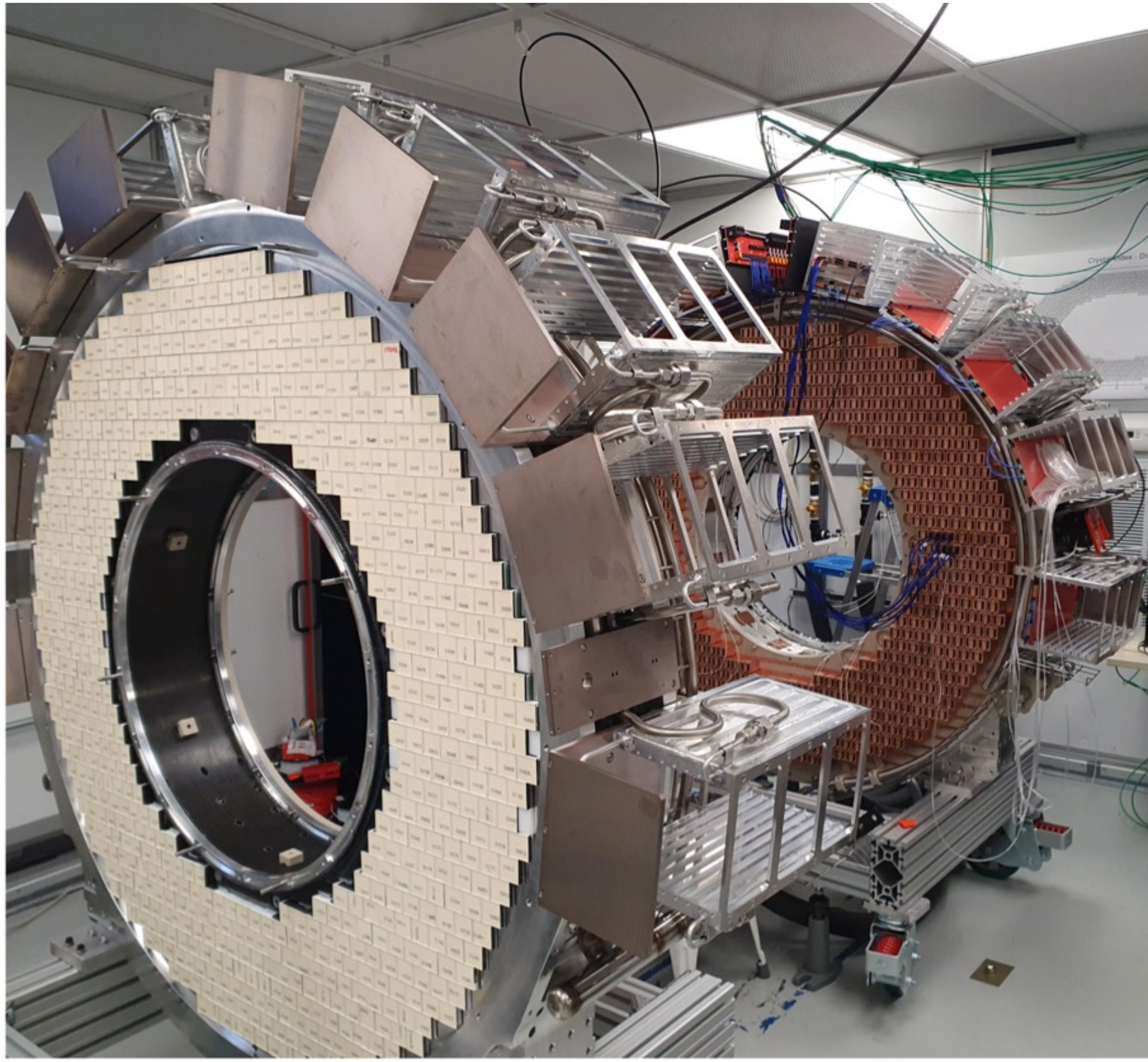
- 1 T and 10^{-4} Torr,
- Redundancy in RO,
- Radiation hard: 90 krad and 3×10^{12} n_{1MeV}/cm^2





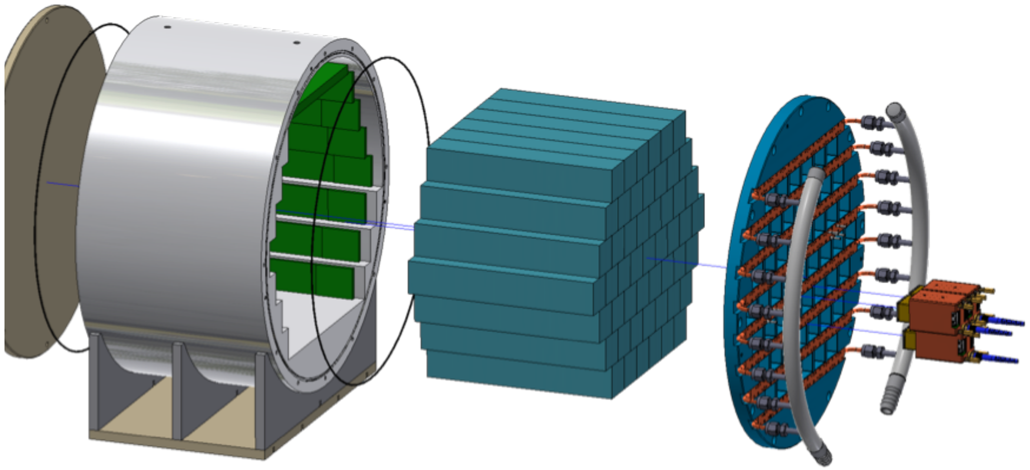
Calorimeter status as today

- Mechanics for 2 disks installed ✅
- Basic components (CsI+SiPMs +FEE) produced and installed ✅
- RO assembly ~ done (68 to go/1348) ✅
- Digital electronic under production 🔜
- Test 1/2 disk per time at SIDET 🔜



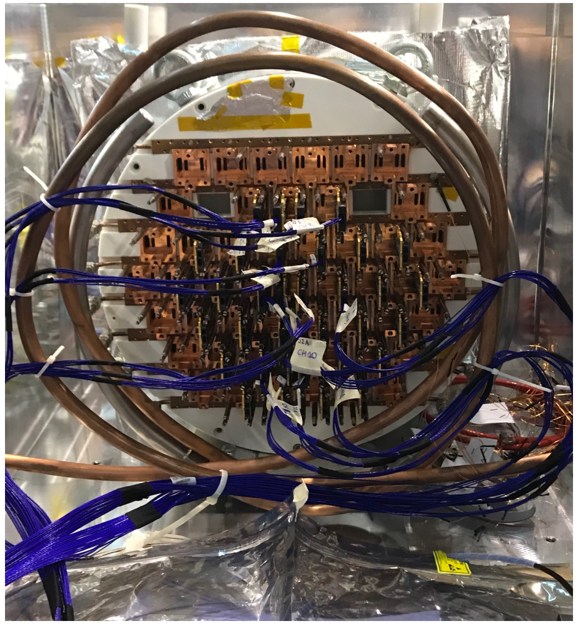
Vertical Slice Test

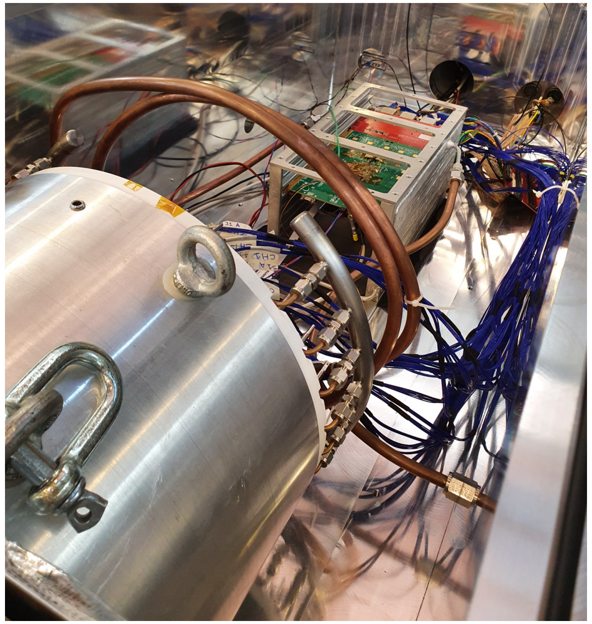
The Module-0



- **Large scale prototype w/51 crystals matrix**
- Same cooling system as final Calorimeter
- Same fibre optic laser calibration system as final Calorimeter
- Possibility to verify the installation procedures

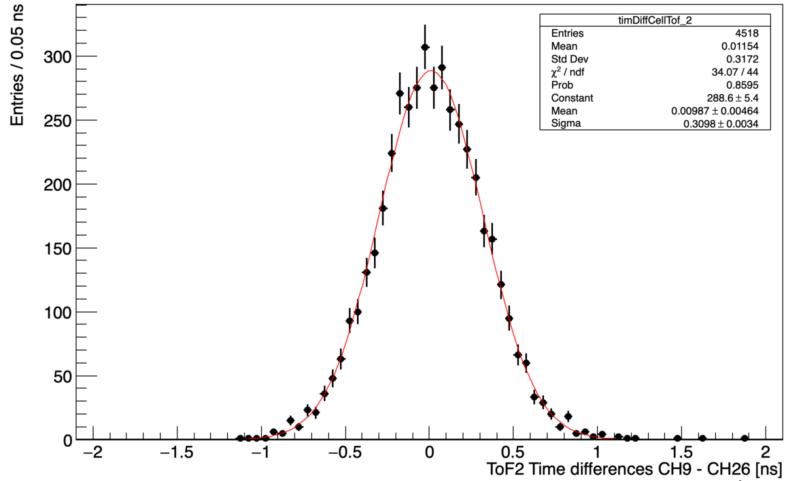
- Final MB and DIRAC boards installed on electronics crate
- Final Mu2e readout chain implemented from FEE to DIRAC digitizer
- Cosmic Ray tagger to test whole signal chain with MIPs
- Validation of energy and timing calibration algorithms
- Tests in vacuum and with cooling system
- Test of stability and noise
- Test with irradiated sensors



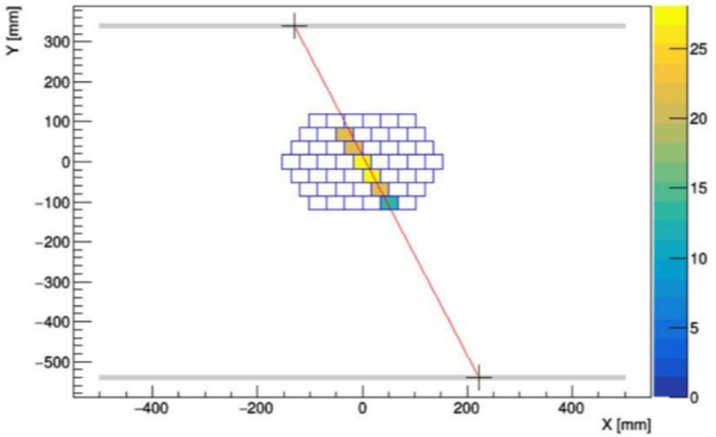


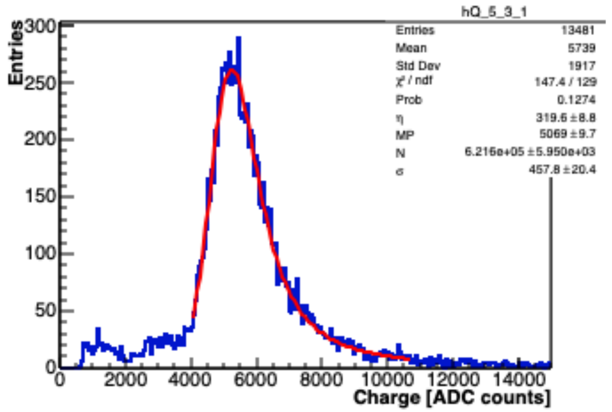
Summary of the calorimeter performances

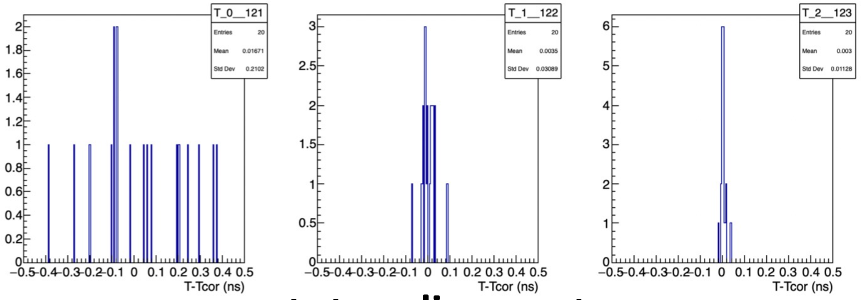
- Module-0 w/ final readout chain
- XY (+ YZ slope) MIP track reconstruction
- Energy equalization on 21 MeV MIP peak
- NPE (from asymmetry) and SiPM gain stability check (+1.6 % /°C for SiPM gain)
- Equivalent noise ≈ 200 KeV
- Readout channels timing offset correction trough iterative algorithm to a level < 5 ps RMS
- Cell mean time resolution w/ MIPs ≈ 210 ps



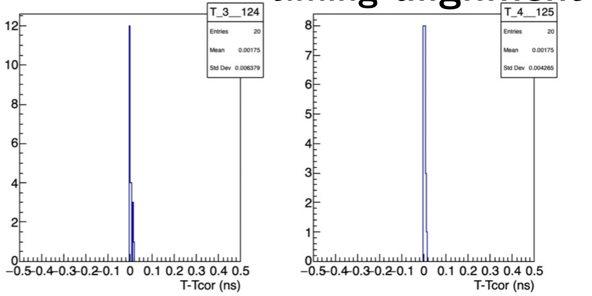
mean time difference between 2 crystals w/ 2D ToF



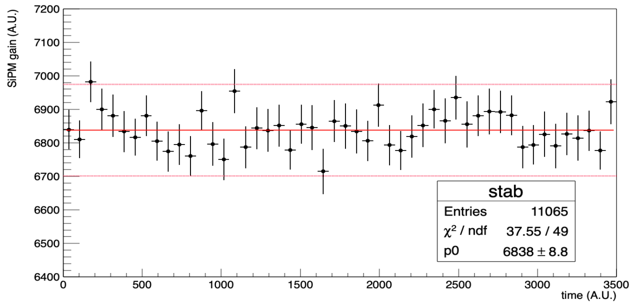




timing alignment



SIPM gain stability over 2 weeks

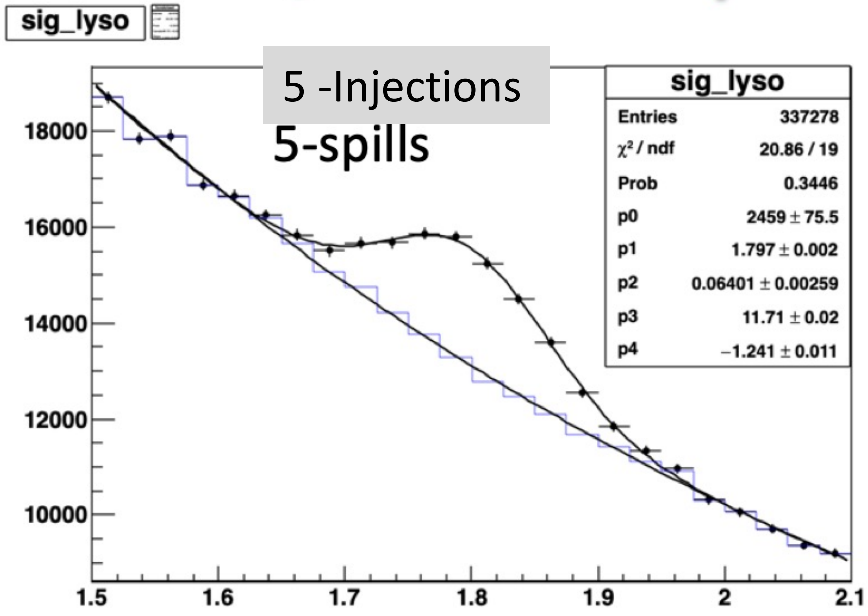


Measuring $R_{\mu e}$ denominator: CAPHRI

$$R_{\mu e} = \frac{\Gamma(\mu^- + A(Z,N) \to e^- + A(Z,N))}{\Gamma(\mu^- + A(Z,N) \to \nu_\mu + A(Z-1,N))}$$

Category	Process	Energy [keV]	Time
Prompt X-rays	μstop (2p$\to$1s)	347	$\mathcal{O}$(ps)
Semi-prompt γ-rays	μcapture	1809	$\mathcal{O}(\tau(Al_\mu)) \sim 860$ ns
Delayed γ-rays	μcapture	844	$\sim$ 13 min

- **Baseline solution**: Stopping Target Monitor (HPGe + $LaBr_3$): dedicated detectors 16 m downstream the DS
- **Calorimeter-based monitor**: CAPHRI (CAlorimeter PRecise High-resolution Intensity detector)
  - 4 LYSO crystals in the calorimeter Disk-0 to measure the 1.8 MeV muon capture "golden line"
  - Simulations demonstrated O(3%) counting error per injection cycle (1.4 sec)
  - LYSO characterization with PMT and SIPM read-out carried out with 511 keV line (^{22}Na source)
    ➔ $< \sigma/\mu > \sim$7.5% when $<$ LY $> \sim$1000 Np.e./MeV

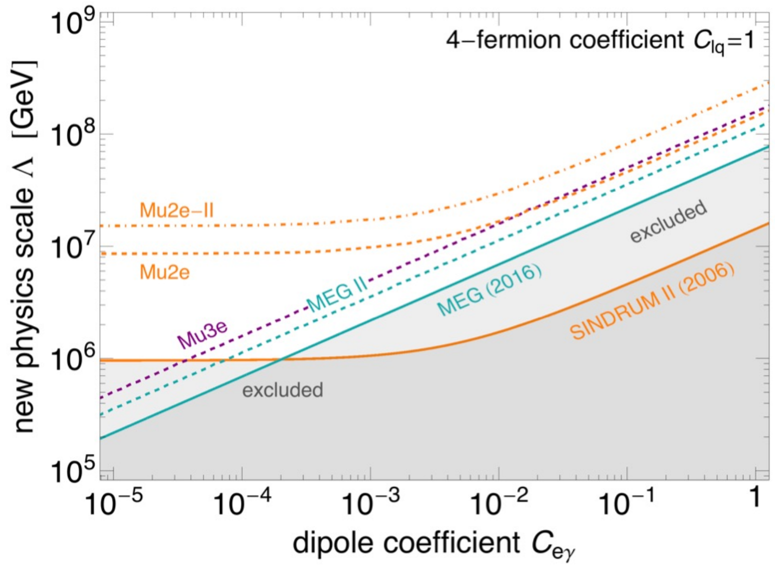


Motivation to Mu2e-II

- Two scenarios possible at the end of the Mu2e data taking > 2030

Mu2e does not find a signal:

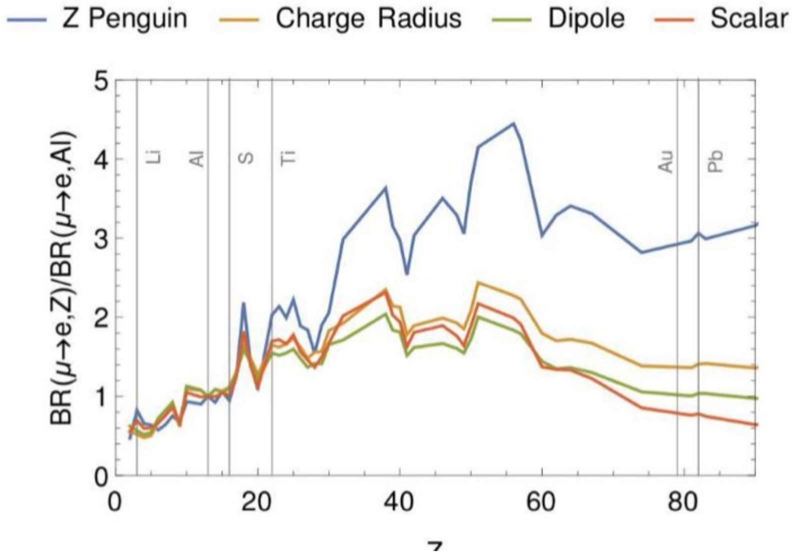
- improve sensitivity
- probe higher mass scales



arXiv:2203.07569

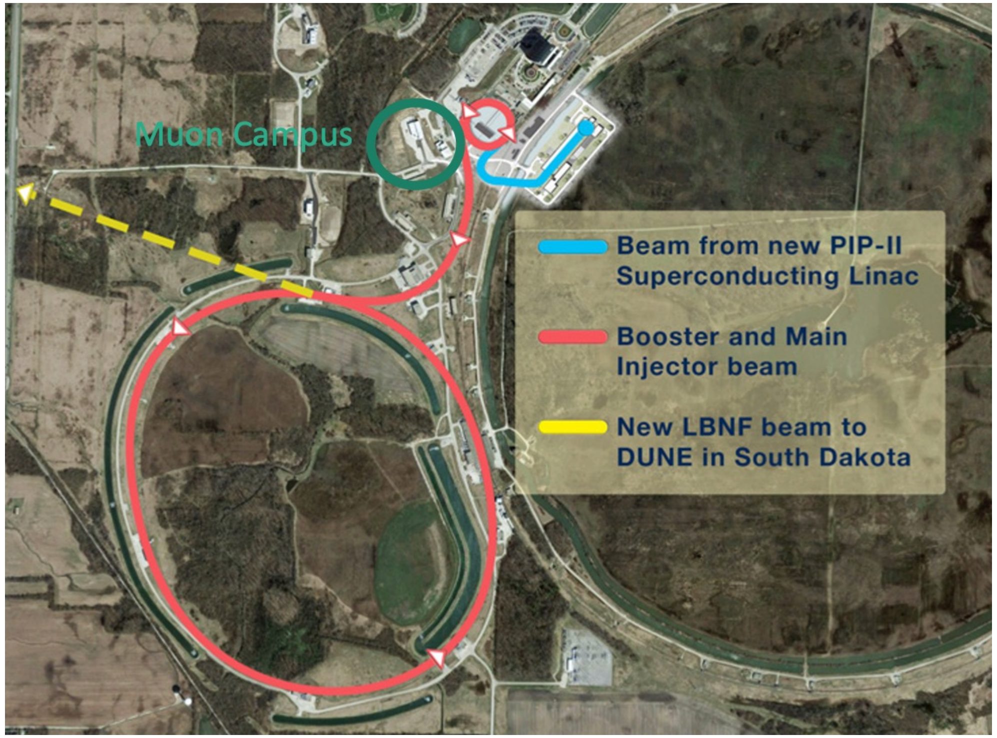
Mu2e discovers CLFV in Al:

- measure with different target materials
- pin down NP parameters

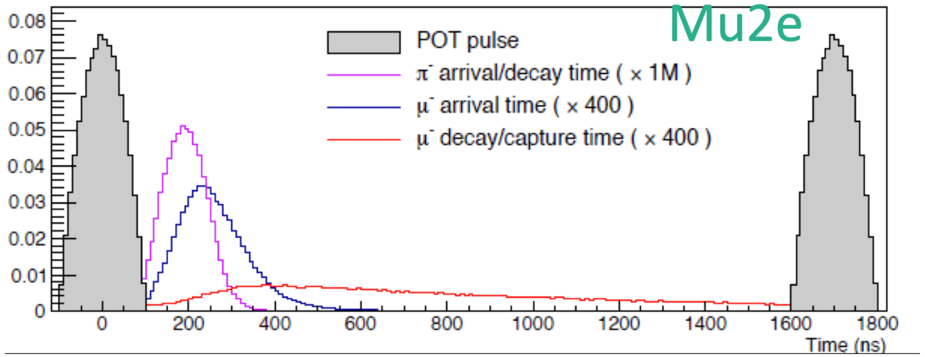


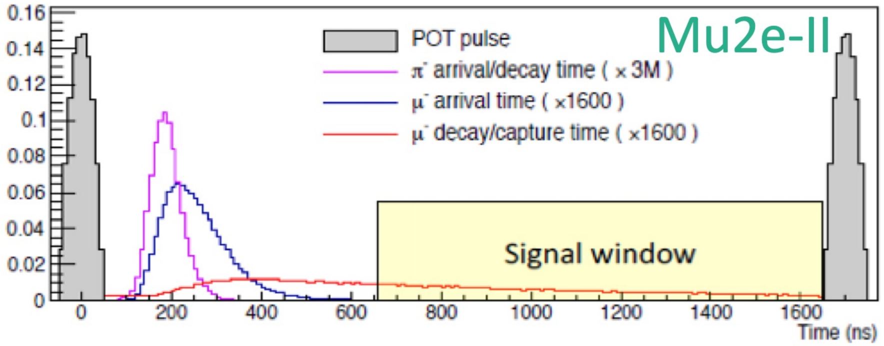
arXiv:2203.00702

The PIP-II project



- 250-meter-long LINAC to accelerate a 2 mA proton beam to 800 MeV corresponding to a power of 1.6 MW
- Designed to deliver 800 MeV H- beam to the Booster - can produce proton bunches at a maximum frequency of 162.5 MHz





Parameter	Mu2e	Mu2e-II	Comment
Proton source	Slow extraction from DR	PIP-II Linac	
Proton kinetic energy	8 GeV	0.8 GeV	
Beam Power for expt.	8 kW	100 kW	Mu2e-II can be increased
Protons/s	6.25×10^{12}	7.8×10^{14}	
Pulse Cycle Length	1.693 μs	1.693 μs	variable for Mu2e-II
Proton rms emittance	2.7	0.25	mm-mrad, normalized
Proton geometric emittance	0.29	0.16	mm-mrad, unnormalized
Proton Energy Spread (σ_E)	20 MeV	0.275 MeV	
$\delta p/p$	2.25×10^{-3}	2.2×10^{-4}	
Stopped μ per proton	1.59×10^{-3}	9.1×10^{-5}	
Stopped μ per cycle		1.2×10^{5}	

Mu2e-II calorimeter requirements

The Mu2e-II calorimeter should have the **same energy ($<$ 10%)** and **time ($<$ 500 ps)** resolution as in Mu2e and:

- Provide a standalone trigger, track seeding and PID
- Provide independent muon stop normalization
- Be resistant to the strong radiation environment and cope with intensity increase (x 10 dose/flux , x 3 occupancy/single pulse) :
  - From 10^{12} to 10^{13} $n_{1\ MeV}/cm^2$ neutrons flux on photosensors → SiPMs leakage current increase makes impossible to operate current sensors at -10 °C
  - From 0.1 to 1 Mrad fluence on crystals → CsI LY reduced to a few photo-electrons (pe)/MeV with a signal width of O(100) ns
  - Assuming no change in shielding the x3 occupancy will require a drastic reduction of the signal widths, which need to be kept below of O (30 ns).

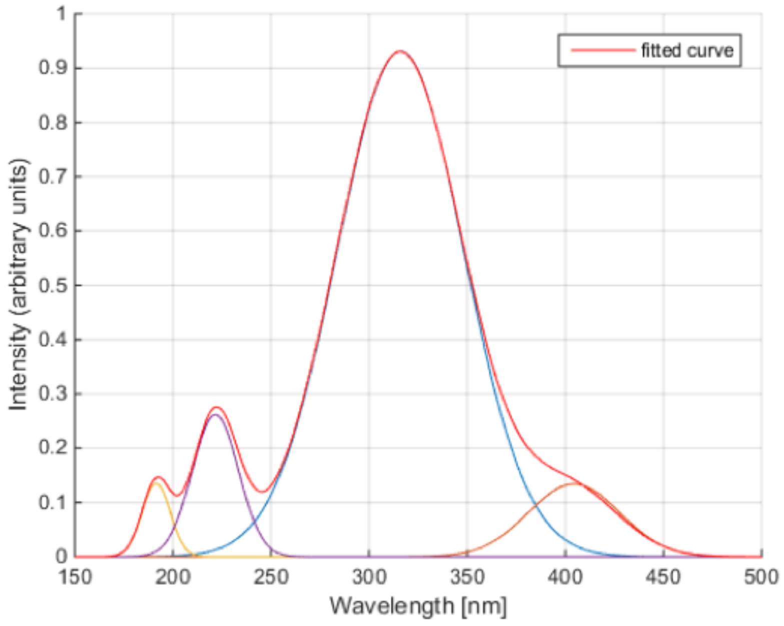
Necessary to design an alternative calorimeter

R&D for Mu2e-II calorimeter crystals

- BaF_2 is an excellent candidate for a fast, high rate, radiation- hard crystal for the Mu2e-II calorimeter.
- Must find a way of utilizing the 220 nm fast component without interference from the larger 320 nm slow component.

	$PbWO_4$	PbF_2	BaF_2	CsI	LYSO
Light Yield (pe/MeV)	**10**	**2**	100(400)	100	2000
Wavelength (nm)	420	UV-Blue	220(350)	315	420
Emission time (ns)	10	prompt	0.9**(600)**	**30**	**40**
Rad-hard LY loss @ 1 Mrad	**80%**	-	50%	**80%**	50%
Density (g/cm^3)	7.0	7.0	4.6	4.6	7.0
Radiation Length(cm)	0.9	0.9	1.8	2	0.9

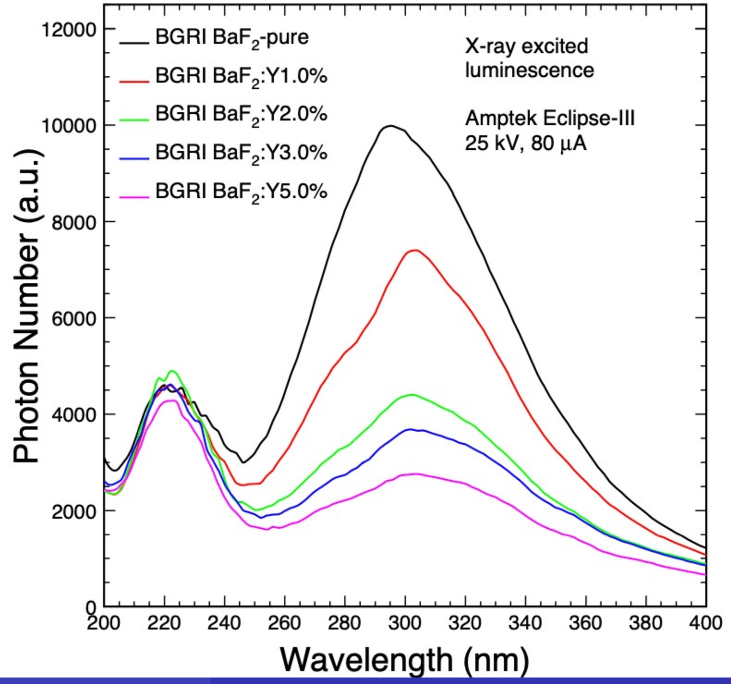
Undoped BaF_2 emission spectra



R&D started on Slow component suppression. Two roads underway:

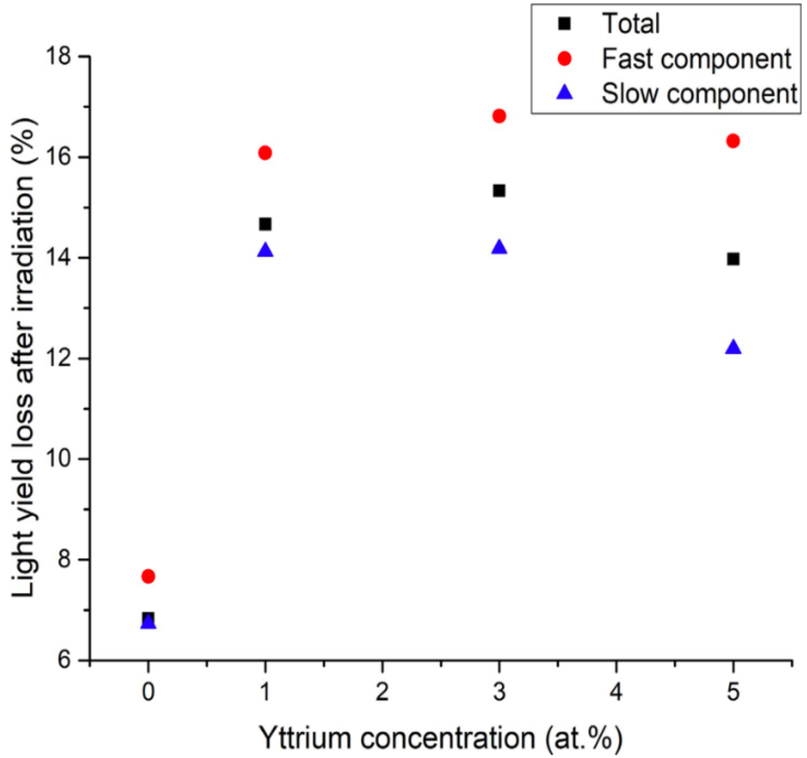
- Rare Earth Doping (Y, La,Ce)
- Develop photodetectors sensitive to UV only:
  - ✓ SiPM with an external filter
  - ✓ UV-sensitive photocathodes
  - ✓ Solar-blind SiPM

X-ray excited emission spectra

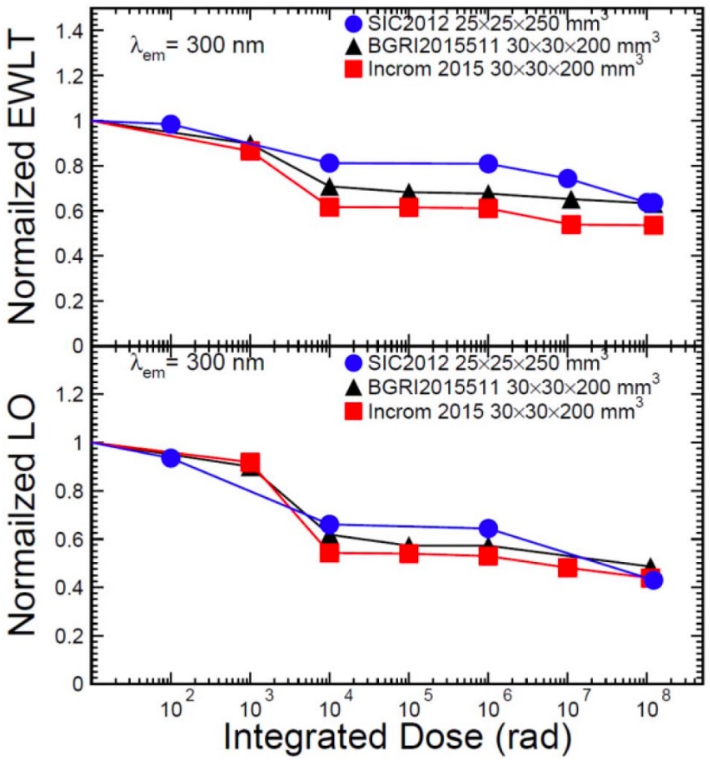


Radiation hardness of BaF_2 crystal

- Tests with reactor neutrons up to $\sim 2.3 \times 10^{14}$ n/cm^2 (**) with BaF2(Y) samples from SICCAS and BGRI (JINR)



- 20 cm long BaF_2 shows ~50% light output loss after 120 Mrad, indicating good radiation resistance against ionization dose.



(**) The neutrons energy spectrum is unknown, so it's difficult to compute fluence in 1 MeVeq n

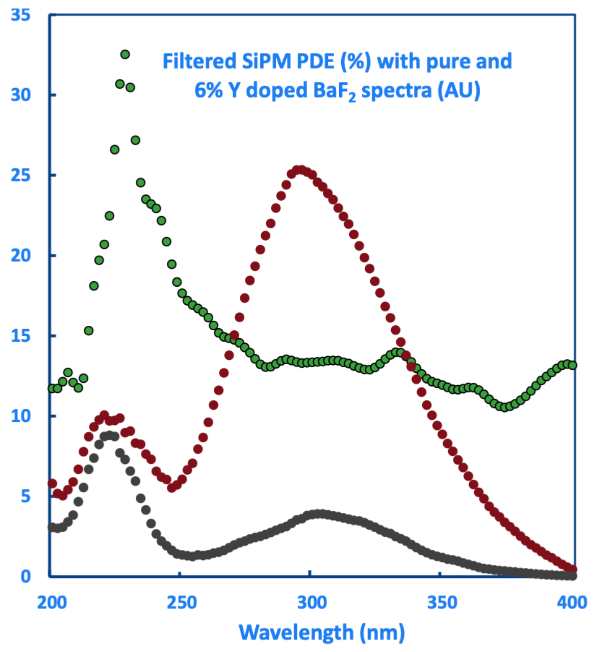
Photosensor options for BaF_2 or BaF_2(Y)

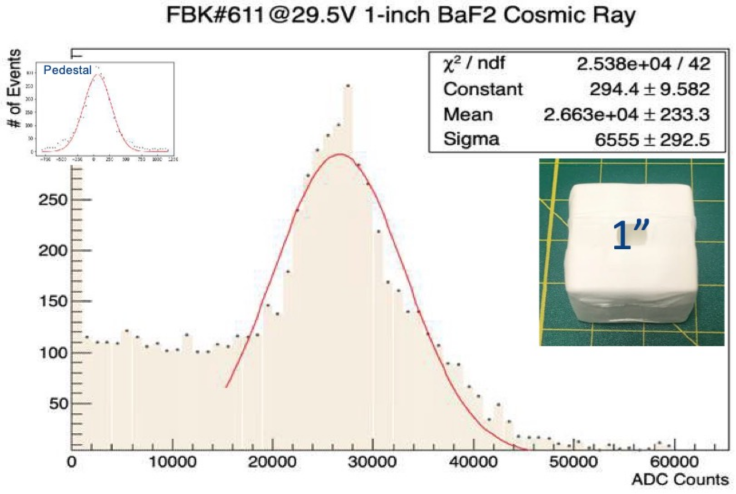
- **Spectral sensitivity** in the 200 nm region for best energy and time resolution
- **Fast/slow component** discrimination for high-rate capability
- Best feasible **rise/fall** time characteristics to fully capitalize on the fast component native time resolution and rate capability
- **Radiation hardness** (photons/neutrons)

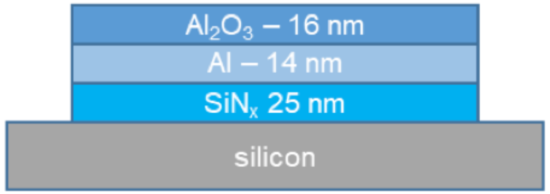
Candidates to be investigated/developed:

- *Large area SiPMs developed for the MEG upgrade, DUNE* having ~25% PDE at 220nm (these already exist – *e.g.*, Hamamatsu, FBK,...), but no fast/slow component discrimination
- SiPMs/APDs with Atomic Layer Deposition integrated filter→ Large dark current and more noise than standard devices, but can be run at reduced temperatures
- Solar blind MCPs with AlGaN on photocatods, LAPPDs→ Longevity issues

NUV SiPM with 3 layers ALD



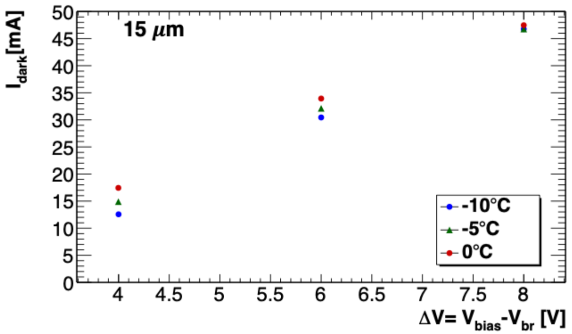




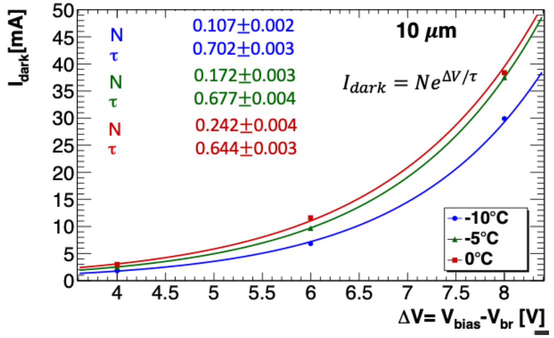
- Atomic-layer-deposition (ALD) bandpass filters integrated with the silicon structure of the photosensor shows several advantages.
  - Possibility to use either with avalanche photodiode or SiPM
- BaF_2 dimension 1” x 1” x 1”, wrapped with Teflon with an opening of 6x6 (mm)
  - Obtained 11 pe/MeV → with 2x3 array, expected 60-70 pe/MeV
- Work with Yttrium doped BaF_2 in progress

SLYER: a LYSO alternative solution?

- Starting point: Radiation hardness test for the SiPMs of the CRILIN calorimeter, an alternative solution for the e.m. calorimeter of the Muon Collider
  - 8 cm length LYSO + 10 µm pixel SiPM
  - no expected degradation in performance after 10^{13} neutrons/cm^2;
  - the high LYSO LY permits the use of the SiPMs at low over-voltage →enhances the radiation resistance and reduces the power dissipation;
- 80 hours neutron irradiation (@FNG,ENEA Frascati) up to 10^{14} n/cm^2 for a series of two 10(15) µm SiPMs



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



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

Conclusions

The Mu2e Calorimeter provides excellent energy (< 10 %) and timing (< 500 ps) resolution necessary to perform PID

- Successful performance validation with e$^-$ TB and cosmics VST
- Production of crystals, SiPMs and FEE completed
- Production of mechanics completed
- Digital electronics in production
- Last calorimeter disk assembly ongoing @ Fermilab

Mu2e-II is a natural follow-up to the Mu2e experiment

- If Mu2e discovers CLFV in aluminum, Mu2e-II can measure with different target materials to pin down NP parameters
- If Mu2e does not find a signal, repeat the measurement to push limits even further reuse as many components of Mu2e as possible

- Still many challenges for Mu2e-II but also many R&D activities already ongoing
  - The baseline solution for the em Calorimeter for Mu2e-II is based on BaF_2 + Solar Blind SiPM
  - LYSO or PbF_2 could represent alternative options with different concept design, but they are still under investigation (simulation and technology choice tests)

Thank you!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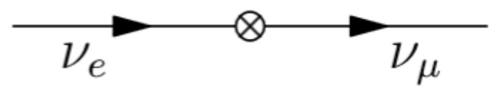
Lisboa
12–14 Sept 2023

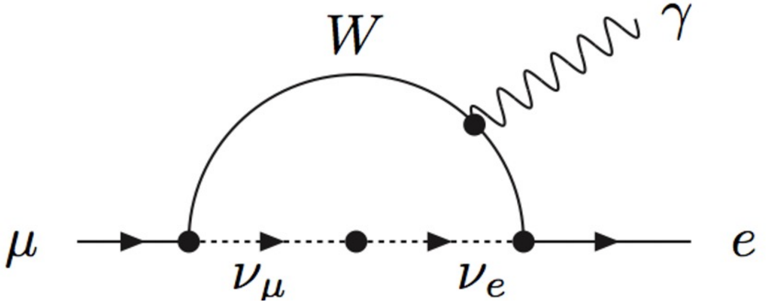
Charged Lepton Flavour Violation

Neutral lepton flavor violation (i.e. neutrino mixing) implies charged lepton flavor violation (CLFV) through neutrino mixing.



However, CLFV processes are strongly suppressed in the Standard Model.

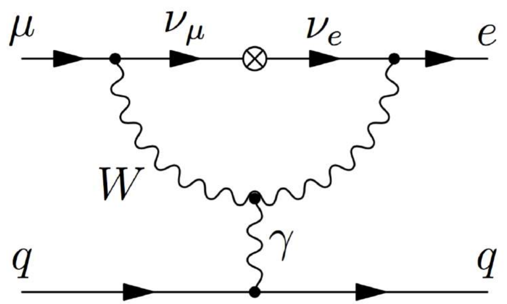
BR($\mu \rightarrow e\,\gamma$) < 10^{-54} in the SM: negligible.



New Physics can enhance CLFV rates to observable values

$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i}U_{ei}\boxed{\frac{\Delta m^2_{1i}}{M_W^2}}\right|^2 < 10^{-54}$$

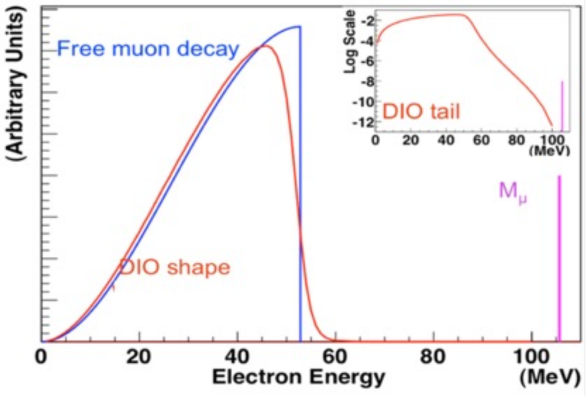
The Mu2e experiment @ FNAL (along with COMET in Japan) searches for muon-to-electron conversion in the coulomb field of a nucleus: ***μ^- Al → e^- Al***



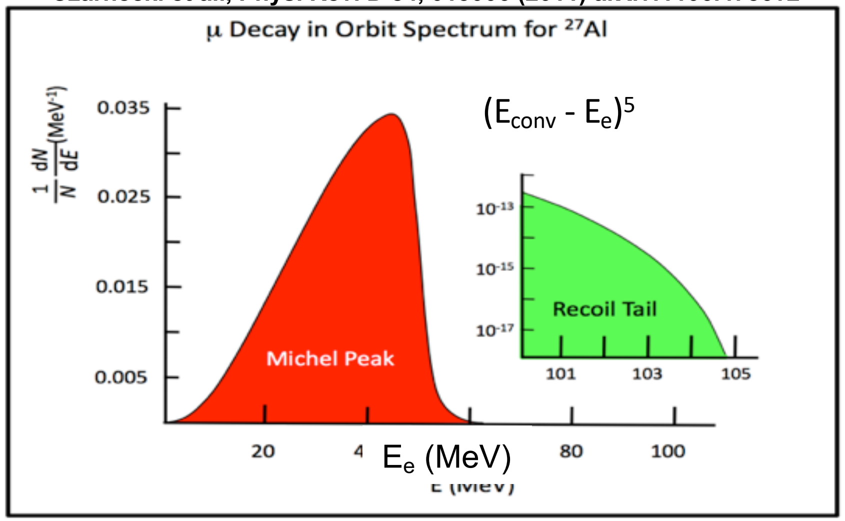
Sensitivity to λ (mass scale) up to hundreds of TeV beyond any current existing accelerator

Main background…

- **Intrinsic** *(scales with μ stopping)*
  - Muon decay in obit (DIO)
  - Radiative μ capture (RMC)



Czarnecki et al., Phys. Rev. D 84, 013006 (2011) arXiv:1106.4756v2



- **Late arriving from prompt processes** *(scales with number of late protons)*
  - Radiative π capture

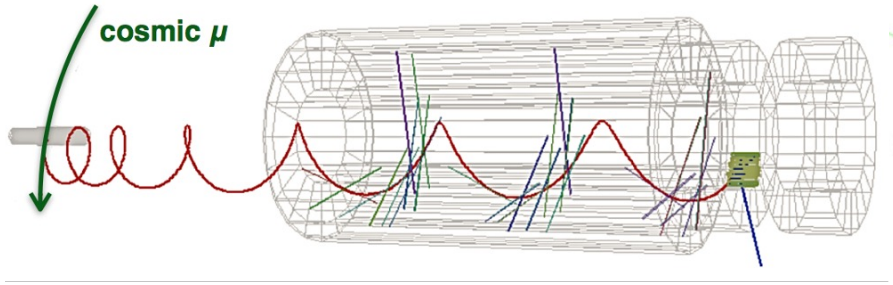
    $\pi^- N \rightarrow \gamma N', \gamma \rightarrow e^+e^-$

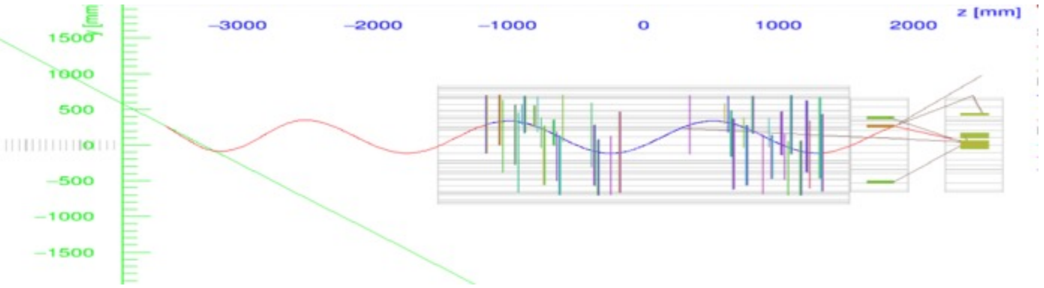
    $\pi^- N \rightarrow e^+e^- N'$
  - μ/π decay ir

Michel spectrum of e from μ decay gets significantly modified by interaction with the nucleus → presence of a recoil tail with a fast-falling slope close to the μ-e conversion endpoint

- **Cosmic rays**

  (1 fake/day)



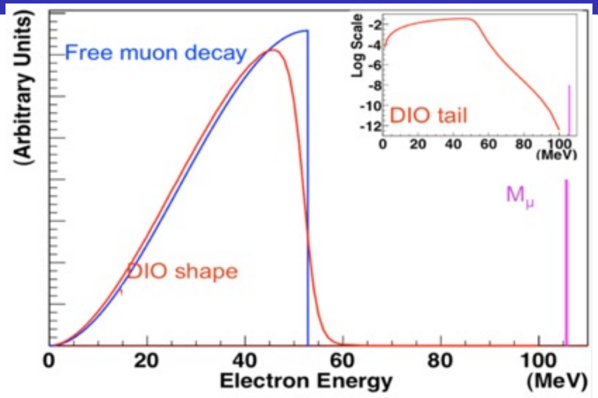


And solutions

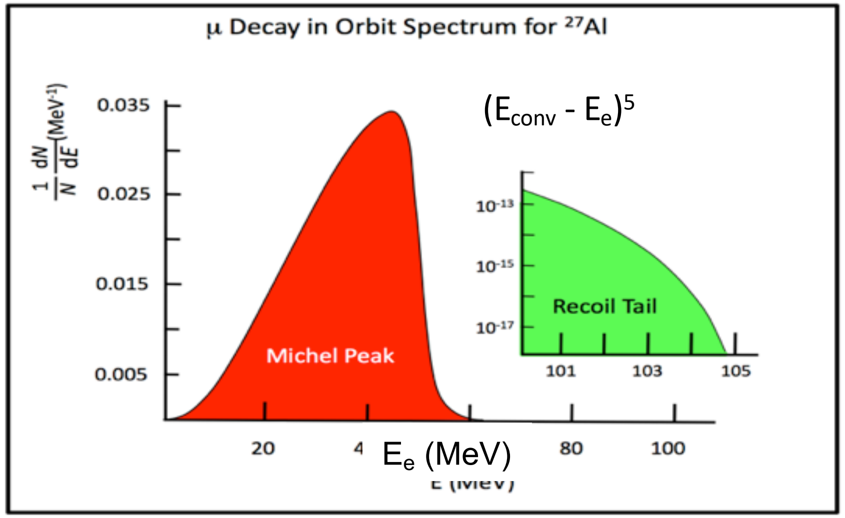
- I... *(scales with μ stopping)*

High performance detectors

  - Muon d... bit (DIO)
  - Radiative μ capture (...



Czarnecki et al., Phys. Rev. D 84, 013006 (2011) arXiv:1106.4756v2



Michel spectrum of e from μ decay gets significantly modified by interaction with the nucleus → presence of a recoil tail with a fast-falling slope close to the μ-e conversion endpoint

- ...riving from prompt processes *(scales with number of late p...*

Pulsed beam

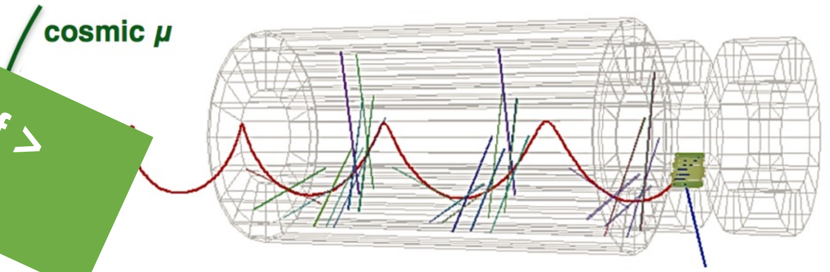
  - Radiati... ...ure

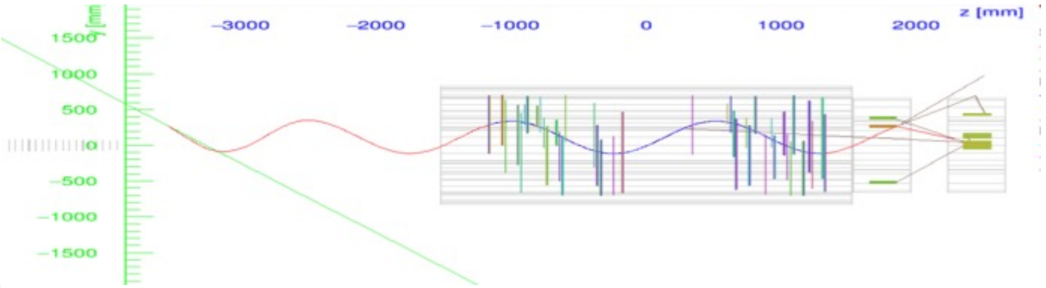
$\pi^- N \rightarrow \gamma N', \gamma \rightarrow e$ ...
$\pi^- N \rightarrow e^+e^- N'$

  - u/π decay in flight

- **Cosmic ...** *(1 fake/day)*

CR veto w/ eff > 0.9999



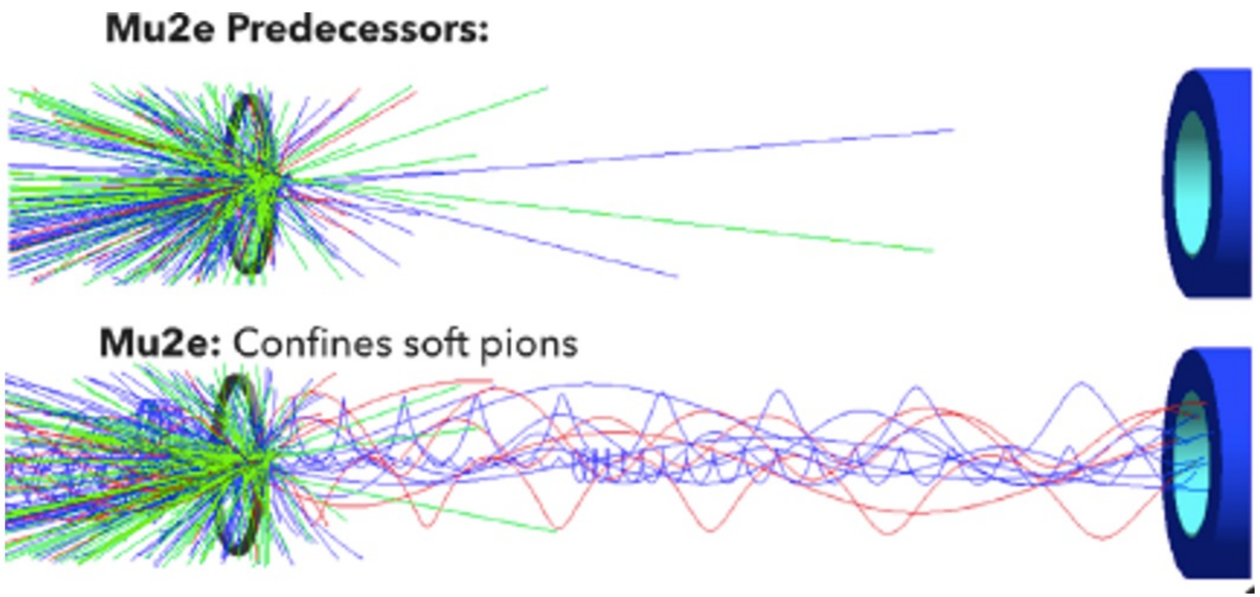


Keys of Mu2e success

- **High intensity pulsed proton beam**
  - Narrow proton pulses (< ± 125 ns)
  - Very few out-of-time protons (extinction < 10^{-10})
  - $3x10^7$ proton/pulse

- **High efficiency in transporting muon to Al target**
  - Need of a sophisticated magnet with gradient fields

- **Excellent detector for 100 MeV electrons**
  - → Excellent momentum resolution (< 200 keV core)
  - → Calorimeter for PID, triggering and track seeding
  - → High Cosmic Ray Veto (CRV) efficiency (>99.99%)
  - → Thin anti-proton annihilation window(s)



Concept by Lobashev and Djilkibaev
Sov.J.Nucl.Phys. 49, 384 (1989)

Why Al?

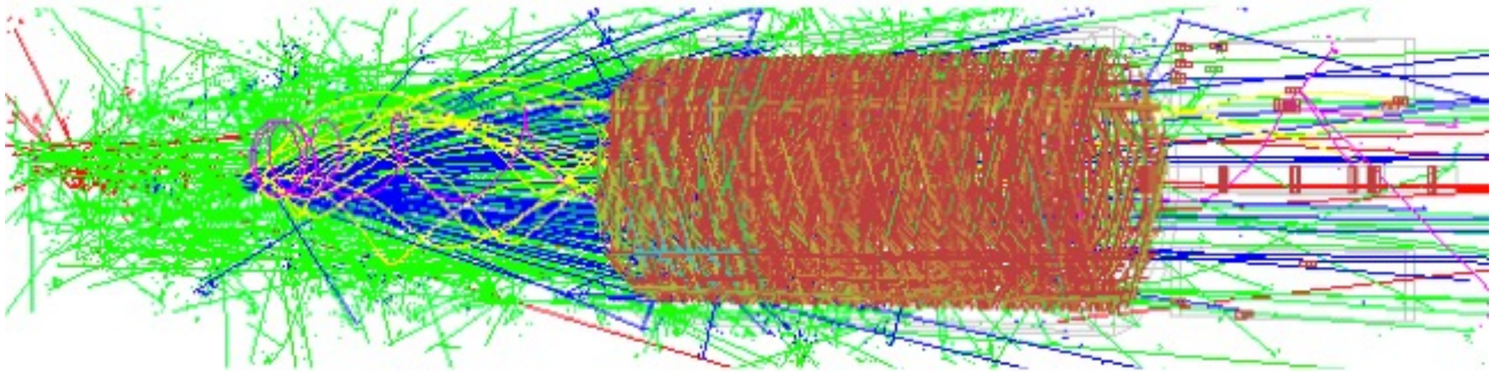
- Determining Z dependence is very important
- Lifetime is *shorter* for high Z -> Decrease in useful search window
- Avoid bkg from radiative muon capture

⇒Aluminum is nominal choice for Mu2e

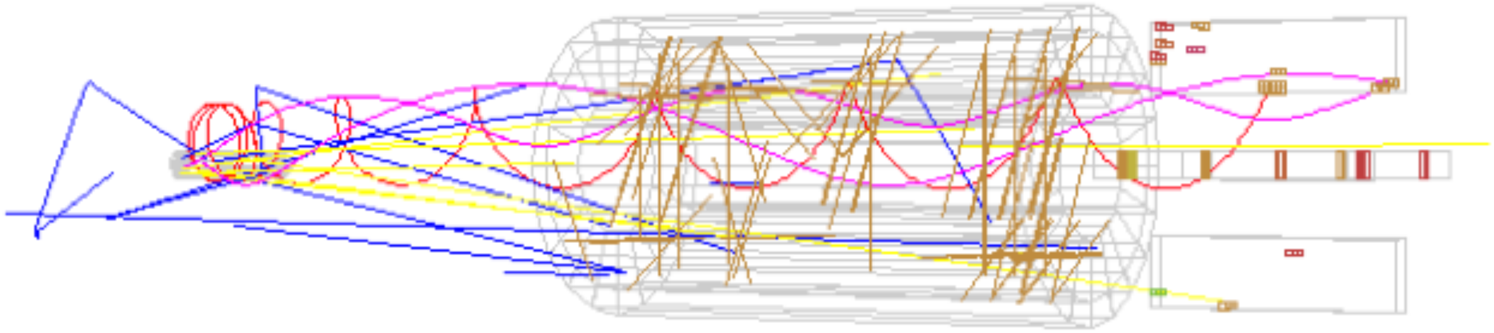
Nucleus	$R_{\mu e}(Z)$ / $R_{\mu e}(Al)$	Bound lifetime	Atomic Bind. Energy(1s)	Conversion Electron Energy	Prob decay >700 ns
Al(13,27)	1.0	.88 μs	0.47 MeV	104.97 MeV	0.45
Ti(22,~48)	1.7	.328 μs	1.36 MeV	104.18 MeV	0.16
Au(79,~197)	~0.8-1.5	.0726 μs	10.08 MeV	95.56 MeV	negligible

EMC based track seeding

500 – 1695 ns window



± 50 ns around conversion electron



The speed and efficiency of tracker reconstruction is improved by selecting tracker hits compatible with the time ($|\Delta T| < 50$ ns) and azimuthal angle of calorimeter clusters → simplification of the pattern recognition.

Crystal Choice

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

LYSO

CDR

- Radiation hard, not hygroscopic
- Excellent LY
- Tau = 40ns
- Emits @ 420 nm,
- Easy to match to APD.
- High cost > 40$/cc

Barium Fluoride (BaF_2)

BASELINE-TDR

- Radiation hard, not hygroscopic
- very fast (220 nm) scintillating light
- Larger slow component at 300 nm. should be suppress for high rate capability
- Photo-sensor should have extended UV sensitivity and be “solar”-blind
- Medium cost 10$/cc

CsI(pure)

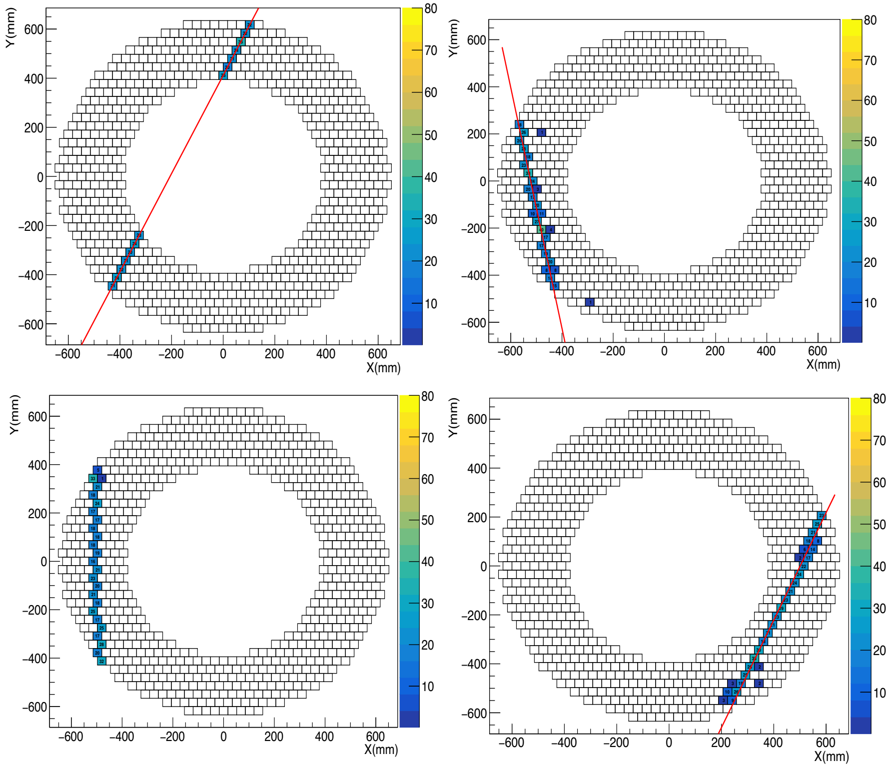
FINAL CHOICE

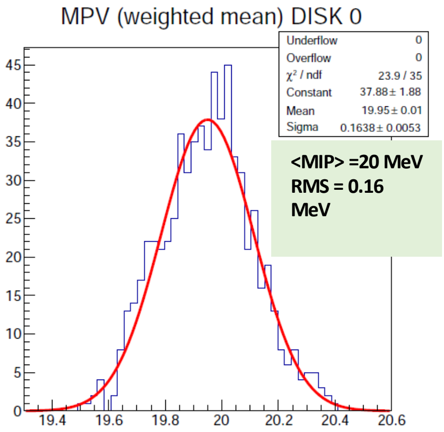
- Not too radiation hard
- Slightly hygroscopic
- 15-20 ns emission time
- Emits @ 320 nm.
- Comparable LY of fast component of BaF_2.
- Cheap (6-8 $/cc)

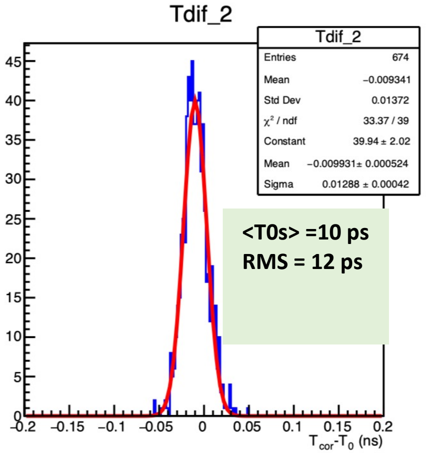
Simulated Cosmic Ray Tracks in

- Software trigger selection completed
- 6 hours needed calibrate:
- energy scale @ 0.8 %
- T0 alignment at 10 ps

→ Time resolution at 200 ps/MIP



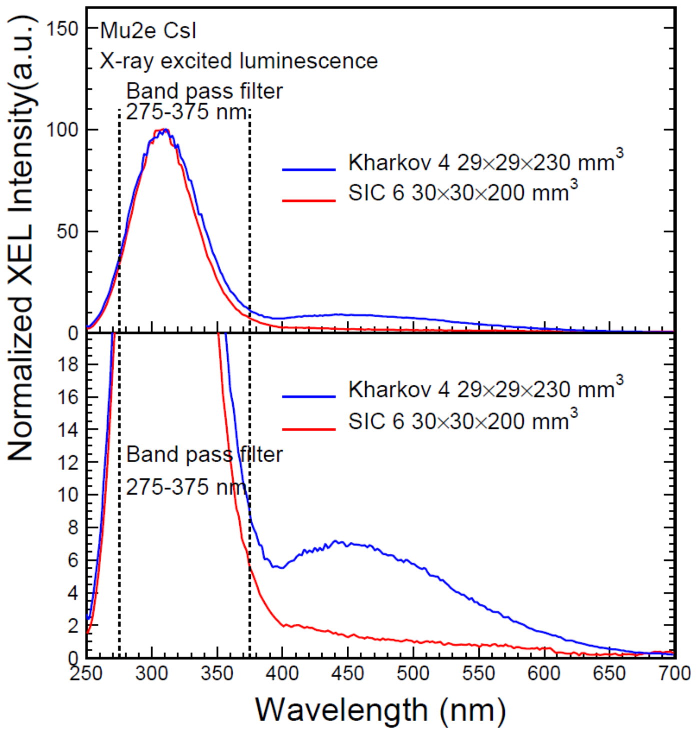




Undoped CsI + UV extended SiPM

Undoped CsI is a good choice

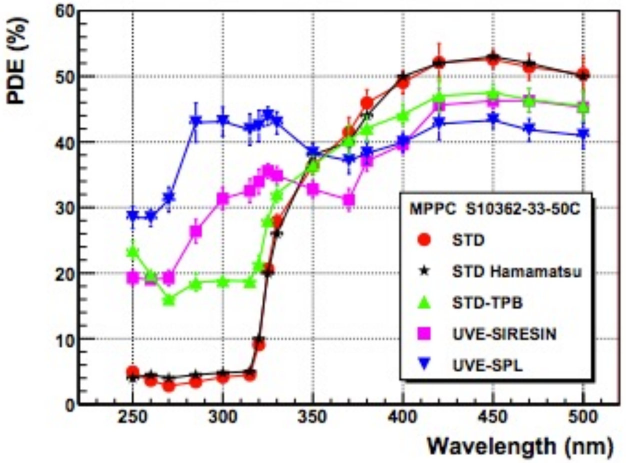
→ It is sufficiently radiation hard up to 100 krad
→ It has a fast emission time
→ It has a large enough LY
→ It emits @ 310 nm.

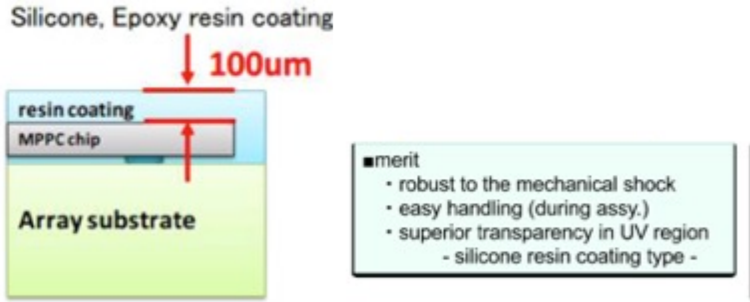


PDE of UV-enhanced SiPM is much higher below 350 nm

→ 30 % @ 310 nm (CsI pure wavelength)
→ New silicon resin window
→ TSV readout, Gain = 10^6

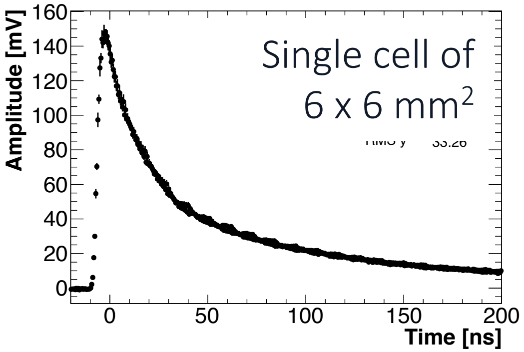
Imaging with SiPMs in noble-gas detectors: arXiv 1210.4746

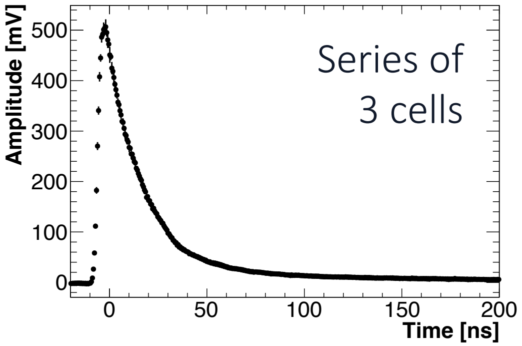


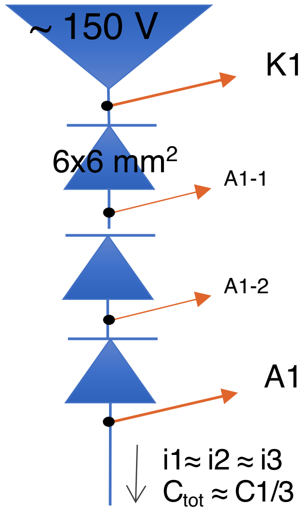


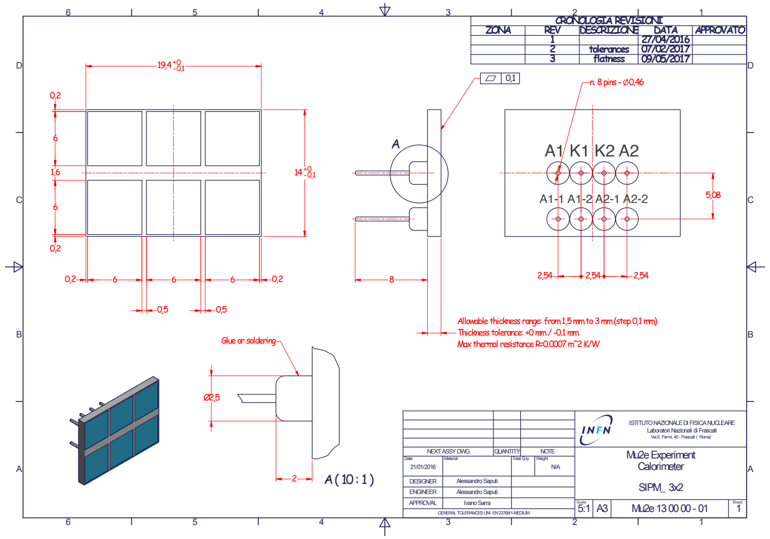
Mu2e custom SiPMs design

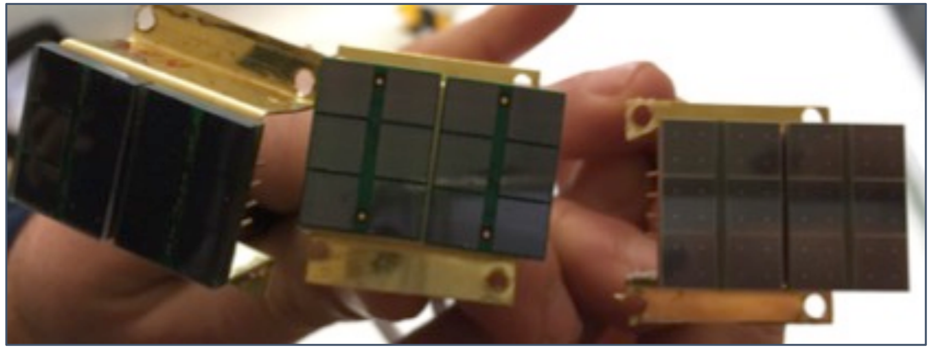
- 2 arrays of 3 6 x 6 mm² UV-extended SiPMs for a total active area of (12x18) mm²
- The series configuration reduces the overall capacity and allows to generate narrower signals



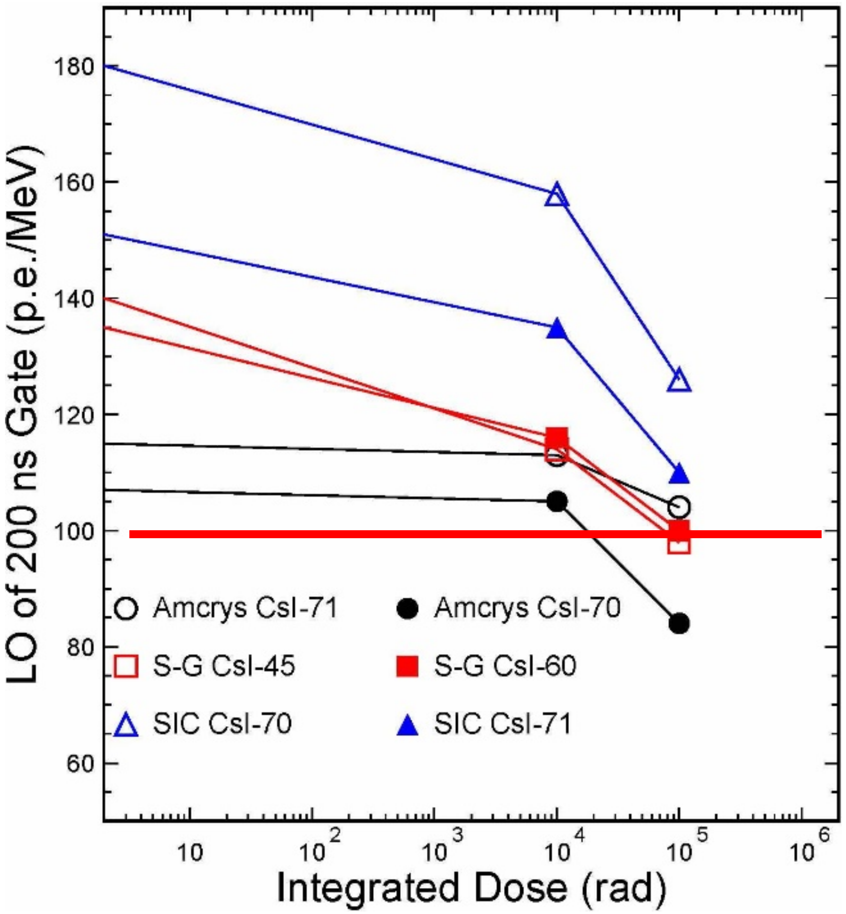


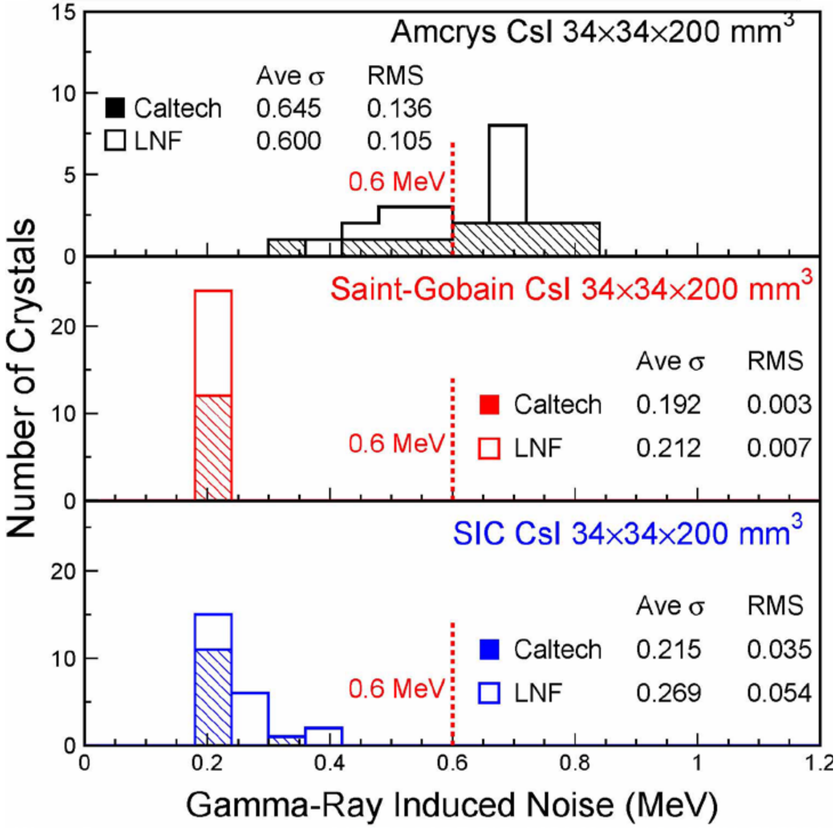






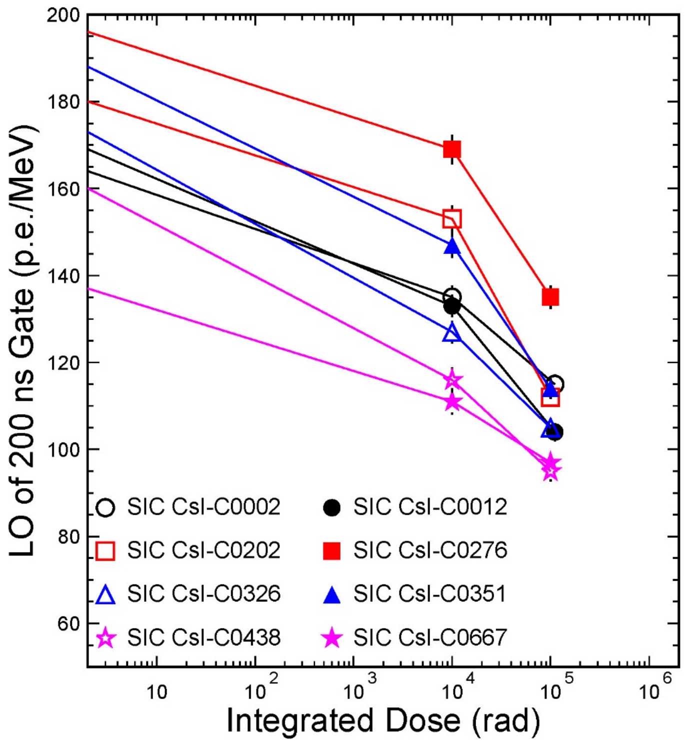
Radiation hardness: dose & neutrons

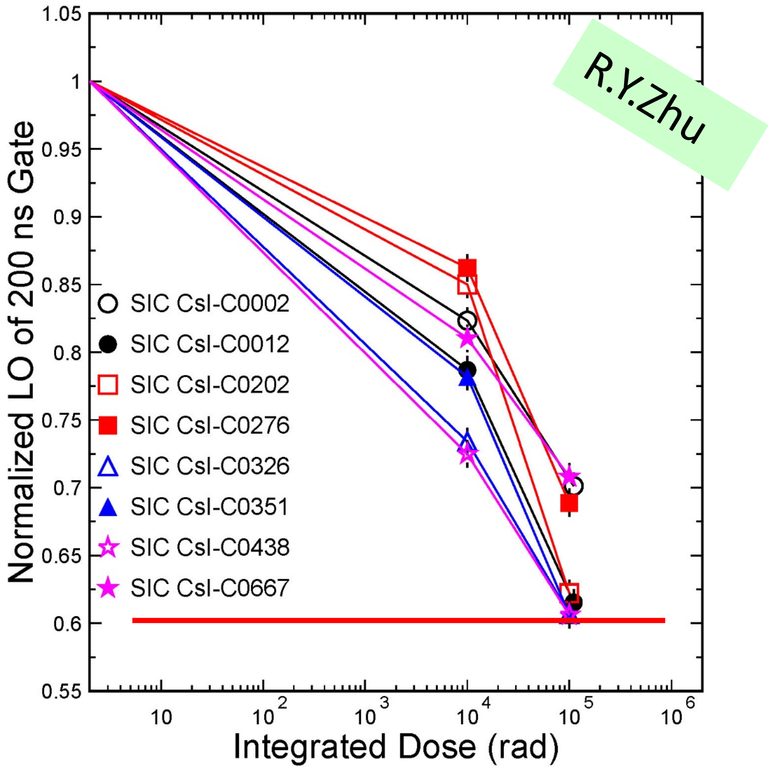


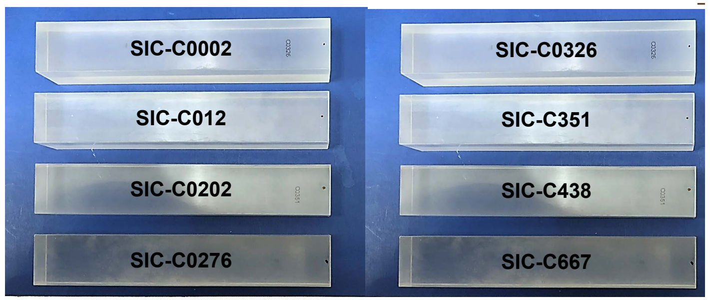


- CsI crystals rad-hard for expected dose in Mu2e-I
- No recovery after annealing
- RIN is larger for ionizing dose than for neutrons

Irradiation of production crystals





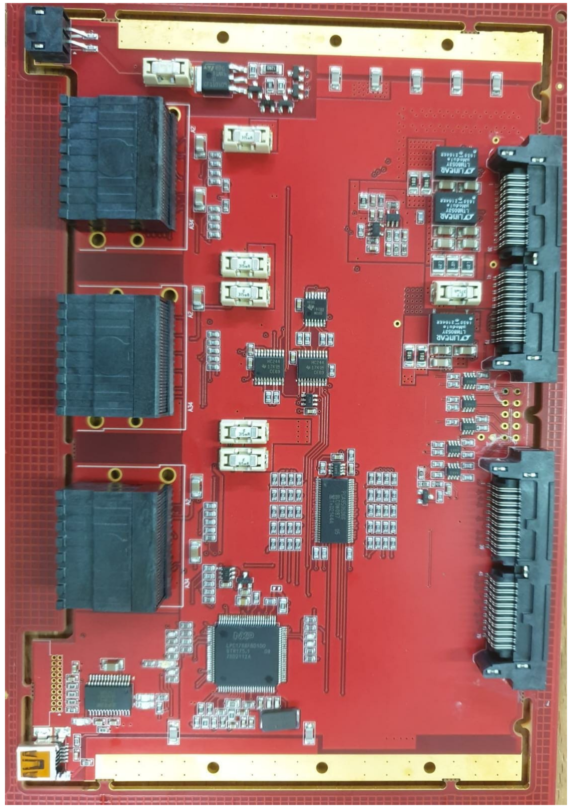


- 8 crystals measured;
- LY OK with requirements
- LRU,FT,Eres in specs
- No recovery observed with time

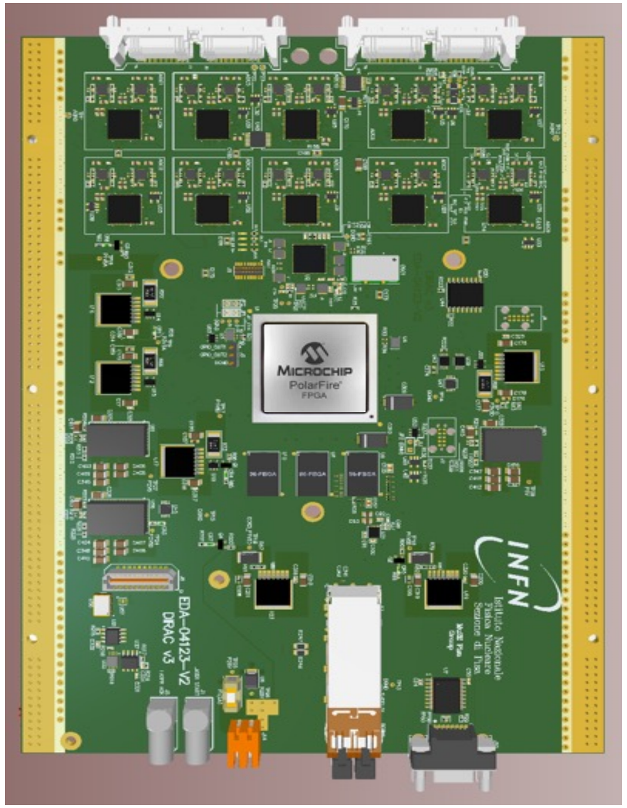
MZB and Dirac

- After final irradiation (TID and neutrons) and B tests → design frozen
- CRR completed in September 2021 and recommendations replied
- Tender assigned. MB pre-series started end of 2021
- First 10 "pre-series" boards delivered in March 2022
  - Test of firmware, QC and Burn In done in June
- After final tests, new **pre-series production of 10 boards expected for september 2022**

- **5 V3 DIRAC prototypes already produced**
  - 5 ns sampling, zero suppression
  - New rad-hard FPGA "POLARFIRE"
  - VTRX for optical link readout
- All componentes ready for DIRAC production apart FPGA due to **Covid supply chain** delay issues → ***delivery expected for spring 2023***



Pre-series Mezzanine board

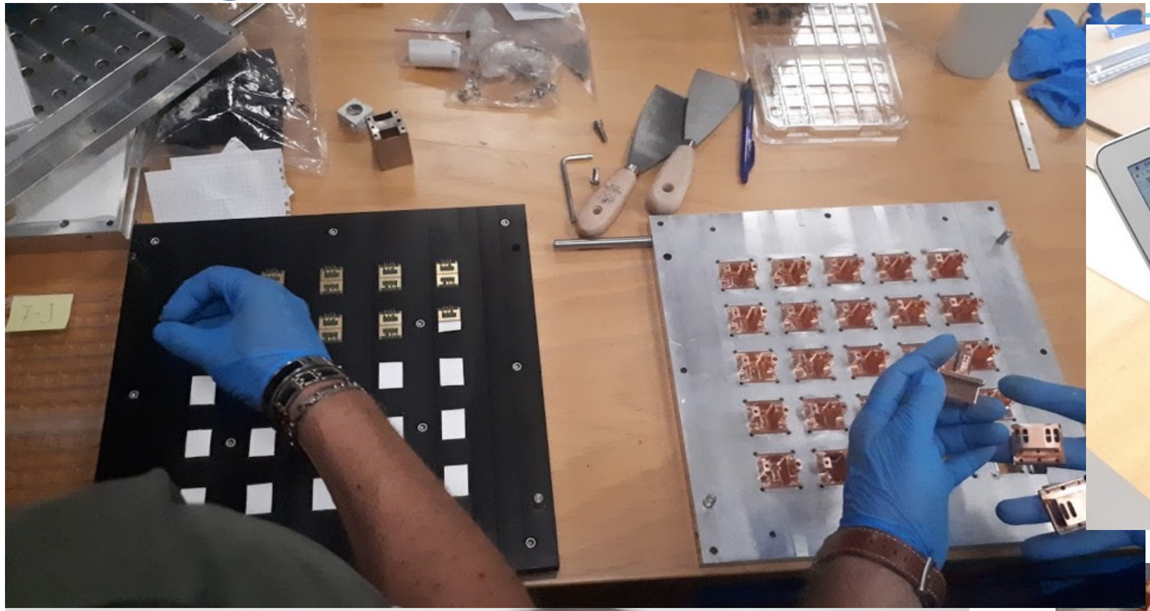


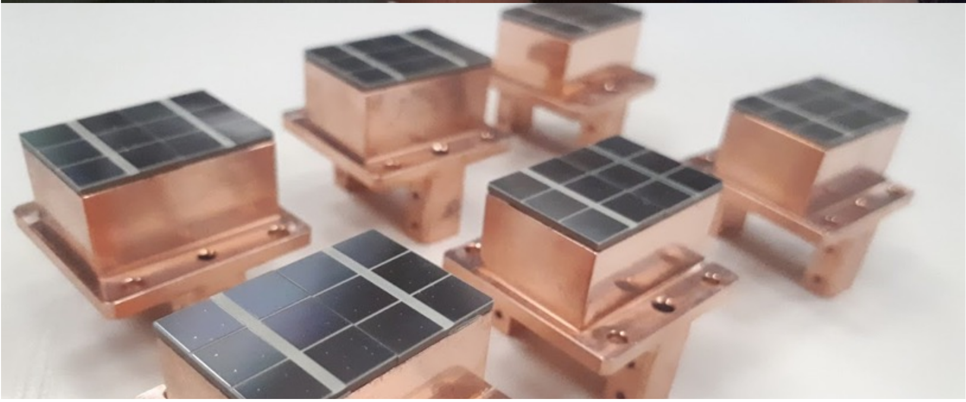
DIRAC board

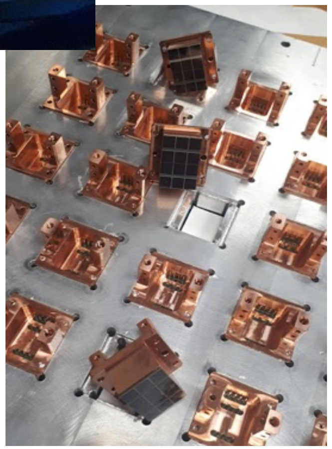
SiPM gluing on copper holders

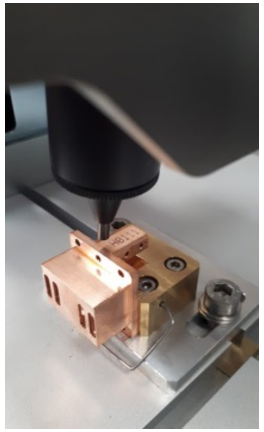
- All SiPM holders produced (1500 pieces)
- All cleaned with ultrasound batch + marked with HW numbering
- 2 SiPMs glued per Holders

1583 x2 SiPMs glued on 1583 Holders





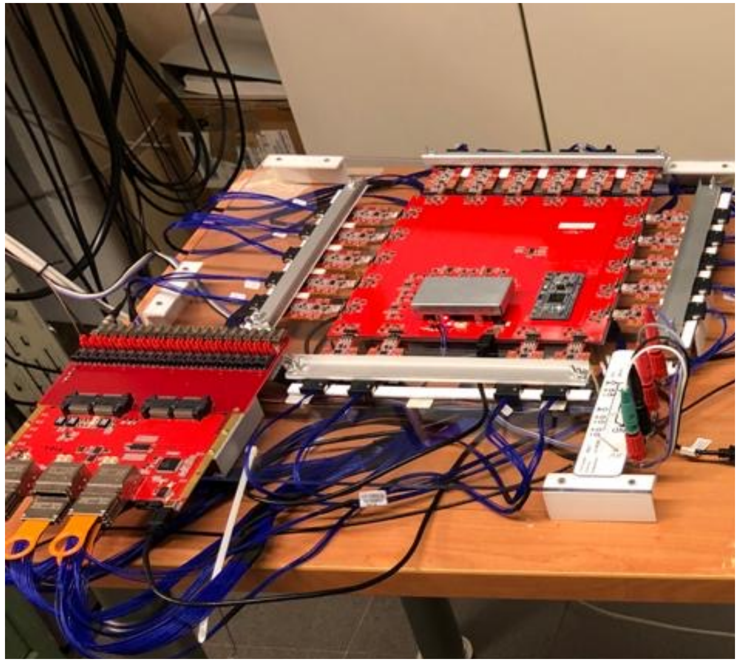


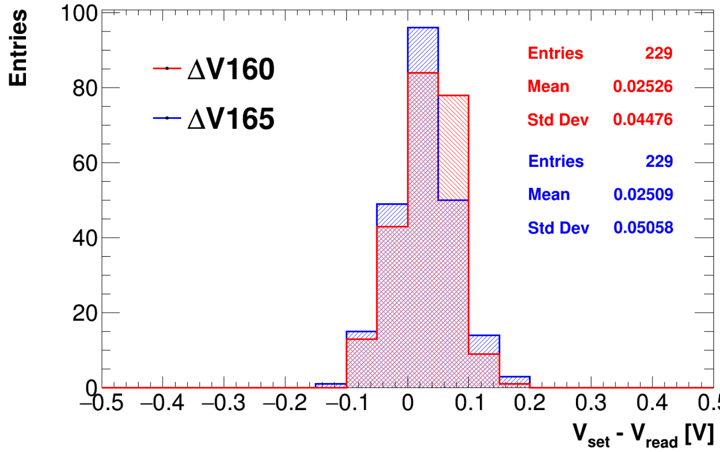


Calo electronics: FEE

- ✓ **3510 FEE boards produced**
- ✓ Two levels QC : Burn-IN in climatic chamber, Calibration of HV, amplification and signal shape.
- ✓ 2500 done and back to LNF → HV calibration performed again @ LNF for cross-check
- ✓ 800 still at JINR ➔ **problems due to Ucrain- Russia war**

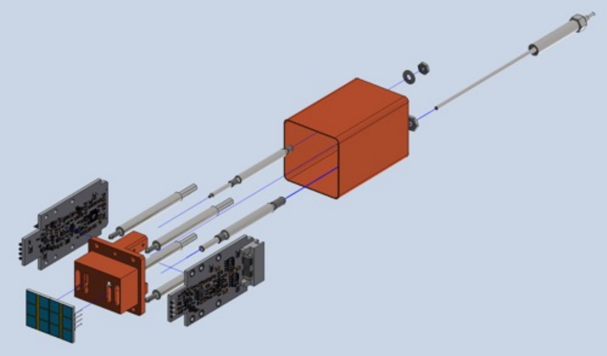
Impossible to get them back
Elevated to Risk

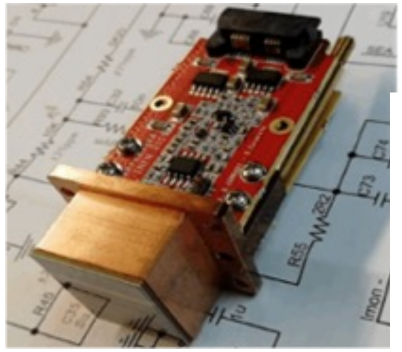


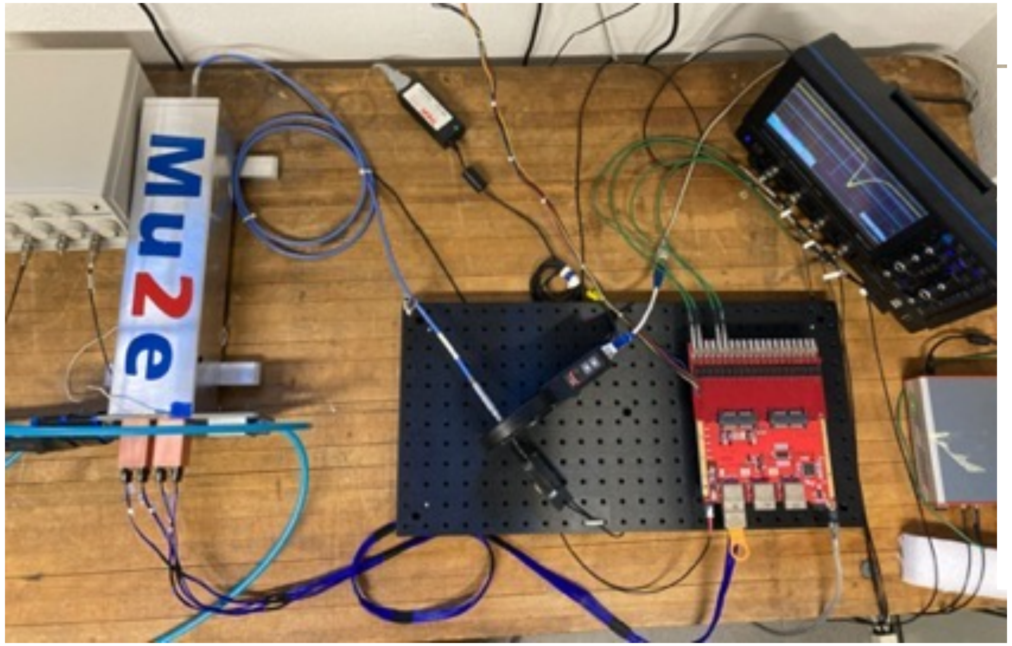


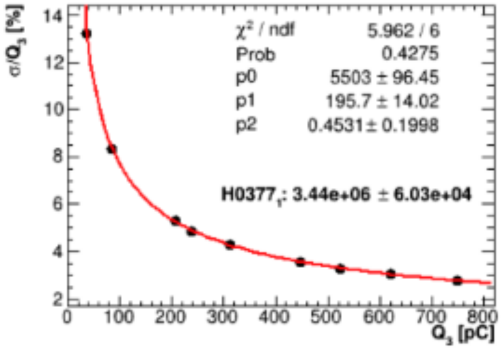
Readout Units (SiPM+FEE+FC) status

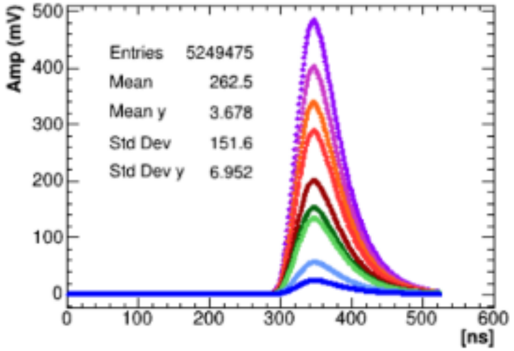
- **1066/1500** Holders + Faraday Cage **(RO)** assembled

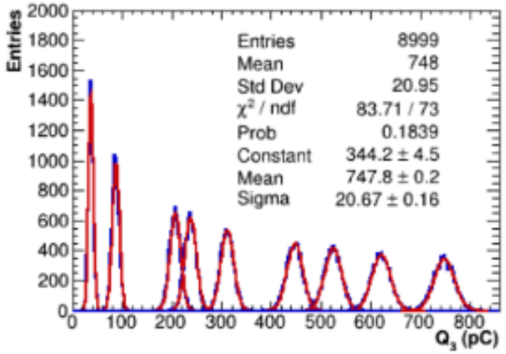


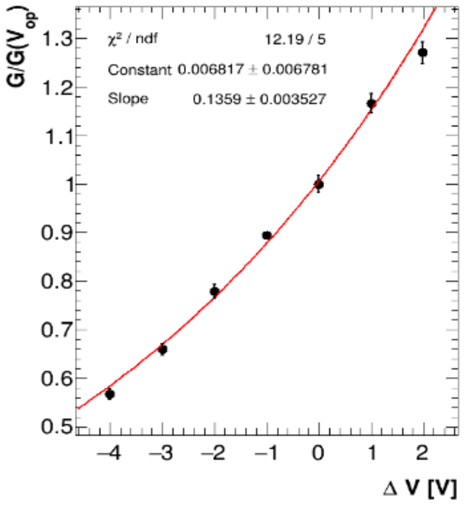


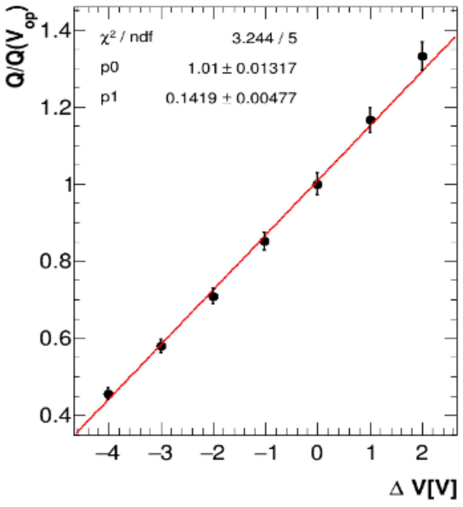


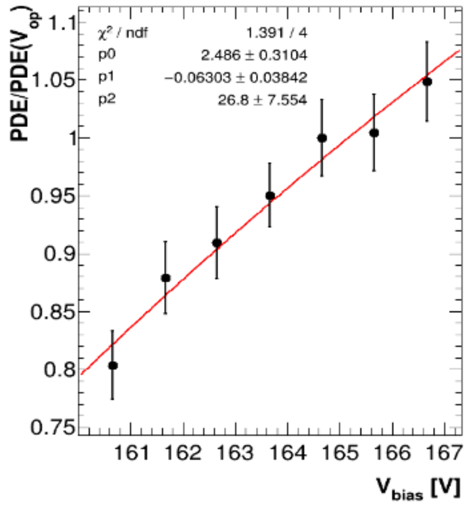




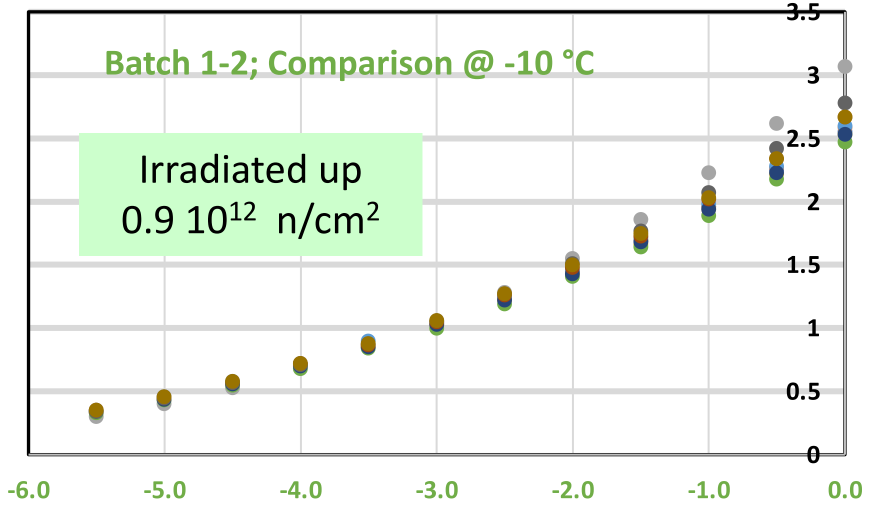


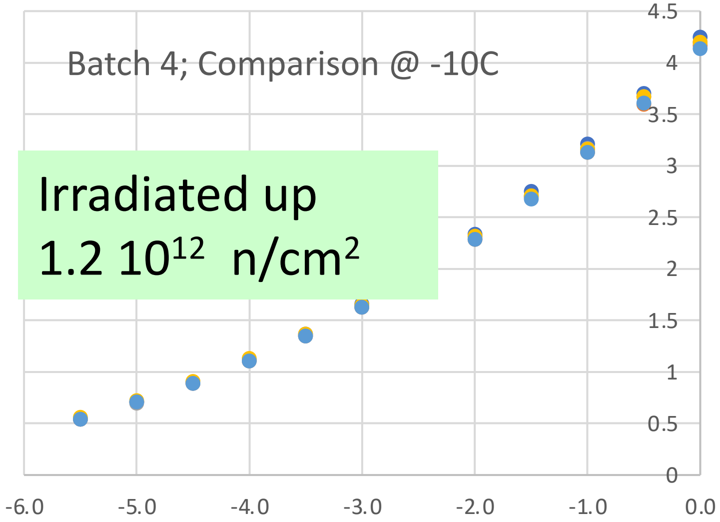


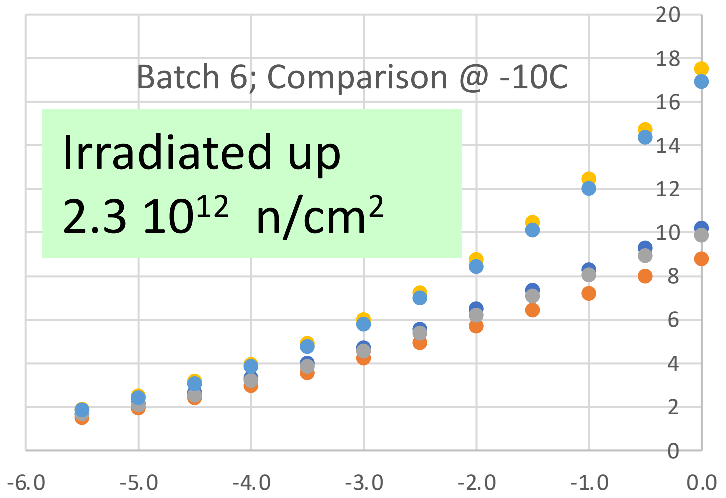




Production SiPM irradiation with neutron





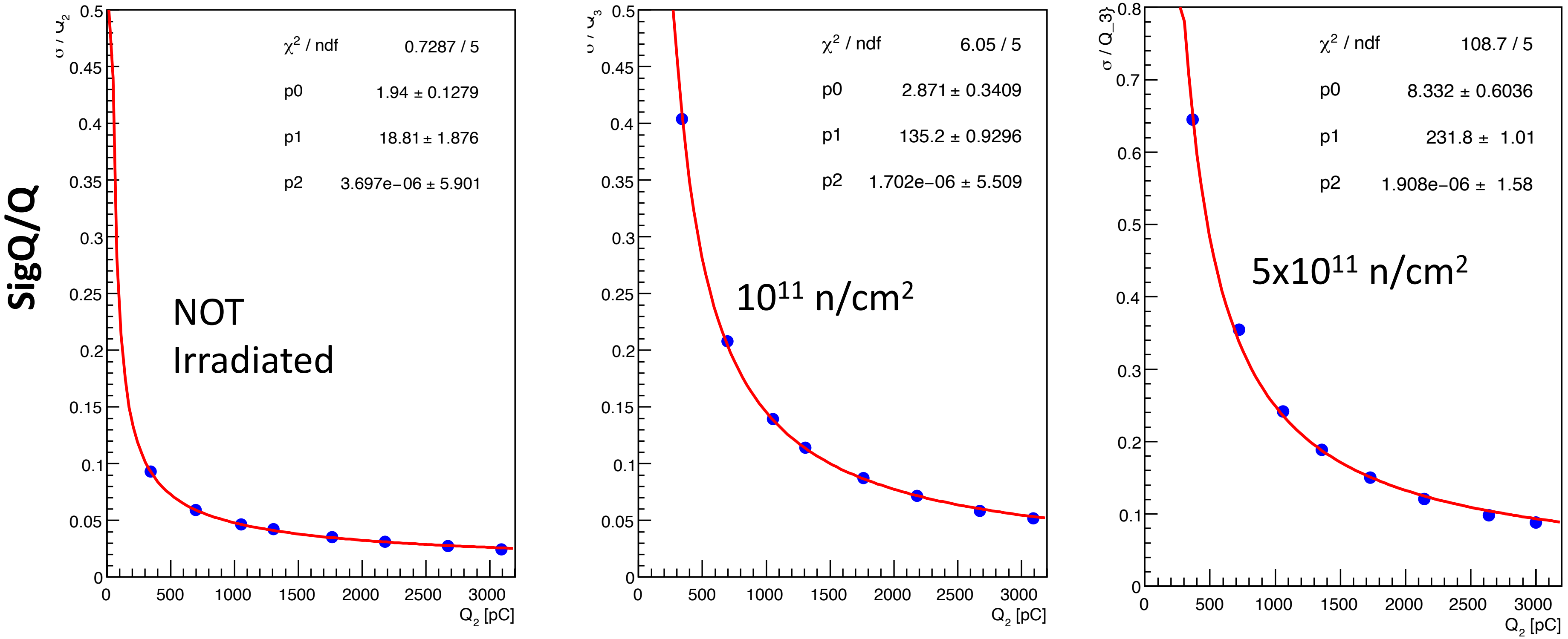


- 5 SiPMs/batch "passively" neutron irradiated @ Dresden
- For Mu2e, the max n-flux in SiPM area is of around 4×10^{10} n/cm^2

- Safety Factor 3(MC)x5(Years)x2(Prod) = 1.2 10^{12} n/cm^2
- Max I-dark current for operation of 2 mA

➔ Requires cooling of -10 C, Lower operation overvoltage to Vop-3V (for the MU2E series) , 20% of PDE relative loss

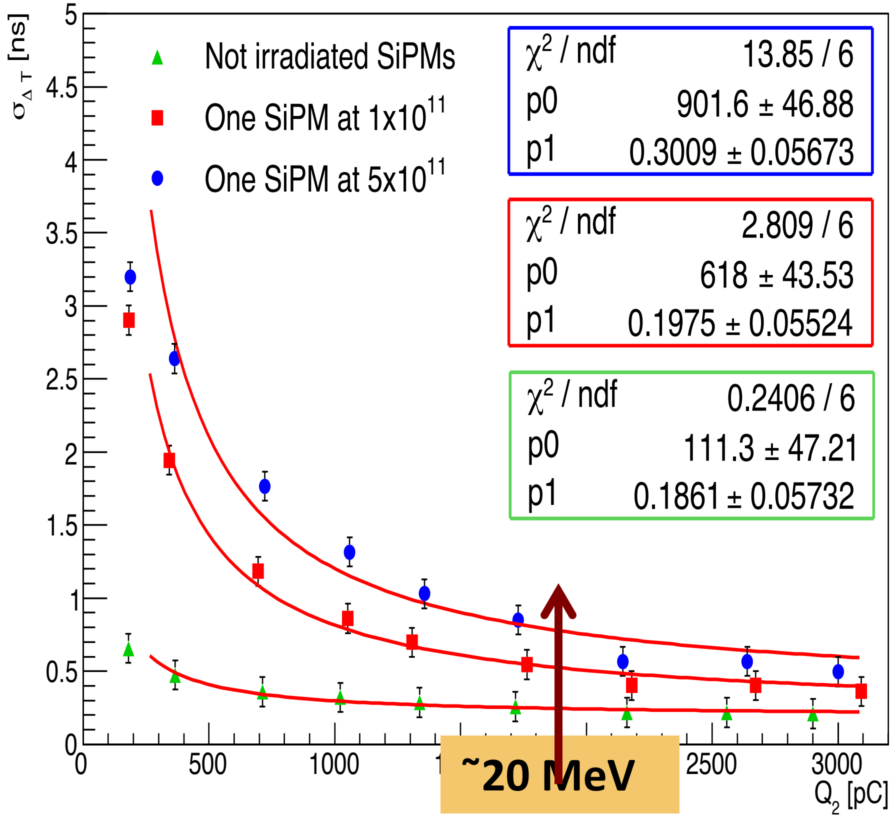
Laser Energy res with irradiated SiPMs @ 0 °C



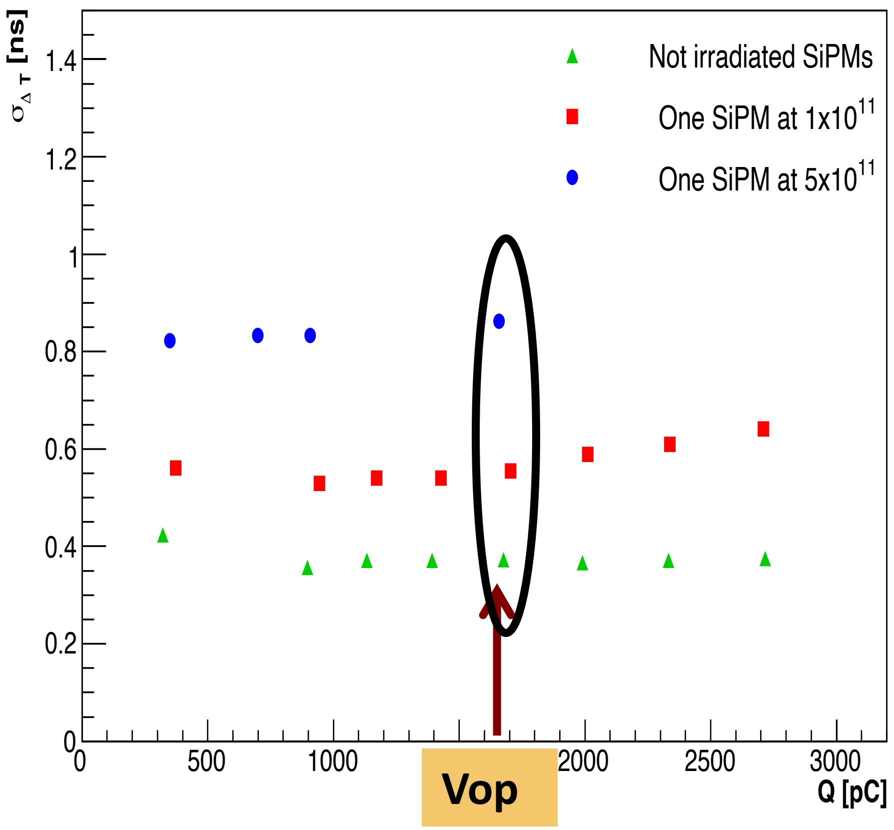
- ➔ Laser light used to illuminate SiPMs in Module-0
- ➔ This allowed to do fast scans + collect a lot of statistics in different configurations
- ➔ Noise increase shown by P1 param → 18 pC, 136 pC, 231 pC for not irradiated, 10^{11} and 5 x 10^{11} n/cm^2 respectively

Summary of “n” SiPM tests with Laser

Time resolution vs Pulse Height

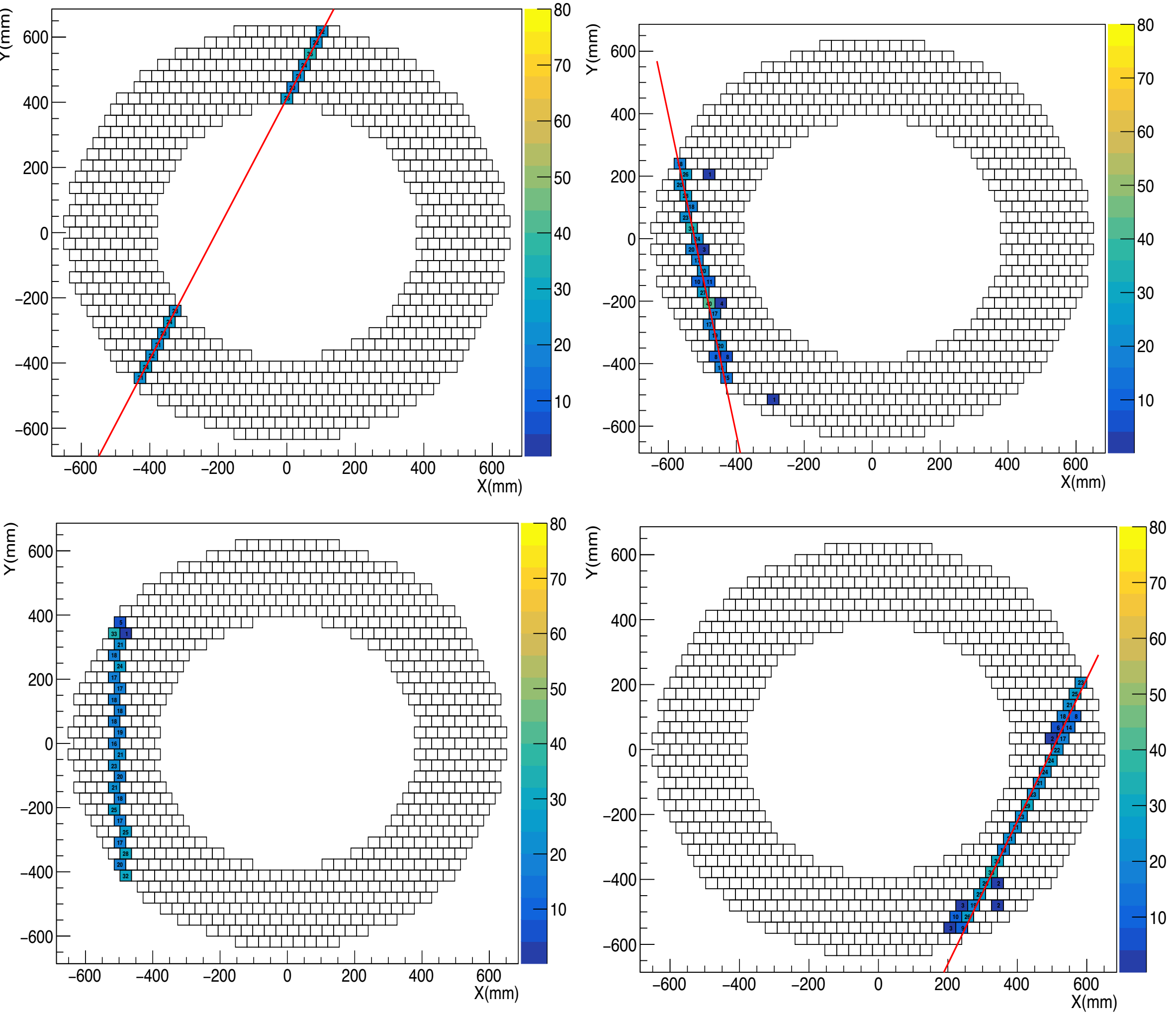


Time resolution vs Vbias



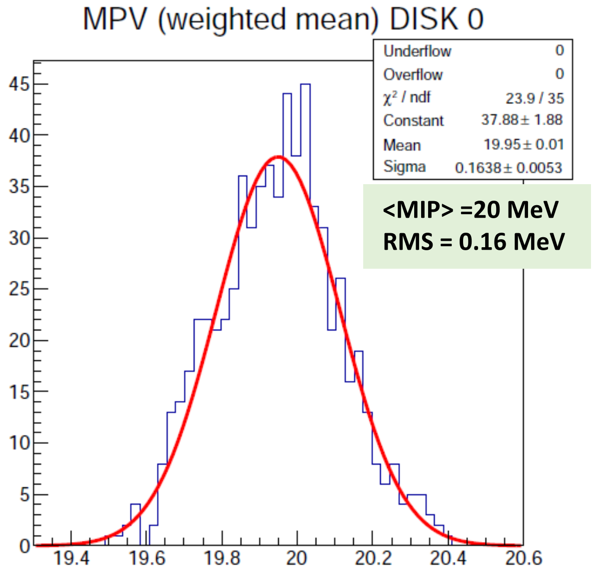
- First estimate is that one single sensor will get around 800 ps resolution at 5×10^{11} n/cm2 for an energy deposit of O(30 MeV).
- Factor of sqrt(2) achieved using two sensors/crystal → **560 ps , close to requirement**

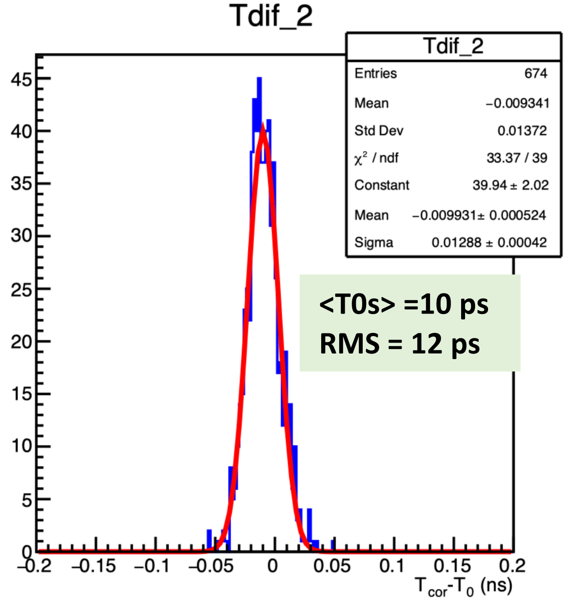
Simulated Cosmic Ray Tracks



- Software trigger selection completed
- 6 hours needed calibrate:
- energy scale @ 0.8 %
- T0 alignment at 10 ps

→ Time resolution at 200 ps/MIP





Calorimeter cooling lines , fluid

- Coolant fluid to be used is: 3M Novec 649 Engineering fluid.

3M™ Novec™ 649 Engineered Fluid is a clear, colorless and low odor fluid, one in a line of 3M products designed as replacements for ozone depleting substances (ODSs) and compounds with high global warming potentials (GWPs) such as sulfur hexafluoride (SF_6) and hydrofluorocarbons (HFCs), such as HFC-134a and HFC 245fa.

3M Novec 649 Engineered Fluid is an advanced heat transfer fluid, balancing customer needs for physical, thermal and electrical properties, with desirable environmental properties.

- MAWP (Maximum Working Pressure) : 10 Bars
- Max/Min Temperature in the pipes: -22 C – room temperature
- Max flow: Line 1 (Crates) 1.36 kg/sec, Line 2 (SiPM) 2.5 kg/sec

Material compatibility:

→Viton is excluded

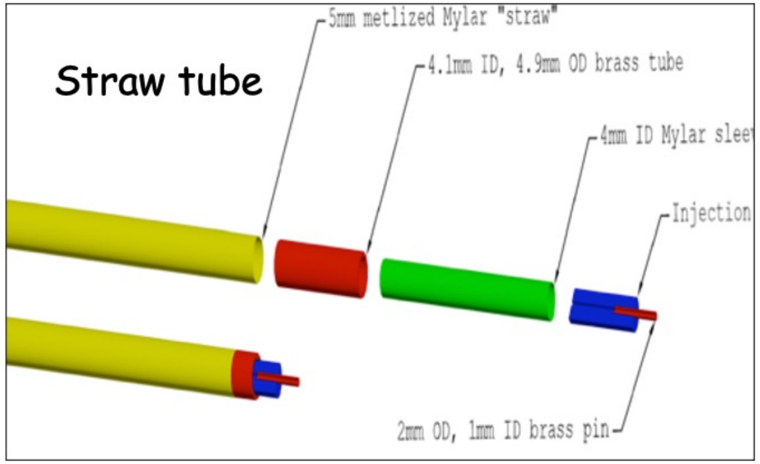
→ Gasket or O-Ring in NBR (Gomma Nitrile Butadiene)

→ Peek

Typical Physical Properties

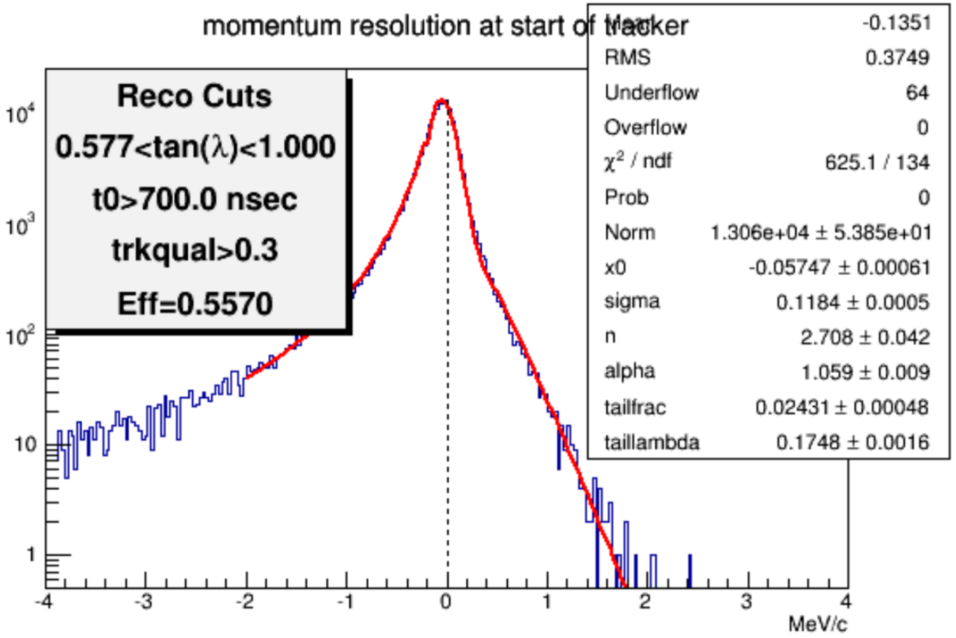
	3M™ Novec™ 649 Flu
Boiling Point(°C)	49
Pour Point (°C)	-108
Molecular Weight (g/mol)	316
Critical Temperature (°C)	169
Critical Pressure (MPa)	1.88
Vapor Pressure (kPa)	40
Heat of Vaporization (kJ/kg)	88
Liquid Density (kg/m^3)	1600
Coefficient of Expansion (K^{-1})	0.0018
Kinematic Viscosity (cSt)	0.40
Absolute Viscosity (cP)	0.64
Specific Heat (J/kg-K)	1103
Thermal Conductivity (W/m-K)	0.059
Surface Tension (mN/m)	10.8
Solubility of Water in Fluid (ppm by wt)	20
Dielectric Strength, 0.1" gap (kV)	>40
Dielectric Constant @ 1kHz	1.8
Volume Resistivity (Ohm-cm)	10^{12}
Global Warming Potential (GWP)	1

tracker

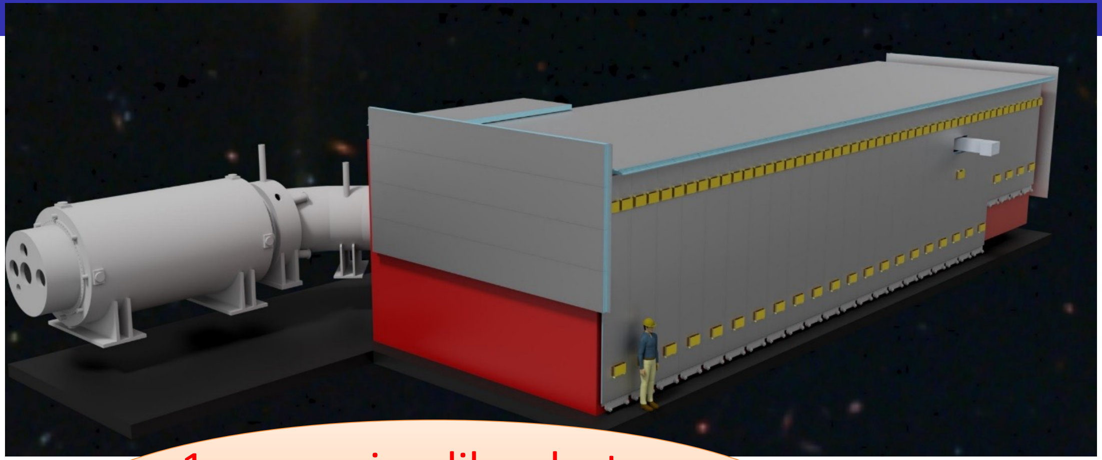


Straw Diameter	5 mm
Straw Length	430 – 1200 mm, 910 mm average
Straw Wall	15 μm Mylar (2×6.25μm plus adhesive)
Straw Metallization	500Å aluminum, inner and outer surface 200Å gold overlaid on inner surface
Gas Volume (straws only)	$4\cdot10^8$ mm³ (0.4 m³)
Sense wire	25 μm gold-plated tungsten
Drift Gas	Ar:CO_2, 80:20
Gas gain	$3\text{-}5\cdot10^4$ (exact value to be set later)
Detector Length	3196 mm (3051 mm active)
Detector Diameter	1620 mm (1400 mm active)

- Proven technology
- Low mass → minimize scattering (track typically sees ~ 0.25 % X_0)
- Modular, connections outside tracking volume
- **Challenge: straw wall thickness (15 μm)**



CRV



1 conversion-like electron per day is produced by cosmic-ray muons

Details:
- Area: 335 m^2
- 83 modules; 10 types
- 5,344 counters
- 10,688 fibers
- 19,392 SiPMs
- 4,848 Counter motherboards
- 339 Front-end Boards
- 17 Readout Controllers

- CRV identifies cosmic ray muons that produce conversion-like backgrounds.
- Design driven by need for excellent efficiency, large area, small gaps, high background rates, access to electronics, and constrained space.
- Technology: Four layers of extruded polystyrene scintillator counters with embedded wavelength shifting fibers, read out with SiPM photodetectors.
- A track stub in 3/4 layers, localized in time+space produces an Offline-veto