The Mu2e undoped CsI crystal Calorimeter

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Calorimetry for the High Energy Frontier

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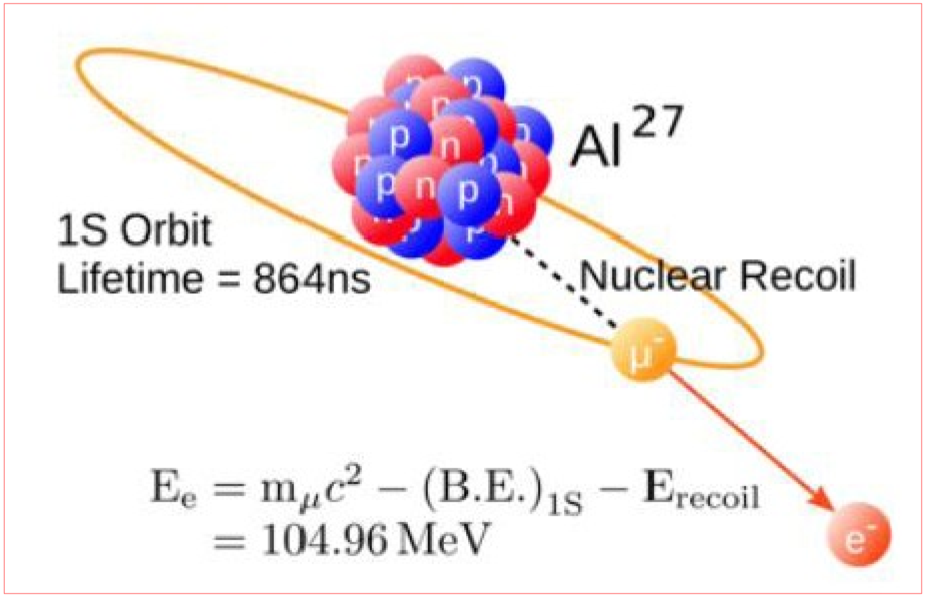
The Mu2e experiment

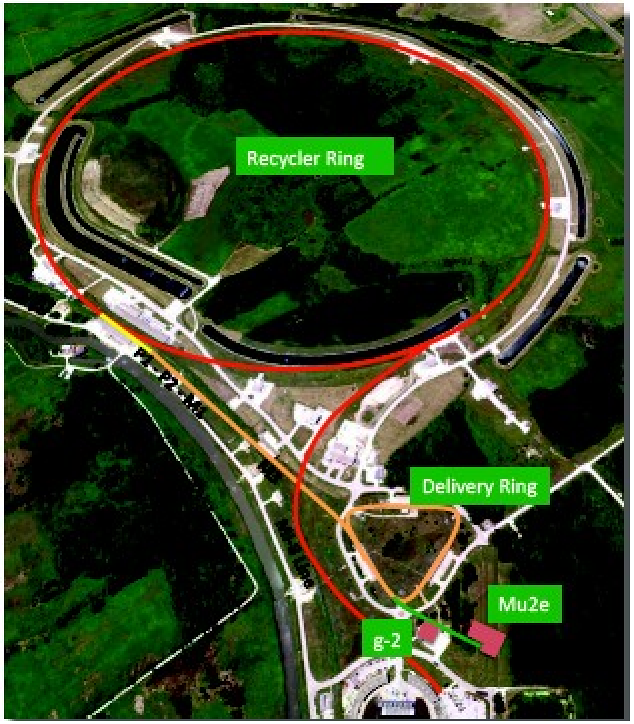
A search for **Charged Lepton Flavor Violation (CLFV)**

via the coherent conversion:

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



At Fermilab Muon Campus



Will improve by **a factor 10^4** the world best sensitivity (SINDRUM II*) on:

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

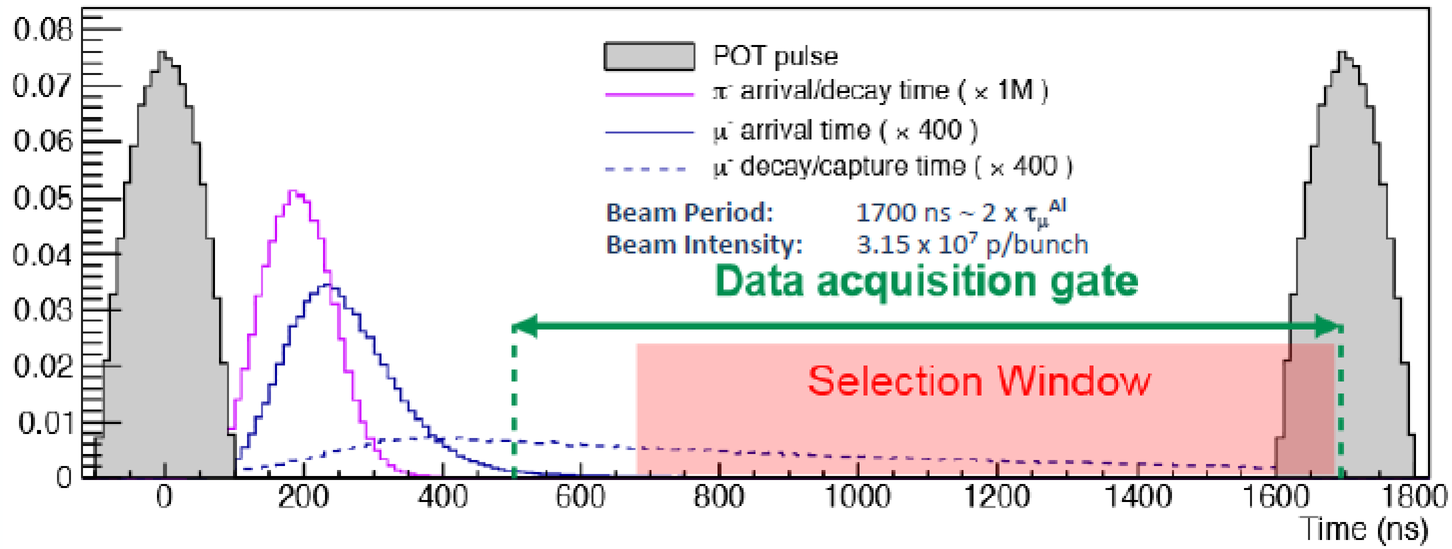
down to $3 \cdot 10^{-17}$

SM prediction is $O(10^{-54})$: any observation will be clear evidence for **New Physics**

*W. Bertl et al., Eur.Phys.J. C47,337 (2006)

The Mu2e Experiment at Fermilab: the muon beam

Pulsed Proton Beam Structure



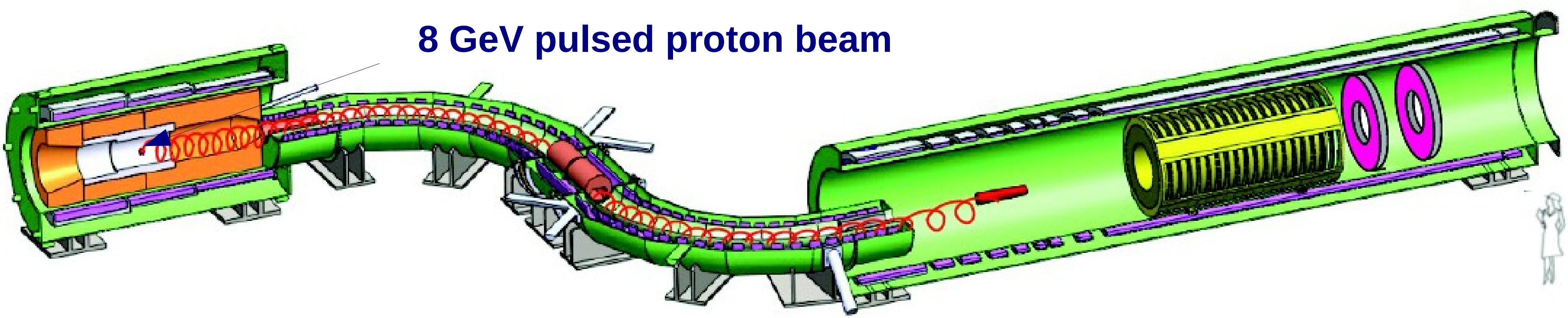
Extinction Factor <10^{-10}
(fraction of protons out of bunch)

Time window to avoid prompt background from beam flash

Production Solenoid

Transport Solenoid

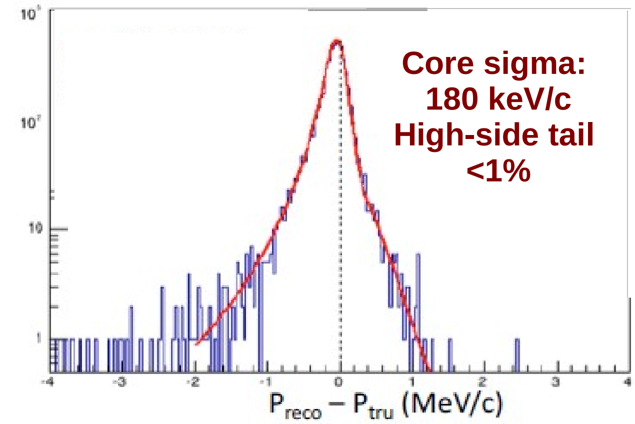
Detector Solenoid



Production Solenoid: *p* on *tungsten*, graded field sweeps low momentum particles downstream
Transport Solenoid: transmit negative particles with the right momentum, antiproton absorber
Detector Solenoid: Al stopping target, proton absorber, graded field to direct to detectors

The Mu2e Experiment at Fermilab: tracker

Momentum resolution

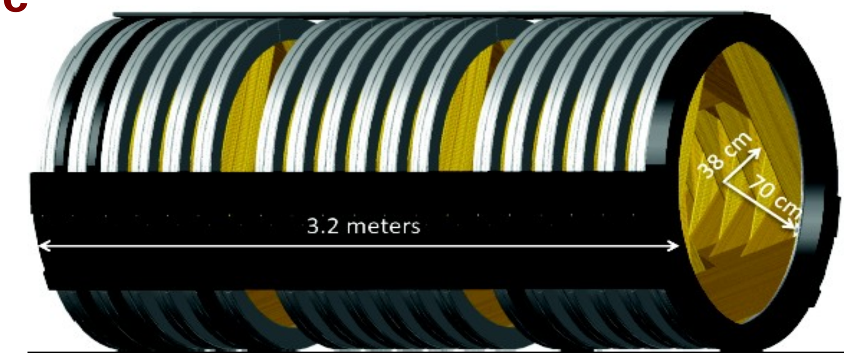


Tracker: >20k straw tubes each read by 2 ADCs and 2 TDCs

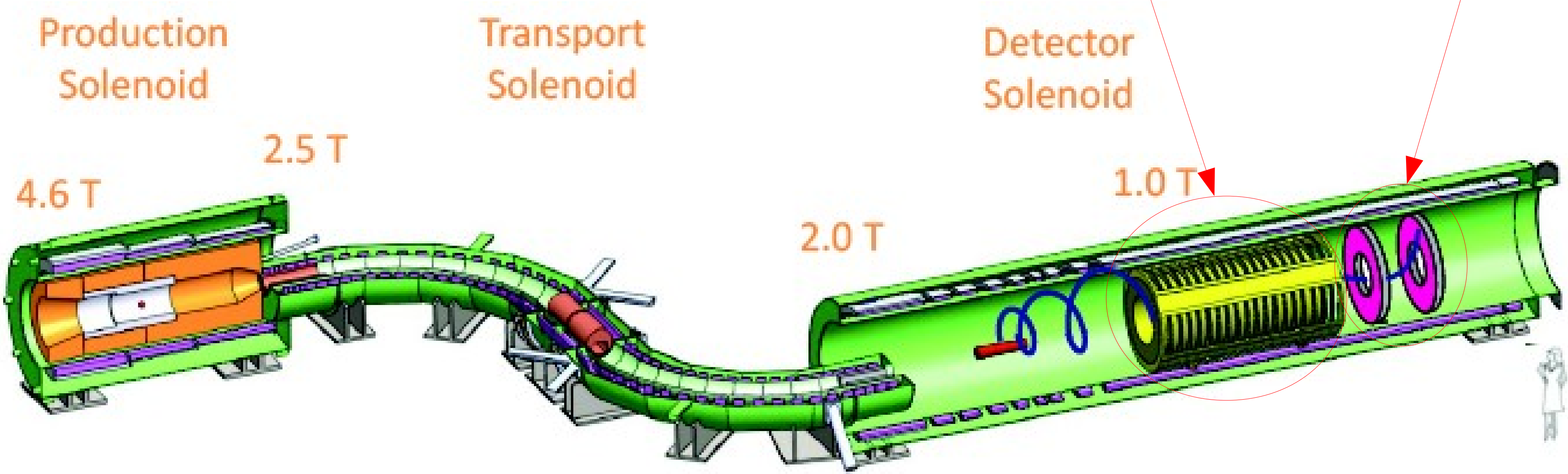
σ_p~180keV/c

σ_t~1 ns

Suppress background due to standard decays



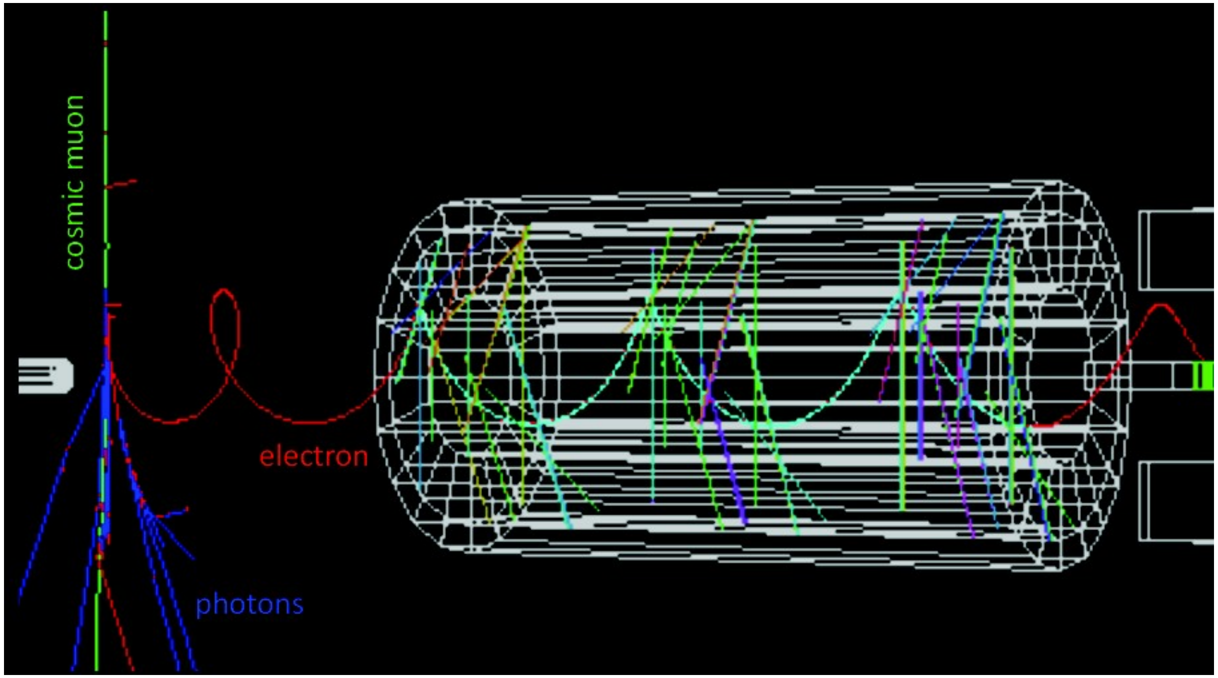
Calorimeter



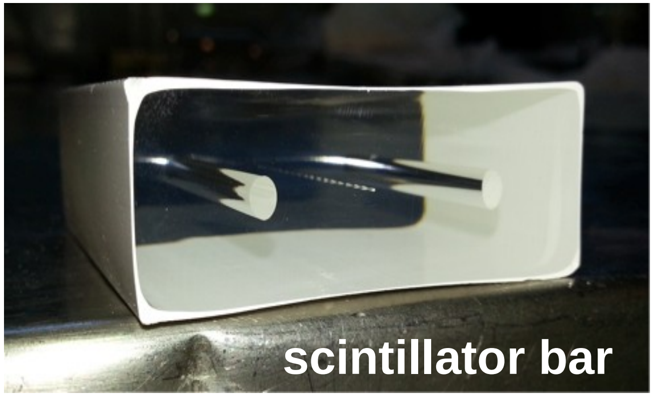
Graded fields:

suppress background, increase sensitivity to muon conversion improving geometrical acceptance

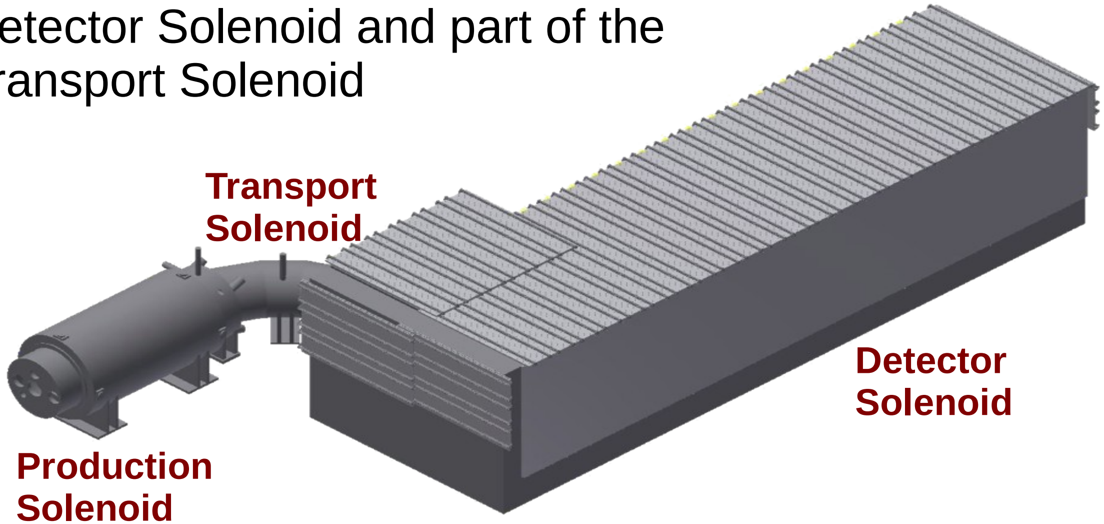
The Mu2e Experiment at Fermilab: cosmic veto

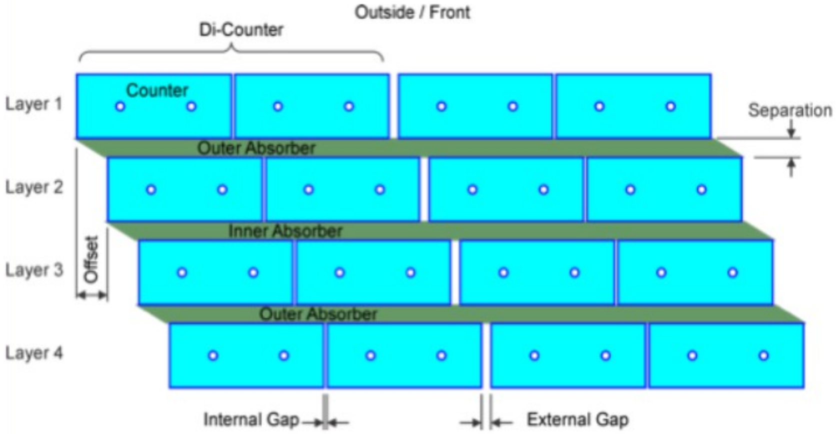


Cosmic ray induced events:
1 per day can mimic
a 105 MeV/c conversion
electron (CE)



Cosmic ray veto system surrounding Detector Solenoid and part of the Transport Solenoid





4 staggered layers of scintillator bars: inefficiency < 10^{-4}

Requirements for Mu2e calorimeter

The Mu2e electromagnetic calorimeter (ECAL) is **needed to:**

- **identify conversion electrons**

- **suppress cosmic muons** by an additional factor ~200

- **provide a tracking independent trigger** to measure tracker trigger and track reconstruction efficiency

- (optional) **seed the tracker pattern recognition** to reduce hit combinations

ECAL must operate in an **harsh experimental environment**:

- **magnetic field**: 1 T

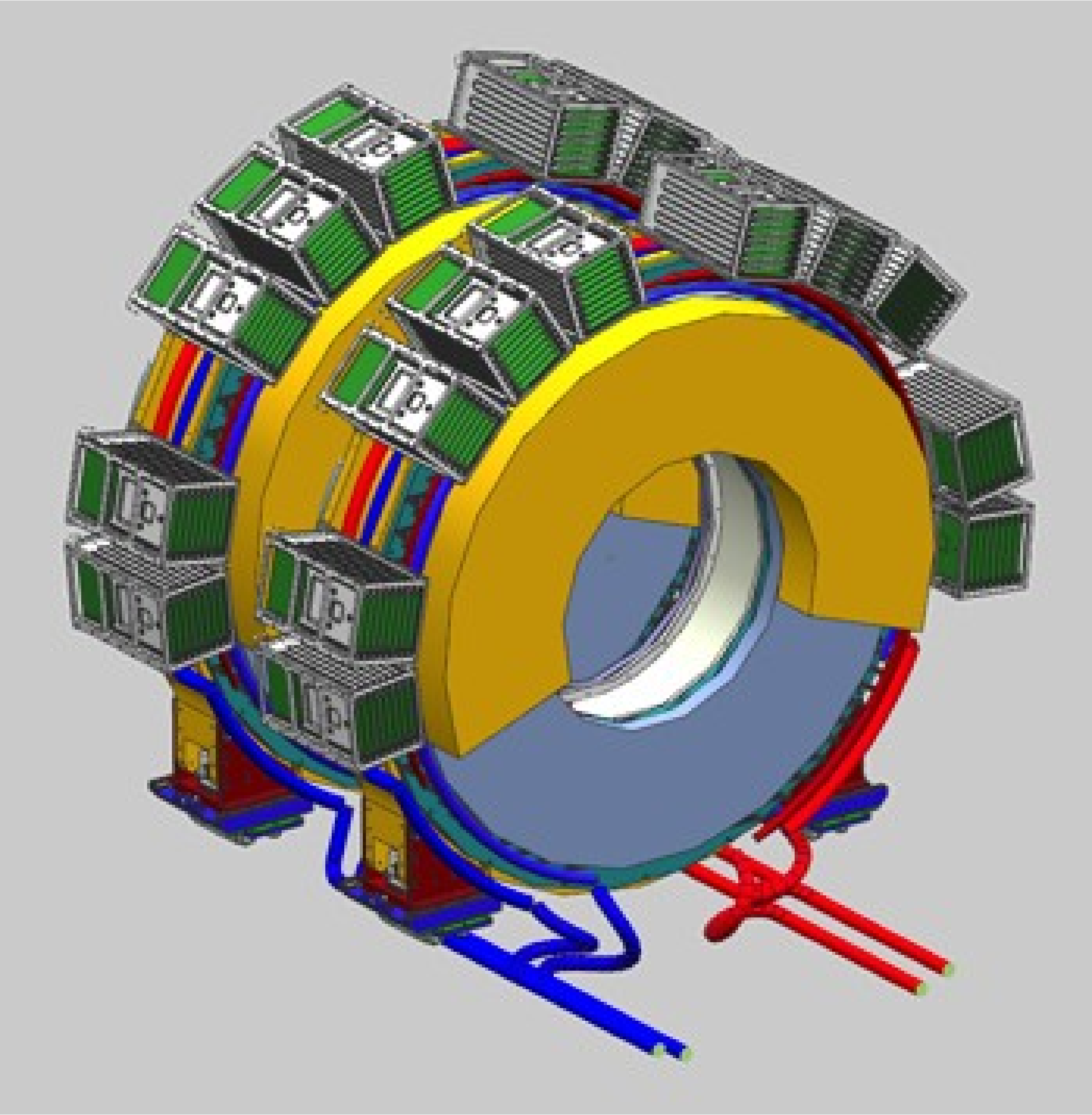
- **vacuum**: 10^{-4} Torr

- **max ionizing dose**: up to 90 krad (in 5 years including a 3 safety factor)

- **max neutron fluence**: $3\text{x}10^{12}$ $n_{(1MeV)}/cm^2$ (in 5 years including a 3 safety factor)

- **high particle rate also in selection window → granularity in time and space**

The Mu2e calorimeter



Geometry (acceptance optimized)
2 disks spaced by 70 cm
inner radius: 37.4 cm
outer radius: 66 cm

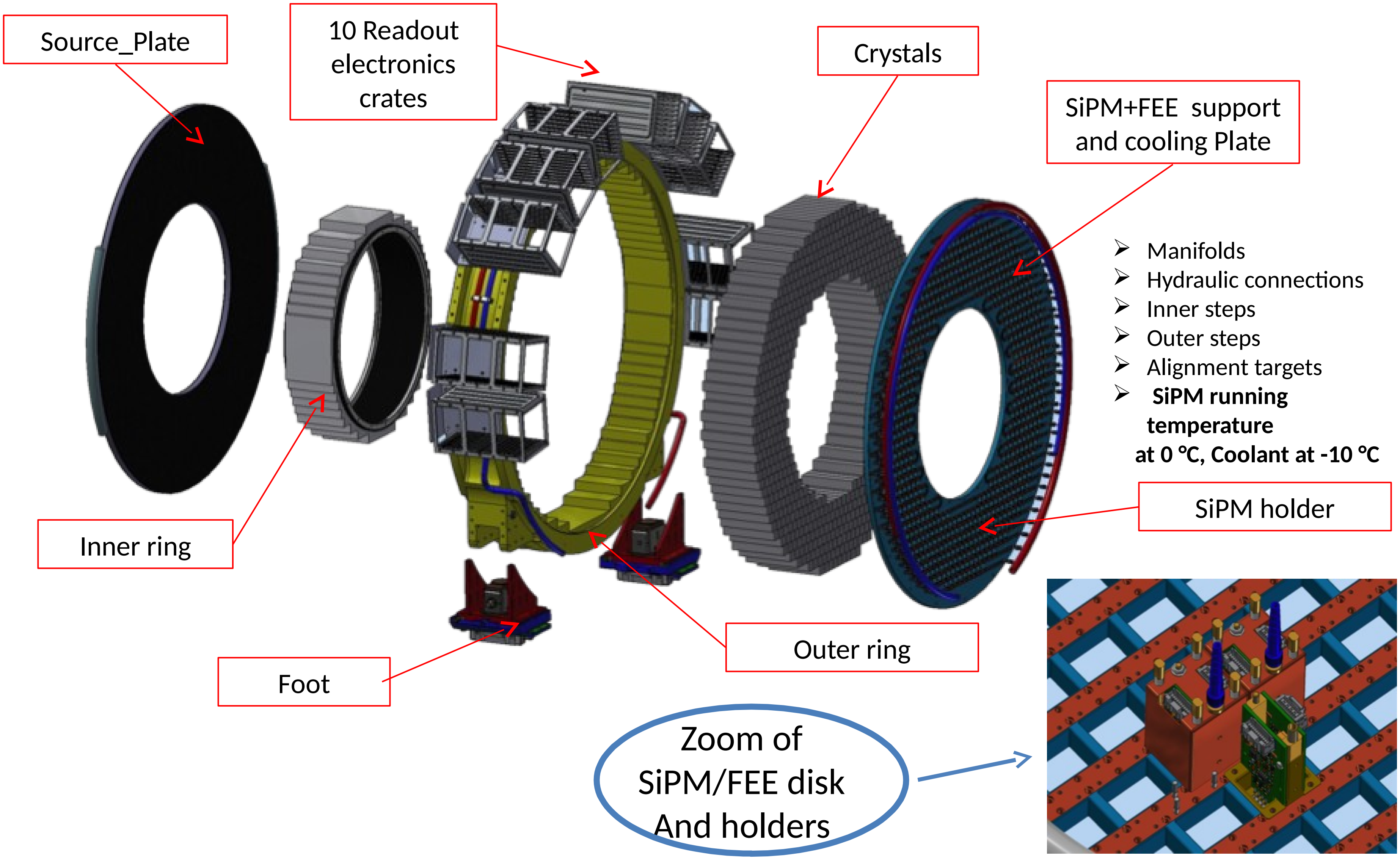
Active material:
pure CsI crystals
674 crystals/disk
3.4x3.4x20 cm^3

Sensors:
Arrays of 6 UV-extended of SiPMs
2 arrays/crystal of 14x20 mm^2 each

Readout electronics:
Preamplifiers on sensors back
Voltage control and Waveform
Digitizers in crates around disks

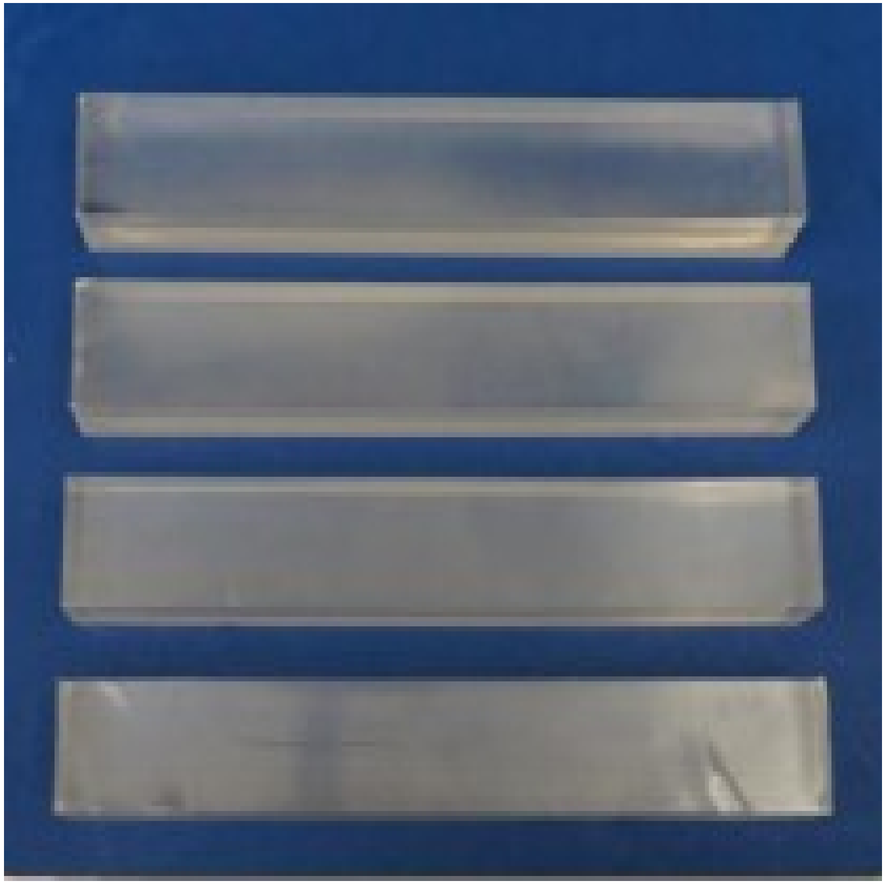
Calibration/monitoring system:
Fluorinert liquid in front of each disk
Laser and electronic pulses

Calorimeter mechanics



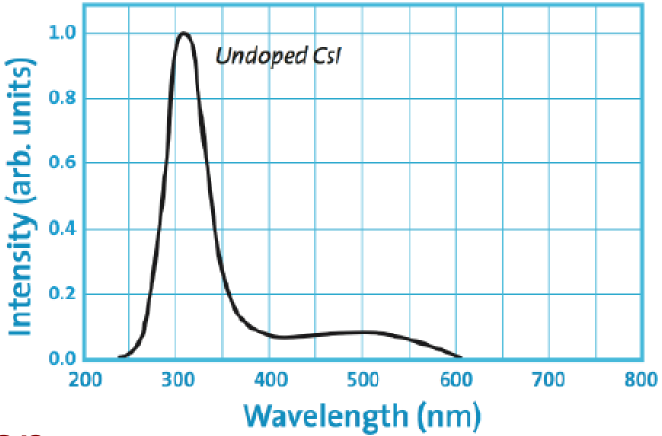
SiPM = Silicon PhotoMultiplier
FEE = Front End Electronics

ECAL CsI crystals



	CsI
Density (g/cm3)	4.51
Radiation length (cm)	1.86
Moliere Radius (cm)	3.57
Interaction length (cm)	39.3
dE/dX (MeV/cm)	5.56
Refractive index	1.95
Peak luminescence (nm)	310
Decay time (ns)	26
Light yield (rel. to NaI)	3.6%
Variation with temperature	-1.4% / deg-C

Wrapping: 150 μm Tyvek foil

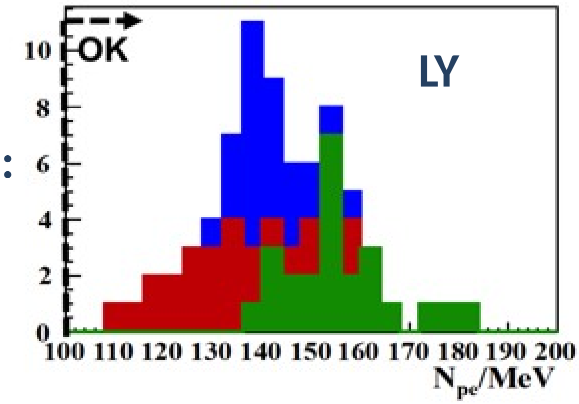


Quality tests in Caltech and Frascati (LNF):
- light yield, transmittance and response uniformity
- time response (slow component)
- ionizing and neutron rad hardness, induced emission

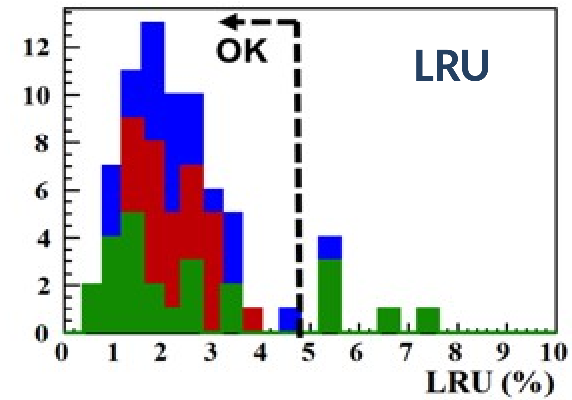
QA Tests on CsI crystals

- **3 Vendors tested: SICCAS, Saint Gobain, Amcrys**
- **First 2 selected because of lower slow component**
- **Measurement of optical properties (511 keV γ along crystal axis):**

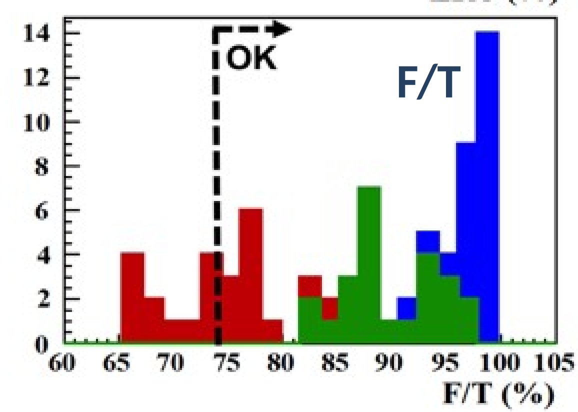
  → Light Yield (LY) > 100 p.e/MeV (with PMT readout)



  → Longitudinal Response Uniformity (LRU) < 5%



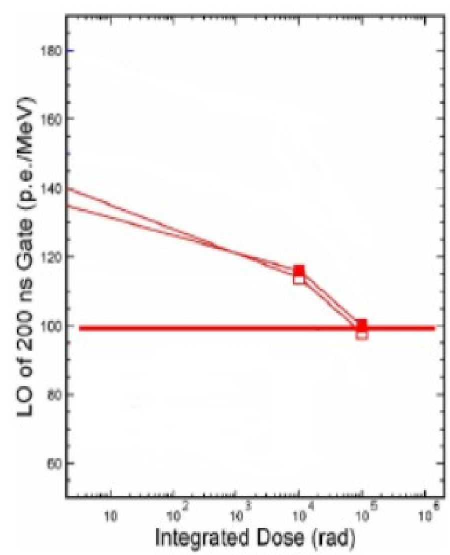
  → Fast component to Total Ratio (F/T) > 75%



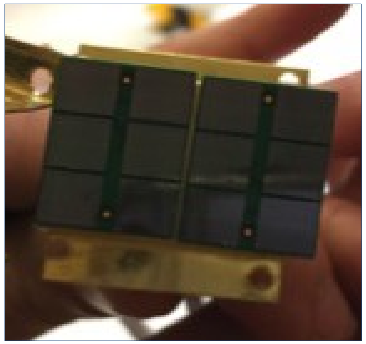
- **Measurements of radiation hardness:**

  → Radiation Induced Noise @1.8 rad/h < 0.6 MeV (phosphorescence)

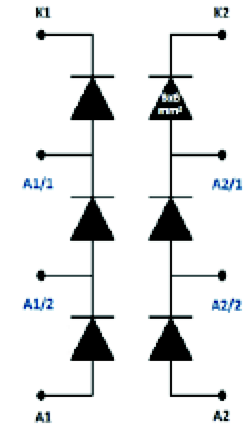
  → LY Degradation < 40% after 100 krad (check 2 crystals/batch)



UV extended SiPMs



Each crystal is coupled with 2 arrays
Each array is the parallel of 2 series
of 3 6x6 mm^2 SiPMs each:
- signal decay time ~100 ns,
- redundancy x2



Pixel pitch [μm]	50
Effective photosensitive area [mm]	6.0×6.0
Number of pixel	14400
Window material	Silicon resin
Gain (at 25° C)	2.4×10^6
PDE @ 310 nm	28%

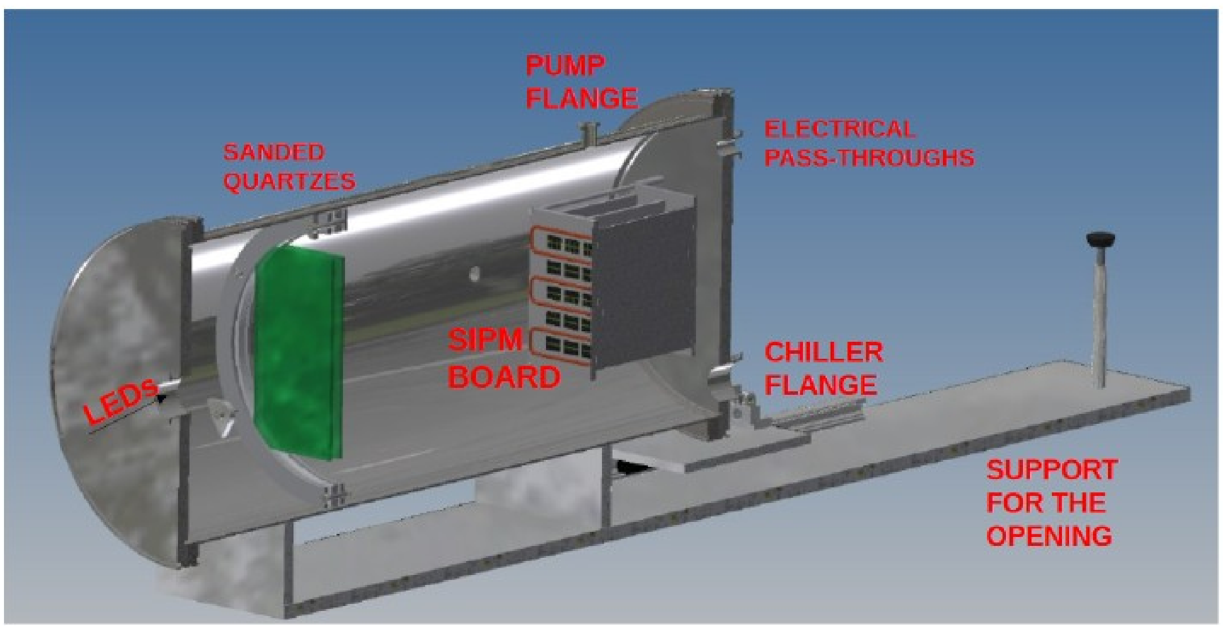
Monolithic UV extended SiPM
Particle Detection Efficiency (PDE):
~30% @ CsI emission peak

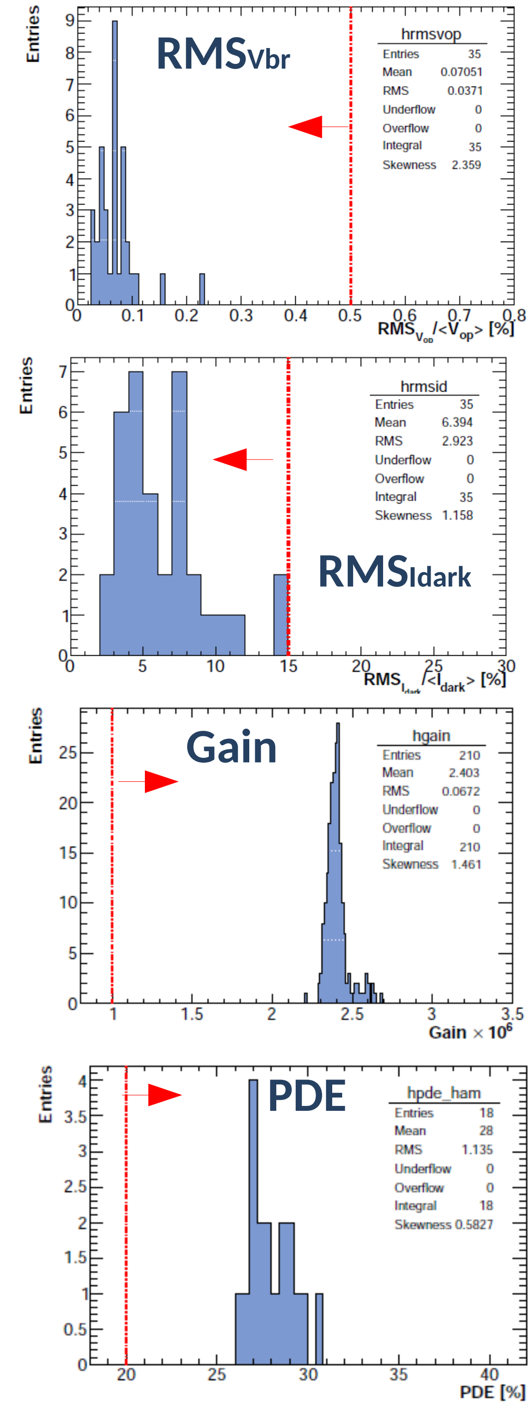
Gain at $V_{OP}=V_{BR}+3V > 10^6$

Quality tests in LNF, Pisa and Caltech:
- dark current, breakdown voltage, PDE and gain vs Temperature
- time response
- hardness to ionizing and neutron radiation, mean time to failure (MTTF)

QA Tests on SiPMs: gain and uniformity

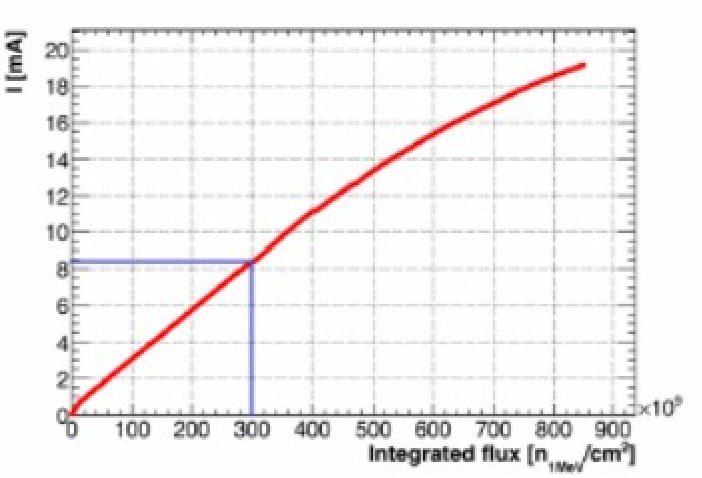
- **3 Vendors tested: Hamamatsu, Advansid, Sensl**
- First selected because of better time response
- Selection criteria ensures sensor uniformity and photoelectrons yield
- Automatized station to test sensors at single cell level:
  - → Breakdown voltage (Vbr) spread in sensor < 0.5%
  - → Dark current spread in sensor < 15%
  - → Gain > 10^6 for each cell (on a 150 ns gate)
  - → PDE > 20% for each cell





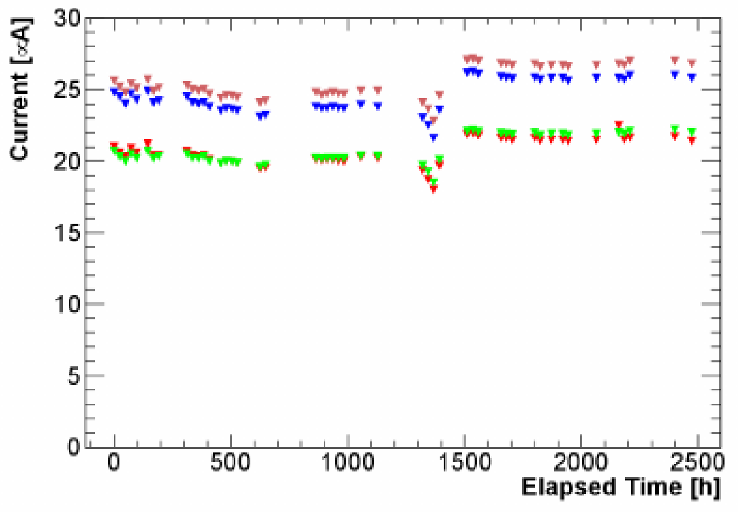
QA Tests on SiPMs: radiation hardness

- 2 samples/batch will be exposed to neutron flux up to 3×10^{11} n_{1MeVeq}/cm^2



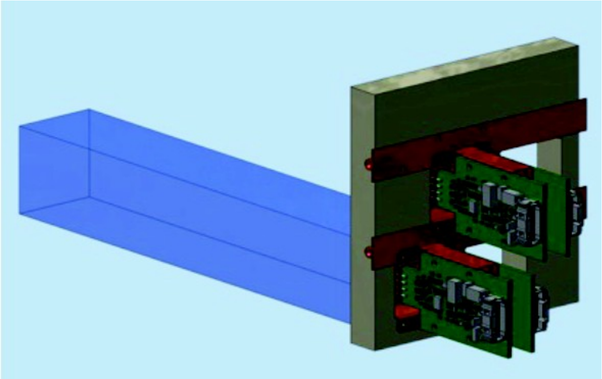
- Requirement after irradiation: **Id < 10 mA**
- In Mu2e SiPMs will operate @ 0 °C to keep the dark current below 2 mA

- 15 samples/batch will be used to estimate the mean time to failure (MTTF)

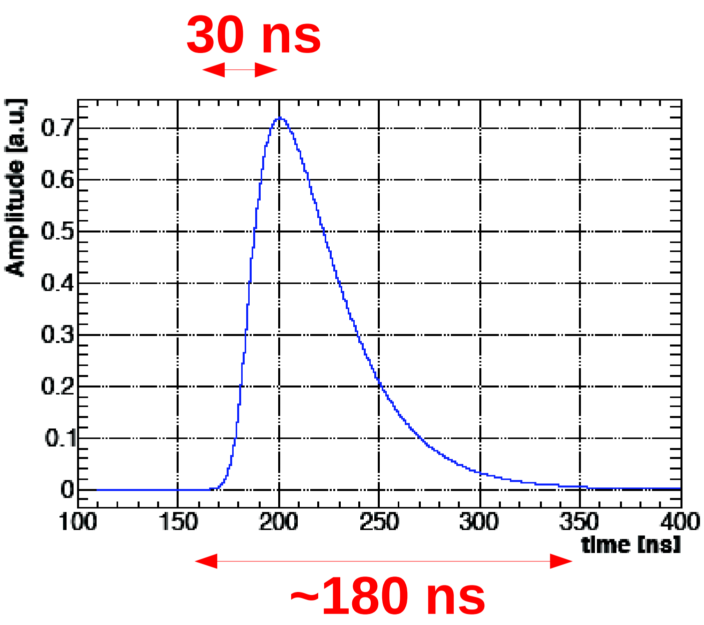


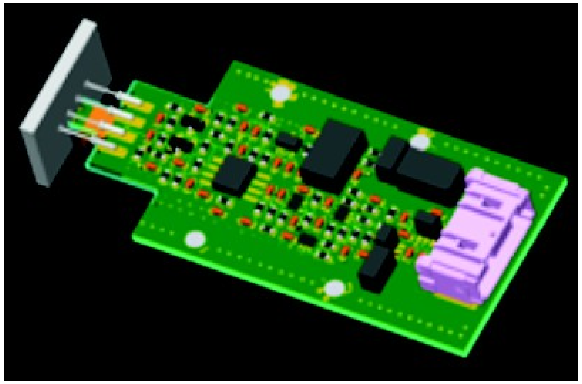
- MTTF will be evaluated operating SiPMs @ 50˚C for 30 days
- No dead channels observed
  -> **MTTF ≥ 6×10^5 hours**

Readout electronics

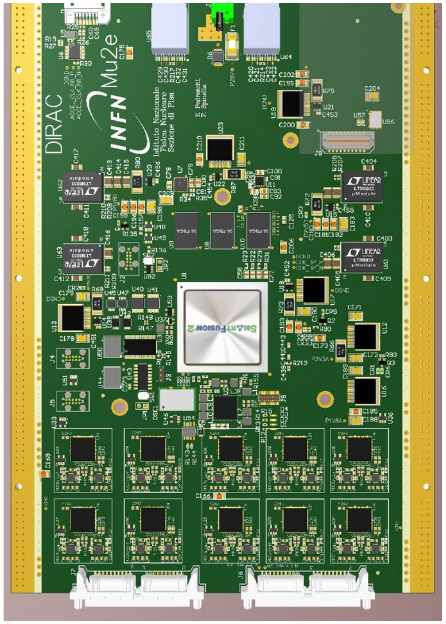


2 SiPM arrays/crystal
1 FEE board/array

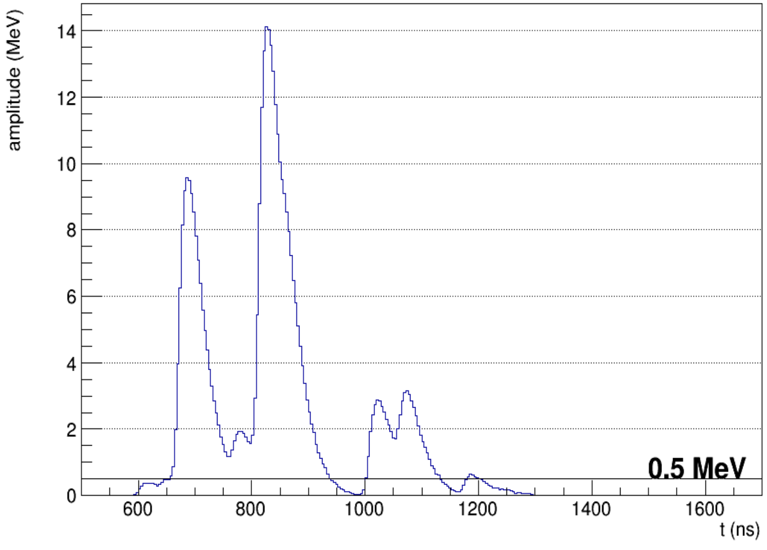




FEE board:
amplification, shaping
and voltage regulation

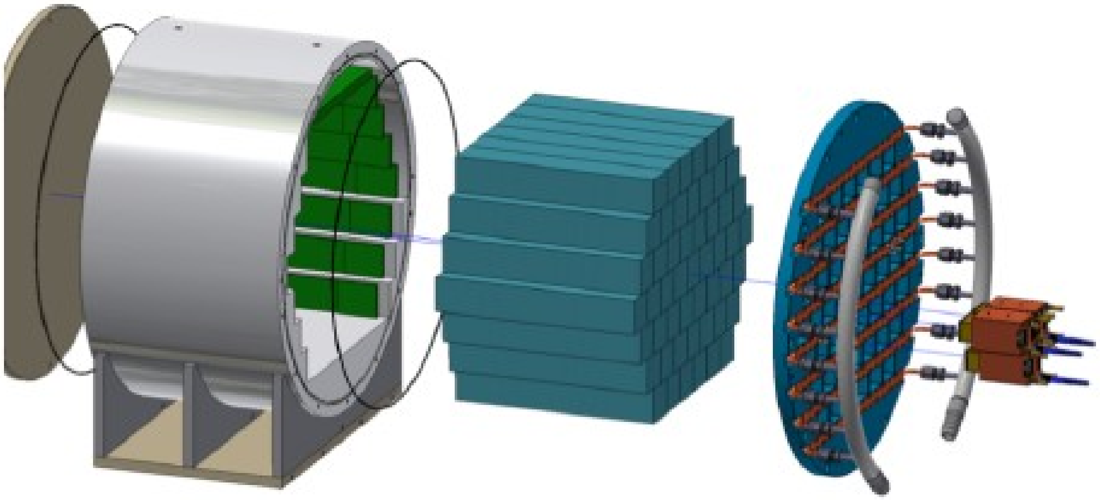


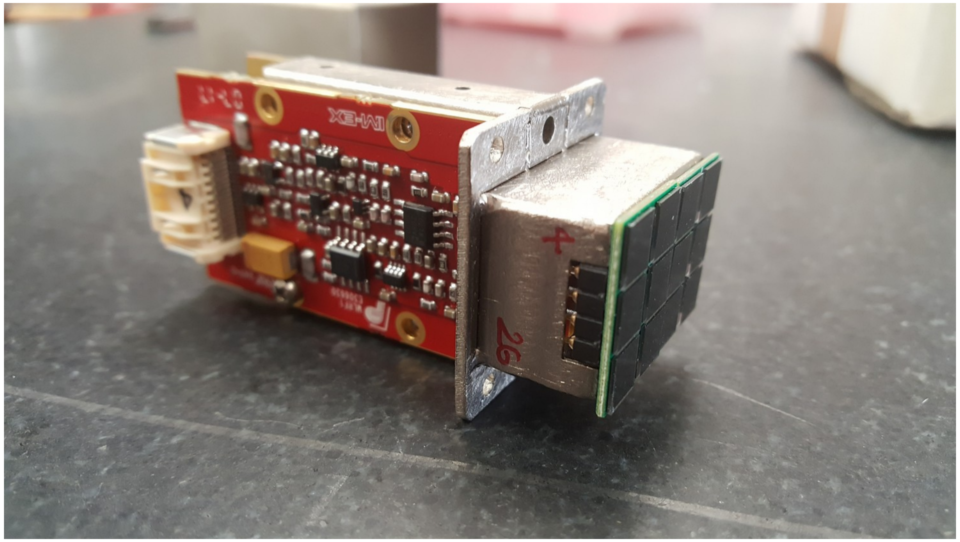
Waveform Digitizer:
Reads 20 channels
at 200 Mhz
(1 sample each 5 ns)

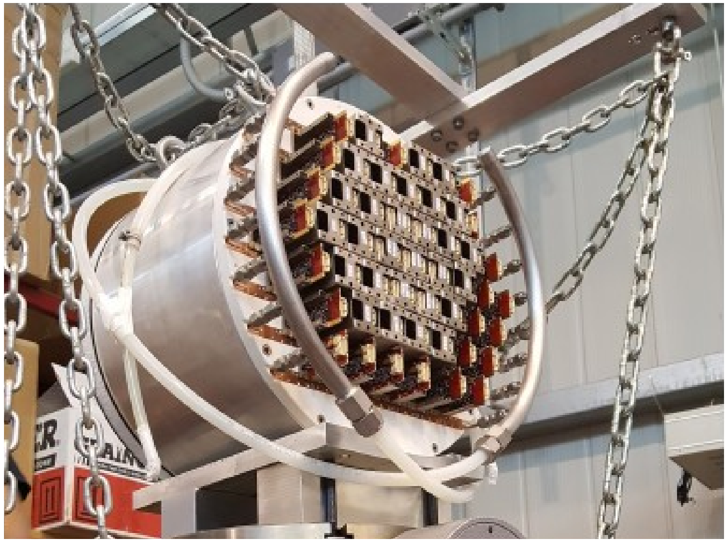


“Module 0” prototype

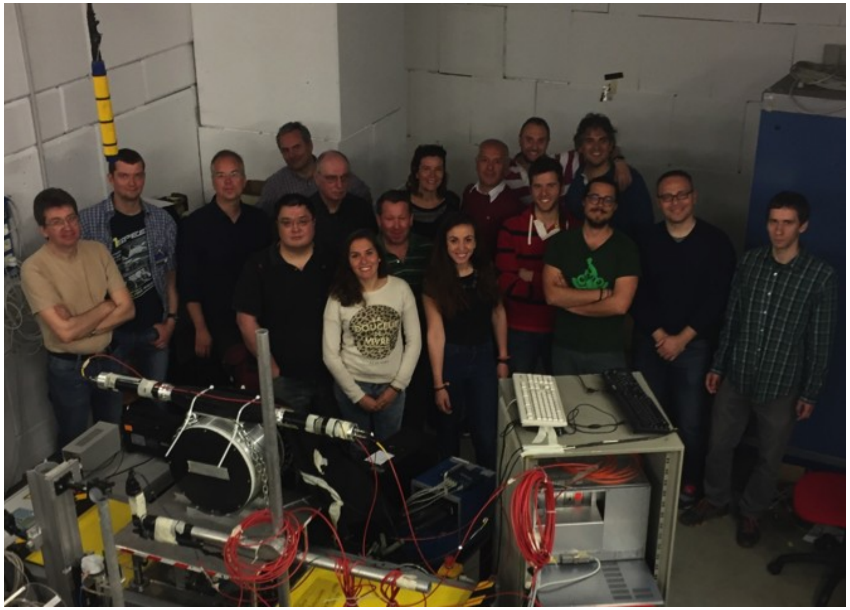
- Large size prototype in April 2017:
  - -> 51 crystals, 102 sensors
  - -> 102 FEE prototype chips
  - -> 5 MB boards prototype
- Assembled with crystals and SiPMs that passed the selection tests
- WD board prototypes under construction



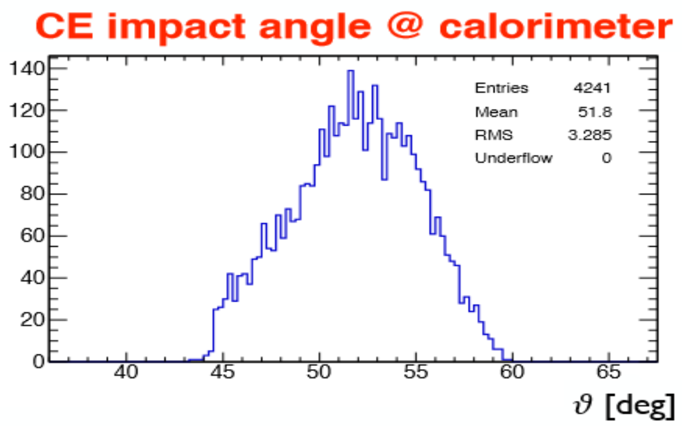




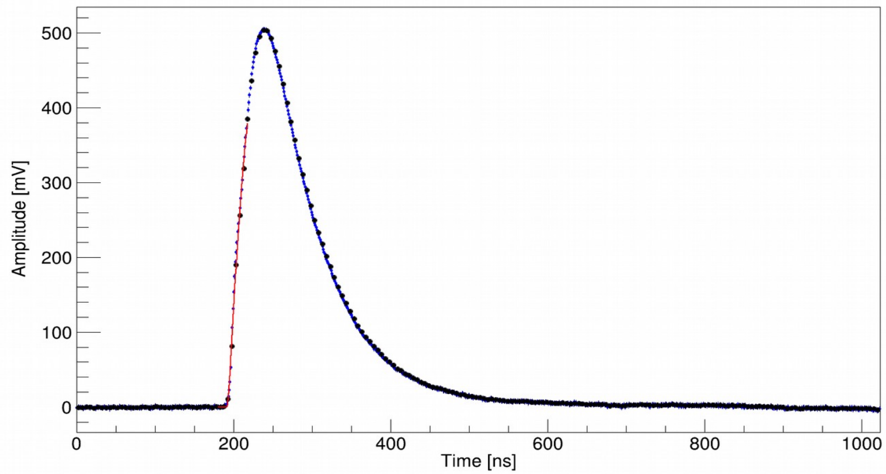
“Module 0” test beam



- Module Zero tested in May 2017 at the BTF Facility (LNF) with a 100 MeV electrons beam
- 1 GHz CAEN high-speed digitizers (DRS4 chip) used as redout (2 boards x 32 channels)
- Waveforms re-sampled at 200 MHz with software algorithm



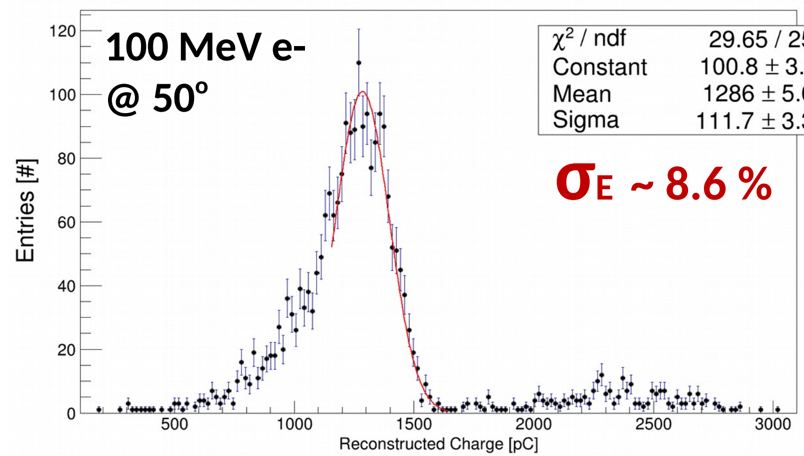
- Run Configuration:
  - Beam orthogonal @ 0 deg, fired on the center of each crystal to equalize channels
  - Beam @ 50 deg, the most probable incidence angle for Conversion Electrons, to evaluate performances

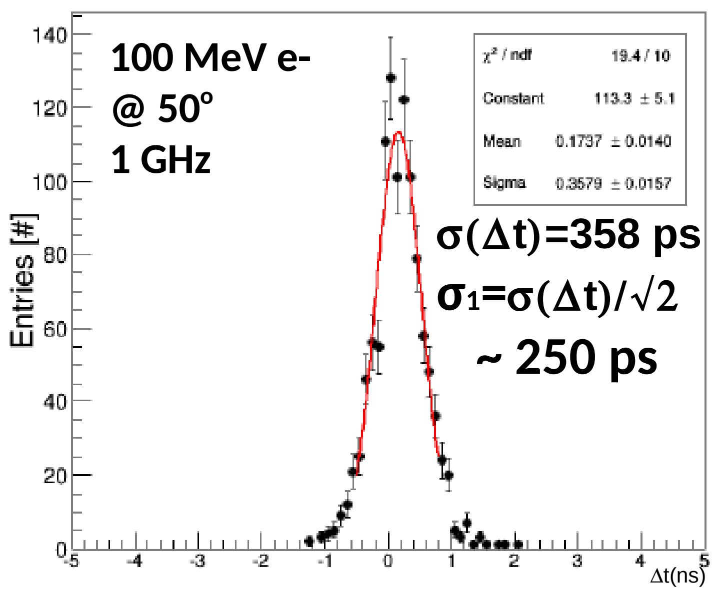


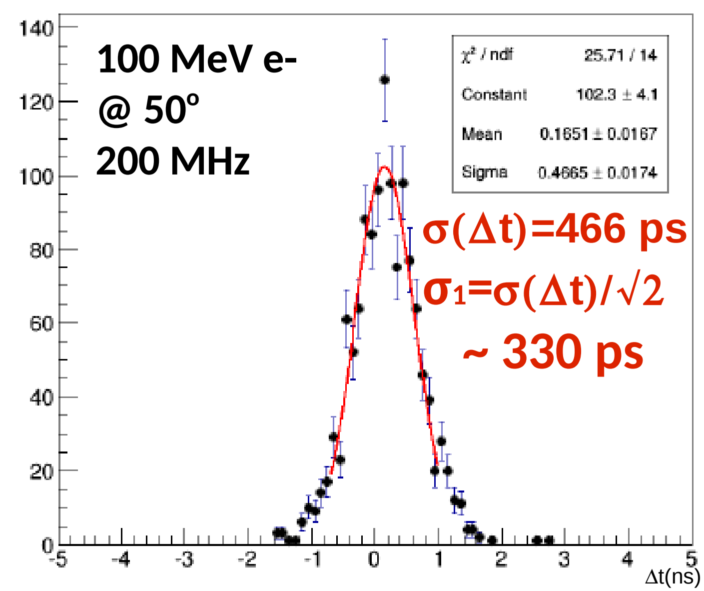
- Charge and time reconstruction:
  - **Charge**: Numerical integration of digitized samples in a 400 ns gate after pedestal subtraction
  - **Time** : Log-normal fit on leading edge, optimized constant fraction method used

“Module 0” performances for 100 MeV e⁻ at 50°

- Energy reconstructed by equalizing and summing first ring of crystals + 3 closer in beam direction
- Time resolution evaluated by the time difference of 2 sensors reading the most energetic crystal







2 sens./crystal: $\sigma_t = \sigma(\Delta t)/2 \sim 180$ ps

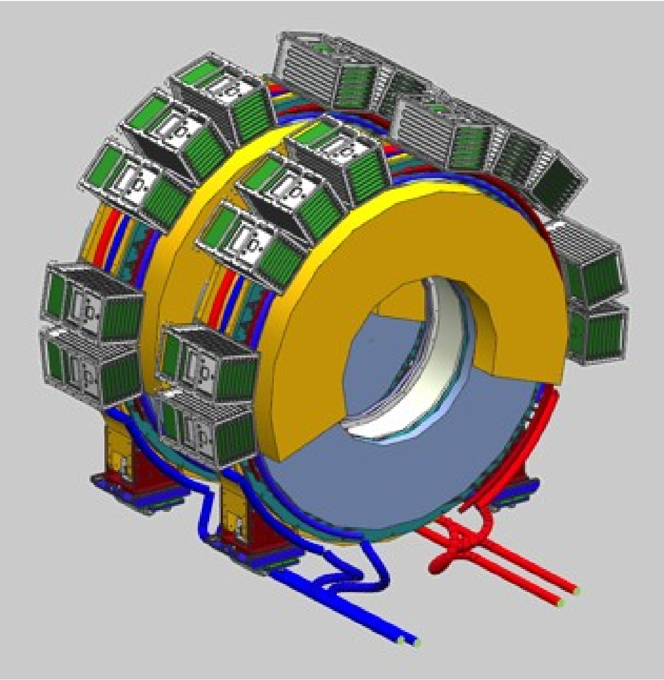
2 sens./crystal: $\sigma_t = \sigma(\Delta t)/2 \sim 230$ ps

Noise in test beam didn't allow to further extend clustering. Better results expected with final electronics. Nonetheless already with these results Calorimeter time and energy resolutions satisfy the requirements

Mu2e Calorimeter tasks

✓ Provide energy resolution σ_E/E of <10 %
✓ Provide timing resolution $\sigma(t)$ < 500 ps

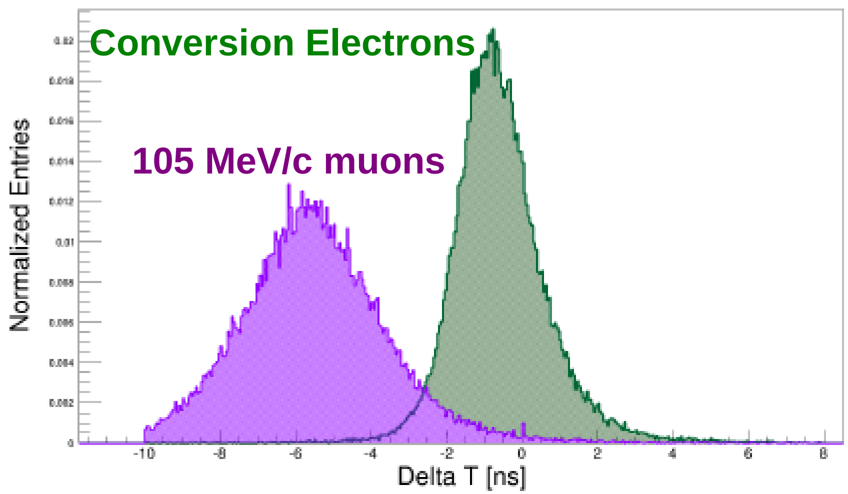
- Particle Identification capabilities with mu/e rejection of 200
- A trigger independent on tracker
- “Seeds” to improve track finding

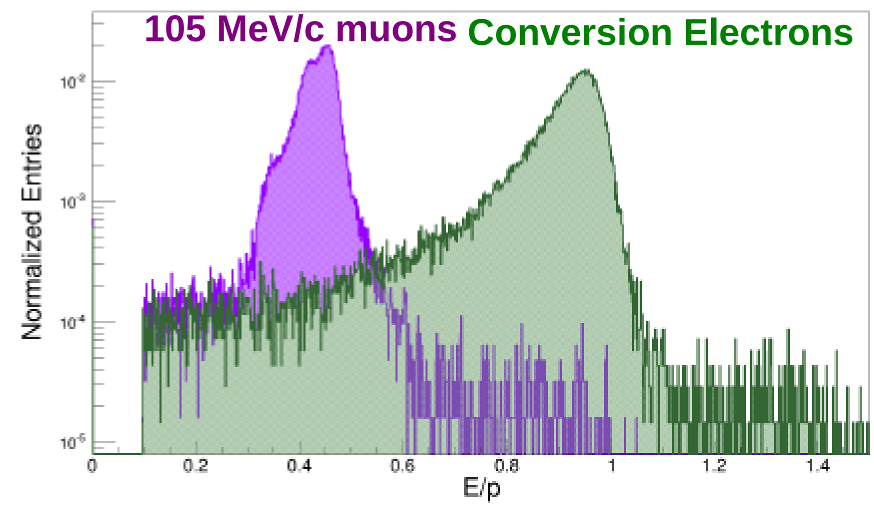


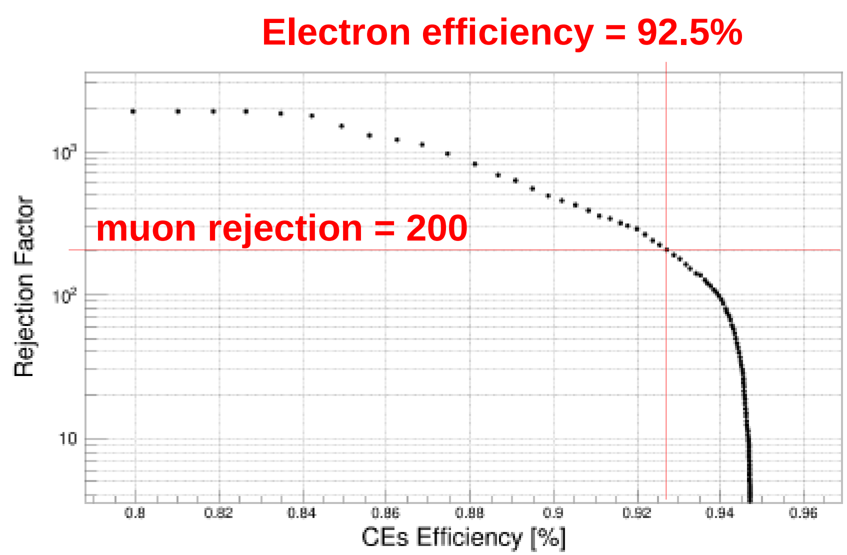
Mu2e particle identification

Tracker track – calorimeter cluster association + likelihood using:

time matching **Energy/momentum ratio**

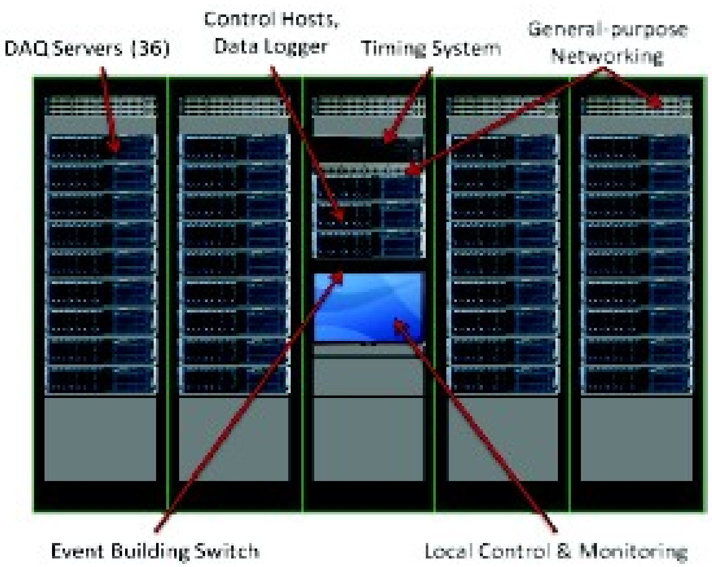






Rejection factor 200 makes cosmic muon background negligible wrt cosmic induced electron background

Mu2e trigger and DAQ



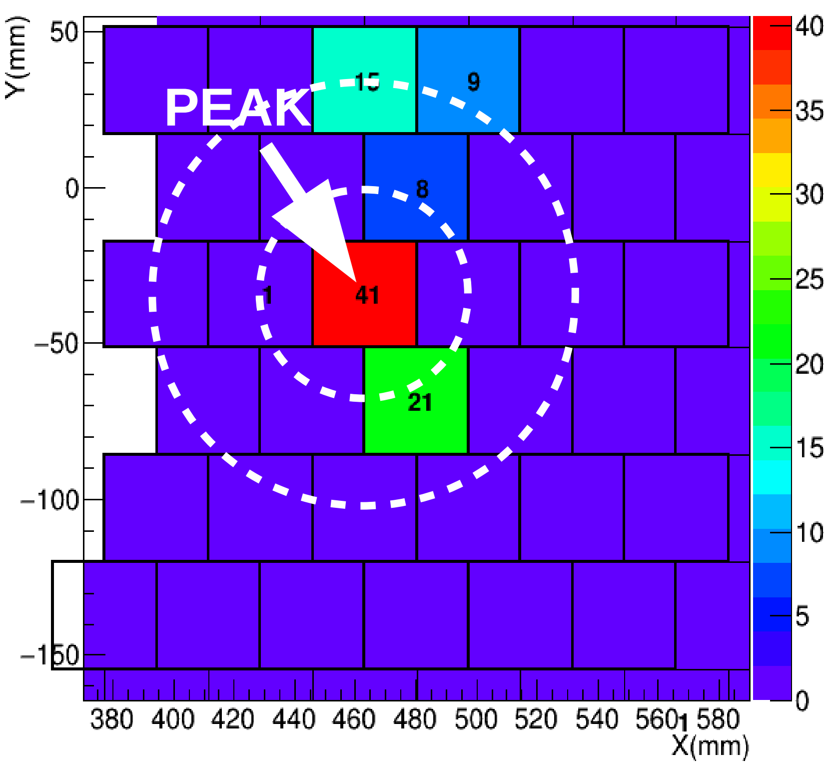
Acquire:

- events (1.7 μs microbunch) with an high momentum electron within tracker acceptance within 500-1700 ns from proton pulse

- calibration events

Bandwidth from average event size: ~31GB/s

Storage limit: 7 PB/y ~ 0.7 GB/s



Trigger requirements:

Event rate suppression: ~100

Event processing time: < 3.6 ms

Trigger Example

Calorimeter trigger using shower peak amplitude, time and position and highest energy deposits in neighbour crystals:

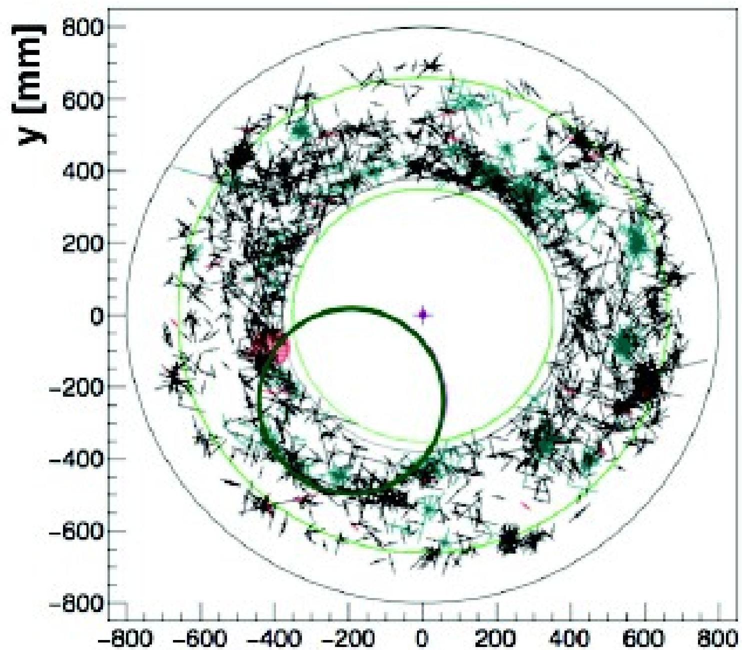
Efficiency on physics dataset: 85-90%

Rejection factor: 100

Processing time: 1 ms

Calorimeter seeded pattern recognition

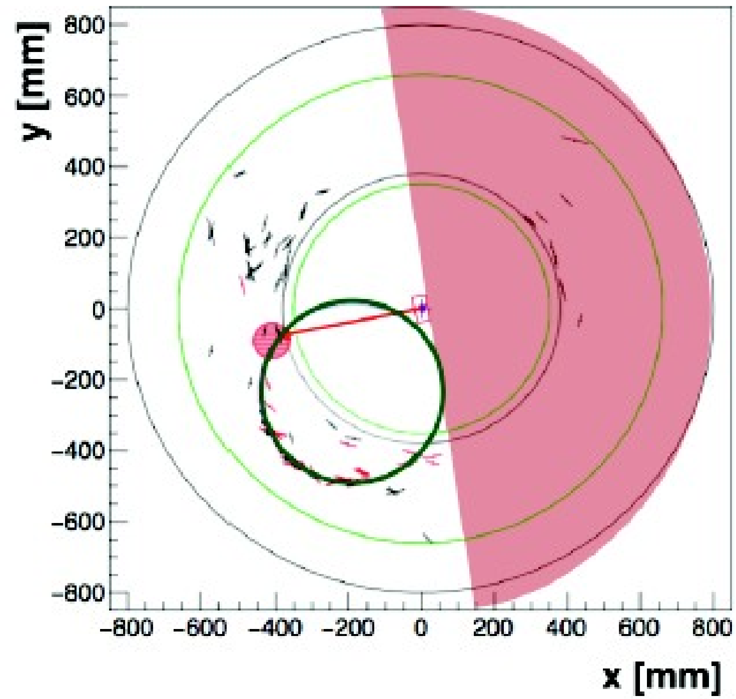
1.7 μs event (no hit selection)

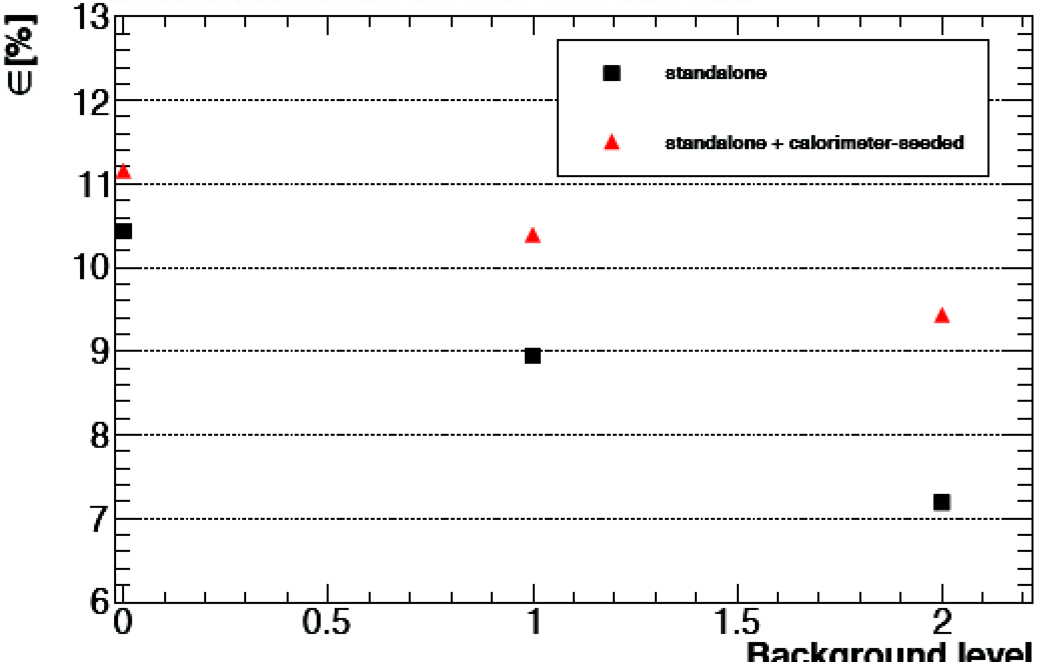


Select tracker hits matching time and position of ECAL cluster

→

1.7 μs event (hit selection)





Track reconstruction efficiency improves and is more stable against background level

Summary and Outlook

- Mu2e calorimeter is a key component of the Mu2e experiment that will improve by a factor 10^4 the existing limit on charged lepton flavor violating conversion of muons to electrons in the atomic field

- Simulation supported by quality tests and test beam results confirms that the proposed ECAL design is able to operate in the Mu2e harsh environment performing muon identification, track seeding and trigger at the desired level

- Preproduction crystals and photosensors have been fully characterized and QA and QC procedures have been set

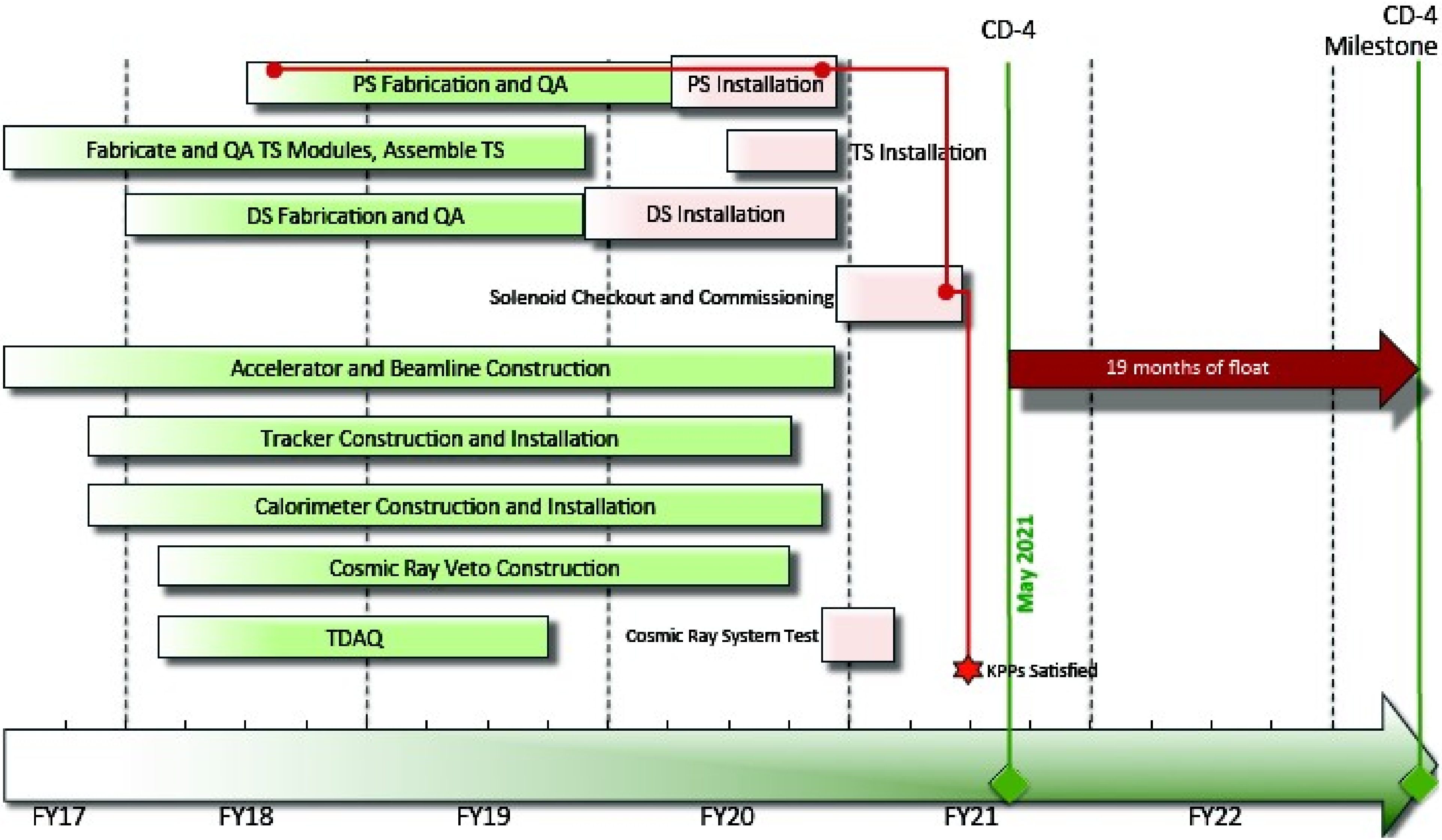
- Crystals and photosensors will start to be produced at the end of 2017 and will undergo massive QA tests in 2018

- Module 0 prototype has been tested. A full scale mockup is underway

- Calorimeter assembly will start at the end of 2018 and will be completed at beginning of 2020 in time for the Mu2e commissioning

Backup

Mu2e schedule



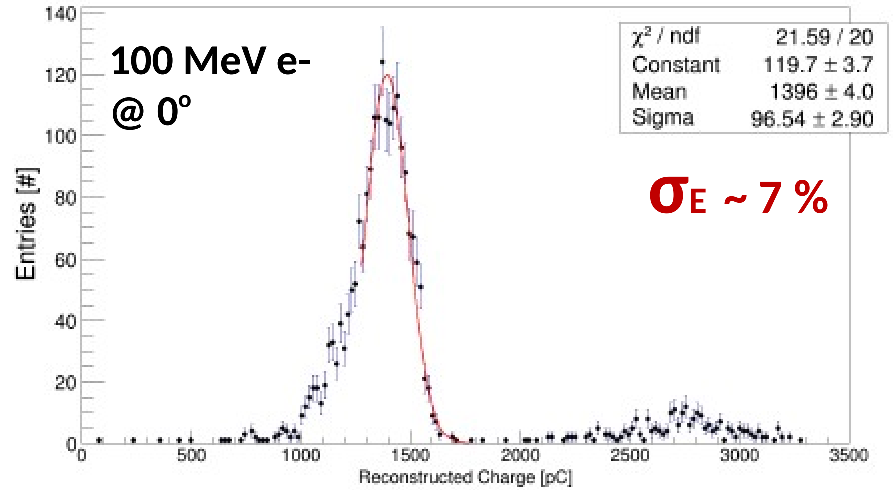
Mu2e background after 3 years ($3.6x10^{20}$ POT)

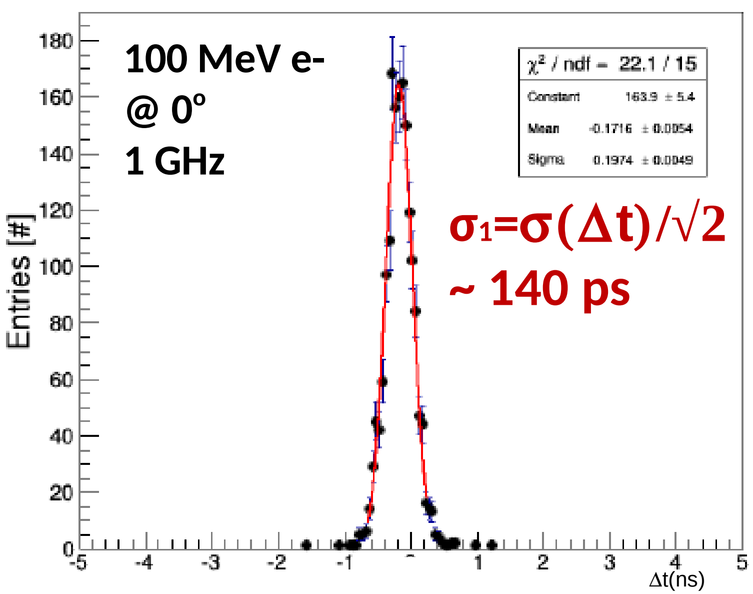
Process	Event Yield	comment
DIO	0.14±0.11	
RMC	<0.004	Kinematically suppressed
Pion capture	0.025±0.003	Cross section can be measured
Muon DIF	<0.003	
Pion DIF	0.001± 0.001	
Beam electrons	$(2.5\pm1.2)x10^{-4}$	Assumes 10^{-10} extinction factor
Antiprotons	0.05±0.02	
Cosmic rays	0.25±0.07	
Total	**0.5±0.1**	

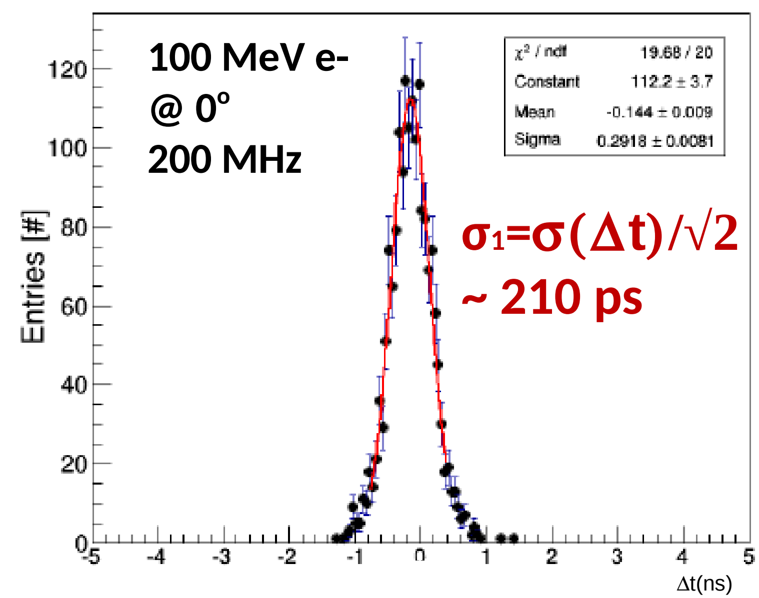
Single Event Sensitivity = [3.01±0.03(stat)±0.41(syst)]$x10^{-17}$

“Modulo 0” performances for 100 MeV e^- at 0^o

- Energy reconstructed by equalizing and summing first ring of crystals + 3 closer in beam direction
- Time resolution evaluated by the time difference of 2 sensors reading the most energetic crystal







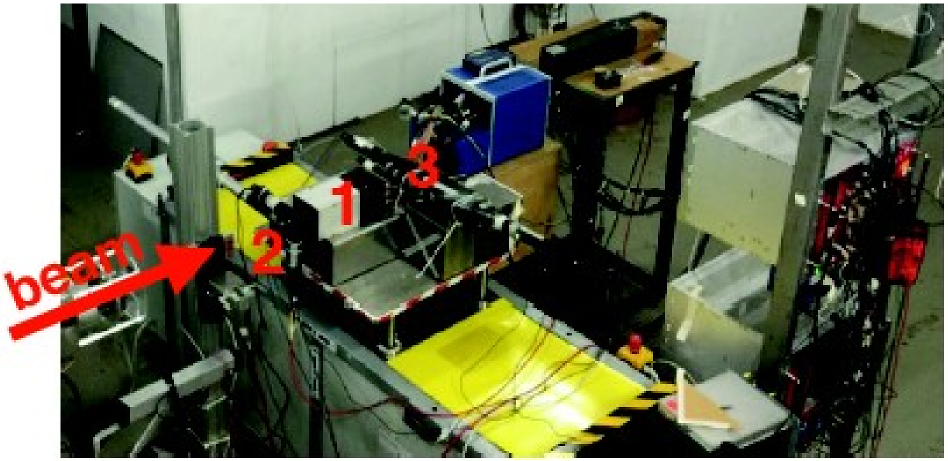
2 sens./crystal: $\sigma_t = \sigma(\Delta t)/2 \sim 100$ ps

2 sens./crystal: $\sigma_t = \sigma(\Delta t)/2 \sim 150$ ps

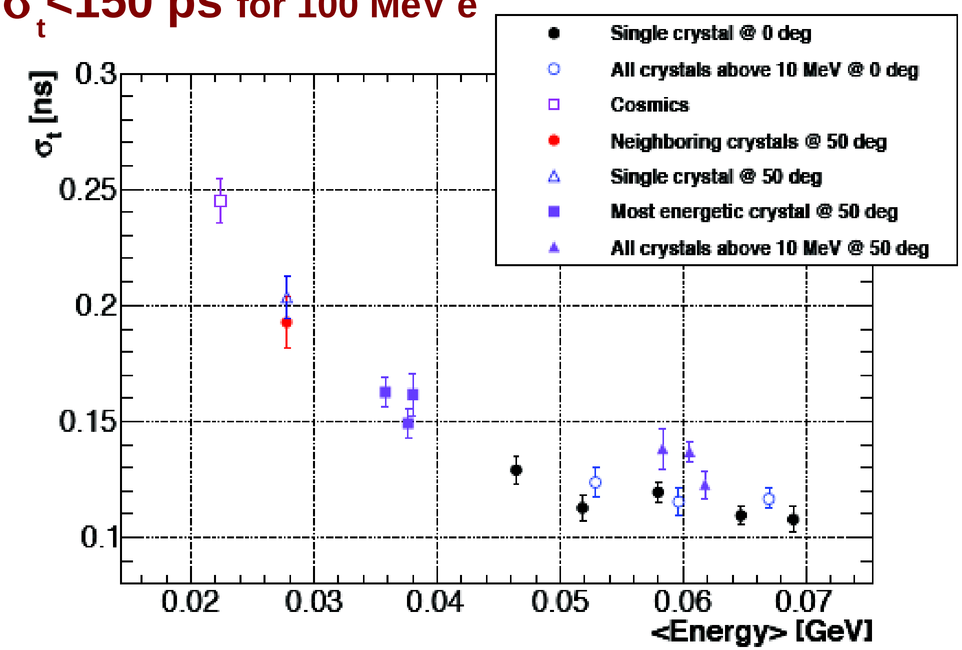
Noise in test beam didn't allow to further extend clustering.
Better results expected with final electronics.

2015 Test beam results

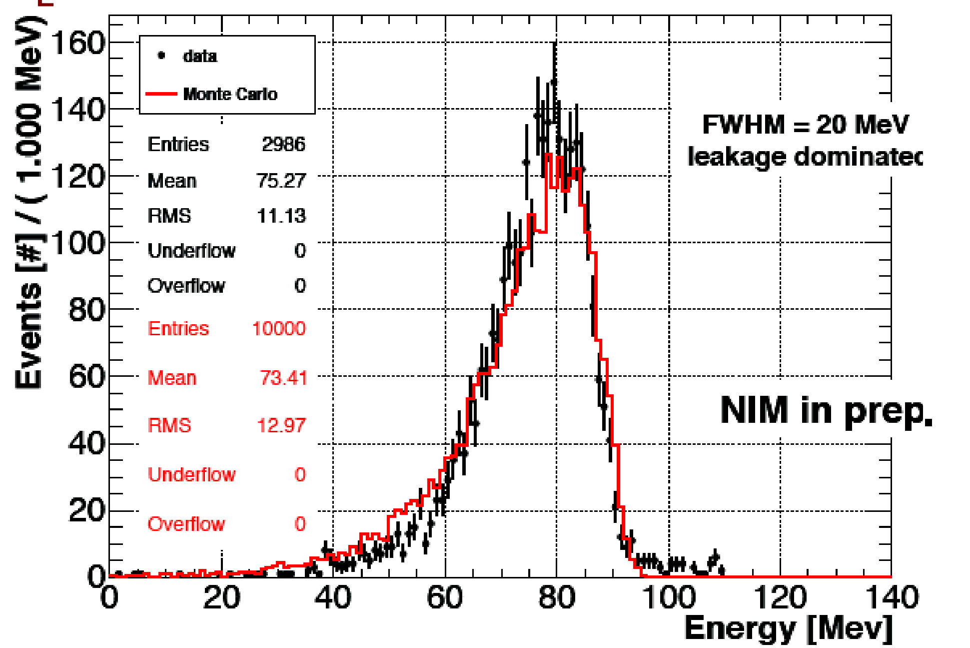
80->120 MeV electron beam at
Beam Test Facility (BTF) in Frascati



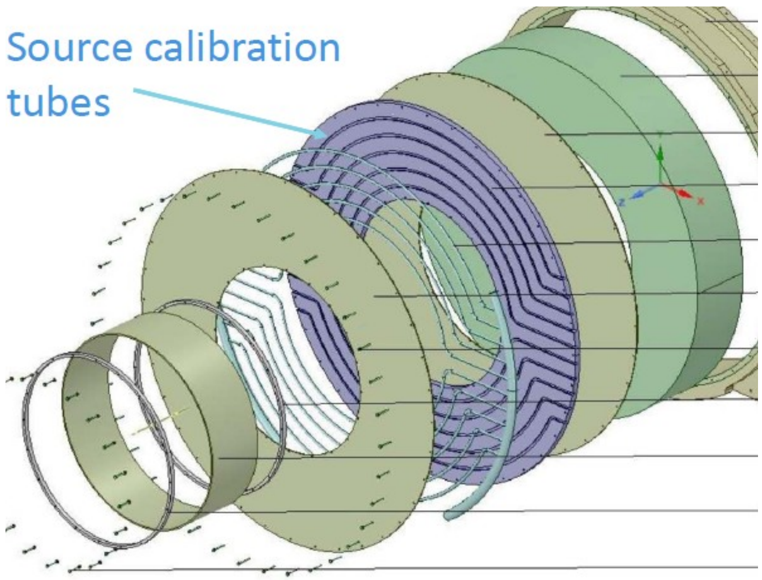
σ_t<150 ps for 100 MeV e^-



σ_E/E~7% for 100 MeV e- at 50° (LEAKAGE dominated)

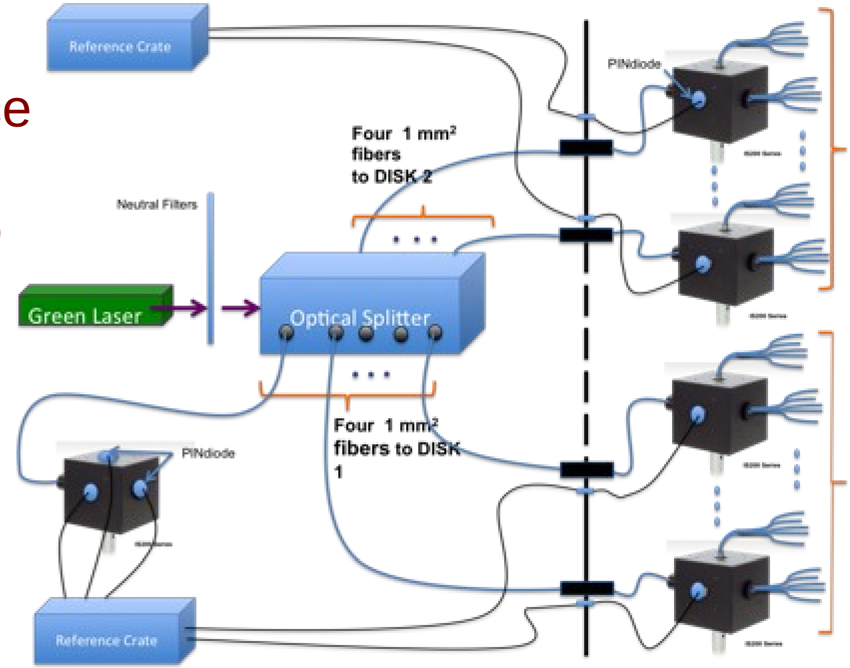


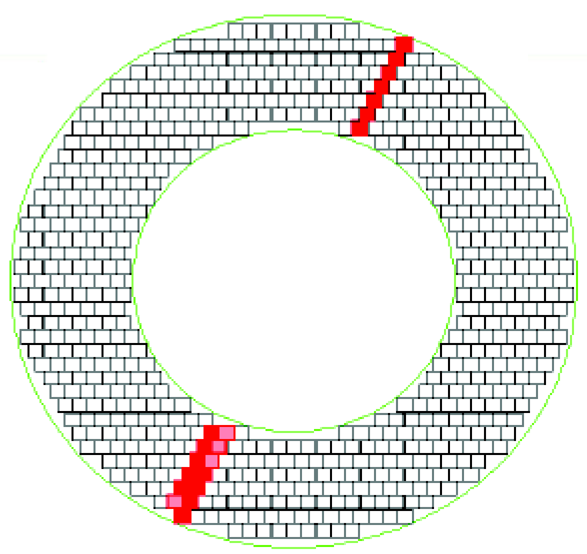
Calorimeter calibration



← 6 MeV liquid source in front of crystals (energy calibration)

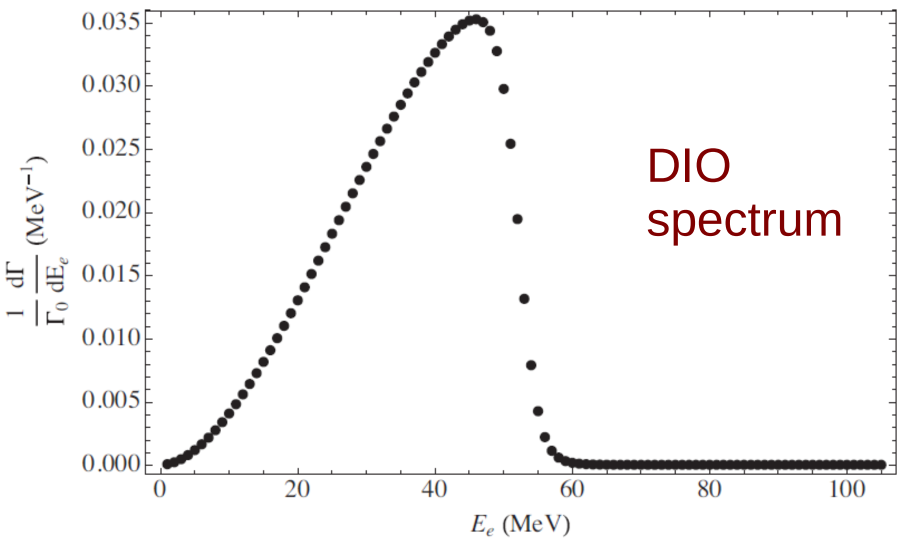
Laser pulses (energy and time Calibration)
FEE pulses →



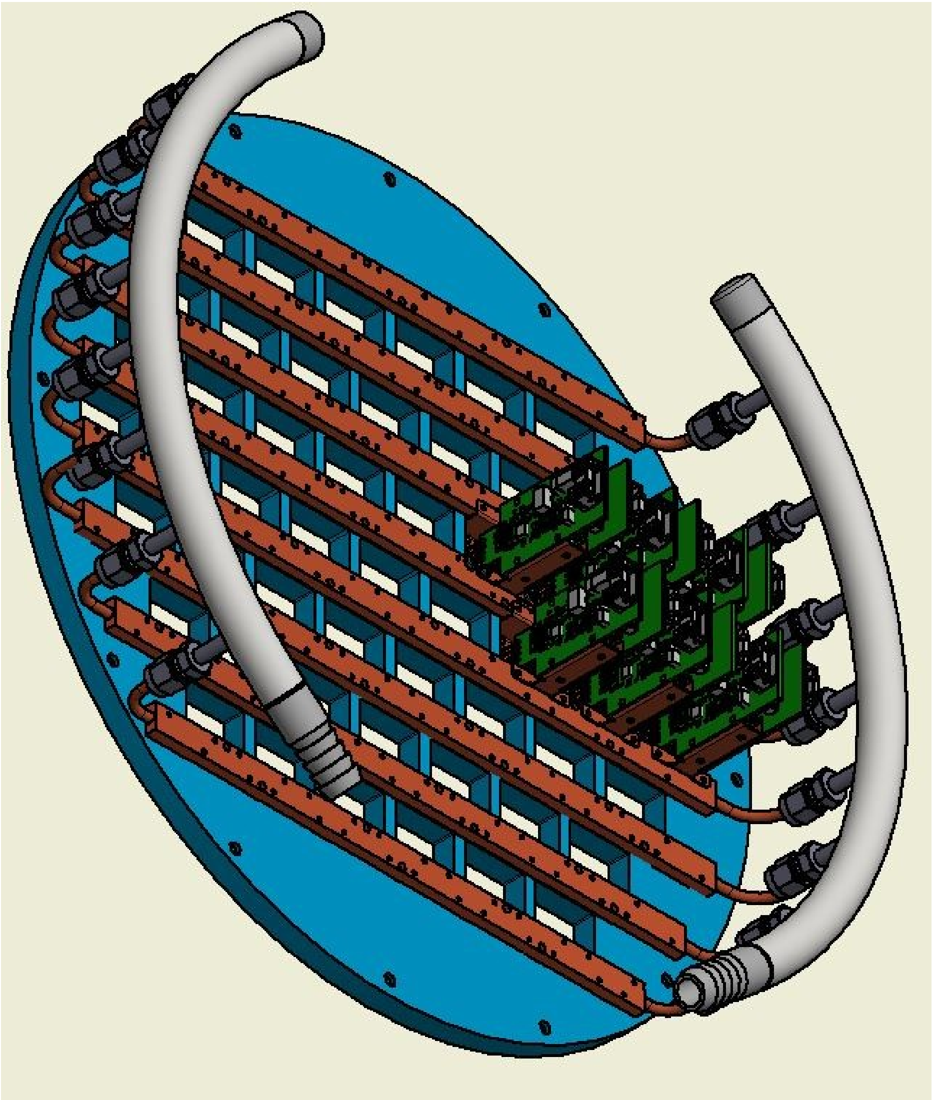


← Cosmic muons (energy and time calibration)

E/p and Δt from muon decays in orbit (DIO) and $\pi \to e\nu$ decays at reduced B field (energy and Tracker-ecal time) →



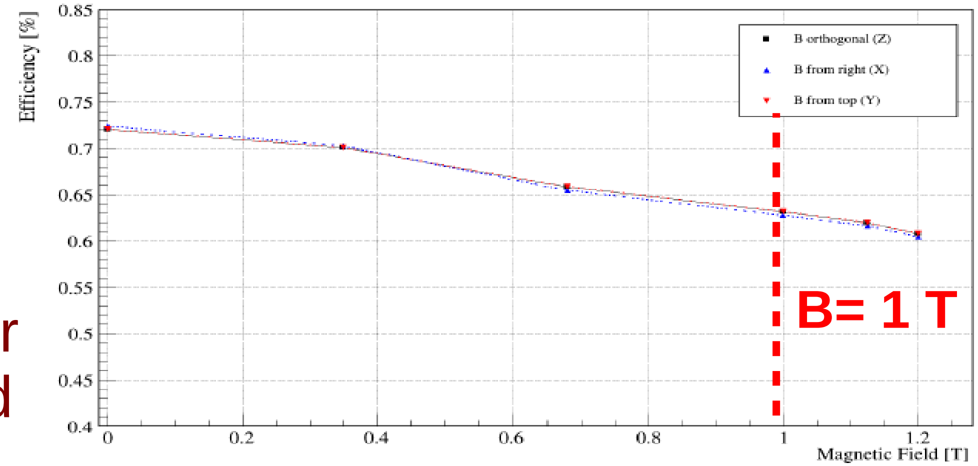
Calorimeter cooling



Qualification of electronic components

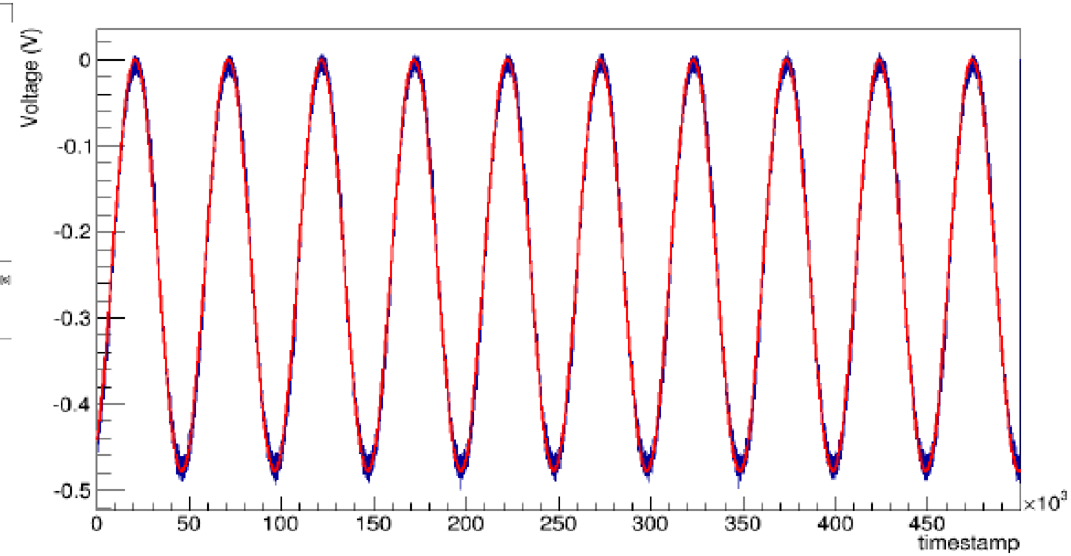
←
FPGA
SEL free
SEU free

→
DCDC converter
in magnetic field

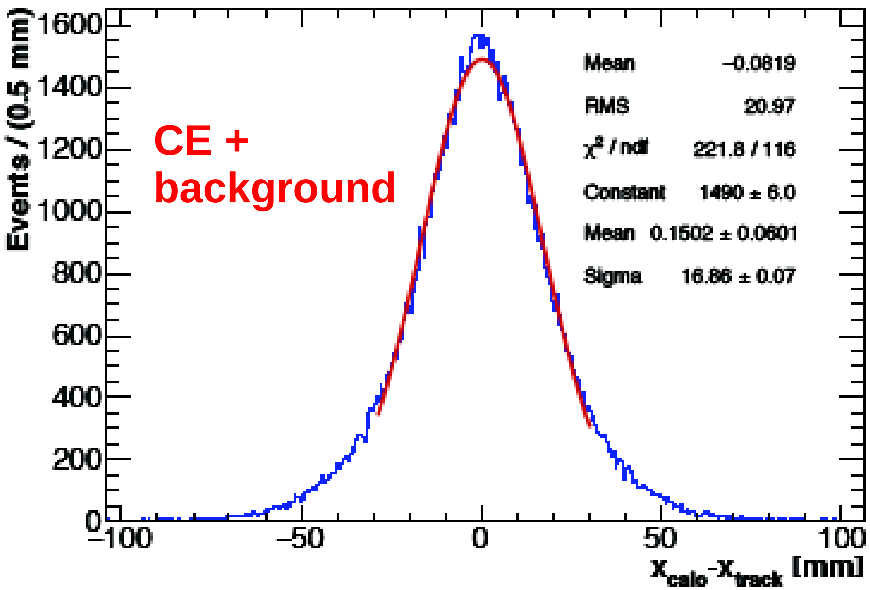


DCDC converter n irradiation
(1.5×10^{11} n/cm2 @ 1 MeV$_{eq}$ = 3 years)

ADC after 20 krad
(1.5krad = 3 years)

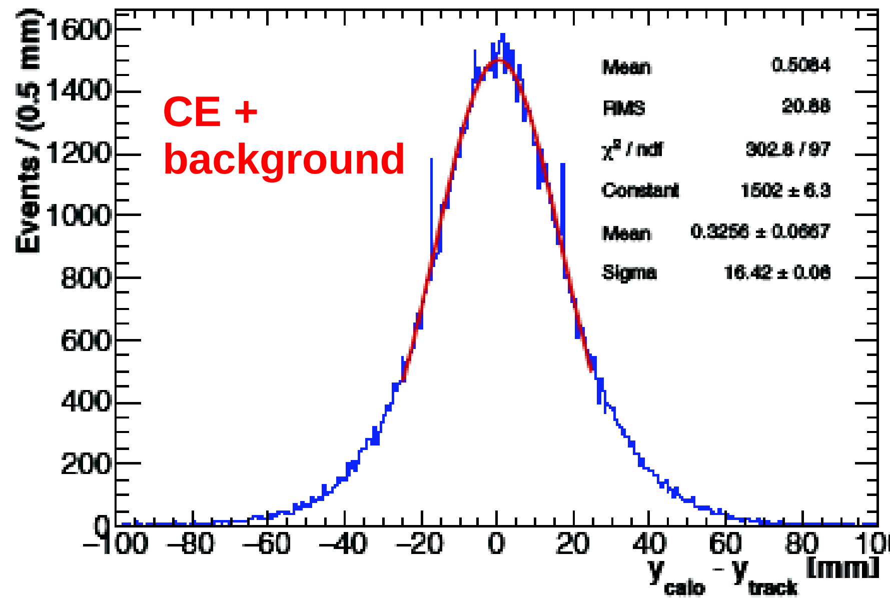


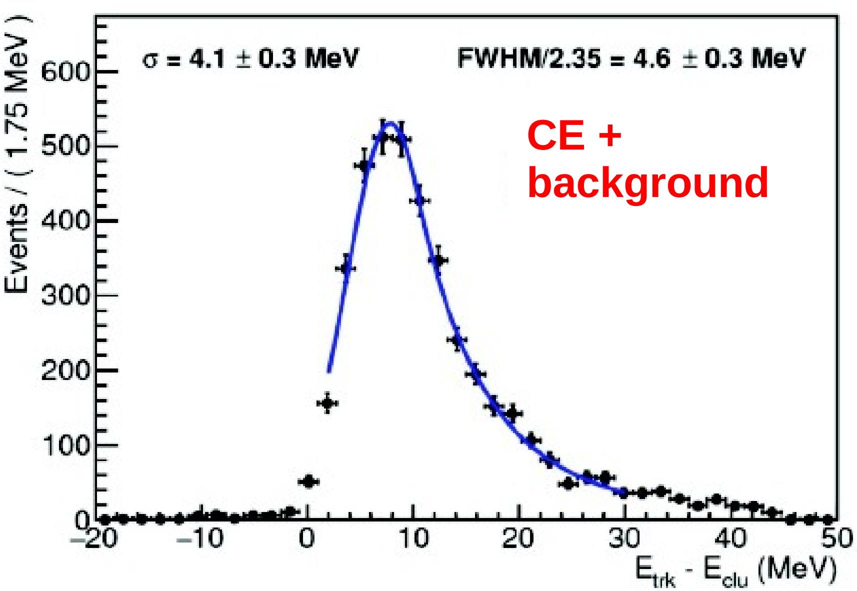
Expected performances from simulation: x,y,E,t



← σ_x~16 mm

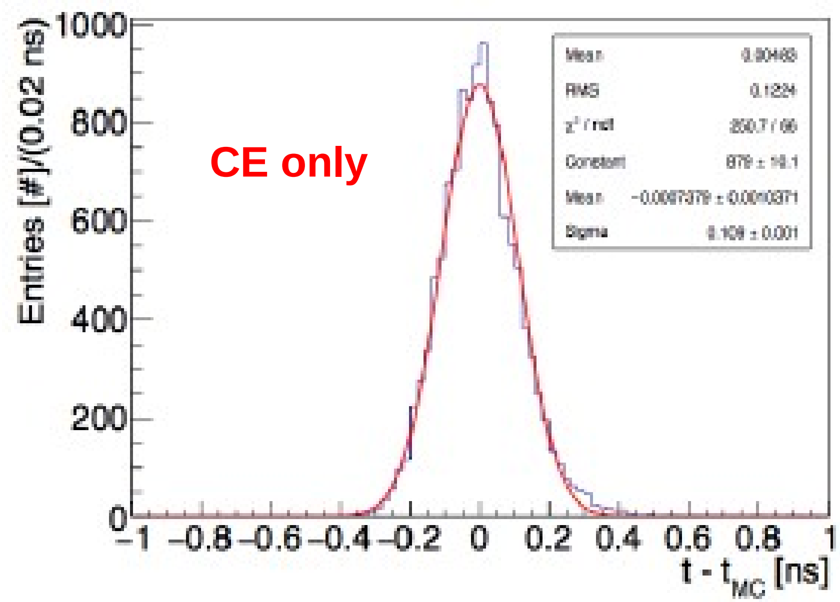
→ σ_y~16 mm



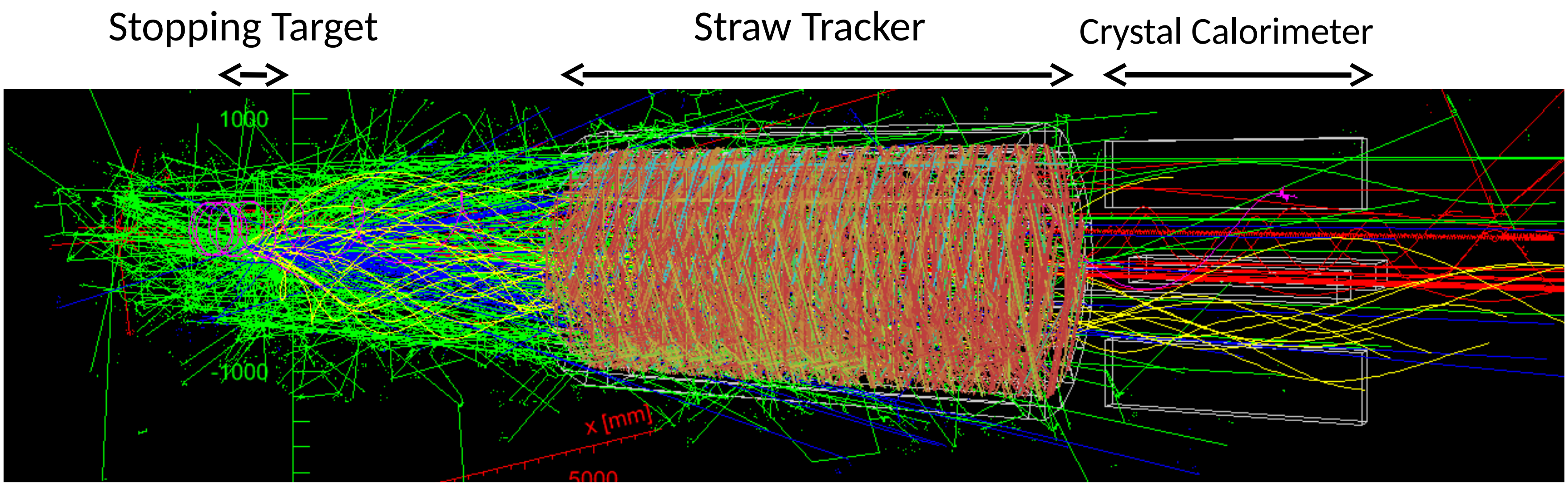


← σ_E/E~4%

→ σ_t~110 ps



Mu2e track reconstruction

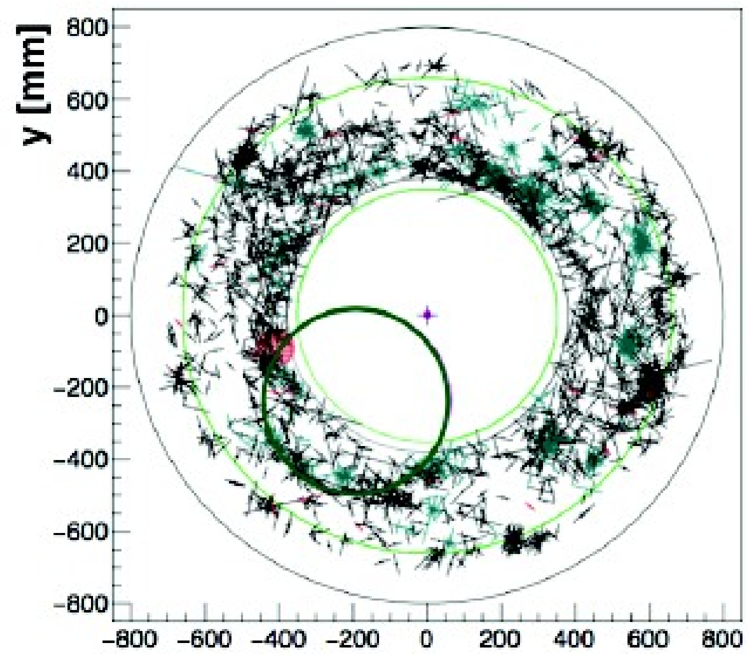


A typical Mu2e tracker event
integrated over 500-1695 ns window

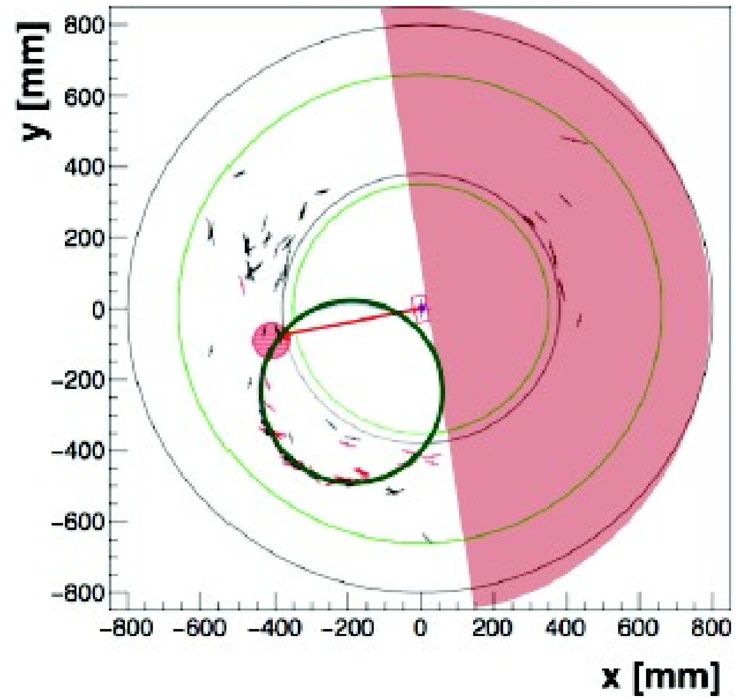
Hits filtered according to their time, energy and position
Low momentum electrons hits rejected by dedicated algorithm
Candidate tracks searched by grouping hits in 50 ns time windows

Mu2e track reconstruction

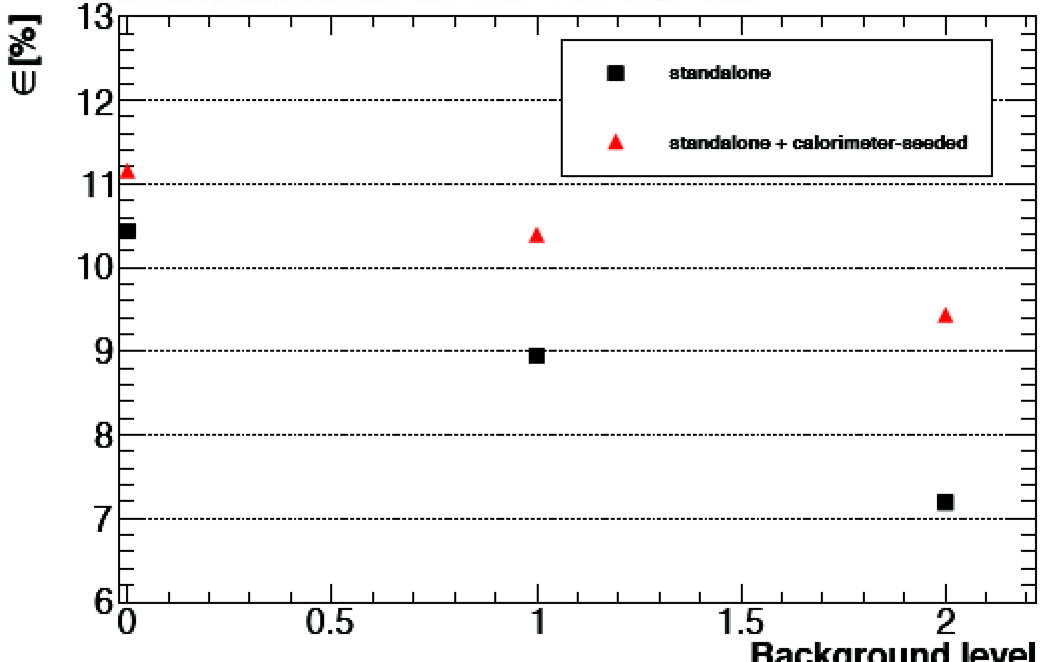
1.7 μs event (no hit selection)



1.7 μs event (ECAL hit selection)



Select tracker hits matching time and position of ECAL cluster →



Calorimeter information helps track reconstruction and makes it more stable against background level