The Mu2e Tracker and Calorimeter Systems

S. Giovannella (INFN LNF)

on behalf of the Mu2e Collaboration

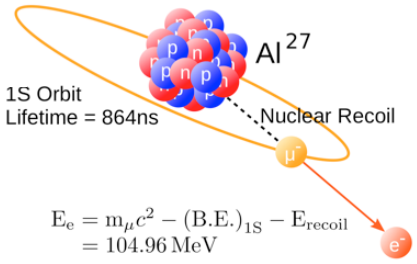
Charge Lepton Flavour Violation

CLFV strongly suppressed in Standard Model: BR ≤10^{-50} ➪ **its observation indicates New Physics**

CLFV@Mu2e: coherent neutrinoless conversion of a muon to an electron in the field of a nucleus ➪ discovery sensitivity on many NP models

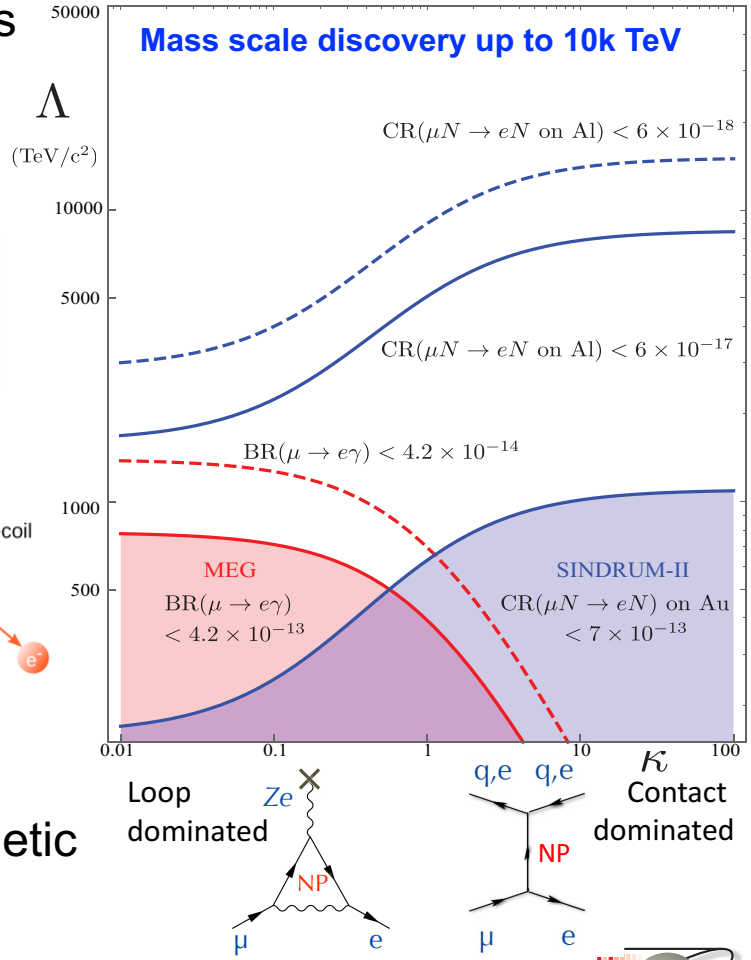
Goal: **10^4 improvement w.r.t. previous conversion experiment** (SINDRUM II)

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z)) \rightarrow e^- + N(A,Z)}{\Gamma(\mu^- + N(A,Z) \rightarrow \text{ all muon capture})} \leq 6 \times 10^{-17} \text{ (@90\%CL)}$$



Experimental technique:

- ✗ Beam of low momentum muons
- ✗ Muons stopped in Al target
- ✗ Muons trapped in orbit around the nucleus
- ✗ Look for $\mu^-N(A,Z) \rightarrow e^-N(A,Z)$ events: mono-energetic e^- with E ~ M_μ, produced with τ_μ^{Al} = 864 ns

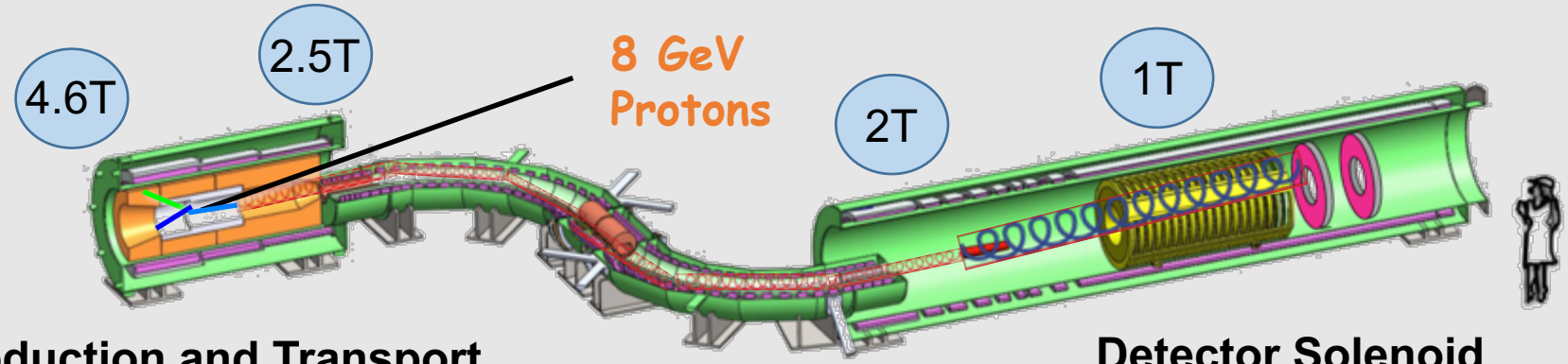


The Mu2e Experiment

SES @ 2.4×10^{-17} requires demanding detector technologies:

- $\rightarrow 10^{18}$ μ stopped
- $\rightarrow 10^{20}$ p on target
- $\rightarrow N_{bckg} < 0.5$

in 3 years running



Production and Transport Solenoids

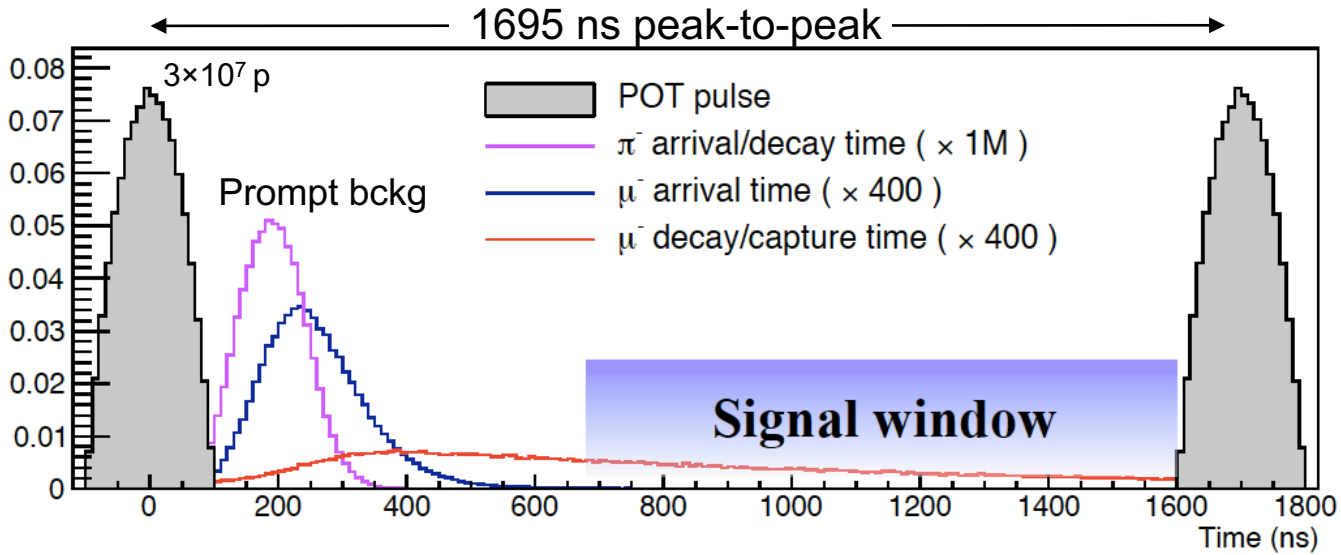
Production, selection and transport of low momentum muon beam

Detector Solenoid

- Muon capture on Al target
- Tracker, EM Calorimeter
- Outside: Cosmic Ray Veto

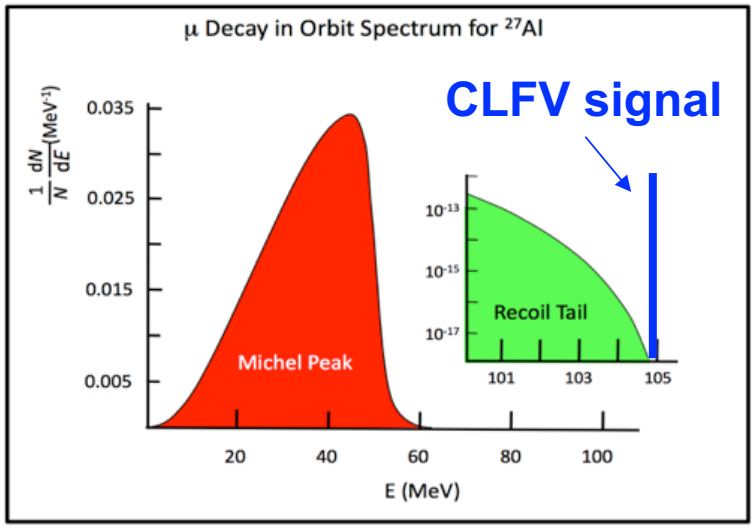
Bunch structure:

- Pulsed proton beam and a delayed live gate to suppress prompt backgrounds
- Narrow proton pulses
- Out-of-time protons suppressed by O(10^{10})



The Tracker

One of two main bckg:
Decay In Orbit
$\mu \rightarrow e\ \nu_\mu\ \nu_e$
(~39% on Al)



✗ Nuclear modifications push DIO spectrum near conversion electron

✗ DIO and CLFV signal, **Conversion Electron** (CE), overlap after energy loss and detector resolution

Detector requirements:

1. Small amount of X_0
2. σ_p < 180 keV @ 105 MeV
3. Good rate capability:
   - 20 kHz/cm^2 in live window
   - Beam flash of 3 MHz/cm^2
4. dE/dx capability to distinguish e^-/p
5. Operate in B = 1 T, 10^{-4} Torr vacuum
6. Maximize/minimize acceptance for CE/DIO

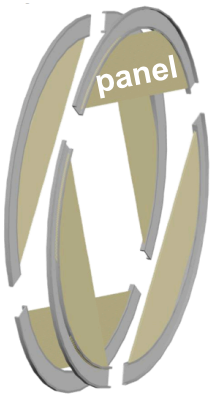
Low mass straw drift tubes design:

- 5 mm diameter, 33 – 117 cm length
- 15 μm Mylar wall, 25 μm Au-plated W wire
- 80:20 Ar:CO_2 @ 1 atm
- Dual-ended readout

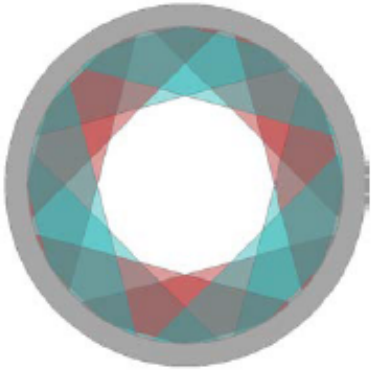
Tracker Design

- ✗ > 20,000 tubes arranged in planes on stations
- ✗ Self-supporting panel consists of 2×48 straws, two staggered layers
- ✗ 6 panels assembled into a plane, 2 planes assembled into a station, 18 stations
- ✗ Rotation of panels and planes for stereo reconstruction

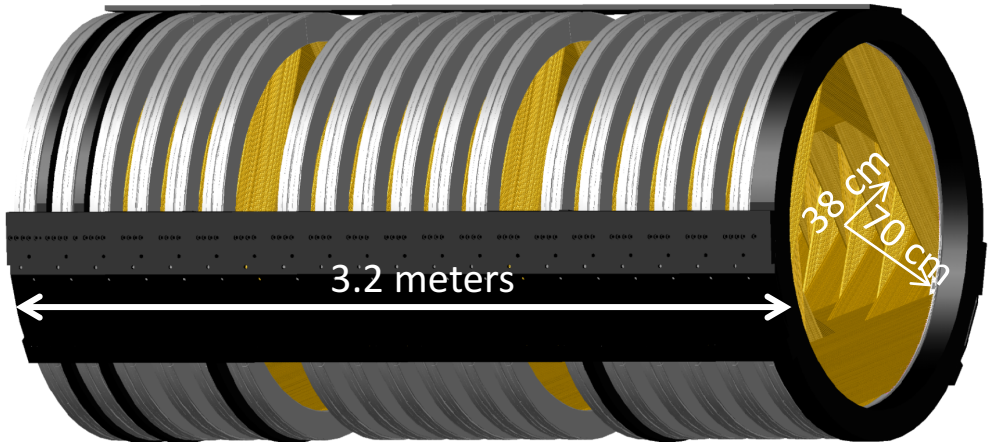
Tracker Plane



Tracker Station:
2 rotated planes



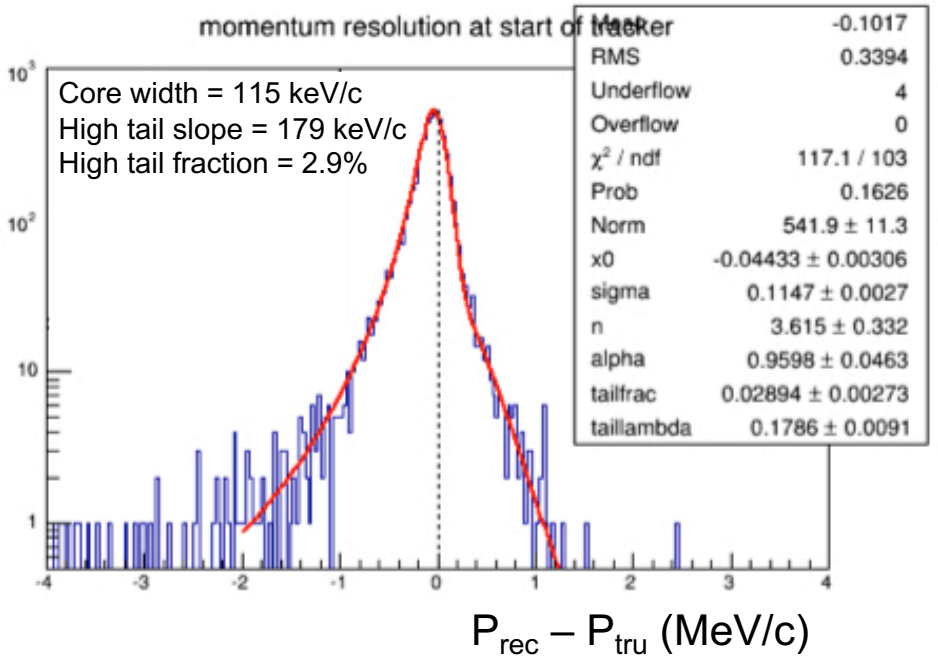
Tracker:18 stations



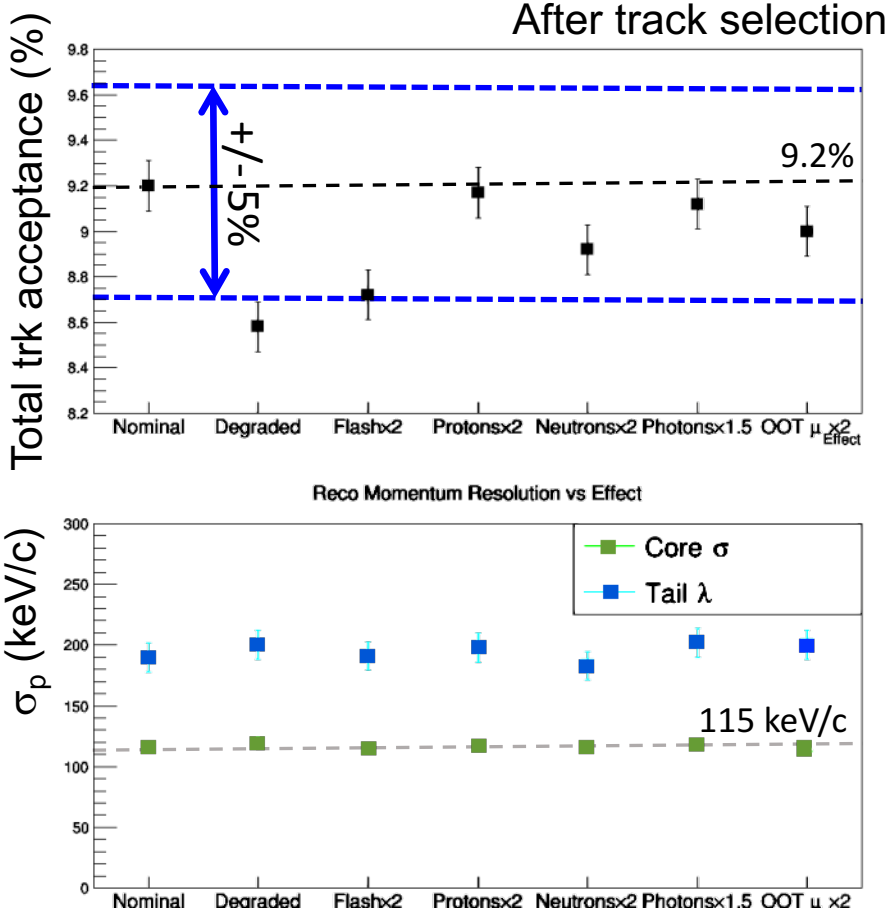
- ✗ Inner 38 cm is purposely un-instrumented
  - ➢ Blind to beam flash (low momentum particles)
  - ➢ Blind to >99% of DIO spectrum

Tracker Performances

Expected tracker performances from full simulation



After track selection

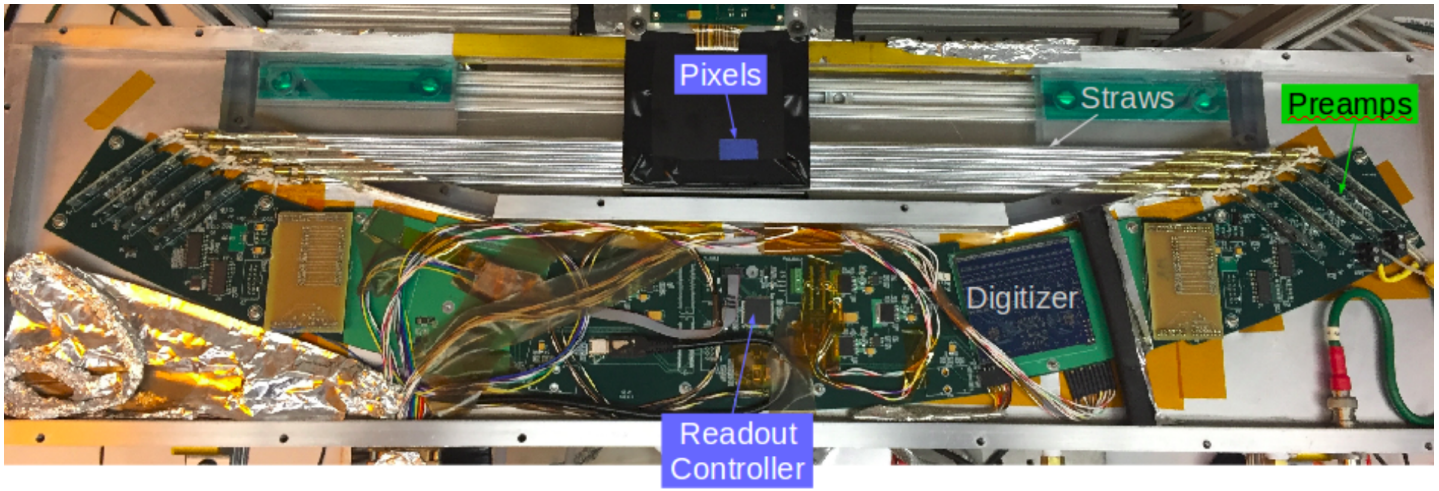


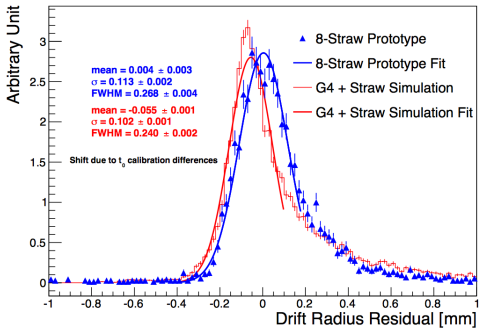
Variations in accidental hit rate

- ✗ Well within physics requirements
- ✗ Robust against increases in rate
- ✗ Inefficiency dominated by geometric acceptance

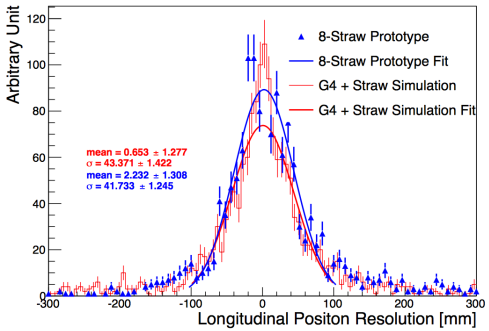
Mu2e Tracker: 8 channel prototype

Test with cosmics to measure gain, resolution…





Transverse Resolution
(Data vs MC)
$\sigma_{data} = 0.113 \pm 0.002$ mm
$\sigma_{MC} = 0.102 \pm 0.001$ mm

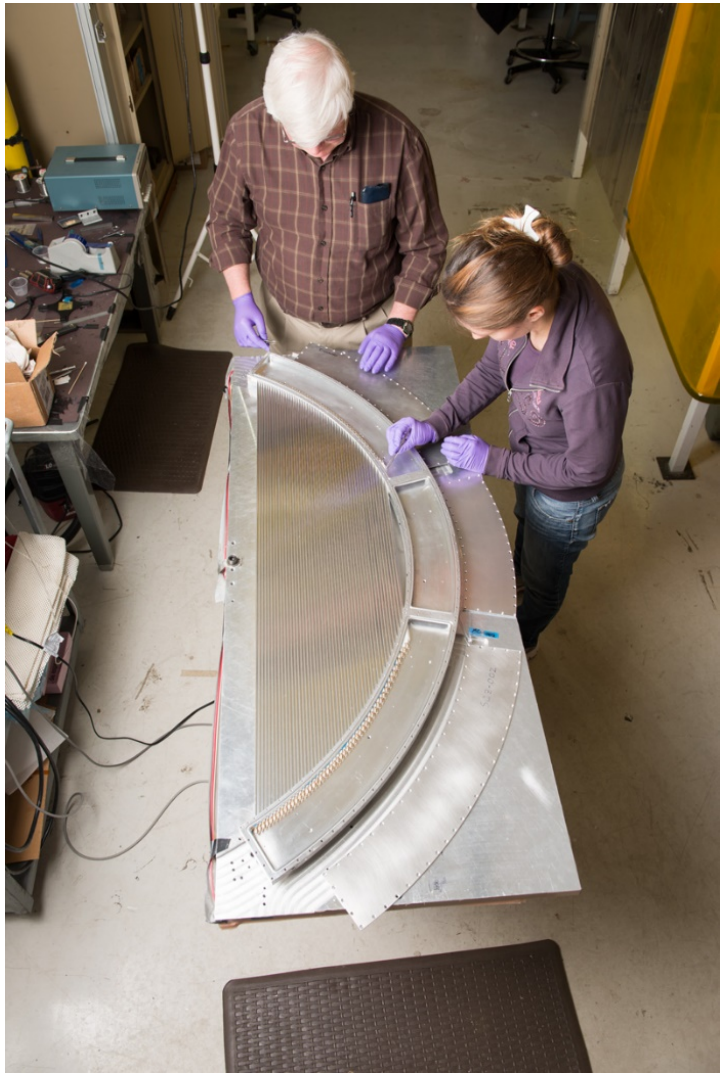


Longitudinal Resolution
(Data vs MC)
$\sigma_{data} = 42 \pm 1$ mm
$\sigma_{MC} = 43 \pm 1$ mm

Parameter	Value	Reference
N electrons per ionization	$< N >= 2$	NIMA 301, 202(1991)
Energy per ionization electron	39 eV	NIST (27-100 eV) and G4
Avg. Straw Gain	70k	Prototype (PAM, ^{55}Fe)
Threshold Value	12 mV	Prototype (DVM, ^{55}Fe)
Threshold Noise	3 mV	Spice Sim. (V. Rusu)
Shaping Time	22 ns	Prototype (^{55}Fe)

Panel Prototype

- ✗ First pre-production prototype, with final design, recently built and being tested
- ✗ Orders placed for final production
- ✗ FEE prototypes tested successfully
- ✗ Vertical slice test to be performed on fully instrumented panels with entire FEE chain



The Electromagnetic Calorimeter

Calorimeter provides confirmation for CE and other crucial functions:

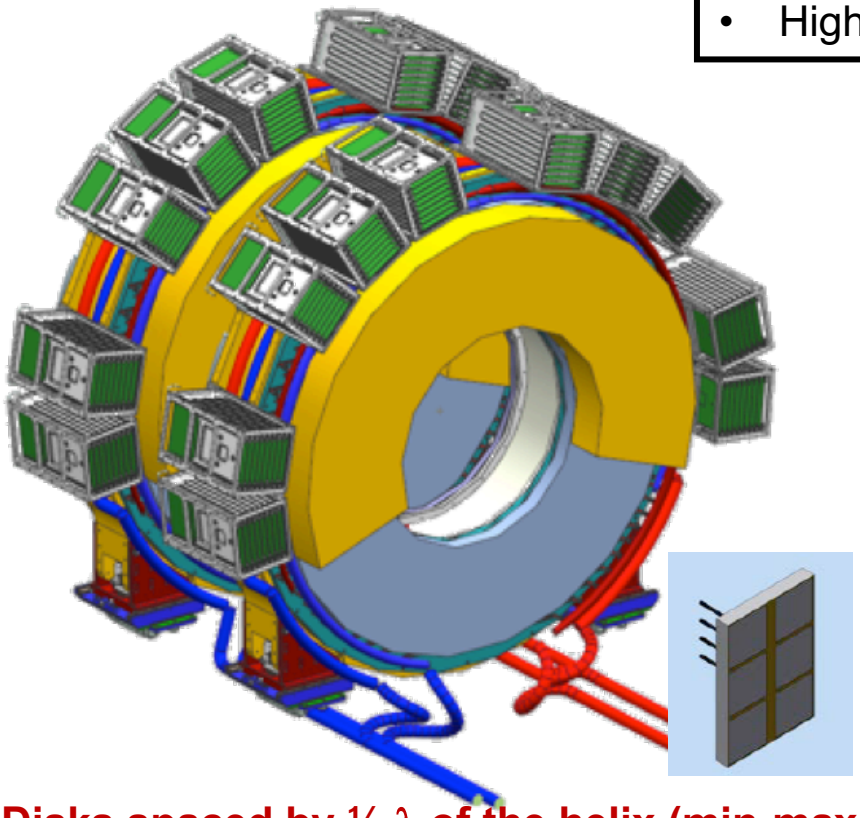
✗ PID: e/μ separation

✗ EMC seeded track finder

✗ Standalone trigger

Requirements:

- $\sigma_E/E = \mathcal{O}(5\%)$ for CE
- $\sigma_T < 500$ ps for CE
- $\sigma_{X,Y} \leq 1$ cm
- High acceptance for CE
- Fast (τ<40 ns)
- Operate in 1T and 10^{-4} Torr
- Redundancy in readout
- Radiation hard: 90 krad photons and 3×10^{12} n/cm^2



EMC Design:

✗ Two disks, R_{in}=374 mm, R_{out}=660 mm, 10X_0 length, ~ 75 cm separation

✗ 674+674 square x-sec **pure CsI crystals**, (34×34×200) mm^3

✗ For each crystal, two custom array (2×3 of 6×6 mm^2) **large area UV-extended SiPMs**

✗ Analog FEE directly mounted on SiPM

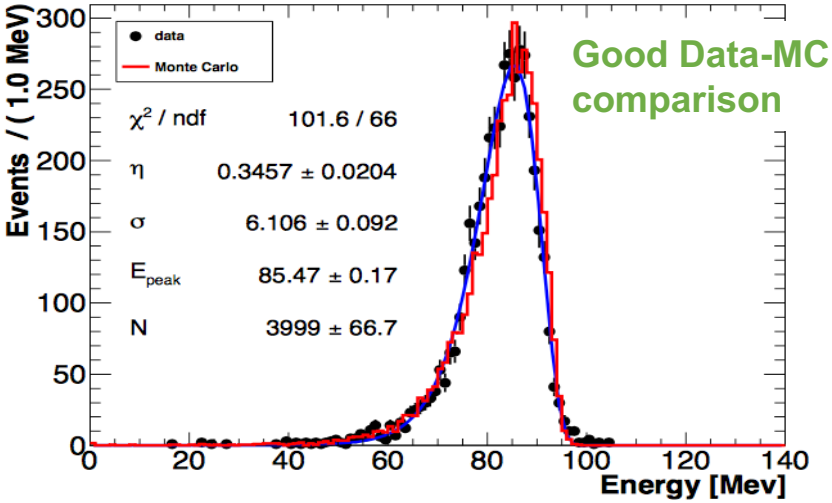
✗ Calibration/Monitoring with 6 MeV radioactive source and a laser system

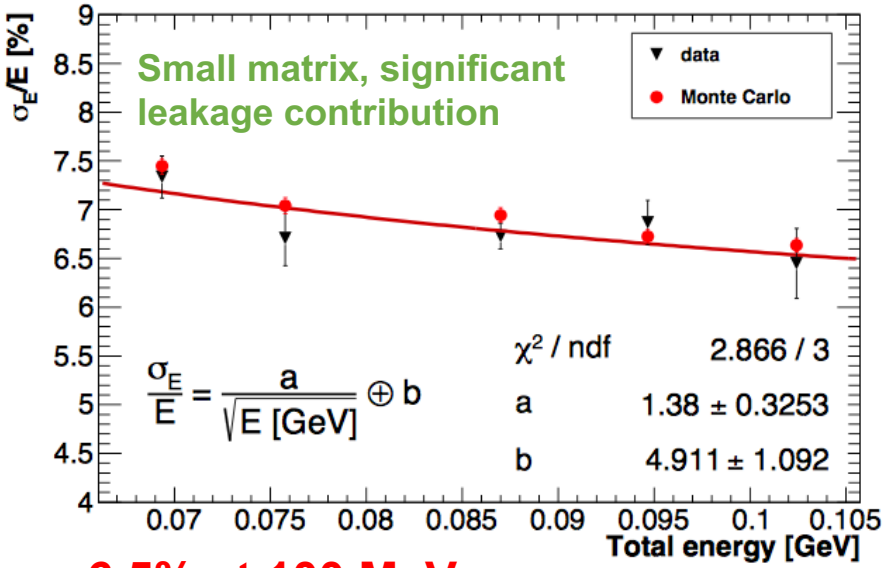
Disks spaced by ½ λ of the helix (min-max distance from axis) for CE tracks

Calorimeter Performances

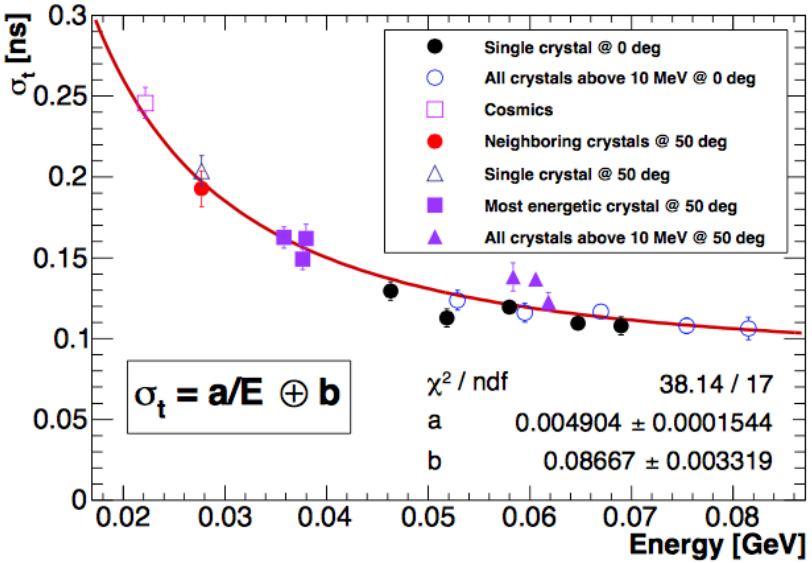
JINST 12 (2017) P05007

- ✗ Small prototype tested @ BTF (Frascati) in April 2015, 80–120 MeV e^-
- ✗ 3×3 array of (30×30×200) mm^2 undoped CsI crystals coupled to Hamamatsu MPPC
- ✗ DAQ readout: 250 Msps CAEN V1720 Wave Form Digitizer





σ_E ~ 6.5% at 100 MeV

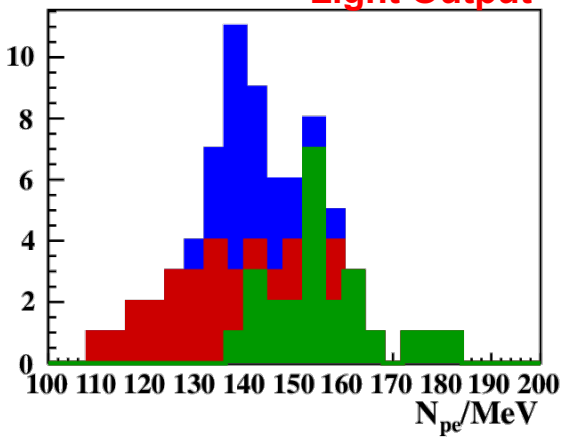


σ_T ~ 110 ps at 100 MeV

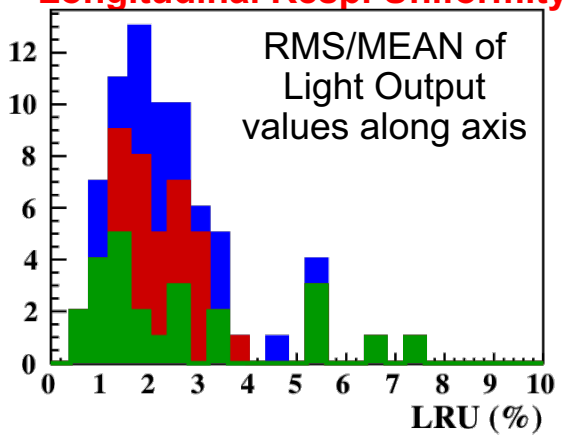
Test of pre-production crystals

- ✗ 3×24 pre-production crystals from three different vendors
- ✗ Optical properties tested with 511 keV γ's along the crystal axis
- ✗ Crystals are wrapped with 150 μm of Tyvek and coupled to an UV-extended PMT

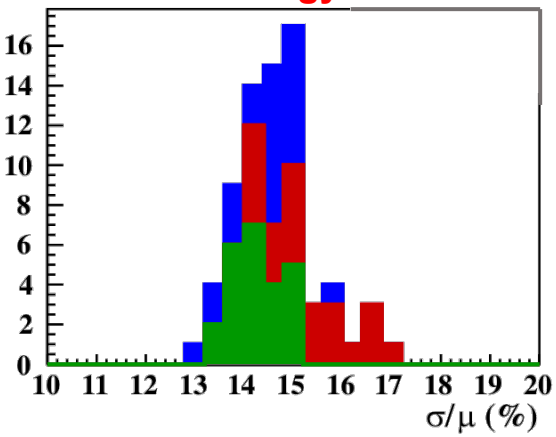
Light Output



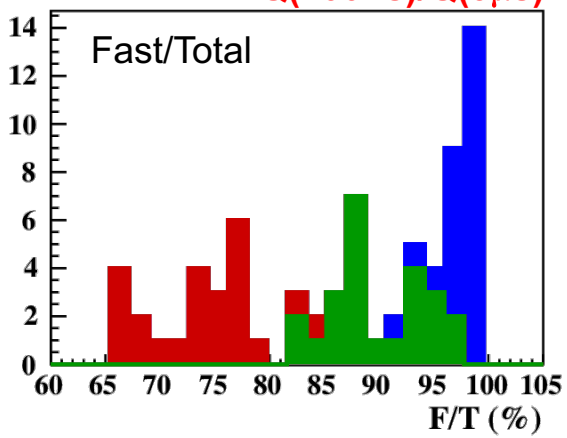
Longitudinal Resp. Uniformity



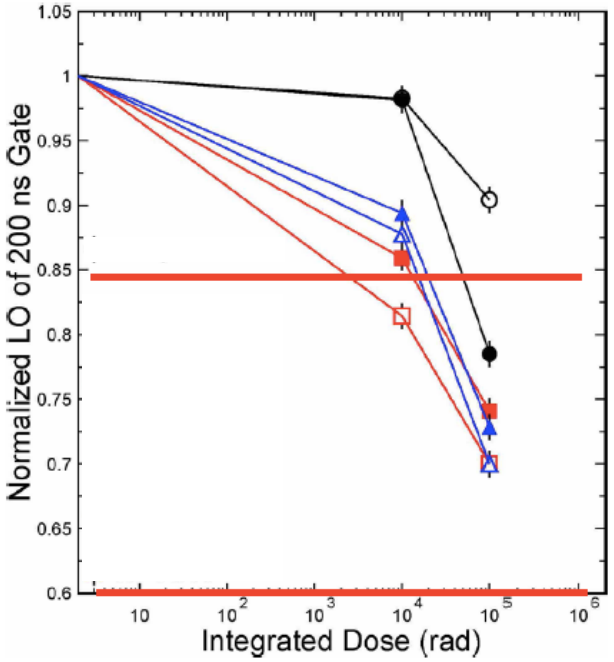
Energy resolution



Q(200ns)/Q(3μs)



Irradiation test up to 100 krad

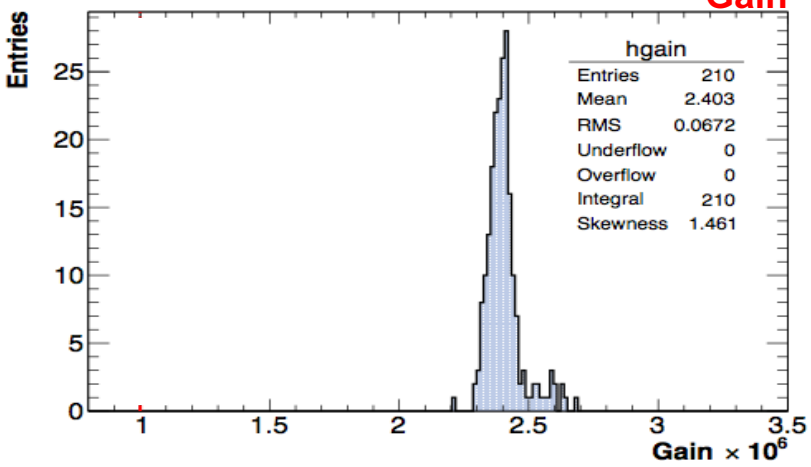


All satisfy Mu2e
100 krad requirement
(40% max. loss)

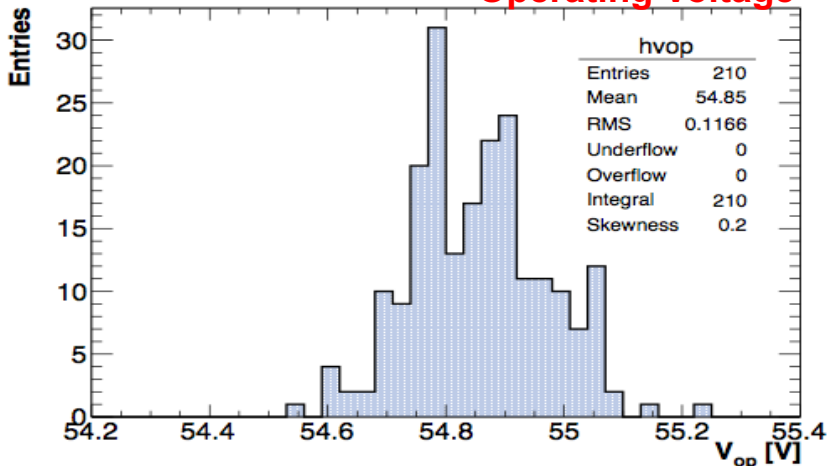
Test of pre-production SiPMs

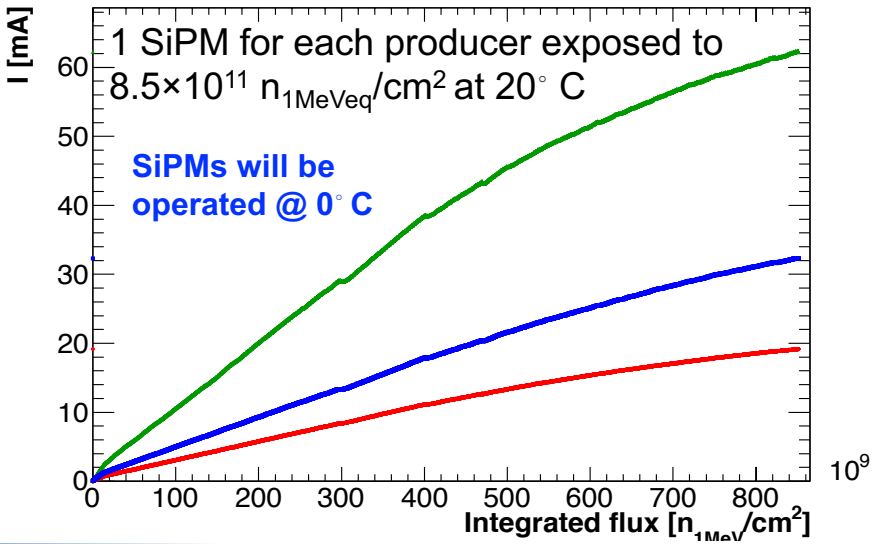
- ✗ 3×50 Mu2e pre-production SiPMs from three different vendors
- ✗ 3×35 were characterized, all six cells in the array

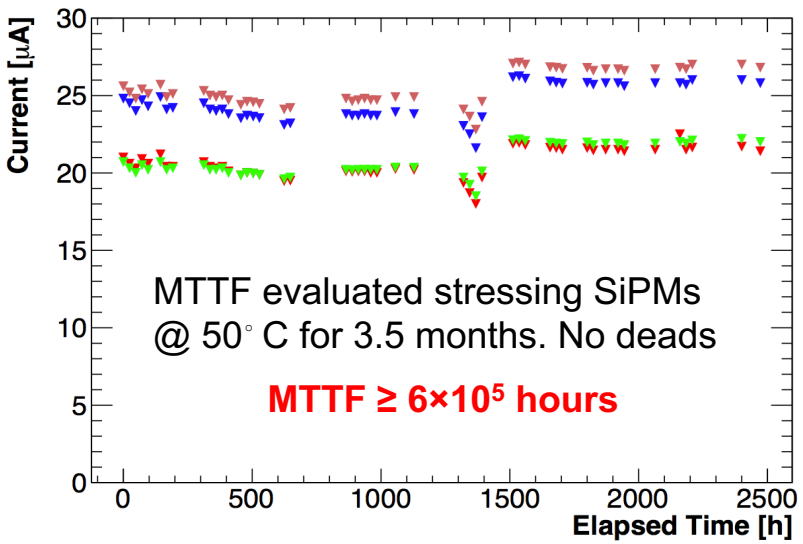
Gain



Operating Voltage







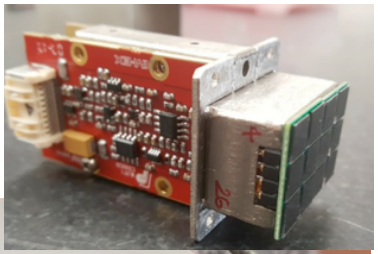
Module 0

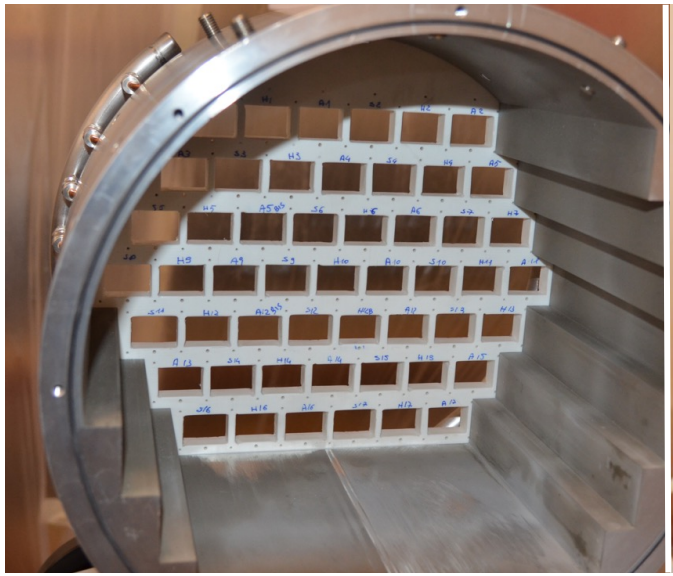
Large EMC prototype: 51 crystals, 102 SiPMs, 102 FEE boards

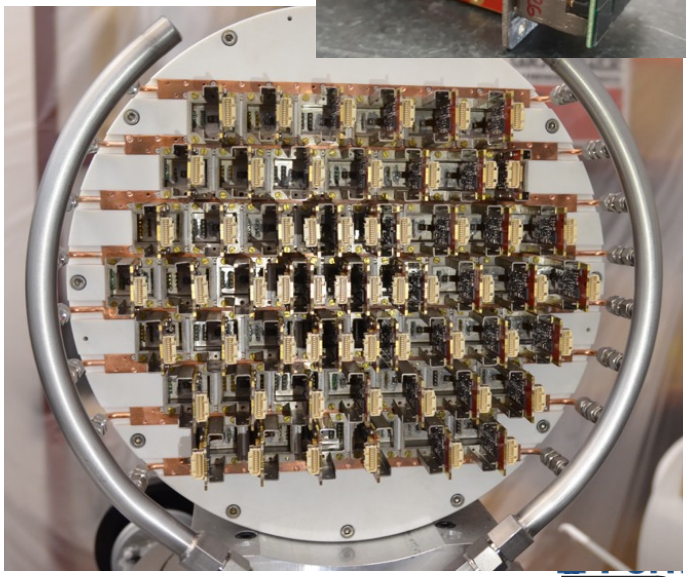
Mechanics and cooling system similar to the final ones

Goals:

- ✗ Integration and assembly procedures
- ✗ Work under vacuum, low temperature, irradiation env.
- ✗ Test beam with 60–120 MeV e^- done, analysis in progress







Conclusions

- ✗ The Mu2e experiment will exploit the world's highest intensity muon beams of the Fermilab Muon Campus to search for CLFV, improving current sensitivity by a factor 10^4
- ✗ A low mass straw tube tracker and a pure CsI crystal calorimeter with SiPM readout have been selected to satisfy the demanding requirements
- ✗ Both systems are concluding the prototyping phase
- ✗ Production phase is starting, moving to full regime for end 2017
- ✗ Detector installation in 2020, followed by Mu2e commissioning and data