The Mu2e Tracker and Calorimeter Systems

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on behalf of the Mu2e Collaboration

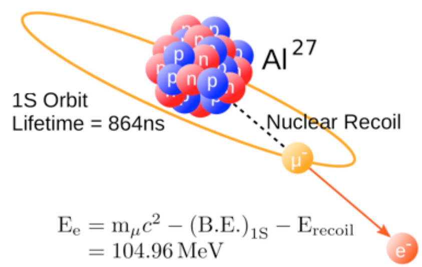
Charge Lepton Flavour Violation

CLFV strongly suppressed in Standard Model: BR $\leq 10^{-50}$ ➪ **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

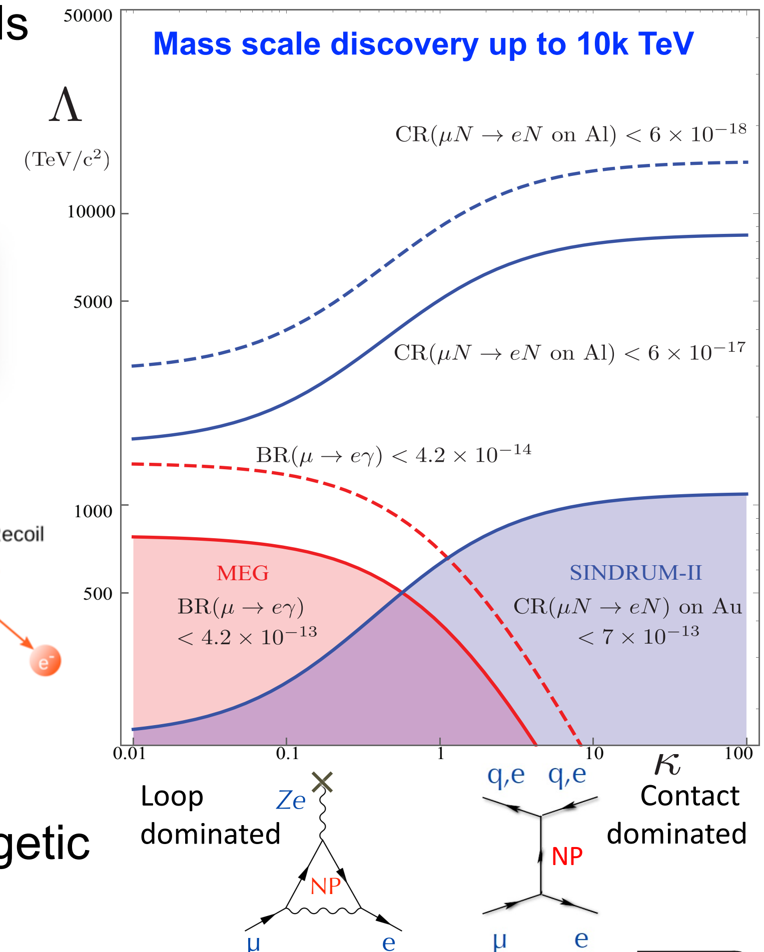
Goal: **10^4 improvement w.r.t. previous conversion experiment** (SINDRUM II)

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



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 $E \sim M_\mu$, produced with $\tau_\mu^{Al} = 864$ ns

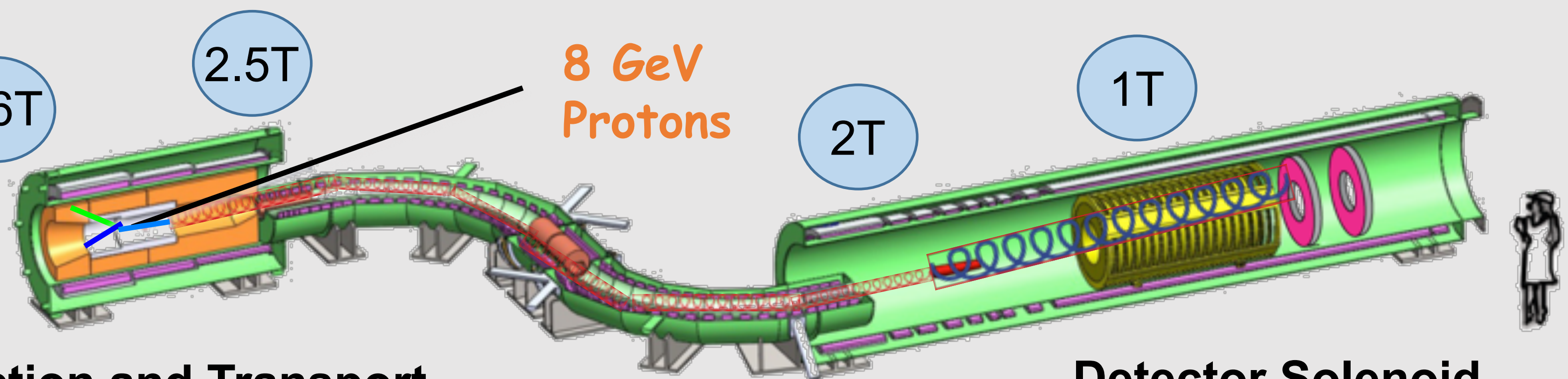


The Mu2e Experiment

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

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

in 3 years running



Production and Transport Solenoids

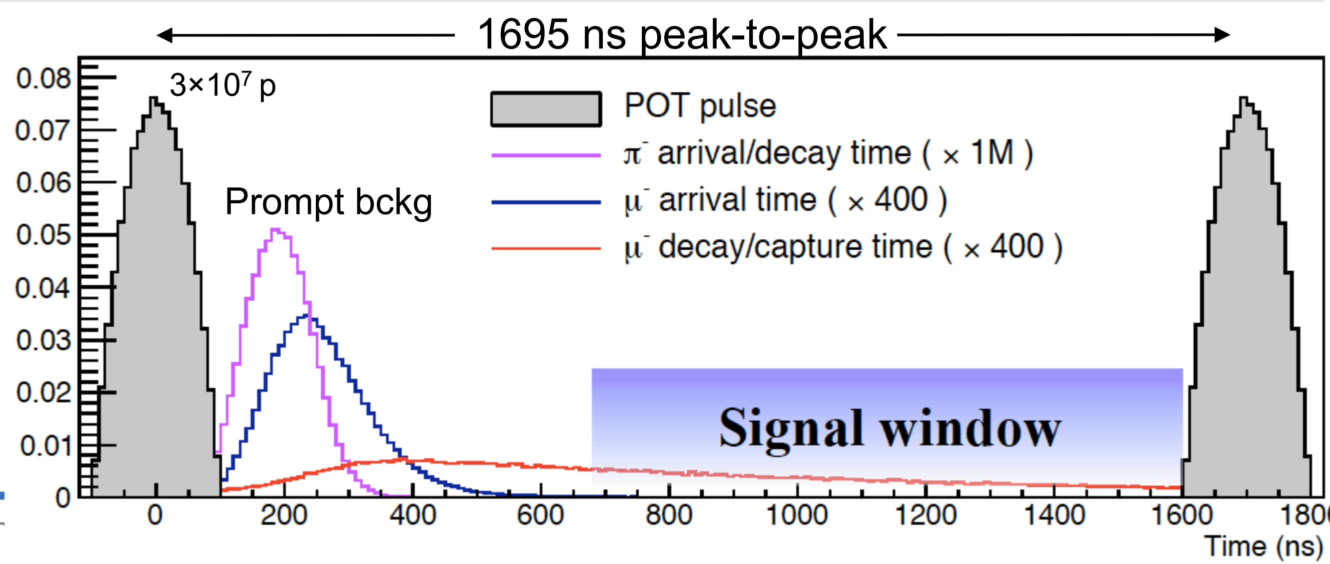
Production, selection and transport of low momentum muon beam

Detector Solenoid

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

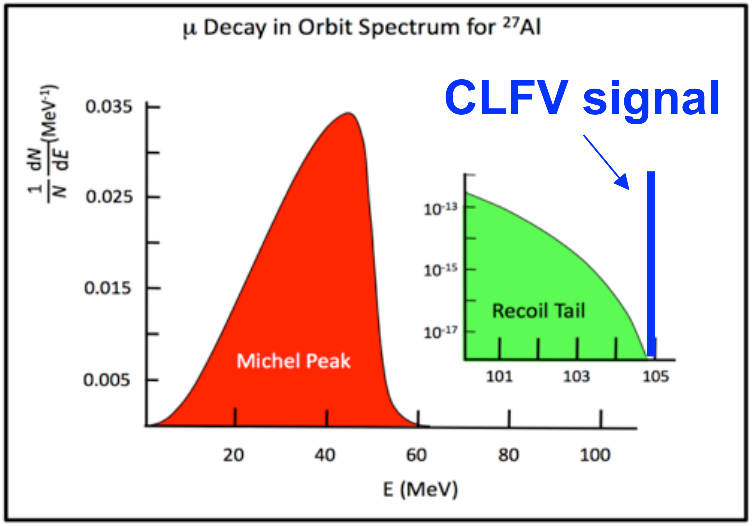
Bunch structure:

- 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

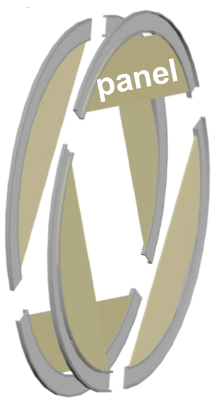
Detector requirements:
1. Small amount of X_0
2. σ_p < 180 keV @ 105 MeV
3. Good rate capability:
   - 20 kHz/cm^2 in live window
   - Beam flash of 3 MHz/cm^2
4. dE/dx capability to distinguish e^-/p
5. Operate in B = 1 T, 10^{-4} Torr vacuum
6. Maximize/minimize acceptance for CE/DIO

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

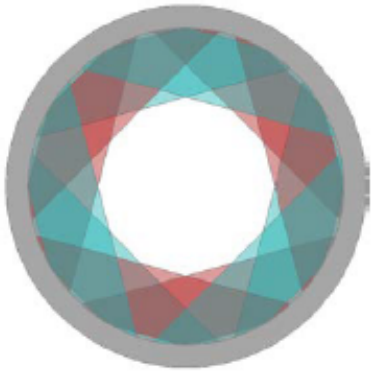
Tracker Design

- ✗ > 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

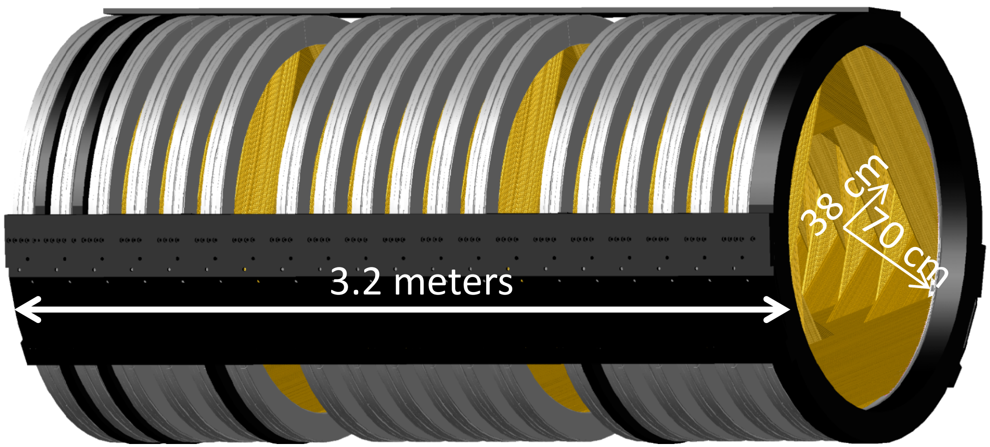
Tracker Plane



Tracker Station:
2 rotated planes



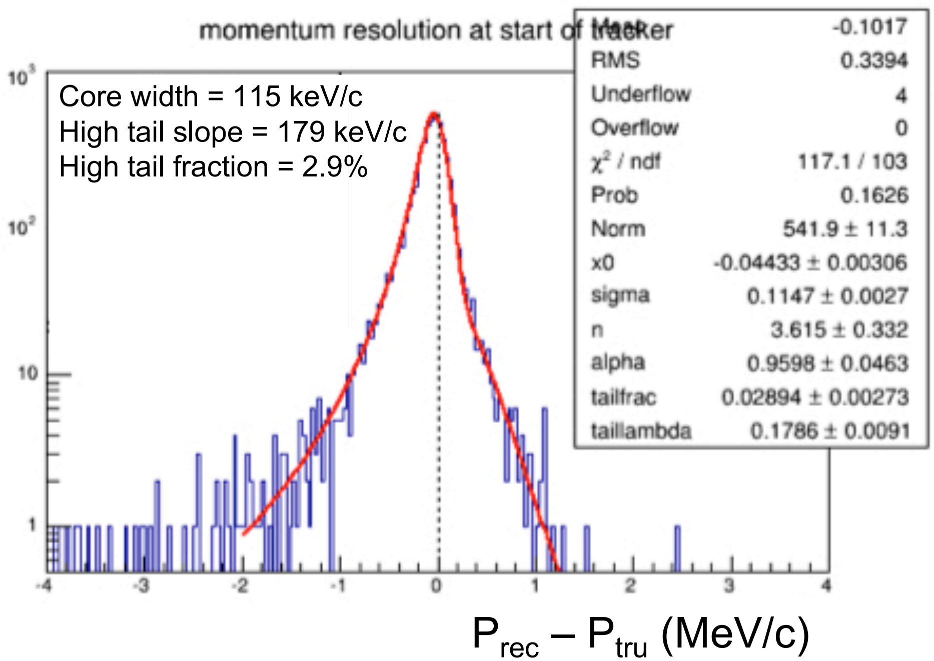
Tracker: 18 stations

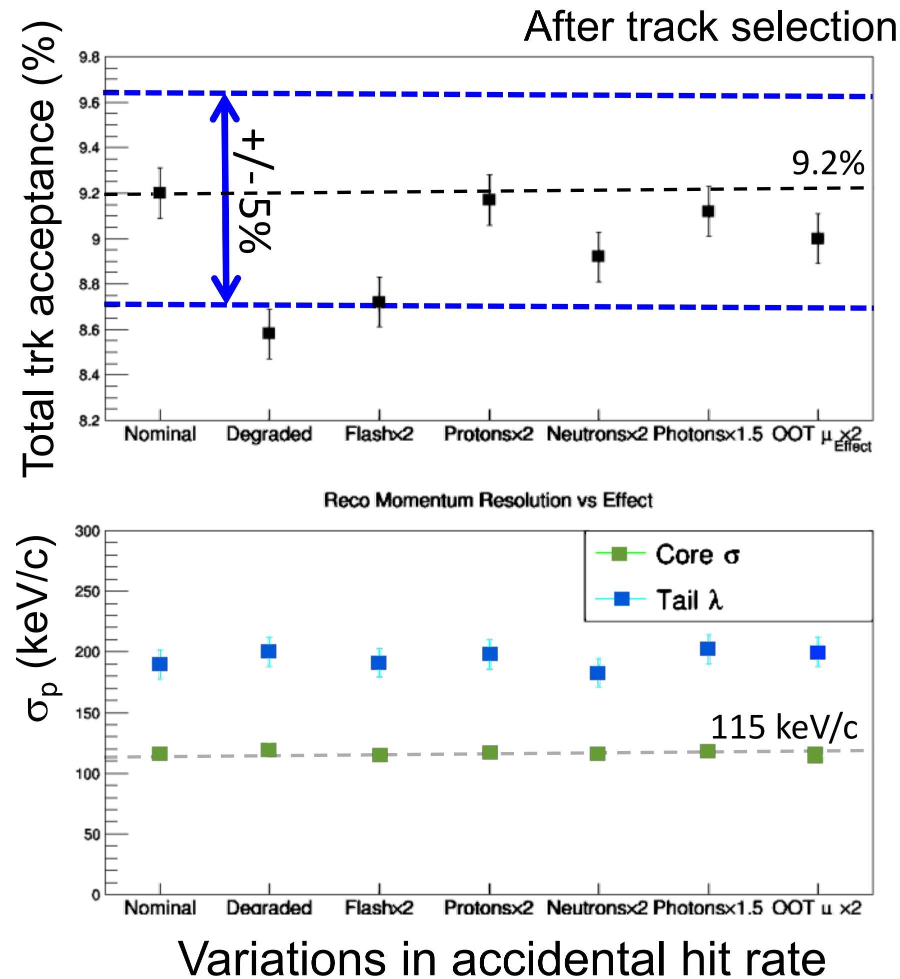


- ✗ Inner 38 cm is purposely un-instrumented
  - ➢ Blind to beam flash (low momentum particles)
  - ➢ Blind to >99% of DIO spectrum

Tracker Performances

Expected tracker performances from full simulation

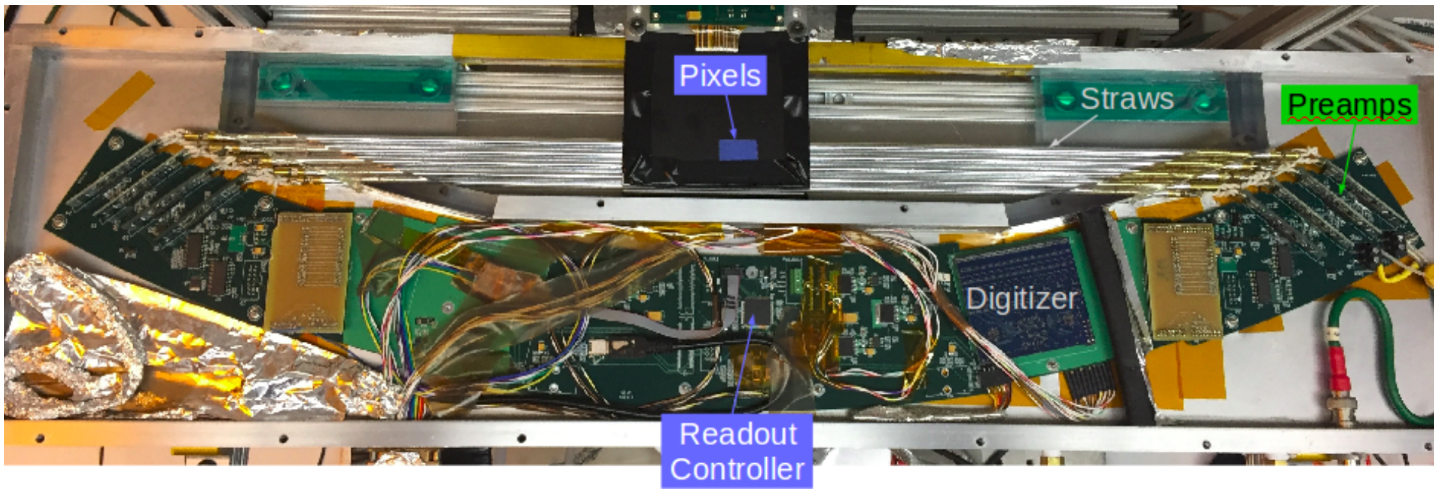


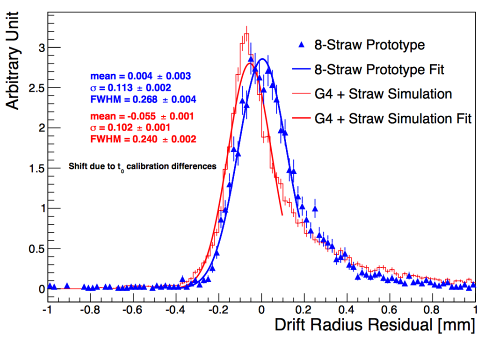


- ✗ Well within physics requirements
- ✗ Robust against increases in rate
- ✗ Inefficiency dominated by geometric acceptance

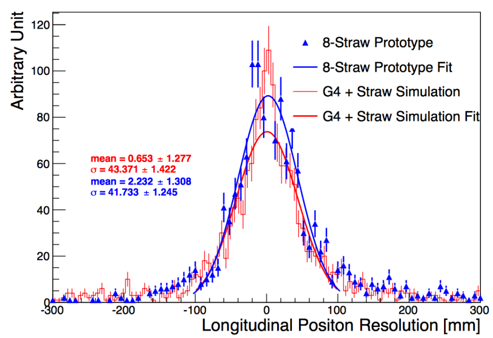
Mu2e Tracker: 8 channel prototype

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

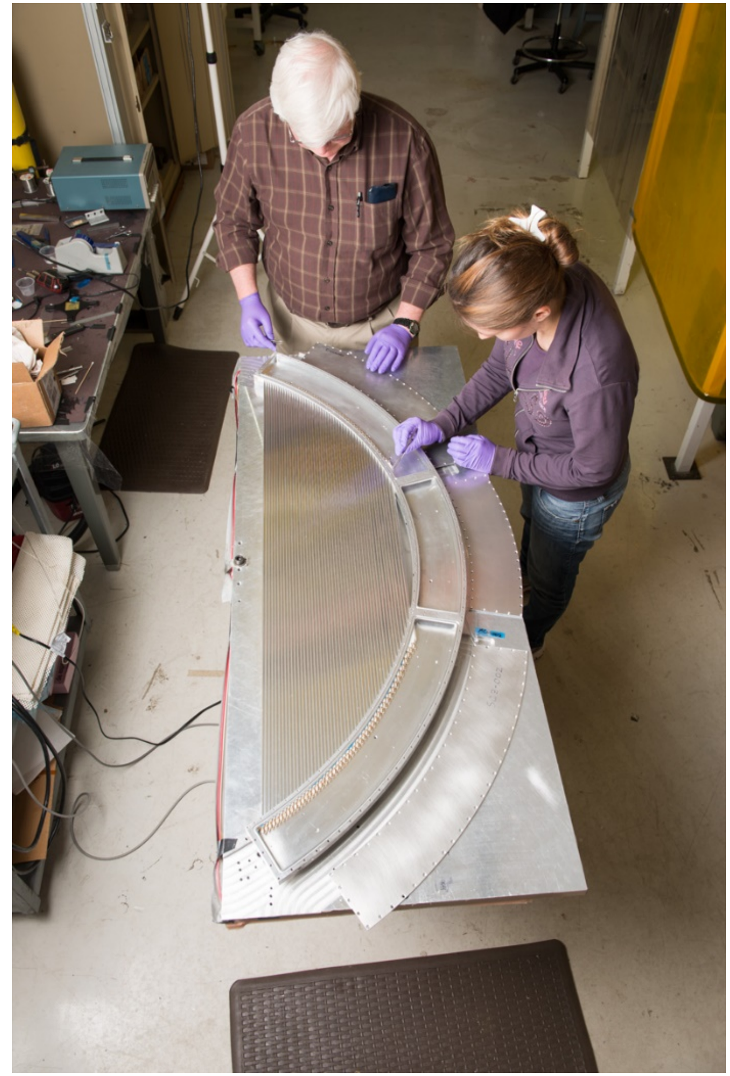


Longitudinal Resolution
(Data vs MC)
$\sigma_{data} = 42 \pm 1$ mm
$\sigma_{MC} = 43 \pm 1$ mm

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

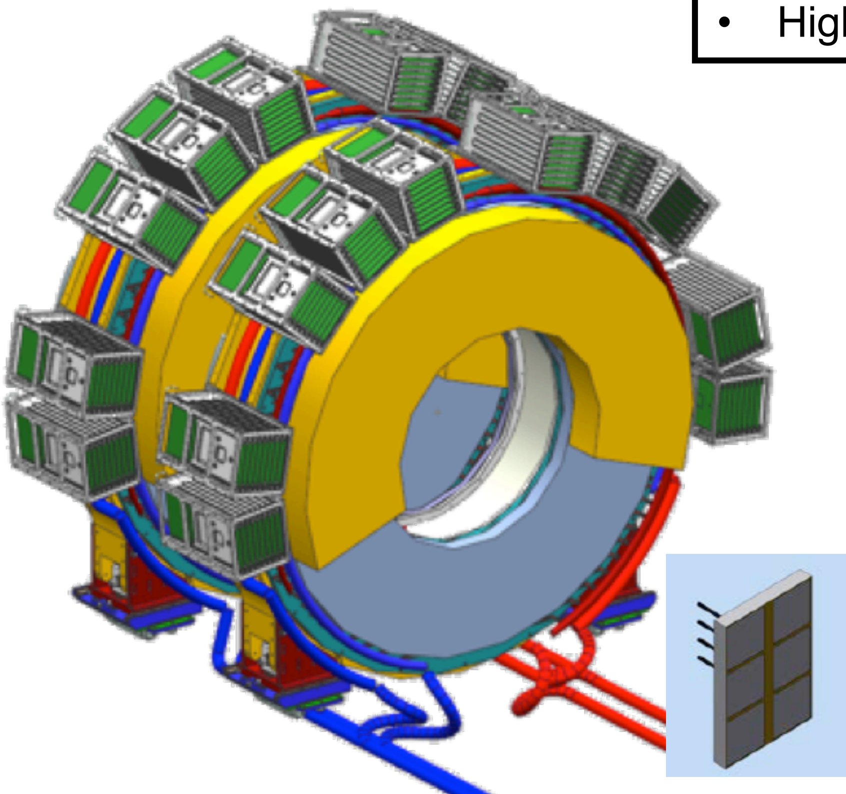
Calorimeter provides confirmation for CE and other crucial functions:

✗ PID: e/μ separation

✗ EMC seeded track finder

✗ Standalone trigger

Requirements:
- $\sigma_E/E = \mathcal{O}(5\%)$ for CE
- σ_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

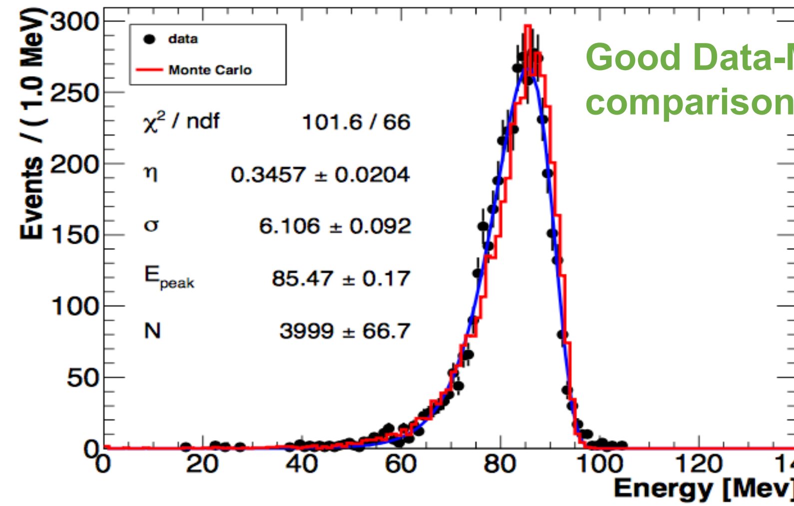
✗ Calibration/Monitoring with 6 MeV radioactive source and a laser system

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

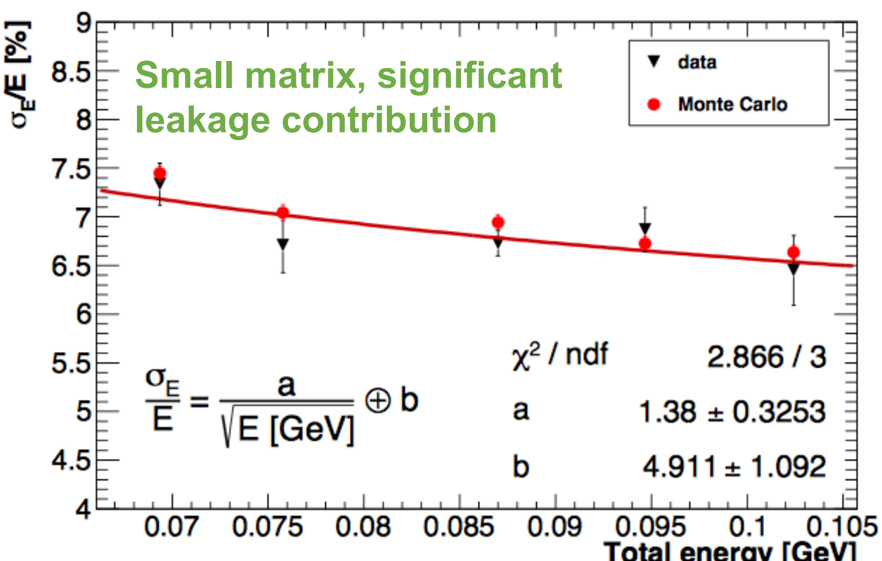
Calorimeter Performances

JINST 12 (2017) P05007

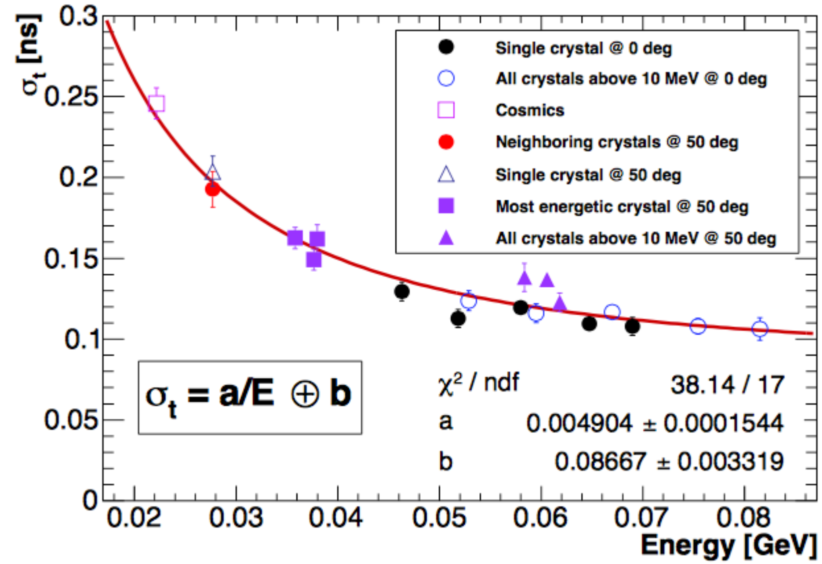
- ✗ Small prototype tested @ BTF (Frascati) in April 2015, 80–120 MeV e^-
- ✗ 3×3 array of (30×30×200) mm^2 undoped CsI crystals coupled to Hamamatsu MPPC
- ✗ DAQ readout: 250 Msps CAEN V1720 Wave Form Digitizer



Good Data-MC comparison



σ_E ~ 6.5% at 100 MeV

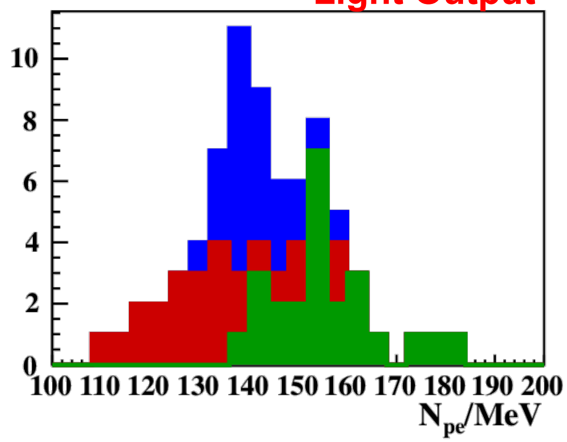


σ_T ~ 110 ps at 100 MeV

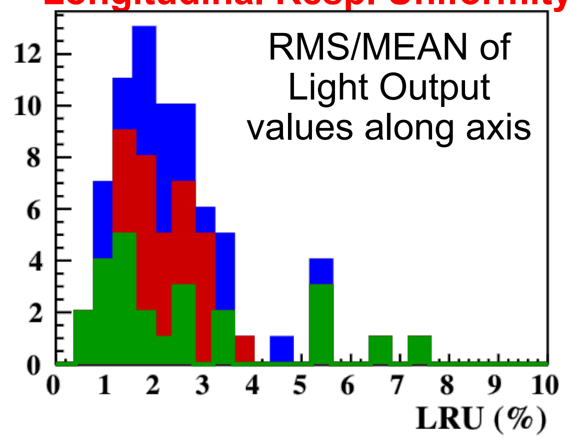
Test of pre-production crystals

- ✗ 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

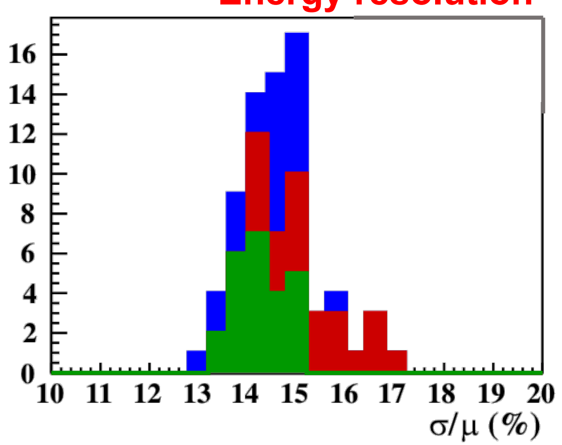
Light Output



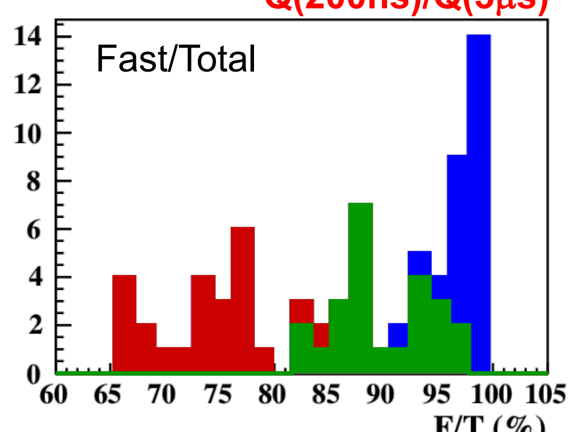
Longitudinal Resp. Uniformity



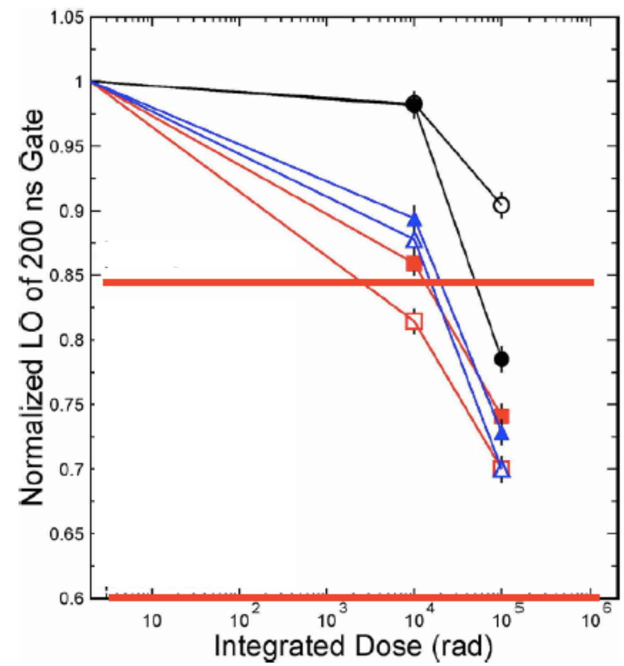
Energy resolution



Q(200ns)/Q(3μs)



Irradiation test up to 100 krad

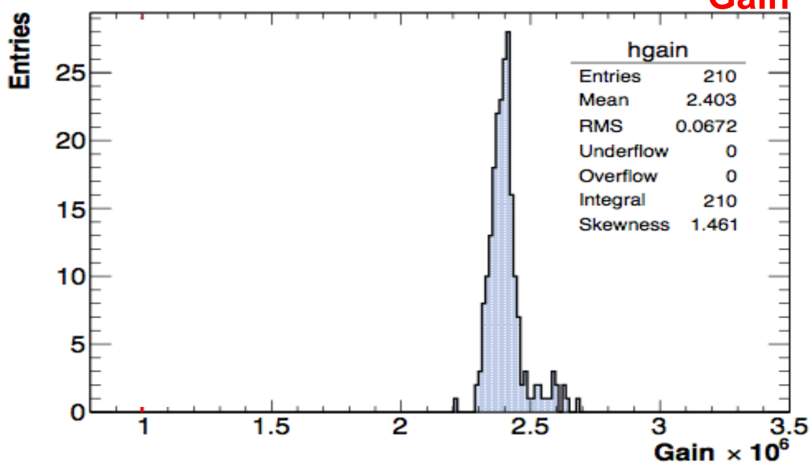


All satisfy Mu2e 100 krad requirement (40% max. loss)

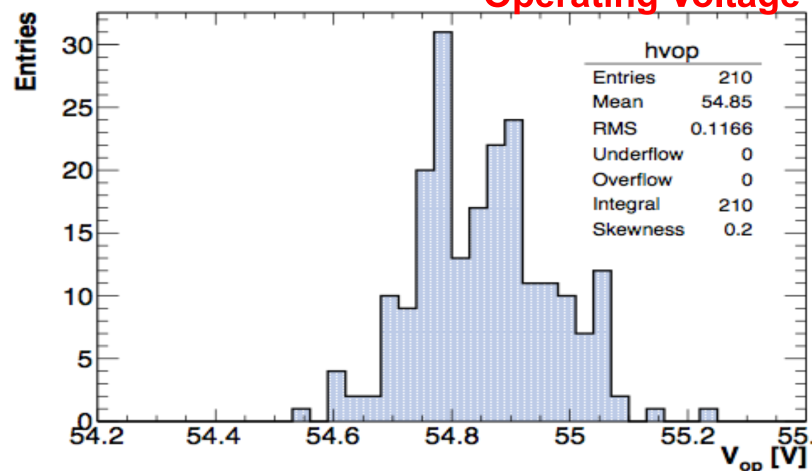
Test of pre-production SiPMs

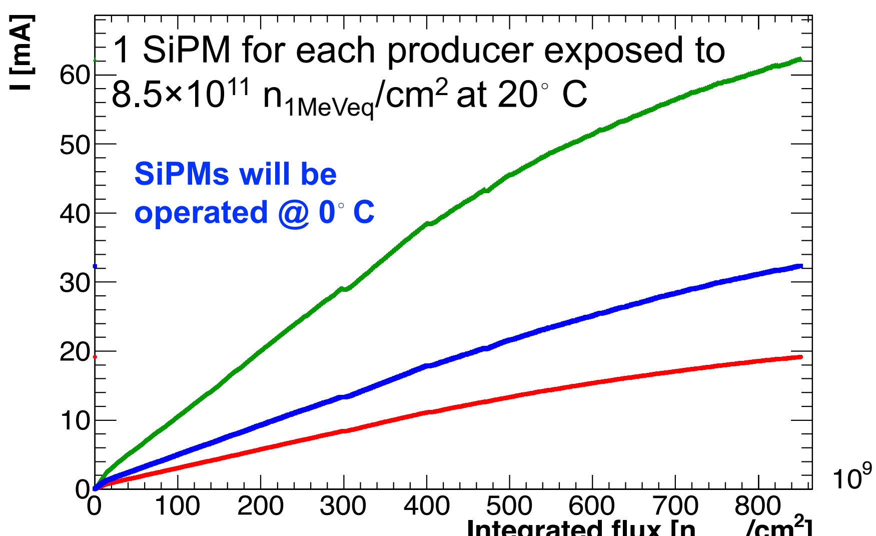
- ✗ 3×50 Mu2e pre-production SiPMs from three different vendors
- ✗ 3×35 were characterized, all six cells in the array

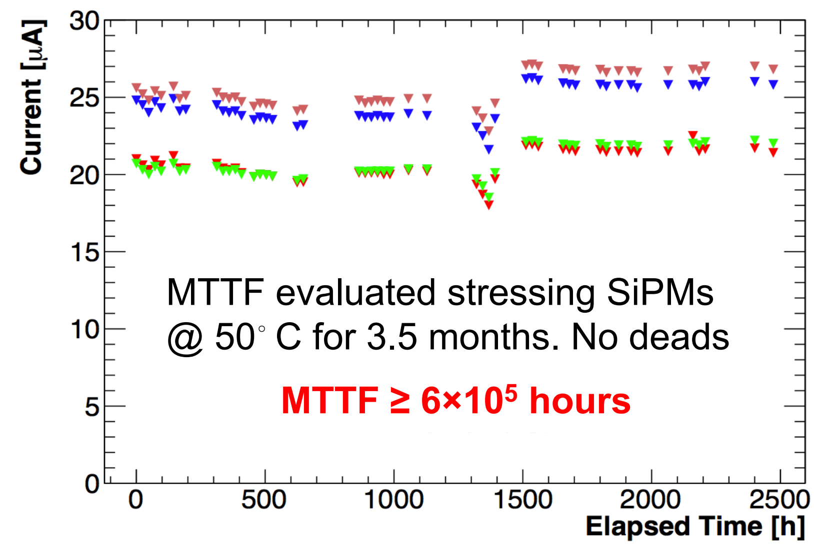
Gain



Operating Voltage







Module 0

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

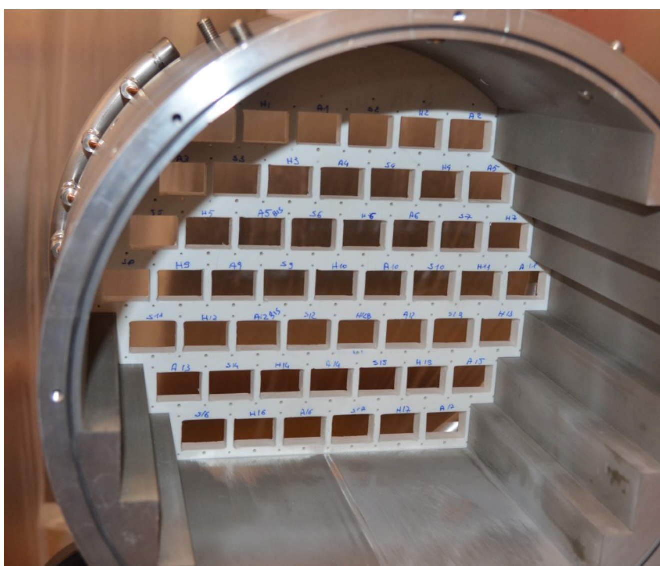
Mechanics and cooling system similar to the final ones

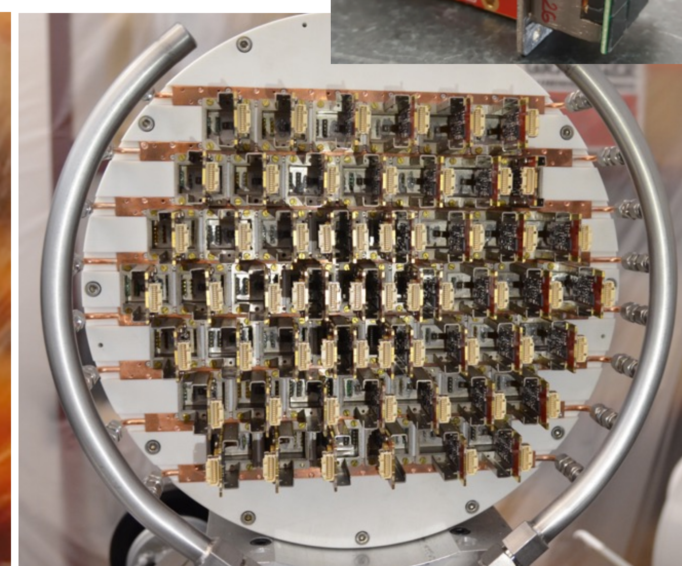
Goals:

✗ Integration and assembly procedures

✗ Work under vacuum, low temperature, irradiation env.

✗ Test beam with 60–120 MeV e^- done, analysis in progress



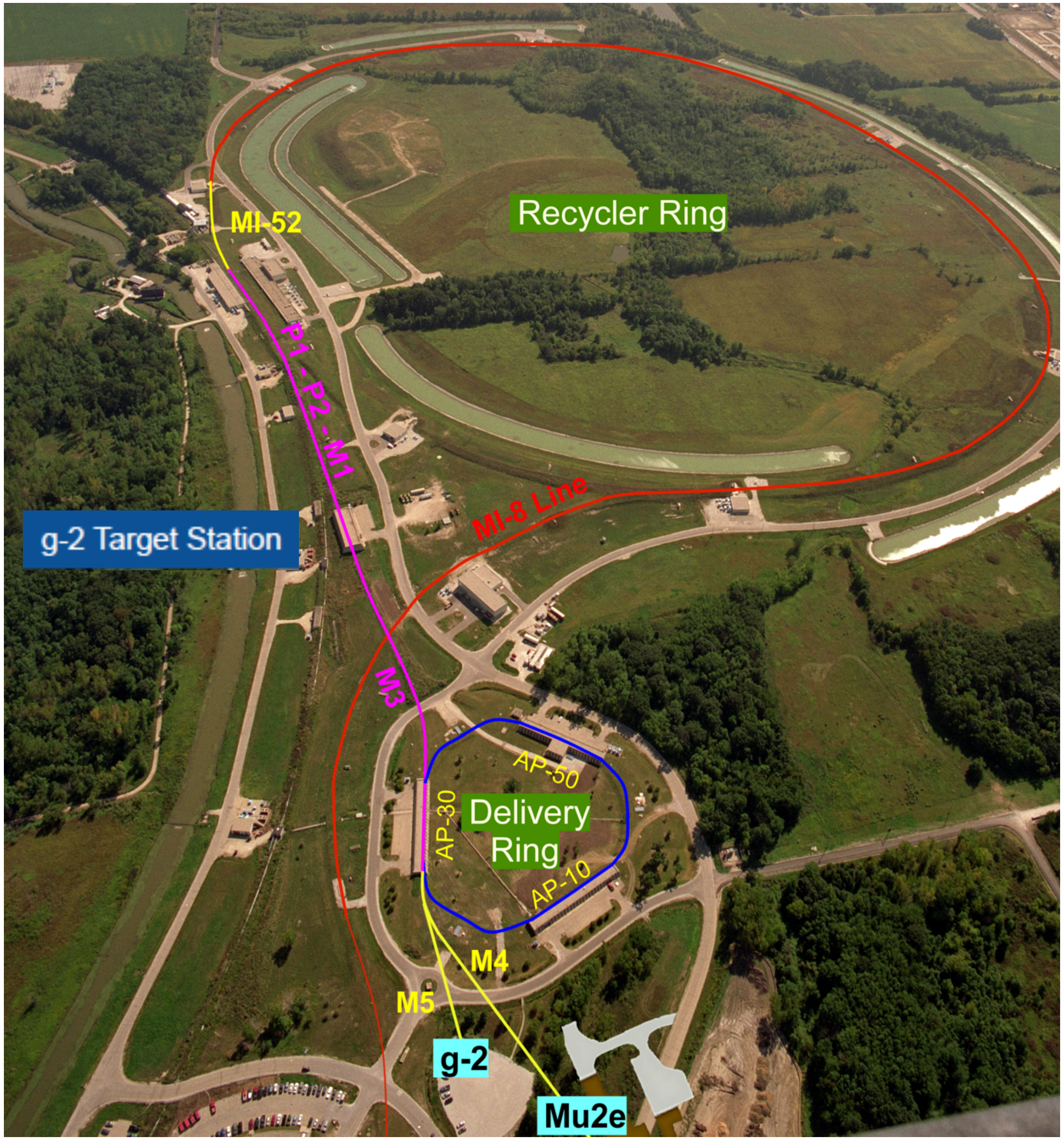


Conclusions

- ✗ 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

The Muon Campus at Fermilab

Beam for Muon Campus



Recycler: fixed 8 GeV proton ring

Beams both to Muon Campus and neutrino experiments

Separate runs for g-2 and Mu2e

g-2: target before the delivery ring, 3.1 GeV π^+ selected, clean, polarized μ^+ beam

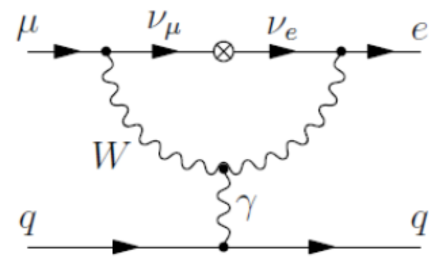
Mu2e: 8 GeV protons to Mu2e hall

Accelerator Readiness Review took place in March 2017

Beam commissioning for g-2 started beginning of April
First $p/\pi/\mu$ beam in the ring in June (no target and del. ring)

CLFV

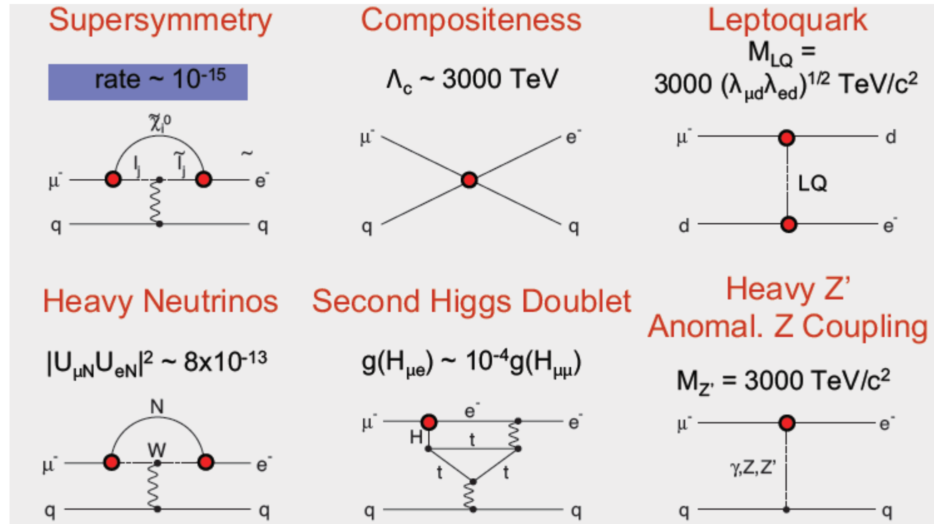
Standard Model
$\mu \rightarrow e$ conversion



W. Altmannshofer, *et al*, arXiv:0909.1333 [hep-ph]

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

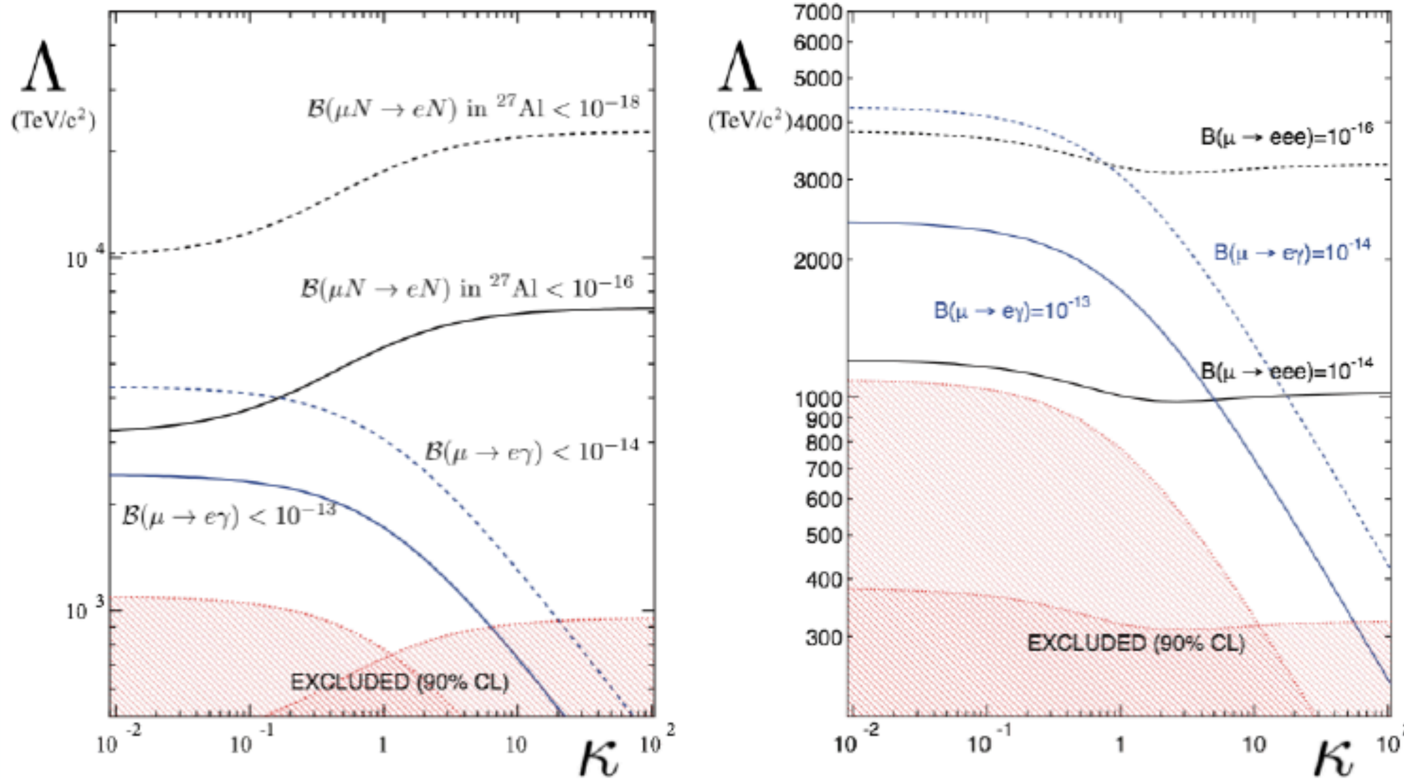


If SUSY seen at LHC → rate ~10^{-15}

Implies O(40) reconstructed signal events with negligible background in Mu2e for many SUSY models.

Mu2e keeps discovery sensitivity for all SUSY benchmark point for LHC Phase2

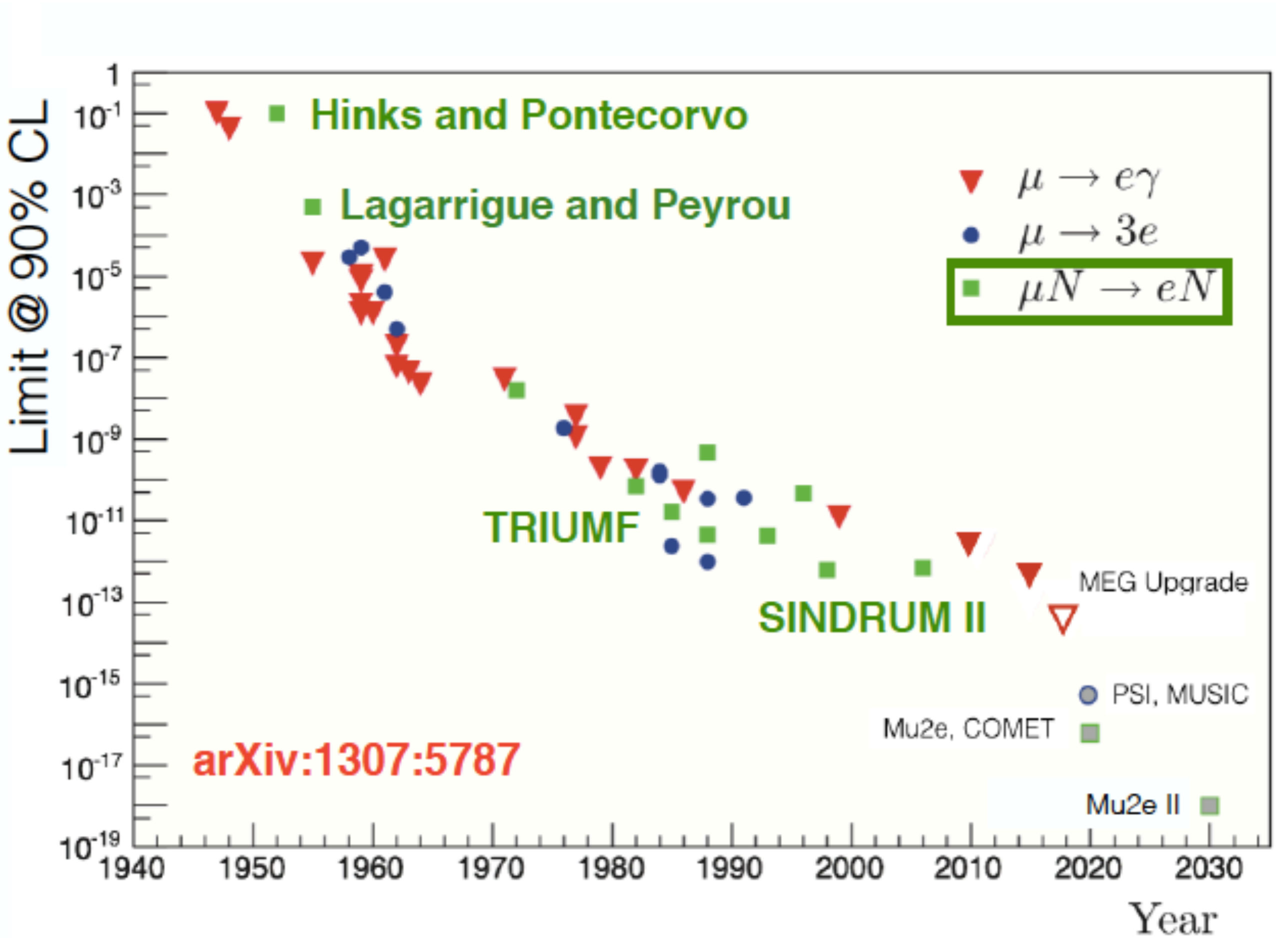
Model independent Lagrangian



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

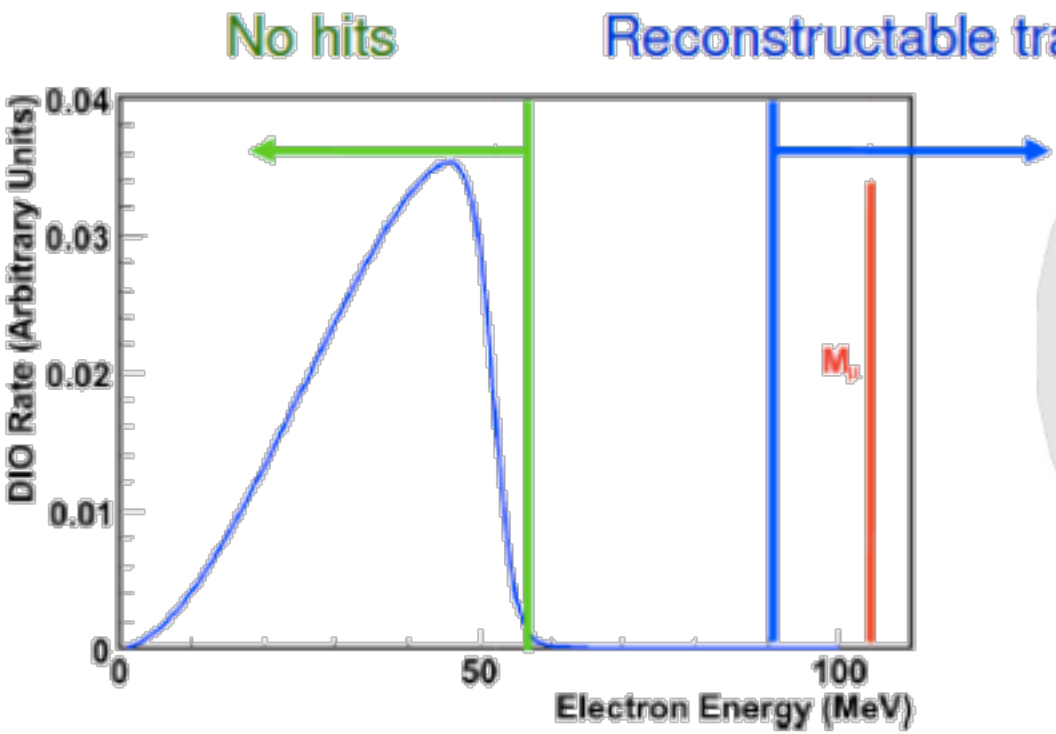
"dipole term" **"contact term"**

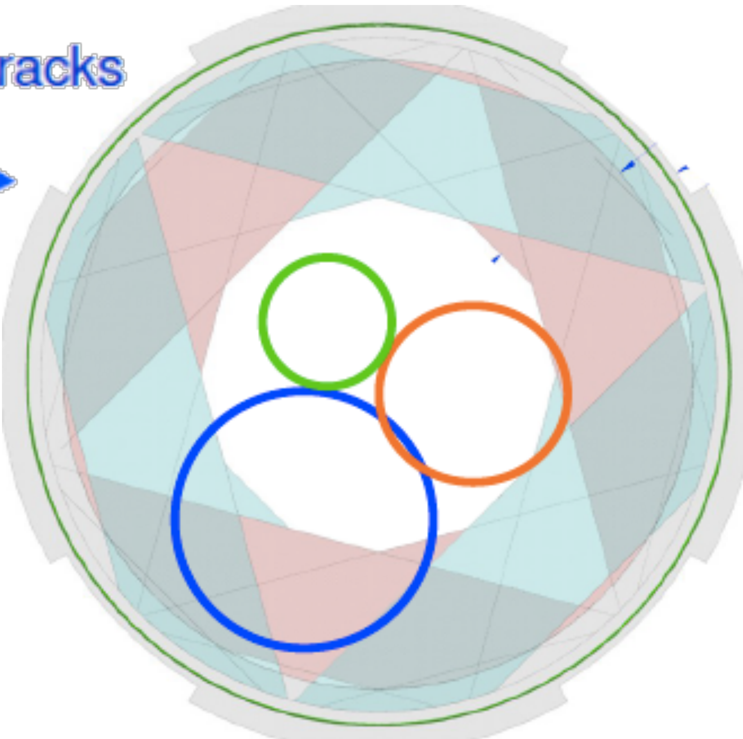
CLFV along the years



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

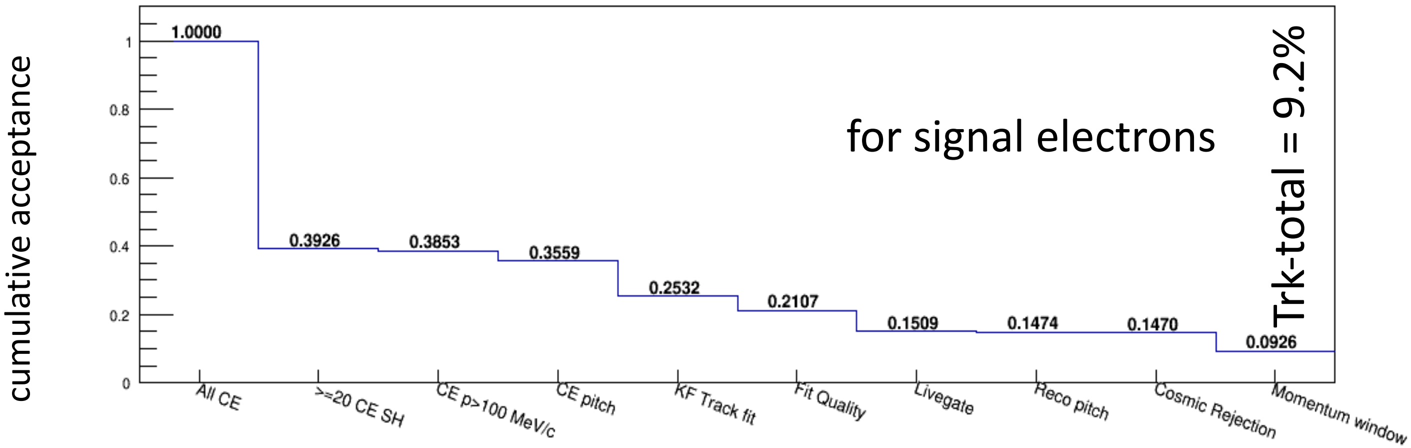
DIO background



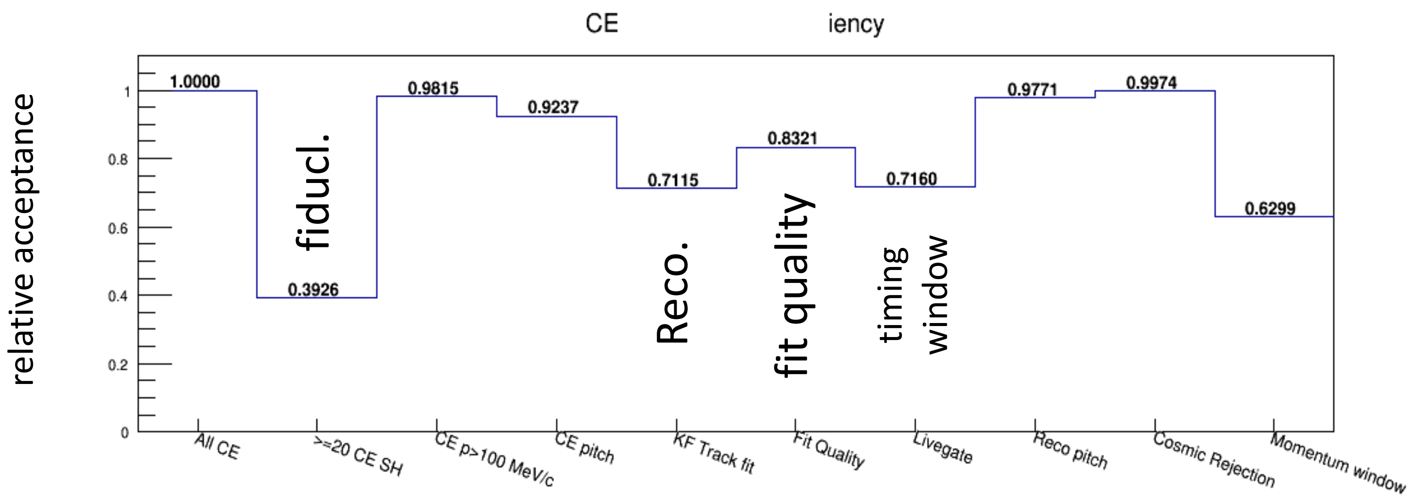


The tracker is blind to most of the DIO background

Track reconstruction and selection



Inefficiency dominated by geometric acceptance

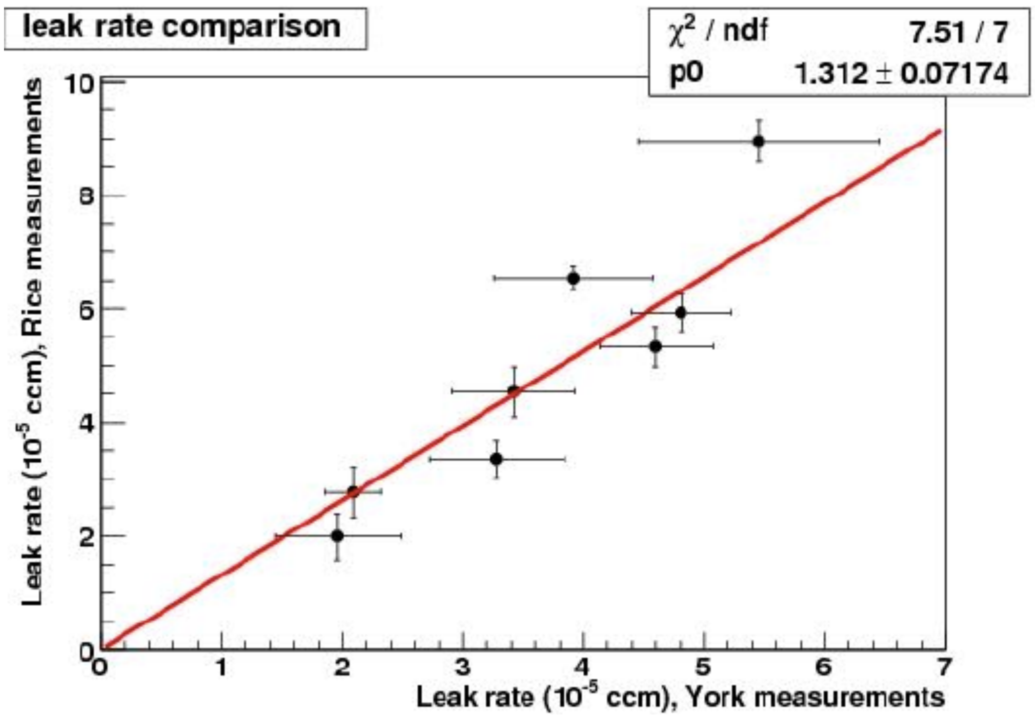


After calorimeter PID and CRV deadtime, Total = 8.5%

Straw leak test

Two methods:

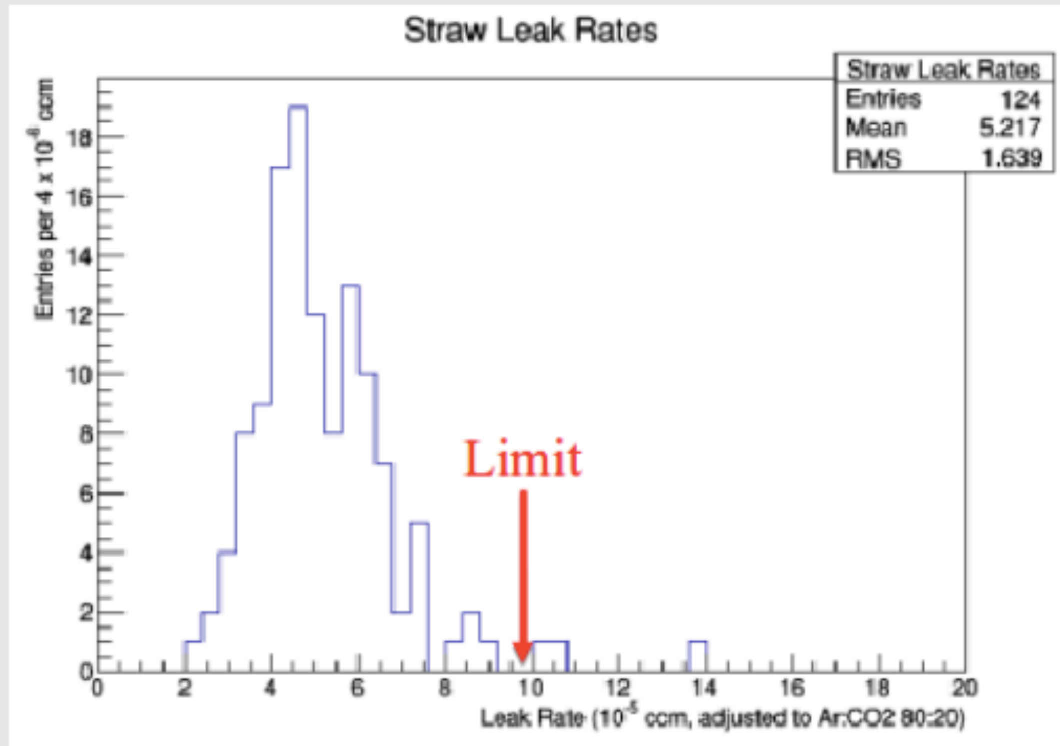
- CO_2 permeation — >100 straw/day: do every straw
  Needs cross calibration
- Vacuum — Absolute measurement
  ~ 1 per day (sample of straw



Agrees within uncertainty in correcting for difference in diffusion of Argon vs CO_2

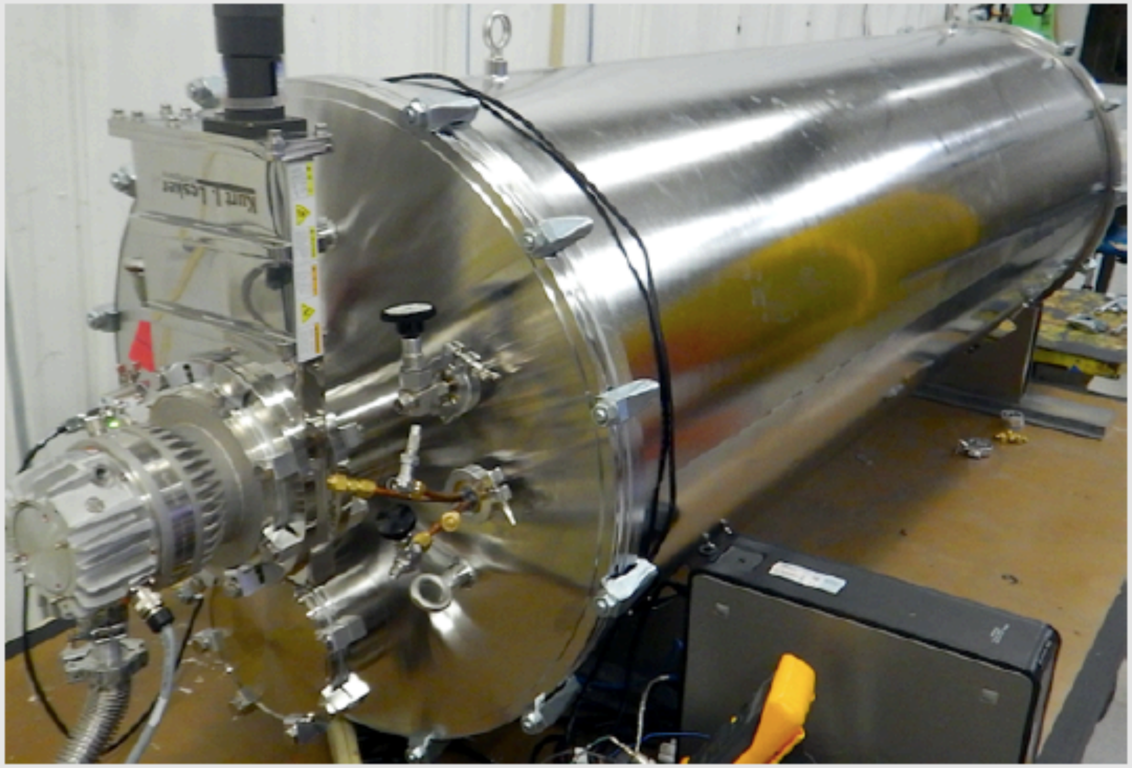
Straw leak test

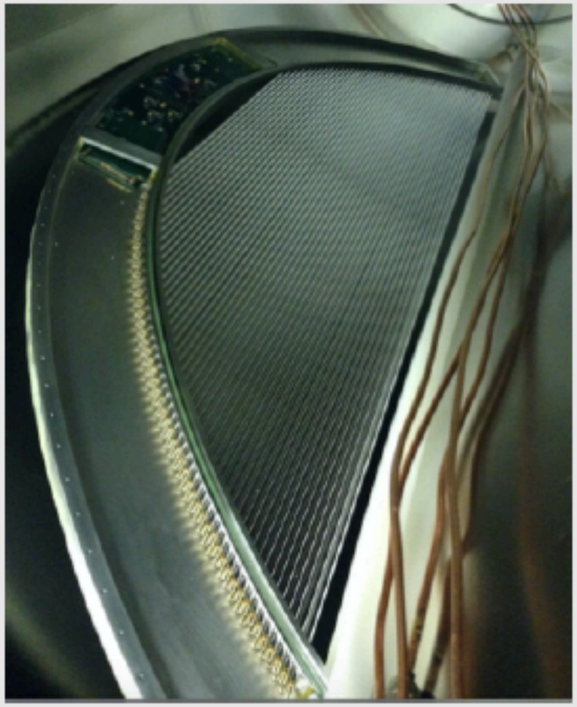
- The full tracker leak rate limit is 6 cm^3/min .
  - many possible sources
  - individual straw leak limit is 9.6×10^{-5} cm^3/min
  - 124 straws tested at FNAL last summer;121 passed



Panel leak test

- Large vacuum vessel to test 6 panels per day





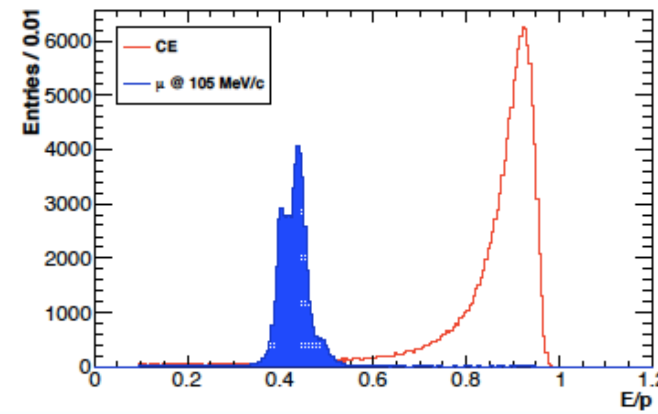
Calorimeter: e/μ separation

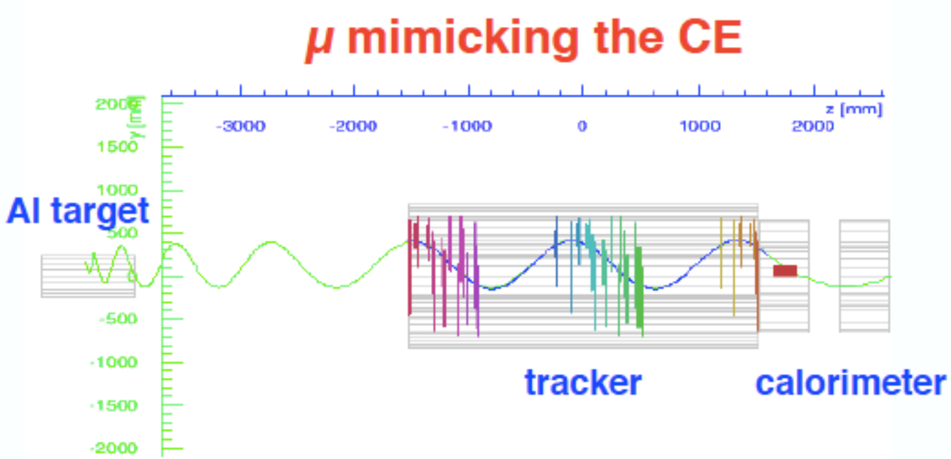
With a CRV inefficiency of 10^{-4} an additional rejection factor of ~ 200 is needed to have < 0.1 fake events from cosmics in the signal window

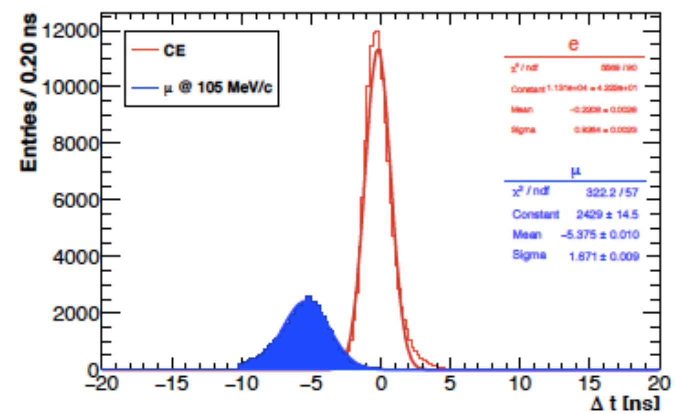
- 105 MeV/c e^- are ultra-relativistic, while 105 MeV/c μ have β~ 0.7 and a kinetic energy of ~ 40 MeV
- Likelihood rejection combines

  $\Delta t = t_{track} - t_{cluster}$ and E/p:

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



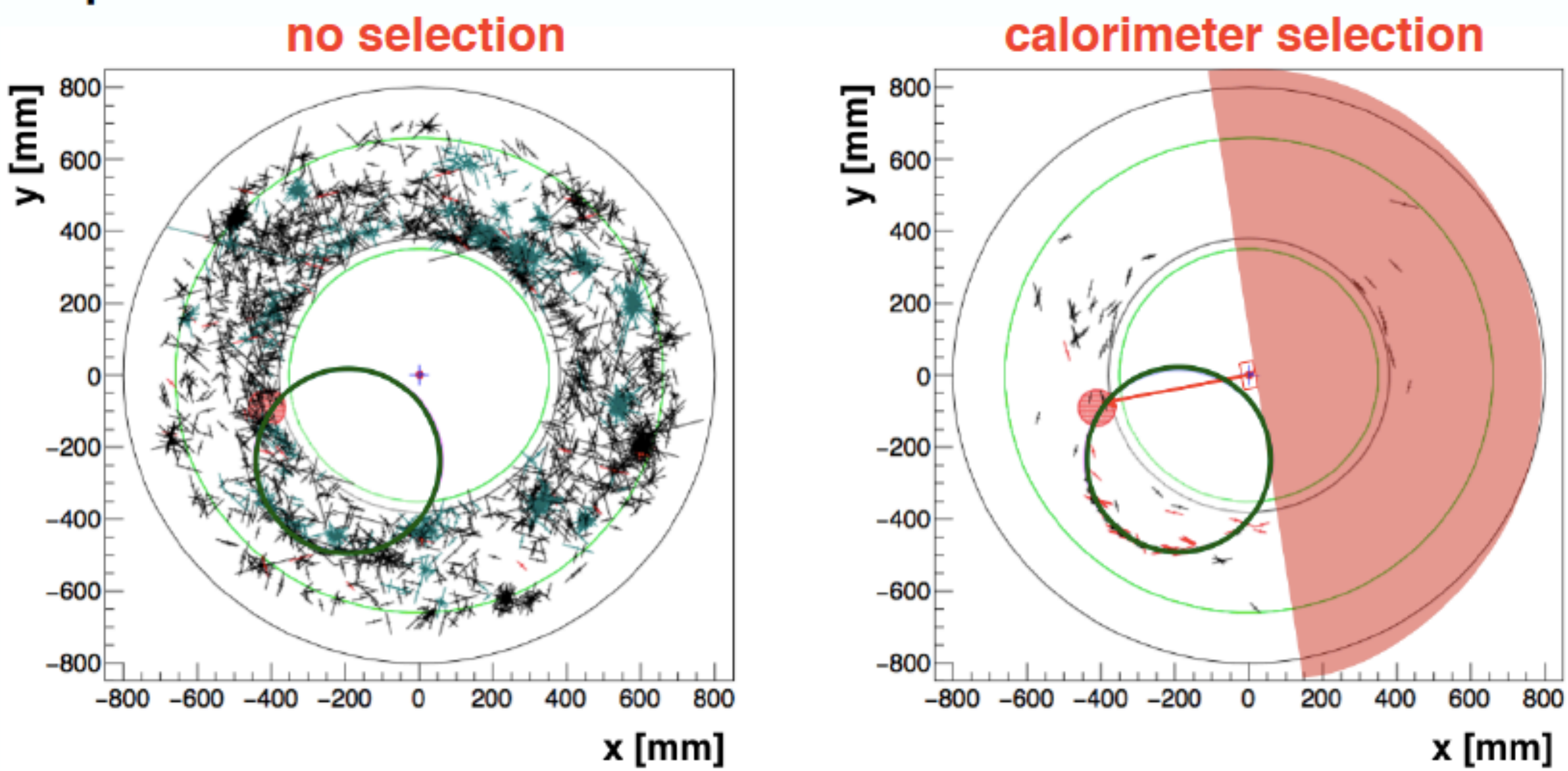




A rejection factor of 200 can be achieved with ~ 95% efficiency for CE

Calorimeter seeded track finder

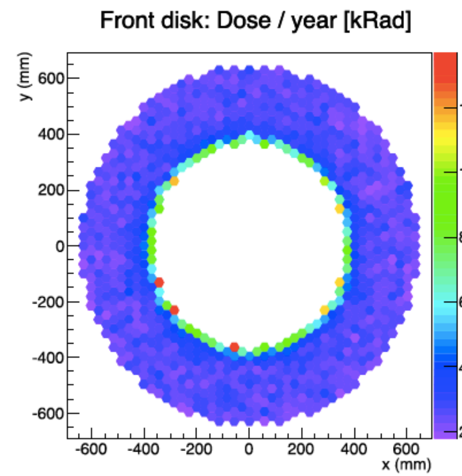
- Cluster time and position are used for filtering the straw hits:
  - ✓ **time window of ~ 80 ns**
  - ✓ **spatial correlation**

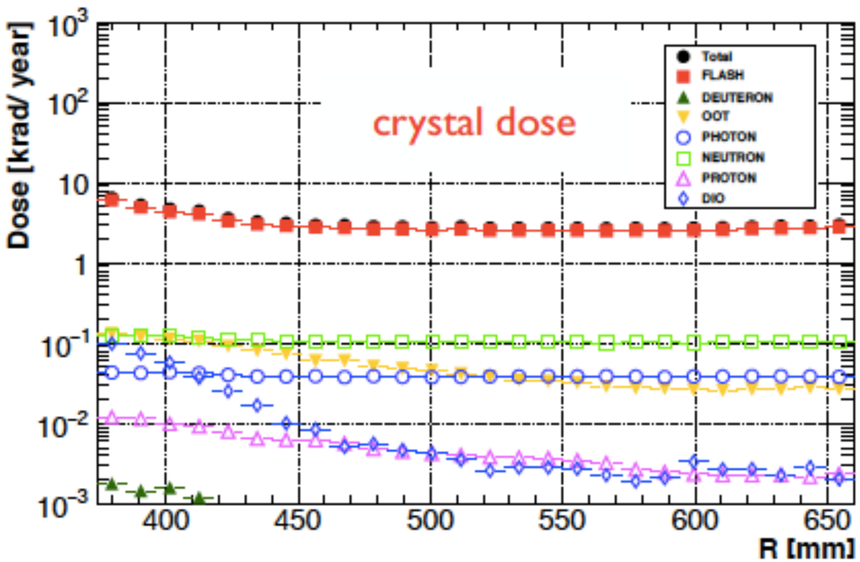


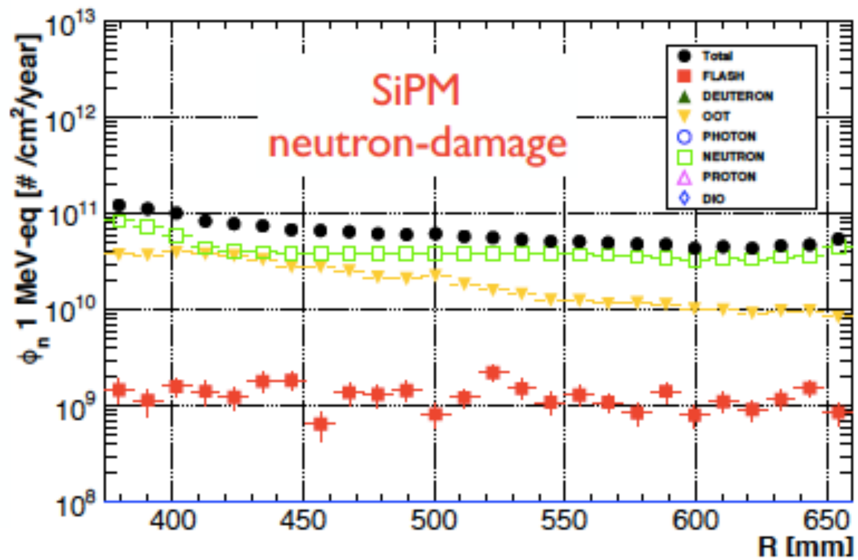
- **black crosses** = straw hits, red circle = calorimeter cluster, green line = CE track

Calorimeter radiation damage

- Calorimeter radiation dose driven by beam flash (interaction of proton beam on target)
- Dose from muon capture is x10 smaller
- Dose is mainly in the inner radius
- Highest dose ~10 krad/year
- Highest n flux on crystals ~ 2×10^{11} n/cm^2/year
- Highest n flux on SiPM ~ 10^{11} n_{1MeVeq}/cm^2/year





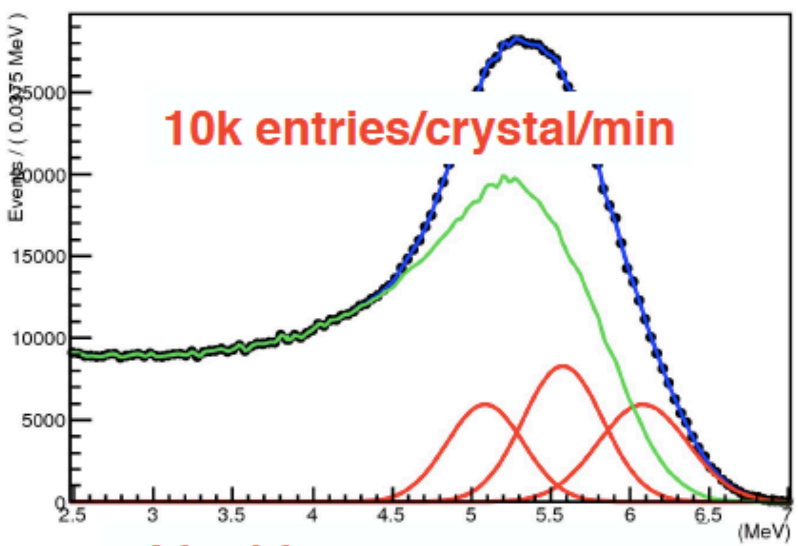


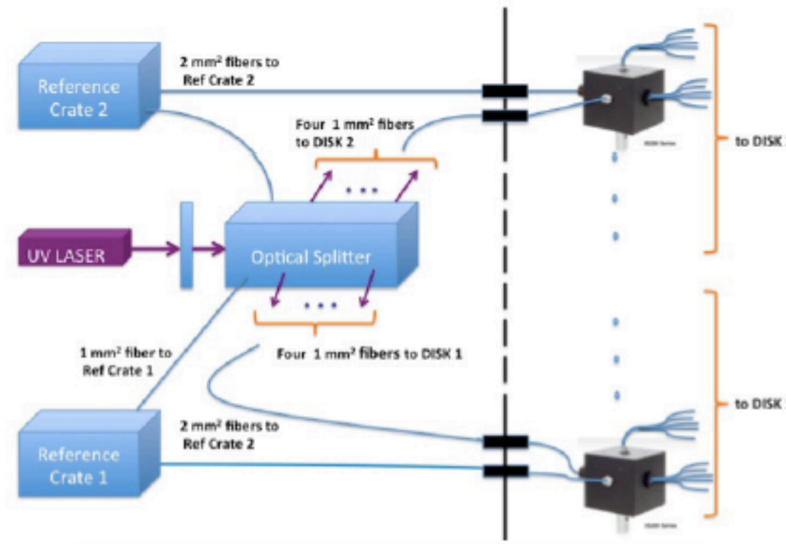
Qualify crystals up to ~ 100 krad, 10^{12} n/cm^2
Qualify SiPM up to ~ 10^{12} n_{1MeVeq}/cm^2

This includes a safety factor of 3 for a 3 year run

Calorimeter calibration

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





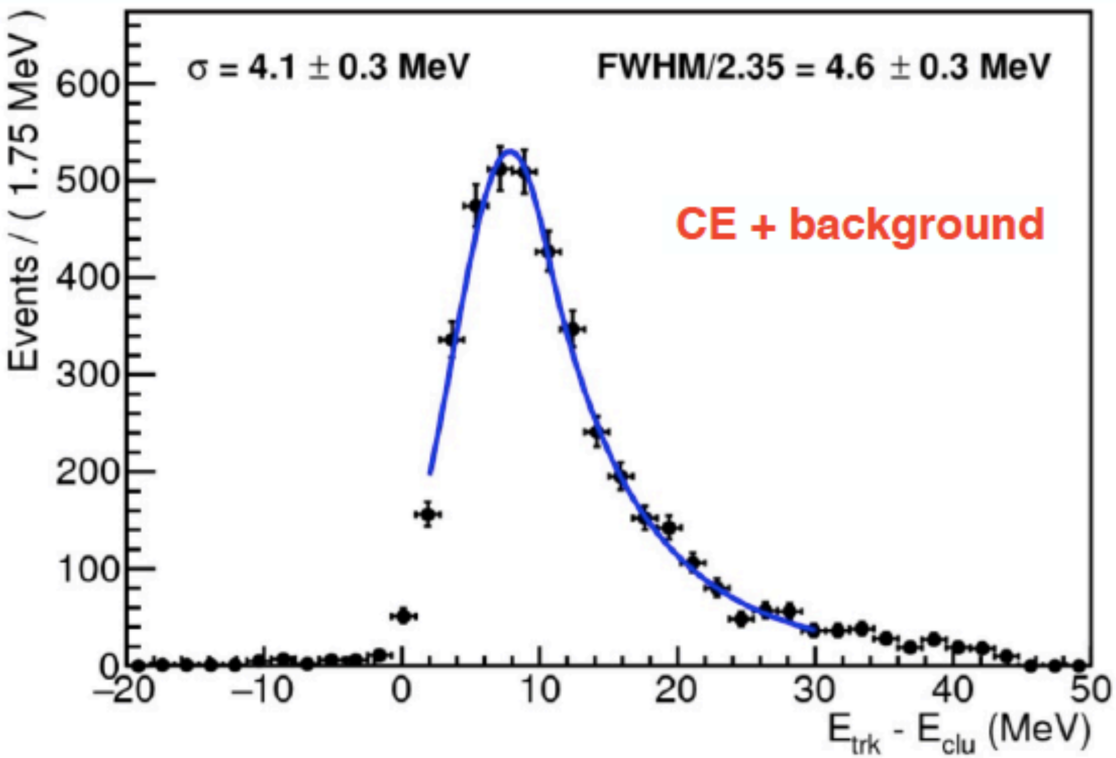
Liquid source prototype

Laser system - test station

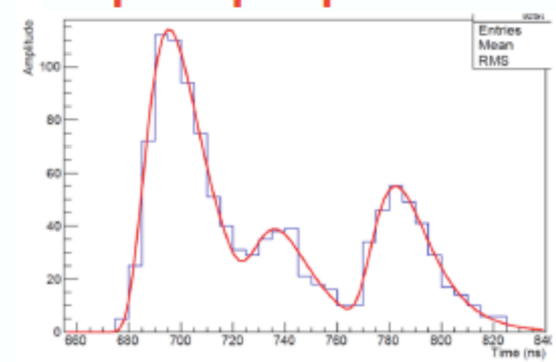
$$^{19}F + n \rightarrow \; ^{16}N + \alpha$$
$$^{16}N \rightarrow \; ^{16}O^* + \beta \quad t_{1/2} = 7\ \mathrm{s}$$
$$^{16}O^* \rightarrow \; ^{16}O + \gamma(6.13\ \mathrm{MeV})$$

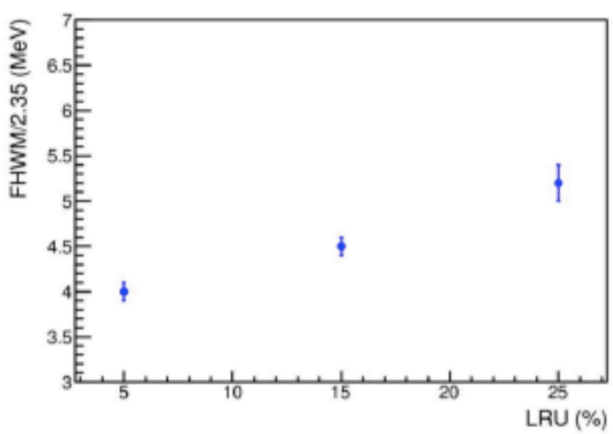
Calorimeter simulation

- Offline simulation including background hits
- Experimental effects included: longitudinal response uniformity (LRU), electronic noise, digitization, etc
- Waveform-based analysis to improve pileup separation



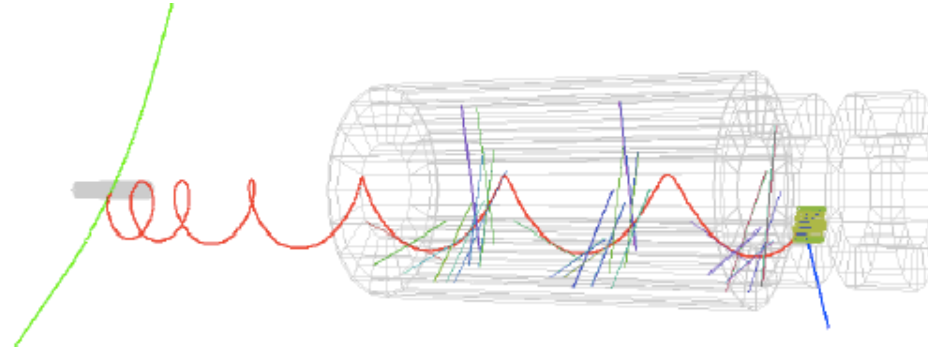
pile-up separation

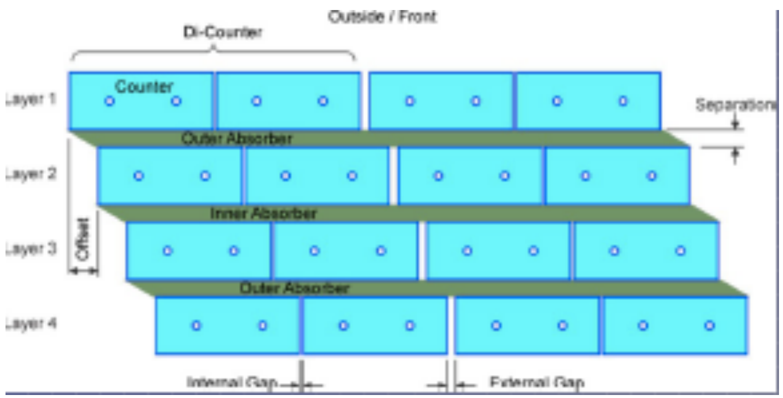




Cosmic Ray Veto

Cosmic ray muons will produce one fake signal event per day without a CRV. The muon itself can fake a 105 MeV e^{-} or it can knock out an e^{-} from material in the detector (delta ray), which can fake the signal
→ Passive shielding + PID trk/EMC + CRV



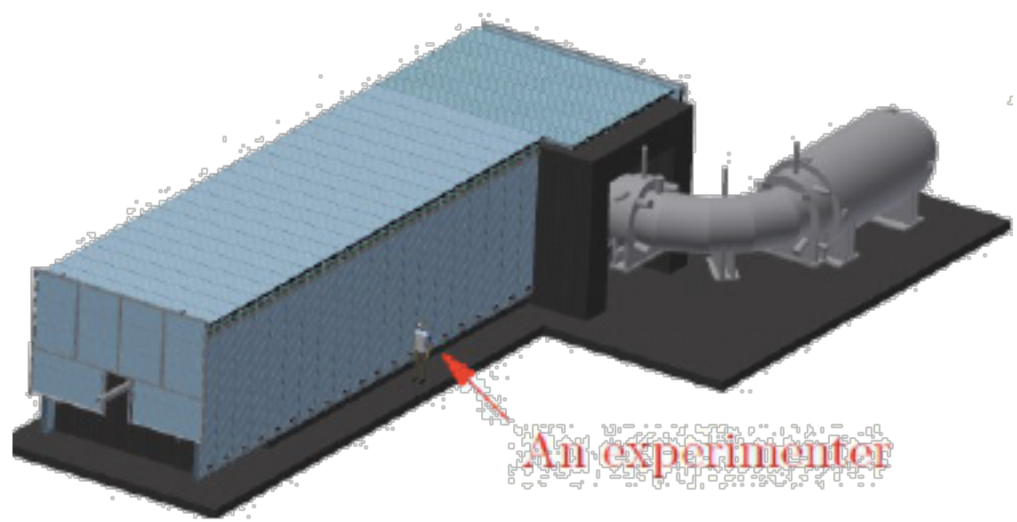


- Four layers of extruded plastic scintillator, $(5\times2)\ \mathrm{cm}^2$
- WLS fiber + SiPM readout

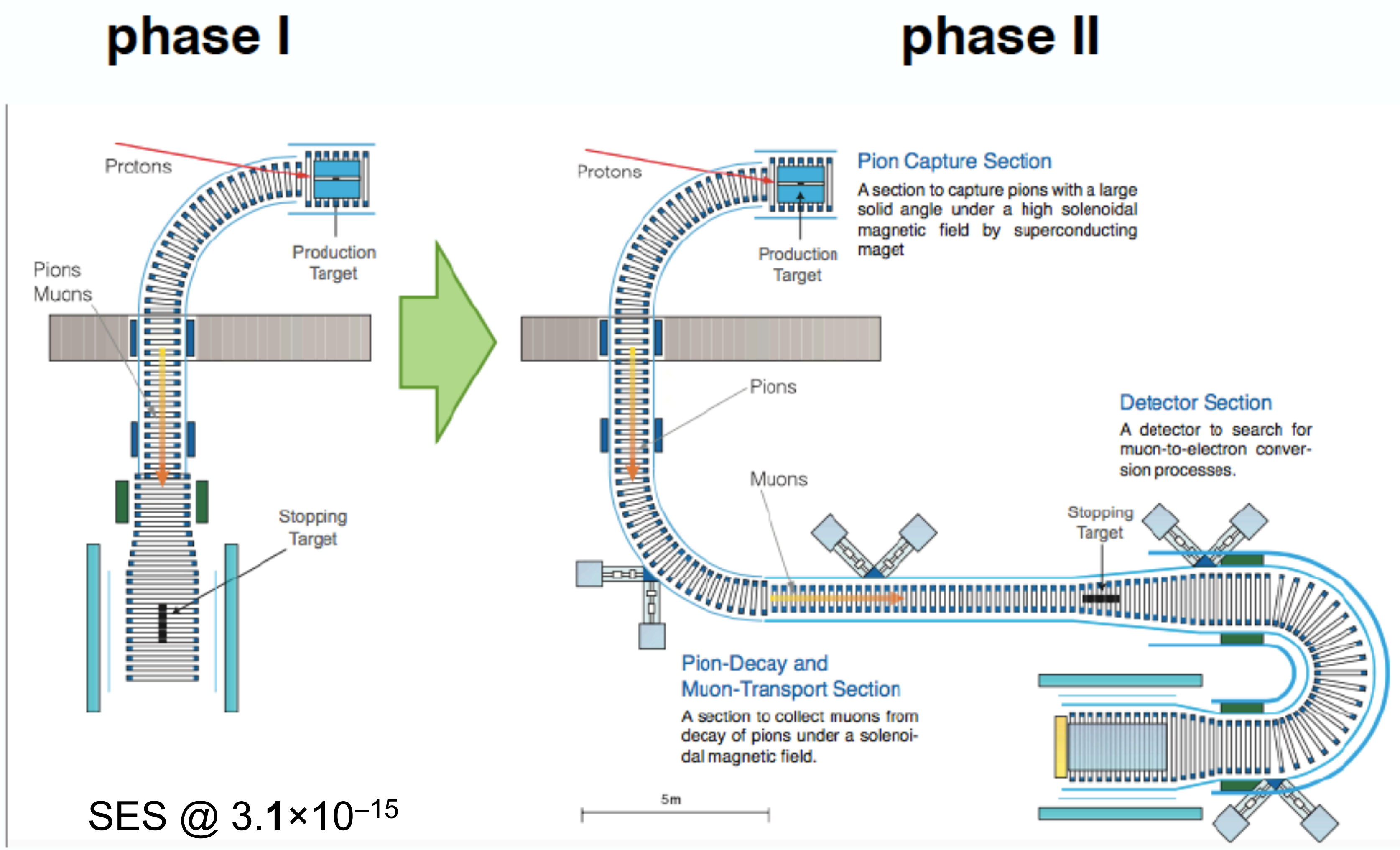
Nbkg (cosmics): 0.05 (3 years run)

- CR veto inefficiency = 10^{-4}
- ε_{CRV} = 99.99%
- $\varepsilon_{CRVplane}$ = 99.6% (14 pe/MeV for longest module)

- Thr @ 0.5-1 MeV to reduce n/γ, avoiding dead time (m.i.p. 2 MeV/cm)
- ¾ layers hit: 125 ns veto



The COMET Experiment



SES @ 3.**1**×10^{-15}