Status of Mu2e Experiment

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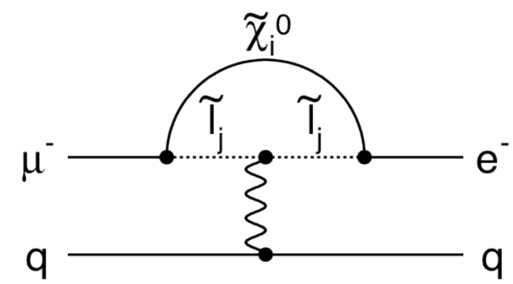
on behalf of the Mu2e Collaboration

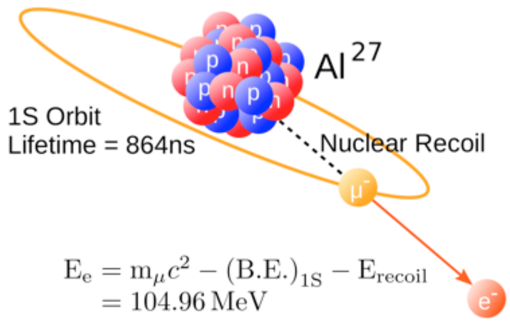
Workshop on “Flavor changing and conserving processes”

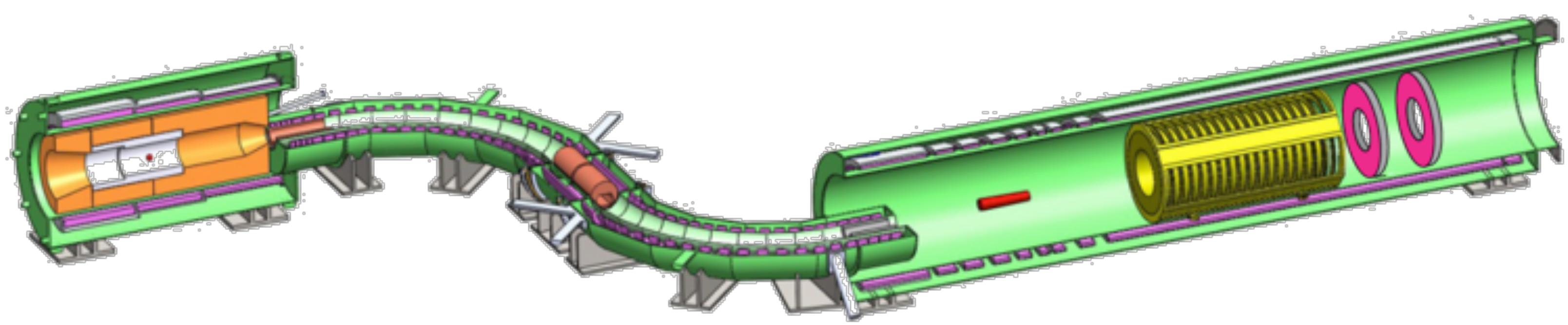
Capri, 7-9 September 2017

Outline

- ✗ Charge Lepton Flavor Violation
- ✗ Mu2e experimental technique
- ✗ Detector layout
- ✗ Status of the experiment
- ✗ Conclusions

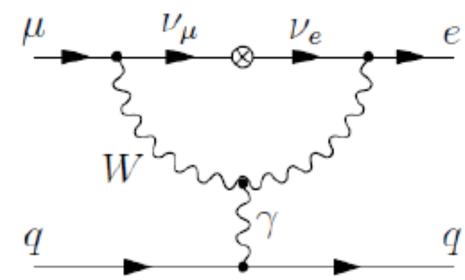






Charge Lepton Flavor Violation

✗ **CLFV** processes **strongly suppressed in Standard Model**
- ✓ in principle, not forbidden due to neutrino oscillation
- ✓ in practice, negligible (rate ~ $\Delta M_{\nu}^{4}/M_{W}^{4} < 10^{-50}$)



✗ Broad array of New Physics models predict rates observable at next generation CLFV experiments

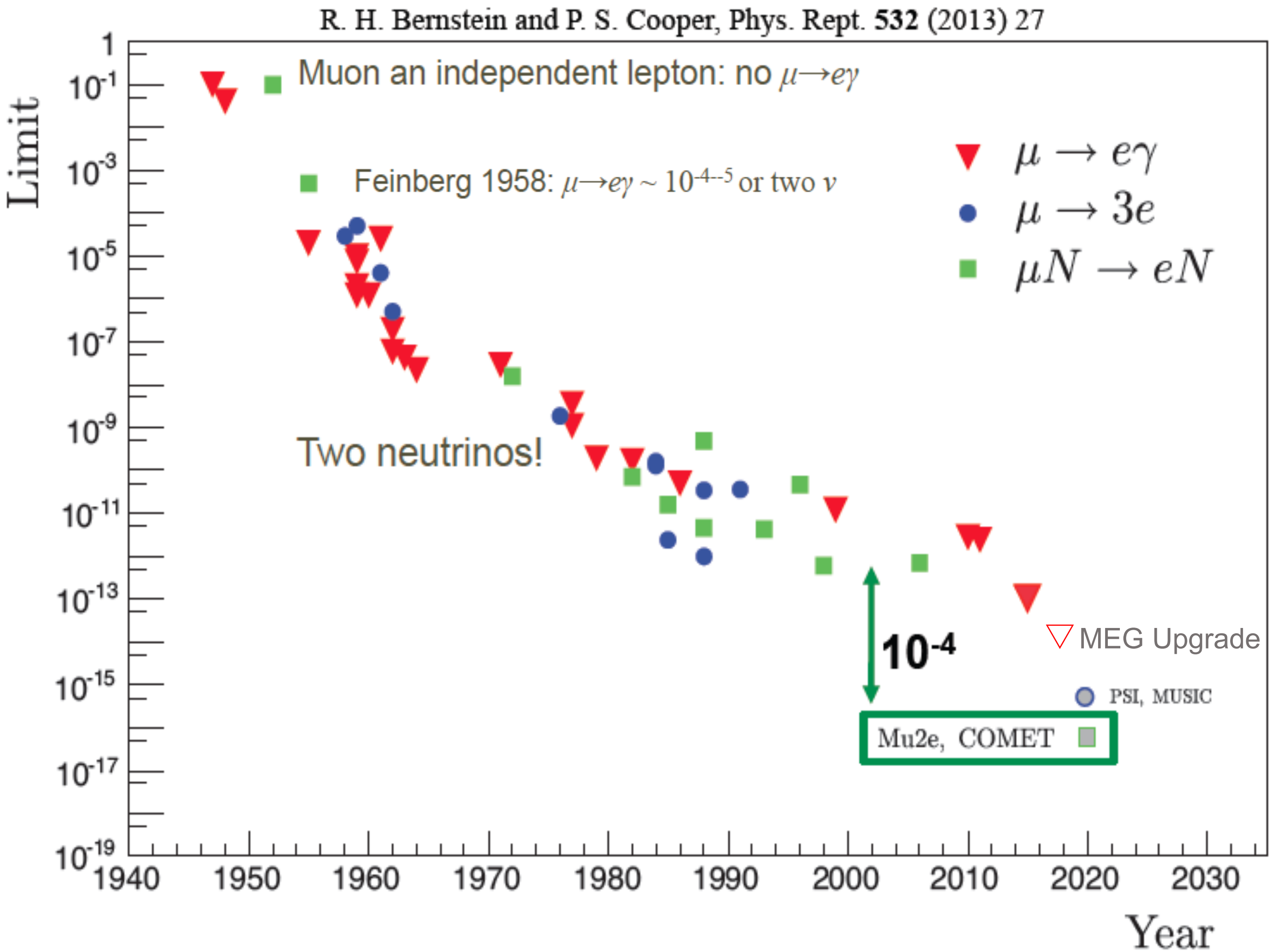
an observation is **unambiguous evidence of beyond-the-standard-model New Physics**

Process	Current Limit	Next Generation exp
$\tau \to \mu\eta$	BR < 6.5 E-8	
$\tau \to \mu\gamma$	BR < 6.8 E-8	10^{-9} - 10^{-10} (Belle II)
$\tau \to \mu\mu\mu$	BR < 3.2 E-8	
$\tau \to eee$	BR < 3.6 E-8	
$K_L \to e\mu$	BR < 4.7 E-12	
$K^+ \to \pi^+ e^- \mu^+$	BR < 1.3 E-11	
$B^0 \to e\mu$	BR < 7.8 E-8	
$B^+ \to K^+ e\mu$	BR < 9.1 E-8	
$\mu^+ \to e^+\gamma$	BR < 4.2 E-13	10^{-14} (MEG)
$\mu^+ \to e^+e^+e^-$	BR < 1.0 E-12	10^{-16} (PSI)
$\mu N \to eN$	$R_{\mu e}$ < 7.0 E-13	10^{-17} (Mu2e, COMET)

Most promising CLFV measurements use muons:
- ➢ clean topologies
- ➢ large rates

Mu2e: muon-to-electron conversion in the field of a nucleus

History of CLFV with muons



Current best limits:

MEG-2016
BR($\mu \rightarrow e\gamma$) < 4.2 x 10^{-13}

SINDRUM-1988
BR($\mu \rightarrow 3e$) < 1 x 10^{-12}

SINDRUM-II 2006
$R_{\mu e}$ < 6.1 x 10^{-13}

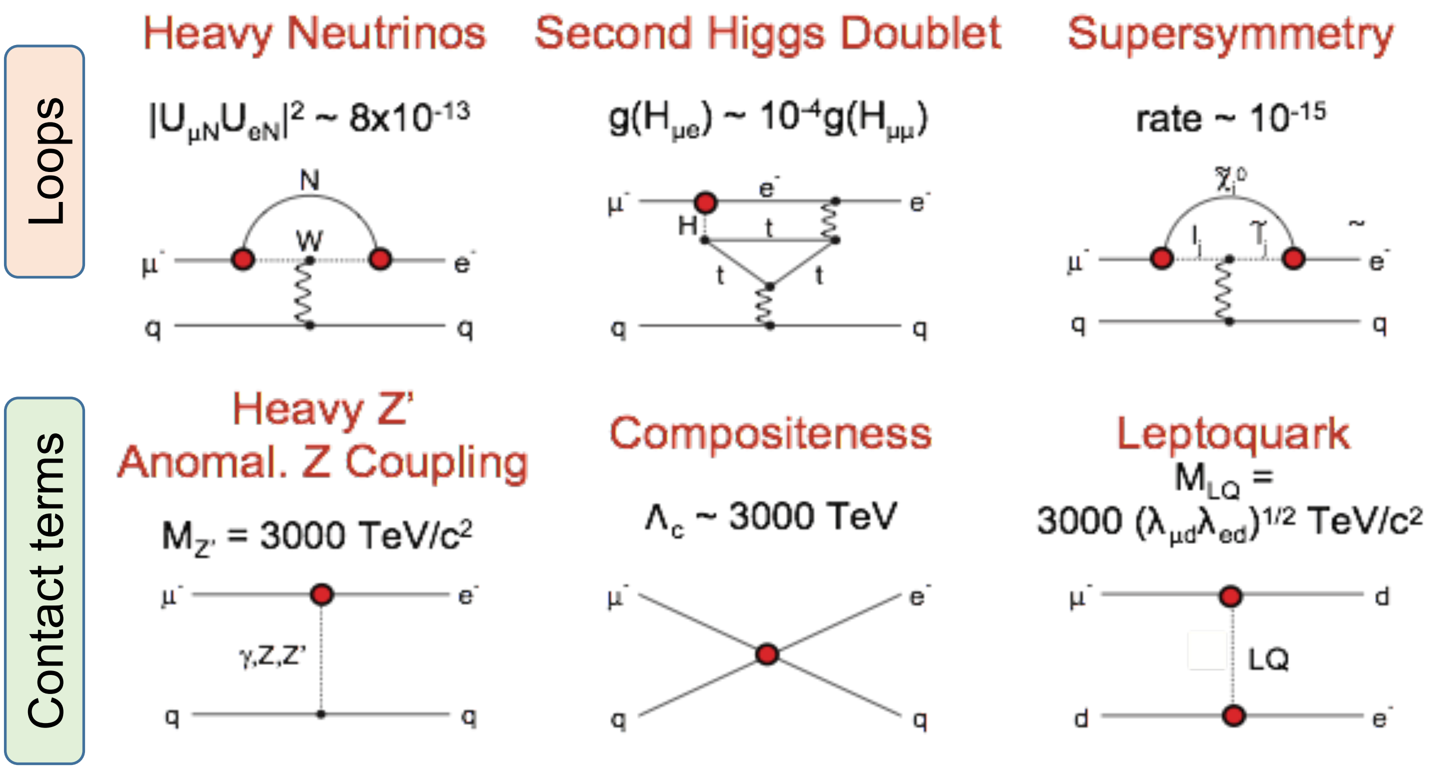
MU2E GOAL:
$R_{\mu e}$ = 6 x 10^{-17}

Mu2e aims to improve by a factor 10^4 the present best limit

Contributions to μN → *e*N

Effective CLFV Lagrangian:

$$L_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$



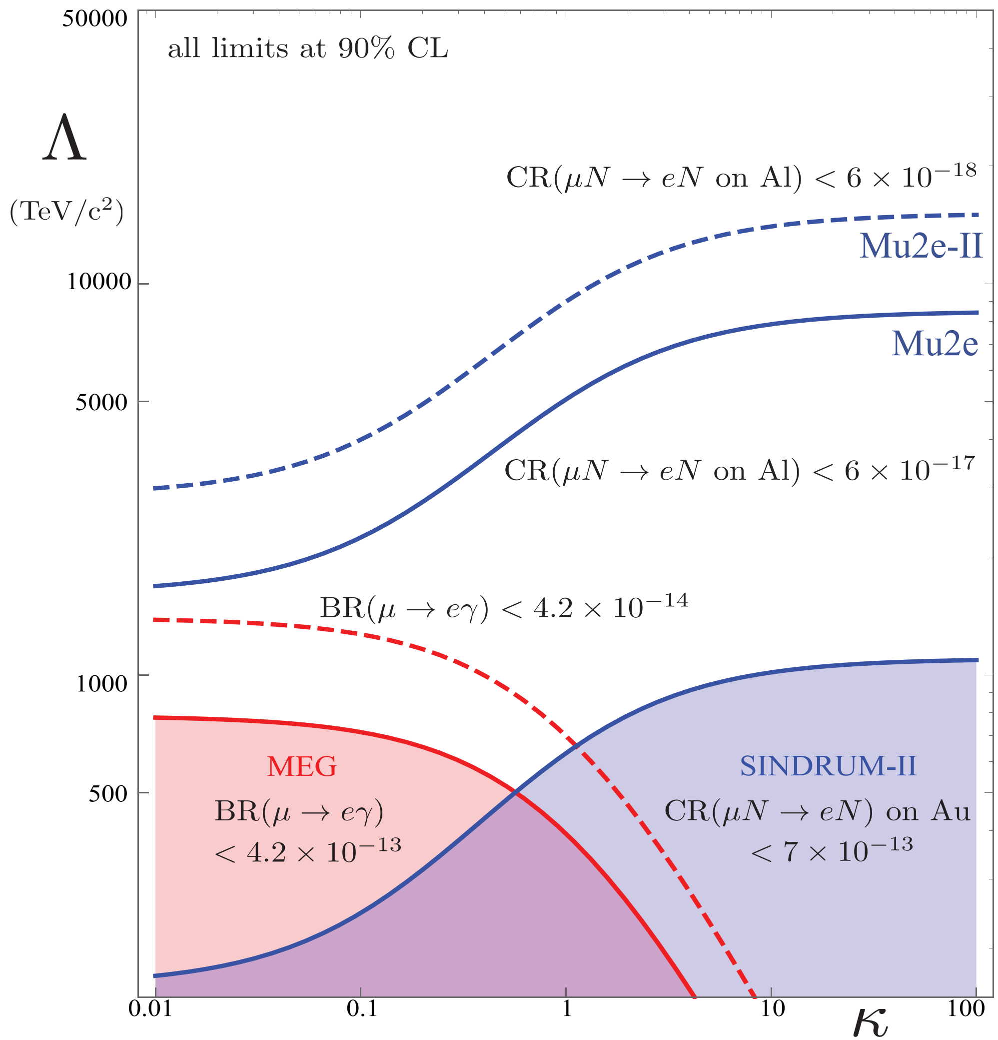
Models which can be probed also by μ→eγ searches

Direct coupling between quarks and leptons, better accessed by $\mu N \rightarrow eN$

Test of Physics BSM: Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58
M. Raidal *et al*, Eur.Phys.J.C57:13-182,2008
A. de Gouvêa, P. Vogel, arXiv:1303.4097

μN → eN sensitive to wide array of New Physics models

Mu2e physics reach



κ <<1:
LOOP DOMINATED

κ >>1:
CONTACT DOMINATED

Mass scale discovery up to ~10k TeV, significantly above the direct reach of LHC

Roughly equal to MEG upgrade in loop-dominated physics

If SUSY seen at LHC → rate ~10^{-15}

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

Experimental technique

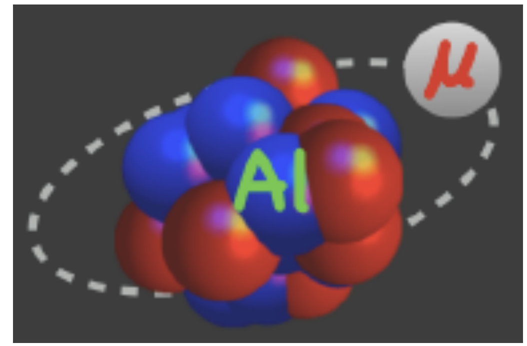
CLFV@Mu2e: coherent neutrinoless conversion of a muon to an electron in the field of a nucleus: $\mu^{-} Al \rightarrow e^{-} Al$

Experimental technique:

✗ Beam of low momentum muons

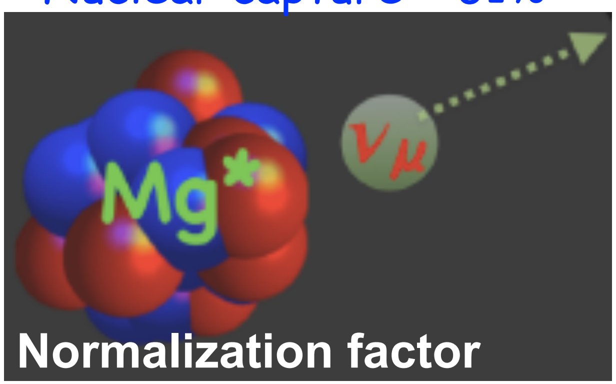
✗ Muons stopped in Al target

✗ Muons trapped in orbit around the nucleus

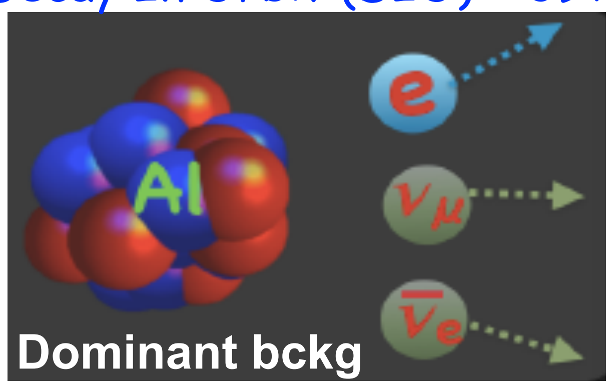


τ_{μ}^{Al} = 864 ns

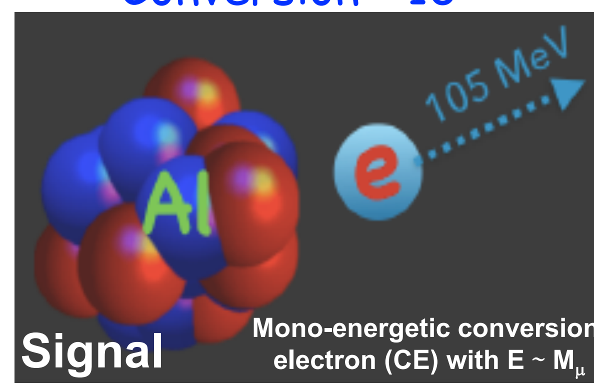
Nuclear capture ~ 61%



Decay In Orbit (DIO) ~ 39%



Conversion < 10^{-12}



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

Mu2e sensitivity

✗ Design goal: single-event-sensitivity of 3 ×10^{-17}

➡ Requires
- **10^{18} stopped muons**
- **10^{20} protons on target**
- high background suppression (**N_{bckg}<0.5**)

in 3 years running

✗ Expected limit: $R_{\mu e}$ < 6.1×10^{-17} @ 90% CL

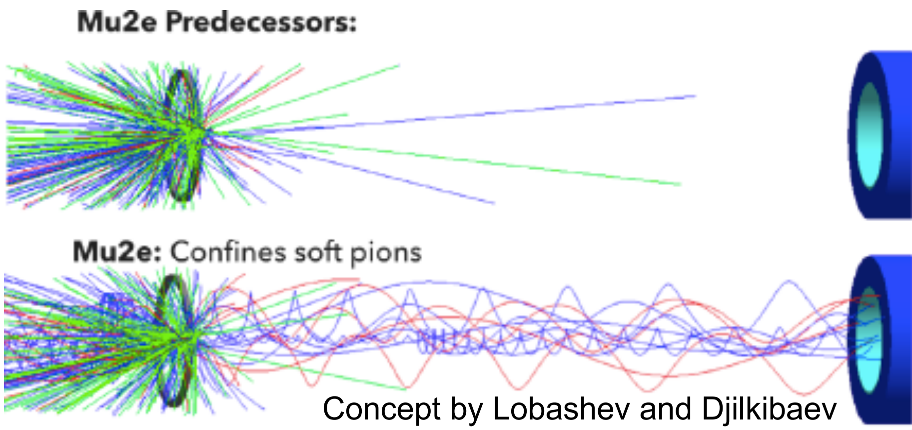
- Factor 10^4 improvement

✗ Discovery reach (5σ): $R_{\mu e}$ > 1.9 ×10^{-16}

- Covers broad range of new physics theories

Maximizing muons

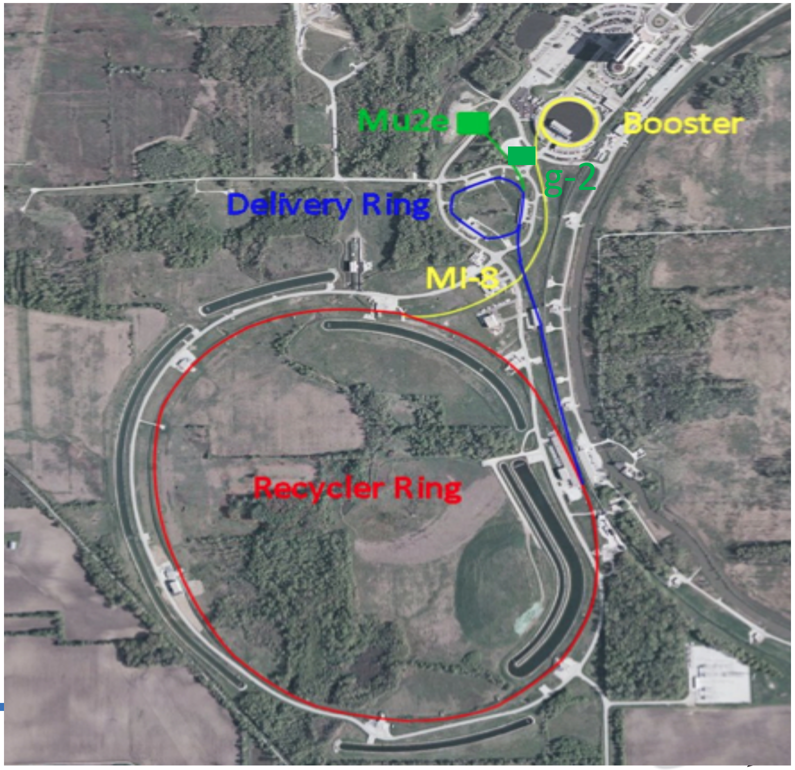
- ✗ World's hottest muon source: 8 GeV, 8 kW proton beam on a tungsten target
- ✗ Soft pions confined with a solenoidal B field
- ✗ Strong gradient to increase the yield through magnetic reflection



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

Mu2e will reuse much of the Tevatron anti-proton complex to produce muons:

- ➢ 8 GeV protons from the **Booster**
- ➢ **Recycler** divides proton batches into 4 smaller bunches
- ➢ **Delivery ring** gets 1 out of 4 bunches from recycler
- ➢ **Mu2e** gets the proton beam every 1695 ns



Minimizing prompt background

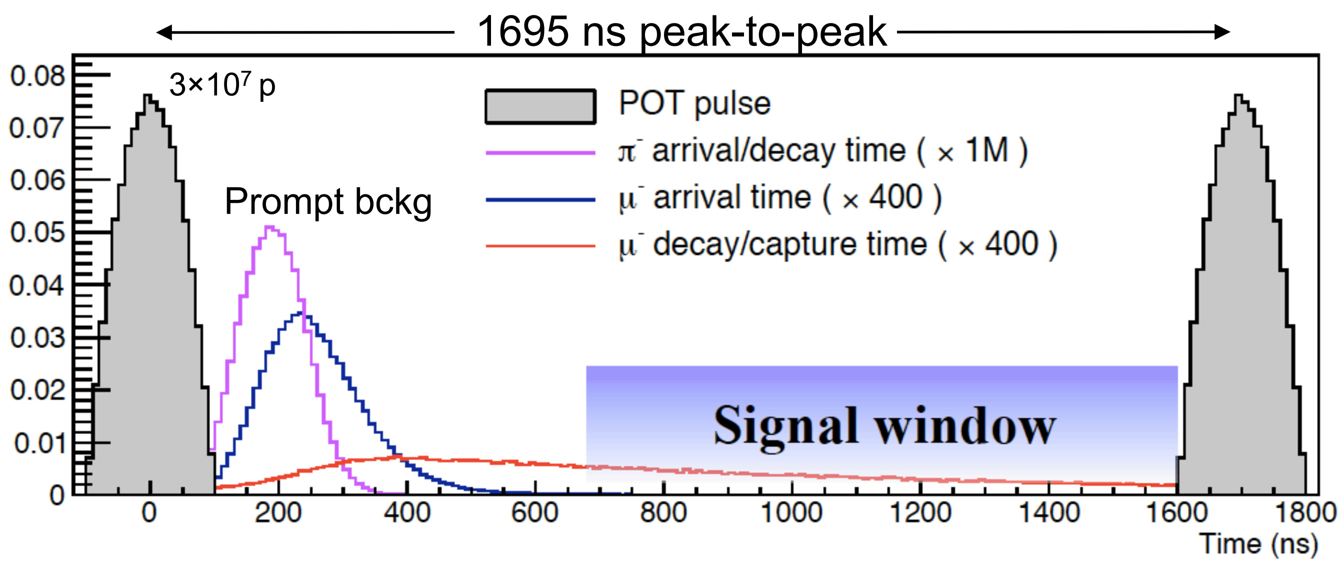
Prompt background arise from interactions which occur at the stopping target:

✗ Radiative Pion Capture (τ_π^{Al} = 26 ns) $\pi^- N \to \gamma N^* \to e^+ e^- N^*$

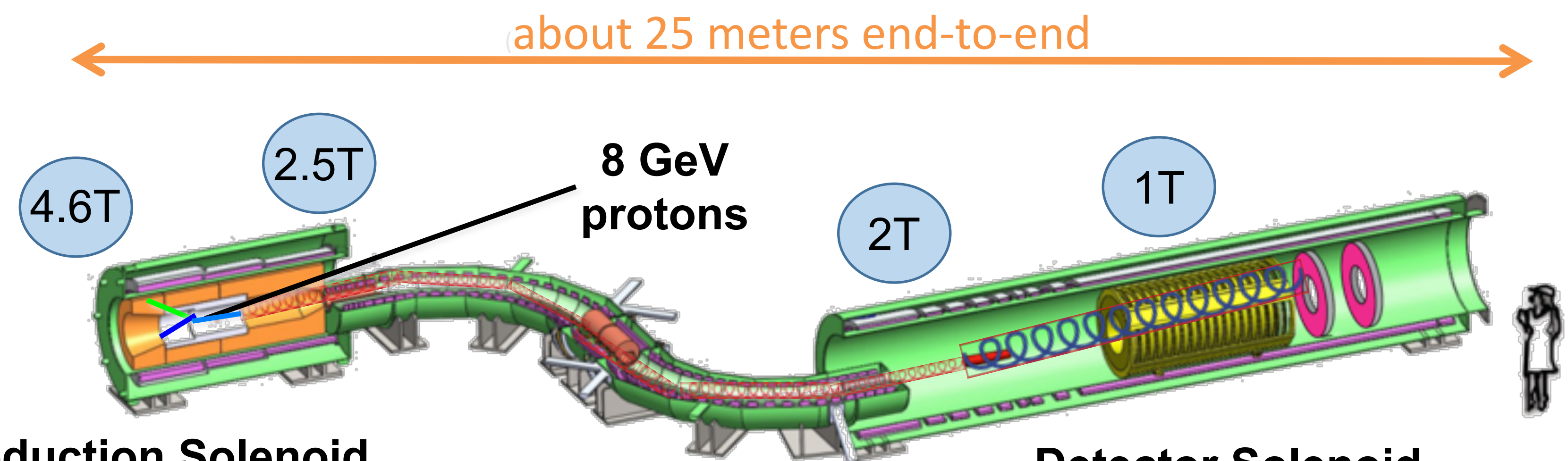
✗ μ/π decay in flight

- Narrow pulsed proton beam
- Delayed signal window starting 700 ns after the initial proton pulse
- Out-of-time protons suppressed by O(10^{10})

Pion bckg reduced by >10^{-9}



The Mu2e Experiment



Production Solenoid

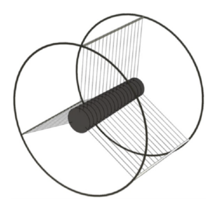
- 8 GeV p beam on target, producing mostly pions
- Graded magnetic field contains backward π/μ and reflects slow forward π/μ

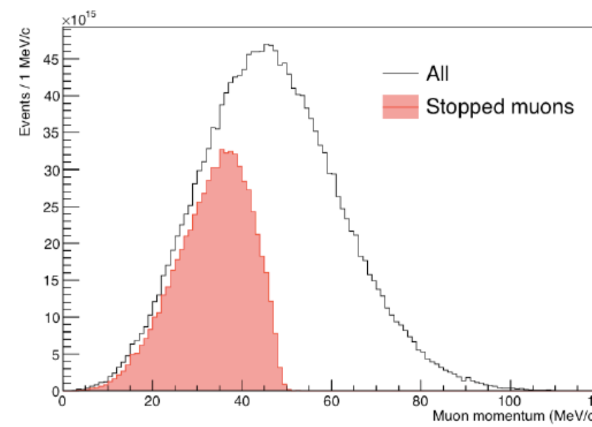
Transport Solenoid

- Selects low momentum negative muons
- Anti-proton absorber in the mid-section

Detector Solenoid

- Upstream: Al stopping target
- Downstream: tracker, calorimeter



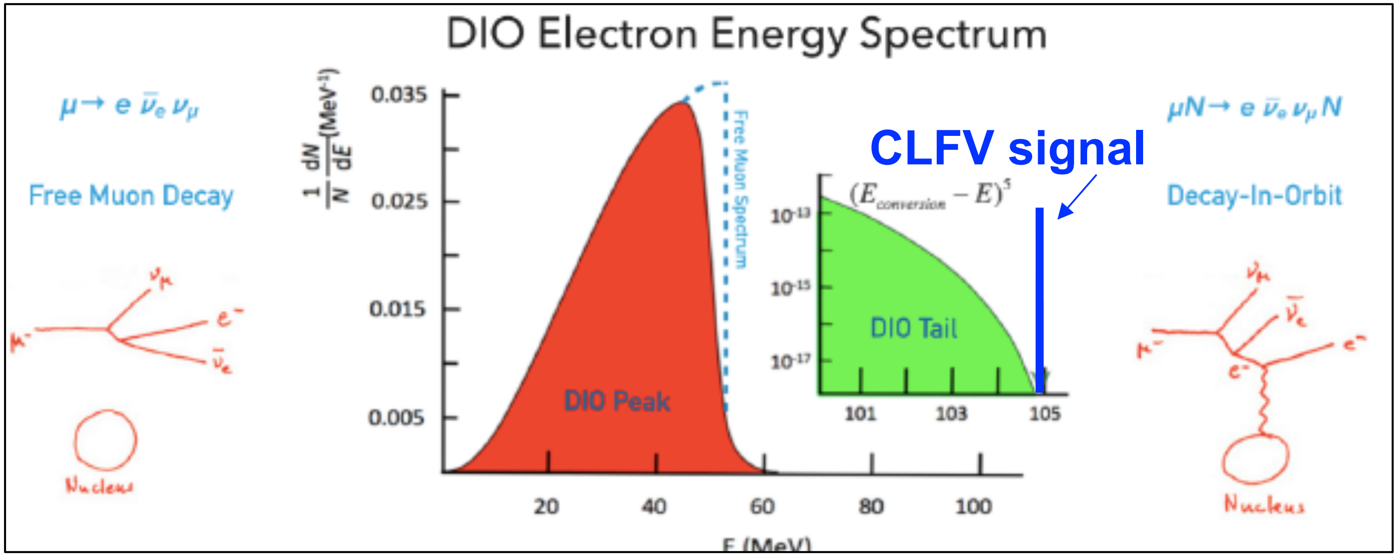


Graded fields important to suppress backgrounds, to increase muon yield, and to improve geometric acceptance for signal electrons

Not shown: cosmic ray veto system, extinction monitor, target monitor

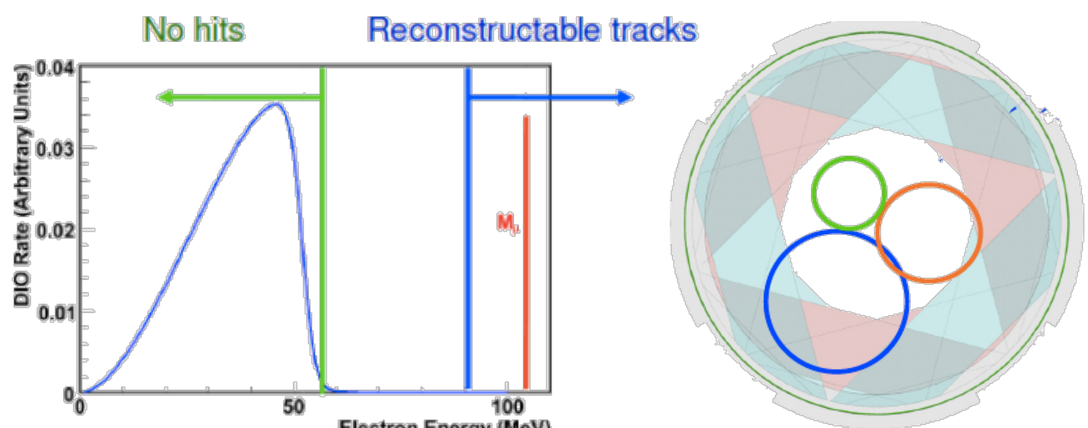
DIO background

One of two Mu2e main bckg: **Decay In Orbit** $\mu N \rightarrow e\ \nu_\mu \nu_e N$ (~39% on Al)



- ✗ Nuclear modifications push DIO spectrum near conversion e^-
- ✗ DIO and CLFV signal, **Conversion Electron** (CE), overlap after energy loss and detector resolution

1. Minimize scattering, E_{loss}
2. High resolution spectrometer
3. Inner 38 cm un-instrumented:
   - ✗ Blind to beam flash (low momentum particles)
   - ✗ Blind to 99% of DIOs



The Tracker

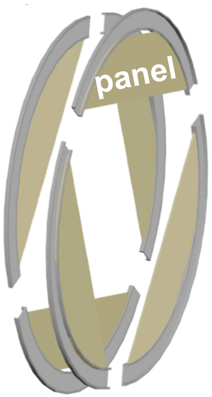
Detector requirements:

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

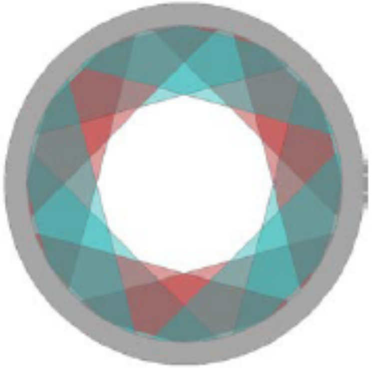
Low mass straw drift tubes design:

- 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

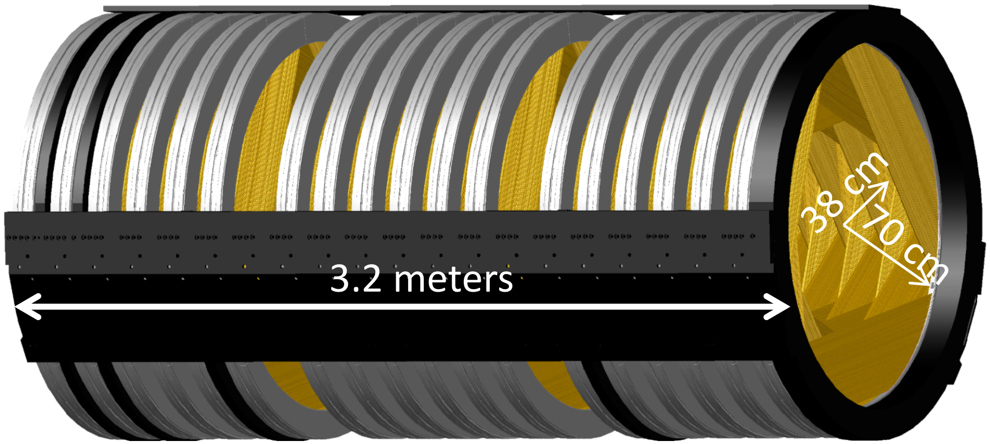
Tracker Plane



Tracker Station: 2 rotated planes

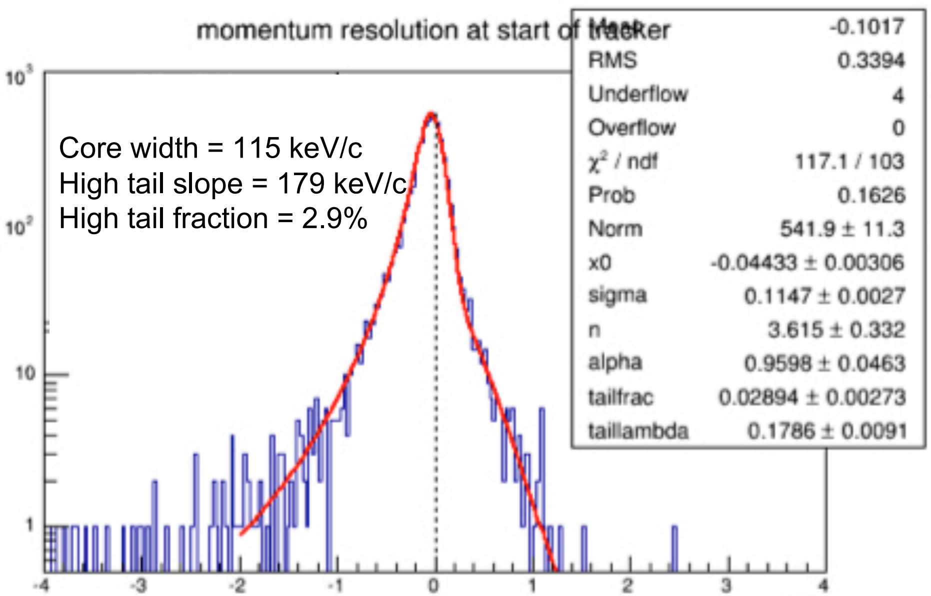


Tracker: 18 stations (>20k tubes)



Tracker Performances

Full simulation

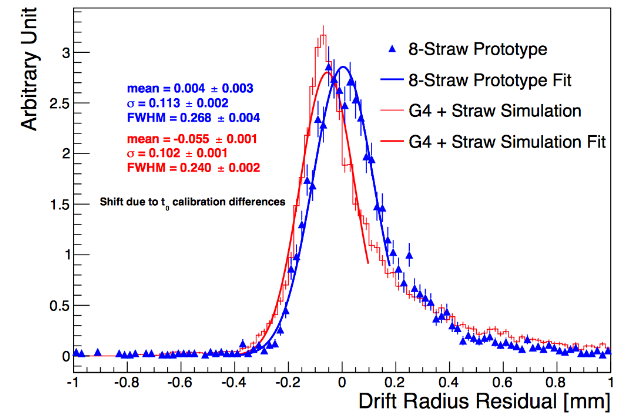


$P_{rec} - P_{tru}$ (MeV/c)

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

Cosmics, 8 channel prototype

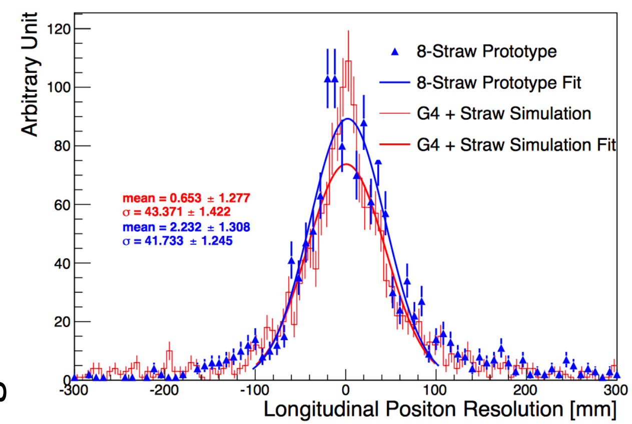
Transverse resolution



σ_{data} = 0.133 ± 0.022 mm

σ_{MC} = 0.102 ± 0.001 mm

Longitudinal resolution

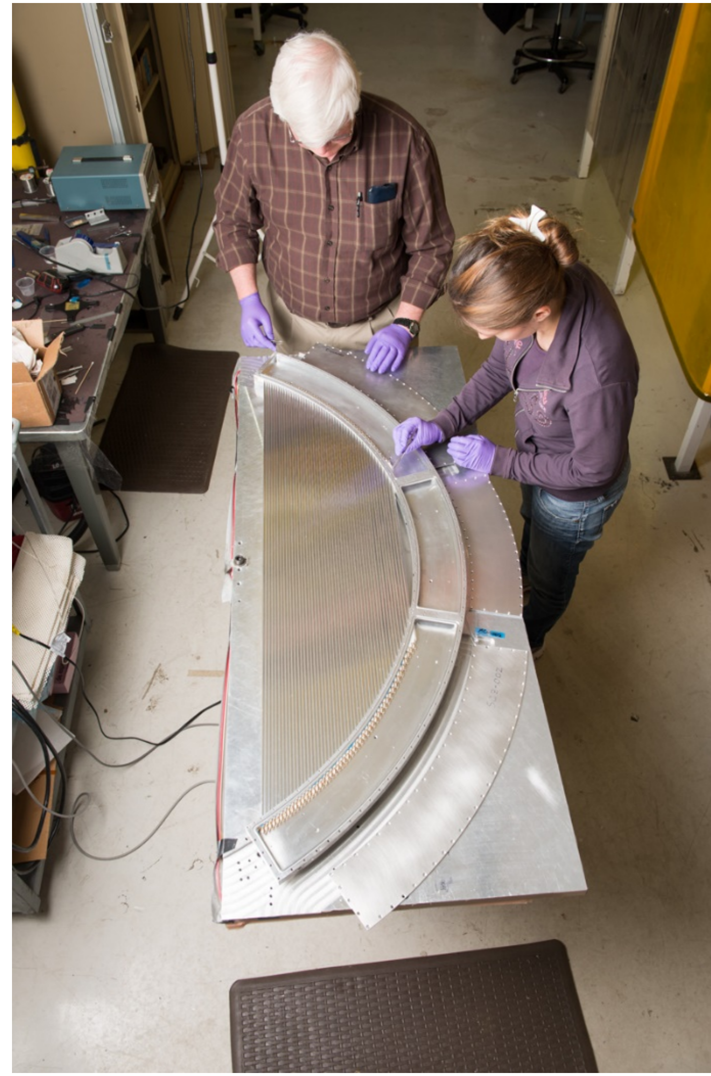


σ_{data} = 42 ± 1 mm

σ_{MC} = 43 ± 1 mm

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



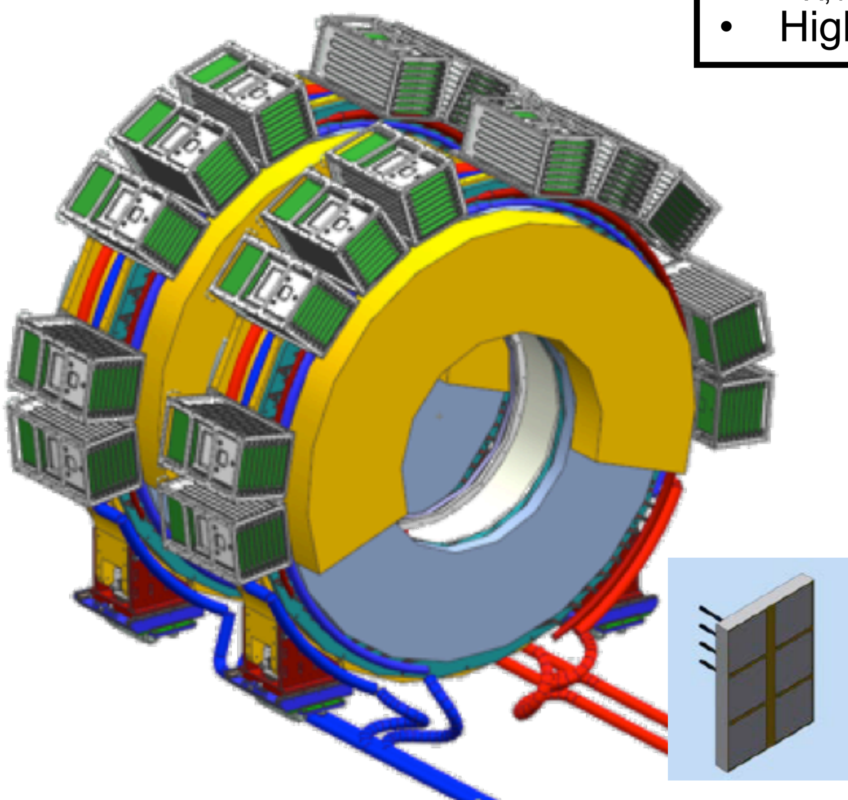
The Electromagnetic Calorimeter

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:

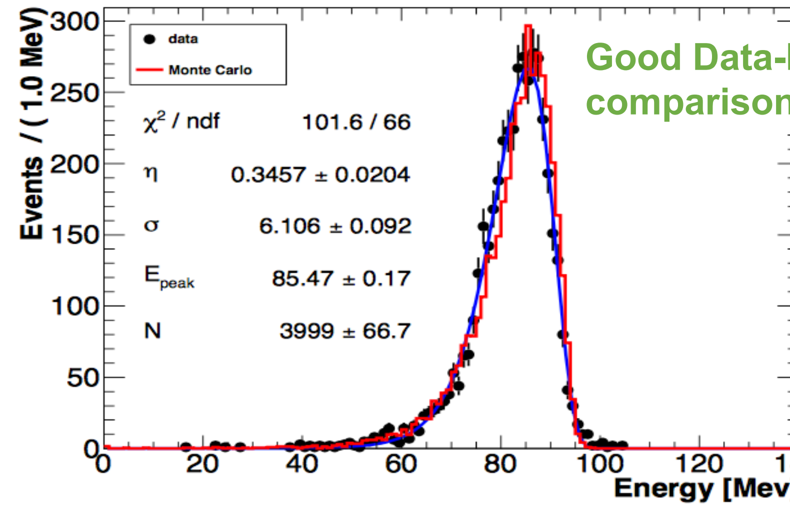
- ✗ Two disks, R_{in}=374 mm, R_{out}=660 mm, $10X_0$ length, ~ 75 cm separation
- ✗ 674+674 square x-sec **pure CsI crystals**, (34×34×200) mm^3
- ✗ For each crystal, two custom array (2×3 of 6×6 mm^2) **large area UV-extended SiPMs**
- ✗ Analog FEE directly mounted on SiPM
- ✗ Calibration/Monitoring 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

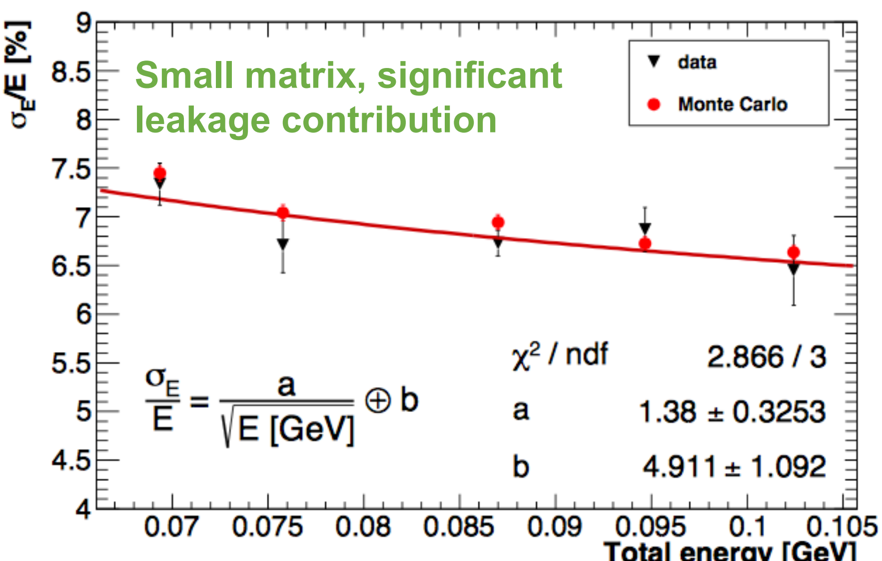
Calorimeter Performances

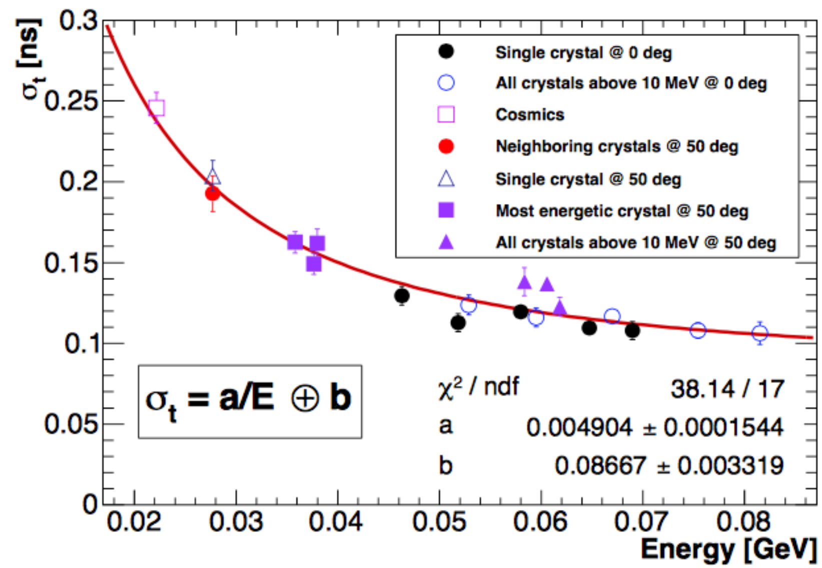
JINST 12 (2017) P05007

- ✗ 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





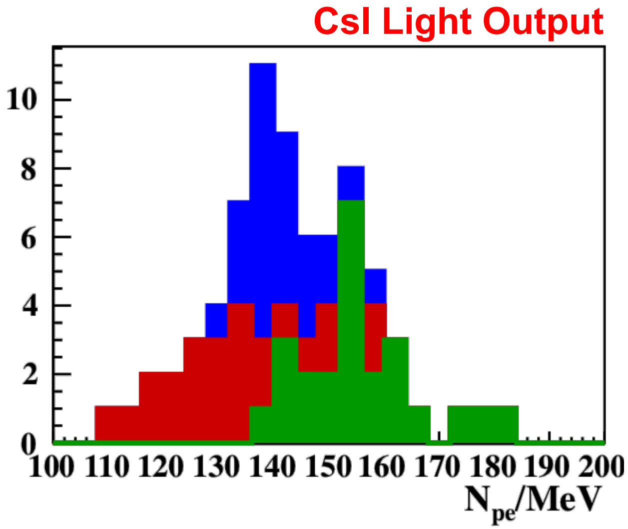
σ_E ~ 6.5% at 100 MeV

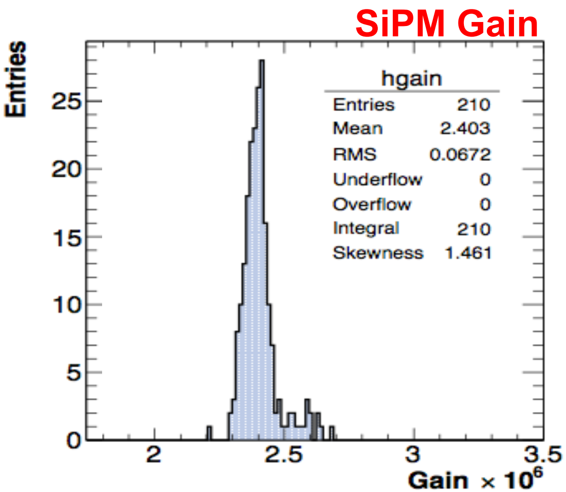
σ_T ~ 110 ps at 100 MeV

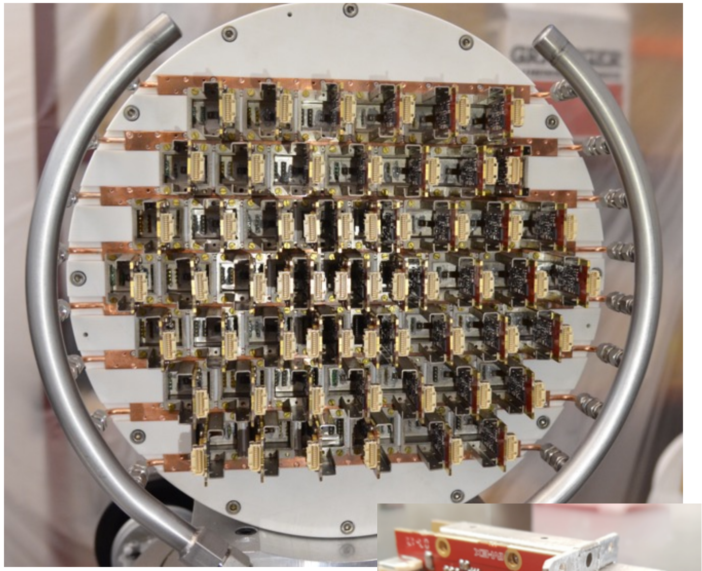
EMC pre-production

Vendors selected
Procurement already started

- ✗ 3×24 pre-production crystals from three different vendors
  - ➢ Optical properties tested for all, irradiation test for six crystals up to 100 krad
- ✗ 3×50 pre-production SiPMs from three different vendors
  - ➢ 3×35 characterized, irradiation test for three SiPMs up to 8.5×10^{11} n_{1MeVeq}/cm^2, MTTF ≥ 6×10^{5} hours
- ✗ Large EMC prototype (51 crystals, 102 SiPMs, 102 FEE boards) with pre-productions and mechanics cooling systems similar to the final ones
  - ➢ Test of integration and assembly procedures, test beam with 60-120 MeV e^-

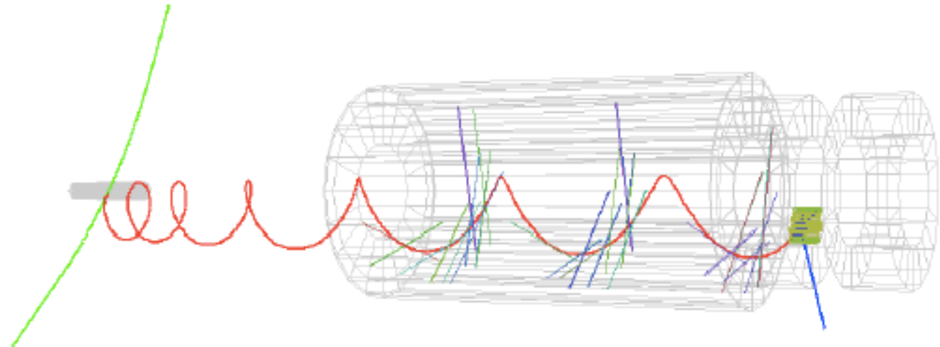


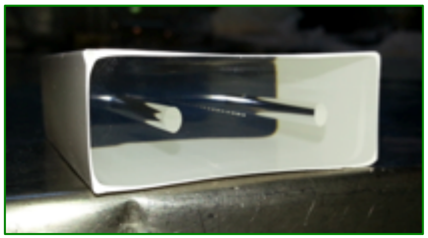




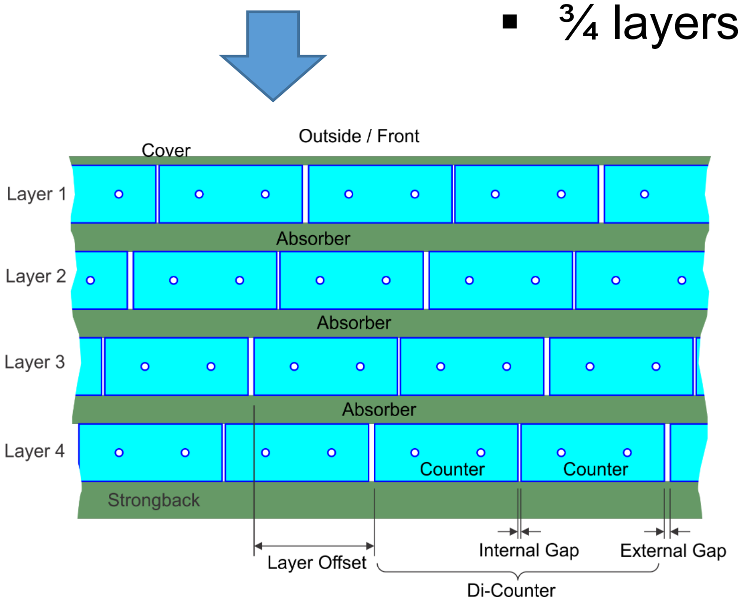
Cosmic Ray Veto

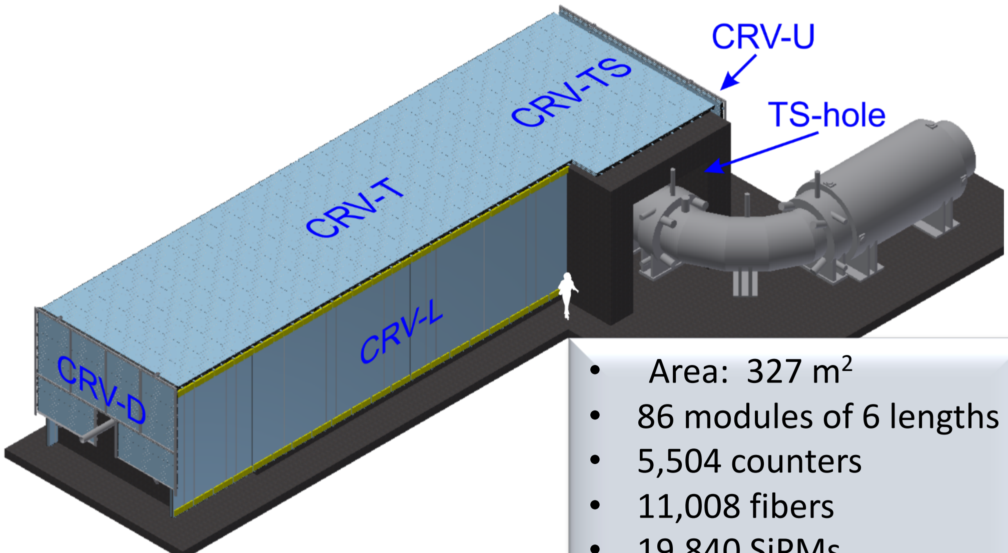
Cosmic ray muons will produce one fake signal event per day without a CRV. The muon itself can fake a 105 MeV e^- or it can knock out an e^-





- **High efficiency (0.9999) veto needed**
- Four layers of extruded plastic scintillator, (5×2) cm^2
- 2 WLS fibers (1.4 mm diameter) + (2×2) mm^2 SiPM readout
- ¾ layers hit: 125 ns veto



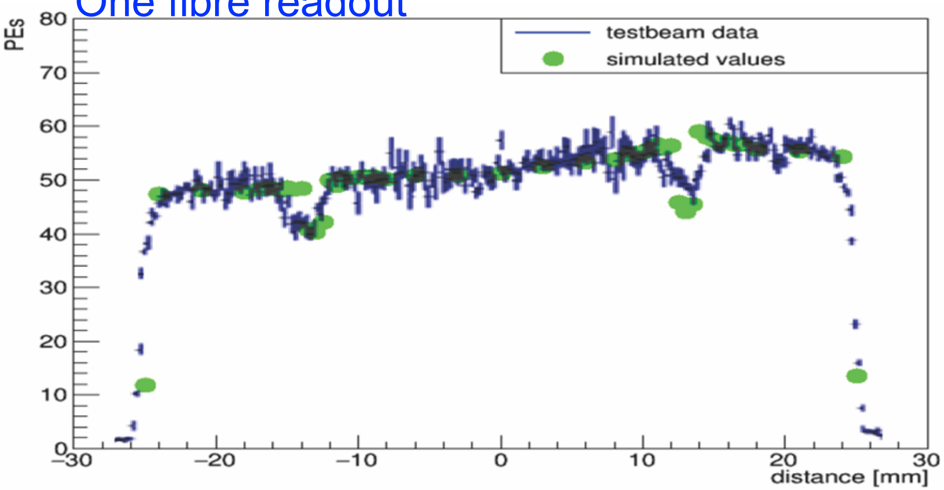


- Area: 327 m^2
- 86 modules of 6 lengths
- 5,504 counters
- 11,008 fibers
- 19,840 SiPMs
- 310 Front-end Boards

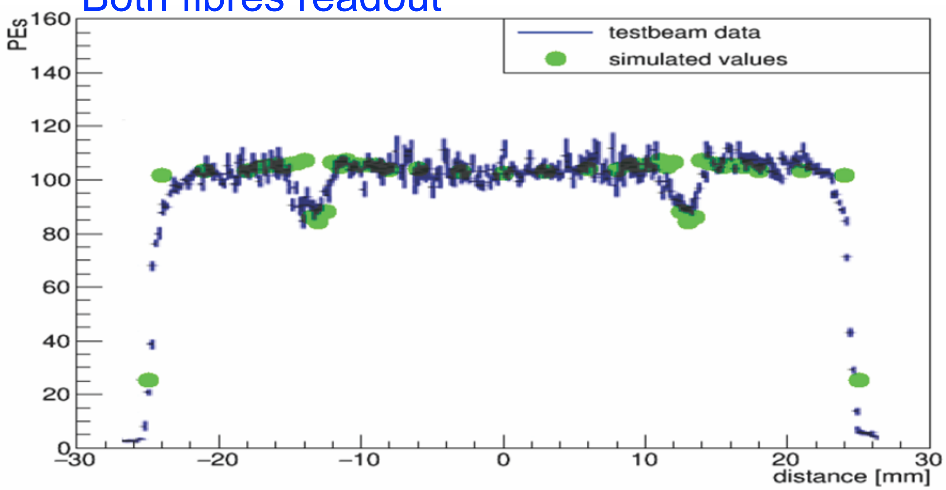
Cosmic Ray Veto

MC well describes test beam data

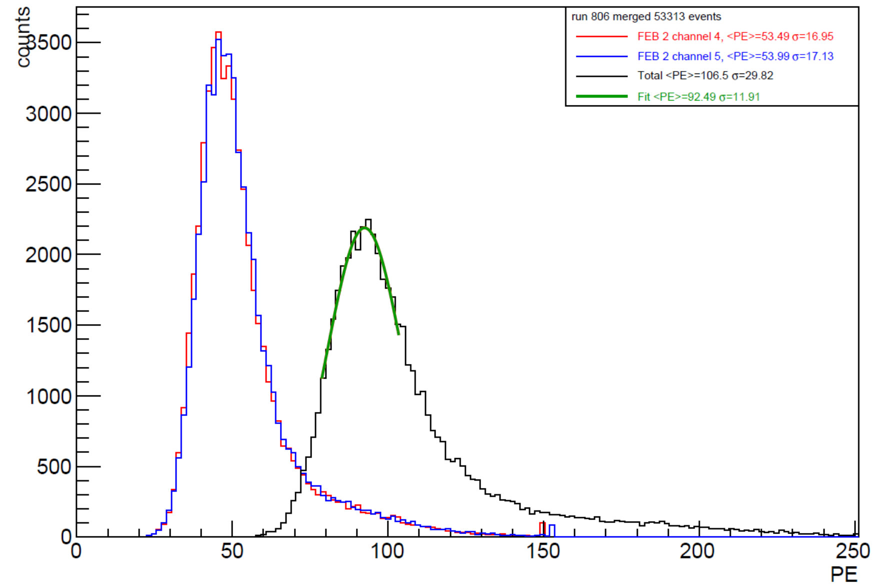
One fibre readout



Both fibres readout



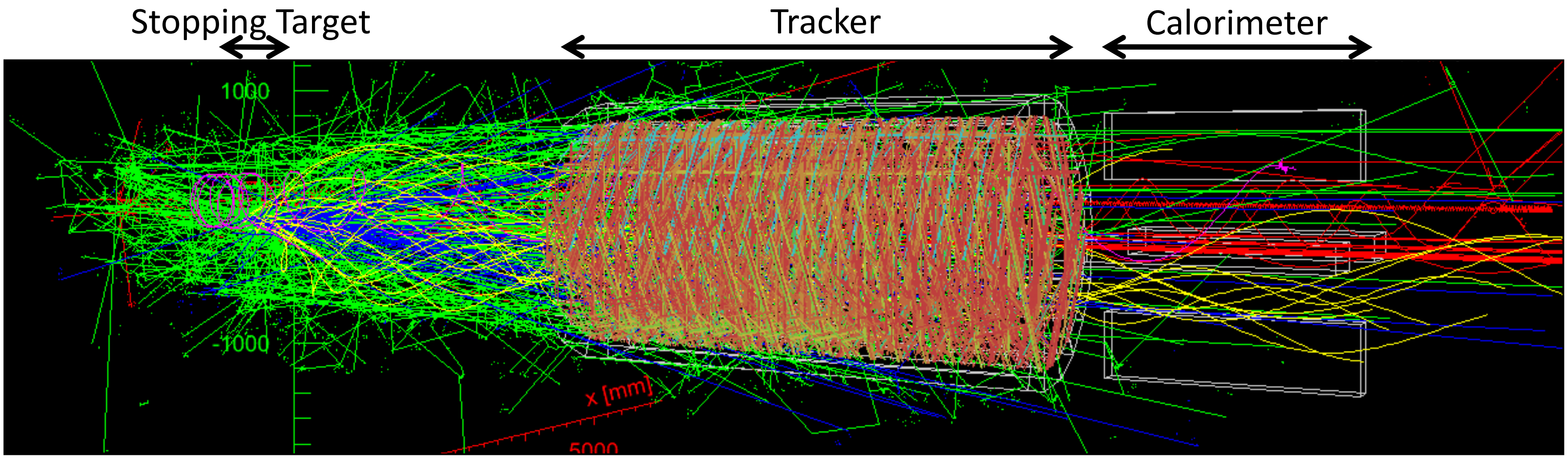
Test beam results with beam centered on counter 1 m from readout end

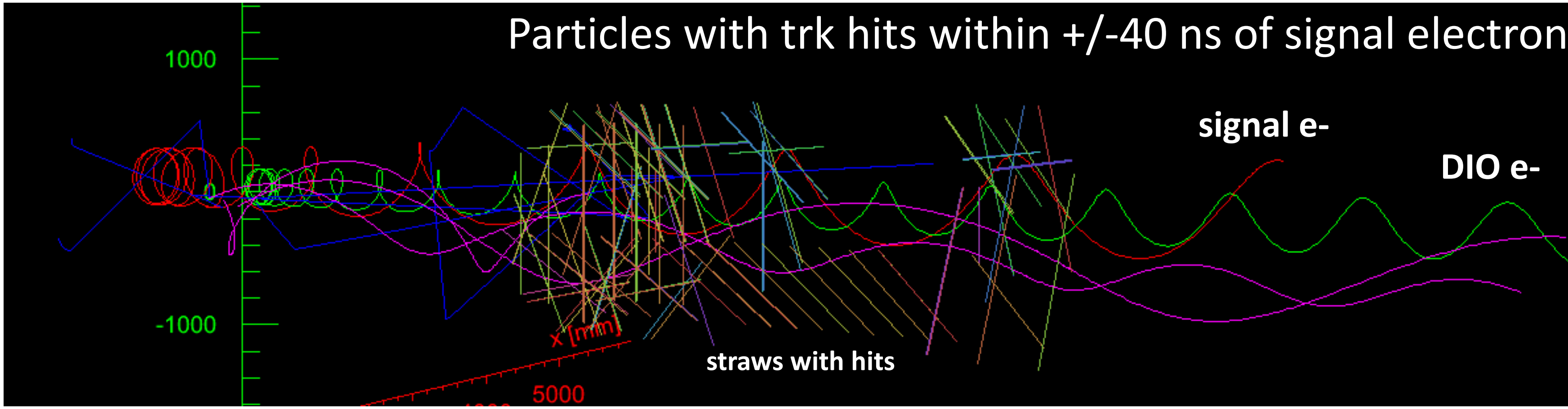


- ✗ The single-plane requirement is $\varepsilon > 99.5\%$
  - ➪ yield of **66 photo-electrons** at 1 m from readout end
- ✗ Test beam results give **92 photo-electrons**: safety factor of ~ 40%.

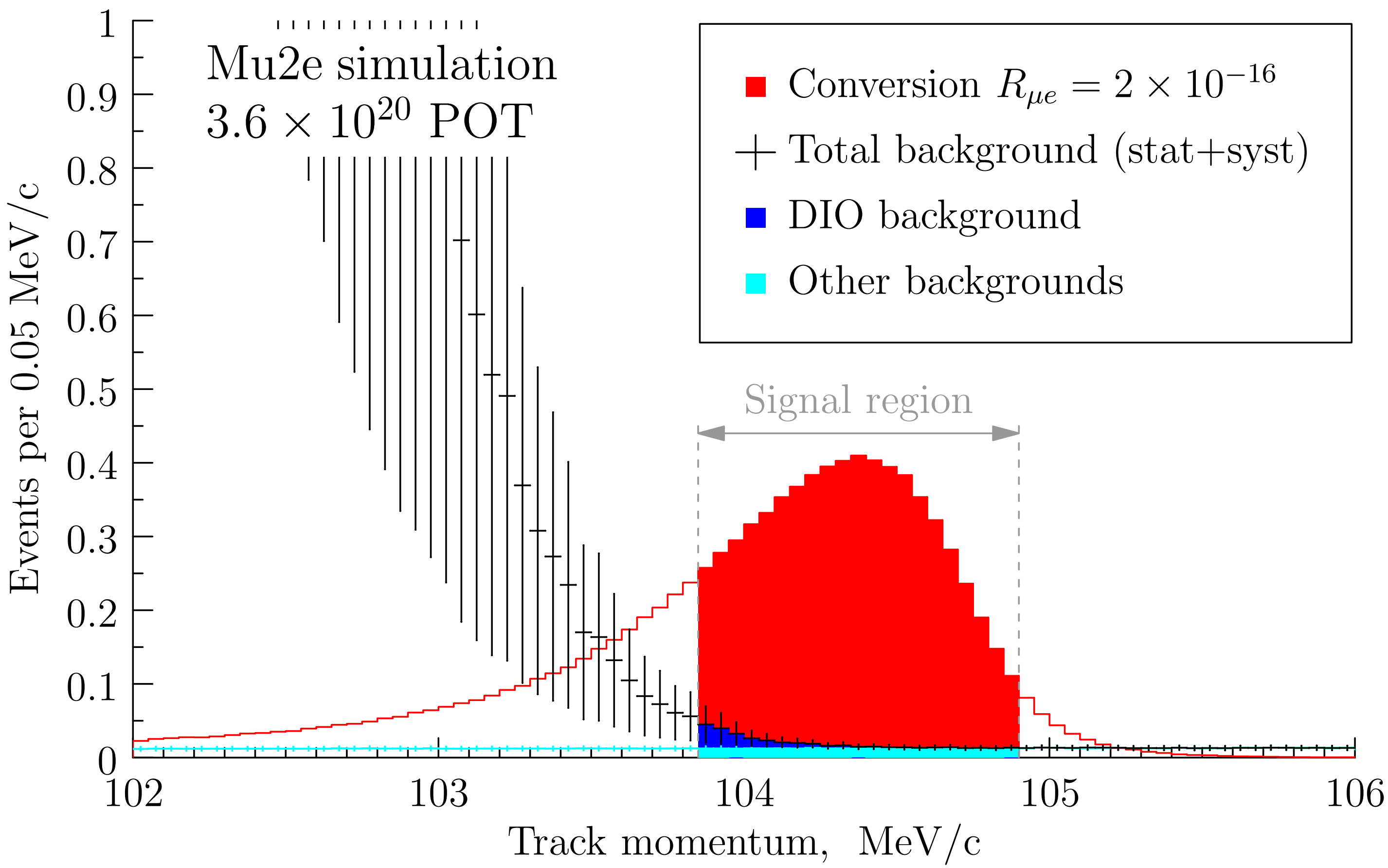
Mu2e signal event

Signal electron, together with all the other "stuff" occurring simultaneously, integrated over 500-1695 ns window





Expectation with full simulation



Discovery sensitivity accomplished with three years of running and suppressing backgrounds to < 0.4 event total (50% cosmics, 35% DIOs)

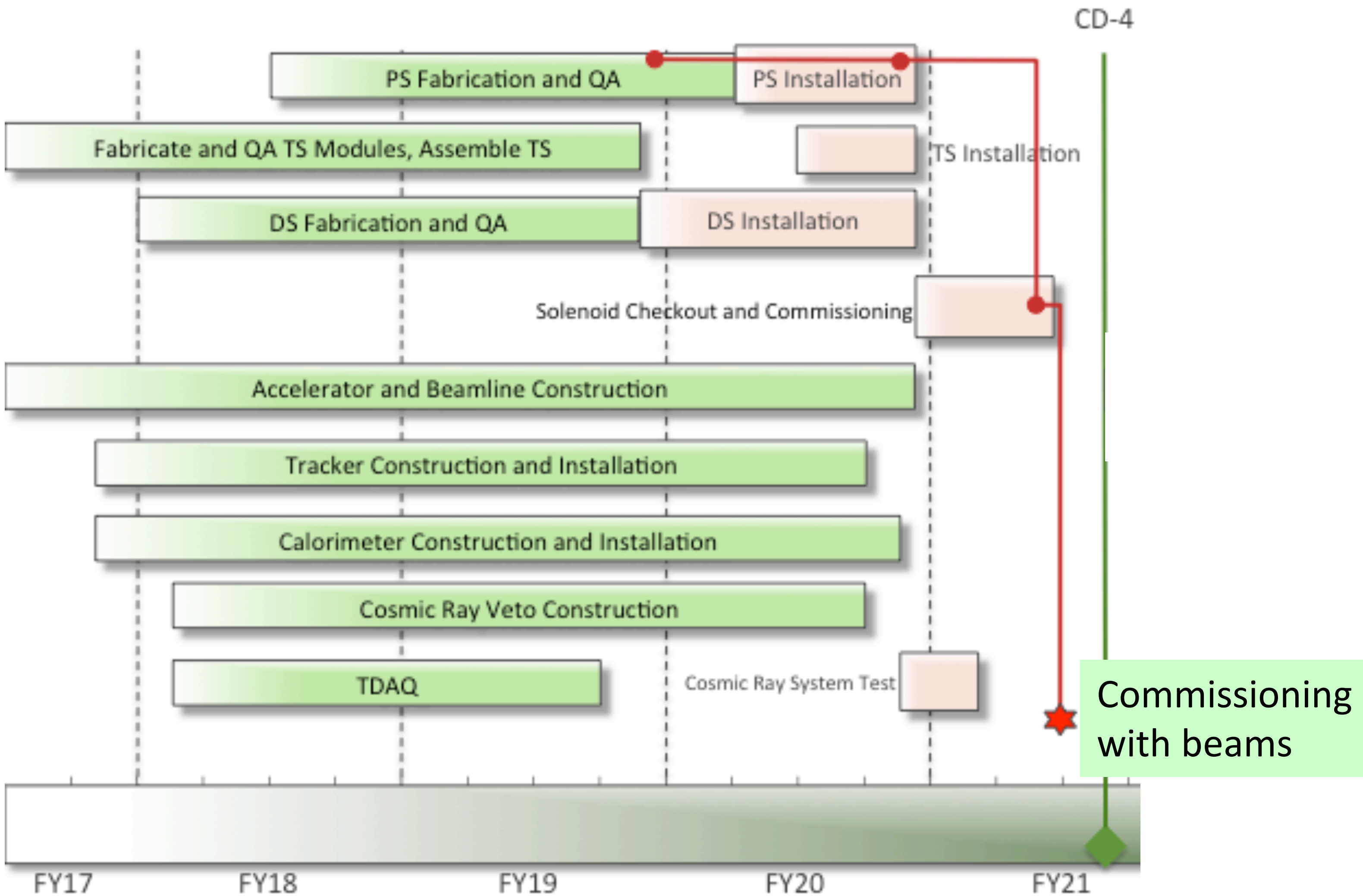
$R_{\mu e} < 8 \times 10^{-17}$ @ 90% C.L.

Civil construction completed

Fermilab Muon Campus:

- Two new experimental halls and the associated beamlines
- Will produce world's highest intensity muon beams
- First beam delivered in 2017 (Muon g-2)

Schedule



Three years run expected 2022-2025

Conclusions

The Mu2e experiment will exploit the world's highest intensity muon beams of the Fermilab Muon Campus to search for CLFV

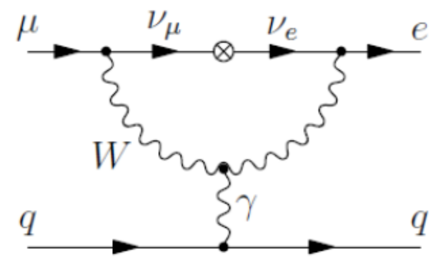
- ✗ Current sensitivity will be improved by a factor 10^4
- ✗ Discovery capability over a wide range of New Physics models
- ✗ Complementarity with LHC, heavy flavor, dark matter and neutrino experiments
- ✗ Production phase is starting, moving to full regime for end 2017
- ✗ Detector installation in 2020, followed by Mu2e commissioning and data

Mu2e Solenoids

- ✗ 75 km of superconducting cable procured and tested
- ✗ Solenoid design completed
- ✗ TS fabrication has begun at ASG Superconducting in Genova (Italy)
- ✗ PS, DS fabrication started at General Atomic (USA)

CLFV

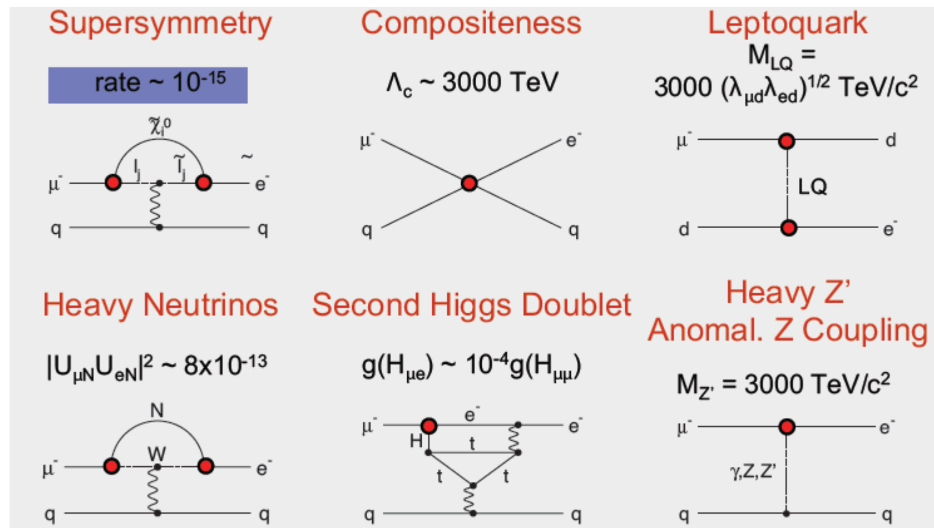
Standard Model
$\mu \rightarrow e$ conversion



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

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

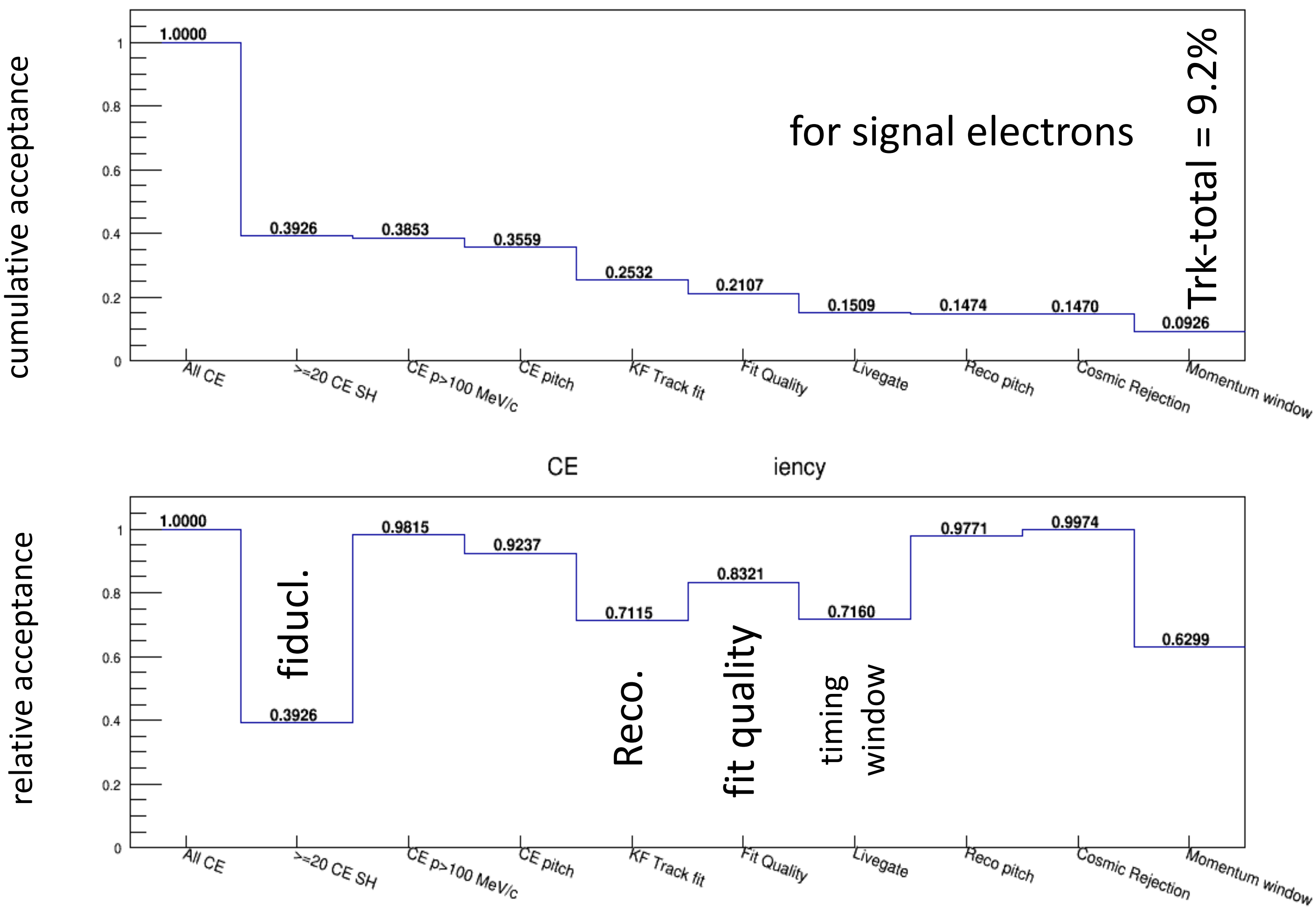
Implies O(40) reconstructed signal events with negligible background in Mu2e for many SUSY models.

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

Background

Category	Background Process	Estimated Yield
Intrinsic (scale with number of stopped muons)	Decay In Orbit (DIO)	0.144 ± 0.028(stat) ± 0.11(syst)
	Muon Capture (RMC)	0
Late Arriving (scale with number of late protons)	Pion Capture (RPC)	0.021 ± 0.001(stat) ± 0.002(syst)
	Muon Decay in Flight	< 0.003
	Pion Decay in Flight	0.001 ± <0.001
	Beam Electrons	$(2.1 \pm 1.0) \times 10^{-4}$
Miscellaneous	Cosmic Ray Induced	0.209 ± 0.022(stat) ± 0.055(syst)
	Antiproton Induced	0.040 ± 0.001(stat) ± 0.020(syst)
Total		**0.41 ± 0.13(stat + syst)**

Track reconstruction and selection

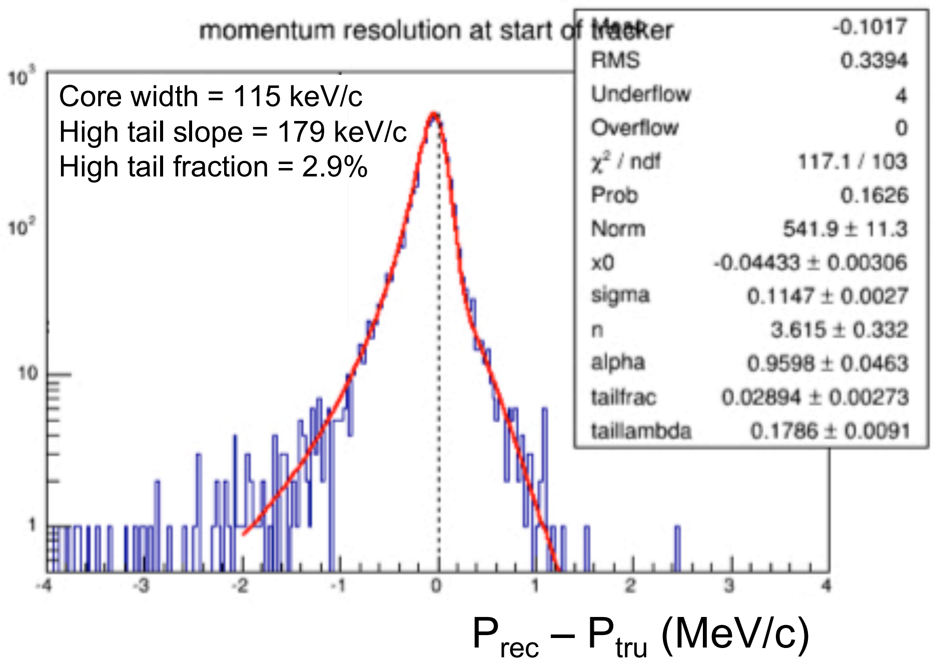


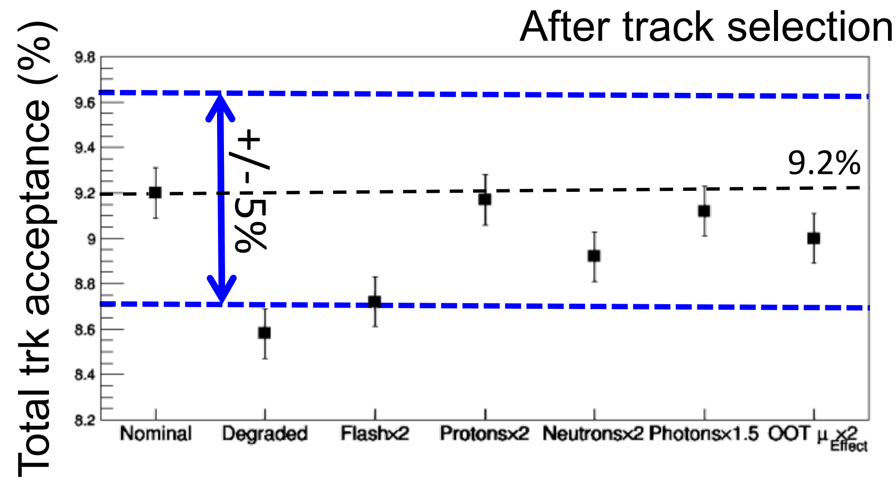
Inefficiency dominated by geometric acceptance

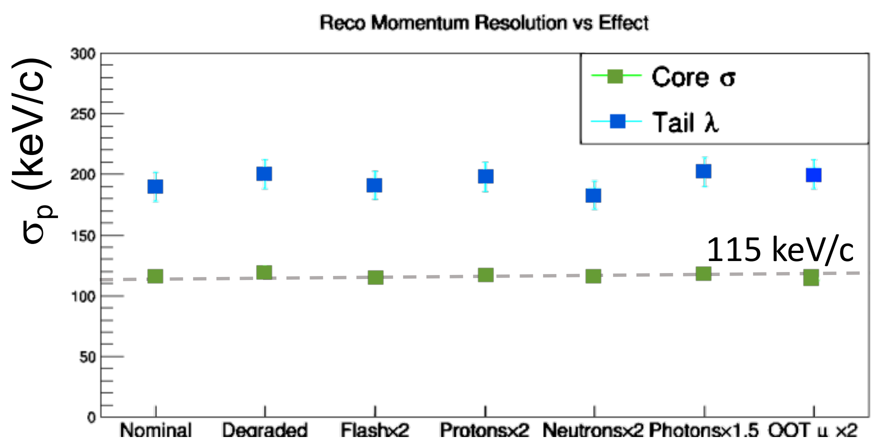
After calorimeter PID and CRV deadtime, Total = 8.5%

Tracker Performances

Expected tracker performances from full simulation







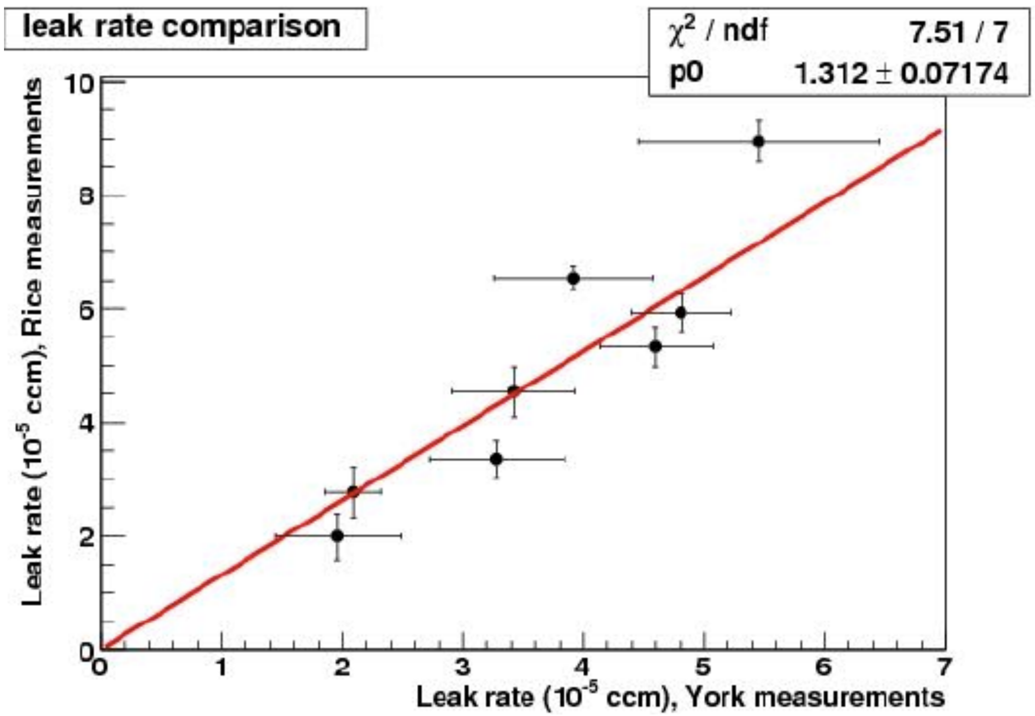
Variations in accidental hit rate

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

Straw leak test

Two methods:

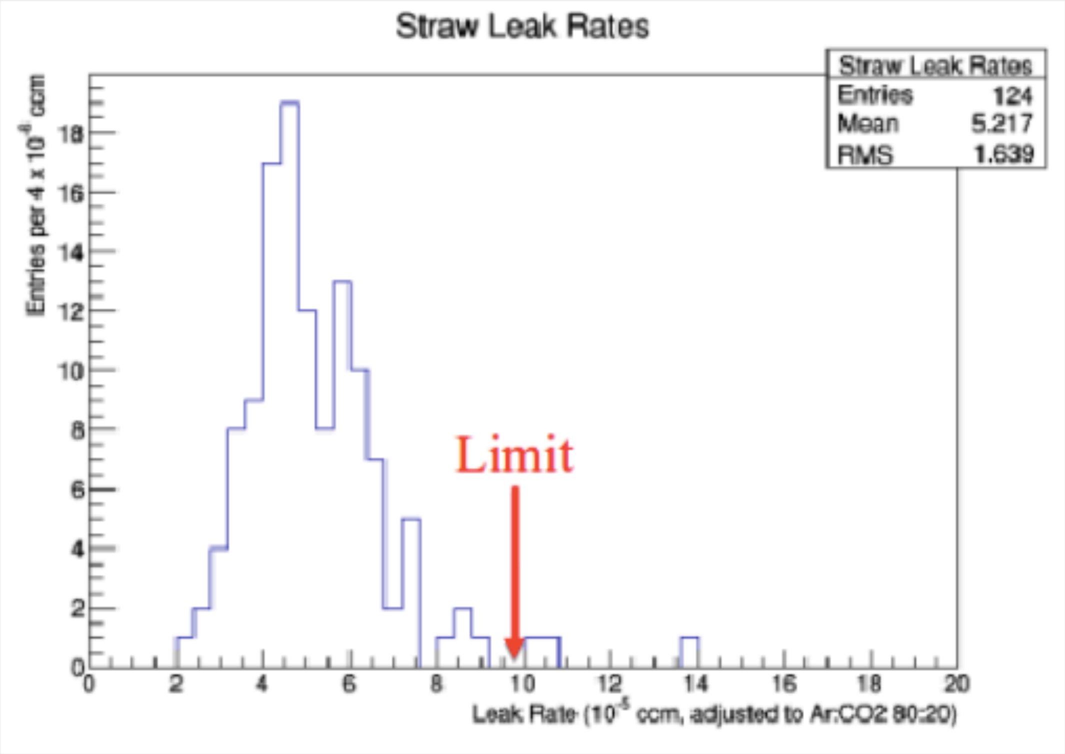
- CO_2 permeation — >100 straw/day: do every straw; Needs cross calibration
- Vacuum — Absolute measurement; ~ 1 per day (sample of straws)



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

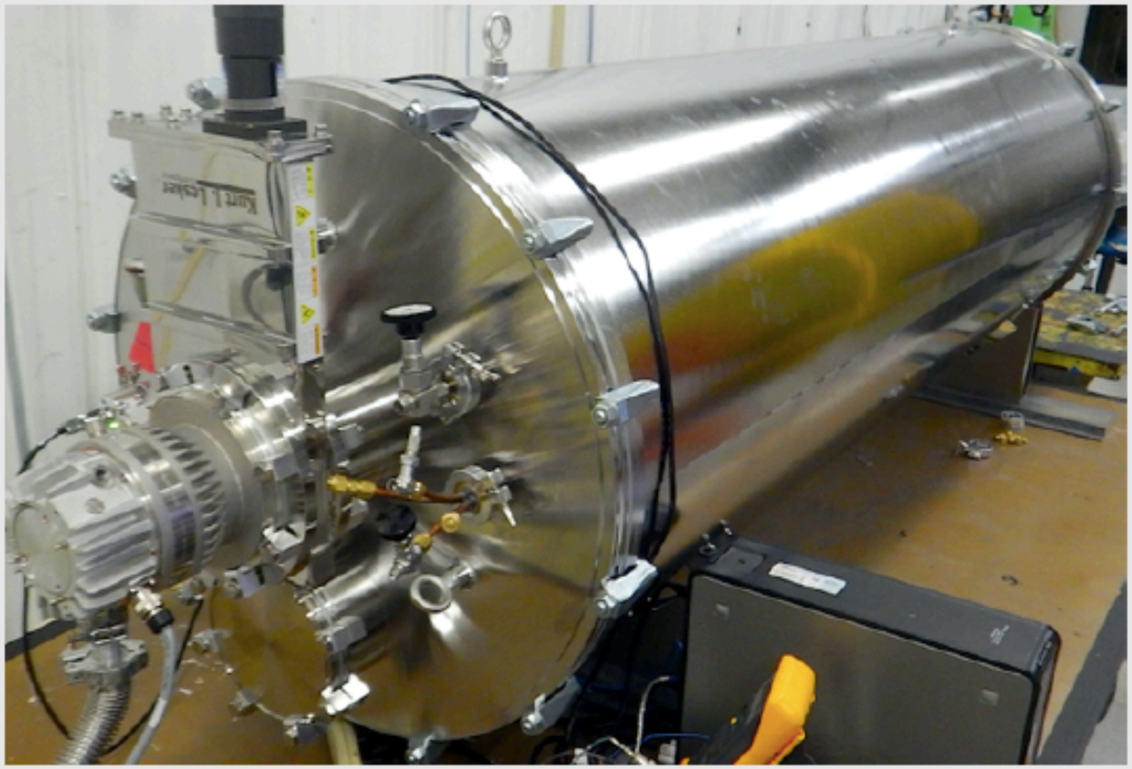
Straw leak test

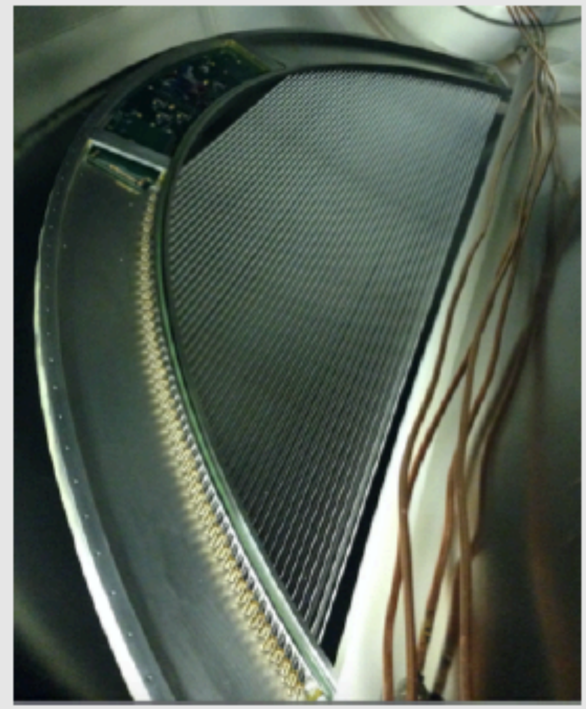
- The full tracker leak rate limit is 6 cm³/min .
  - many possible sources
  - individual straw leak limit is 9.6×10^{-5} cm³/min
  - 124 straws tested at FNAL last summer;121 passed



Panel leak test

- Large vacuum vessel to test 6 panels per day





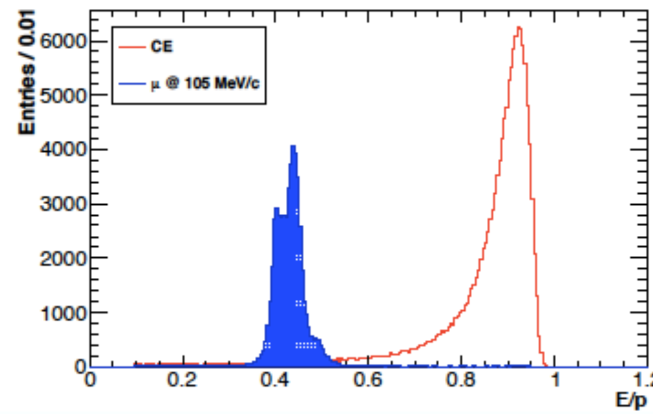
Calorimeter: e/μ separation

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

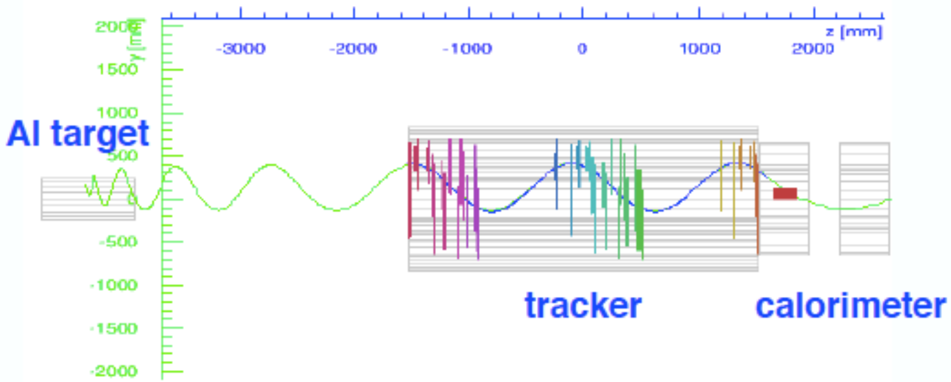
- 105 MeV/c e^- are ultra-relativistic, while 105 MeV/c μ have β~ 0.7 and a kinetic energy of ~ 40 MeV
- Likelihood rejection combines

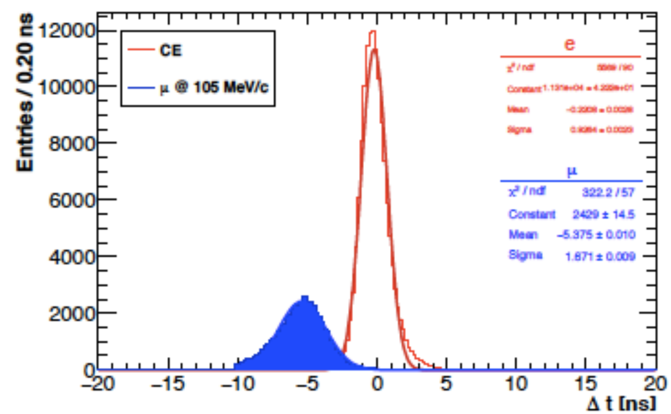
  $\Delta t = t_{track} - t_{cluster}$ and E/p:

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



μ mimicking the CE

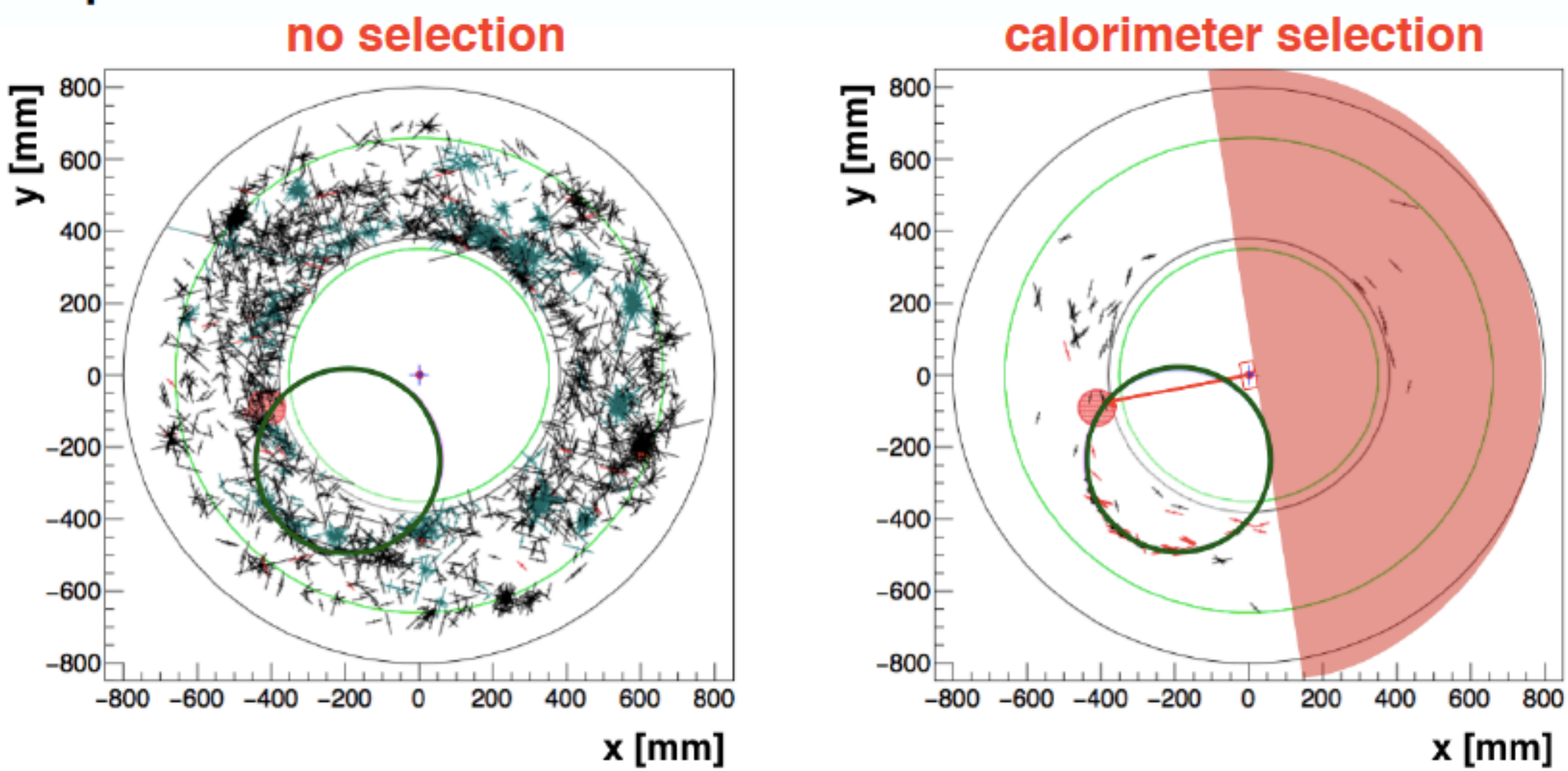




A rejection factor of 200 can be achieved with ~ 95% efficiency for CE

Calorimeter seeded track finder

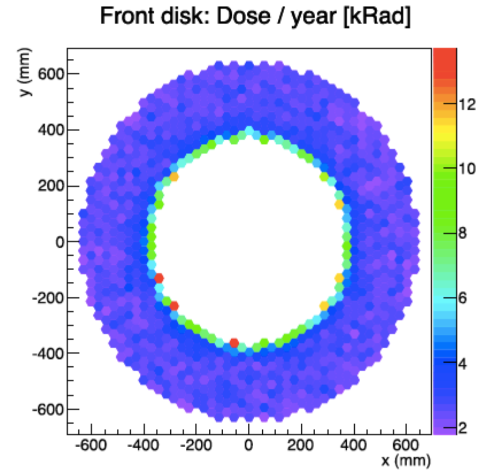
- Cluster time and position are used for filtering the straw hits:
  - ✓ time window of ~ 80 ns
  - ✓ spatial correlation

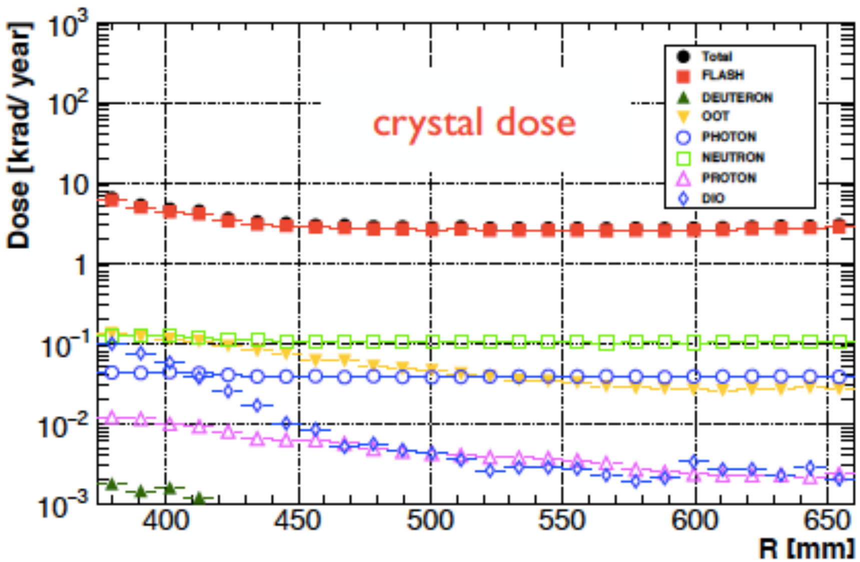


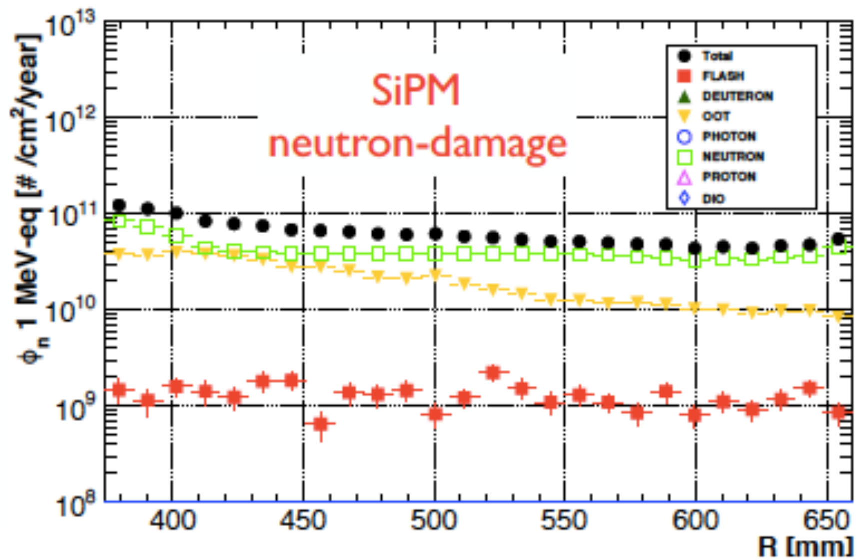
- **black crosses** = straw hits, **red circle** = calorimeter cluster, **green line** = CE track

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





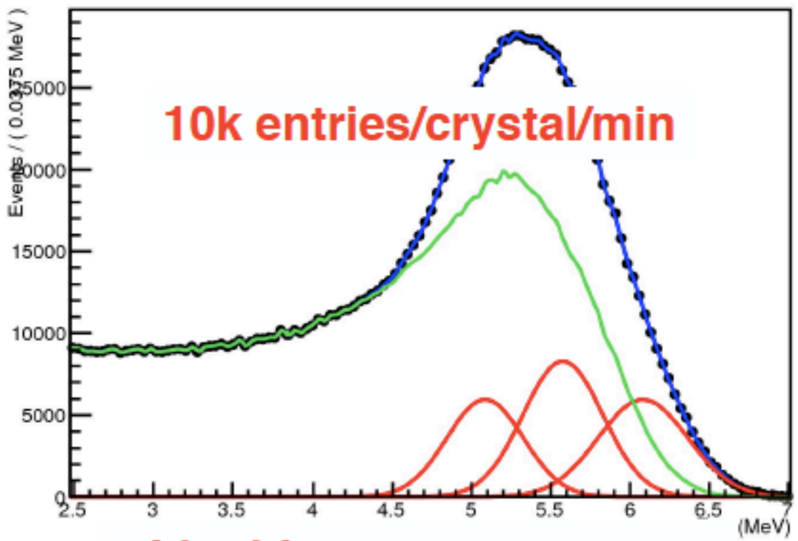


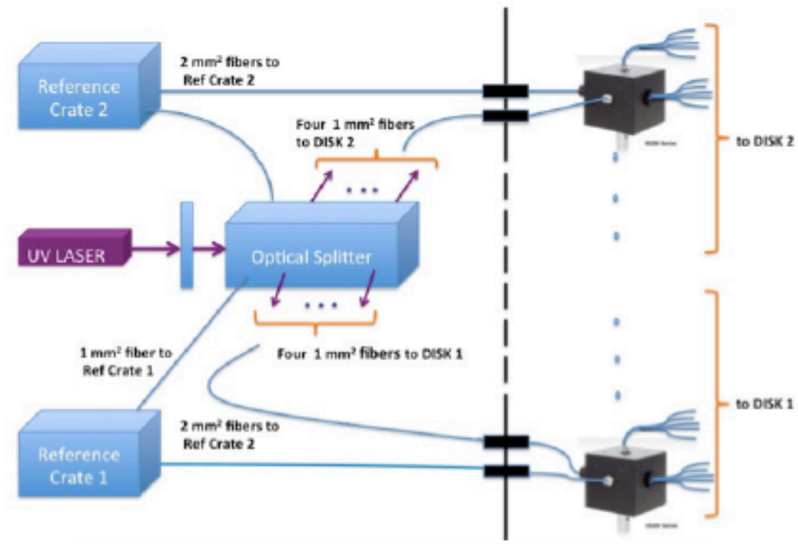
Qualify crystals up to ~ 100 krad, 10^{12} n/cm^2
Qualify SiPM up to ~ 10^{12} n_{1MeVeq}/cm^2

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





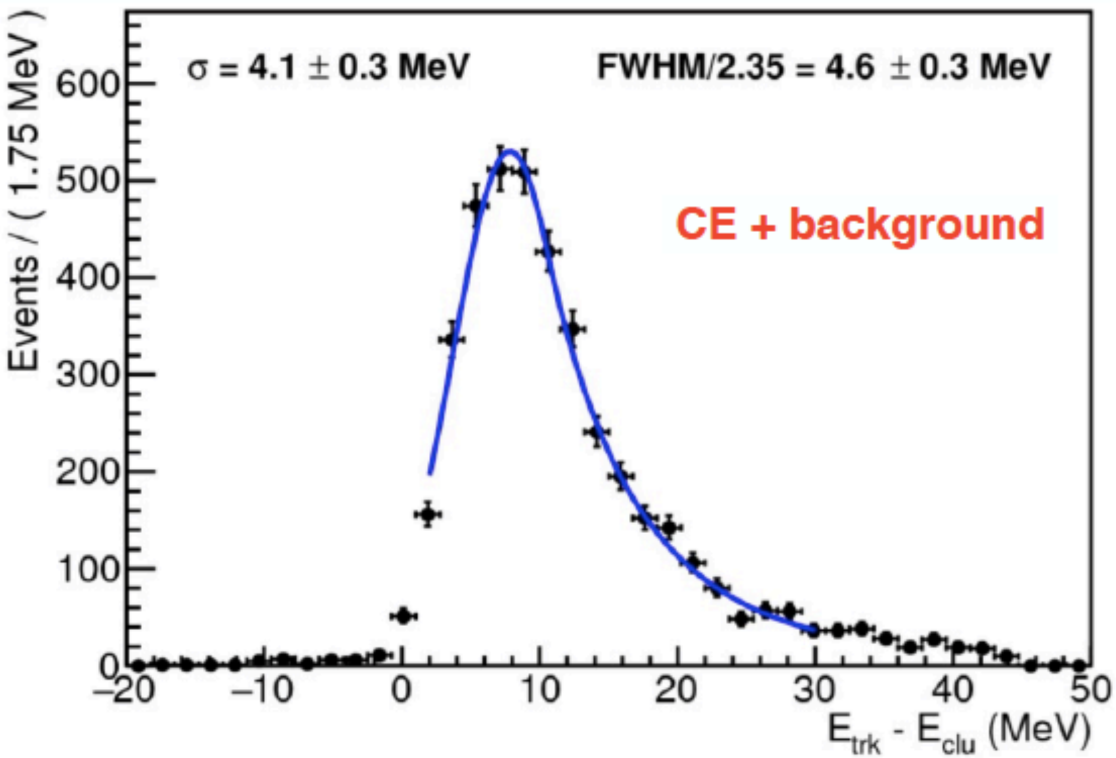
Liquid source prototype

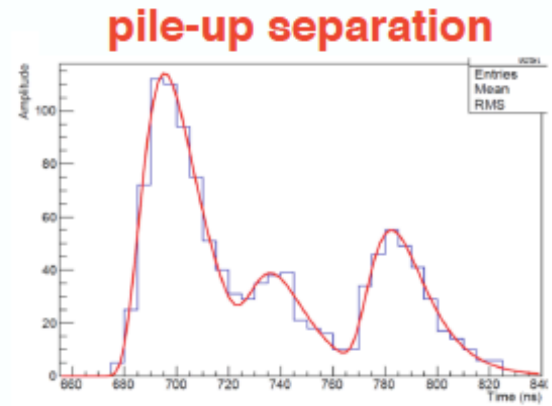
Laser system - test station

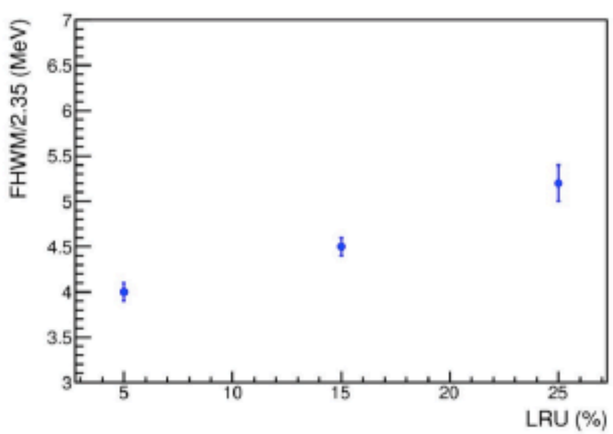
$$^{19}F + n \rightarrow \ ^{16}N + \alpha$$
$$^{16}N \rightarrow \ ^{16}O^* + \beta \quad t_{1/2} = 7\ \mathrm{s}$$
$$^{16}O^* \rightarrow \ ^{16}O + \gamma(6.13\ \mathrm{MeV})$$

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



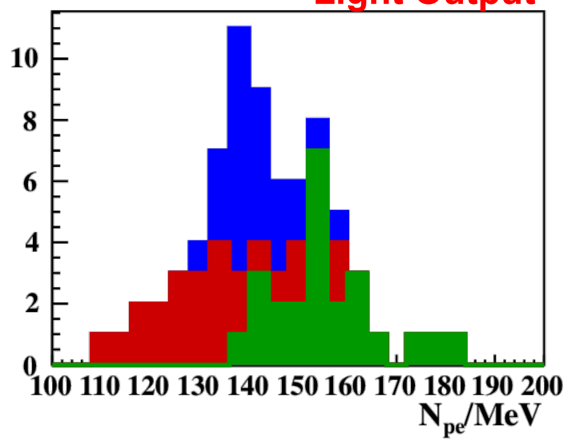




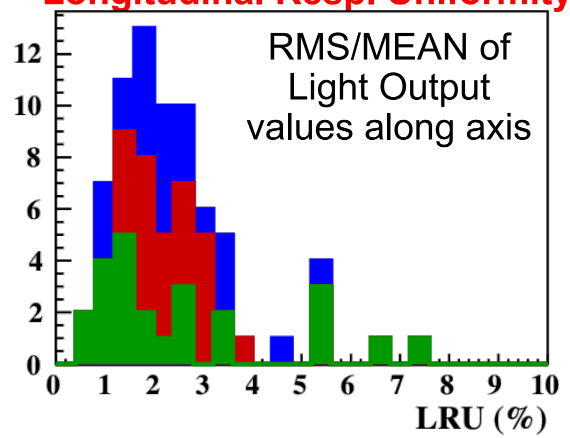
Test of pre-production crystals

- ✗ 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

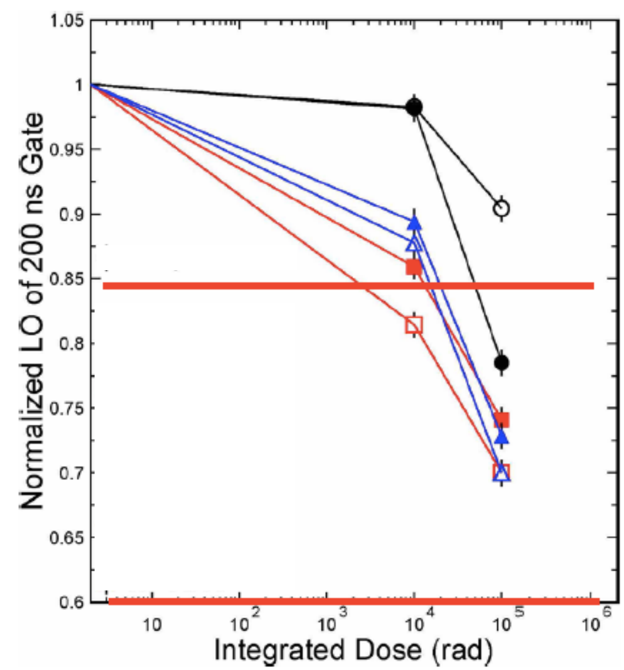
Light Output



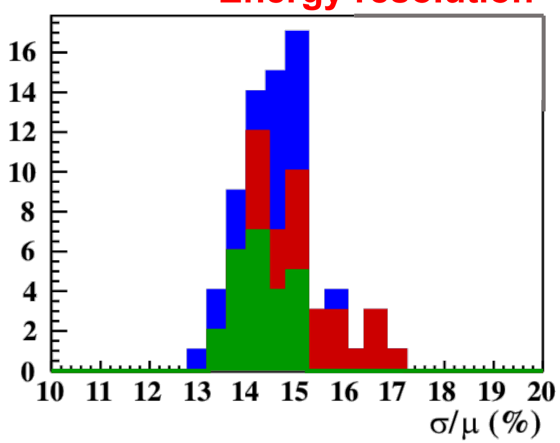
Longitudinal Resp. Uniformity



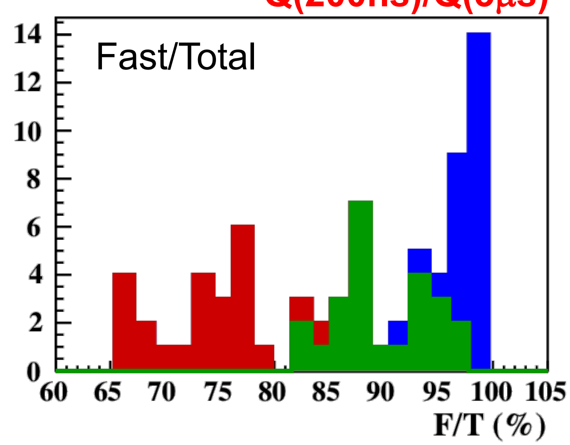
Irradiation test up to 100 krad



Energy resolution



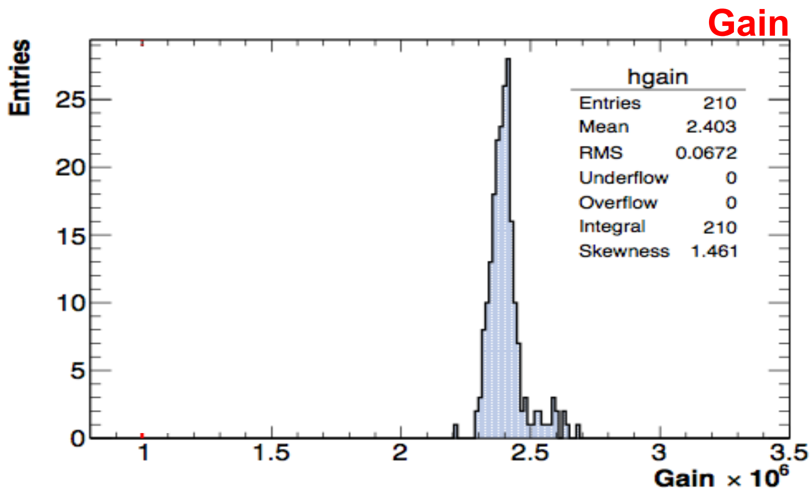
Q(200ns)/Q(3μs)

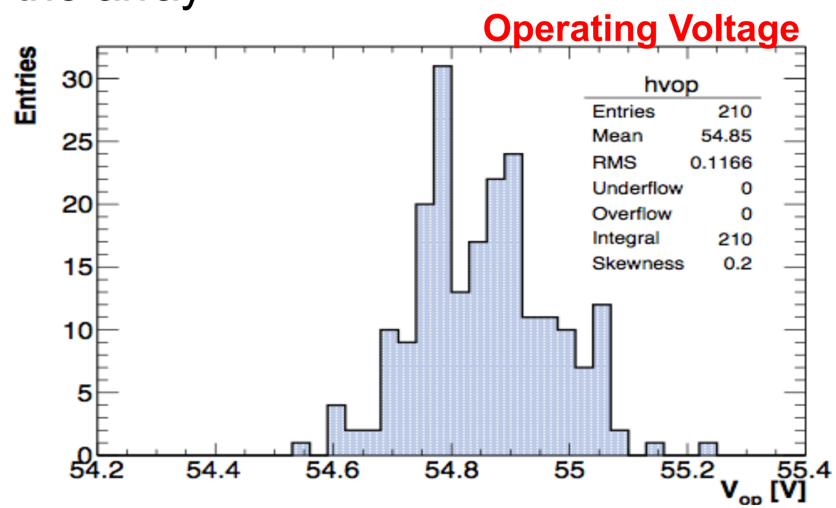


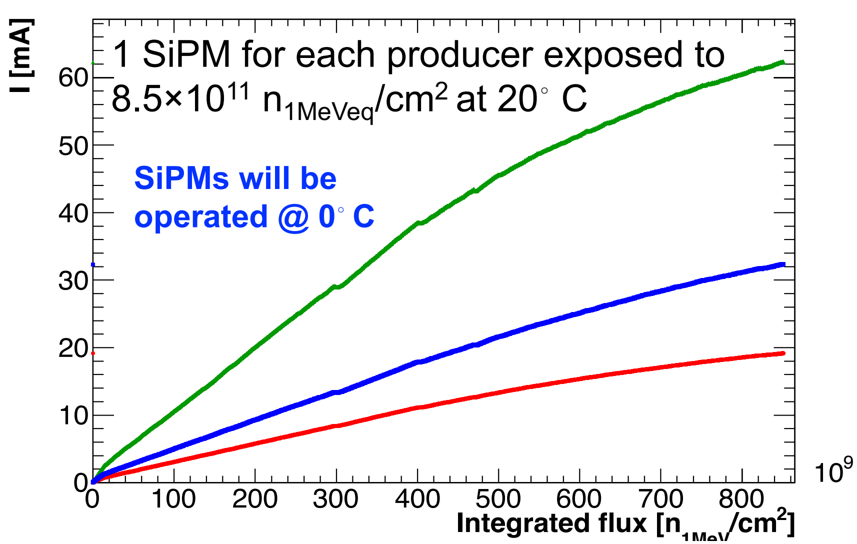
All satisfy Mu2e
100 krad requirement
(40% max. loss)

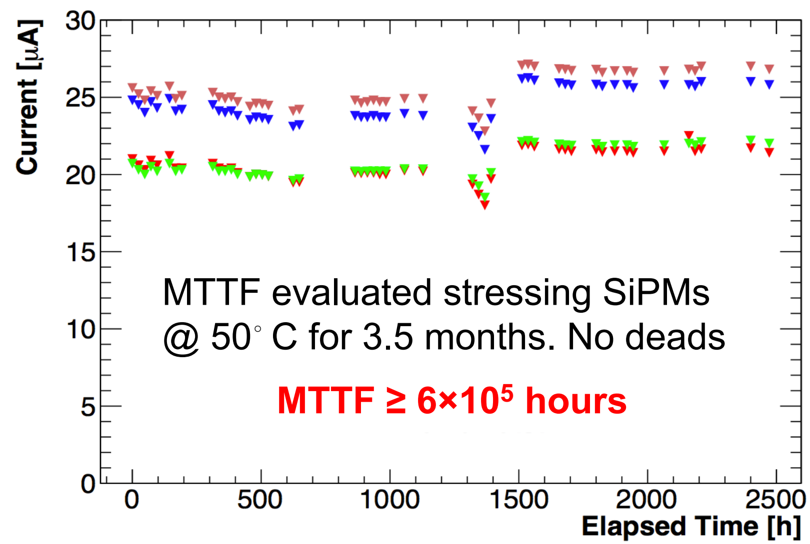
Test of pre-production SiPMs

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

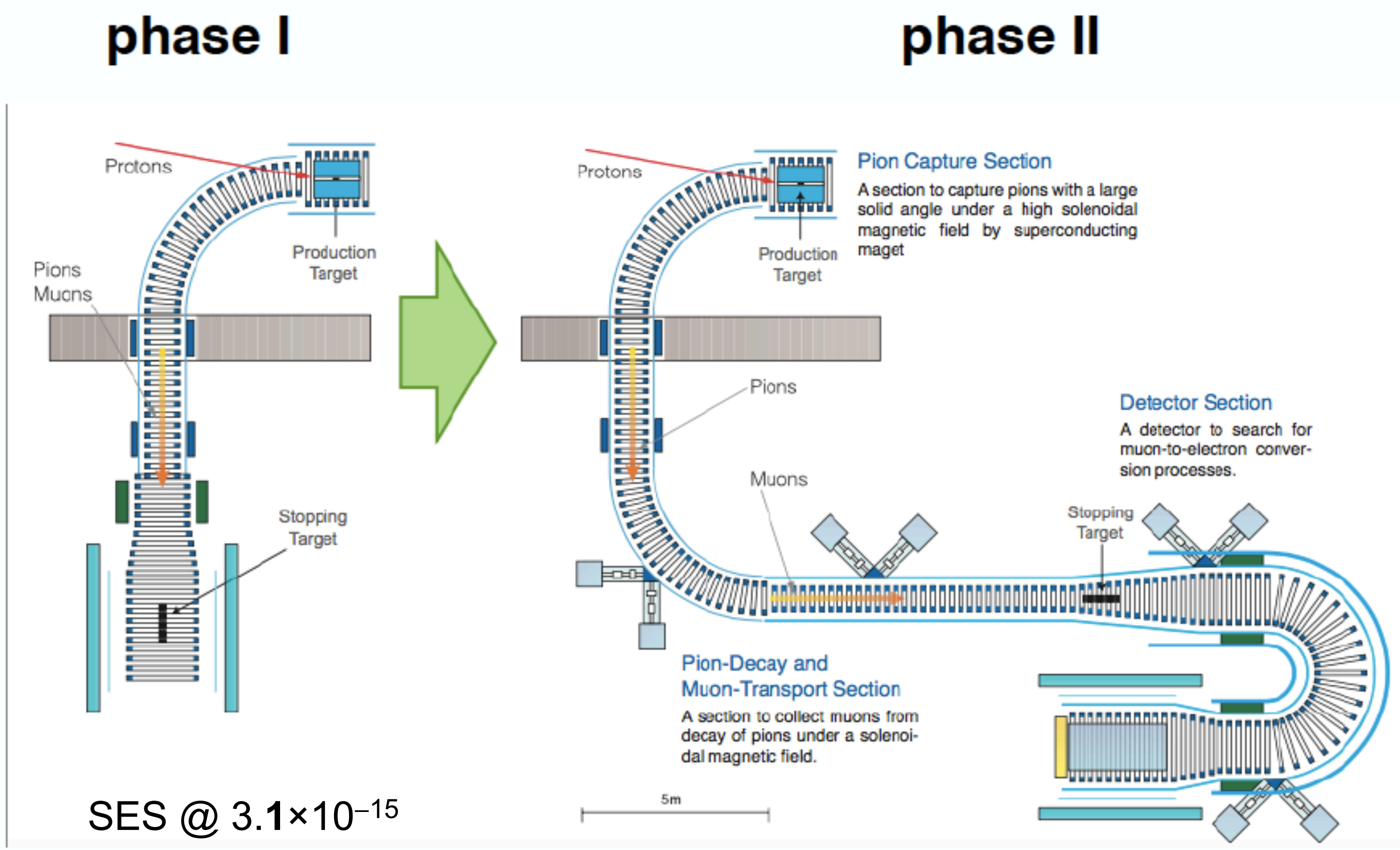








The COMET Experiment



SES @ 3.**1**×10^{-15}

The Muon Campus at Fermilab