The Mu2e experiment

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INFN Pisa

on behalf of the Mu2e Collaboration

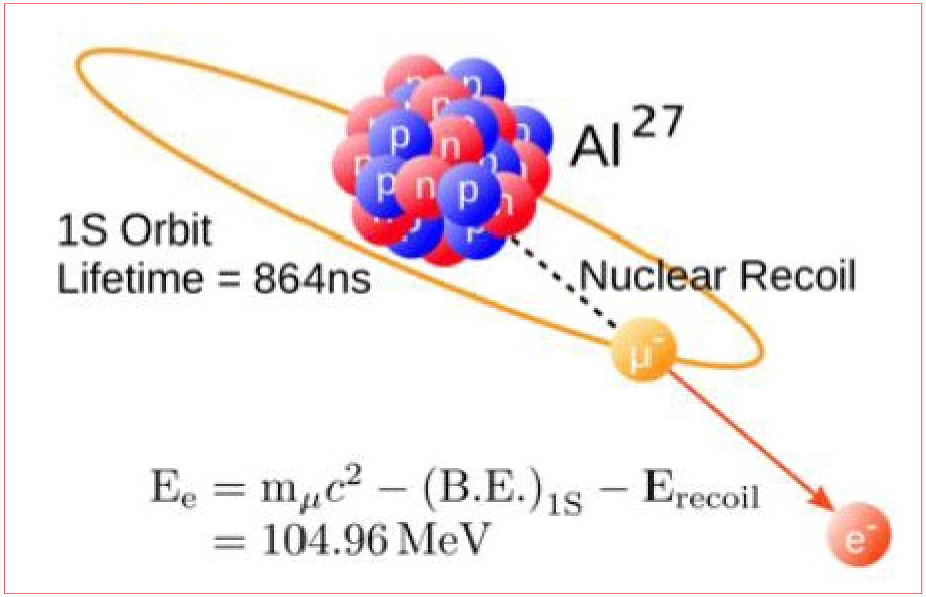
The Mu2e experiment

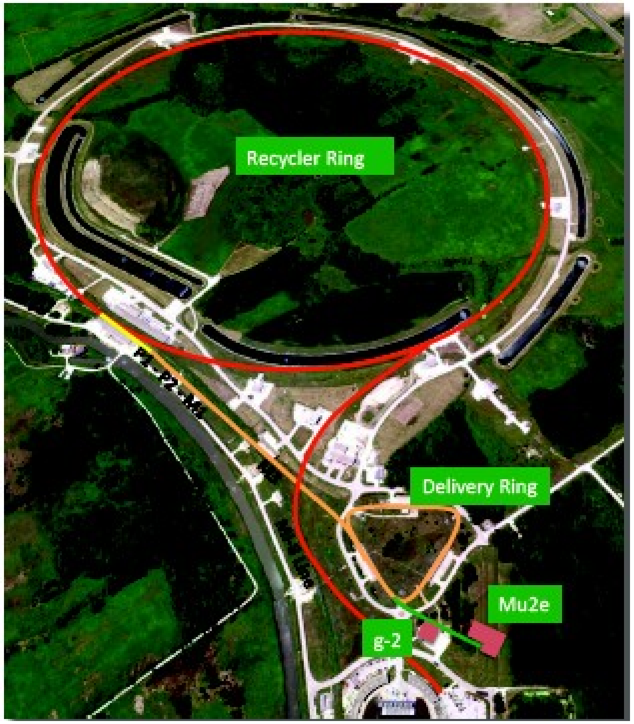
A search for **Charged Lepton Flavor Violation (CLFV)**

via the coherent conversion:

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

At the Fermilab Muon Campus





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

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

down to a Single Event Sensitivity of $3{\cdot}10^{-17}$
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)

CLFV searches

Muon sector currently provides the most stringent limits to CLFV

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

"3 stars" discovery capability in many theoretical frameworks

Different sensibility to different processes makes the 3 experimental searches complementary

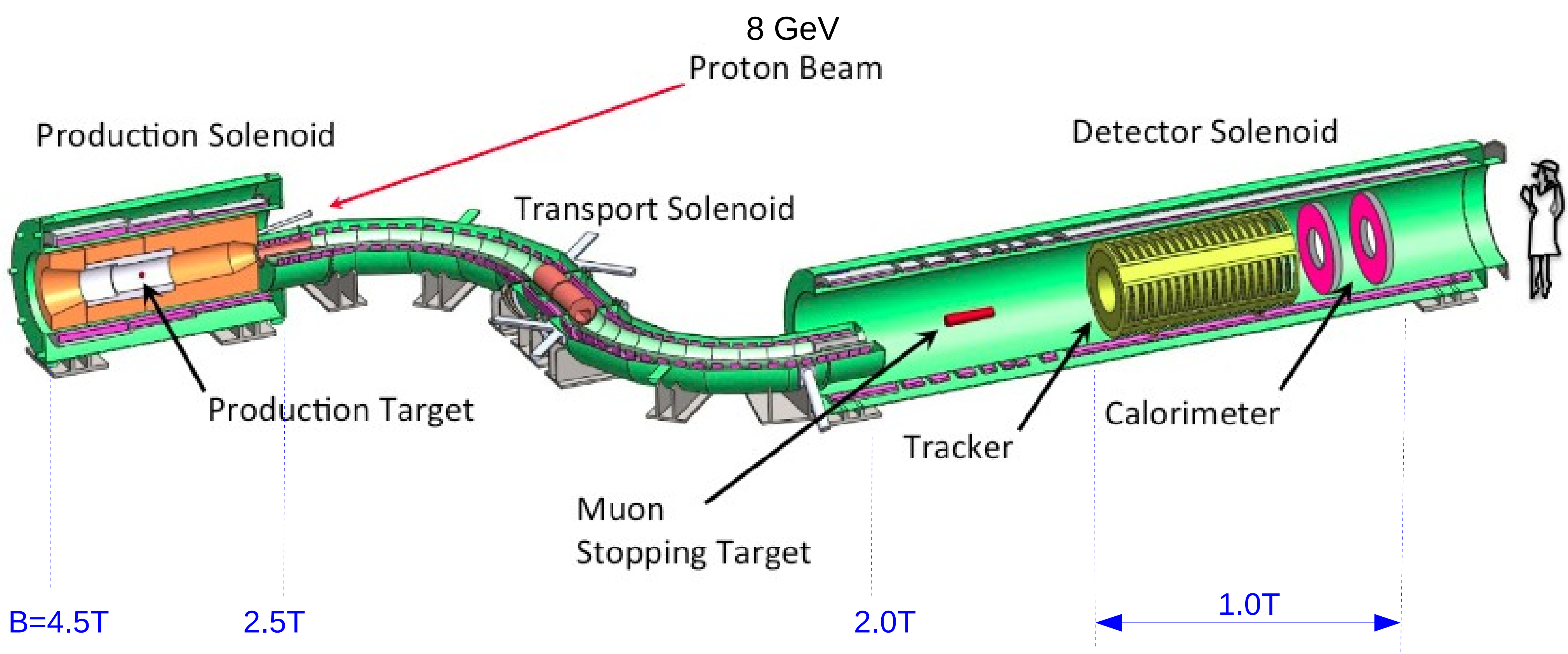
	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?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

W.Altmanshofer at al. arxiv 0909.1333v2

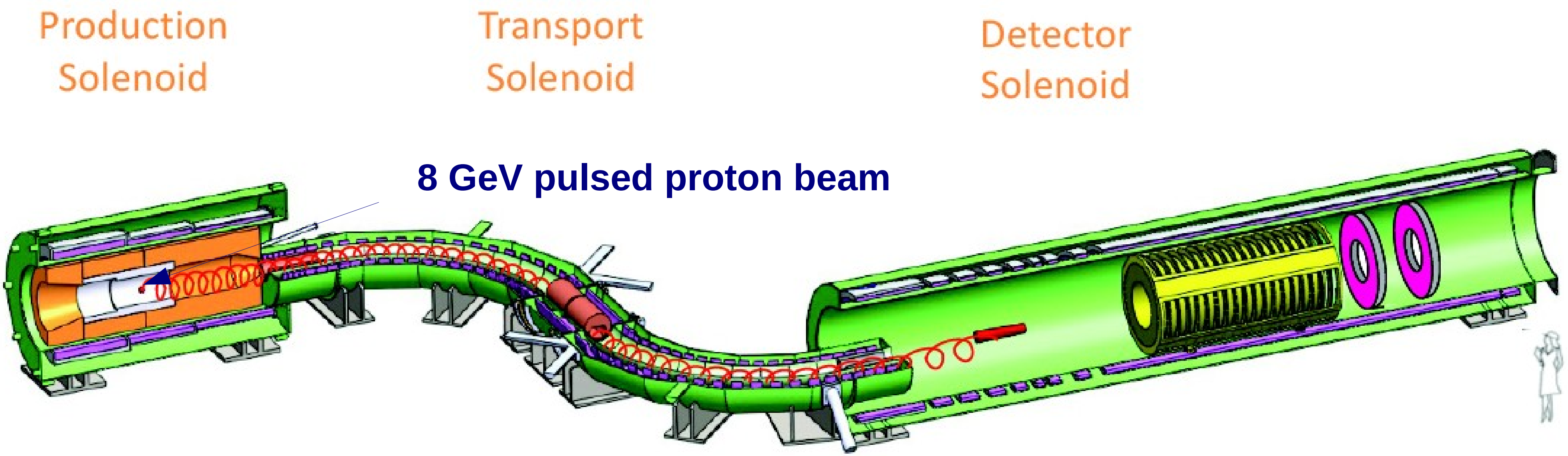
See more in Angela Papa's talk

The Mu2e Experiment at Fermilab: the beam line

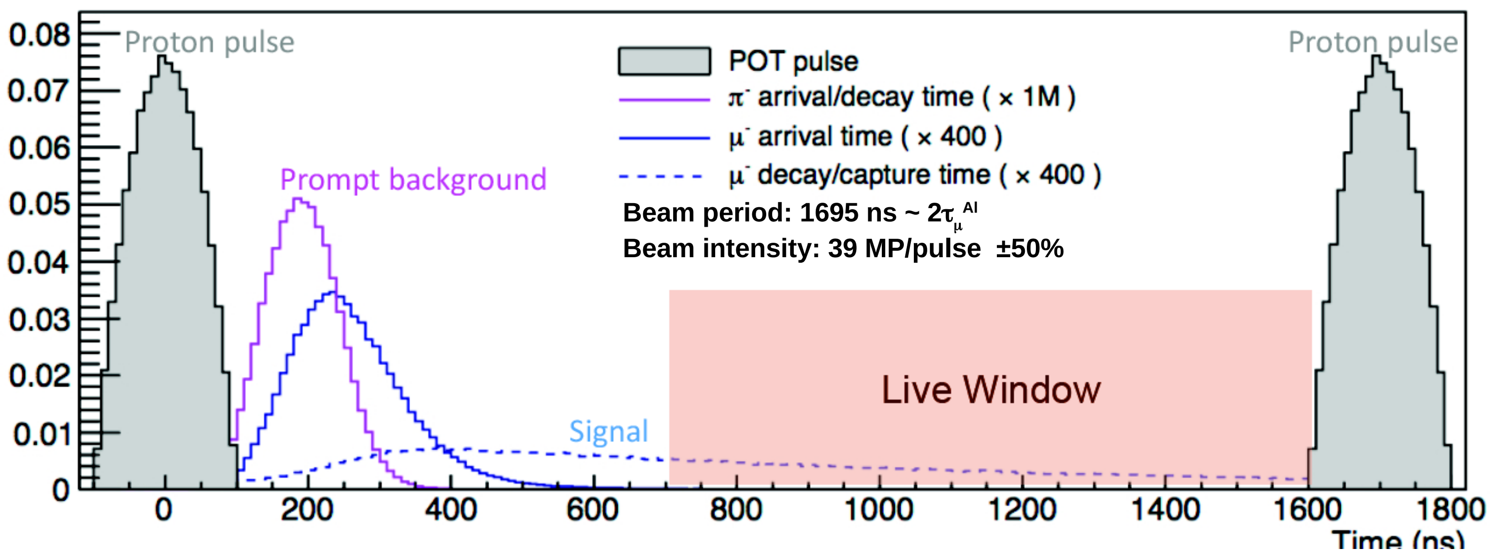


Production Solenoid: *p* on *tungsten*, graded field sweeps low momentum particles downstream
Transport Solenoid: transmit negative particles with the right momentum, antiproton absorber
Detector Solenoid: Al stopping target, proton absorber, graded field to direct to detectors

The Mu2e Experiment at Fermilab: the beam line



Pulsed Proton Beam Structure

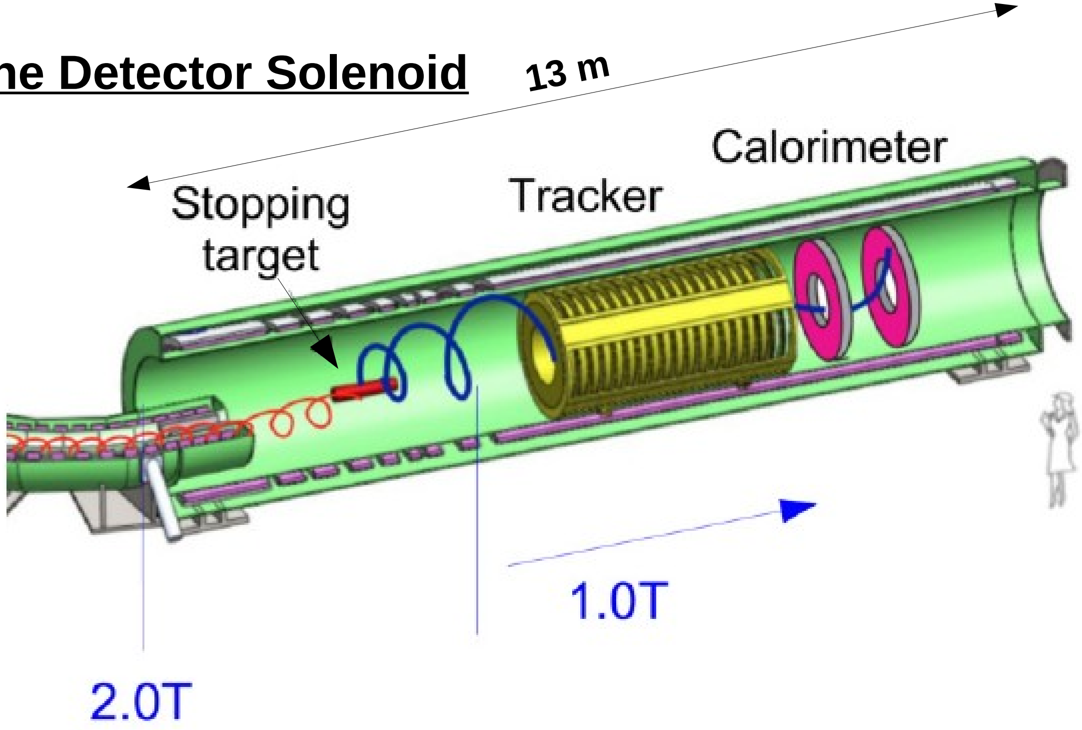


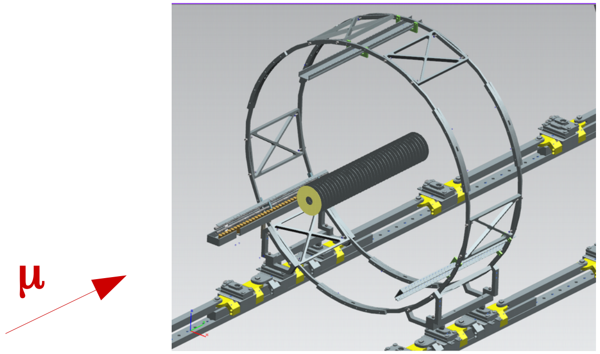
Extinction Factor $<10^{-10}$ (fraction of protons out of bunch)

Time window to avoid prompt background from beam flash

The Mu2e Experiment at Fermilab: detectors region

The Detector Solenoid



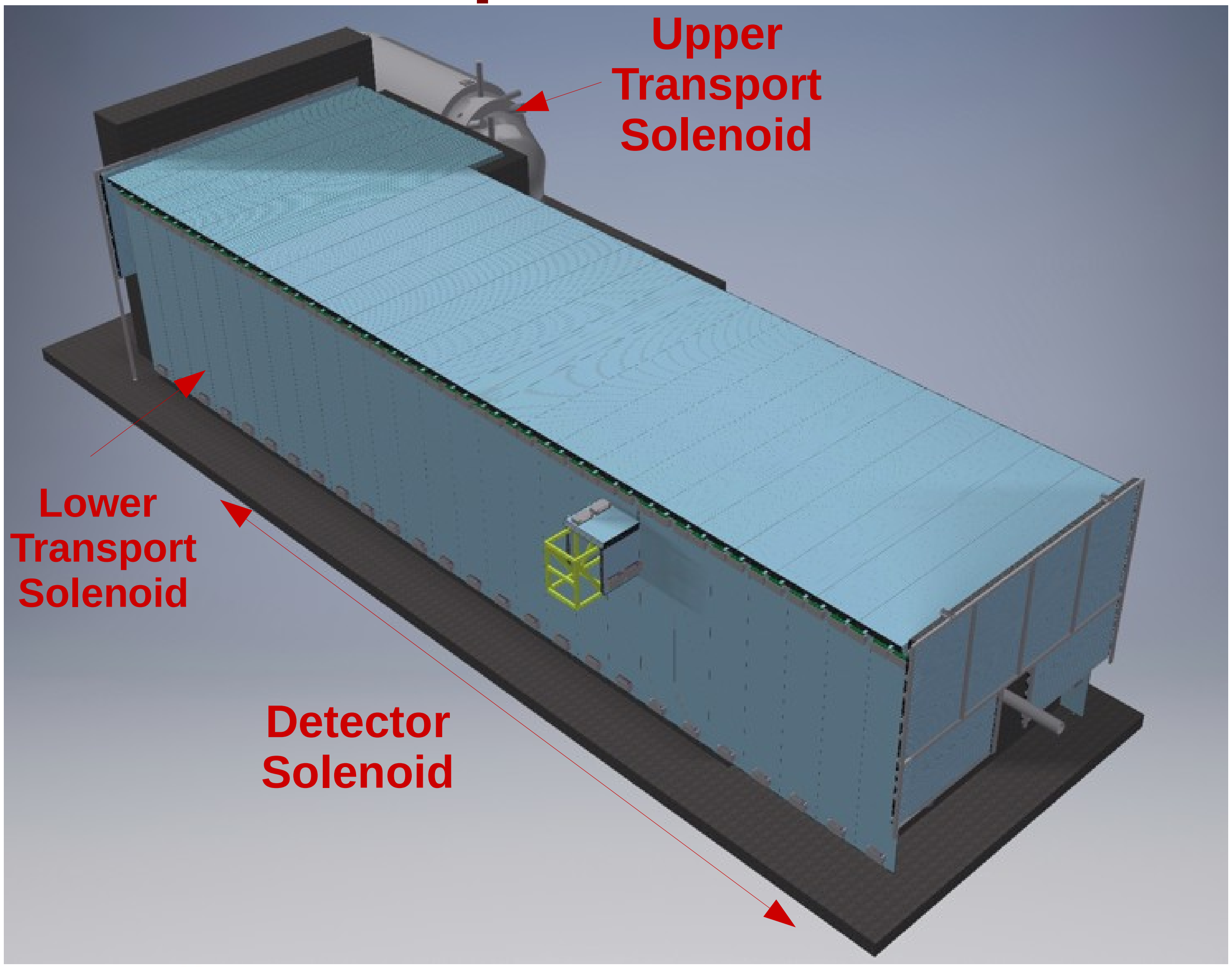


The stopping target

37 foils of Al
100 μm thick
150 mm diameter
43 mm diameter central hole

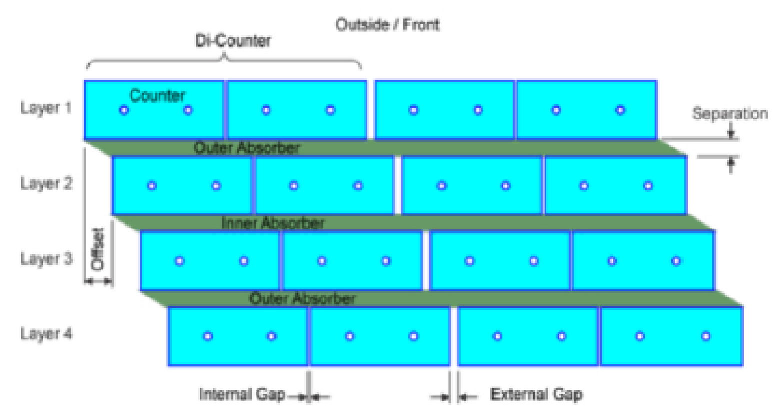
Acceptance improved by magnetic gradient
Minimum amount of material before momentum measurement
Constant field in the tracking volume
18 straw tube tracker stations, 2 CsI crystals calorimeter disks

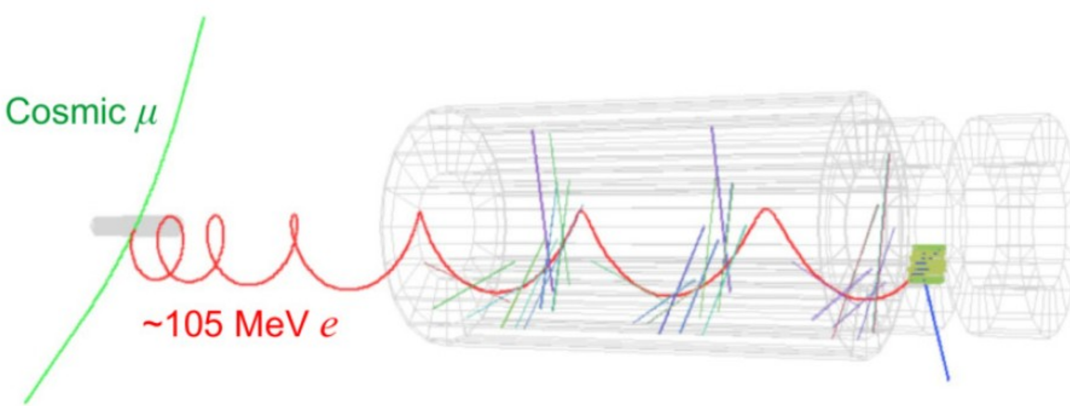
The Mu2e Experiment at Fermilab: Cosmic Rate Veto



Cosmic Ray Veto:

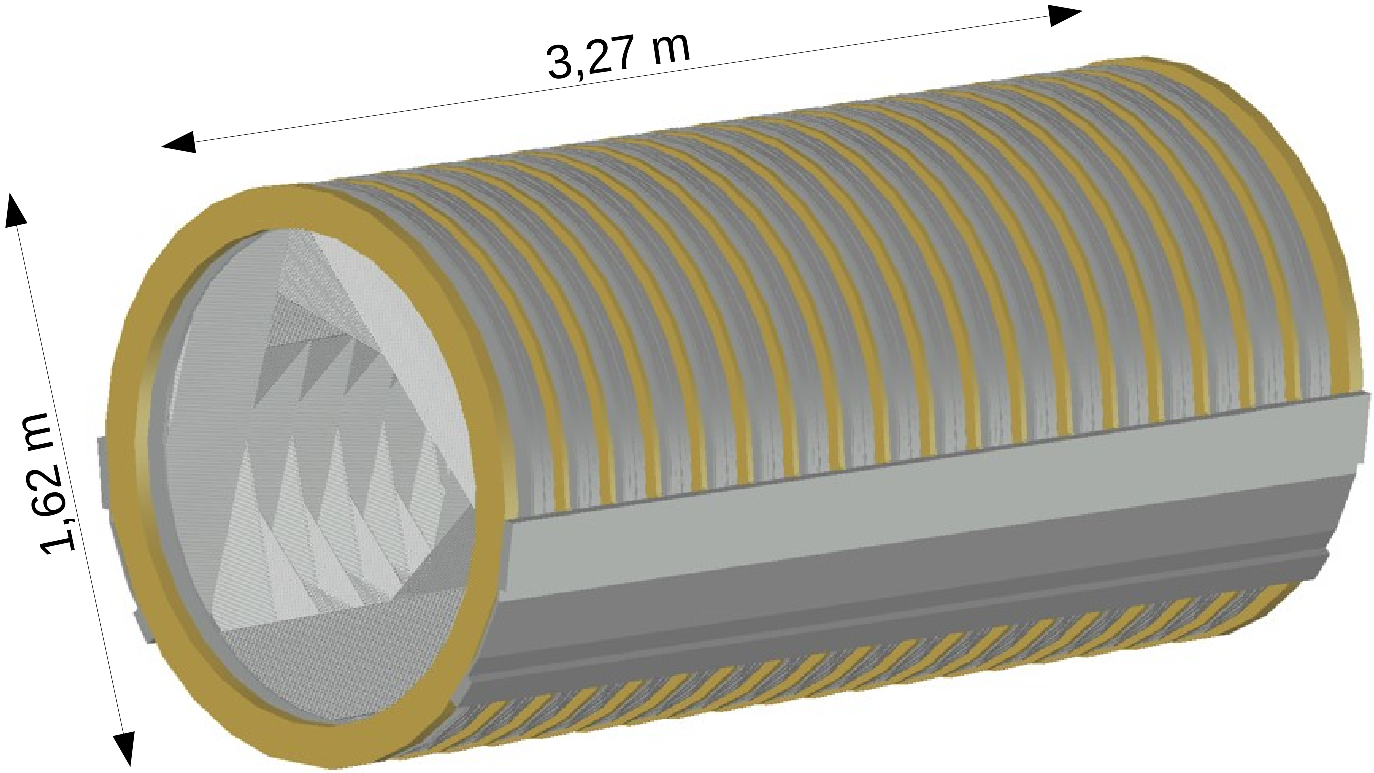
4 layers of scintillator counters covering Detector Solenoid and Lower Transport Solenoid



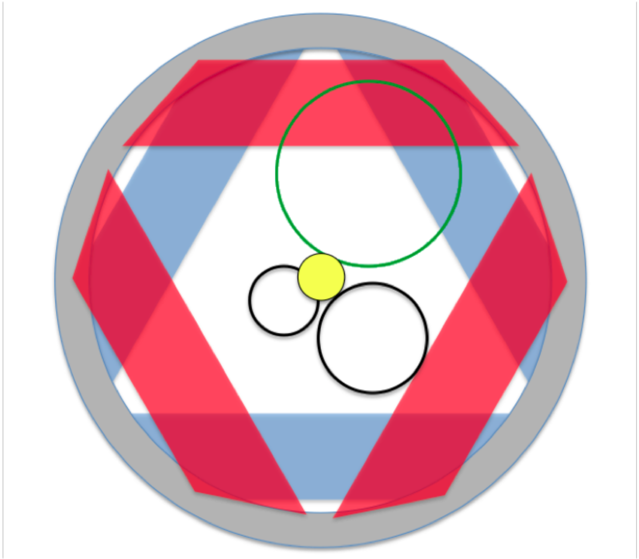


About 1 cosmic event/day emulating a 105 MeV electron

The Mu2e Experiment at Fermilab: tracker

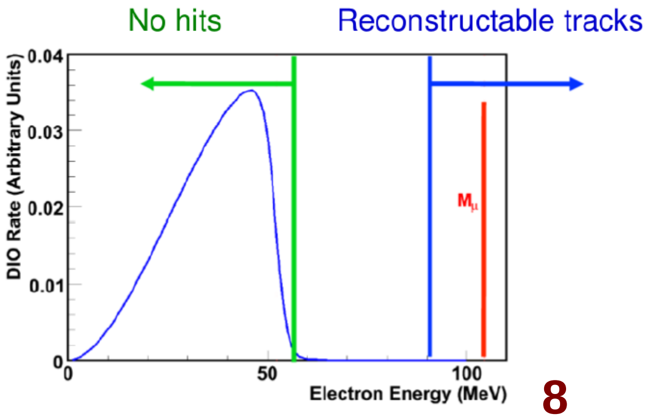


18 stations of 12 panels covering 120° each (stereo view)

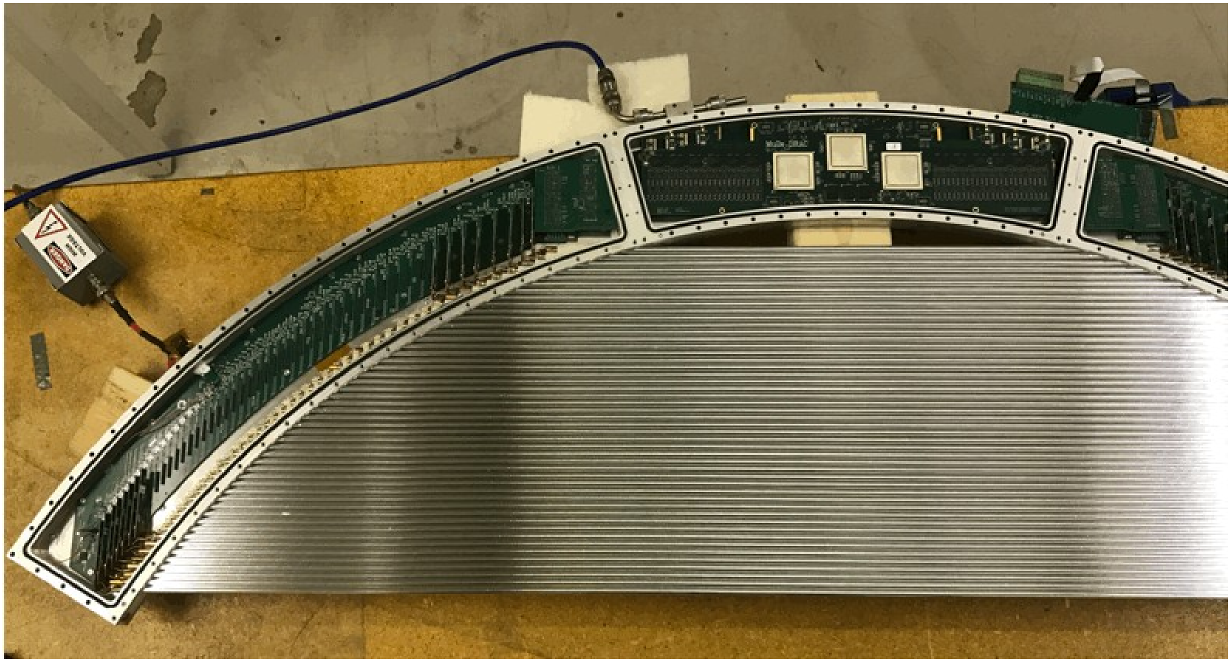


Tracker not sensitive to particles with p_T<80 MeV/c (beam flash and most of DIOs)

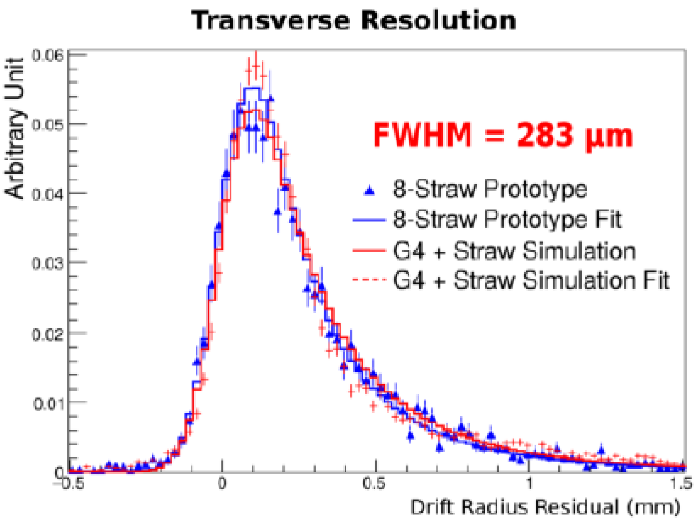
~21000 straw tubes
5 mm diameter, 15μm mylar
25 μm tungsten wire @1450V
80:20 $ArCO_2$ gas mixture
Each read by 2 ADCs & 2 TDCs

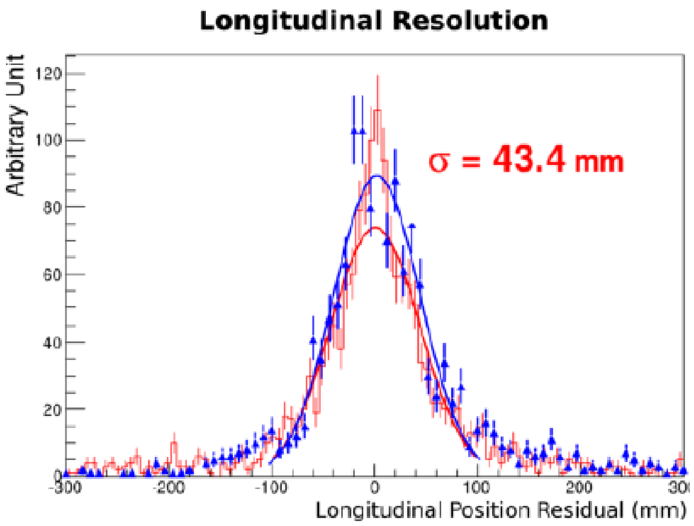


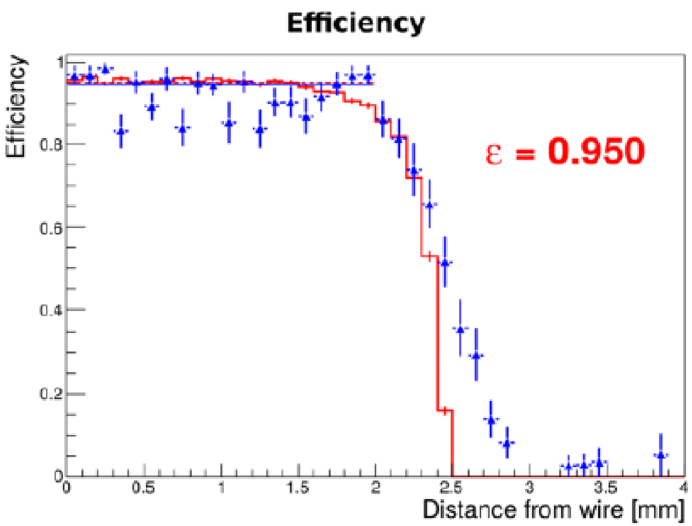
The Mu2e Experiment at Fermilab: tracker



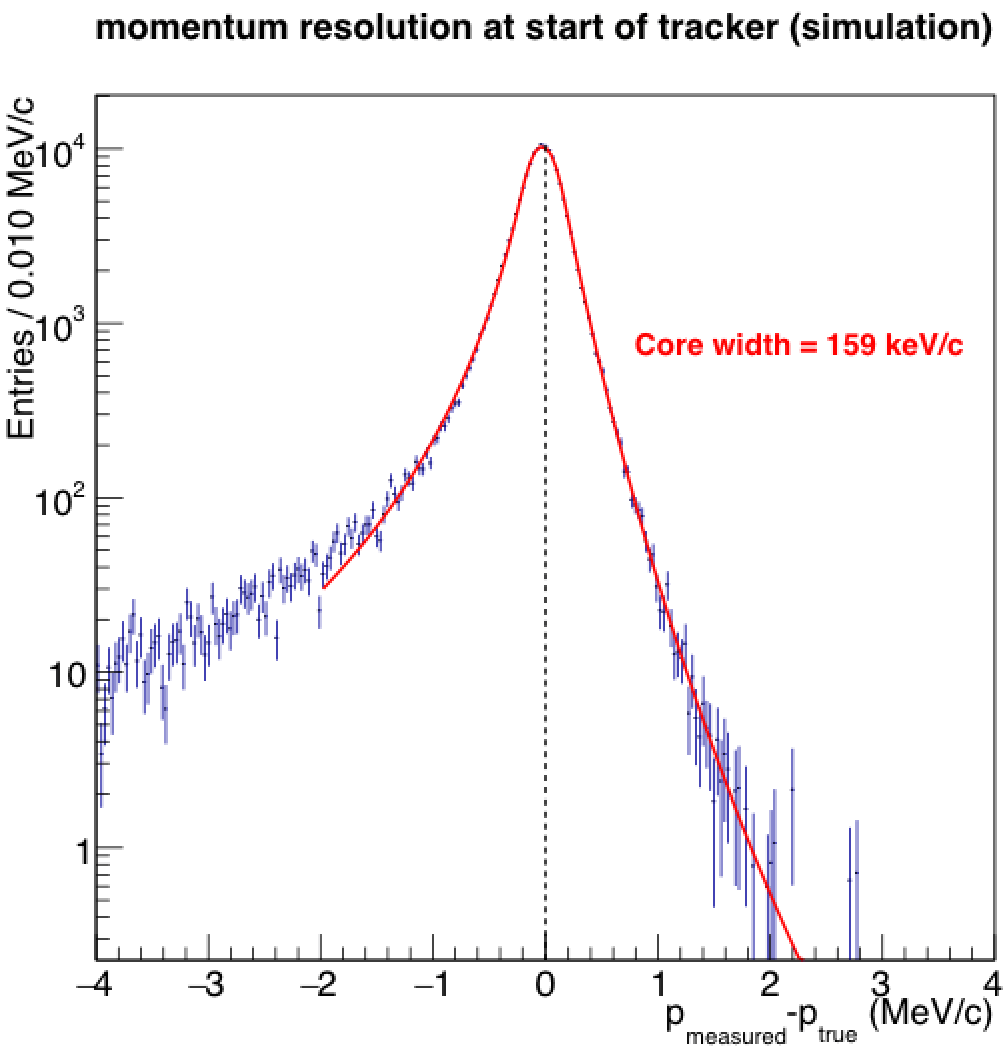
Results of tests on prototypes





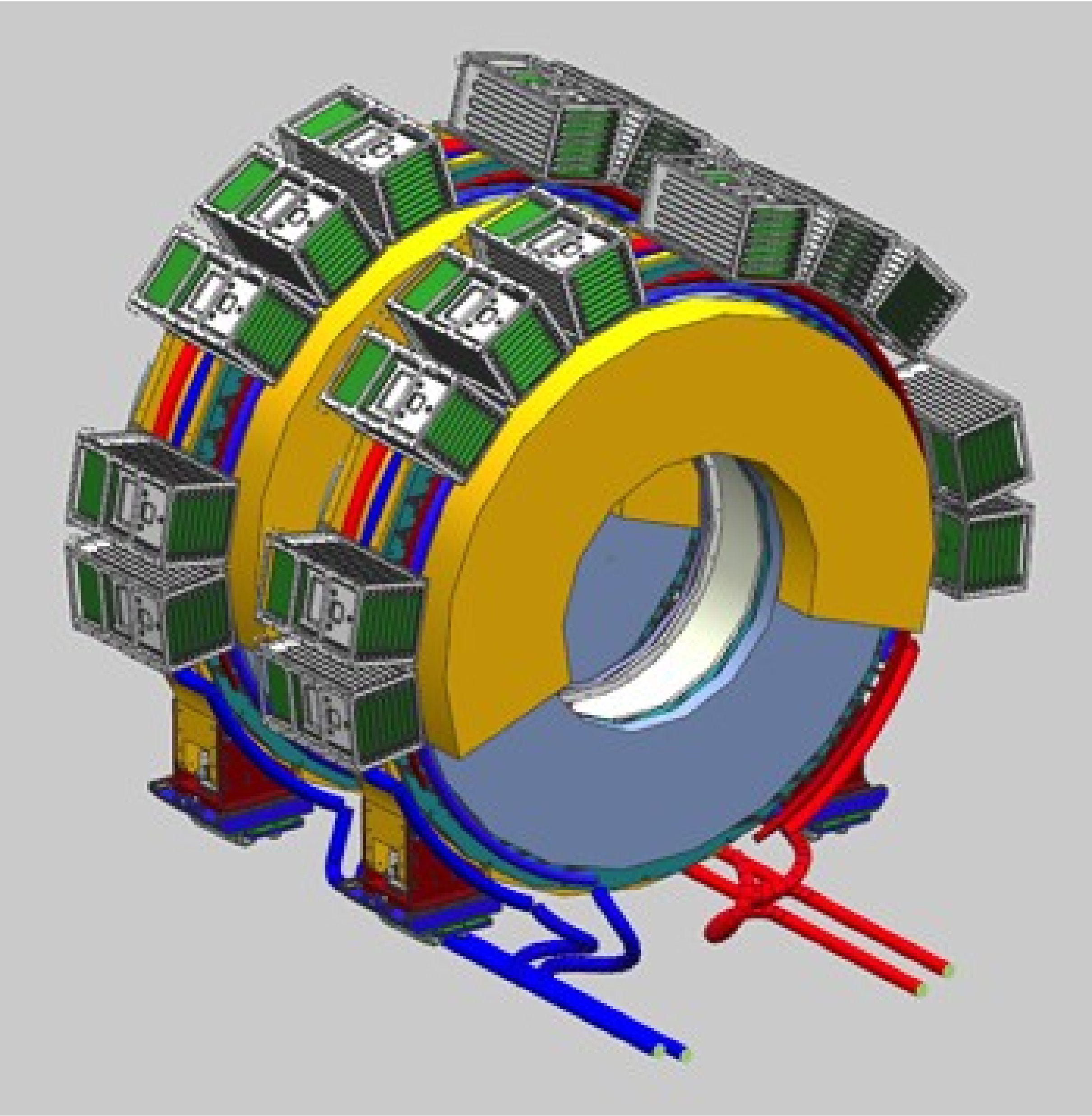


The Mu2e Experiment at Fermilab: tracker

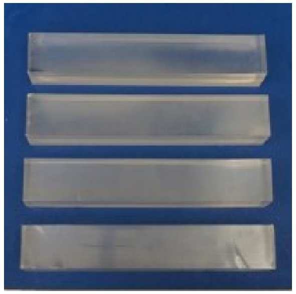


Left tail due to energy loss in material

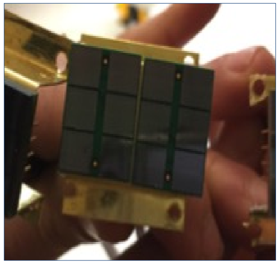
The Mu2e Experiment at Fermilab: calorimeter



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



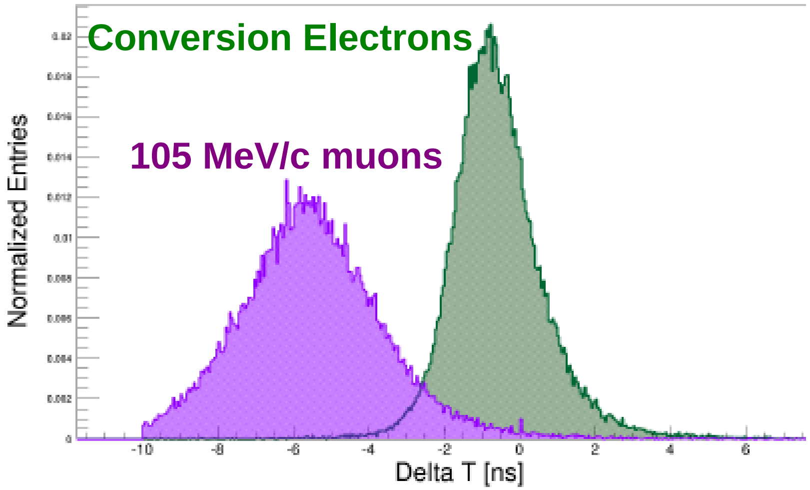
Sensors:
Arrays of 6 SiPMs
2 arrays/crystal
14x20 mm^2 each

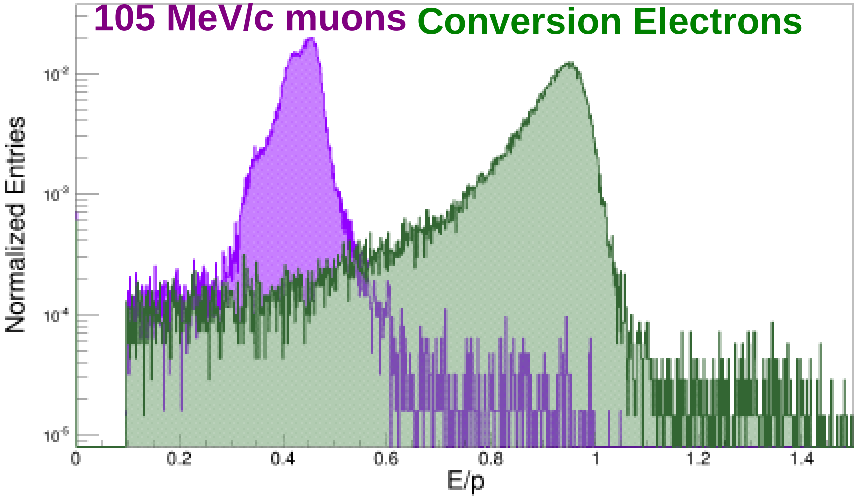
Readout electronics:
Preamplifiers on sensors back
Voltage control and Waveform
Digitizers in crates around disks

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

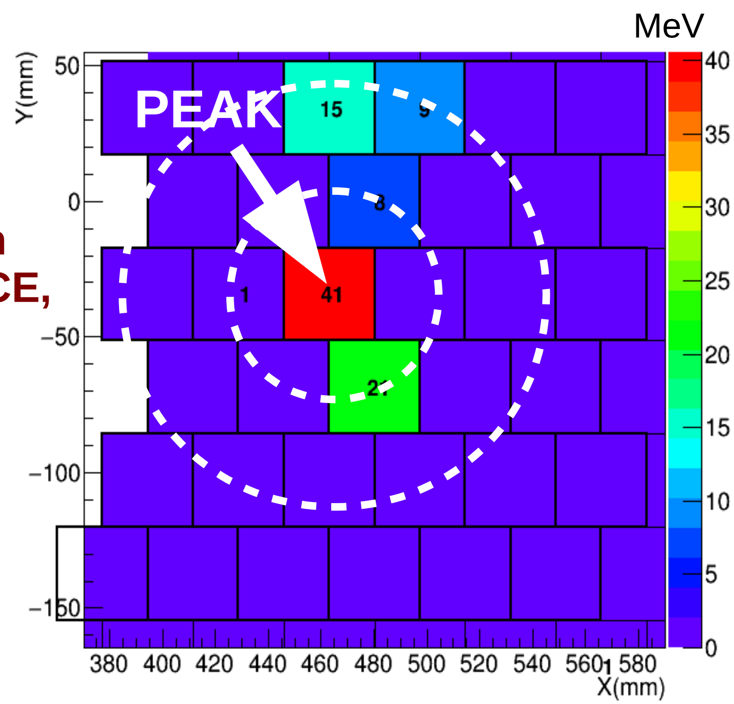
The Mu2e Experiment at Fermilab: calorimeter

Particle identification:
105 MeV/c Muon rejection factor ~400

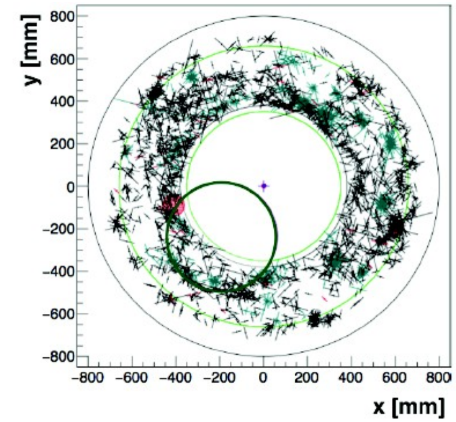


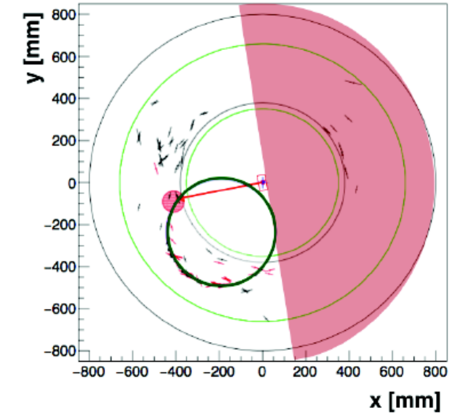


Trigger:
90% efficiency on reconstructable CE, 97% if combined with straw hit information

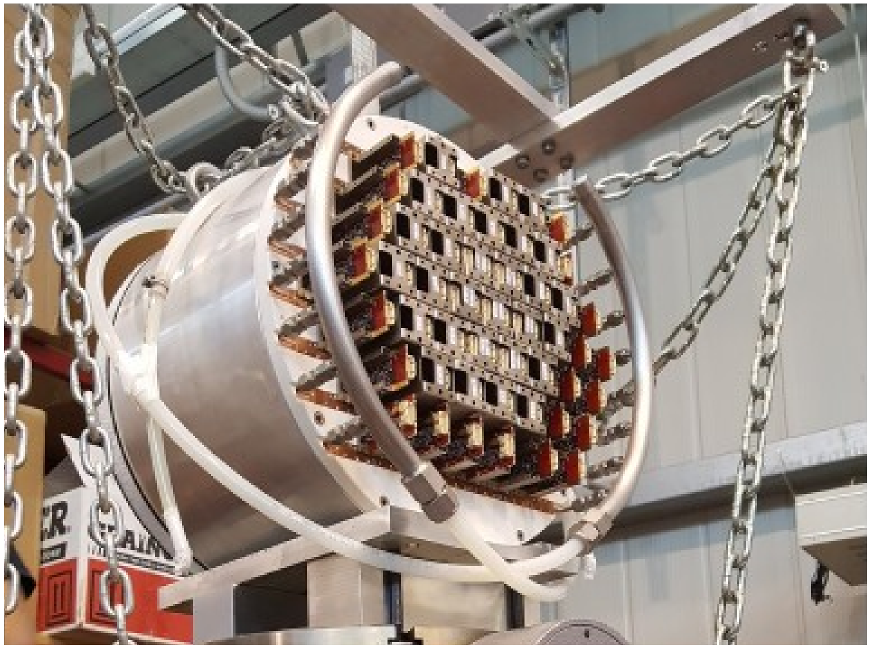


Pattern recognition:
use calorimeter cluster time to reduce combinatorial of tracker hits





The Mu2e Experiment at Fermilab: calorimeter



Test on a 51 crystal prototype with electrons and cosmic μ at Frascati Beam Test Facility

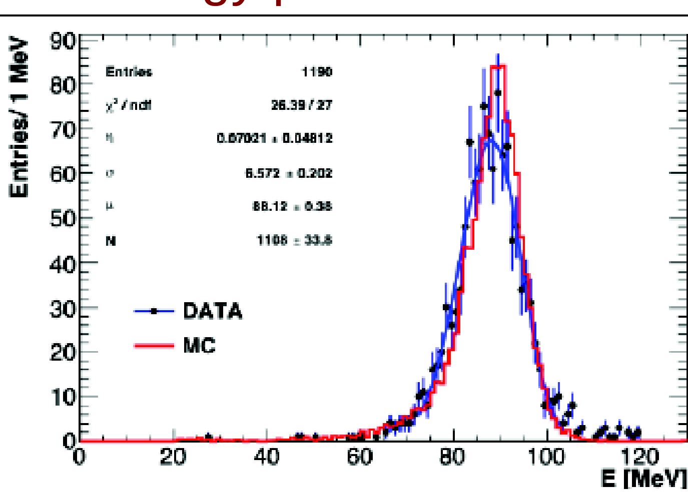
For 100 MeV electrons:

	0^o	50^o (CE peak)
Energy resolution	5.4%	7.3%
Time resolution*	160 ps	230 ps

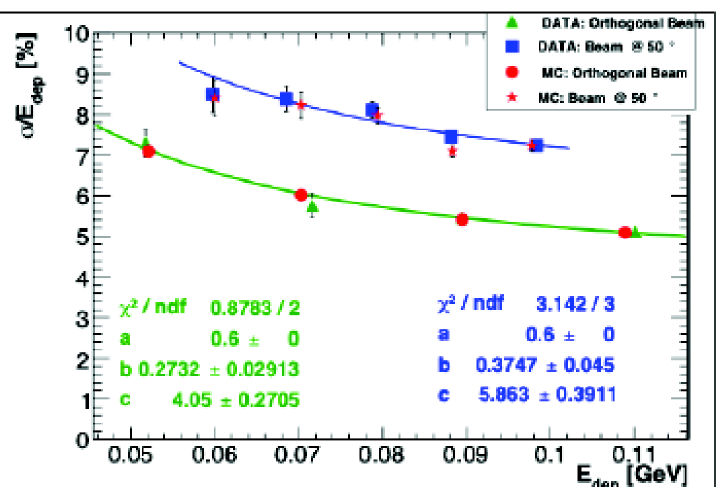
*Obtained for 1 sensor from the time difference of 2 sensors

Mu2e requirements satisfied

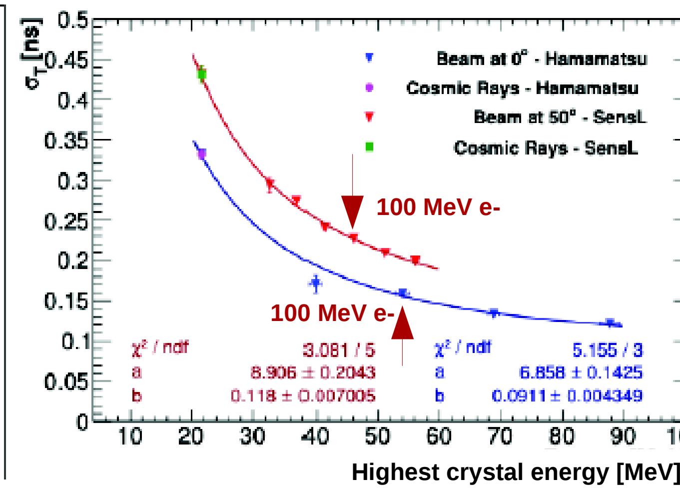
Energy profile



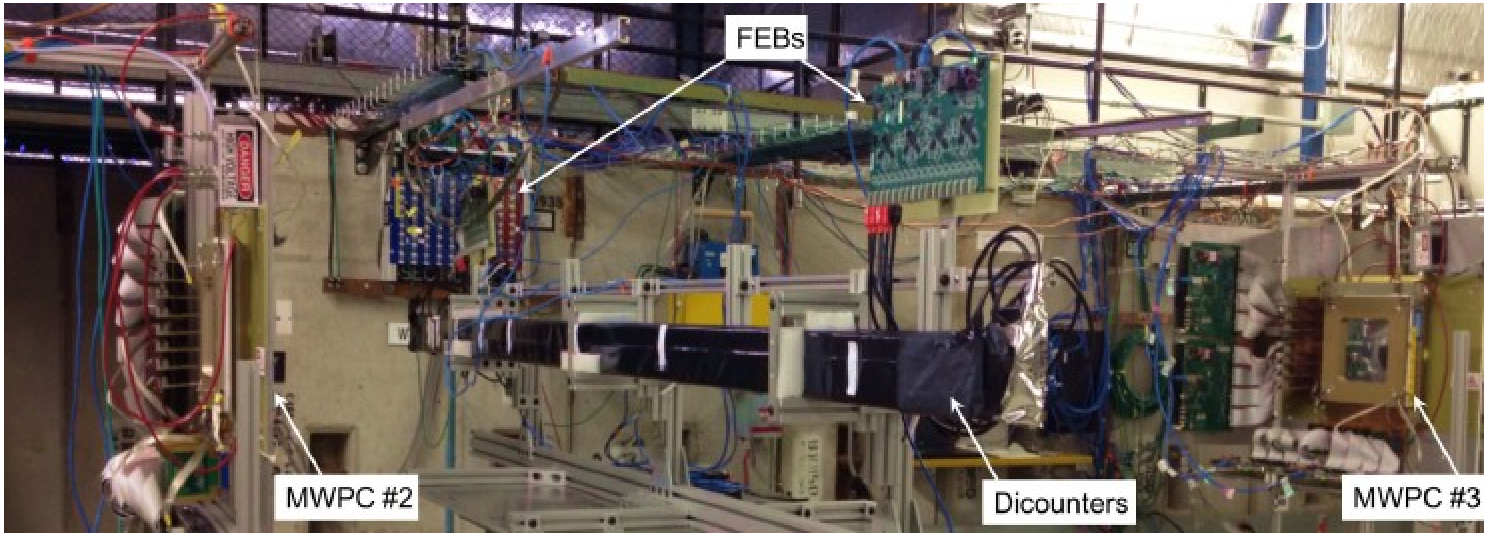
Energy resolution

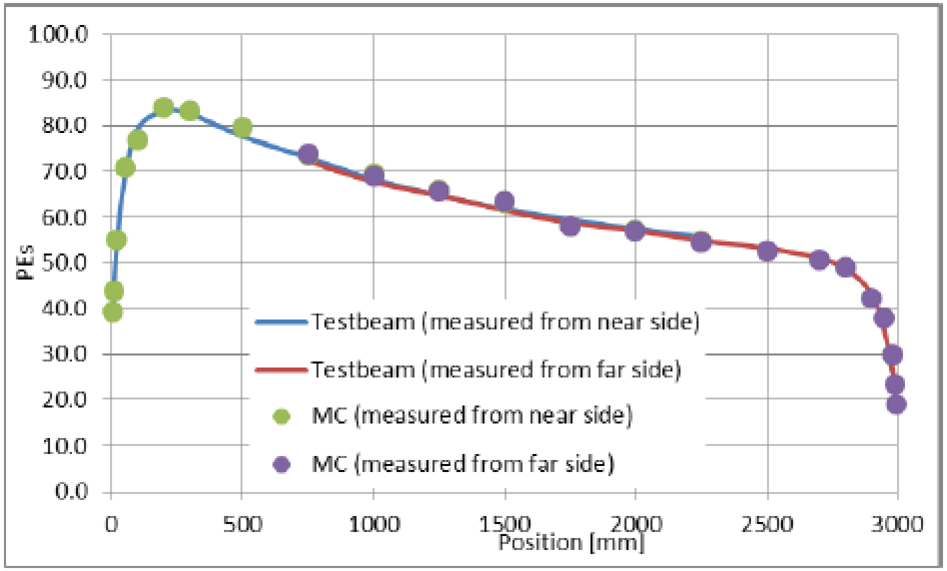


Time resolution



The Mu2e Experiment at Fermilab: cosmic veto





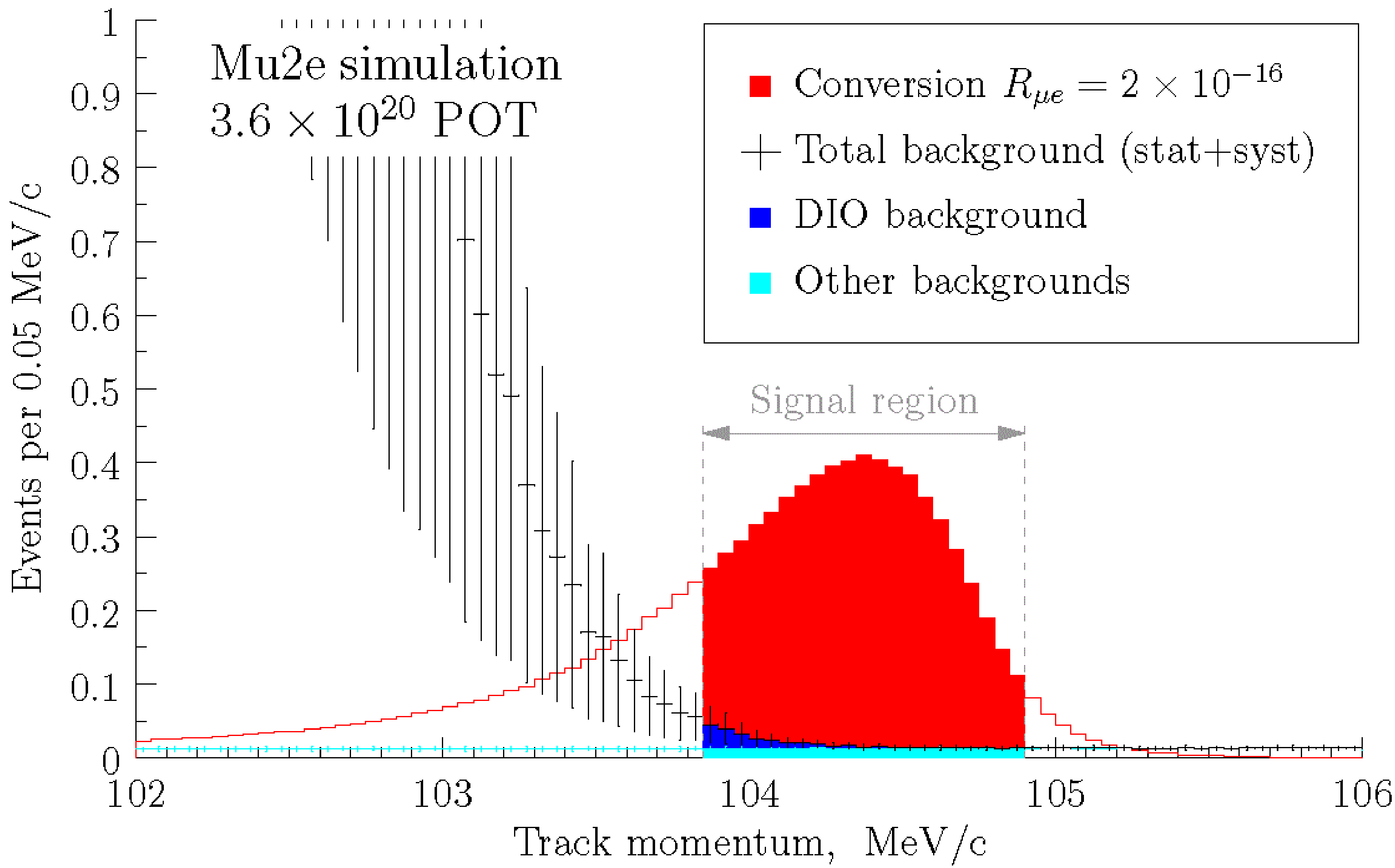
Light yield measured at Fermilab test beam

Efficiency compatible with Mu2e requirement: $1\text{-}\varepsilon \sim 10^{-4}$

Current Background estimate

Process	Expected event yield	Mitigation startegy
Cosmic rays	**0.209 ± 0.022 ± 0.055**	**Cosmic veto, PID**
Decay in orbit	**0.144 ± 0.028 ± 0.11**	**Momentum resolution**
Antiprotons	0.040 ± 0.001 ± 0.020	Absorbers
Rad. Pion captures	0.021 ± 0.001 ± 0.002	Delayed Analysis Window
Muon decay in flight	< 0.003	
Pion decay in flight	0.001 ± < 0.001	
Beam electrons	$(2.1 \pm 1.0) \cdot 10^{-4}$	
Rad. Muon captures	$0.000^{+0.004}_{-0.000}$	Kinematic end point
TOTAL	**0.41 ± 0.13(stat+syst)**	

Current sensitivity estimate



Discovery reach (5σ): $R_{\mu e} \geq 2 \cdot 10^{-16}$

Exclusion power (90% C.L.): $R_{\mu e} \geq 8 \cdot 10^{-17}$

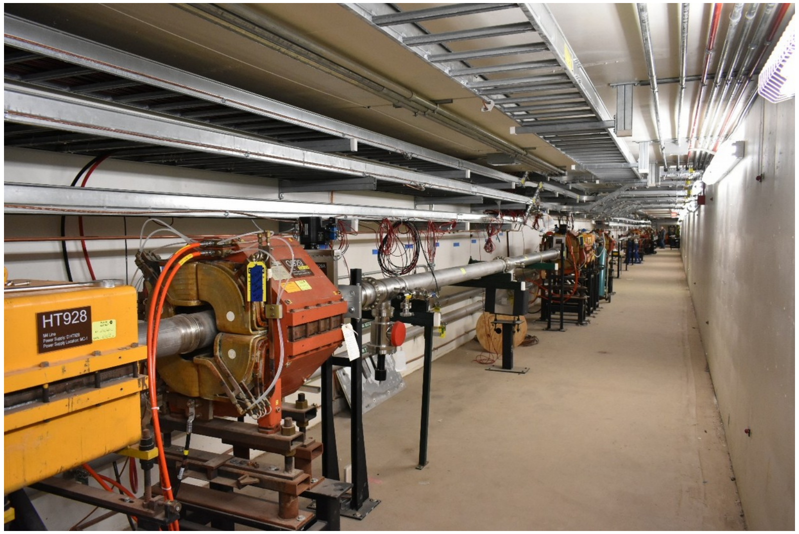
Mu2e status: detector hall

Mu2e status: detector hall

Mu2e status: beam line

M4 beamline completed up to the diagnostic absorber
First 8 GeV proton beam expected for April 2020

Final focus installation is in progress



M4 beam line

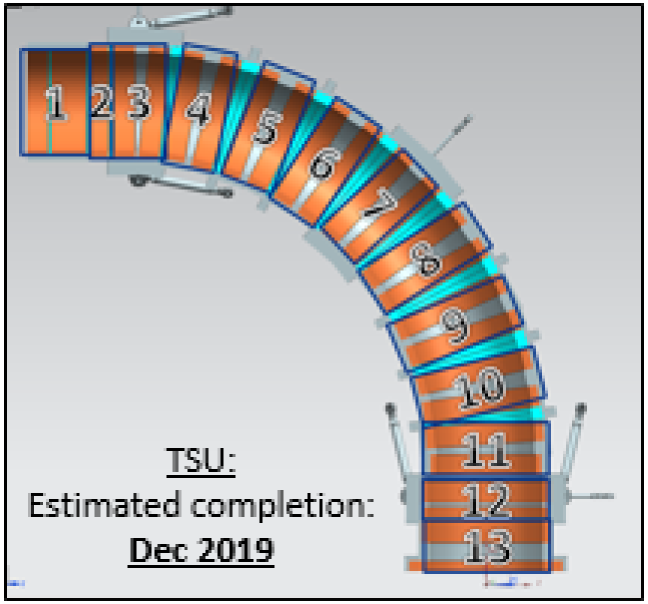
Diagnostic absorber wall

Final focus: large quadrupoles

Mu2e status: transport solenoid

TS Coils at ASG

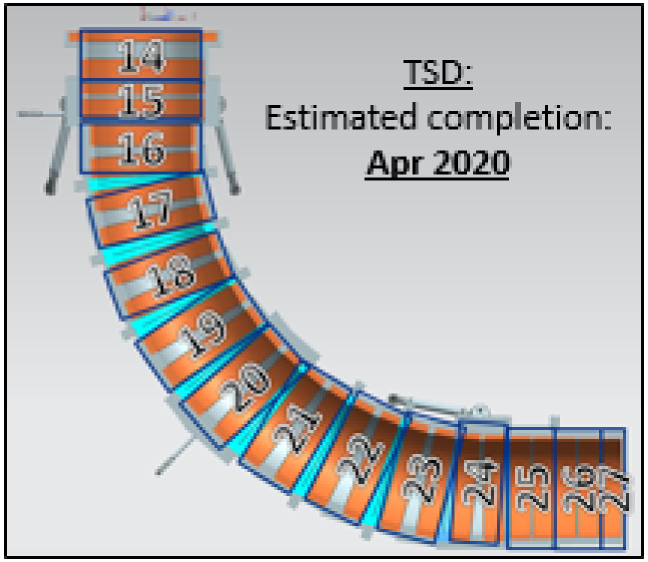
All coils wound at AGS (Genova, Italy)



Fermilab Test Facility

6/14 modules delivered to Fermilab

Under test at Fermilab Test Facility



Mu2e status: production/detector solenoid

In production at General Atomics (Tupelo, US)

First DS module completed! (244 turns 1 layer)

DS10 module

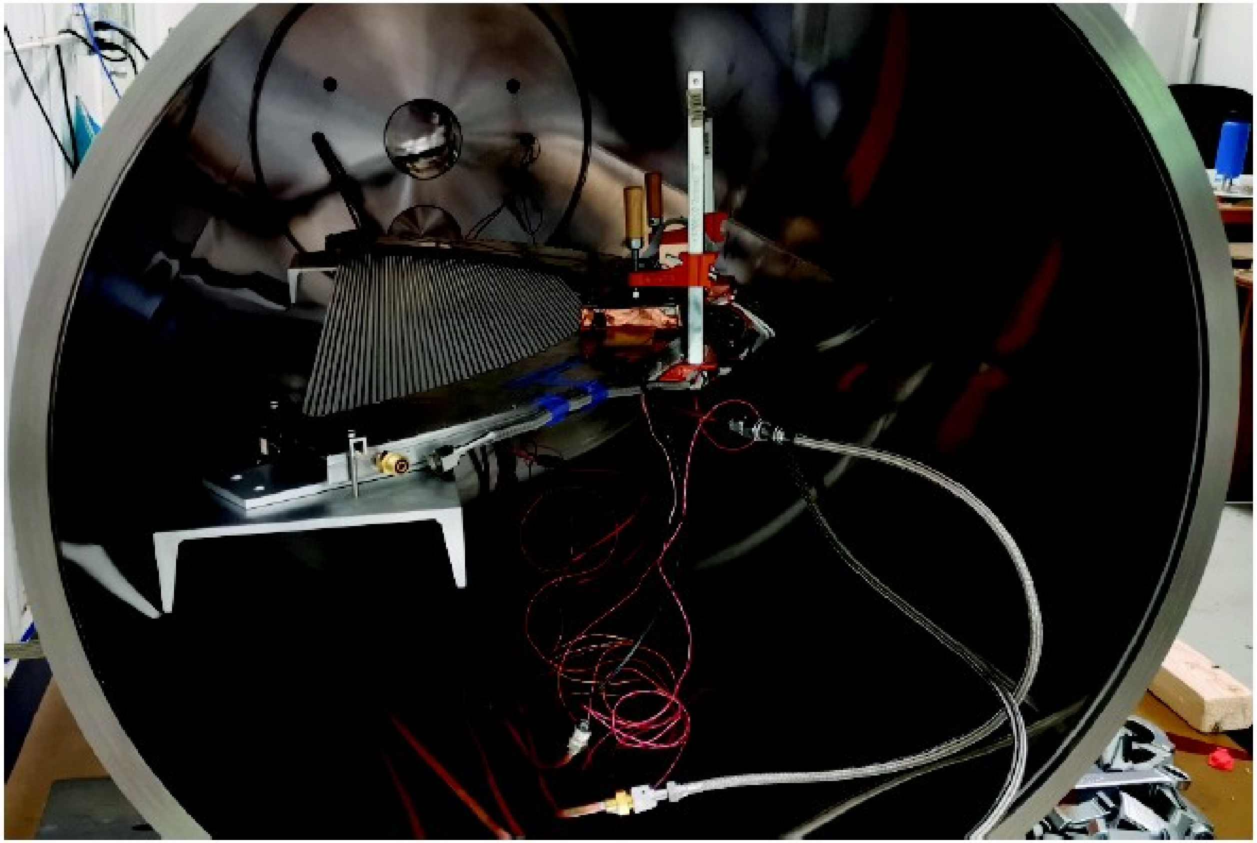
PS cryostat

DS cryostat

Mu2e status: tracker

All straws produced
15 pre-production panels built using final procedure
1 panel/day production starting

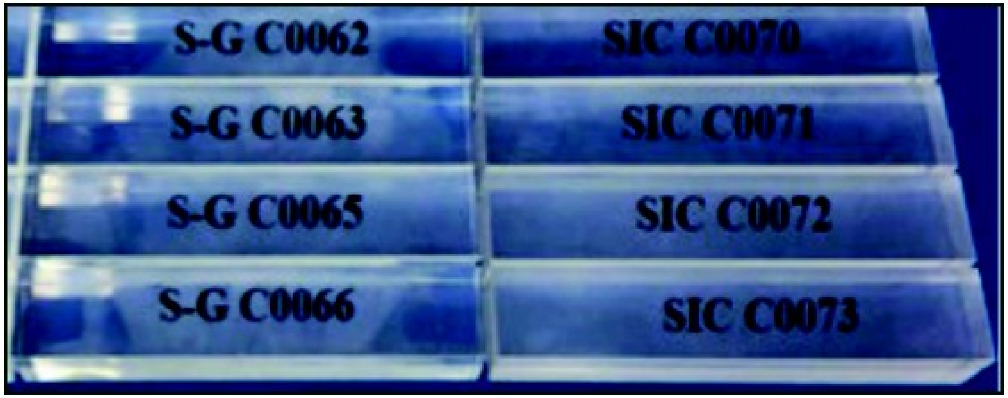
Panel assembly at U. of Minnesota



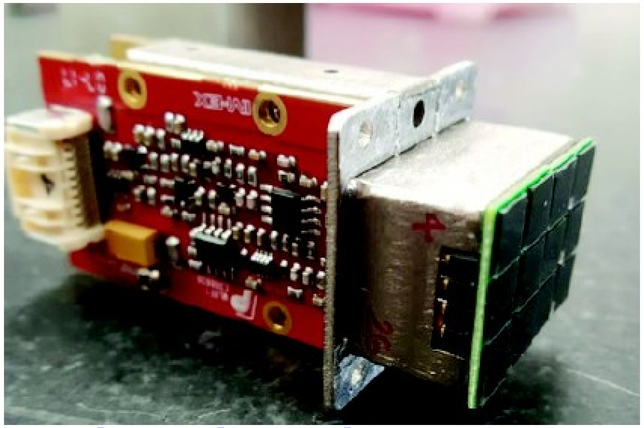
Panel vacuum test at Fermilab

Mu2e status: calorimeter

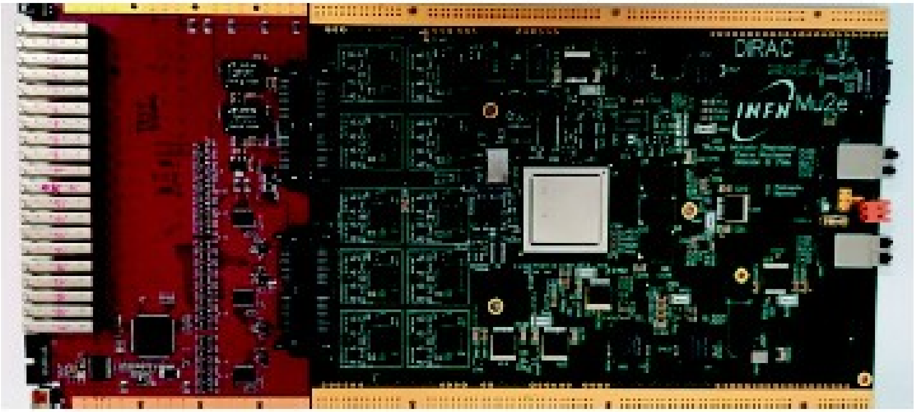
All SiPM delivered, QA test completed
1134/1450 crystals delivered and tested
Radiation hard electronics tested, starting production



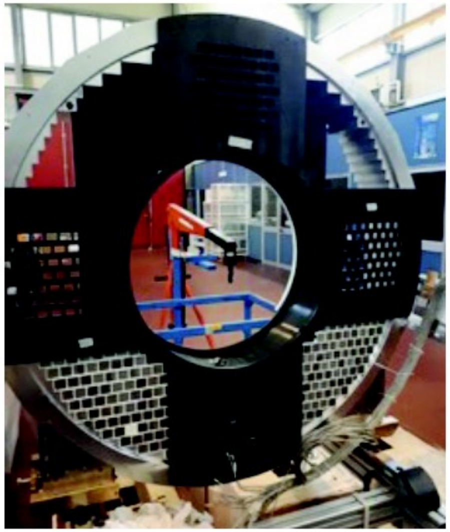
CsI crystals



FEE boards + SiPM arrays

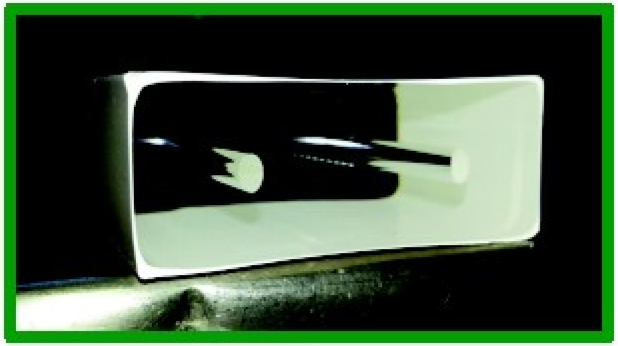


Voltage control and Digitizer board



Disk mechanical mockup

Mu2e status: cosmic ray veto



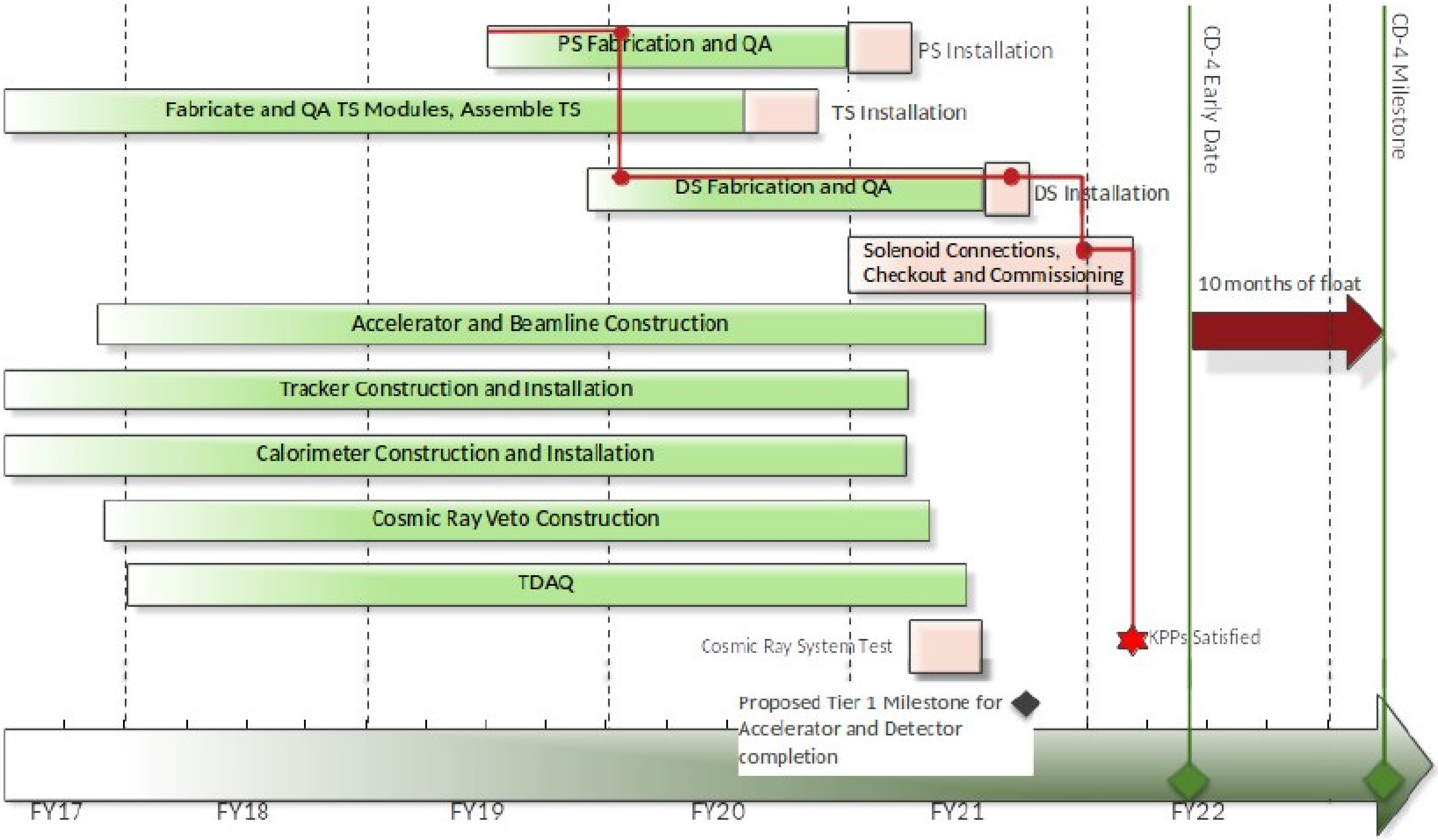
CRV counter

1229/2736 di-counters produced

5 pilot production modules completed and tested

4 layer module at U. of Virginia

Mu2e schedule



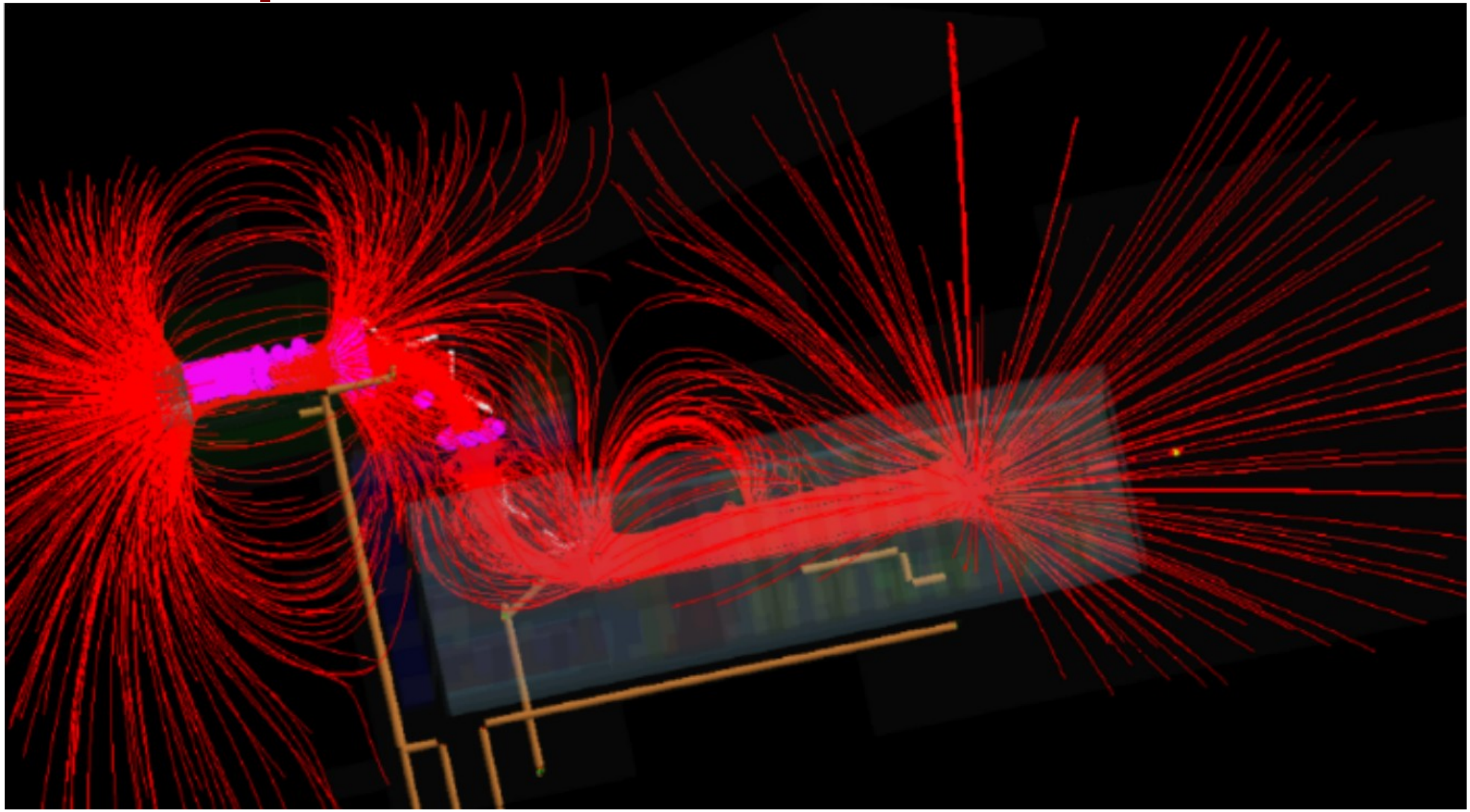
- Begin commissioning beam line: mid 2021
- Begin commissioning detector: early 2022
- First data taking: early-mid 2023
- Anticipate 4-5 years of run time for full data set (including calibration, ...)

Conclusion

- CLFV sensitivity in the muon sector is expected to be improved in the very next future by the experiments looking for $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$ or $\mu N \rightarrow eN$
- If a violation will be observed in one of these processes, it will be very important to have the complementary information from the other two to investigate the origin of the violation
- Mu2e will improve by 4 order of magnitudes the current world sensitivity on muon conversion to electron
- Prototypes test and simulation are confirming the design detector performances
- Construction of the beam line, solenoids and detectors is under way
- Expect to start physics data taking in 2023.

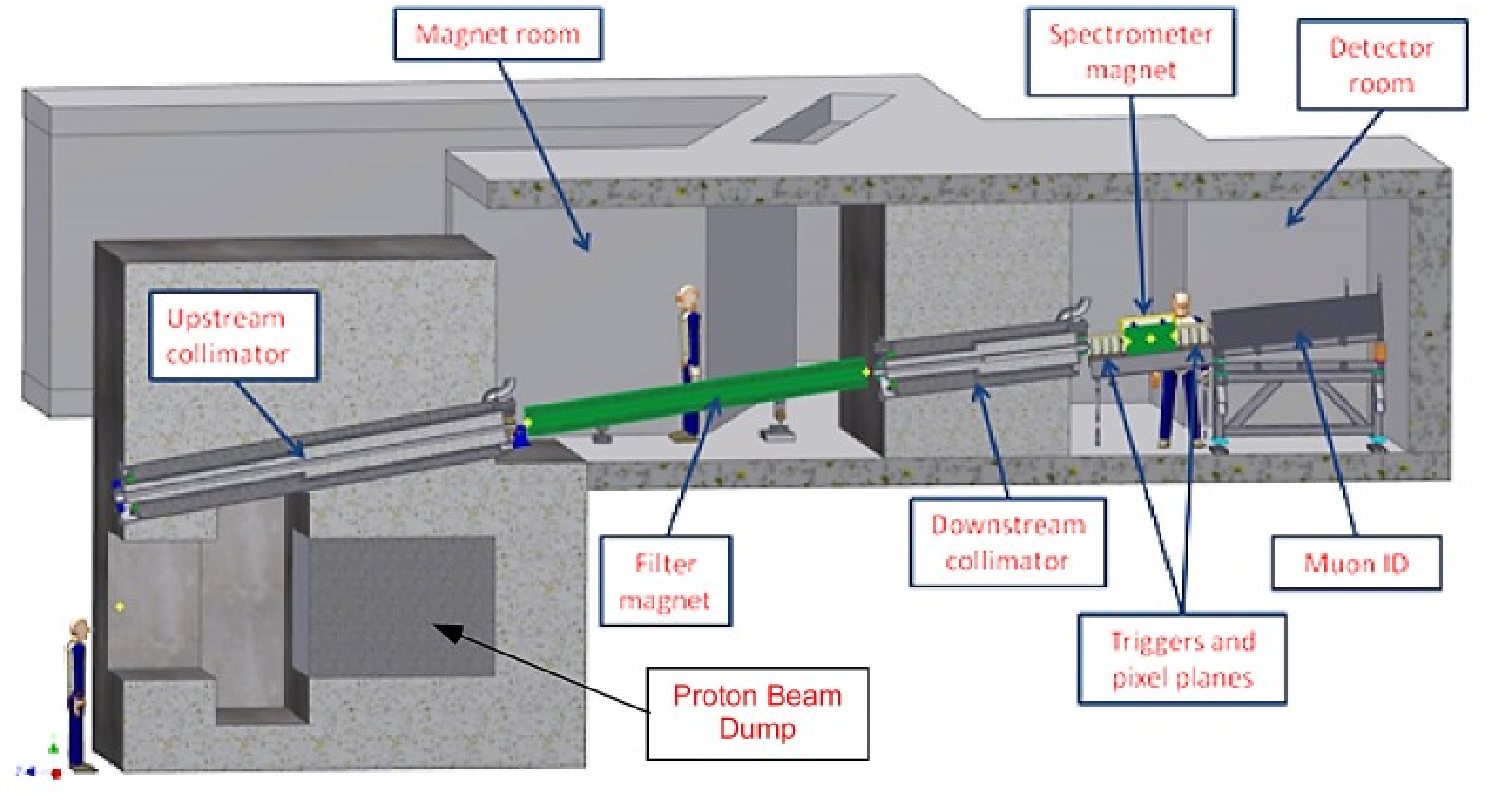
Backup

The Mu2e Experiment at Fermilab: the beam line



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

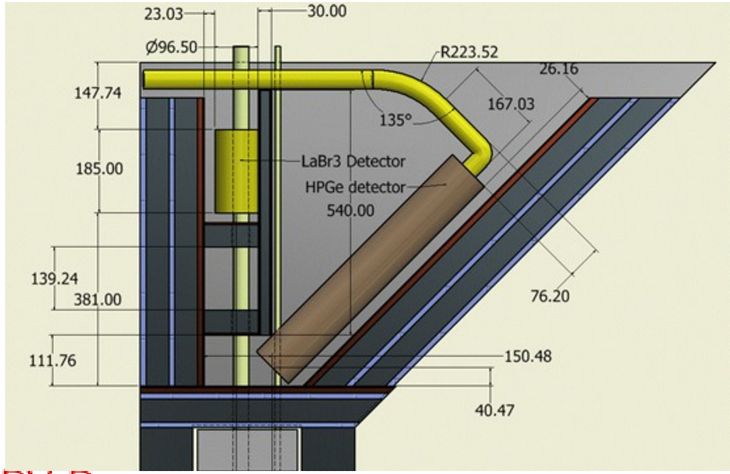
Extinction monitor

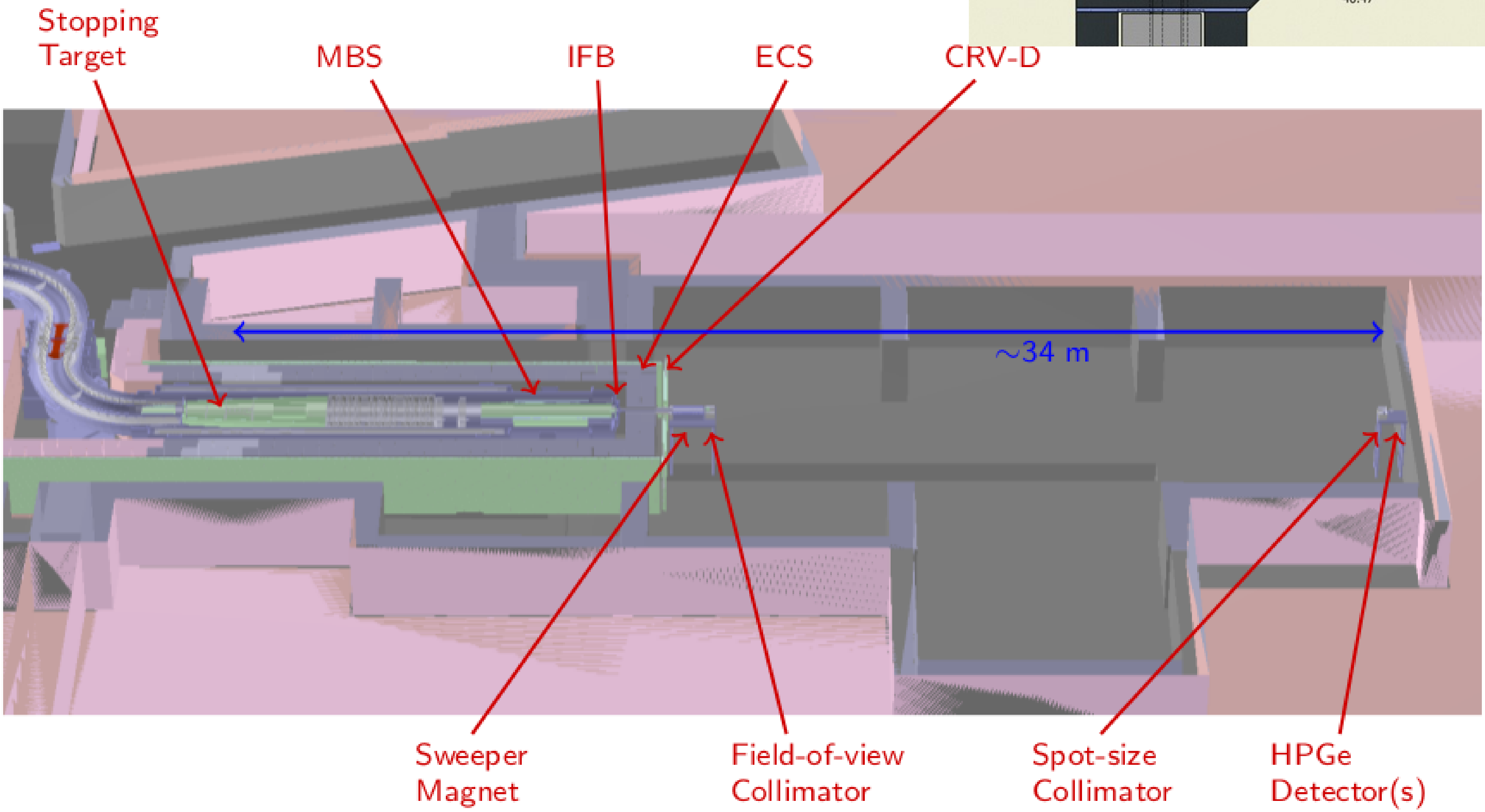


Validates the assumption of an extinction factor $<10^{-10}$

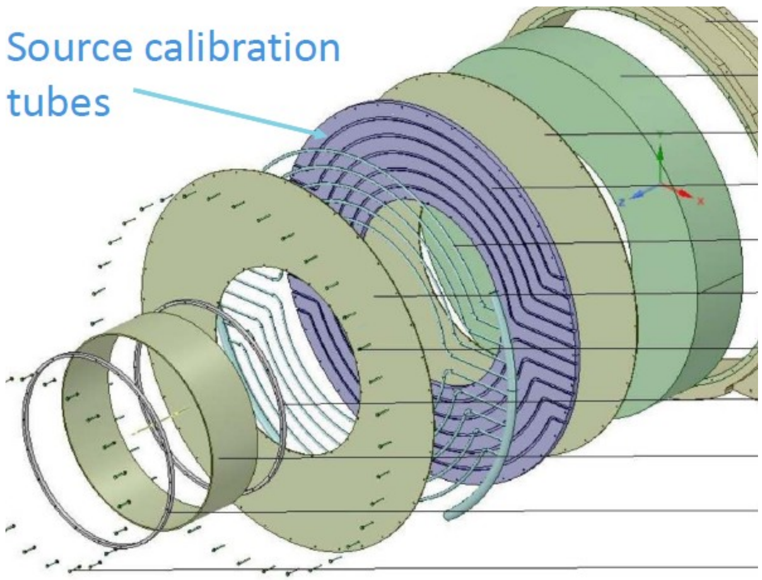
Stopping target monitor

Ge and LaBr detectors to detect the monochromatic X and γ rays produced by muon captures in Al with a statistical error <10%



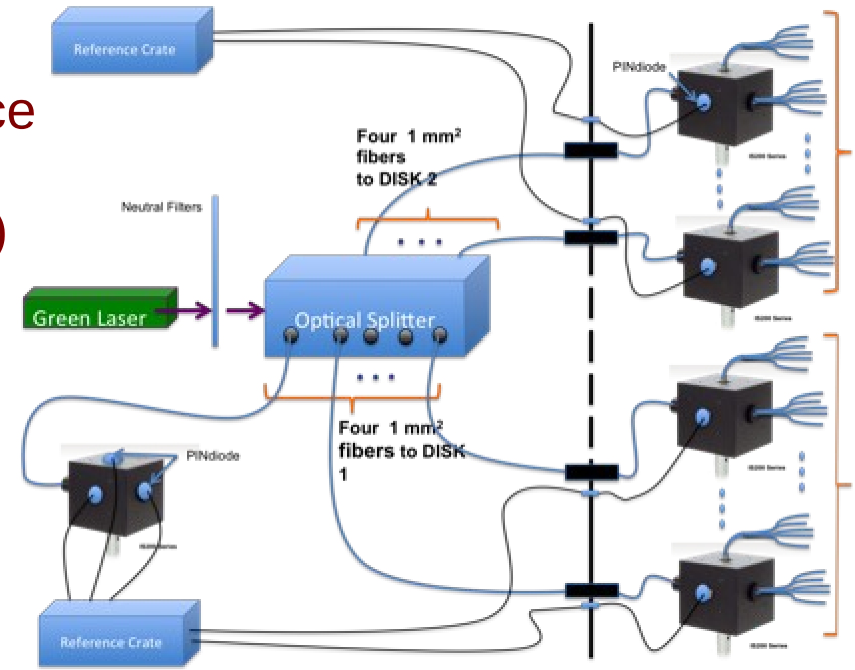


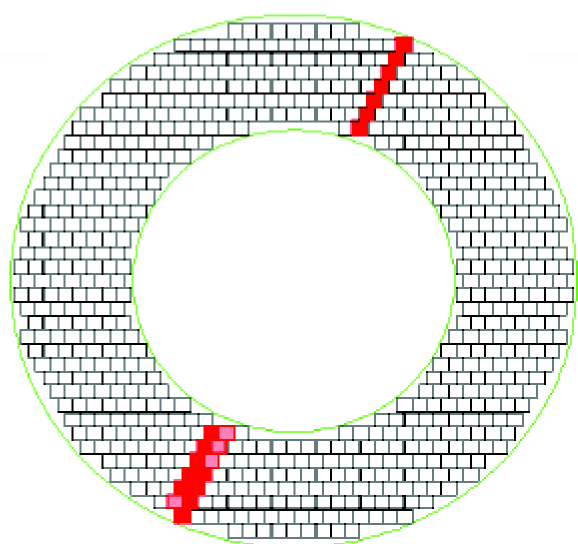
Calorimeter calibration



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

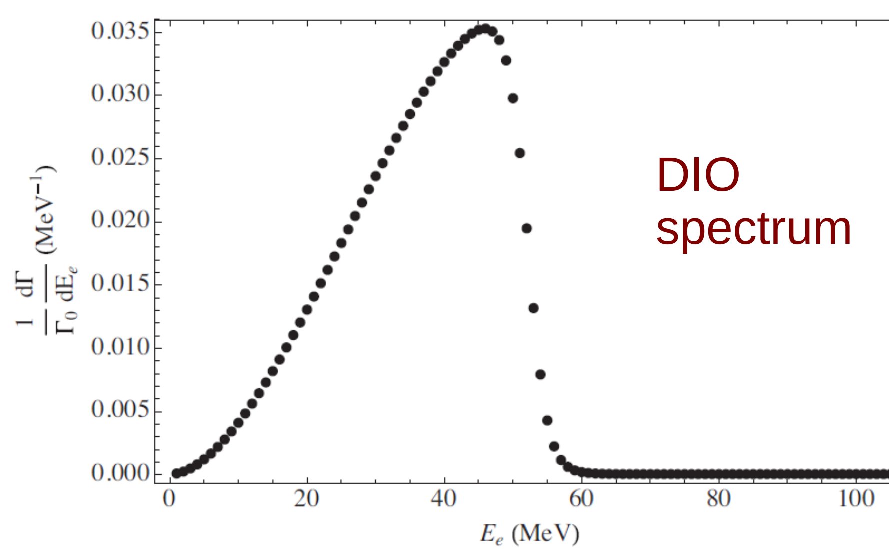
Laser pulses (energy and time Calibration)
FEE pulses
→



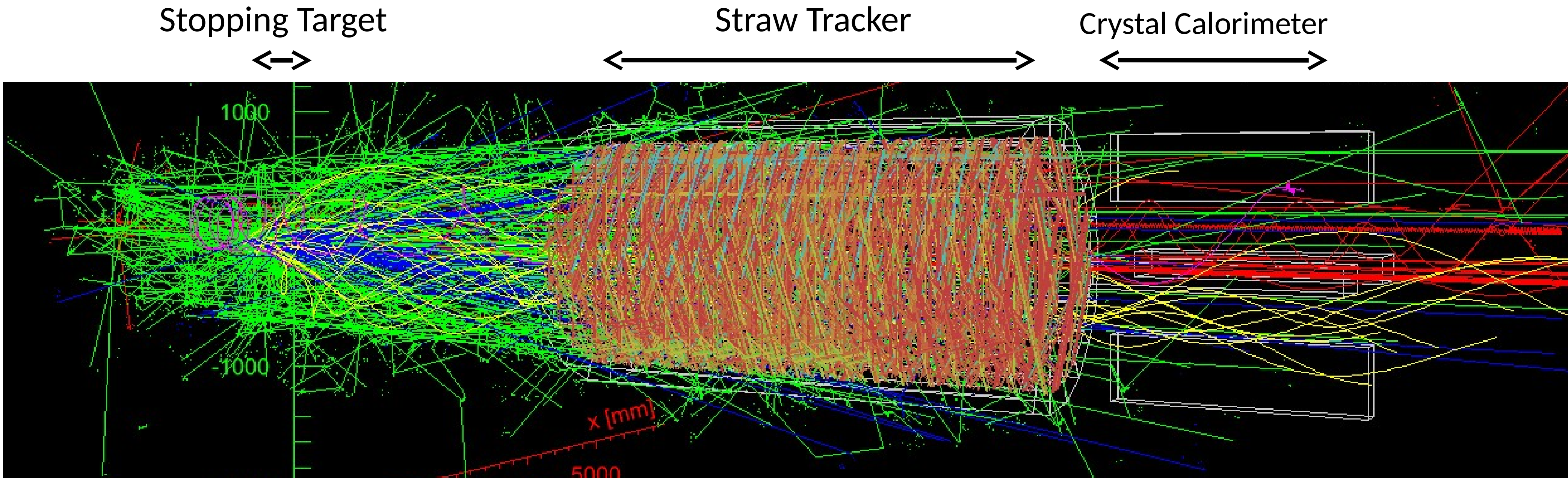


←
Cosmic muons (energy and time calibration)

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



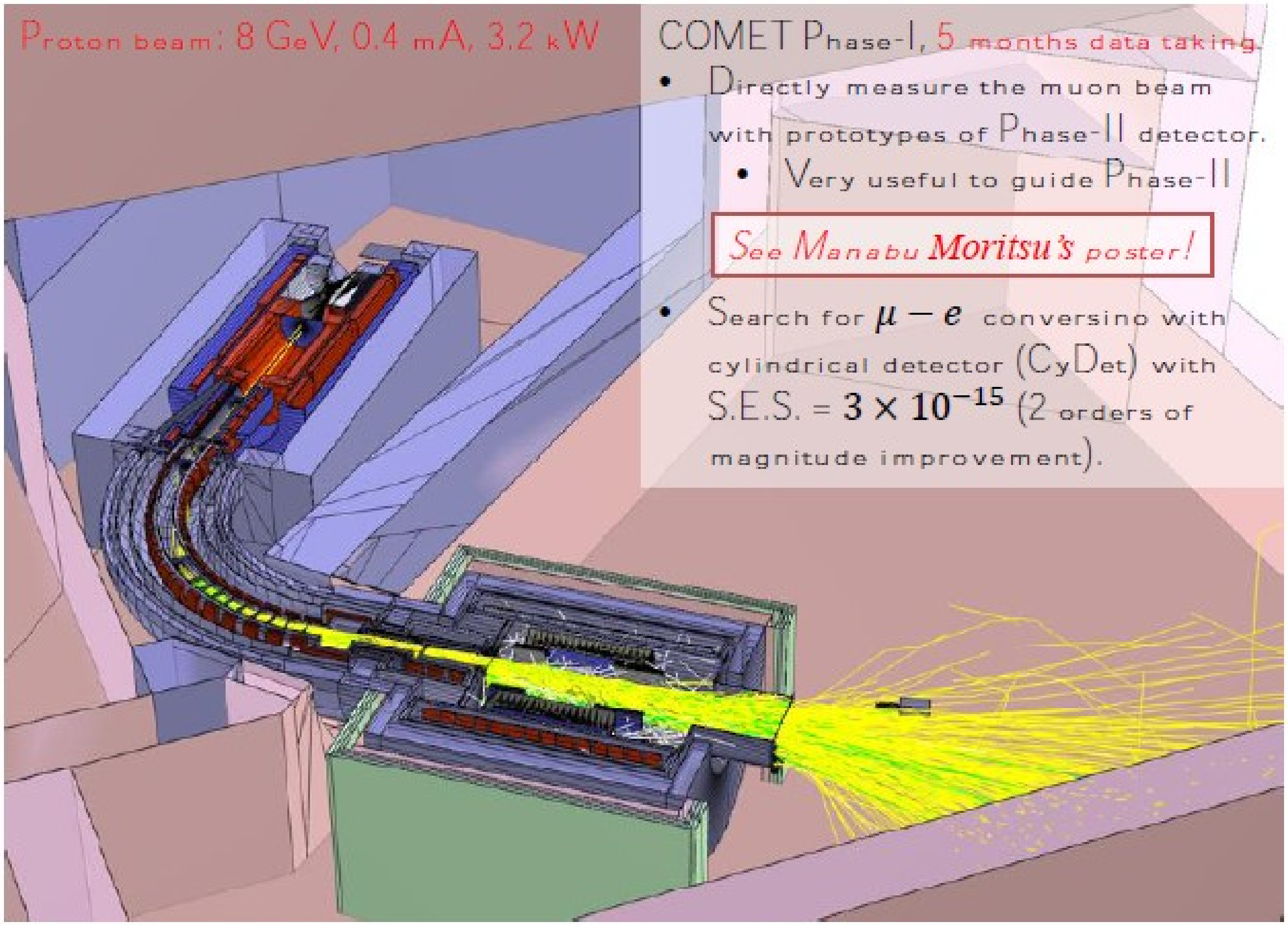
Mu2e track reconstruction

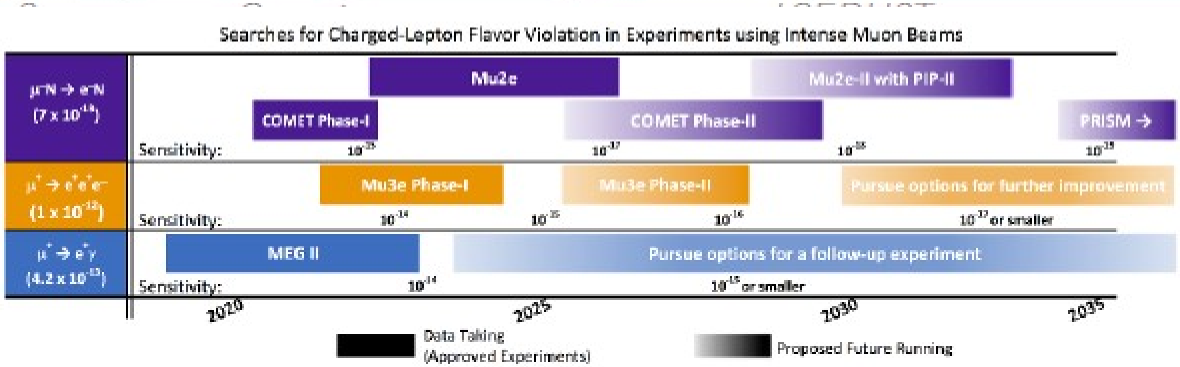


A typical Mu2e tracker event
integrated over the 500-1695 ns daq window

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

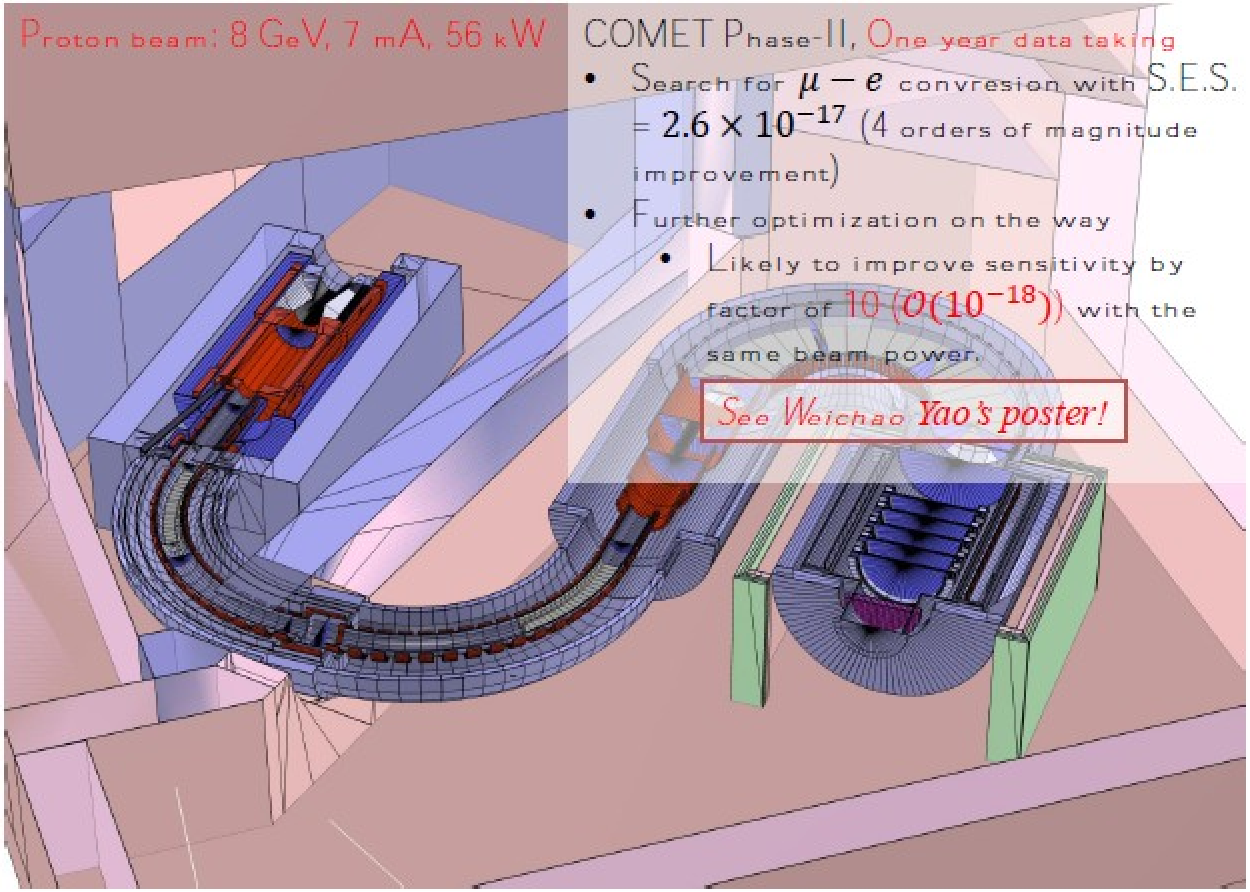
COMET Phase I

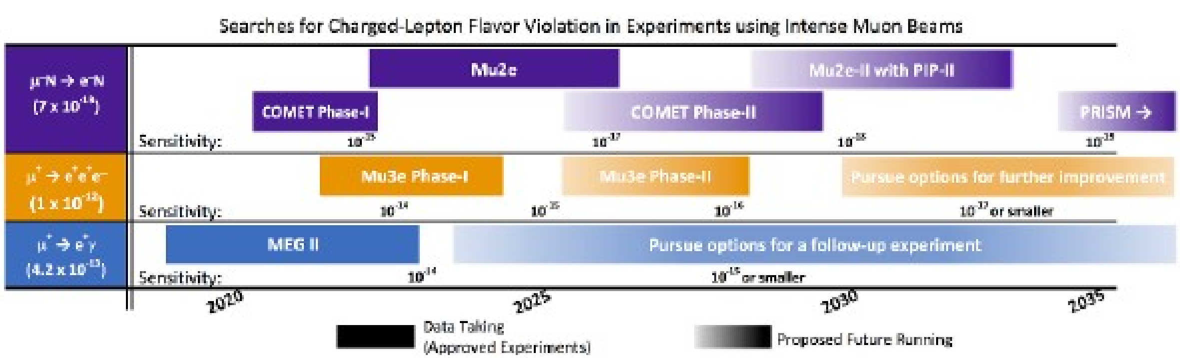




From Wu Chen's presentation at CLFV2019

COMET Phase II





From Wu Chen's presentation at CLFV2019