The Mu2e Experiment at Fermilab

Fabio Happacher, LNF-INFN

On behalf of the Mu2e Collaboration

INFN
Istituto Nazionale
di Fisica Nucleare
Laboratori Nazionali di Frascati

Presentation outline

- Why Mu2e
- Experimental technique
- Accelerator complex
- Detectors layout with a zoom into the calorimeter
- Status of Mu2e
- Conclusions

What is Mu2e?

- A search for Charged-Lepton Flavor Violation via

$$\mu^- N \rightarrow e^- N$$

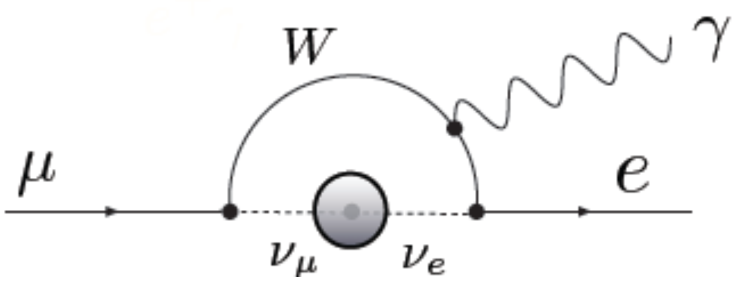
- Will use *current* Fermilab accelerator complex to reach a sensitivity 10 000 better than current world's best
- Will have *discovery* sensitivity over broad swath of New Physics parameter space
- Mu2e will detect the electron coming from the decay of a muon in the field of a nucleus with respect to standard muon capture

$$R_{\mu e} = \frac{\mu^- Al \rightarrow e^- Al}{\mu^- Al \rightarrow capture} < 6 \times 10^{-17} \; (90\% \; C.L.)$$

$\mu^- N \to e^- N$

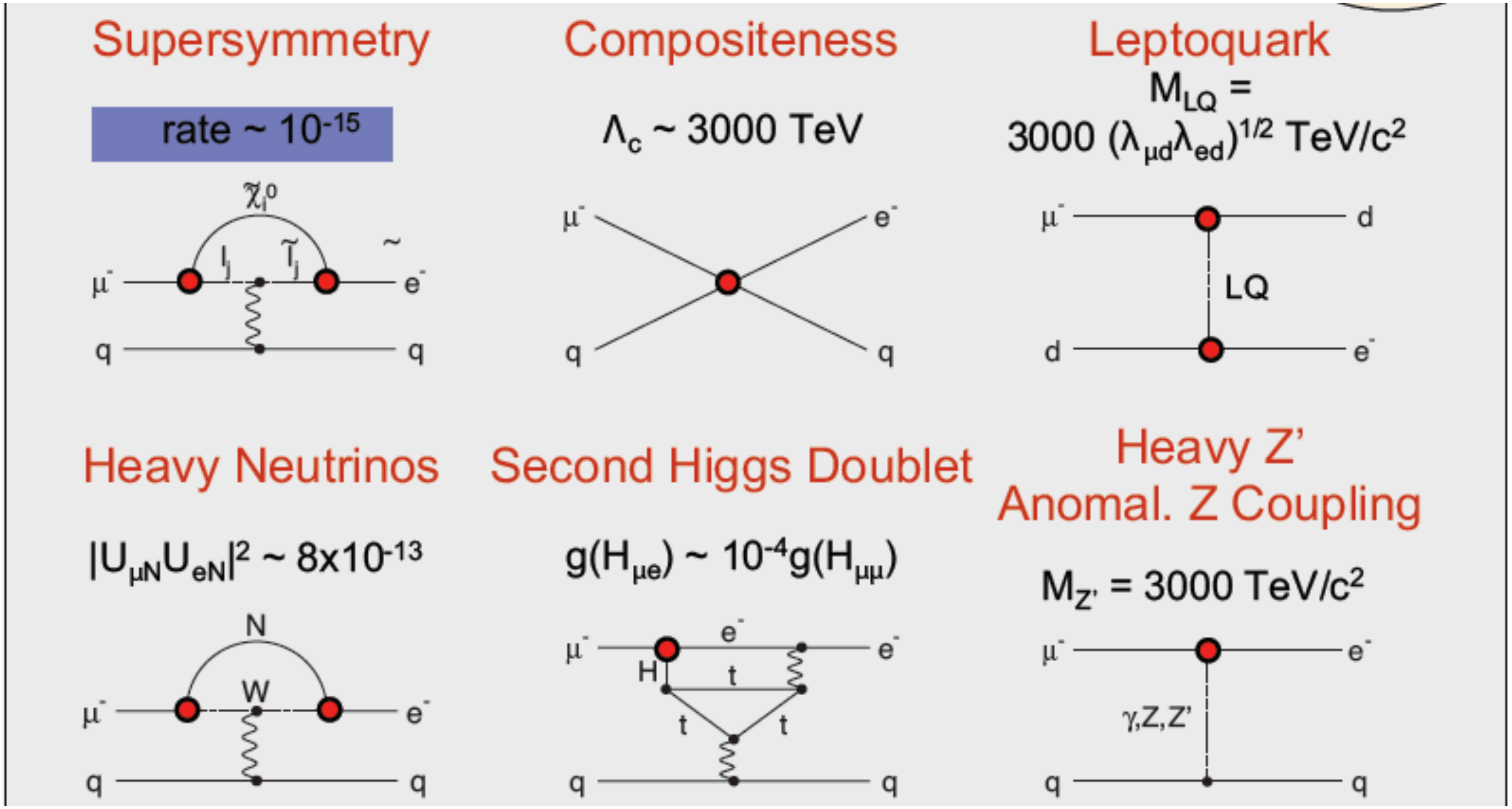
- Muon-to-electron conversion is similar but complementary to other CLFV processes as μ→ eγ and μ → 3e.
- The Mu2e experiment searches for muon-to-electron conversion in the coulomb field of a nucleus: $\mu^- Al \to e^- Al$
- CLFV processes are strongly suppressed in the Standard Model
  - it is not forbidden due to neutrino oscillations
  - In practice BR($\mu \to e\gamma$) ~ $\Delta m_\nu^2 / M_W^2 < 10^{-54}$

    is negligible



- New Physics could enhance CLFV rates to observable values
- A detected signal from Mu2e would be clear evidence of physics beyond the SM, NP, Susy, Compositeness, Leptoquark, Heavy neutrinos, Second Higgs Doublet, Heavy Z'

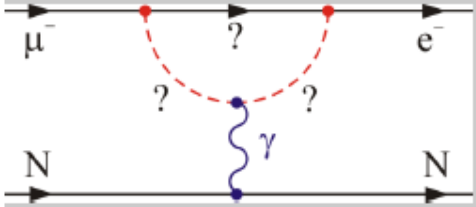
μ conversion is sensitive to wide array of NP models



Mu2e Sensitivty

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

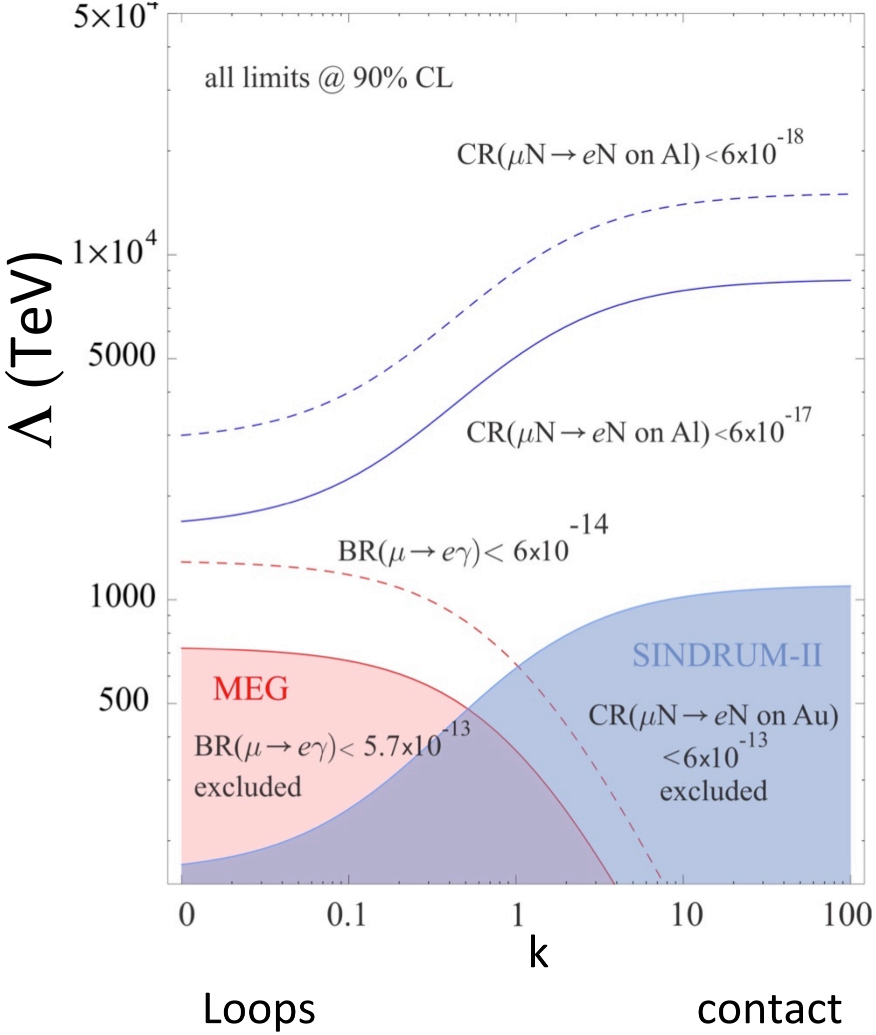
Loops



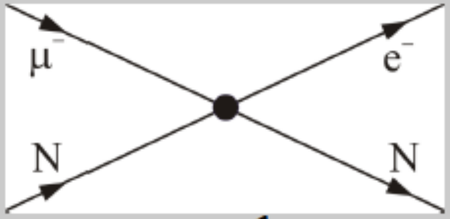
κ<< 1

magnetic moment type operator

μ→ eγ rate ~300X μN → eN rate



Contact Interactions



κ>> 1

four-fermion interaction

μN→ eN rate >> μ→ eγ rate

Mu2e Sensitivity best in all scenarios

Mu2e operating principle

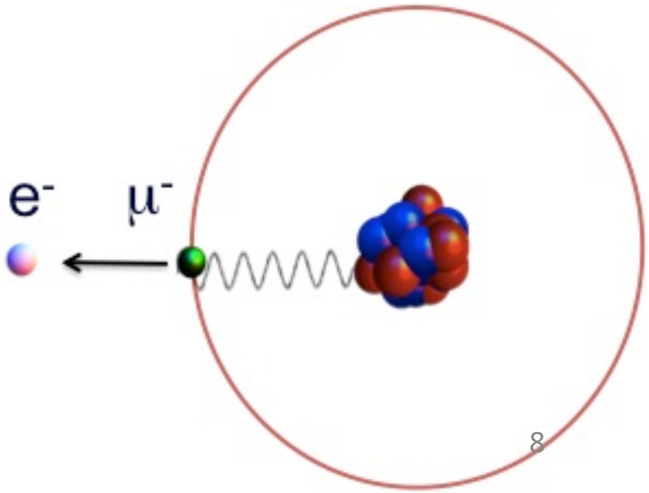
- Generate a intense beam (10^{10}/s) of low momentum (p_T<100 MeV/c) negative μ
- Stop the muons in a target
  - Mu2e plans to use Aluminum
  - Sensitivity goal requires ~10^{18} stopped muons
  - 10^{20} protons on target (2 year run – 2×10^7 s)
- The stopped muons are trapped in orbit around the nucleus
  - In orbit around aluminum: $\tau_\mu^{Al} = 864$ ns
  - Large τ_μ^N important for discriminating background
- Look for events consistent with $\mu N \rightarrow eN$

Mu2e Signal

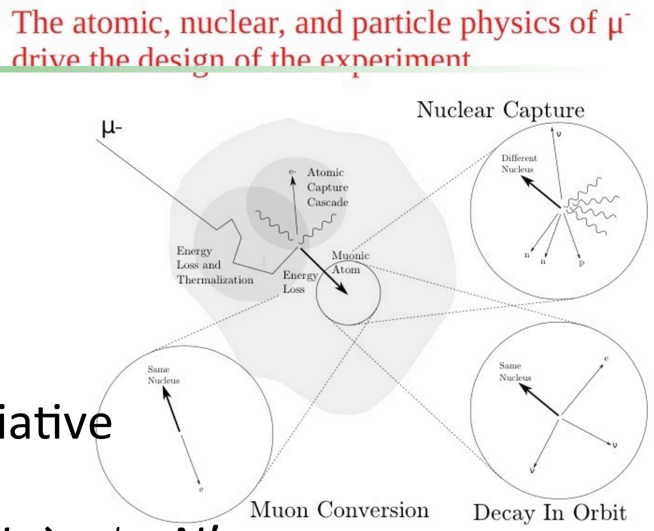
μ^{-}' s captured in the stopping target falls to a 1S bound state giving origin to:

- The muon decays in orbit (DIO): $\mu^{-} + Al \rightarrow e^{-}\bar{\nu}_{e}\nu_{\mu} + Al$ (40%)
- Muon capture: the wave function of muons and nuclei overlap, the nucleus can trap the muon: $\mu^{-} + Al \rightarrow \nu_{\mu} + Mg$ (60%)

  generating a flux of p,n and γ
- Neutrinoless muon to electron conversion $\mu^{-} + Al \rightarrow e^{-} + Al$
  - Results in an electron of 104.97 MeV
  - $$E_{CE} = m_{\mu}c^{2} - B_{\mu}(Z=13) - C_{\mu}(A=27)$$
    - M_{μ} muon mass, 105.66 MeV/c^2
    - B_{μ} binding energy of a muon in the 1S orbit of Al, 0.48 MeV
    - C_{μ} nuclear recoil of Al, 0.21 MeV



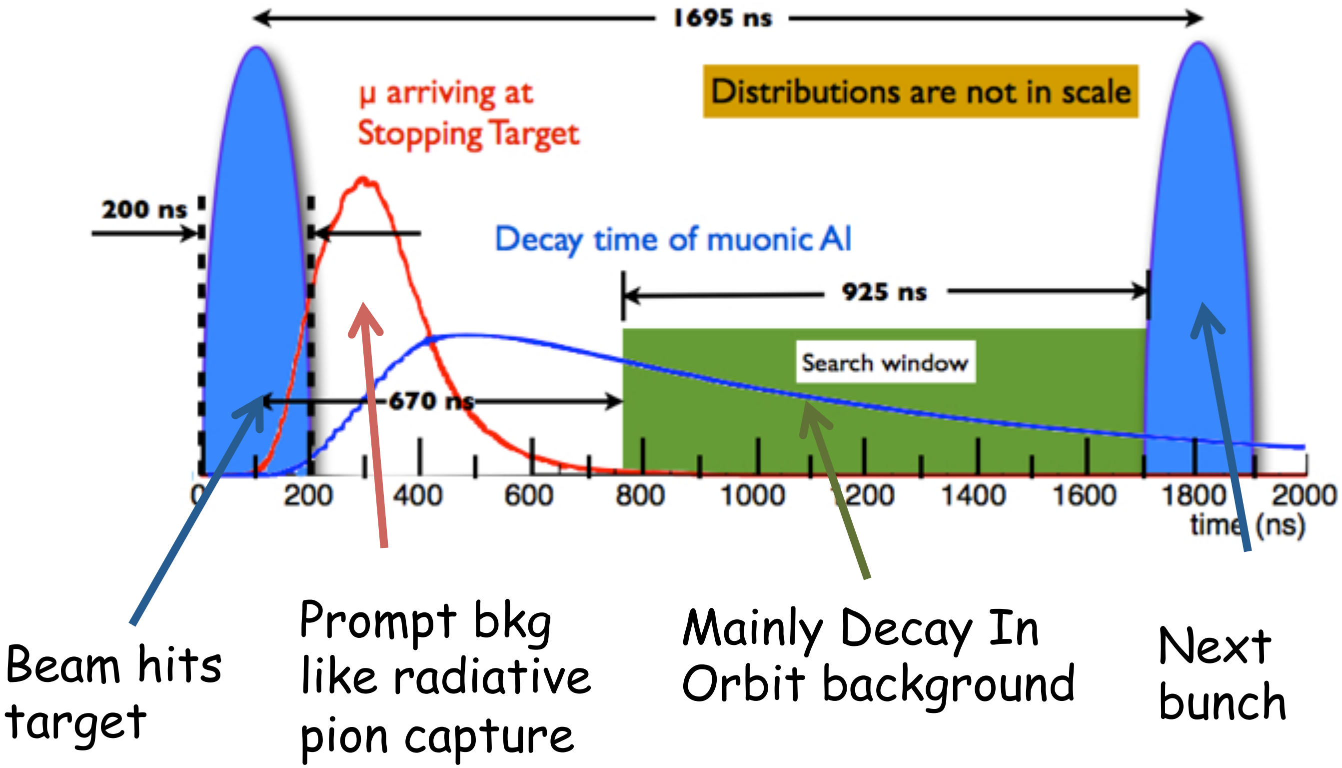
Backgrounds to deal with


The atomic, nuclear, and particle physics of μ^- drive the design of the experiment

- Muon decay in orbit (DIO)
- Radiative muon capture
- Pions from the muon beam can undergo radiative capture (RPC) $\pi^- N \rightarrow \gamma N'$, $\gamma \rightarrow e^+e^-$ and $\pi^- N \rightarrow e^+e^- N'$
- Antiprotons: produce pions when they annihilate in the target: are negative and they can be slow
- Pion/muon decay in flight
- Electrons from beam
- Cosmic rays

Category	Source	Events
Intrinsic	μ Decay in Orbit	0.20
	Radiative μ Capture	<0.01
Late Arriving	Radiative π Capture	0.02
	Beam electrons	<0.01
	μ Decay in Flight	<0.01
	π Decay in Flight	<0.01
Miscellaneous	Anti-proton induced	0.05
	Cosmic Ray induced	0.10
Total Background		0.37

Beam structure

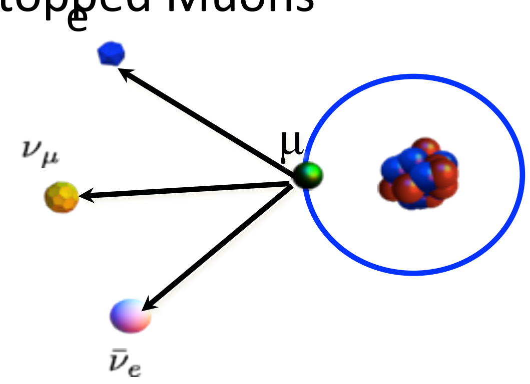


- ☐ **Use the fact that muonic atomic lifetime >> prompt background**
  Need a pulsed beam to wait for prompt background to reach acceptable levels
  → Fermilab provides the beam we need !

- ☐ **OUT of time protons are also a problem->prompt bkg arriving late…**
  To keep associated background low we need proton extinction of 10^{-10} :
  proton extinction (between pulses) → # protons out of beam/# protons in pulse

Muon from decay in orbit: DIO

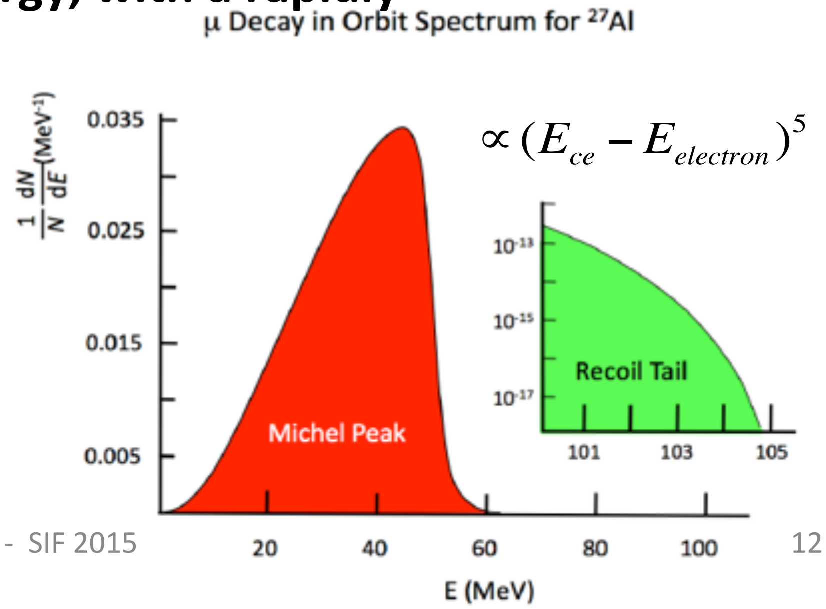
- The most sneaky source of background comes from Stopped Muons



$$[\mu^- + A(N,Z)]^{1S}_{bound} \rightarrow A(N,Z) + e^- + \bar{\nu}_e + \nu_\mu$$

- Electrons from decay of bound muons (DIO)
- If the neutrinos are at rest the e^- can have exactly the conversion energy E_{CE}=104.97 MeV
- **Recoil tail extends to conversion energy, with a rapidly falling spectrum near the endpoint**

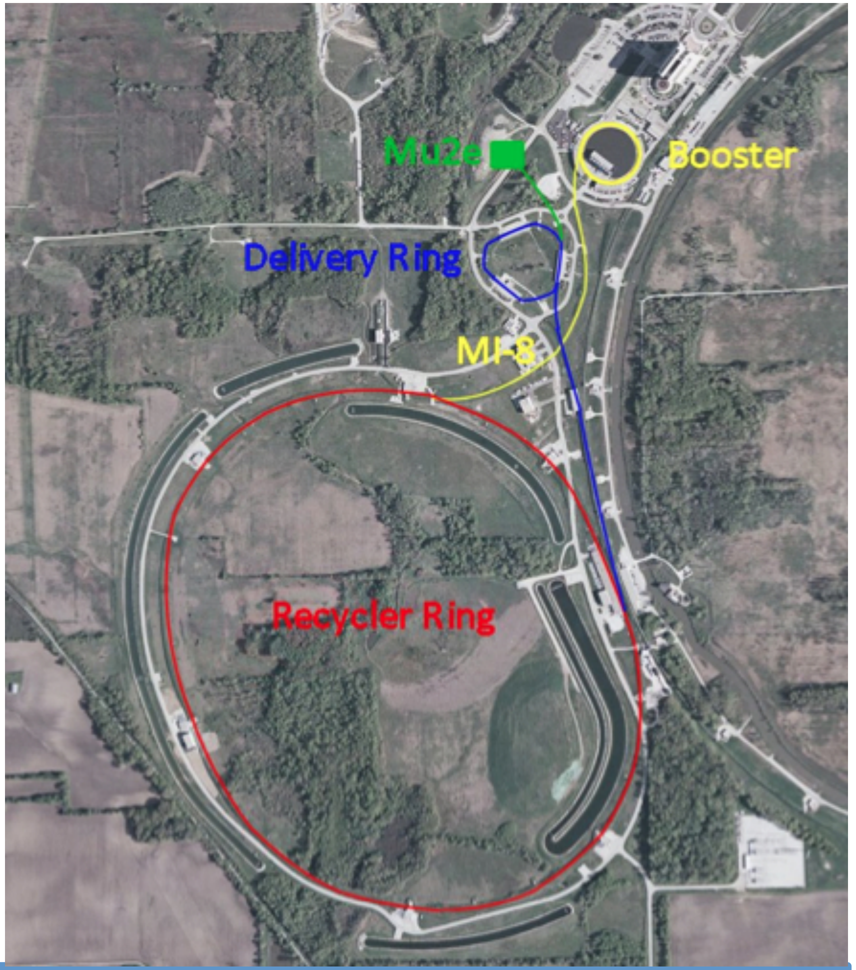
$$E_{\max} = \frac{m_\mu^2 + m_e^2}{2m_\mu} \approx 52.8 \text{ MeV}$$


μ Decay in Orbit Spectrum for ^{27}Al

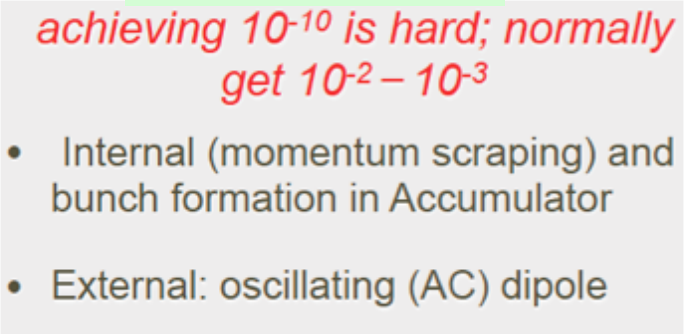
$$\propto (E_{ce} - E_{electron})^5$$

Accelerator Scheme & Proton extinction

- Booster: batch of 4×10^{12} protons every 1/15th second
- Booster "batch" is injected into the Recycler ring and re-bunched into 4 bunches
- These are extracted one at a time to the Delivery ring
- As a bunch circulates, protons are extracted to produce the desired beam structure → **bunches of ~$3\text{x}10^7$ protons each, separated by 1.7 μs**



Proton Extinction



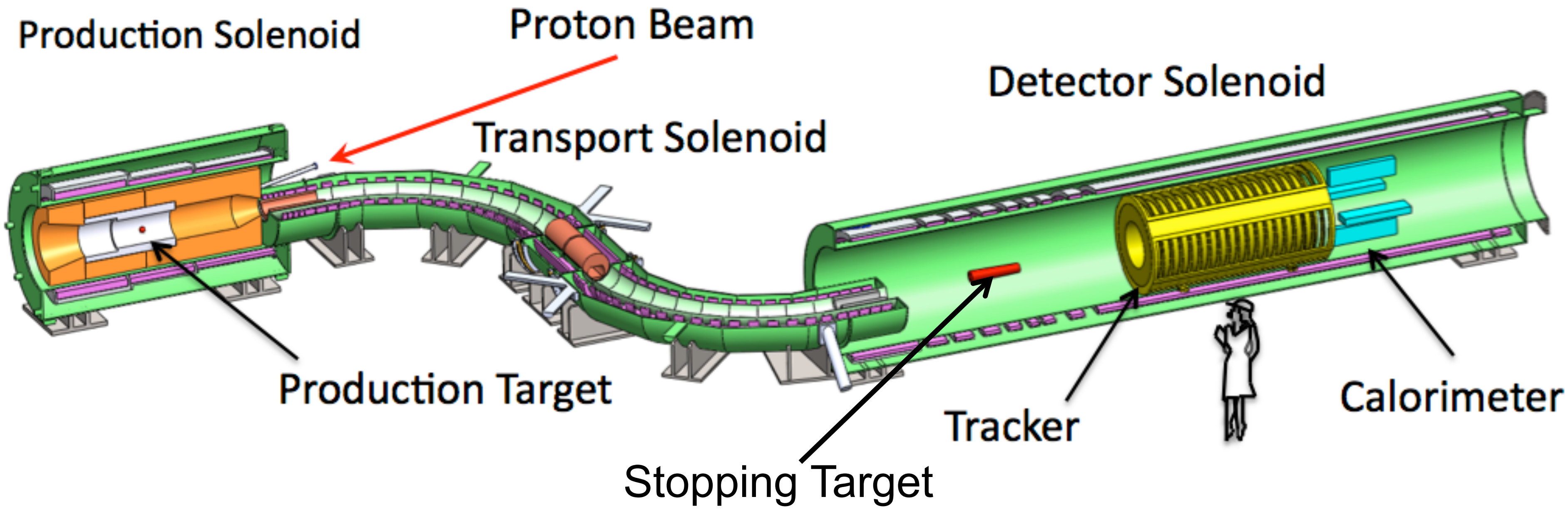
achieving 10^{-10} is hard; normally get $10^{-2} – 10^{-3}$

- Internal (momentum scraping) and bunch formation in Accumulator
- External: oscillating (AC) dipole

Calculations based on accelerator models
That take into account collective effects
Shows that this combination gets ~ 10^{-12}

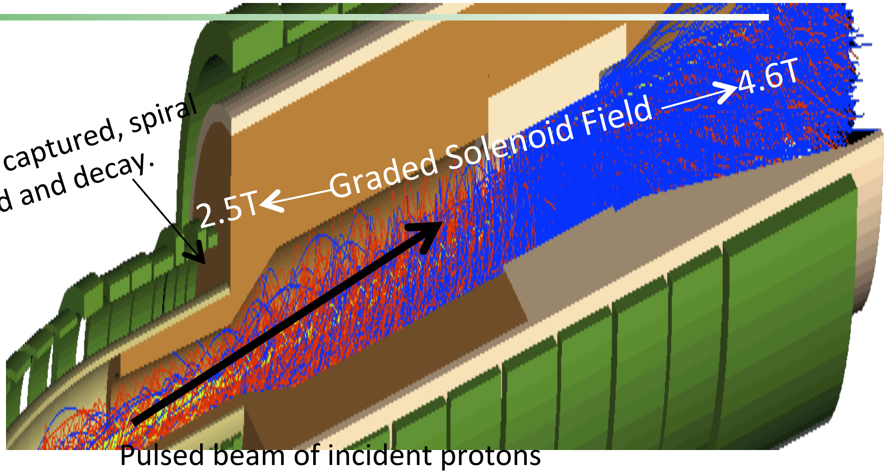
The Mu2e beamline

- Mu2e Solenoid System
  - Superconducting
    - Requires a cryogenic system
  - Inner bore evacuated to 10^{-4} Torr to limit background due to interactions of the charged particles with air



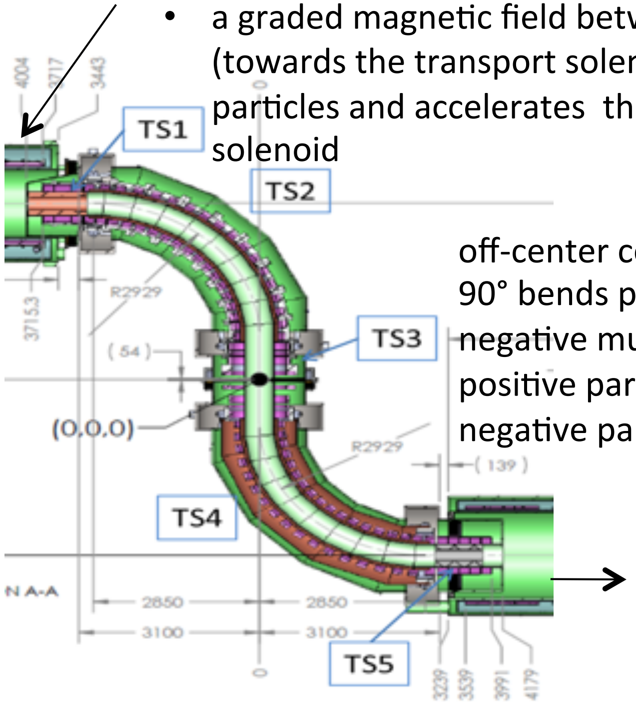
The Mu2e beamline

- Production Solenoid
  - Pulsed proton beam coming from Debuncher hit the target
    - 8 GeV protons
    - every 1695 ns / 200 ns width
  - Production target
    - tungsten rod, 16 cm long with a 3 mm radius
    - produces pions
  - Solenoid
    - a graded magnetic field between 4.6 T (at end) and 2.5 T (towards the transport solenoid) traps the charged particles and accelerates them toward the transport solenoid



π's are captured, spiral around and decay.

Pulsed beam of incident protons

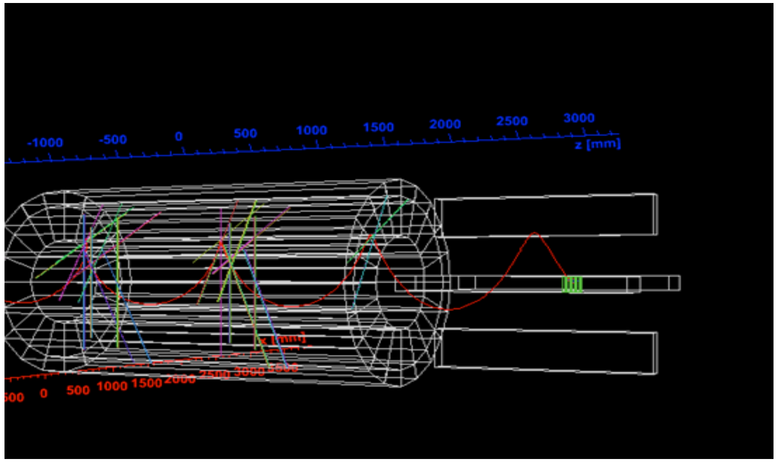


off-center central TS collimator and 90° bends passes low momentum negative muons and suppresses positive particle and high momentum negative particles.

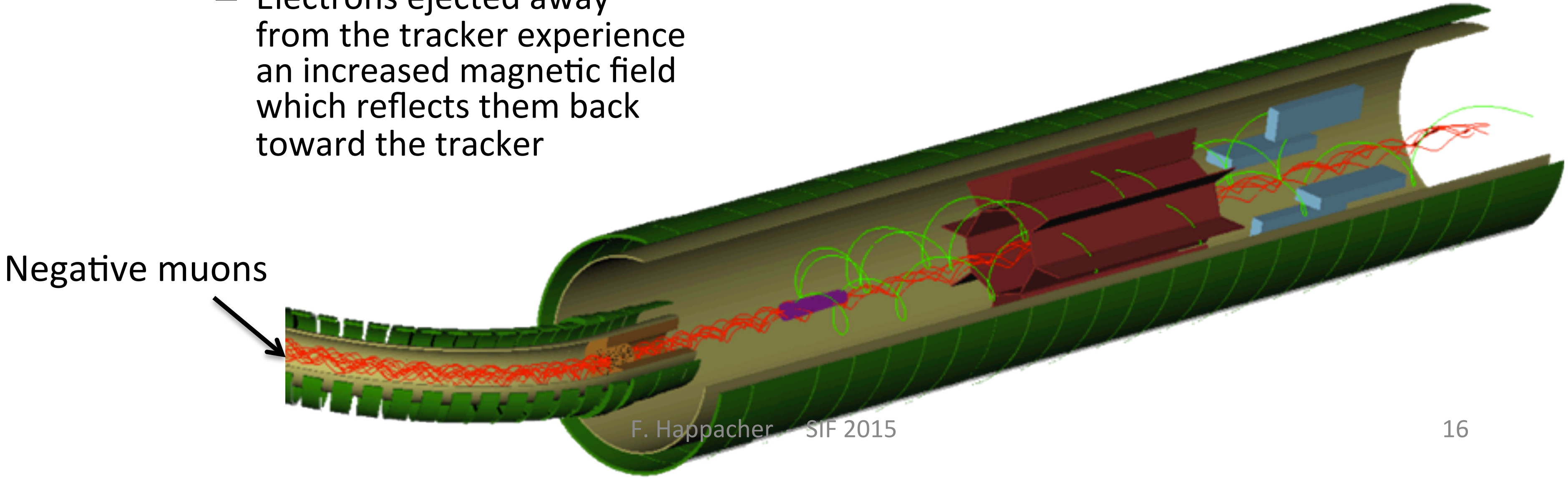
- Transport Solenoid
  - Graded magnetic from 2.5 T (at the production solenoid entrance) to 2.0 T (at the detector solenoid entrance)
    - Allows muons to travel on a helical path from the production solenoid to the detector solenoid
  - S-shaped to remove the detector solenoid out of the line of sight from the production solenoid
    - No neutral particles produced in the production solenoid enter the detector solenoid

Mu2e Beamline

- The Detector Solenoid houses the Al target and the two main detectors: the tracker and the calorimeter
  - 17 Aluminum disks, 0.2 mm thick, radius between 83 mm (upstream) and 63 mm (downstream)

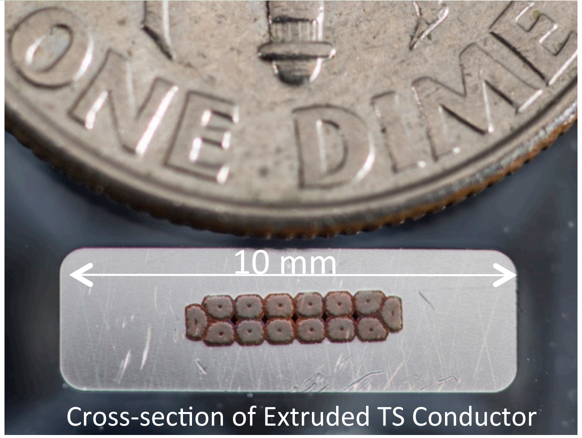


  - Surrounded by graded magnetic field from 2.0 T (upstream) to 1.0 T (downstream)
    - Conversion electrons will travel on a helical path toward the tracker and then hit the calorimeter
    - Electrons ejected away from the tracker experience an increased magnetic field which reflects them back toward the tracker

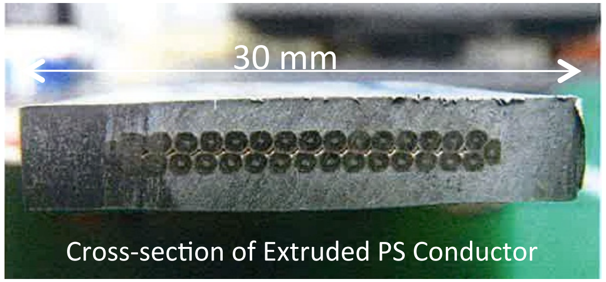


Solenoid status


SSW to determine dual coil magnetic axes



Cross-section of Extruded TS Conductor



Cross-section of Extruded PS Conductor

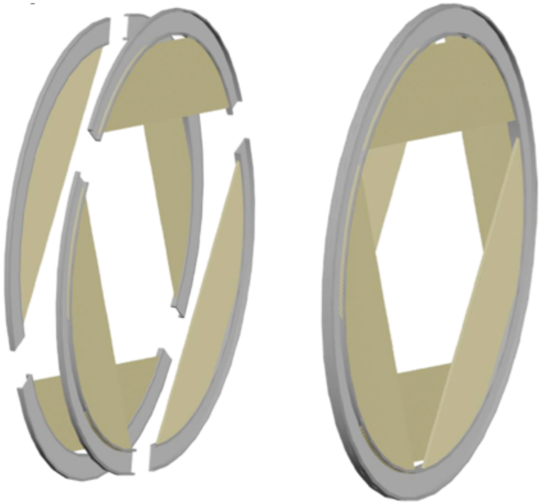
- ☐ **The Super Conducting magnets are the heart of MU2E Apparatus**
- ☐ PS and DS bid is over. **They will be built by General Atomics, USA**
- ☐ TS prototype manufactured by ASG Superconductors, INFN Genova and Fermilab Technical division.
- ☐ **TS proto @ FNAL since December 2014.**
- ☐ Three final tests done in August 2015: alignment, current and temperature
  → Results were really satisfactory …. exceeding expectation

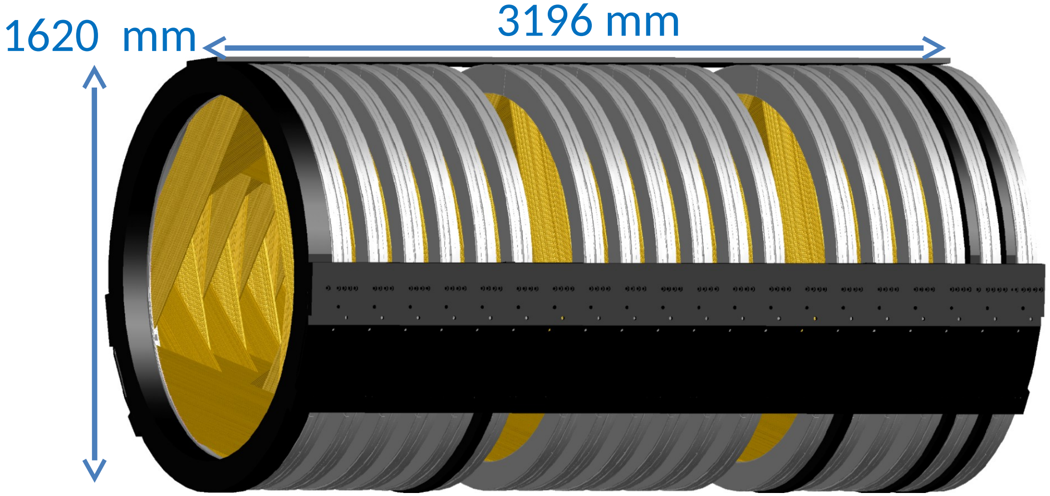
The Mu2e Tracker

- The Tracker will employ low mass straw drift tubes with tubes transverse to secondary beam
- 15 mm thick straw walls, dual-ended readout,

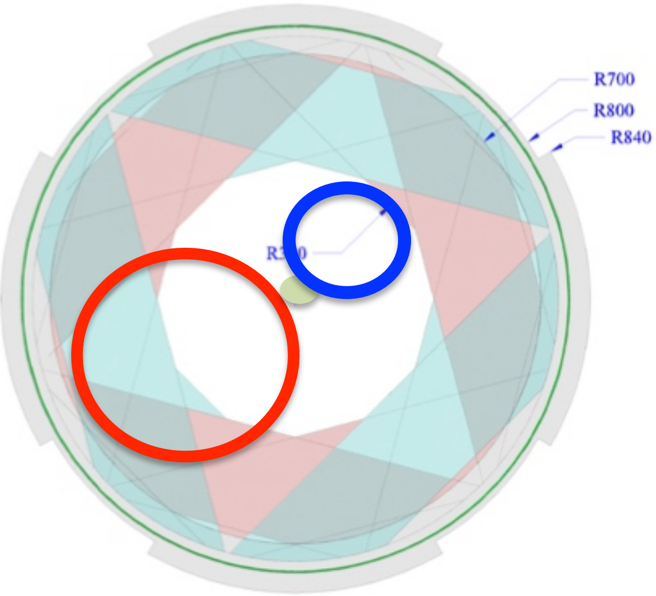
  length 430 – 1120 mm.
- It must operate in vacuum
- Self-supporting “panel” consists of 100 straws
- 6 panels assembled to make a “plane”
- 2 planes assembled to make a “station” -> 18 stations
- Rotation of panels and planes improves stereo information
- >20k straws total

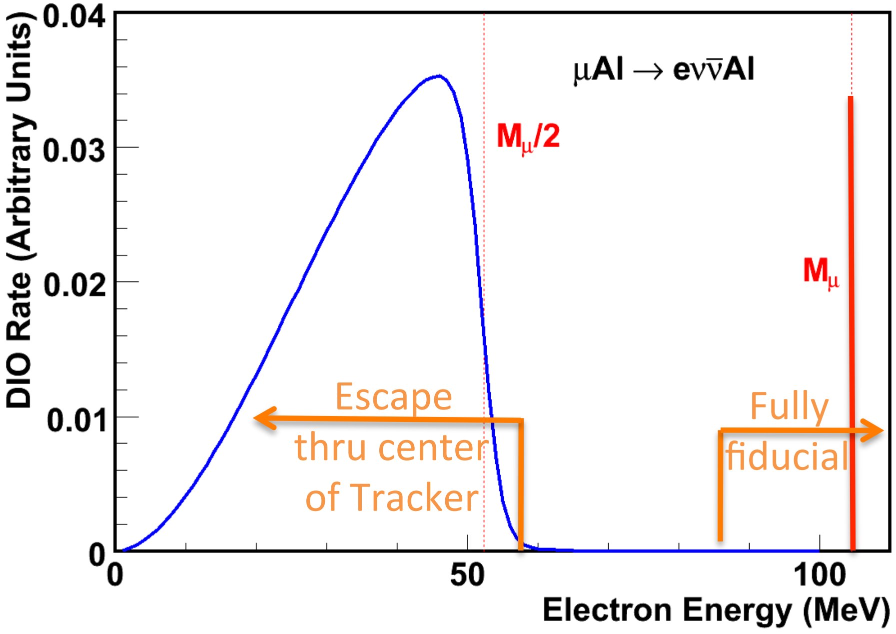
- 5 mm diameter straw
- Spiral wound
- Walls: 12 μm Mylar + 3 μm epoxy + 200 Å Au + 500 Å Al
- 25 μm Au-plated W sense wire
- 33 – 117 cm in length
- 80/20 Ar/CO2 with HV < 1500 V





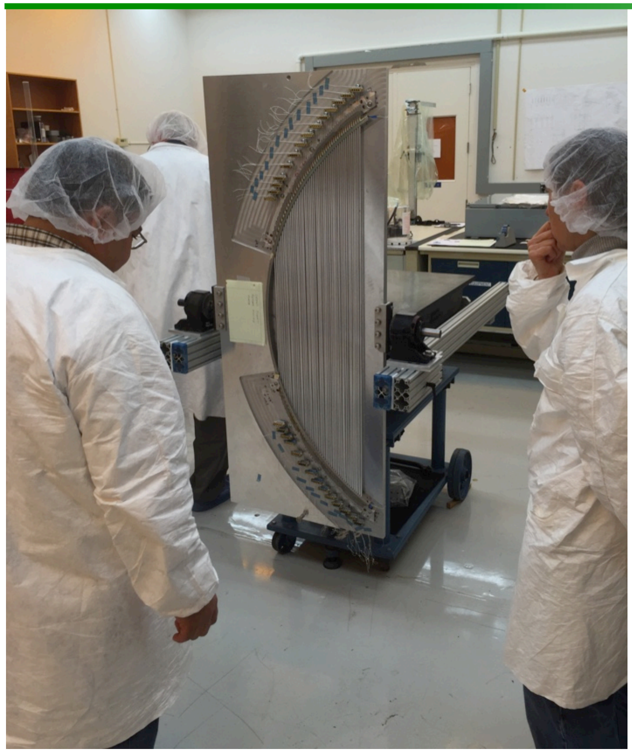
The Mu2e Tracker





- Inner 38 cm is purposefully un-instrumented
  - Blind to beam flash
  - Blind to >99% of DIO spectrum

First Prototype Panel

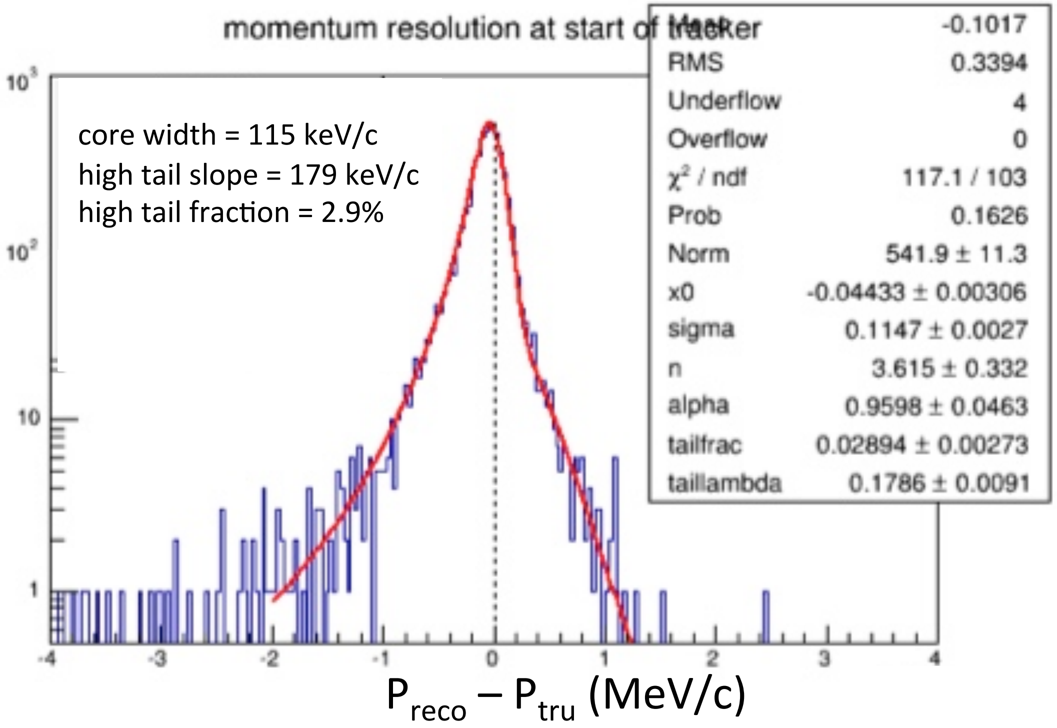


Fermilab, November 2014

Fermilab, March 2015

- Starting to test in vacuum

Mu2e Spectrometer Performance



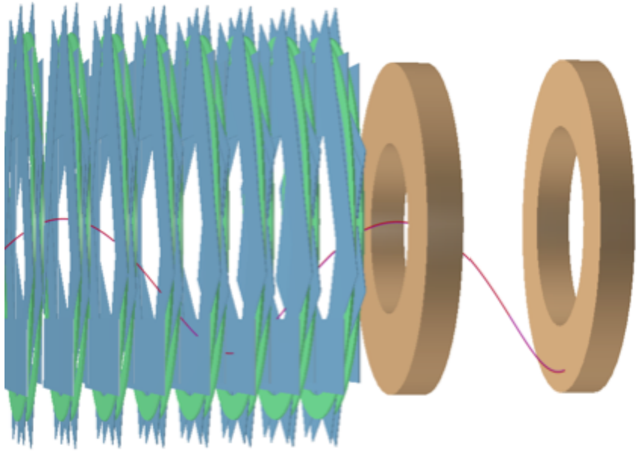
core width = 115 keV/c
high tail slope = 179 keV/c
high tail fraction = 2.9%

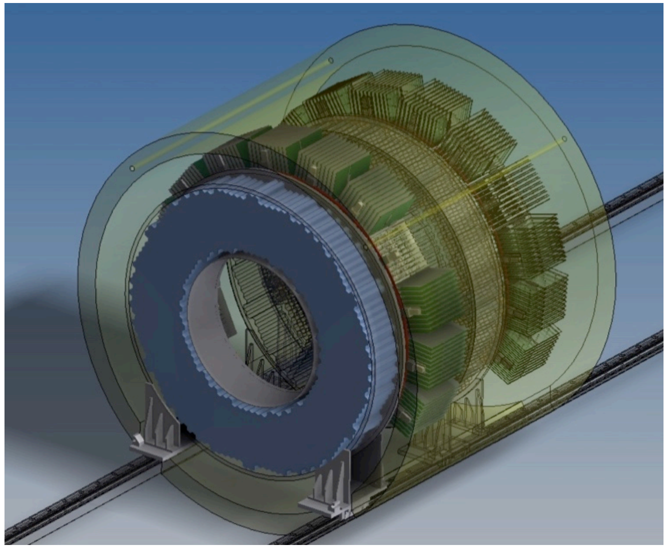
Mean	-0.1017
RMS	0.3394
Underflow	4
Overflow	0
χ^2 / ndf	117.1 / 103
Prob	0.1626
Norm	541.9 ± 11.3
x0	-0.04433 ± 0.00306
sigma	0.1147 ± 0.0027
n	3.615 ± 0.332
alpha	0.9598 ± 0.0463
tailfrac	0.02894 ± 0.00273
taillambda	0.1786 ± 0.0091

- Performance well within physics requirements

The Mu2e Calorimeter

- Crystal calorimeter
  - Compact
  - Radiation hard
  - Good timing and energy resolution





- ➢ Particle Identification to distinguish e/μ
- ➢ Seed for track pattern recognition
- ➢ Tracking independent trigger
- ➢ Work in 1 T field and 10^{-4} Torr vacuum
- ➢ RadHard up to 30 krad, 10^{12} n/cm^2/year

High granularity crystal based calorimeter with:

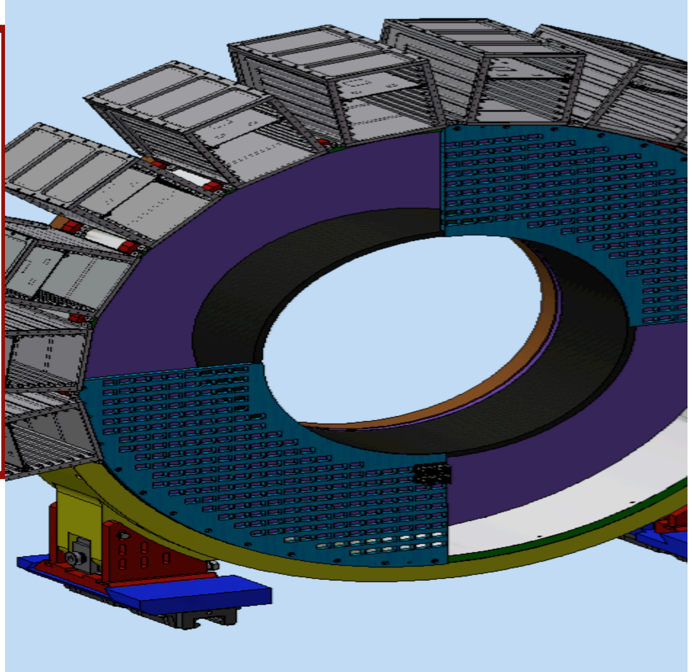
- ➢ σ/E of O(5%) and Time resolution < 500 ps
- ➢ Position resolution of O(1 cm)
- ➢ O(98%) acceptance

for CE signal @ 100 MeV

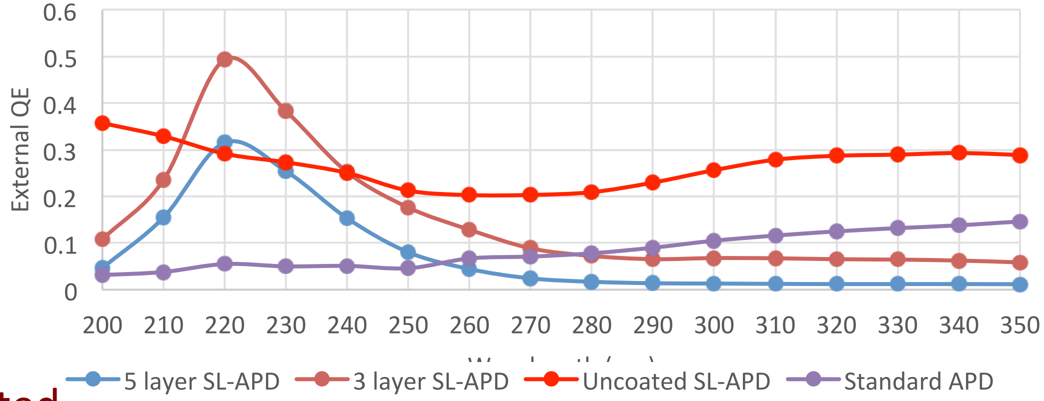
The Mu2e Calorimeter

The Calorimeter consists of two disks with 1650 BaF_2 square crystals (30x30x200) mm^3

- ☐ R_{IN} = 351 mm, R_{OUT} = 660 mm, Depth = 10 X_0 (200 mm)
- ☐ Each crystal readout by two SL APDs (9x9 mm^2)
- ☐ Analog FEE and digital electronics located on calo
- ☐ Radioactive source and laser systems provide absolute calibration and monitoring capability.



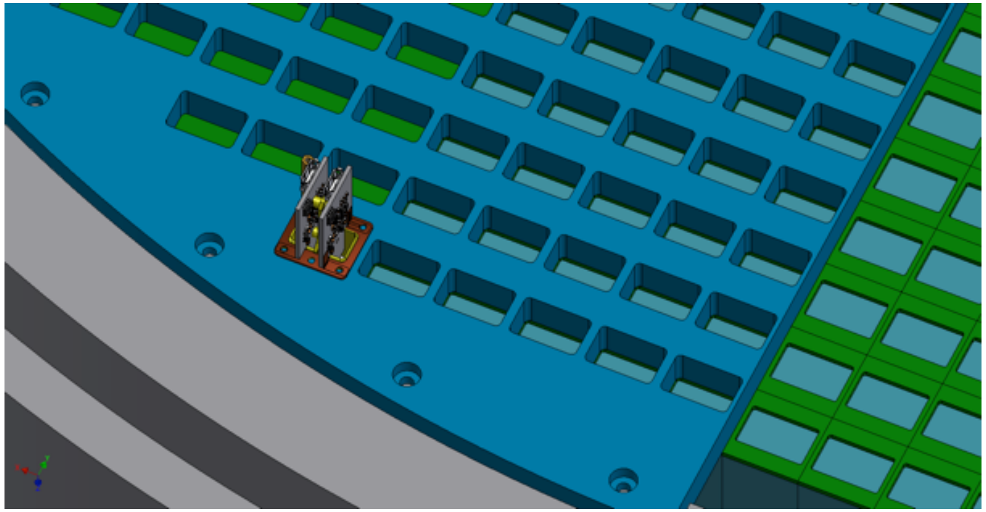
To reduce the slow BaF_2 component at higher wavelengths , a Caltech/JPL/RMD consortium was formed to develop a RMD APD **into a super-lattice APD with high Q.E. @ 220 nm** that incorporates also **an Atomic Layer Deposition antireflection filter** to reduce efficiency for λ > 300 nm.

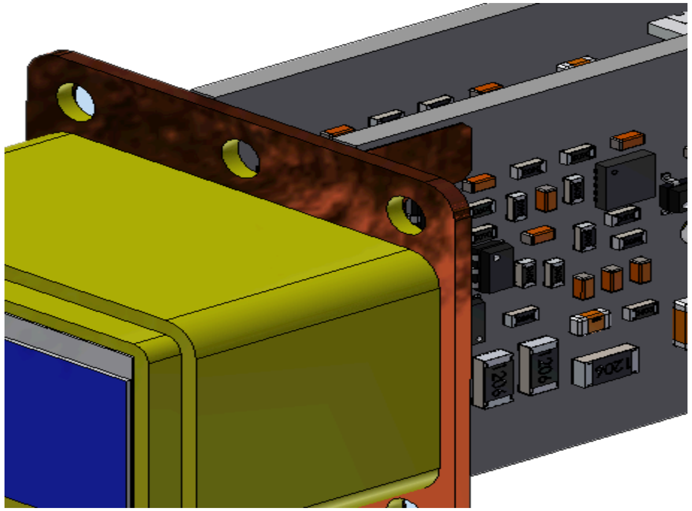


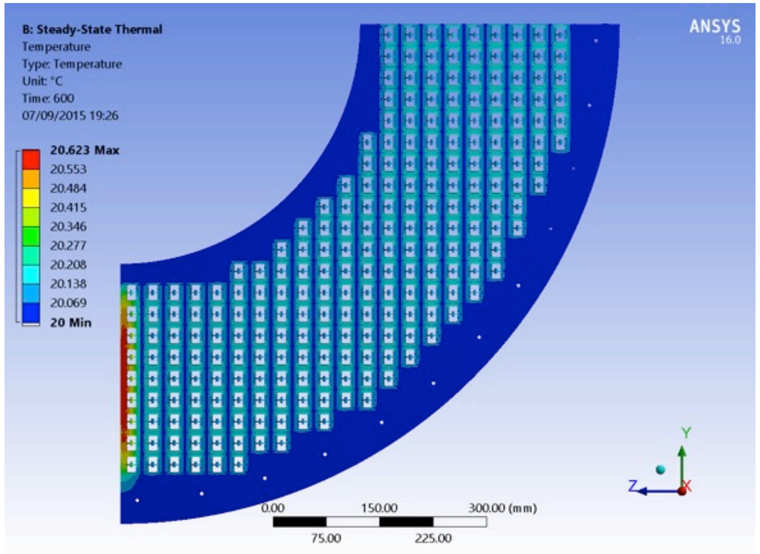
Prototypes with LYSO+APD, CsI+MPPC tested
Next one with BaF_2 + SL APDs in progress

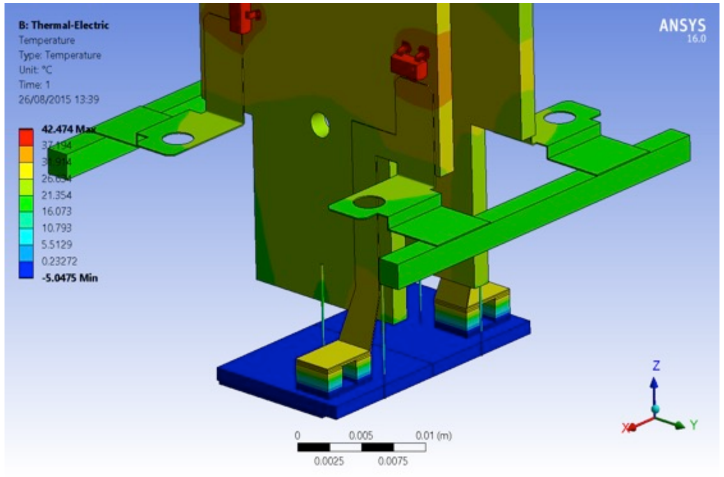
Good progresses on FEE and mechanics

The Calorimeter engineering







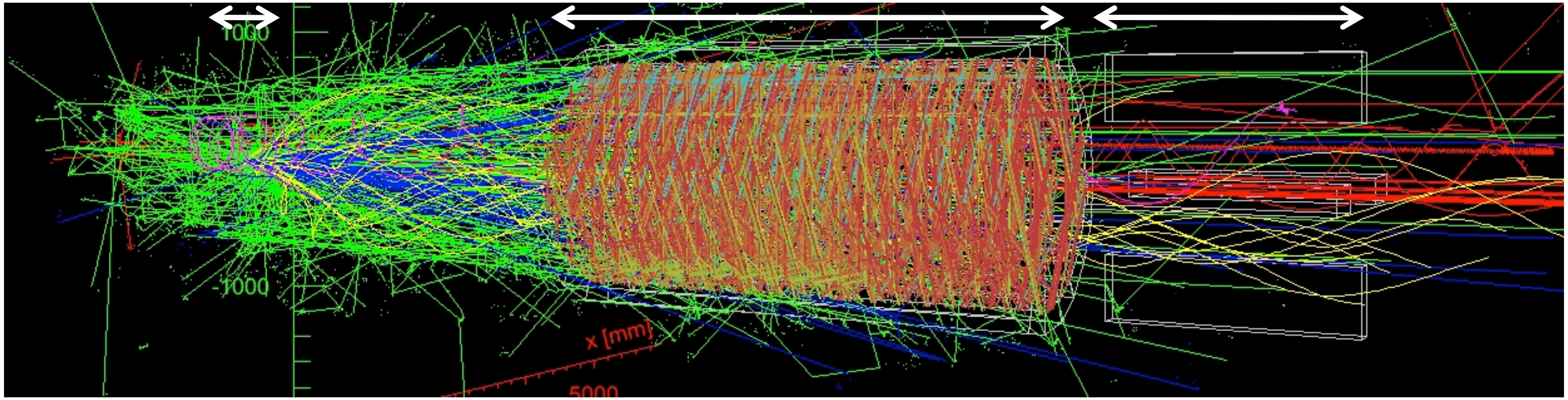


Mu2e Pattern Recognition

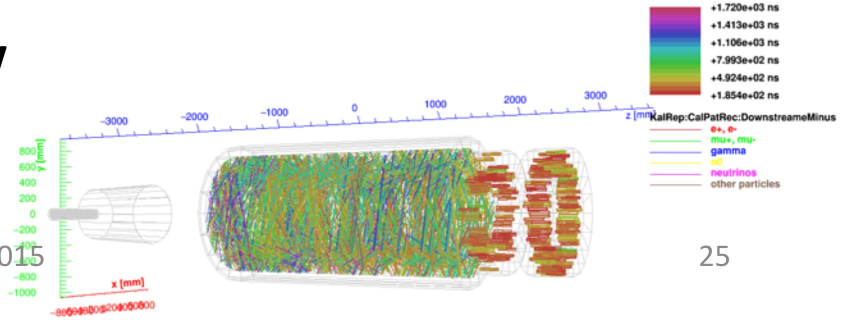
Stopping Target

Straw Tracker

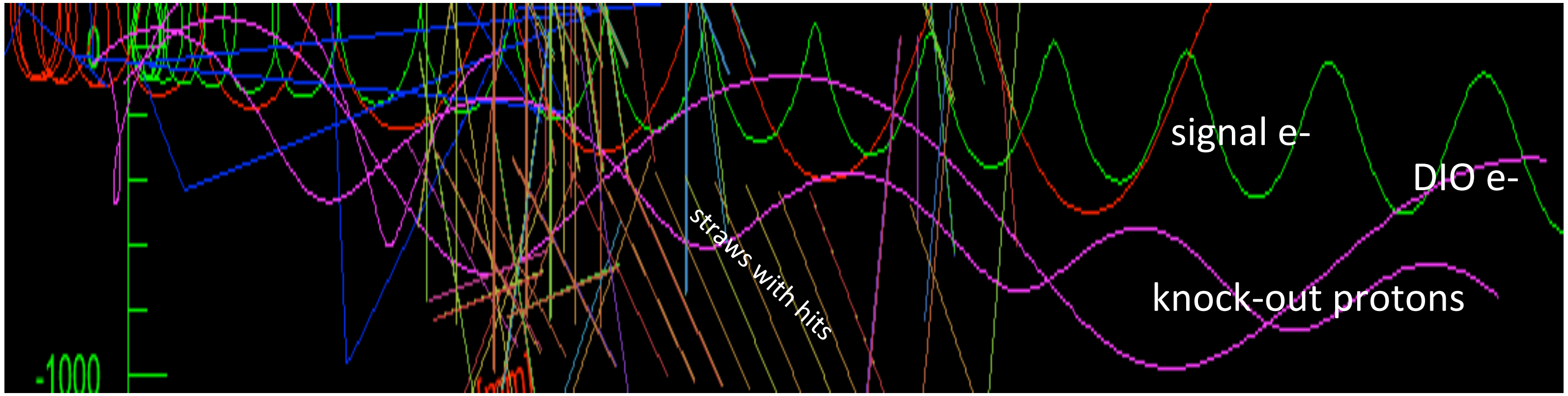
Crystal Calorimeter



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

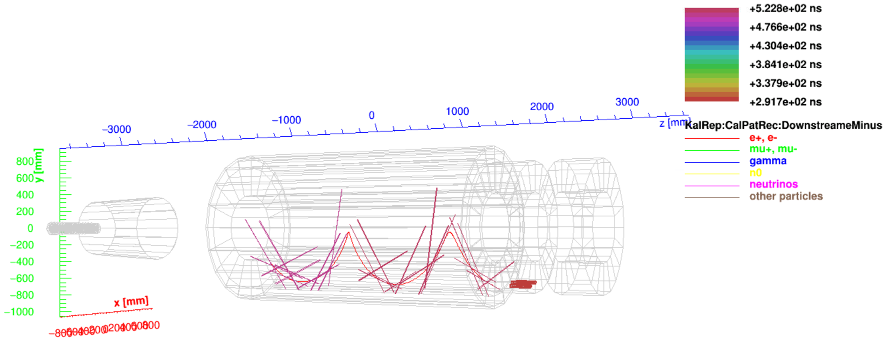


Mu2e Pattern Recognition

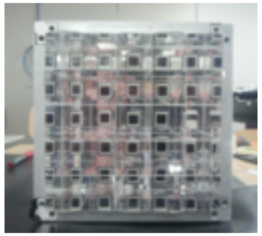


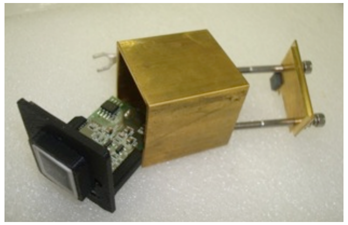
(particles with hits within +/-50 ns of signal electron t_{mean})

- ☐ Search for tracking hits with time and azimuthal angle compatible with the calorimeter clusters (|ΔT| < 50 ns) → simplification of pattern recognition
- ☐ Add search of an Helix passing through cluster and selected hits + use calorimeter time to calculate tracking Hit drift times
- ☐ → Reduce the wrong drift sign assignments i.e. **smaller positive momentum tail**

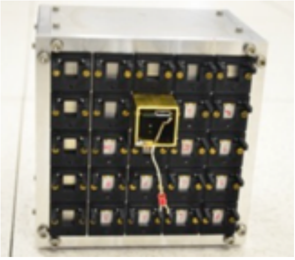


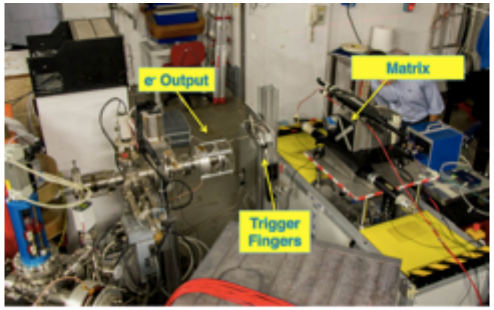
Calo prototyping and beam testing

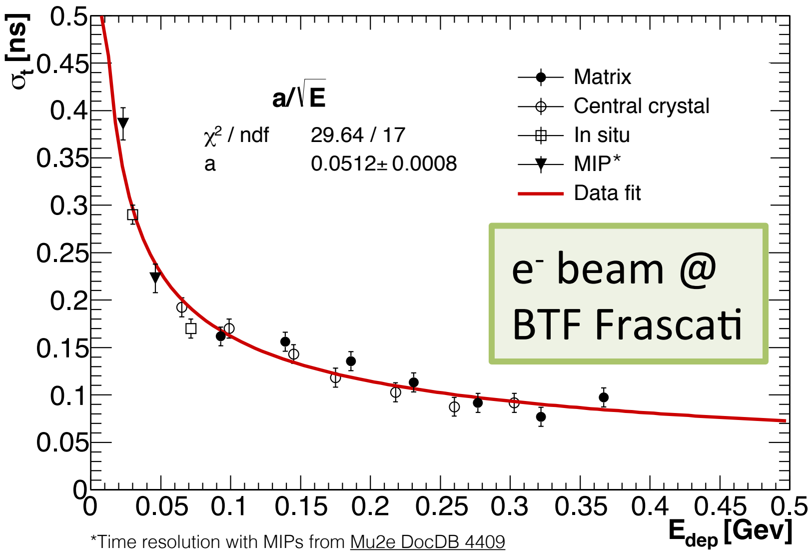




LYSO



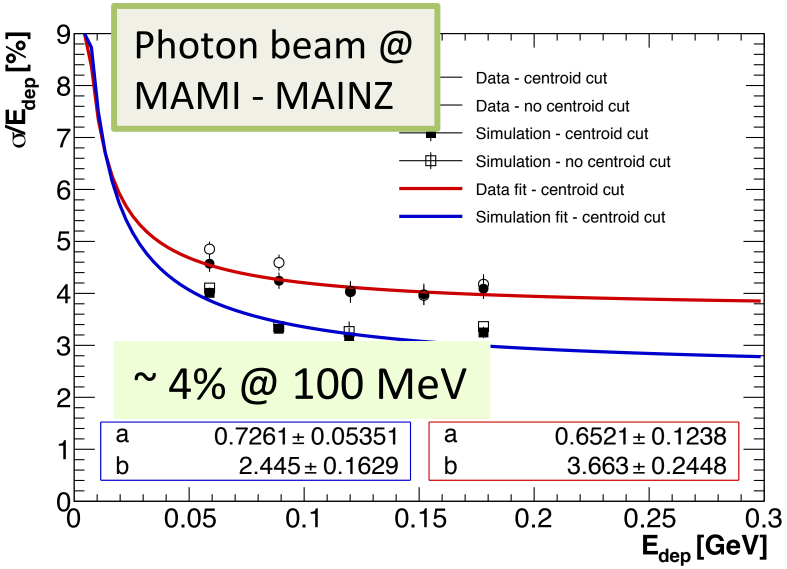




e⁻ beam @ BTF Frascati

*Time resolution with MIPs from Mu2e DocDB 4409

σ_T = 51 ps/sqrt(E/GeV)



Photon beam @ MAMI - MAINZ

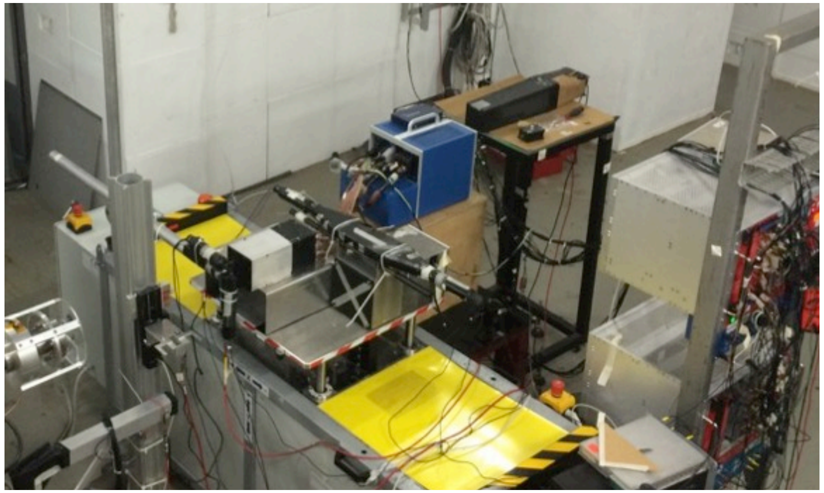
~ 4% @ 100 MeV

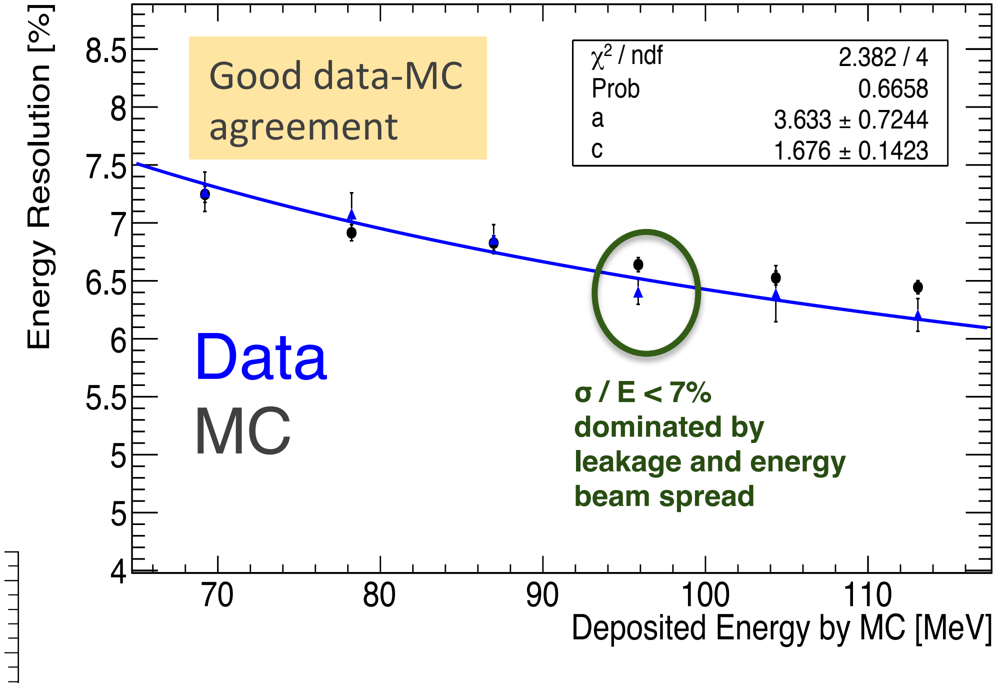
Energy resolution as a function of the energy deposition fitted with the function:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Noise term *b* considered negligible (~0.1% in quadrature).

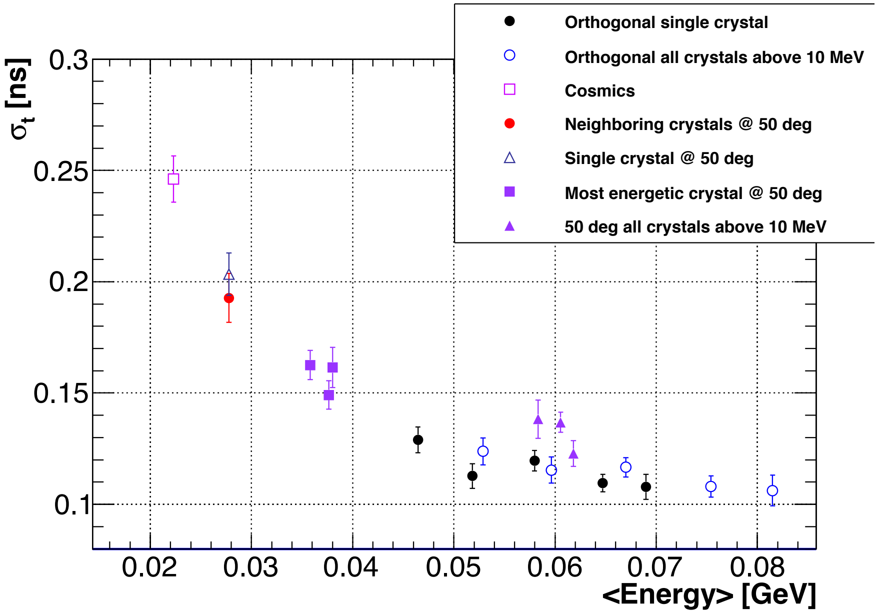
CsI+MPPC tests





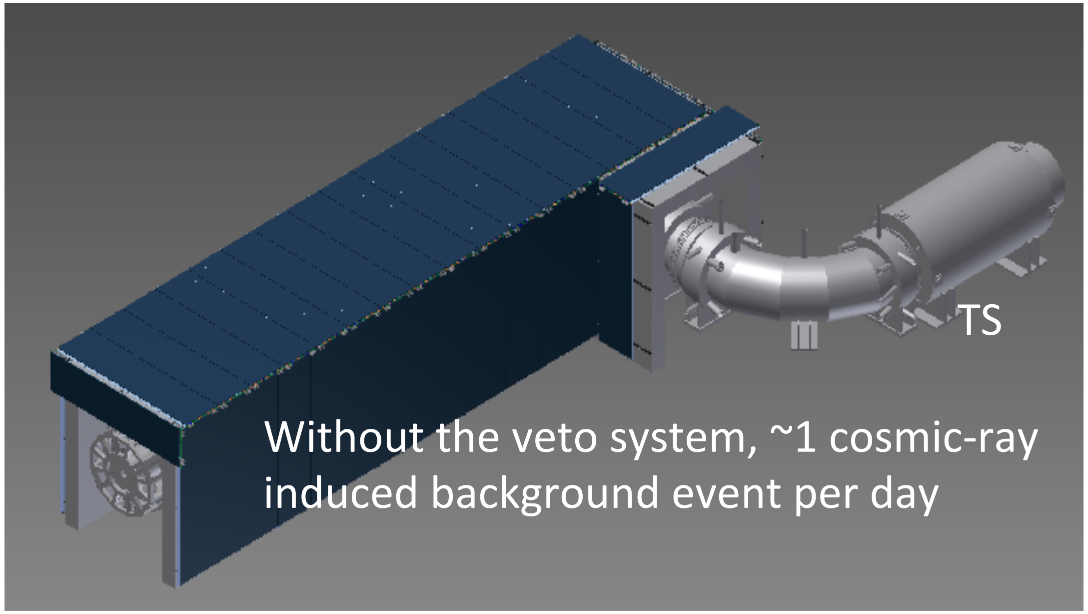
Good data-MC agreement

σ / E < 7% dominated by leakage and energy beam spread

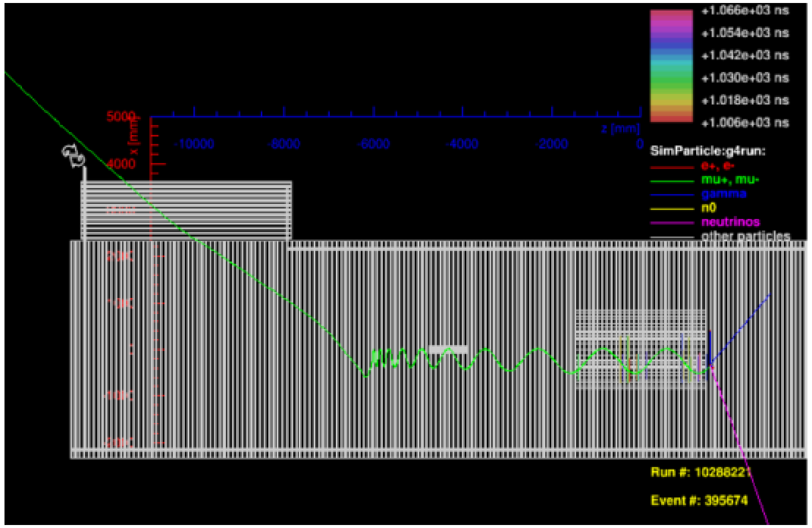


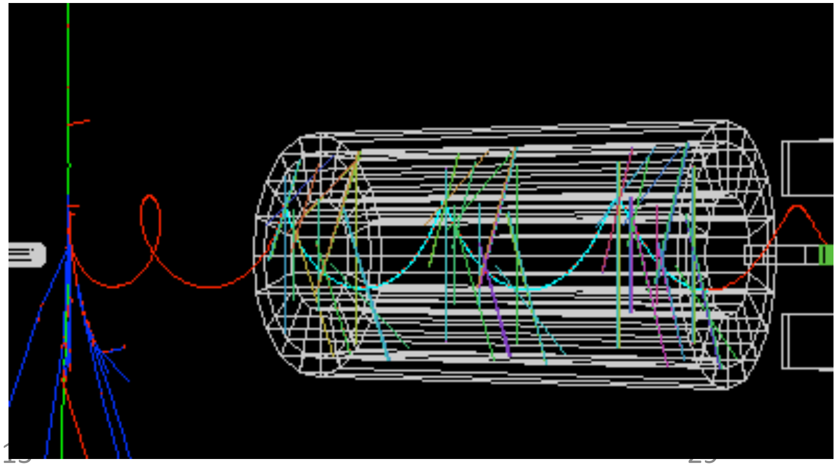
The Cosmic ray Veto

Veto system covers entire DS and half TS



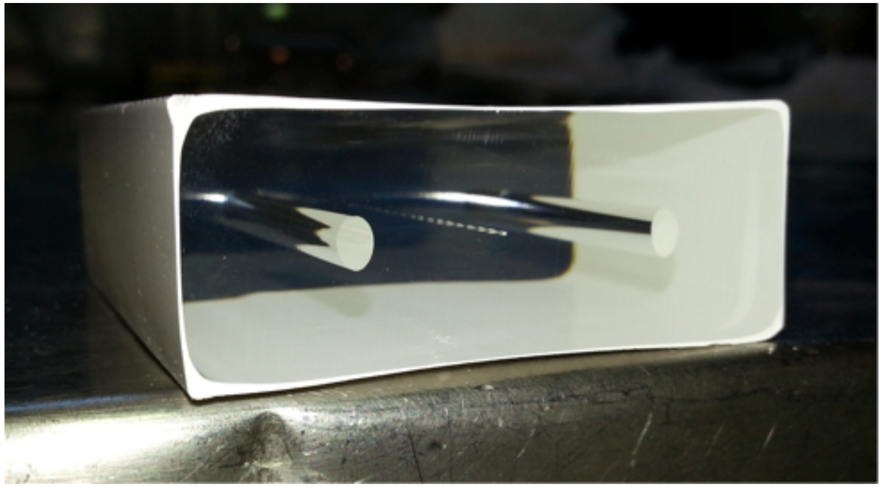
Without the veto system, ~1 cosmic-ray induced background event per day

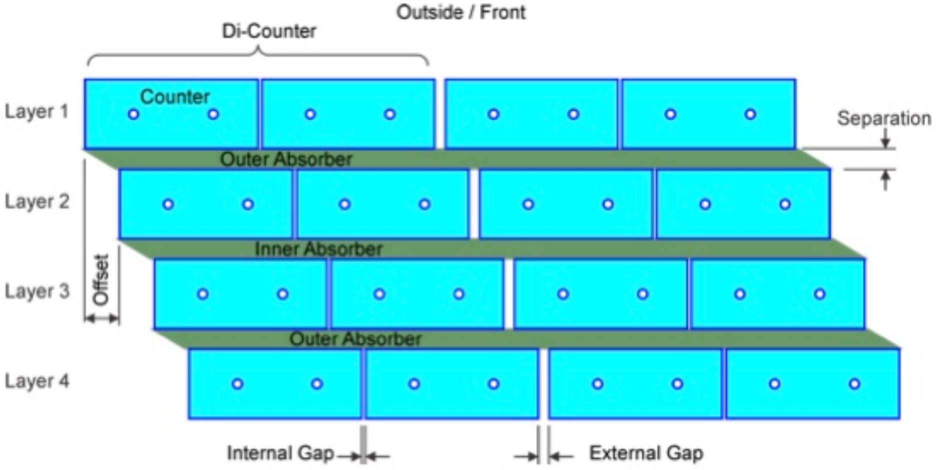




Cosmic μ can generate background events via decay, scattering, or material interactions

Mu2e Cosmic-Ray Veto





- Will use 4 overlapping layers of scintillator
  - Each bar is 5 x 2 x ~450 cm^3
  - 2 WLS fibers / bar
  - Read-out both ends of each fiber with SiPM
  - Have achieved $\varepsilon > 99.4\%$ (per layer) in test beam

Mu2e Detector Hall

Graphic of proposed Mu2e Detector Hall

- Construction well along
  - – Expect to warm it up sometime in the summer of 2016

Apr 18, 2015: Mu2e groundbreaking

Construction Photos

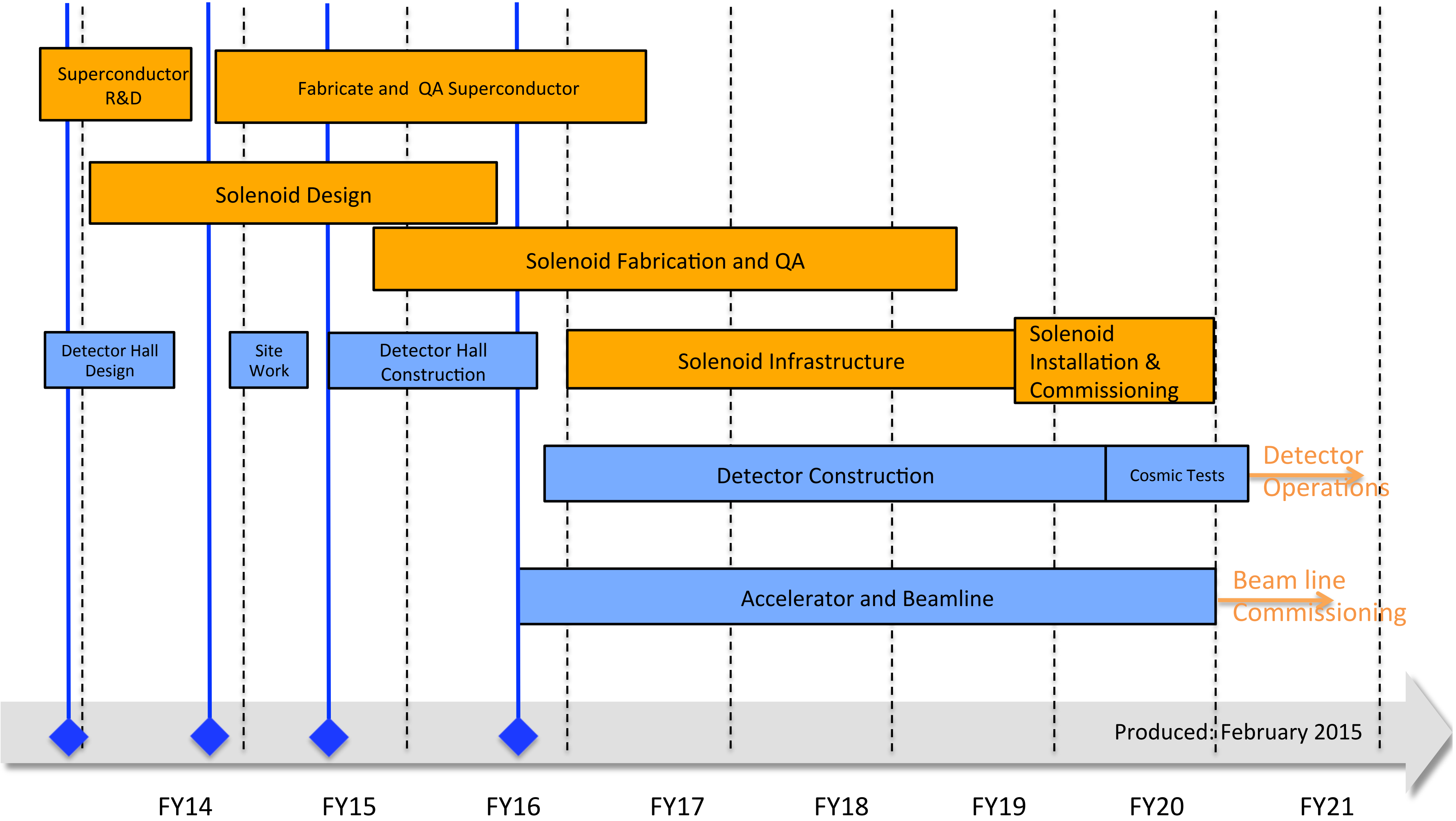

July 2015
Concrete floor being poured


August, 2015


September, 2015

- Steady progress being made

Mu2e Schedule



Summary

The Mu2e experiment:

- Improves sensitivity by a factor of 10^4
- Provides discovery capability over a wide range of New Physics models
- is complementary to LHC, heavy-flavor, and neutrino experiments
- **Mu2e has completed the CD-2 and CD3 for the long lead items**

→ Construction of the solenoids will start next year.

→ Detector Review in spring 2016 to freeze detector with CD3 in summer 2016

→ civil construction ongoing

→ Construction period 2016-2018 followed by installation in 2019