The Mu2e Experiment at Fermilab

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On behalf of the Mu2e Collaboration

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Fermilab

The Mu2e collaboration

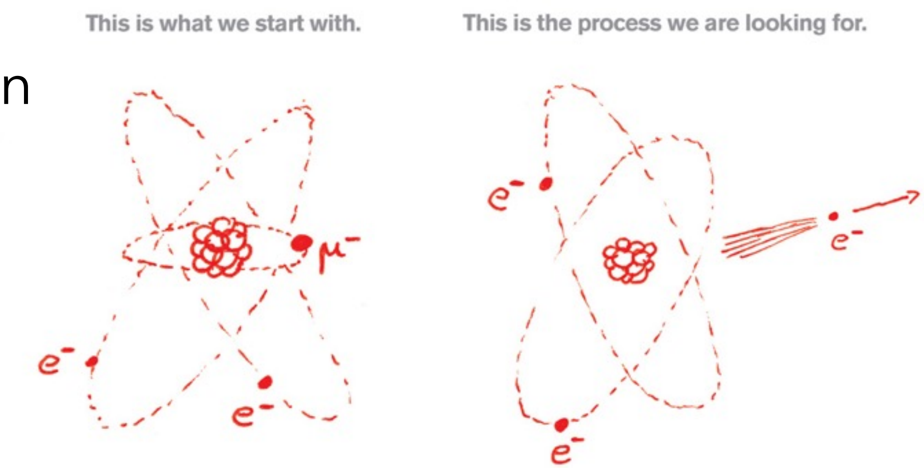
Argonne National Laboratory, Boston University, Brookhaven National Laboratory
University of California, Berkeley, University of California, Irvine, California Institute of Technology, City University of New York, Joint Institute for Nuclear Research, Dubna, Duke University, Fermi National Accelerator Laboratory, Laboratori Nazionali di Frascati, Helmholtz-Zentrum Dresden-Rossendorf, University of Houston, University of Illinois, INFN Genova, Kansas State University, Lawrence Berkeley National Laboratory, INFN Lecce and Università del Salento, Lewis University, University of Louisville, Laboratori Nazionali di Frascati and Università Marconi Roma, University of Minnesota, Muons Inc., Northern Illinois University, Northwestern University, Novosibirsk State University/Budker Institute of Nuclear Physics, Institute for Nuclear Research, Moscow, INFN Pisa, Purdue University, Rice University, University of South Alabama, Sun Yat Sen University, University of Virginia, University of Washington, Yale University

Presentation outline

- Why Mu2e
- Experimental technique
- Accelerator complex
- Detectors layout
- Status of Mu2e
- Conclusions

What is Mu2e

- Mu2e is a highly sensitive search for Charged-Lepton Flavor Violation (CLFV)
- Will search neutrinoless conversion of a muon into an electron in the Coulomb field of a nucleus

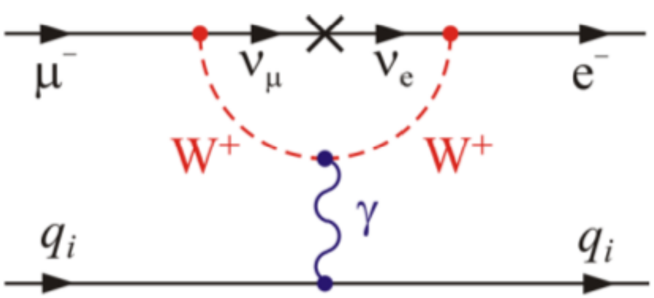


- Will use current Fermilab accelerator complex to reach a single event sensitivity of 2.4 x10^{-17}sensitivity 10^4 better than current world's best
- Will have *discovery* sensitivity over broad swath of New Physics parameter space
- Mu2e will detect and count the electrons coming from the conversion decay of a muon with respect to standard muon capture

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

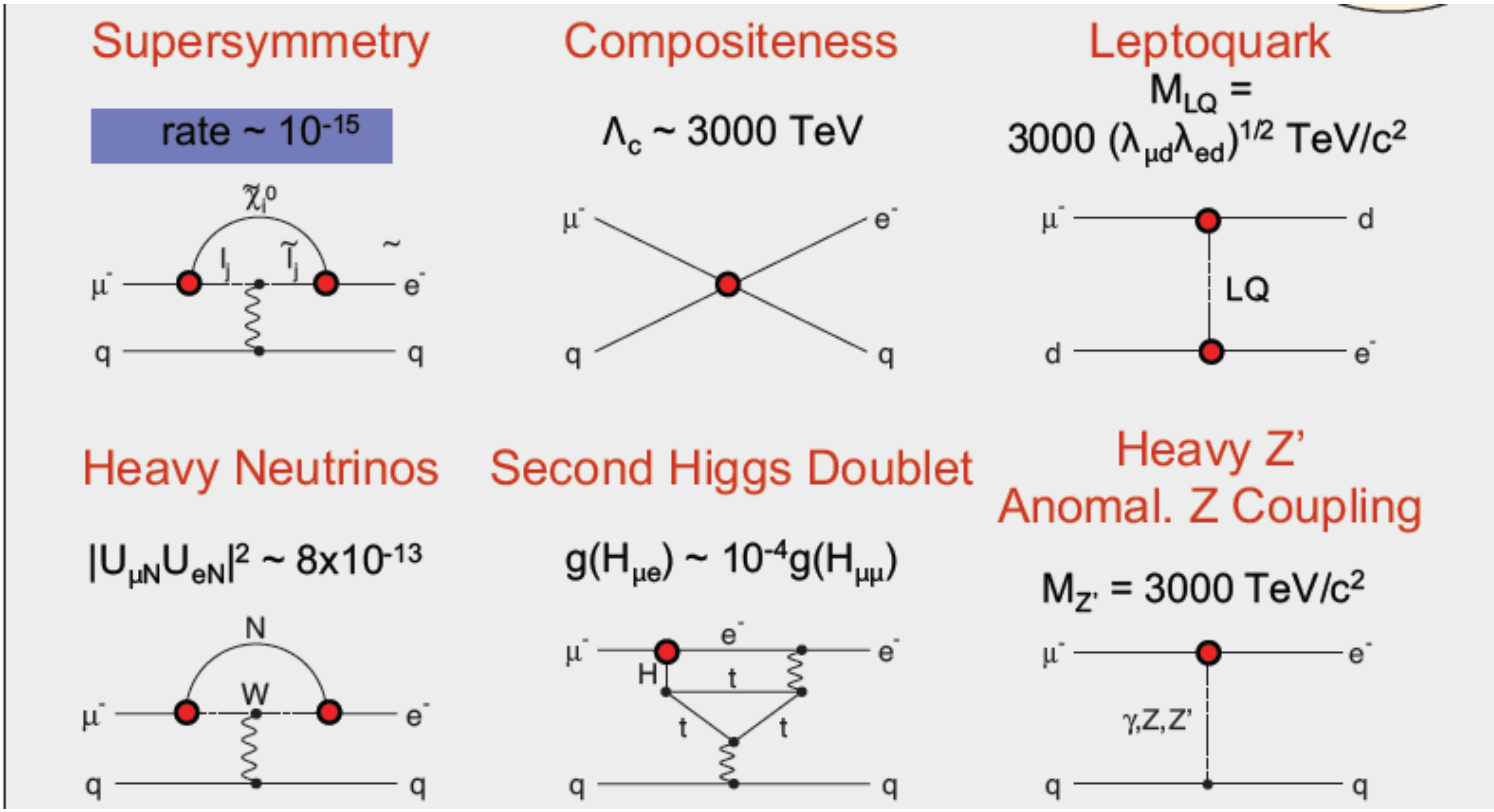
$\mu^- N \rightarrow e^- N$

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



- 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′

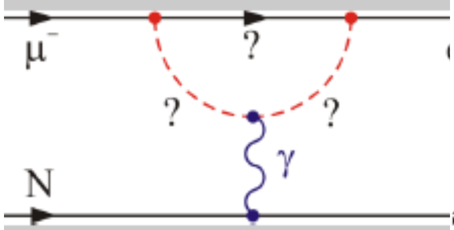
μ->e is a signature of NP models



Mu2e Sensitivty

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

Loops

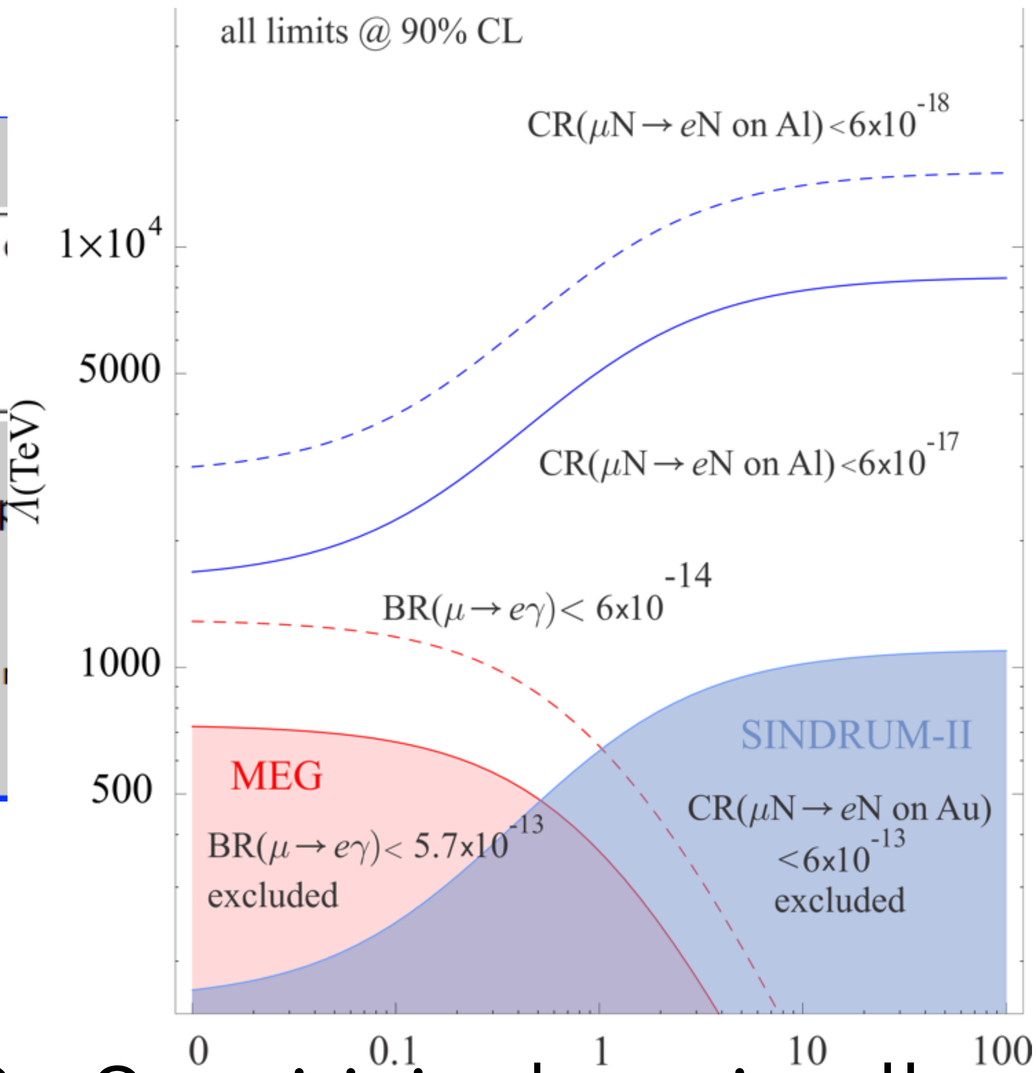


κ<< 1

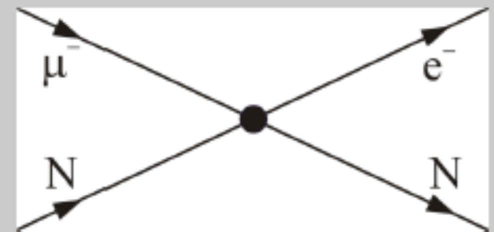
magnetic moment typ

operator

μ→ eγ rate ~300X μN → eN r



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's
- 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 1S around the nucleus
  - In aluminum: τ_μ^{Al} = 864 ns
  - Large τ_μ^{N} important for discriminating background
- Look for events consistent with $\mu N \rightarrow eN$

Mu2e Signal

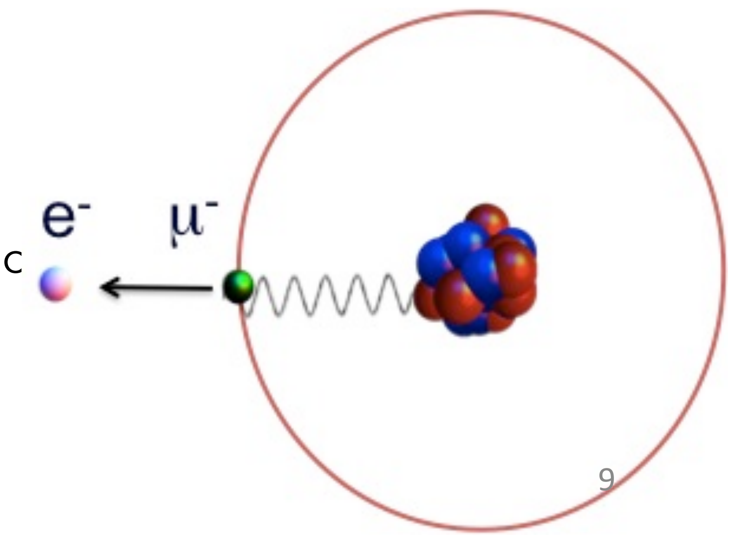
μ^-'s captured in the Al target fall to a 1S bound state giving origin to:

- muon decays in orbit (DIO): $\mu^- + Al \to e^- \bar{\nu}_e \nu_\mu + Al$ (40%)
- Muon capture: the wave function of muons and nuclei overlap, the nucleus can trap the muon: $\mu^- + Al \to \nu_\mu + Mg$ (61%)

  generating a flux of p,n and γ
- Neutrinoless muon to electron conversion $\mu^- + Al \to e^- + Al$

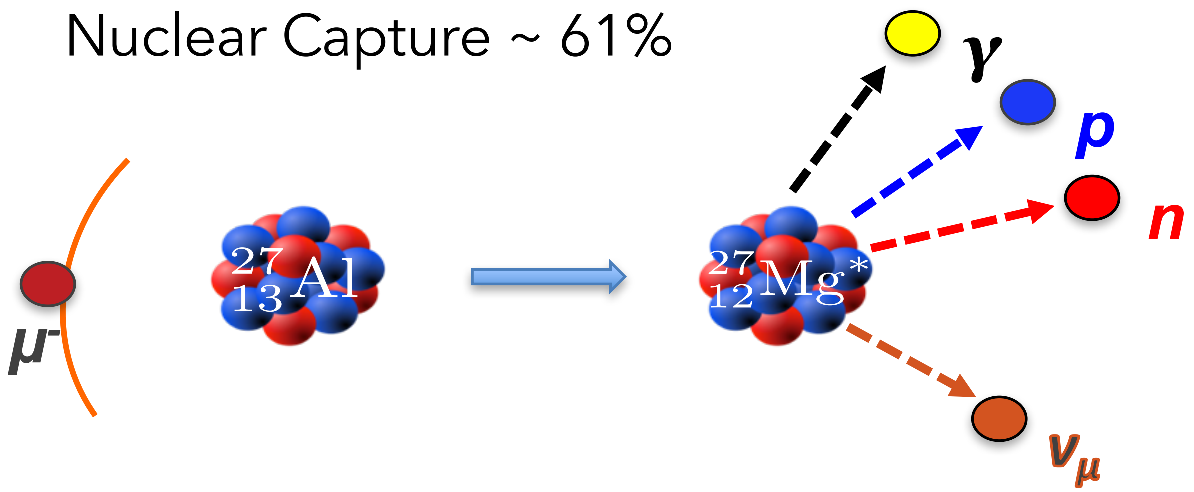
  - Results in a monoenergetic electron of 104.97 MeV
  - $E_{CE} = m_\mu c^2 - B_\mu(Z=13) - C_\mu(A=27)$

    - M_μ muon mass, 105.66 MeV/c^2
    - B_μ binding energy of a muon in the 1S orbit c
      0.48 MeV
    - C_μ nuclear recoil of Al, 0.21 MeV



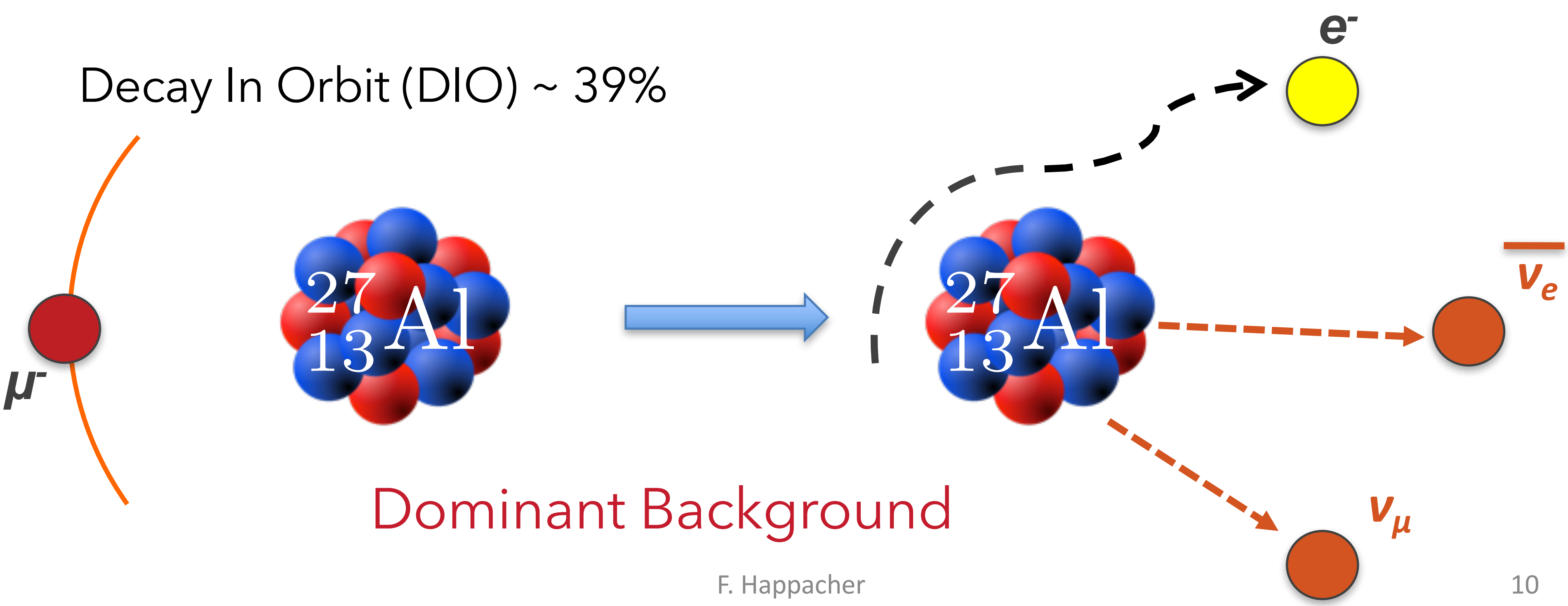
Mu2e processes

Nuclear Capture ~ 61%



Normalization Factor

Decay In Orbit (DIO) ~ 39%



Dominant Background

Backgrounds to deal with

Stopped μ's

- Muon decay in orbit (DIO)
- muon capture

Late protons

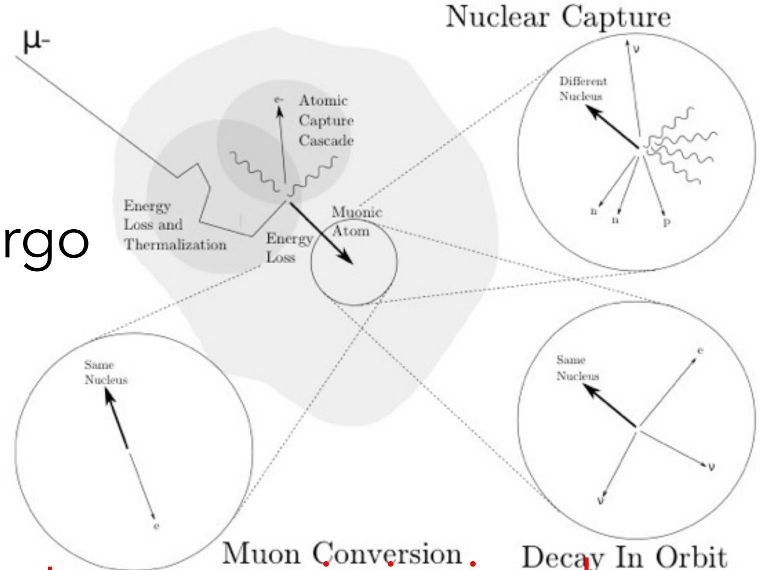
- Pions from the muon beam can undergo radiative capture (RPC)

$$\pi^- + N \rightarrow \gamma_{e^+e^-} + N'$$

γ up to m_π , peak at 110 KeV. One electron can mimic signal

- Pions/muons decay in flight

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



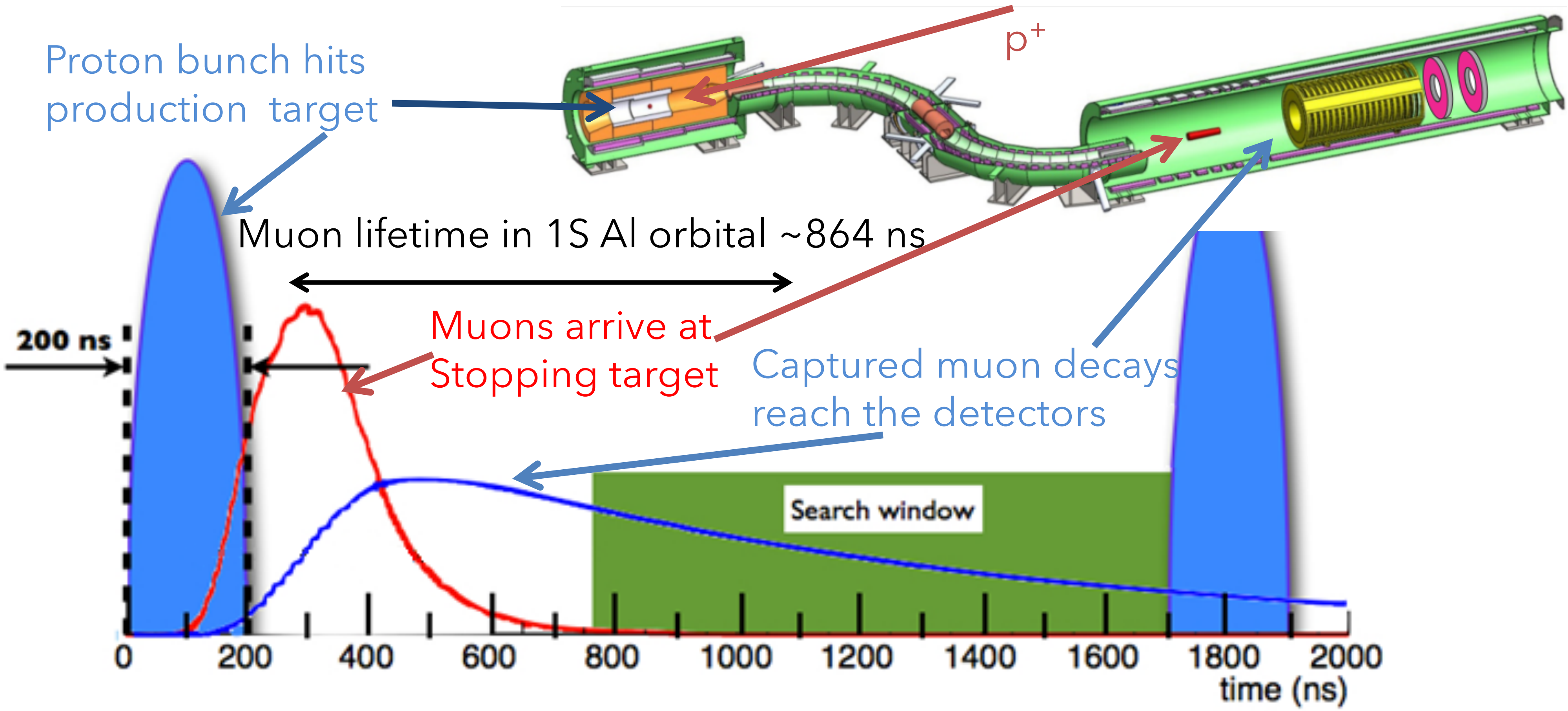
- Antiprotons produce pions when they annihilate in the target: are negative and they can be slow
- Electrons from beam
- Cosmic rays

Category	Background process	Estimated yield

PROMPT vs Late arriving

Prompt background like radiative pion capture decreases rapidly (~10^{11} reduction after 700 ns)

Pulsed beam structure



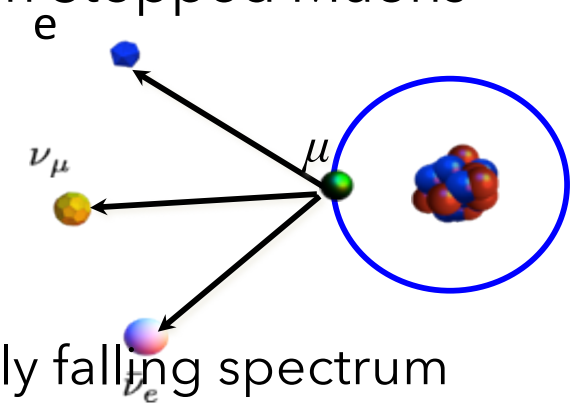
- ❑ Use the fact that muonic atomic lifetime >> prompt background
  Need a pulsed beam to wait for prompt background to reach acceptable levels
  → Fermilab accelerator complex provides ideal pulse spacing

- ❑ OUT of time protons are also a problem->prompt bkg arriving late
  To keep associated background low we need proton extinction
  (N_p out of bunch)/(N_p in bunch)<10^{-10}

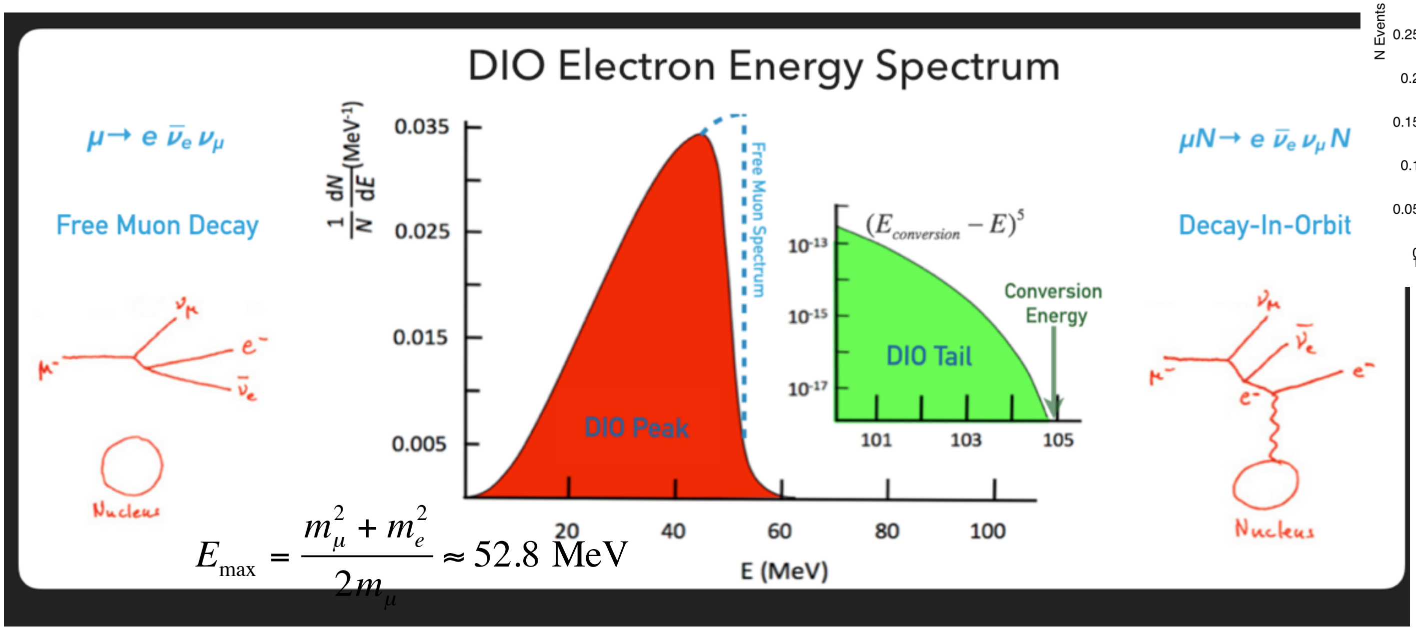
Muon from decay in orbit: DIO

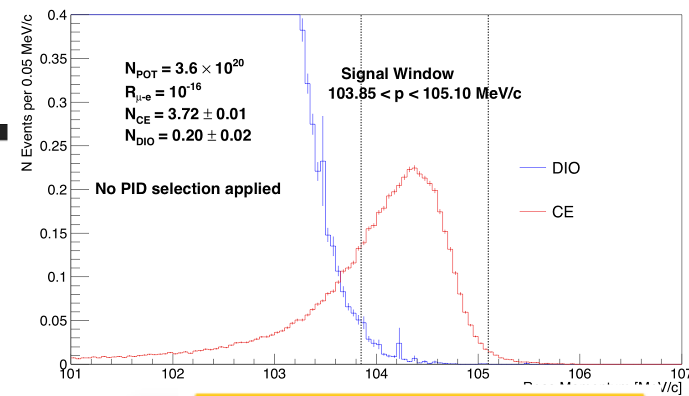
- The most sneaky source of background comes from Stopped Muons

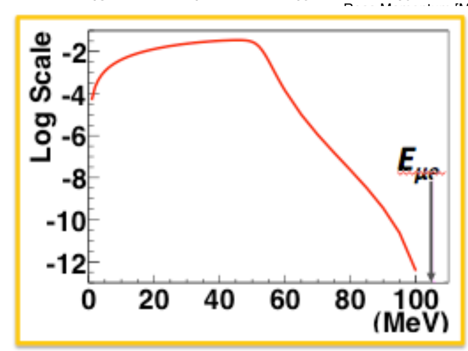
$$[\mu^- + A(N,Z)]^{1S}_{bound} \rightarrow A(N,Z) + e^- + \bar{\nu}_e + \nu_\mu$$



- 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
- Drives resolution requirements

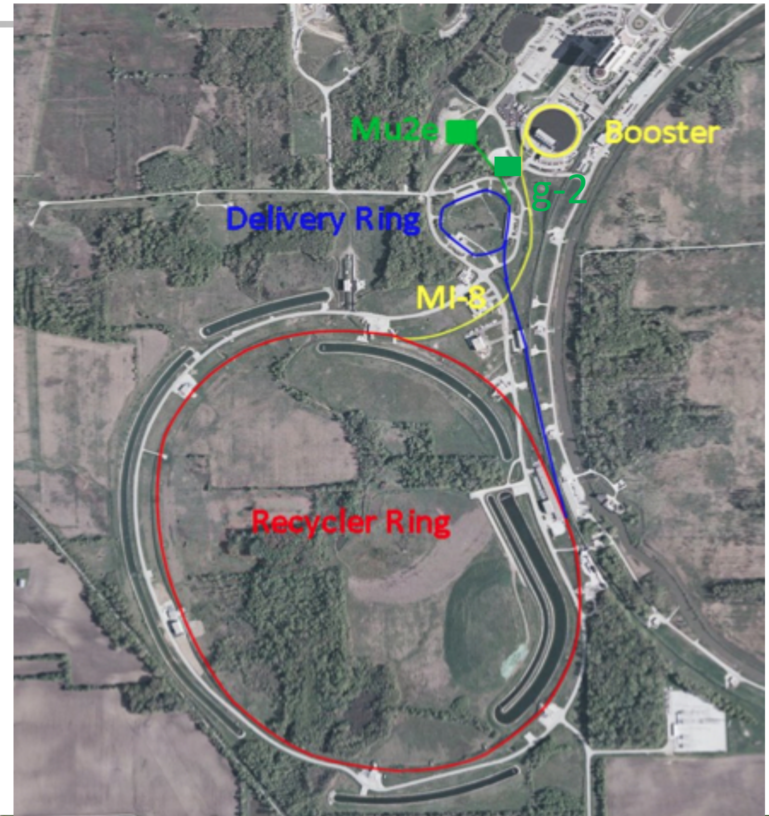






Accelerator Scheme & Proton extinction

- Booster: 21 batches 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 → **pulses of ~3x10^7 protons each, separated by 1.7 μs**



Proton Extinction

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

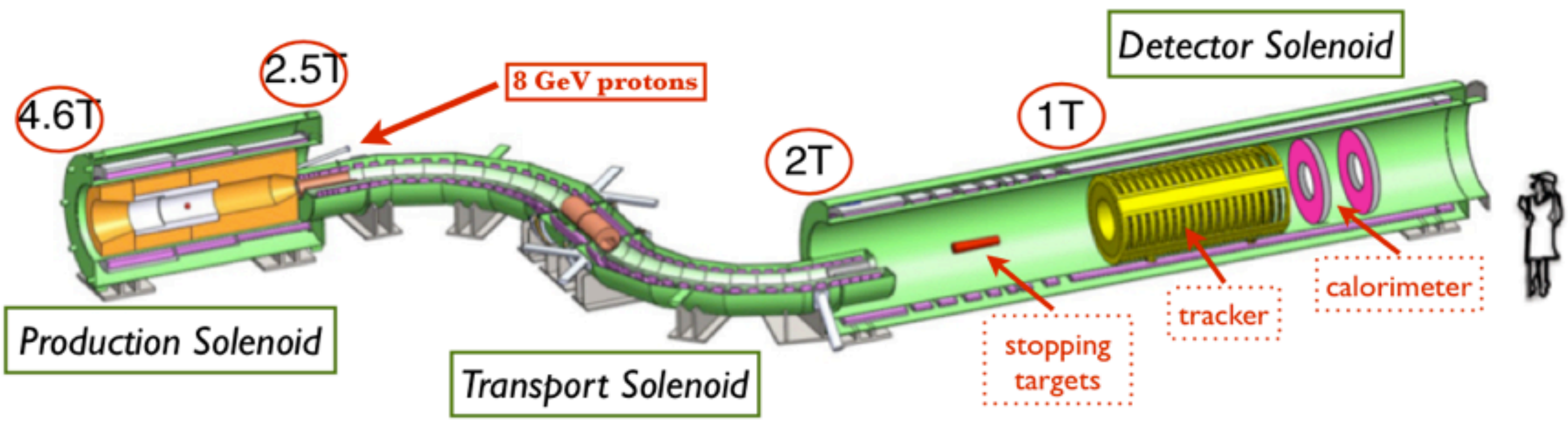
- Internal (momentum scraping) and bunch formation in Accumulator
- External: oscillating (AC) dipole

Accelerator models take into account collective effects show that this combination gets ~ 10^{-12}

F. Happache

The Mu2e beamline

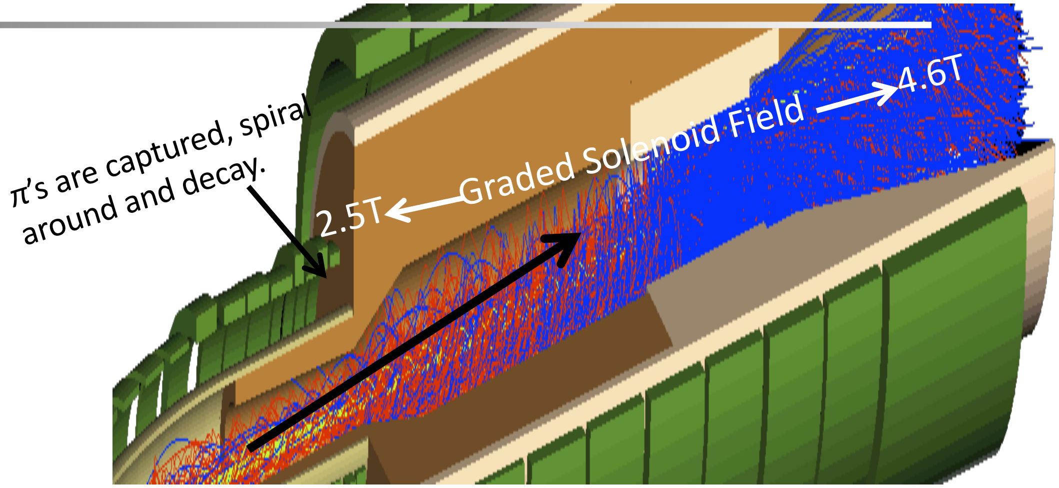
- Mu2e Solenoid System
  - Superconducting
    - Requires a cryogenic system
  - Inner bore evacuated to 10^{-4} Torr to limit background due to interactions of the charged particles with air



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 that then decay to muons
  - 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



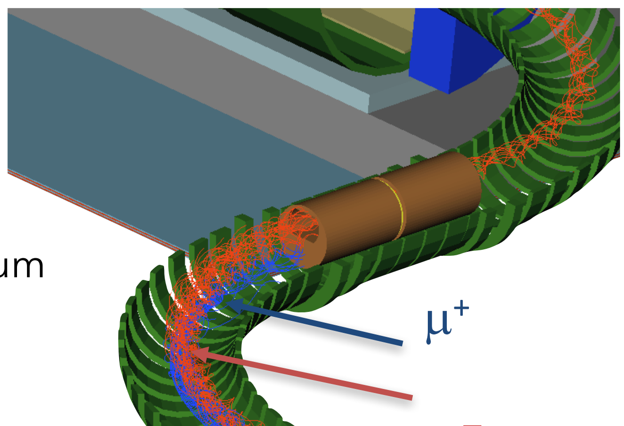
Pulsed beam of incident protons

- 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

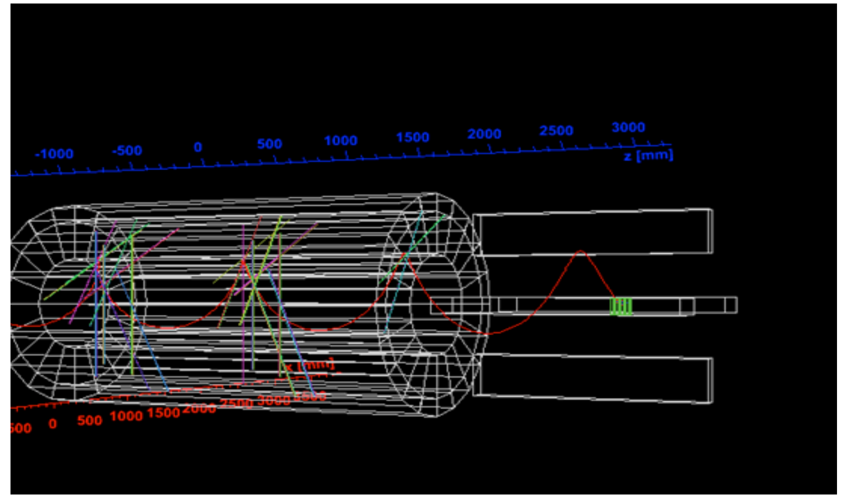
- No neutral particles produced in the production solenoid enter the detector solenoid, photons, neutrons

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



The Mu2e Beamline

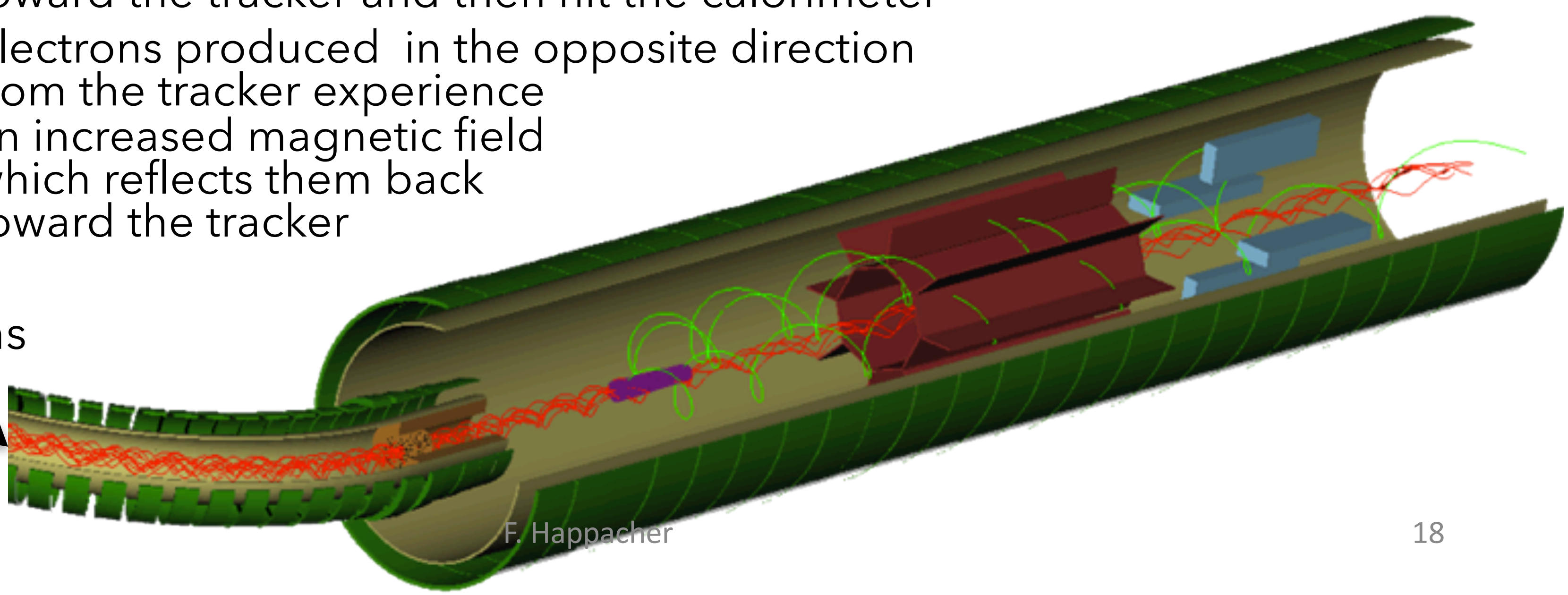
- The Detector Solenoid houses the Al target and the two main detectors: the tracker and the calorimeter



  – 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 produced in the opposite direction from the tracker experience an increased magnetic field which reflects them back toward the tracker

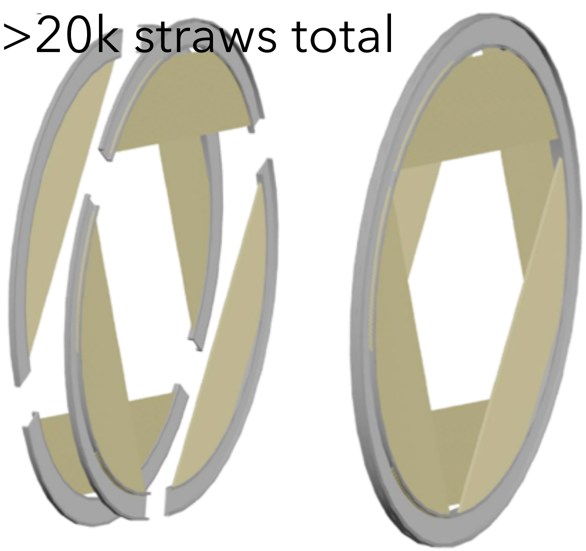
Negative muons

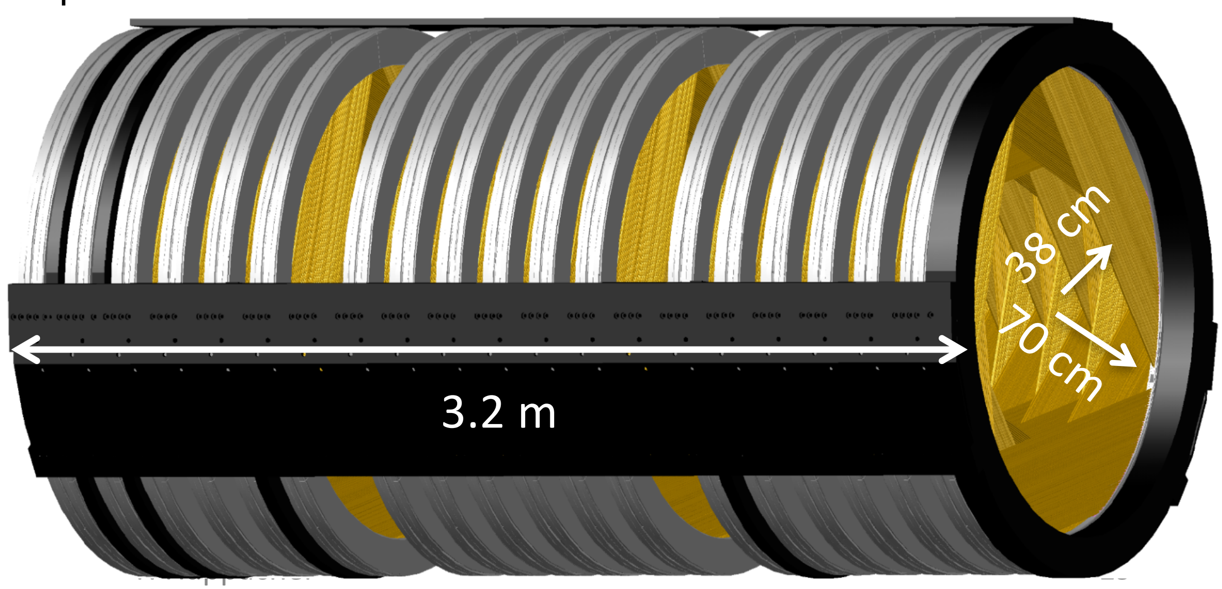


The Mu2e Tracker

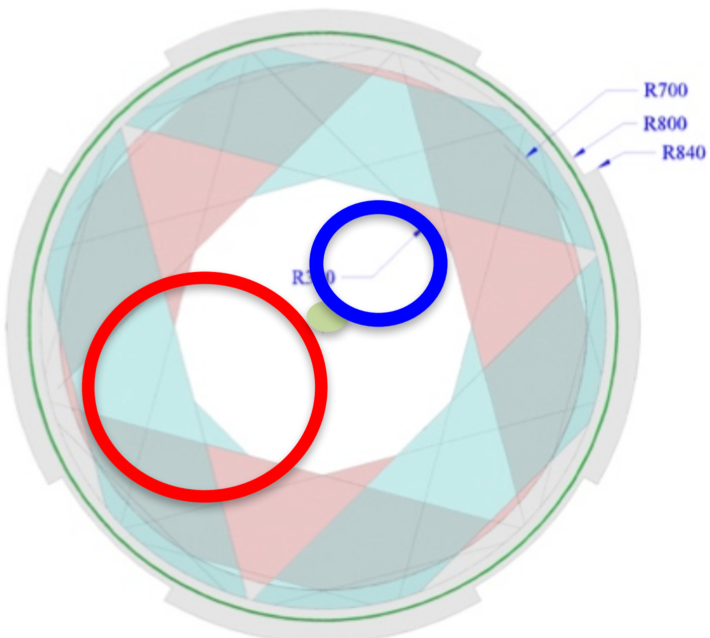
- The Tracker will employ low mass straw drift tubes with tubes transverse to secondary beam
- 15 mm thick straw walls, dual-ended readout (ADC-TDC) length 430 – 1120 mm.
- It must operate in vacuum
- Self-supporting "panel" consists of 100 straws
- 6 panels assembled to make a "plane"
- 2 planes assembled to make a "station" -> 18 stations
- Rotation of panels and planes improves stereo information
- >20k straws total

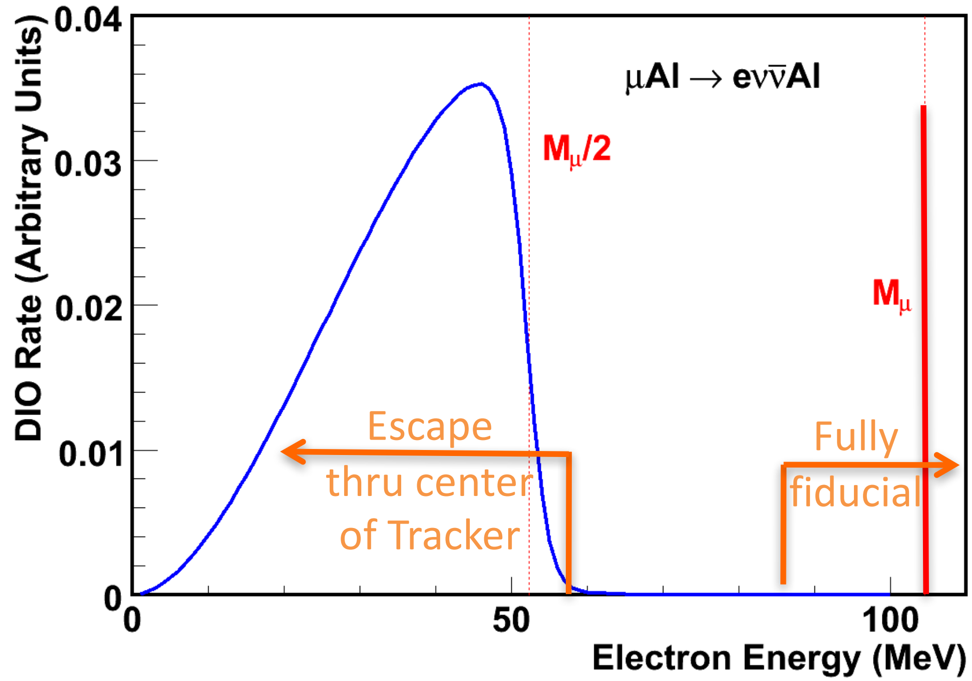
- 5 mm diameter straw
- Spiral wound
- Walls: 12 mm Mylar + 3 mm epoxy + 200 Å Au + 500 Å Al
- 25 μm Au-plated W sense wire
- 33 – 117 cm in length
- 80/20 Ar/CO_2 with HV < 1500 V





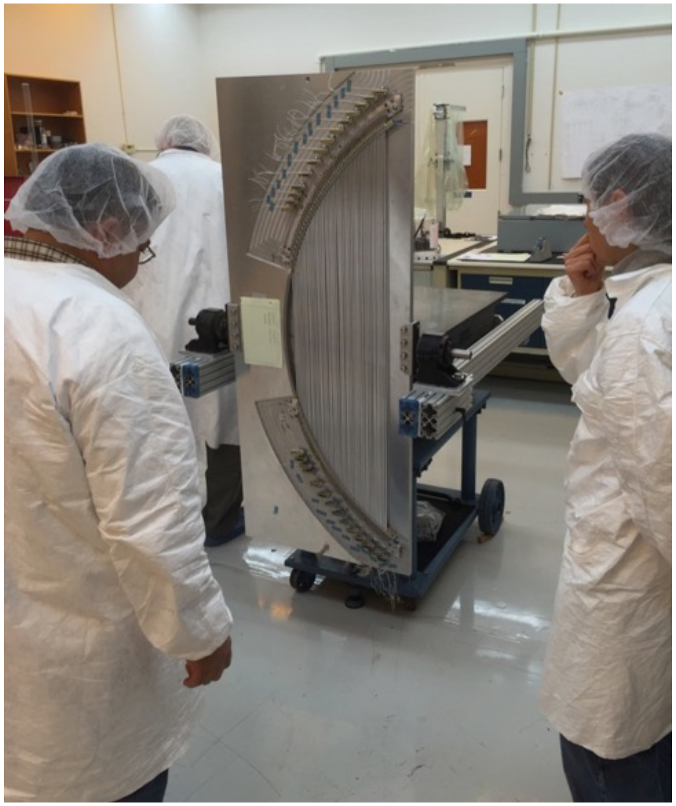
The Mu2e Tracker





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

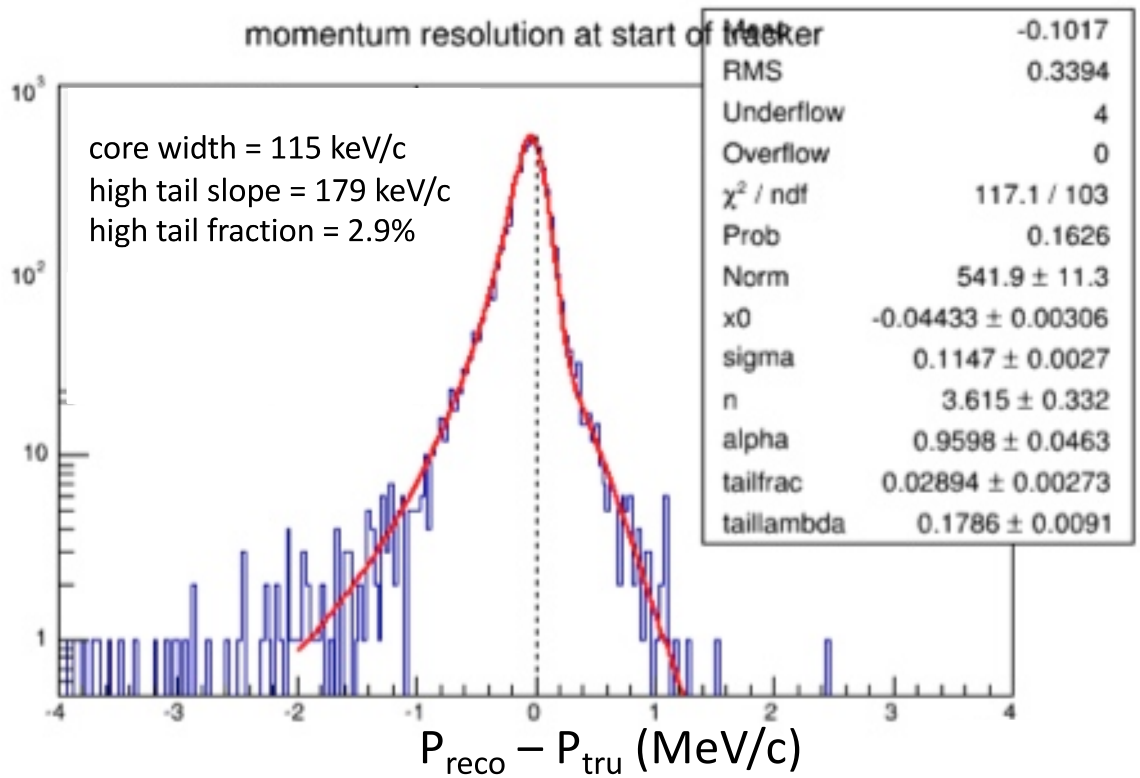
First Prototype Panel



Fermilab, March 2015

- Starting pre-production prototype now

Mu2e Spectrometer Performance



- Performance well within physics requirements
  115 keV/c momentum resolution

The Mu2e calorimeter

The calorimeter has to:

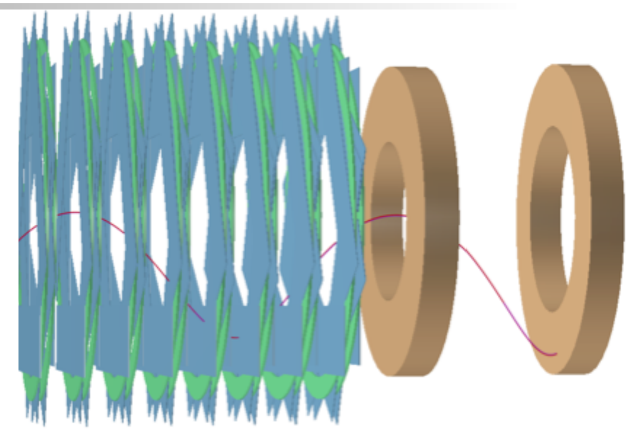
- Provide high e- reconstruction efficiency for μ rejection of 200
- Provide cluster-based additional seeding for track finding
- Provide online software trigger capability
- Stand the radiation environment of Mu2e
- Operate for 1 year w.o. interruption in DS w/o reducing performance

the calorimeter needs to fulfill the following

→ Provide energy resolution σ_E/E of O(6 %)
→ Provide timing resolution σ(t) < 200 ps
→ Provide position resolution < 1 cm
→ Provide almost full acceptance **for CE signal @ 100 MeV**
→ Redundancy in FEE and photo-sensors

A crystal based disk calorimeter

The Mu2e Calorimeter



High granularity crystal based calorimeter with:

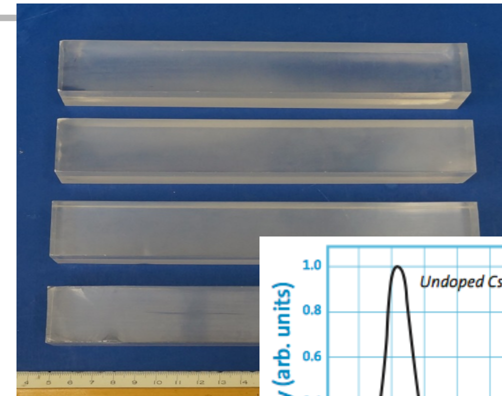
- 2 Disks (Annuli) geometry to optimize acceptance for spiraling electrons
- Crystals with high Light Yield for timing/energy resolution → **LY(photosensors) > 60 pe/MeV**
- **2 photo-sensors/preamps/crystal** for redundancy and reduce MTTF requirement → now set to 1 million hours/SIPM
- Fast signal for Pileup and Timing resolution → **τ of emission < 40 ns + Fast preamps**
- **Fast WFD to disentangle signals in pileup**
- **Crystal dimension optimized** to stay inside DS envelope
  → reduce number of photo-sensor, FEE, WFD (cost and bandwidth)
  while keeping pileup under control and position resolution < 1 cm.
- Crystals and sensors should work in 1 T B-field and in vacuum of 10^{-4} Torr and:

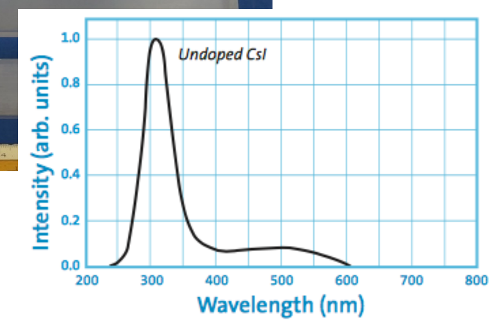
→ **Crystals survive a dose of 100 krad and a neutron fluency of 10^{12} n/cm^2**

→ **Photo-sensors survive 20 krad and a neutron fluency of 3×10^{11} n_1MeV/cm^2**

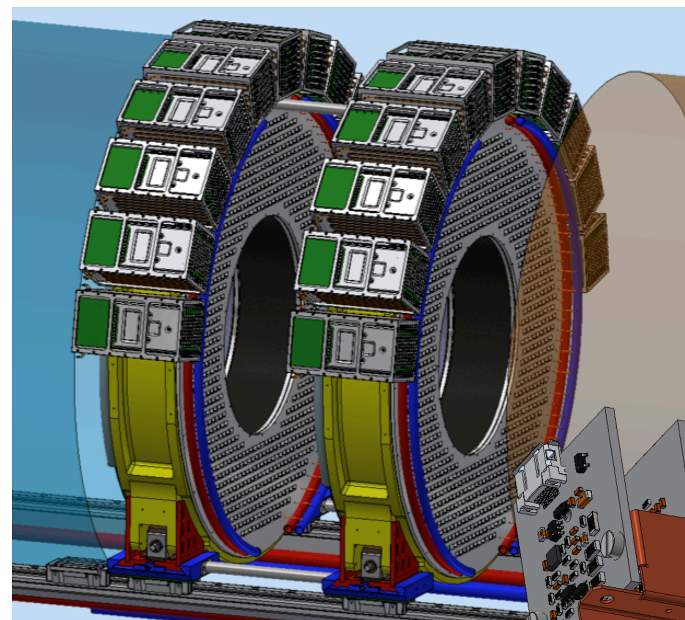
The Mu2e Calorimeter

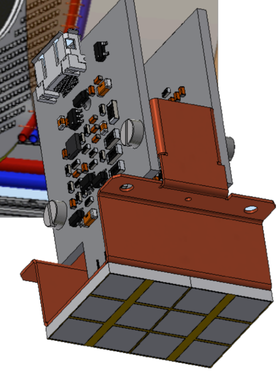
The Calorimeter consists of two disks containing 674 34x34x200 mm^3 pure CsI crystals each



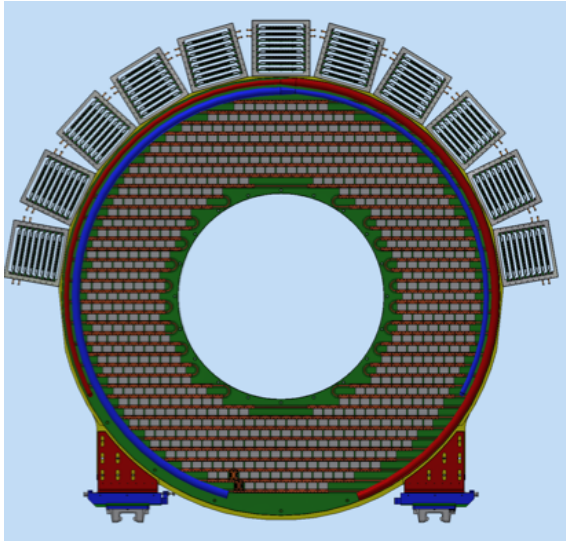


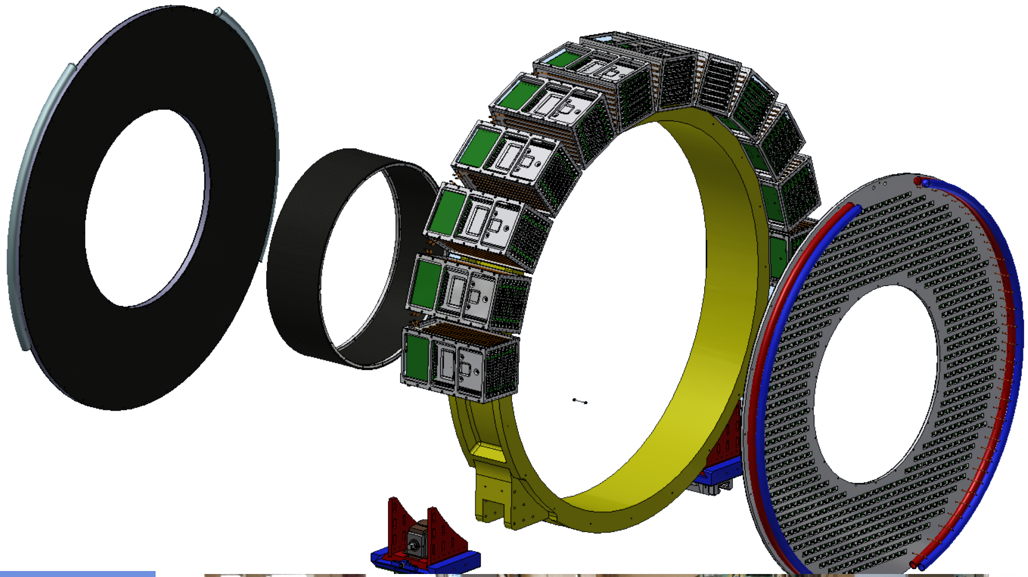
- → R_{inner} = 374 mm, R_{outer}=660 mm, depth = 10 X_0 (200 mm)
- → Disks separated by 75 cm, half helix length
- → Each crystal is readout by two large area UV extended SIPM's (14x20 mm^2) maximizing light collection. PDE=30% @ CsI emission peak =315 nm. GAIN ~10^6
- → TYVEK wrapping
- → Analog FEE is onboard to the SiPM (signal amplification and shaping) and digital electronics located in electronics crates (200 MhZ sampling)
- → Cooling system – SiPM cooling, Electronic dissipation
- → Radioactive source and laser system provide absolute calibration and monitoring capability

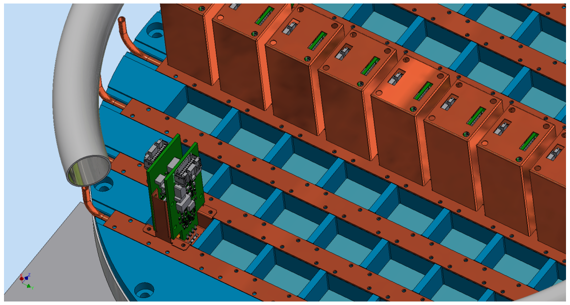


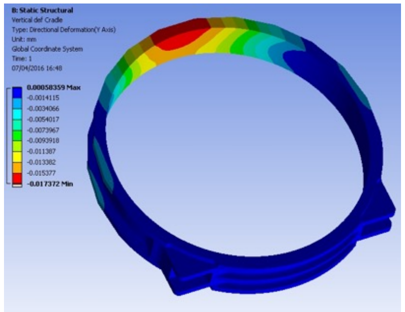


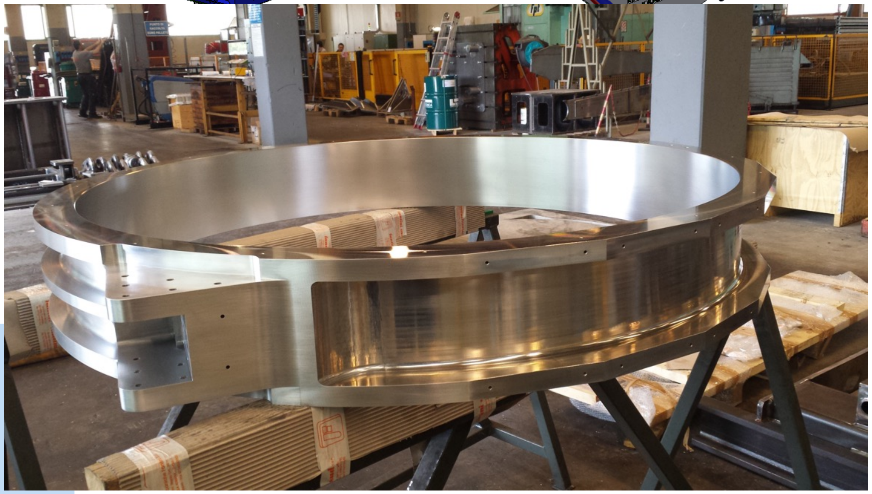
The Calorimeter engineering

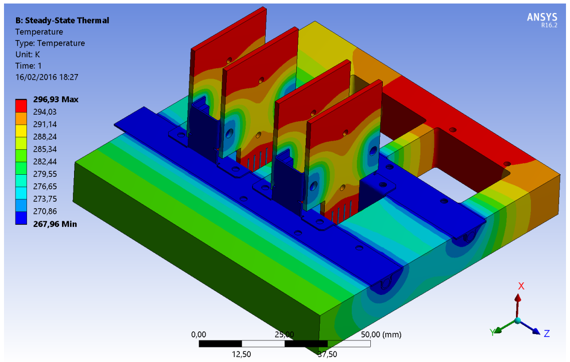


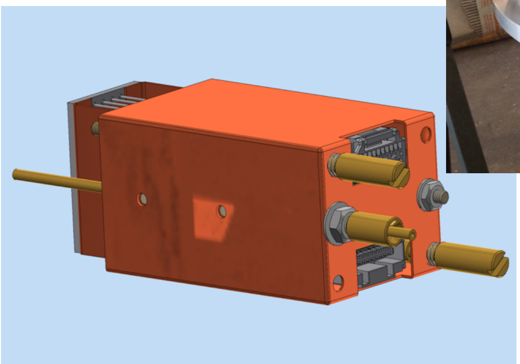




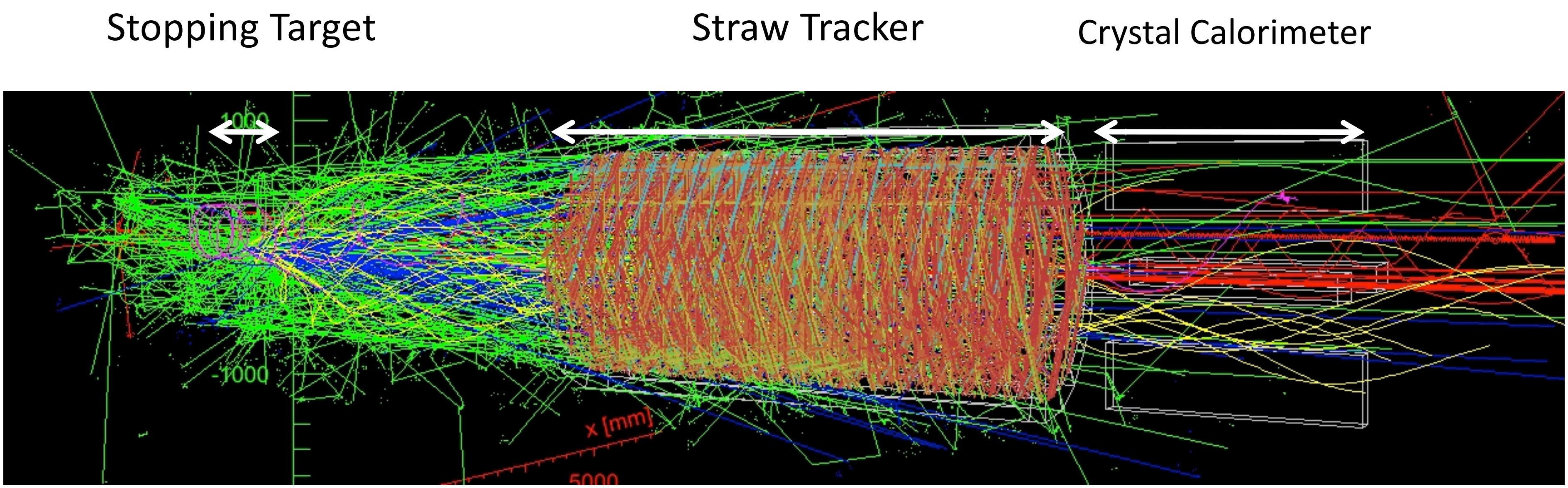




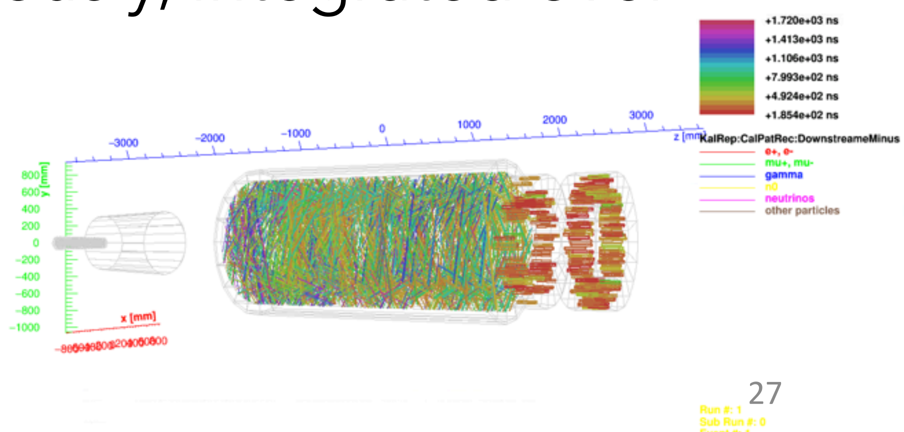




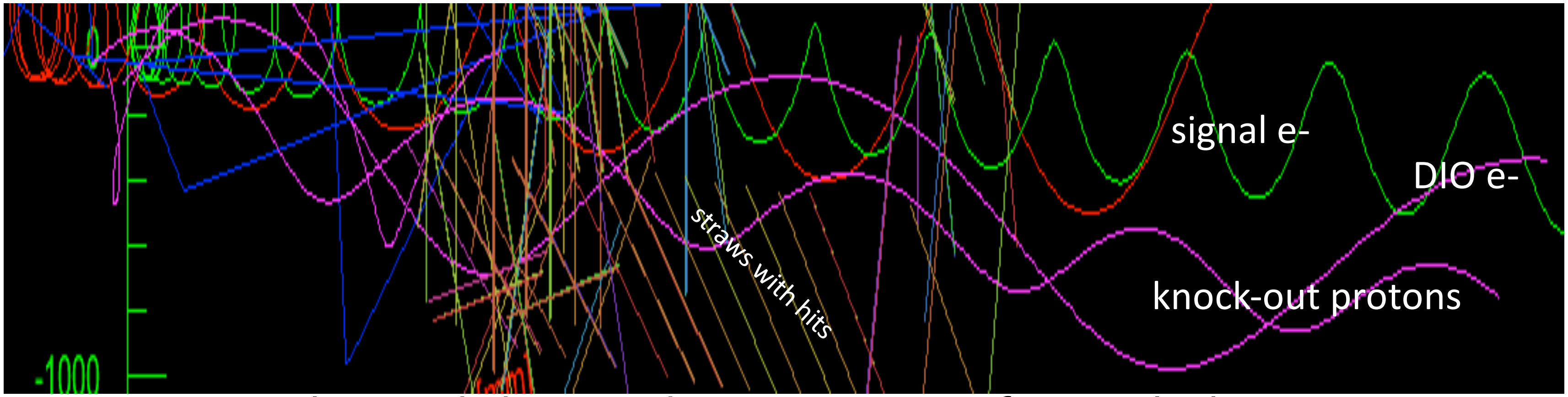
Mu2e Pattern Recognition



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

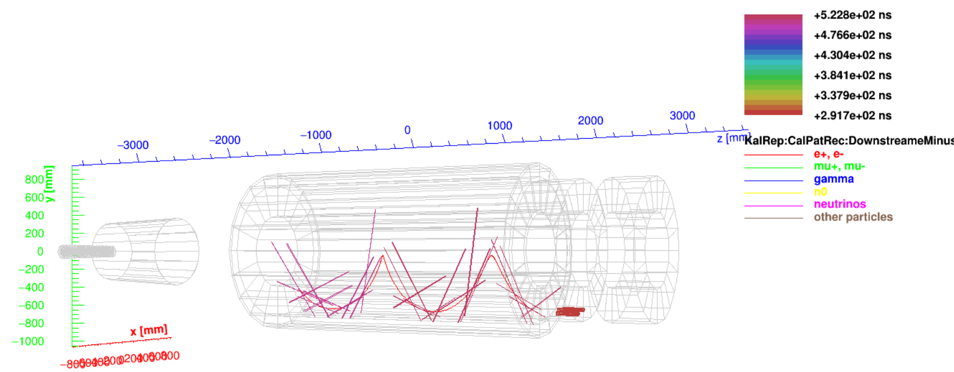


Mu2e Pattern Recognition



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

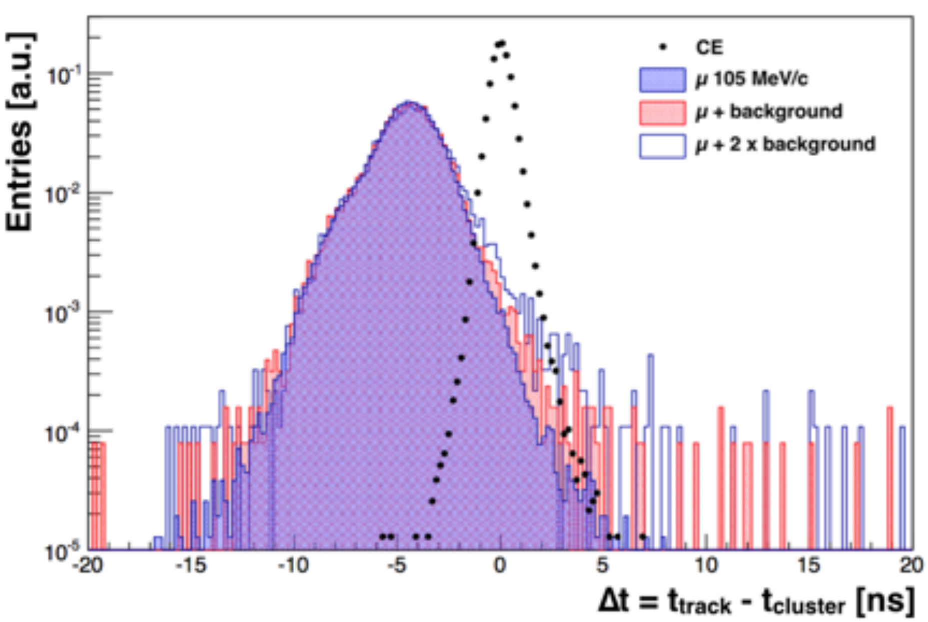
- Search for tracking hits with time and azimuthal angle compatible with the calorimeter clusters ($|\Delta T| < 50$ ns) → simplification of pattern recognition
- Add search of an Helix passing through cluster and selected hits + use calorimeter time to calculate tracking Hit drift times
- Reduce the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

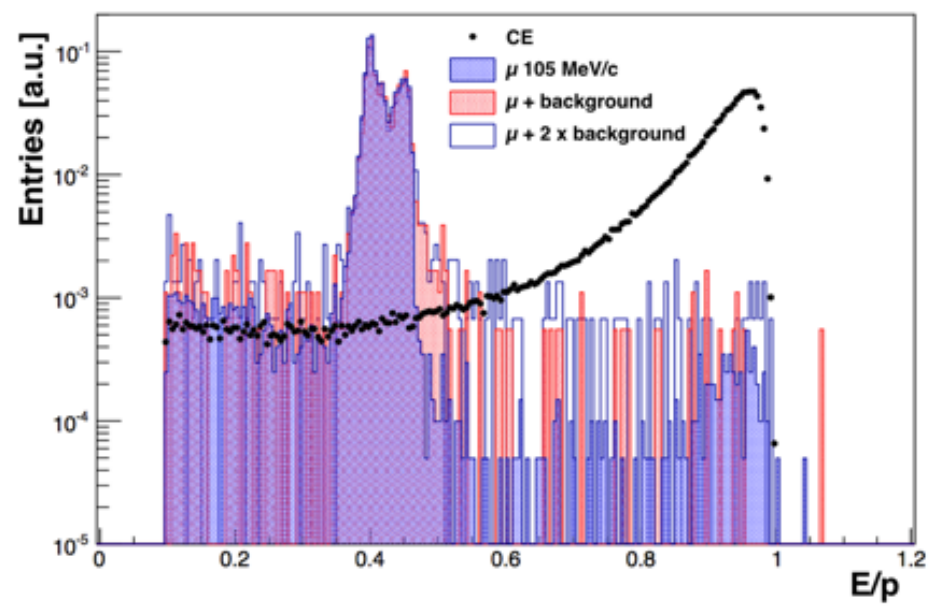


Cosmic μ rejection

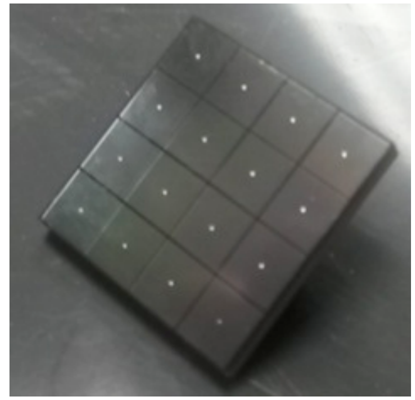
- 105 MeV/c e^- are ultra-relativistic, while 105 MeV/c μ have β ~ 0.7 and a kinetic energy of ~ 40 MeV;
- Likelihood rejection combines **Δ**t = t_{track} - $t_{cluster}$ and E/p:

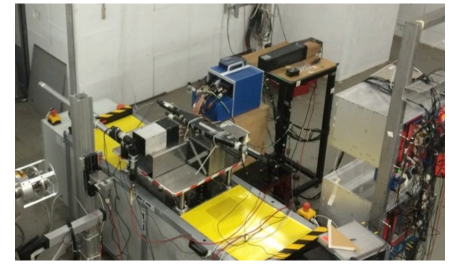
$$\ln L_{e,\mu} = \ln P_{e,\mu}(\Delta t) + \ln P_{e,\mu}(E/p)$$



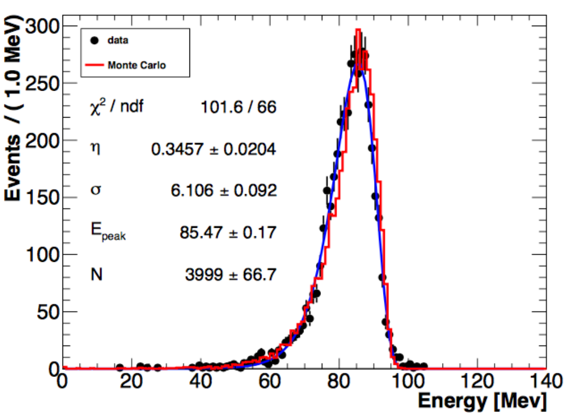


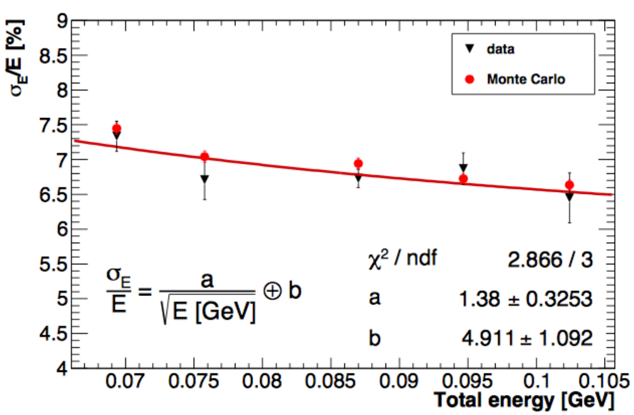
CsI+MPPC tests

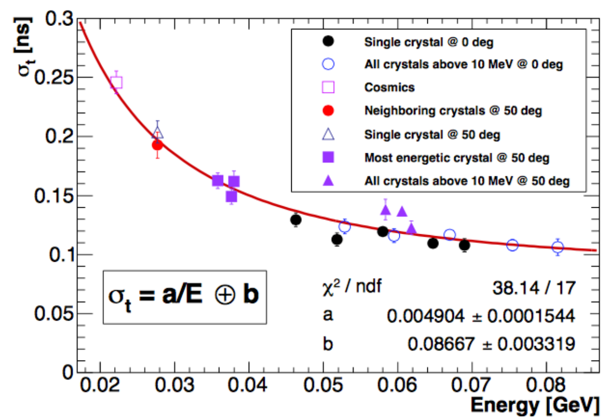




- A small crystal prototype has been built and tested in Frascati in April 2015
- 3x3 matrix of 3x3x20 cm^3 un-doped CsI crystal coupled with UV-extended MPPC.
- Test with e- between 80 and 120 MeV



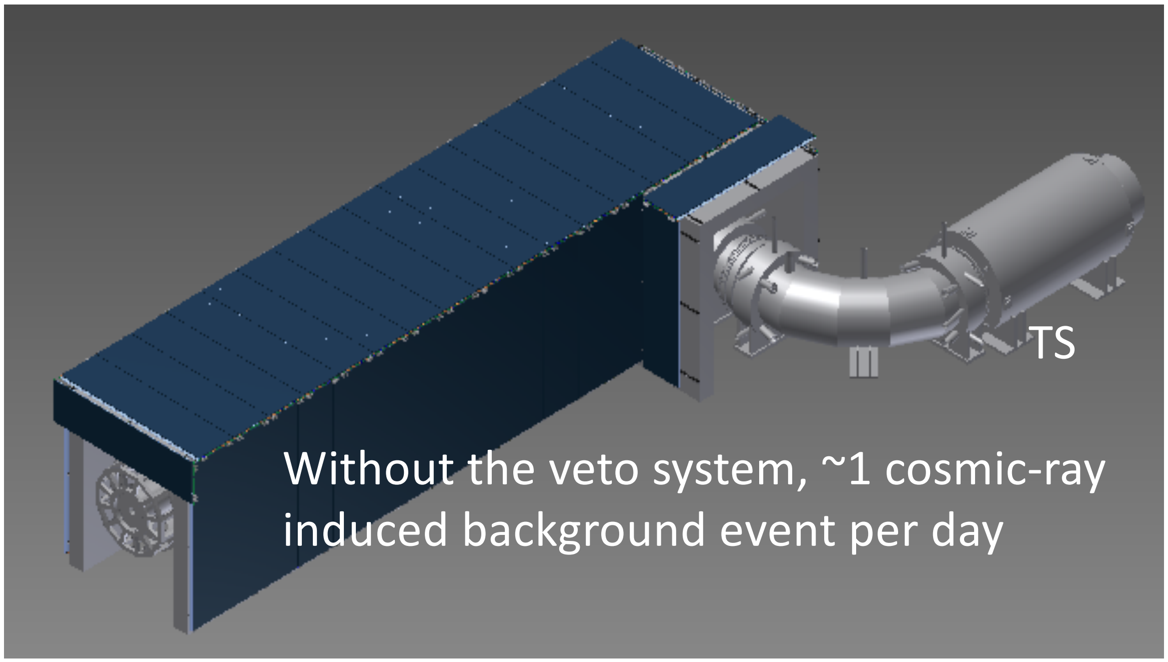


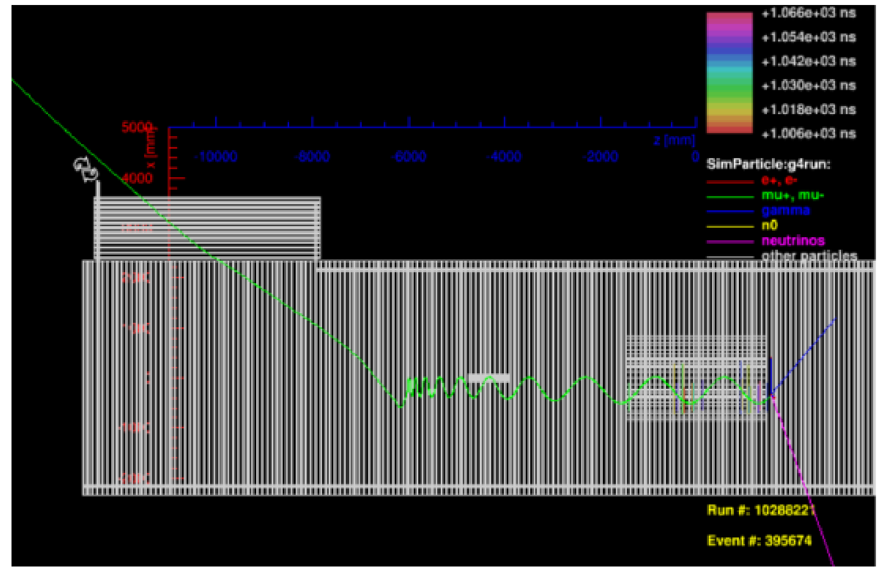


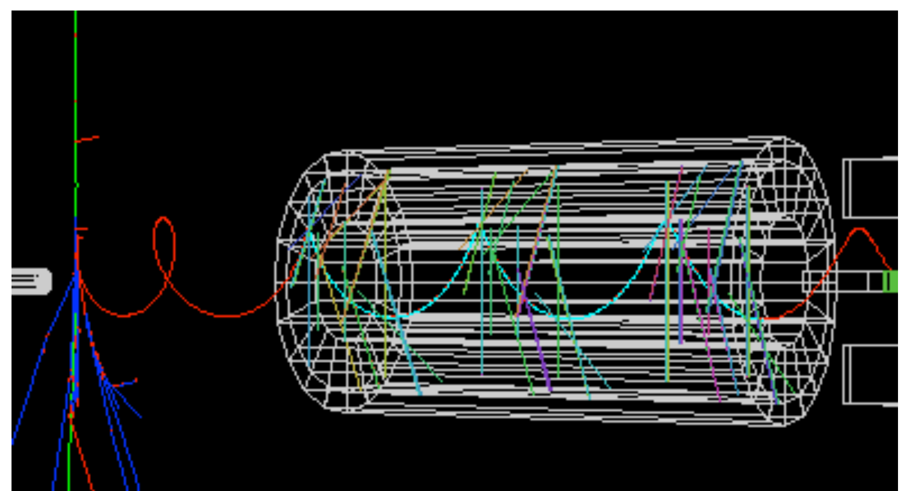
- @100 MeV: Good energy (6-7%) and timing (110 ps) resolution
- Leakage dominated

The Cosmic ray Veto

Veto system covers entire DS and half TS

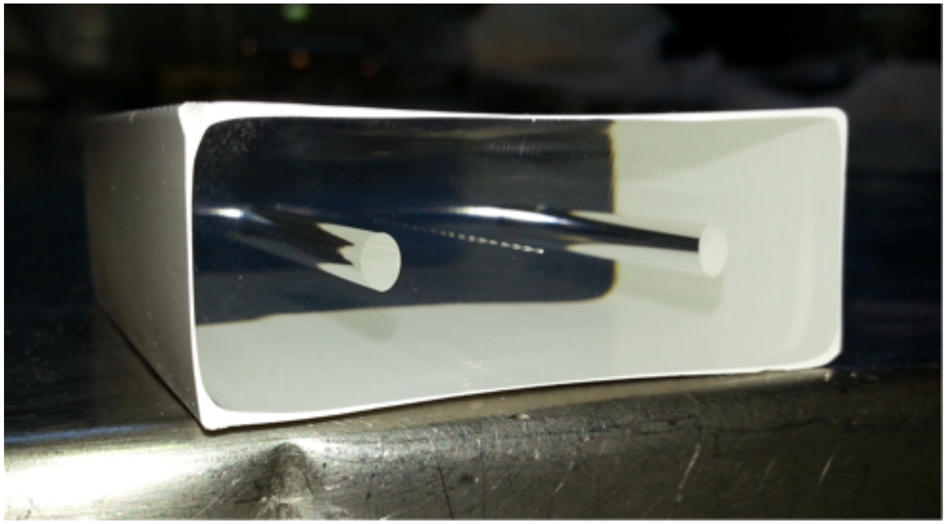


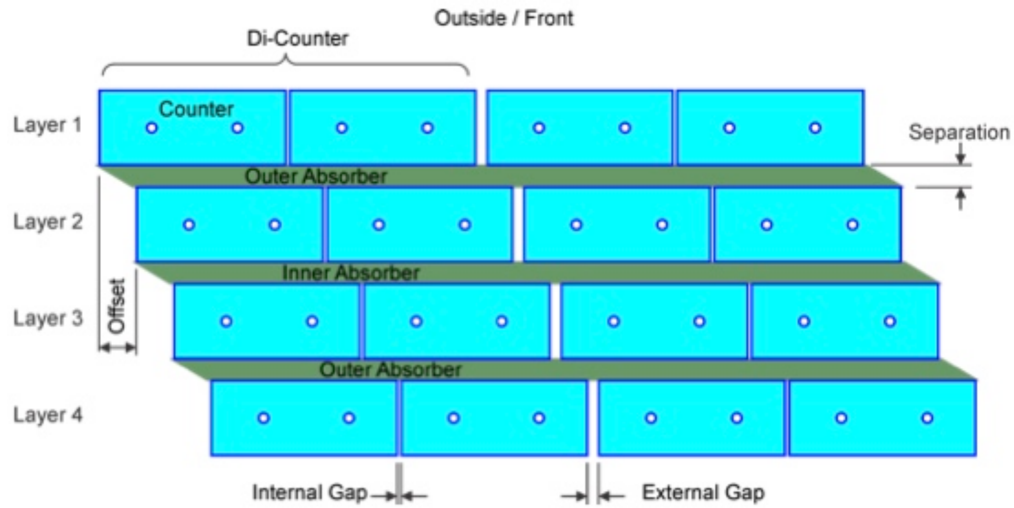




Cosmic μ can generate background events via decay, scattering, or material interactions

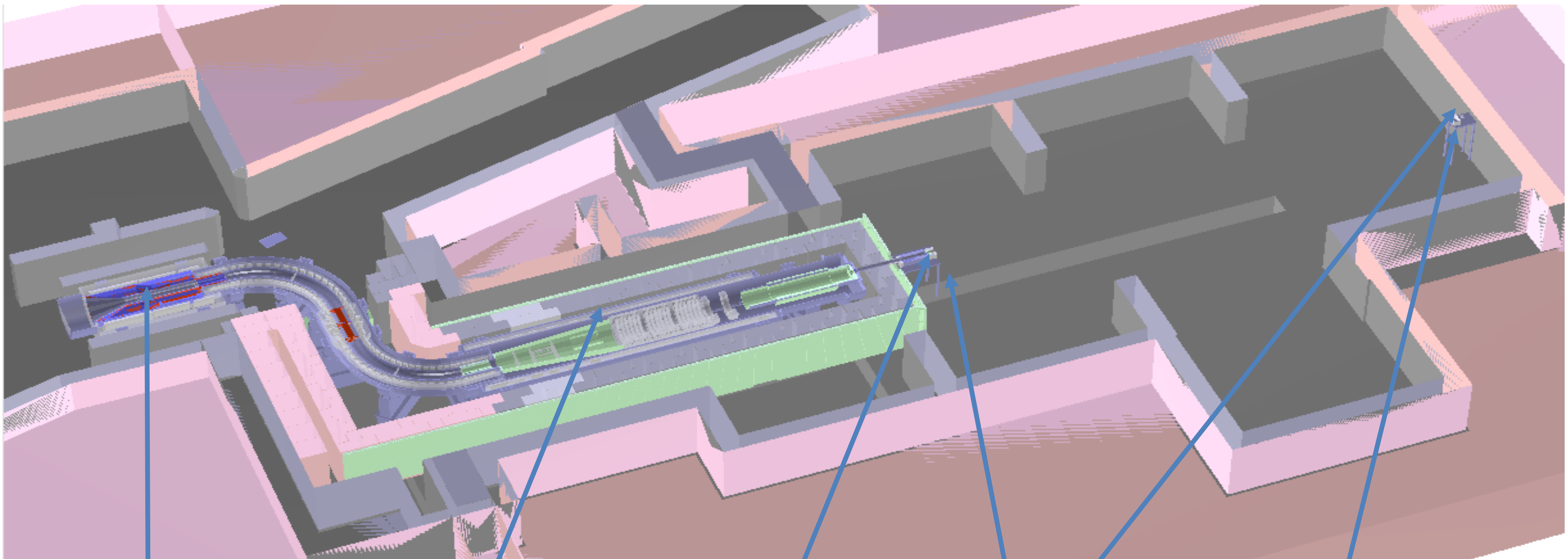
Mu2e Cosmic-Ray Veto





- 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 e > 99.4% (per layer) in test beam

Normalization, $R = \frac{\Gamma(\mu Al \rightarrow eAl)}{\Gamma_{capture}(\mu Al)}$



Design of Stopping Target monitor

- High purity Germanium (HPGe) detector
  - Determines the muon capture rate on Al to about 10% level
  - Measures X and γ rays from Muonic Al
    347 keV 2p-1s X-ray (80% of μ stops)
    844 keV γ-ray (4%)
    1809 keV eV γ-ray (30%)
- Downstream to the Detector Solenoid
- Line-of-sight view of Muon Stopping Target
- Sweeper magnet
  - Reduces charged bkg
  - Reduces radiation damage

Apr 18, 2015: Mu2e groundbreaking

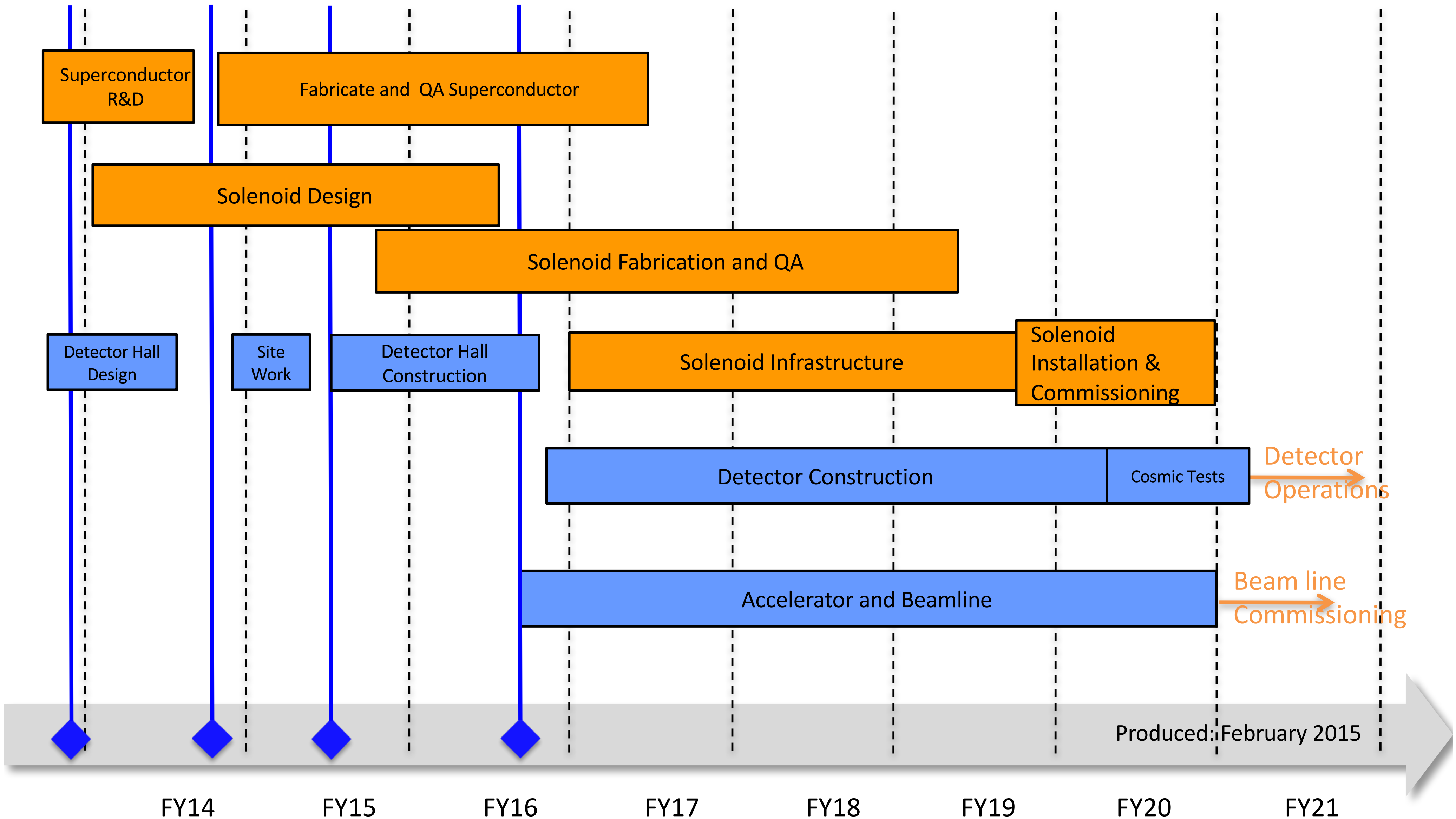
Mu2e Detector Hall

Graphic of proposed Mu2e Detector Hall

Construction well along

- Expect to warm it up sometime in the fall of 2016

Mu2e Schedule



F. Happacher

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 CD-3**

→ civil construction ongoing

→ Detector construction period 2017-2018 followed by installation in 2019