The Mu2e Experiment at Fermilab

Fabio Happacher, LNF-INFN
On behalf of the Mu2e Collaboration

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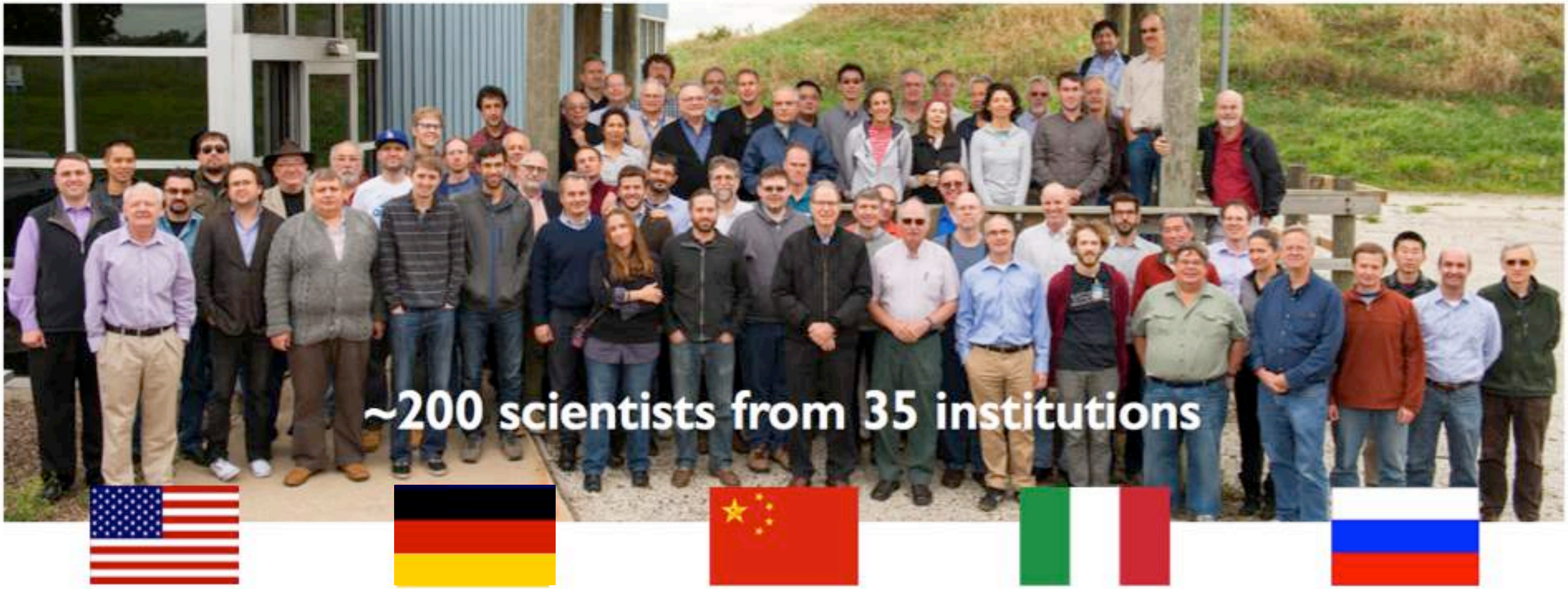
Laboratori Nazionali di Frascati

Fermilab

The Mu2e collaboration



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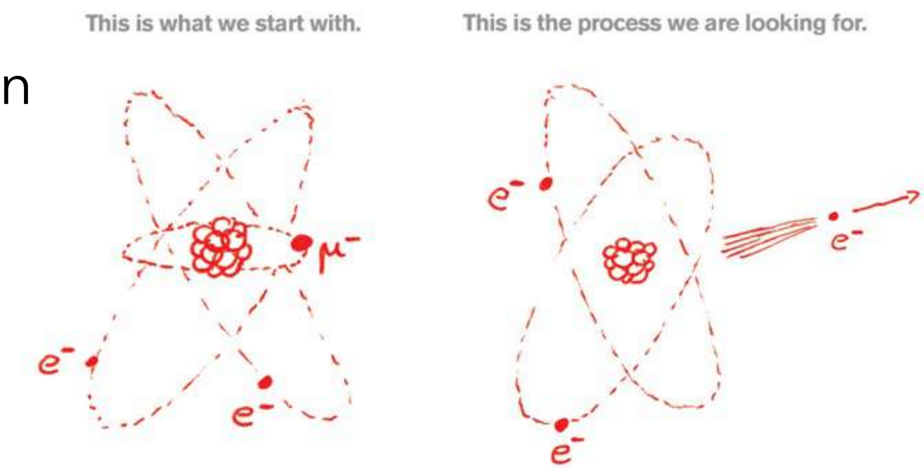
Presentation outline

- 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



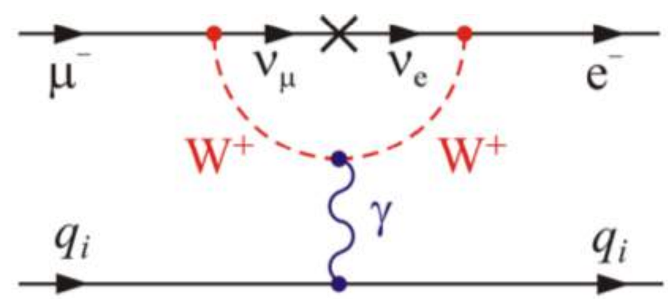
- Will use current Fermilab accelerator complex to reach a single event sensitivity of 2.4 x10^{-17}sensitivity 10^4 better than current world's best
- Will have *discovery* sensitivity over broad swath of New Physics parameter space
- Mu2e will detect and count the electrons coming from the conversion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

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

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

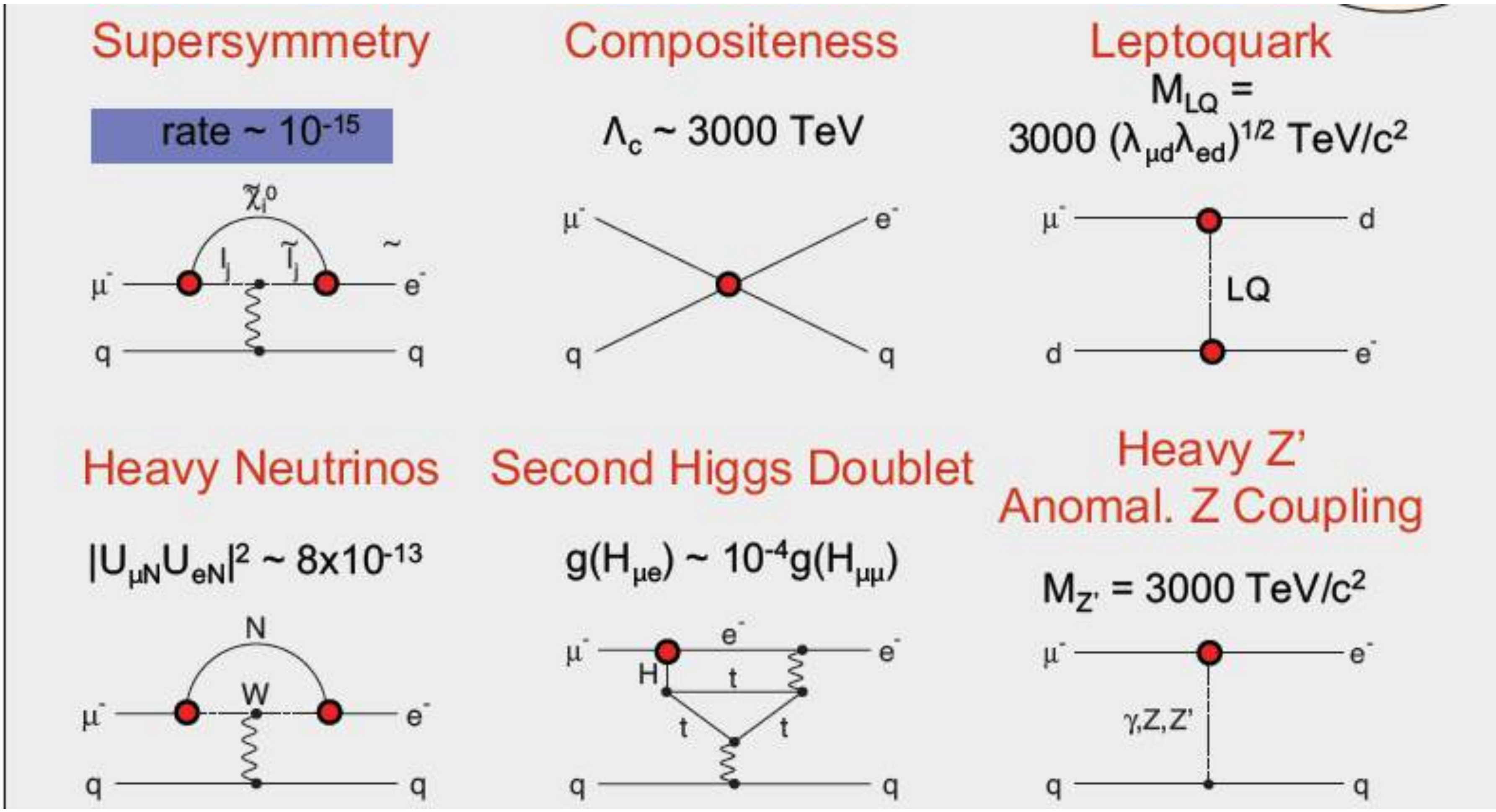
- Muon-to-electron conversion is similar but complementary to other CLFV processes as μ→ eγ and μ → 3e.
- The Mu2e experiment searches for muon-to-electron conversion in the coulomb field of a nucleus: $\mu^- Al \to e^- Al$
- CLFV processes are strongly suppressed in the Standard Model
  - it is not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

    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'

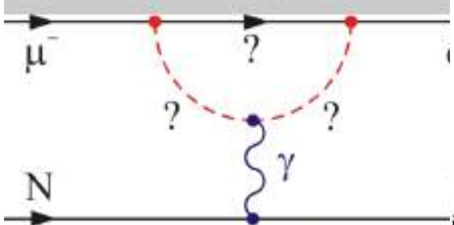
μ->e is a signature of NP models



Mu2e Sensitivty

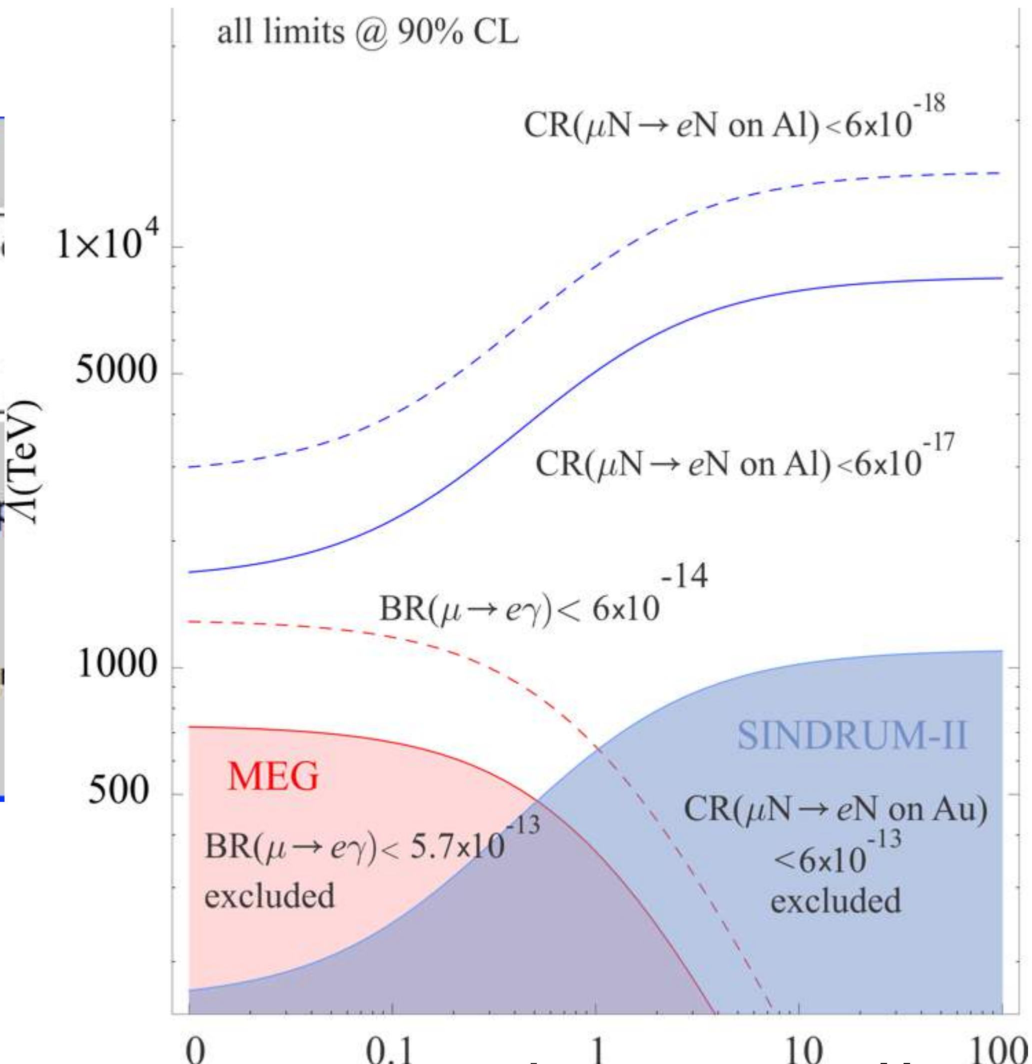
$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

Loops

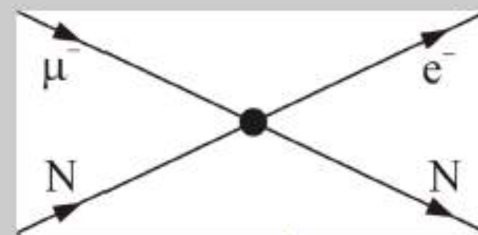


κ<< 1
magnetic moment typ
operator

μ→ eγ rate ~300X μN → eN r



Contact Interactions



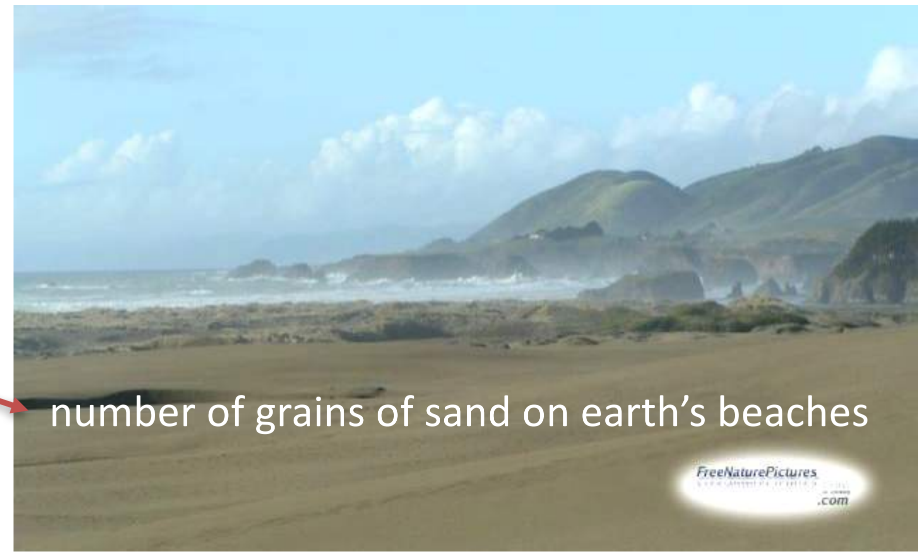
κ>> 1
four-fermion
interaction

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 $\mu N \rightarrow eN$

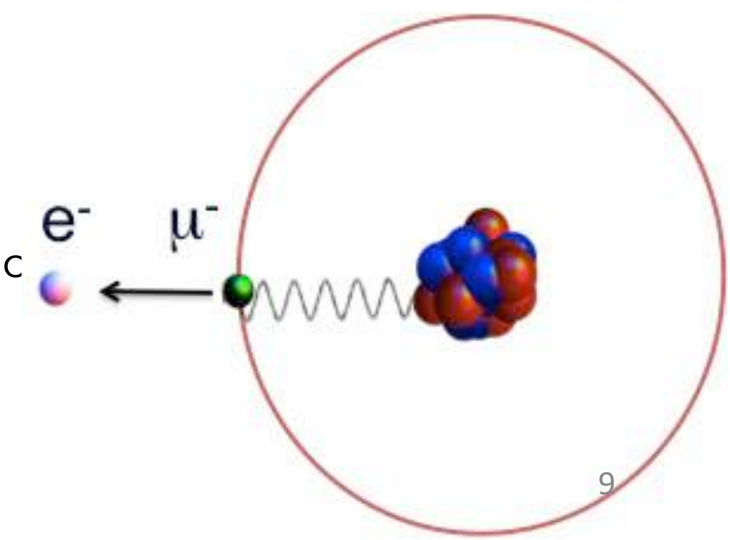
Mu2e Signal

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

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

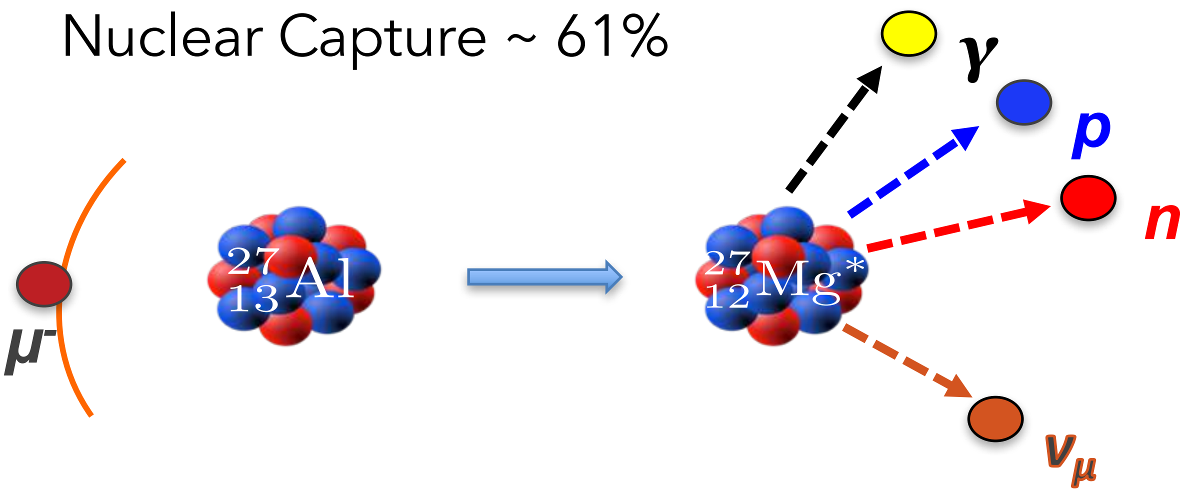
  generating a flux of p,n and γ
- Neutrinoless muon to electron conversion $\mu^- + Al \rightarrow e^- + Al$

  - 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



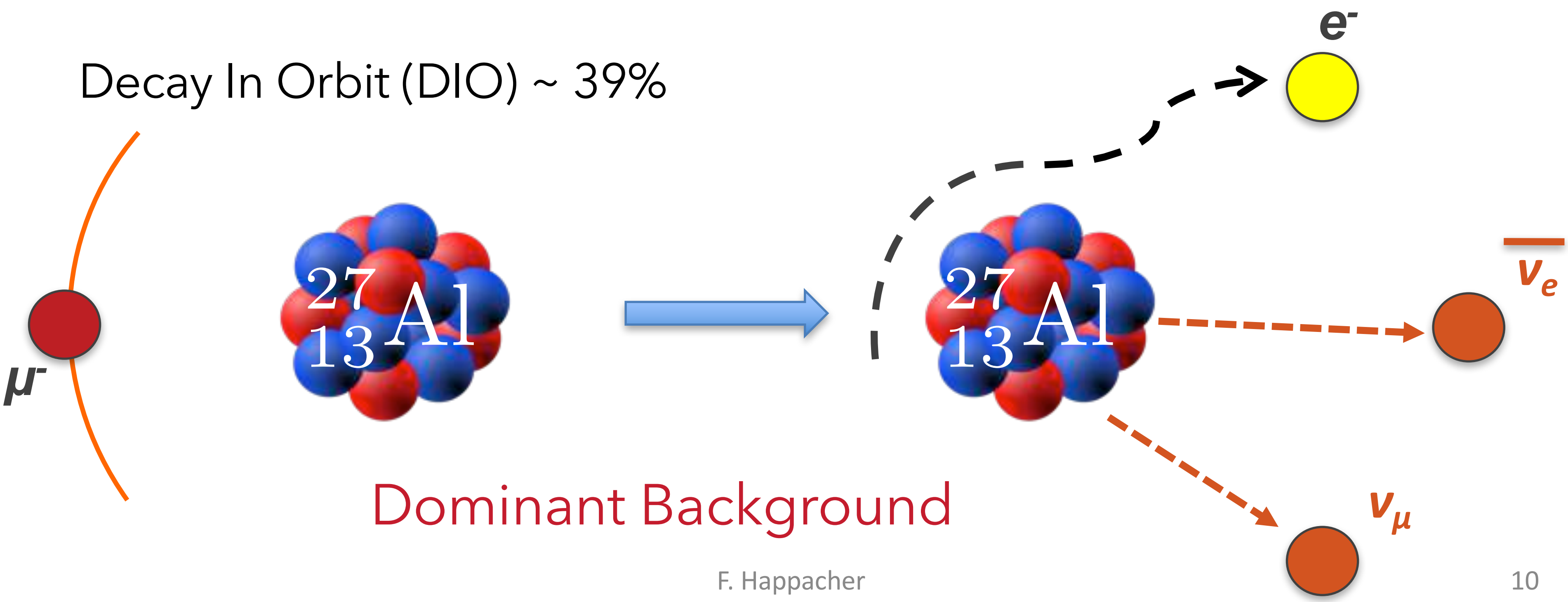
Mu2e processes

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

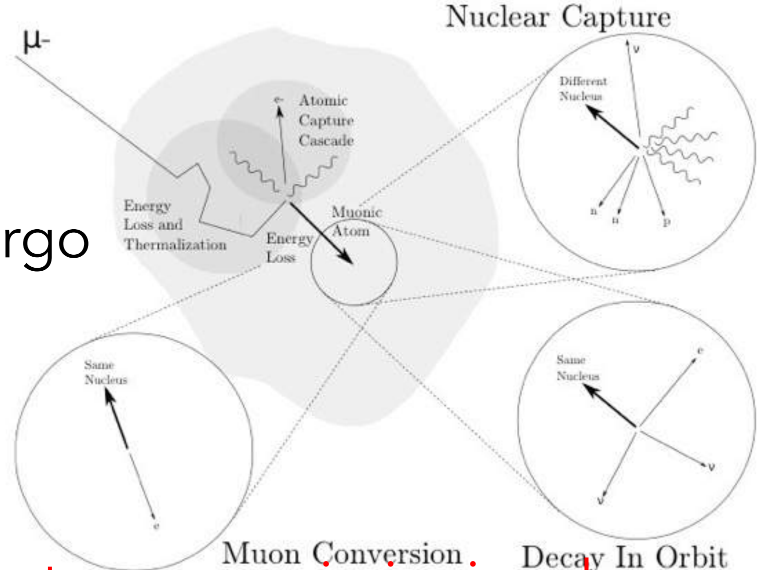
- Pions from the muon beam can undergo radiative capture (RPC)

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

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

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

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

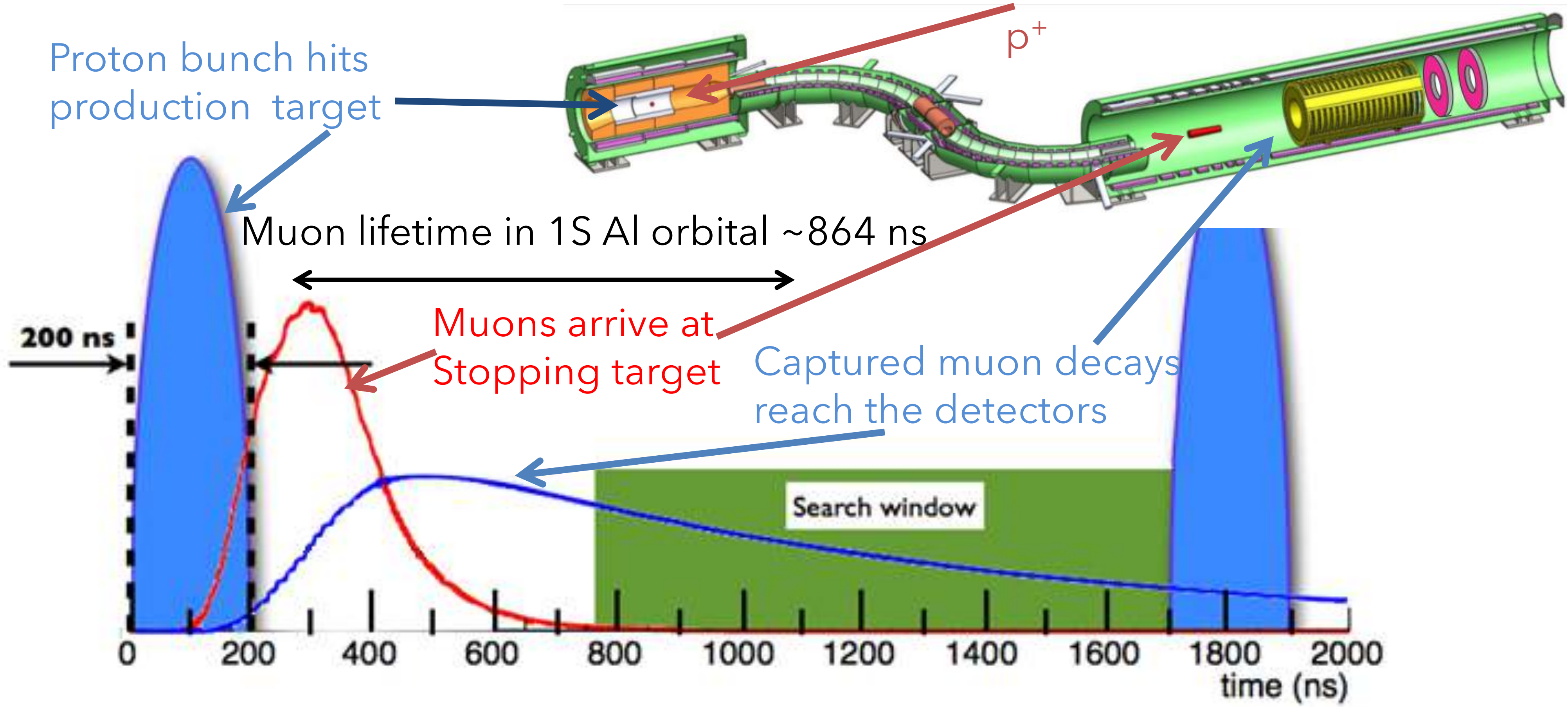


Category	Background process	Estimated yield (events)
Intrinsic	Muon decay-in-orbit (DIO)	0.199 ± 0.092
	Muon capture (RMC)	$0.000^{+0.004}_{-0.000}$
Late Arriving	Pion capture (RPC)	0.023 ± 0.006
	Muon decay-in-flight (μ-DIF)	<0.003
	Pion decay-in-flight (π-DIF)	$0.001 \pm <0.001$
	Beam electrons	0.003 ± 0.001
Miscellaneous	Antiproton induced	0.047 ± 0.024
	Cosmic ray induced	0.082 ± 0.018
	Total	0.36 ± 0.10

PROMPT vs Late arriving

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

Pulsed beam structure



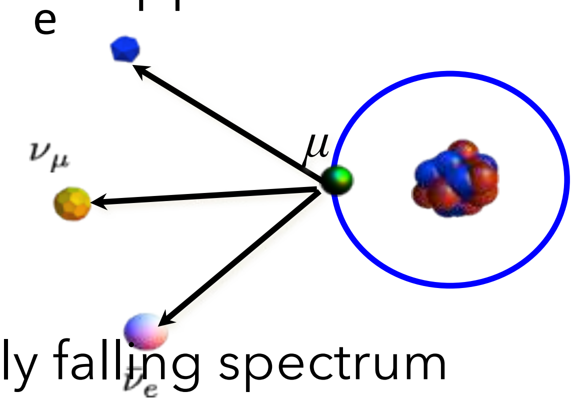
- ❑ Use the fact that muonic atomic lifetime >> prompt background
  Need a pulsed beam to wait for prompt background to reach acceptable levels
  → Fermilab accelerator complex provides ideal pulse spacing

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

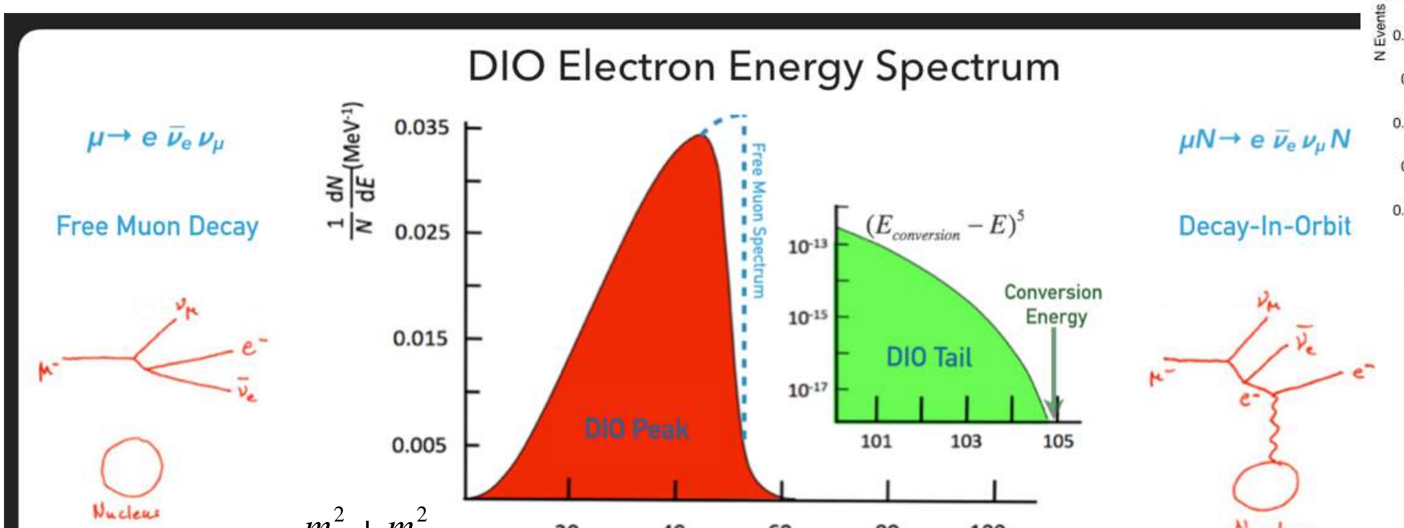
Muon from decay in orbit: DIO

- The most sneaky source of background comes from Stopped Muons

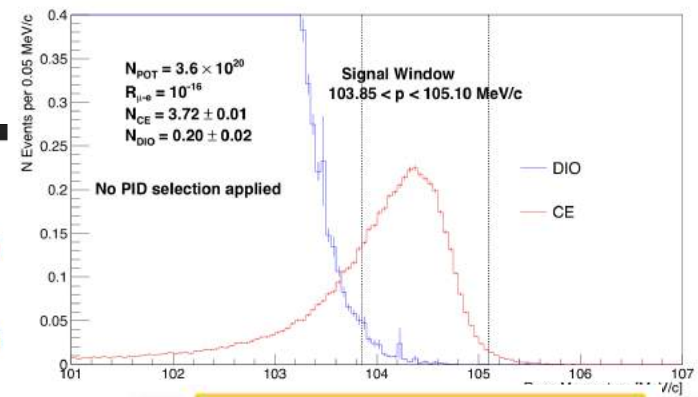
$$[\mu^- + A(N,Z)]^{1S}_{bound} \rightarrow A(N,Z) + e^- + \bar{\nu}_e + \nu_\mu$$

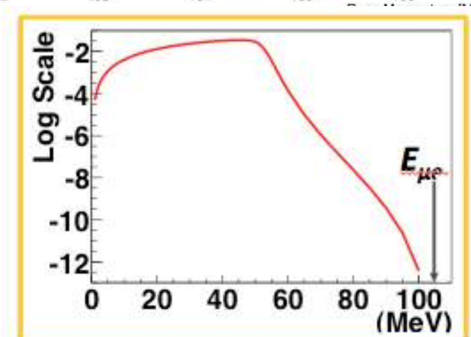


- Electrons from decay of bound muons (DIO)
- If the neutrinos are at rest the e^- can have exactly the conversion energy E_{CE}=104.97 MeV
- Recoil tail extends to conversion energy, with a rapidly falling spectrum near the endpoint
- Drives resolution requirements



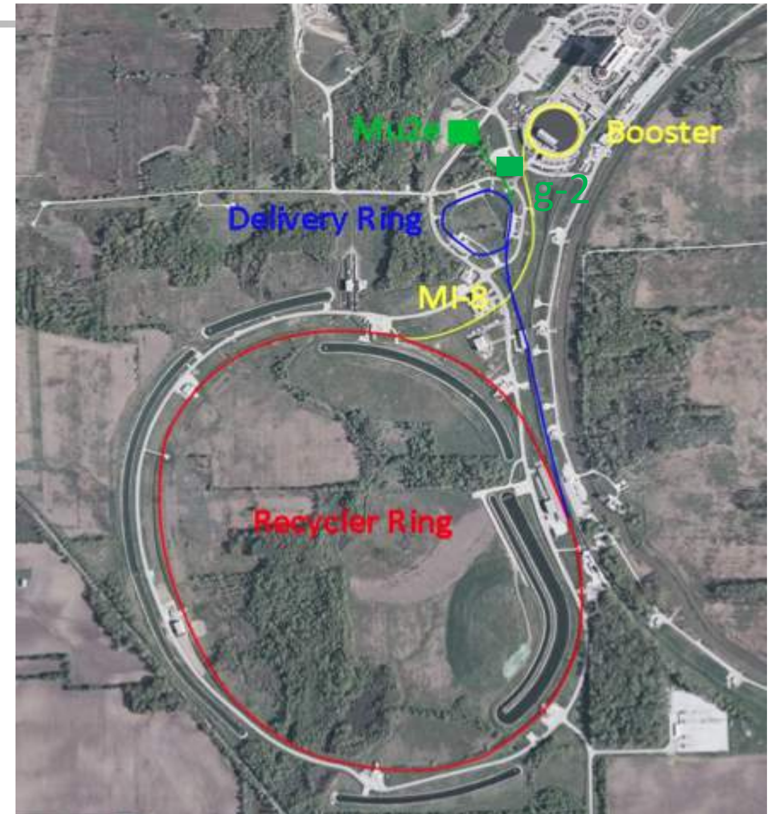
$$E_{max} = \frac{m_\mu^2 + m_e^2}{2m_\mu} \approx 52.8 \text{ MeV}$$





Accelerator Scheme & Proton extinction

- Booster: 21 batches of 4×10^{12} protons every $1/15^{th}$ 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 ~$3\text{x}10^7$ protons each, separated by 1.7 μs**



Proton Extinction

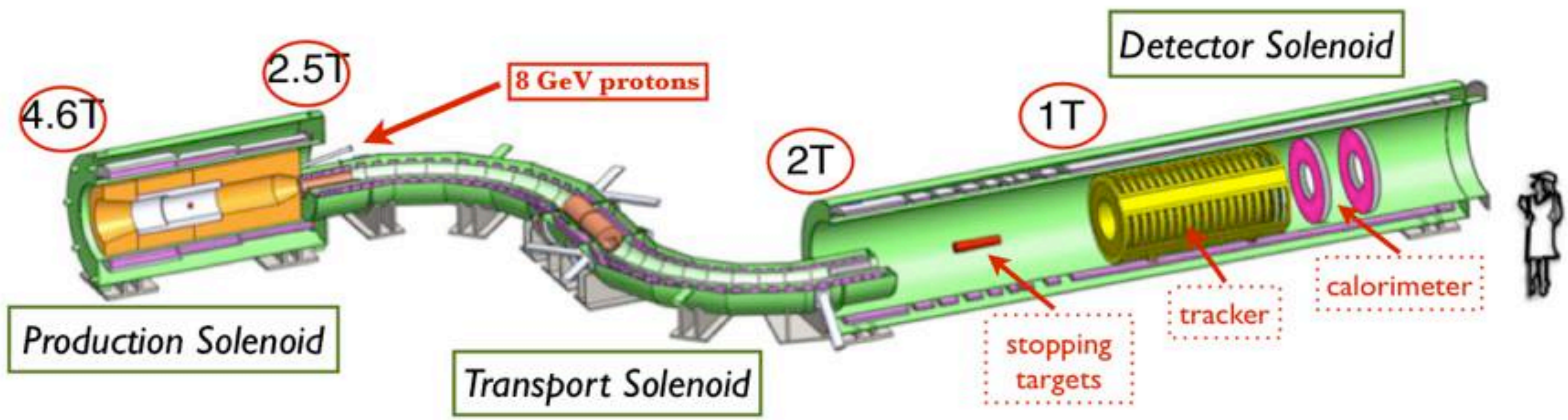
achieving 10^{-10} is hard; normally get $10^{-2} – 10^{-3}$

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

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

The Mu2e beamline

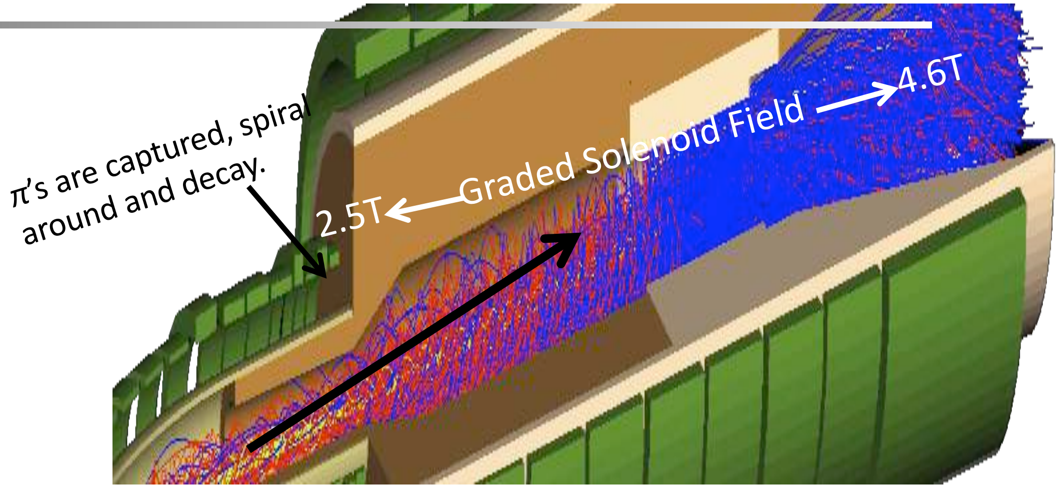
- Mu2e Solenoid System
  - Superconducting
    - Requires a cryogenic system
  - Inner bore evacuated to 10^{-4} Torr to limit background due to interactions of the charged particles with air



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 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



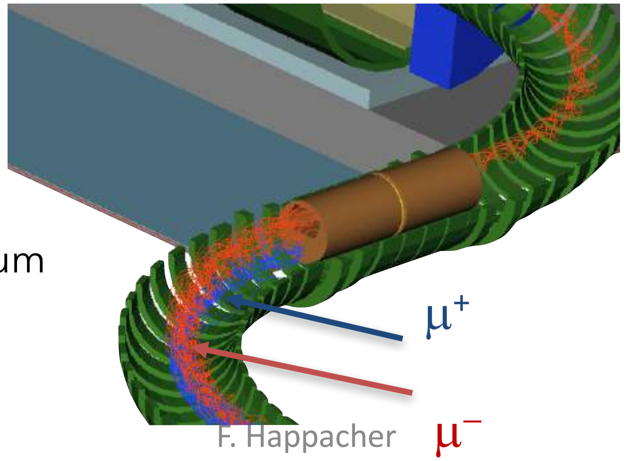
Pulsed beam of incident protons

- 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

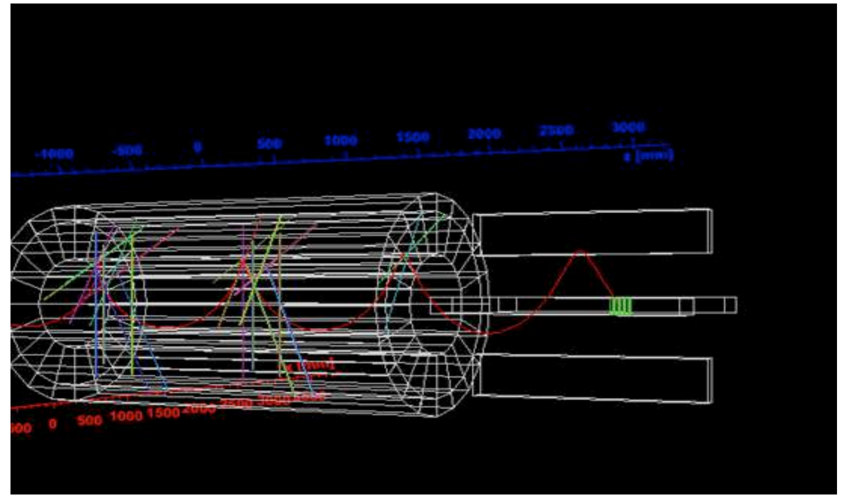
- No neutral particles produced in the production solenoid enter the detector solenoid, photons, neutrons

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

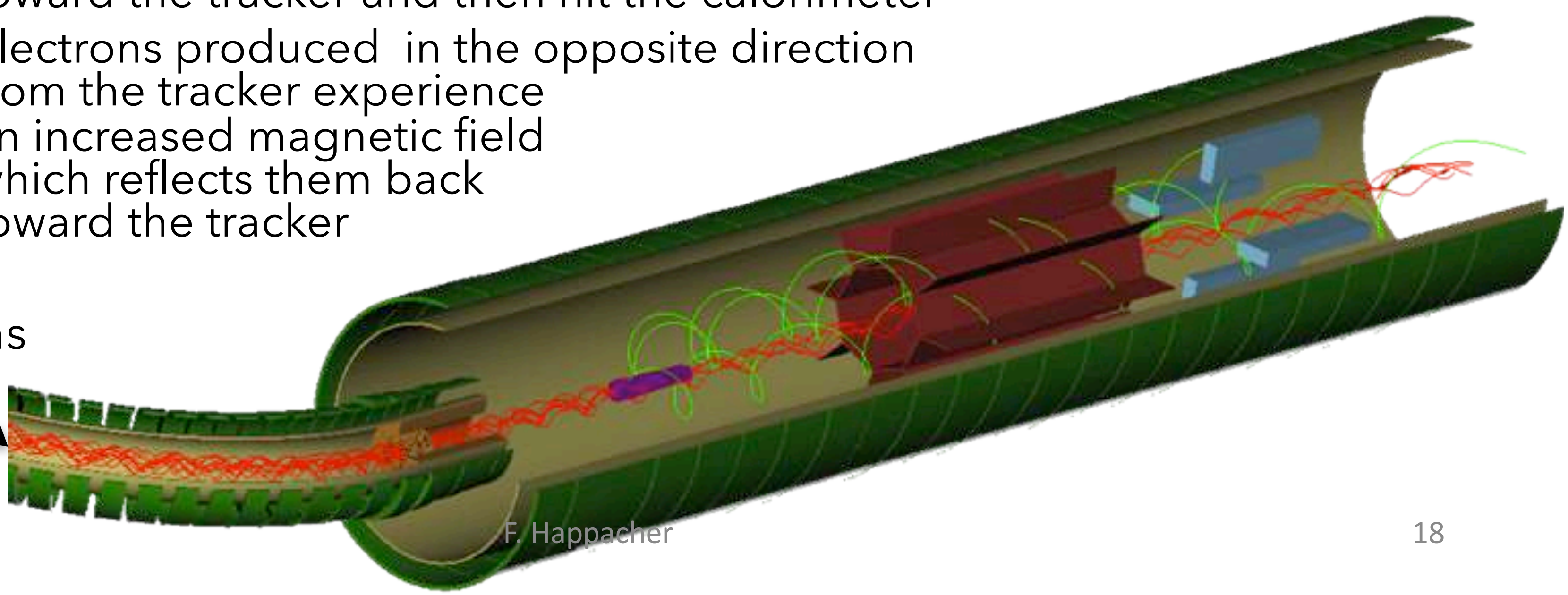
- The Detector Solenoid houses the Al target and the two main detectors: the tracker and the calorimeter



  – 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

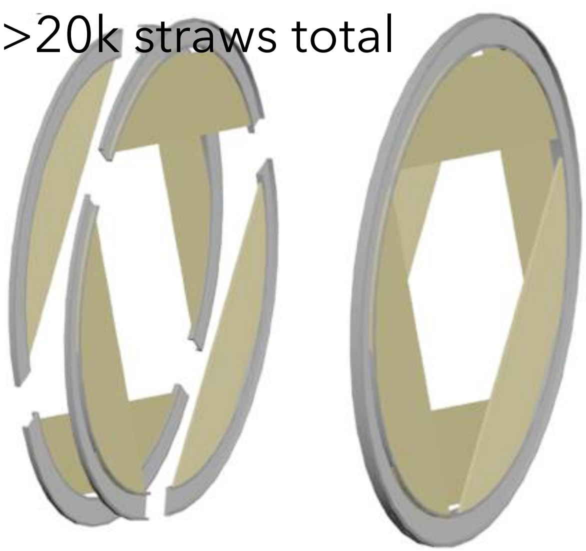
Negative muons

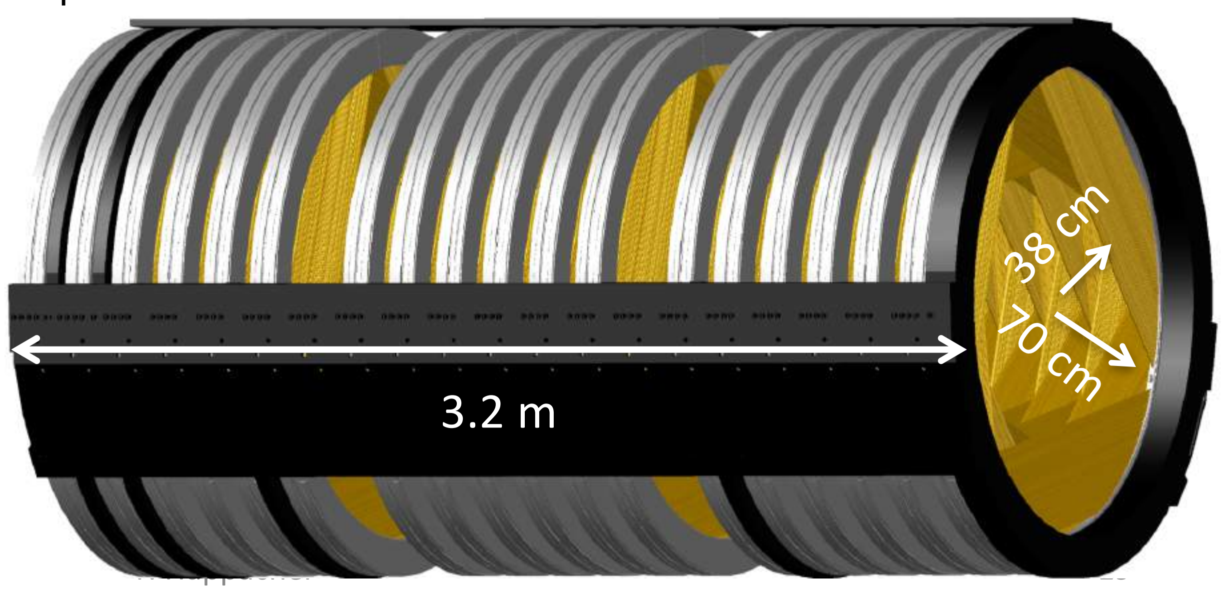


The Mu2e Tracker

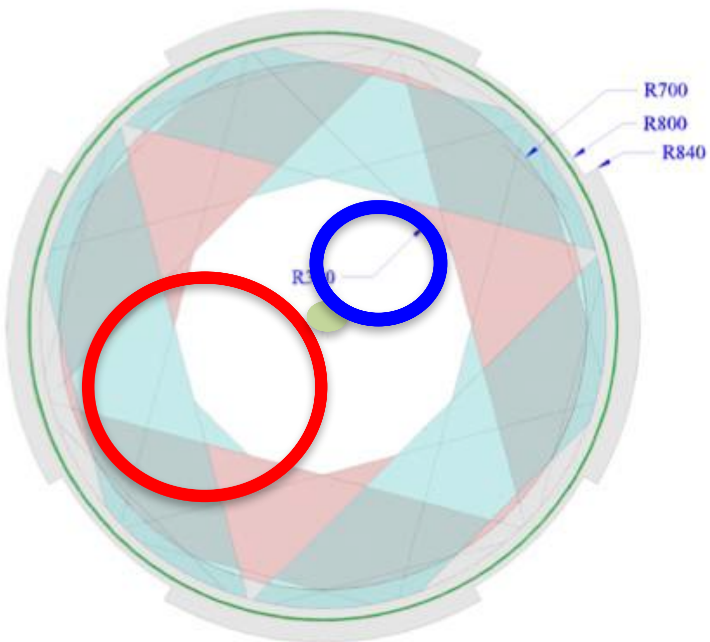
- The Tracker will employ low mass straw drift tubes with tubes transverse to secondary beam
- 15 mm thick straw walls, dual-ended readout (ADC-TDC) length 430 – 1120 mm.
- It must operate in vacuum
- Self-supporting "panel" consists of 100 straws
- 6 panels assembled to make a "plane"
- 2 planes assembled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

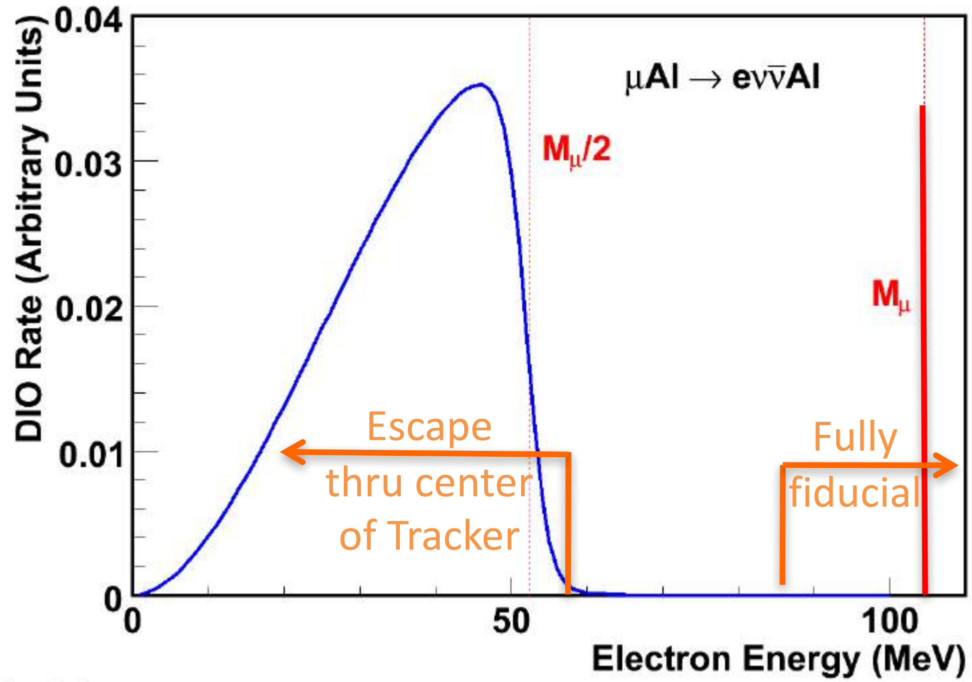
- 5 mm diameter straw
- Spiral wound
- Walls: 12 mm Mylar + 3 mm epoxy + 200 Å Au + 500 Å Al
- 25 μm Au-plated W sense wire
- 33 – 117 cm in length
- 80/20 Ar/CO_2 with HV < 1500 V





The Mu2e Tracker

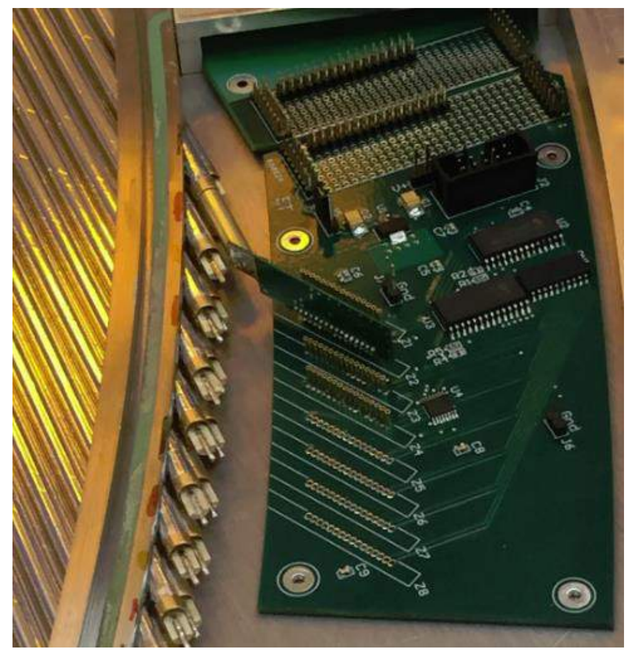




- Inner 38 cm is purposefully un-instrumented
  - Blind to beam flash
  - Blind to >99% of DIO spectrum

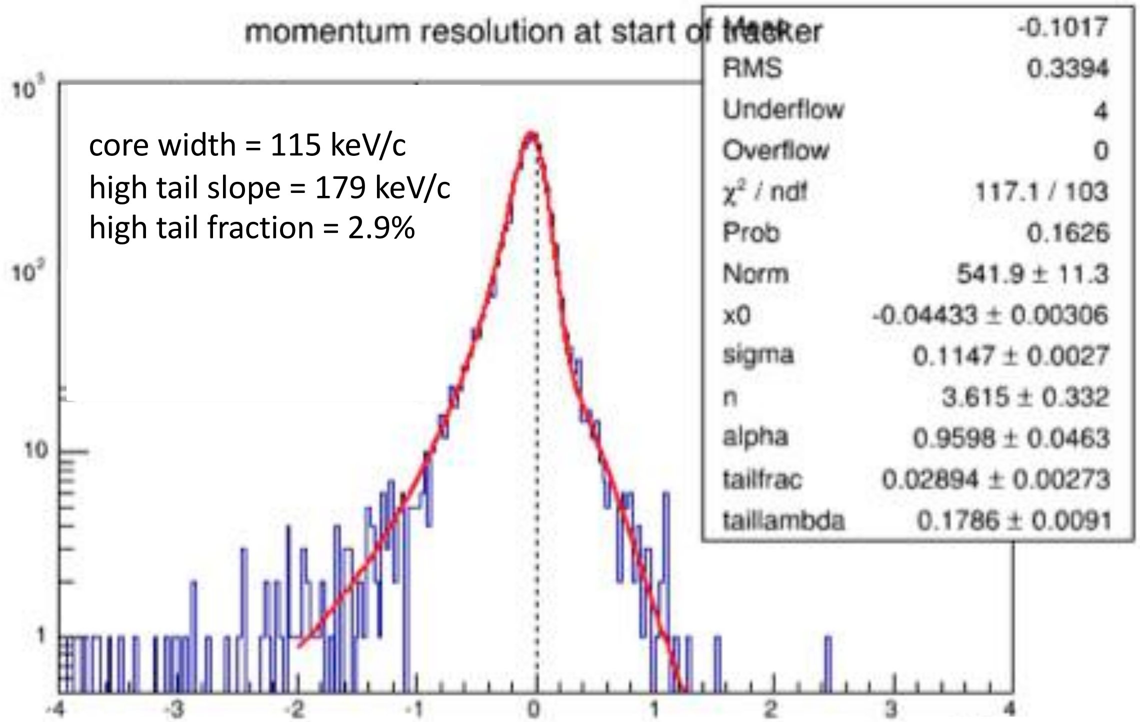
First Prototype Panel

Fermilab, March 2015



- Starting pre-production prototype now

Mu2e Spectrometer Performance



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

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

The Mu2e calorimeter

The calorimeter has to:

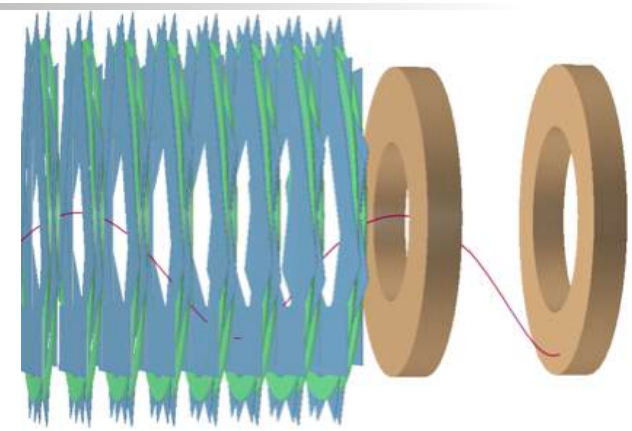
- Provide high e- reconstruction efficiency for μ rejection of 200
- Provide cluster-based additional seeding for track finding
- Provide online software trigger capability
- Stand the radiation environment of Mu2e
- Operate for 1 year w.o. interruption in DS w/o reducing performance

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:

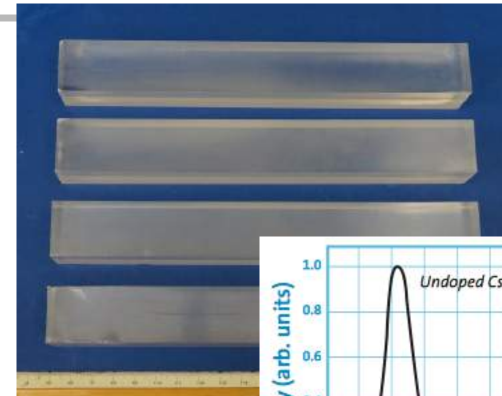
- 2 Disks (Annuli) geometry to optimize acceptance for spiraling electrons
- Crystals with high Light Yield for timing/energy resolution → **LY(photosensors) > 60 pe/MeV**
- **2 photo-sensors/preamps/crystal** for redundancy and reduce MTTF requirement → now set to 1 million hours/SIPM
- Fast signal 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:

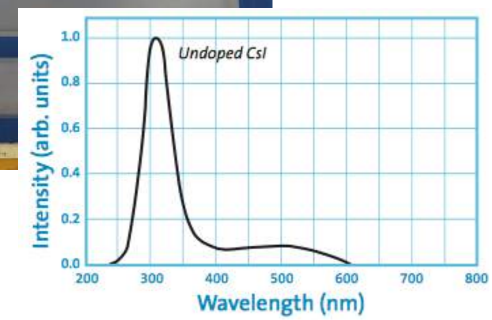
→ **Crystals survive a dose of 100 krad and a neutron fluency of 10^{12} n/cm^2**

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

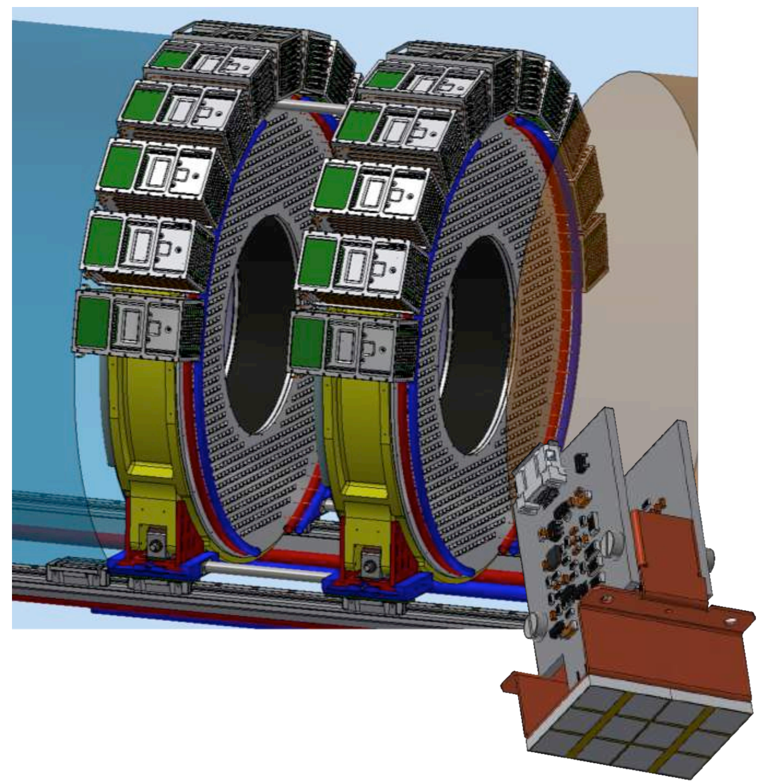
The Mu2e Calorimeter

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

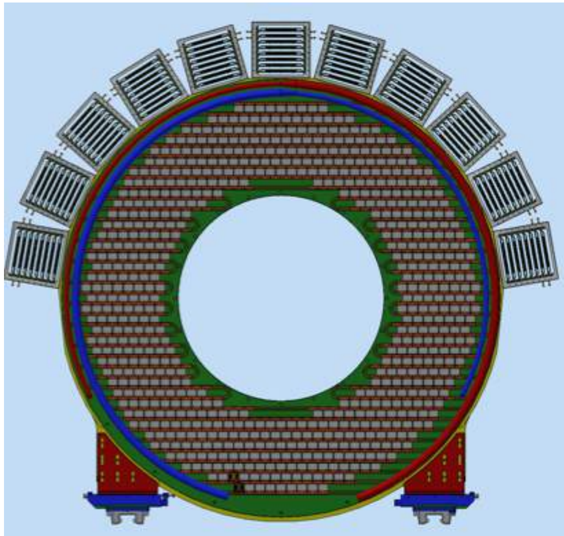


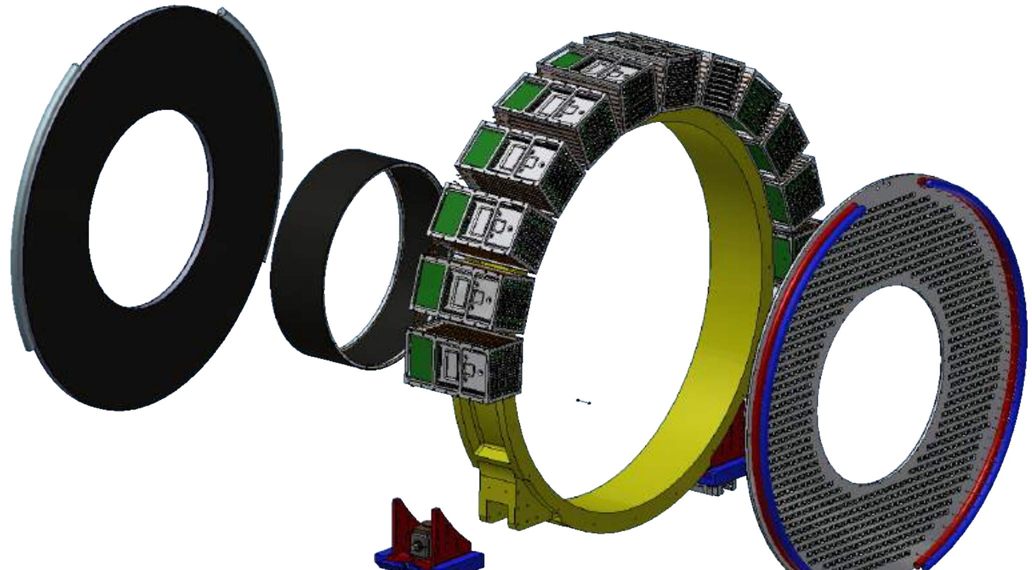


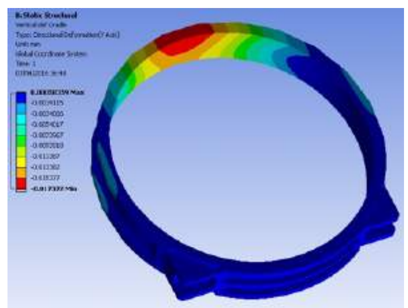
- → R_{inner} = 374 mm, R_{outer}=660 mm, depth = 10 X_0 (200 mm)
- → Disks separated by 75 cm, half helix length
- → Each crystal is readout by two large area UV extended SIPM's (14x20 mm^2) maximizing light collection. PDE=30% @ CsI emission peak =315 nm. GAIN ~10^6
- → TYVEK wrapping
- → Analog FEE 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

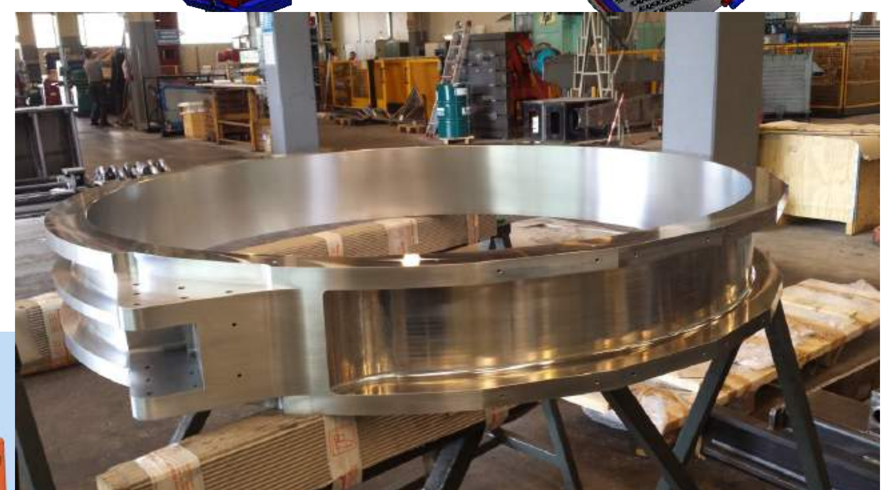


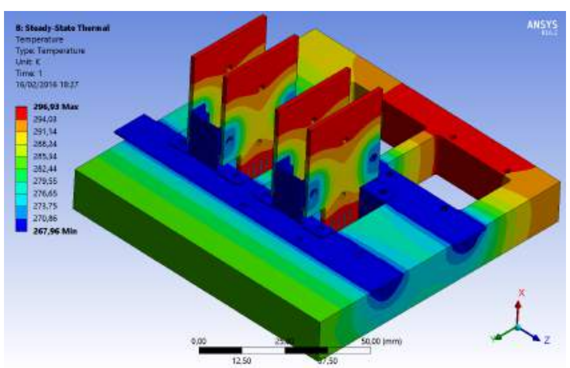
The Calorimeter engineering

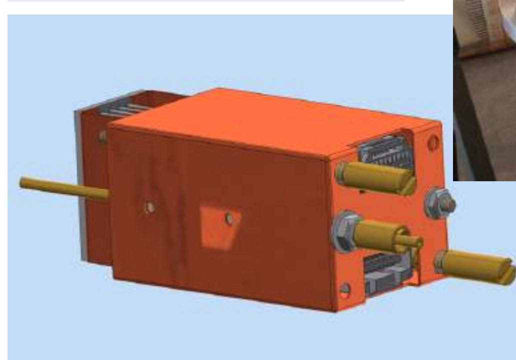






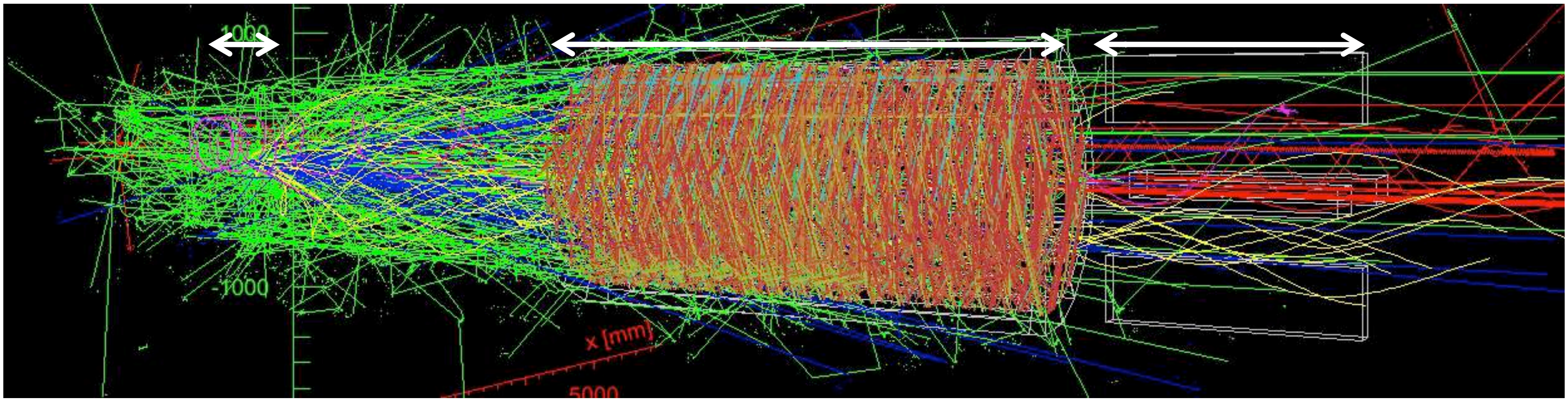




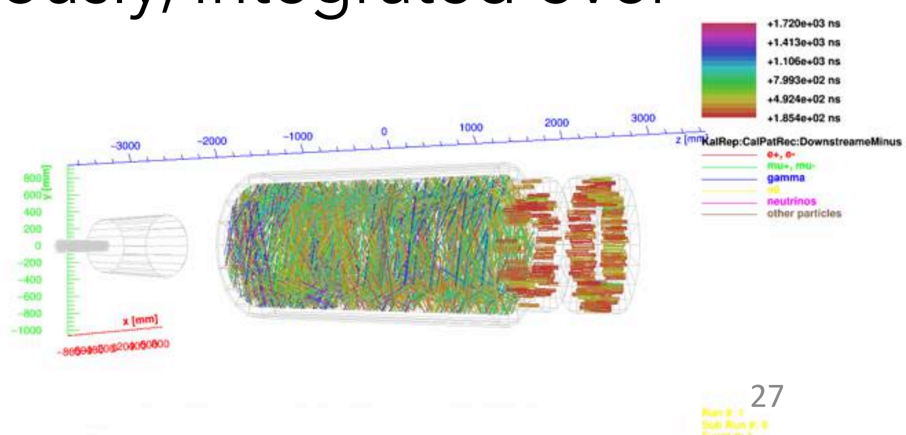


Mu2e Pattern Recognition

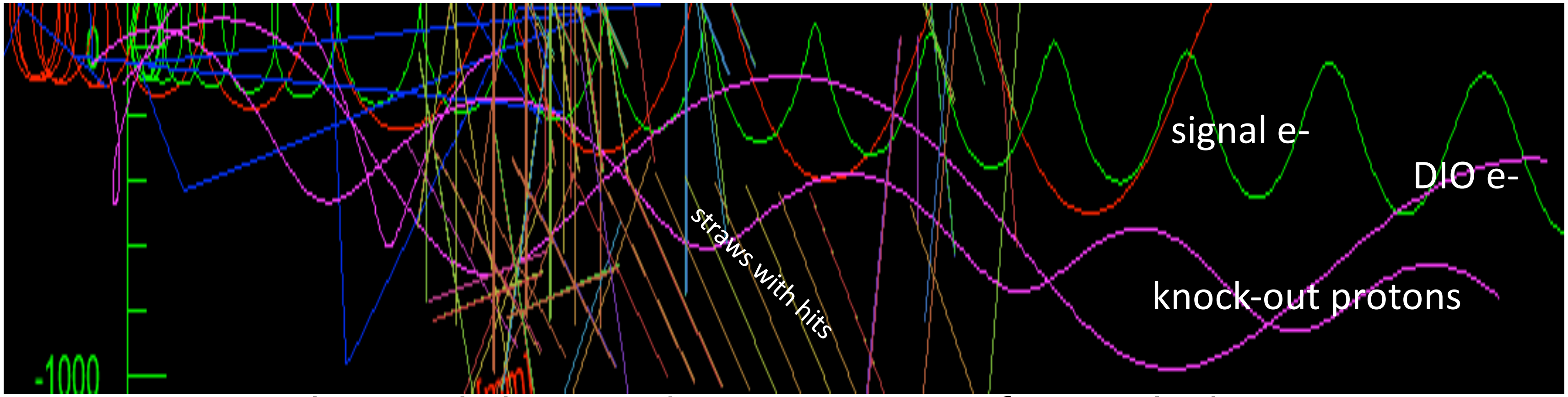
Stopping Target — Straw Tracker — Crystal Calorimeter



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

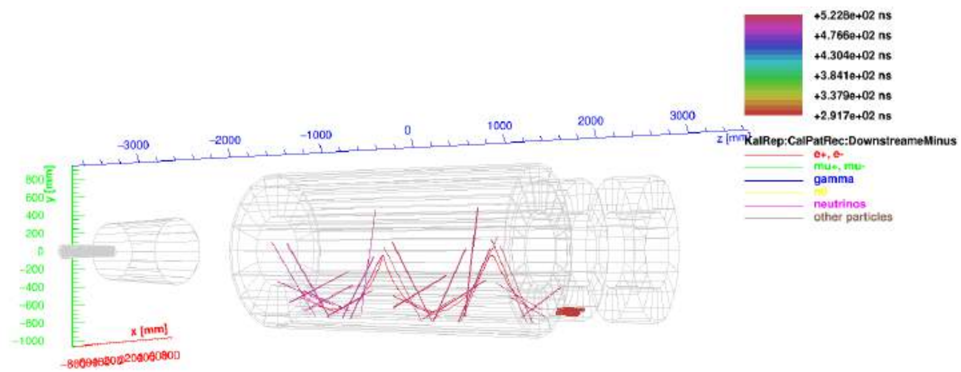


Mu2e Pattern Recognition



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

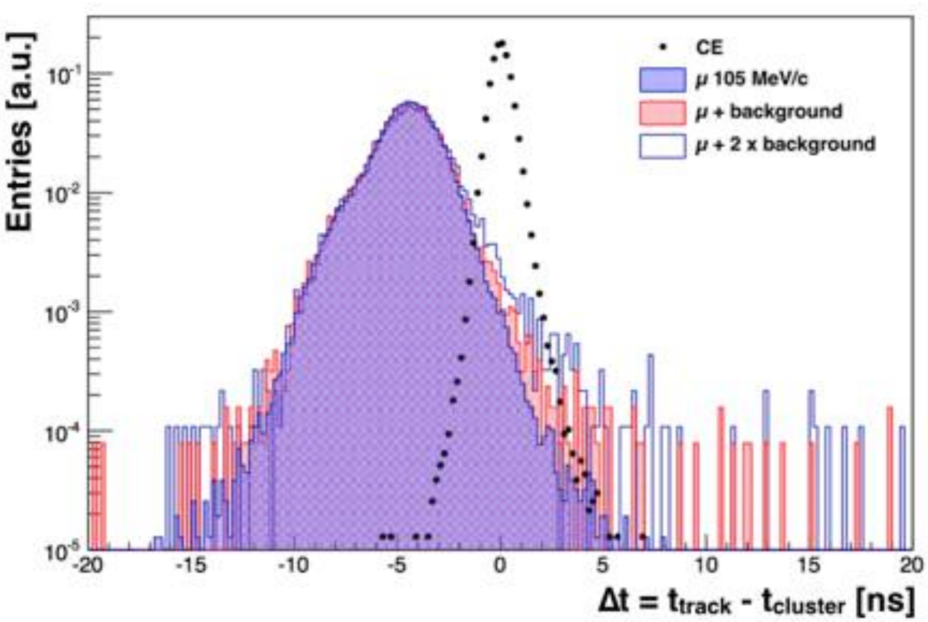
- Search for tracking hits with time and azimuthal angle compatible with the calorimeter clusters ($|\Delta T| < 50$ ns) → simplification of pattern recognition
- Add search of an Helix passing through cluster and selected hits + use calorimeter time to calculate tracking Hit drift times
- Reduce the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

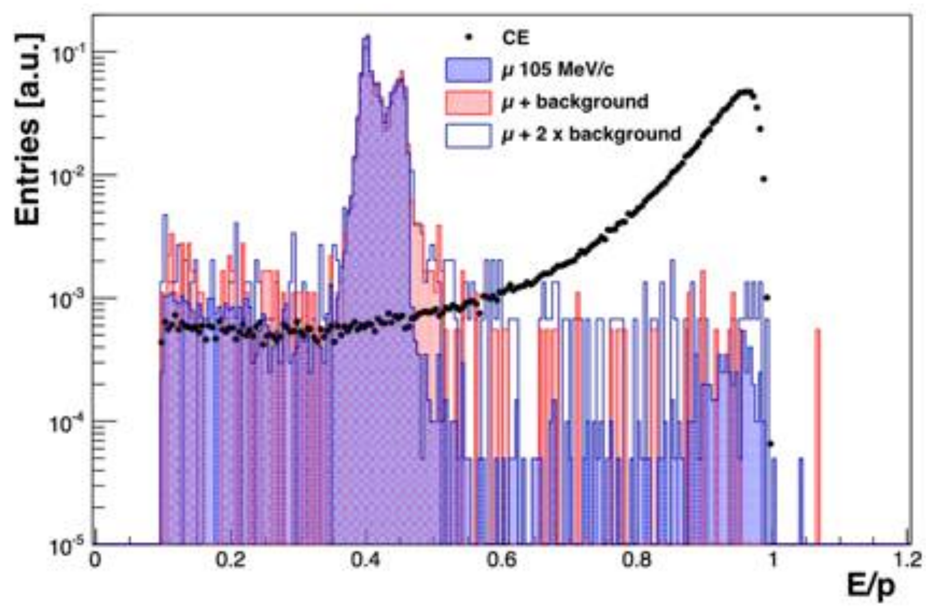


Cosmic μ rejection

- 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:

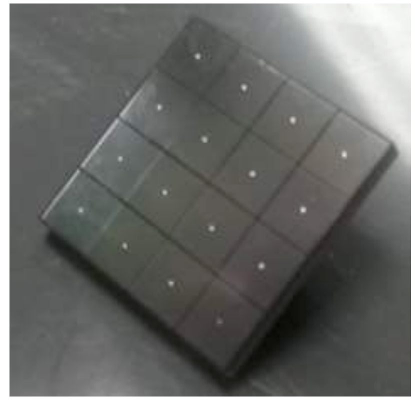
$$\ln L_{e,\mu} = \ln P_{e,\mu}(\Delta \mathrm{t}) + \ln P_{e,\mu}(\mathrm{E/p})$$

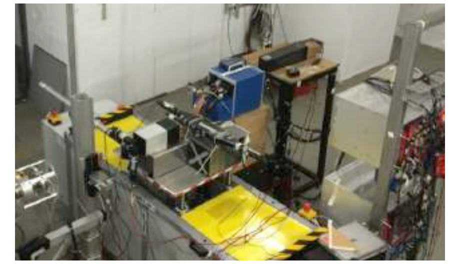


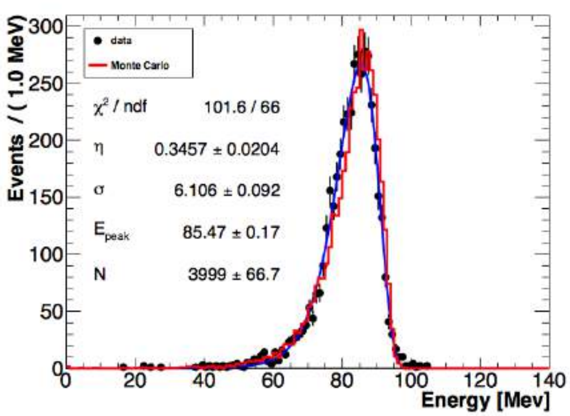


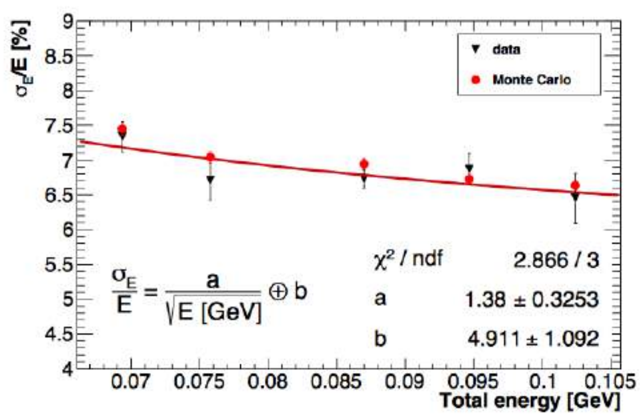
CsI+MPPC tests

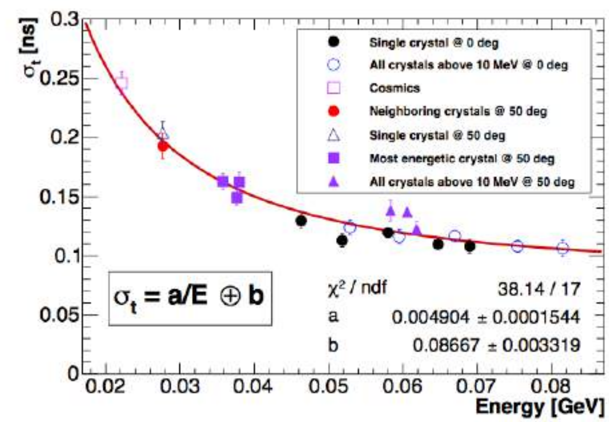
- A small crystal prototype has been built and tested in Frascati in April 2015
- 3x3 matrix of 3x3x20 cm^3 un-doped CsI crystal coupled with UV-extended MPPC.
- Test with e- between 80 and 120 MeV







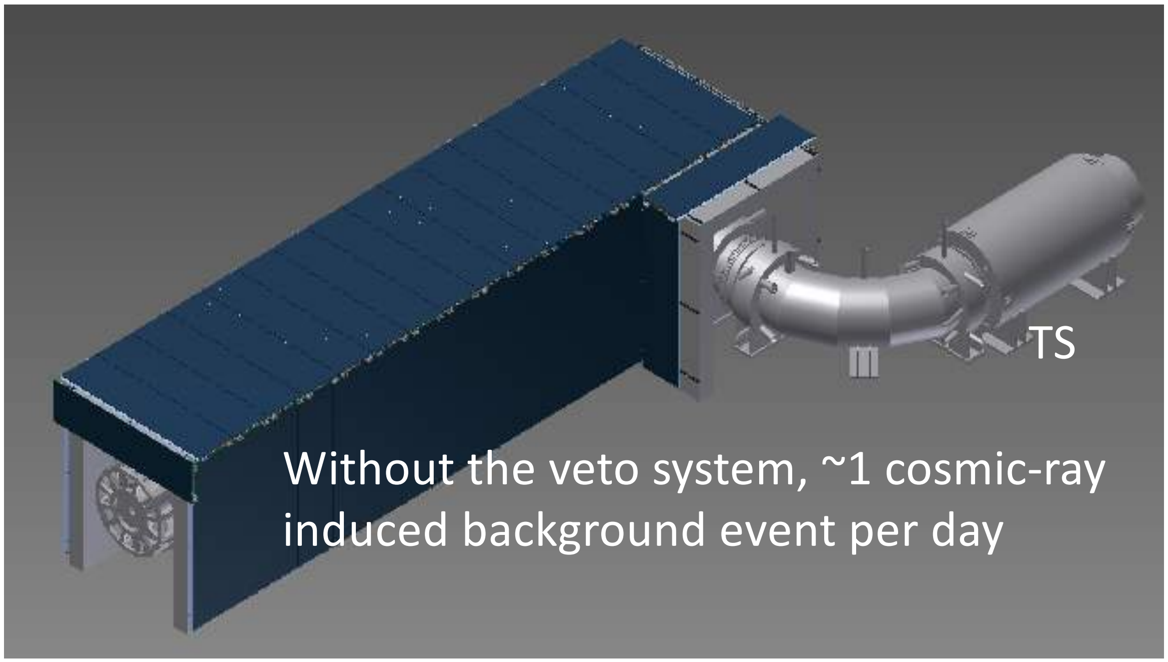


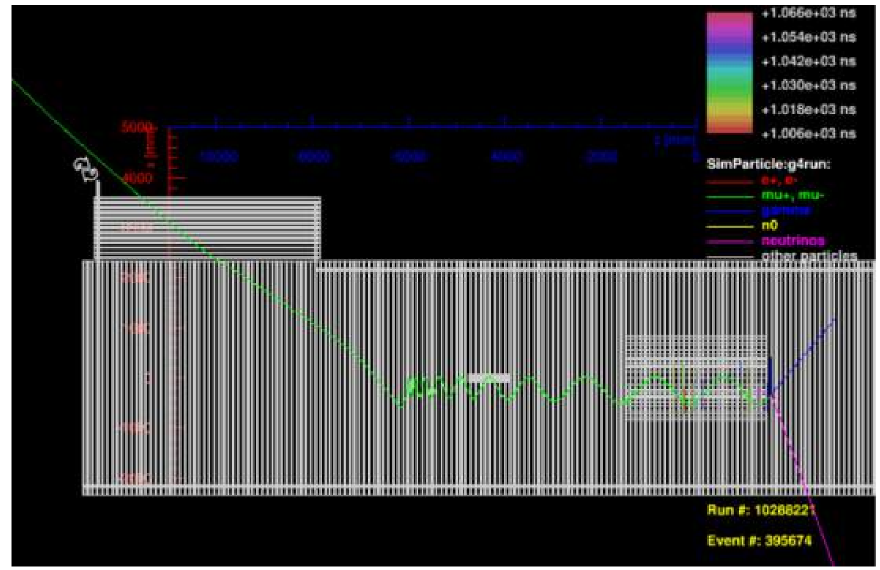


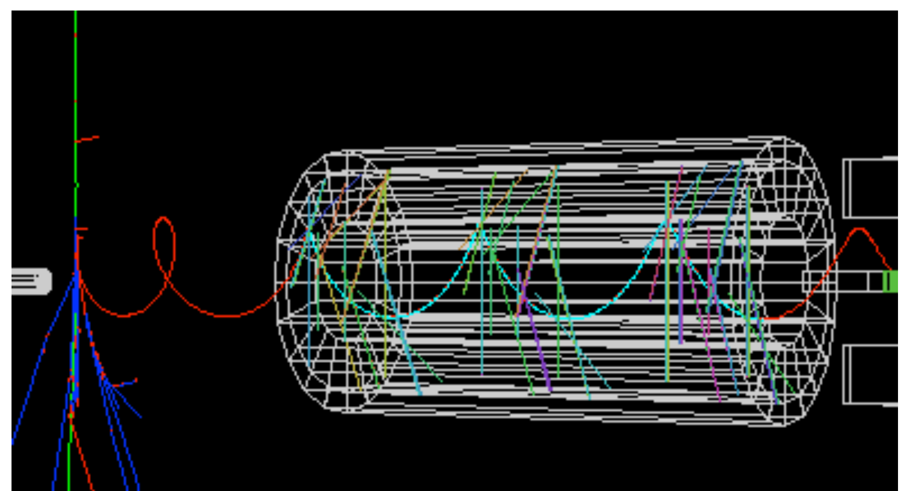
- @100 MeV: Good energy (6-7%) and timing (110 ps) resolution
- Leakage dominated

The Cosmic ray Veto

Veto system covers entire DS and half TS

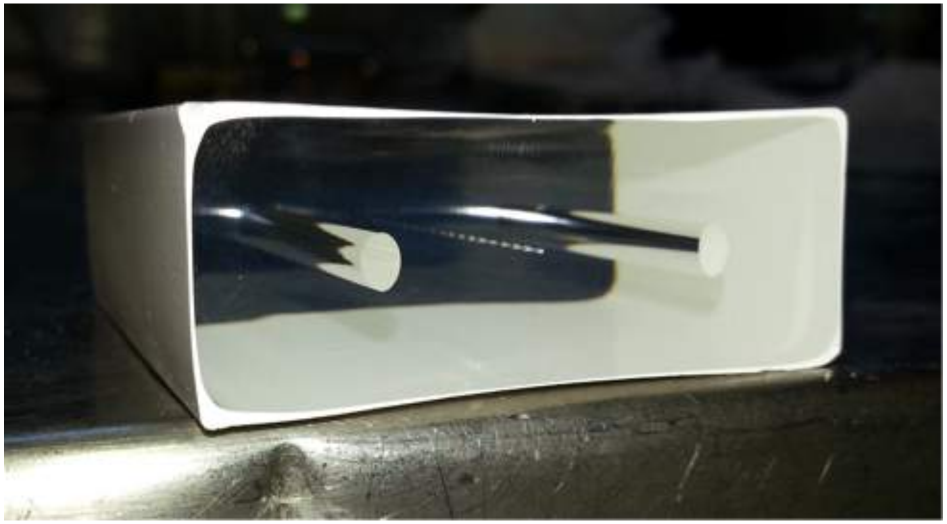


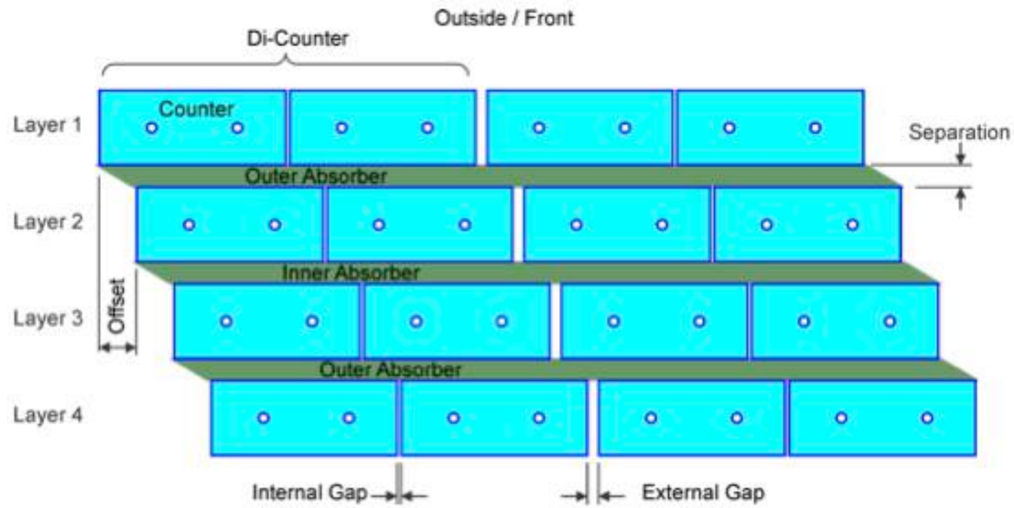




Cosmic μ can generate background events via decay, scattering, or material interactions

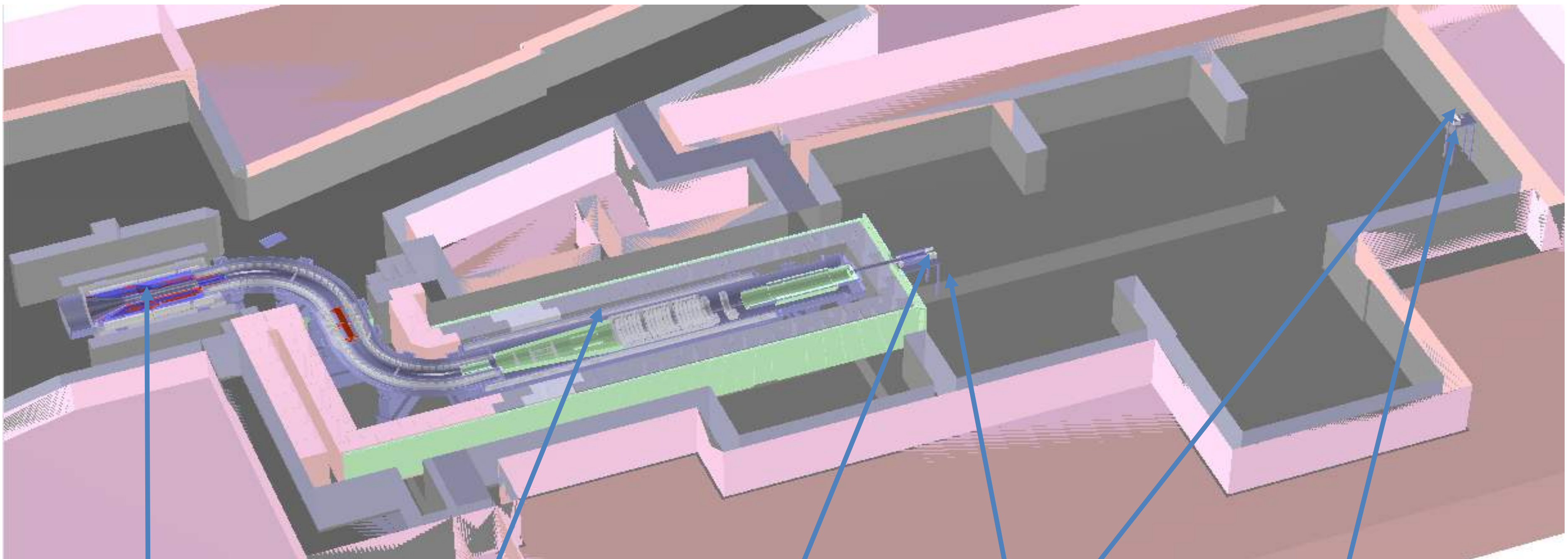
Mu2e Cosmic-Ray Veto





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



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

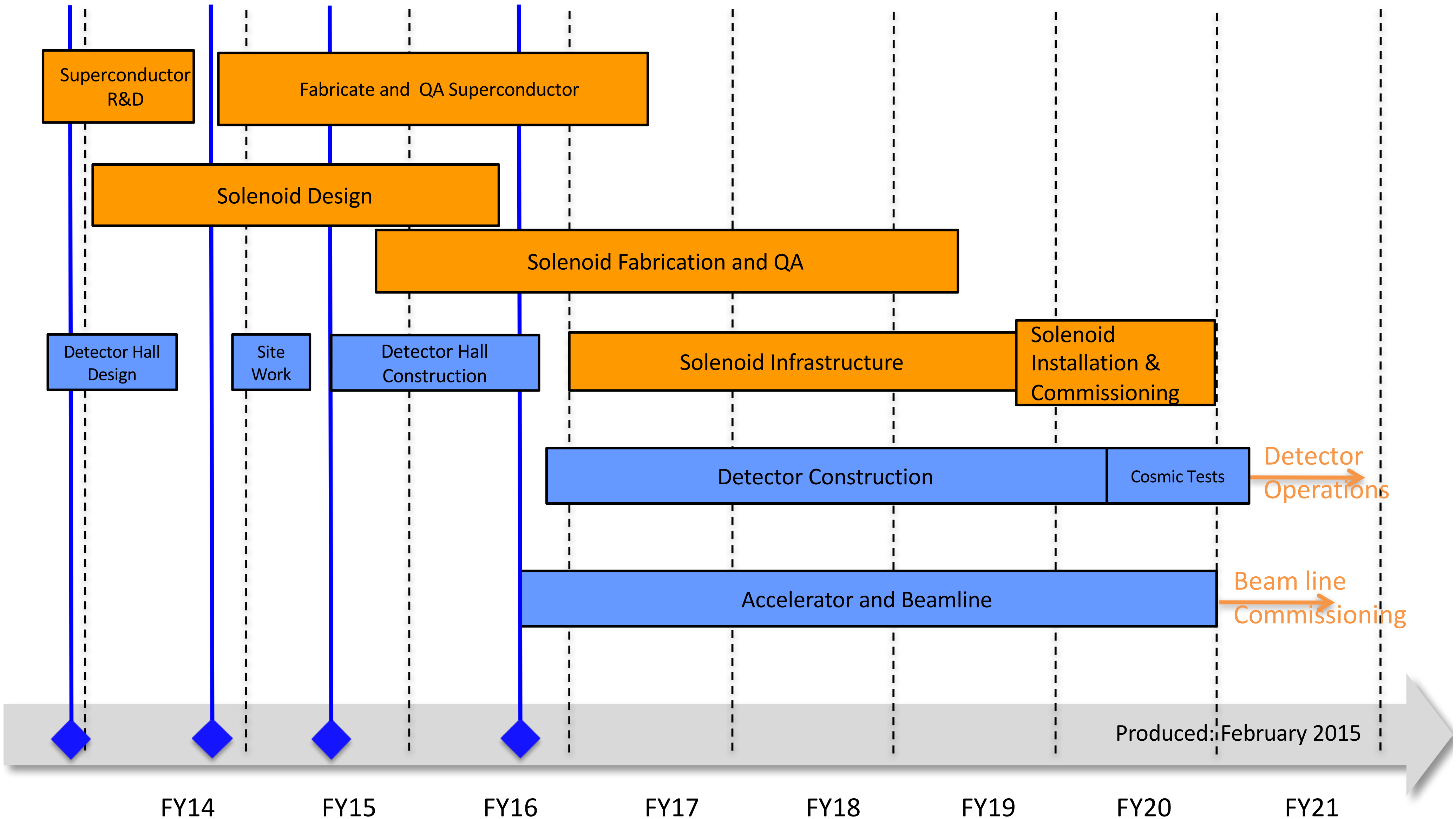
Mu2e Detector Hall

Graphic of proposed Mu2e Detector Hall

Construction well along

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

Mu2e Schedule



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