The Mu2e Experiment at Fermilab

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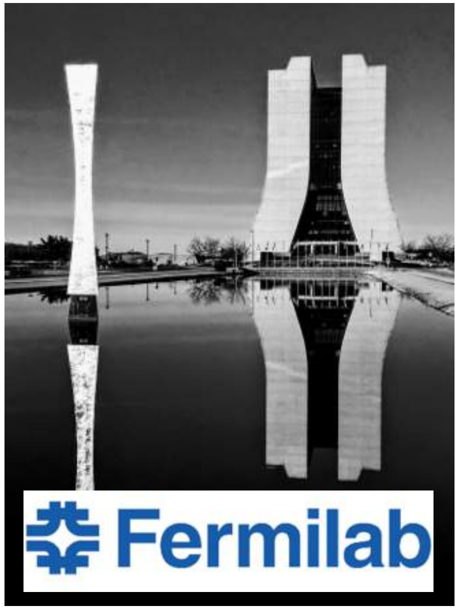
On behalf of the Mu2e Collaboration

Universita' di Tor Vergata 15 Maggio 2017



INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Presentation outline

- Where, Why Mu2e
- Experimental technique
- Accelerator complex
- Detectors layout indulging on the Calorimeter
- Status of Mu2e
- Conclusions

Fermilab

- Fermi National Accelerator Laboratory
- www.fnal.gov
- Located west of Chicago, IL
- Founded 50 years ago
  - 50.fnal.gov

The Muon campus

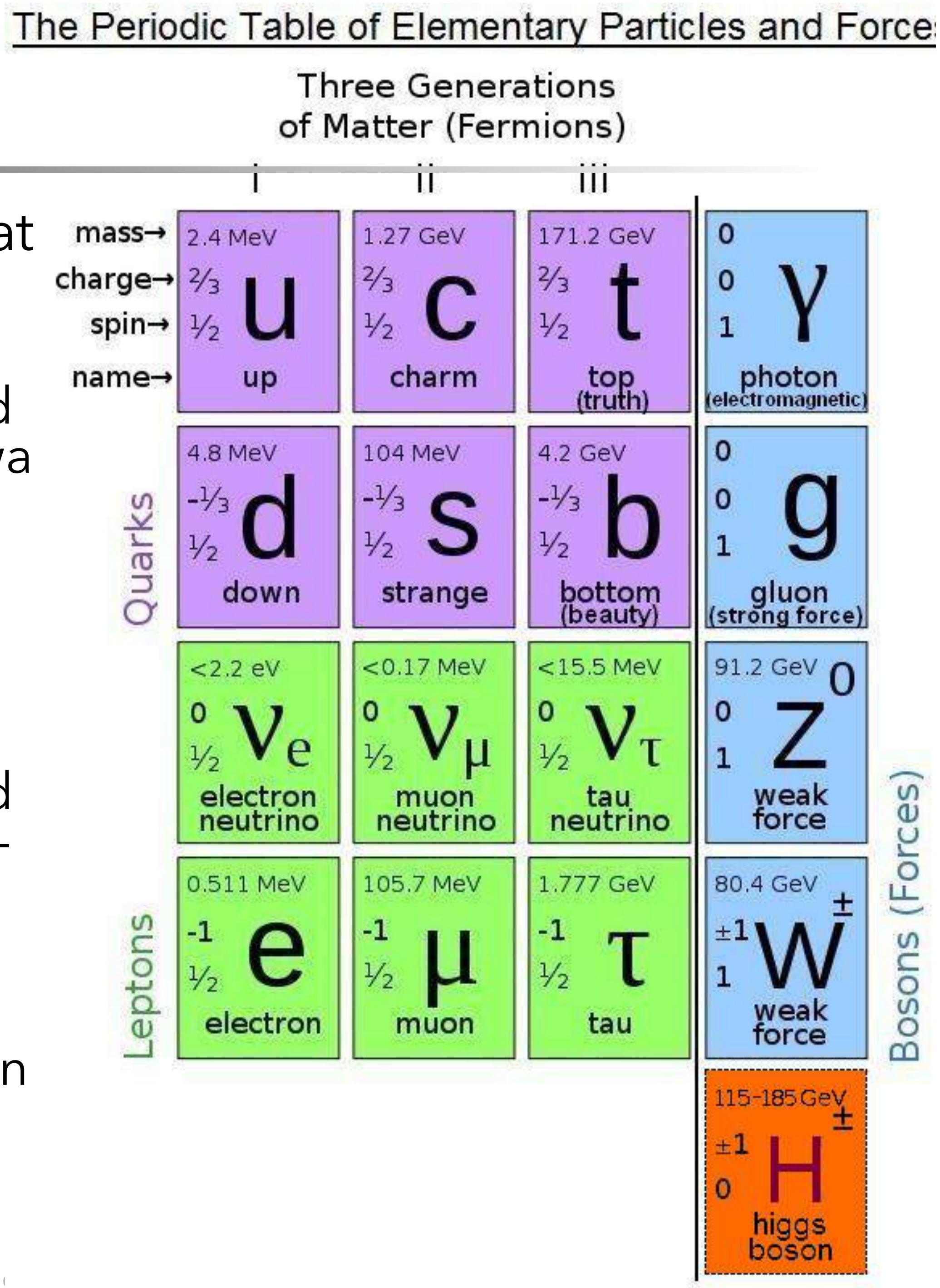
The Mu2e collaboration

~230 Scientists from 37 Institutions

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 of Nuclear Research Dubna,** Duke University, Fermi National Accelerator Laboratory, **Laboratori Nazionali di Frascati**, University of Houston**, Helmholtz-Zentrum Dresden-Rossendorf,** University of Illinois, **INFN Genova,** Lawrence Berkeley National Laboratory, **INFN Lecce, University Marconi Rome, Institute for High Energy Physics Protvino,** Kansas State University, Lewis University, **University of Liverpool, University College London,** University of Louisville, **University of Manchester,** University of Minnesota, Muons Inc., Northwestern University, Institute for Nuclear Research Moscow, Northern Illinois University, **INFN Pisa**, Purdue University, Novosibirsk State University/Budker Institute of Nuclear Physics, Rice University, University of South Alabama, University of Virginia, University of Washington, Yale University

Intro

- We've known for a long time that quarks mix → (Quark) Flavor Violation
  - Mixing strengths parameterized by Cabbibo-Kobayashi-Maskawa - CKM matrix
- In last 15 years we've come to know that neutrinos mix → Lepton Flavor Violation (LFV)
  - Mixing strengths parameterized by Pontecorvo-Maki-Nakagawa-Sakata - PMNS matrix
- Why not charged leptons?
  - Charged Lepton Flavor Violation (CLFV)



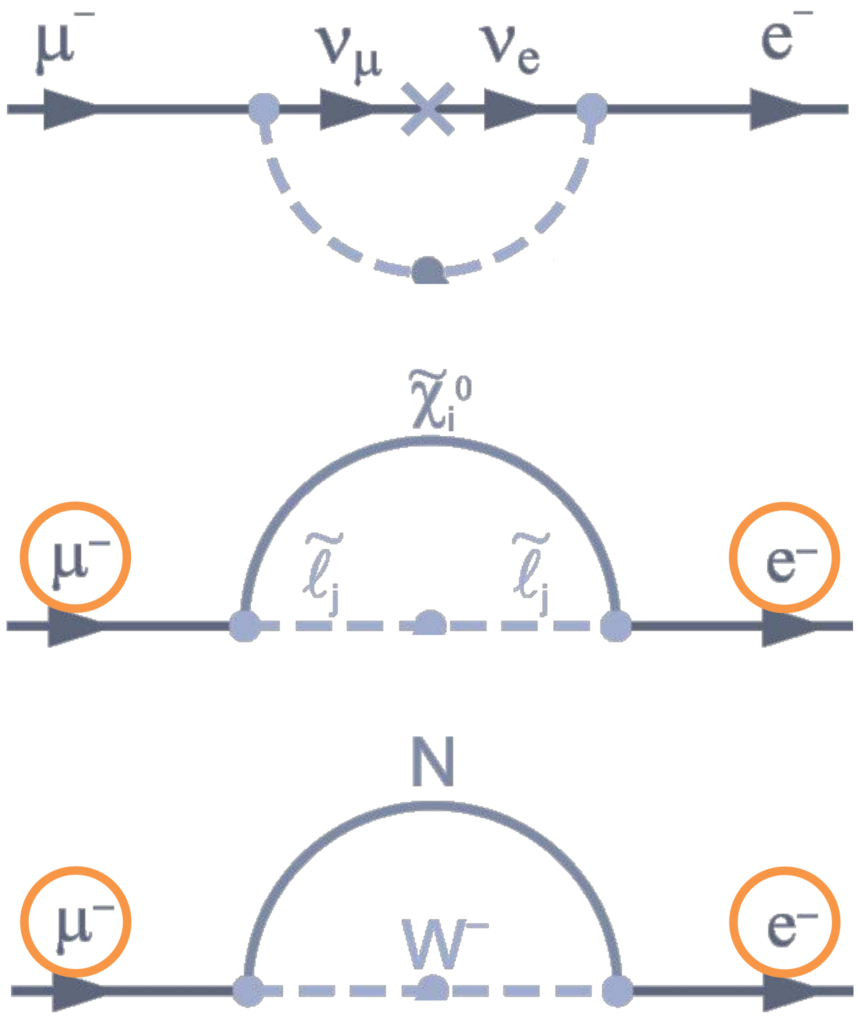
Why Search for Lepton Flavor Violation?

- No lepton flavor violation in Standard Model!

- **Any signal would be unambiguous evidence of new physics!**

- What's beyond the Standard Model?
  - Supersymmetry?
  - New Heavy Neutrino?

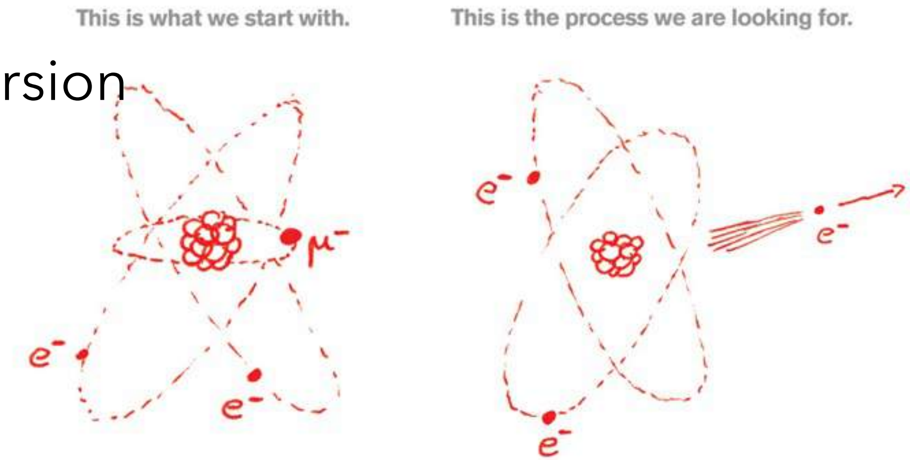
- Many new models produce $\mu^{-}N \rightarrow e^{-}N$ at levels that will be probed by Mu2e.



What is Mu2e

– Mu2e is a highly sensitive search for Charged-Lepton Flavor Violation (CLFV)

– Will search the neutrinoless conversion of a muon into an electron in the Coulomb field of a nucleus



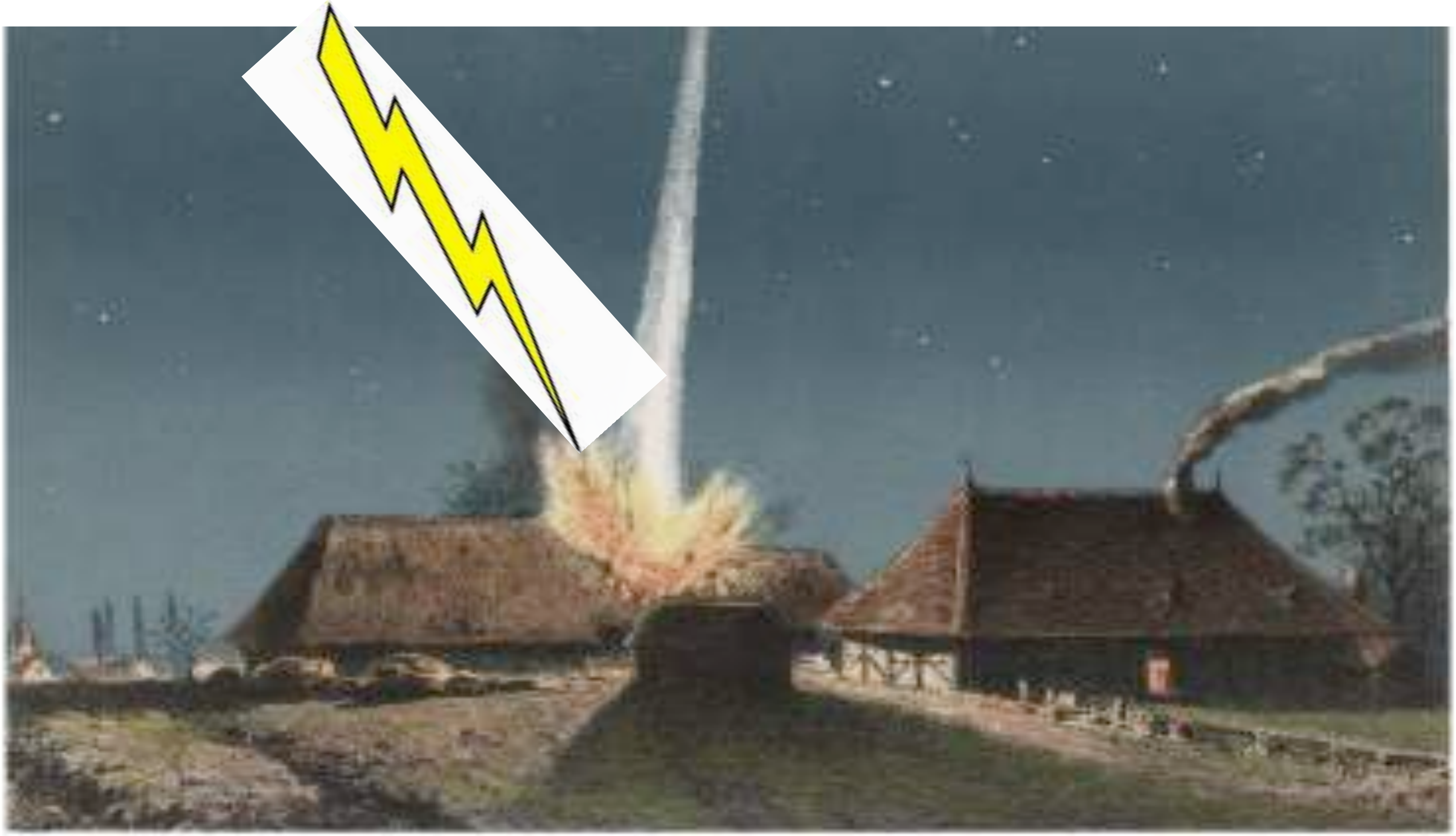
– Will use current Fermilab accelerator complex to reach a single event sensitivity of 2.4 x10^{-17}sensitivity 10^4 better than current world's best

– 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

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

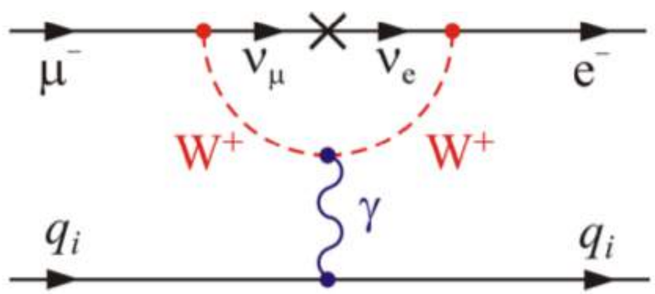
As low probability as this!



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

- 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'

Some CLFV Processes

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)

- There is a global interest in CLFV

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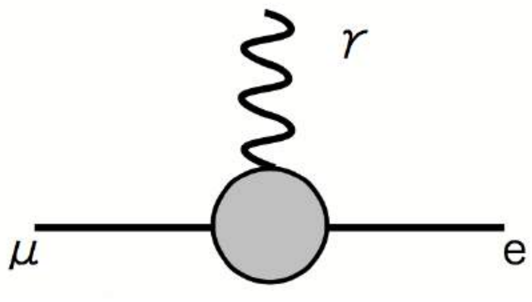
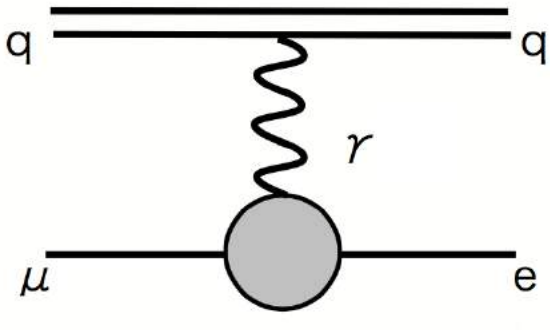
- Most promising CLFV measurements use μ

CLFV Predictions

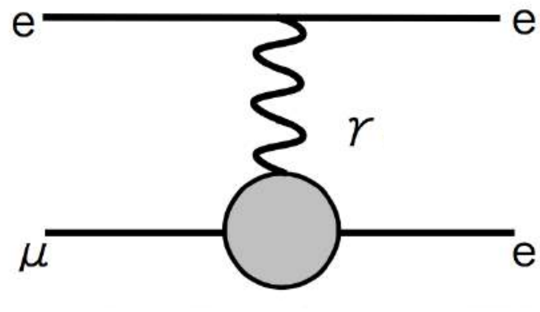
$\mu^+ \rightarrow e^+\gamma$



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



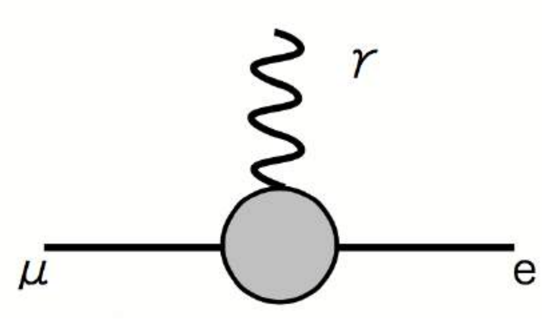
$\mu^+ \rightarrow e^+e^+e^-$



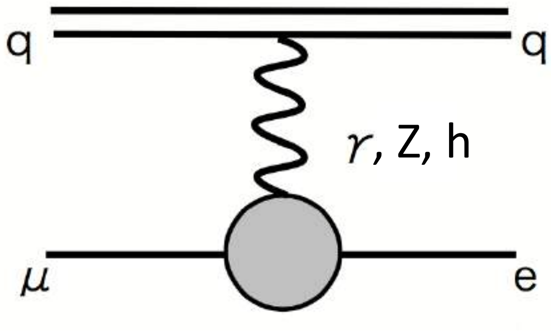
CLFV rates and ratios are sensitive probes of underlying model

CLFV Predictions

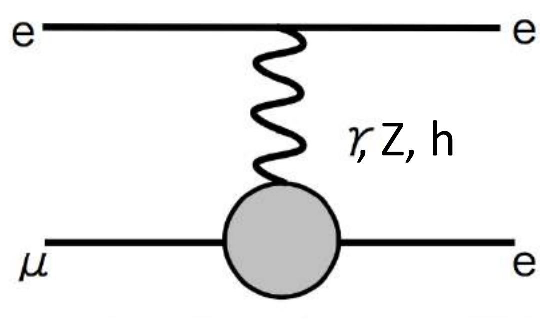
$\mu^+ \to e^+\gamma$



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



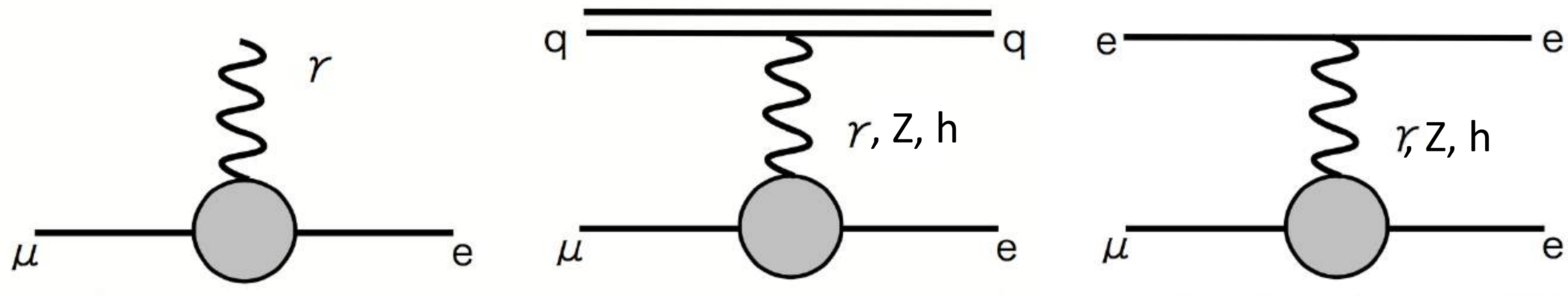
$\mu^+ \to e^+e^+e^-$

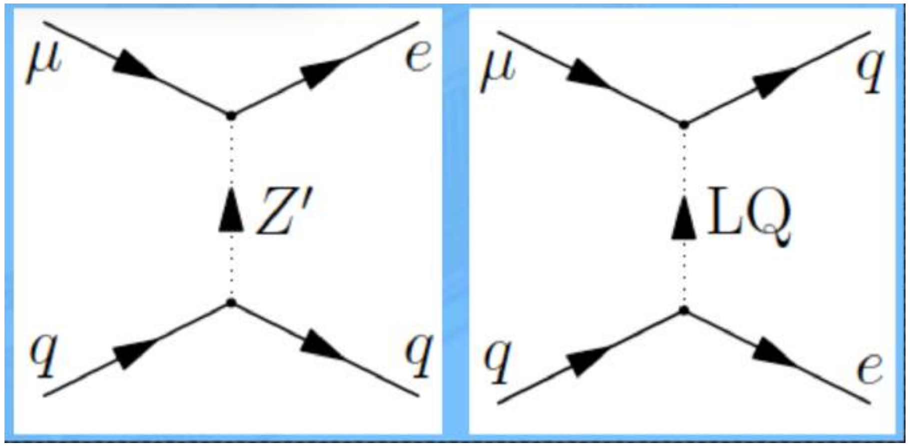


CLFV rates and ratios are sensitive probes of underlying model

CLFV Predictions

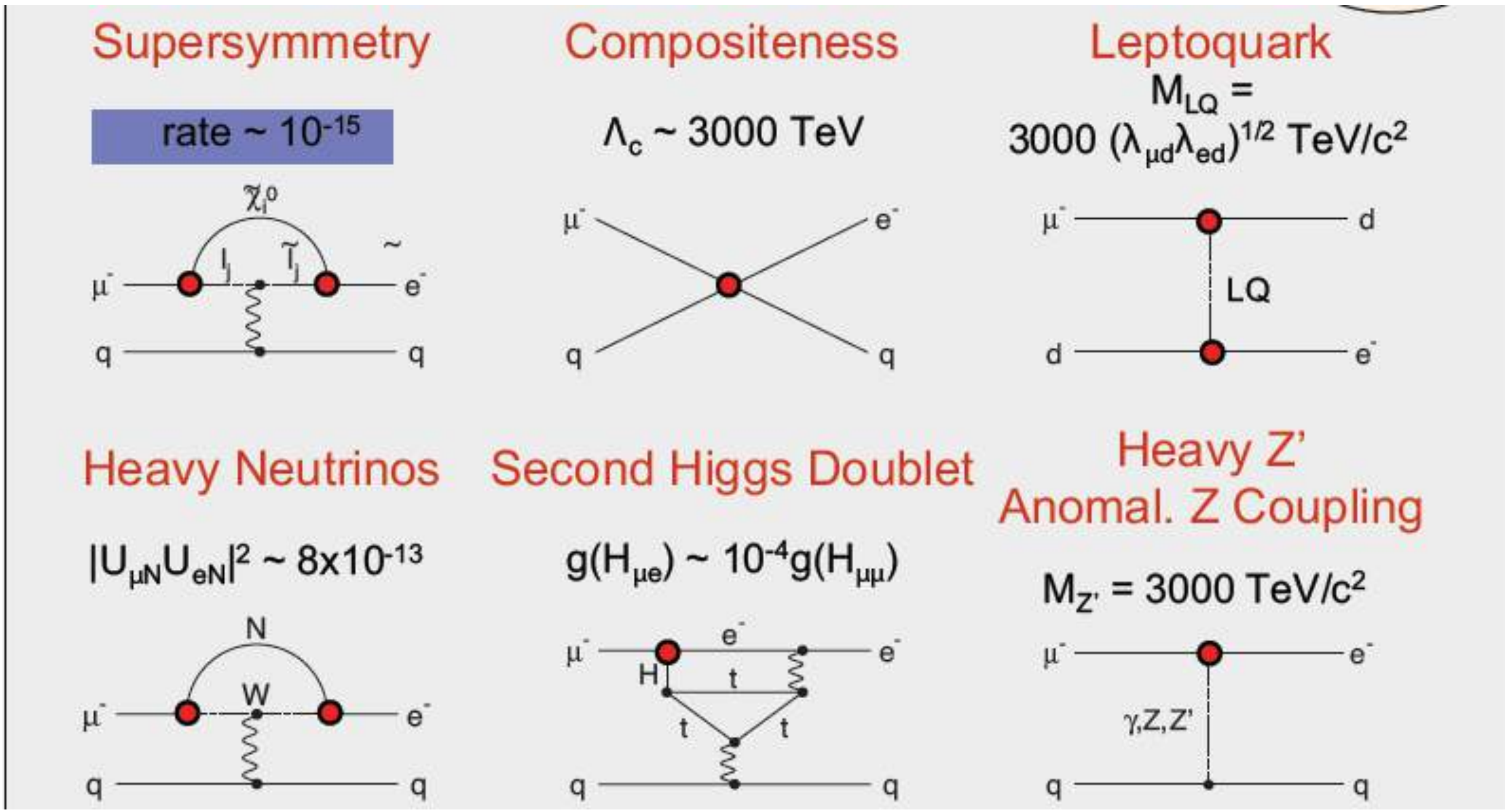
$\mu^+ \rightarrow e^+\gamma$ $\mu^- N \rightarrow e^- N$ $\mu^+ \rightarrow e^+e^+e^-$





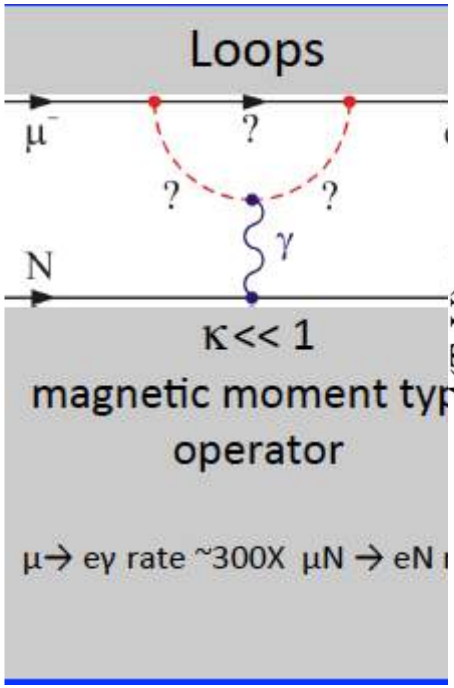
CLFV rates and ratios are sensitive probes of underlying model

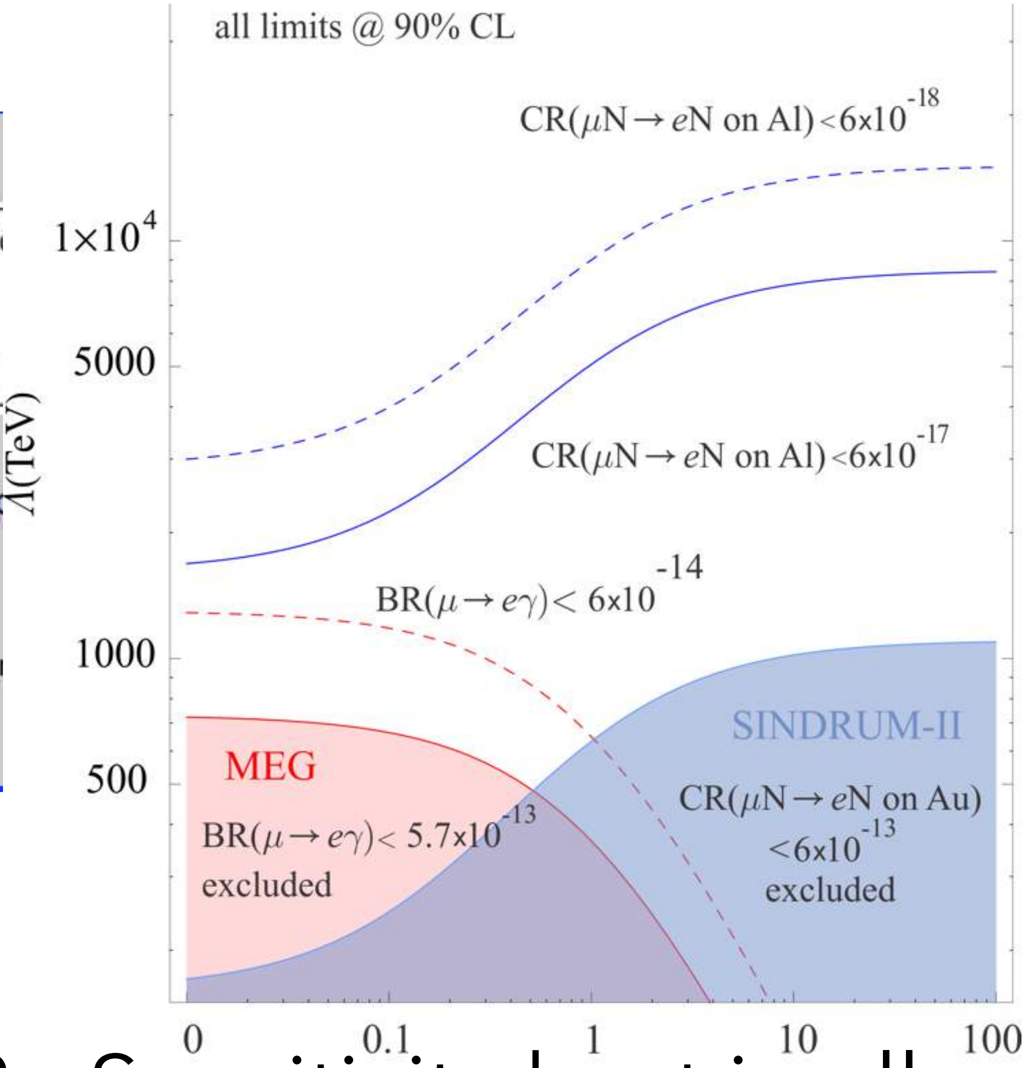
μ->e is a signature of NP models

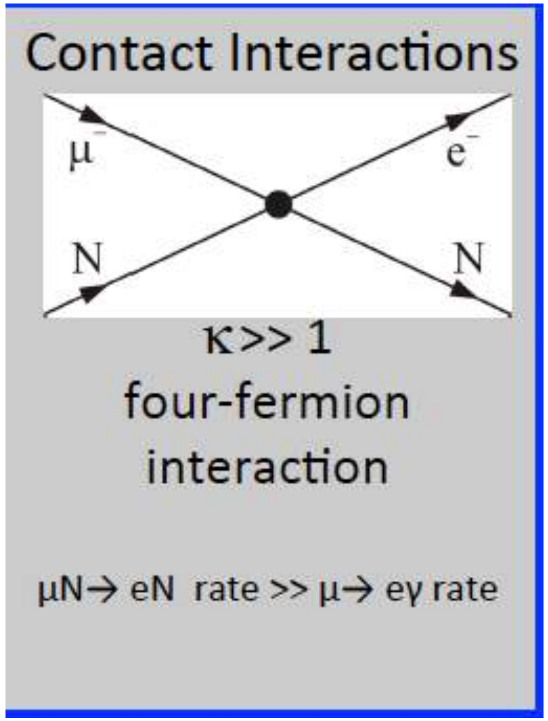


Mu2e Sensitivty

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







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
- p + nucleus $\rightarrow \pi^- \rightarrow \mu^- \nu_\mu$

- Every 1 second Mu2e will
  - Send 7,000,000,000,000 protons to the Production Solenoid
  - Send 26,000,000,000 μs through the Transport Solenoid
  - Stop 13,000,000,000, μs in the Detector Solenoid

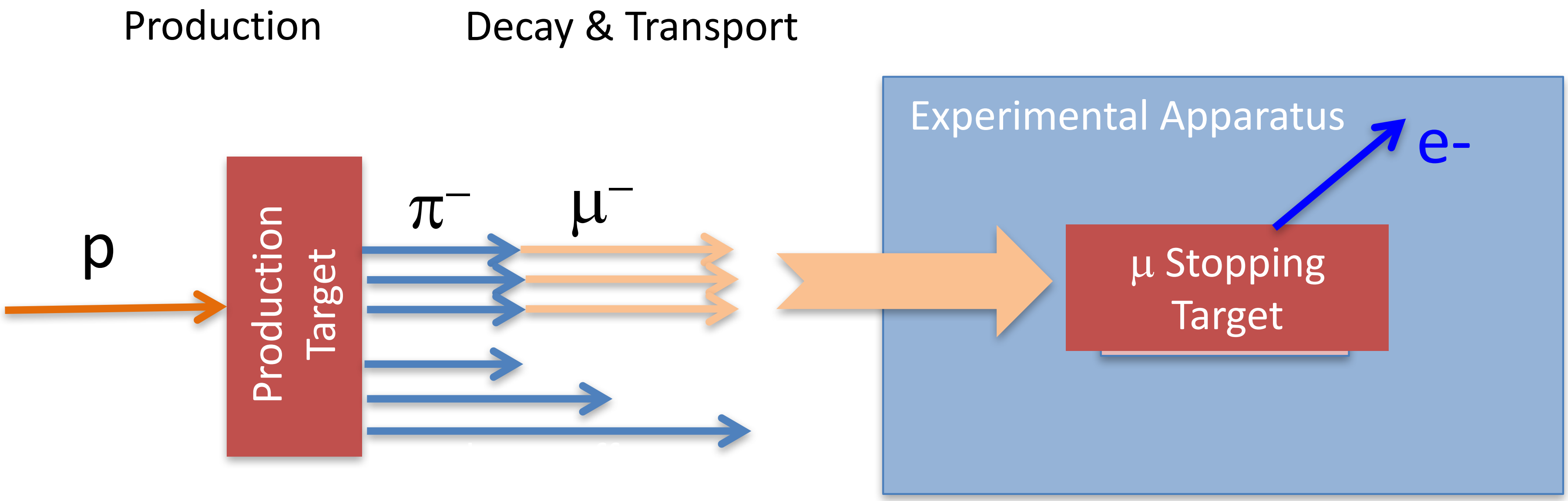
- Stop the muons in a target
  - Mu2e plans to use Aluminum
  - Sensitivity goal requires ~10^{18} stopped muons
  - 10^{20} protons on target (2 year run – 2×10^7 s)

- 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 $\mu N \rightarrow eN$

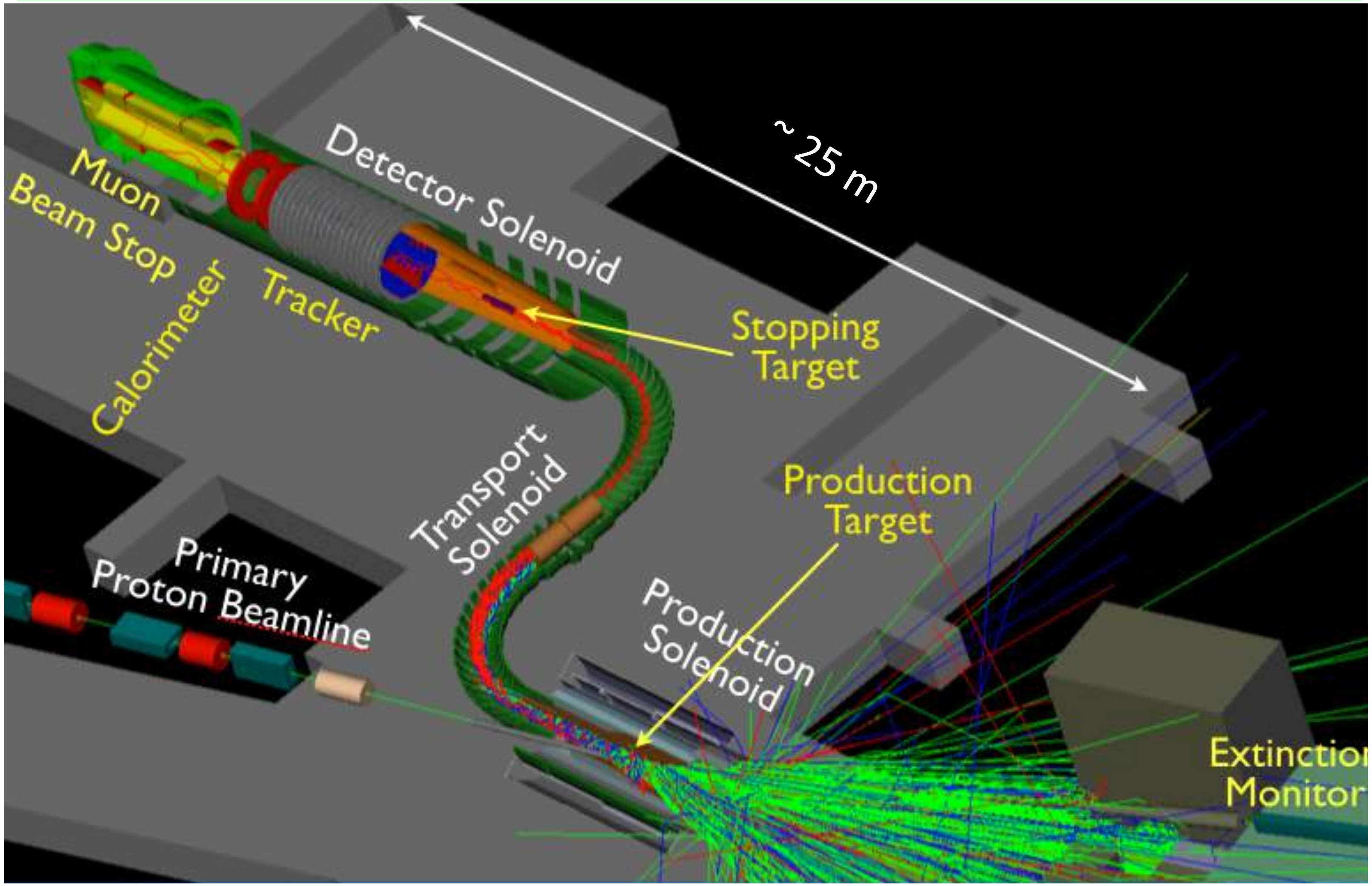
Some Perspective

1,000,000,000,000,000,000
 = number of stopped Mu2e muons
 = number of grains of sand on earth's beaches

Mu2e Concept

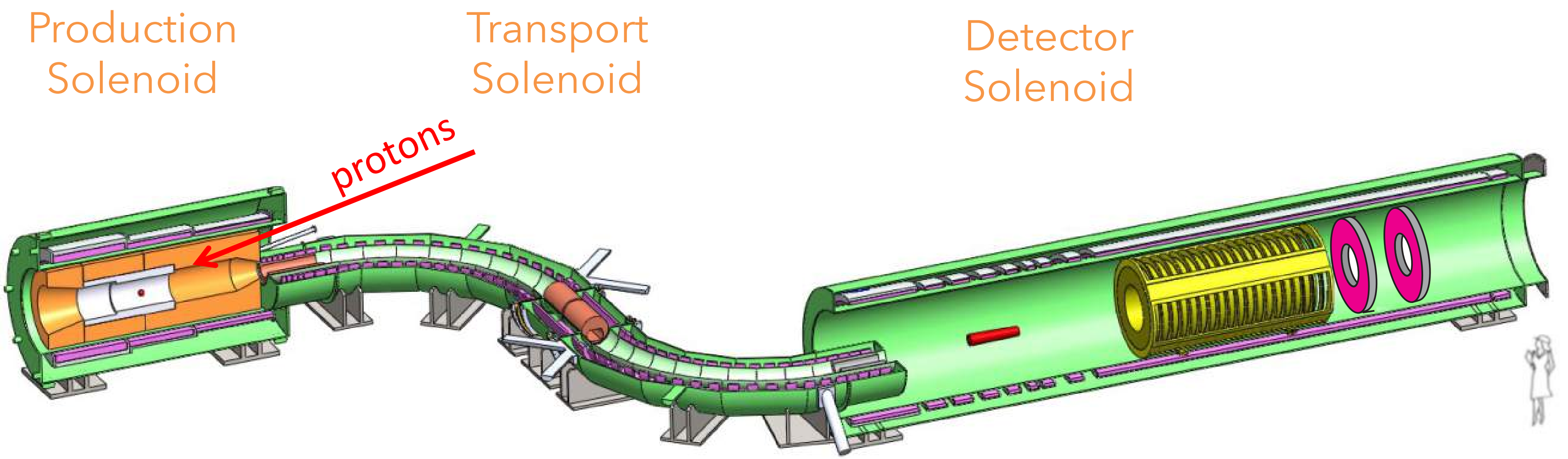


Mu2e Experimental Apparatus



- Derived from MELC concept originated by Lobashev and Djilkibaev in 1989

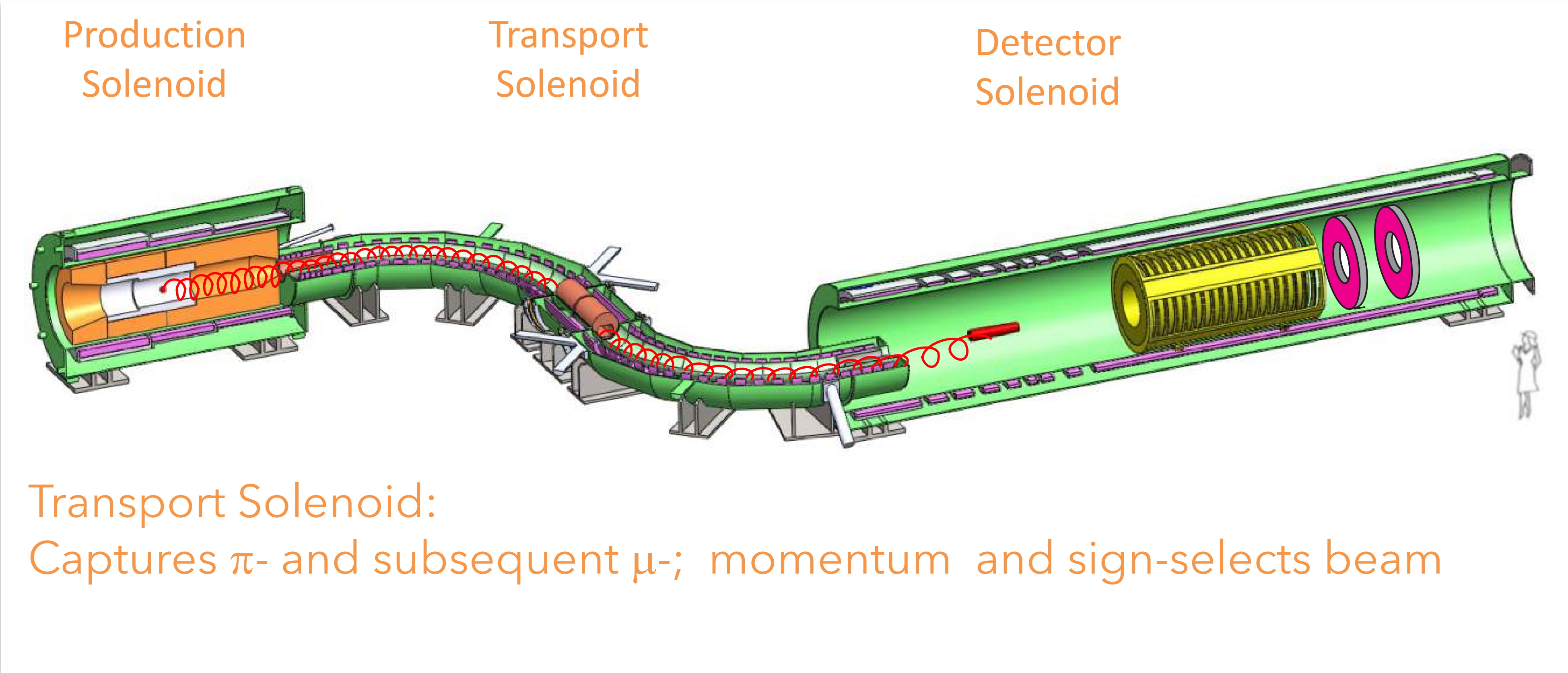
Mu2e Experimental Apparatus



Production Solenoid:
8 GeV protons interact with a tungsten target to produce μ- (from π- decay)

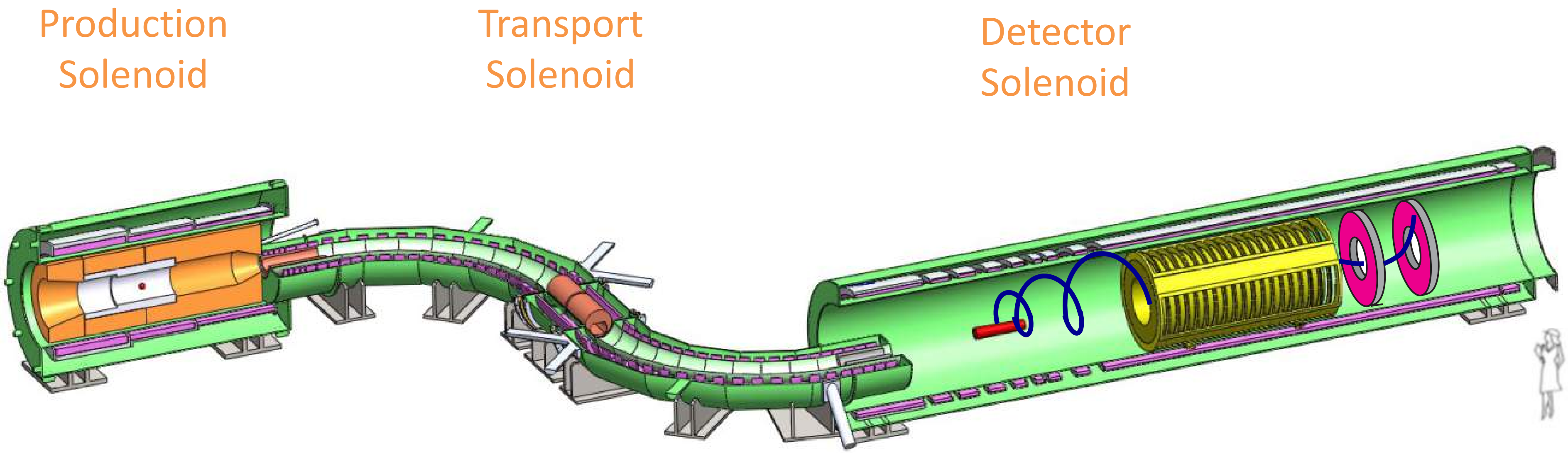
- Consists of 3 solenoid systems

Mu2e Experimental Apparatus



- Consists of 3 solenoid systems

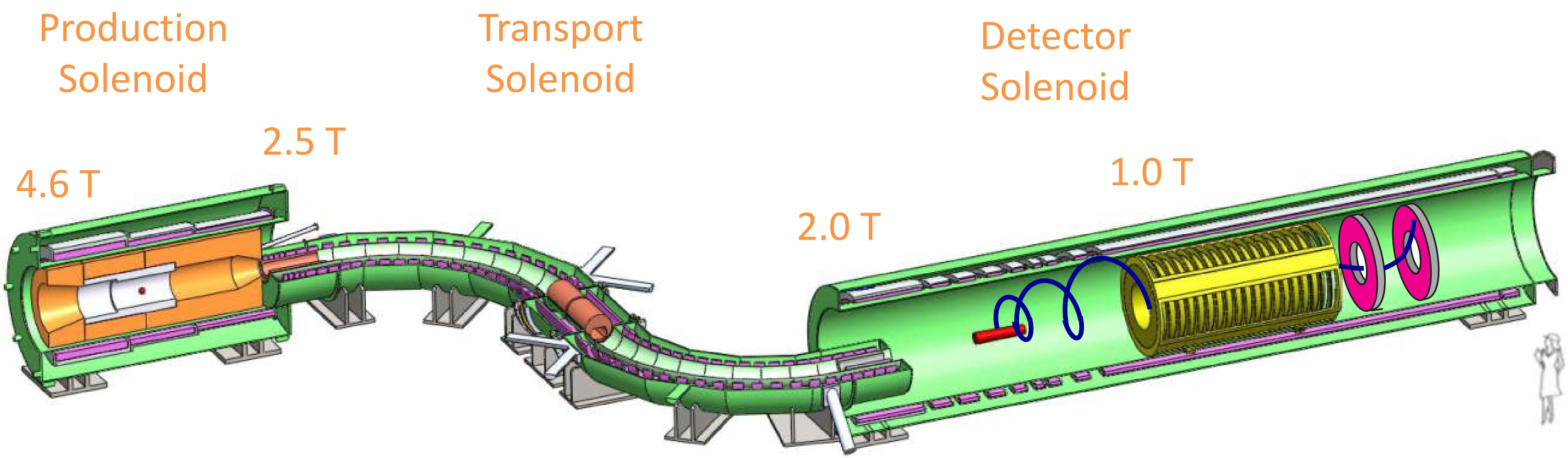
Mu2e Experimental Apparatus



Detector Solenoid:
Upstream – Al. stopping target, Downstream – tracker, calorimeter
(not shown – cosmic ray veto system, extinction monitor, target monitor)

- Consists of 3 solenoid systems

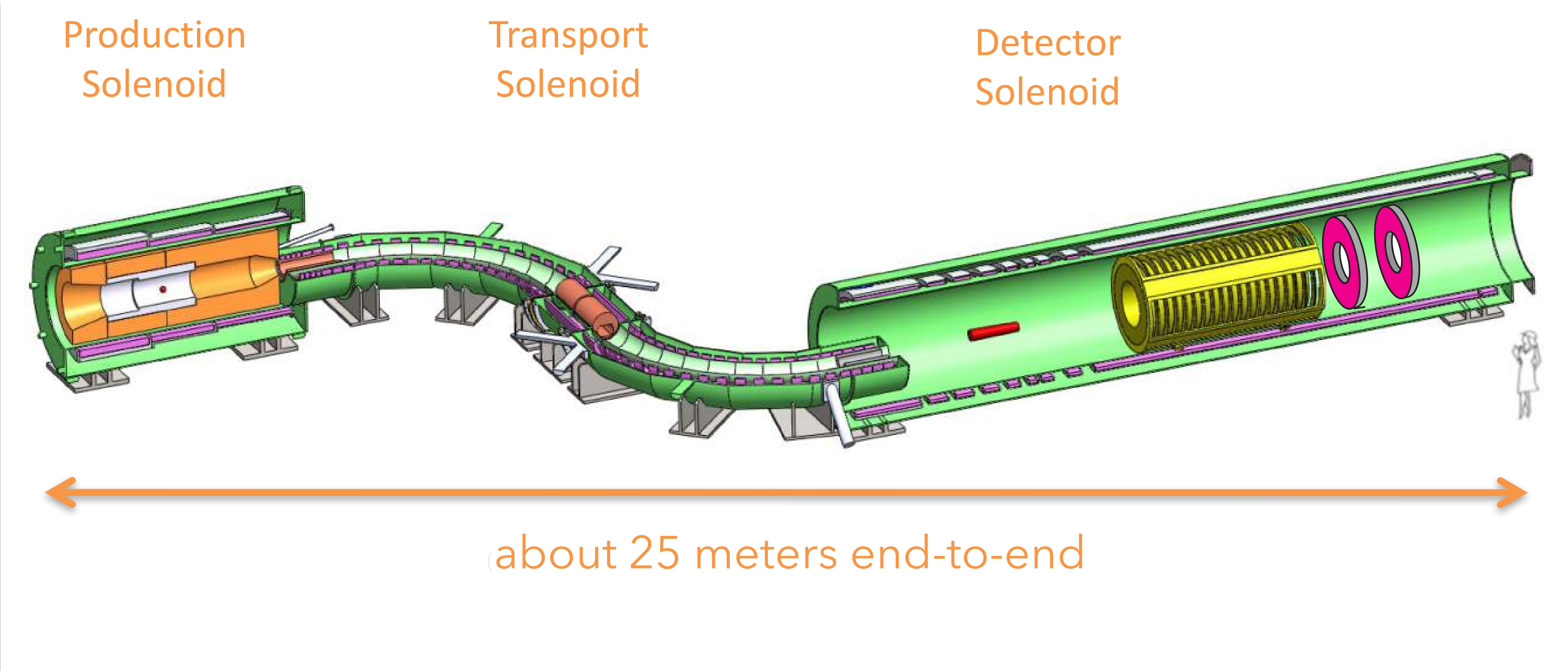
Mu2e Experimental Apparatus



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

- Consists of 3 solenoid systems

Mu2e Experimental Apparatus



- Consists of 3 solenoid systems

Muonic Al atom

- Stopped μ^- is captured in atomic orbit
  - Quickly (~fs) cascades to 1*s* state emitting *X*-rays
- Bohr radius ~20 fm (for aluminum)
  - Significant overlap of μ^- and Nucleus wave functions
- Once in orbit, 3 things can happen
  - Decay : $\mu^- N(A,Z) \rightarrow e^- \nu\nu N(A,Z)$ (39%)
  - Capture : $\mu^- N(A,Z) \rightarrow \nu N^*(A,Z\text{-}1)$ (61%)
  - Conversion : $\mu^- N(A,Z) \rightarrow e^- N(A,Z)$ (signal)

Produces
1n, 2γ, 0.1p
per capture

Mu2e Signal

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

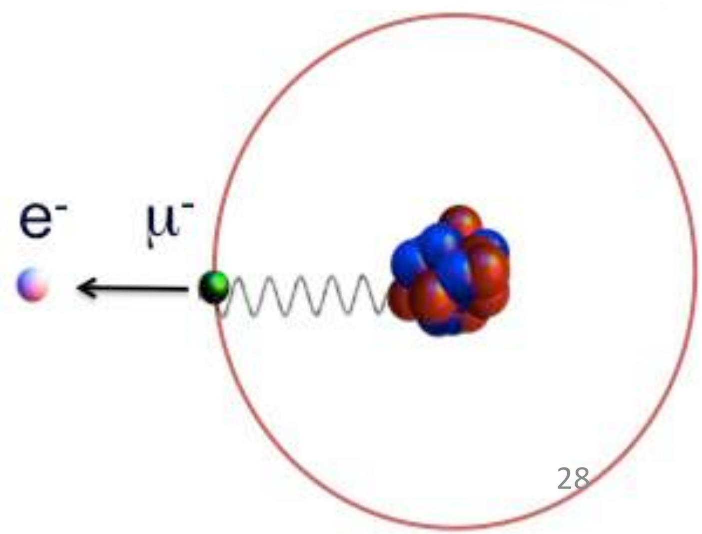
- Neutrinoless muon to electron conversion

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

- 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 (
  0.48 MeV
- C_μ nuclear recoil of Al, 0.21 MeV

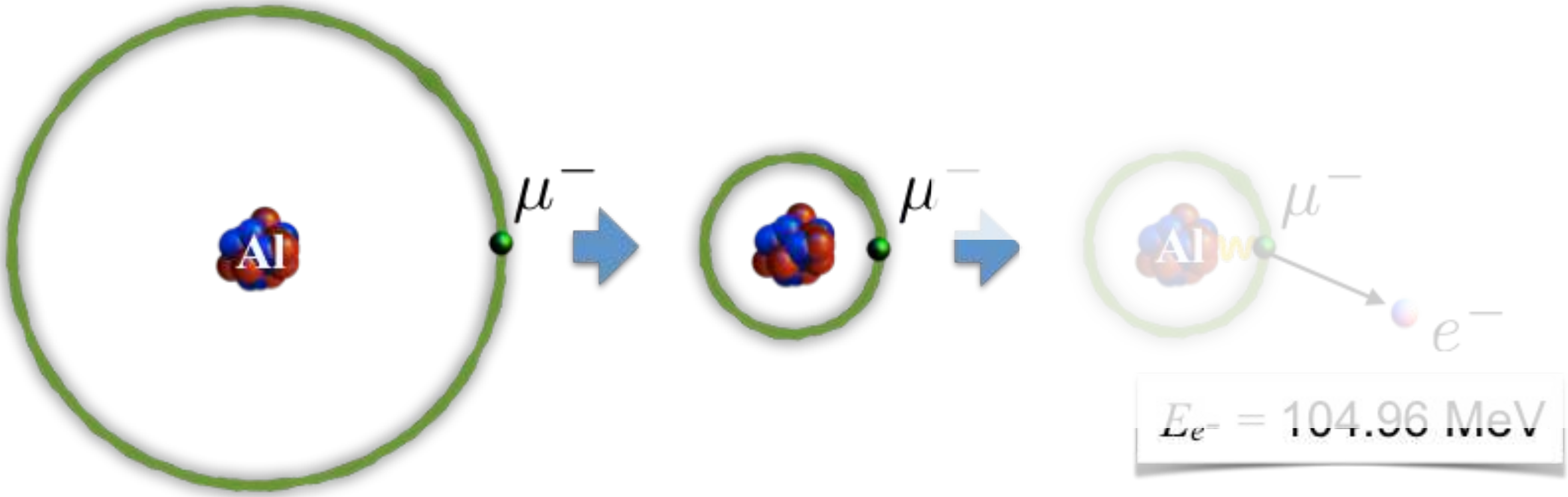


Mu2e Measurement ingredients

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

- Muon is captured by Aluminum

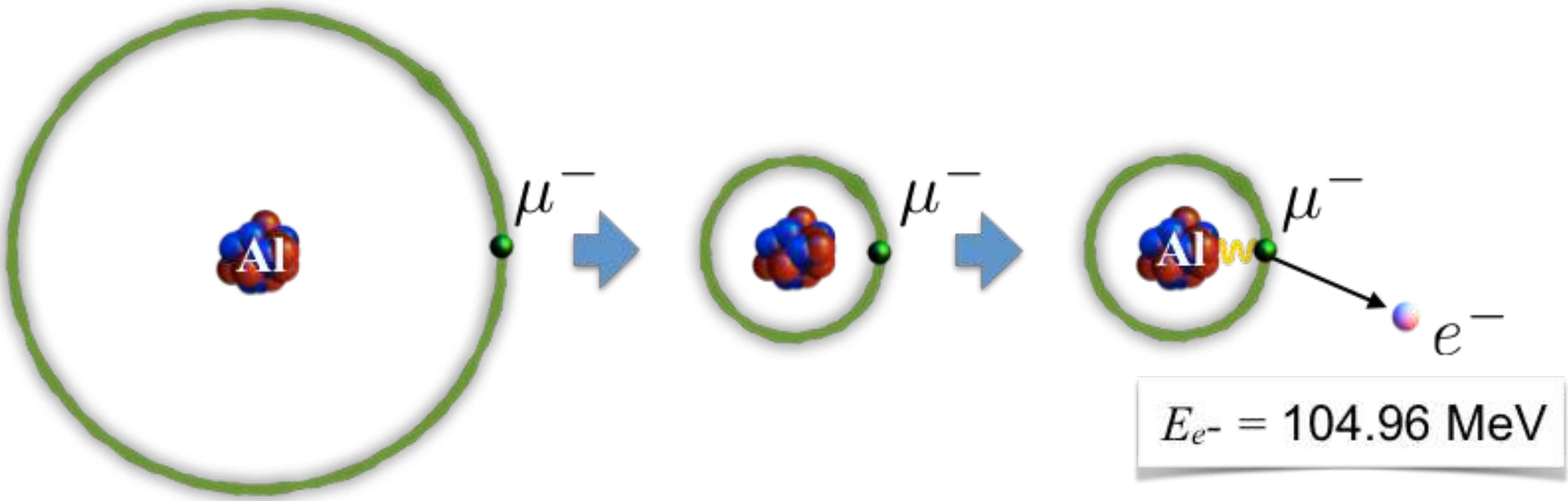
$\mu^- + \mathrm{Al}$



Mu2e Measurement ingredients

- Muon is captured by Aluminum
  - and then neutrinoless converts to an electron.

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

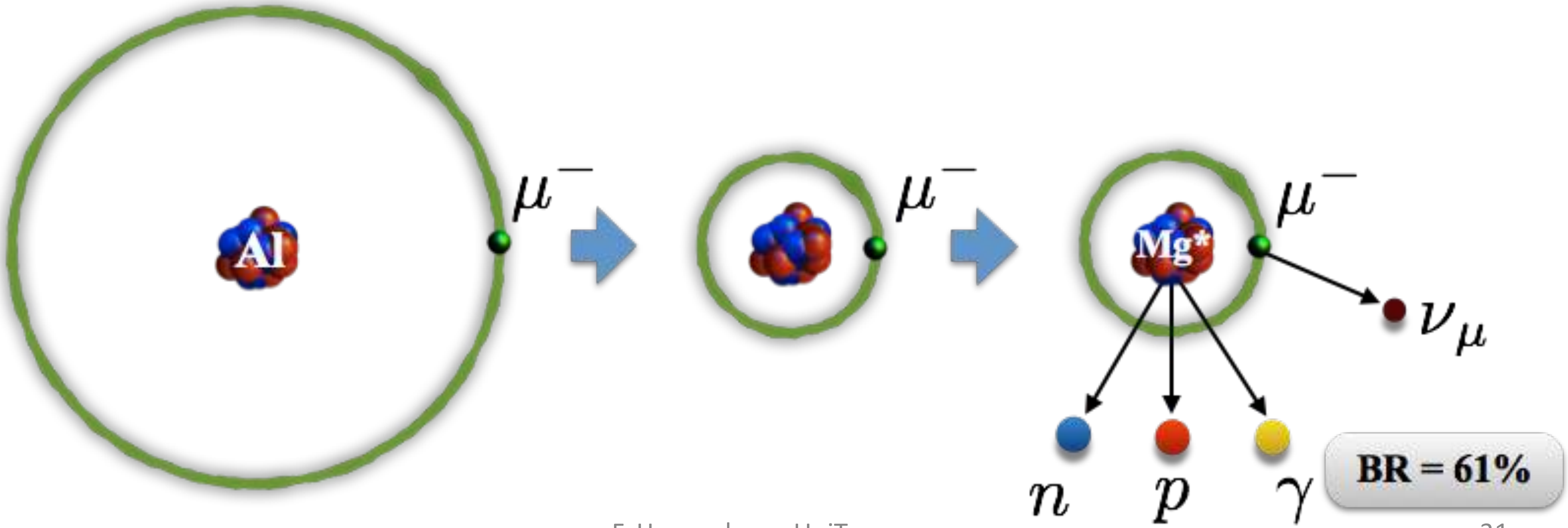


Mu2e Measurement ingredients

- Muon is captured by Aluminum
  - and then interacts with the Aluminum nucleus to form Magnesium.

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

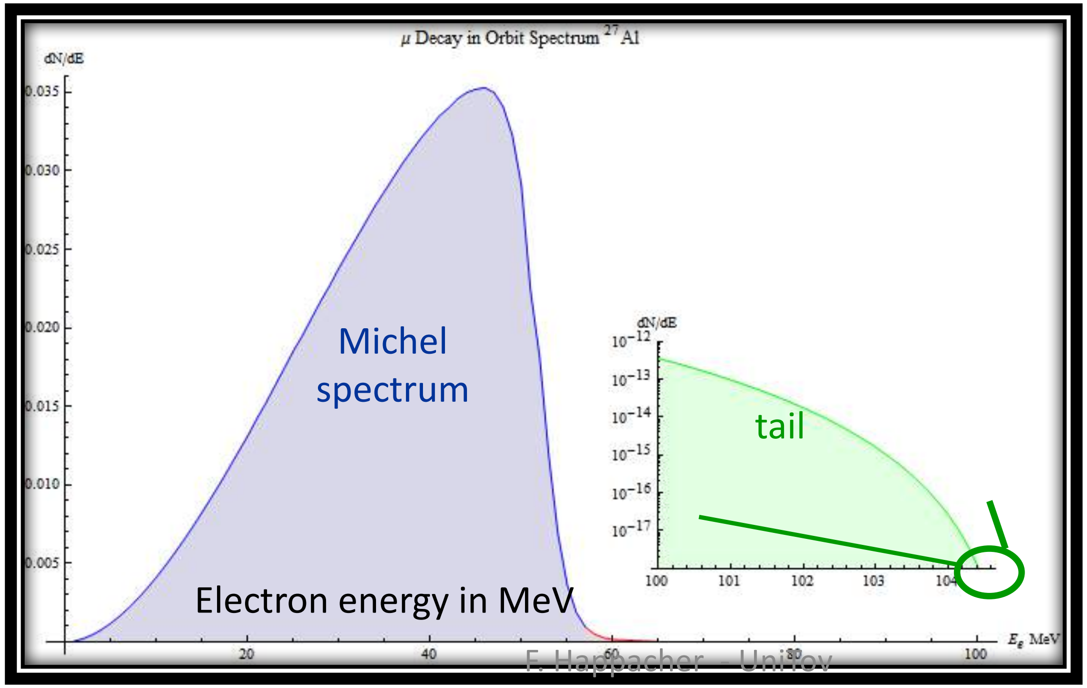
$$\mu^- + Al \rightarrow \nu_\mu + Mg$$



Mu2e intrinsic backgrounds

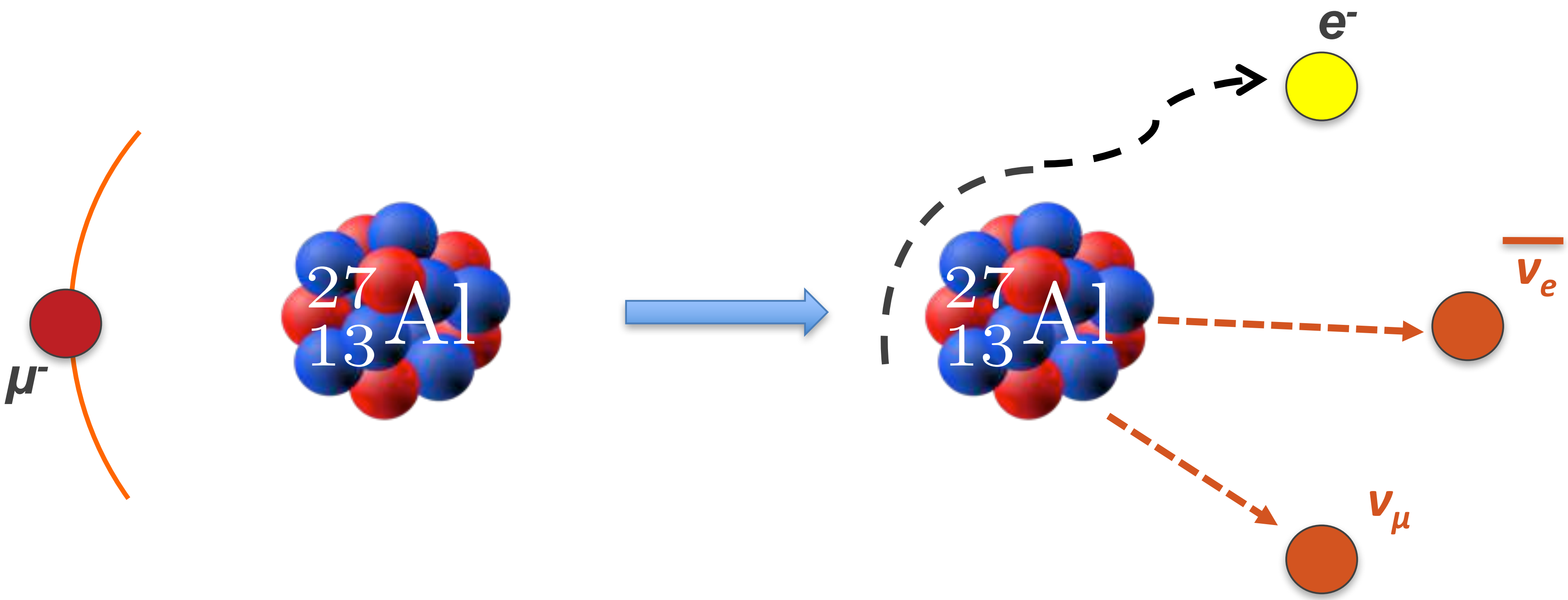
Once trapped in orbit, muons will:

1) Decay in orbit (DIO): $\mu^- N \to e^- \nu_\mu \nu_e N$
   - For Al. DIO fraction is 39%
   - Electron spectrum has tail out to 104.96 MeV
   - Accounts for ~55% of total background



Decay in orbit

Decay In Orbit (DIO) ~ 39%



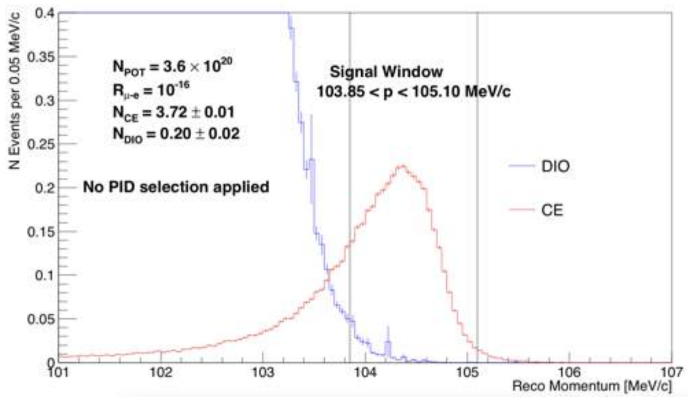
Mu2e Intrinsic Background

Decay in orbit

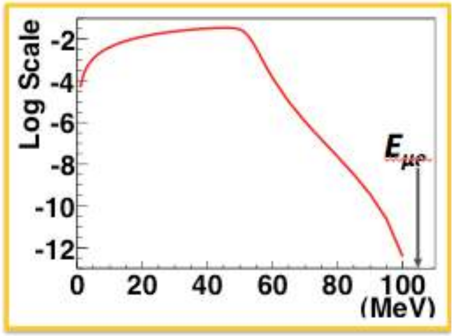
$$[\mu^- + A(N,Z)]^{1S}_{bound} \rightarrow A(N,Z) + e^- + \bar{\nu}_e + \nu_\mu \text{ e}$$

- Electrons from decay of bound muons
- The Michel spectrum is distorted by the presence of the nucleus
- If the neutrinos are at rest the e^- can have exactly the conversion energy E_{CE}=104.97 MeV

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



- Recoil tail extends to conversion energy, with a rapidly falling spectrum near the endpoint
- Drives resolution requirements



Mu2e Intrinsic Backgrounds

Once trapped in orbit, muons will:

2) Capture on the nucleus:

- For Al. capture fraction is 61%
- Ordinary μ Capture
  - $\mu^- N_Z \rightarrow \nu N^*_{Z-1}$
  - Used for normalization
- Radiative μ capture
  - $\mu^- N_Z \rightarrow \nu N^*_{Z-1} + \gamma$
  - (# Radiative / # Ordinary) ~ 1 / 100,000
  - E_γ kinematic end-point ~102 MeV
  - Asymmetric $\gamma \rightarrow e^+ e^-$ pair production can yield a background electron

Backgrounds to deal with

Stopped μ's

- Muon decay in orbit (DIO)
- Radiative muon capture (RMC)

Late protons

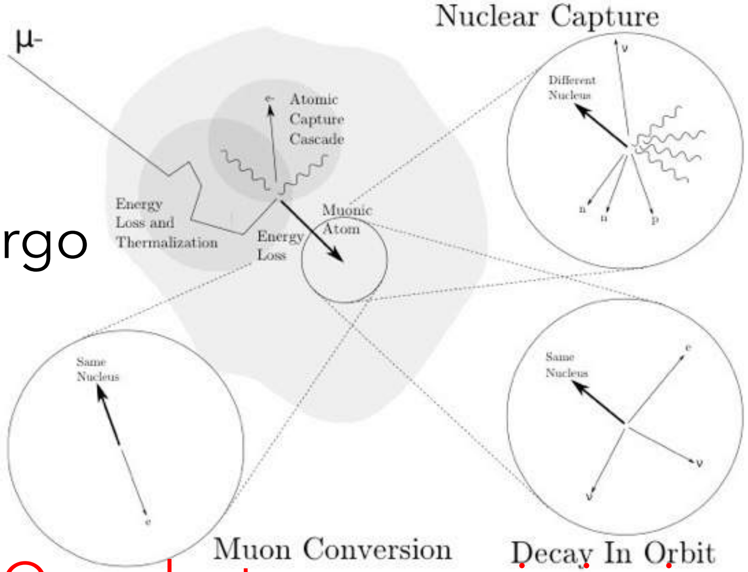
- Pions from the muon beam can undergo radiative capture (RPC)

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

γ energy 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



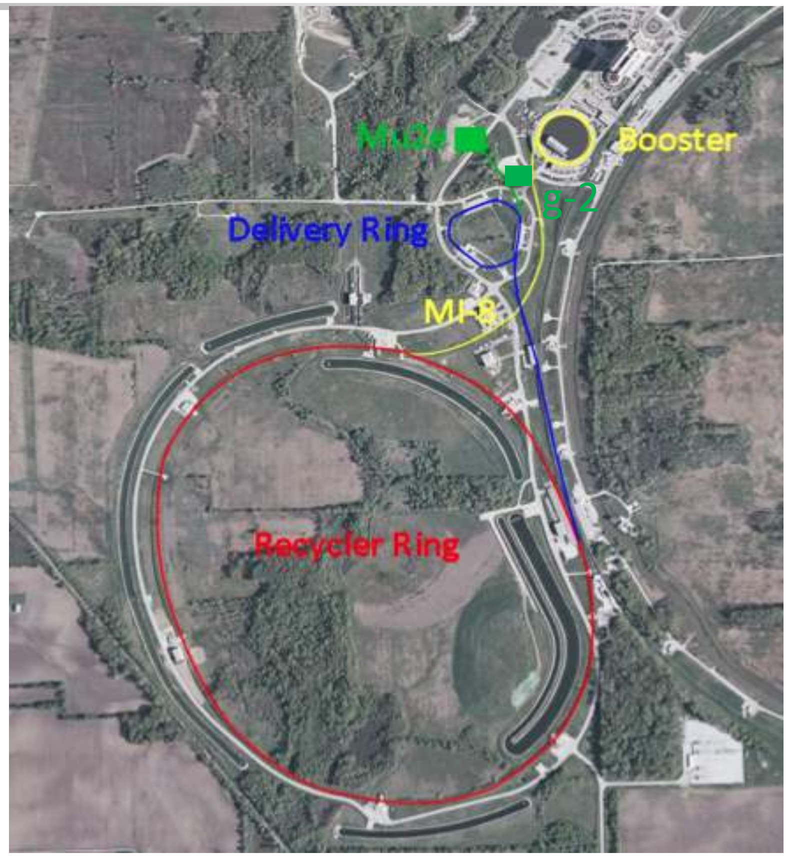
Category	Background process	Estimated yield (events)
Intrinsic	Muon decay-in-orbit (DIO)	0.199 ± 0.092
	Muon capture (RMC)	$0.000^{+0.004}_{-0.000}$
Late Arriving	Pion capture (RPC)	0.023 ± 0.006
	Muon decay-in-flight (μ-DIF)	<0.003
	Pion decay-in-flight (π-DIF)	$0.001 \pm <0.001$
	Beam electrons	0.003 ± 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 (~10^{11} reduction after 700 ns)

Accelerator & Proton extinction

- Mu2e will repurpose much of the Tevatron anti-proton complex to instead produce muons.
- Booster: 21 batches of 4×10^{12} of 8 GeV 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**



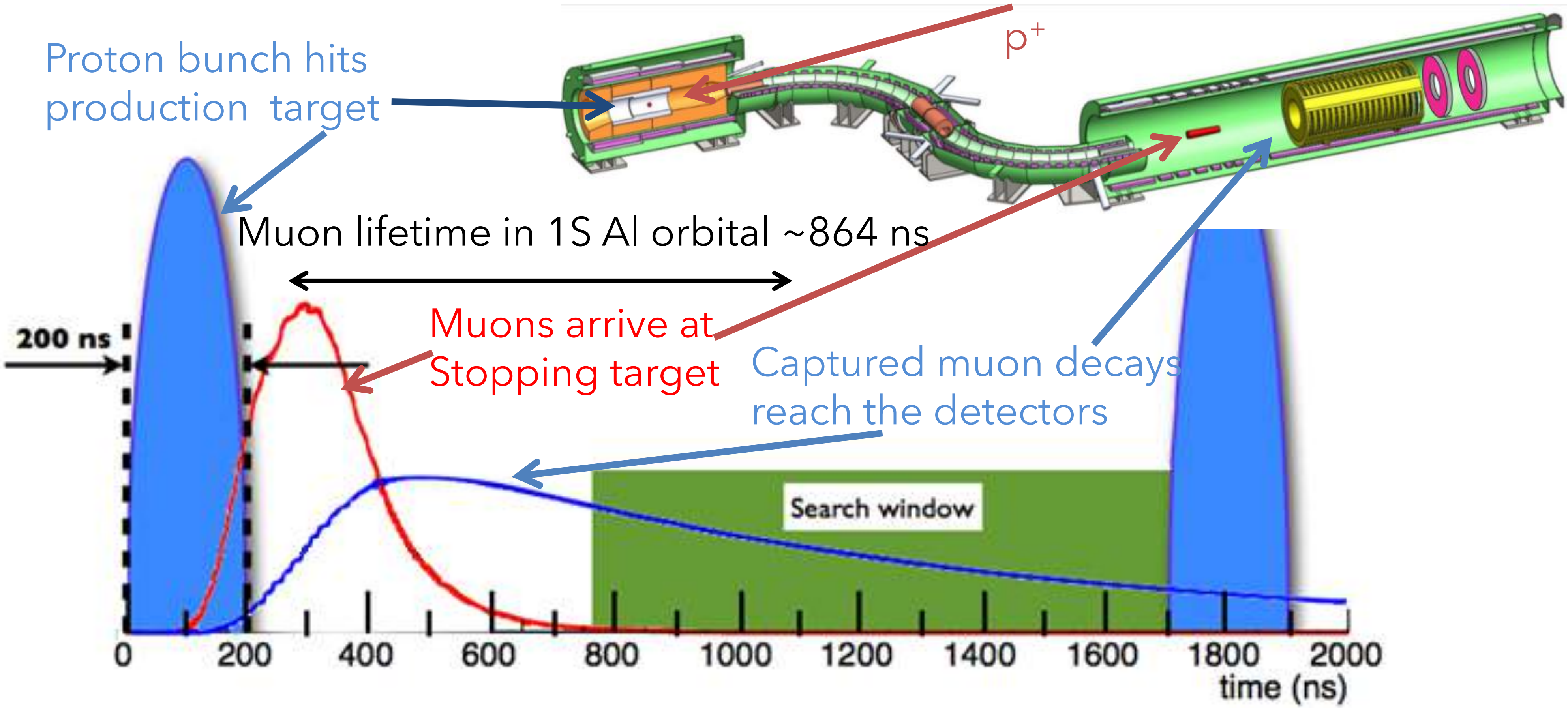
Proton Extinction

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}

Pulsed beam structure

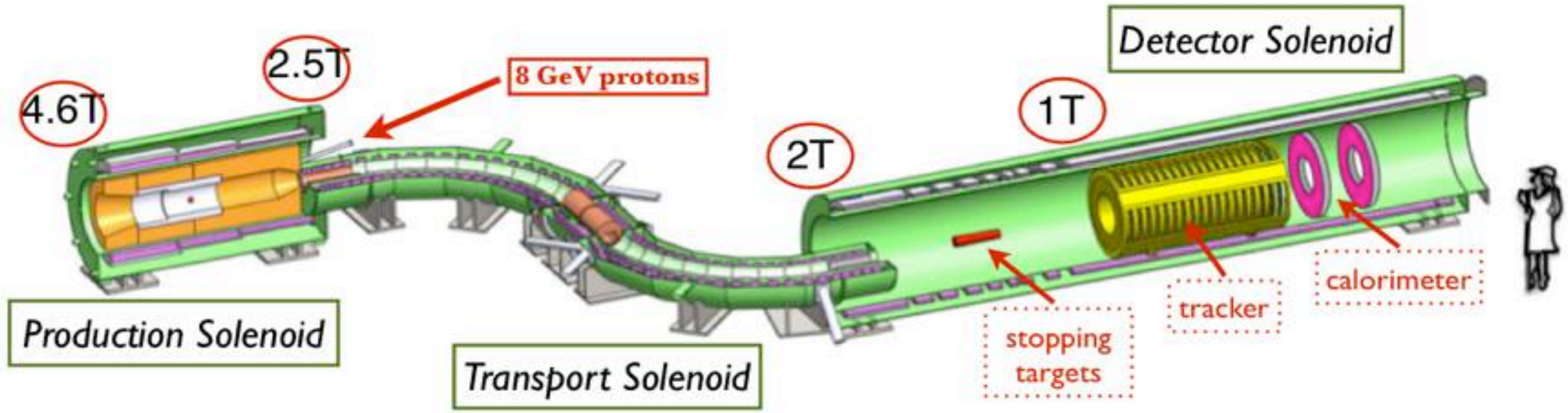


- ❑ Use the fact that muonic atomic lifetime >> prompt background
  Need a pulsed beam to wait for prompt background to reach acceptable levels
  → Fermilab accelerator complex provides ideal pulse spacing

- ❑ 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)$<10^{-10}$

The Mu2e beamline

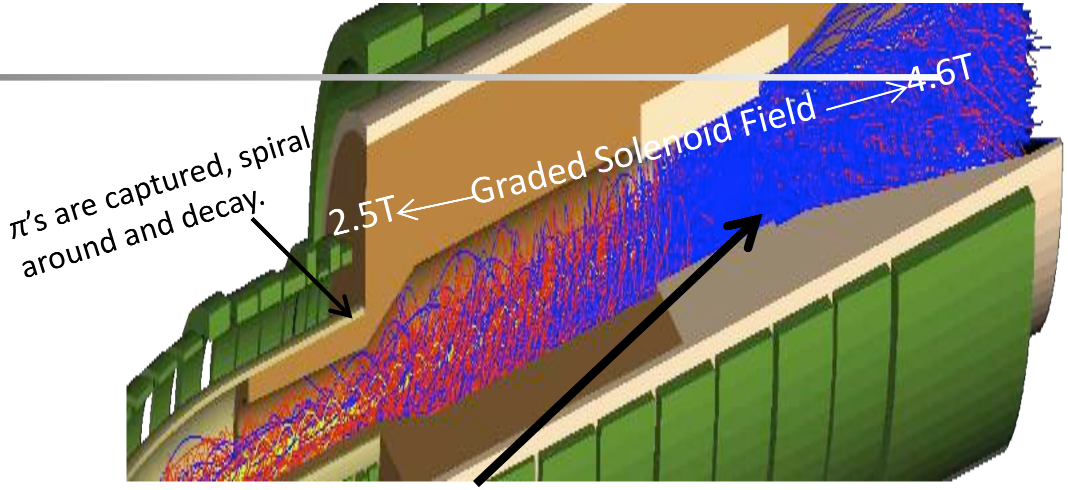
- Mu2e Solenoid System
  - Superconducting
    - Requires a cryogenic system
  - Inner bore evacuated to 10^{-4} Torr to limit background due to interactions of the charged particles with air



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

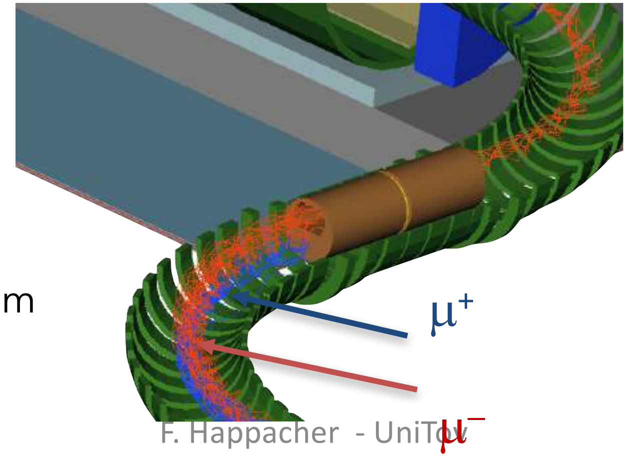


- Transport Solenoid
  - Graded magnetic from 2.5 T (at the production solenoid entrance) to 2.0 T (at the detector solenoid entrance)
    - Allows muons to travel on a helical path from the production solenoid to the detector solenoid

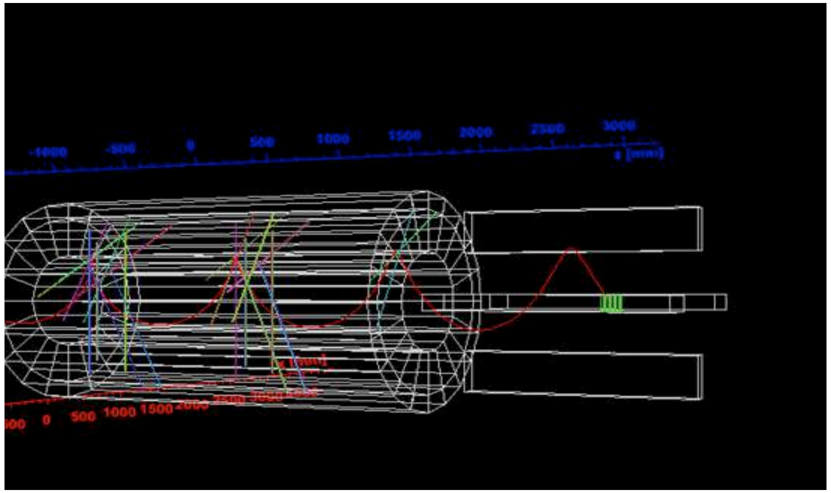
S-shaped to remove the detector solenoid out of the line of sight from the production solenoid

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

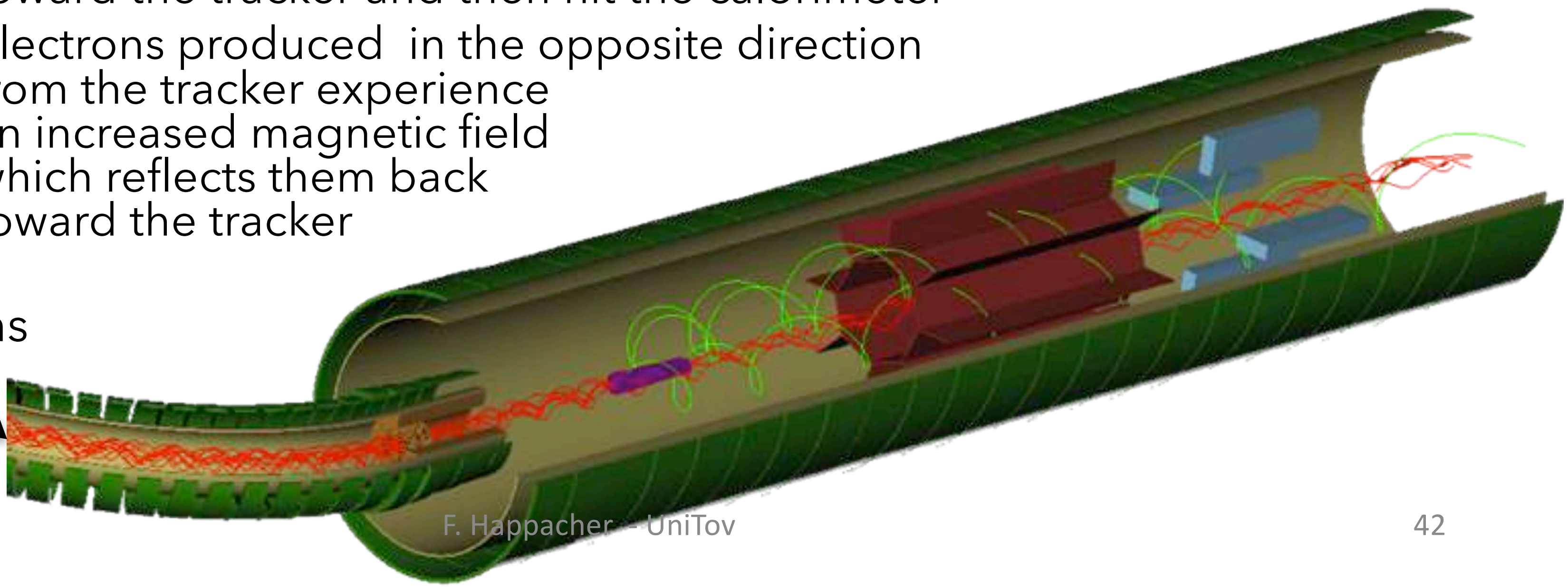
off-center central TS collimator and 90° bends passes low momentum negative muons and suppresses positive particle and high momentum negative particles.



The Mu2e Beamline



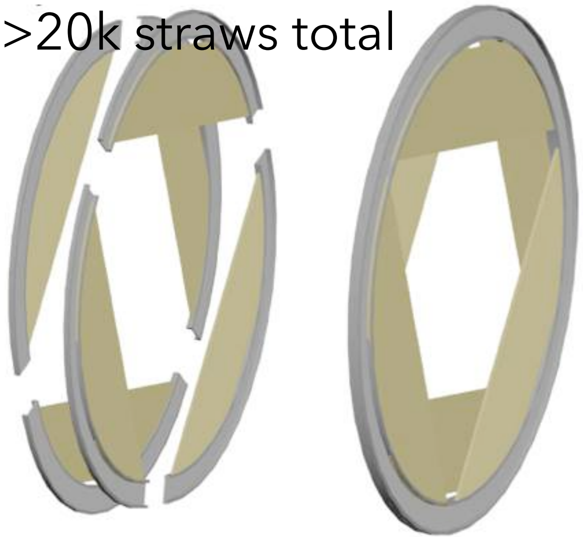
- The Detector Solenoid houses the Al target and the two main detectors: the tracker and the calorimeter
  - 17 Aluminum disks, 0.2 mm thick, radius between 83 mm (upstream) and 63 mm (downstream)
  - Surrounded by graded magnetic field from 2.0 T (upstream) to 1.0 T (downstream)
    - Conversion electrons 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

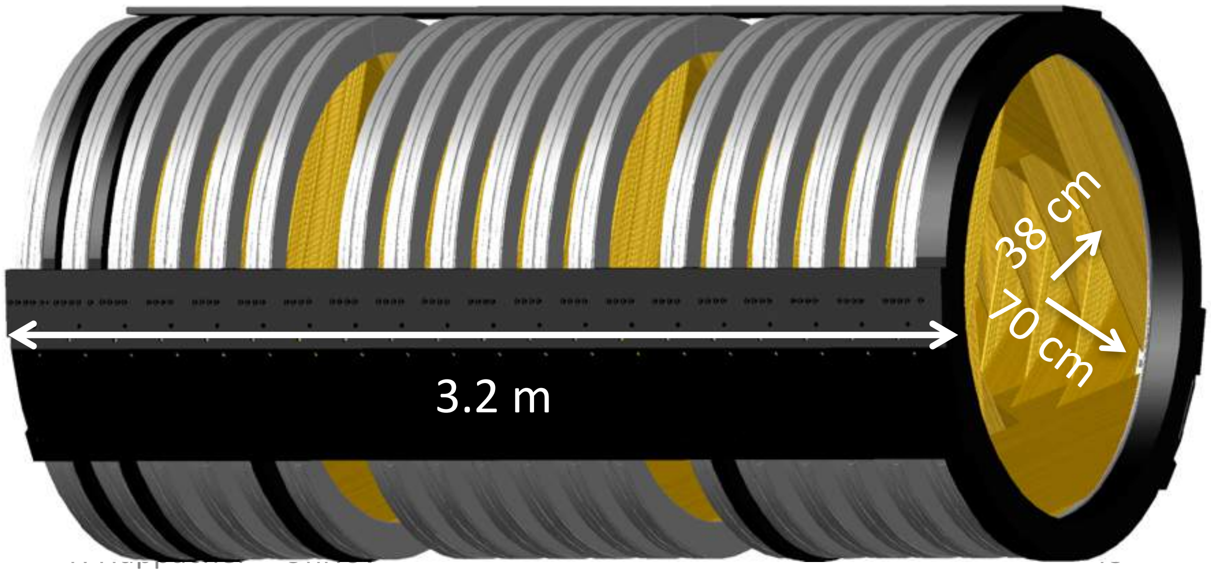


The Mu2e Tracker

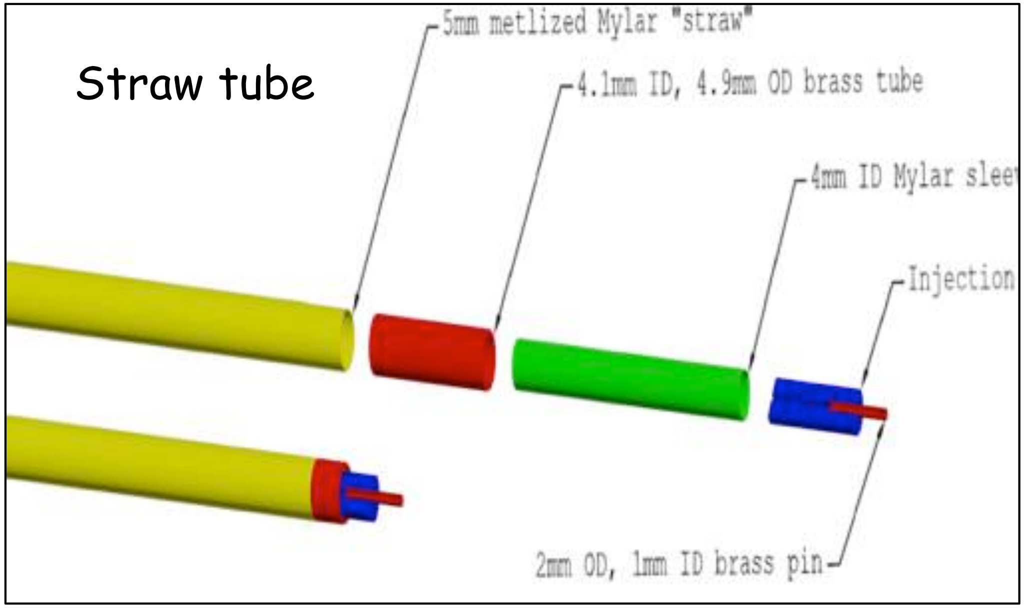
- The Tracker will employ low mass straw drift tubes with tubes transverse to secondary beam
- 15 mm thick straw walls, dual-ended readout (ADC-TDC) length 430 – 1120 mm.
- It must operate in vacuum
- Self-supporting "panel" consists of 100 straws
- 6 panels assembled to make a "plane"
- 2 planes assembled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

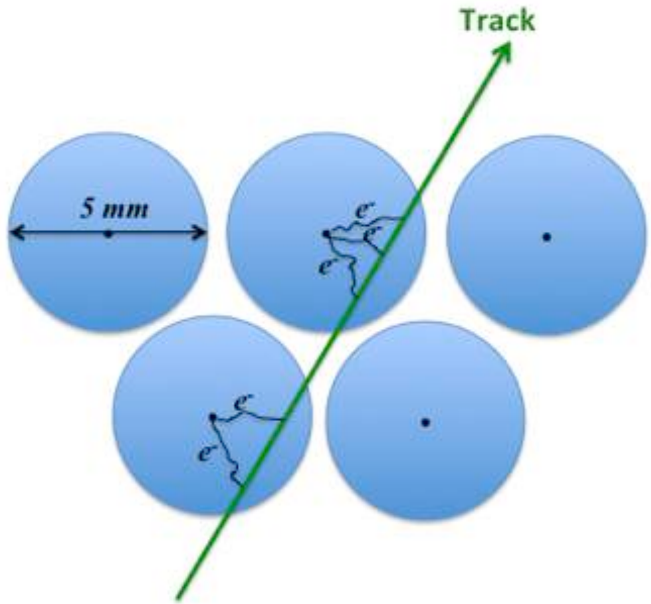
- 5 mm diameter straw
- Spiral wound
- Walls: 12 mm Mylar + 3 mm epoxy + 200 Å Au + 500 Å Al
- 25 μm Au-plated W sense wire
- 33 – 117 cm in length
- 80/20 Ar/CO_2 with HV < 1500 V





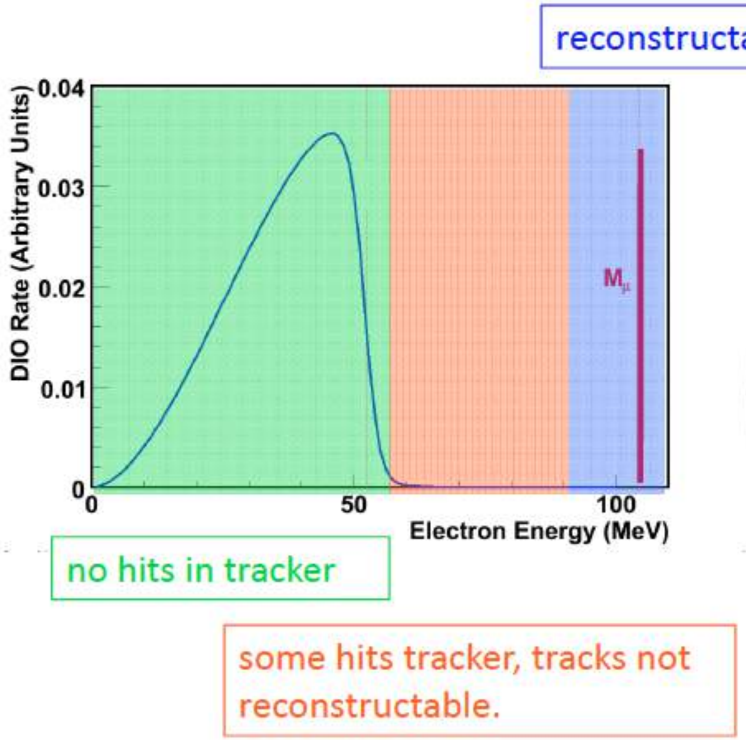
Straw tube tracker

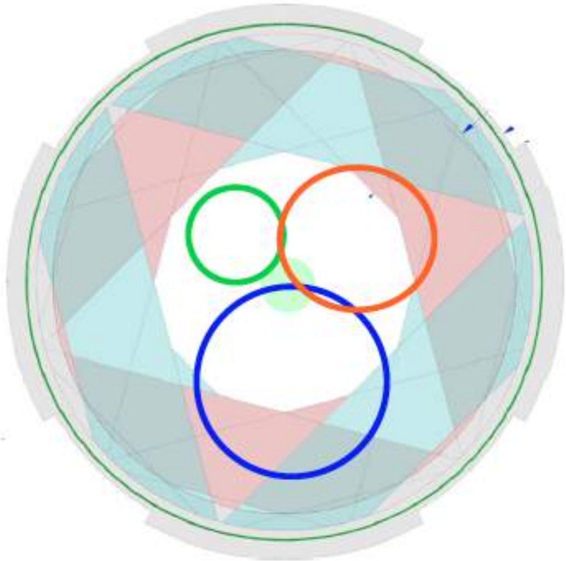




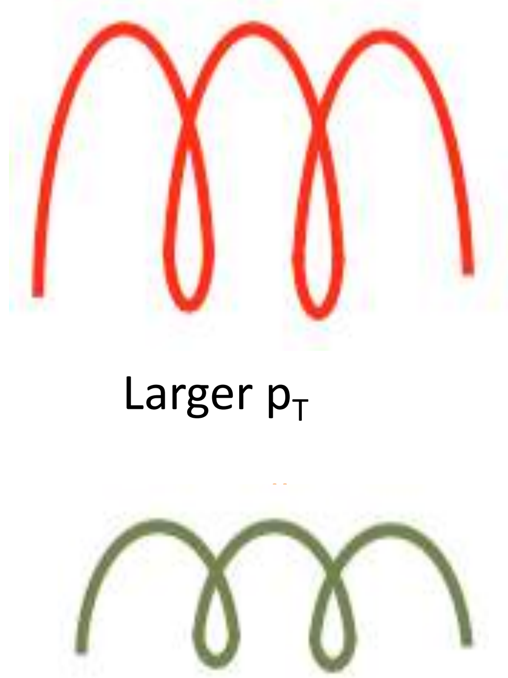
- Proven technology
- Low mass → minimize scattering (track typically sees ~ 0.25 % X_0)
- Modular, connections outside tracking volume
- **Challenge: straw wall thickness (15 μm)**

The Mu2e Tracker





beam's-eye view of the tracker



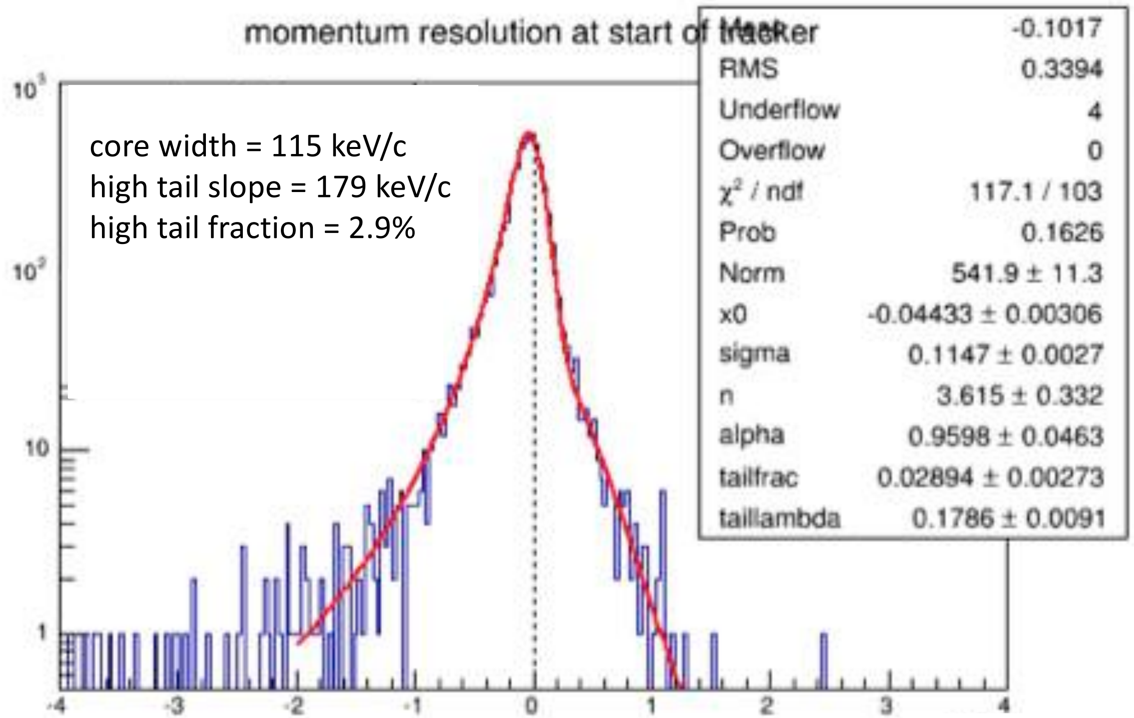
- Inner 38 cm is purposefully un-instrumented
  - Blind to beam flash
  - Blind to >99% of DIO spectrum

First Prototype Panel

Fermilab, March 2015

- Starting pre-production prototype now

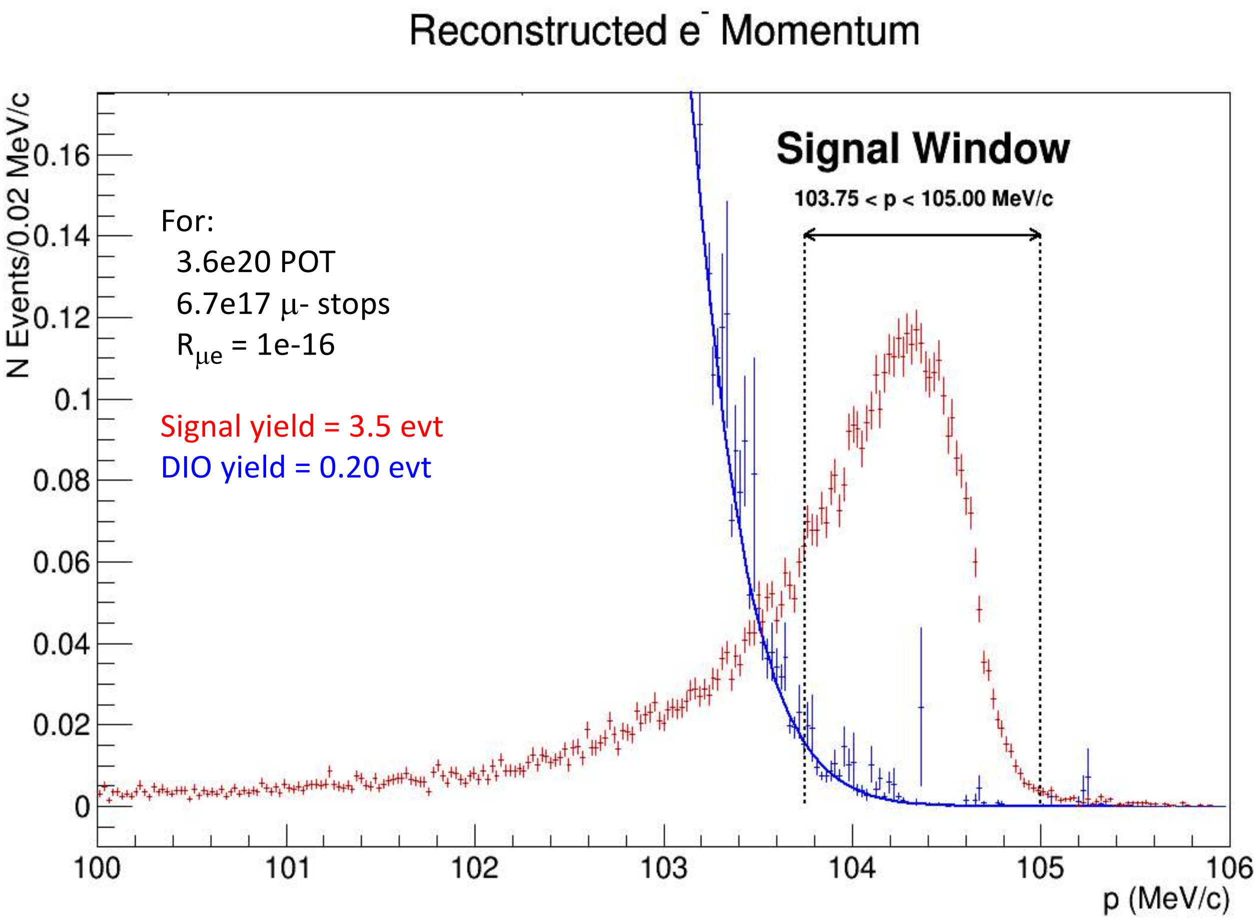
Mu2e Tracker Performance



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

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

Signal extraction



- Single-event-sensitivity = 2.9×10^{-17} (goal 2.4×10^{-17})
- Total background < 0.5 events

The Mu2e calorimeter

The calorimeter has to:

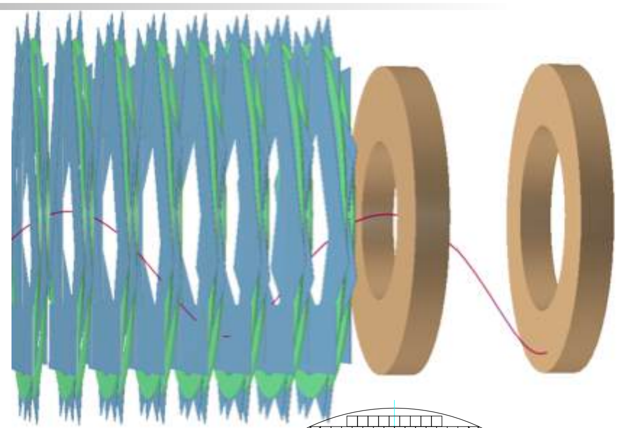
- Provide high e- reconstruction efficiency for μ rejection of 200
- Provide cluster-based additional seeding for track finding
- Provide online software trigger capability
- Stand the radiation environment of Mu2e
- Operate for 1 year w.o. interruption in DS w/o reducing performance

the calorimeter needs to fulfill the following

→ Provide energy resolution σ_E/E of O(6 %)
→ Provide timing resolution $\sigma(t) < 200$ 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

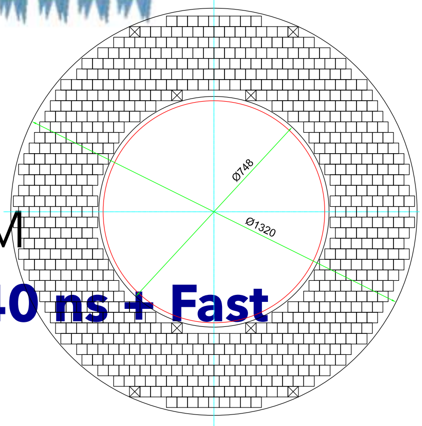


High granularity crystal based calorimeter with:

- 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/cm²**

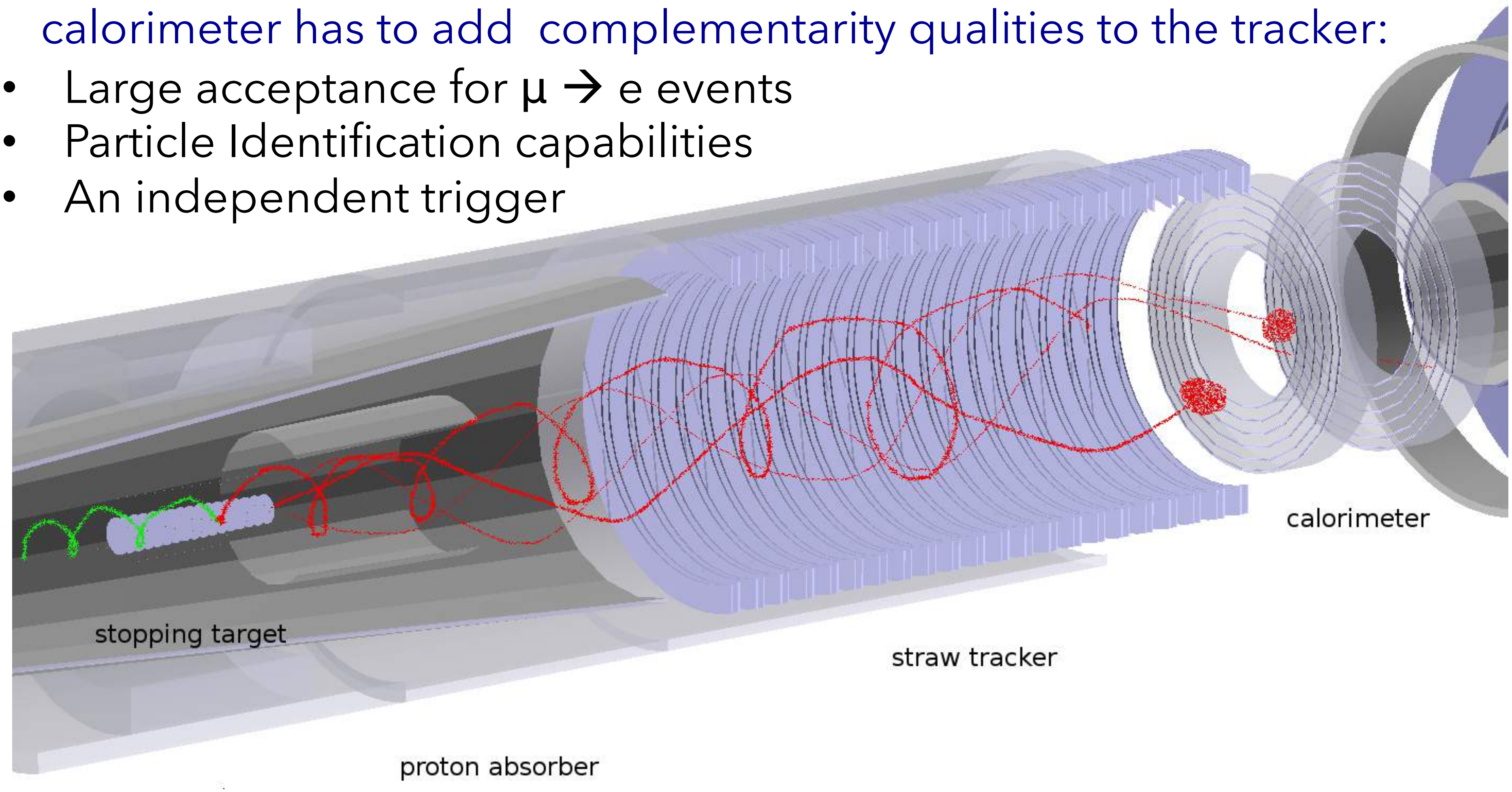
  → **Photo-sensors survive 20 krad and a neutron fluency of 3×10^{11} n_1MeV/cm²**



The Mu2e Calorimeter

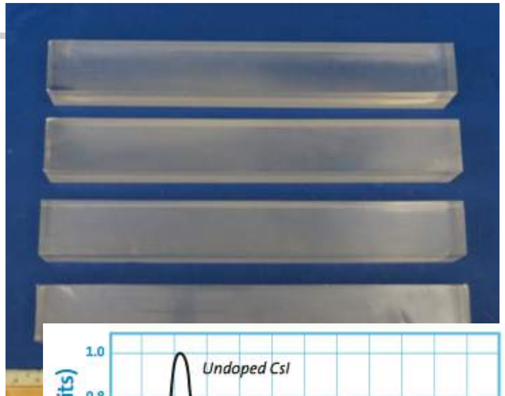
In order to add redundancy to this "super-rare" search, the calorimeter has to add complementarity qualities to the tracker:

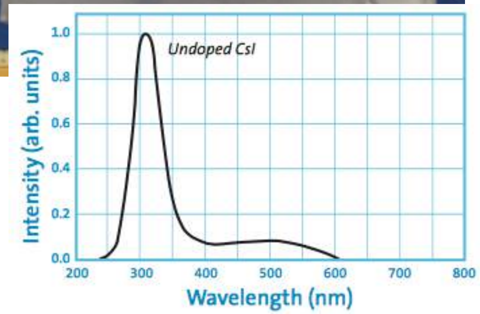
- Large acceptance for μ → e events
- Particle Identification capabilities
- An independent trigger



- "seeds" to improve track finding efficiency at high occupancy
- Resistant to radiation dose and working in vacuum @ 10^{-4} Torr

The Mu2e Calorimeter

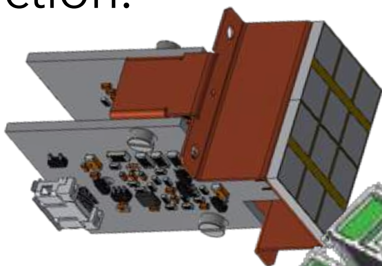




The Calorimeter consists of two disks containing 674 34x34x200 mm³ pure CsI crystals each

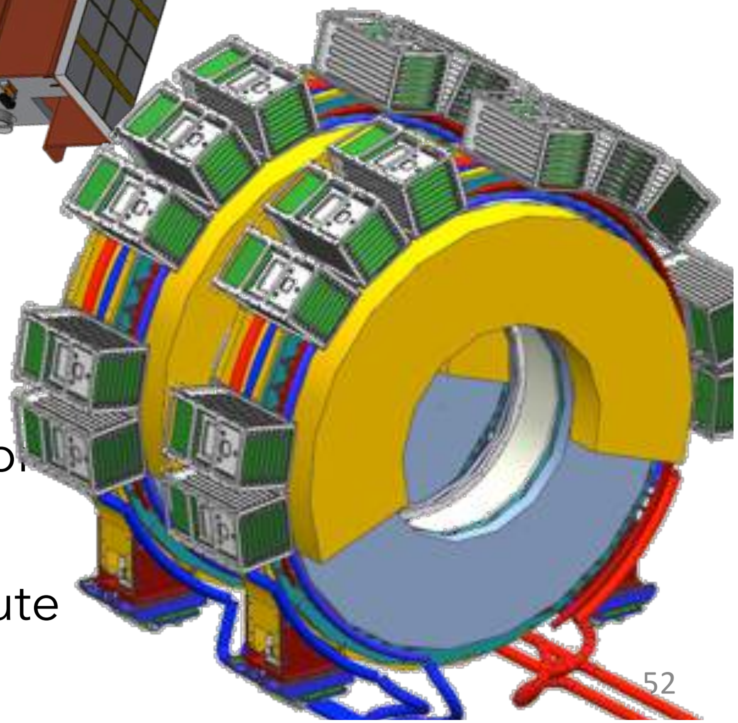
→ R_{inner} = 374 mm, R_{outer}=660 mm, depth = 10 X_0 (200 mm)
→ Disks separated by 75 cm, half helix length

→ Each crystal is readout by two large area UV extended SIPM's (14x20 mm²) maximizing light collection.
PDE=30% @ CsI emission peak =315 nm.
GAIN ~10^6

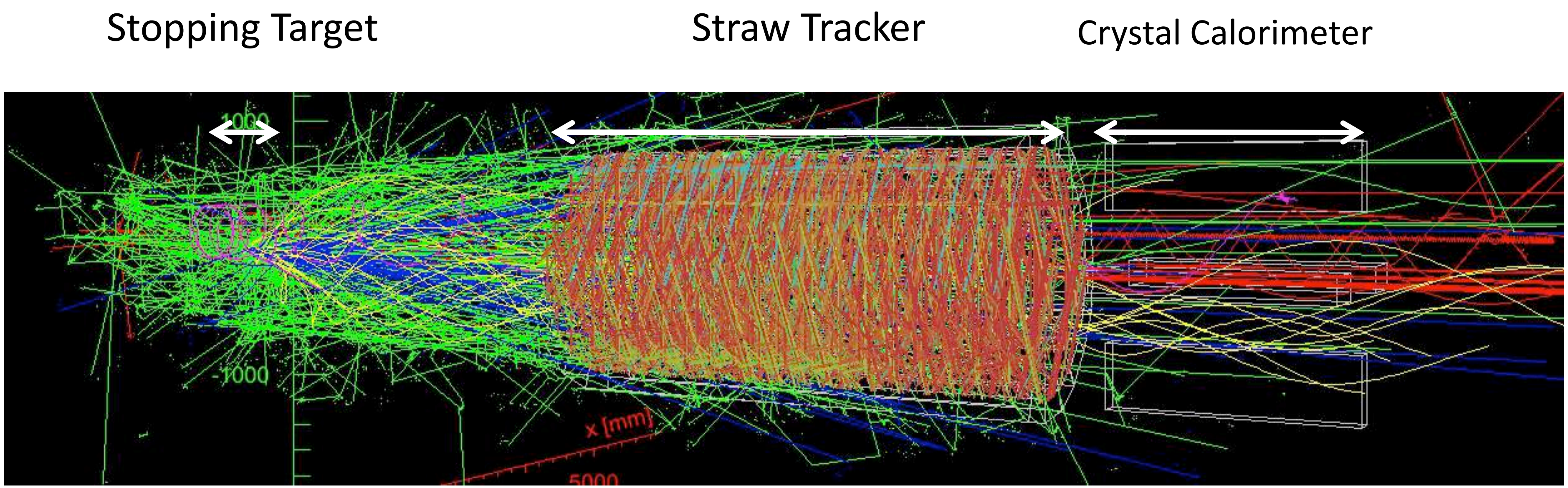


→ TYVEK wrapping
→ Analog FEE is onboard to the SiPM (amplification and shaping) and digital electronics located in electronics crates (200 MhZ sampling)
→ Cooling system – SiPM cooling, Electronic dissipatio

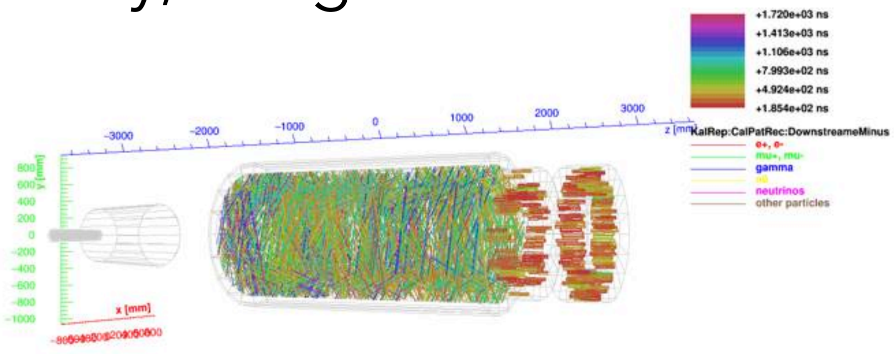
→ Radioactive source and laser system provide absolute calibration and monitoring capability



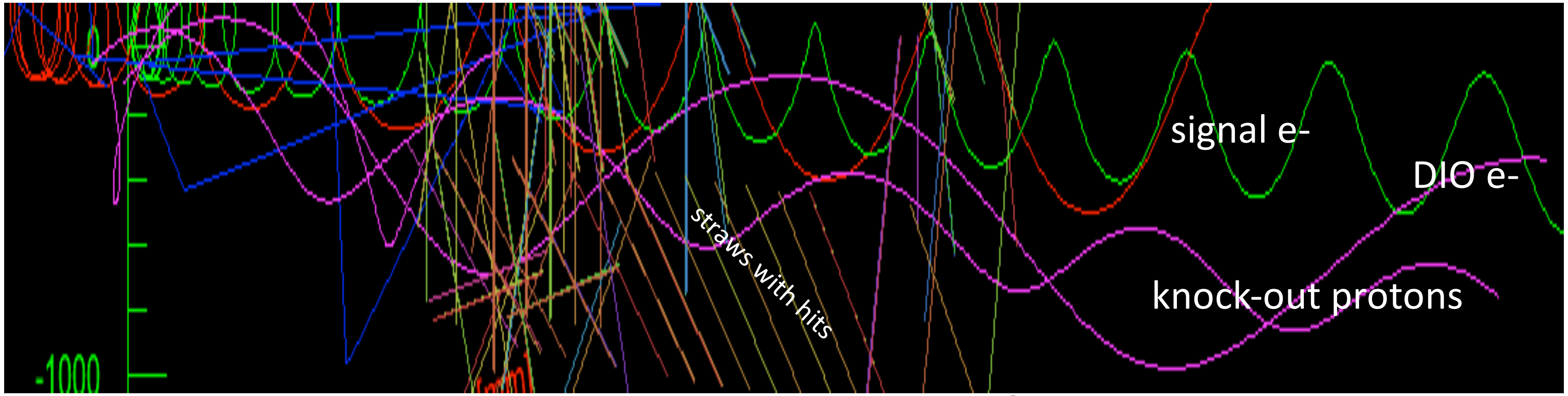
Mu2e Pattern Recognition



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

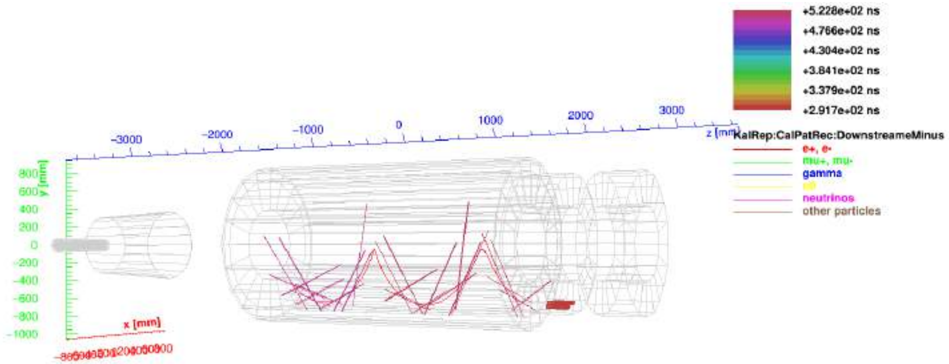


Mu2e Pattern Recognition



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

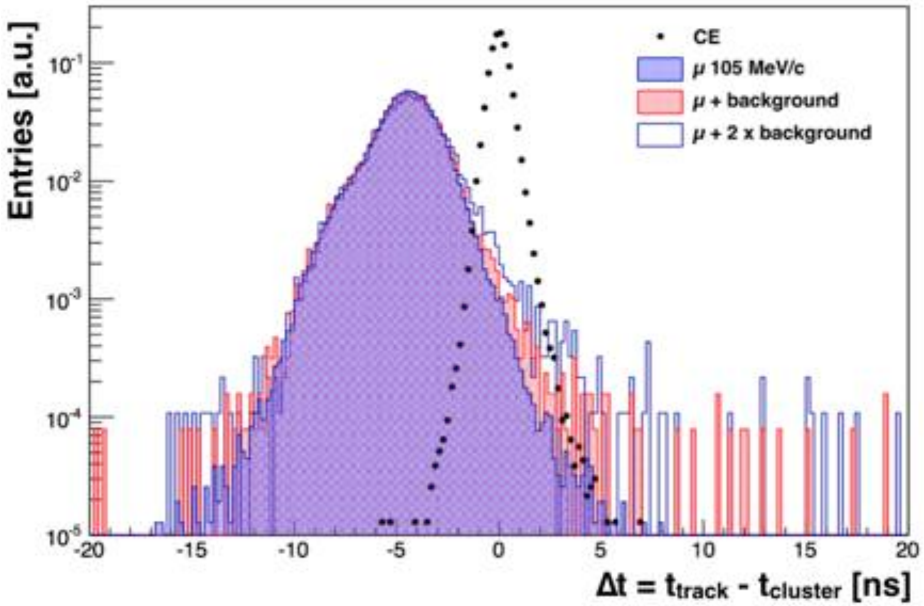
- ❑ Search for tracking hits with time and azimuthal angle compatible with the calorimeter clusters (|ΔT| < 50 ns) → simplification of pattern recognition
- ❑ Add search of an Helix passing through cluster and selected hits + use calorimeter time to calculate tracking Hit drift times
- ❑ Reduce the wrong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

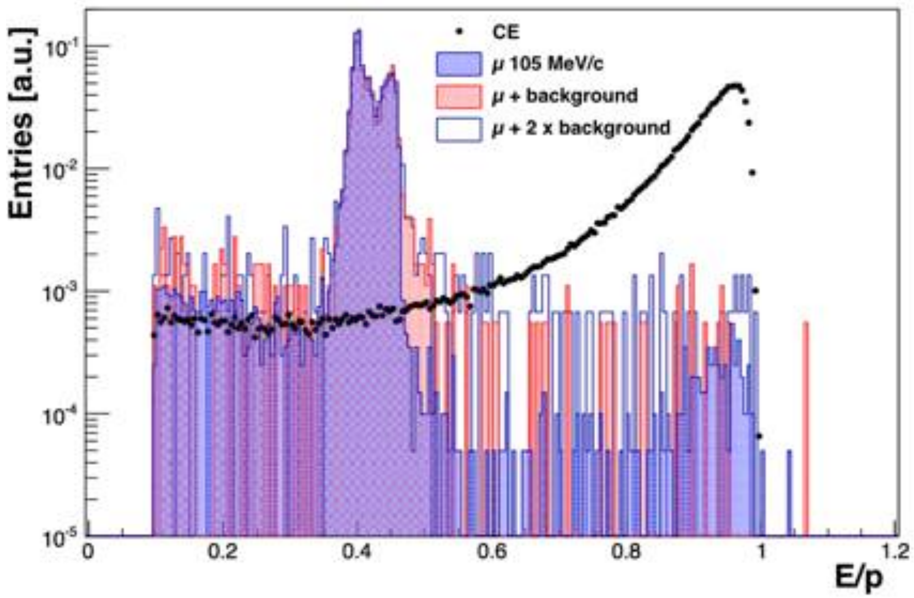


PID - μ rejection

- 105 MeV/c e^- are ultra-relativistic, while 105 MeV/c μ's have β ~ 0.7 and a kinetic energy of ~ 40 MeV;
- Likelihood rejection combines **Δ**t = t_{track} - $t_{cluster}$ and E/p:

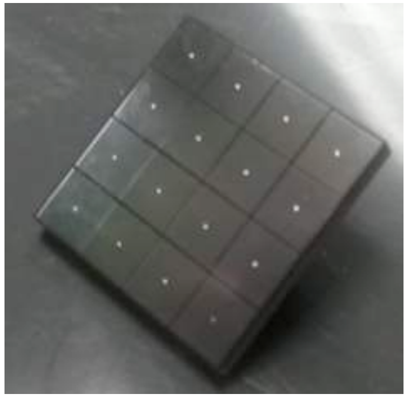
$$\ln L_{e,\mu} = \ln P_{e,\mu}(\Delta \mathrm{t}) + \ln P_{e,\mu}(\mathrm{E/p})$$

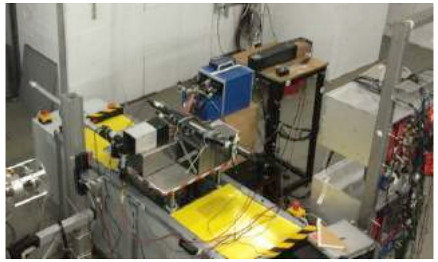


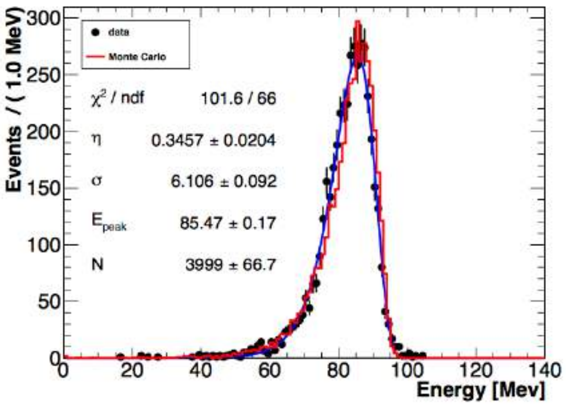


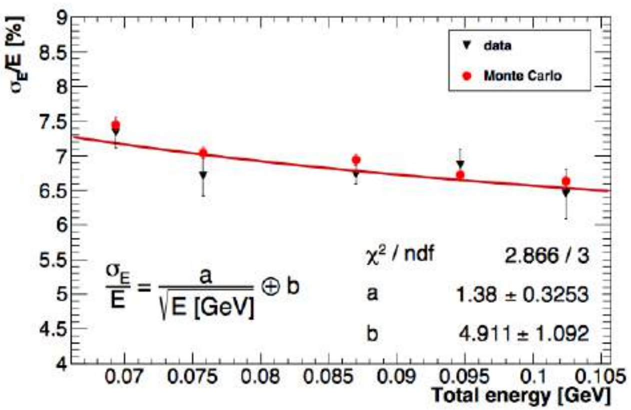
CsI+SiPM tests

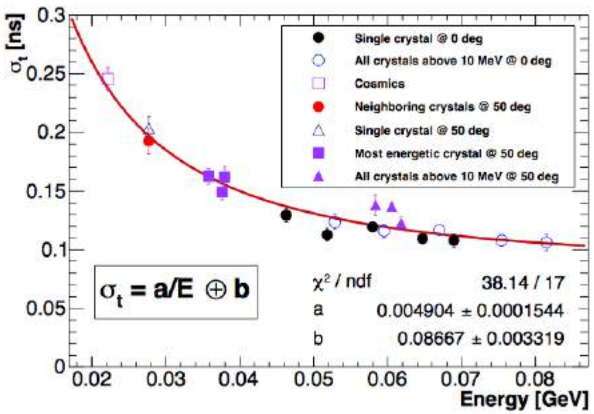
- A small crystal prototype has been built and tested in Frascati in April 2015
- 3x3 matrix of 3x3x20 cm^3 un-doped CsI crystal coupled with UV-extended SiPM.
- Test with e- between 80 and 120 MeV





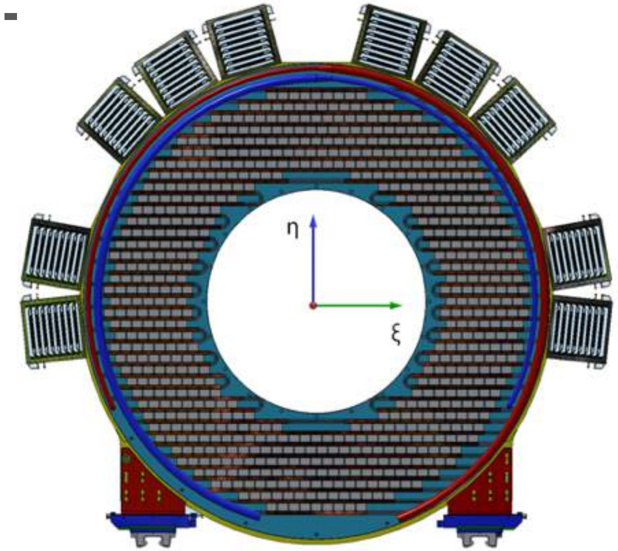


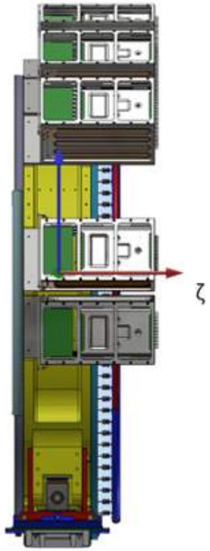


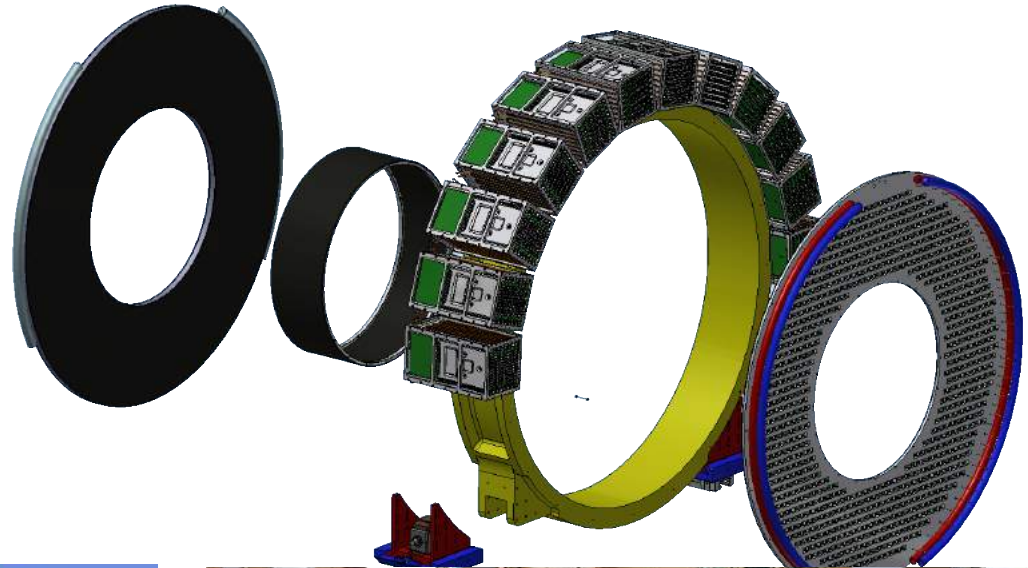


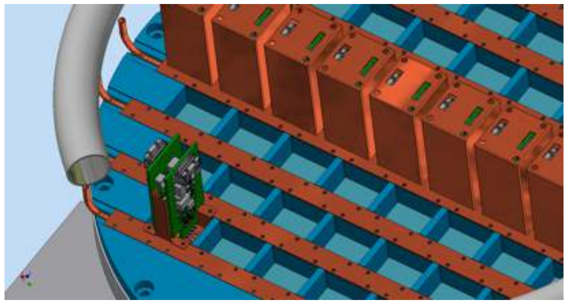
- @100 MeV: Good energy (6-7%) and timing (110 ps) resolution
- Leakage dominated

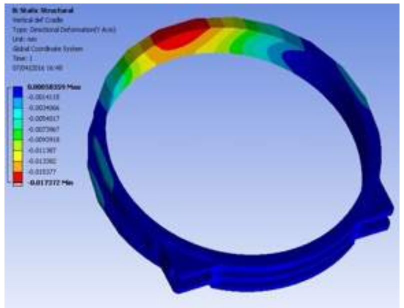
The Calorimeter engineering

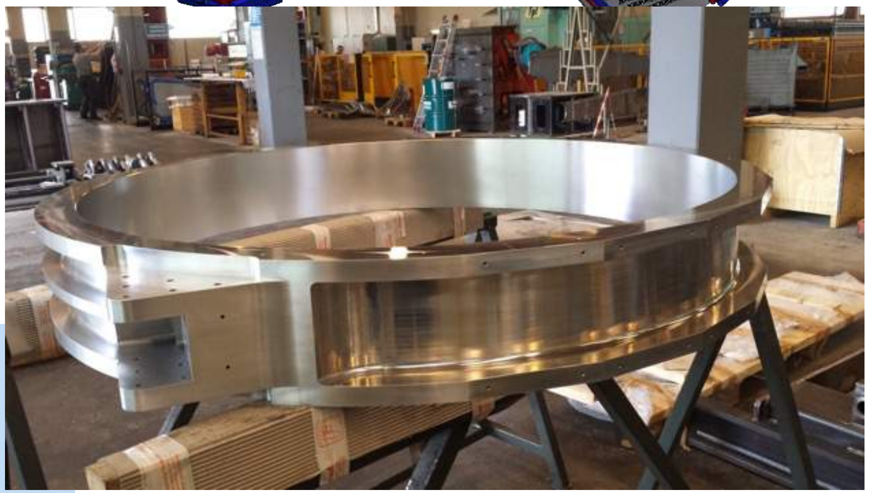


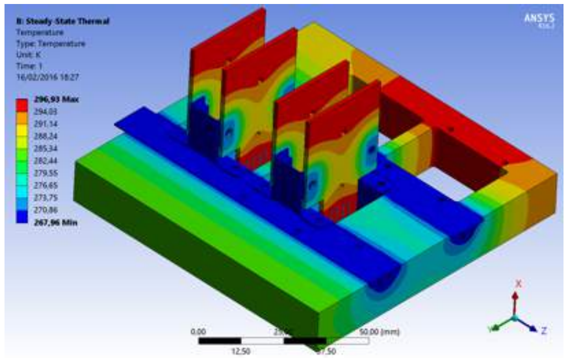


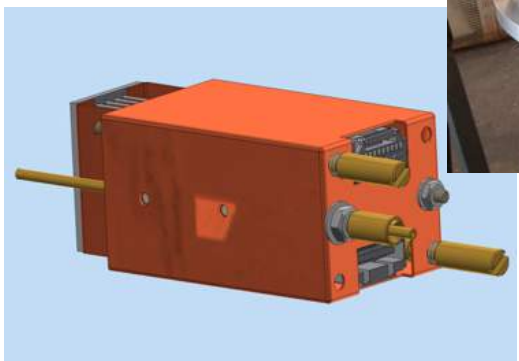




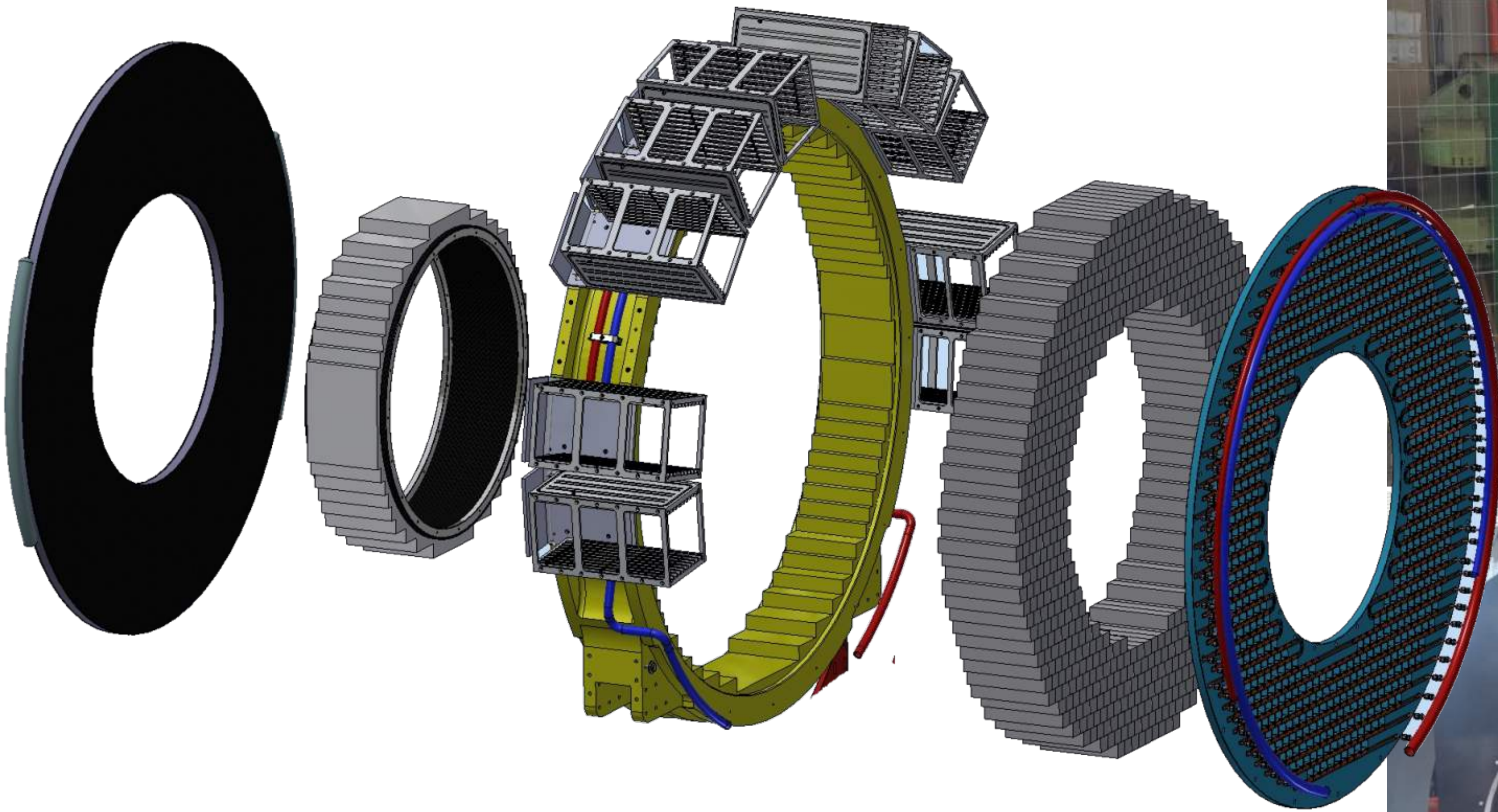


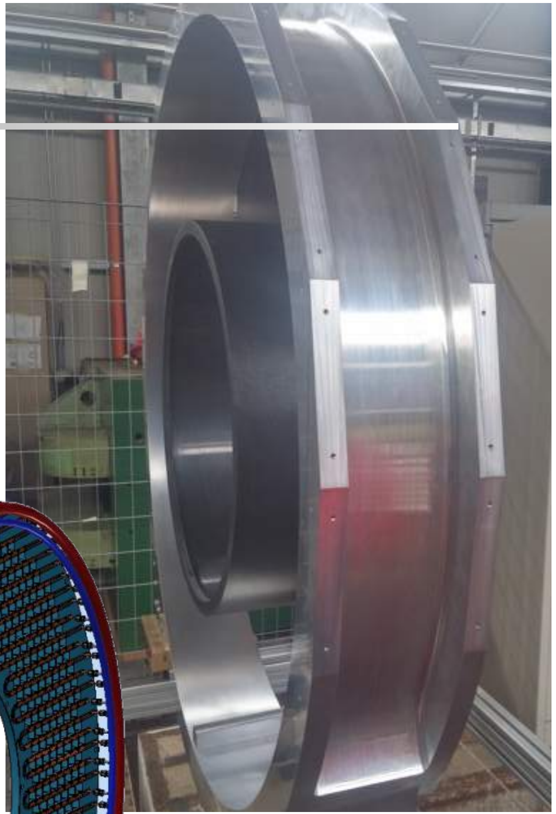


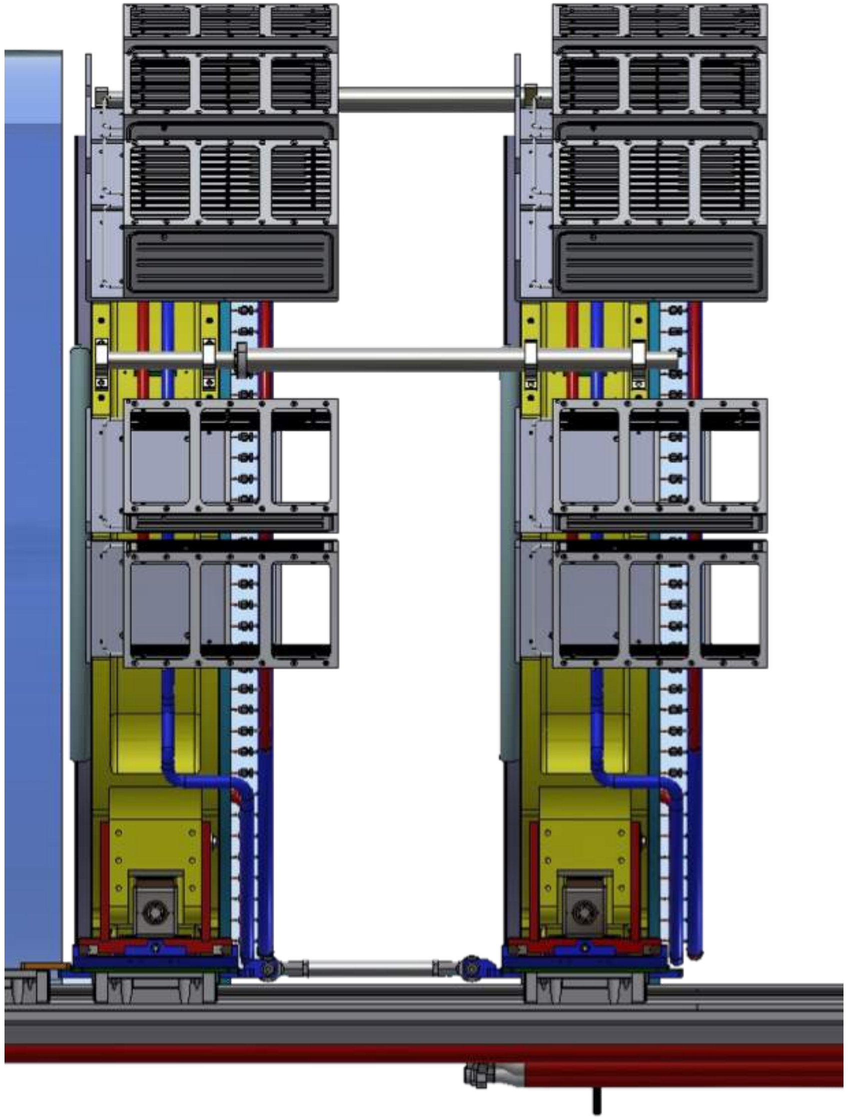




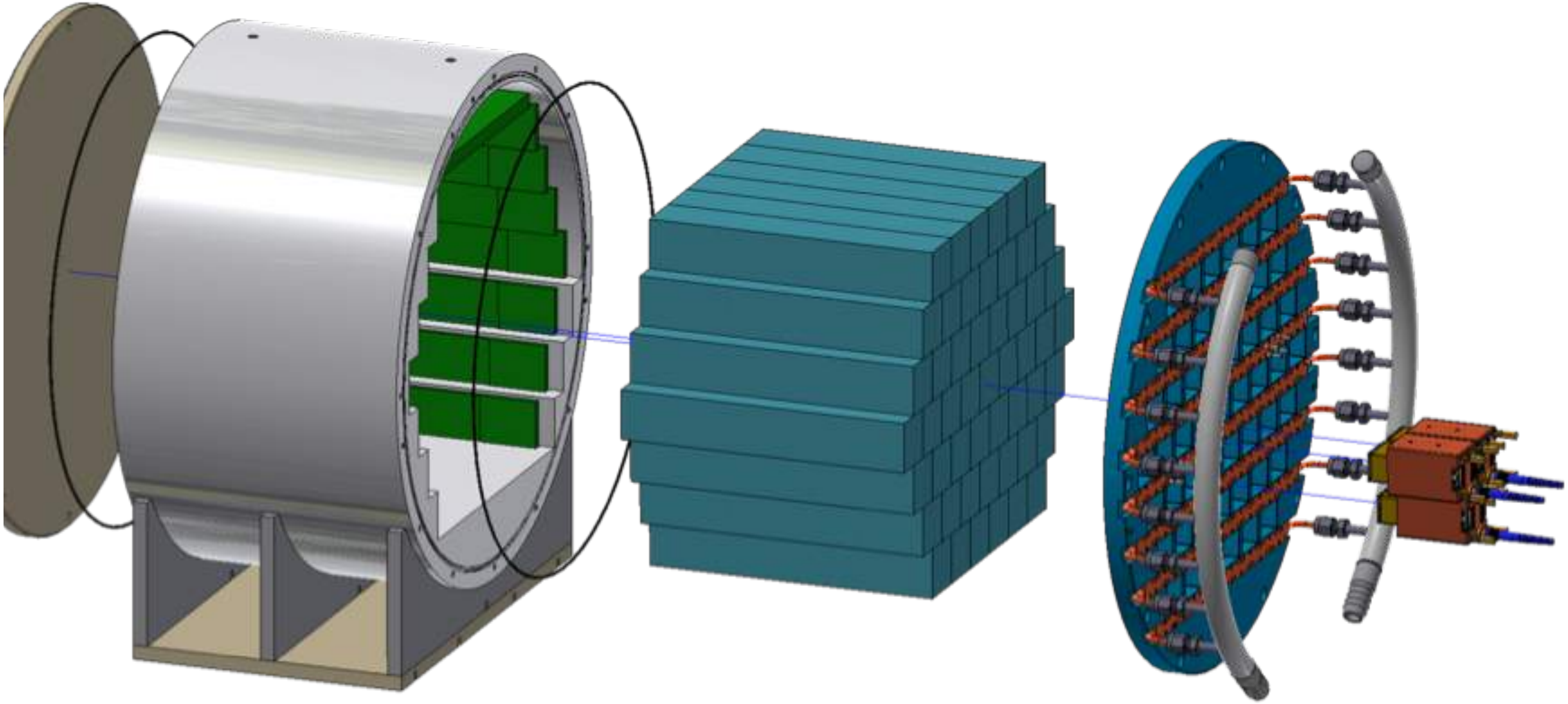
prototyping



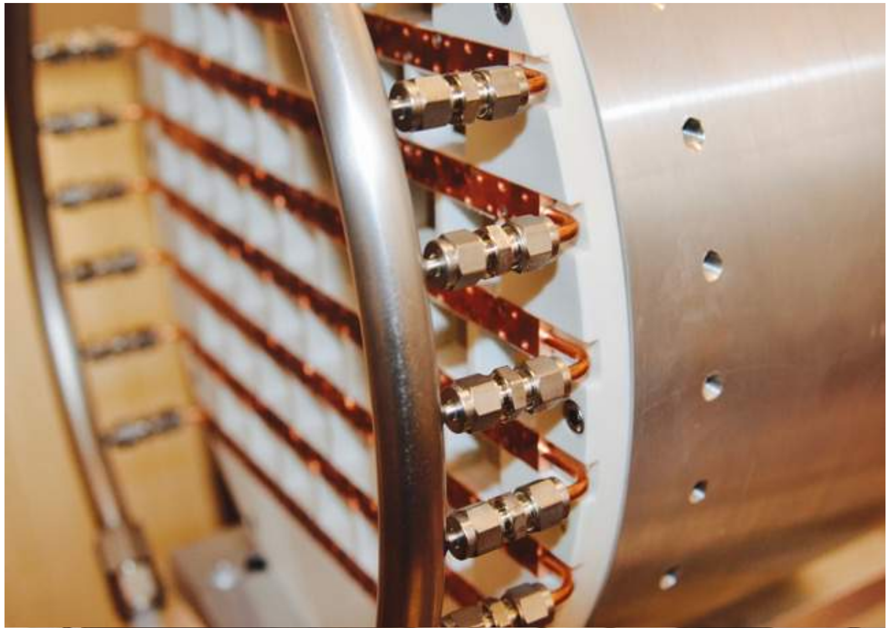


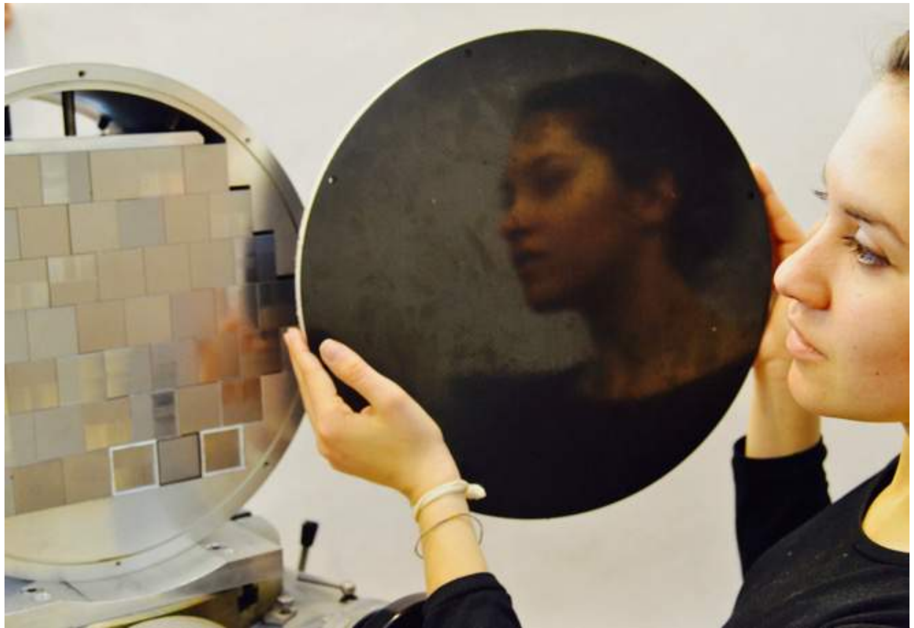


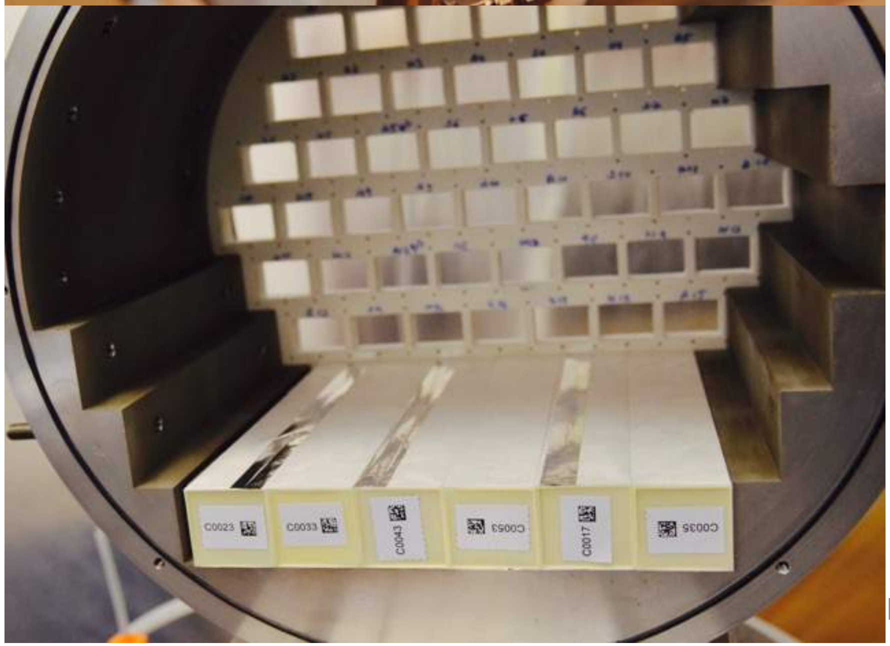
Module 0

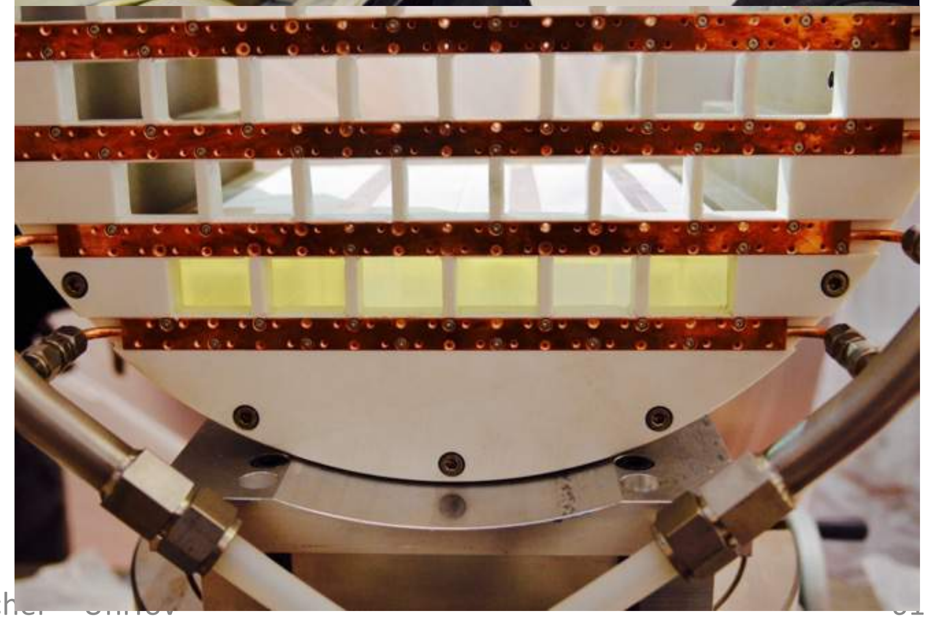


Module 0 prototyping

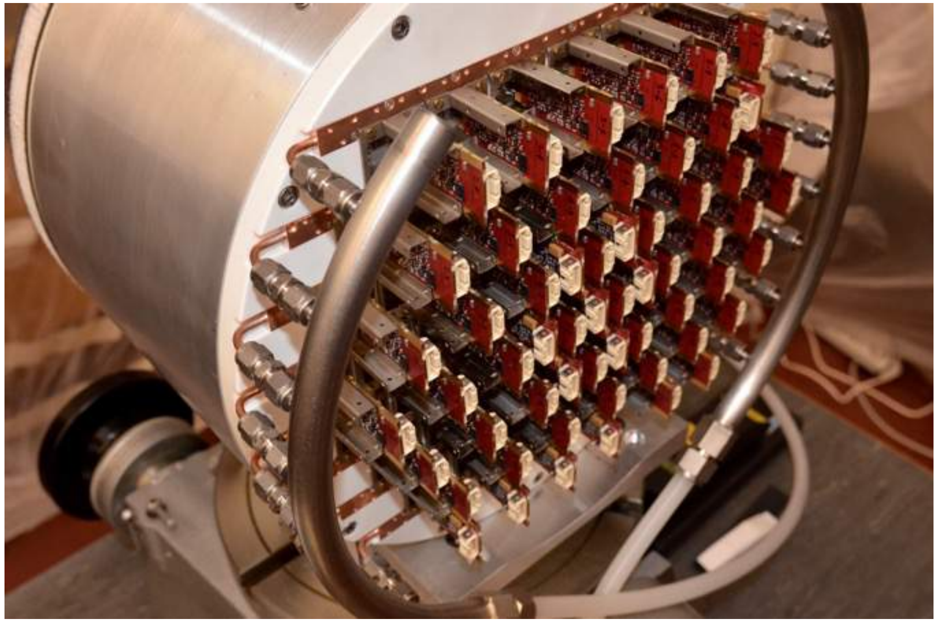


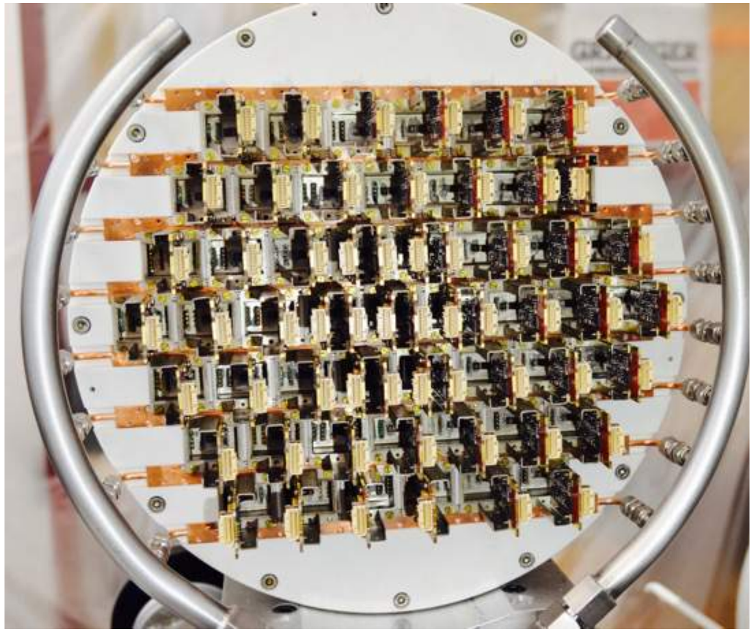


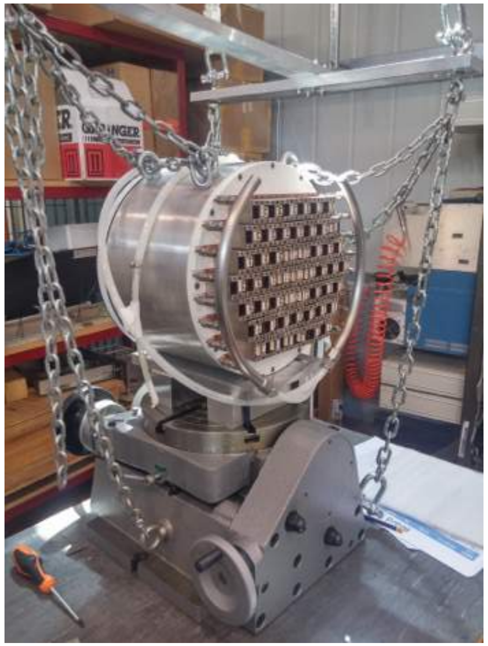




Module 0 prototyping

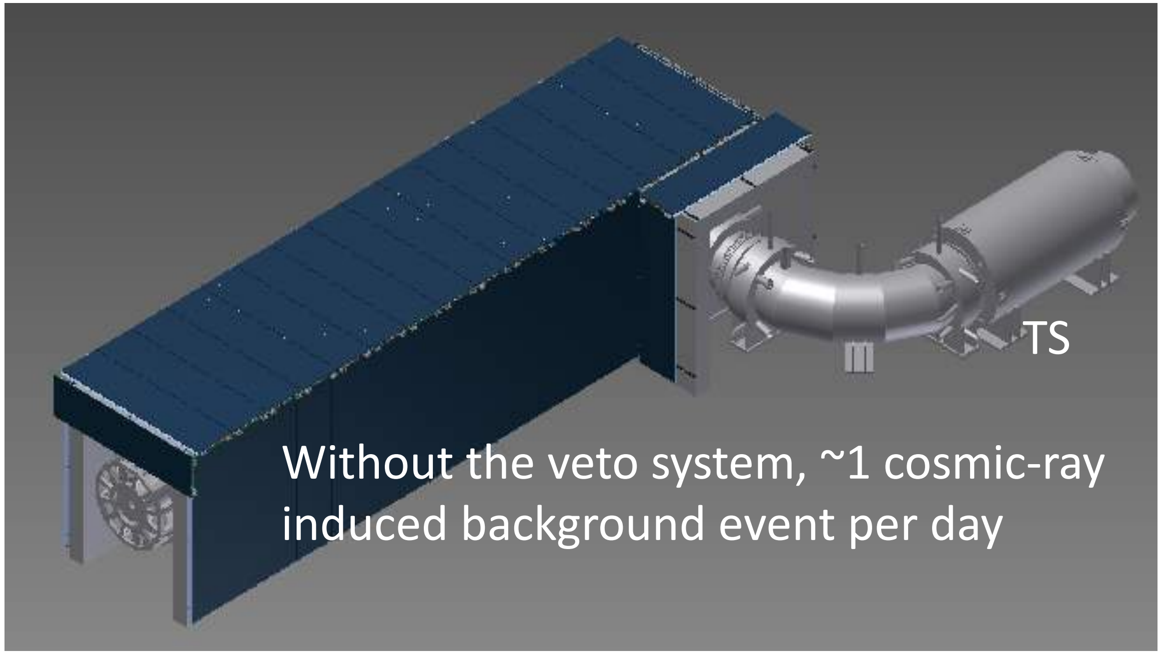


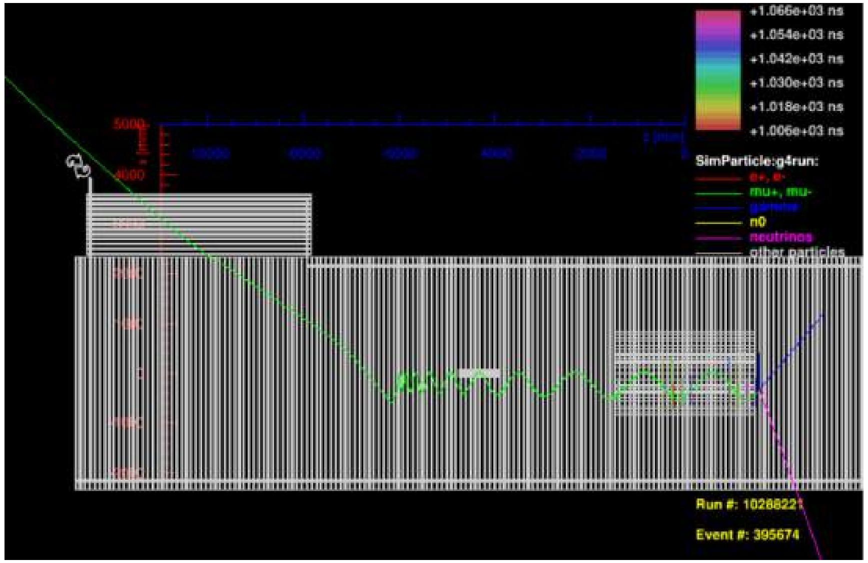




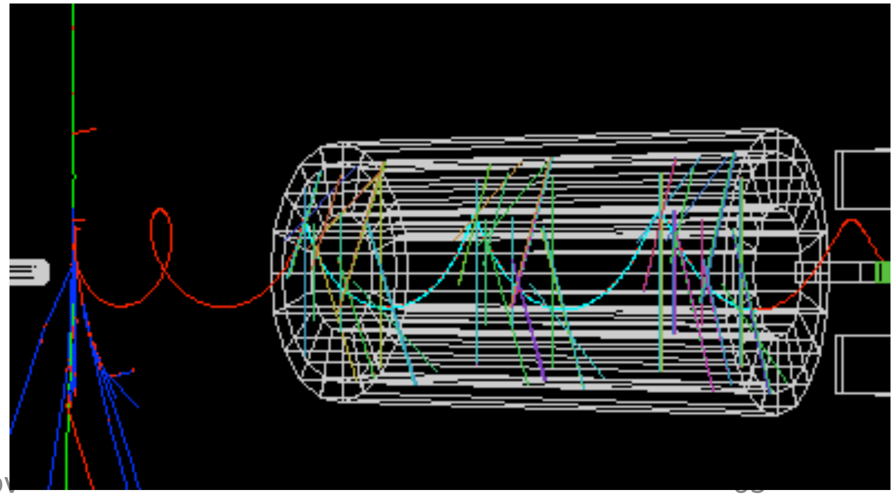
The Cosmic ray Veto

Veto system covers entire DS and half TS

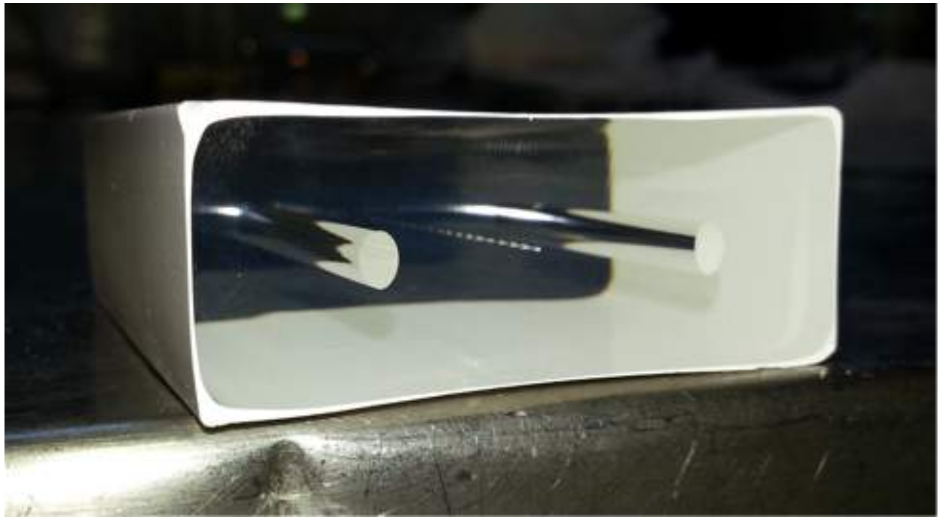


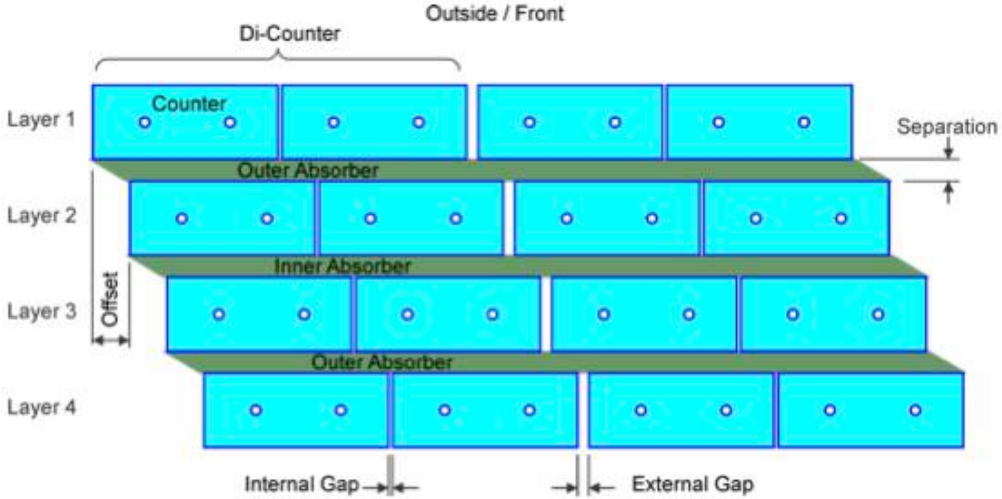


Cosmic μ can generate background events via decay, scattering, or material interactions



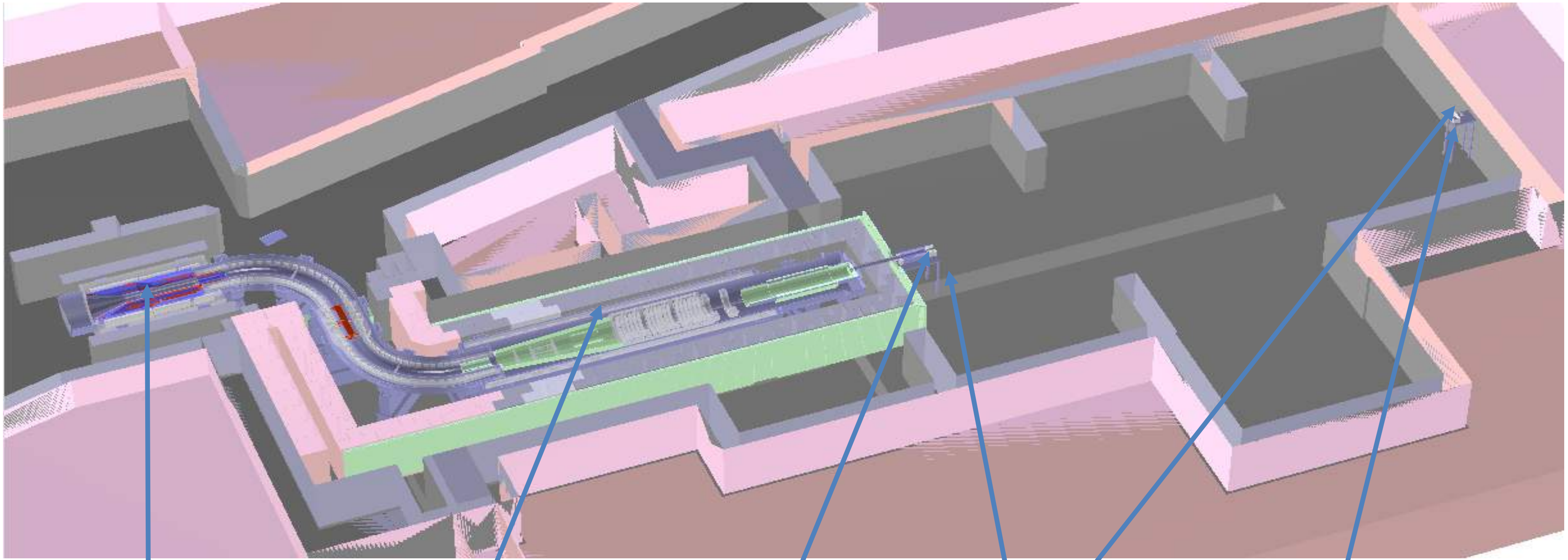
Mu2e Cosmic-Ray Veto





- 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%)

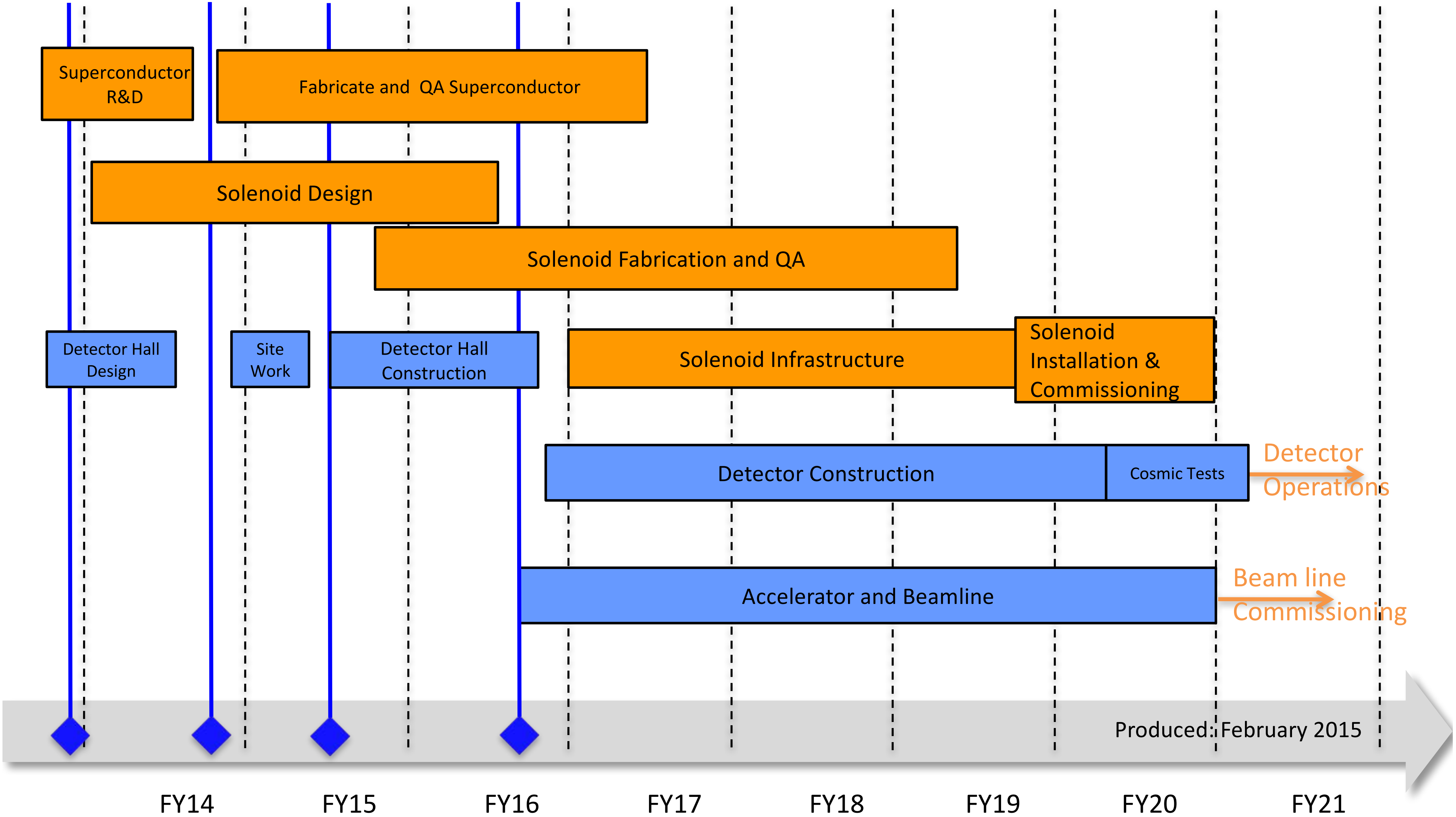
- Downstream to the Detector Solenoid
- Line-of-sight view of Muon Stopping Target
- Sweeper magnet
  - Reduces charged bkg
  - Reduces radiation damage

Apr 18, 2015: Mu2e groundbreaking

Mu2e Detector Hall

Construction completed warmed it up 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-3 review**

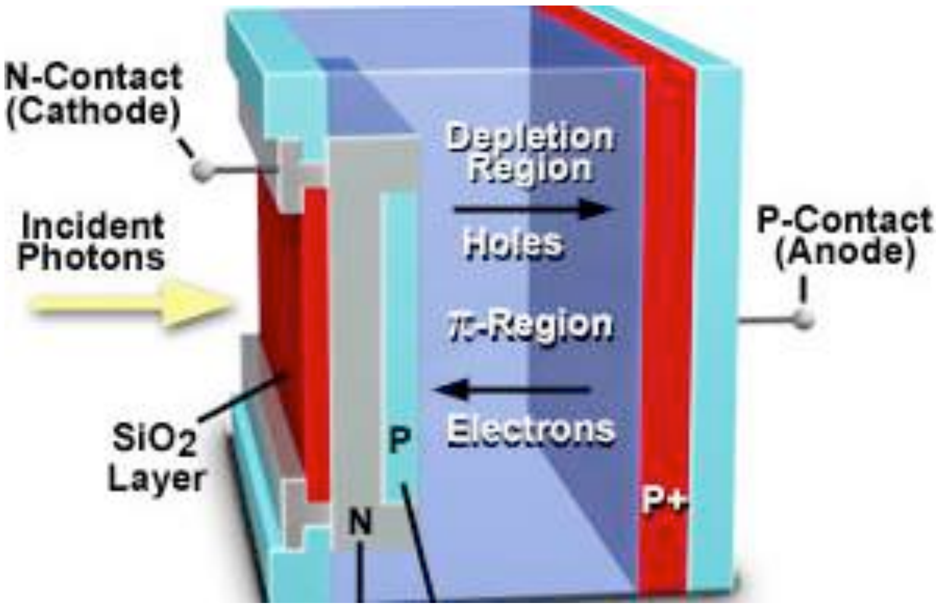
→ civil construction completed

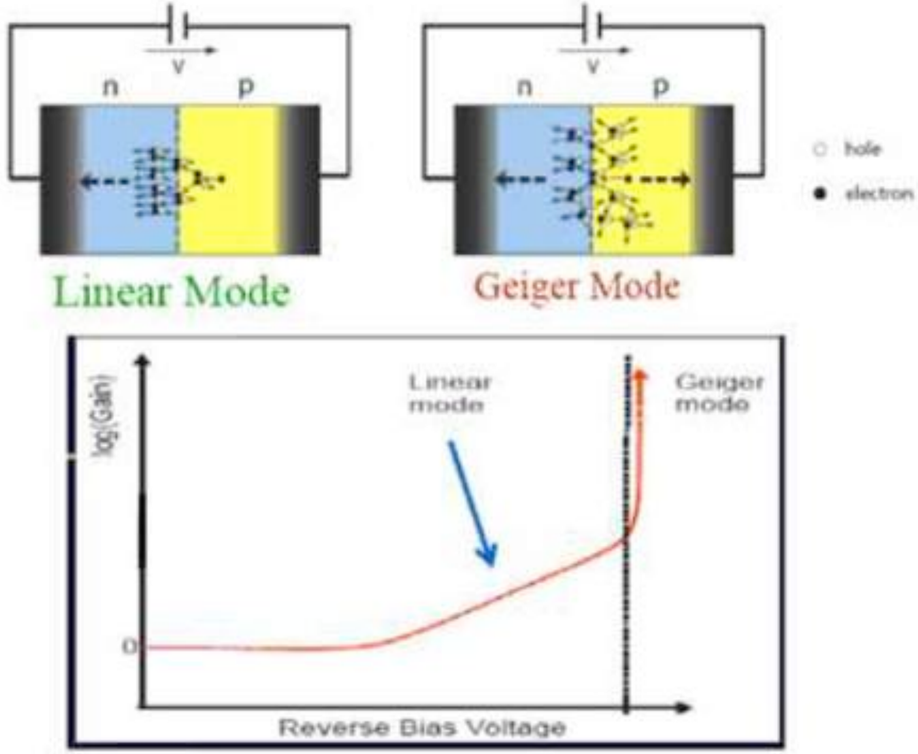
→ Detector construction period 2017-2018 followed by installation in 2019

spares

Silicon Photosensors

- A silicon photo-sensor is "in practice" a reverse Silicon N-P junction with a photo sensitive layer where "photo"electrons are extracted.
- The reverse bias helps to create a large depleted region and reduce to negligible values the "dark current", Id, i.e. the current seen without any signal in input
- **3 work regimes:**
  - → **Photodiode (G=1)** all e- produced in the photosensitive layer are collected at the anode.
  - → **APD (G=50-2000)** , or Avalanche Photodiode, working in proportional regime and
  - → **Geiger APD (G=10^5-10^6)** working in Geiger mode





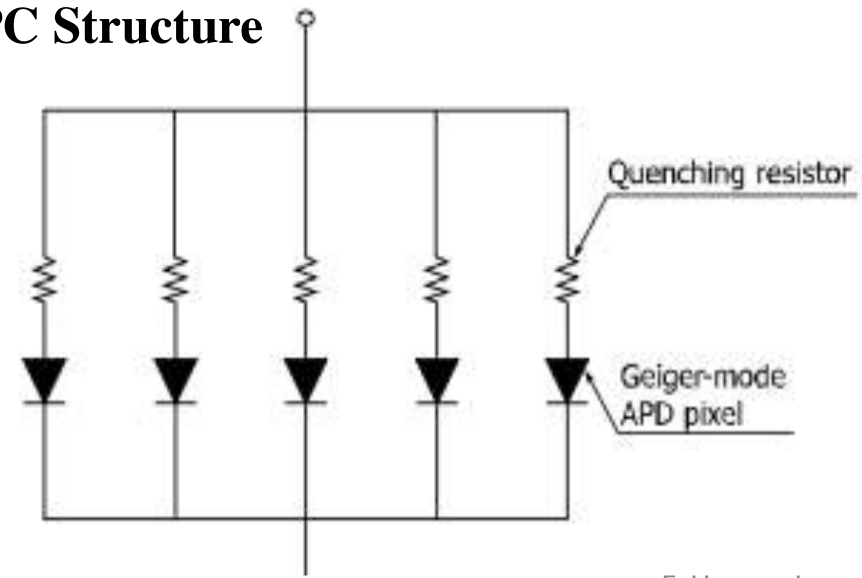
Silicon PMT (1)

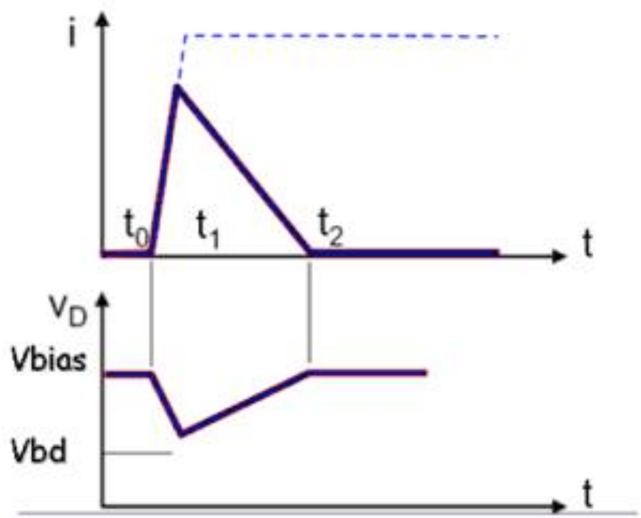
- The MPPC (multi-pixel photon counter) is one of the devices called silicon photomultipliers (SiPM) or Geiger APD. It is a photon-counting device **that uses multiple APD pixels operating in Geiger mode;**

- The Geiger mode allows obtaining a **large output by the discharge even when detecting a single photon**. Once the Geiger discharge begins, it continues as long as the electric field is maintained.

- One specific example for halting the Geiger discharge is a technique using a so-called quenching resistor connected in series with each APD pixel. This quickly stops the multiplication in the APD since a voltage drop occurs when the output current flows.

MPPC Structure





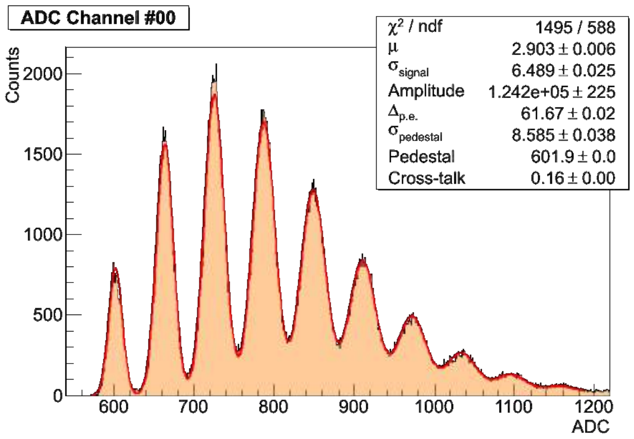
Silicon PMT (2)

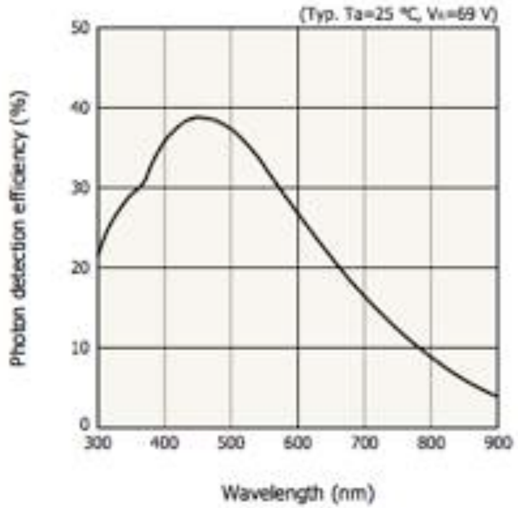
The basic SIPM element (pixel) is a combination of the Geiger-APD and quenching resistor

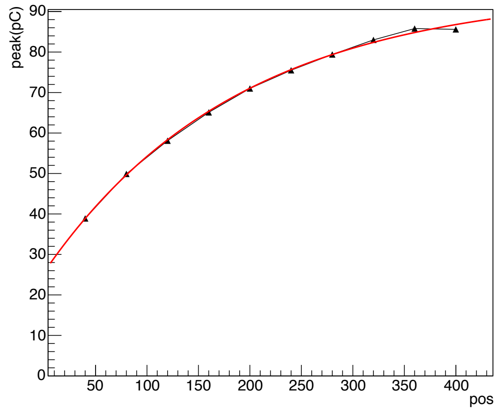
→ a large number of these pixels are electrically connected and arranged in two dimensions;

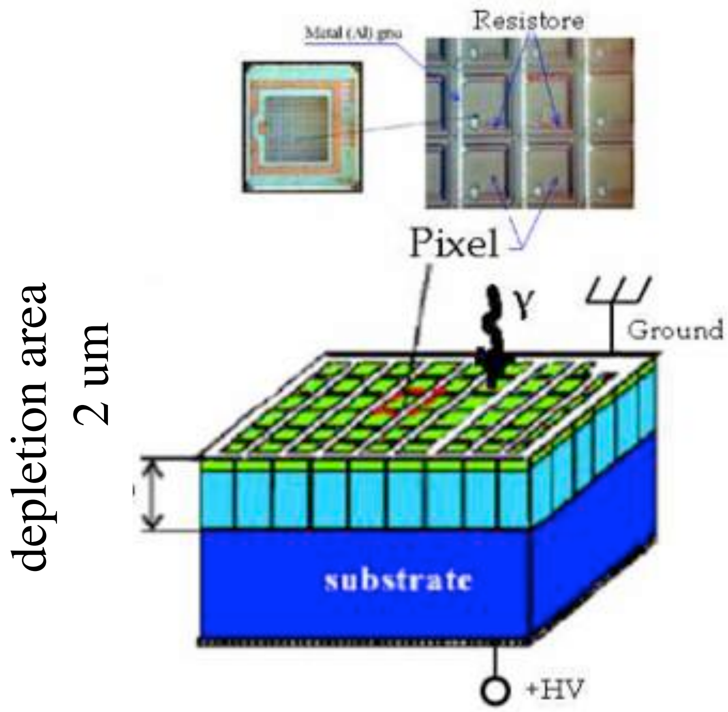
→ Each pixel generates a pulse of the same amplitude when it detects a photon .

→ The output signal from multiple pixels is the superimposition of single pixel pulses.









- ➢ Single photon counting
- ➢ Photon Detection Efficiency
- ➢ “Intrinsic” not-linearity on the response.