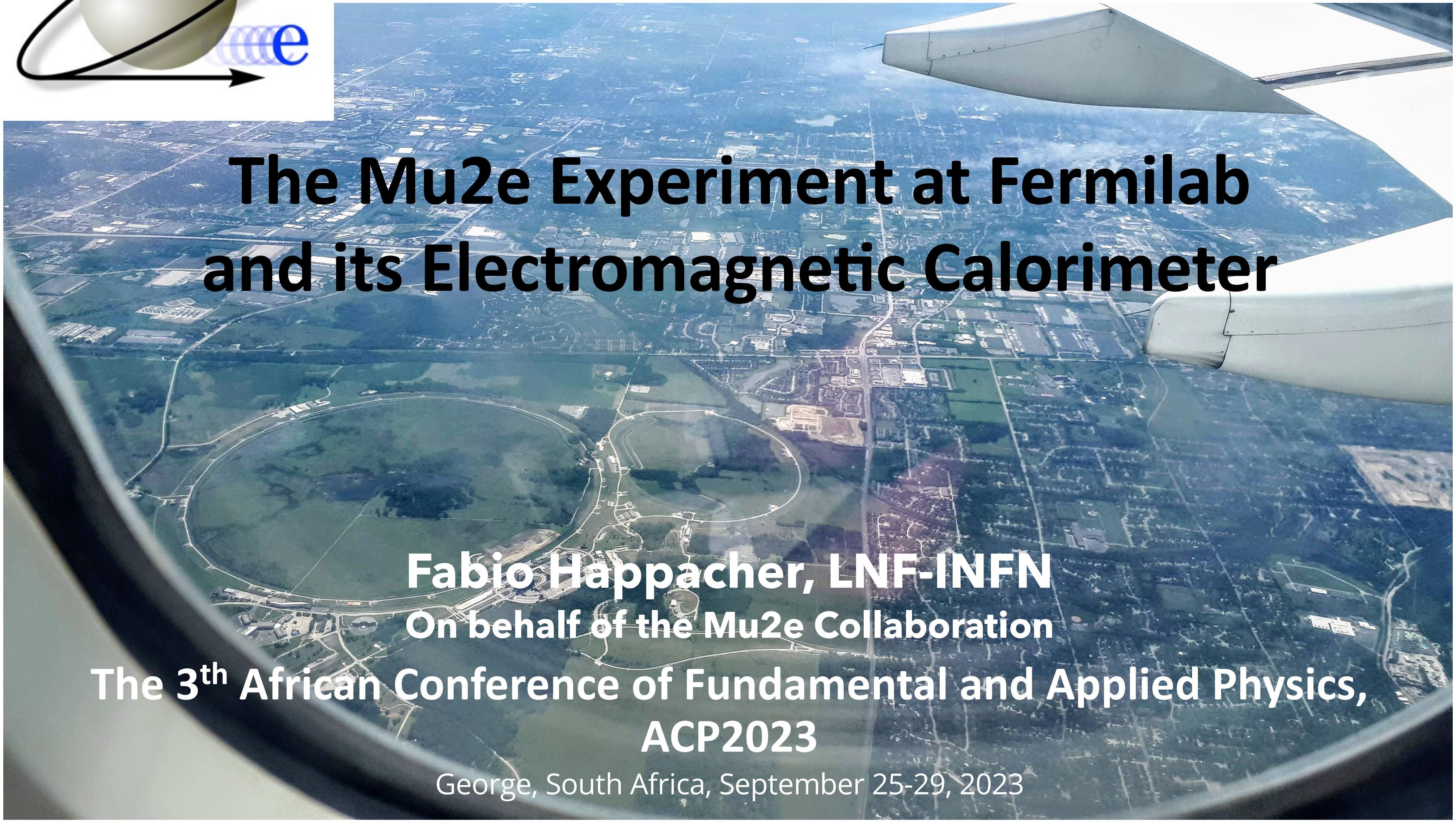


The Mu2e Experiment at Fermilab and its Electromagnetic Calorimeter

Fabio Happacher, LNF-INFN

On behalf of the Mu2e Collaboration

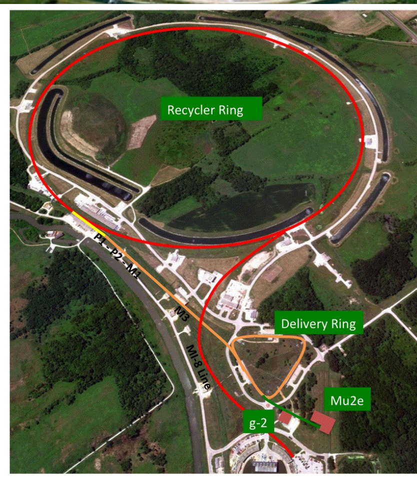
The 3th African Conference of Fundamental and Applied Physics, ACP2023

George, South Africa, September 25-29, 2023

Presentation outline

- Where, Why Muon to Electron conversion
- How, the experimental technique
- Accelerator complex
- Detectors layout, **indulging on the Calorimeter**
- Status of Mu2e construction
- Conclusions

The Mu2e collaboration @FNAL muon campus

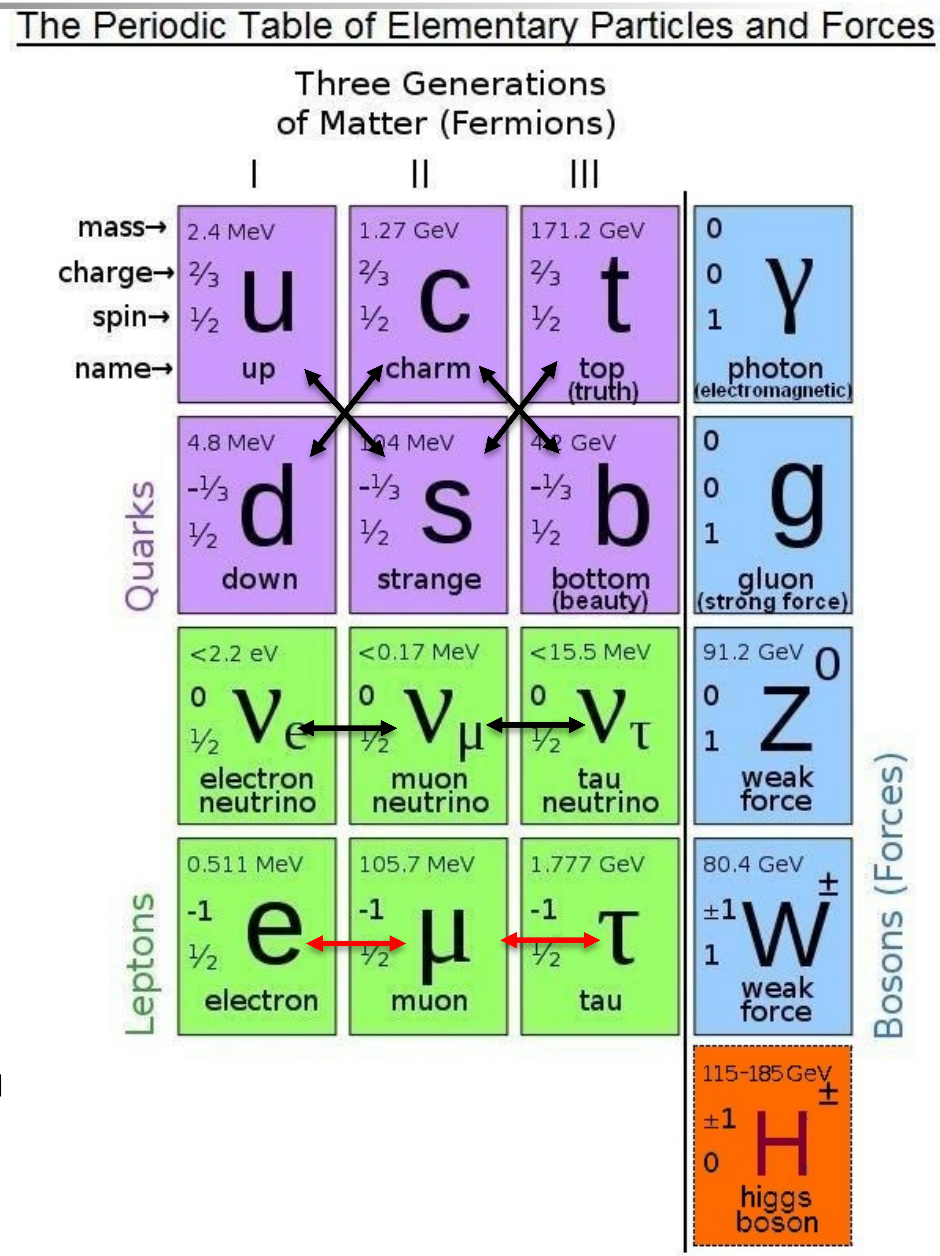


~236 Scientists from 38 Institutions

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

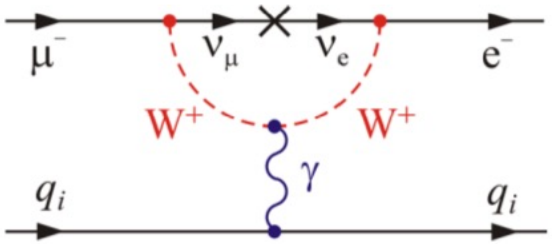
Why?

- We've known for a long time that quarks mix via W→ (Quark) Flavor Violation
  - Mixing strengths parameterized by Cabbibo-Kobayashi-Maskawa - CKM matrix
- In last 15 years we learned 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 a Search for $\mu^- N \rightarrow e^- N$?

- Mu2e searches for muon-to-electron conversion in the coulomb field of a nucleus
- CLFV strongly suppressed in in SM not forbidden due to neutrino oscillation



$$B(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi}\left(\frac{1}{4}\right) sin^2 2\theta_{13} sin^2\theta_{23}\left|\frac{\Delta m^2_{13}}{M^2_W}\right|^2$$

$\sim \Delta m_\nu^2 / M_W^2 < 10^{-54}$, not observable!

- physics beyond SM (BSM), instead, enhances CLFV rates to observable values
- Muon-to-electron conversion is similar but complementary to other CLFV processes as $\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$.
- A detected signal would indicate the validity of BSM theories: Susy, Compositeness, Leptoquark, Heavy neutrinos, Second Higgs Doublet, Heavy Z′

No outgoing neutrinos!

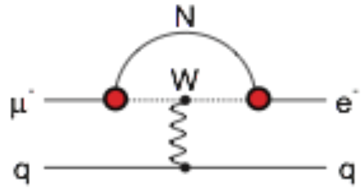
$\mu^- N \rightarrow e^- N$ signature of BSM models

$$\mathcal{L}_{CLFV} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\sum_{q=u,d}\bar{q}_L\gamma^\mu q_L\right)$$

Loop terms

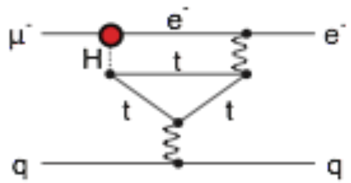
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2 \sim 8\times10^{-13}$



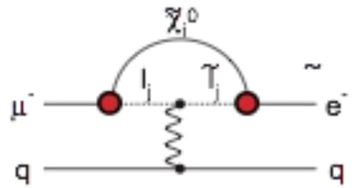
Second Higgs Doublet

$g(H_{\mu e}) \sim 10^{-4} g(H_{\mu\mu})$

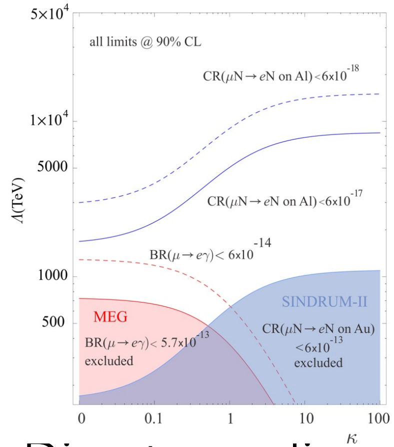


Supersymmetry

rate ~ 10^{-15}



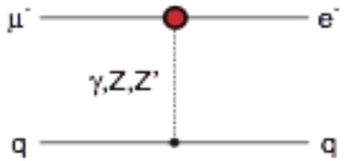
Models which can be probed also by μ→eγ searches



Contact terms

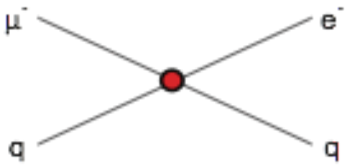
Heavy Z'
Anomal. Z Coupling

$M_{Z'} = 3000\ \mathrm{TeV}/c^2$



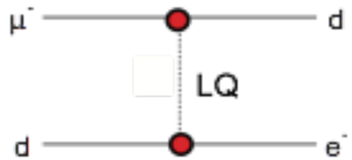
Compositeness

$\Lambda_c \sim 3000$ TeV



Leptoquark

$M_{LQ} = 3000\,(\lambda_{\mu d}\lambda_{ed})^{1/2}\ \mathrm{TeV}/c^2$



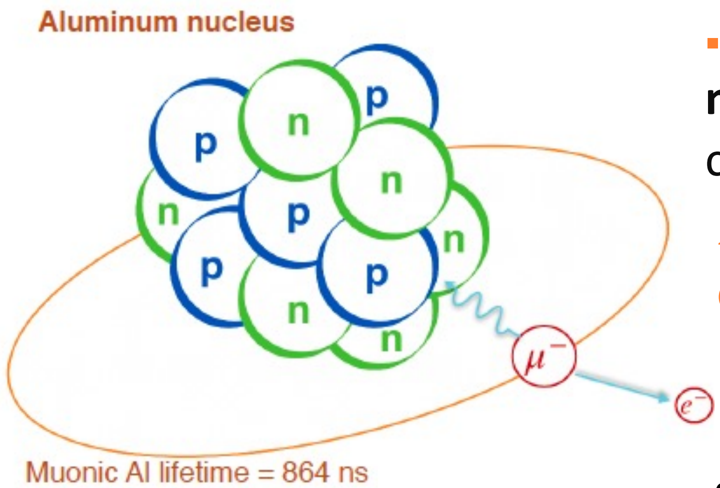
Direct coupling between quarks and leptons, better accessed by *μN→eN*

What is Mu2e

– Will search the conversion of a muon into an electron after stopping it in an AL nucleus

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

$\tau_\mu^{Al} = 864$ ns



- **Clear Event Signature: monoenergetic electron** consistent with:

$$E_e = m_\mu - E_{recoil} - E_{1S\ B.E}\ ,$$

e.g For Al: E_e = 104.97 MeV.

– Will use current the intense proton beam of the Fermilab accelerator to reach a single event sensitivity of ~3 x10^{-17} i.e. 10^4 better than current world's best (Sindrum II)

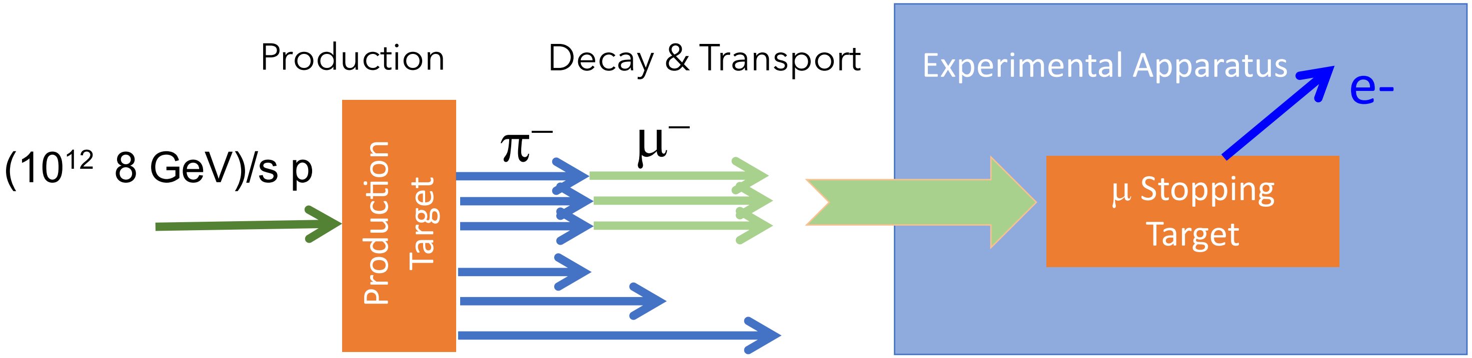
– Will have *discovery* sensitivity over broad swath of BSM parameter space

– Mu2e will detect and count the electrons coming from the conversion decay of a muon with respect to standard muon capture

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

Mu2e Concept in a sketch

1. High intensity Muon Beams (> x 100 w.r.t. existing facility up to 10^{10} mu/sec)
2. Pulsed beam to eliminate prompt background
3. High proton extinction between pulses
4. High precision spectrometer and calorimeter



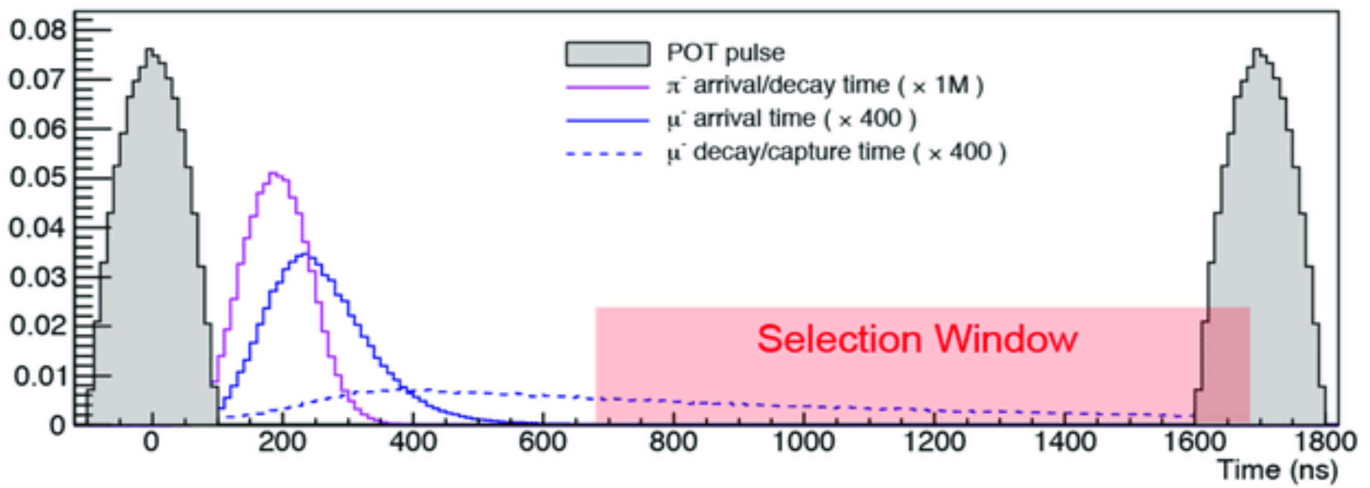
τ_μ^{Al} μ lifetime in 1S Al ~864 ns

Delayed live-gate helps remove pion and beam backgrounds (Affecting Sindrum II).

Radiative Pion Capture Backgrounds

- Radiative pion capture backgrounds: $\pi^- + N(A, Z) \rightarrow \gamma^{(*)} + N(A, Z-1)$ followed by $\gamma^{(*)} \rightarrow e^+ + e^-$.
- Pion lifetime 26 ns at rest. Pulsed proton beam (250 ns wide, pulses 1695 ns apart) → wait out pion decay.
- In addition, upstream extinction removes out-of-time protons.

Delayed live-gate helps remove pion and beam backgrounds.



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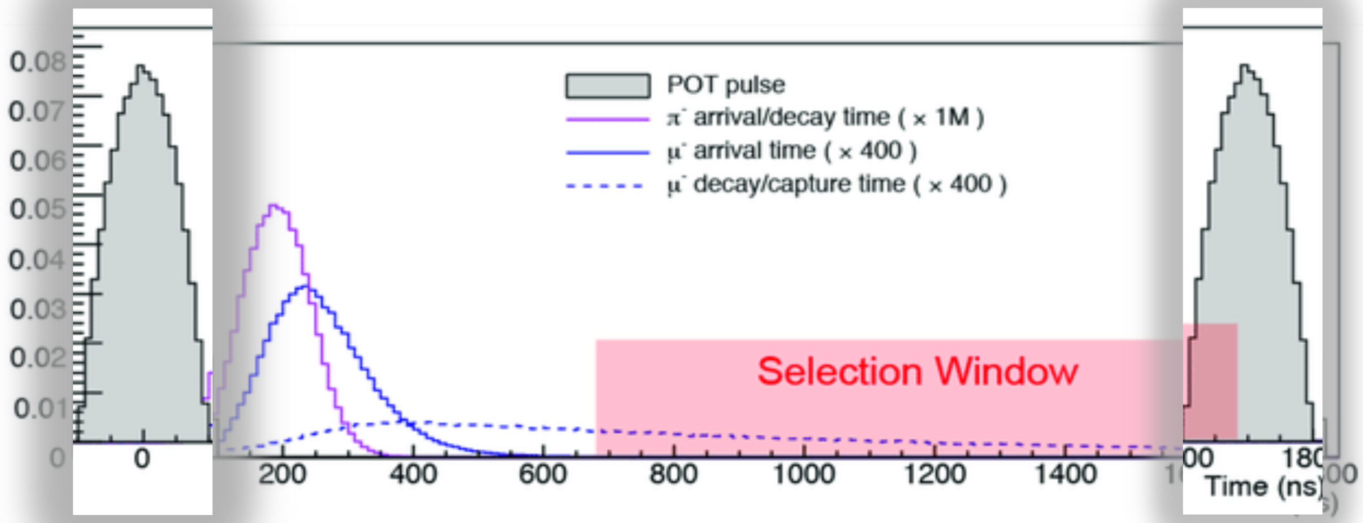

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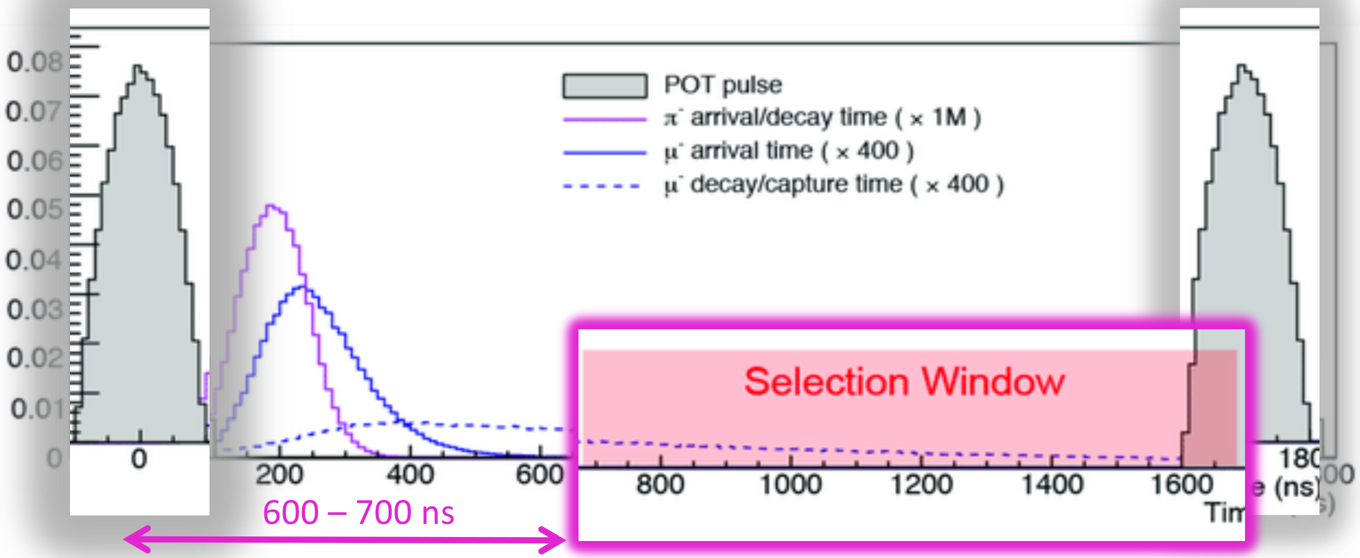
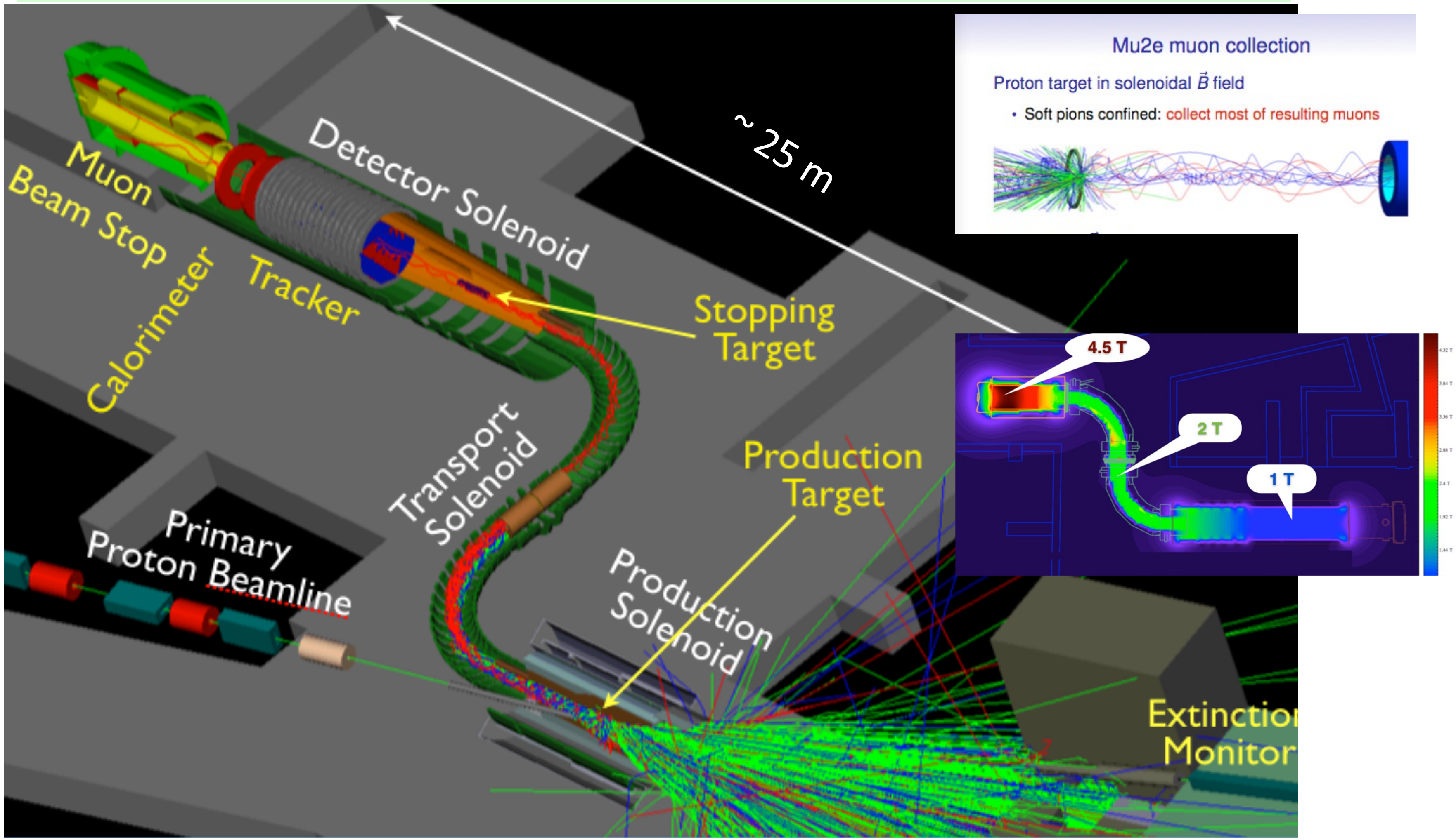
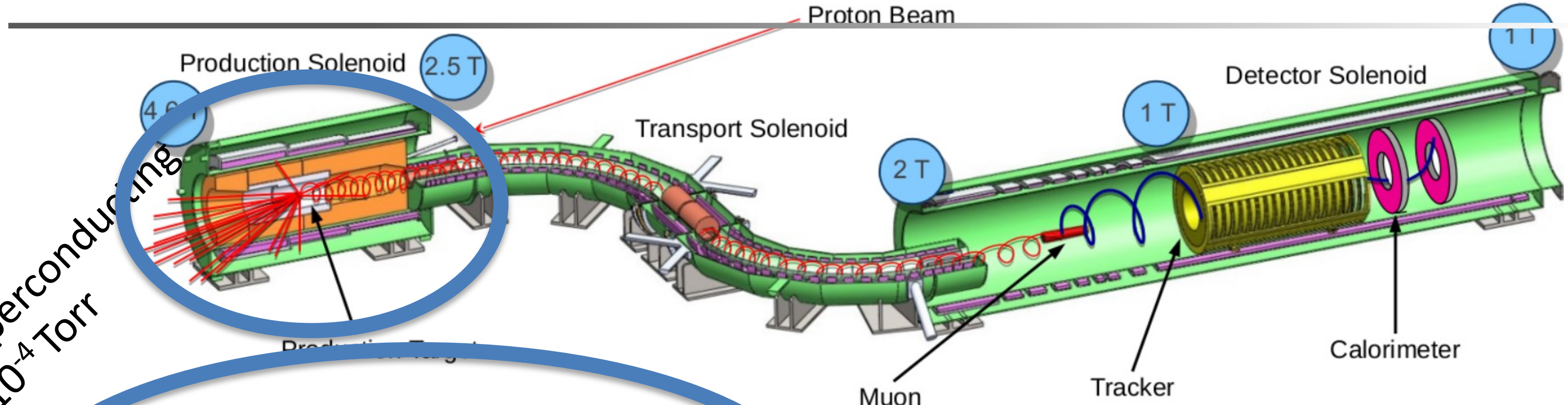


Mu2e Experimental Apparatus



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

Mu2e Experimental Apparatus



- Superconducting
- 10^{-4} Torr
- Production Solenoid
  - $6x10^{12}$/s, 8 GeV, pulsed proton beam hits a tungsten production target
  - pions collected by the graded solenoidal magnetic field
- Transport Solenoid pions decay to muons
  - " S" shape to remove line of sight backgrounds
  - charge and momentum selection
- Detector Solenoid
  - 10^{10} **μ/s** stop in thin Al foils
  - muonic atom decays, resulting electrons are detected by a tracker and a calorimeter
  - a cosmic ray veto covers the whole detector solenoid and half the transport solenoid (not shown)

- Need to stop O(10^{18}) muons and have << 1 background event

2026 – 27 Run-I:
- 1×10^{-15} 5σ discovery,
- Single-Event-Sensitivity = 2×10^{-16}
- U.L : 6×10^{-16} (90% C.L.)
  - **1000 x current limit.**
  - **Universe 2023, 9, 54.**

Total (Run-I + Run-II) end-goal (2033):
- 2×10^{-16} 5σ discovery,
- Single-Event-Sensitivity = 3×10^{-17}
- U.L : 8×10^{-17} (90% C.L.)
  - **10000 x current limit.**

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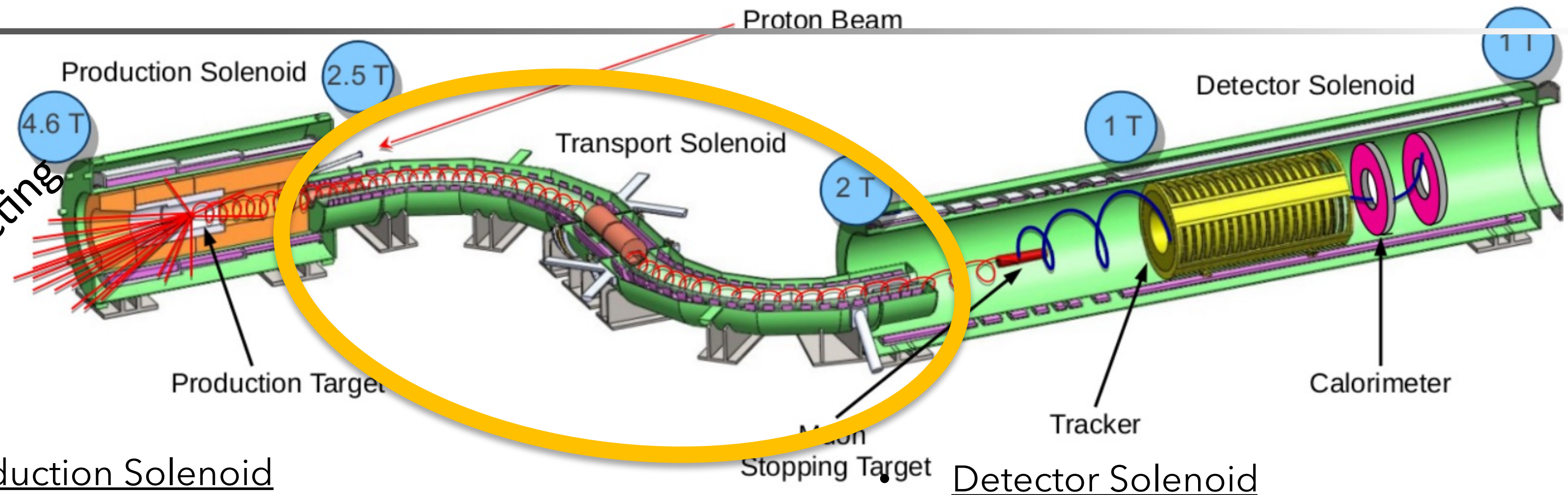

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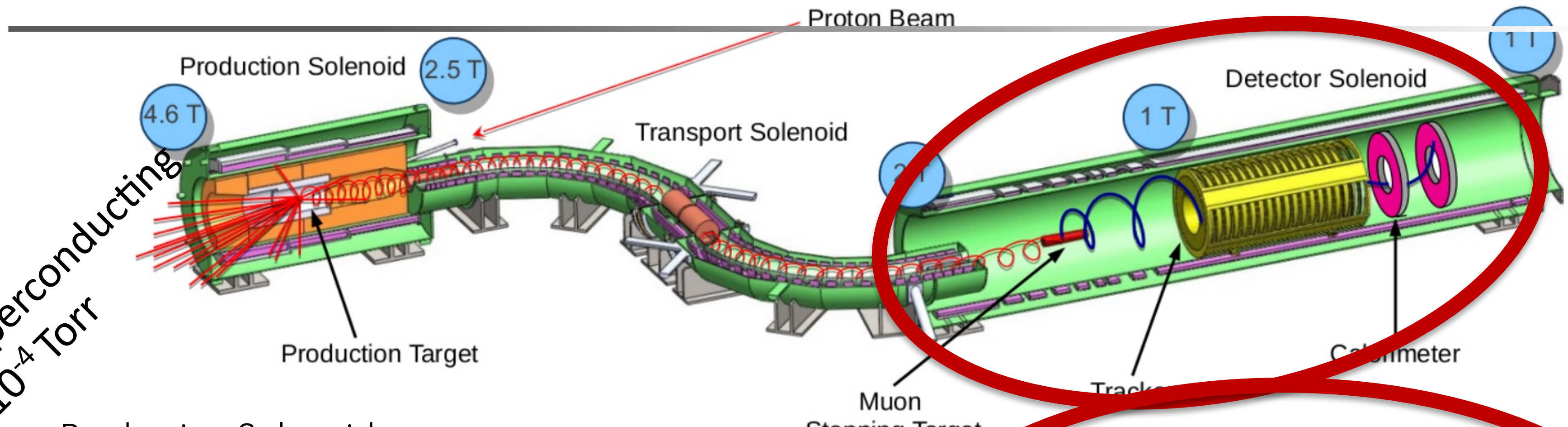

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- U.L : 8×10^{-17} (90% C.L.)
  - **10000 x current limit.**

Solenoid construction status

Production Solenoid:

- Consists of 3 coils, all wound at vendor.
- Undergoing final assembly.
- Arrives at Fermilab in Fall 2023.

Transport Solenoid:

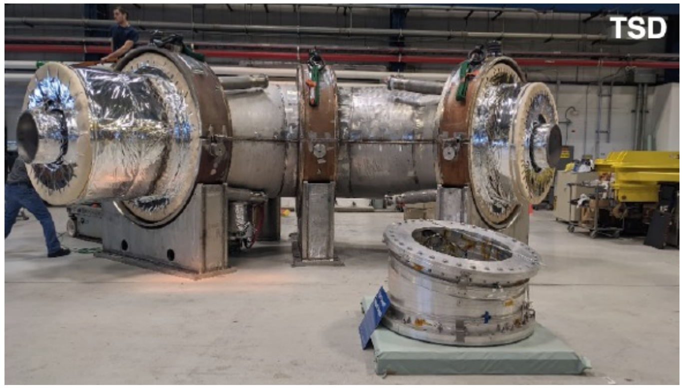
- Assembly being completed on-site
- Move to Mu2e Hall in Fall 2023.

Detector Solenoid:

- All coils fabricated at vendor.
- Cold mass cryo. supports prepared
- Delivery to Fermilab expected early 2024.

PS cold mass – inner shield dry run insertion

PS wires being routed to chimney area



DS9 coil OD mac

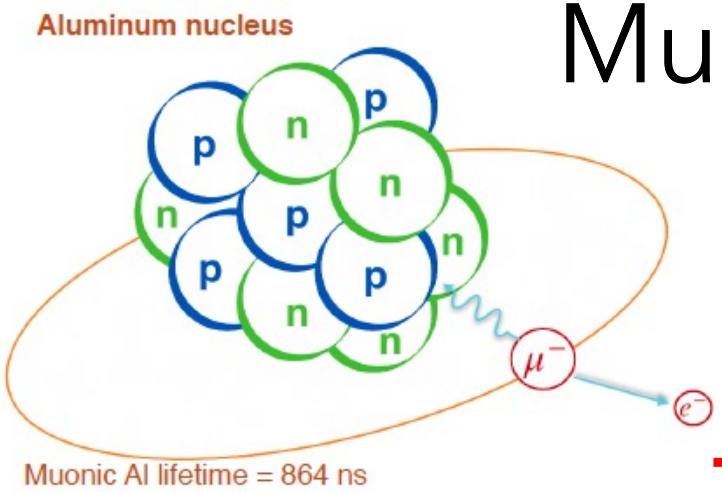
DS11.2: Coil winding complete

Muonic Al atom

A look at the topology of the events we are dealing with.

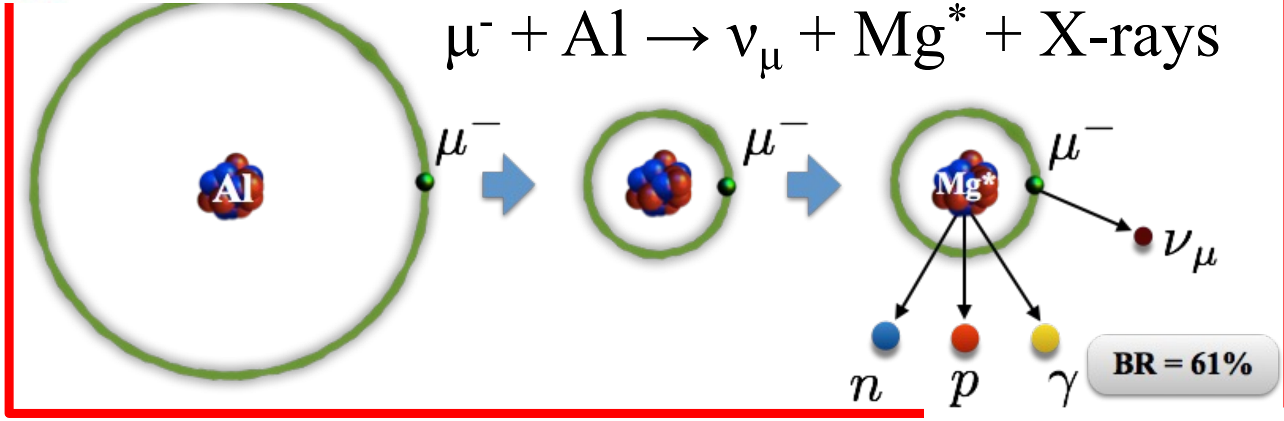
- Low momentum μ^- is captured in atomic orbit
  - Quickly (~fs) cascades to 1*s* state emitting *X*-rays
- Bohr radius ~20 fm (for aluminum)
  - Significant overlap of μ^- and Nucleus wave functions
- Once at "rest" in 1S state, 3 main processes (might) take place:
  - Conversion : $\mu^- N_{(A,Z)} \rightarrow e^- N_{(A,Z)}$ (signal). ***< 7 x 10^{-13}***
  - Muon Capture : $\mu^- N_{(A,Z)} \rightarrow \nu N^*_{(A,Z-1)}$ (normalization) ***61 %***
  - Decay in Orbit: $\mu^- N_{(A,Z)} \rightarrow e^- \nu\nu N_{(A,Z)}$ (39%) (main bkg) ***39 %***

Muonic Al atom in pictures



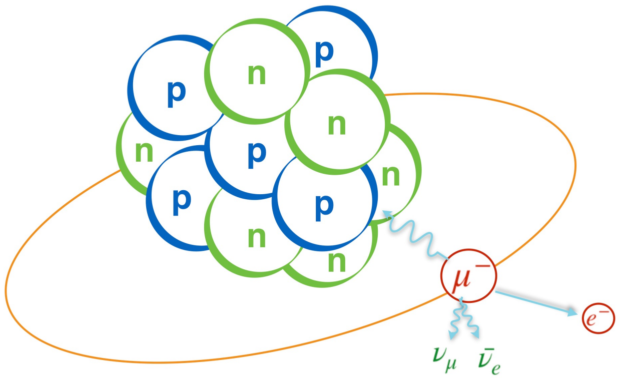
The signal

$$\mu^- + Al \rightarrow \nu_\mu + Mg^* + \text{X-rays}$$



The normalization

Weak decay in orbit (DIO)
Intrinsic background (39%)



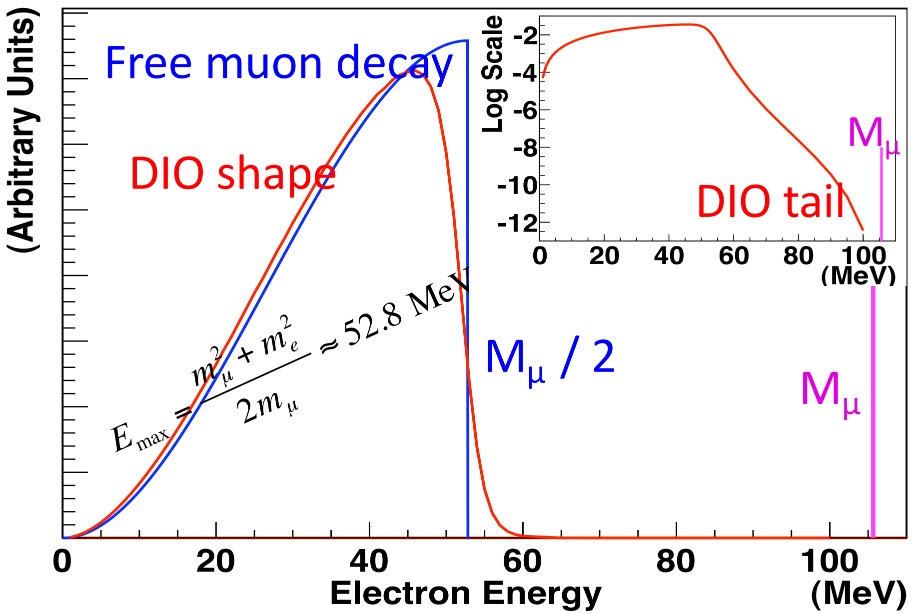
DIO: Mu2e intrinsic background

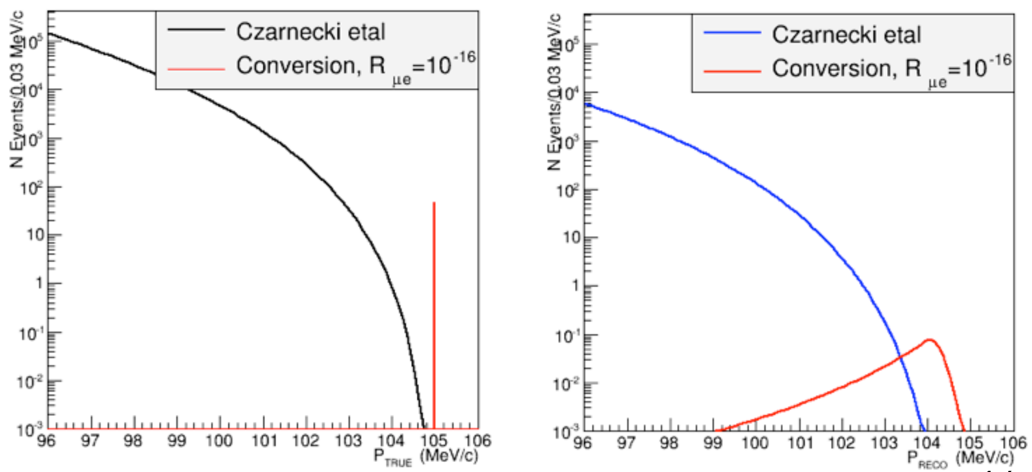
39 % of the time:

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

- 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, contaminating the signal region
- Electron spectrum has tail out to 104.96 MeV
- Accounts for ~55% of total background

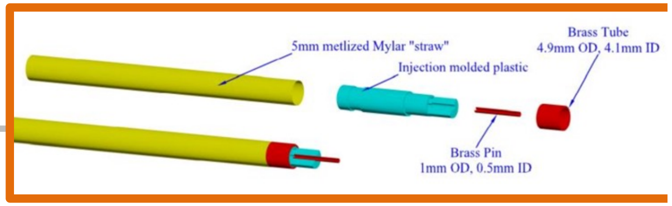
Drives exp. resolution





Separation of ~few 100 keV for $R_{\mu e} = 10^{-16}$

The Mu2e Tracker



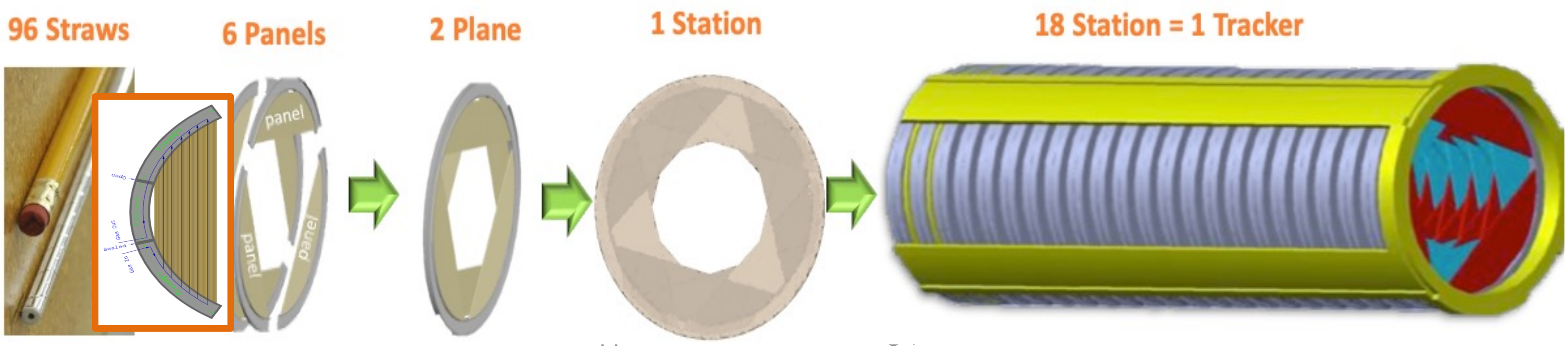
Detector requirements:

1. Small amount of budget material, maximizing X_0
2. $\sigma_p < 115$ keV @ 105 MeV
3. Good rate capability:
   - 20 kHz/cm^2 in live window
   - Beam flash of 3 MHz/cm^2
4. dE/dx capability to distinguish e^-/p
5. Operate in B = 1 T, 10^{-4} Torr vacuum
6. Optimize acceptance for CE, reject DIO

straws

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

•Self-supporting "panel" consists of 96 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



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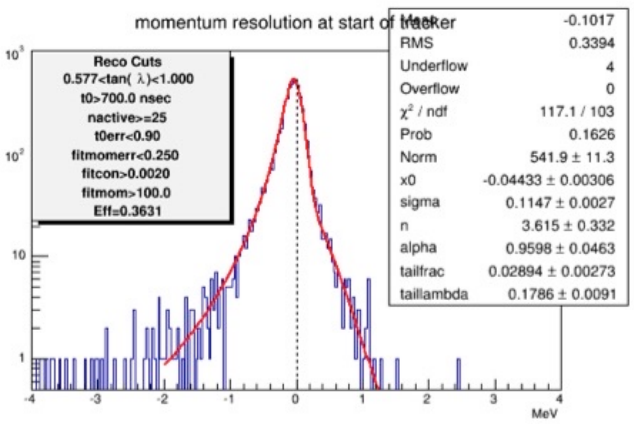
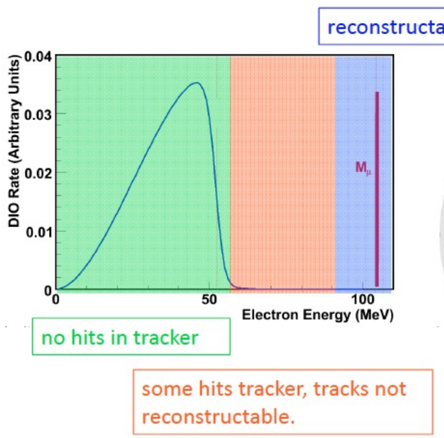
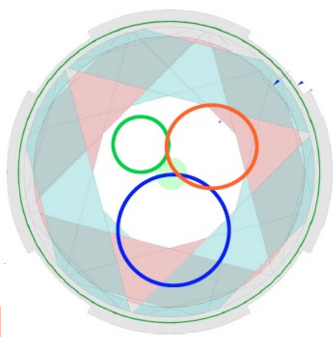
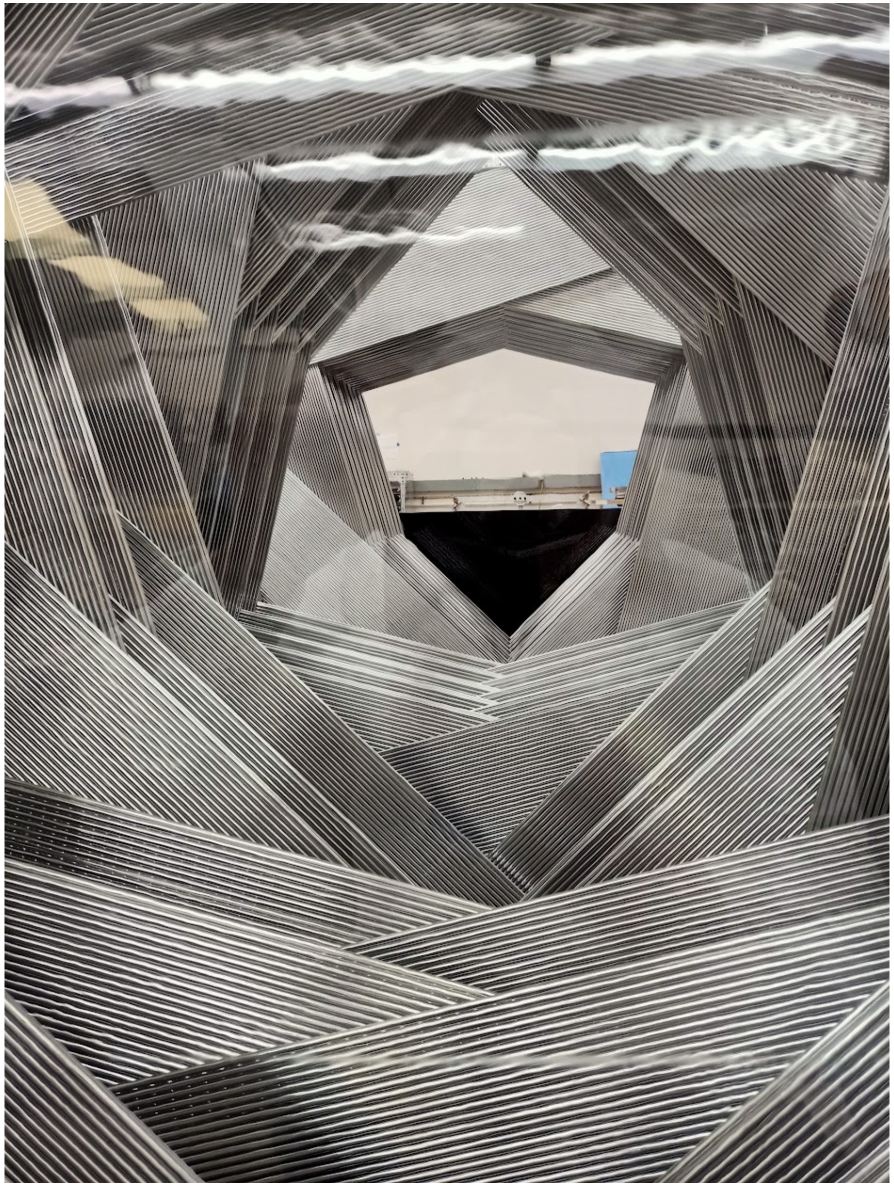




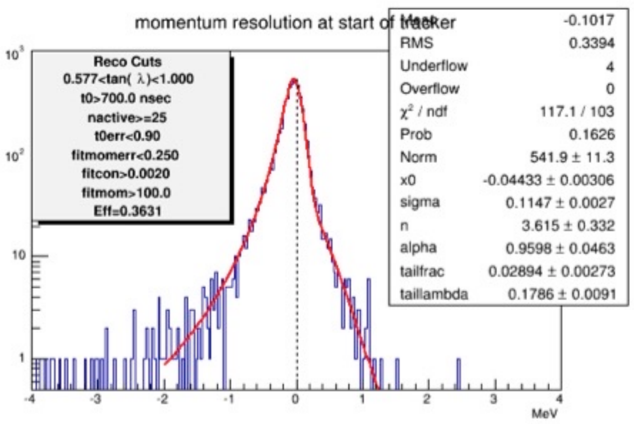


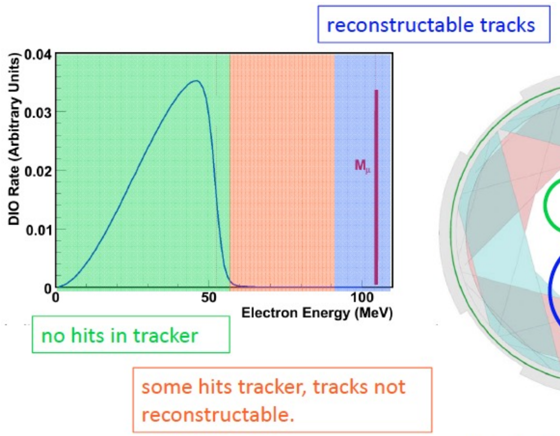
beam's-eye view of the tracker

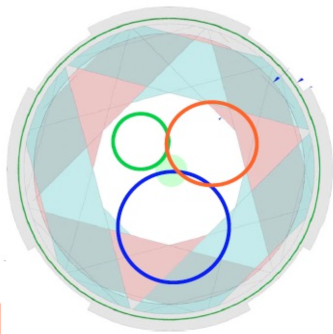


- Inner 38 cm is purposefully un-instrumented
  - Blind to beam flash
  - Blind to >99% of DIO spectrum

The Mu2e Tracker







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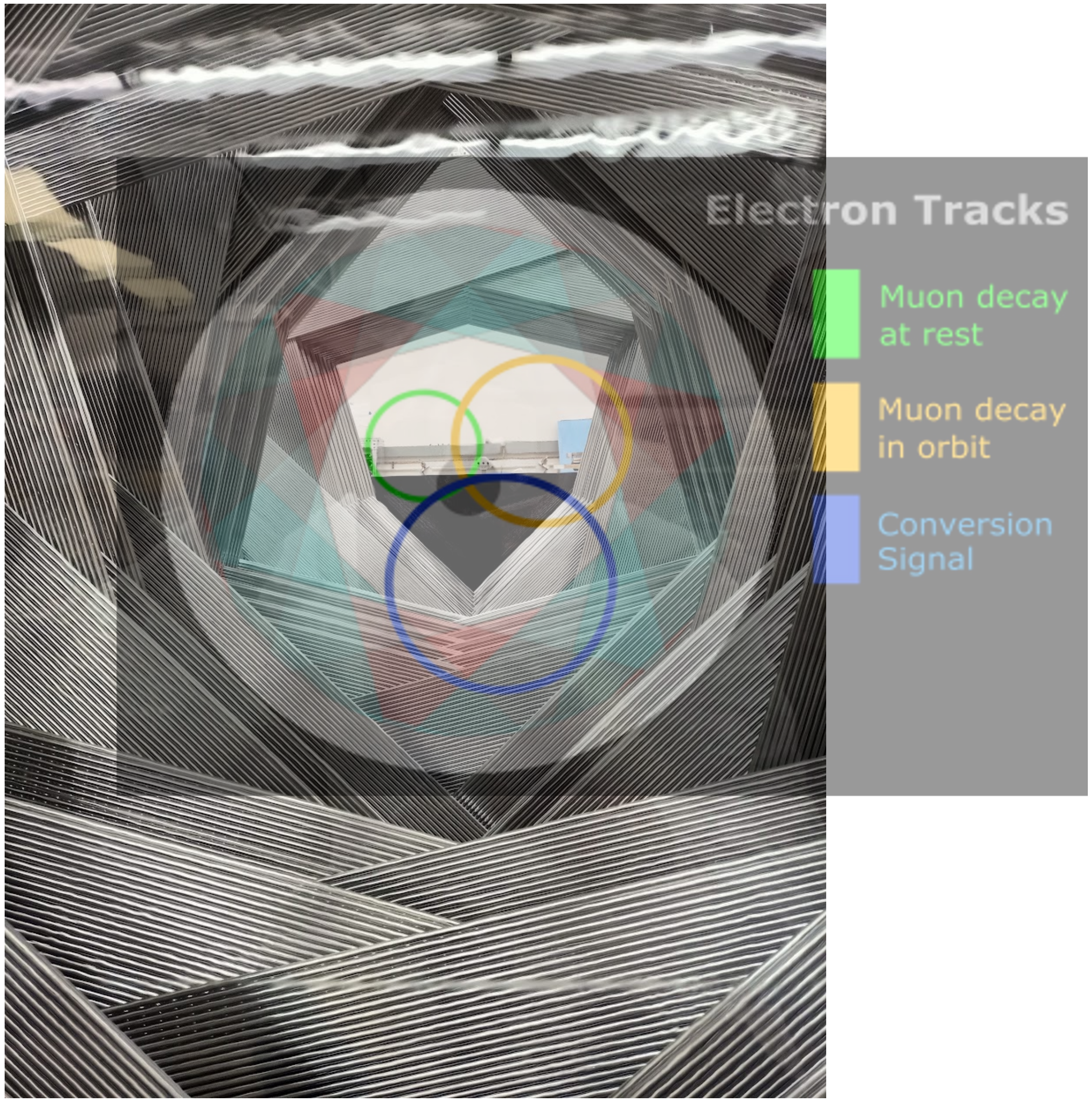

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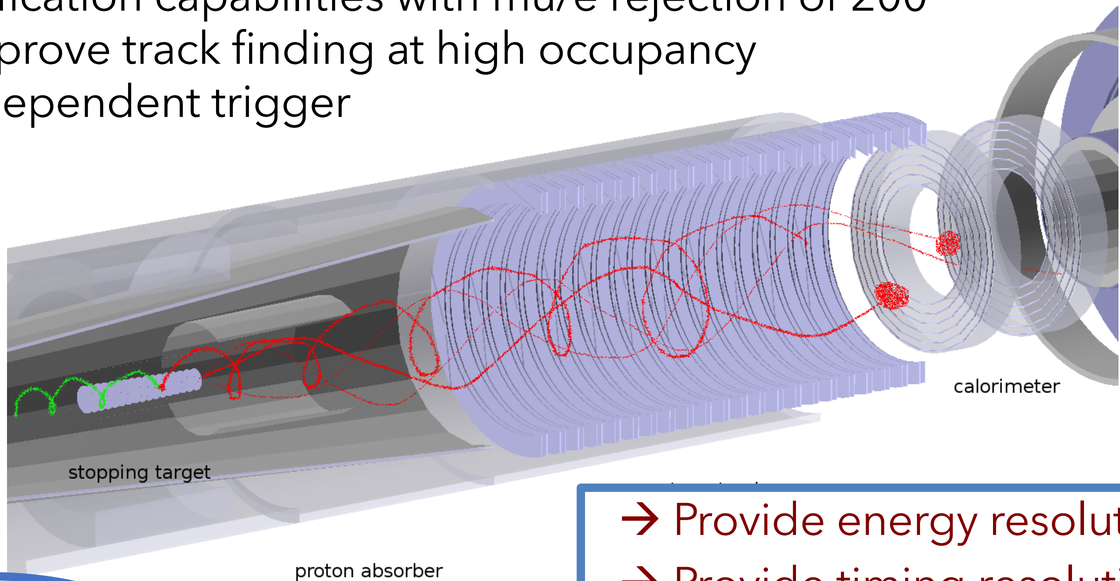
Calorimeter scope and requirements

For the μ → e conversion search, the calorimeter adds redundancy and complementary qualities with respect to the high precision tracking system

- Large acceptance for the mono-energetic electron candidate events
- Particle Identification capabilities with mu/e rejection of 200
- "Seeds" to improve track finding at high occupancy
- A tracking independent trigger



For 100 MeV electrons @ 50 degrees impact angle

→ Provide energy resolution σ_E/E of O(< 10 %)
→ Provide timing resolution σ(t) < 500 ps
→ Provide position resolution < 1 cm
→ Work in vacuum @ 10-4 Torr and 1 T B-Field
→ stand the harsh radiation environment

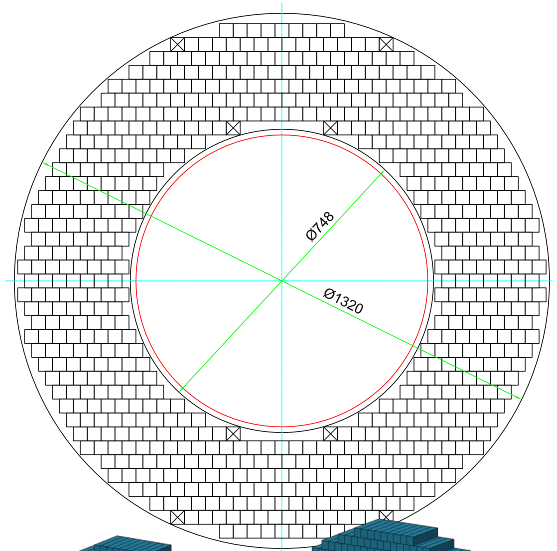
Technical specifications

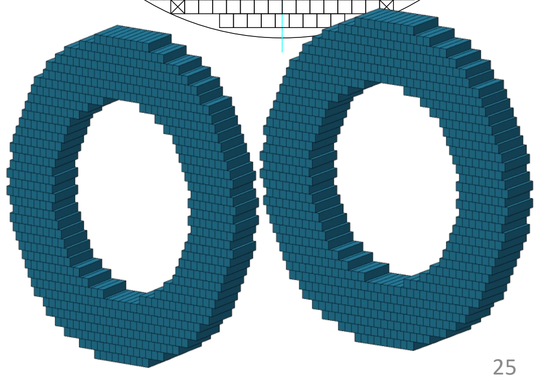
- Chosen Technical Solution → **High Granularity Crystal calorimeter with SiPMs readout**
- 2 Disks (Annuli) geometry to improve acceptance spaced by 70 cm; half helics path wave length
- Crystals with high Light Yield for time/energy resolution → **LY(SiPM) > 20 pe/MeV**
- **2 SiPMs/preamps/crystal** for redundancy and MTTF requirement → **1 million hours/SIPM**
- **SiPM thermal control down to -10**°C **to reduce dark noise from radiation damage**
  (factor of 3 ↘ every 10 °C 30mA ->3mA, 25–>5 °C)
- Fast signal and Digitization for Pileup and Timing → **τ of emission < 40 ns + Fast preamps**
- **Crystals should withstand a TID** of 90 krad and a fluence of $3\times\frac{10^{12} n_{1\text{MeV}}}{cm^2}$
- **SiPM/FEE should withstand** 45 krad and a fluence of $1.2\times\frac{10^{12} n_{1\text{MeV}}}{cm^2}$
- **Digital electronics should withstand :**
  → a TID of 15 krad
  → a neutron fluence of 3×10^{11} n/cm^2.
  → Charged Hadron (>20MeV) 10^{10}/cm^2

Calorimeter active area

- The bulk of the calorimeter is the array of pure CsI crystals. The single crystal dimensions and the 2 annuli geometry have been chosen to achieve:
  - Max Acceptance for conversion electrons
  - Evade low momentum background
  - Good Spatial resolution
  - > 10 radiation length for shower containment
  - Perfect symmetry for e+ and e-
  - Photosensor and FEE shielding
  - Comply with the constraints of the detector solenoid

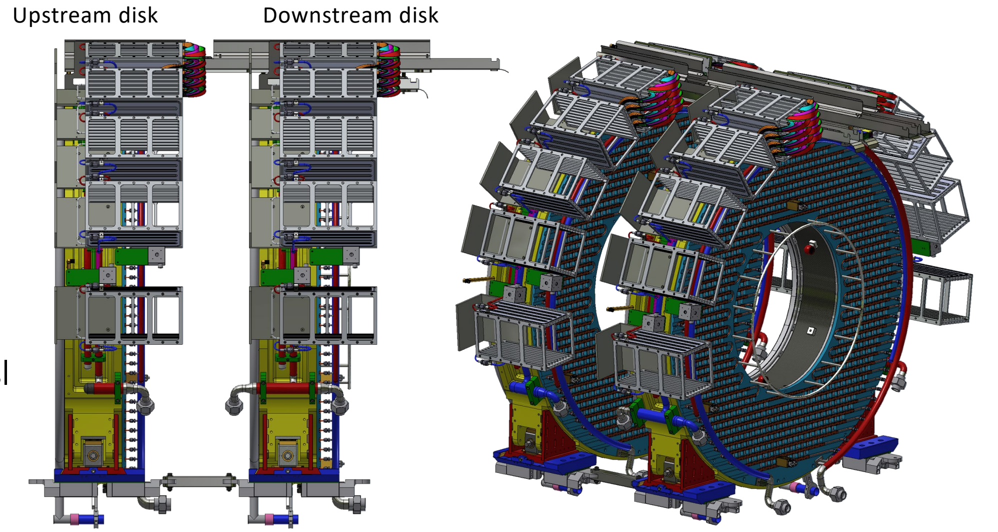
The 2 arrays are shifted by 70 cm, 1/2 wave length, along *z* to detect signal electron escaping the first annulus

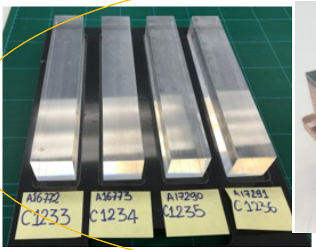




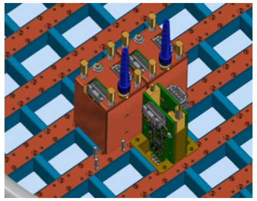
Mu2e calorimeter design

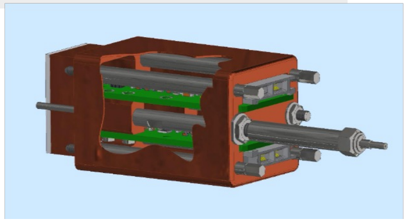
- ✓ Two annular disks, each one with 674 un-doped CsI parallelepiped crystals with square faces:
  - ➔ Crystal dimensions (34 x 34 x 200 mm^3) ~ 10 X_0
  - ➔ Inner/Outer Radius = 374/660 mm
- ✓ Each crystal is read out by two large area UV extended Mu2e SiPM's (14x20 mm^2) coupled in air, 2mm gap PDE=30% @ CsI emission peak =315 nm. Gain ~10^6
  - Tyvek+Tedlar wrapping (LY↗ and cross talk↘)
- ✓ SiPM glued on copper holders for heat dissipation, solidal to FEE mounted on SiPM pins
- ✓ Cooling system
- ✓ Digital electronics at 200 Msps on-board custom crates
- ✓ Radioactive source (a la Babar) and green laser systems provide absolute calibration and monitoring capability



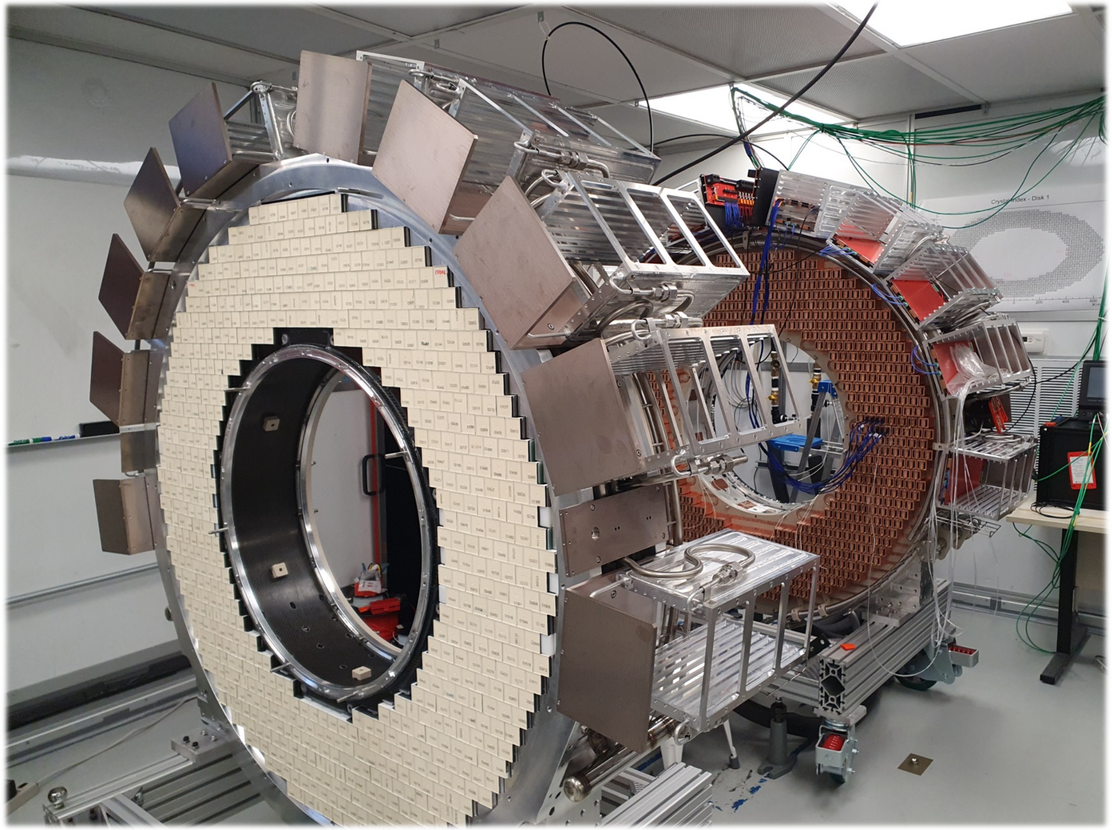


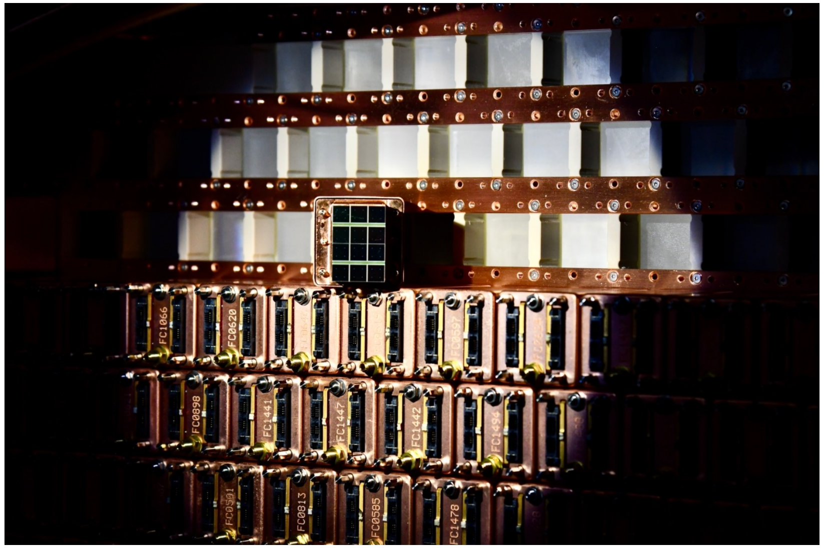
Operate with very high reliability in vacuum and radiation harsh environment → -10 °C for SiPMs

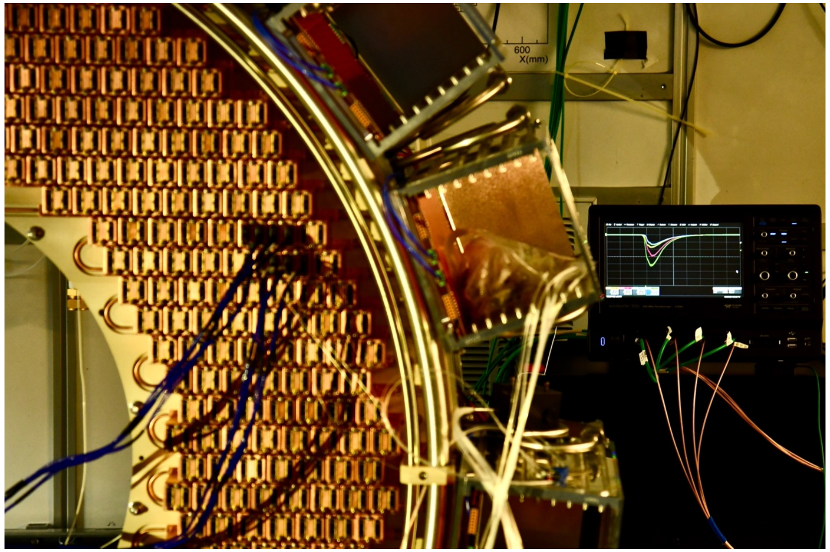




The Mu2e Calorimeter

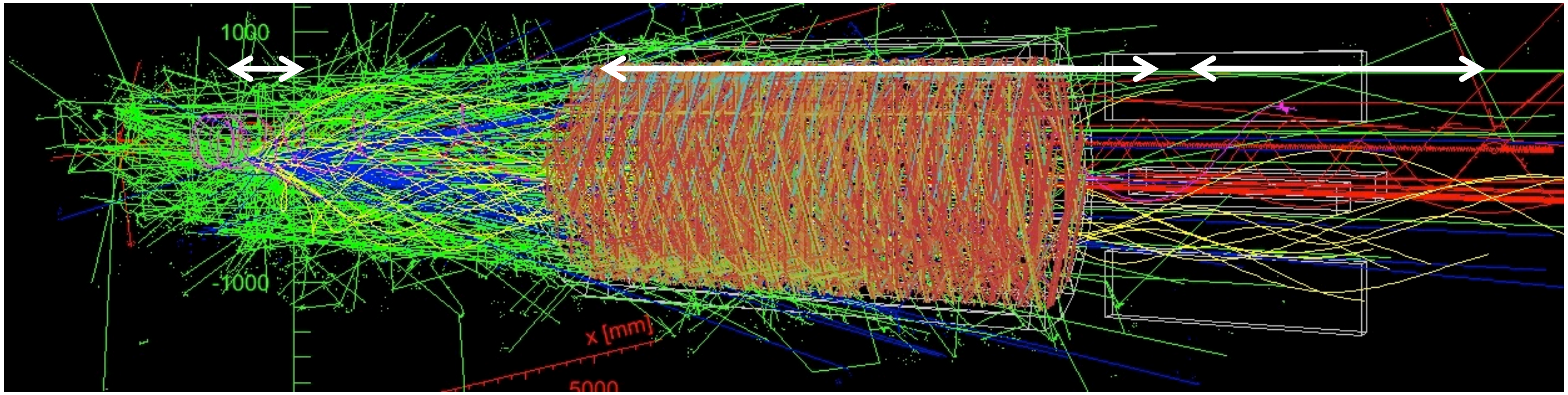




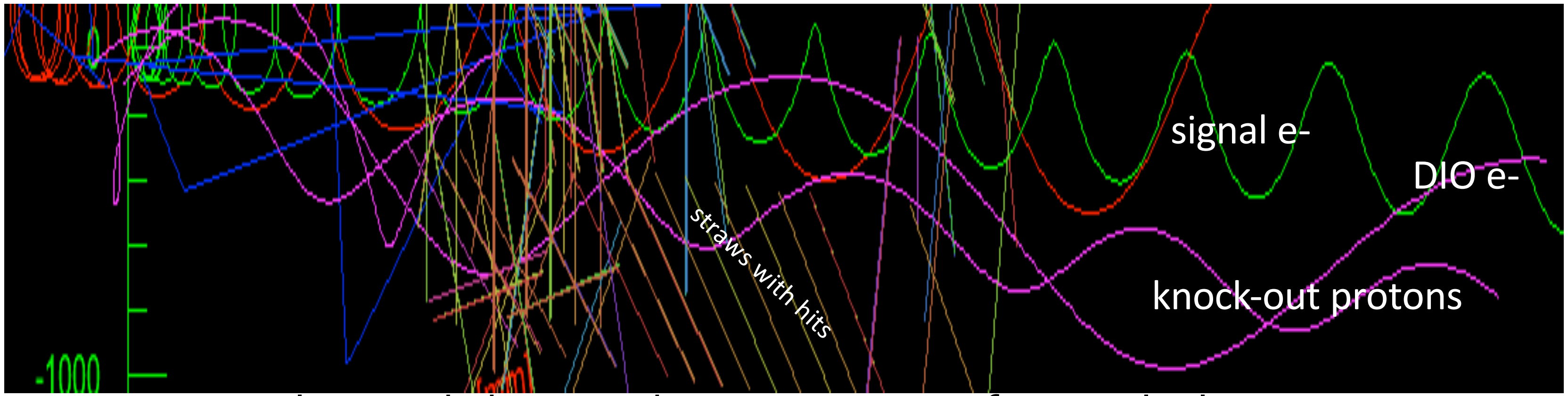


Mu2e Pattern Recognition

Stopping Target Straw Tracker Crystal Calorimeter



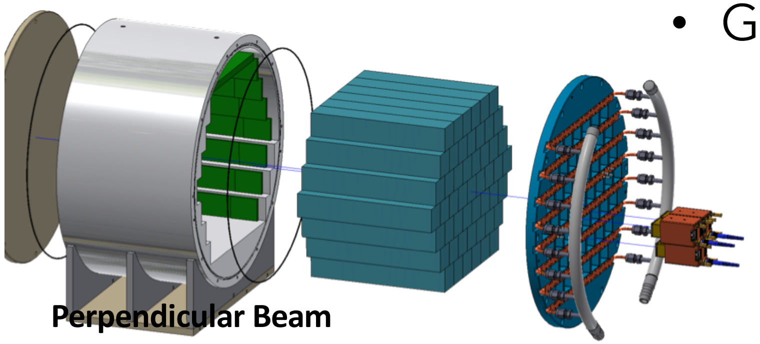
A signal electron, together with all the other interactions



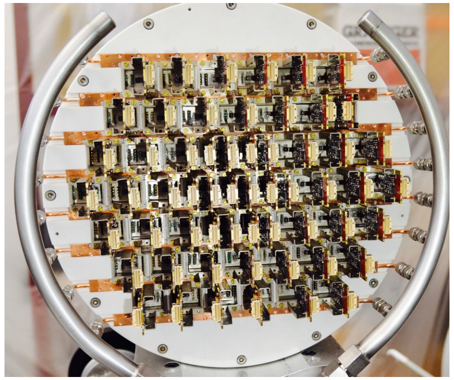
particles with hits within +/-50 ns of signal electron t_{mean}

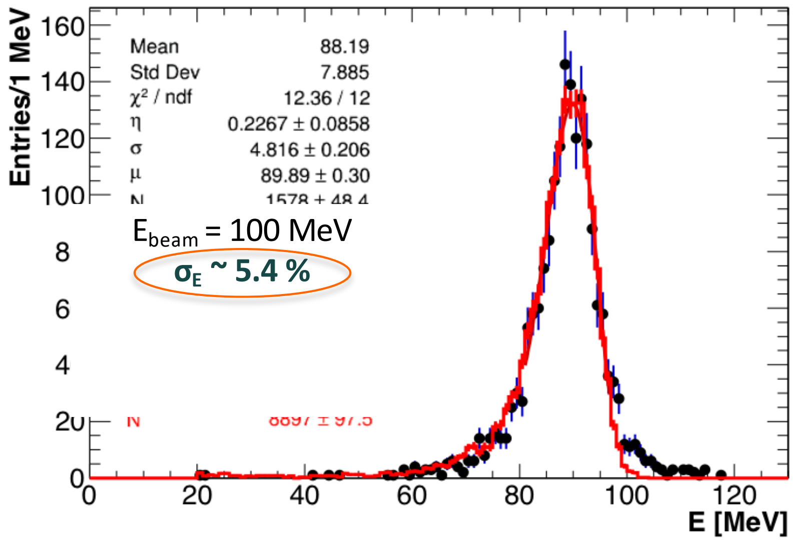
Module 0 and test beam - 2017

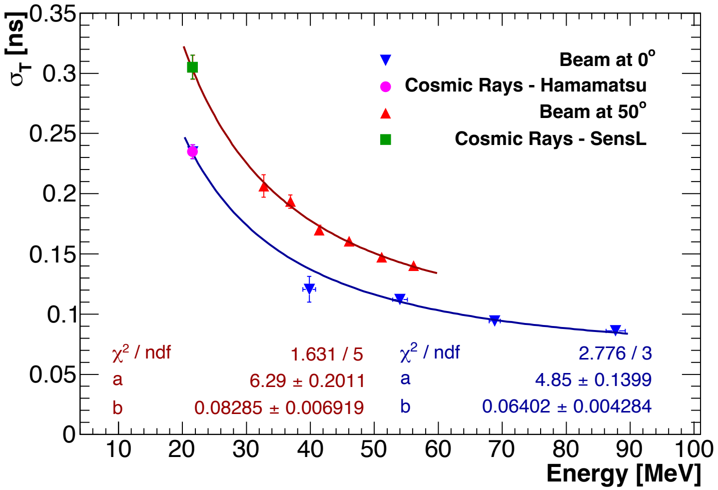
Large EMC prototype: 51 crystals, 102 SiPMs, 102 FEE boards



- Goals:
  - Test the performances
  - Test integration and assembly procedures
  - Test of temperature stability
  - Next: operate under vacuum, temperature and irradiation

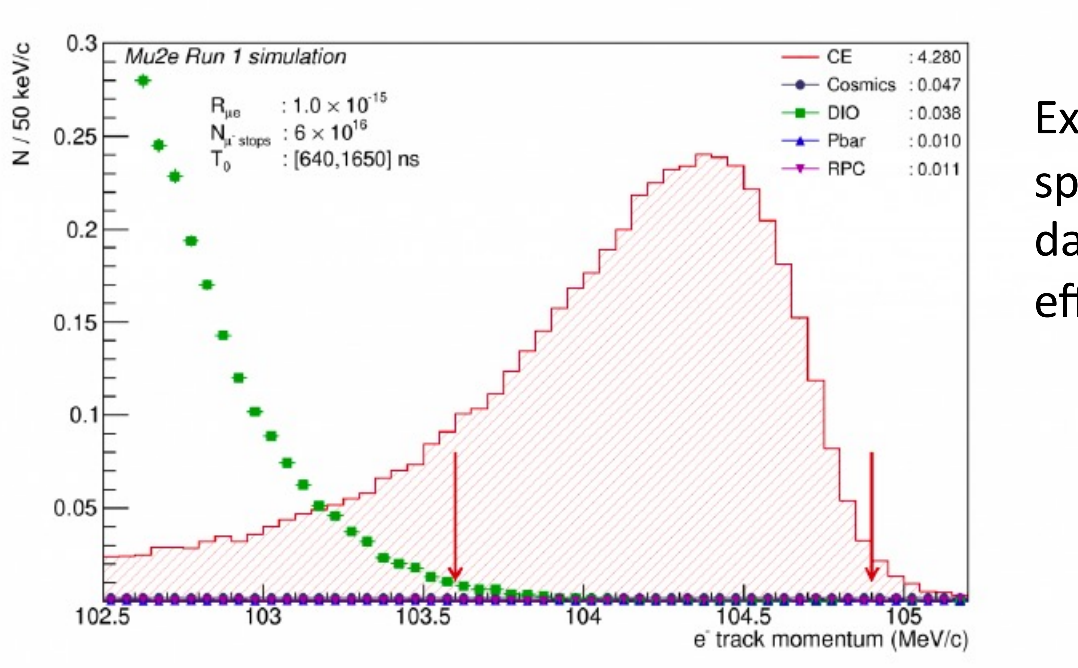






- Cosmic equalization provide **energy res at the level of 5 %**
- $\Delta T = t_{SiPM1} - t_{SiPM2}$ $\sigma_T \sim 130$ ps @$E_{beam} = 100$ MeV

Signal extraction and sensitivity RUN1



Expected signal ($R_{\mu e} = 10^{-15}$) and DIO spectra from Run_I simulation (~10% of final dataset, includes resolution and energy loss effects):

$N_{\mu e}$ = 5

N_{DIO} = 0.03

N_{Other} = 0.10

- Design goal: single-event-sensitivity of 3×10^{-17}

  Requires **10^{18} stopped muons**
  10^{20} protons on target
  high background suppression (**N_{bckg}<0.5**)

- Expected limit: $R_{\mu e} < 6.2\times10^{-16}$ @ 90% CL
  - Factor 10^4 improvement

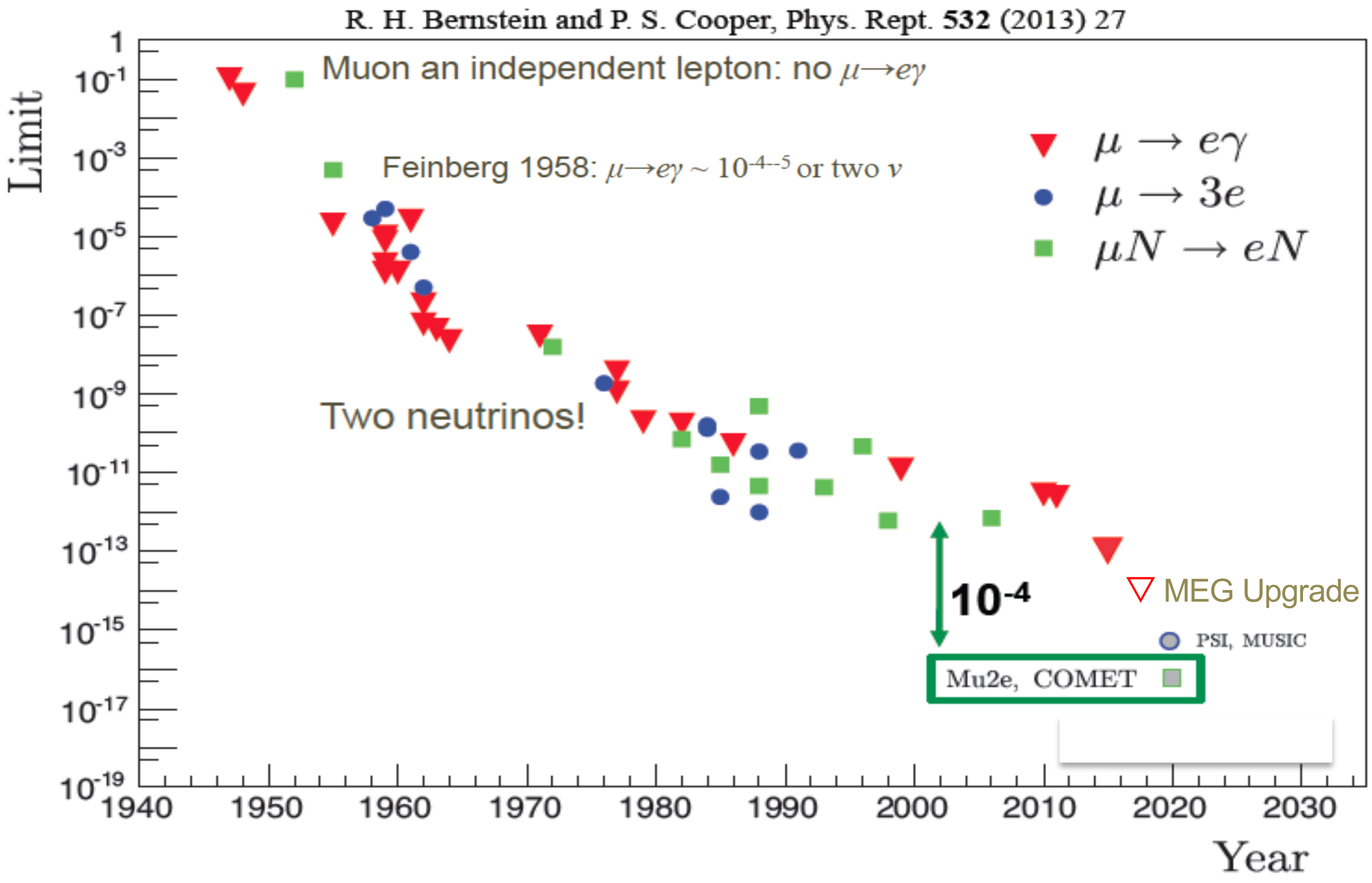
- Discovery reach (5σ): $R_{\mu e} > 1.1 \times 10^{-15}$
  - Covers broad range of new physics theories

Summary

- Mu2e will search for the CLFV in muon to electron conversion with a 90% CL upper limit of < 6.2 x 10^{-16} in the first RUN.
- Muon CLFV channels offer deep indirect probes into BSM. Discovery potential over a wide range of BSM models.
- The construction of the Solenoid system and detectors is well ongoing
- Mu2e commissioning with cosmics begins in 2024, commissioning with beam in 2025 and physics data taking begins in 2026.

- spares

CLFV searches history



Current best limits:

MEG-2016
BR(μ→eγ) < 4.2 x 10^{-13}

SINDRUM-1988
BR(μ→3e) < 1 x 10^{-12}

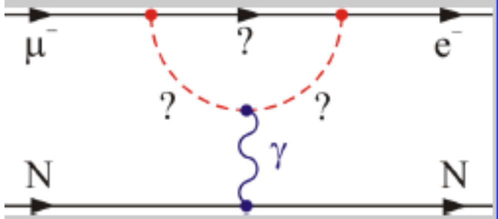
SINDRUM-II 2006
$R_{\mu e}$ < 6.1 x 10^{-13}

MU2E GOAL:
$R_{\mu e}$ = 2.5 x 10^{-17}

Mu2e Sensitivty

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

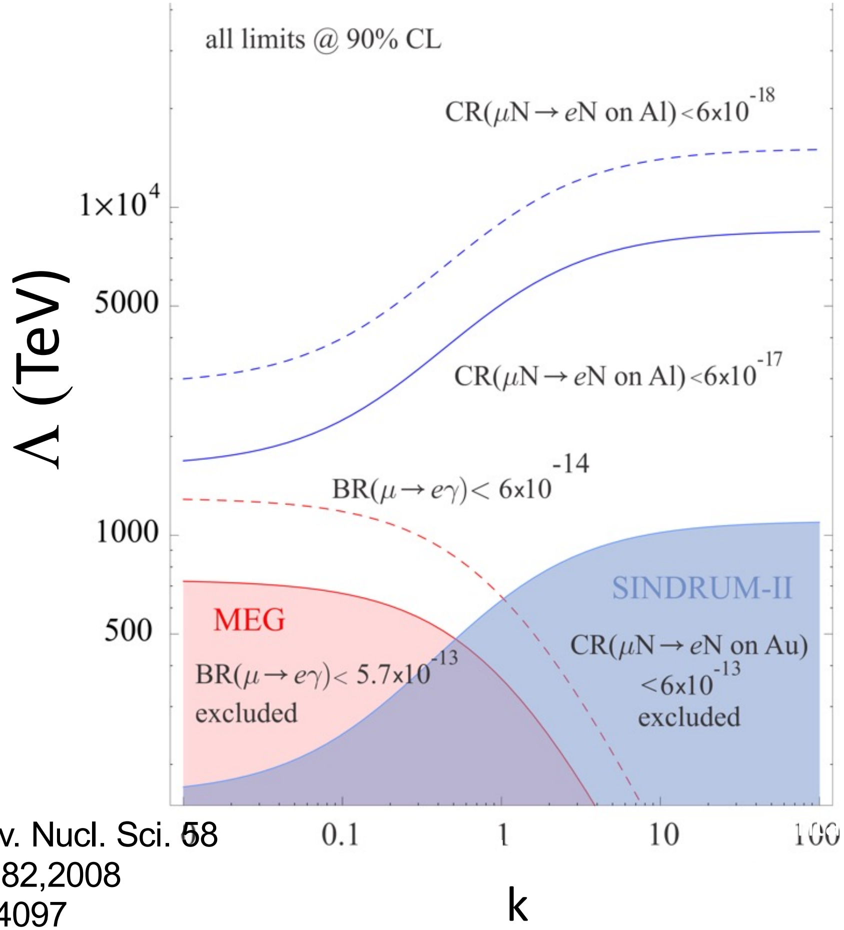
Loops



κ<< 1

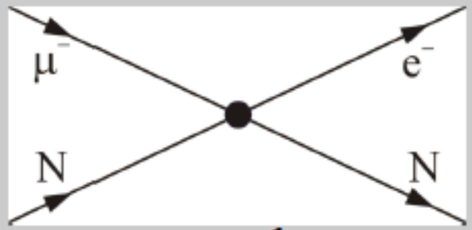
magnetic moment type operator

μ→ eγ rate ~300X μN → eN rate



Loops contact

Contact Interactions



κ>> 1

four-fermion interaction

μN→ eN rate >> μ→ eγ rate

Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58
M. Raidal *et al*, Eur.Phys.J.C57:13-182,2008
A. de Gouvêa, P. Vogel, arXiv:1303.4097

Mu2e Sensitivity best in all scenarios

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
- Most promising CLFV measurements use μ
- in most BSM models CLFV effects are present at rates that some next generation experiments will be sensitive to

As low probability as this!

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 Al target
  - 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 reducing background
- Look for events consistent with $\mu N \rightarrow eN$

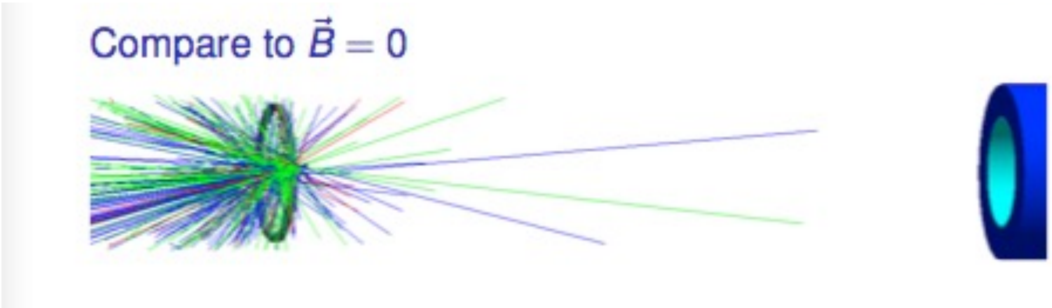
Some Perspective

1,000,000,000,000,000,000

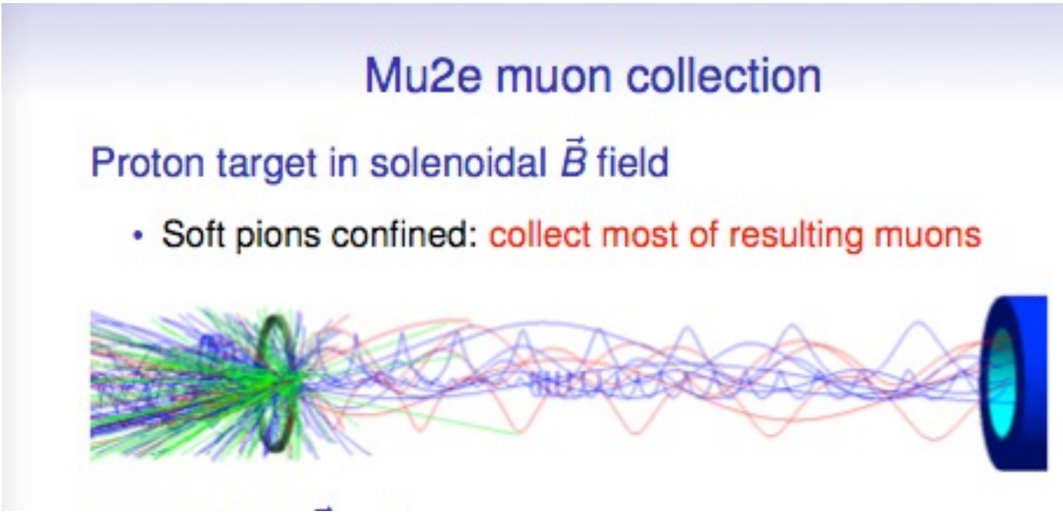
= number of stopped Mu2e muons

= number of grains of sand on earth's beaches

Using Solenoids to Collect Muons



- SINDRUM-II used ~1 MW beam to produce ~10^{7-8} stopped μ/s



- Solenoids enable us to collect ~10^{10} μ/s using an 8kW beam.

Backgrounds to deal with

Stopped μ's

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

Late protons

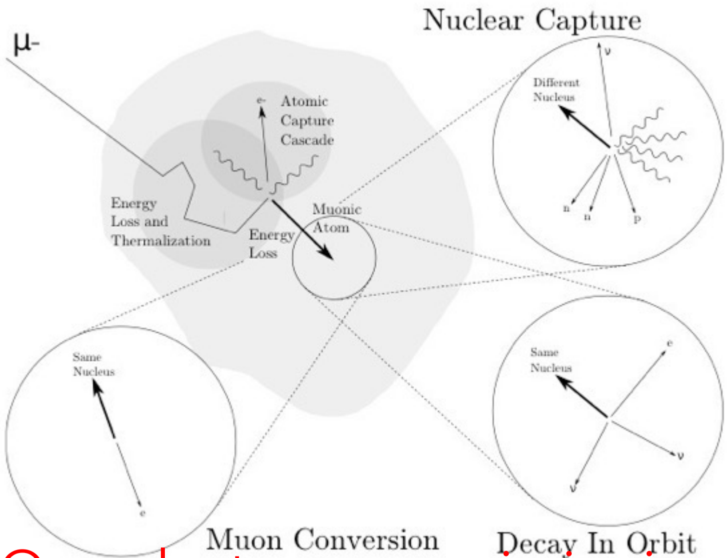
- Pions from late protons can undergo radiative capture (RPC) (τ_π^{Al} = 26 ns)

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

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



prompt vs late arriving bkg

Category	Background Process	Estimated Yield
Intrinsic	Decay In Orbit (DIO)	$0.144 \pm 0.028(stat) \pm 0.11(syst)$
	Muon Capture (RMC)	0
Late Arriving	Pion Capture (RPC)	$0.021 \pm 0.001(stat) \pm 0.002(syst)$
	Muon Decay in Flight	< 0.003
	Pion Decay in Flight	$0.001 \pm <0.001$
	Beam Electrons	$(2.1 \pm 1.0) \times 10^{-4}$
Miscellaneous	Cosmic Ray Induced	$0.209 \pm 0.022(stat) \pm 0.055(syst)$
	Antiproton Induced	$0.040 \pm 0.001(stat) \pm 0.020(syst)$
Total		**$0.41 \pm 0.13(stat + syst)$**

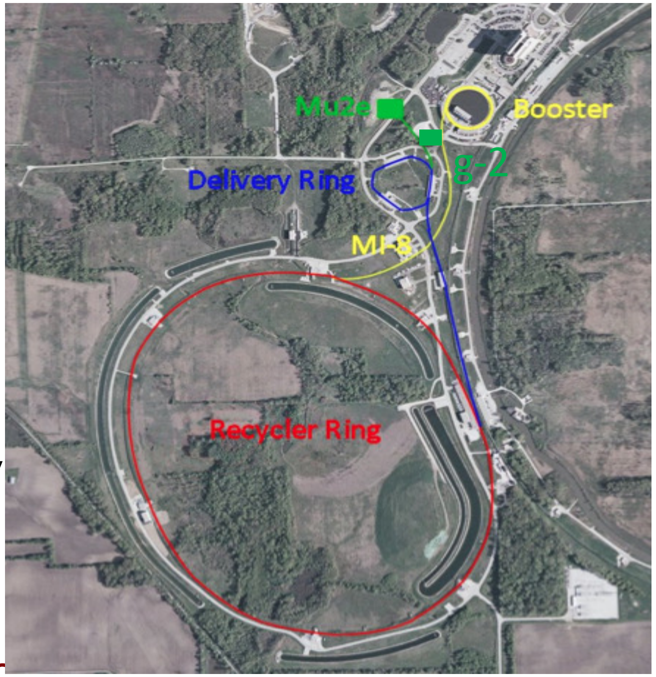
Prompt background, like radiative pion capture, decreases rapidly ($\sim 10^{11}$ reduction after 700 ns). RPC was limiting Sindrum II current limit. Mu2e scheme is capable to keep it under control.

Accelerator & proton extinction

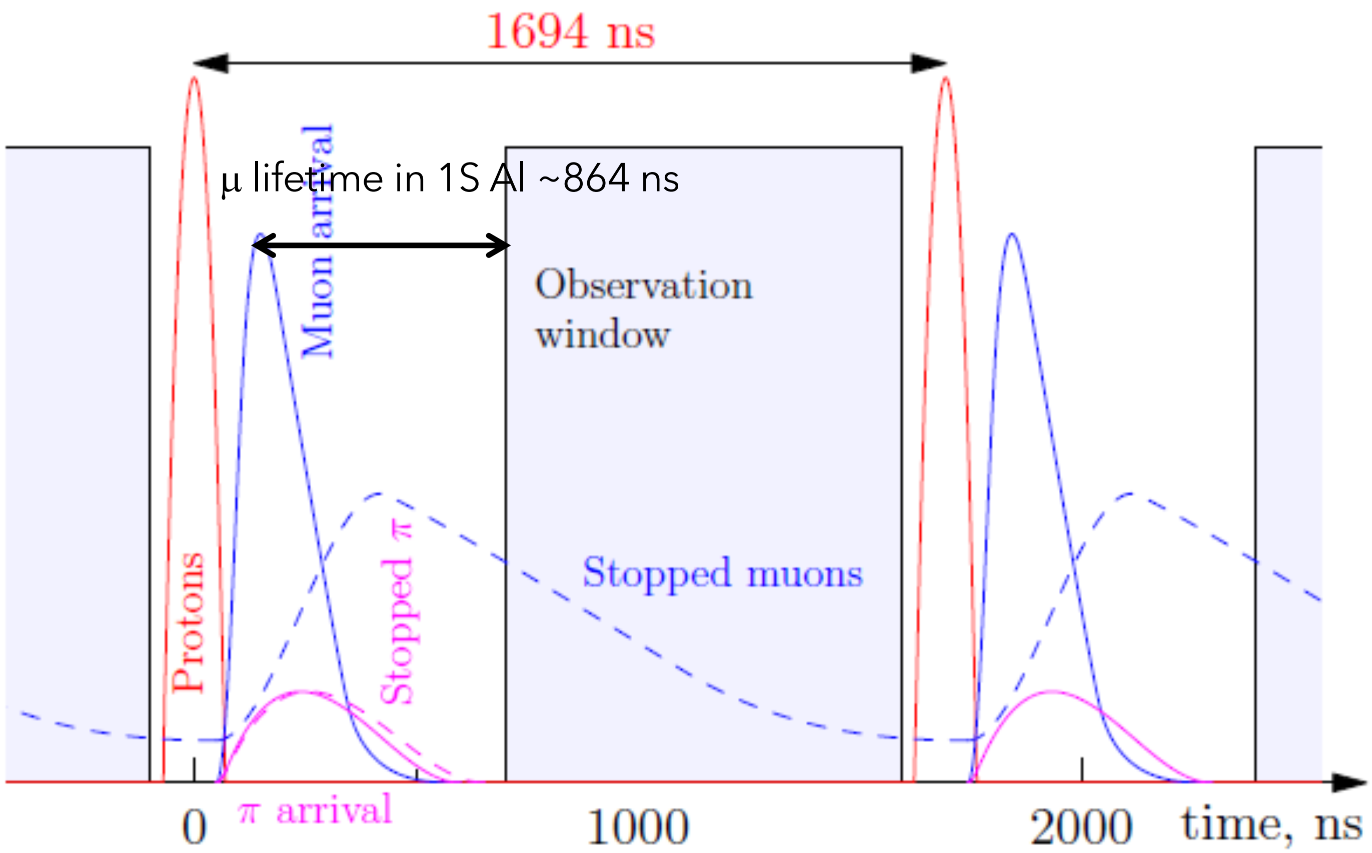
- Mu2e will repurpose much of the Tevatron anti-proton complex to instead produce muons.
- Booster: 21 batches of 4×10^{12} of 8 GeV protons every 1/15th second
- Booster "batch" is injected into the Recycler ring and re-bunched into 4 smaller bunches
- These are extracted one at a time to the Delivery ring
- As a bunch circulates, protons are extracted to produce the desired beam structure → pulses of ~3×10^{7} protons each, separated by 1.7 μs
- **Proton Extinction** between bunches

  (N_p out of bunch)/(N_p in bunch)
  - Internal: momentum scraping and bunch formation
  - External: oscillating AC dipole

  Accelerator models show that this combination ensures ~ 10^{-12}



Pulsed beam structure

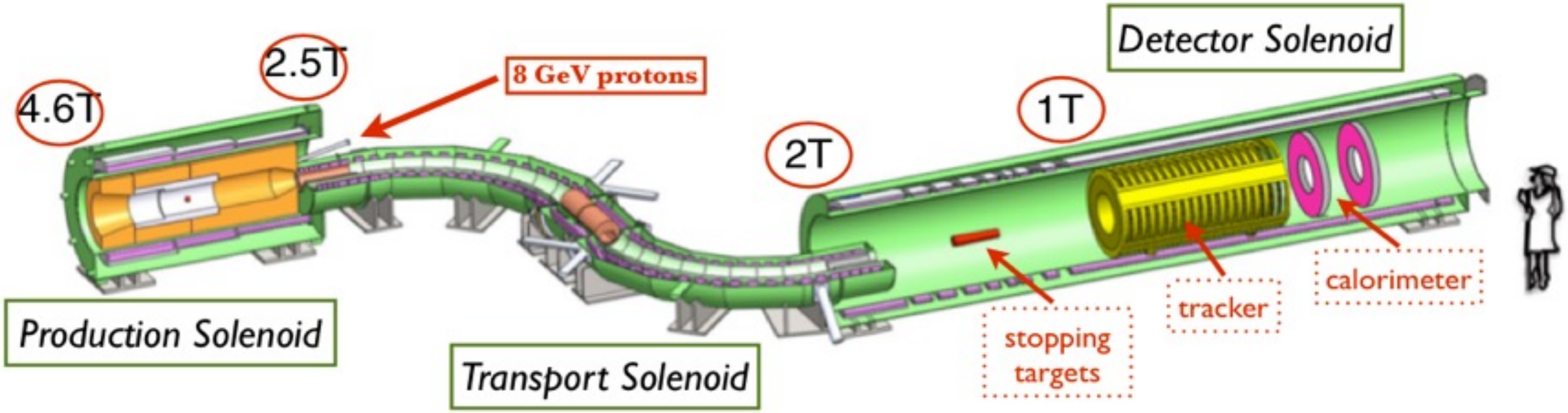


- Use the fact that muonic atomic lifetime >> prompt background
  Need a pulsed beam to wait for prompt background to reach acceptable levels
  → Fermilab accelerator complex provides ideal pulse spacing
  a 700 ns delay reduces pion background by $>10^{-9}$

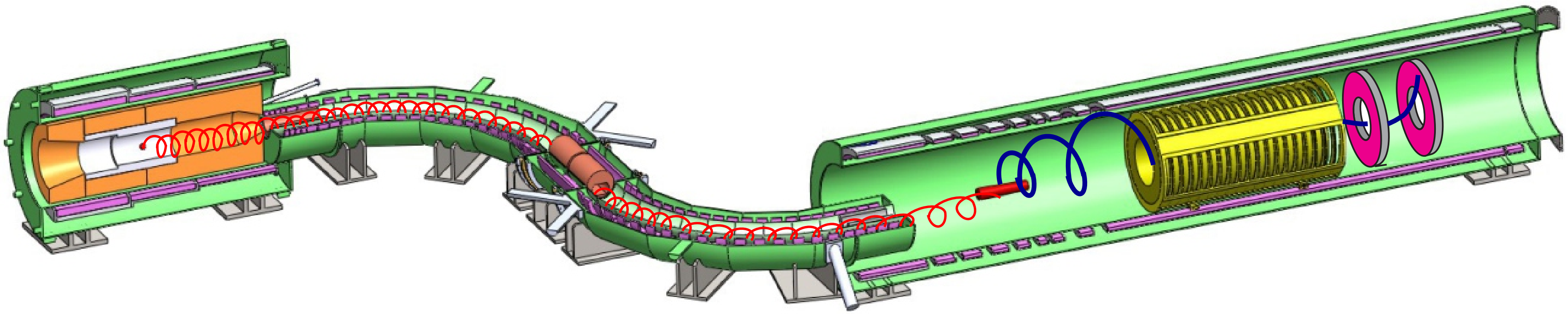
- Out of time protons are also a problem->prompt bkg arriving late
  To keep background low we need proton extinction extintion$<10^{-10}$

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

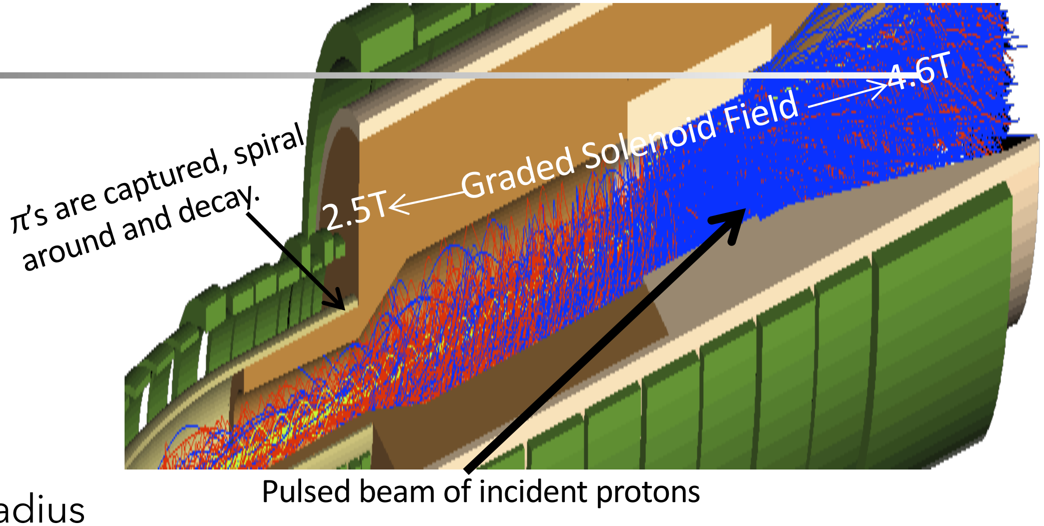


Signal event in the apparatus

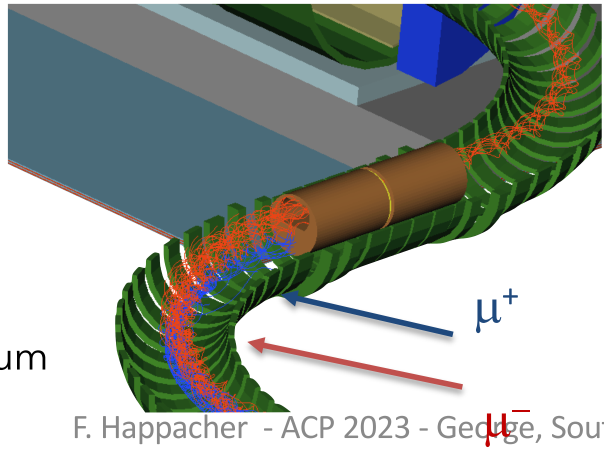


The Mu2e beamline

- Production Solenoid
  - Pulsed proton beam coming from Debuncher hits 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



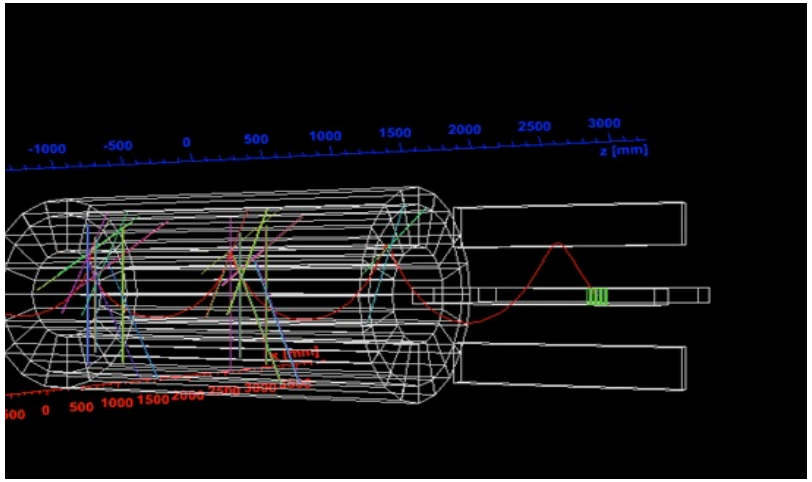
- Transport Solenoid
  - Graded magnetic from 2.5 T (at the entrance) to 2.0 T (at the exit)
    - Allows muons to travel on a helical path from the production solenoid to the detector solenoid
  - S-shaped to remove the detector solenoid out of the line of sight from the production solenoid
    - No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



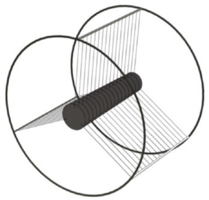
off-center central TS collimator and 90° bends passes low momentum negative muons and suppresses positive particle and high momentum negative particles.

The Mu2e Beamline

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

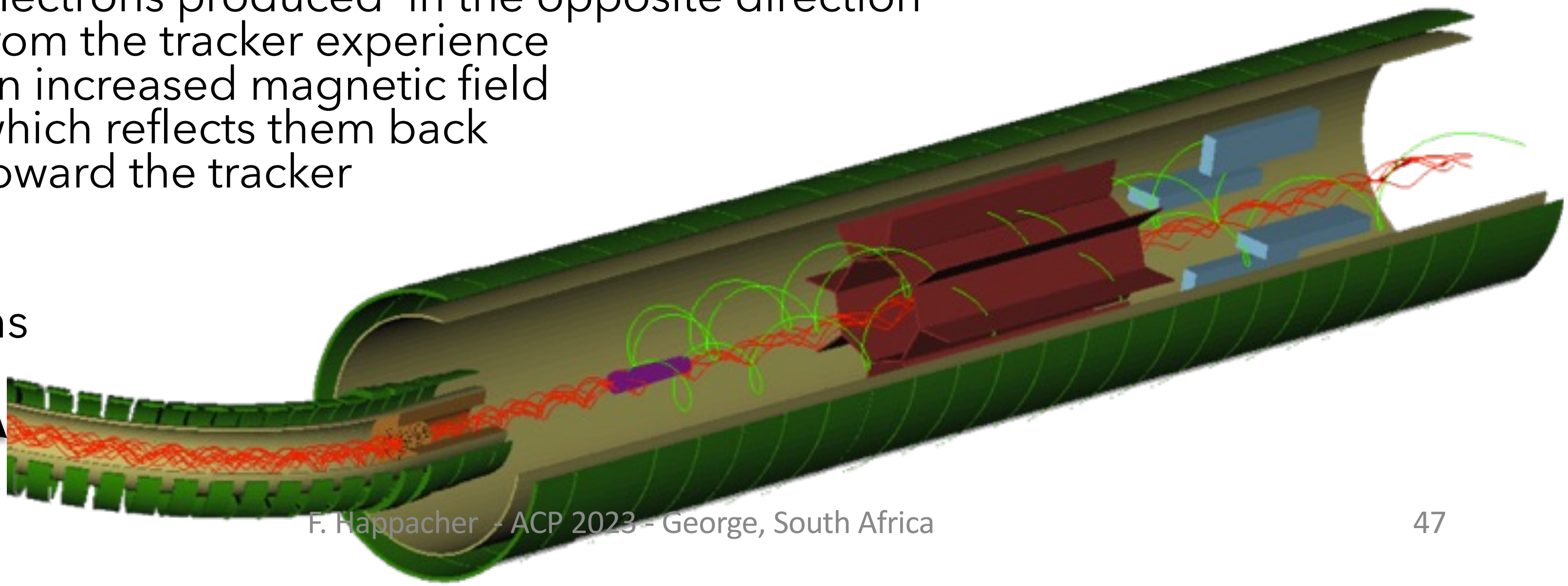


  – 17 Aluminum disks, 0.2 mm thick, radius between 83 mm (upstream) and 63 mm (downstream)



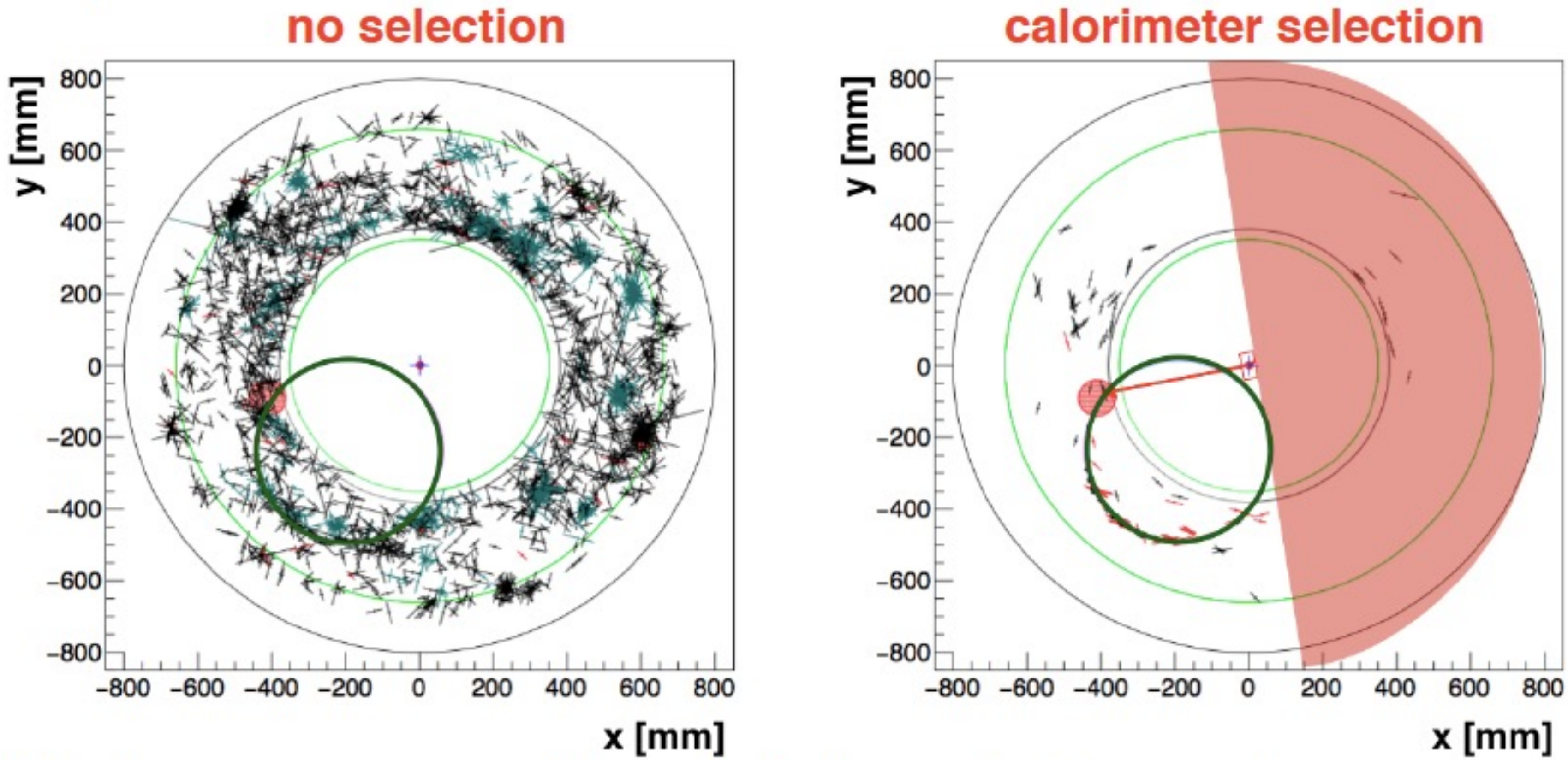
  – Surrounded by graded magnetic field from 2.0 T (entrance) to 1.0 T (exit)
    – Conversion electrons will travel on a helical path toward the tracker and then hit the calorimeter
    – Electrons produced in the opposite direction from the tracker experience an increased magnetic field which reflects them back toward the tracker

Negative muons



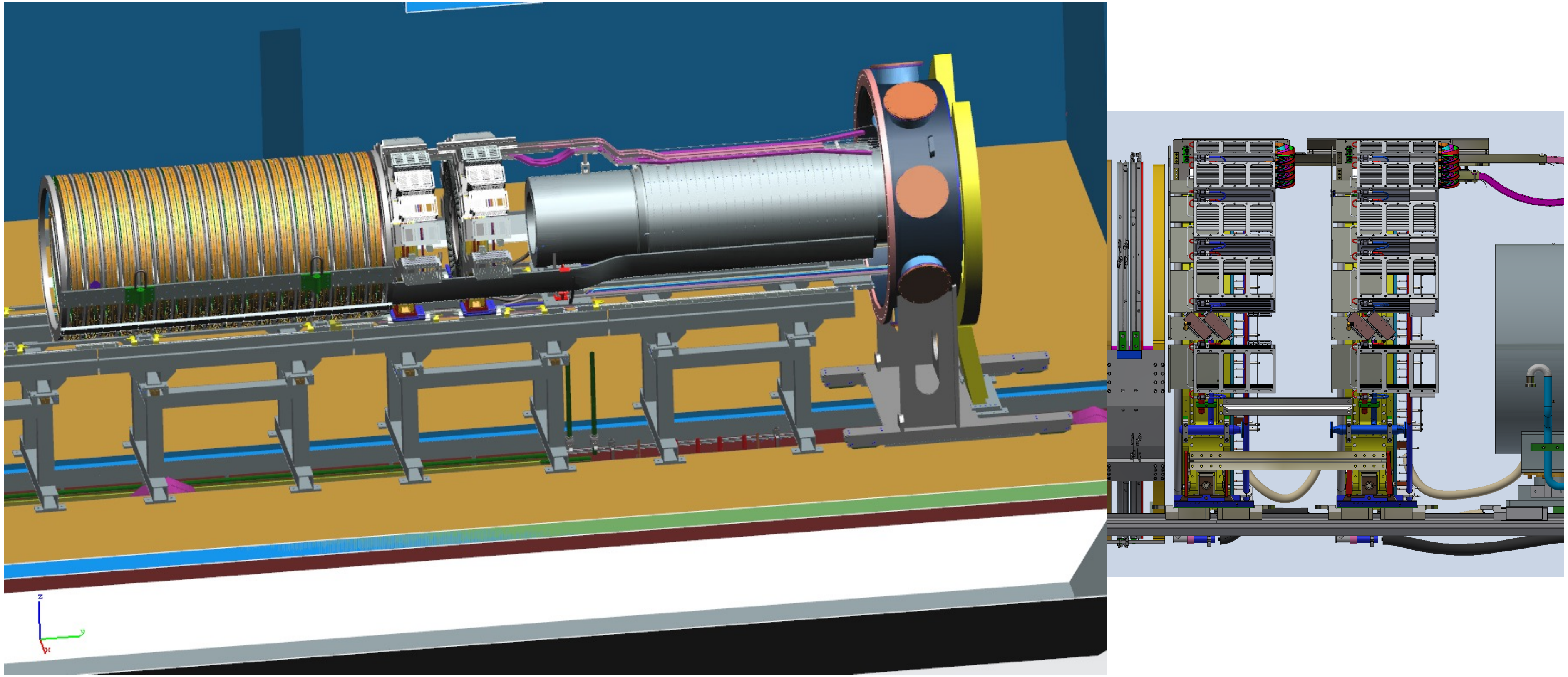
Mu2e Pattern Recognition

- Cluster time and position are used for filtering the straw hits:
  - ✓ **time window of ~ 80 ns**
  - ✓ **spatial correlation**



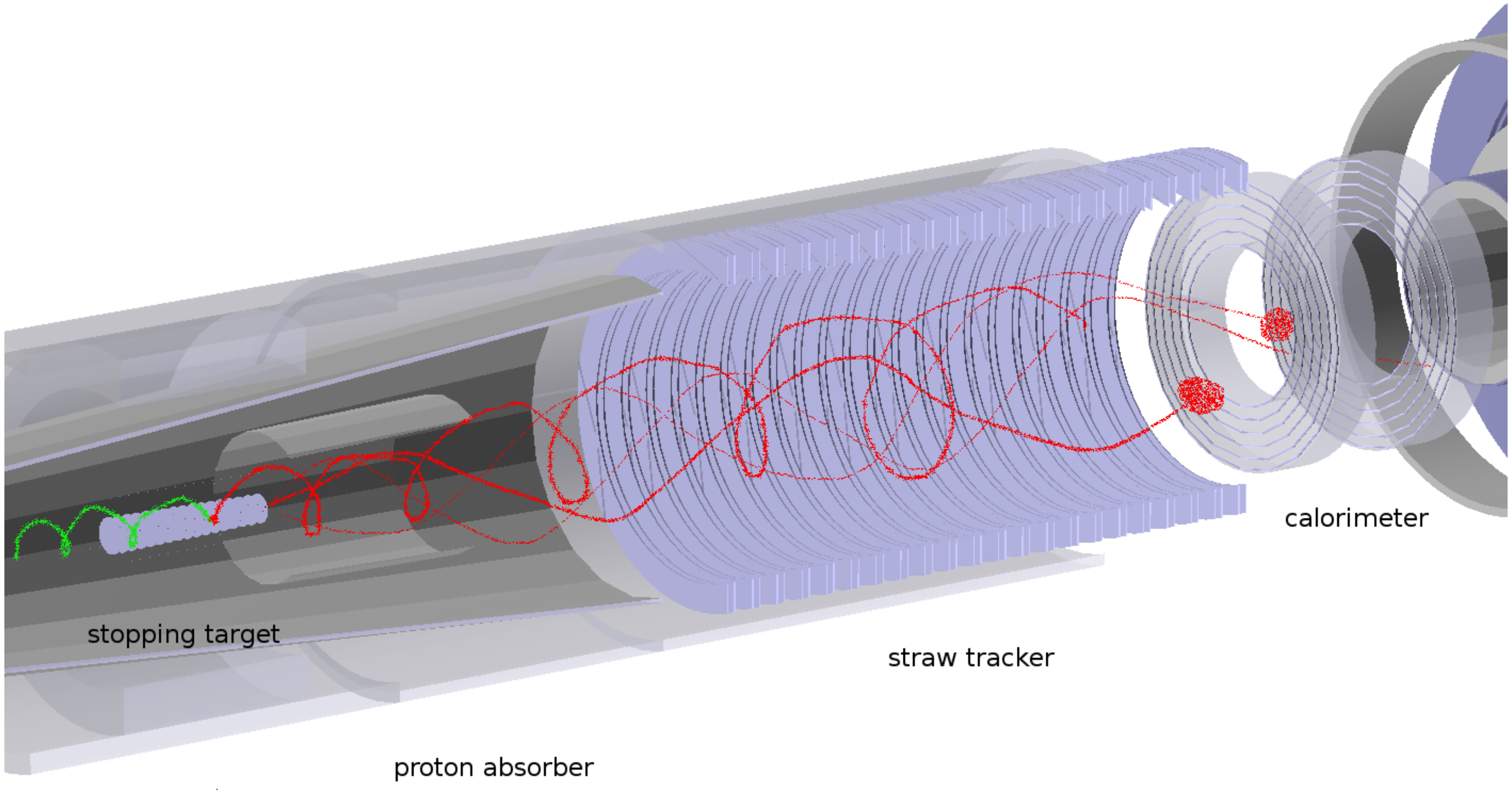
- **black crosses** = straw hits, **red circle** = calorimeter cluster, **green line** = CE track

Calorimeter Integration in the Muon Beam line



The Calorimeter is fully integrated in the Mu2e detector train, all services routed.

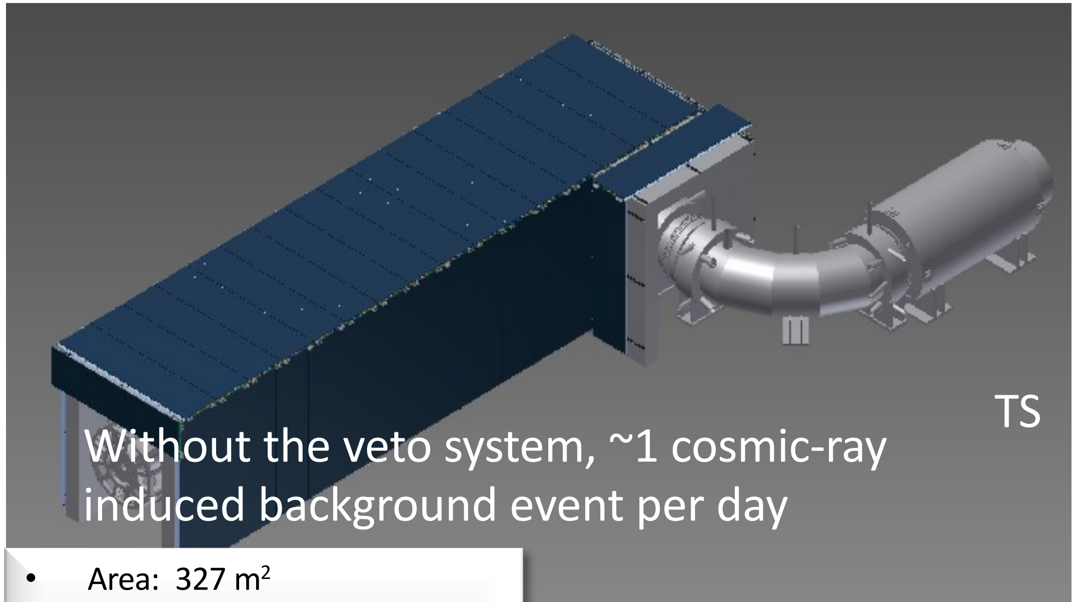
Mu2e Pattern Recognition

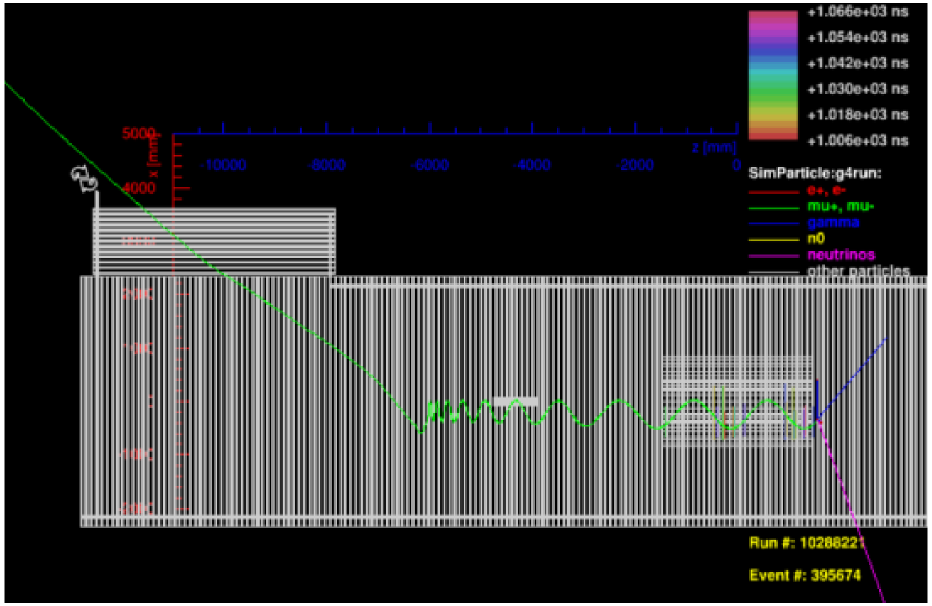


- ❑ Search for tracking hits with time and azimuthal angle compatible with the calorimeter clusters ($|\Delta T| < 50$ ns) → simplification of pattern recognition
- ❑ Add search of an Helix passing through cluster and selected hits + use calorimeter time to calculate tracking Hit drift times

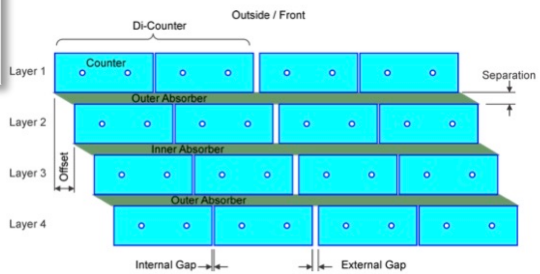
The Cosmic ray Veto

Cosmic μ can generate background events via decay, scattering, or material interactions. Veto system covers entire DS and half TS

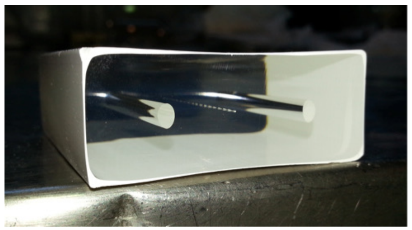




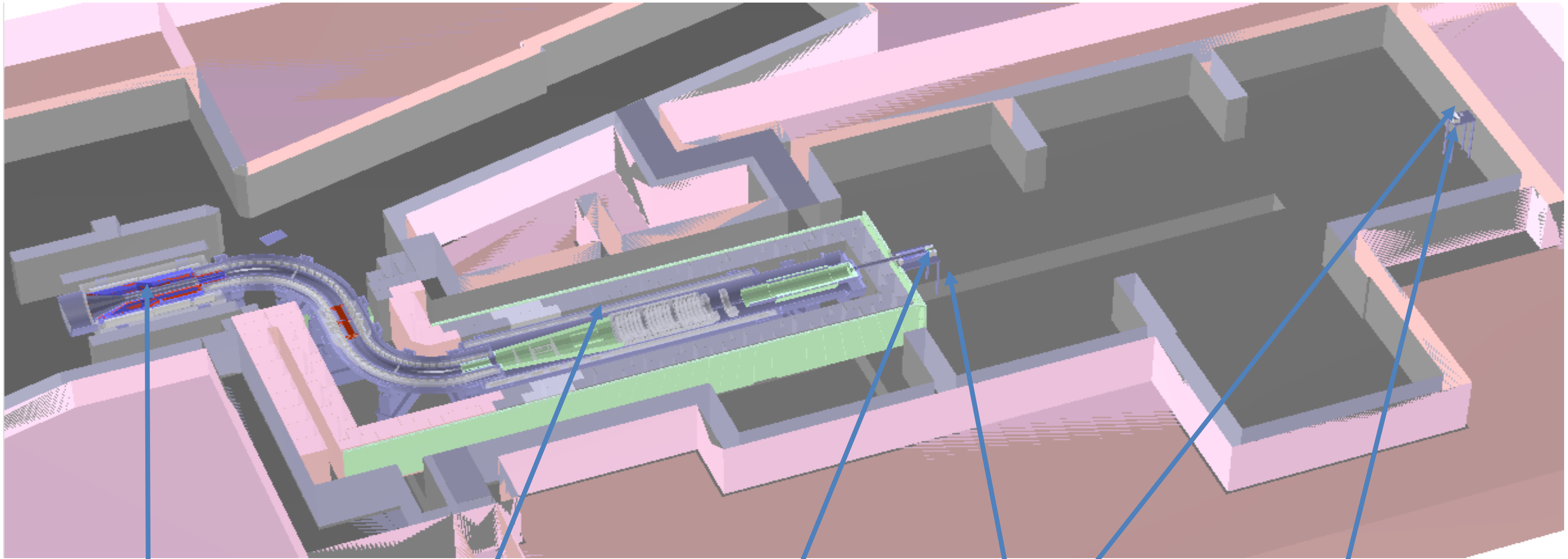
- Area: 327 m^2
- 86 modules of 6 lengths
- 5,504 counters
- 11,008 fibers
- 19,840 SiPMs
- 310 Front-end Boards



- Will use 4 overlapping layers of extruded plastic scintillator
  - Each bar is 5 x 2 x ~450 cm^3
  - 2 (1,4 mm Ø) WLS fibers / bar
  - Read-out both ends of each fiber with 2 x2 mm^2 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