The Mu2e Experiment at Fermilab

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On behalf of the Mu2e Collaboration

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Presentation outline

- Where, Why Muon 2 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

~230 Scientists from 37 Institutions

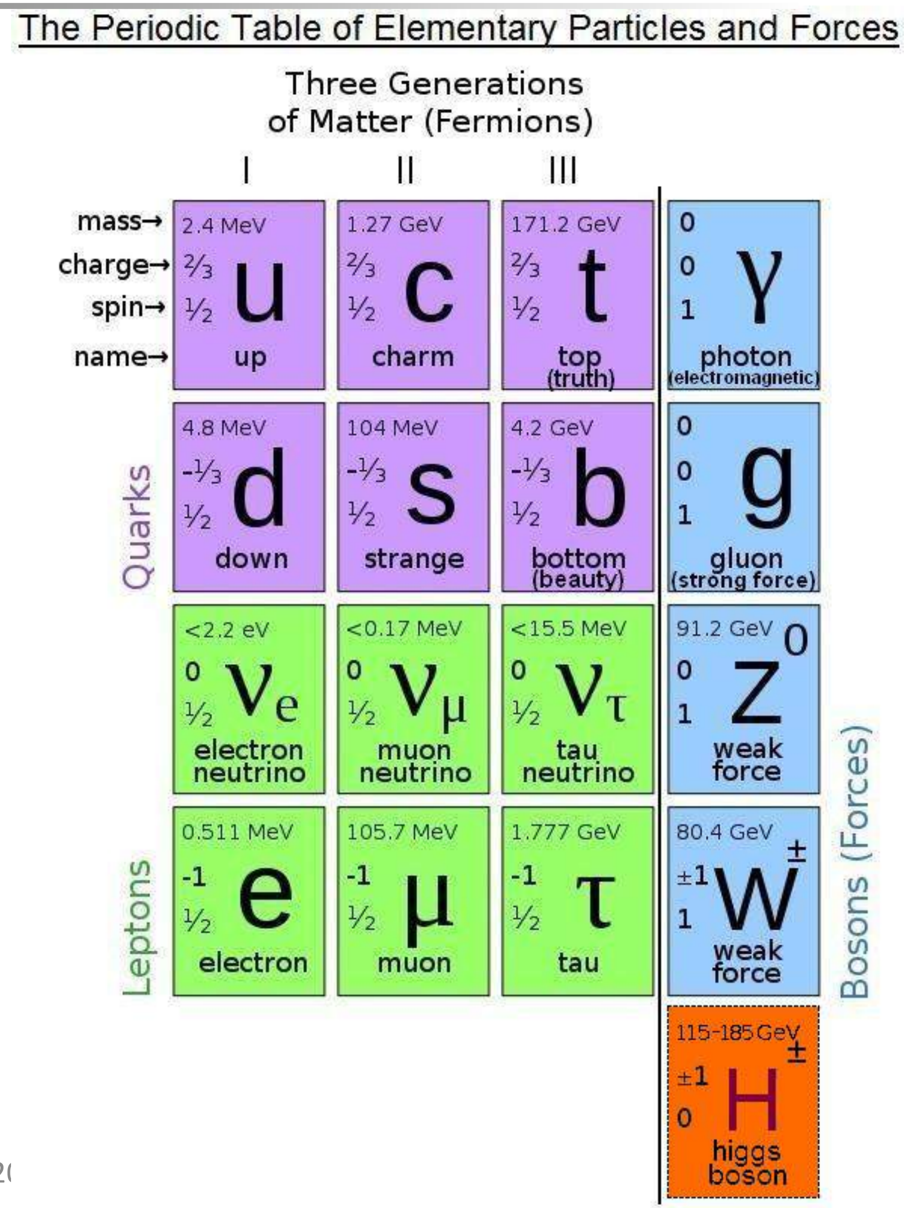
Argonne National Laboratory, Boston University, Brookhaven National Laboratory, University of California Berkeley, University of California Irvine, California Institute of Technology, City University of New York, **Joint Institute of Nuclear Research Dubna,** Duke University, Fermi National Accelerator 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 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

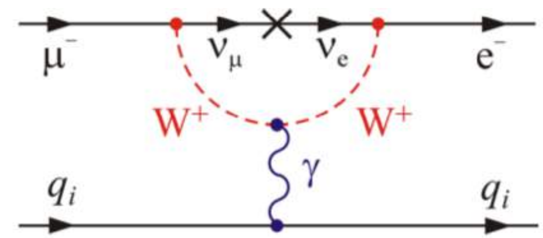
- Why not charged leptons?
  - Charged Lepton Flavor Violation (CLFV)



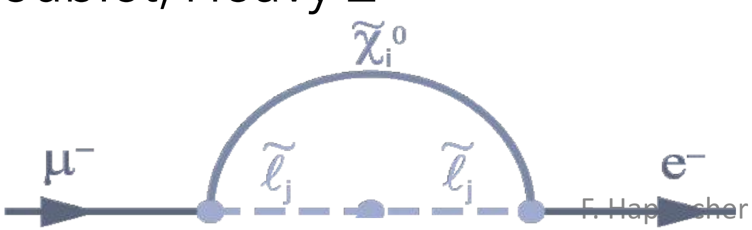
Why a Search for $\mu^- N \rightarrow e^- N$?

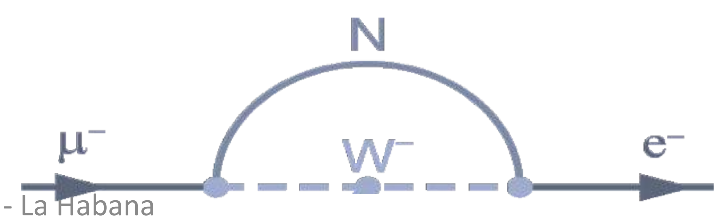
- Mu2e searches for muon-to-electron conversion in the coulomb field of a nucleus
- CLFV processes are strongly suppressed in the Standard Model
  - it is not forbidden due to neutrino oscillations
  - In practice $BR(\mu \rightarrow e\gamma) \sim \Delta m_\nu^2 / M_W^2 < 10^{-54}$

    thus not observable



- BSM Physics could enhance CLFV rates to observable values
- Muon-to-electron conversion is similar but complementary to other CLFV processes as μ→ eγ and μ → 3e.
- A detected signal would be evidence of physics beyond the SM (BSM) - 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)

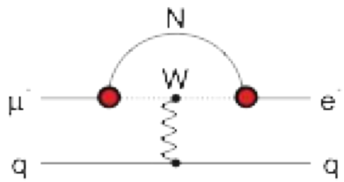
- There is a global interest in CLFV
- Most promising CLFV measurements use μ
- in most BSM models CLFV effects are present at rates that some next generation experiments will be sensitive to

μ->e is a signature of BSM models

Loop terms

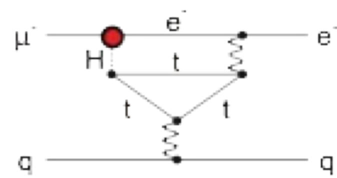
Heavy Neutrinos

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



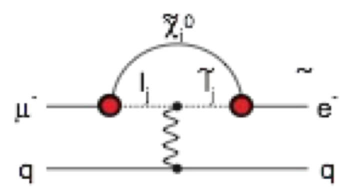
Second Higgs Doublet

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



Supersymmetry

rate ~ 10^{-15}

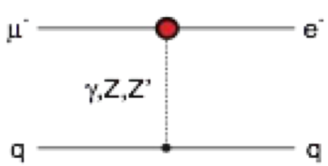


Models which can be probed also by μ→eγ searches

Contect terms

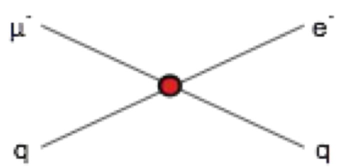
Heavy Z' Anomal. Z Coupling

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



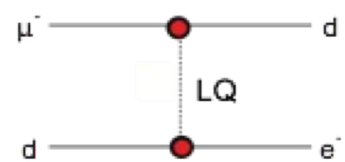
Compositeness

$\Lambda_c \sim 3000\ \mathrm{TeV}$



Leptoquark

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

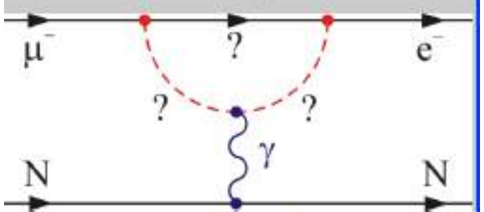


Direct coupling between quarks and leptons, better accessed by $\mu N \to eN$

Mu2e Sensitivty

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

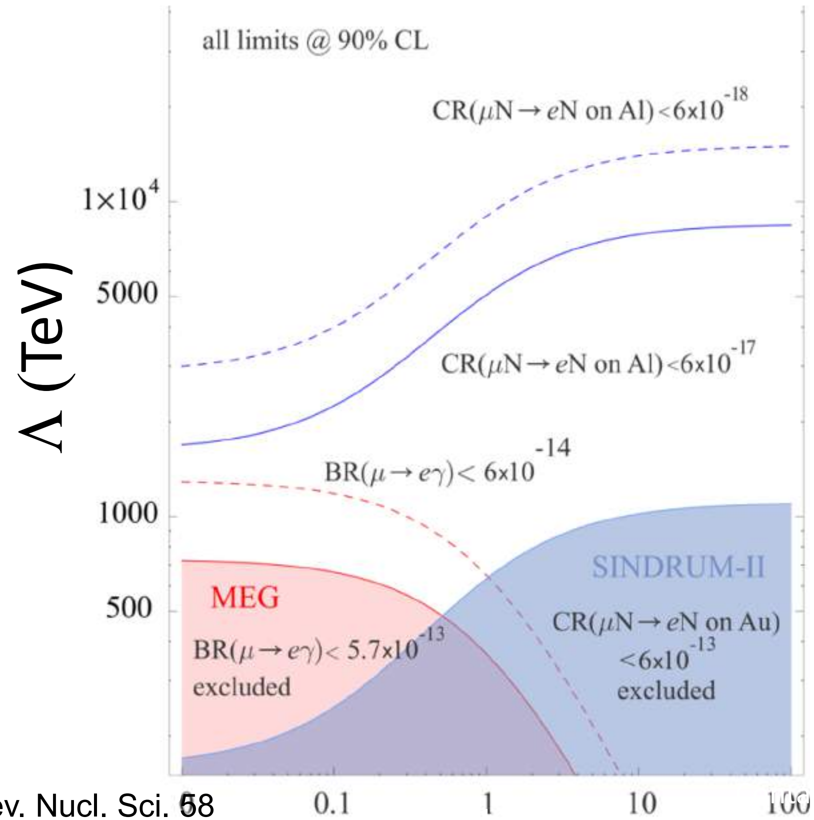
Loops



κ<< 1

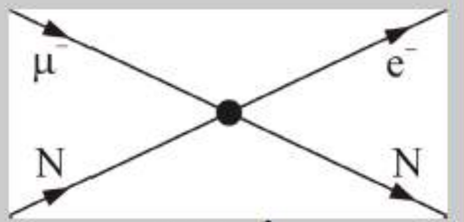
magnetic moment type operator

μ→ eγ rate ~300X μN → eN rate



Loops contact

Contact Interactions



κ>> 1

four-fermion interaction

μN→ eN rate >> μ→ eγ rate

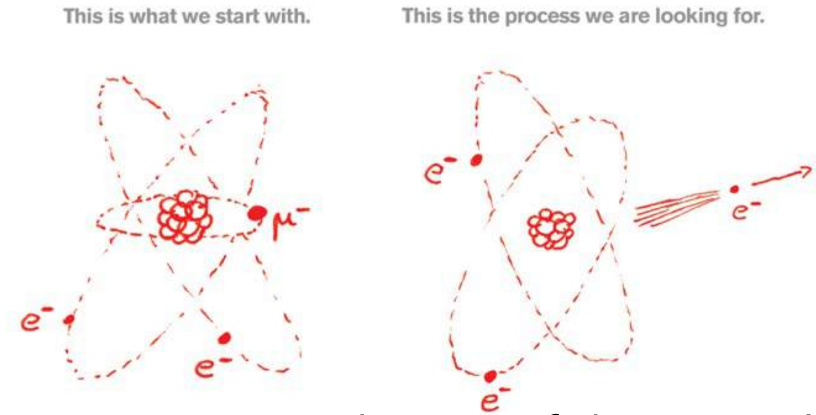
Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58
M. Raidal *et al*, Eur.Phys.J.C57:13-182,2008
A. de Gouvêa, P. Vogel, arXiv:1303.4097

Mu2e Sensitivity best in all scenarios

What is Mu2e

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

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



– Will use current the intense proton beam of the Fermilab accelerator complex to reach a single event sensitivity of ~2.5 x10^{-17} i.e. 10^4 better than current world's best (Sindrum II)

– Will have *discovery* sensitivity over broad swath of BSM 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!

Mu2e operating principle

- Generate a intense beam (10^{10}/s) of low momentum (p_T<100 MeV/c) negative μ's
- p + nucleus $\rightarrow \pi^- \rightarrow \mu^- \nu_\mu$

- <u>Every 1 second Mu2e will</u>
  - 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

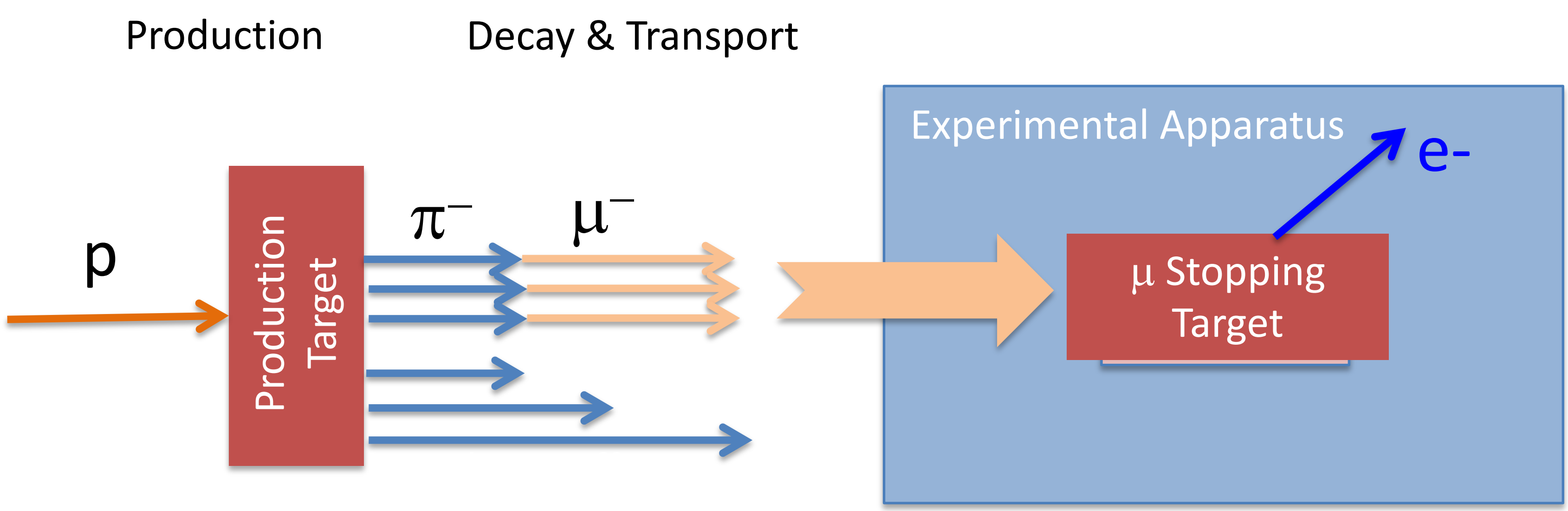
- <u>Stop the muons in Al target</u>
  - Sensitivity goal requires ~10^{18} stopped muons
  - 10^{20} protons on target (2 year run – 2×10^7 s)

- 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

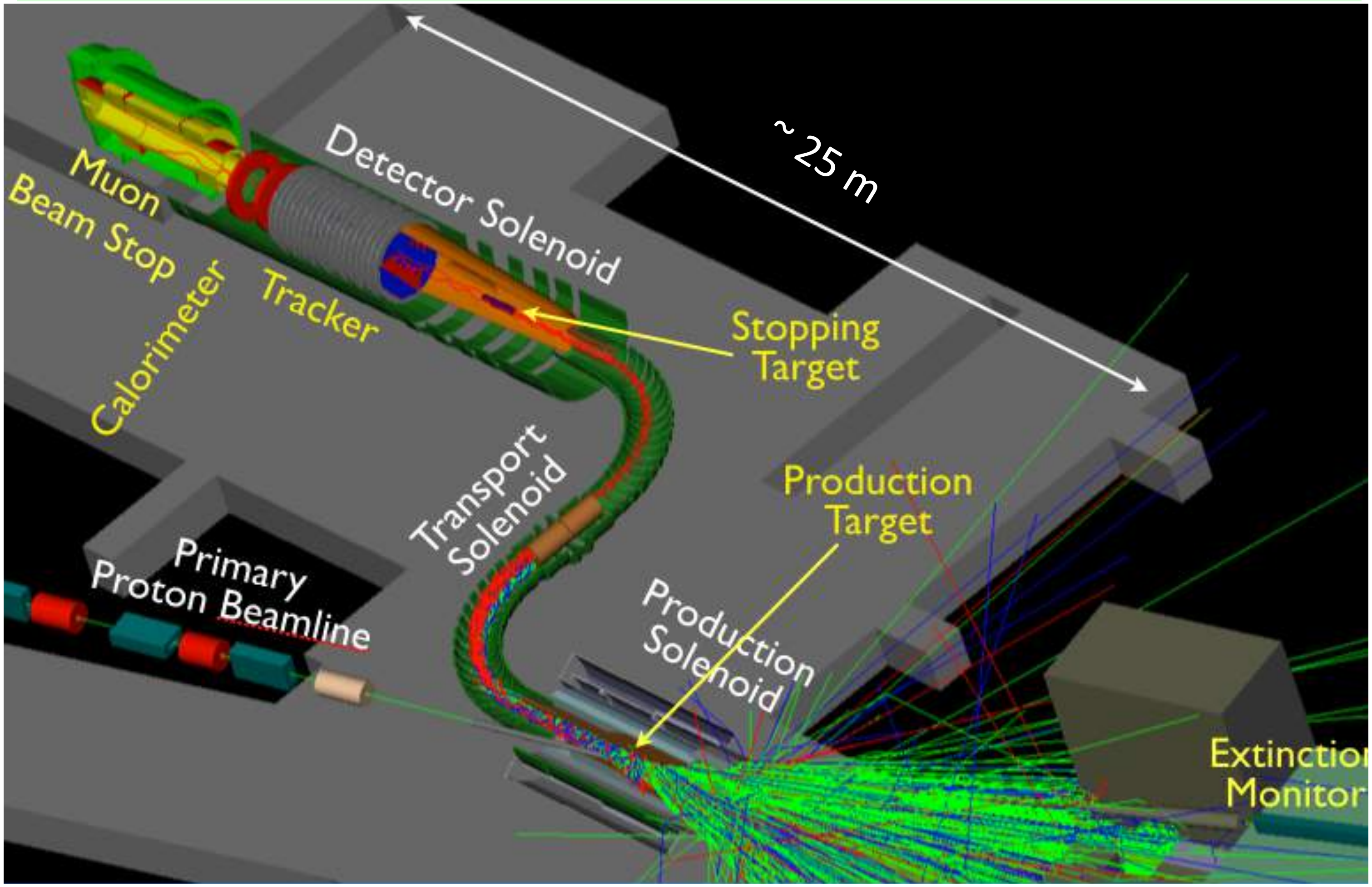
1,000,000,000,000,000,000
= number of stopped Mu2e muons
= number of grains of sand on earth's beaches

Mu2e Concept in a sketch



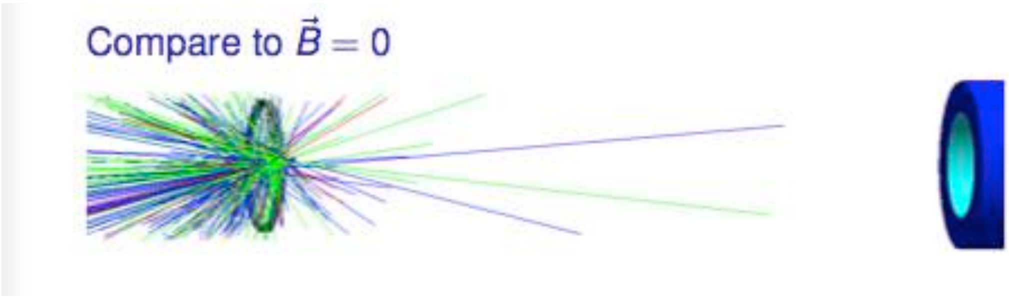
From the cartoons …. To real tough life

Mu2e Experimental Apparatus

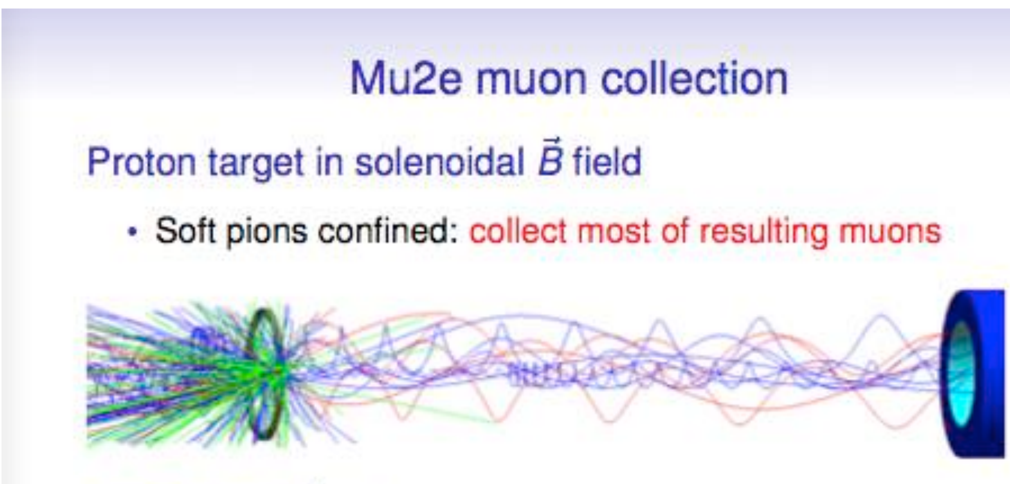


- Derived from MELC concept originated by Lobashev and Djilkibaev in 1989

Using Solenoids to Collect Muons



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



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

Muonic Al atom

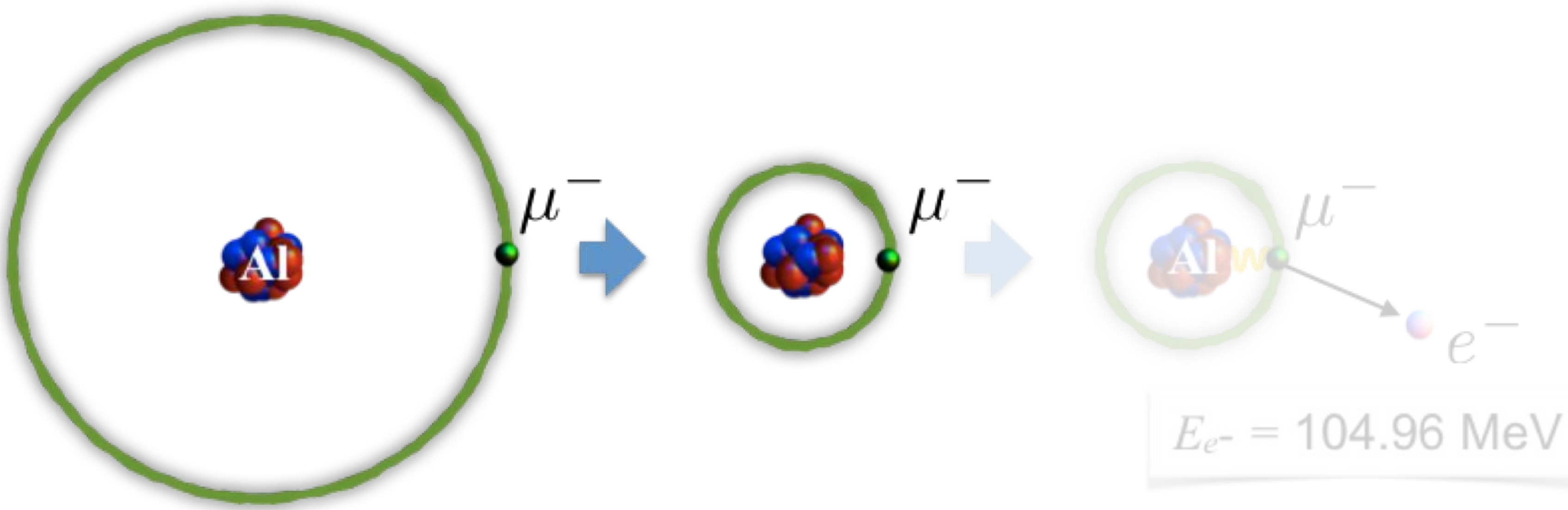
Before going to the experimental setup, let's see the topology of the events we are dealing with.

- 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 in 1s state, 3 main process (might) take place
  - Conversion : $\mu^- N_{(A,Z)} \rightarrow e^- N_{(A,Z)}$ (signal)
  - Muon Capture : $\mu^- N_{(A,Z)} \rightarrow \nu N^*_{(A,Z-1)}$ (61%) (normalization)
  - Decay : $\mu^- N_{(A,Z)} \rightarrow e^- \nu\nu N_{(A,Z)}$ (39%) (main bkg)

Mu2e Measurement factors

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

- Muon is trapped on Aluminum

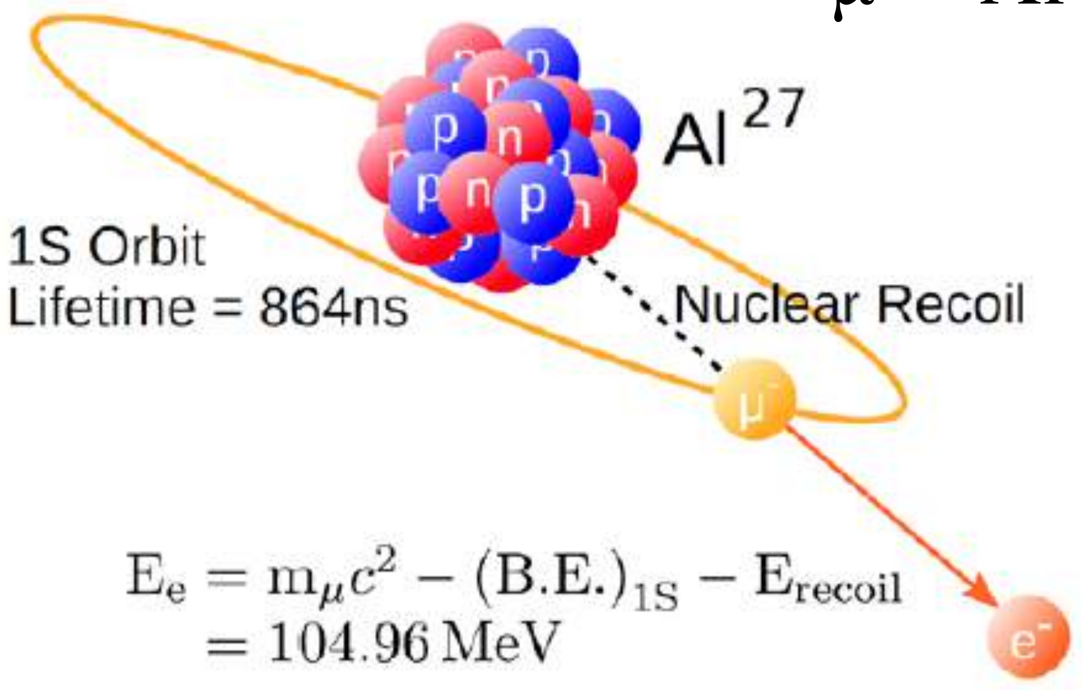


and…

The numerator, i.e. **the signal**

…neutrinoless converts to a monoenergetic electron.

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

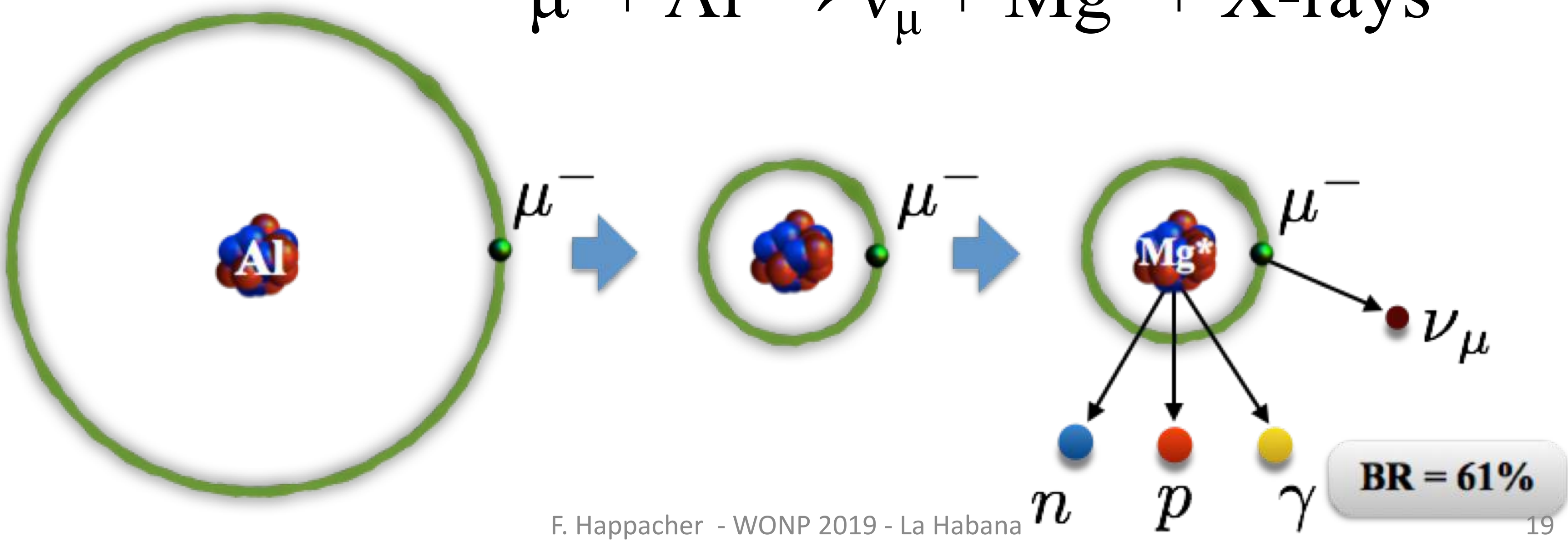


or..

The denominator, i.e. the normalization

…61 % of the time, interacts with the Aluminum nucleus to form Magnesium. We know well the X ray emissions of capture processes and relative rates: we measure their rate and know how many muons have been stopped

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



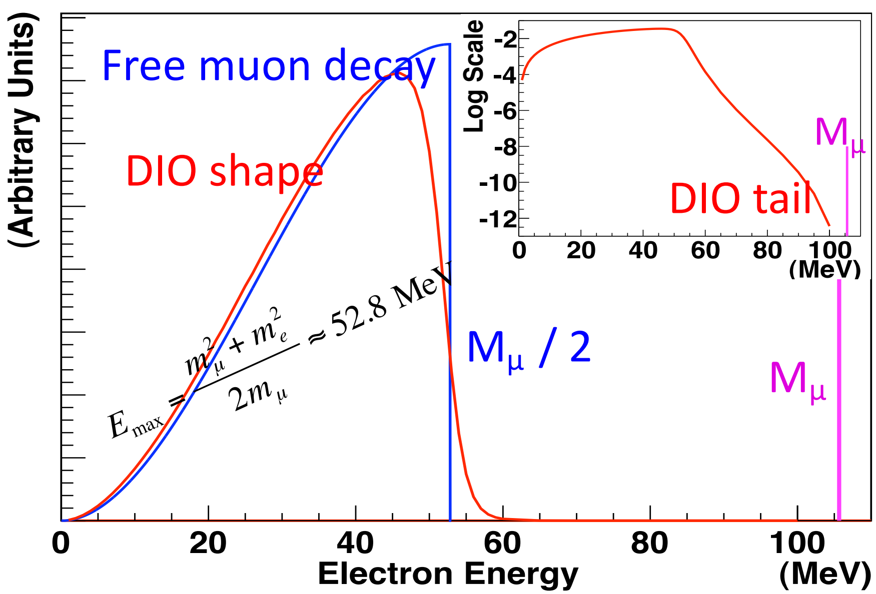
Mu2e intrinsic backgrounds

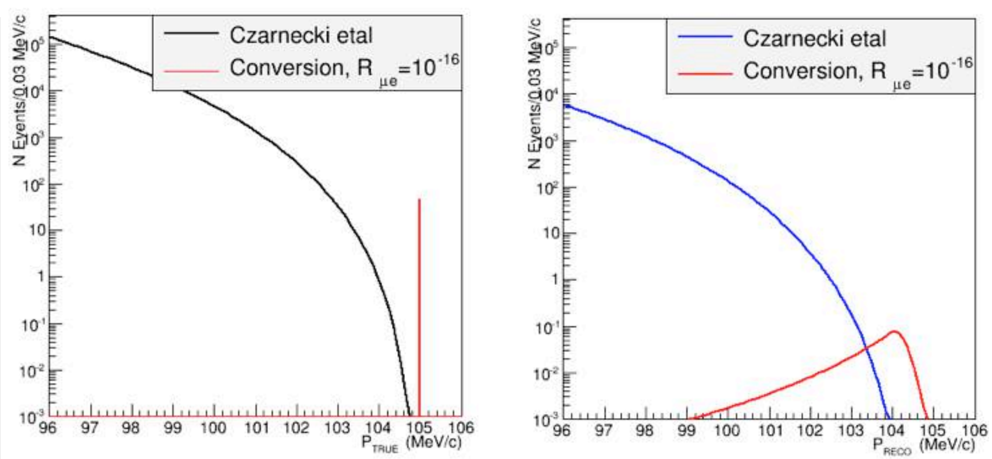
Unfortunately, 39 % of the time, muons can also:

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

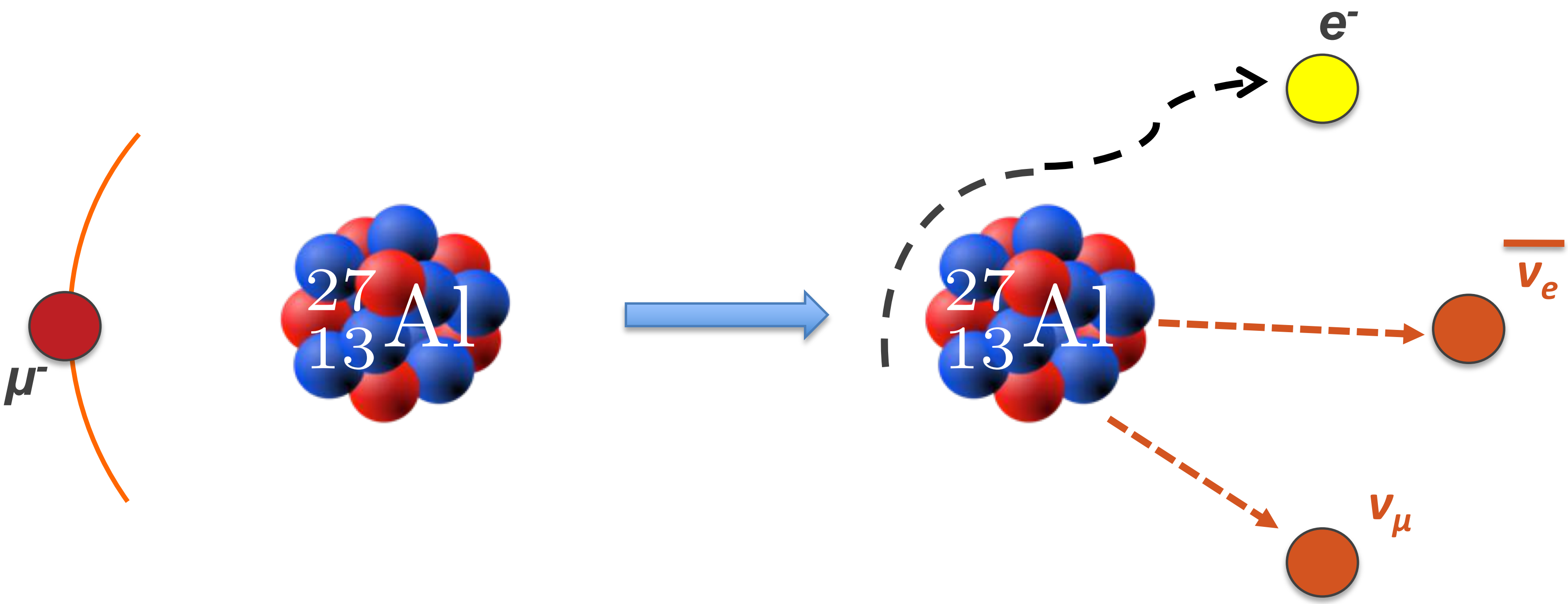




Separation of ~few 100 keV for $R_{\mu e} = 10^{-16}$

Decay in orbit

Decay In Orbit (DIO) ~ 39%



Mu2e Intrinsic Background

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)

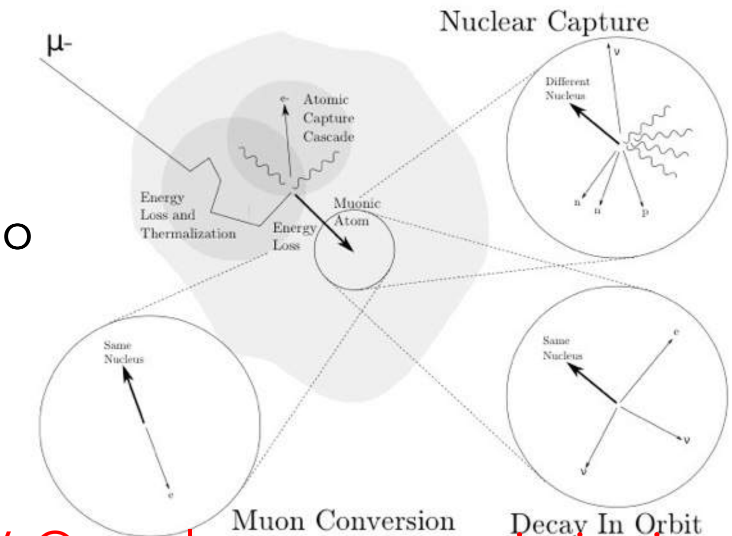
$$\pi^{-} + N \rightarrow \gamma_{e^{+}e^{-}} + N^{'}$$

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 ± 0.028(stat) ± 0.11(syst)
	Muon Capture (RMC)	0
Late Arriving	Pion Capture (RPC)	0.021 ± 0.001(stat) ± 0.002(syst)
	Muon Decay in Flight	< 0.003
	Pion Decay in Flight	0.001 ± <0.001
	Beam Electrons	$(2.1 \pm 1.0) \times 10^{-4}$
Miscellaneous	Cosmic Ray Induced	0.209 ± 0.022(stat) ± 0.055(syst)
	Antiproton Induced	0.040 ± 0.001(stat) ± 0.020(syst)
Total		**0.41 ± 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.

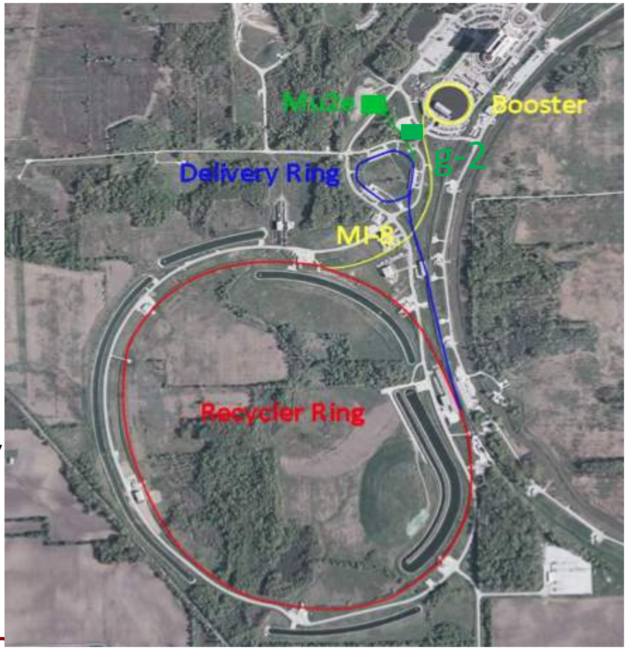
Accelerator & proton extinction

- 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

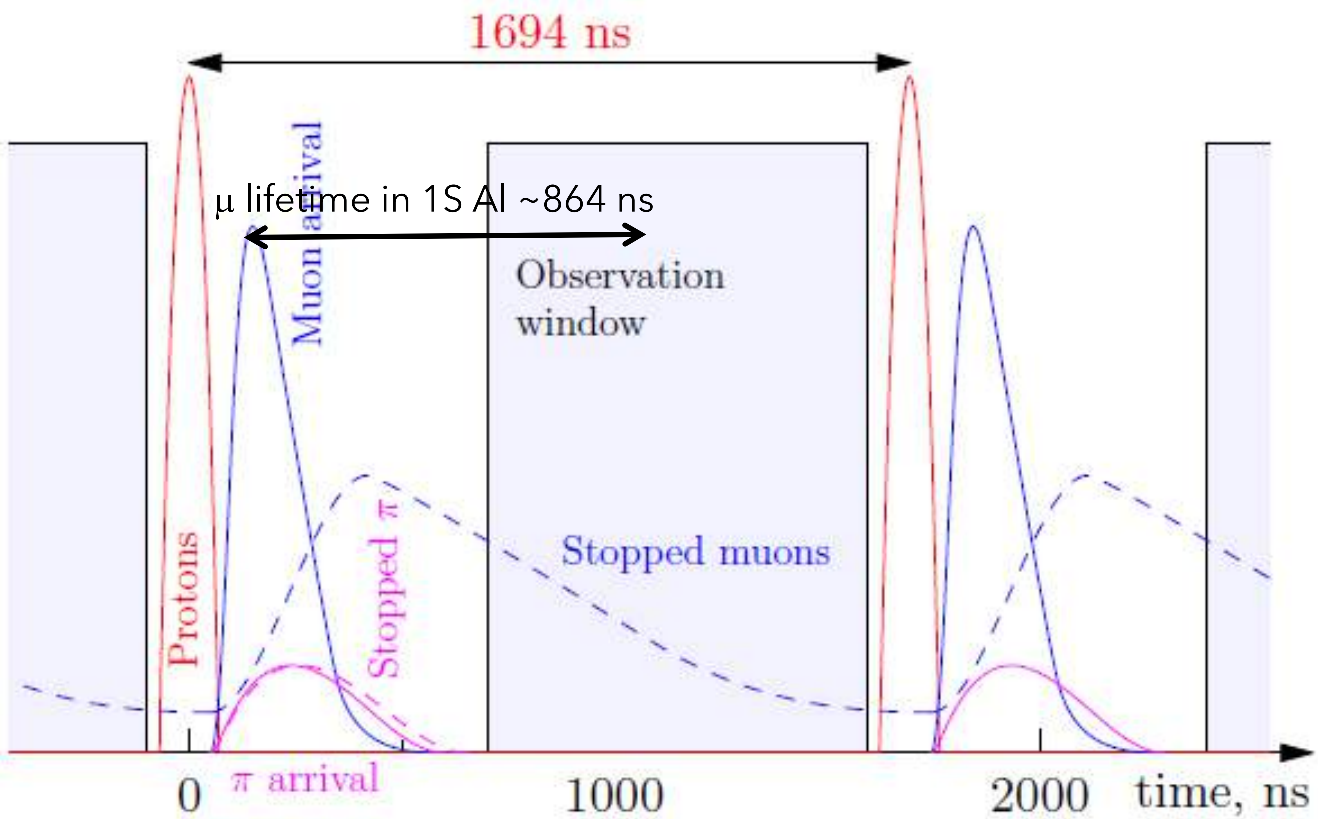
(N$_p$ out of bunch)/(N$_p$ in bunch)

  - Internal: momentum scraping and bunch formation
  - External: oscillating AC dipole

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



Pulsed beam structure

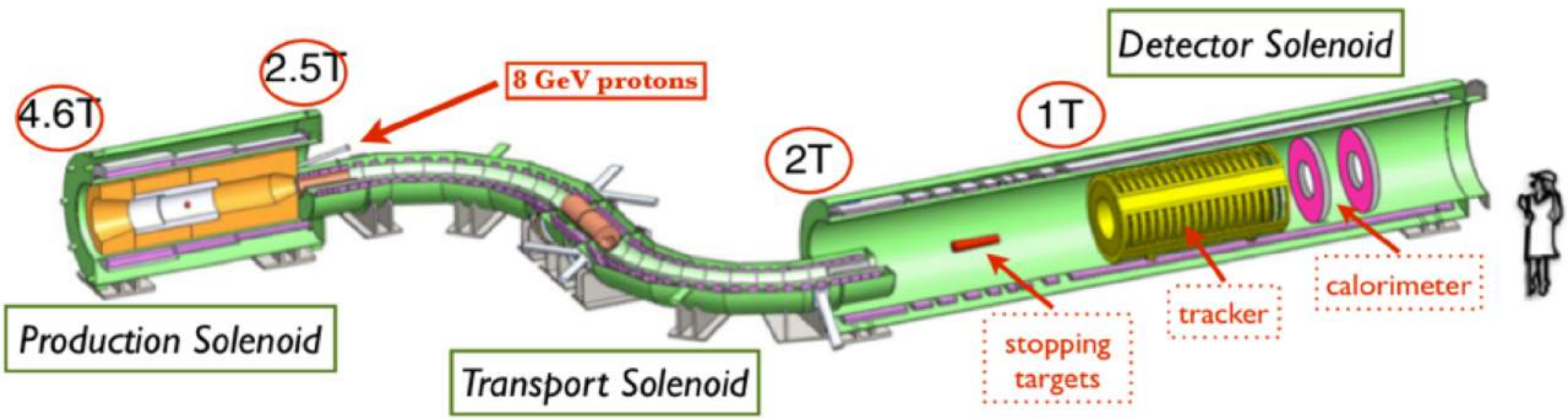


- Use the fact that muonic atomic lifetime >> prompt background
  Need a pulsed beam to wait for prompt background to reach acceptable levels
  → Fermilab accelerator complex provides ideal pulse spacing
  a 700 ns delay reduces pion background by $>10^{-9}$

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

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

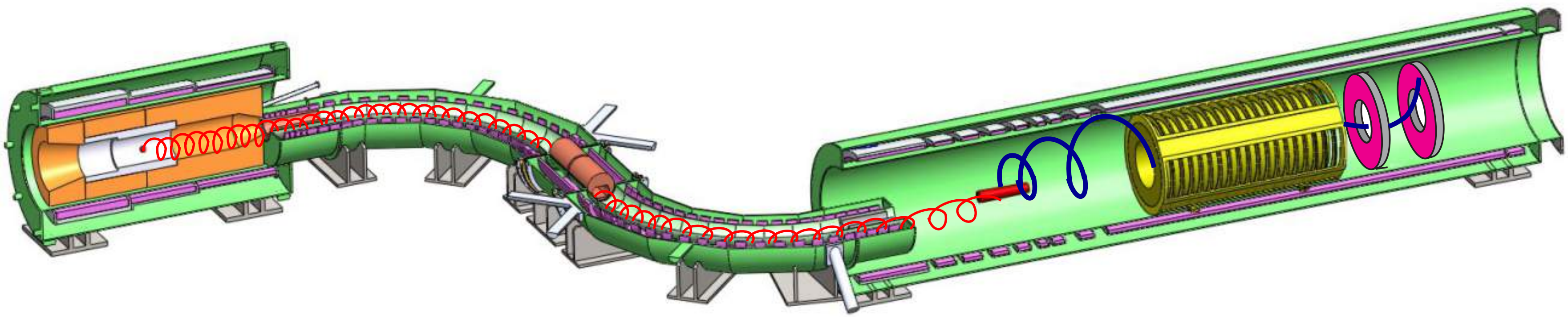


Signal event in the apparatus

Production Solenoid

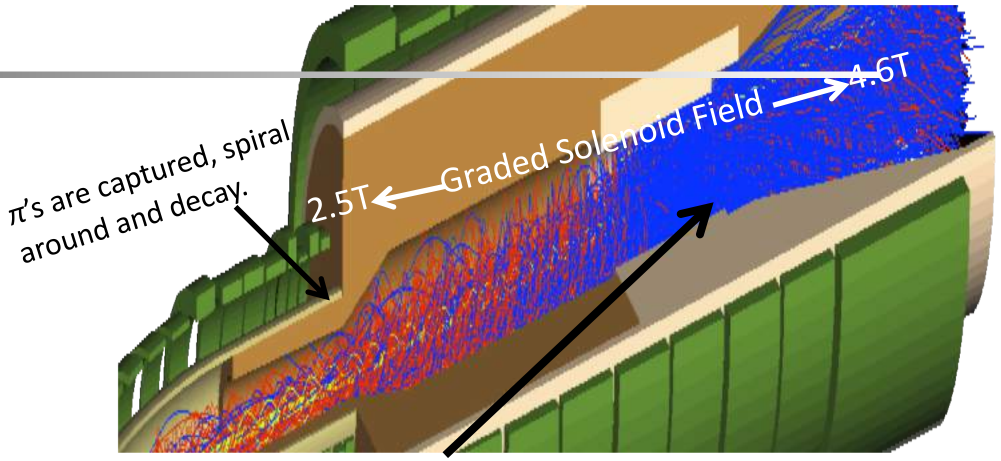
Transport Solenoid

Detector Solenoid



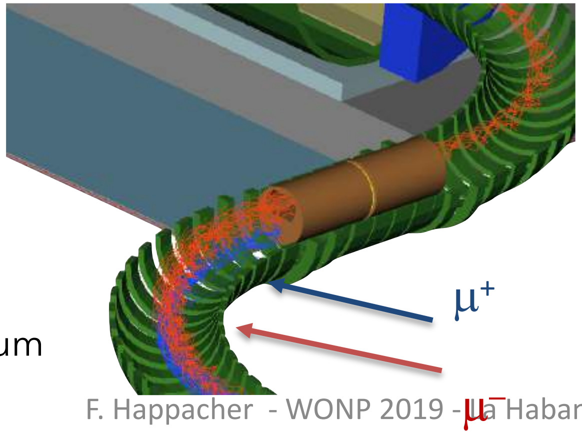
The Mu2e beamline

- 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



Pulsed beam of incident protons

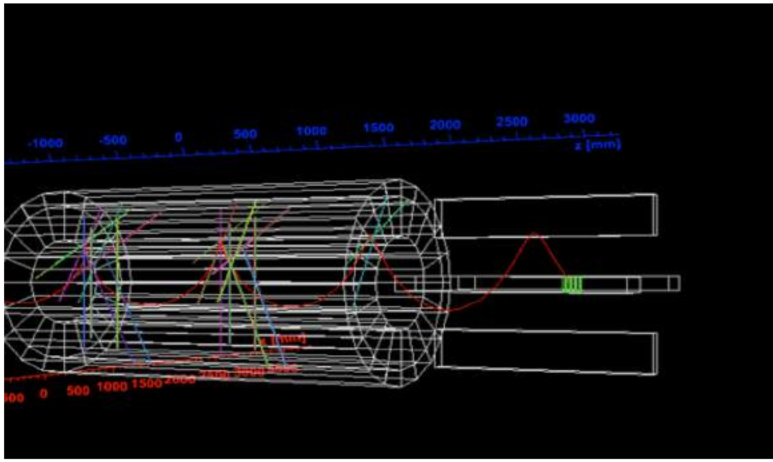
- Transport Solenoid
  - Graded magnetic from 2.5 T (at the entrance) to 2.0 T (at the exit)
    - Allows muons to travel on a helical path from the production solenoid to the detector solenoid
  - S-shaped to remove the detector solenoid out of the line of sight from the production solenoid
    - No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



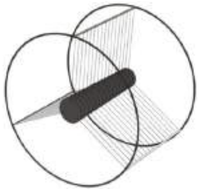
off-center central TS collimator and 90° bends passes low momentum negative muons and suppresses positive particle and high momentum negative particles.

The Mu2e Beamline

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

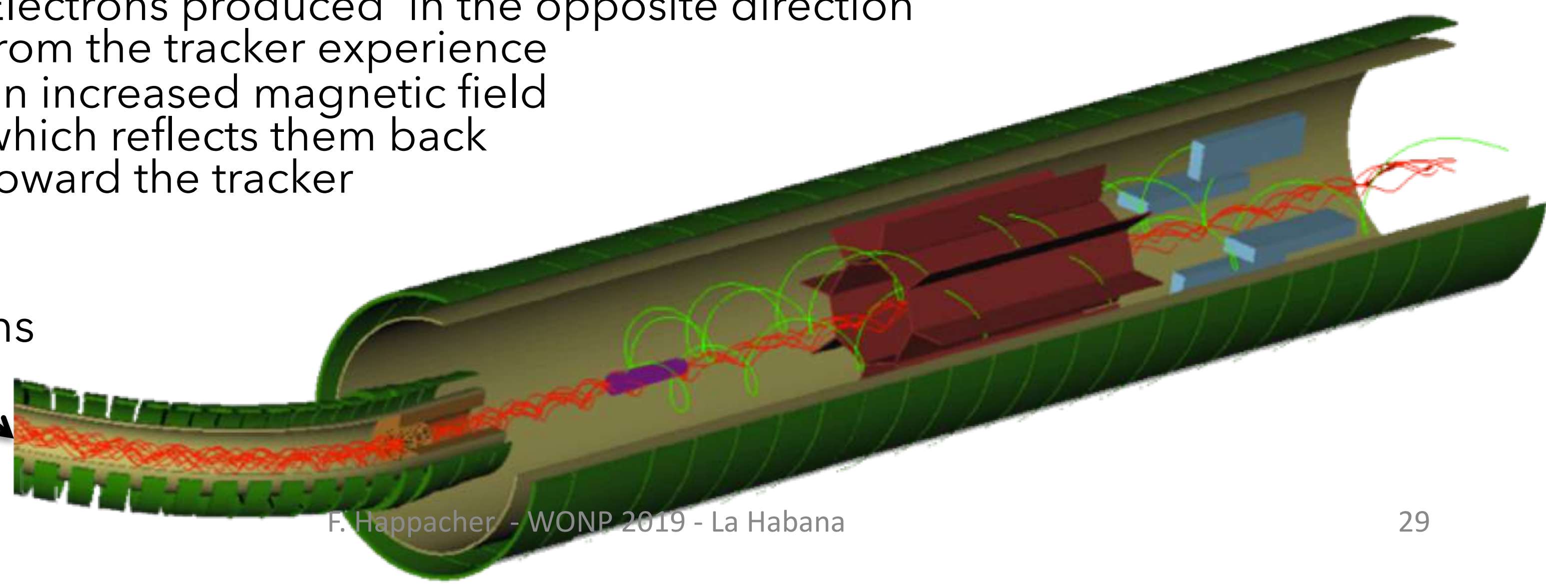


  – 17 Aluminum disks, 0.2 mm thick, radius between 83 mm (upstream) and 63 mm (downstream)



  – 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



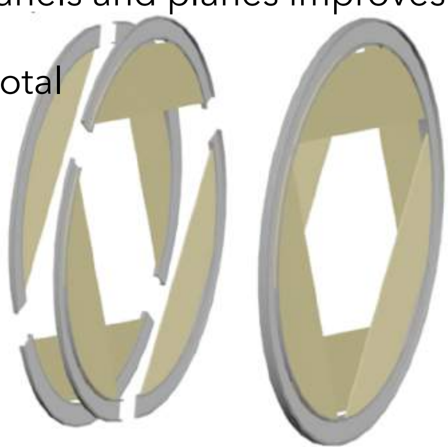
The Mu2e Tracker

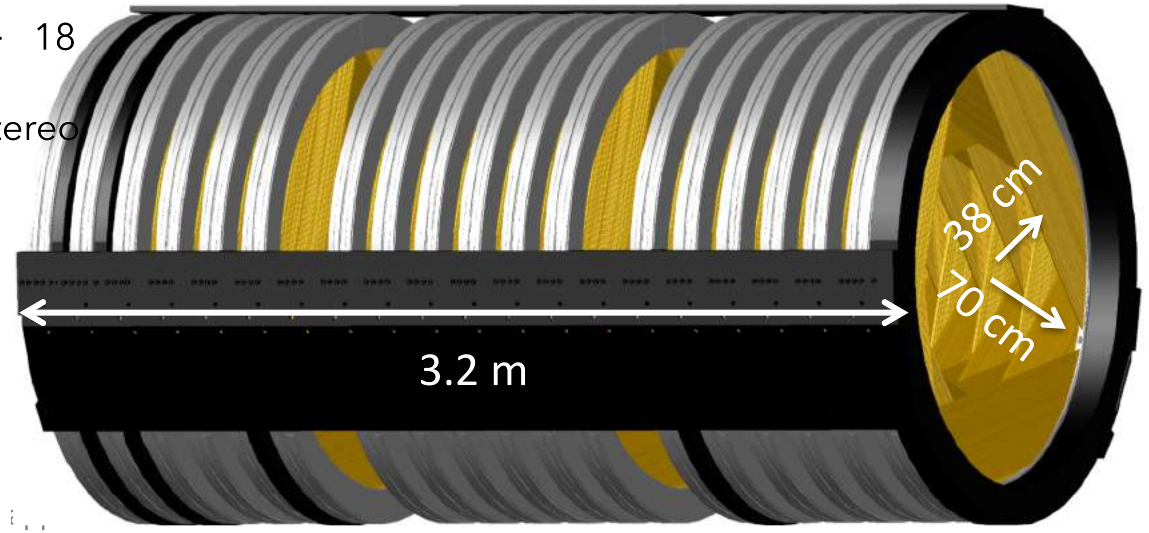
Detector requirements:

1. Small amount of budget material, maximizing X_0
2. σ_p < 115 keV @ 105 MeV
3. Good rate capability:
   - 20 kHz/cm² in live window
   - Beam flash of 3 MHz/cm²
4. dE/dx capability to distinguish e^-/p
5. Operate in B = 1 T, 10^{-4} Torr vacuum
6. Maximize/minimize acceptance for CE/DIO

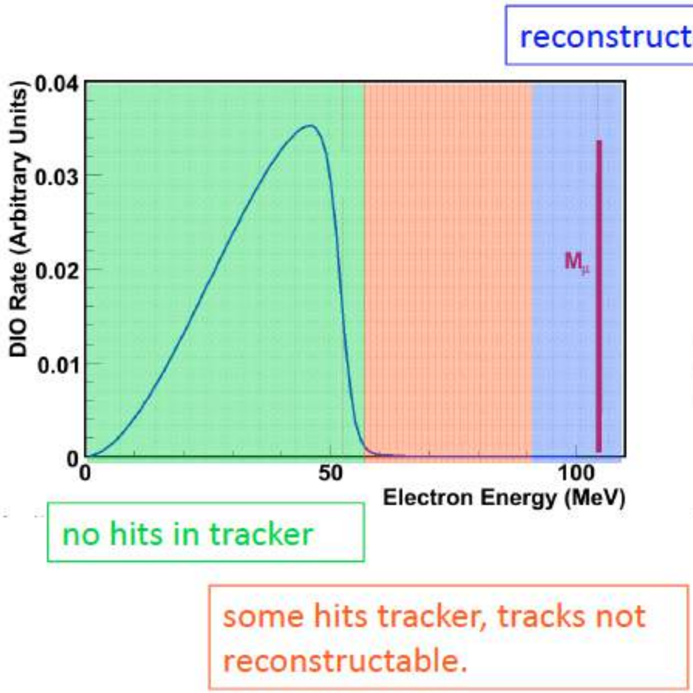
- dual ended TDC/ADC readout large Radii
- 5 mm diameter straw
- Spiral wound
- Walls: 12 µm Mylar + 3 µm epoxy + 200 Å Au + 500 Å Al
- 25 µm Au-plated W sense wire
- 33 – 117 cm in length

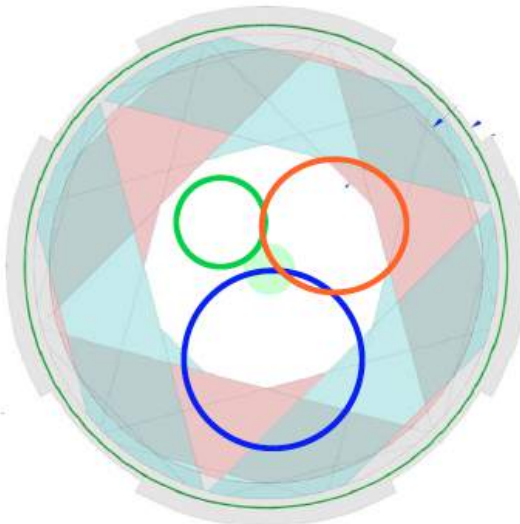
- Self-supporting "panel" consists of 100 straws
- 6 panels assembled to make a "plane"
- 2 planes assembled to make a "station" -> 18 stations
- Rotation of panels and planes improves stereo information
- >20k straws total



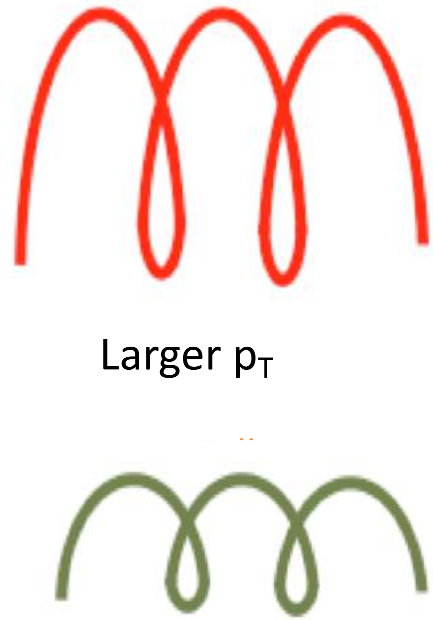


The Mu2e Tracker





beam's-eye view of the tracker



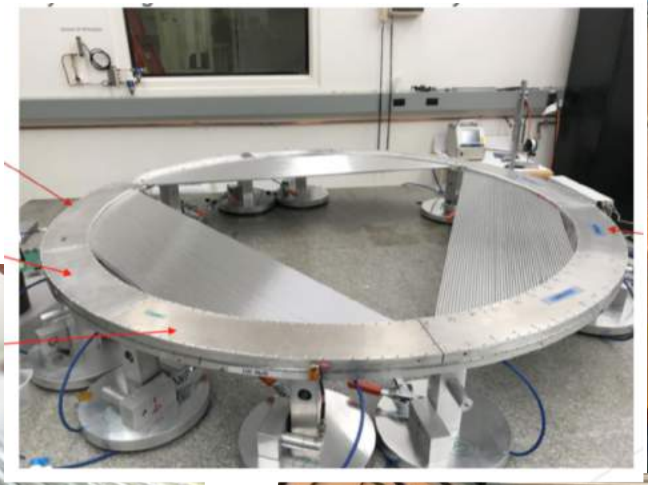
Larger p_T

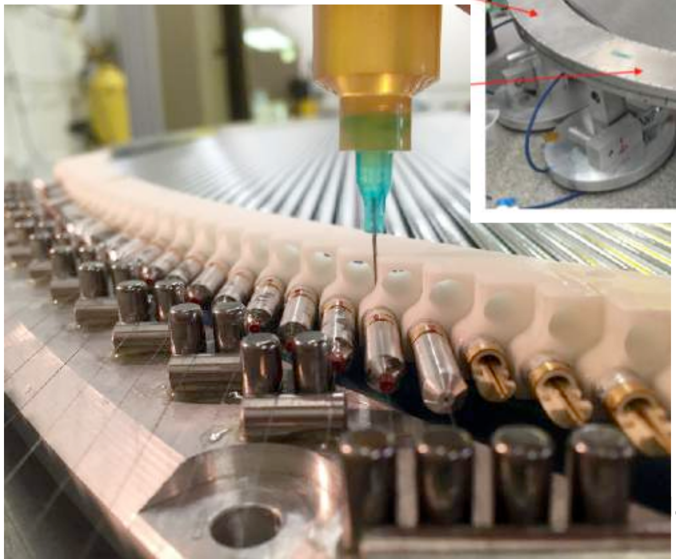
Lower p_T

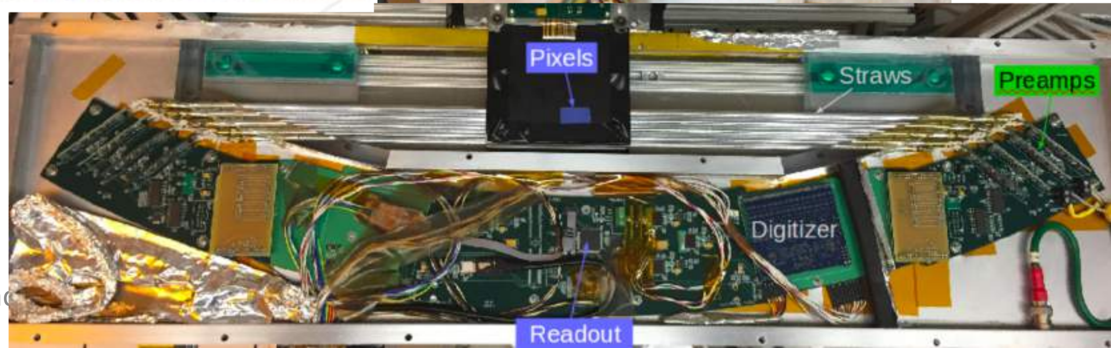
- Inner 38 cm is purposefully un-instrumented
  - Blind to beam flash
  - Blind to >99% of DIO spectrum

The Mu2e tracker

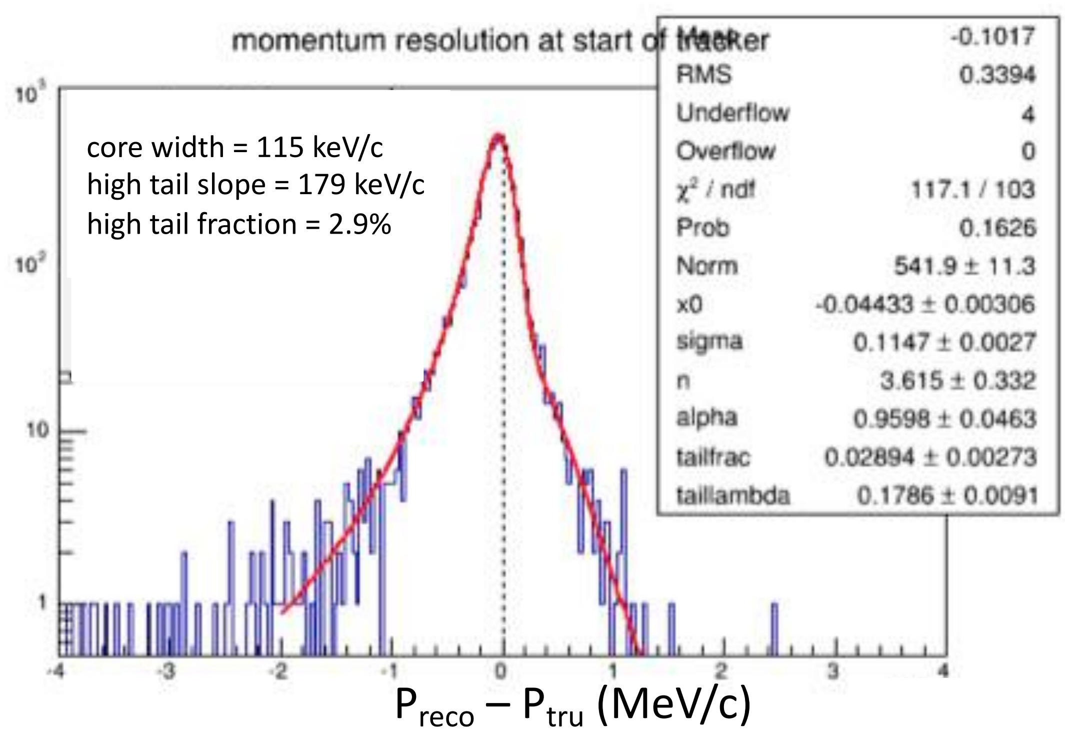
- Prototype panels complete, ramping-up production line
- Preparing to assemble planes
- Orders placed for final production
- FEE prototypes tested successfully







Mu2e Tracker Performance



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

The Mu2e calorimeter

The calorimeter has to:

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

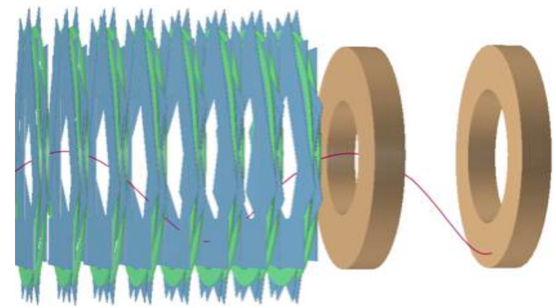
the calorimeter needs to fulfill the following

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



- 2 Disks (Annuli) geometry to optimize acceptance for spiraling electrons
- Crystals with high Light Yield for timing/energy resolution → **LY(photosensors) > 30 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:

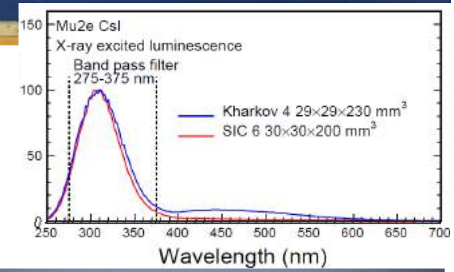
→ **Crystals survive TID of 90 krad and a neutron fluency of 3×10^{12} n/cm^2**

→ **Photo-sensors survive 45 krad and a neutron fluency of 1.2×10^{12} n/cm^2**

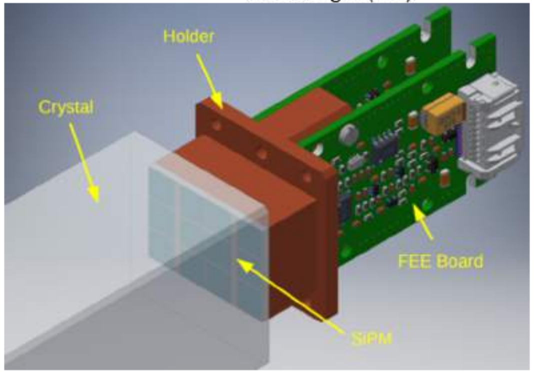
The Mu2e Calorimeter

The Calorimeter consists of two disks containing 674 34x34x200 mm^3 un-doped 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



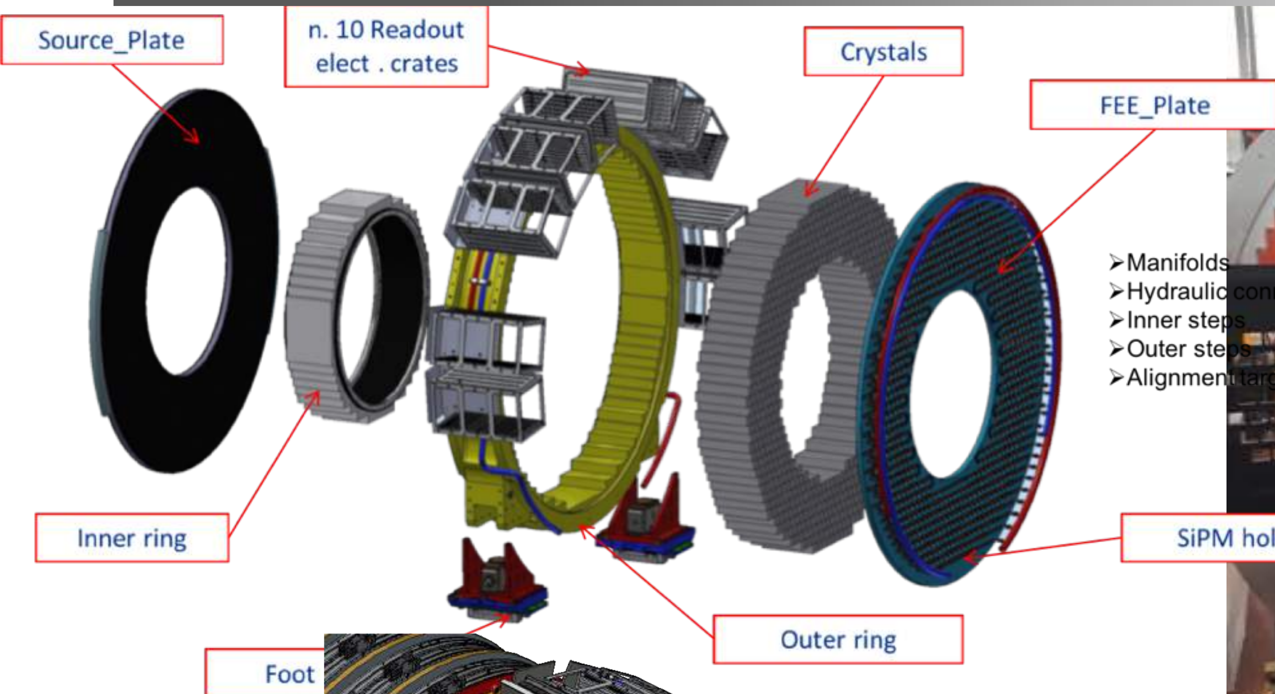
- → Each crystal is readout by two array UV extended SIPM's (14x20 mm^2) maximizing light collection.
  PDE=30% @ CsI emission peak =315 nm.
  GAIN ~10^6

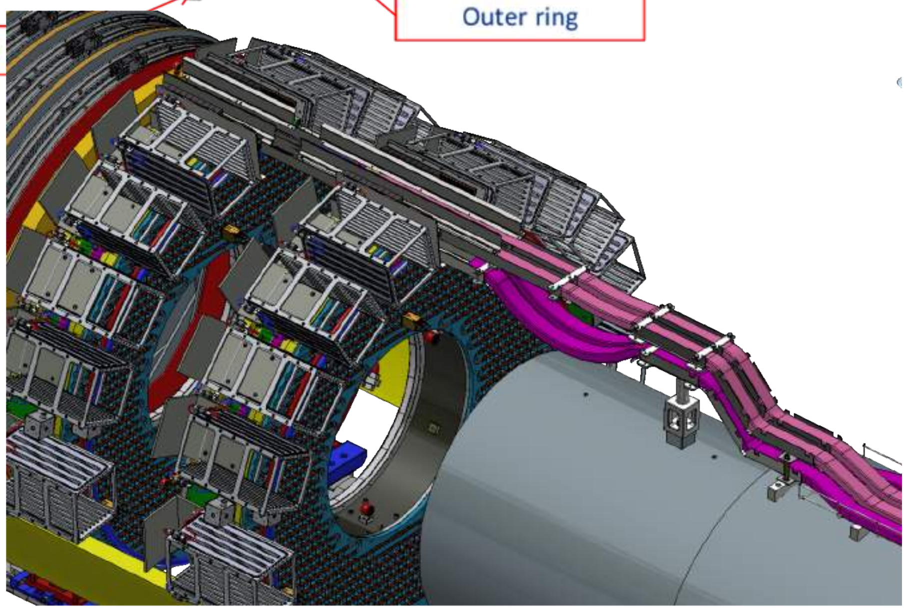


- → TYVEK wrapping
- → Analog FEE is onboard to the SiPM (amplification and shaping) and digital electronics located in electronics crates (200 MhZ sampling)
- → Cooling system – SiPM cooling, Electronic dissipation

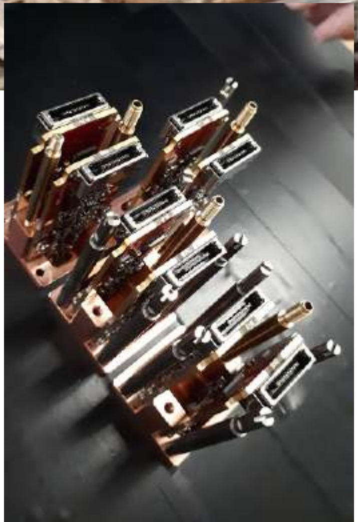
- → Radioactive source and laser system provide absolute calibration and monitoring capability

The Mu2e Calorimeter

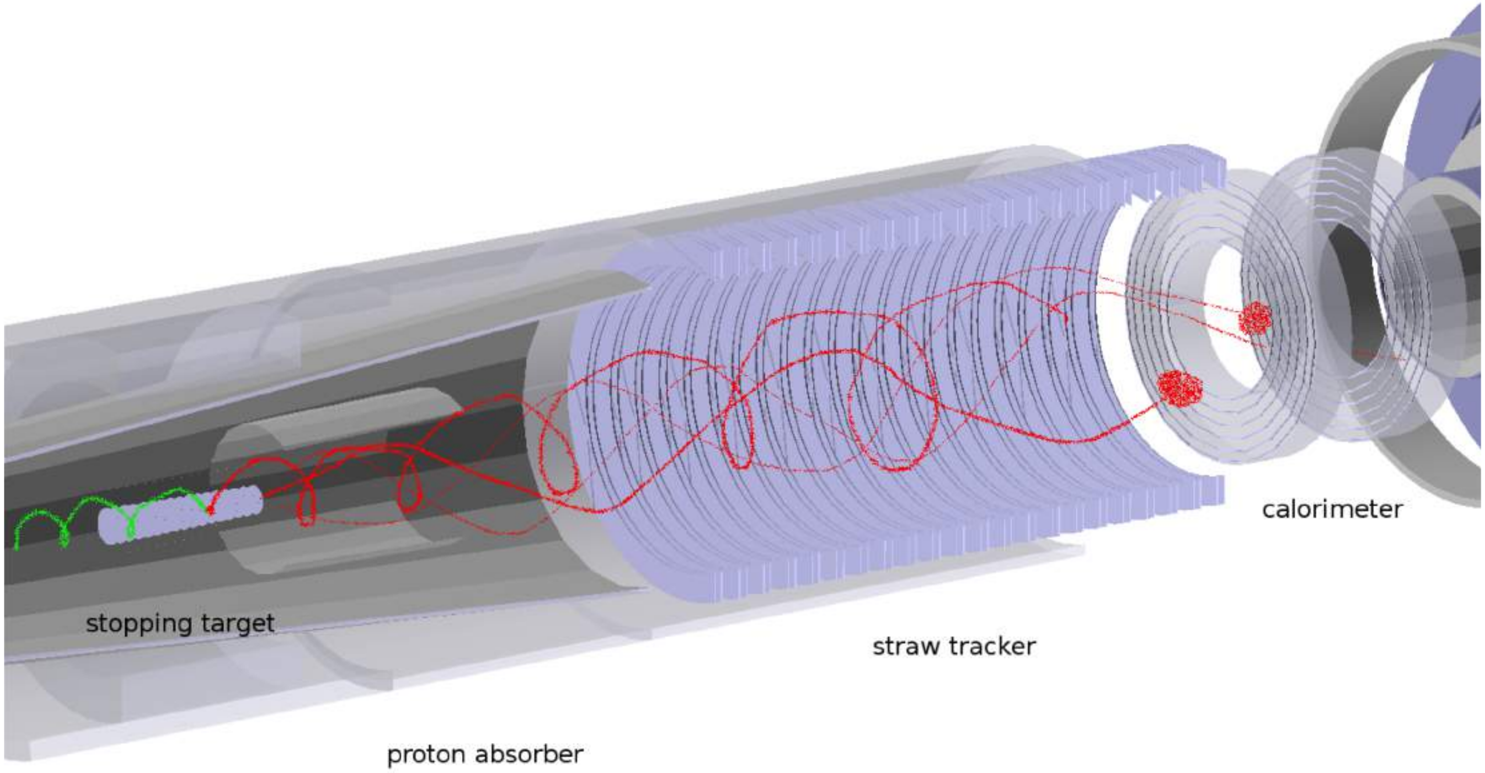




- Manifolds
- Hydraulic connections
- Inner steps
- Outer steps
- Alignment targets



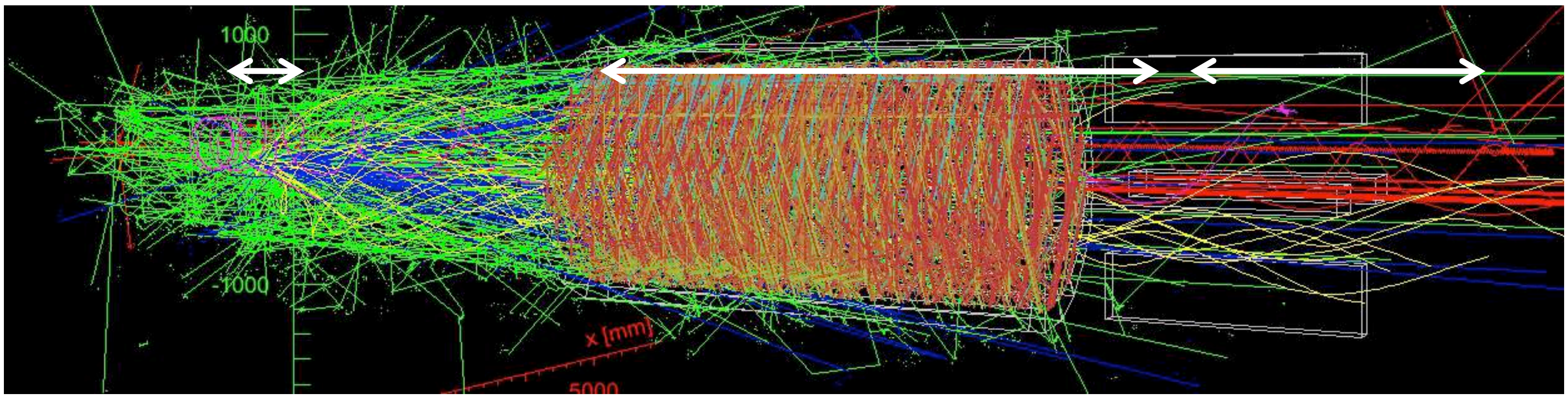
Mu2e Pattern Recognition



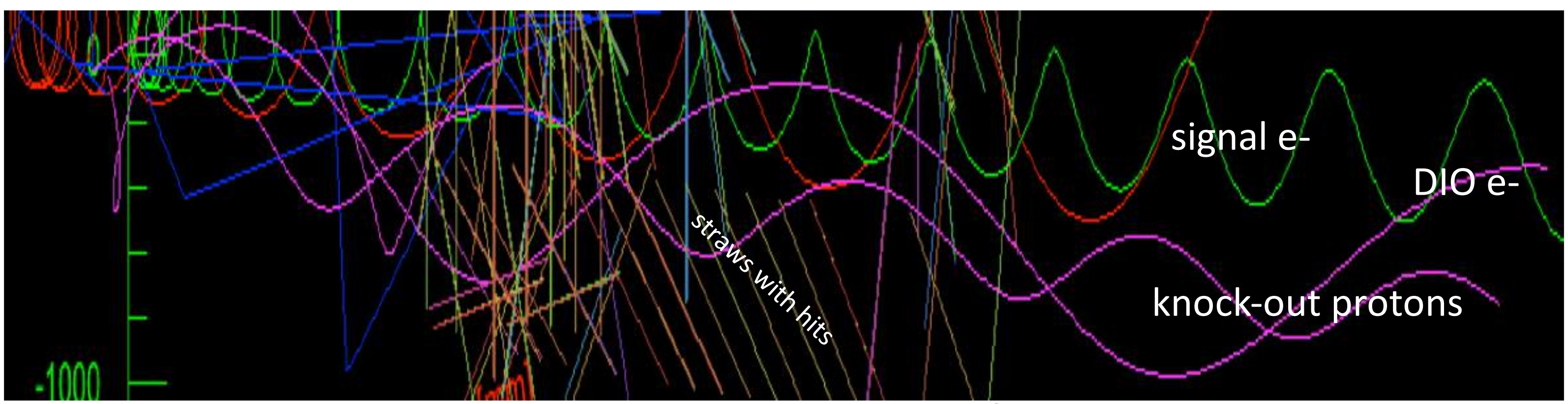
- Search for tracking hits with time and azimuthal angle compatible with the calorimeter clusters ($|\Delta T| < 50$ ns) → simplification of pattern recognition
- Add search of an Helix passing through cluster and selected hits + use calorimeter time to calculate tracking Hit drift times

Mu2e Pattern Recognition

Stopping Target Straw Tracker Crystal Calorimeter



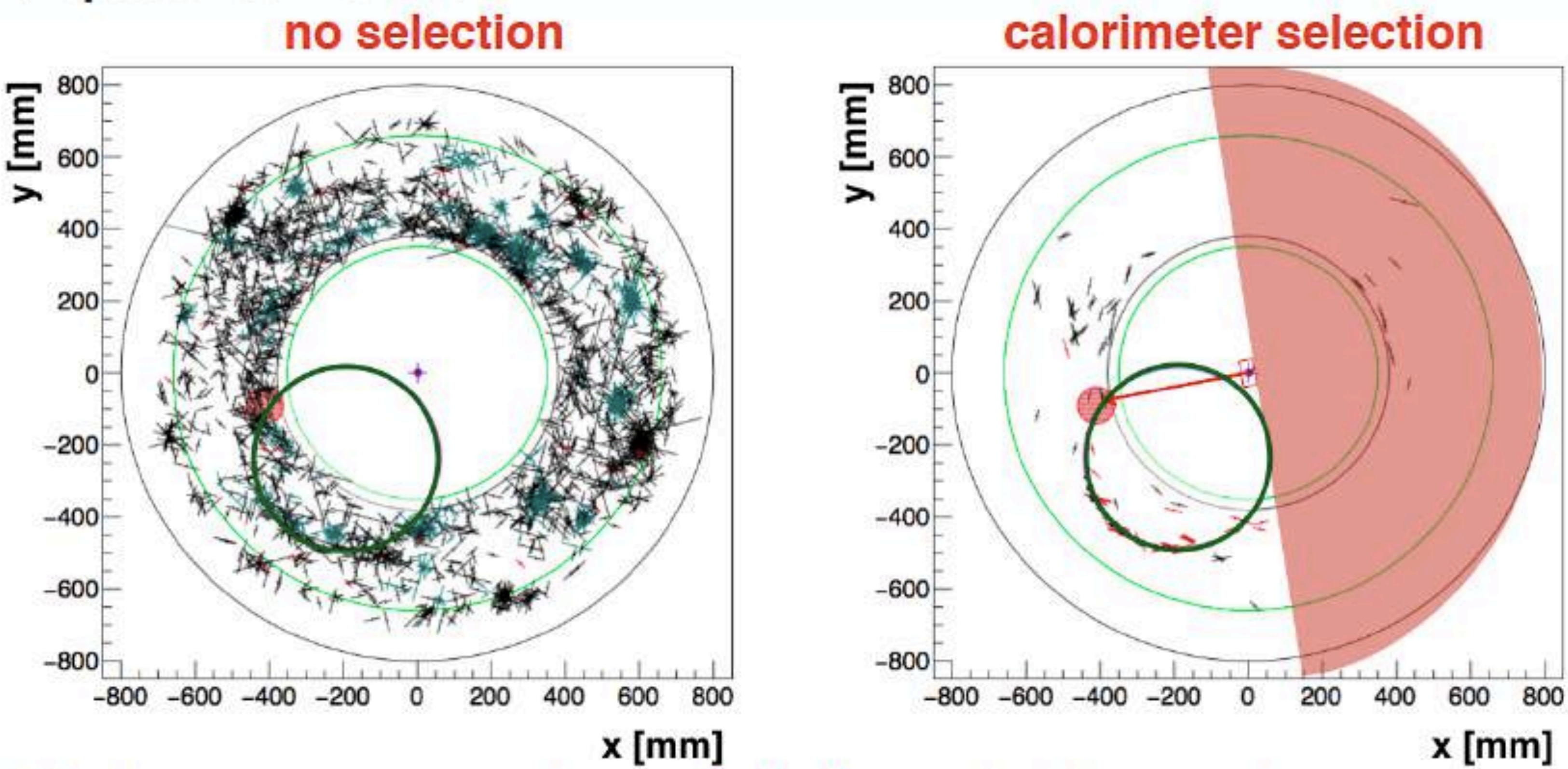
A signal electron, together with all the other interactions



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

Mu2e Pattern Recognition

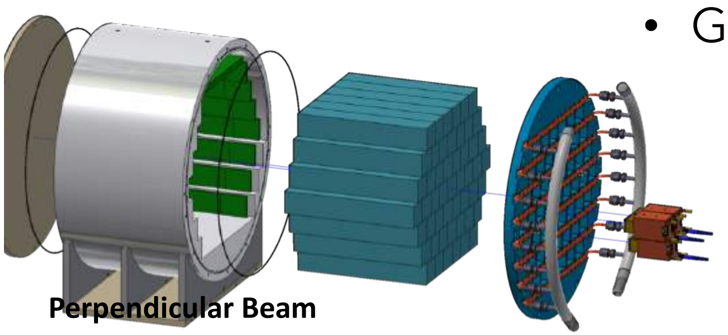
- Cluster time and position are used for filtering the straw hits:
  - ✓ **time window of ~ 80 ns**
  - ✓ **spatial correlation**



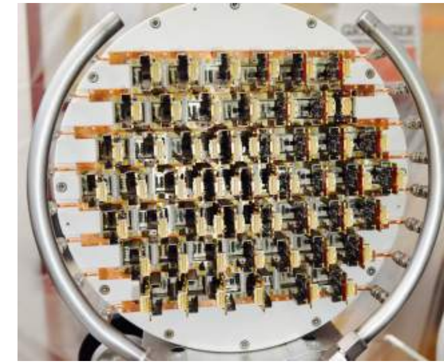
- **black crosses** = straw hits, **red circle** = calorimeter cluster, **green line** = CE track

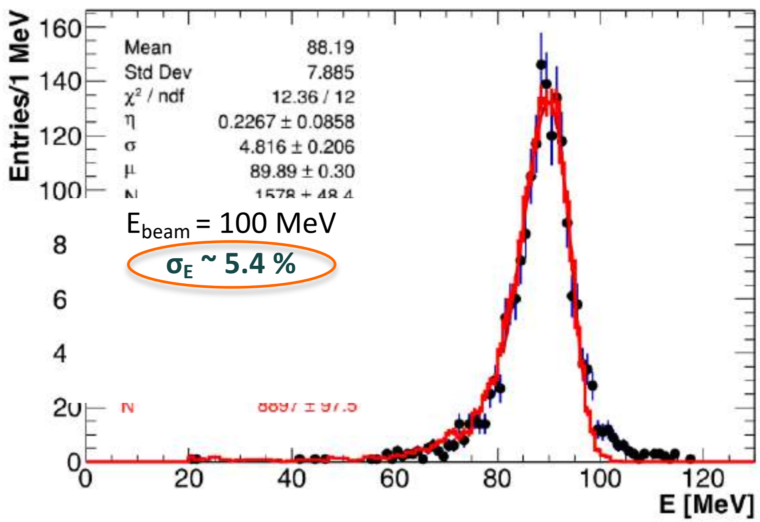
Module 0 and test beam - 2017

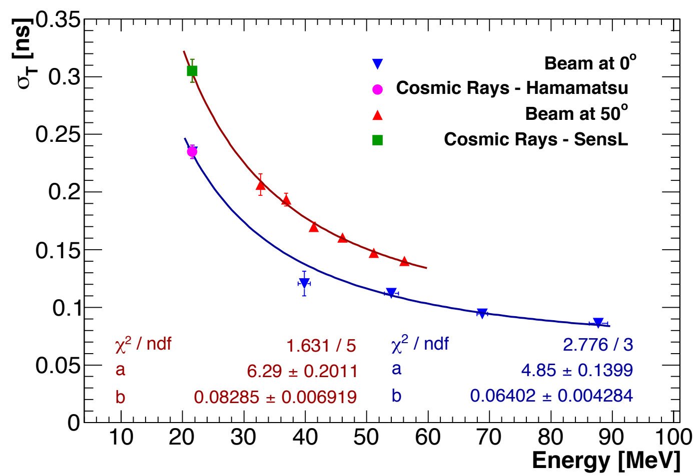
Large EMC prototype: 51 crystals, 102 SiPMs, 102 FEE boards



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

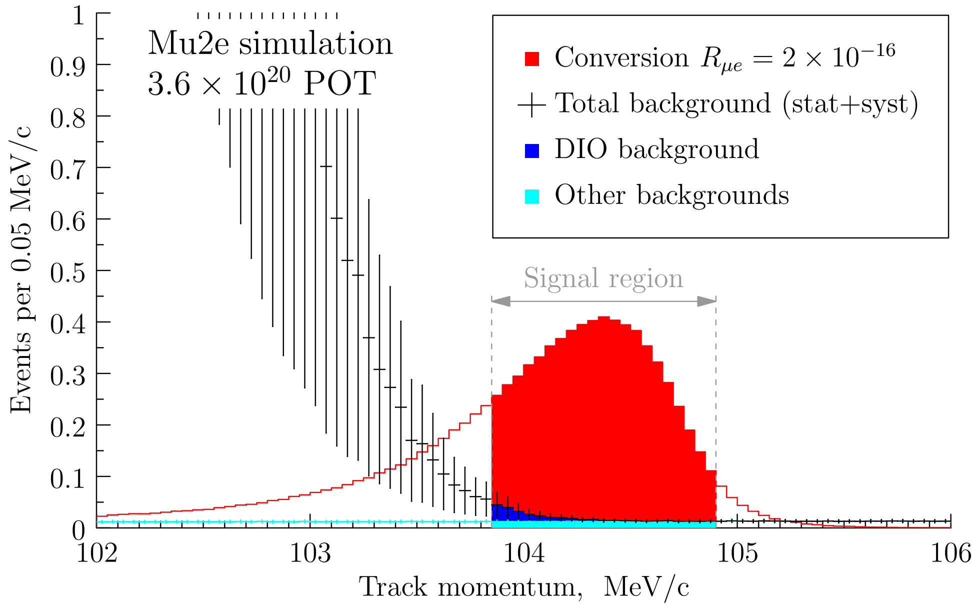






- Cosmic equalization provide **energy res at the level of 5 %**
- $\Delta T = t_{SiPM1} - t_{SiPM2}$ $\sigma_T \sim 130$ ps @$E_{beam} = 100$ MeV

Signal extraction and sensitivity



Expected background contributions and possible conversion signal in Mu2e

$N_{\mu e}$ = 7.9

N_{DIO} = 0.14

N_{Other} = 0.27

- ✗ 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: $R_{\mu e} < 2.5\times10^{-17}$ @ 90% CL
  - ➢ Factor 10^4 improvement

- ✗ Discovery reach (5s): $R_{\mu e} > 1.9 \times10^{-16}$
  - ➢ Covers broad range of new physics theories

Summary

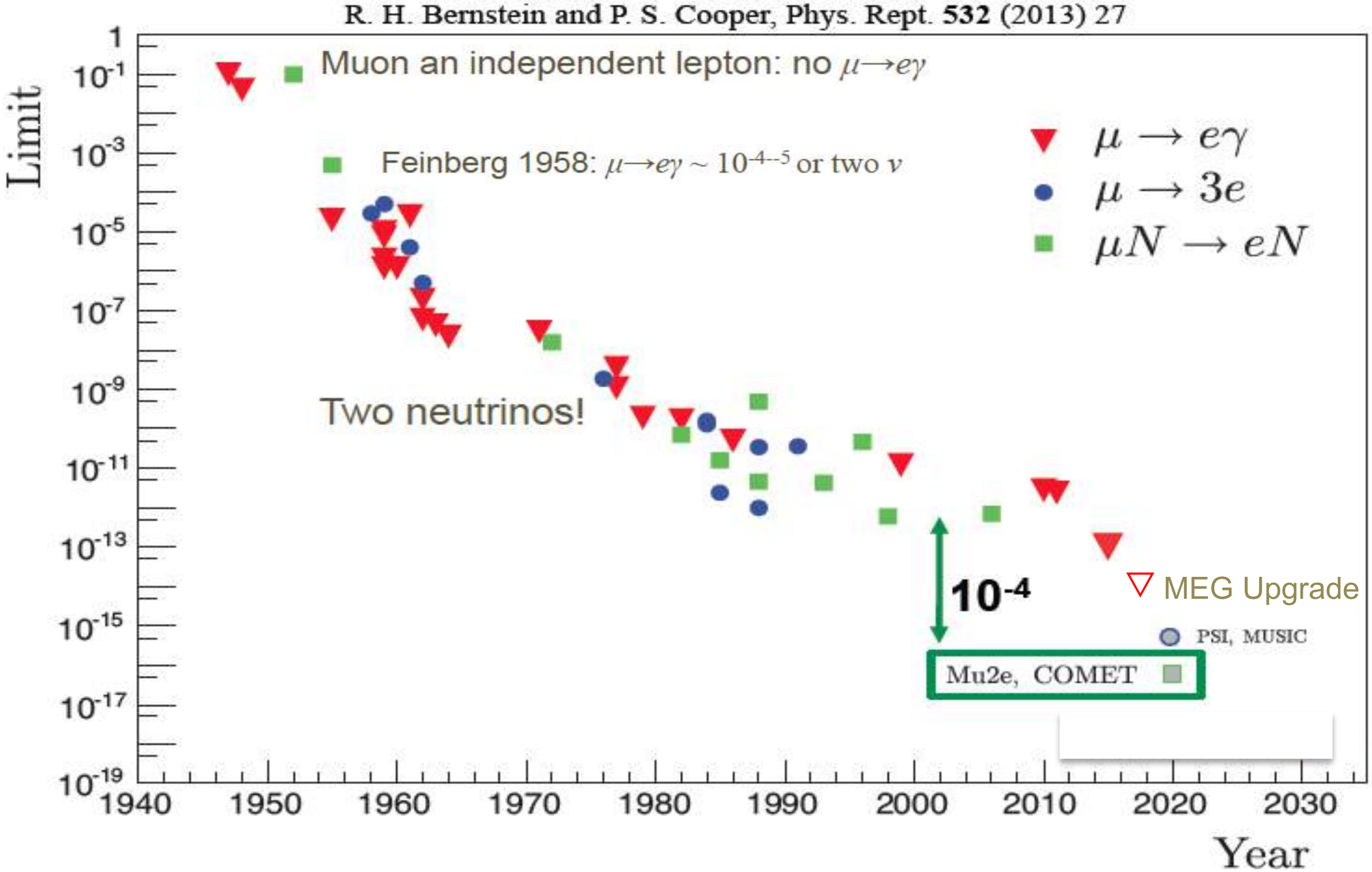
- Improves sensitivity by a factor of 10^4 SINDRUM II limit
  - Reach Sindrum-II sensitivity in 100 min
  - x10 in 17 hours running
  - x100 in 7 days running
  - x10000 in 700 days running
- Provides discovery capability over a wide range of NP
- is complementary to LHC, heavy-flavor, and neutrino experiments

Schedule:

- Full scale solenoid construction started in 2017
- Full scale detector construction started in 2018
- Solenoid and detector installation in 2020-2021
- Initial commissioning in 2022
- First physics running in 2023

- spares

CLFV searches history



Current best limits:

MEG-2016
BR($\mu \to e\gamma$) < 4.2 x 10^{-13}

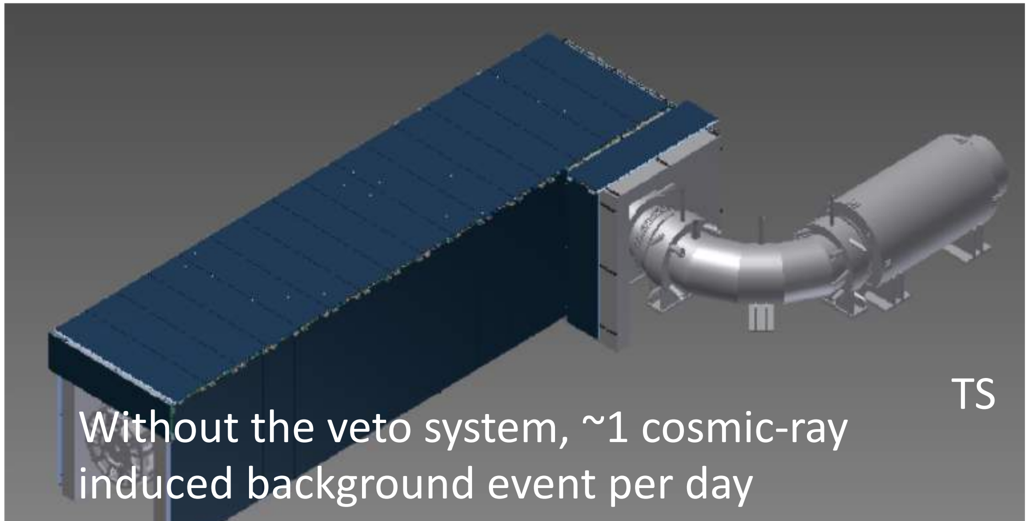
SINDRUM-1988
BR($\mu \to 3e$) < 1 x 10^{-12}

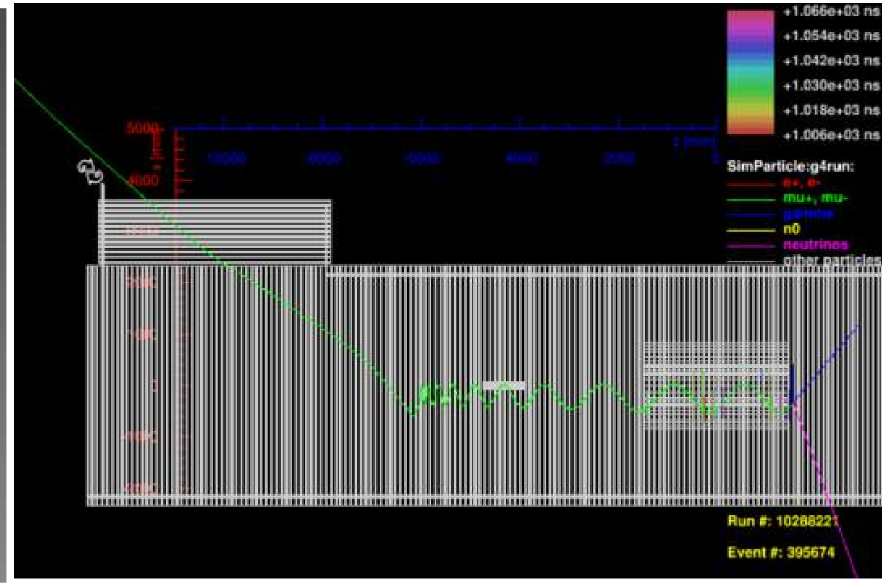
SINDRUM-II 2006
$R_{\mu e}$ < 6.1 x 10^{-13}

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

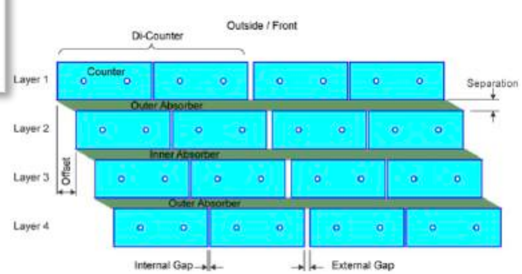
The Cosmic ray Veto

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



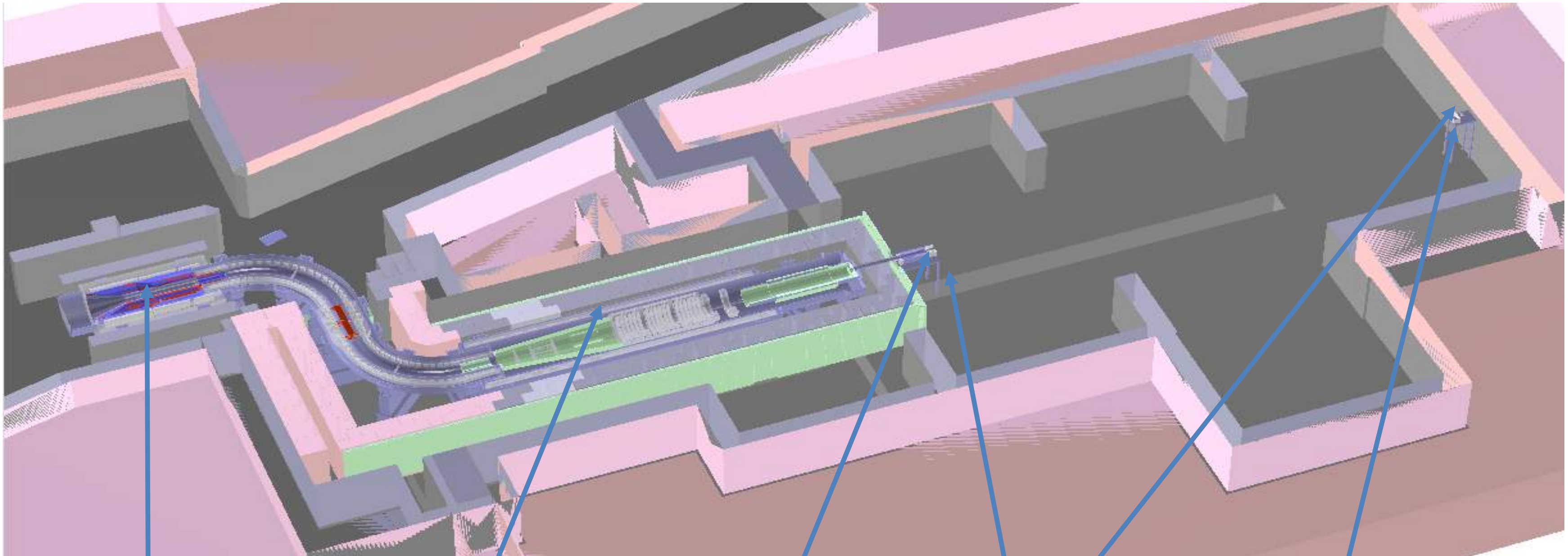


- Area: 327 m^2
- 86 modules of 6 lengths
- 5,504 counters
- 11,008 fibers
- 19,840 SiPMs
- 310 Front-end Boards



- 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