Searching for Muon to electron conversion: The design of the Mu2e experiment

Richie Bonventre

Physics 290e

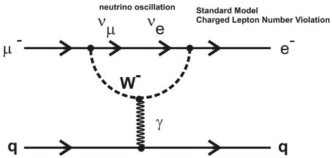
Lawrence Berkeley National Lab

The physics of Mu2e

- Mu2e will search for neutrinoless conversion of a muon to an electron in a nuclear environment:

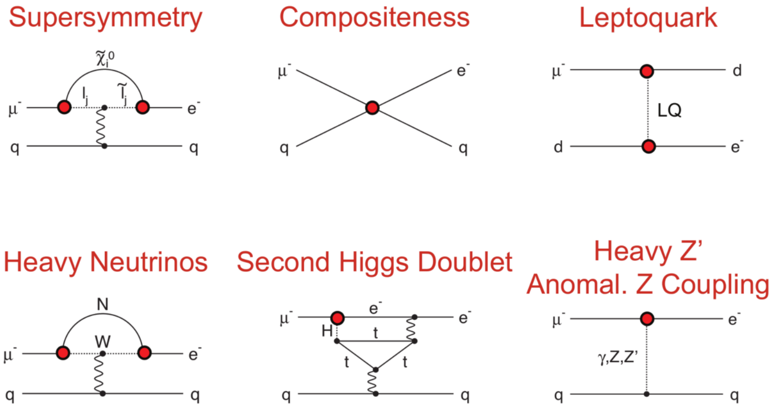
$$\mu^- N \to e^- N$$

- This would violate **charged lepton flavor**, something that has never been seen before
- Any detection of charged lepton flavor violation would be an unambiguous sign of new physics! (SM contribution is $< 10^{-50}$)

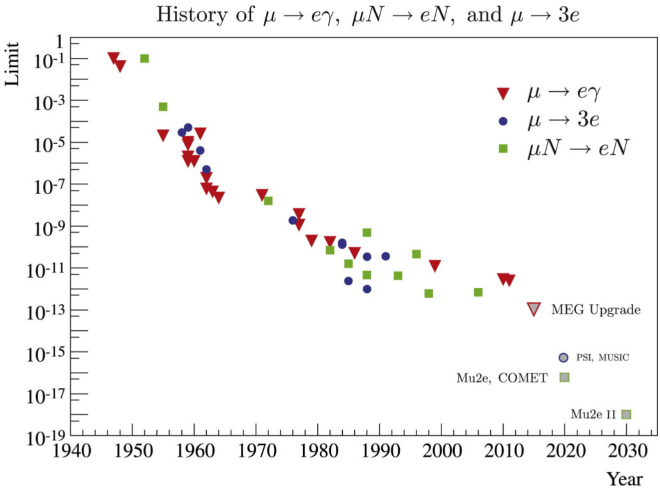


Charged Lepton Flavor Violation

- Neutrino oscillation shows that Lepton Flavor is NOT a fundamental symmetry. No reason new physics should conserve it
- Many models of new physics predict contributions to CLFV:



History



Mu2e goal is a 10^4 improvement!

Types of CLFV measurements

Process	Current Limit	Next Generation exp.
$\tau \to \mu\eta$	BR < 6.5 E-8	10^{-9} - 10^{-10} (Belle II, LHCb)
$\tau \to \mu\gamma$	BR < 6.8 E-8	
$\tau \to \mu\mu\mu$	BR < 3.2 E-8	
$\tau \to$ eee	BR < 3.6 E-8	
$K_L \to e\mu$	BR < 4.7 E-12	
$K^+ \to \pi^+ e^- \mu^+$	BR < 1.3 E-11	
$B^0 \to e\mu$	BR < 7.8 E-8	
$B^+ \to K^+ e\mu$	BR < 9.1 E-8	
$\mu^+ \to e^+\gamma$	BR < 4.2 E-13	10^{-14} (MEG)
$\mu^+ \to e^+e^+e^-$	BR < 1.0 E-12	10^{-16} (PSI)
$\mu^- N \to e^- N$	$R_{\mu e}$ < 7.0 E-13	10^{-17} (Mu2e, COMET)

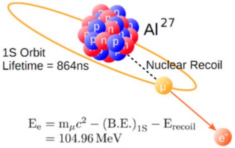
How to search for CLFV

- τ seems easiest at first
  - Larger mass reduces GIM suppression, most models predict larger BF
  - Larger mass means more possible decay modes
- But lifetime is very short
- Much easier to produce a lot of muons (which is good because we need 10^{18}!)

$$
\begin{aligned}
p + p/n &\rightarrow n + p/n + \pi \\
\pi &\rightarrow \mu + \nu
\end{aligned}
$$

Muon CLFV processes: $\mu \to e\gamma$, $\mu \to eee$, μN$\to e$N

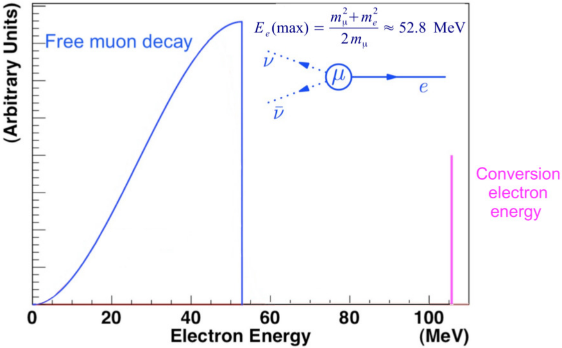
- $\mu \to e\gamma$
  - Signal is back-to-back monoenergetic electron, gamma at 52.8 MeV ($M_\mu/2$)
  - Energy, time, angular coincidence
- $\mu \to eee$
  - Signal is three electrons with total energy of 105 MeV (M_μ)
- μN$\to e$N
  - Signal is single monoenergetic electron at 105 MeV



Backgrounds

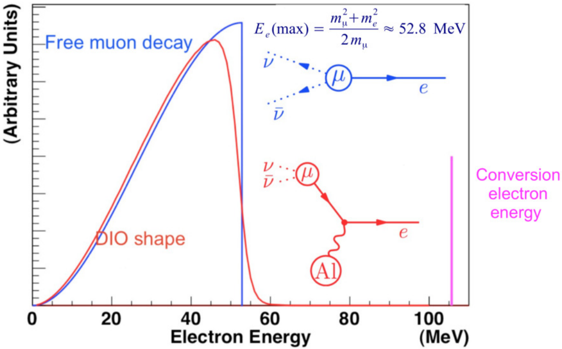
- $\mu \to e\gamma$, $\mu \to eee$
    - Michel decay
    - Radiative muon decay
    - Accidental coincidence
- μN$\to$ eN
    - Decay in orbit
    - Cosmic ray induced delta rays
    - Backgrounds from muon production

Michel decay, radiative muon decay, accidental coincidence



- Michel decay: $\mu^+ \to e^+ \overline{\nu_\mu} \nu_e$
- Radiative muon decay: $\mu^+ \to e^+ \gamma \overline{\nu_\mu} \nu_e$
- Maximum energy 52.8 MeV, need coincidence to reject
- Accidental coincident gammas from annihilation, electron scattering

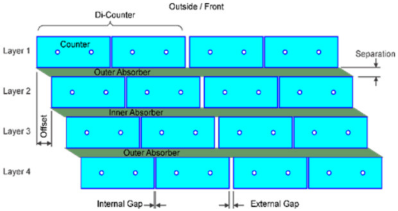
Decay in Orbit (DIO)



- Muon conversion energy well above Michel endpoint, but when in orbit nuclear recoil creates tail up to endpoint
- Falling as $(E_{\text{conv}} - E)^5$, energy resolution is key

Backgrounds from Cosmic rays

- Cosmic rays can create delta rays at energies >= 105 MeV that look identical to signal
- No coincidence for this measurement to allow us to reject it
- Active cosmic veto required!



- Mu2e veto: 4 layers, requires 3 out of 4 coincidence

Backgrounds from muon production

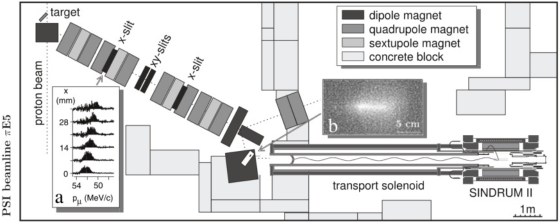
$$p + N \to \pi^+ \to \mu^+ \nu_\mu$$

vs

$$p + N \to \pi^- \to \mu^- \overline{\nu}_\mu$$

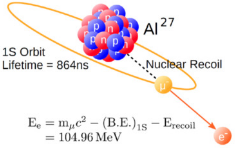
- $\mu \to e\gamma$ can use μ^+, but muon conversion requires μ^- so they can form muonic atoms
  - In addition to forming muonic atoms, they can capture on nucleus producing protons and neutrons
  - Risk of overwhelming detector
- More dangerously, μ^- produced by π^-
  - π^-N$\to \gamma$N*, γ converts, can be well above 105 MeV

Previous muon conversion experiment: SINDRUM II



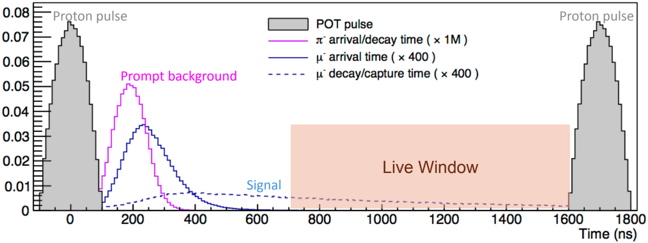
- Beam backgrounds reduced by degrader
  - Pions have half the range in CH_2 compared to muons
- Limit: 7x10^{-13} (90% confidence) on Au

Improving over SINDRUM II



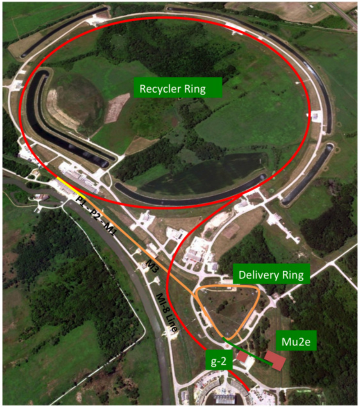
- Muons stopped in aluminum have 864 ns lifetime
- Use pulsed proton beam!
  - Beam flash and pions occur immediately following the proton beam arrival
  - Can wait longer for the muons to decay

Reducing beam backgrounds in Mu2e



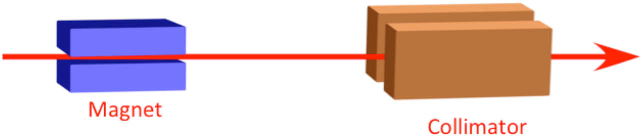
- 700 ns delay followed by 1 μs livegate
- Extinction factor (ratio of out-of-time protons to in-time protons) of 10^{-10} is needed

Mu2e Proton Beam



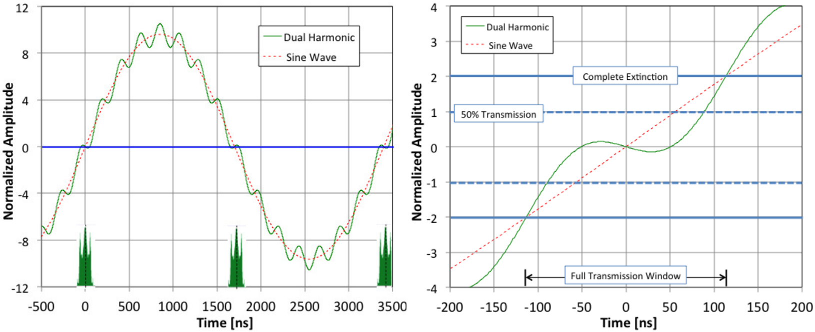
- 8 GeV 8 kW proton beam using protons from booster
- Resonantly extracted to get pulses of 4x10^7 protons separated by 1.7 μs

Achieving required beam extinction

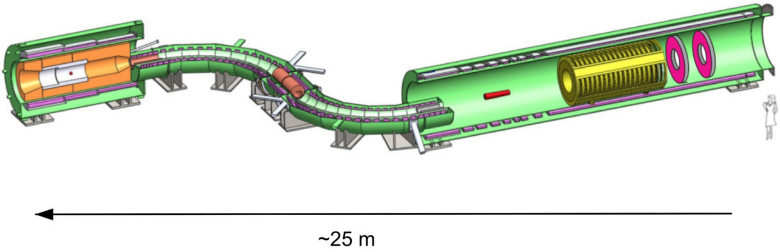


- Beam from delivery ring starts with 10^{-4} extinction
- 2 AC dipoles coupled with collimators expected to bring extinction to 10^{-12}

Achieving required beam extinction

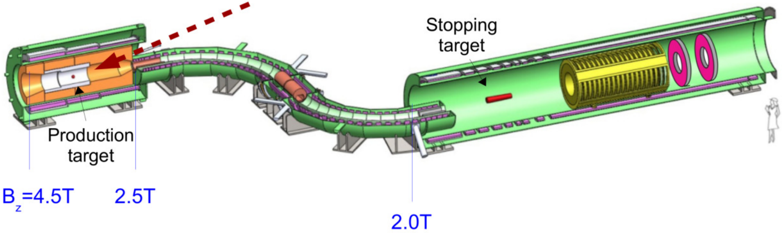


Mu2e experimental setup



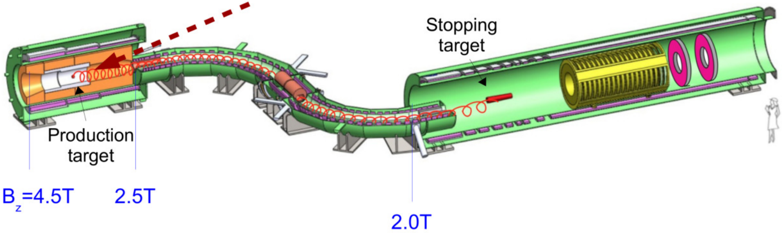
- Curved solenoid to eliminate neutrals, sign and momentum select
- Slow low energy muons hit stopping target and form muonic atoms
- Detector downstream of stopping target, in flat field
- Graded field solenoids (magnetic mirrors) to greatly increase efficiency

Mu2e experimental setup



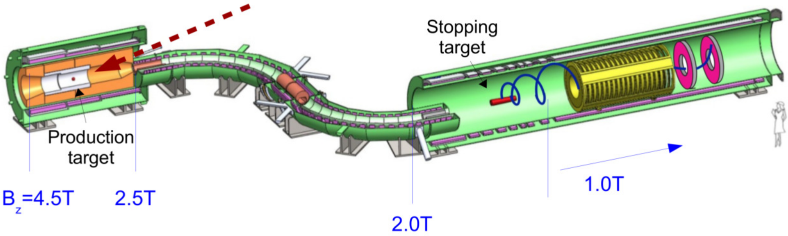
- Curved solenoid to eliminate neutrals, sign and momentum select
- Slow low energy muons hit stopping target and form muonic atoms
- Detector downstream of stopping target, in flat field
- Graded field solenoids (magnetic mirrors) to greatly increase efficiency

Mu2e experimental setup



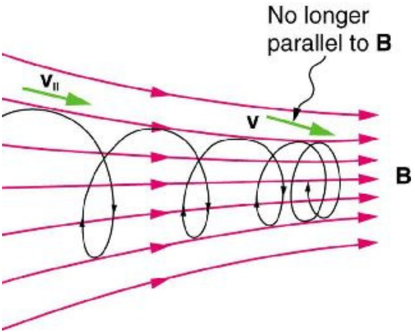
- Curved solenoid to eliminate neutrals, sign and momentum select
- Slow low energy muons hit stopping target and form muonic atoms
- Detector downstream of stopping target, in flat field
- Graded field solenoids (magnetic mirrors) to greatly increase efficiency

Mu2e experimental setup



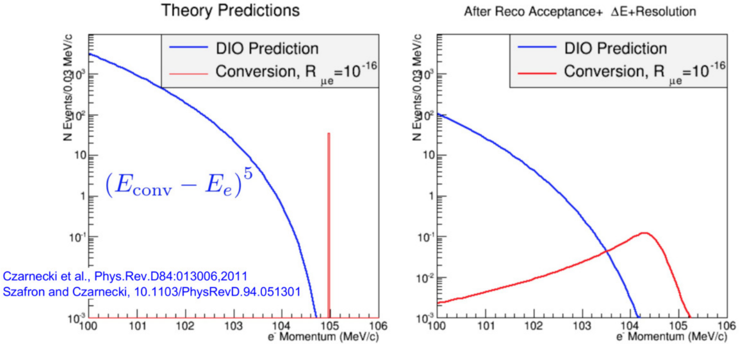
- Curved solenoid to eliminate neutrals, sign and momentum select
- Slow low energy muons hit stopping target and form muonic atoms
- Detector downstream of stopping target, in flat field
- Graded field solenoids (magnetic mirrors) to greatly increase efficiency

Magnetic mirror



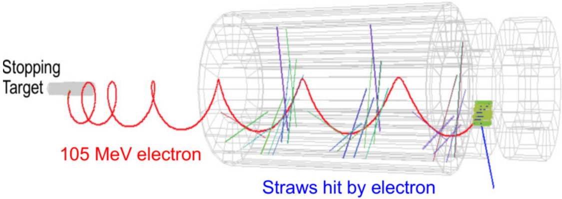
- In solenoid constant B field, $p_T = qBR$, particle follows helical path
- Magnetic moment $\mu = \frac{v_T^2}{2B}$ adiabatic invariant
- p_T increasing but no work being done so $p_{||}$ must decrease
- Eventually can reverse directions

Detecting the electron energy



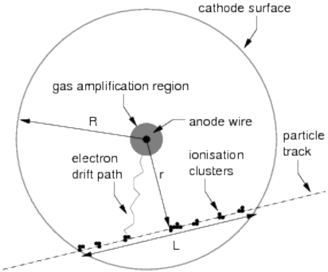
- Need energy resolution of 0.1% at 105 MeV to reject DIO background
- Needs to deal with very high rate, survive beam flash
- $\rightarrow$ Magnetic field and tracking detector to get momentum
  - Calorimeter to distinguish electrons and muons

Tracking Detectors



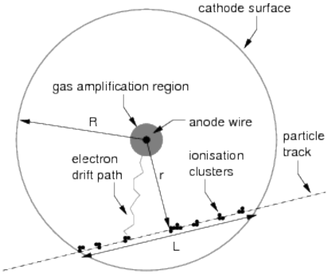
- Straw tracker: large, low mass, highly segmented
- Track reconstructed from:
    - position of hit straws
    - radial position of track in each straw
    - longitudinal position of track along each straw

Straw drift trackers



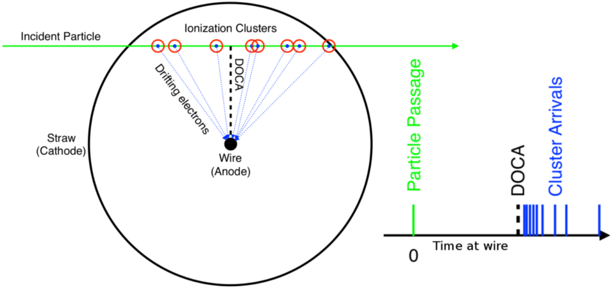
- Straw cathode and wire anode with high voltage applied
- Gas ionized by charged particles ($\sim$100 e^- per cm)
- Electrons and ions produced by charged particle drift to anode and cathode respectively
- Velocity mostly constant over a large range of E field
- Not nearly enough charge produced to be detected

Straw drift trackers



- Electric field for a cylindrical capacitor $\propto \frac{1}{r}$
- close enough to the wire electrons accelerated enough to produce secondary ionization, avalanche
- At low gain, output proportional to initial ionzation
- As gain increases, may go to streamer or Geiger mode
  - Can add quenching gas to stop this (organic compound that absorbs to vibrational modes etc)

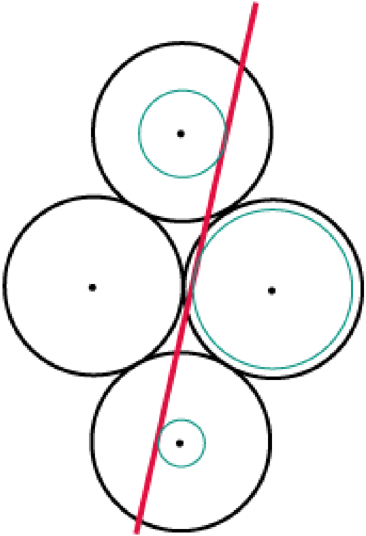
Transverse position measurement with drift time



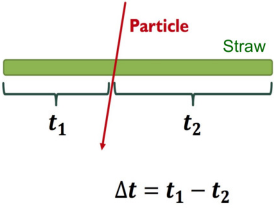
- Charge drifts to wire with nearly constant velocity, relatively slowly (v$\sim$50μm/ns)
- Drift time is a measure of DOCA between track and wire
- Mu2e requires $\sim$100 μm resolution

Transverse position measurement with drift time

- Precise track reconstruction using radial position
- Reconstruct must solve “left-right” ambiguity

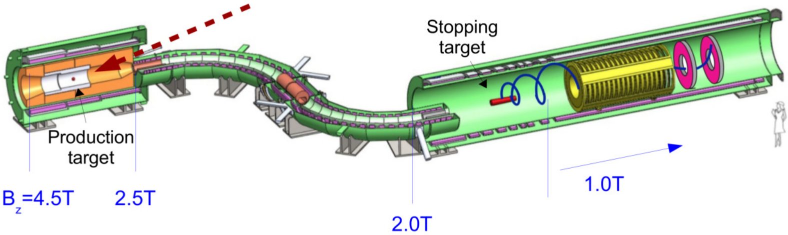


Longitudinal position measurement with time division



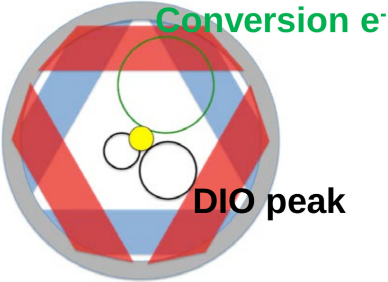
- Once charge drifts to wire it must propagate along it to electronics
- If time of arrival measured at both ends of straw, can measure longitudinal position
- Propagation speed is nearly speed of light, need very precise time measurement
- Mu2e requires ∼4 cm resolution → 200*ps*

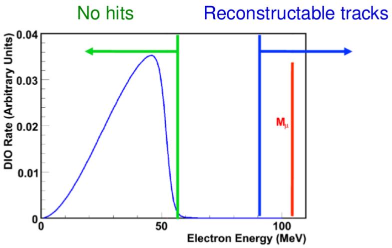
Mu2e straw tracker design



- Constrained by magnetic field, size, cost of cryostat
- $p(\text{GeV}/c) = 0.3\ B(\text{T})R(\text{m})$, so 1 Tesla field → 0.7 m maximum radius for 105 MeV/c

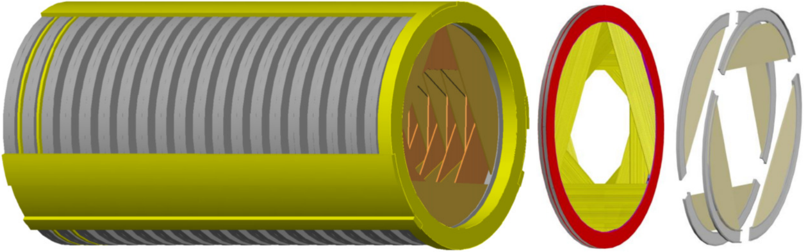
Mu2e straw tracker design





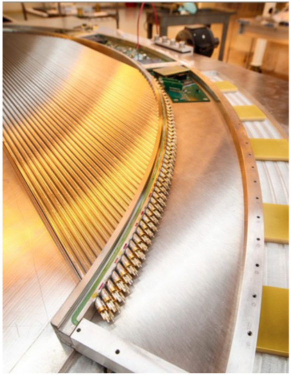
- Annular shape, noninstrumented inner radius allows beam flash and DIOs through
  - DIO peak is 52.8 MeV/c, 0.35m maximum radius
  - Tracker has nothing within 0.38m radius
- 97% of DIO produces no hits in tracker

Mu2e straw tracker design



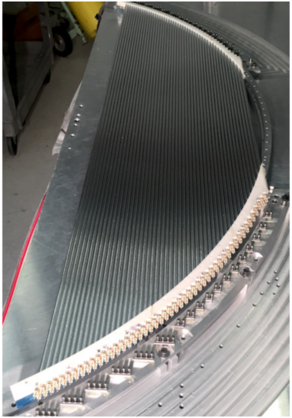
- Ambient vacuum, 20000 very thin straws holding 1 atmosphere of $ArCO_2$
- straws perpendicular to beam axis, rotate direction for stereo position information

Mu2e straw tracker design



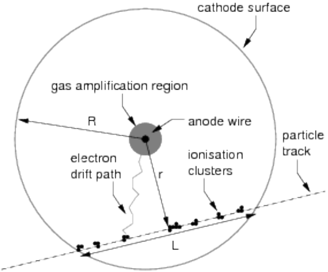
- Straws are 5 mm diameter, 15 μm thick walls
- Held at tension, no support structure inside active volume
- 25 μm tungsten wire at 1425V

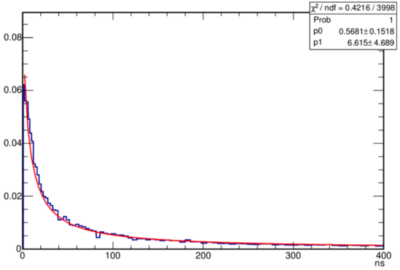
Tracker construction and alignment



- Curved gas manifold - 3D printed plastic
- Fixtures for precise alignment of straws, wires, panels
- X-ray scan of wire position

Expected signal from a straw tube



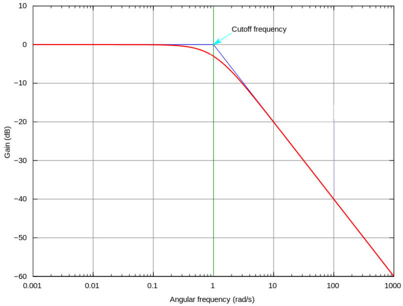


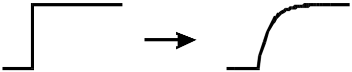
- Signal on wire is actually induced charge: $i_{\text{ind}} = E_v q v$
- Most of the electrons produced very close to wire
- Measured current signal is actually induced by ions drifting all the way back to cathode
- Ions drift slowly, signal has sharp rising edge and long tail

Tracker electronics

- Need to amplify signal, measure time of arrival at both ends of each straw, measure current pulse size
- Want $\sim$100 ps time resolution for time division
- Needs to recover quickly after large proton hits
- Operating within cryostat, needs limited power usage, footprint
- Needs to be rad hard to survive

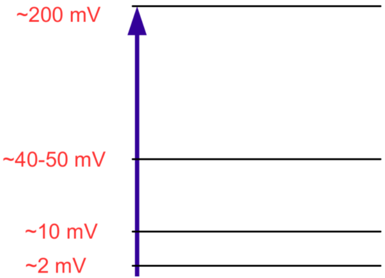
Preamplifiers





- Amplify signal, shape so that get best timing resolution and signal to noise ratio
- Low pass filter: too high a bandwidth just increases noise without improving signal resolution

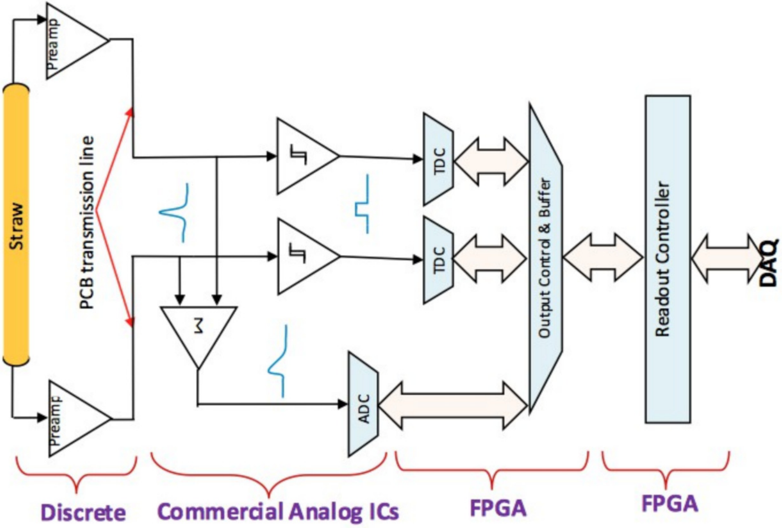
Preamplifiers: competing requirements



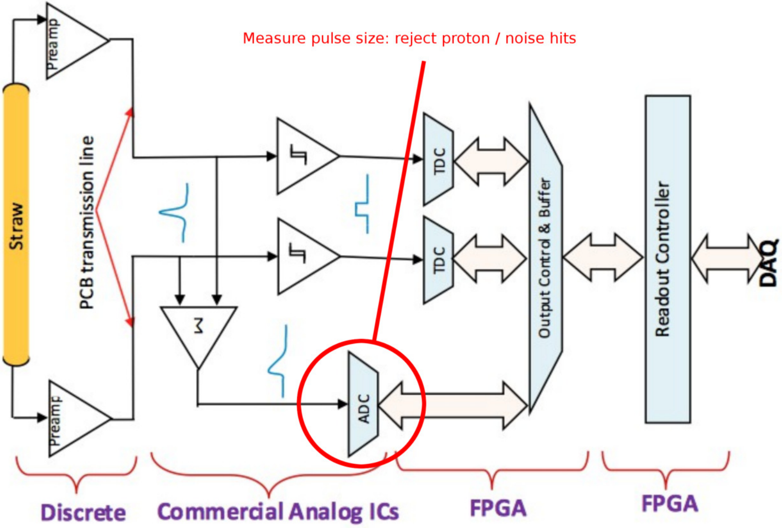
Signal level at preamp output

- Maximum signal range: larger allows better proton rejection, but limits resolution
- Average e^- signal: at 5x threshold for high efficiency
- Threshold: at 5x noise rms to limit hit rate
- Noise RMS: mostly proportional to bandwidth, lower bandwith limits resolution

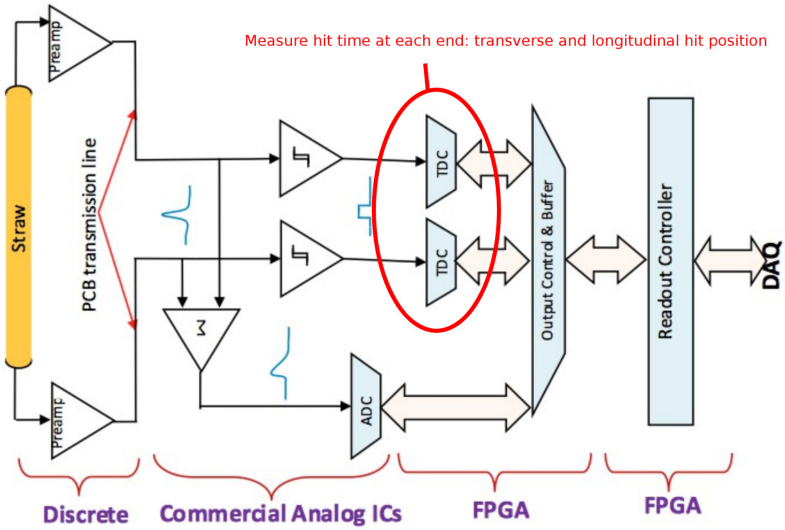
Digitization and Readout



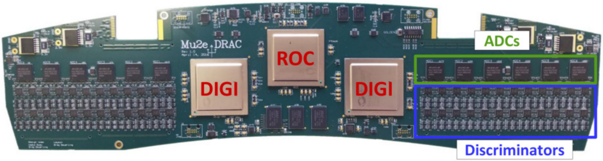
Digitization and Readout

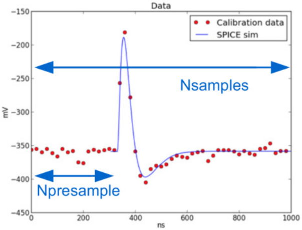


Digitization and Readout



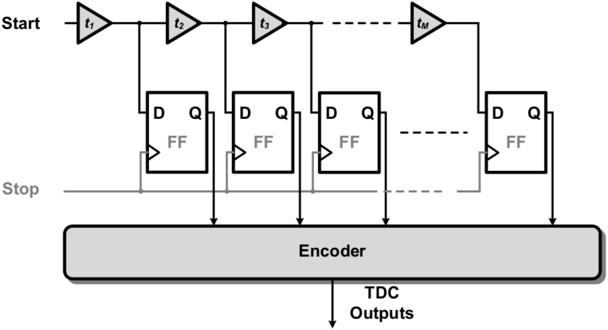
Digitization and Readout





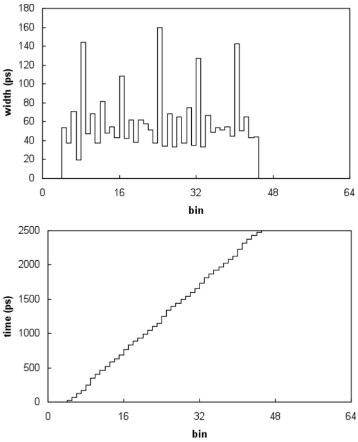
- Output of preamps discriminated and digitized with firmware TDC
- Outputs also shaped, analog summed into ADC, 50 MHz samples read out by FPGA
- FPGA pushes TDC and ADC data over optical links to DAQ

FPGA TDC



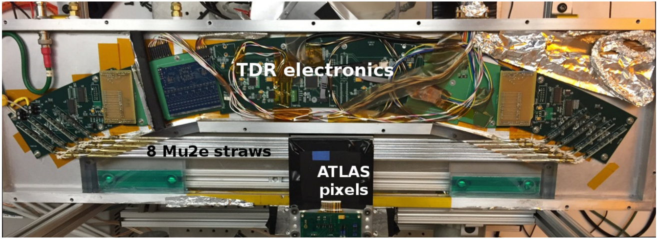
- Maximum clock frequency limits resolution of simple time measurement in FPGA (400 MHz $\rightarrow$ 2.5 ns)
- Subdivide between clock ticks using delay chain
- In FPGA, limited by minimum cell delay, routing differences, temperature variations

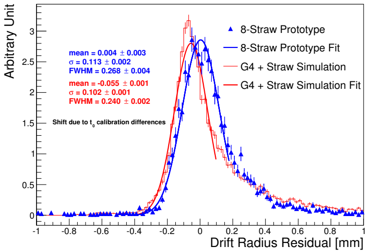
FPGA TDC: Tricks to improve resolution

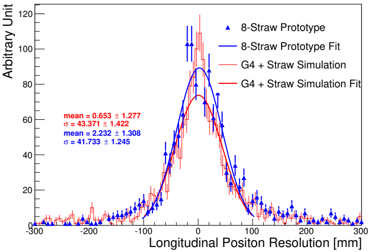


- Use specialized carry-adder cells in FPGA
- Auto-calibrate bin widths using pseudo-random test pulser
- Combine results of multiple edges (wave union TDC) or multiple delay chains to average over larger bins
- Able to improve our TDC resolution to < 70 ps

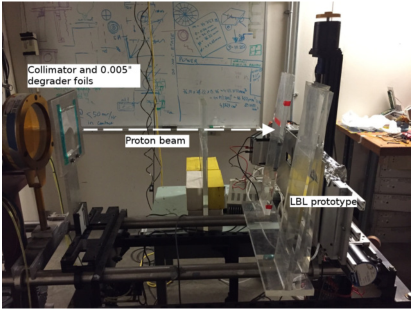
LBL Tracker prototype





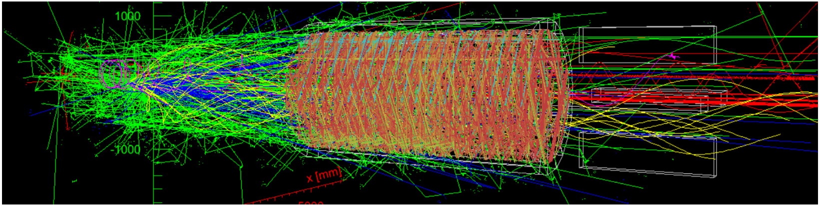


Radiation Tolerance



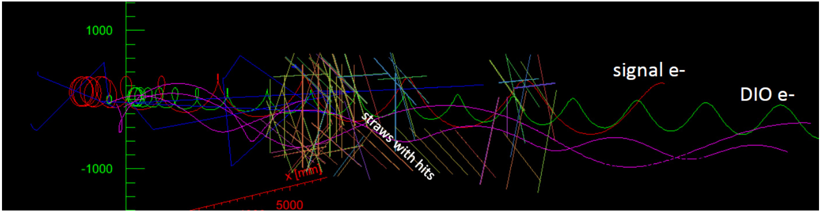
- Single even upsets: a single particle causes a bit to flip, corrupting data or even FPGA design
    - Tested using 88' cyclotron, initial Altera FPGAs failed
    - Switched to Microsemi FPGAs
    - All flash memory, much larger charges required to flip
- Total Ionizing Dose: long term effects
    - SEU immunity comes at cost of increased TID susceptibility
    - Tested using X-ray linac, cell delays increase
    - Newer FPGA line more resistant to these effects

Readout and Trigger



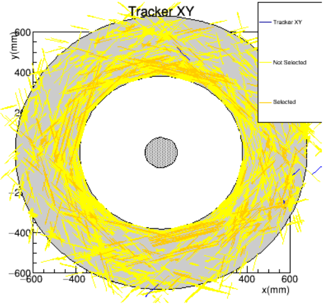
- 4Gb x 200 connection from front end to DAQ, ∼ 16 Gbps on average from tracker
- Want <7 Pb/year to disk, requires ∼100x rejection
- No easy signal to trigger on (1 μs window following beam pulse, exponential decay signal)
- Need to do quick track reconstruction, keep only hits that could be part of ∼105 MeV electron track

Readout and Trigger

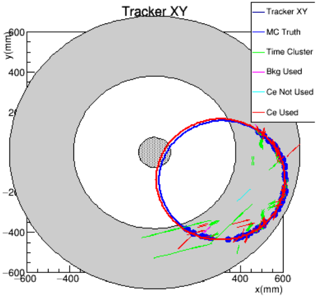


- 4Gb x 200 connection from front end to DAQ, $\sim$ 16 Gbps on average from tracker
- Want <7 Pb/year to disk, requires $\sim$100x rejection
- No easy signal to trigger on (1 μs window following beam pulse, exponential decay signal)
- Need to do quick track reconstruction, keep only hits that could be part of $\sim$105 MeV electron track

Track Reconstruction



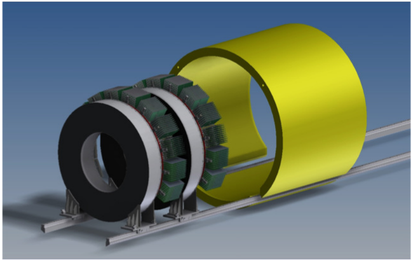
1 μs window after beam pulse



$\pm$50 ns window

- Find peaks hit in time distribution
- Filter background hits (protons / Compton electrons)
- Least squares helix fit, followed by iterative Kalman Filter track fit

Calorimeter



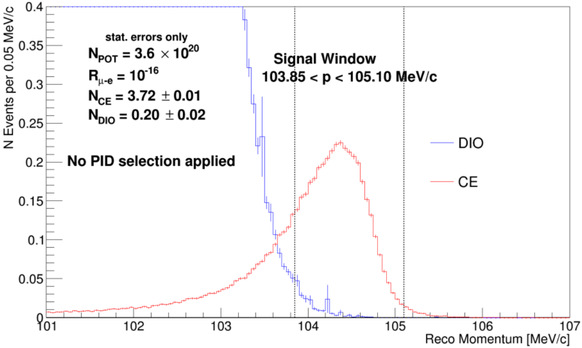
- Muons with correct momentum can look like 105 MeV electrons to tracker, need a way to reject
- Two annular disks separated by half a "wavelength" (70cm) of electron's helical path
  - Maximize probability to hit at least one disk
- Each disk contains 860 CsI crystals read out by SiPMs
- 5% energy, 0.5 ns time, 1 cm position measurement independent of straw tracker

Expected backgrounds for 3 year run

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

- Fewer than $\sim$0.5 background events expected over entire run
- 3.6 x 10^{20} protons on target over 3 years $\rightarrow \sim 10^{18}$ stopped muons

Sensitivity

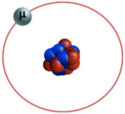


- Single event sensitivity: $R_{\mu e} < 3x10^{-17}$
- Typical SUSY prediction of 10^{-15} $\rightarrow$ $\sim$50 signal events

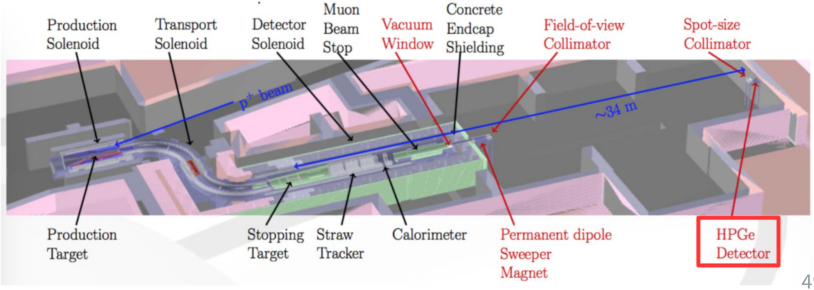
Backup

Civil construction

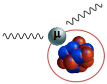
Stopping Target Monitor measures capture rate



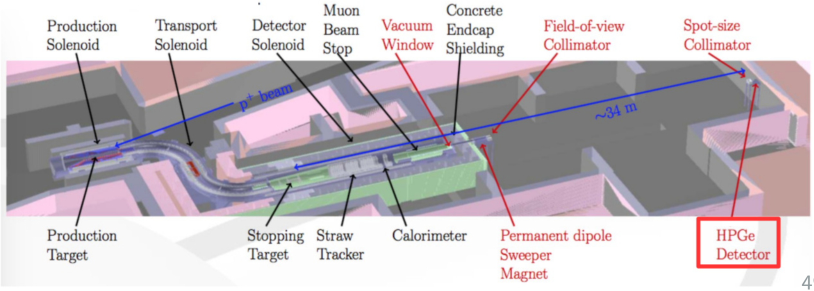
- Muons cascade to 1s state emitting x-rays
- HPGe detector monitor these x-rays to measure capture rate
- Normalization of measurement $R_{\mu e} = \frac{\mu^- + A(Z,N) \to e^- + A(Z,N)}{\mu^- + A(Z,N) \to \nu_\mu + A(Z-1,N)}$



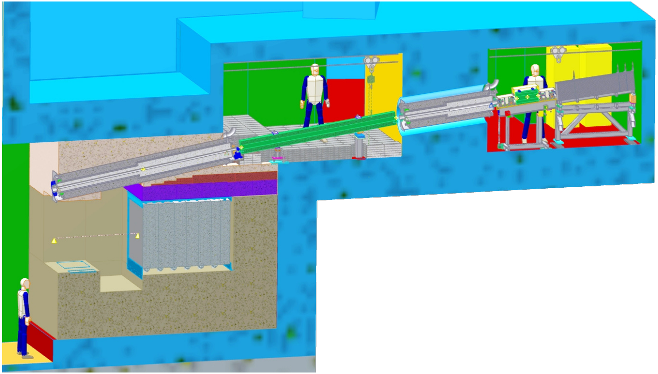
Stopping Target Monitor measures capture rate



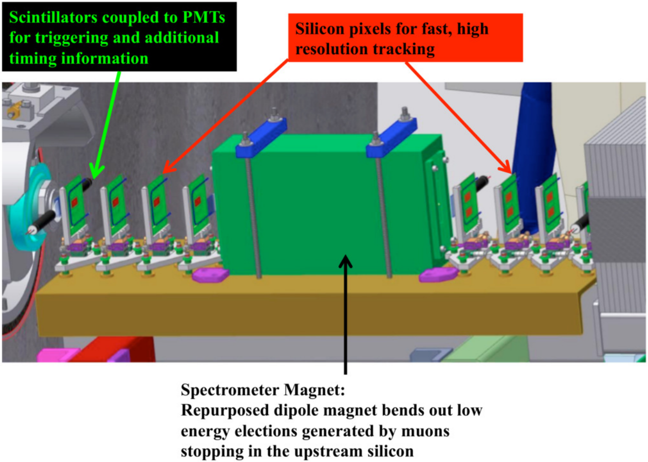
- Muons cascade to 1s state emitting x-rays
- HPGe detector monitor these x-rays to measure capture rate
- Normalization of measurement $R_{\mu e} = \frac{\mu^- + A(Z,N) \to e^- + A(Z,N)}{\mu^- + A(Z,N) \to \nu_\mu + A(Z-1,N)}$



Extinction Monitor located downstream of production target

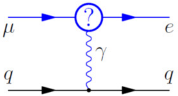


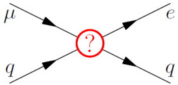
Extinction Monitor located downstream of production target

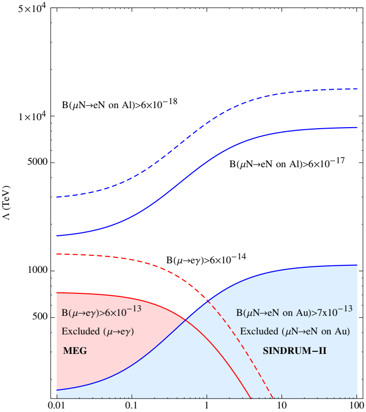


CLFV Effective Lagrangian

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







Bernstein, de Gouvea$^\kappa$

- loop: $\kappa \ll 1$, μN$\rightarrow$ eN and $\mu \rightarrow e\gamma$
- contact: $\kappa \gg 1$, μN$\rightarrow$ eN only
- Complementary to LHC: can probe mass scales up to 10^4 TeV

Determining model with CLFV

V. Cirigliano, R. Kitano, Y. Okada, P. Tuzon, Phys. Rev. **D80** 013002 (2009)