The Mu2e experiment at Fermilab

The search for charged lepton flavor violation

03.09.2013

Aim of the Mu2e experiment at Fermilab

Measuring the muon-electron conversion rate to a precision of 6e-17 at 90% CL at the Mu2e experiment at Fermilab, probing up to 1e4 TeV in effective energy.

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

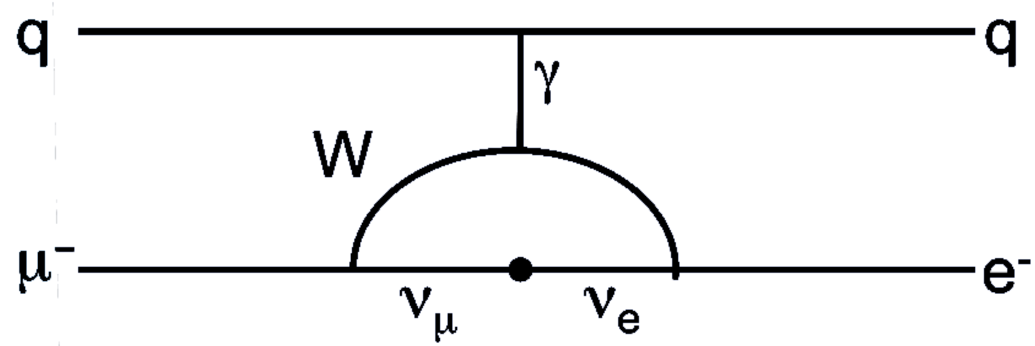
When a slow moving muon meets an atom a muonic atom can be formed. The captured muon will spiral very quickly towards the 1s orbital, emitting x-rays along the way. Once there the muon may convert to a neutrino, or, if cLFV exists, into an electron.

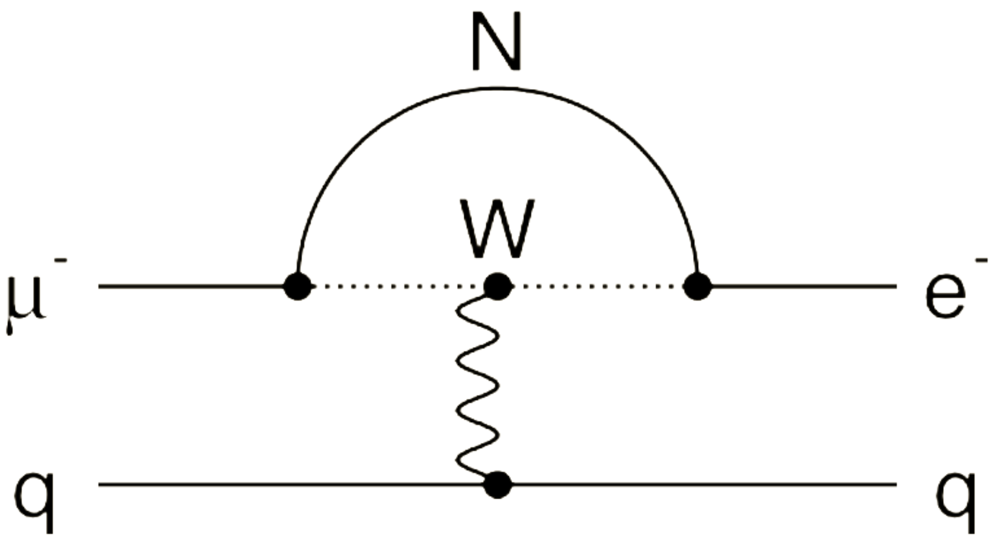
Because the atom is much heavier than the electron, the electron will inherit almost all of the energy of the muon.

Charged lepton flavor violation

In the SM with neutrino mixing cLFV can occur but is very GIM suppressed.

Many methods of generating neutrino masses including seesaw mechanisms will feature much larger cLFV rates which are within the proposed Mu2e sensitivity.





Charged lepton flavor violation is an important consequence of many proposed new physics models including SUSY (with or without R-parity), leptoquarks, large extra dimensions and models featuring additional gauge bosons such as Z' as well as those with an extended Higgs sector.

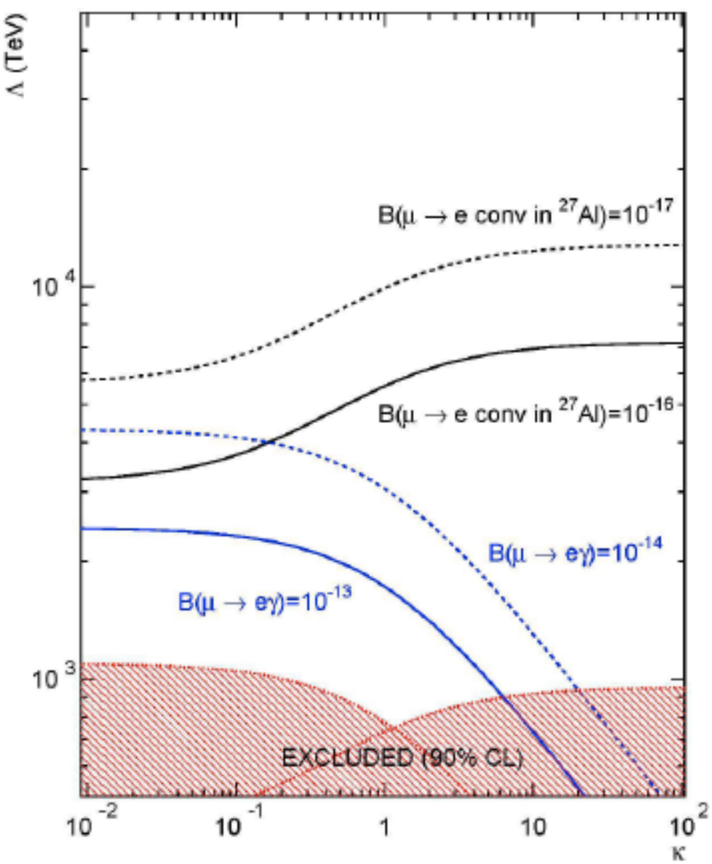
Electron-muon conversion near a nucleus

Virtually all cLFV terms can be captured in two effective terms. With kappa governing the relative sizes, and lambda the new physics energy scale.

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

muon decay to electron+photon

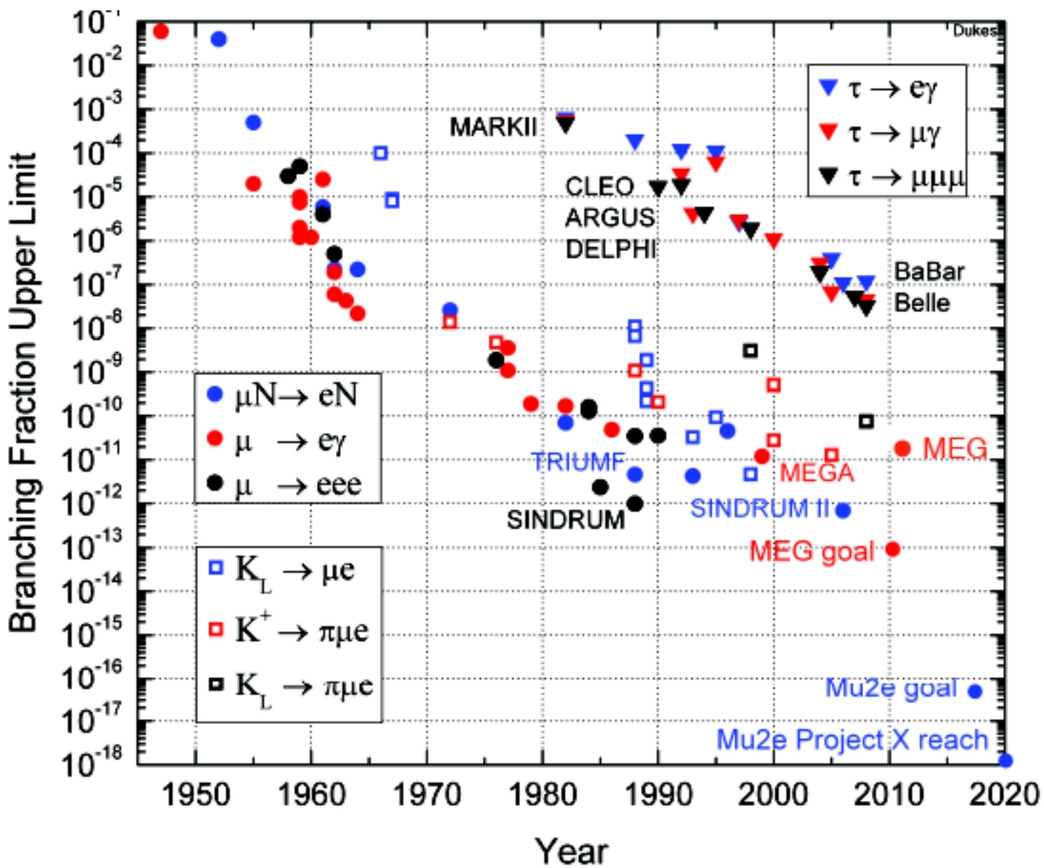
muon-electron conversion (and some other effects)

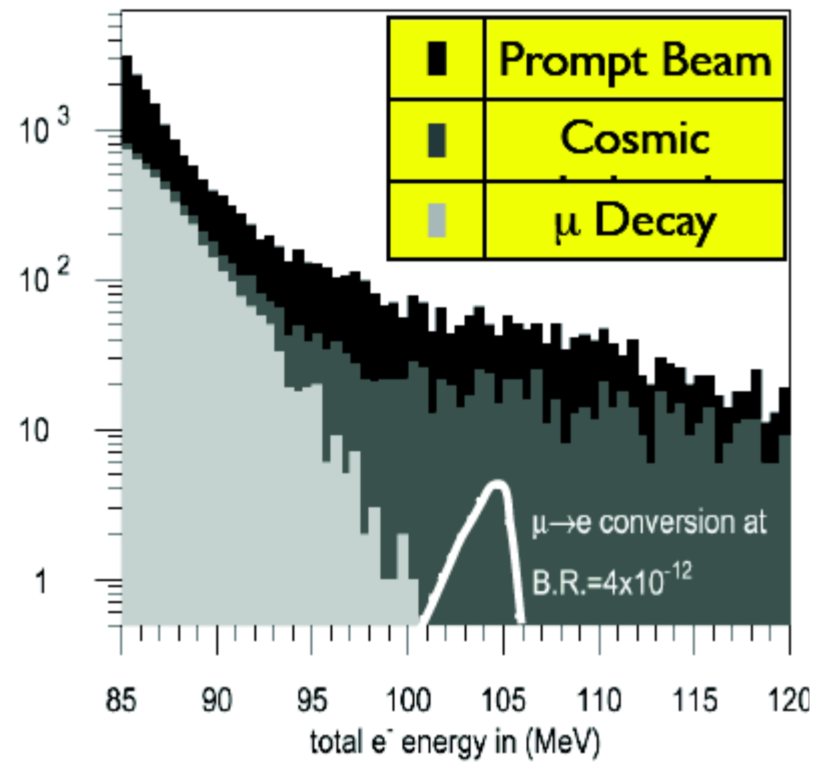


The MEG experiment at PSI is sensitive to the first term, Mu2e will be sensitive to the second one.

But the experiments are complementary; two positive signals allow one to constrain both kappa and lambda aiding in the identification of the cLFV mechanism.

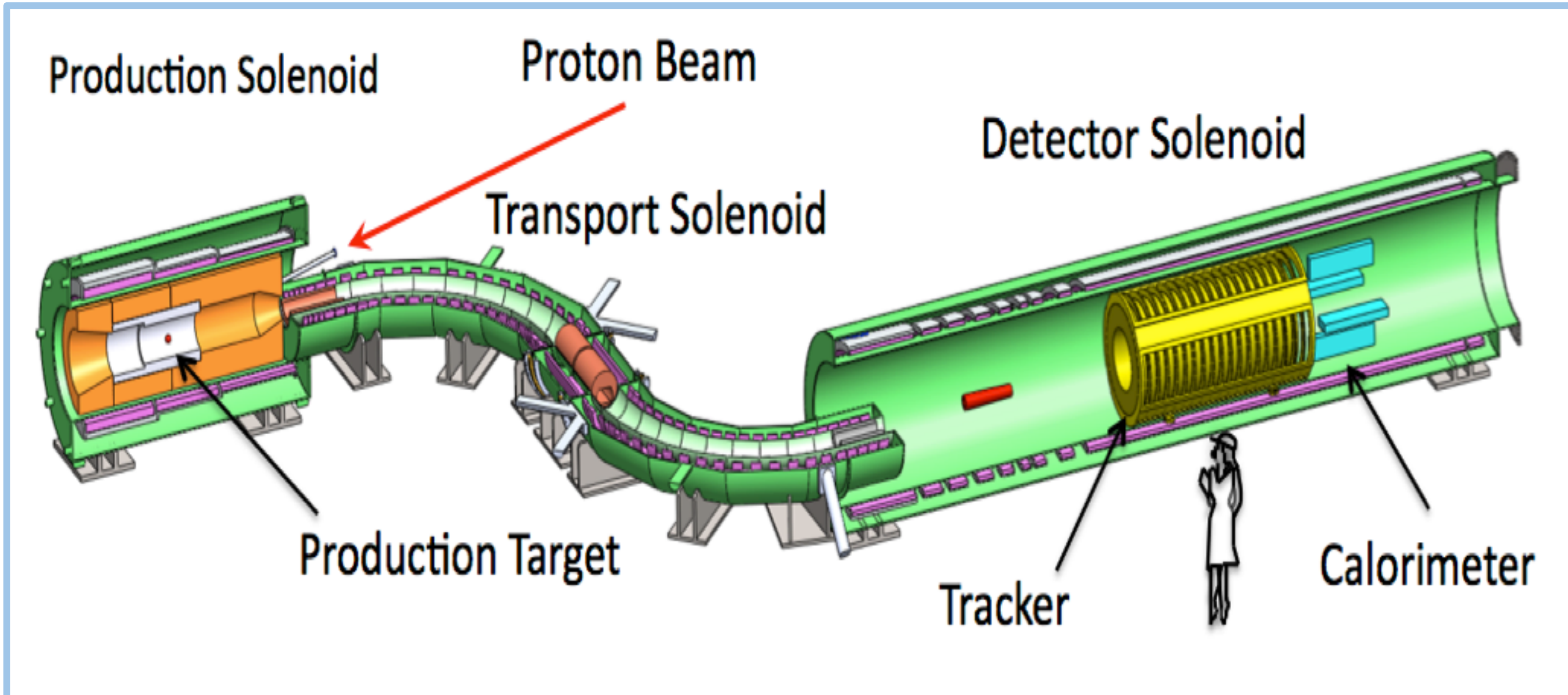
State of searches for CFLV





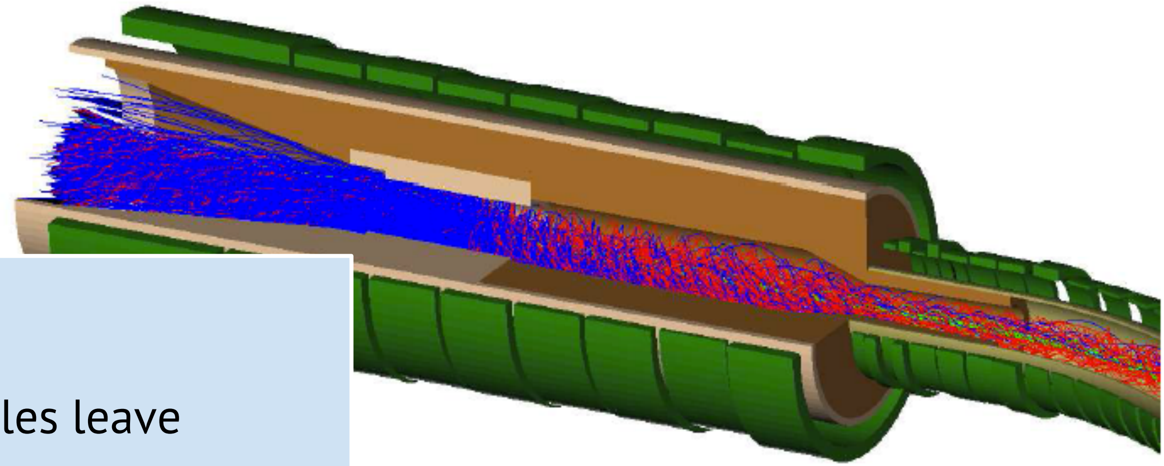
Mu2e apparatus

- 8 GeV **pulsed proton beam** - time between bunches 1695 ns ($\rightarrow$ bckg red.)



- shoot p^+ onto production target $\rightarrow$ bunch of pions, kaons...

Beam line



Production Solenoid

- protons and secondary particles leave opposite to produced pions
- graded B-field ensures high π/μ capture efficiency

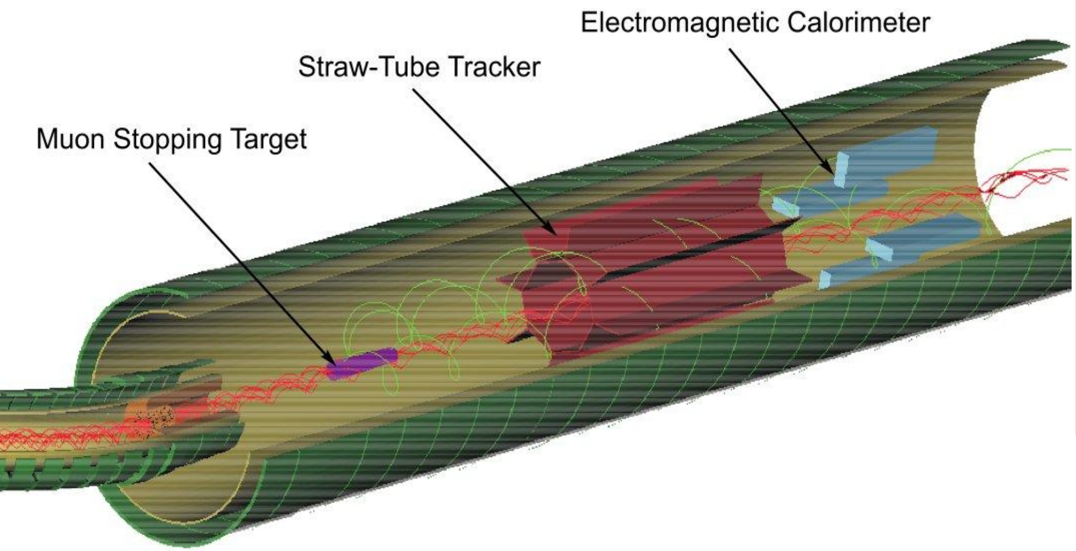
S-shaped Transport Solenoid

- collimators select low p_T, negative charged particles: $\pi^- \rightarrow \mu^-$
- shape eliminates neutral particles
- anti-protons are stopped by thin absorption window in the middle

Detector solenoid

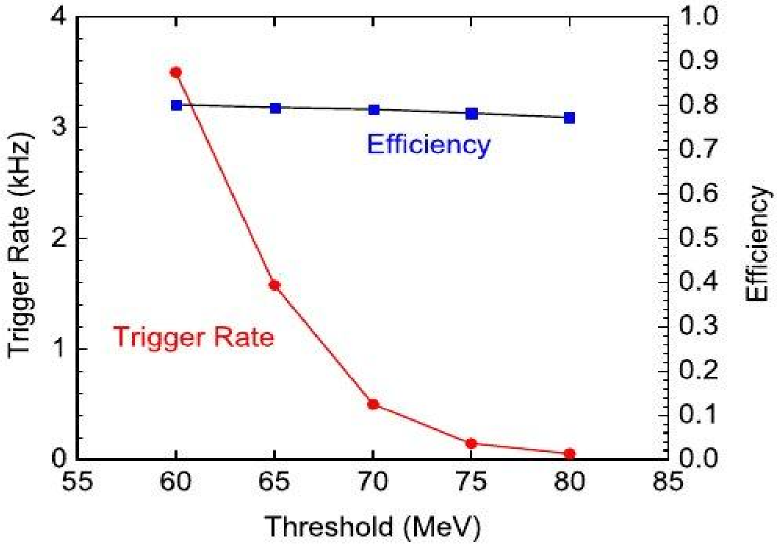
- low pt muons are stopped in target (17 0.02cm thin Al foils)
- graded B-field reflects upstream going electrons back to the detector
- active and passive shielding from cosmic rays

Mu2e detector in the Detector Solenoid



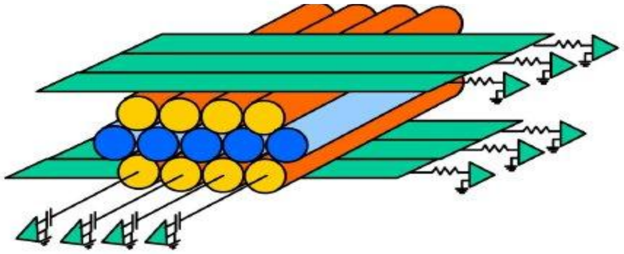
ECal ($PbWO_4$ Crystals)

- Requirement: enable trigger to run at a **rate of ~1 kHz**
- We want to provide reference time of ~1 ns,space point resolution of ~1 cm



Tracker

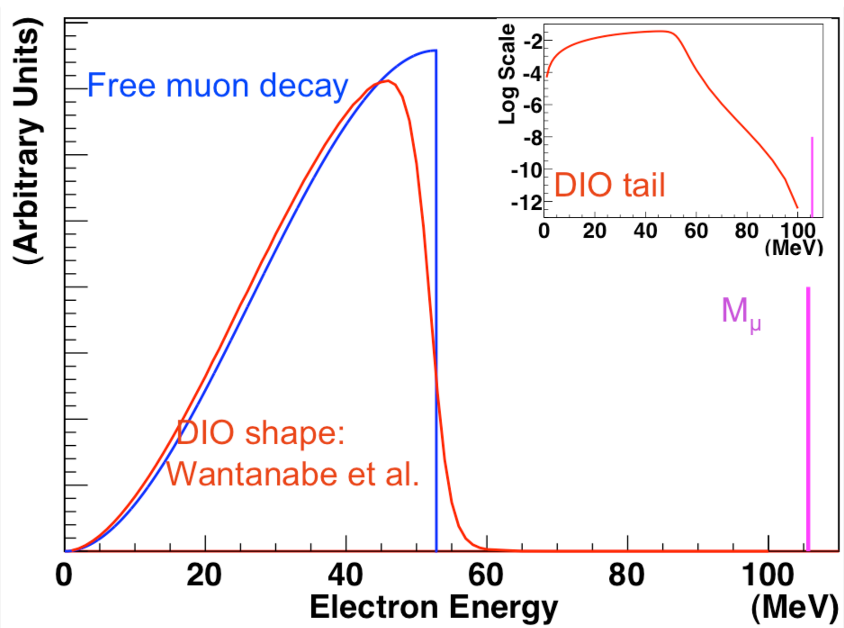
- Requirement: trajectory of signal at **105 MeV/c with resolution of 190 keV/c**
- Located in a uniform 1 T magnetic field.
- **Detectors:**Straw tubes / strips: <u>200 µm</u> **position resolution** (drift coordinate)



Decays of muons in orbit

- Signal: electrons from CLFV muon decays
- Energy spectrum can be used to suppress SM backgrounds with N_μ = 10^18, $R_{\mu e}$ = 10^-16 and eff = 5%

=> Nsig = $N_\mu R_{\mu e}$eff = 5



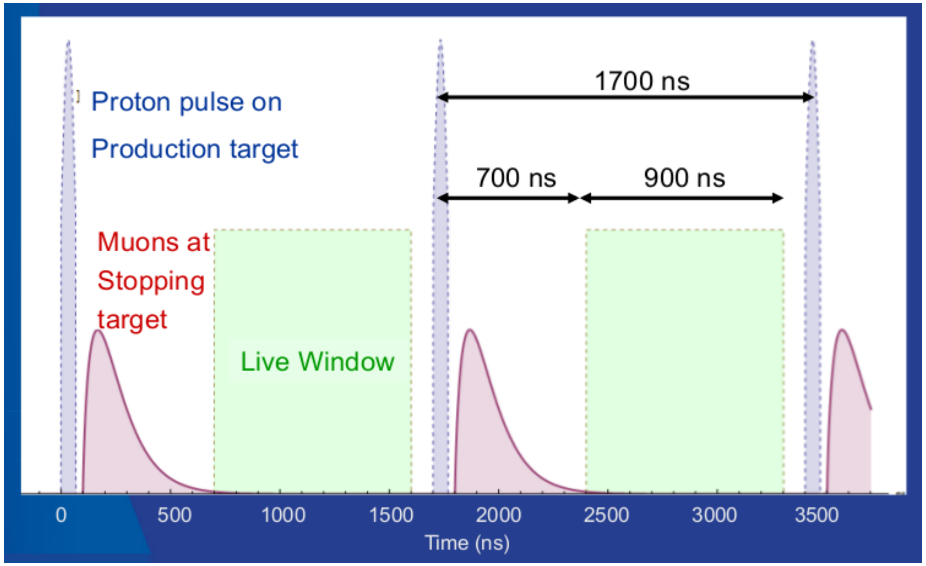
Process		Events
signal	$\mu^- N \to e^- N$	5
➔ for Al, m_μ = 105.66 MeV: $E_e = m_\mu + E_{recoil} + E_{1S}$ = 104.96 MeV		
μ decay in orbit (DIO)	$\mu^- N \to e^- \nu_e \nu_\mu N$	0.225
➔ E_e has tail up to m_μ, about 50% of total bkg		
radiative μ capture	$\mu^- N_Z \to \nu_\mu N_{Z-1} + \gamma$	< 0.002
➔ E_γ < 102 MeV, $\gamma \to e^+ e^-$		

Reducible backgrounds

- Backgrounds from prompt decays are reduced by dead time (700 ns) after proton pulses.
- Can create signal if initial particles are delayed by slow propagation through beam pipe.

=> Proportional to $N_{pulse}/N_{delayed} < 10^{-9}$

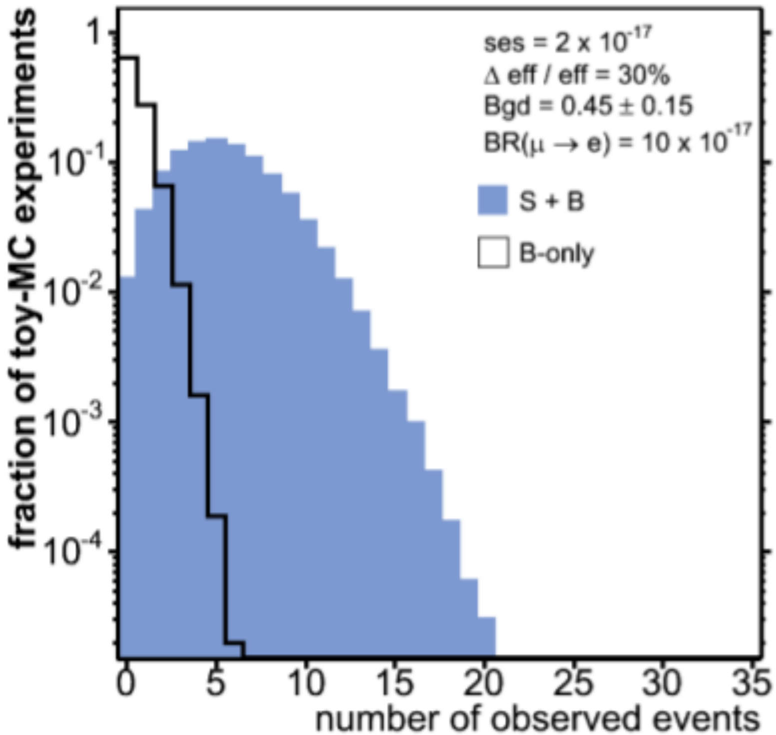
- Lifetime of 1S muons in Al: $\tau = 864\ \mu s$

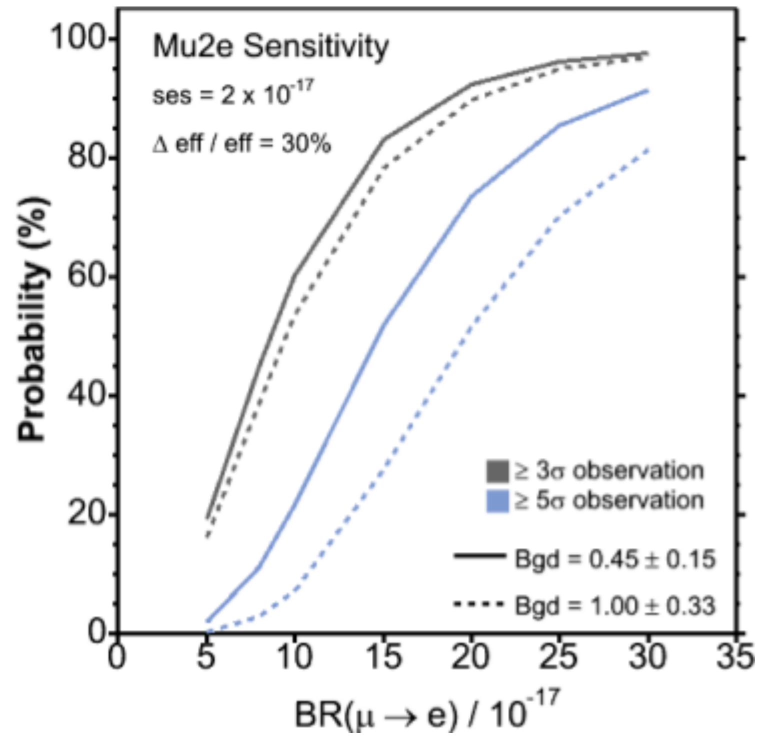


Delayed backgrounds		Events
radiative π capture	$\pi^- N_Z \to N_{Z-1} + \gamma$	0.072
➔ $E_\gamma < m_\pi = 139.57$ MeV, $\gamma \to e^+ e^-$		
beam electron		0.036
➔ electron from π decays in beam, scatter in target		
μ decay in flight (DIF)		< 0.063
π decay in flight (DIF)		< 0.001

Other backgrounds	Events
anti-protons	0.006
➔ beam energy above pp-pair threshold, can reach target (negative charge)	
cosmic rays	0.016
➔ μ DIF or e / γ production. reduced by passive and active shielding	
pattern recognition	< 0.002

Sensitivity





Test statistic from toy experiments

- with N_μ = 10^18 and eff = 5%

=> single-event-sensitivity:
ses = 1 / (eff * N_μ) = 2*10^-17

- and $R_{\mu e}$ = 10^-16

=> mean of S+B = 5 + 0.45 events

- Derived 3σ (black) and 5σ (blue) sensitivities
- Default background estimation (solid) and pessimistic (dashed)
- E.g: about 60% probability of finding a 3σ signal with $R_{\mu e}$ = 10^{-16}

Infrastructure, Schedule & Cost, Upgrade

Why Mu2e at Fermilab?

- existing time-structured high intensity proton beam
- required accelerator modifications shared with g-2 and NOvA
  → unique world-class muon experiments at Fermilab very cost efficient

Schedule & Costs

- **total project cost** range: **$208M- $287M** → project management, accelerator modifications, construction of the experiment and trigger and DAQ
- **start running already in 2017**

Long-term Prospects

Upgrade to **Project X** - intense proton source → Mu2e increased sensitivity of **two orders of magnitude**

Conclusion & Involvement

- Charged lepton flavor violations are an important probe for physics beyond the Standard Model
- u->e conversion one of the most sensitive processes of cLFV
- Improves current limit by 4 orders of magnitude
- Probes mass scales well beyond LHC reach

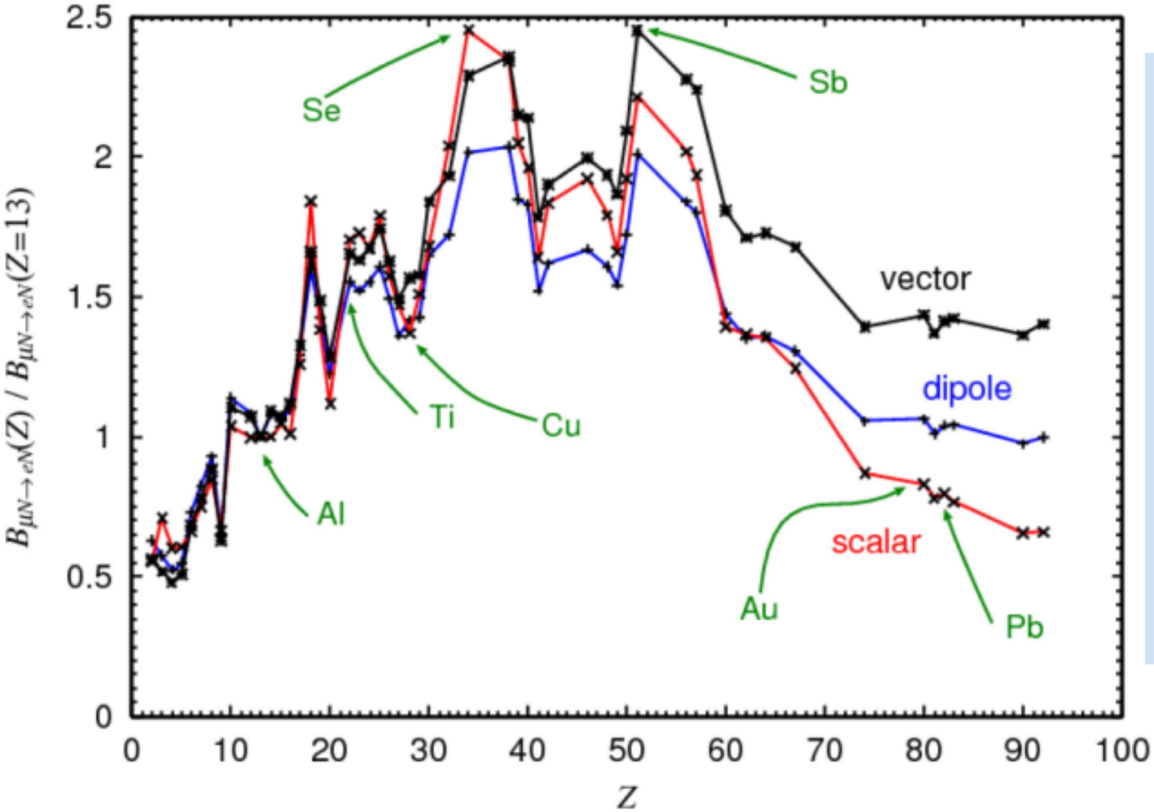
- Fermilab well suited to deliver needed beams
- Opportunity to host multiple unique experiments (Costs shared with other Fermilab experiments)
- Clear upgrade path for an additional increase in sensitivity by two orders of magnitude

  (Project X)

As a new group: Use full manpower and expertise for high resolution track reconstruction - the most important part to fulfill the expected sensitivity

Backup

Target material flexibility



Muon Stopping Target

- Sufficiently thick to stop large fraction of muons.
- Aluminum and titanium are viable targets.
- Higher Z targets possible but at a considerable loss of data rate.
- The conversion rate in Ti is about a factor of 1.7 that of Al.

Infrastructure, Schedule & Cost, Upgrade

Why Mu2e at Fermilab?

- to take advantage of the time-structured high intensity proton beam that can be delivered by the existing Booster-Debuncher-Accumulator complex
- required modifications to the accelerator complex are shared with two other experiments (g-2, NOvA) allowing Fermilab to host unique world-class muon experiments for less than the cost of the individual programs executed independently

Schedule & Costs

- the **total project cost** range is **$208M- $287M** covering project management, accelerator modifications, construction of the detector facility, solenoids, beamline and detector as well as trigger and DAQ
- a **schedule range of 56 - 80 months** is estimated for the duration of the construction project
- **the solenoids are both the cost and schedule driver for the project** the **total life cycle cost** of **$39M** assumes a 4-year run to commission the accelerator and detector and accumulate data followed by two years of data analysis – including decontamination and decommissioning

Future Prospects/Improvements

A **Project X** upgrade to Fermilab - a proposed intense proton source - could allow an upgraded Mu2e with an increased sensitivity of two orders of magnitude allowing detailed measurements of the source and magnitude of the effect