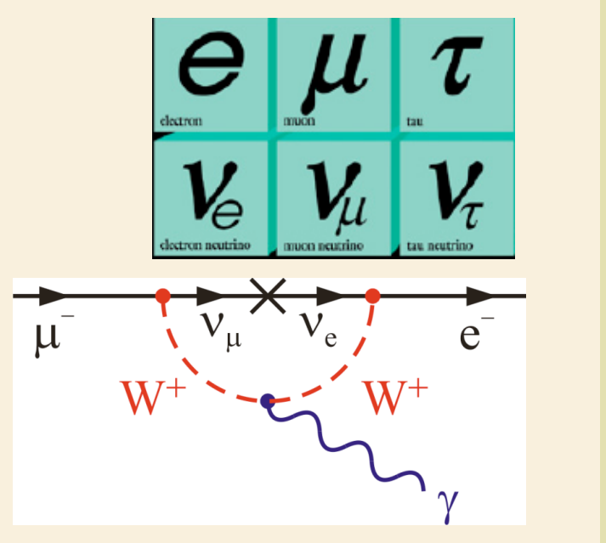
Mu2e Experiment at Fermilab

A New Sensitive Search for Muon to Electron Conversion

Lepton Flavor Violation



• Charged Lepton flavor: accidental symmetry in the Standard Model

Lepton flavor violation is forbidden in the Standard Model if neutrinos are massless. A very small SM effect due to finite neutrino mass produces negligibly small rates: $BR(\mu \to e\gamma) \sim 10^{-52}$

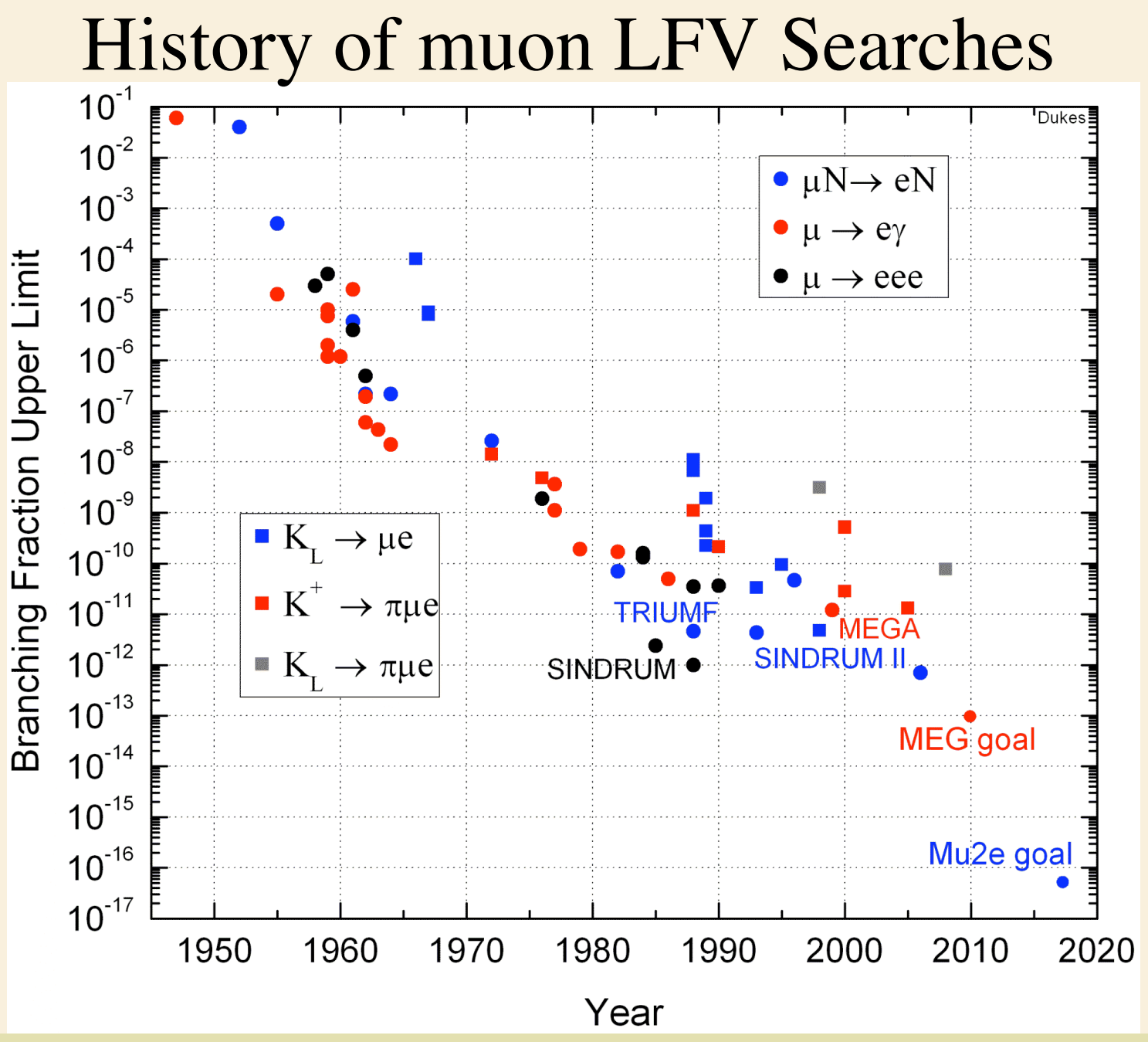
• CLFV: an unambiguous signature of new physics

Such small SM rates make charged lepton flavor violation an ideal place to look for new physics, with mass scale sensitivity far beyond the reach of direct searches. The next generation experiments will have sensitivity to directly test predictions of many BSM theories. The Fermilab Mu2e experiment will search for coherent, neutrinoless μ→e conversion in the field of a nucleus with a sensitivity of 4 orders of magnitude better than existing limits. Mu2e will measure the normalized conversion rate

$$R_{\mu e} = \frac{\Gamma(\mu^- N \to e^- N)}{\Gamma(\mu^- N \to \nu_\mu N')}$$

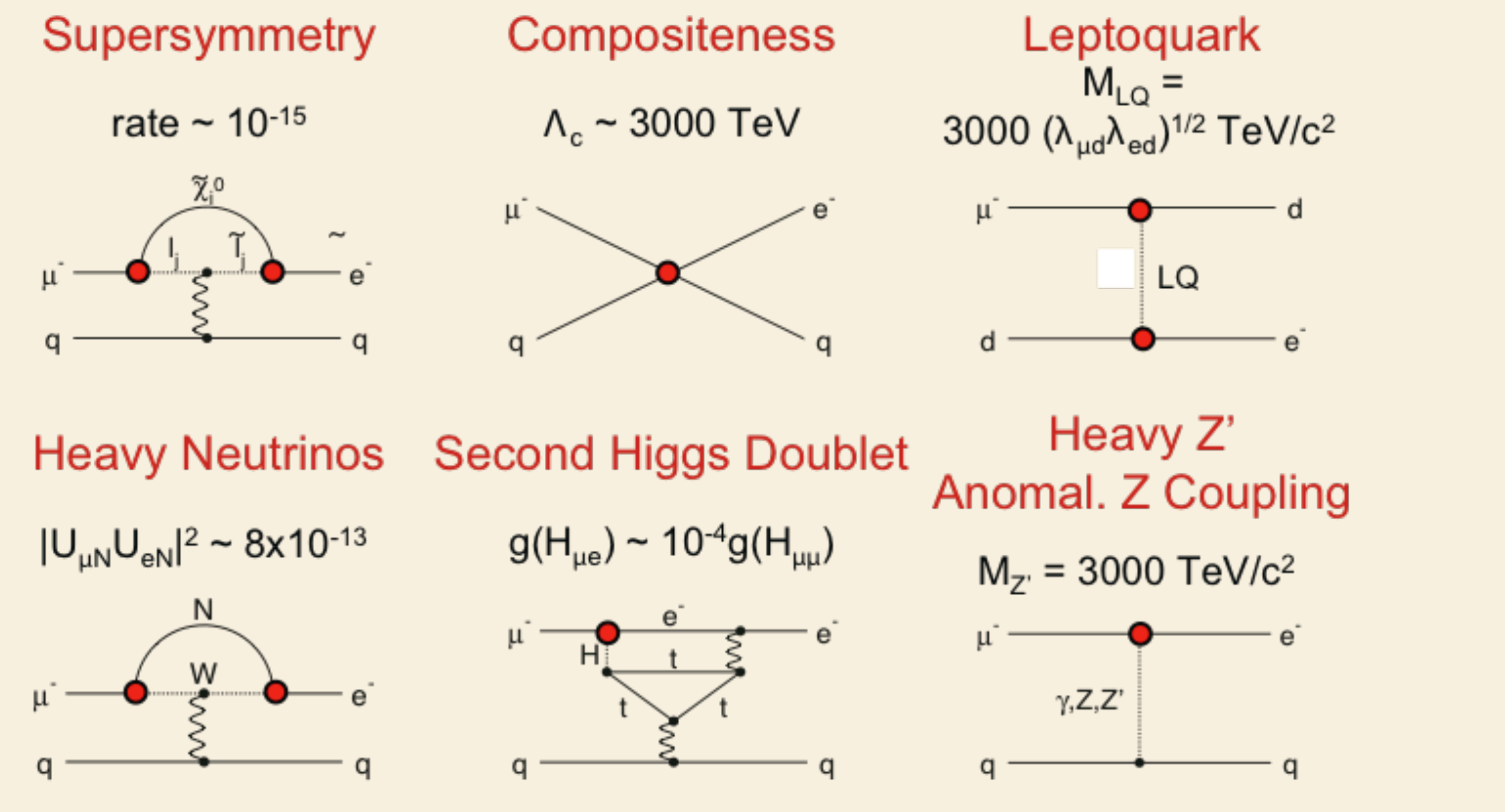
Our goal is to measure $R_{\mu e}$ with a single-event sensitivity $R_{\mu e} = 2.5\times10^{-17}$

History of muon LFV Searches



Sensitivity to New Physics

Possible New Physics Contributions



Supersymmetry
rate ~ 10^{-15}

Compositeness
Λ_c ~ 3000 TeV

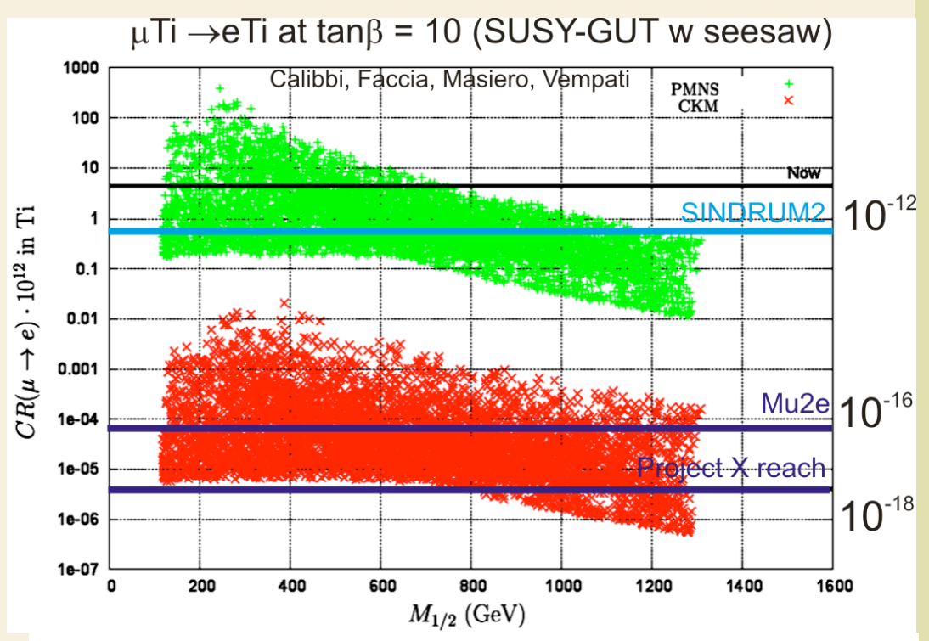
Leptoquark
$M_{LQ} = 3000\,(\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c²

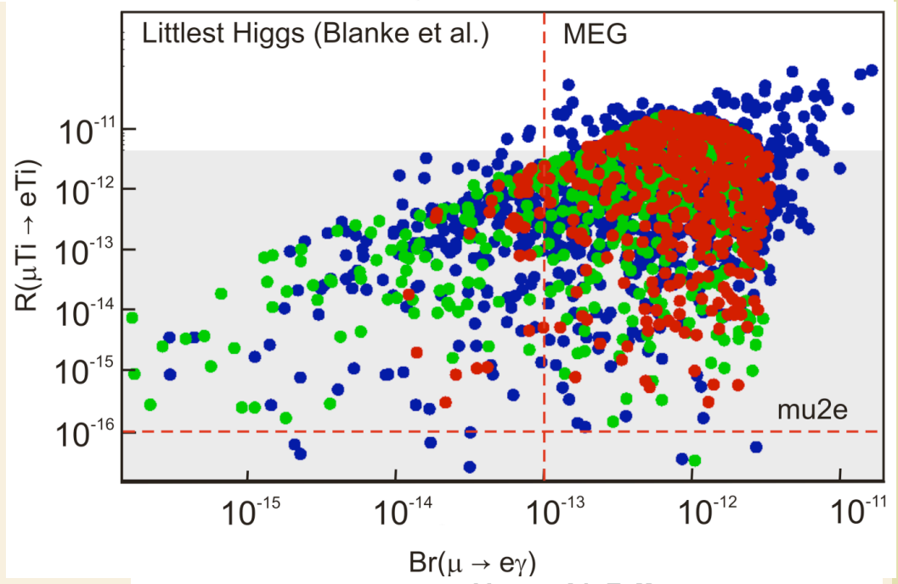
Heavy Neutrinos
$|U_{\mu N}U_{eN}|^2$ ~ 8×10^{-13}

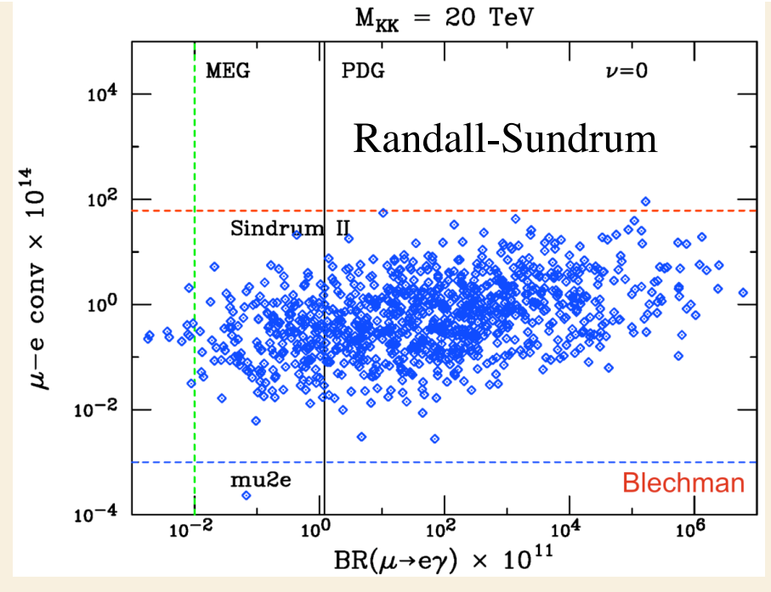
Second Higgs Doublet
$g(H_{\mu e})$ ~ $10^{-4}g(H_{\mu\mu})$

Heavy Z' Anomal. Z Coupling
$M_{Z'}$ = 3000 TeV/c²

Required Sensitivity







~10^{-16} constrains many models

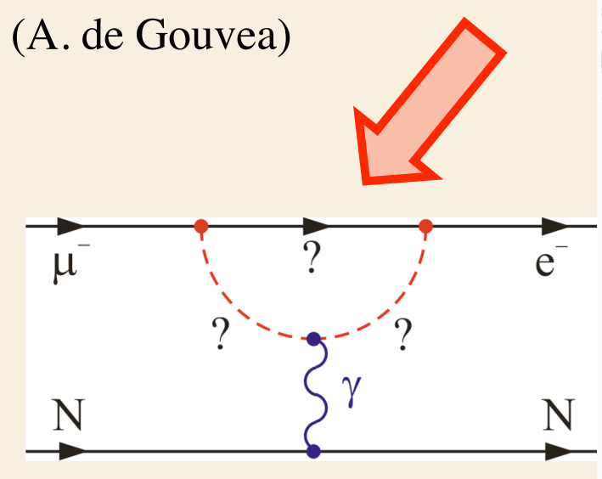
~10^{-18} ultimate goal

Sensitivity to 10^4 TeV scales: compelling physics case with or without LHC discoveries

$\mu^-N\to e^-N'$ and $\mu^+\to e^+\gamma$ are Complementary

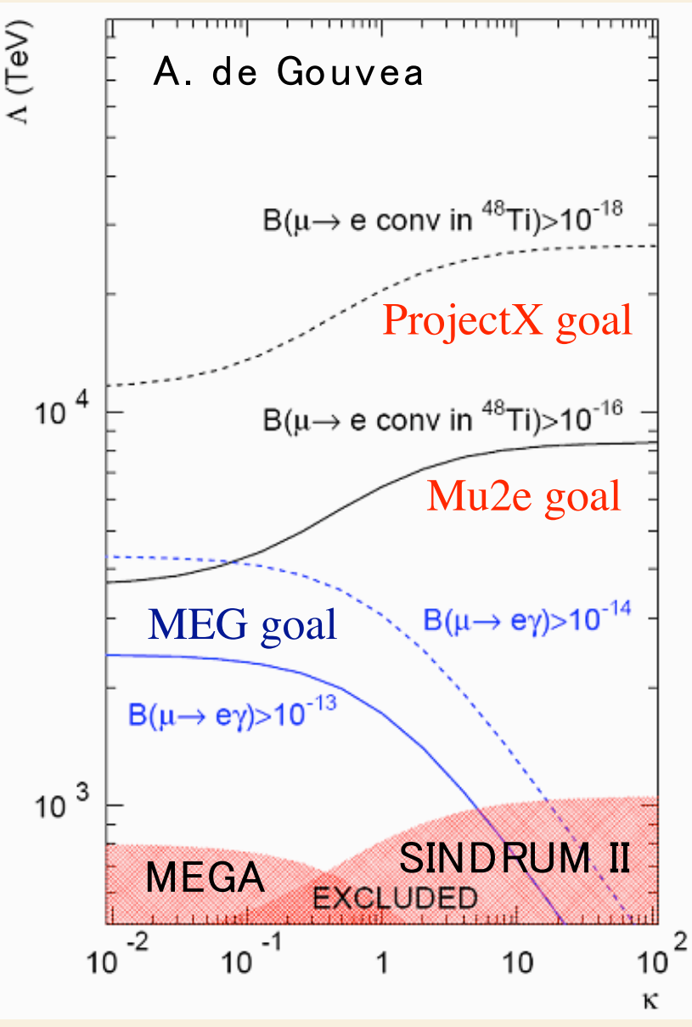
Model independent CLFV Lagrangian: (A. de Gouvea)

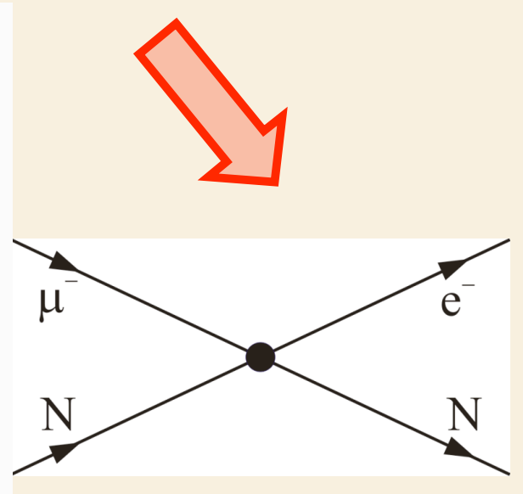
$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}R\sigma_{\mu\nu}e_L F_{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L \sum_{q=u,d}\bar{q}_L\gamma^\mu q_L$$



κ<<1
magnetic moment type operator

μ → eγ rate ~300x μN → eN' rate



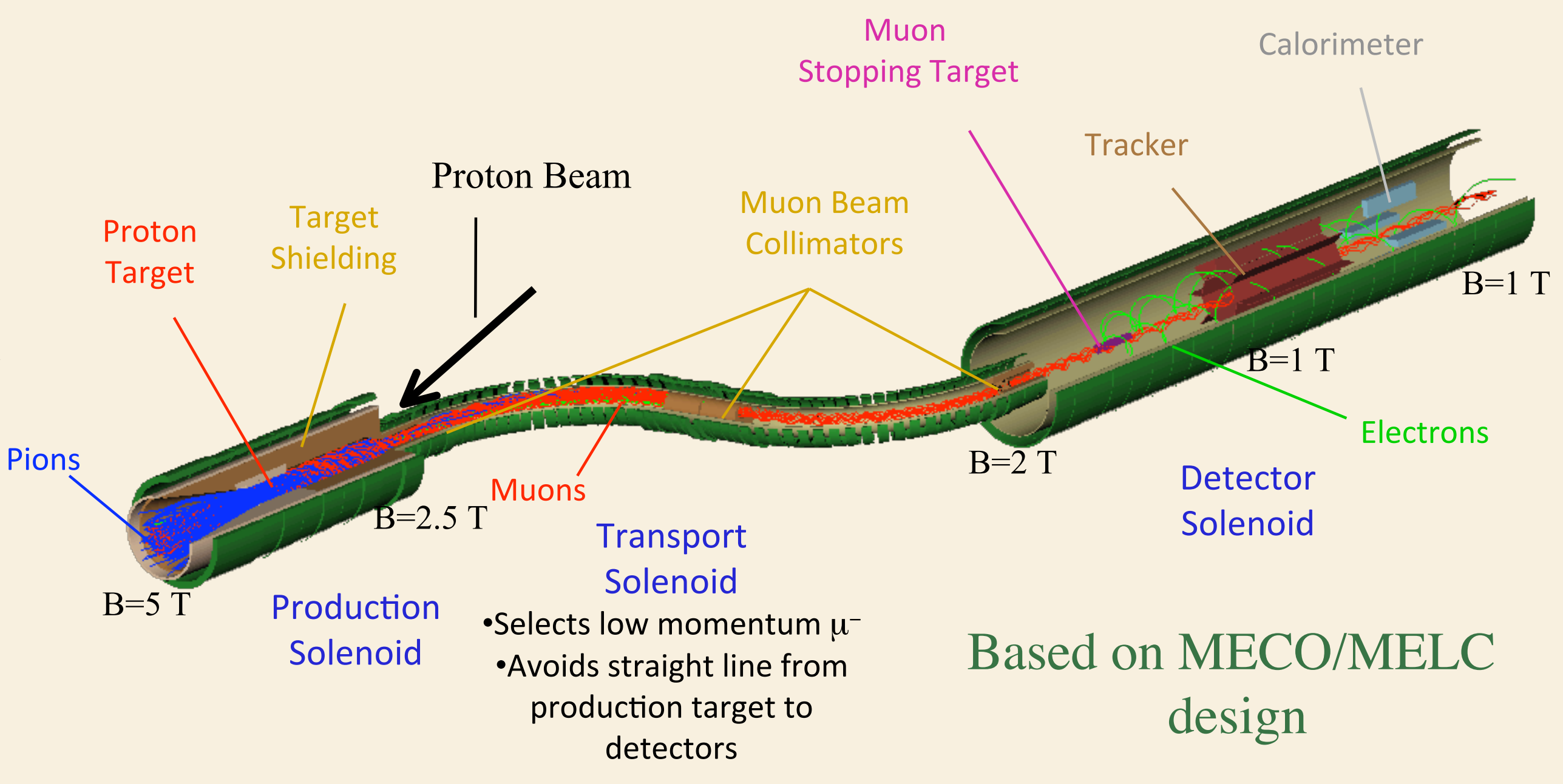


κ>>1
four-fermion interaction

μN → eN' greatly enhanced over μ → eγ rate

Experimental Apparatus

Muons are collected, transported, and detected in superconducting solenoidal magnets.



•Selects low momentum μ^-
•Avoids straight line from production target to detectors

Based on MECO/MELC design

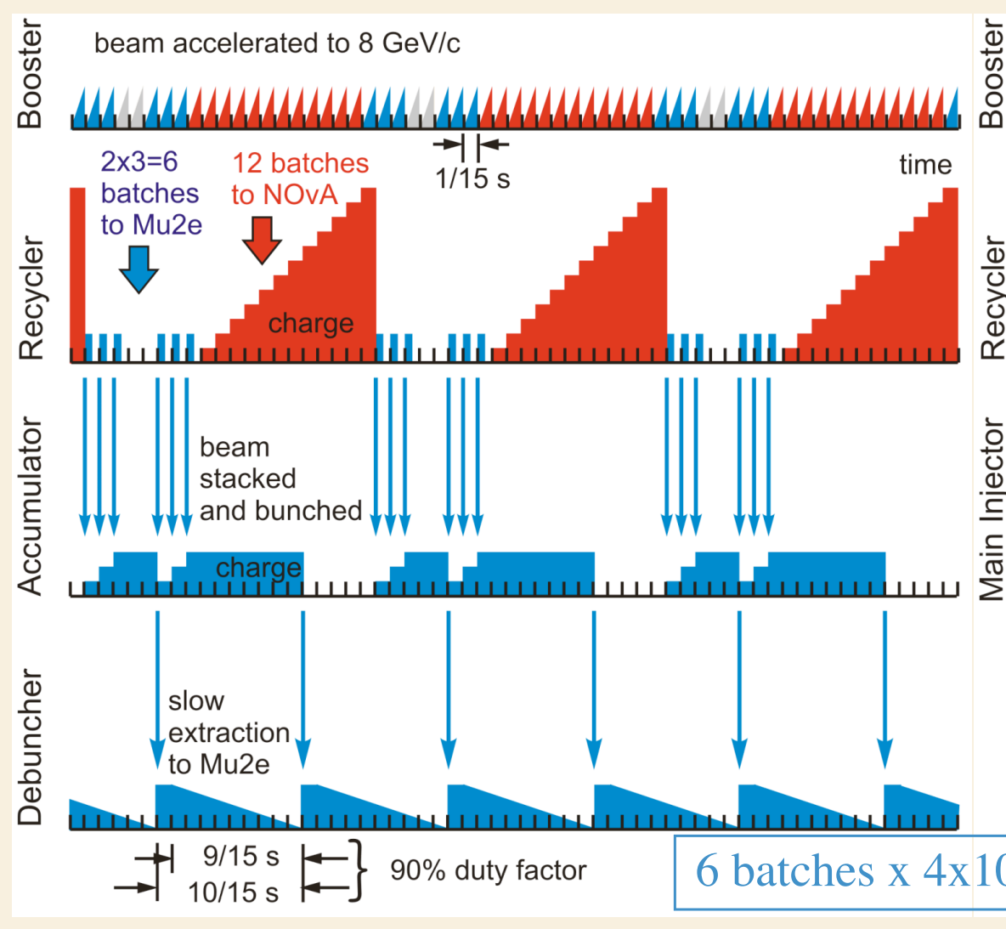
Key features:

- ✓ High acceptance: delivers 0.0025 stopped muons per 8 GeV proton
- ✓ Chicane geometry shields the detector from production target
- ✓ Separation of positive and negative particles, momentum selection
- ✓ Low-mass tracking detector with excellent momentum resolution (σ~0.3 MeV)
- ✓ Electromagnetic calorimeter provides robust trigger and particle ID for electrons
- ✓ Cosmic Ray Veto (not shown) rejects cosmic-ray induced background with 99.99% efficiency

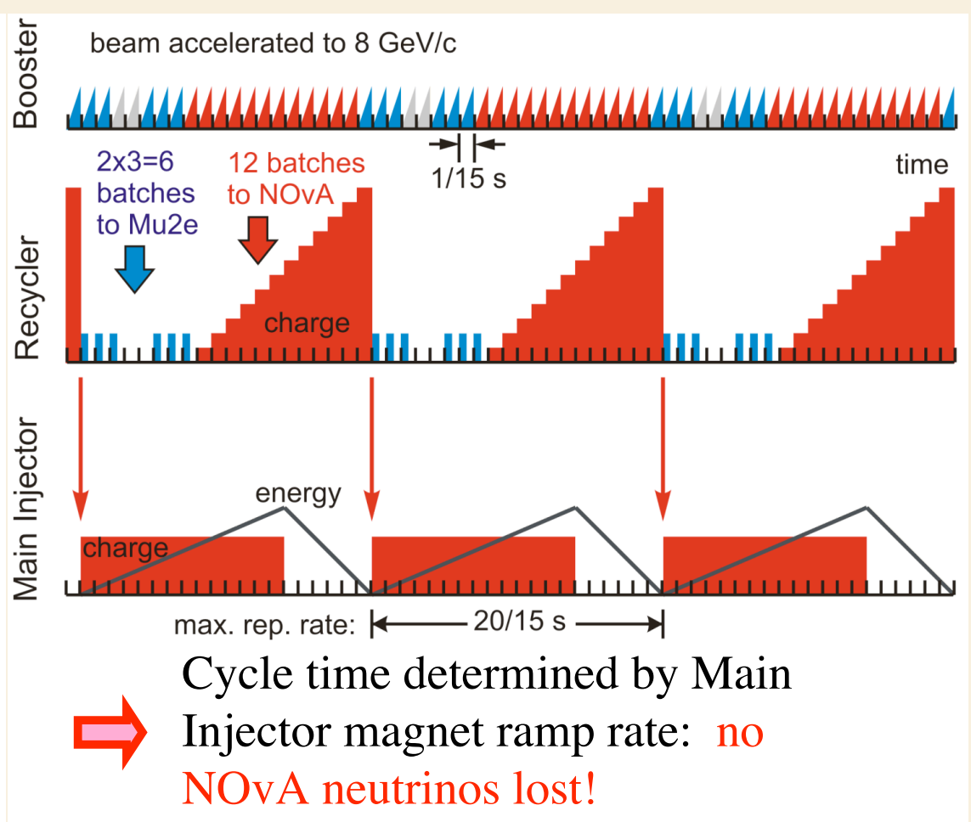
Proton Beamlines

Fermilab has a number of rings that become available after the end of the Tevatron operations. The accelerator complex is ideally suited for a broad intensity frontier program. Example: concurrent NOvA and Mu2e beam delivery with minimal accelerator upgrades.

Mu2e beam



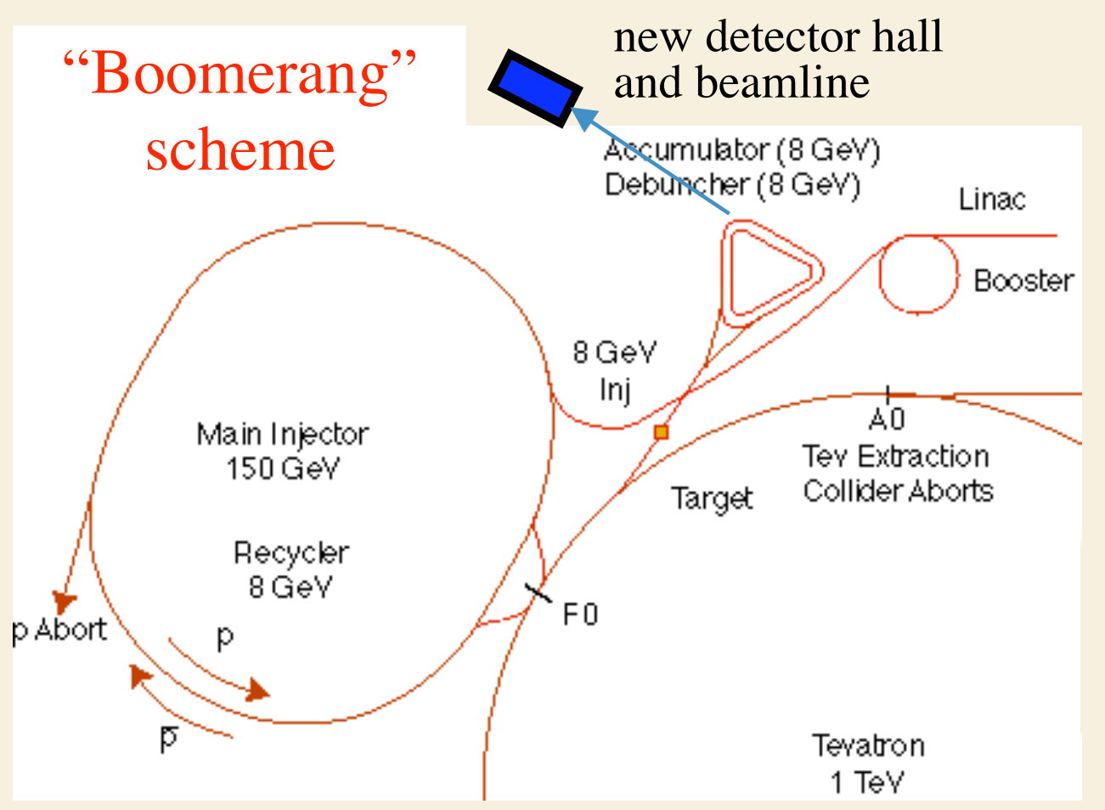
NOvA beam



Cycle time determined by Main Injector magnet ramp rate: no NOvA neutrinos lost!

6 batches x 4×10^{12} / 1.33 s x 2×10^7 s/yr = 3.6×10^{20} protons/yr

"Boomerang" scheme



Minimal accelerator modifications needed:

1. new switch magnet needed to transfer beam from Recycler to Antiproton Accumulator
2. upgrade for 15 Hz Booster rate

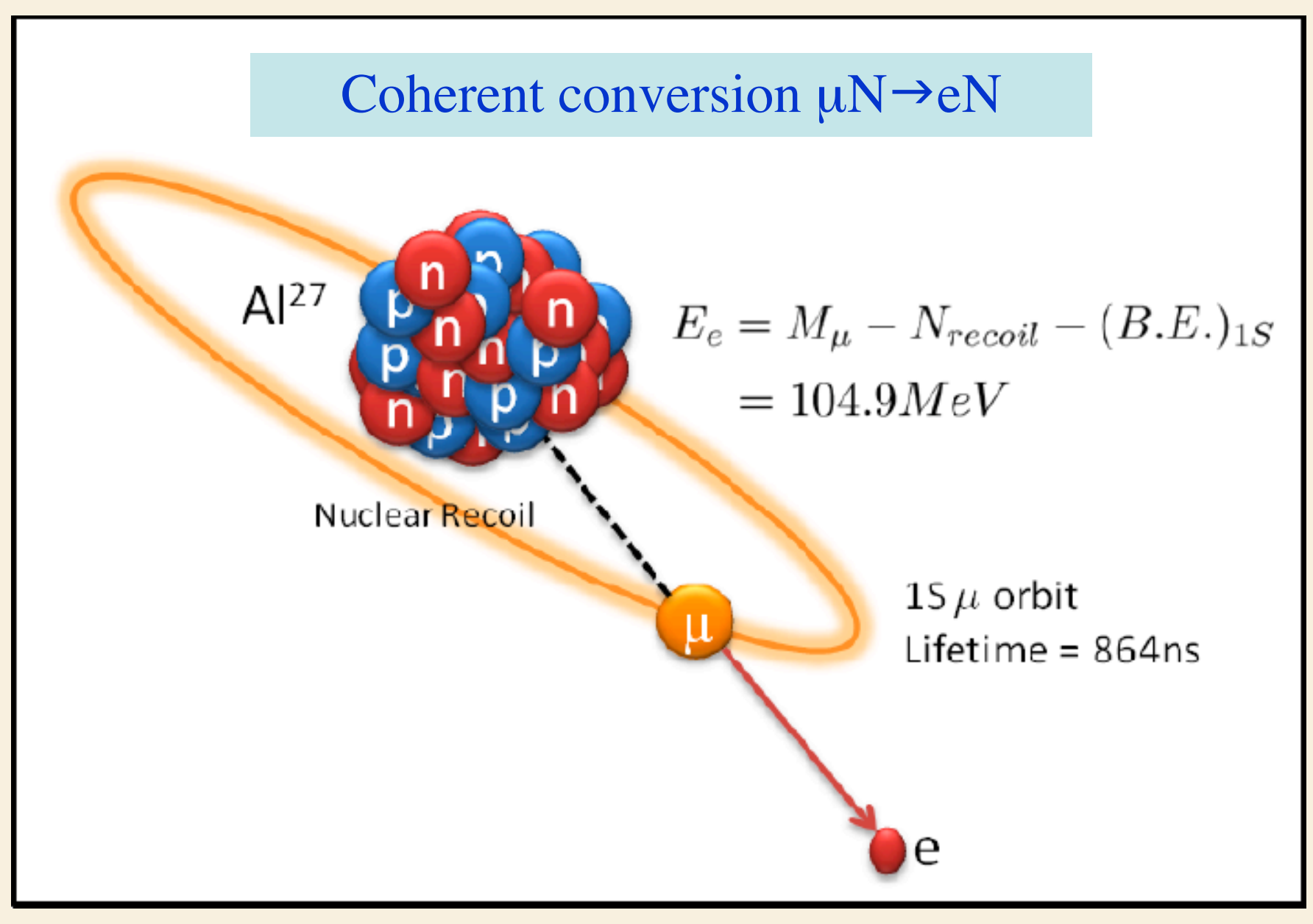
Experimental Technique

Negative muons stopped in an Aluminum target form muonic atoms with 1S binding energy of 500 keV and a lifetime of 864 nsec (40% decay, 60% nuclear capture). While the muon and nuclear wavefunctions overlap, the muons can undergo a coherent neutrinoless conversion of a muon to electron:

$$\mu^- + {}^{27}_{13}Al \to {}^{27}_{13}Al + e^- \qquad \text{Electron energy}\sim105\text{ MeV}$$

Choice of a nucleus is a tradeoff between higher conversion BR (↑with N²), longer lifetime (↓with Z³), and higher endpoint energy (N_{recoil} ↓ with N, B.E. ↑with Z²). Al and Ti have comparable sensitivities.

Coherent conversion μN→eN



$$E_e = M_\mu - N_{recoil} - (B.E.)_{1S} = 104.9 MeV$$

Key Experimental Features:

- ⇨ Pulsed, high-intensity proton beam (2×10^{13} Hz, 8 GeV @ Fermilab) with duty cycle matched to muon lifetime.
- ⇨ Solenoidal muon collection and transfer scheme with high acceptance (5×10^{10} Hz muon rate).
- ⇨ Muons with low momentum and narrow momentum spread to maximize stopping rate and avoid 105 MeV electrons from muon decays in flight.
- ⇨ Excellent momentum resolution for detected electrons, particle ID capabilities.

Backgrounds

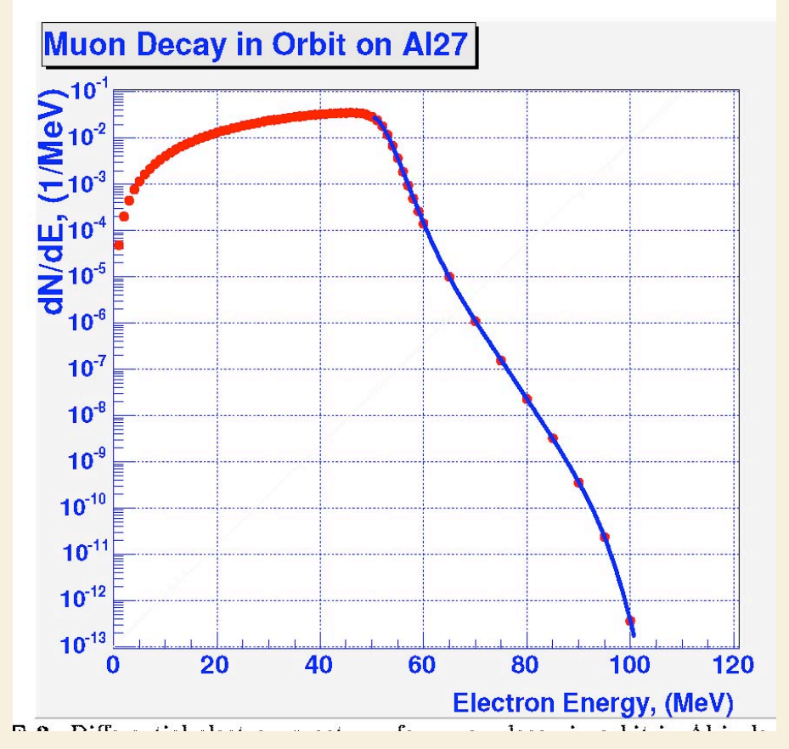
Muon Decays in Orbit

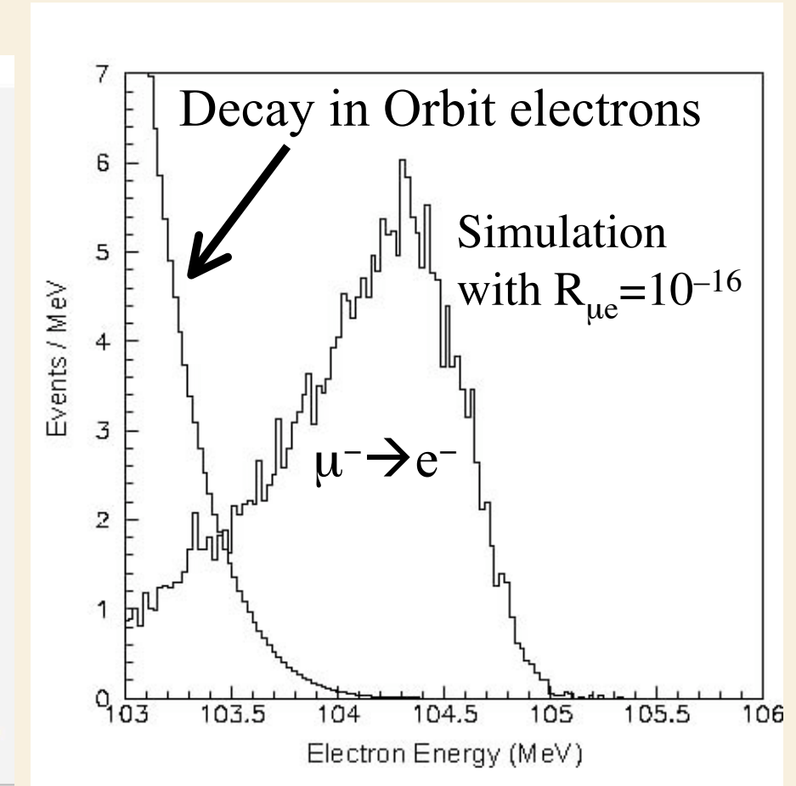
Electrons from muon decays in the bound state

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

have an endpoint energy of 105 MeV. The endpoint spectrum falls sharply as $prob \propto (E_{endpt} - E)^5$

This background is minimized by optimizing the electron spectrometer for resolution and reducing multiple scattering. Mu2e goal: FWHM ~0.9 MeV @ p=105 MeV, with σ~0.3 MeV on the high side.





Other Muon-induced Backgrounds

Ordinary muon capture on nucleus: $\mu^- + A(N,Z) \to A'(N',Z') + \nu_\mu + an + bp + c\gamma$, <a>~2, <b>~0.1, <c>~2
Neutral backgrounds produce high-rate environment in the detector. Suppressed by displacing the detectors from the direct line-of-sight from the stopping target and reducing their sensitivity to neutrons and gammas (low-mass gas straw tubes). Proton absorbers downstream of the stopping target reduce charge proton rate. Tracking detectors will also discriminate with dE/dx.

Radiative muon capture on nucleus: produces γ near conversion energy with probability of $O(10^{-5})$, can be followed by $\gamma\to e^+e^-$ conversion. Endpoint energy for Al is 102.4 MeV, 2.5 MeV below μ→e conversion energy. Rate is lower than DIO.

Muon decays in flight: suppress contribution to signal region by limiting the muon transport line acceptance to p_μ<75 MeV.

Radiative Pion Capture Backgrounds

Pions captured on the stopping target emit high-energy photons, which could convert in material and produce an electron in the signal region:

$$\pi^- + A(N,Z) \to A'(N',Z') + X + \gamma$$
$$\pi^- + {}^{27}_{13}Al \to {}^{27}_{12}Mg + \gamma,\ E \sim 137\text{ MeV}$$

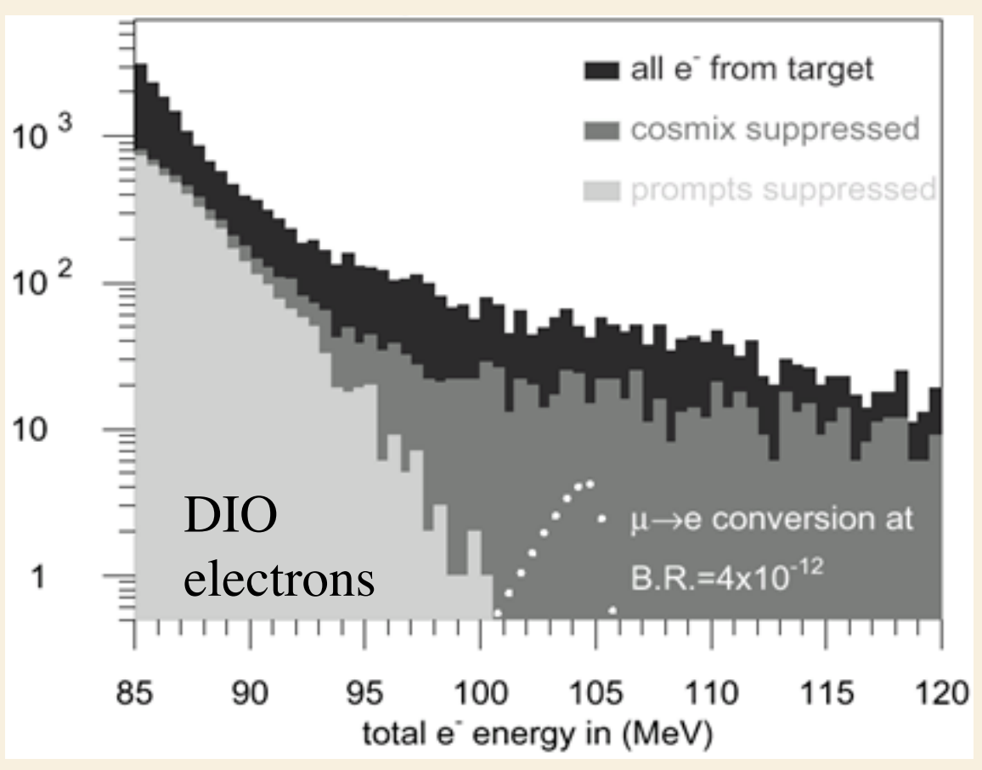
Pion stopping rate: 3×10^{-7} stopped pions per incident proton. This gives 1.7×10^{-13} fake electrons per incident proton. Radiative pion capture is prompt: suppress this background with pulsed beam.
Requirements: short (<100 nsec) bunches separated by 1.7 μs; 10^{-9} proton extinction between bunches.

Cosmic Ray Induced Backgrounds

Fake electrons in the region of interest can also be produced by cosmic ray interaction with the detector material and shielding. Suppress these by modest overburden (~6 m of Earth, concrete shielding, magnet yoke steel), pattern recognition in the tracker, and active Cosmic Ray Veto.

Summary of Background Contributions

SINDRUM-II (current best limit, DC beam)

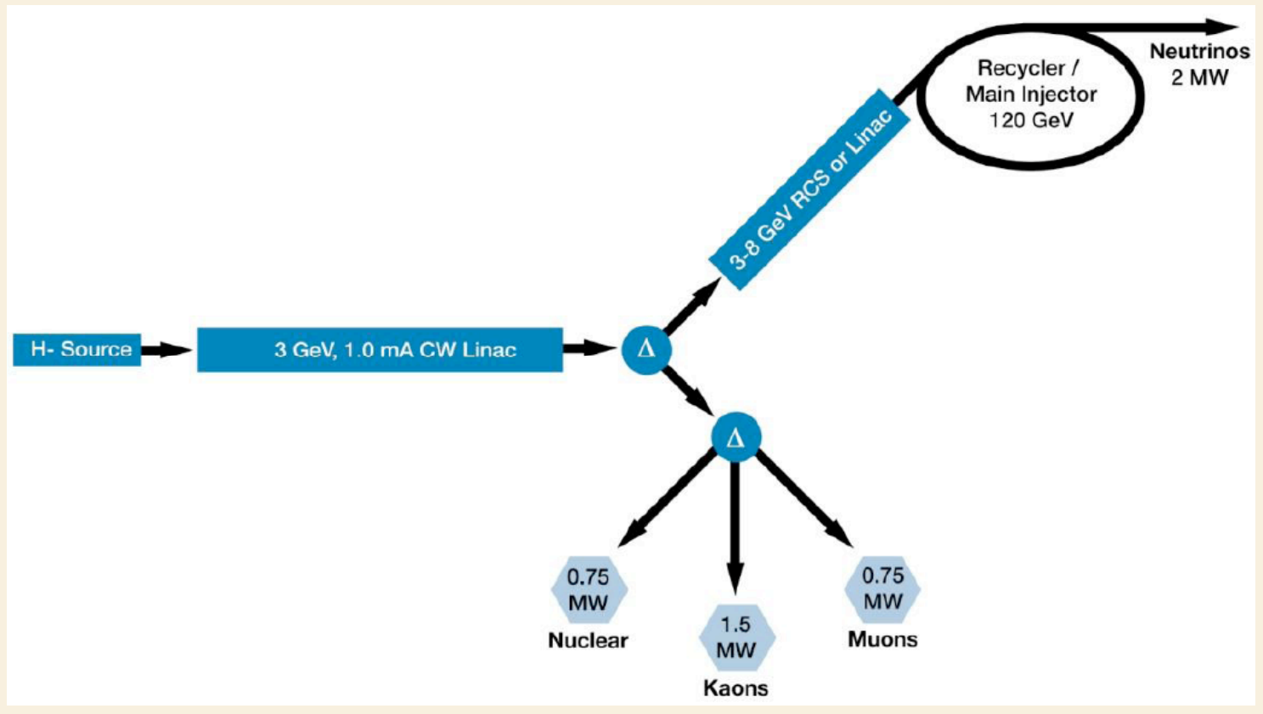


Mu2e Estimates

Source	Events	Comment
μ decay in orbit	0.225	signal/noise = 20 for $R_{\mu e} = 10^{-16}$
Pattern recognition errors	< 0.002	
Radiative μ capture	< 0.002	
Beam electrons*	0.036	
μ decay in flight*	< 0.027	without scatter in target
μ decay in flight*	0.036	with scatter in target
π decay in flight*	< 0.001	
Radiative π^- capture*	0.063	from protons during detection time
Radiative π^- capture	0.001	from late arriving π^-
Anti-proton induced	0.006	
Cosmic ray induced	0.016	assuming 10^{-4} CR veto inefficiency
Total background	0.41	

Expect 4 μ→e conversion events for $R_{\mu e}=10^{-16}$

Towards 10^{-18} Sensitivity: Project X



~40x increase in beam power to muon beamline with options for more. Broad scope.

Intensity sufficient to reach $R_{\mu e}$ ~ 10^{-18}
Will need to upgrade Mu2e to take advantage of the rates

Upgrade path will depend on the results from Mu2e. If a signal is observed at $R_{\mu e}$~10^{-16} or above, then precision exploration of CLFV mechanisms will require high statistics, and runs with heavier targets (various New Physics couplings scale differently with Z). This will require detector upgrades to handle higher instantaneous rates and shorter muon lifetime. If no signal was seen at Mu2e sensitivity, will improve sensitivity by increasing rates and reducing backgrounds. This will require a redesign of the beamline and detector.

Mu2e Collaboration: Boston U, BNL, UC Berkeley & LBNL, UC Irvine, CUNY, College of William & Mary, FNAL, JINR, UIUC, INR Troitsk, INFN Lecce, INFN Pisa & U di Pisa, LNF Frascati, UMass Amherst, LANL, Muons Inc, Northwestern U, Rice U, Syracuse U, U of Virginia, U of Washington

http://mu2e.fnal.gov