Lepton Flavor Violation Search via Muon to Electron Conversion

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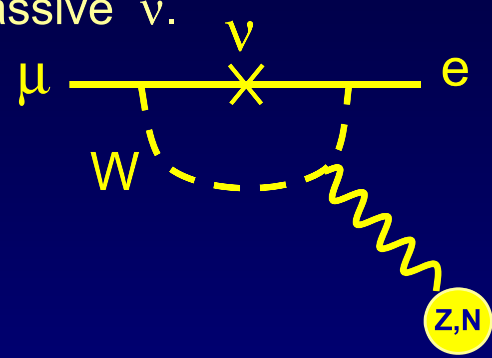
Outline:

- Physics motivation for lepton flavor violation experiments
- Experimental status of LFV
- Prospects for improvement
- Concept of $\mu^- N \rightarrow e^- N$ experiment
  - Physics of the conversion process
  - Background sources
  - Detector requirements
- Possible Fermilab and JPARC implementations

What Will Observation of $\mu \to e\gamma$ or $\mu^- N \to e^- N$ Teach Us?

Discovery of $\mu^- N \to e^- N$ or a similar charged lepton flavor violating (LFV) process will be unambiguous evidence for physics beyond the Standard Model. This process is completely free of *background* from Standard Model processes.

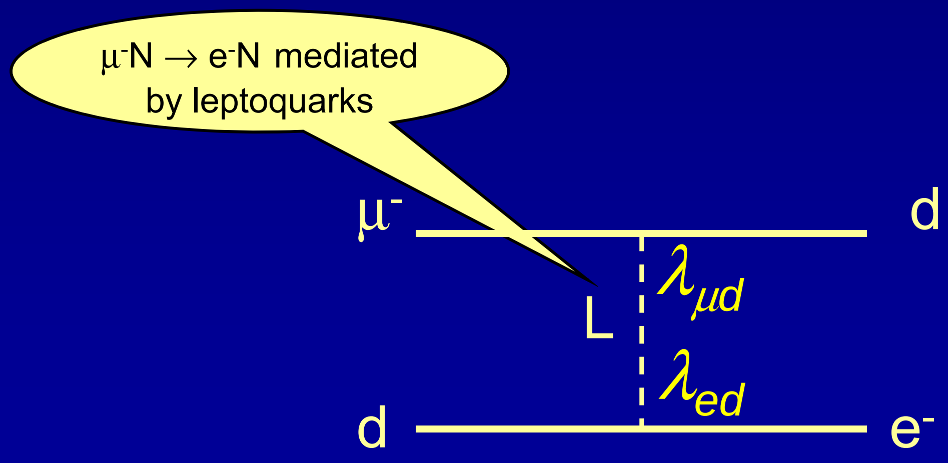
- For non-degenerate neutrino masses, ν oscillations can occur. Discovery of neutrino oscillations required changing the Standard Model to include massive ν.
- Charged LFV processes occur through intermediate states with ν mixing. Small ν mass differences and mixing angles $\Rightarrow$ expected rate is well below what is experimentally accessible: rate is proportional to $[\Delta(M_\nu)^2/(M_W)^2]^2$.



- Current limits on LFV in charged sector provides severe constraints on models for physics beyond the Standard Model and occur in nearly all scenarios for physics beyond the SM, in many scenarios at a level that current generation experiments could detect.
- Effective mass reach of sensitive searches is enormous, well beyond that accessible with direct searches.

$$R_{\mu e} \equiv \frac{\Gamma(\mu^- N \to e^- N)}{\Gamma(\mu^- N \to \nu_\mu N')} = 10^{-16}$$

$$\Rightarrow \quad M_L = 3000\sqrt{\lambda_{\mu d}\lambda_{ed}}\ \text{TeV}/c^2$$



Coherent Conversion of Muon to Electrons ($\mu^- N \to e^- N$)

- Muons stop in matter and form a muonic atom.
- They cascade down to the 1S state in less than 10^{-16} s.
- They coherently interact with a nucleus (leaving the nucleus in its ground state) and convert to an electron, without emitting neutrinos $\Rightarrow$ $E_e = M_\mu - E_{NR} - E_B$.
  Coherence gives extra factor of Z with respect to capture process, reduced for large Z by nuclear form factor.
- Experimental signature is an electron with E_e=105.1 MeV emerging from stopping target, with no incoming particle near in time: background/signal independent of rate.
- More often, they are captured on the nucleus: $\mu^-(N,Z) \to \nu_\mu(N,Z-1)$
  or decay in the Coulomb bound orbit: $\mu^-(N,Z) \to \nu_\mu(N,Z)\nu_e$
  (τ_μ = 2.2 μs in vacuum, ~0.9 μs in Al)
- Rate is normalized to the kinematically similar weak capture process:

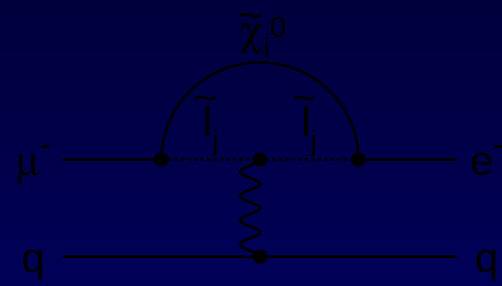
$$R_{\mu e} \equiv \frac{\Gamma(\mu^- N \to e^- N)}{\Gamma(\mu^- N \to \nu_\mu N(Z-1))}$$

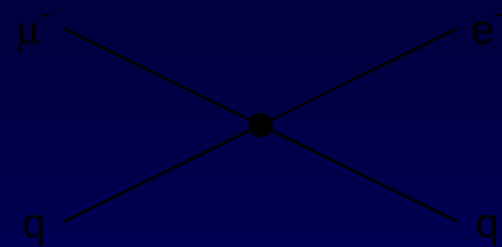
Goal of new experiment is to detect $\mu^- N \to e^- N$ if $R_{\mu e}$ is at least 2×10^{-17} with one event providing compelling evidence of a discovery.

Sensitivity to Different Muon Conversion Mechanisms

Supersymmetry

Predictions at 10^{-15}



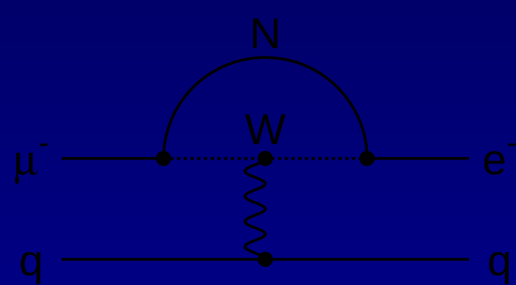


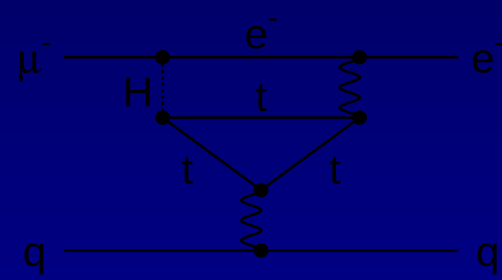
Compositeness

$\Lambda_C = 3000$ TeV

Heavy Neutrinos

$\left|U^*_{\mu N} U_{eN}\right|^2 = 8 \times 10^{-13}$



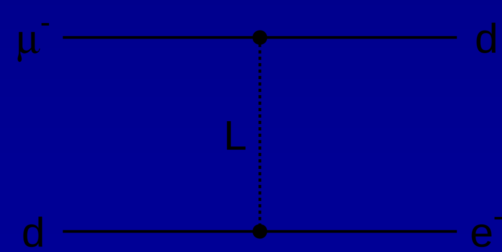


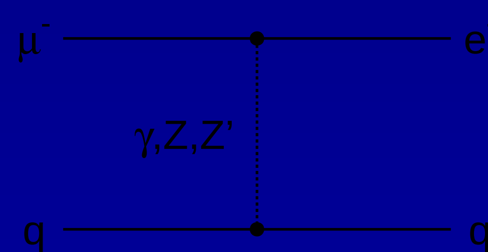
Second Higgs doublet

$g_{H_{\mu e}} = 10^{-4} \times g_{H_{\mu\mu}}$

Leptoquarks

$M_L = 3000\sqrt{\lambda_{\mu d}\lambda_{ed}}$ TeV/c^2





Heavy Z', Anomalous Z coupling

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

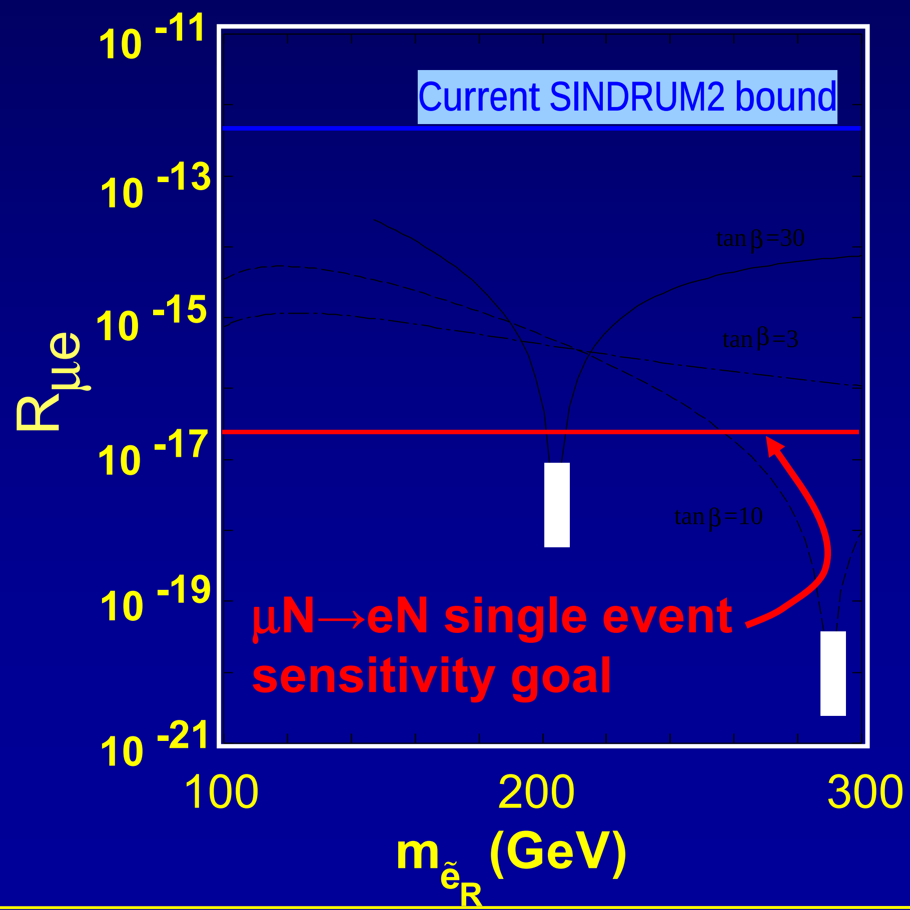
$B(Z \to \mu e) < 10^{-17}$

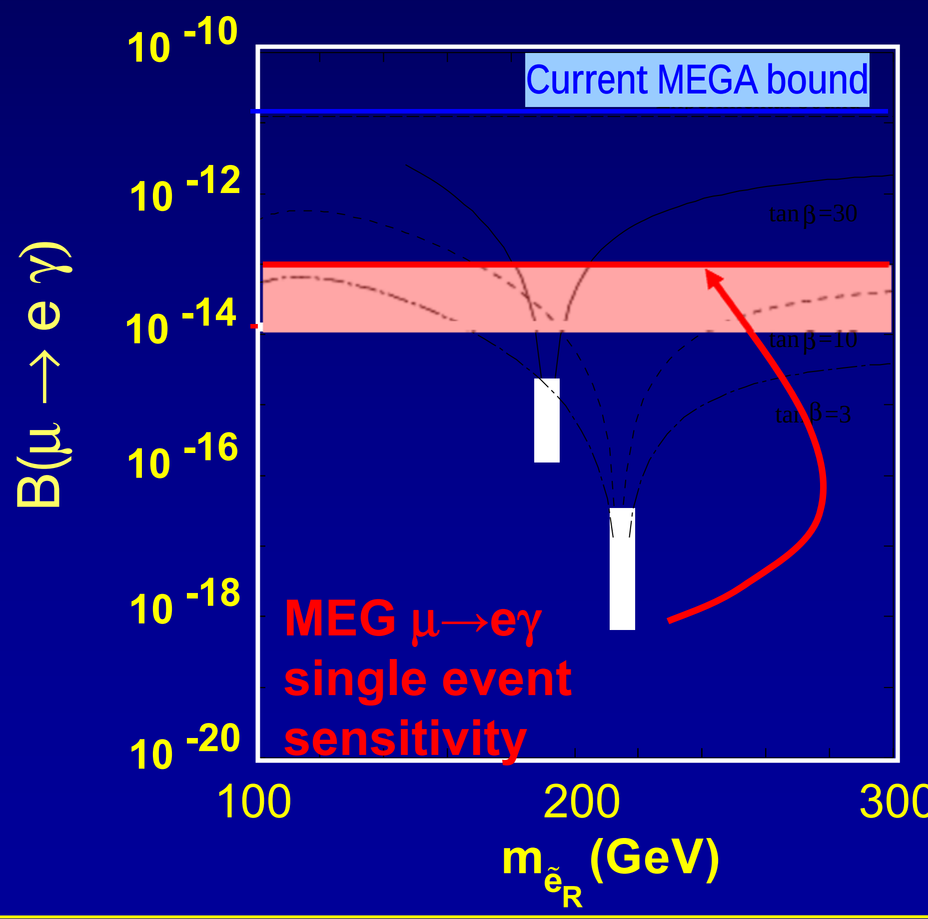
After W. Marciano

Supersymmetry Predictions for LFV Processes

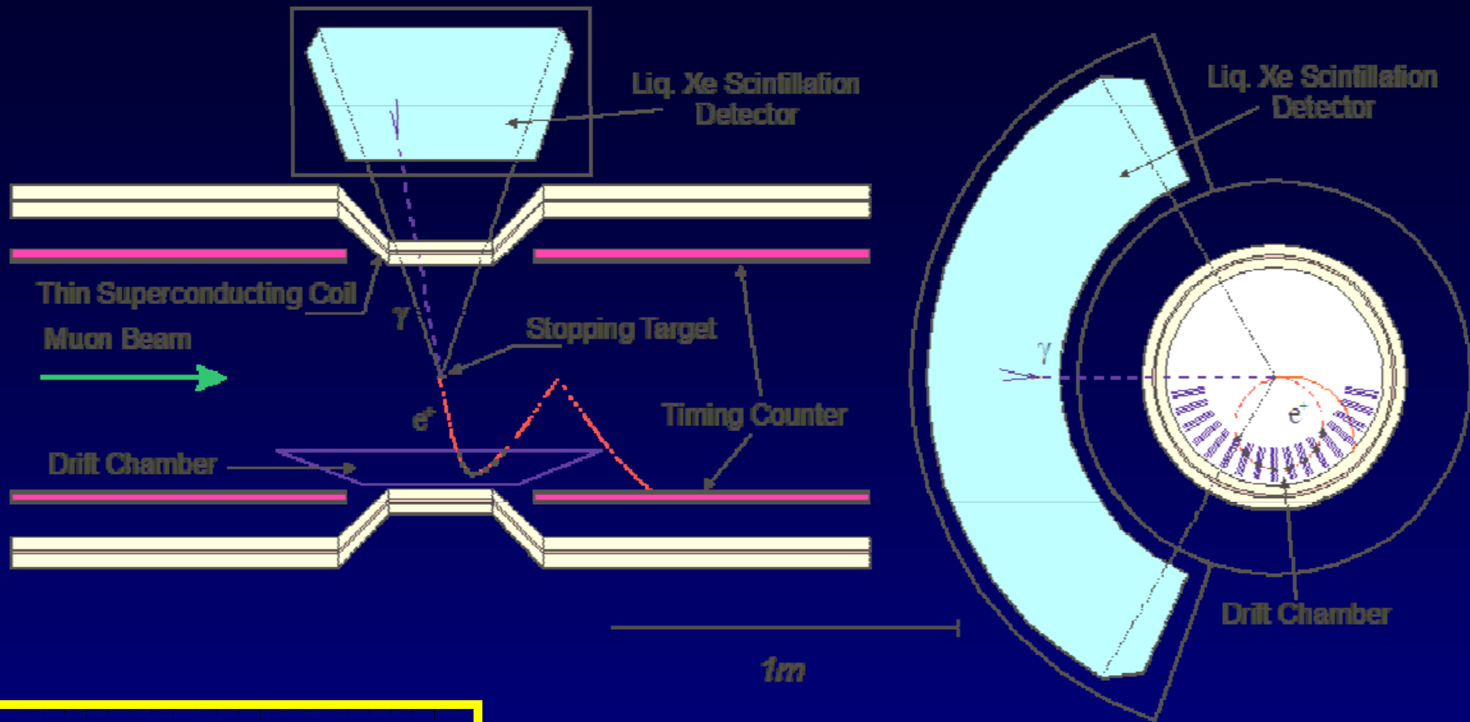
- From Hall and Barbieri
  Large t quark Yukawa couplings imply observable levels of LFV in supersymmetric grand unified models
- Extent of lepton flavor violation in grand unified supersymmetry related to quark mixing
- Original ideas extended by Hisano, et al.

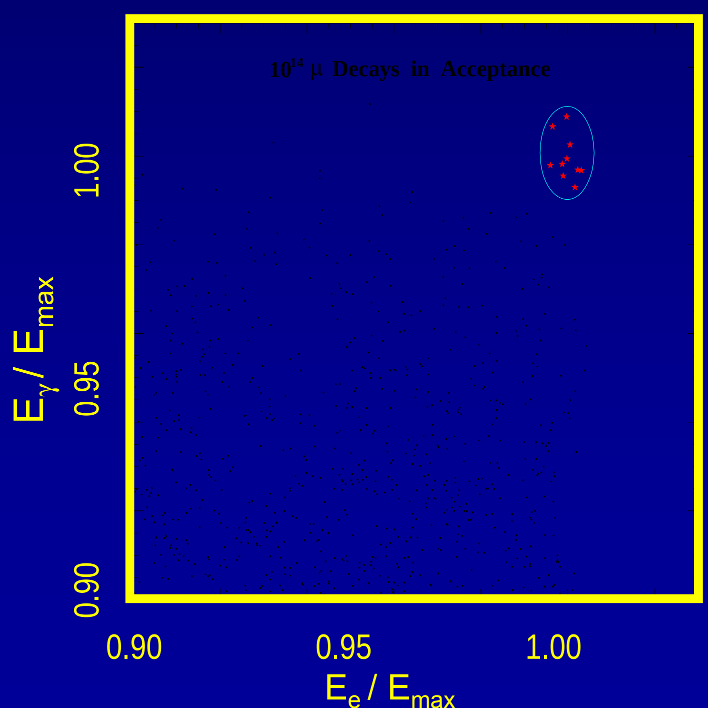
Process	Current Limit	SUSY level
$\mu^- N \to e^- N$	10^{-12}	10^{-15}
$\mu^+ \to e^+ \gamma$	10^{-11}	10^{-13}
$\tau \to \mu\gamma$	10^{-7}	10^{-9}





The MEG Experiment at PSI





- Experiment limited by accidental backgrounds: e^+ from Michel decay, γ from radiative decay or annihilation in flight. S/N proportional to 1/Rate.
  - ΔE_e : 0.8% (FWHM) ΔE_γ : 4.5% (FWHM)
  - $\Delta\theta_{e\gamma}$: 18 mrad (FWHM) $\Delta t_{e\gamma}$: 141ps (FWHM)
- MEG uses the PSI cyclotron (1.8 mA at ~600 MeV) to produce 10^8 μ^+ per second (surface muon beam)
- Engineering run this autumn with full detector
- First physics run Spring 2008
- Sensitivity of 10^{-13} with 2 years running (c.f. MEGA 1.2×10^{-11})
- Possibility of detector improvements to reach 10^{-14} in subsequent 2 year run

Why $\mu^- N \rightarrow e^- N$ Conversion Experiment?

- Rate for τ LFV processes might be significantly higher, but reaching equivalent sensitivity in popular models is very difficult, requiring new accelerator and very large improvement in experimental techniques – significant progress is unlikely to be made in next decade

- $\mu \rightarrow e\gamma$ decay is more sensitive at same branching fraction for the most popular extensions to the Standard Model, but is less sensitive for other modes and appears to be limited by background considerations at 100-1000 times larger branching fraction than could be achieved in next generation conversion experiment. Conversion experiment has possibility of both helicity changing and helicity conserving amplitudes.

- Most robust channel for discovering LFV in charged sector (funding and other non-technical considerations aside) appears to be in $\mu^- N \rightarrow e^- N$ experiment. This is the only channel that can be pushed to significantly higher sensitivity due to backgrounds in other modes.

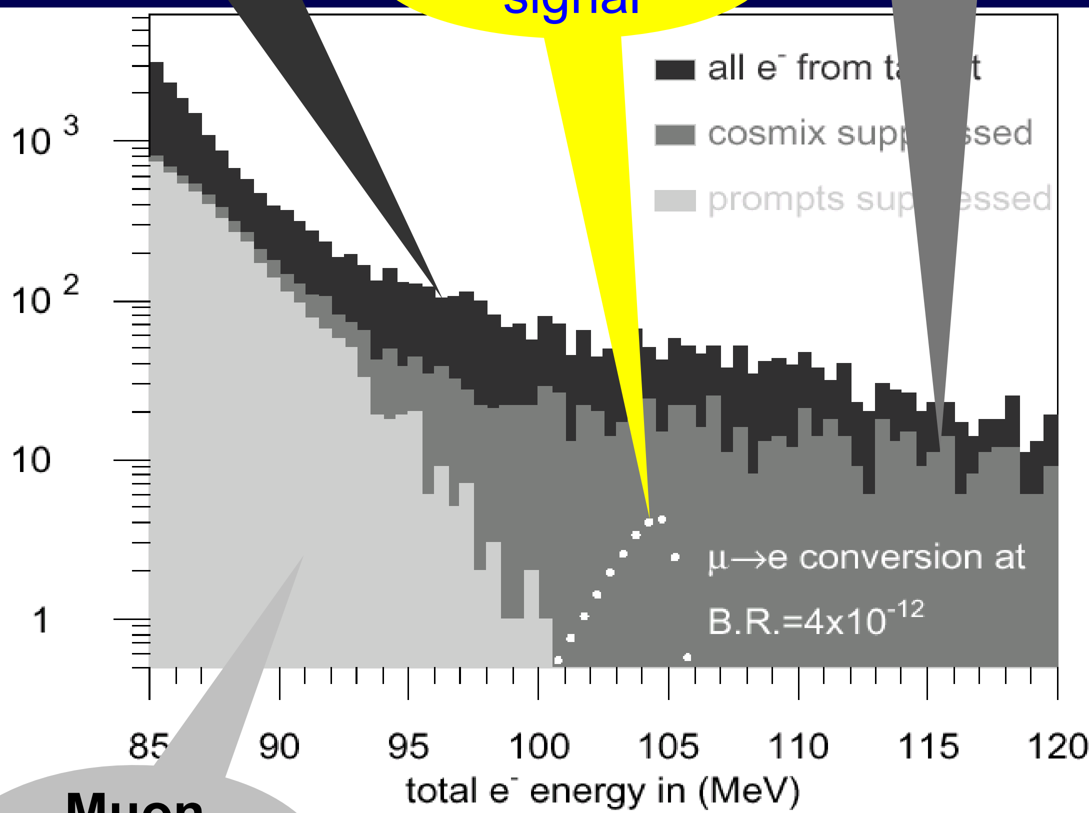
What Drives the Design of the Next-Generation Conversion Experiment?

Considerations of potential sources of fake backgrounds specify much of the design of the beam and experimental apparatus.

Prompt background

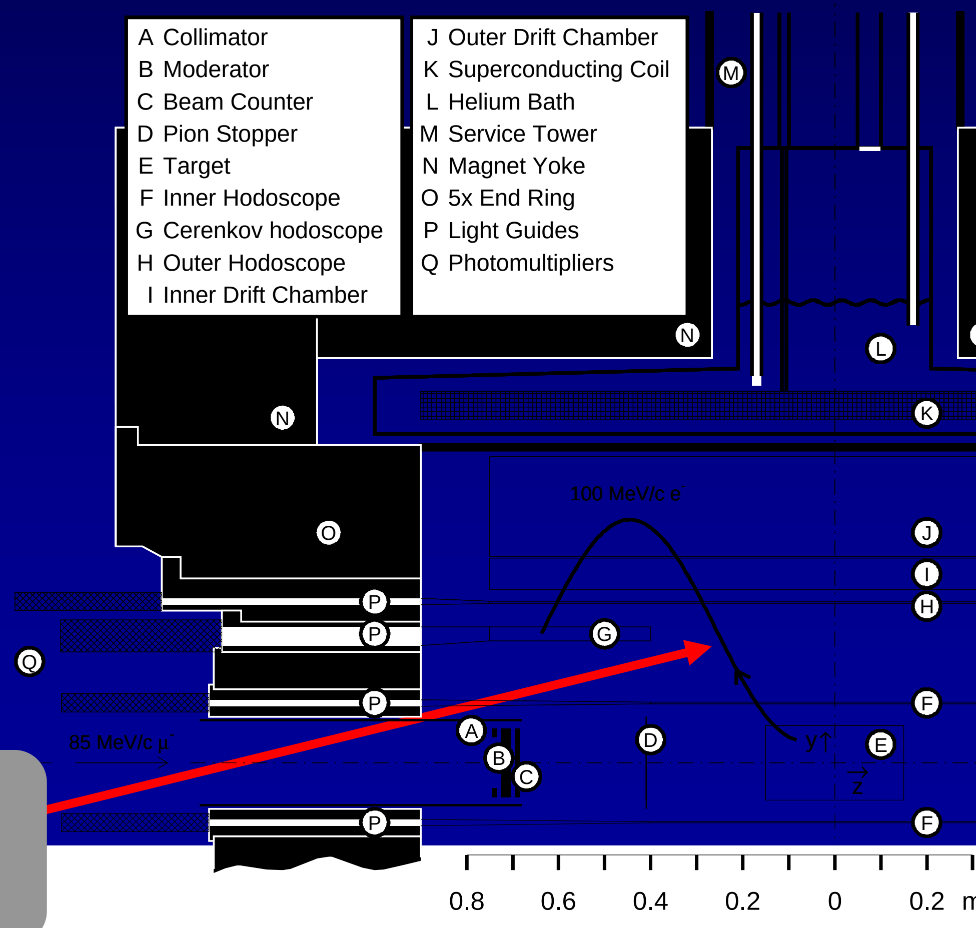
Expected signal

Cosmic ray background



Muon decay in orbit

SINDRUM2 currently has the best limit on this process:



Experimental signature is 105 MeV e^- originating in a thin stopping target.

Features of a New $\mu^- N \rightarrow e^- N$ Experiment

- 1000 fold increase in muon intensity using an idea from MELC at MMF
  - High Z target for improved pion production
  - Graded solenoidal field to maximize pion capture
  - Produce $\approx 10^{-2}$ m^-/p at 8 GeV (SINDRUM2 $\approx 10^{-8}$, MELC $\approx 10^{-4}$, Muon Collider ≈ 0.3)
  - Muon transport in curved solenoid suppressing high momentum negatives and all positives and neutrals

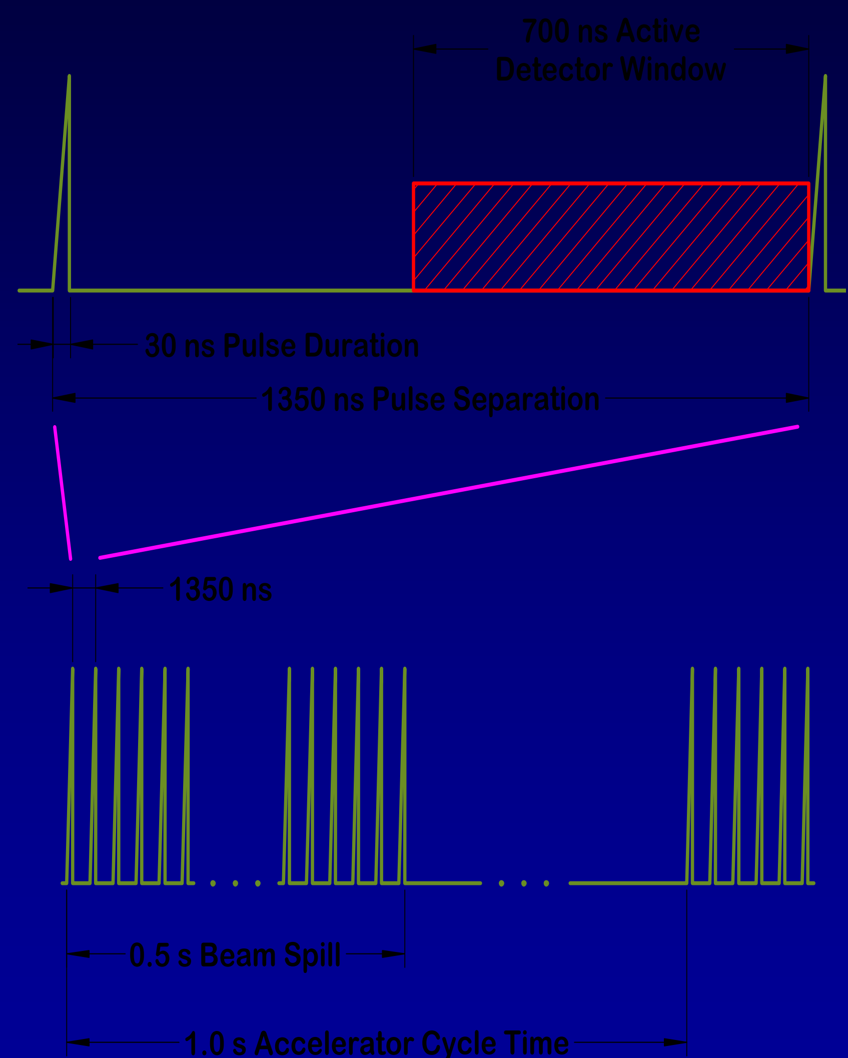
- Pulsed beam to eliminate prompt backgrounds following PSI method (A. Badertscher, et al. 1981)
  - Beam pulse duration << t_m
  - Pulse separation $\approx t_m$
  - Large duty cycle (50%)
  - Extinction between pulses < 10^{-9}

- Improved detector resolution and rate capability
  - Detector in graded solenoid field for improved acceptance, rate handling, background rejection following MELC concept
  - Spectrometer with nearly axial components and very high resolution

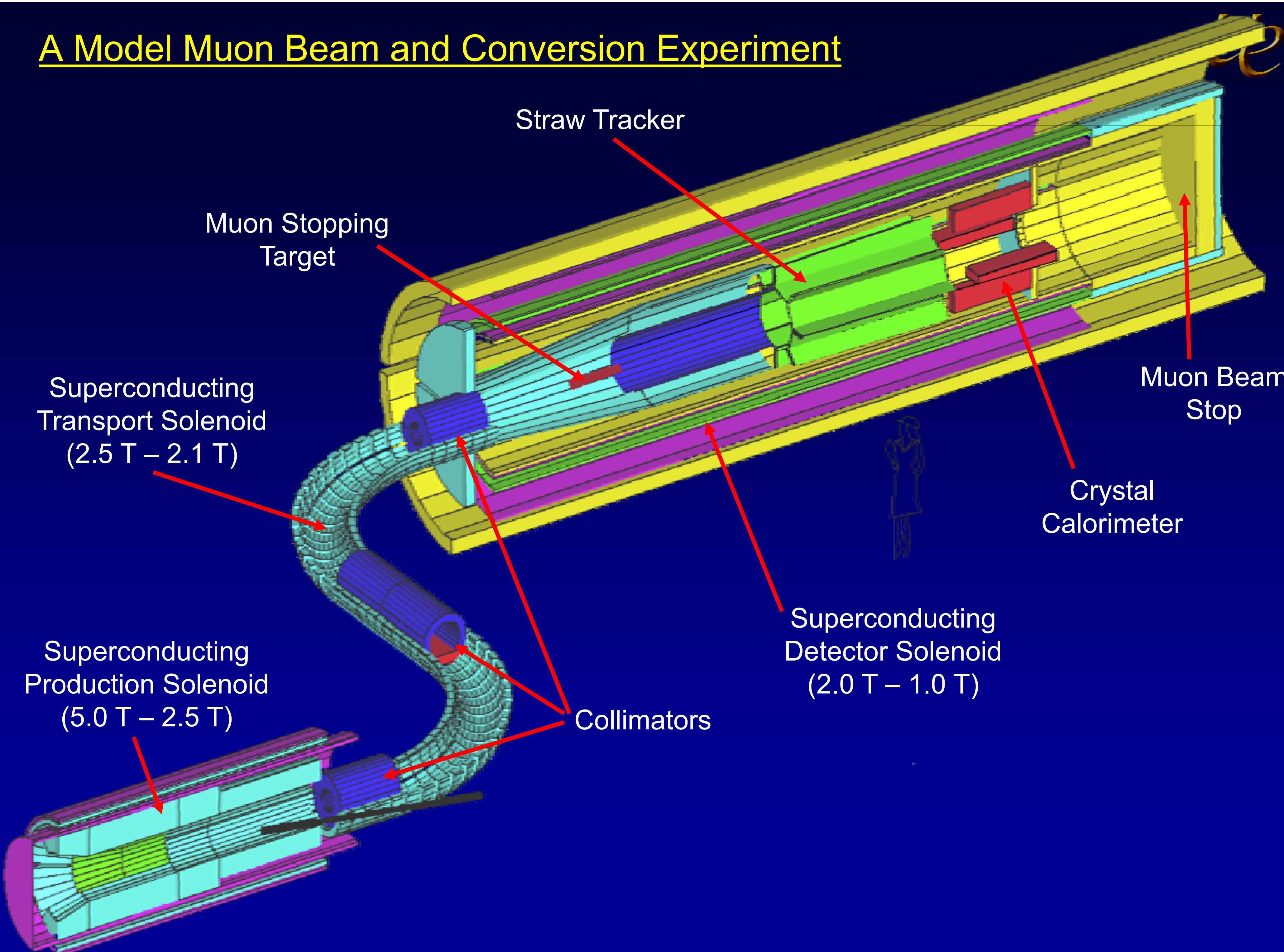
These features were captured in the MECO experiment that was designed, approved for construction and operation at BNL, and subsequently cancelled.

Pulsed Proton Beam Requirement for $\mu^- N \rightarrow e^- N$ Experiment

- Subsequent discussion focuses on accelerator operating 8 GeV with 4×10^{13} protons per second and 50% duty cycle – 50 kW instantaneous beam power at 8 GeV
- Pulsed proton beam generated using RF structure of appropriate accelerator or storage ring
- To eliminate prompt backgrounds, we require $< 10^{-9}$ protons between bunches for each proton in bunch. We call this the beam extinction.
- Gap between proton pulse and start of detection time largely set by pion lifetime ($\sim 25\ \tau_\pi$)

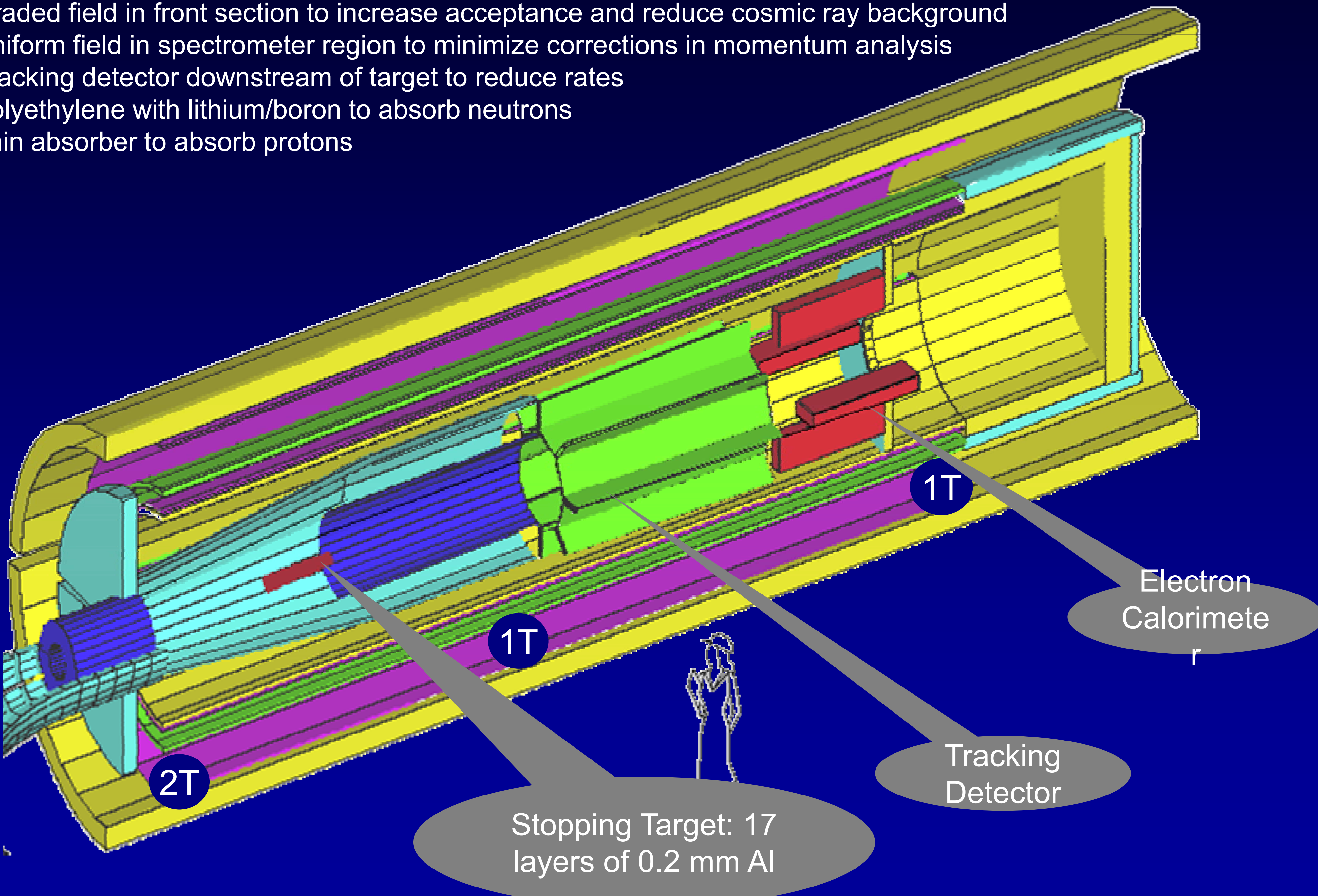


A Model Muon Beam and Conversion Experiment

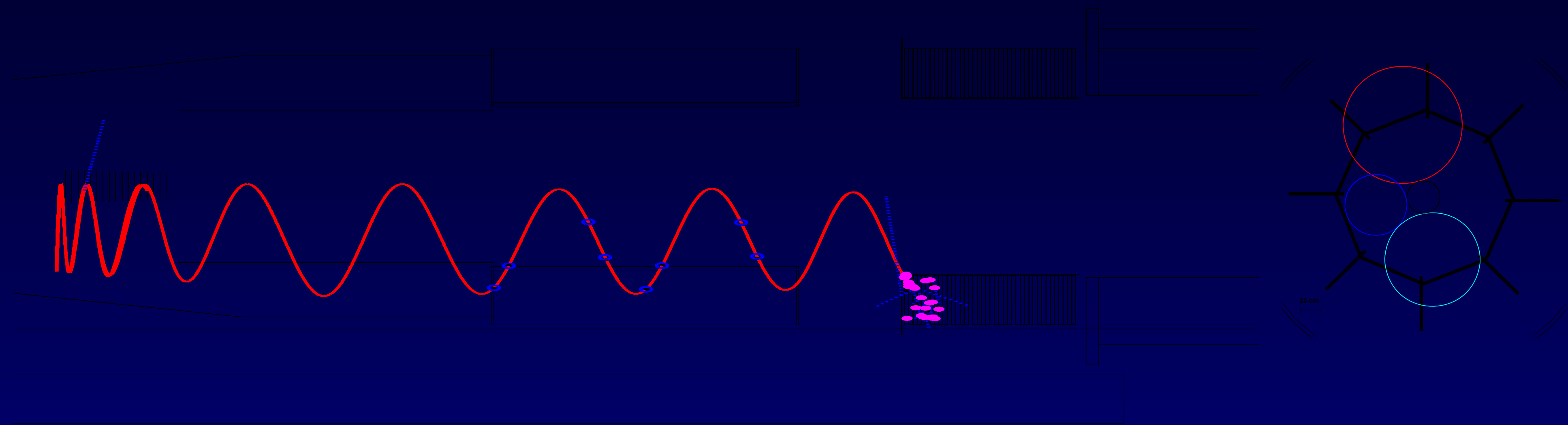


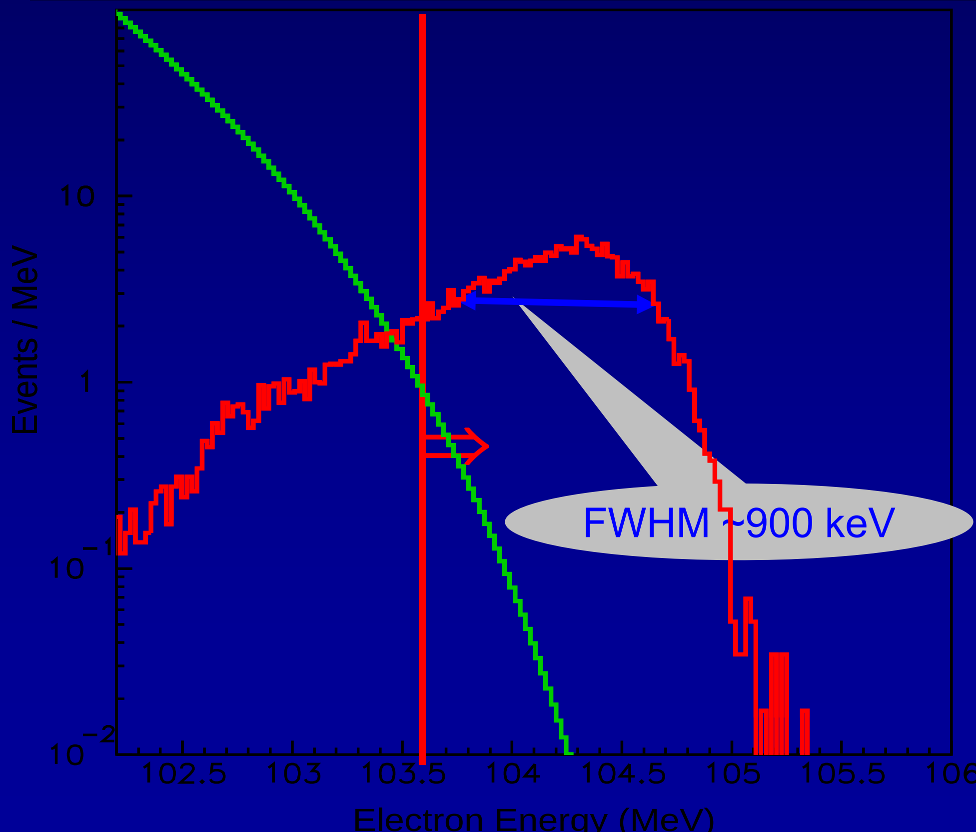
Stopping Target and Experiment in Detector Solenoid

- Graded field in front section to increase acceptance and reduce cosmic ray background
- Uniform field in spectrometer region to minimize corrections in momentum analysis
- Tracking detector downstream of target to reduce rates
- Polyethylene with lithium/boron to absorb neutrons
- Thin absorber to absorb protons



Spectrometer Performance Calculations





- Performance calculated using Monte Carlo simulation of all physical effects
- Resolution dominated by multiple scattering in tracker and energy loss in target
- Resolution function of spectrometer convolved with theoretical calculation of muon decay in orbit to get expected background.
- Geometrical acceptance ~50% (60°-120°)
- *Alternate transverse geometry has similarly good tracking performance with sophisticated fitting.*

Expected Signal and Background with 4×10^{20} Protons

Background Source	Events	Comments
μ decay in orbit	0.25	S/N = 4 for $R_{\mu e} = 2 \times 10^{-17}$
Tracking errors	< 0.006	
Beam e^-	< 0.04	
μ decay in flight	< 0.03	No scattering in target
μ decay in flight	0.04	Scattering in target
Radiative π capture	0.07	From out of time protons
Radiative π capture	0.001	From late arriving pions
Anti-proton induced	0.007	Mostly from π^-
Cosmic ray induced	0.004	10^{-4} CR veto inefficiency
Total Background	0.45	With 10^{-9} inter-bunch extinction

Background calculated for 10^7 s running time at intensity giving 5 signal event for $R_{\mu e} = 10^{-16}$.

Sources of background can be identified and understood by studying data.

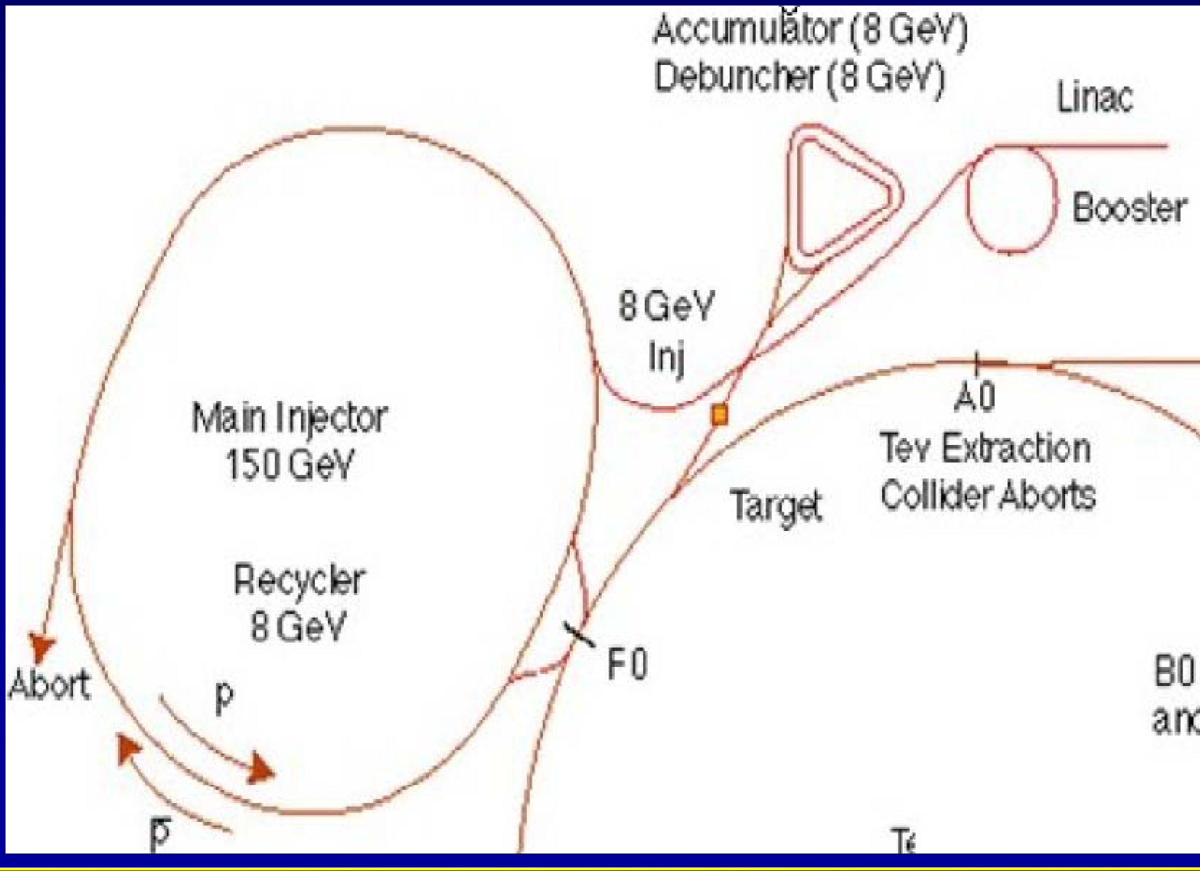
5 signal events with 0.5 background events in 10^7 s running if $R_{\mu e} = 10^{-16}$

Factors affecting the Signal Rate	Factor
Running time (s)	10^7
Proton flux (Hz) (50% duty factor, 740 kHz μpulse)	4×10^{13}
μ entering transport solenoid / incident proton	0.0043
μ stopping probability	0.58
μ capture probability	0.60
Fraction of μ capture in detection time window	0.49
Electron trigger efficiency	0.90
Geometrical acceptance, fitting and selection criteria efficiency	0.19
Detected events for $R_{\mu e} = 10^{-16}$	5.0

Implementing a MECO Experiment at Fermilab

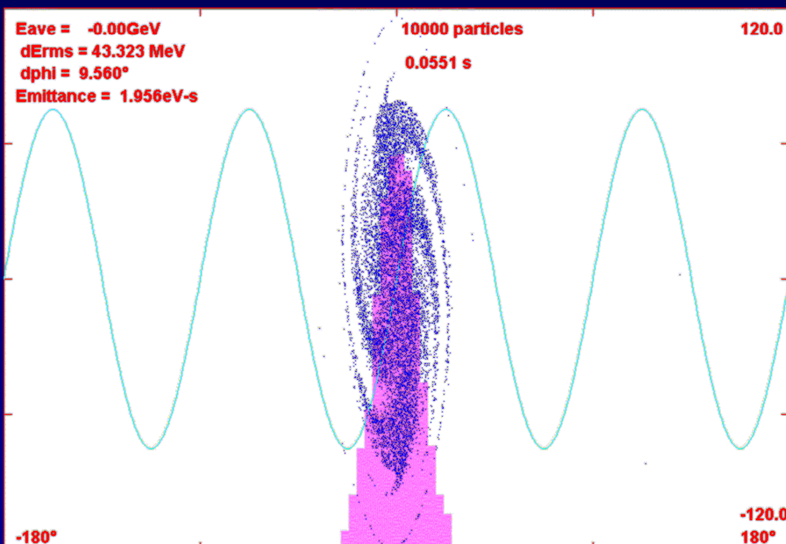
- Complex of accelerators underused after Tevatron run finished
- Proton beam could be shared with neutrino program – "15-20% loss of protons to neutrino experiments not a problem for a second high quality physics program" (P. Odone)
- Encouraged by Fermilab director, especially in context of less than most optimistic ILC ramp-up

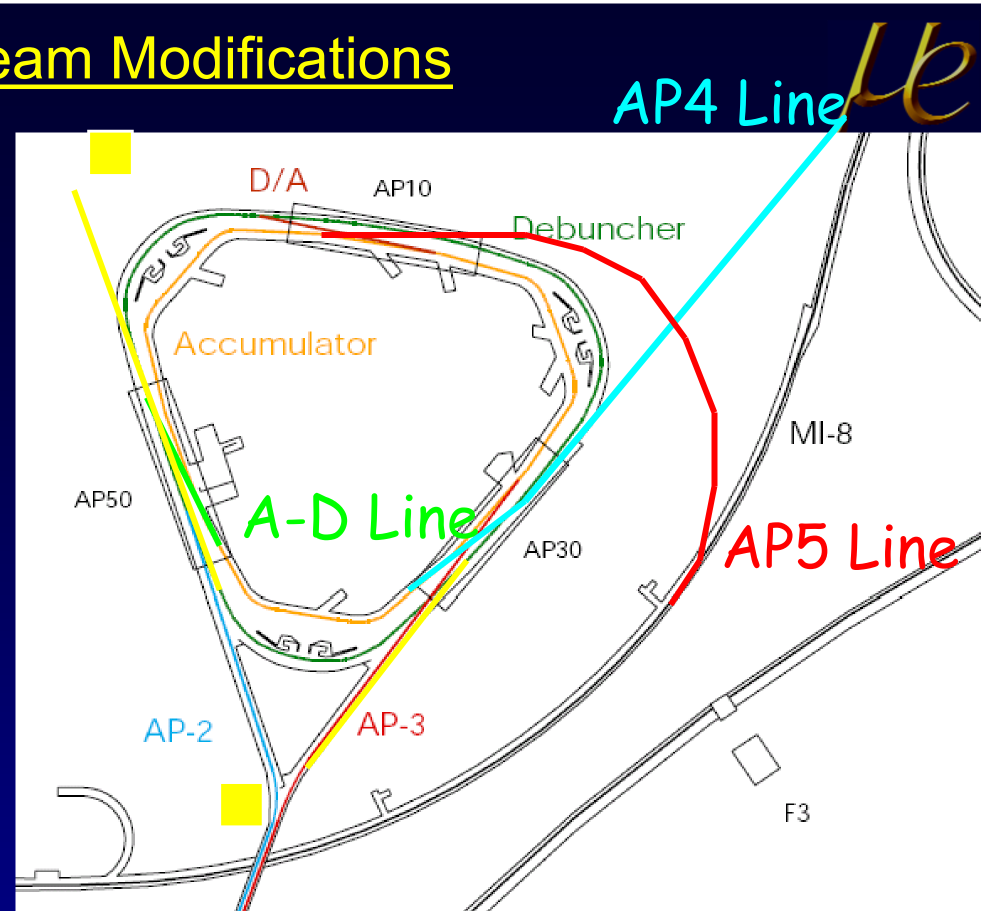
- Implementation builds on mostly available accelerators, concepts of the MECO experiment
  - Momentum stack 3-4 booster bunches in the accumulator
  - Transfer to the debuncher
  - Rebunch the beam with RF (bunch spacing 1.6 μs)
  - Slow extract to new area
  - Very good macro duty cycle
  - Proton beamline, target station, muon beamline, experiment following MECO



Required Fermilab Beam Modifications

- Increased booster throughput (approved)
- Transfer line from booster→accumulator symbiotic with neutrino program (unapproved) (Alternate transfer through MI is possible)
- Transfer line accumulator→debuncher
- RF for rebunching





- Slow extraction
- Secondary beamline, experimental hall …
- Concerns
  - Impact on protons for neutrino program
  - Radiation impact (losses, shielding)
  - Resource availability (ILC)

Conservative intensity projection

Beam Energy	8 GeV
Bunch Trains / sec: f_{TRAIN}	0.682
Bunch Spacing: ΔT_B	**1.6 μs**
No. of bunches/train: N_B	85×10^4
No. protons/bunch: n_P	2.16×10^7
Bunch Length (2.5s) : t_B	150 ns (σ=60ns)
Protons/train (4 batches)	1.84×10^{13}
Protons/year (10^7 secs)	1.25×10^{20} (1.44×10^{20} MECO)

Steering Group Appointed by Director to Develop Plan for Accelerator-Based Particle Physics in U.S.

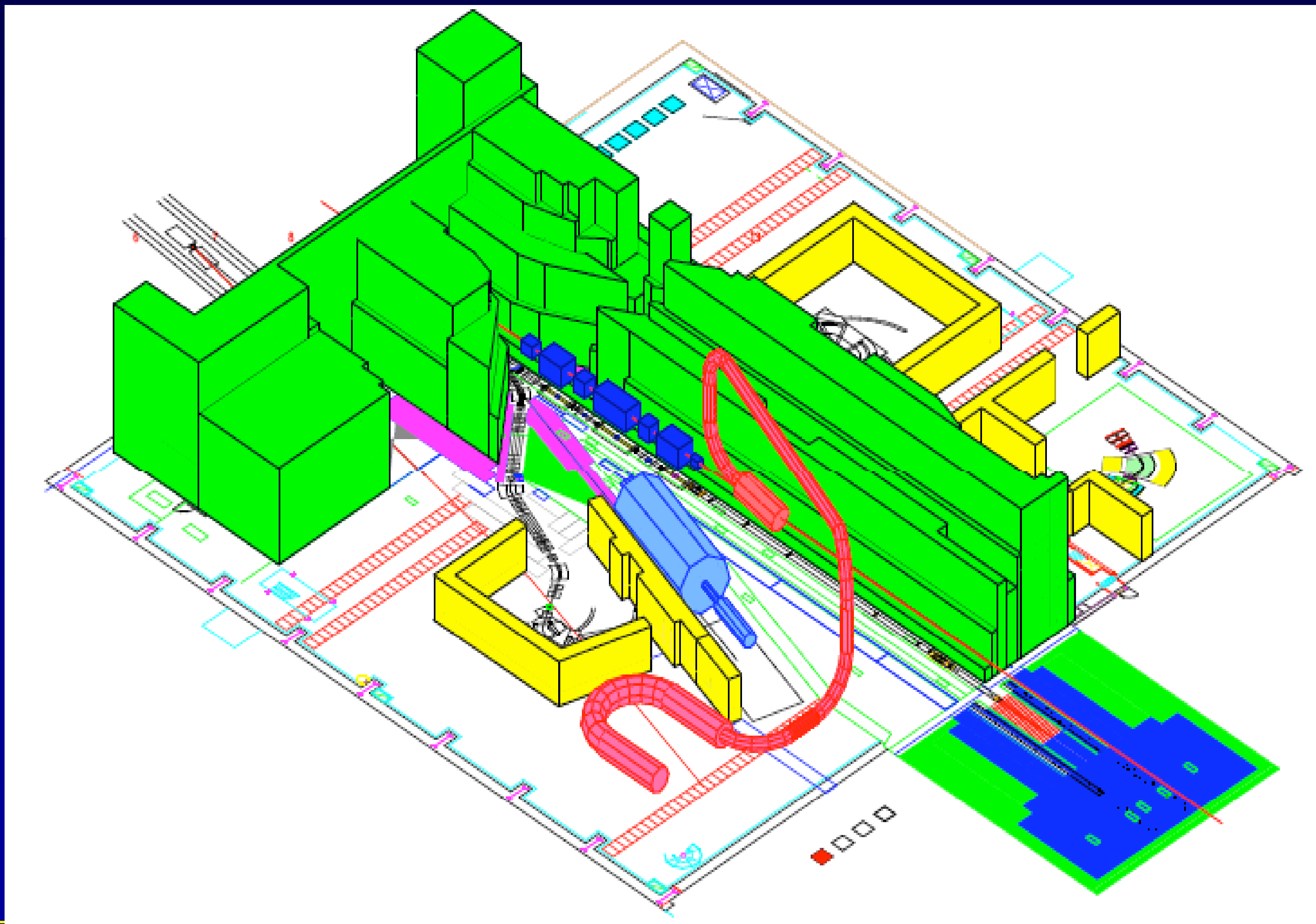
"The Fermilab Steering Group has developed a plan to keep U.S. accelerator-based particle physics on the pathway to discovery, both at the Terascale with the LHC and ILC and in the domain of neutrinos and precision physics with a high-intensity accelerator. The plan puts discovering Terascale physics with the LHC and the ILC at Fermilab's highest priority. While supporting ILC development, the plan creates opportunities for exciting science at the intensity frontier."

	Now	Proton Plan	NOvA *	SNuMI	Project X	
Batch Intensity (8 GeV)	4.4×10^{12}	4.3×10^{12}	4.1×10^{12}	4.5×10^{12}	5.6×10^{13}	protons/pulse
Rep Rate	7	9	12	13.5	5	Hz
Protons/hour	1.1×10^{17}	1.4×10^{17}	1.8×10^{17}	2.2×10^{17}	1.0×10^{18}	
Main Injector batches	7	11	12	18	3	
MI batches to pbar target	2	2	0	0	0	
MI Cycle Time	2.4	2.2	1.33	1.33	1.4	sec
MI Beam Power (120 GeV)	176	338	710	1169	2314	kW
8 GeV Beam Power (available)	18	17	16 *	0	206	kW
Injection energy into 1st synchrotron	400	400	400	400	8000	MeV

* NOvA column includes a potential upgrade of the Booster repetition rate to support simultaneous delivery of ~2×10^{20} protons per year at 8 GeV. NOvA itself requires Booster operations at 9Hz.

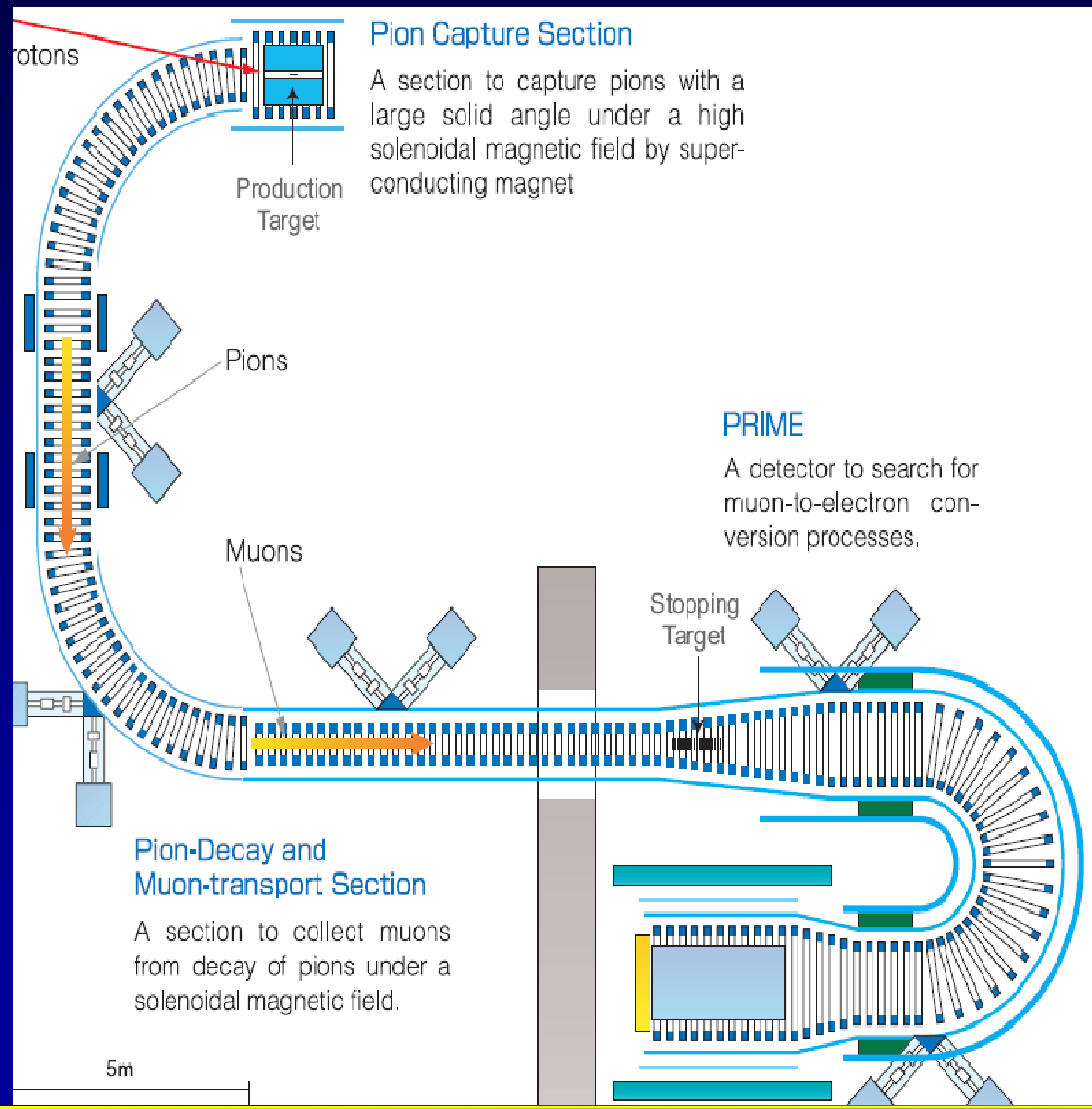
LOI to Implement a MECO Like Experiment at JPARC

- Uses JPARC high energy synchrotron running at 8 GeV
  - 4×10^{13} protons per second
  - 2×10^{7} seconds running time
  - 7×10^{-4} muon stops per proton
  - Pulsed, slow extracted proton beam with good extinction, 1.17 μs pulse spacing



JPARC Muon Beamline and Detector Schematic

- Backward pion collection, production solenoid much smaller than MECO version
- Transport with constant direction bend, drift compensated with dipole field
- Converstion electrons transported to detectors in curved solenoid
  - Suppresses transport of low energy electrons
  - Transverse drift compensated by superimposed dipole field
  - Non-monotonic field gradient in transport region – allows for gradient in electron transport to improve acceptance
- Expected sensitivity of 1 event for $R_{\mu e}$ 4×10^{-17} for 2×10^{7} s running with 0.34 expected background events



Summary

- A muon-to-electron conversion experiment at sensitivity below 10^{-16} has excellent capabilities to search for evidence of new physics and to study the flavor structure of new physics if it is discovered elsewhere first.
- A well studied, costed, and reviewed experimental design exists that could be the starting point for a new effort at Fermilab.
- This experiment would complement the neutrino program at Fermilab in the decade following the end of the Tevatron program and preceding a major new program. An appropriate proton beam can probably be built and operated for such an experiment at Fermilab.
- The possibility of doing a similar experiment is being investigated at JPARC.

END