A New Muon Beamline and Lepton Flavor Violation Experiment at Fermilab

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Fermilab Joint Experimental-Theoretical Seminar
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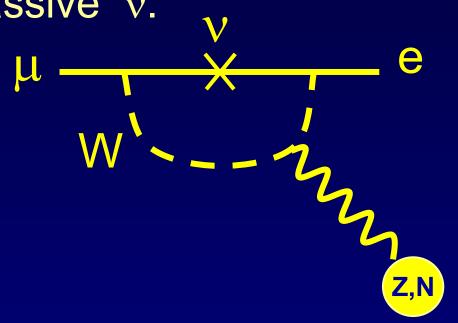
Outline:

- 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 implementation based on MECO experiment design
  - Proton source – deferred to Dave McGinnis's talk
  - Proton beamline and monitoring
  - Muon beamline
  - Detector systems
  - Anticipated performance

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

Discovery of $\mu^- N \rightarrow e^- N$ 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.

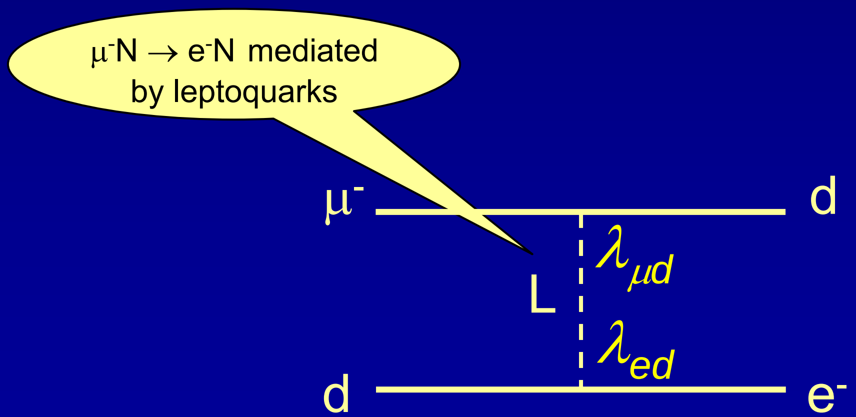
- For non-degenerate neutrino masses, ν oscillations can occur. Discovery of neutrino oscillations required changing the Standard Model to include massive ν.
- Charged LFV processes occur through intermediate states with ν mixing. Small ν mass differences and mixing angles $\Rightarrow$ expected rate 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
- Charged LFV processes 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.

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

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



Why Here, Why Now?

- Cancellation of RSVP provides an opportunity in the U.S. for a great experiment that builds on an extensive development effort over a number of years (thanks to the NSF).
  - Many tens of person years of effort on beam and experiment design, most of it directly applicable to an experiment at Fermilab
  - Physics case for the experiment reviewed by committees appointed by BNL and funding agencies numerous times, all with excellent outcome
  - Well developed conceptual design of experiment and beam exists, partly to the level of engineering designs, and with some prototype development done
  - Technical feasibility reviewed by the Laboratory and Agencies, all with excellent outcome for the level of design maturity achieved
  - Cost and schedule developed and reviewed, relatively stable for the last few years
  - The cancellation of RSVP was not due to a lack of physics motivation for MECO nor was it due to the construction cost (escalation) of MECO

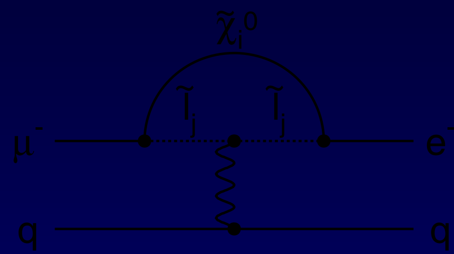
- Anticipated end of the Fermilab Collider program and the anticipated continuation of a vibrant neutrino program will provide facilities (accelerators and storage rings) and an operating, high power accelerator complex well matched to the experiment's needs.
  - These facilities weren't available in 1997 when some of us explored doing the experiment here
  - There is now a group of physicists working on understanding how to make the required beams

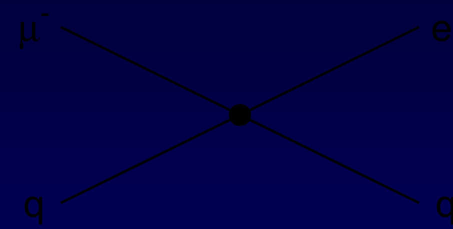
- We hope that these opportunities are embraced by particle and accelerator physicists interested in the physics and by the Laboratory to add to the scientific productivity of the Fermilab-based program in the next 10 years

Sensitivity to Different Muon Conversion Mechanisms

Supersymmetry

Predictions at 10^{-15}



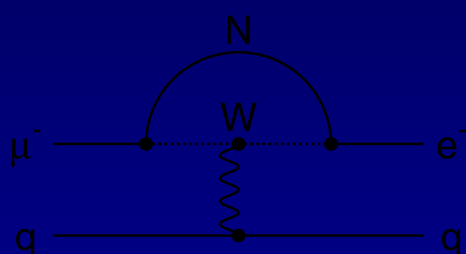


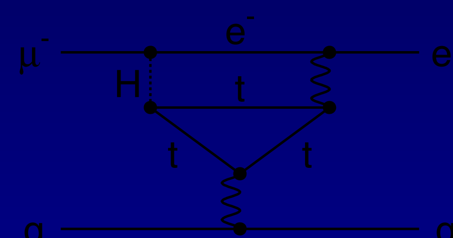
Compositeness

$\Lambda_C = 3000$ TeV

Heavy Neutrinos

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



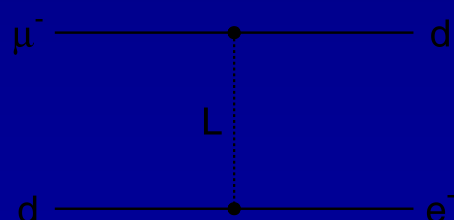


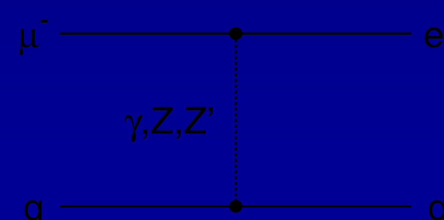
Second Higgs doublet

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

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

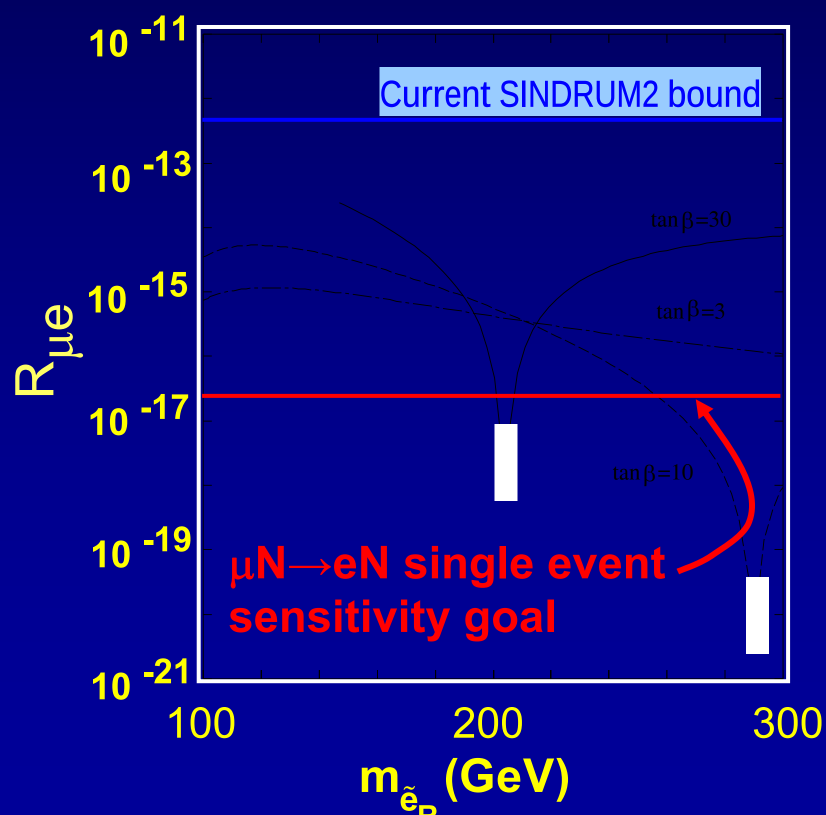
Supersymmetry Predictions for LFV Processes

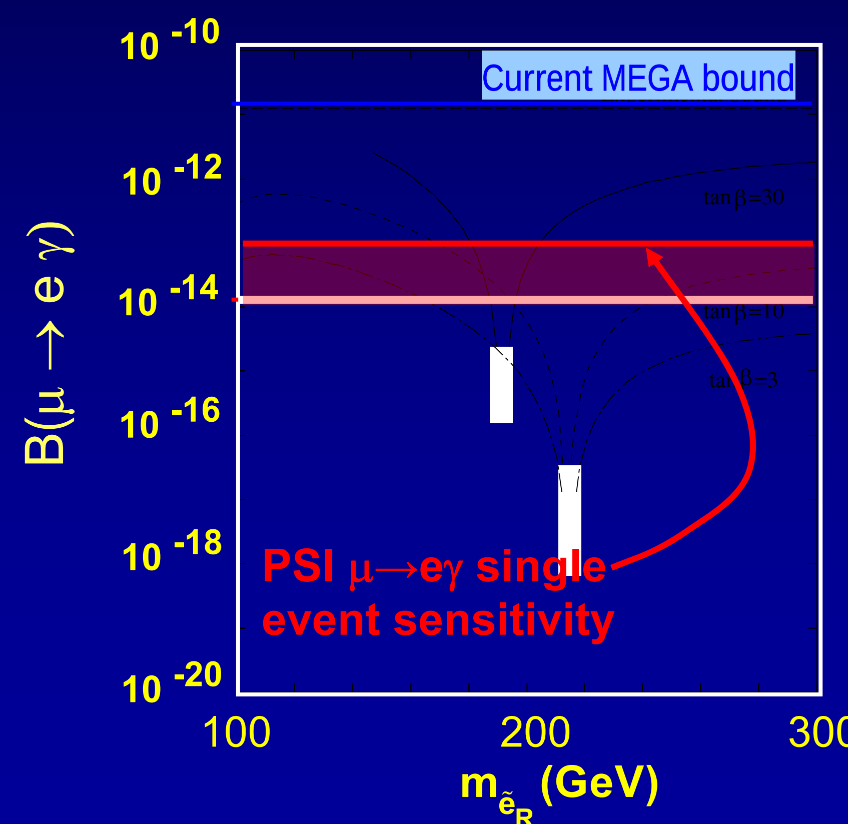
- From Hall and Barbieri

  Large t quark Yukawa couplings imply observable levels of LFV in supersymmetric grand unified models

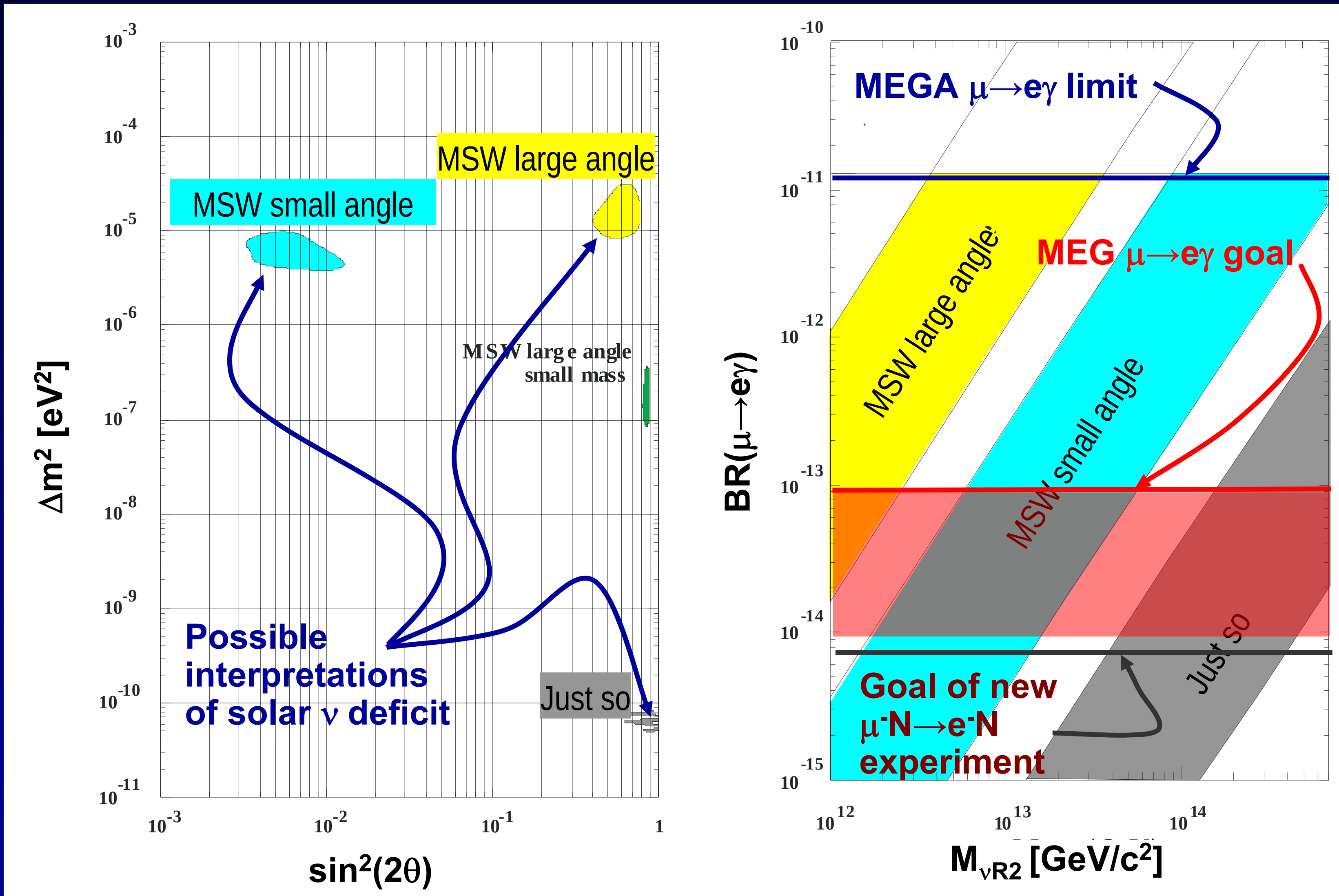
- Extent of lepton flavor violation in grand unified supersymmetry related to quark mixing
- Original ideas extended by Hisano, et al.

Process	Current Limit	SUSY level
$\mu^- N \rightarrow e^- N$	10^{-12}	10^{-15}
$\mu^+ \rightarrow e^+\gamma$	10^{-11}	10^{-13}
$\tau \rightarrow \mu\gamma$	10^{-6}	10^{-9}





Rates for LFV Processes Linked to ν Oscillations

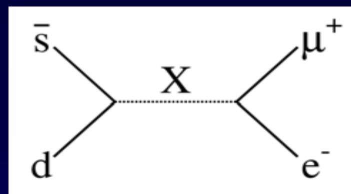


From the model of J. Hisano and D. Nomura, Phys. Rev. D59 (1999):
SU(5) grand unified model with heavy, right-handed neutrinos

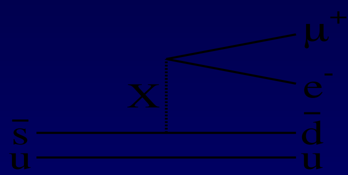
Current Limits on Muon Number Violating Processes

Mass limit

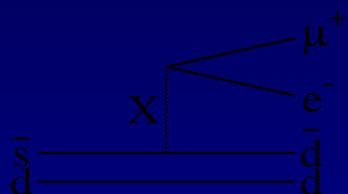
ΔG=0



$B(K_L^0 \to \mu^{\pm} e^{\mp}) < 4.7 \times 10^{-12}$ — 150 TeV/c²

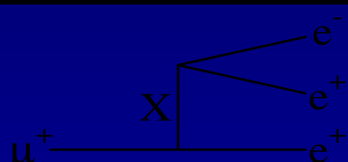


$B(K^{+} \to \pi^{+} \mu^{+} e^{-}) < 4 \times 10^{-11}$ — 31 TeV/c²

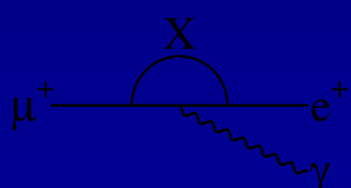


$B(K_L^0 \to \pi^{0} \mu^{+} e^{-}) < 3.2 \times 10^{-10}$ — 37 TeV/c²

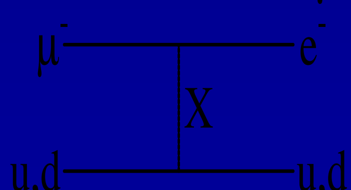
ΔG=1



$B(\mu^{+} \to e^{+} e^{+} e^{-}) < 1 \times 10^{-12}$ — 86 TeV/c²

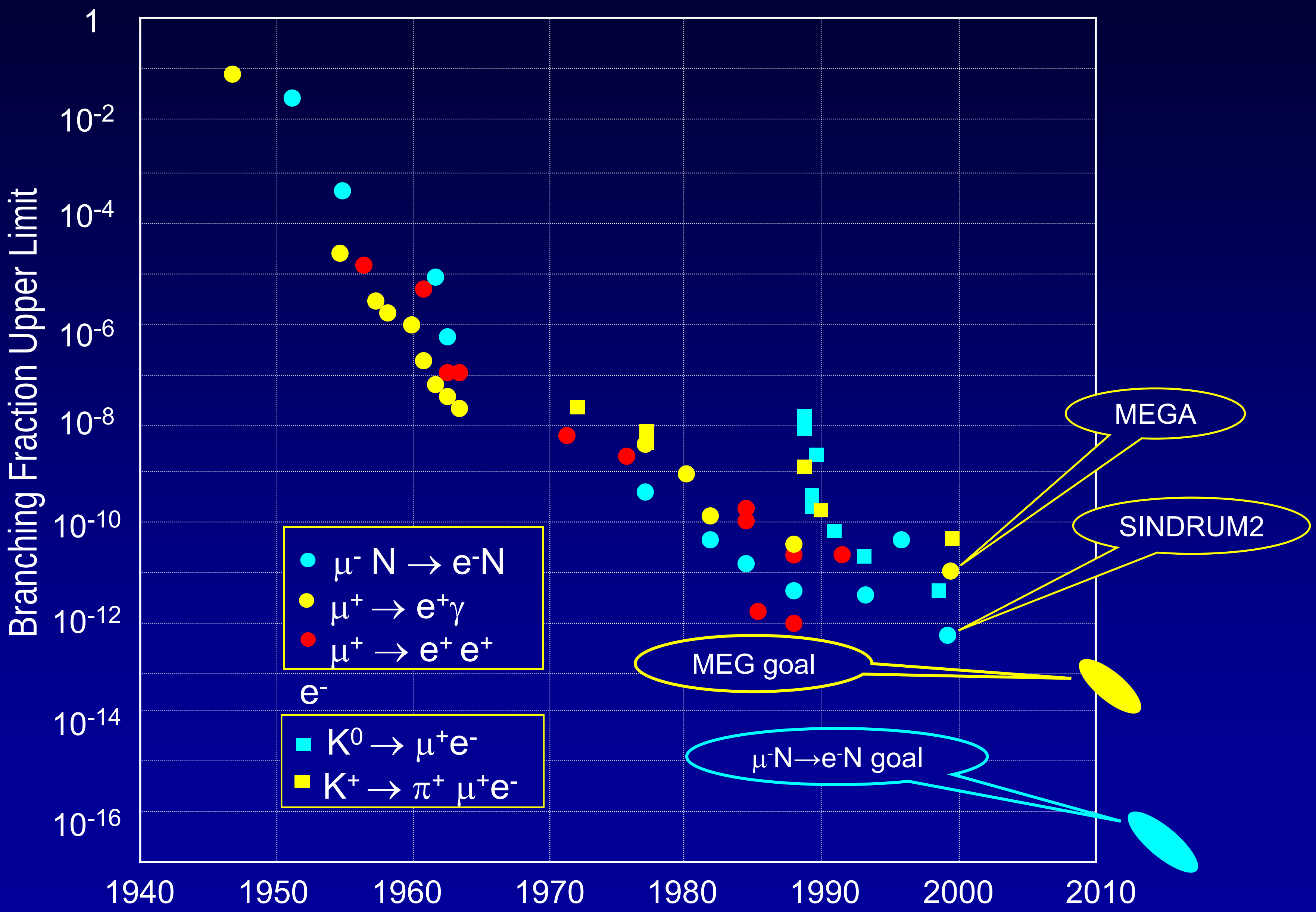


$B(\mu^{+} \to e^{+} \gamma) < 1.2 \times 10^{-11}$ — 21 TeV/c²



$\dfrac{\Gamma(\mu^{-} A \to e^{-} A)}{\Gamma(\mu^{-} A \to \nu A')} < 6.1 \times 10^{-13}$ — 365 TeV/c²

History of Lepton Flavor Violation Searches

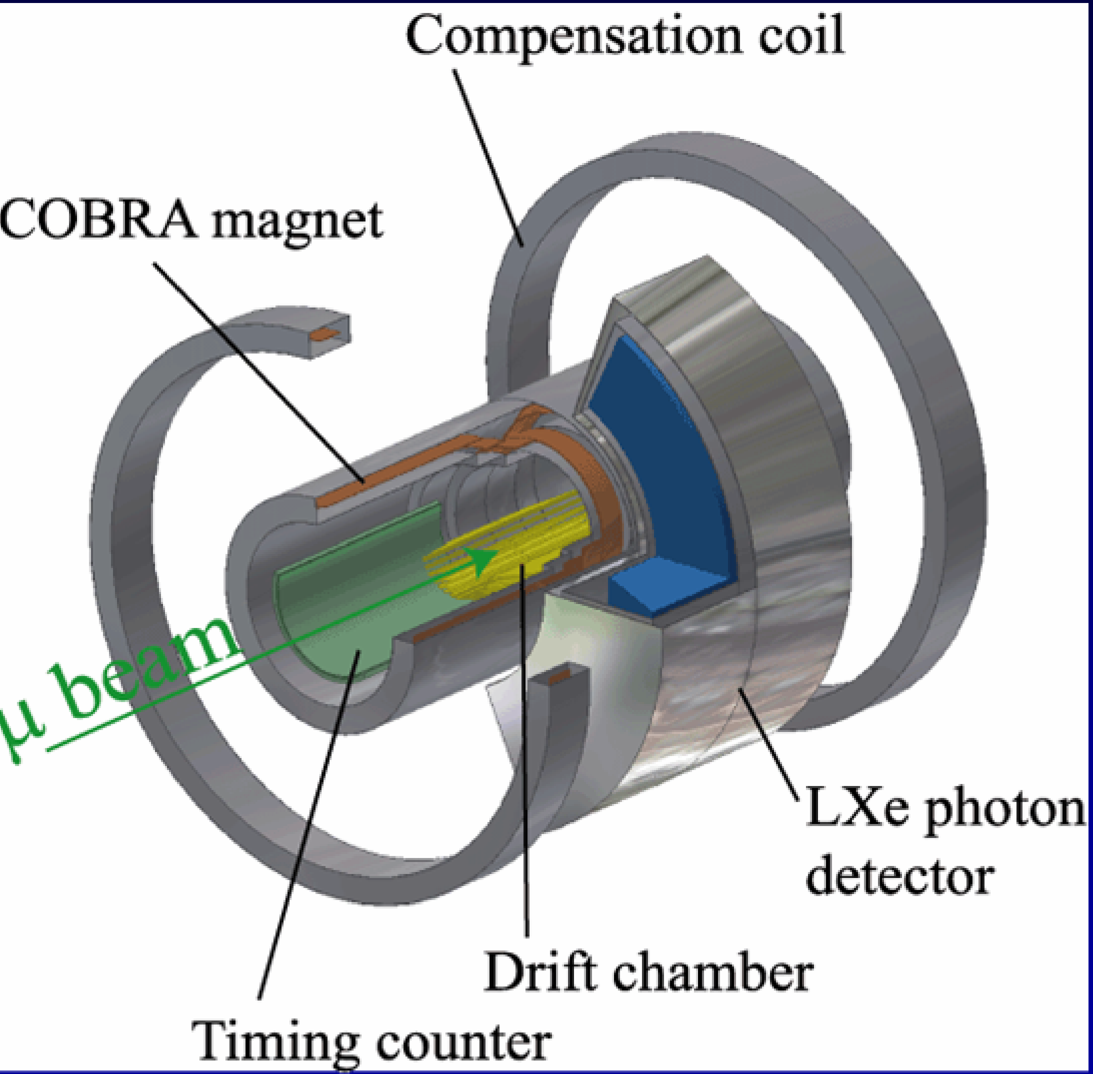


Why $\mu^- N \rightarrow e^- N$ Conversion Experiment?

- 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
- Improvements in kaon processes appear very difficult, and rates are not higher in most model predictions.
- $\mu \rightarrow e\gamma$ 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.
- Things are likely to change before a new conversion experiment is done:
  - MEG may see $\mu \rightarrow e\gamma$ at PSI – rates for other LFV processes will be needed to understand the underlying mechanism.
  - MEG may set a limit of 10^{-13} to 10^{-14} – more sensitive experiments will be needed, probably not possible with $\mu \rightarrow e\gamma$.
  - LHC my discover supersymmetric particles or evidence of other new physics at the TeV scale – experiments to probe the flavor structure of new physics will be equally as important as without such new results.

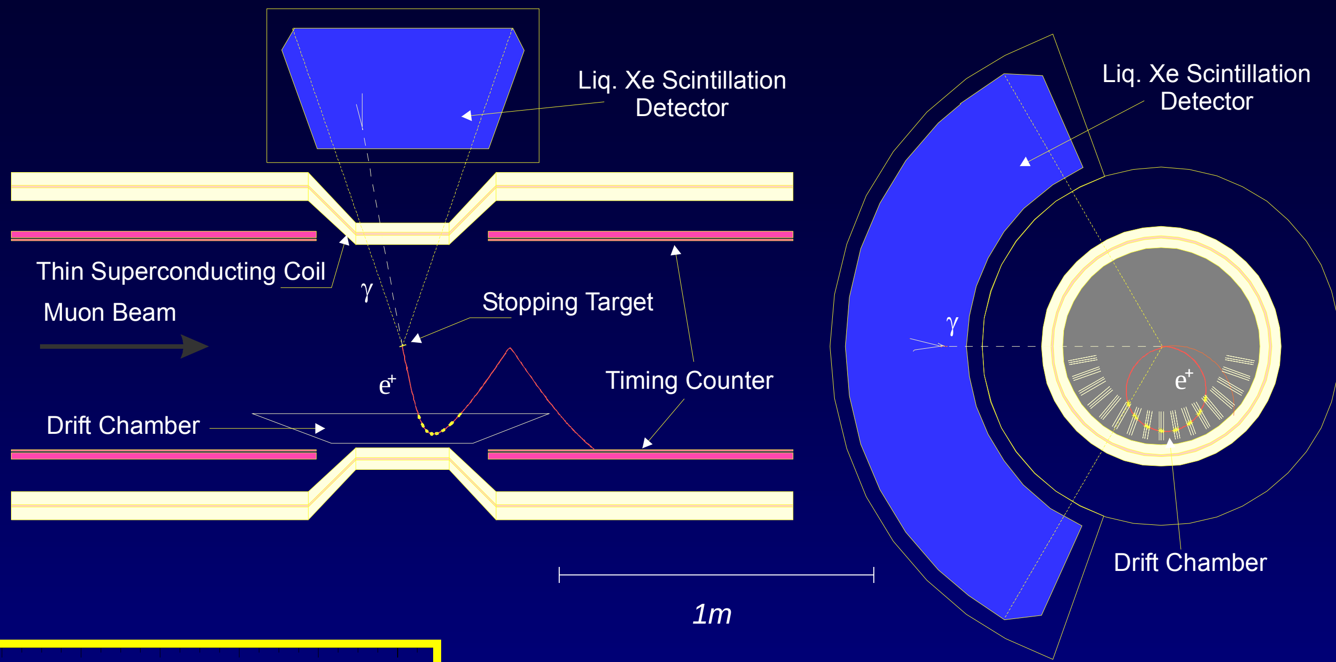
PSI-MEG $\mu^+ \to e^+\gamma$ Experiment

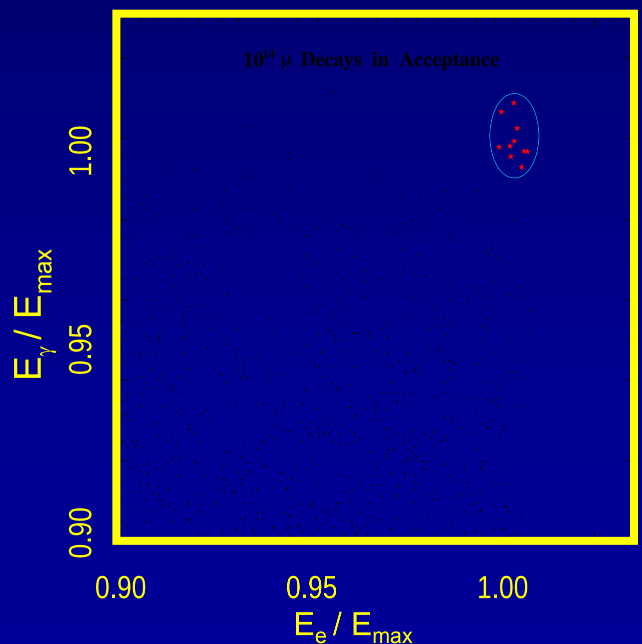
Search for $\mu^+ \to e+\ \gamma$ with sensitivity of 1 event for $B(\mu \to e\ \gamma) = 10^{-13}$



- Italy
  - INFN and University of Genoa
  - INFN and University of Lecce
  - INFN and University Pavia
  - INFN Pisa
  - INFN and University of Roma
- Japan
  - ICEPP, University of Tokyo
  - KEK
  - Waseda University
- Russia
  - JINR, Dubna
  - BINP
  - Novosibirsk
- Switzerland
  - Paul Scherrer Institute
- United States
  - University of California, Irvine

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)
- Partial engineering run this autumn
- First physics run Spring 2007
- 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

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

- 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: $\mu^-(N,Z)\rightarrow\nu_\mu(N,Z-1)$
  or decay in the Coulomb bound orbit: $\mu\text{-}(N,Z)\rightarrow\nu_\mu(N,Z)\nu_e$
  (τ_μ = 2.2 μs in vacuum, ~0.9 μs in Al)
- Rate is normalized to the kinematically similar weak capture process:

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

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

The First $\mu^- N \to e^- N$ Experiment – Steinberger and Wolf

- After the discovery of the muon, it was realized it could decay into an electron and a photon or convert to an electron in the field of a nucleus.
- Without any flavor conservation, the expected branching fraction for $\mu^+ \to e^+ \gamma$ is about 10^{-5}.
- Steinberger and Wolf looked for $\mu^- N \to e^- N$ for the first time, publishing a null result in 1955, with a limit

  $R_{\mu e} < 2 \times 10^{-4}$

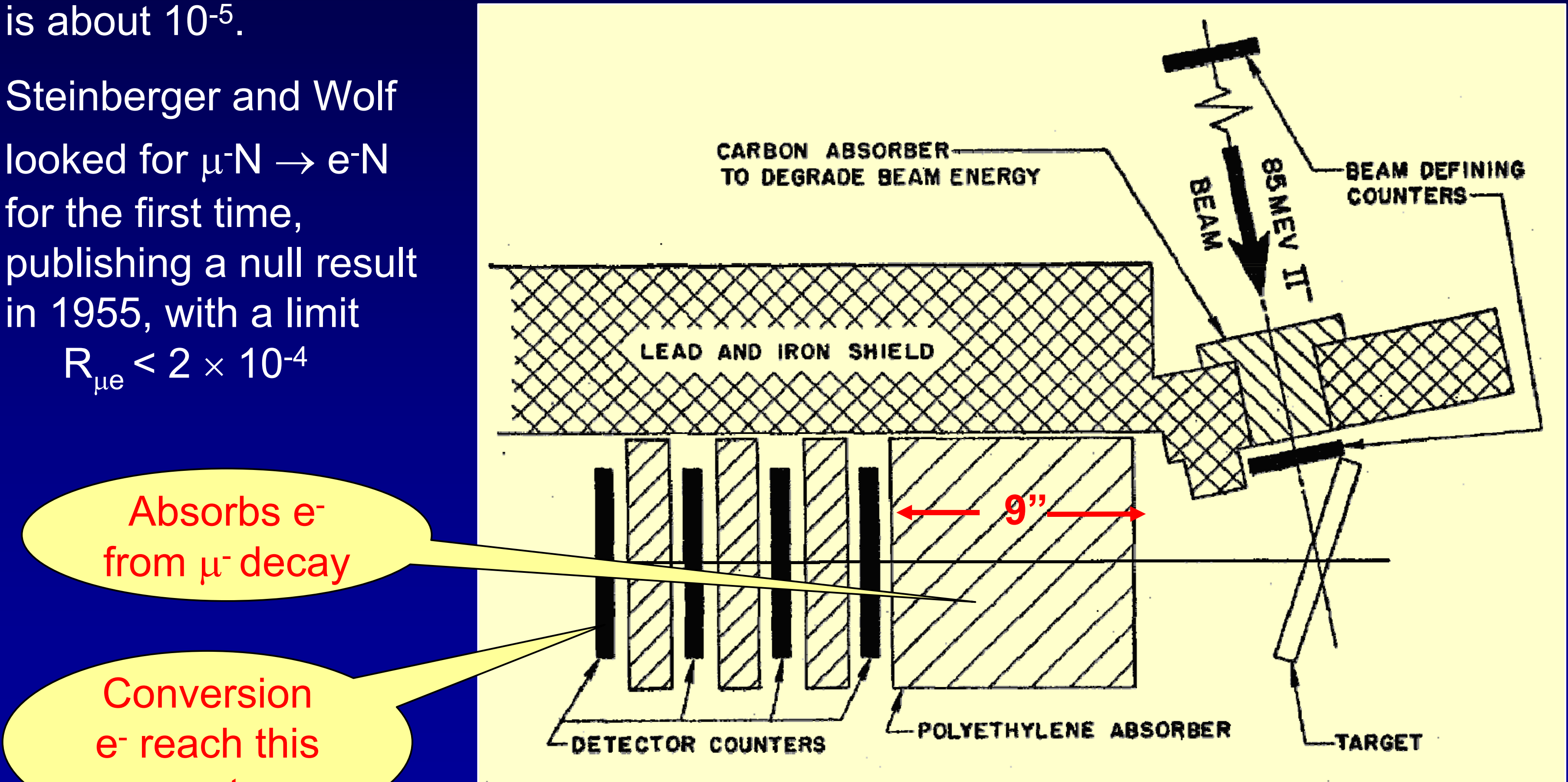
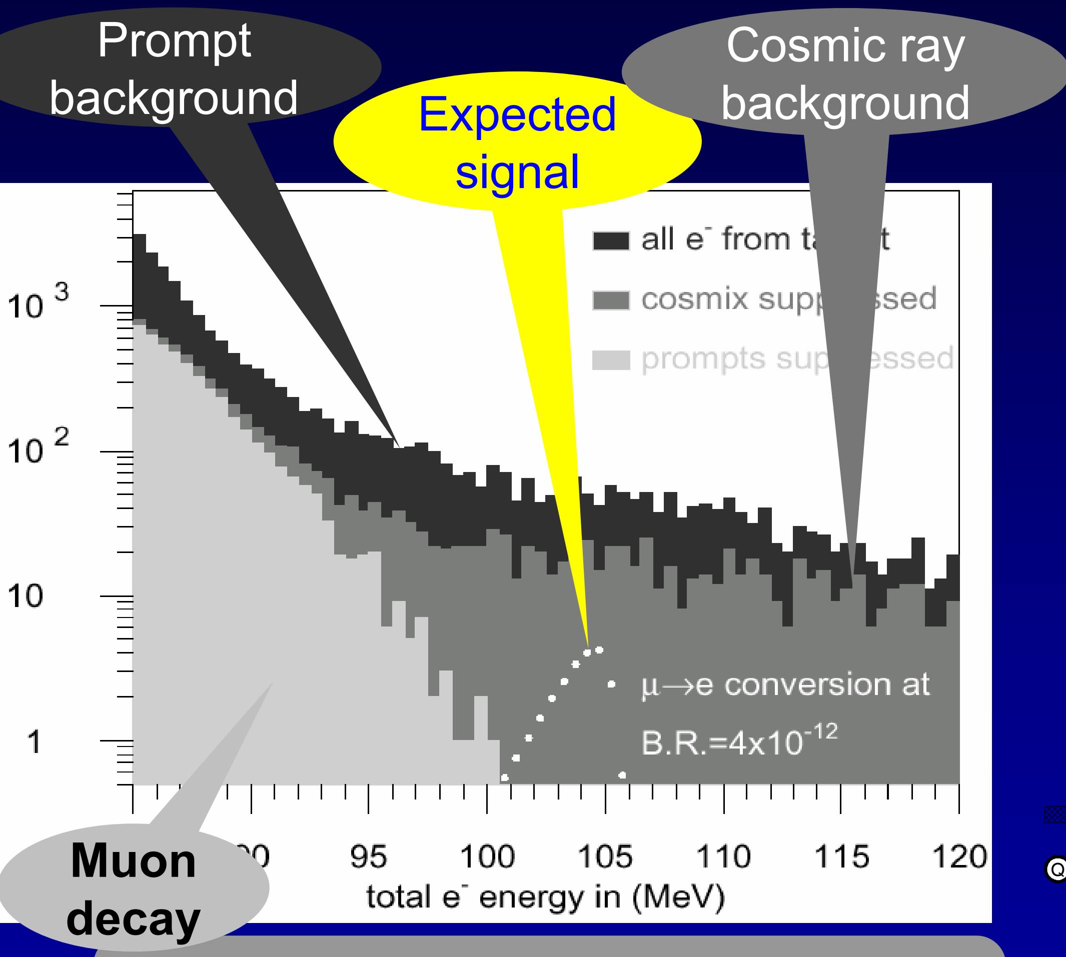


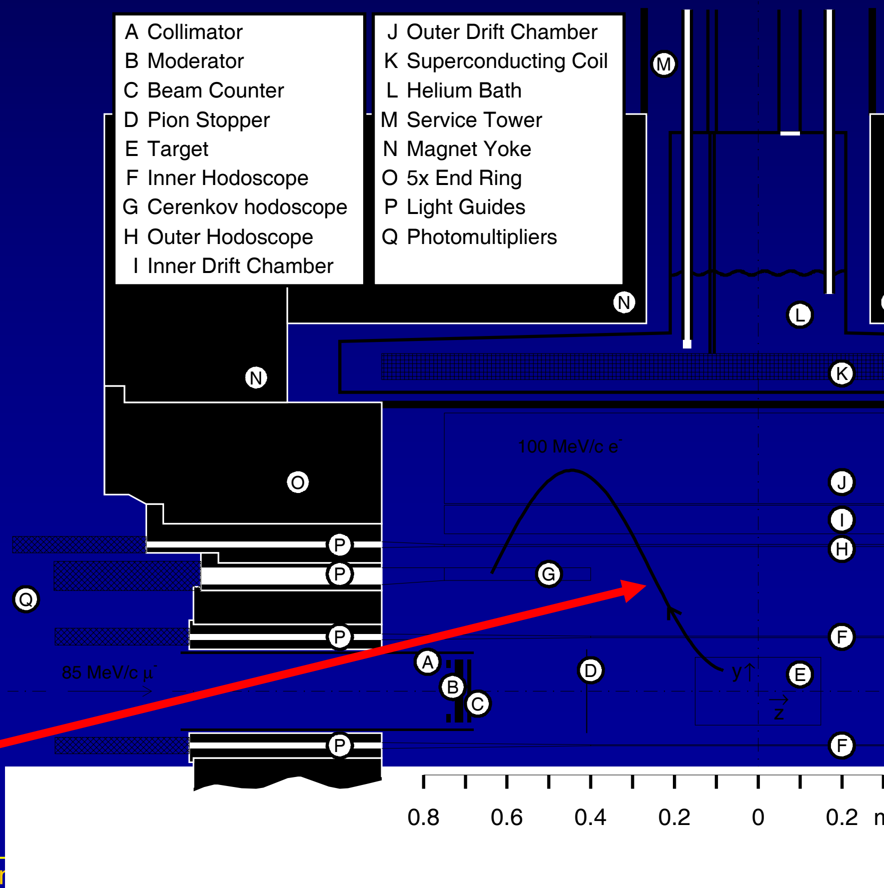
FIG. 1. Experimental arrangement.

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.



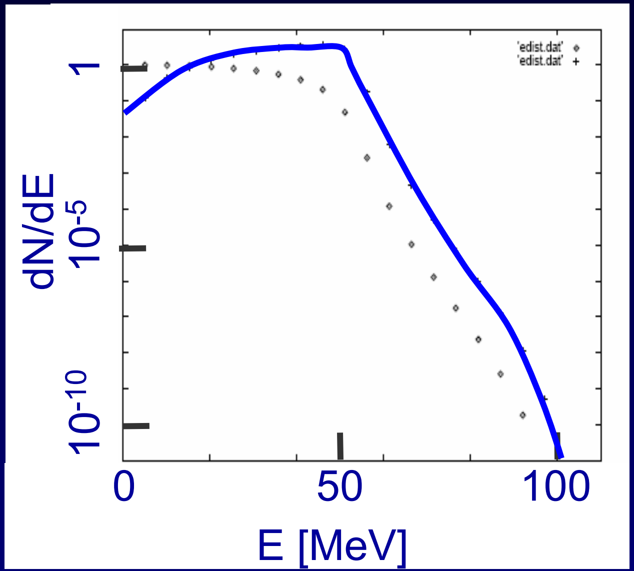
SINDRUM2 currently has the best limit on this process:



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

Potential Sources of Background

1. Muon decay in orbit –
   - $E_{max} = E_{conversion}$ when neutrinos have zero energy
   - $dN/dE_e \propto (E_{max} - E_e)^5$
   - Energy resolution of ~200 keV required



2. Radiative muon capture: $\mu^- N \to \nu_\mu N(Z-1) \gamma$
   - For Al, $E_\gamma^{max} = 102.5$ MeV/c^2, $P(E_\gamma > 100.5 \text{ MeV/c}^2) = 4 \times 10^{-9}$
   - $P(\gamma \to e^+e^-, E_e > 100.5 \text{ MeV/c}^2) = 2.5 \times 10^{-5}$
   - Restricts choice of stopping targets: $M_{z-1} > M_z$

3. Radiative pion capture: $\pi^- N \to N(Z-1) \gamma$
   - Branching fraction ~ 1.2% for $E_g > 105$ MeV/c^2
   - $P(\gamma \to e^+e^-, 103.5 < E_e < 100.5 \text{ MeV/c}^2) = 3.5 \times 10^{-5}$
   - Limits allowed pion contamination in beam during detection time

Other Potential Sources of Backgrounds

4. Muon decay in flight + e^- scattering in stopping target

5. Beam e^- scattering in stopping target
   - Limits allowed electron flux in beam

6. Antiproton induced e^-
   - Annihilation in stopping target or beamline
   - Requires thin absorber to stop antiprotons in transport line
   - Motivates proton energy not much above anti-proton production threshold

7. Cosmic ray induced e^- – seen in earlier experiments
   - Primarily muon decay and interactions
   - Scales with running time, not beam luminosity
   - Requires the addition of active and passive shielding

MECO Experiment Design as a Template for Fermilab Experiment

MECO collaborators at various stages in the experiment

Boston University

I. Logashenko, J. Miller, B. L. Roberts

Brookhaven National Laboratory

K. Brown, M. Brennan, W. Marciano, W. Morse, P. Pile, Y. Semertzidis, P. Yamin

University of California, Berkeley

Y. Kolomensky

University of California, Irvine

M. Bachman, C. Chen, M. Hebert, T. J. Liu, W. Molzon, J. Popp, V. Tumakov

University of Houston

Y. Cui, E. V. Hungerford, N. Elkhayari, N. Klantarians, K. A. Lan

University of Massachusetts, Amherst

K. Kumar

Institute for Nuclear Research, Moscow

V. M. Lobashev, V. Matushka

New York University

R. M. Djilkibaev, A. Mincer, P. Nemethy, J. Sculli, A.N. Toropin

Osaka University

M. Aoki, Y. Kuno, A. Sato

Syracuse University

R. Holmes, P. Souder

University of Virginia

C. Dukes, K. Nelson, A. Norman

College of William and Mary

M. Eckhause, J. Kane, R. Welsh

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

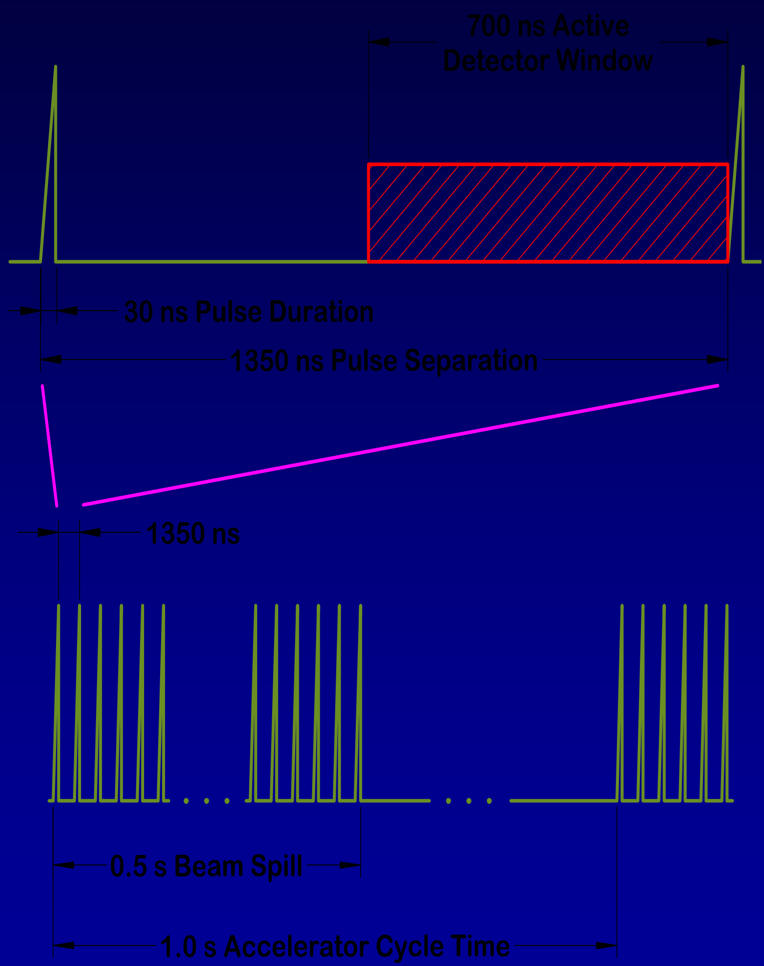
- 1000 fold increase in muon intensity using an idea from MELC at MMF
  - High Z target for improved pion production
  - Graded solenoidal field to maximize pion capture
  - Produce $\approx 10^{-2}$ m^{-}/p at 8 GeV (SINDRUM2 $\approx 10^{-8}$, MELC $\approx 10^{-4}$, Muon Collider ≈ 0.3)
  - Muon transport 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 $< 10^{-9}$

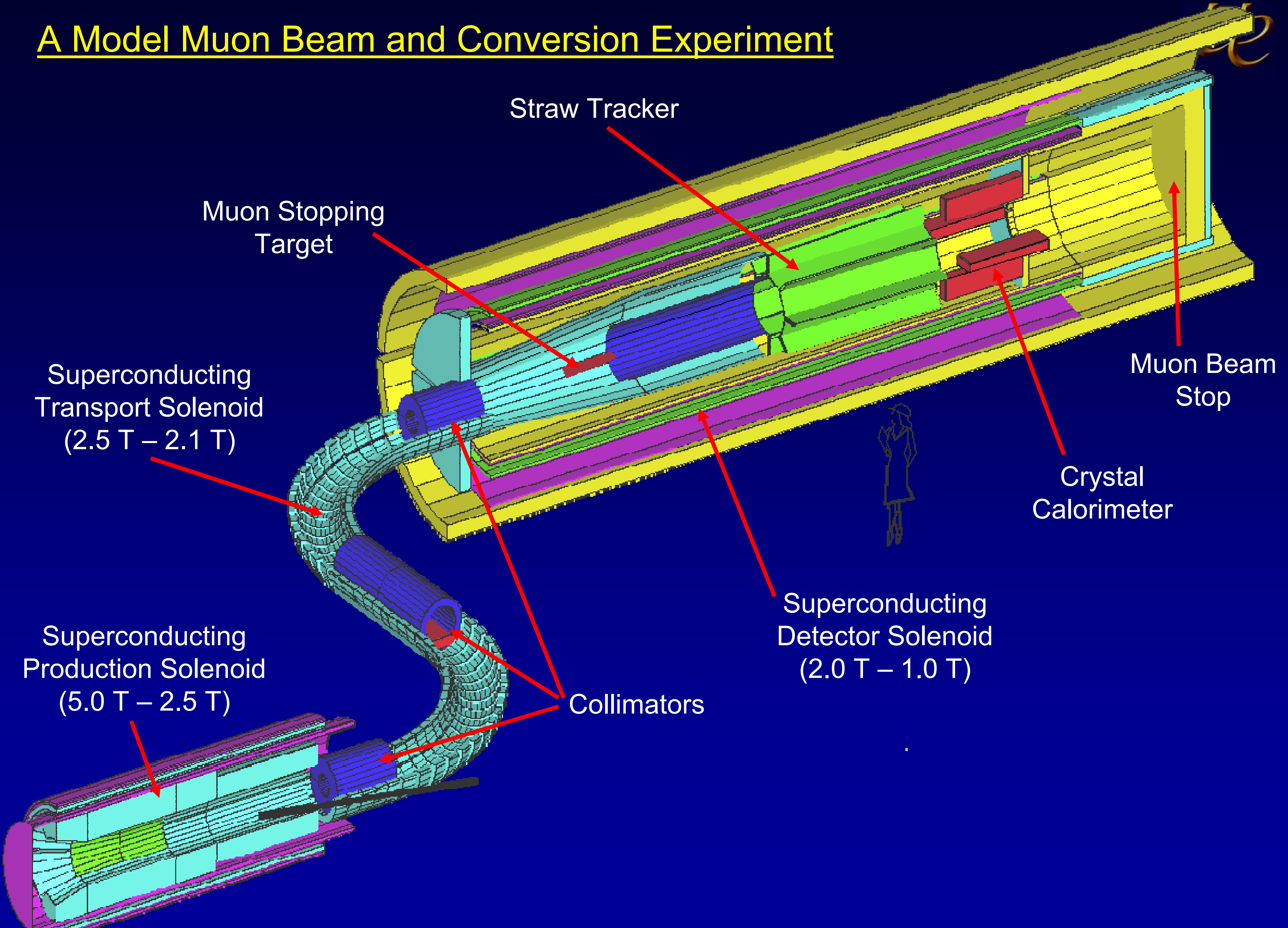
- Improved detector resolution and rate capability
  - Detector in graded solenoid field for improved acceptance, rate handling, background rejection following MELC concept
  - Spectrometer with nearly axial components and very high resolution

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

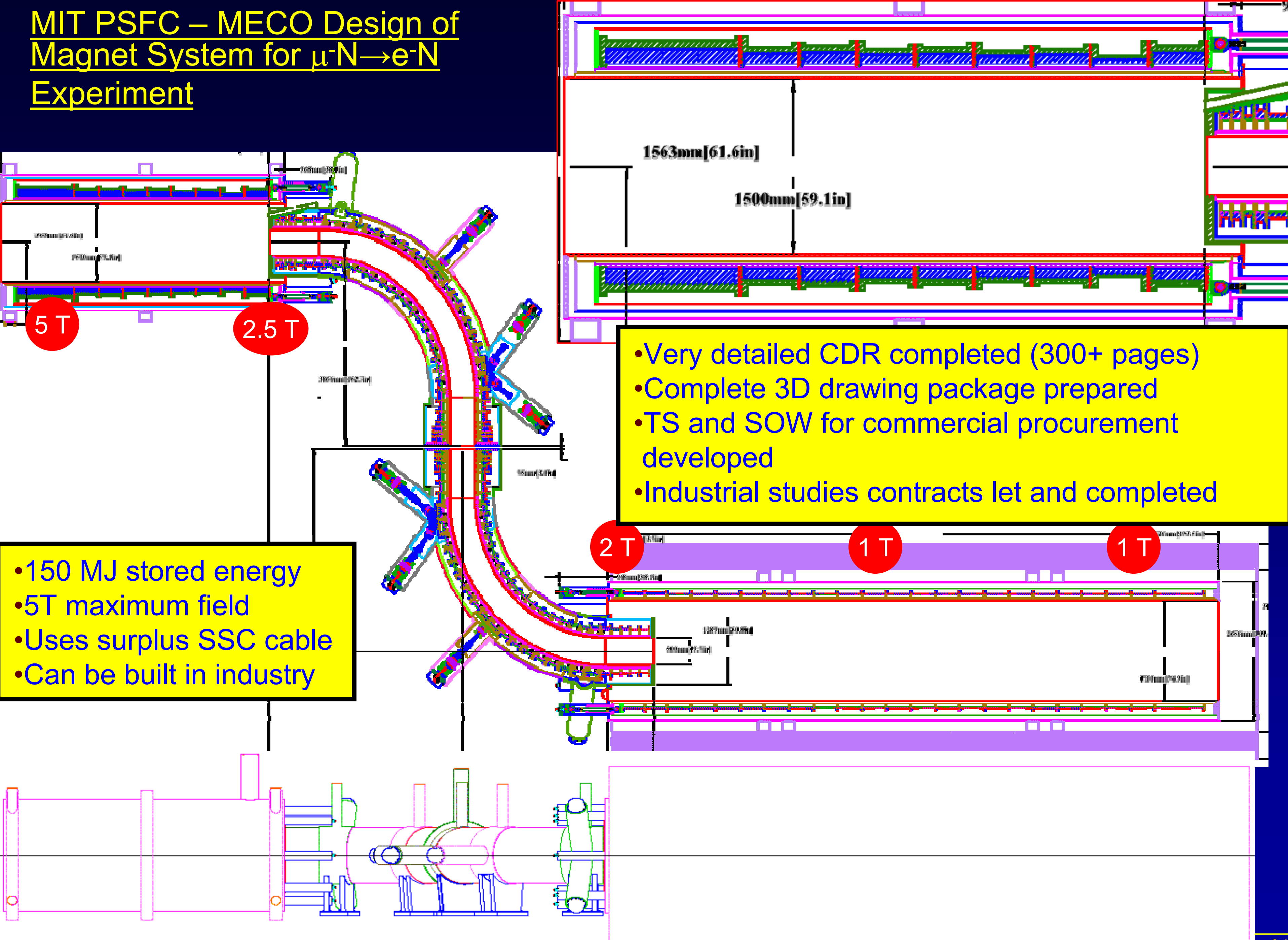
- Subsequent discussion focuses on accelerator operating 8 GeV with 4×10^{13} protons per second and 50% duty cycle – 50 kW instantaneous beam power at 8 GeV
- Pulsed proton beam generated using RF structure of appropriate accelerator or storage ring
- To eliminate prompt backgrounds, we require $< 10^{-9}$ 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



MIT PSFC – MECO Design of Magnet System for $\mu^- N \rightarrow e^- N$ Experiment



- Very detailed CDR completed (300+ pages)
- Complete 3D drawing package prepared
- TS and SOW for commercial procurement developed
- Industrial studies contracts let and completed

- 150 MJ stored energy
- 5T maximum field
- Uses surplus SSC cable
- Can be built in industry

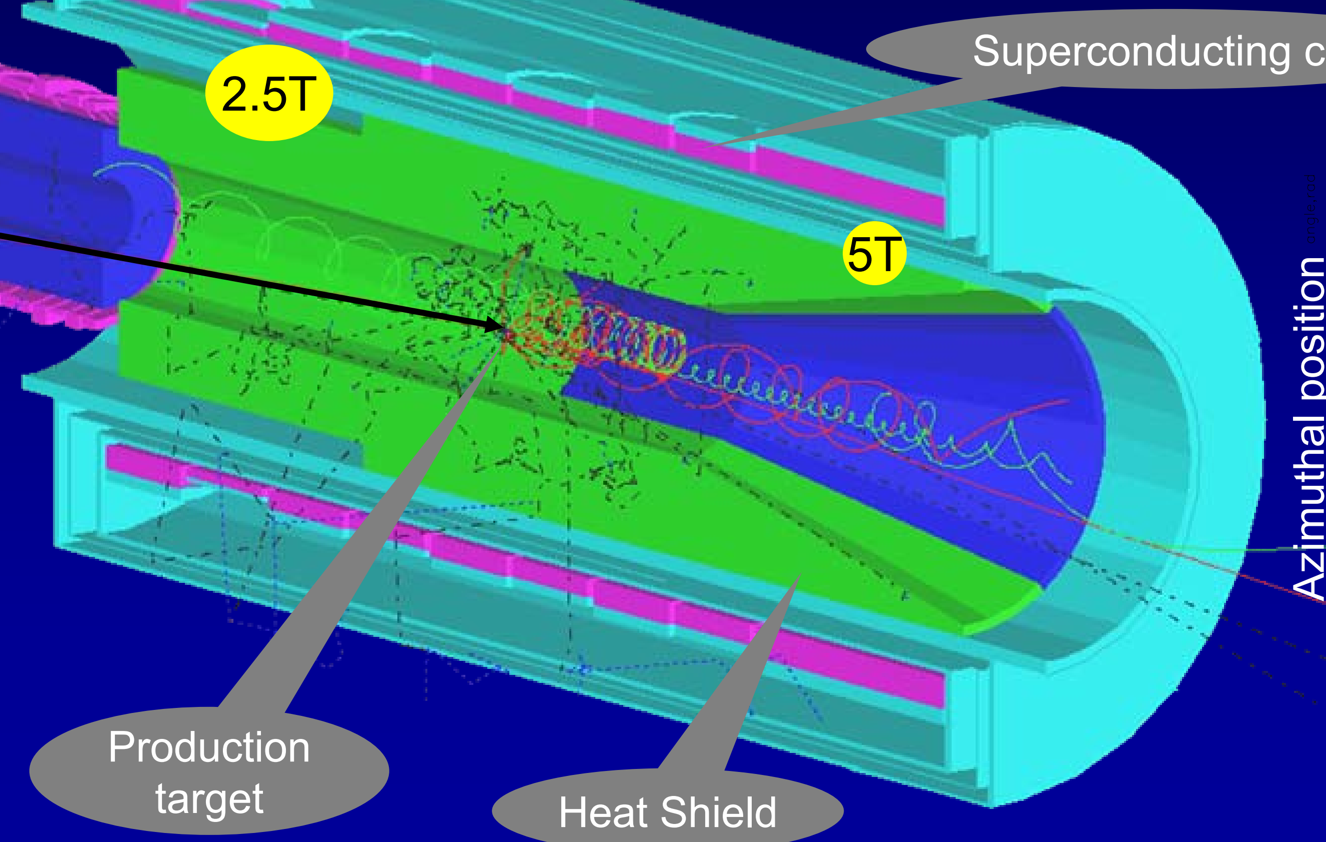
Muons Production and Capture in Graded Magnetic Field

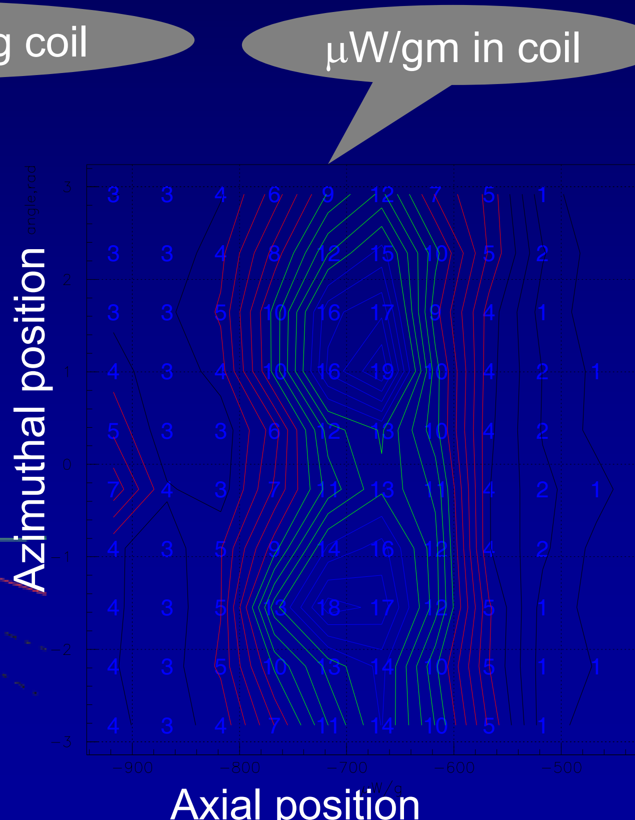
Pions produced in a target located in an axially graded magnetic field:

- 50 kW beam incident on gold target
  - Charged particles are trapped in 5 – 2.5 T, axial magnetic field
  - Pions and muons moving away from the experiment are reflected

150 W load on cold mass
15 μW/g in superconductor
20 Mrad integrated dose

- Superconducting magnet is protected by Cu and W heat and radiation shield

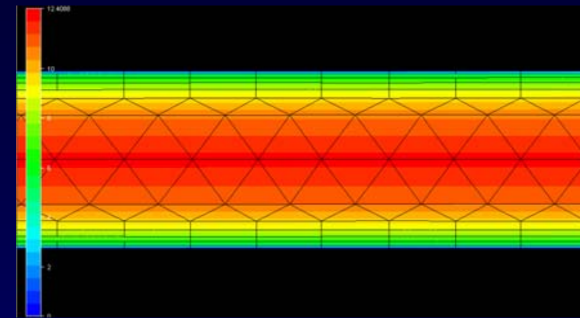




Production Target for Large Muon Yield

Production target region designed for high yield of low energy muons:

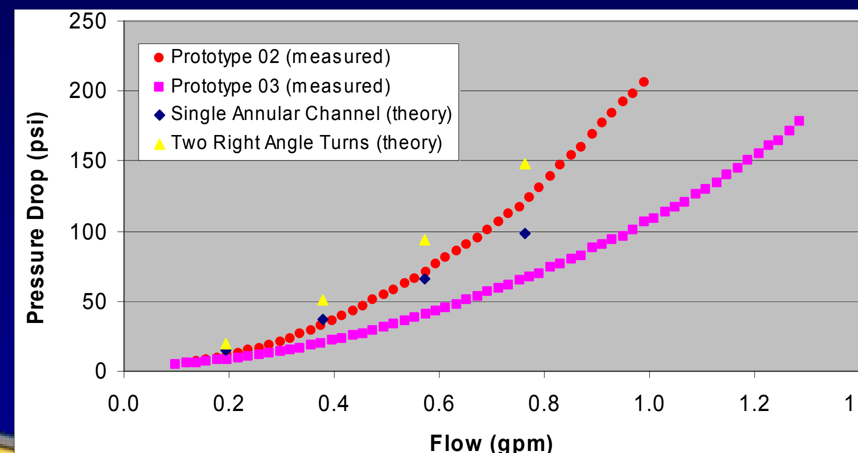
- High Z target material
- Little extraneous material in bore to absorb π/μ
- Diameter 0.6 - 0.8 mm, length 160 mm
- ~5 kW of deposited energy

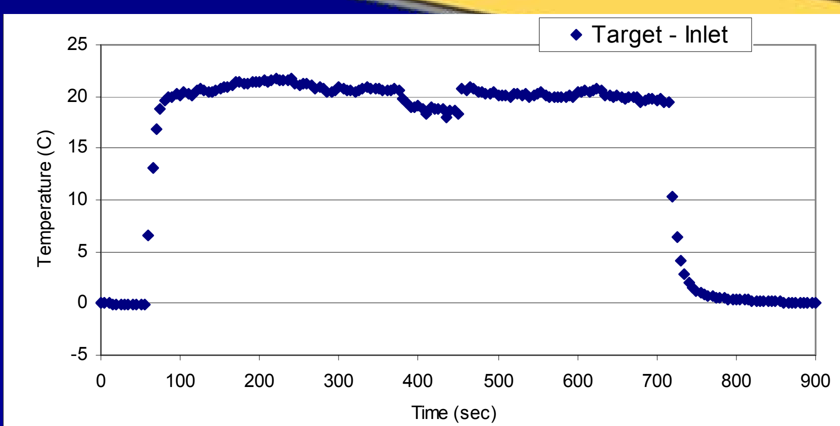


Fully developed turbulent flow in 300 μm water channel

Water cooling in 0.3 mm cylindrical shell surrounding target

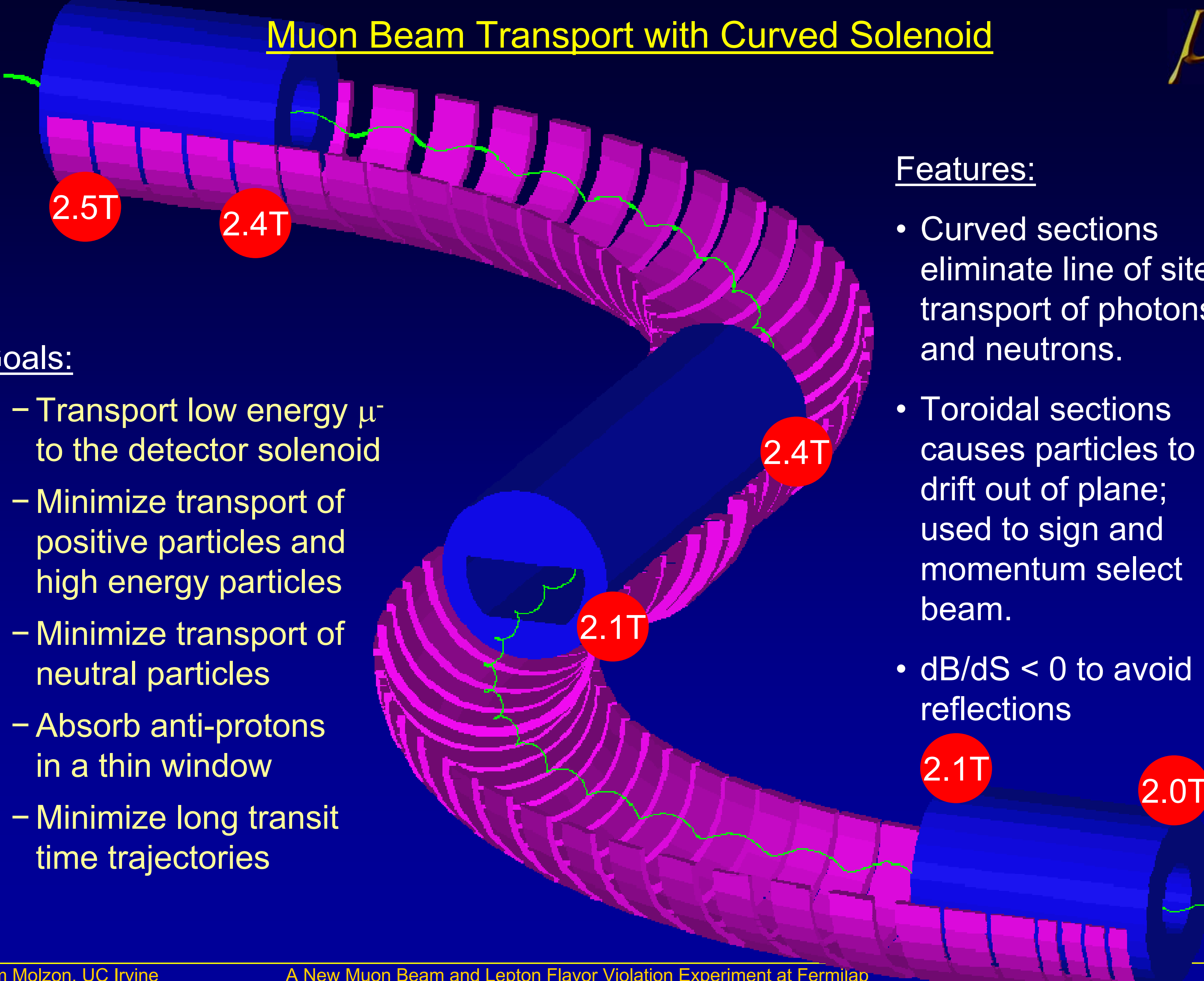
- Simulated with 2D and 3D thermal and turbulent fluid flow finite element analysis
- Target temperature well below 100° C
- Pressure drop is acceptable (~10 Atm)
- Prototype built, tested for pressure and flow





Preliminary cooling tests using induction heating completed

Muon Beam Transport with Curved Solenoid



Goals:

- Transport low energy μ^- to the detector solenoid
- Minimize transport of positive particles and high energy particles
- Minimize transport of neutral particles
- Absorb anti-protons in a thin window
- Minimize long transit time trajectories

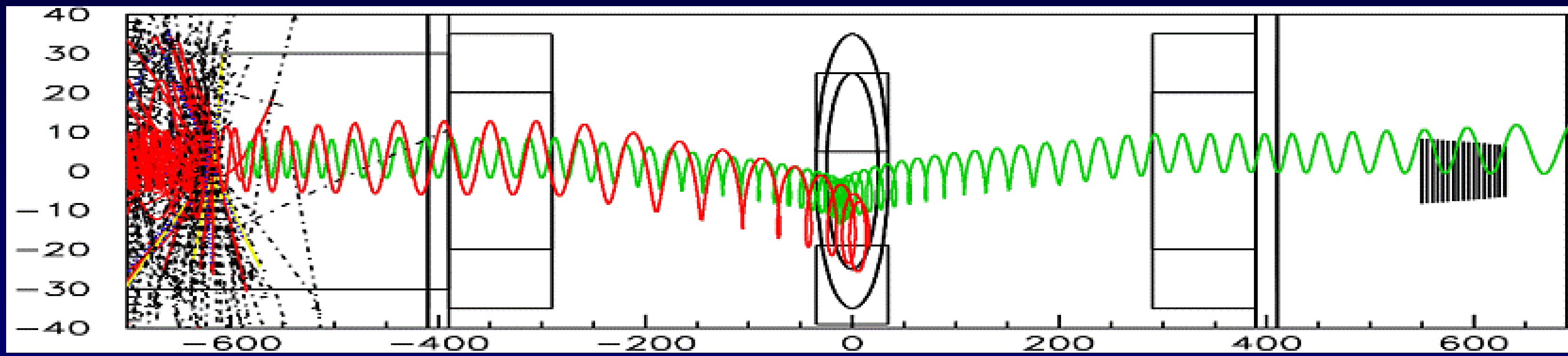
Features:

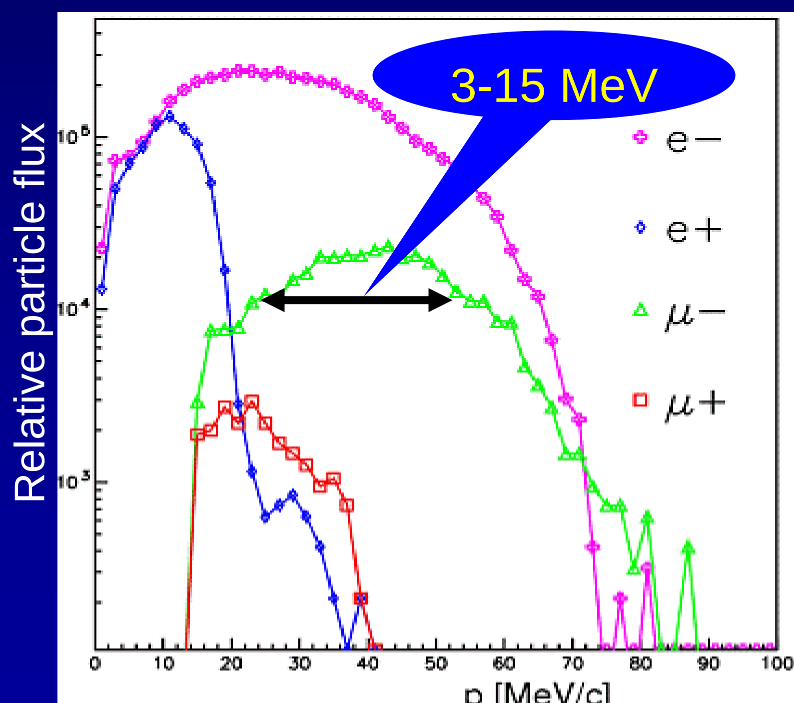
- Curved sections eliminate line of site transport of photons and neutrons.
- Toroidal sections causes particles to drift out of plane; used to sign and momentum select beam.
- dB/dS < 0 to avoid reflections

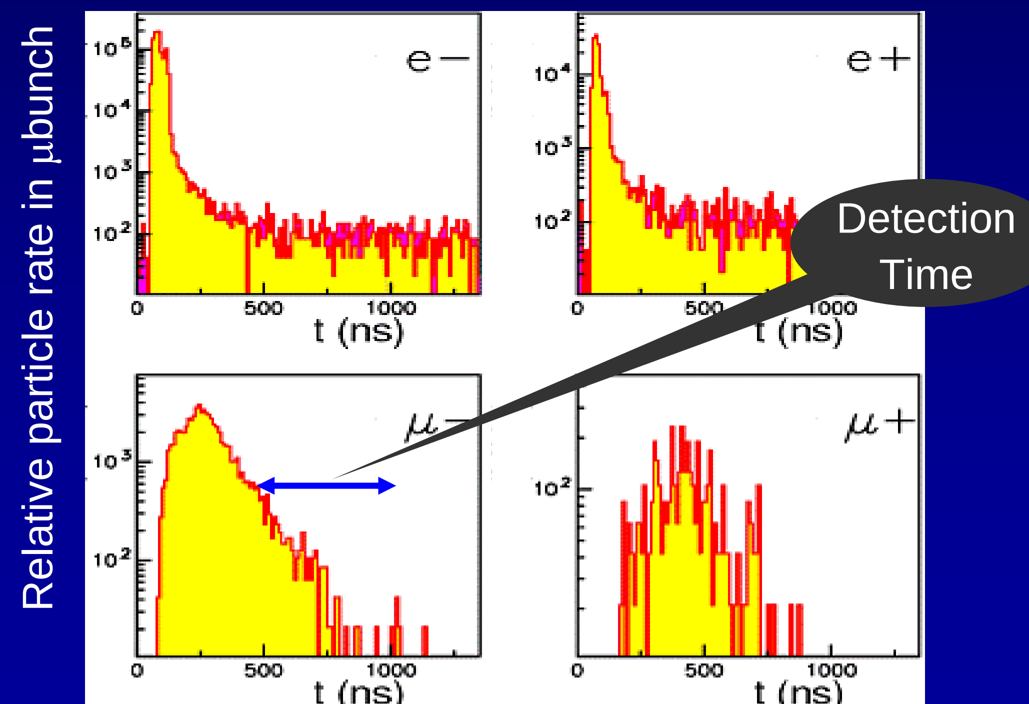
Sign and Momentum Selection in the Curved Transport Solenoid

Transport in a torus results in charge and momentum selection: positive particles and low momentum particles absorbed in collimators.

$$D = \frac{1}{0.3B} \times \frac{s}{R} \times \frac{p_s^2 + \frac{1}{2}p_t^2}{p_s}$$

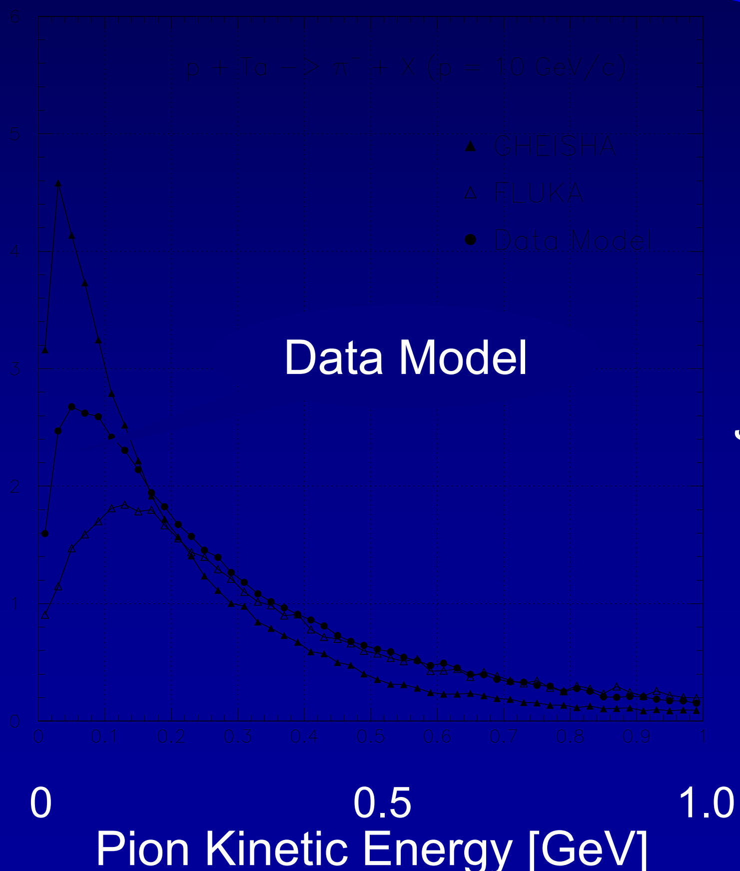


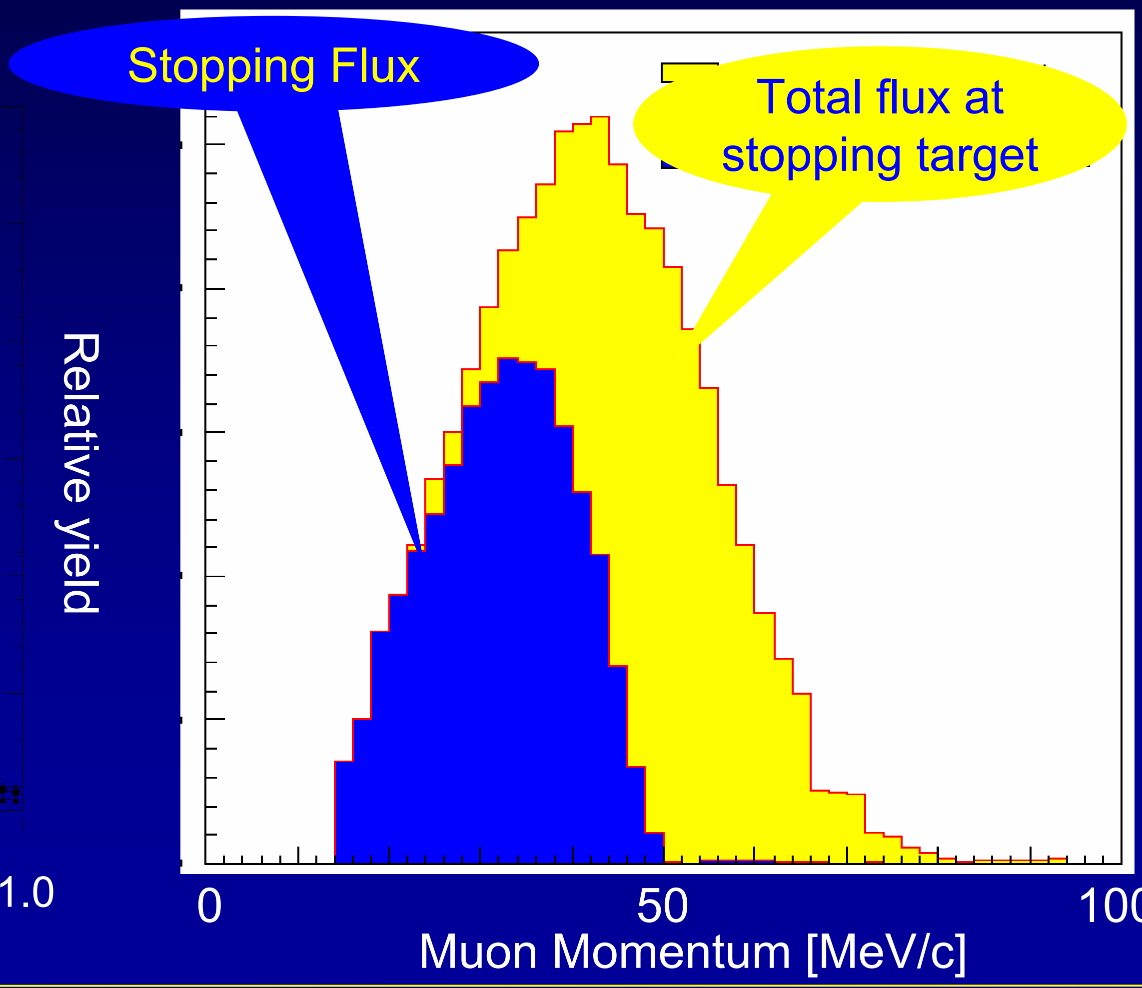




Muon Beam Studies

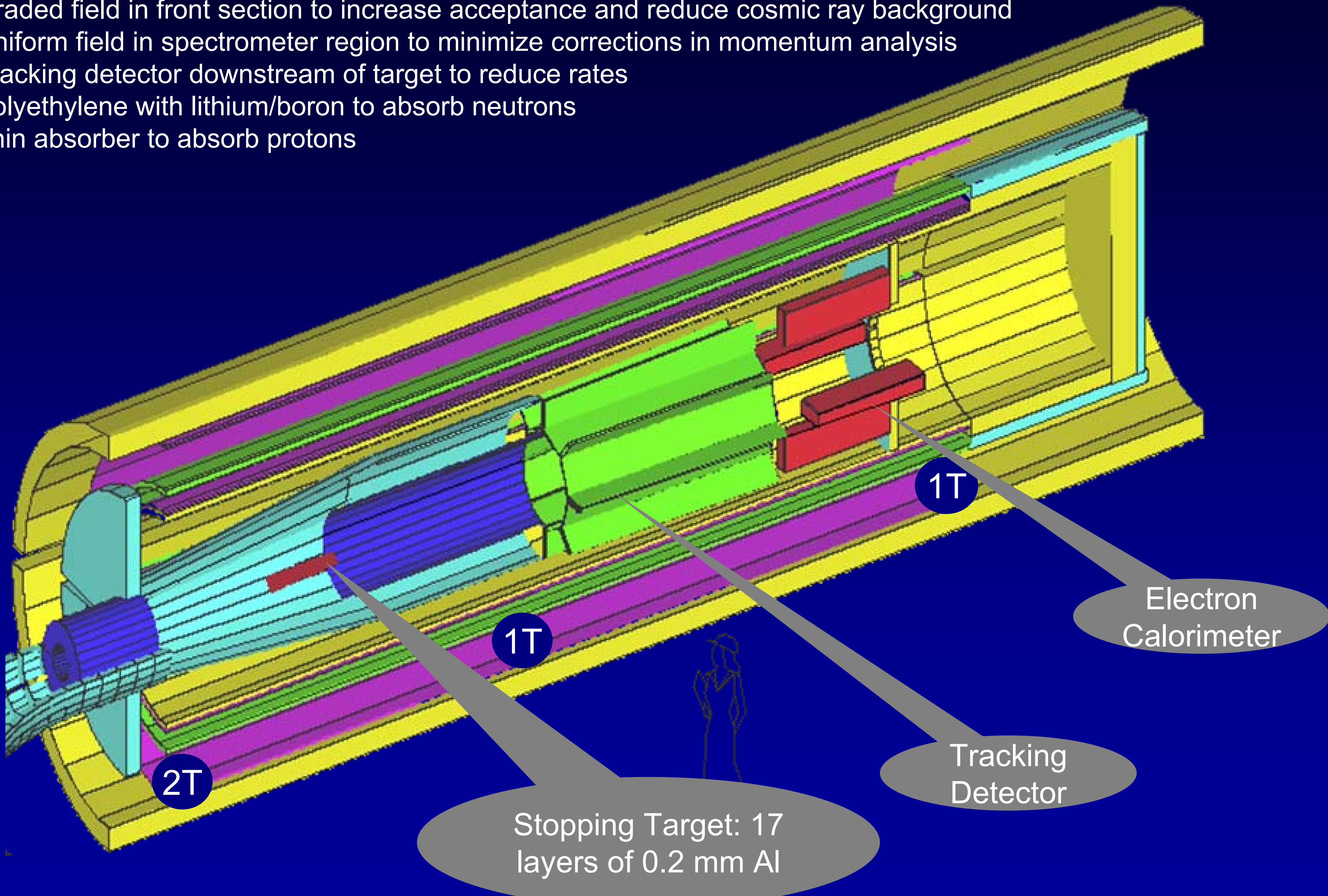
- Muon flux estimated with Monte Carlo calculation including models of π^- production and simulation of decays, interactions and magnetic transport.
- Estimates scaled to measured pion production on similar targets at similar energy
- Expected yield is about 0.0025 μ^- stops per proton





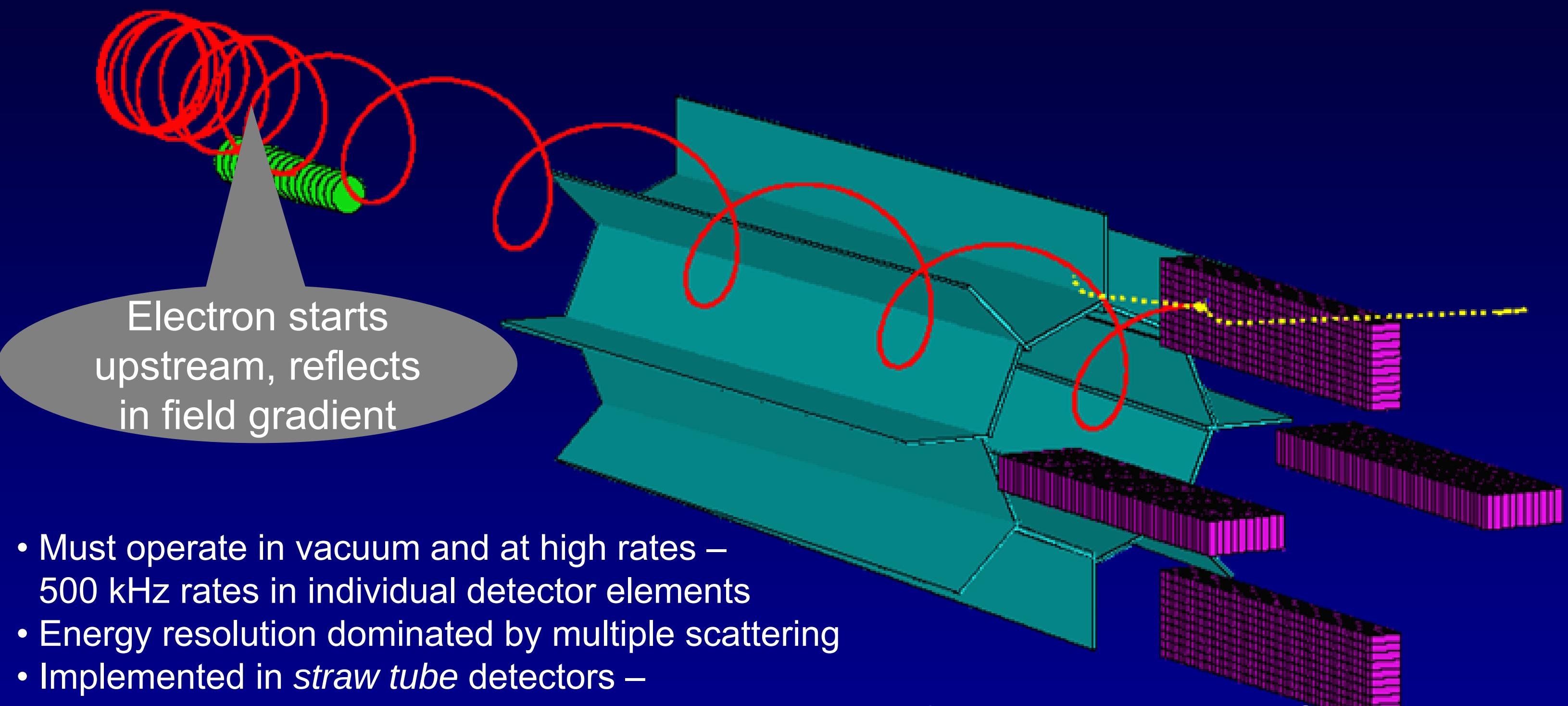
Stopping Target and Experiment in Detector Solenoid

- 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



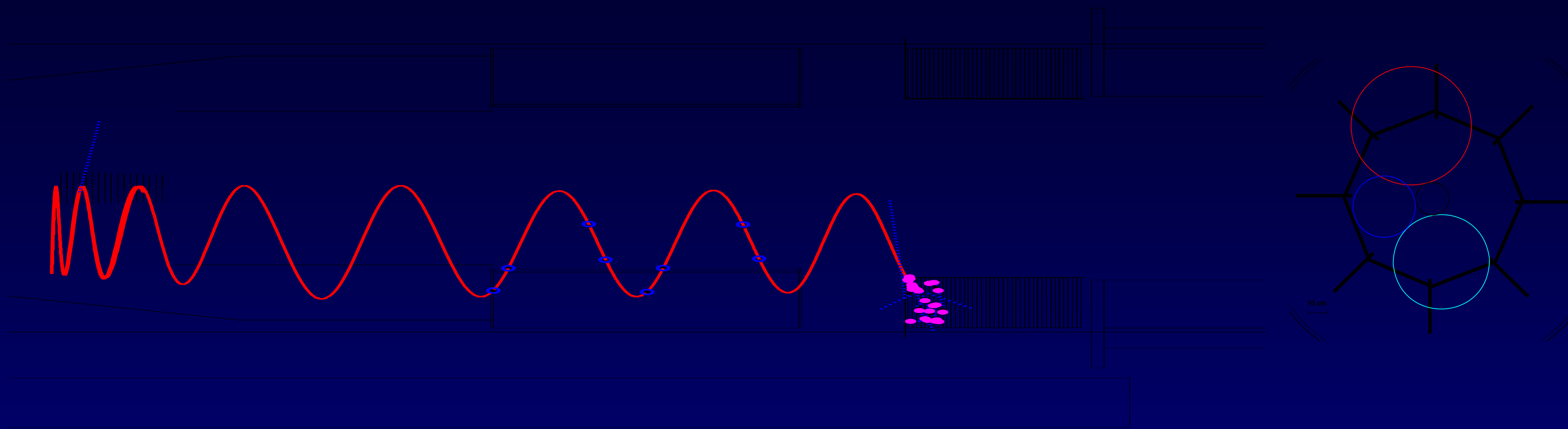
Magnetic Spectrometer to Measure Electron Momentum

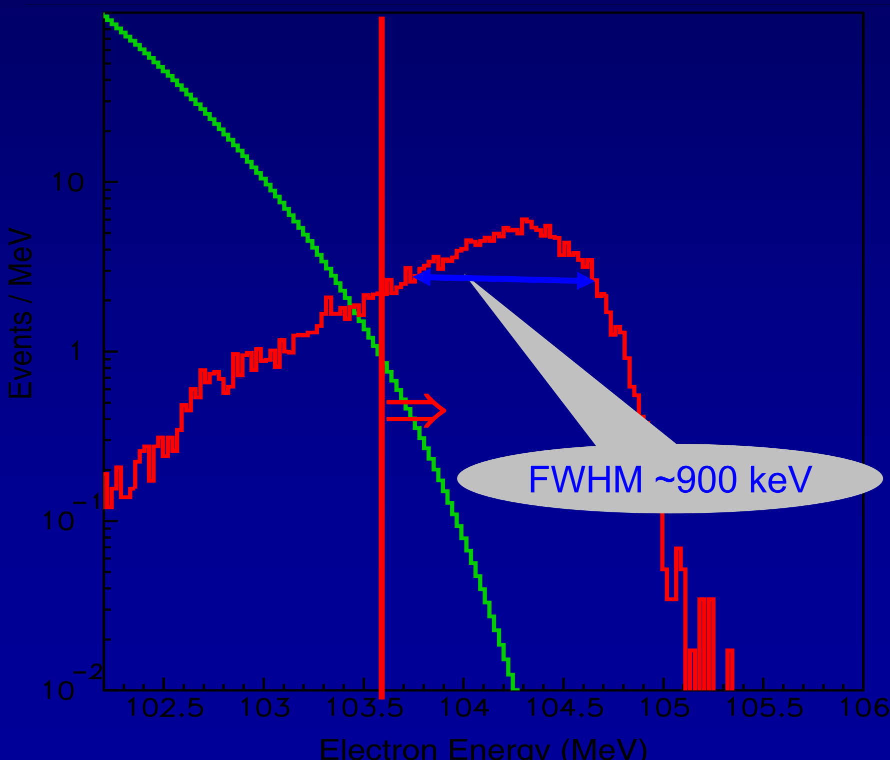
Measures electron momentum with precision of about 0.3% (RMS) – essential to eliminate muon decay in orbit background



- Must operate in vacuum and at high rates –
  500 kHz rates in individual detector elements
- Energy resolution dominated by multiple scattering
- Implemented in *straw tube* detectors –
  - *Vanes* and *octants,* each nearly axial, and each with 3 close-packed layers of straws
  - 2800 detectors, 2.6-3.0 m long, 5 mm diameter, 0.025 mm wall thickness – issues with straightness, wire supports, low mass end manifolds, mounting system
  - r-ϕ position resolution of 0.2 mm from drift time
  - axial resolution of 1.5 mm from induced charge on cathode pads – requires resistive straws, typically carbon loaded polyester film
    - High resistivity to maximize induced signal
    - Low resistivity to carry cathode current in high rates
- Alternate implementation in straw tubes perpendicular to magnet axis has comparable performance

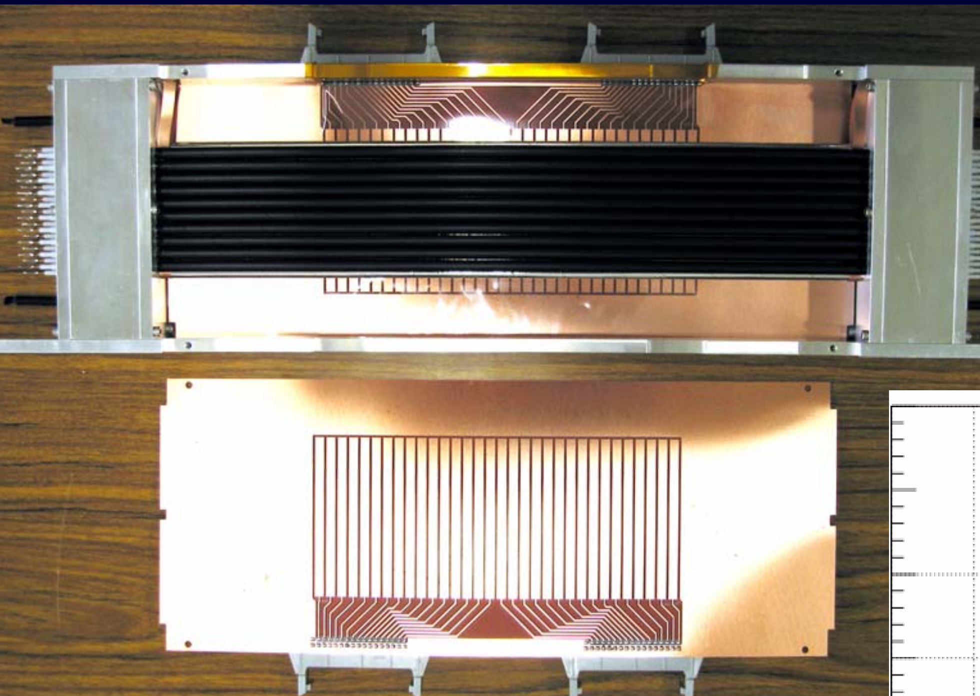
Spectrometer Performance Calculations

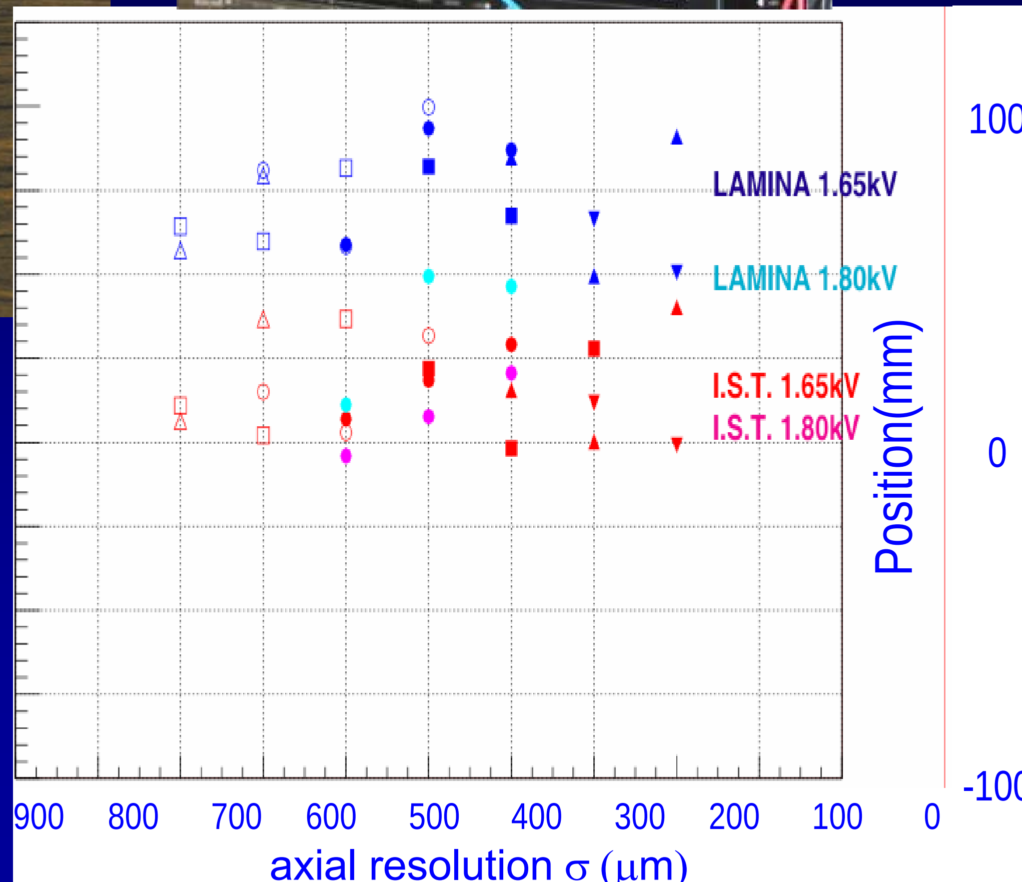




- Performance calculated using Monte Carlo simulation of all physical effects
- Resolution dominated by multiple scattering in tracker and energy loss in target
- Resolution function of spectrometer convolved with theoretical calculation of muon decay in orbit to get expected background.
- Geometrical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

Prototype Resistive Straw Tracking Chamber (Osaka University)





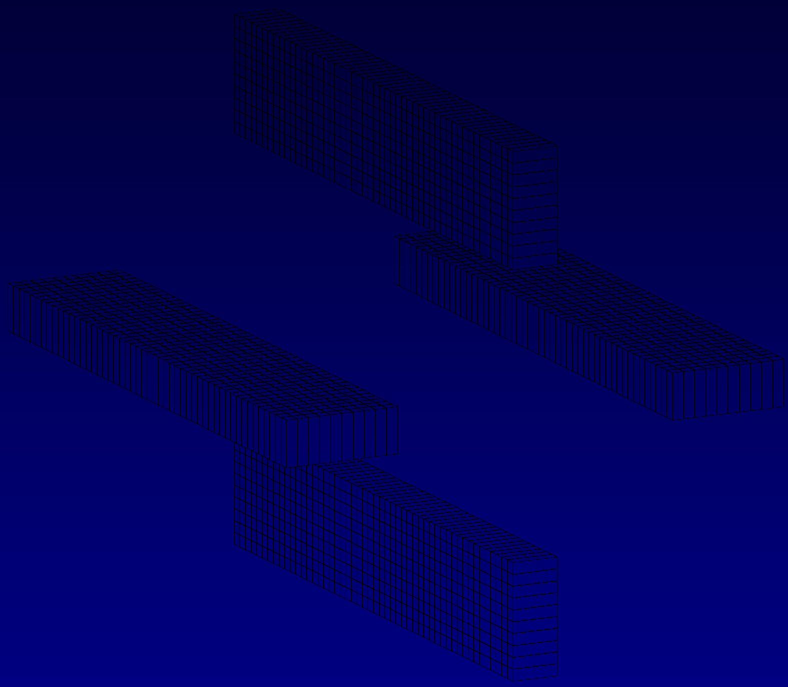
Prototype resistive straw tracking chamber tests

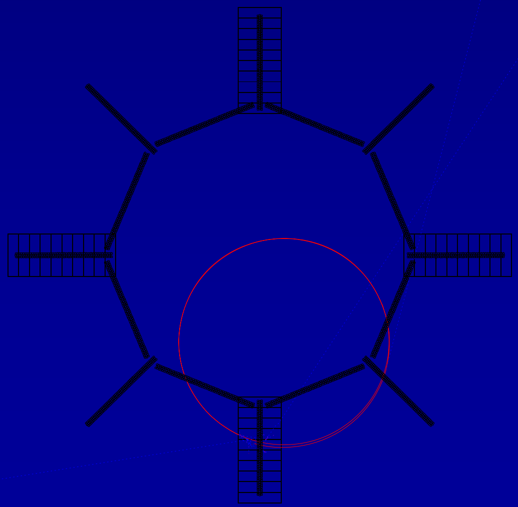
- Seamless and spiral wound straws tested
- Three layers (outer two resistive)
- Axial position measured with pads, interpolating using charge measurements
- Tested in KEK test beam
- Axial position resolution 400-800 μm (MECO requirement 1500 μm)

Scintillating Crystal Absorption Calorimeter

- Provides prompt signal proportional to electron energy for use in online event selection
- Provides position measurement to confirm electron trajectory
- Provides energy measurement to ~5% to confirm electron momentum measurement
- Consists of ~1200 3.75 x 3.75 x 12 cm^3 $PbWO_4$ crystals with APD readout

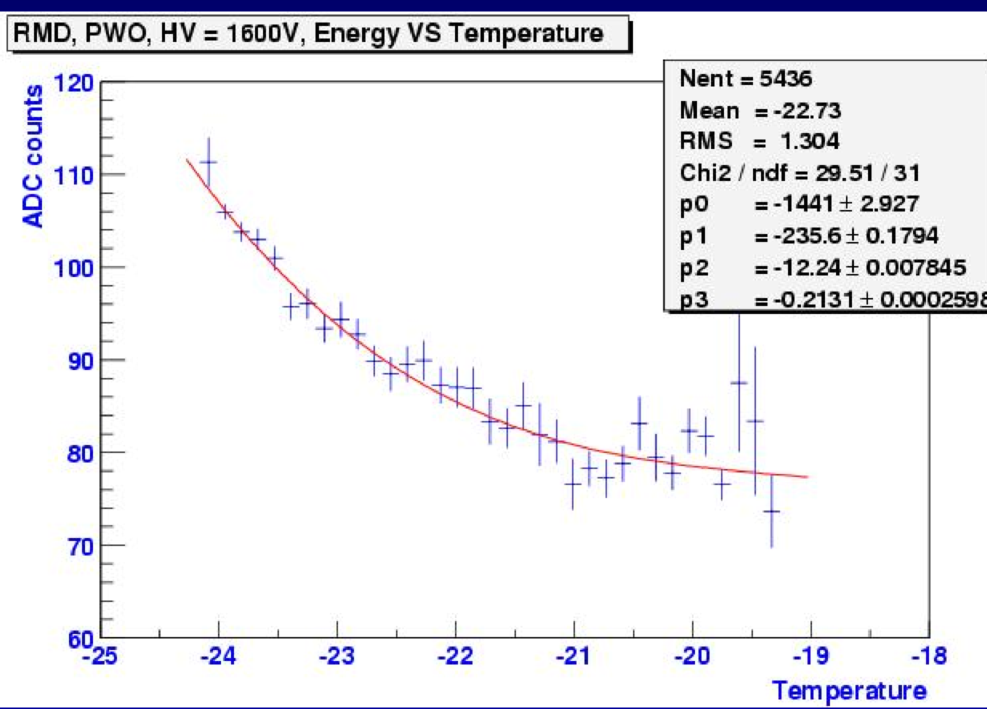
- Small studied for light yield, APD evaluation, electronics development

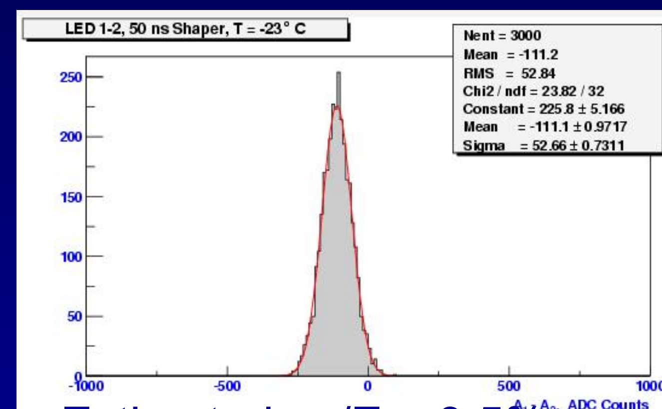




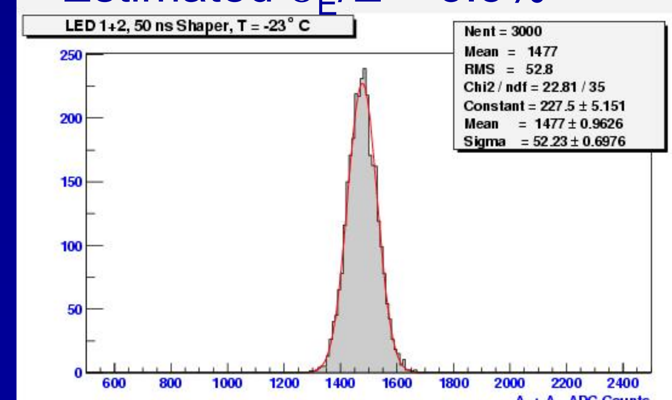
Crystal, APDs and Setup Schematic View

- 3.75 × 3.75 × 12 cm^3 $PbWO_4$ crystals
- Large area (13mm x 13mm) APD from RMD Inc.
- Hamamatsu (5mm x 5mm) APD used by CMS
- Crystal / APD combinations were tested using cosmic rays. The crystal, APD, and preamplifier are cooled, increasing the crystal light yield and decreasing dramatically the APD dark current.



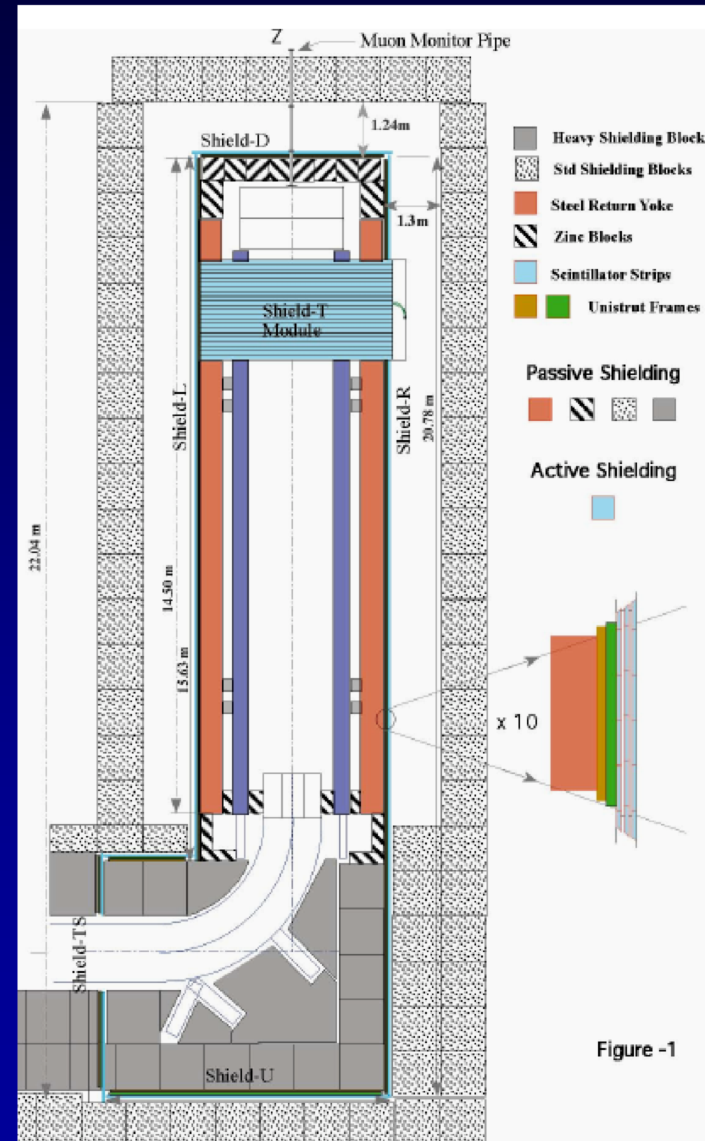


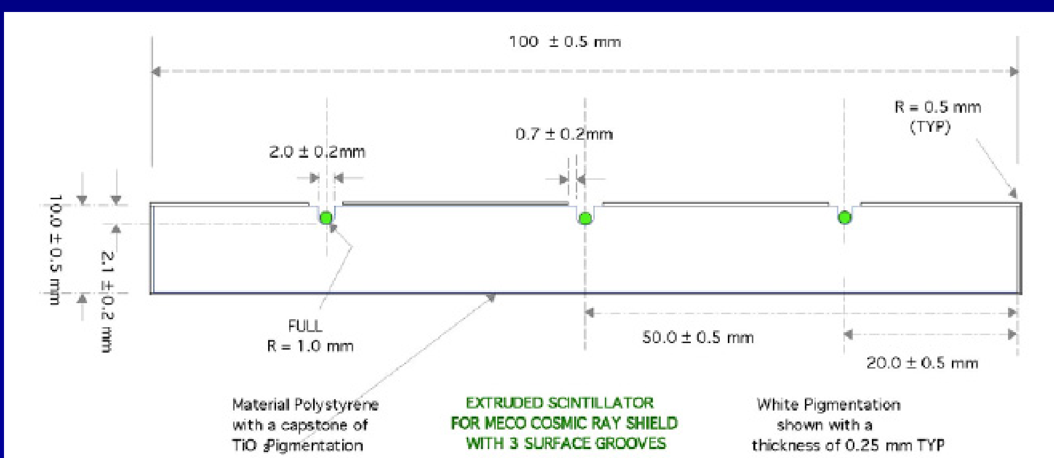
Estimated σ_E/E = 3.5%



Cosmic Ray Veto and Shielding

- Passive shielding: heavy concrete plus 0.5 m magnet return steel. Latter also shields CRV scintillator from neutrons coming from stop target.
- Hermetic active veto: Three overlapping layers of scintillator consisting of 10 cm x 1 cm x 4.7 m strips
- Goal: Inefficiency of active shielding $<10^{-4}$
- Cost-efficient solution: MINOS approach- extruded rather than cast scintillator, read out with 1.4 mm dia. wavelength-shifting fiber.
- Use multi-anode PMT readout





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 will be determined directly from data.

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

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

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.
- A group of physicists is interested in exploring the possibility of doing this experiment at Fermilab and is eager to attract more interested physicists at the beginning of the effort.
- This experiment would complement the neutrino program at Fermilab in the decade following the end of the Tevatron program and the beginning of a major new program.
- An appropriate proton beam can probably be built and operated for such an experiment at Fermilab with net positive impact on the planned neutrino program: Dave McGinnis will discuss the beam and operational issues.

END