Jim Popp, NYU
NUFACT'00, May 25, 2000

# The MECO Experiment

## A search for lepton flavor violation in $\mu^- \mathrm{N} \rightarrow e^- \mathrm{N}$ with sensitivity $R_{\mu e} \lesssim 10^{-16}$.

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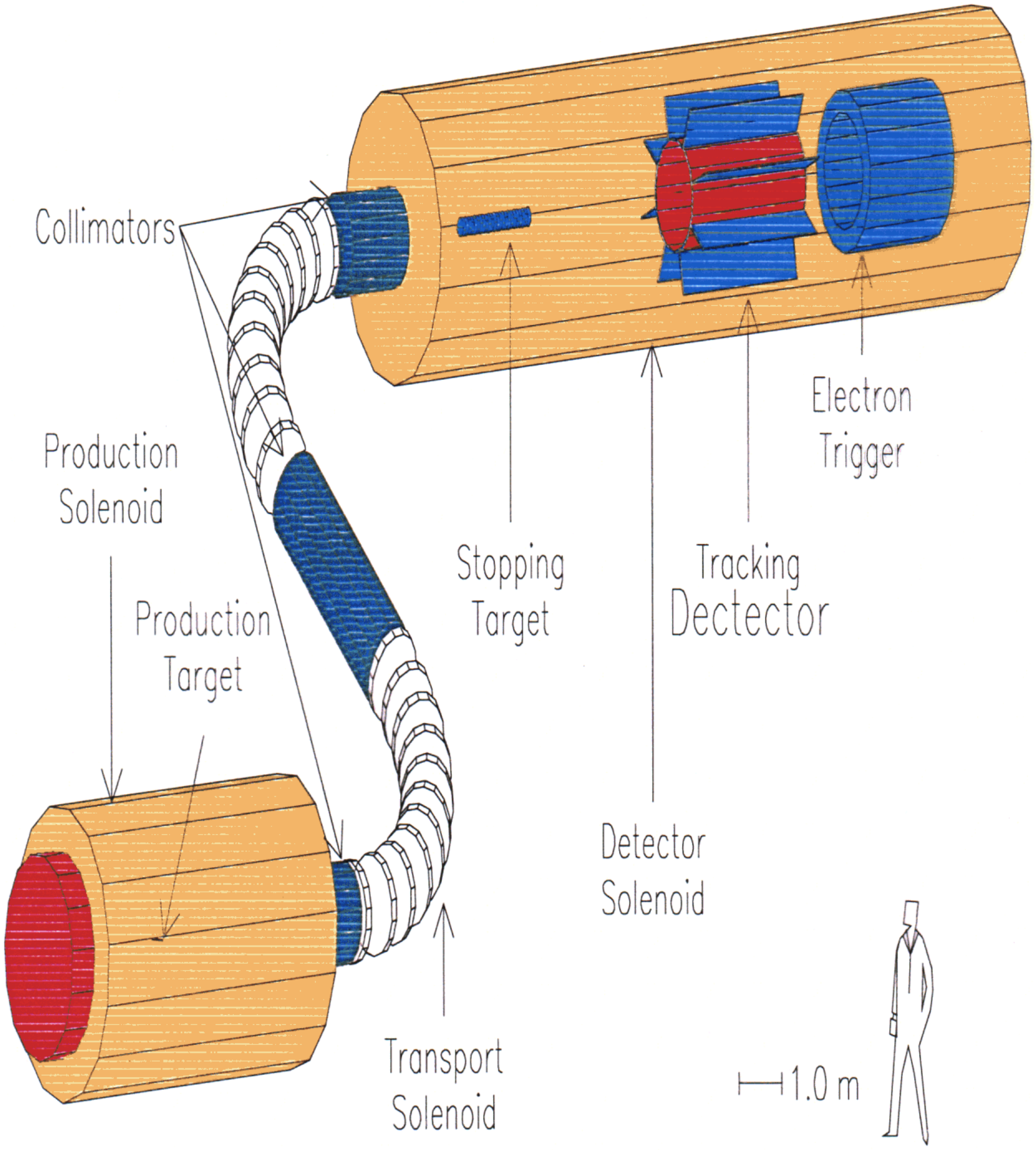
# The proposed MECO experiment

$$\mu^- \mathrm{Al} \rightarrow e^- \mathrm{Al}$$



R.M. Djilkibaev and V.M. Lobashev et. al., 1992 MELC proposal:

- High intensity ($10^{11}$ $\mu^-$/sec), pulsed beam with target in graded field.
- S shaped transport solenoid uses drift and collimators in y dimension to stop fast particles.
- Graded field in detector region to separate conversion $e^-$ from those produced upstream.
- 1.5% FWHM $P_e$ resolution from tracker, trigger calorimeter $\Rightarrow \sim 10^{-16}$

# $\mu \Rightarrow e$ Conversion–Signal

1. Stop muons by trapping them in Coulomb orbits around nuclei.
   - Bohr:

$$E_n = -m_\mu \frac{(Z\alpha)^2}{2n^2} \quad \text{and} \quad r_n = \frac{n^2}{Z\alpha m_\mu} \, .$$

   - For our choice of stopping target: Aluminum ($Z = 13$, $A = 27$)

$$E(1s) = -0.50\,\text{MeV} \quad \text{and} \quad r(1s) = 20.0\,\text{fm} \, .$$

   - Wheeler, RMP **21**, 133 (1949): sphere ($R_{\text{Al}} \sim 4.14\,\text{fm}$) with uniform charge distribution. Other better approximations.
   - Mean bound muon lifetime is $\tau(\text{Al}) = 880\,\text{ns}$, and $\tau(\text{free}) = 2.2\,\mu\text{s}$.

2. Look for distinctive two-body final state:

$$\mu^- + \text{N}(Z, A) \rightarrow e^- + \text{N}(Z, A) \, .$$

   - Initial state and final nuclear state must be the *same*.
   - Signature: Mono-energetic electron

$$E_e = E_\mu - \frac{E_\mu^2}{2M_A} \quad \text{and} \quad E_\mu = m_\mu + E(1s) \, ,$$

     in time window delayed with respect to muon stop.
   - $E_e(\text{Al}) = 105\,\text{MeV}$.
   - Nuclear recoil energy $\sim 0.22\,\text{MeV}$.
   - Average binding energy per nucleon ($A > 4$): 5.5 - 8.6 MeV.

# Measurement

1. Branching fraction relative to muon capture in nucleus:

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

2. Pulsed beam reduces prompt backgrounds to managable level.
3. Neglecting prompts primary background **muon decay in orbit:**

$$\mu^- + \mathrm{Al} \to e^- \nu_\mu \bar{\nu}_e + \mathrm{Al}\,.$$

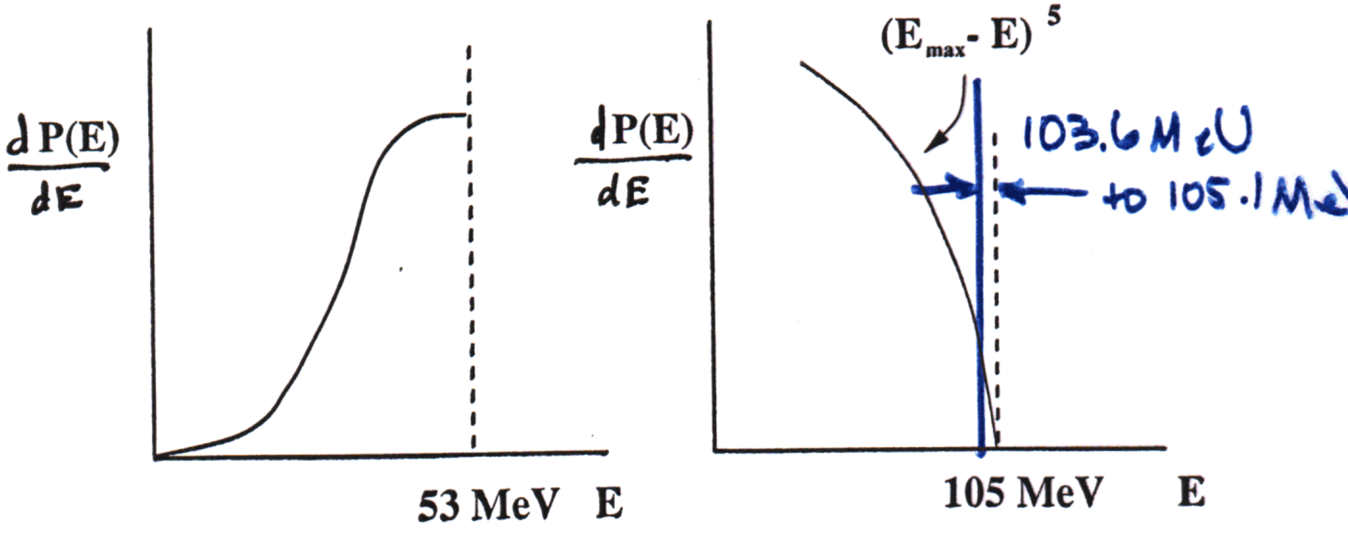
4. Compare electron energy for free vs. bound $\mu^-$ decay:

**Decay at Rest:**

$\mu \longrightarrow e\ \nu\ \nu$

**Bound Decay:**

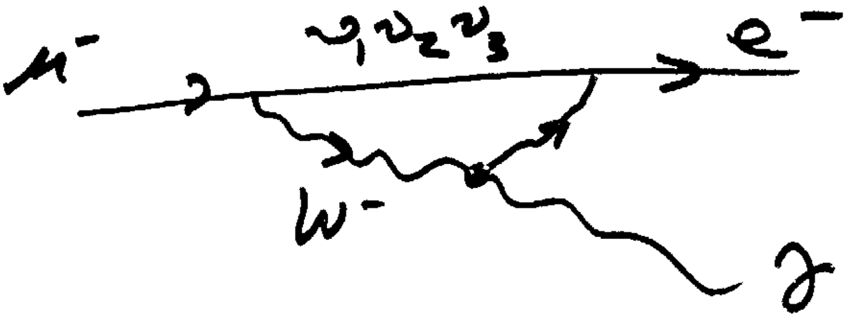
$(\mu, Z, A) \longrightarrow e\ \nu\,\nu\,(Z,A)$



5. Fraction of all muon decays in Aluminum that produce an $e^-$ energy within 3 MeV of endpoint is $5 \times 10^{-15}$.

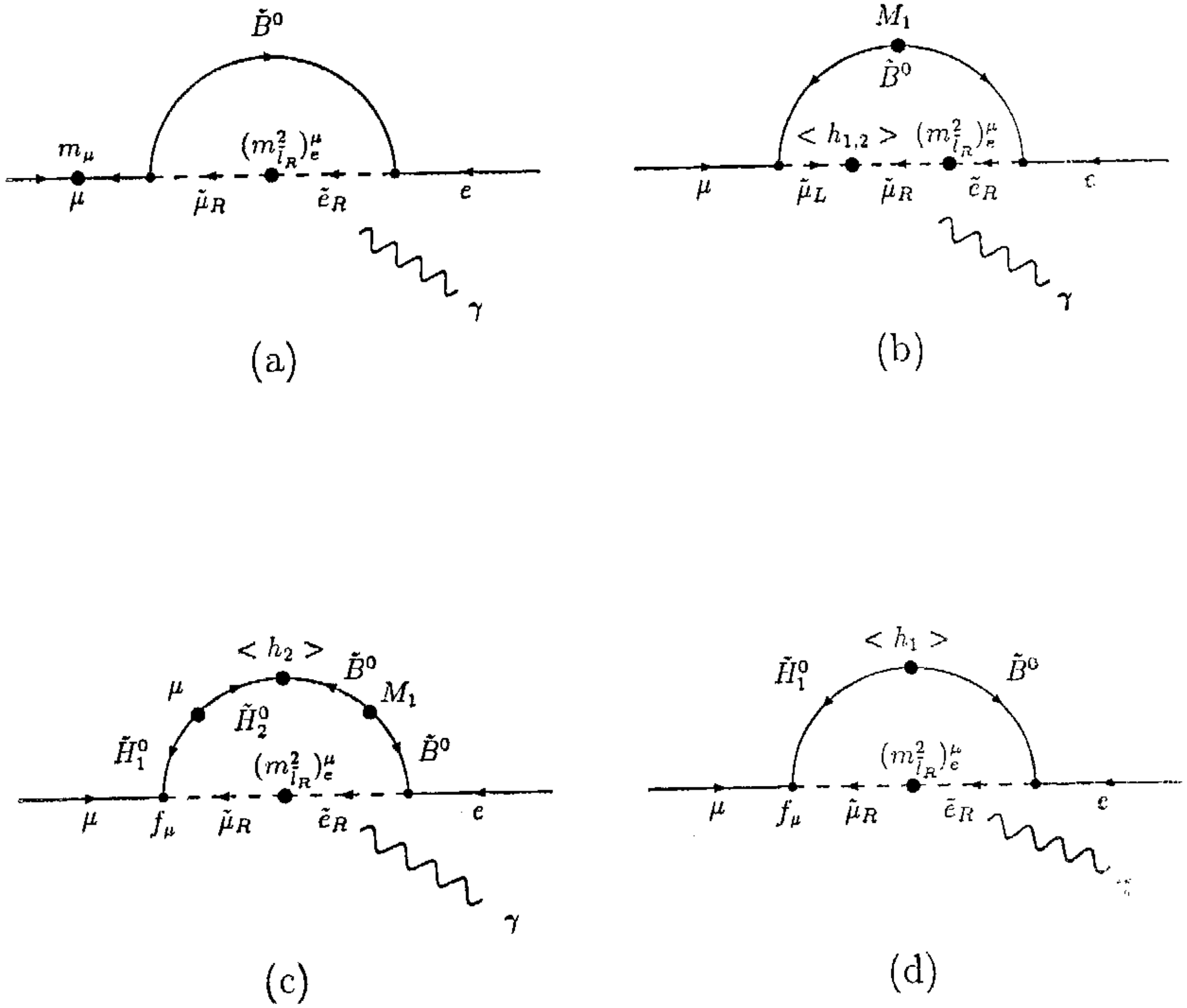
# How would an LFV transition occur?

1. Evidence for lepton flavor symmetry transion from Super-Kamiokande, Phys. Rev. Lett. **81**, 1562 (1998); could be $\nu_\mu \to \nu_\tau$.
   - Neutrinos mix ⇒ there are at least two different $\nu$ masses.
   - Consequences for non-oscillation experiments appear too small: The rate for $\tau \to \mu + \gamma$ are $\propto \delta m_\nu^2 / M_W^2$.



2. Extensions of the Standard Model, including supersymmetric theories, that unify quark and leptons lead to small but observable rates.
   - Minimal SUSY SU(5):
     $R_{\mu e} \sim 10^{-14}$ - $10^{-17}$ over most of the parameter ranges.

# Minimal SUSY SU(5)
# Hisano et al., Phys. Lett. B391, 341 (1997)



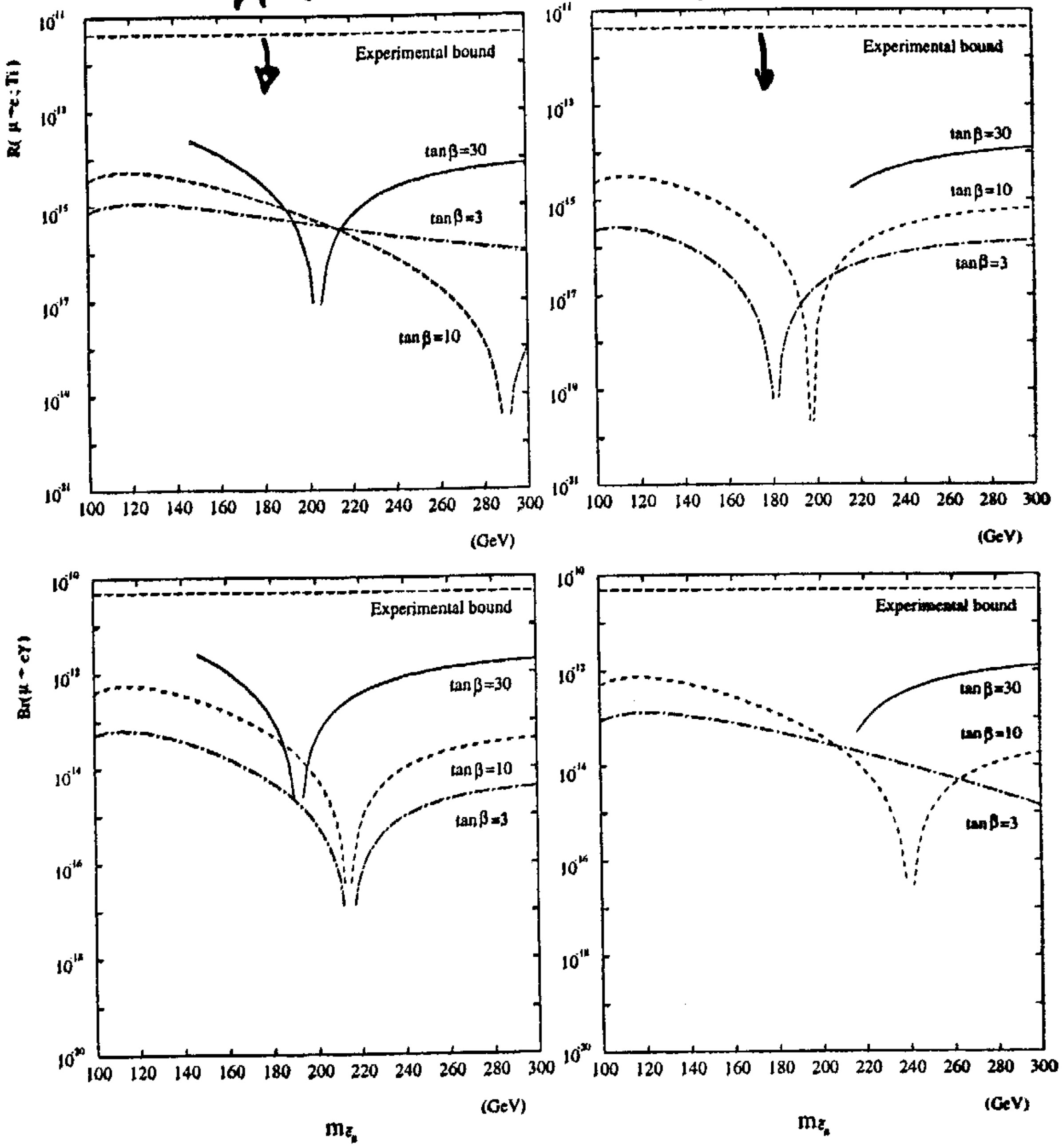
Diagrams contribute to $\mu^- N \to e^- N$ and $\mu^- \to e^- \gamma$.

current limit
$6.10^{-13}$

# MINIMAL SUSY SU(5)

## Hisano et al., Phys. Lett. B391, 341 (1997)

μ<0 μ>0



# A glance at some of the history of $\mu \rightarrow e$ studies

(1955) The search for LFV processes began around the 1950's:

- $\mu^- \rightarrow e^-\gamma$, Lokanathan & Steinberger.
- $\mu^-\mathrm{Cu} \rightarrow e^-\mathrm{Cu}$, found $R_{\mu e} \sim 5 \times 10^{-4}$, Steinberger & Wolfe, PR **100**, 1490 (1955).

(1959) Weinberg & Feinberg, $\mu^- N \rightarrow e^- N$, PRL **3**, 111 (1959).
Authors suggested transition experimentally attractive:

- Transition has a coherent enhancement if the initial and final internal states of the nucleus are the same. The transition amplitude is the coherent process of the $e^-$ to recoil against the entire nucleus, rather than individual nucleons.
- Coherence ⇒ signature mono-energetic two-body final state.
- Unlike the first of the two reactions $\mu^- \rightarrow e^- \gamma$ and $\mu^- N \rightarrow e^- N$, the second is chiral-conserving and thus less restricted by weak interactions.

(1994) Barbieri & Hall, Phys. Lett. **B 338**, 212 (1994).
Noted in studies of minimal supersymmetric models:

- Lepton flavor violating transitions likely to be good test for super-unified theories since the decay rates are often found to be nearest to experimental limits.
- Although the precise predictions of these theories depend on the specific model, the physical mechanisms that lead to LFV are generic to supersymmetric quark-lepton unification.

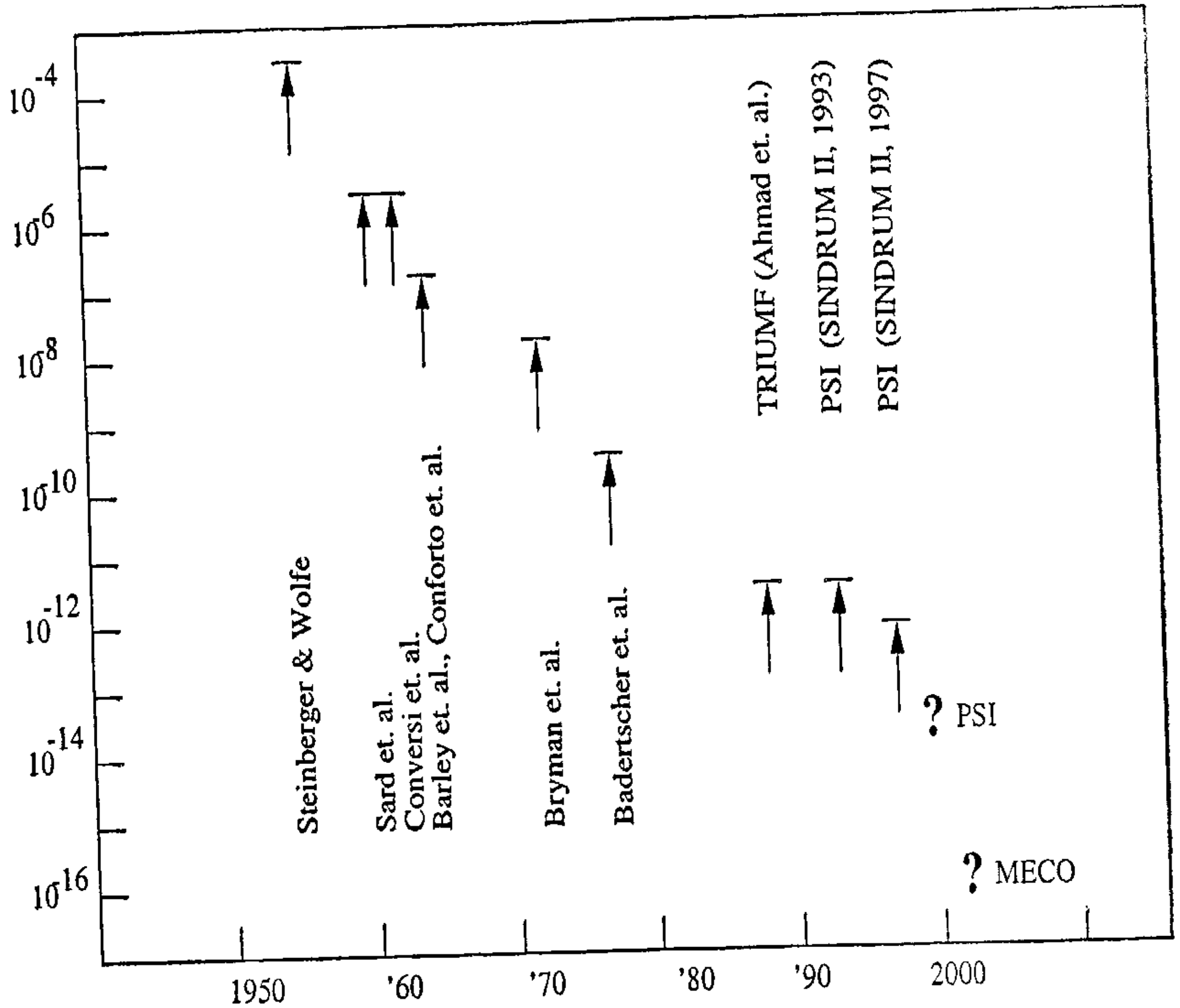
# Some current limits on LFV transitions

| Year | Process | Br. frac. | Reference |
|---|---|---|---|
| 1988 | $\mu^+ \to e^+e^+e^-$ | $1.0 \times 10^{-12}$ | Nucl. Phys. B **299**, 1 (1988) |
| 1990 | $K^+ \to \pi^+\mu^+e^-$ | $2.1 \times 10^{-10}$ | Phys. Rev. Lett. **64**, 165 (1990) |
| 1994 | $K_{\rm L}^0 \to \pi^0\mu^\pm e^\mp$ | $3.2 \times 10^{-10}$ | Phys. Lett. B **320**, 407 (1994) |
| 1997 | $\mu^- N \to e^- N$ | $6.1 \times 10^{-13}$ | See references below |
| 1998 | $K_{\rm L}^0 \to \mu^\pm e^\mp$ | $4.7 \times 10^{-12}$ | Phys. Rev. Lett. **81**, 5734 (1998) |
| 1999 | $\mu^+ \to e^+\gamma$ | $1.2 \times 10^{-11}$ | Phys. Rev. Lett. (1999) |

SINDRUM II:

- Phys. Lett. B **317**, 631 (1993)
- *Proceedings of the 6th Conference on the Intersections of Particle and Nuclear Physics*, ed. T. Donnelly (AIP, New York, 1997), p. 34.
- `http://www1.psi.ch/www_sindrum2_hn/sindrum2.html`

# Fifty Years of $\mu \to e$ Accelerator Experiments



- Latest SINDRUM II result (1997)

$$R_{\mu e} < 6.1 \times 10^{-13}$$

- May to November 1999 run on Ti, 100 days live time.
- Expect to reach $R_{\mu e} \sim 2 \times 10^{-14}$.

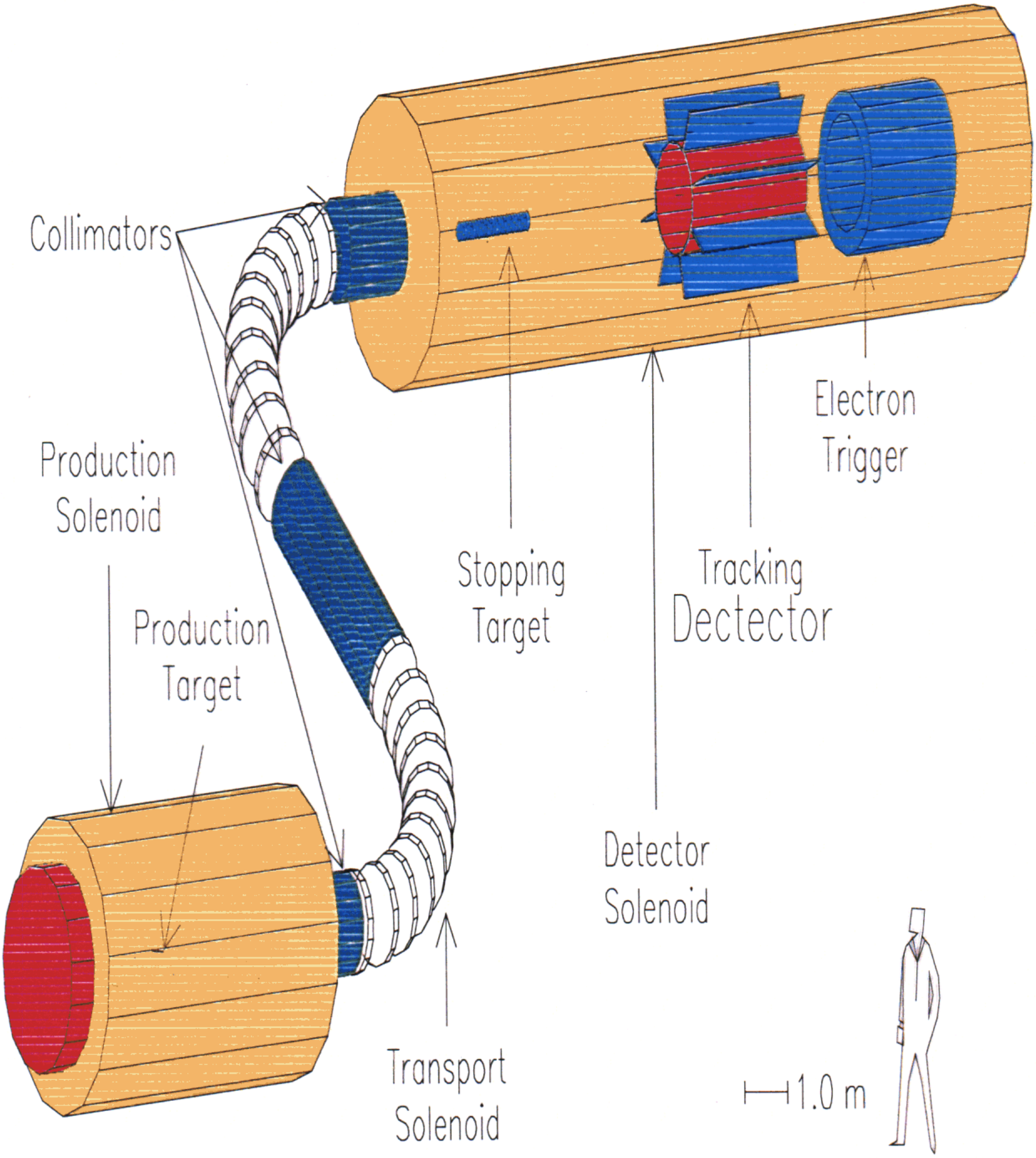
# Most Recent Experiments: $\mu^- N \rightarrow e^- N$

We believe MECO can improve upon these experiments by **three or more orders of magnitude** with a substantially scaled up approach.

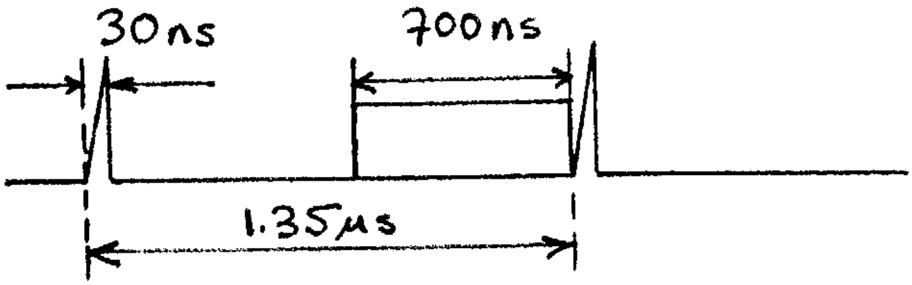
| Features | TRIUMF<br>Ahmad et al.<br>1988 | PSI<br>SINDRUM II<br>Bertl et al.<br>1997 | BNL<br>MECO<br>Proposal 940<br>(?2006?) |
|---|---|---|---|
| Principal Detector | TPC | Drift Chamber | Straw tubes |
| Magnetic field | 0.9 T | 1.2 T | 1.0 T |
| Target Material | Titanium | Titanium | Aluminum |
| Muons In/Stopped | $1.3/1.0 \times 10^6$ Hz | $12.0/3.3 \times 10^6$ Hz | $2.5/1.0 \times 10^{11}$ Hz |
| $\pi/\mu$ stops | $10^{-4}$ | $10^{-7}$ | $10^{-11}$ |
| Reject Prompts | beam counters | beam counters | pulsed beam |
| Resolution FWHM @ 100 MeV | 4.5 MeV | 2.3 MeV | $\lesssim$ 900 keV |
| Exposure time | 100 days | 50 days | 120 days |
| Cosmic Rays | $\sim 0.15/$MeV | Negligible | Negligible |
| 90% CL Limit | $4.6 \times 10^{-12}$ | $6.1 \times 10^{-13}$ | $5 \times 10^{-17}$ |

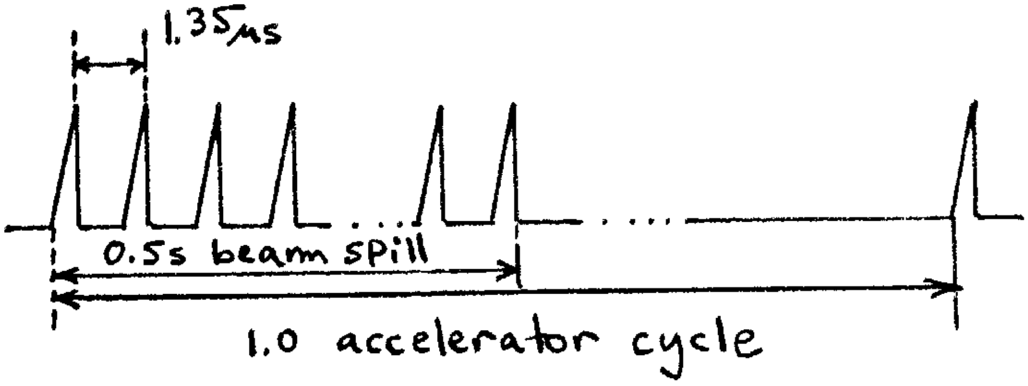
- Exploit existing (known) AGS operating parameter
- Limit $\propto 1/$ (muon captures) × (efficiency) × (running time).
- TRIUMF & PSI results limited by muon flux, **not backgrounds.**

# Three main MECO subsystems



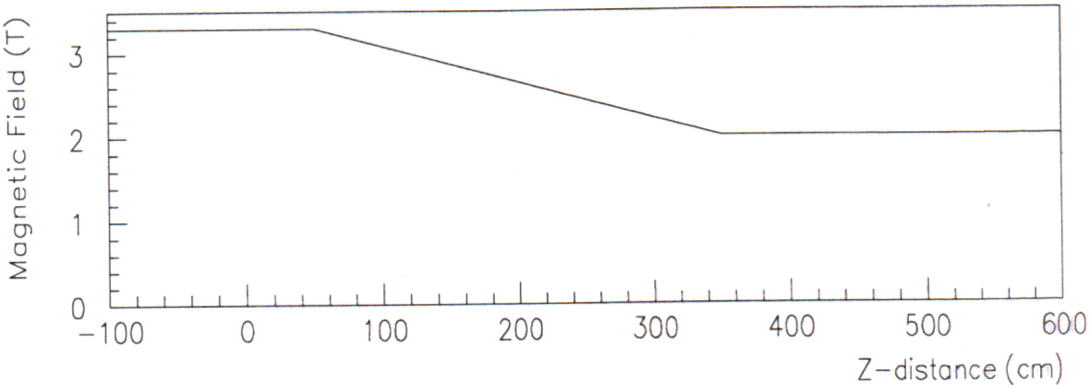
# Time structure of AGS proton beam

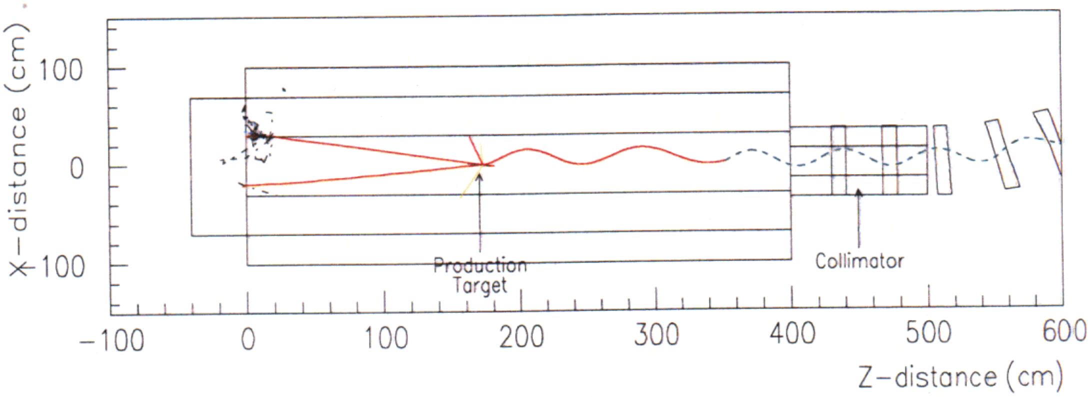




1. Run AGS at 6th harmonic and deliver $E_{\mathrm{proton}} = 7 - 8$ GeV.
   - Initially fill two RF buckets $20 \times 10^{12}$ protons each.
   - Do slow extraction. Beam spill 0.5 s, with 1.0 s acc. cycle.
   - Micro-structure: 1.35 $\mu$s between pulse (30 ns) starts.
2. Observation window delayed 650 ns wrt/ proton pulse: 700 ns.
3. Extinction $\varepsilon \equiv \mathrm{N}_p$ (700 ns window) / $\mathrm{N}_p$ (30 ns pulse) must be low to reject prompt backgrounds.
   - Goal: $\varepsilon \sim 10^{-9}$.

# Muon production solenoid





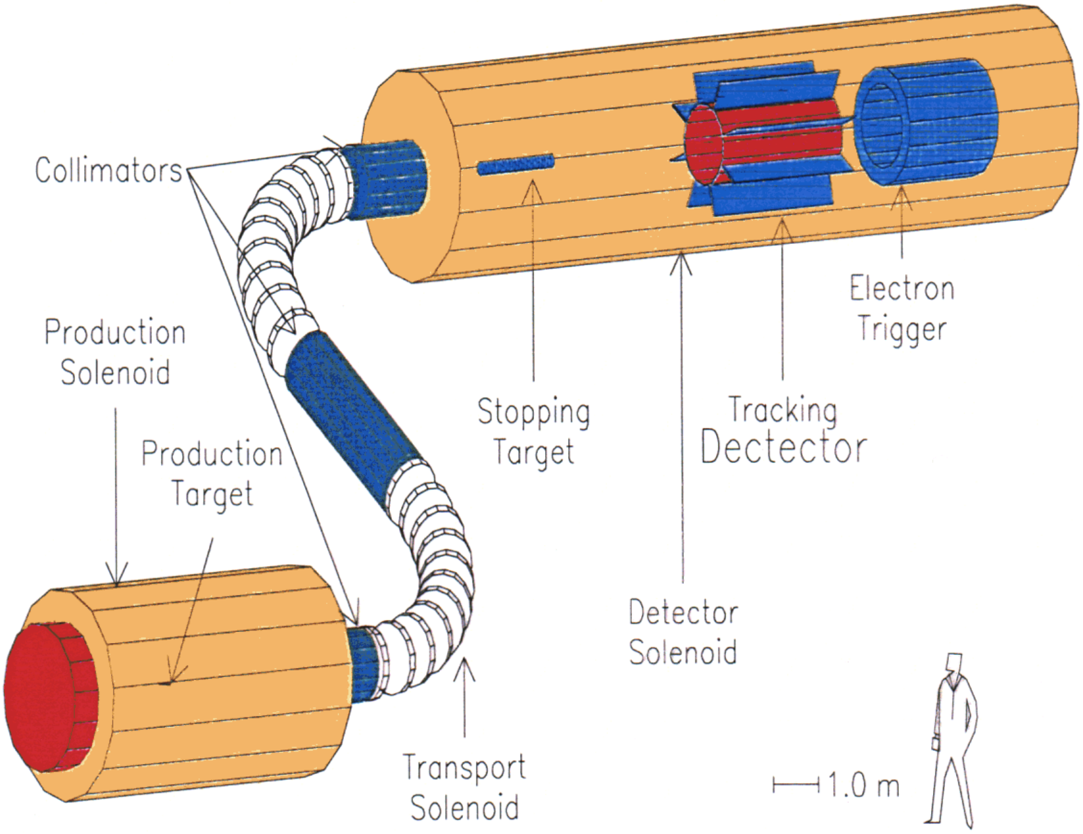
Pulsed low-energy $\mu^-$ beam with $10^{11}$ $\mu^-/\mathrm{s}$ at stopping target.

1. Beam enters at lower right of solenoid, $\sim 10^{\circ}$ with $z$ axis.
2. Strikes cylindrical tungsten target to make $\pi^-$.
   - Length $= 16\,\mathrm{cm}$, radius $= 0.4\,\mathrm{cm}$, mass $= 156\,\mathrm{g}$.
   - Expect $\langle N(\pi^-)\rangle$ per incident $p \sim 1.2$.
3. Graded magnetic field (3.3 T - 2.2 T) reflects charged particles to transport solenoid entrance with $p_\perp < 180\,\mathrm{MeV/c}$ if:
   - Angle with $z$ axis lies outside loss cone from $0^{\circ}$ to $30^{\circ}$.
   - Trajectory lies within inner radius of solenoid, 30 cm.

@ 10GeV

$(p + Ta \to \pi^- + X)$ $1.5\pi$

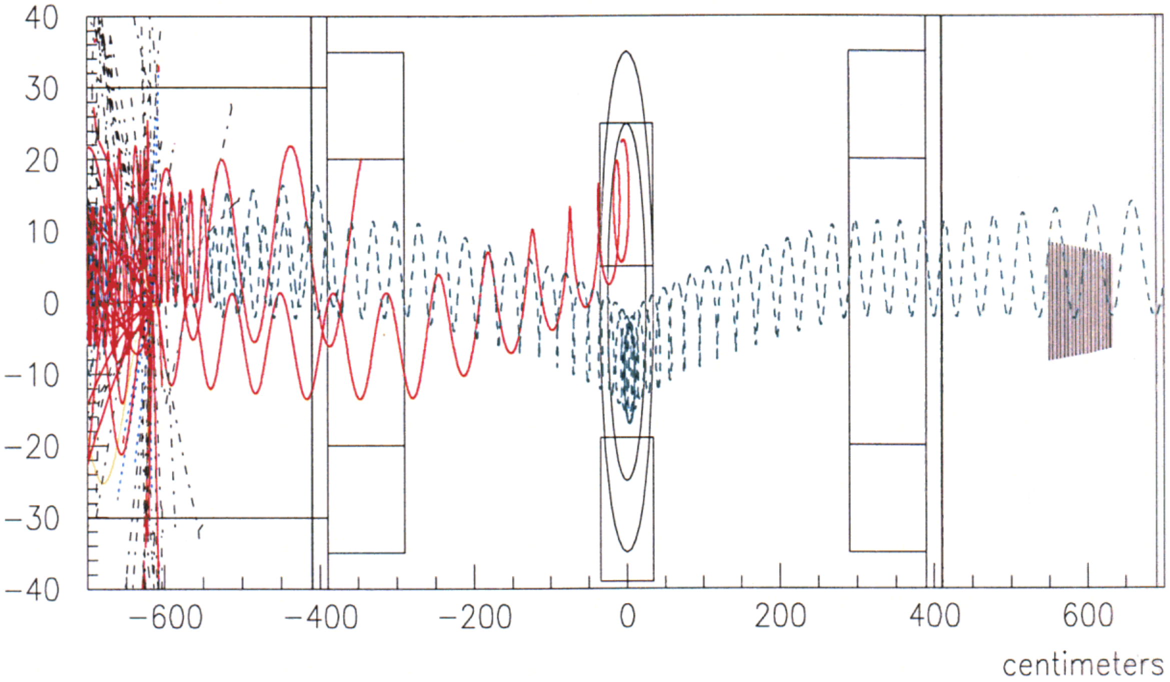
# Transport solenoid



The S-shaped transport solenoid filters the beam to produce a low-energy $\mu^-$ beam with reduced contamination from: $e^{\pm}$, p, $\bar{\text{p}}$, $\pi^{\pm}$.

1. Three collimators in straight sections absorb all positive charges and high energy $\mu^-$ ($p > 100\,\mathrm{MeV/c}$).
2. In the first curved section positive particles drift up and negatives drift down; in the second, drift directions are reversed.

# Transport solenoid: Drift from curved B-fields

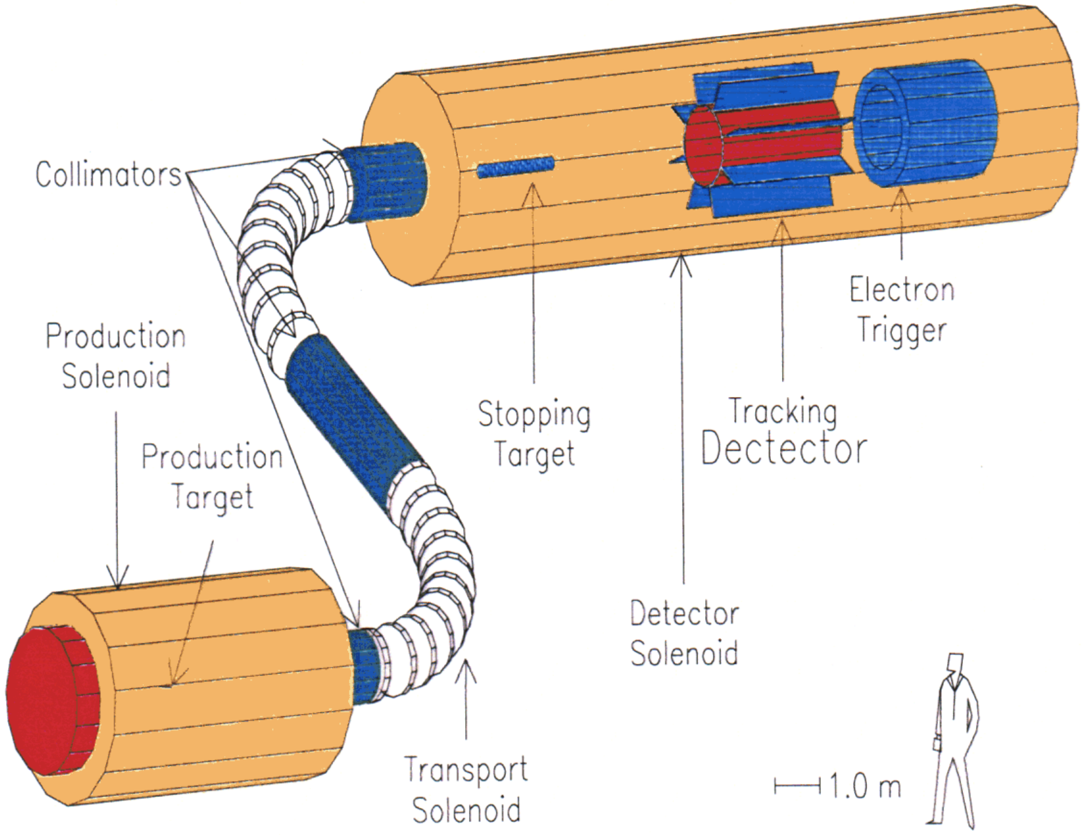


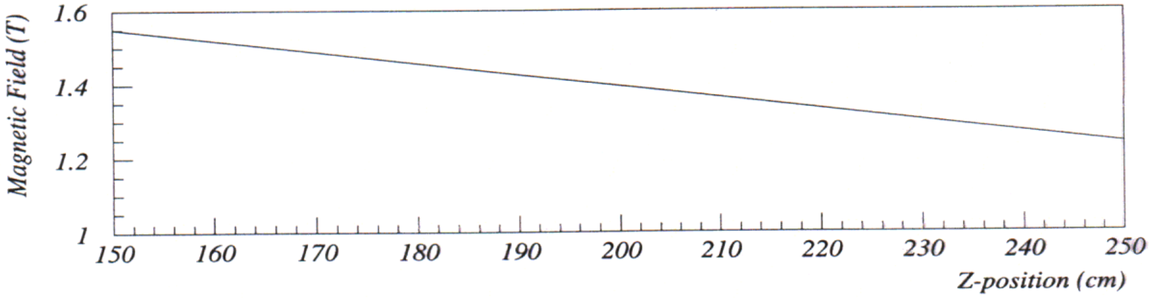
For positive charges:

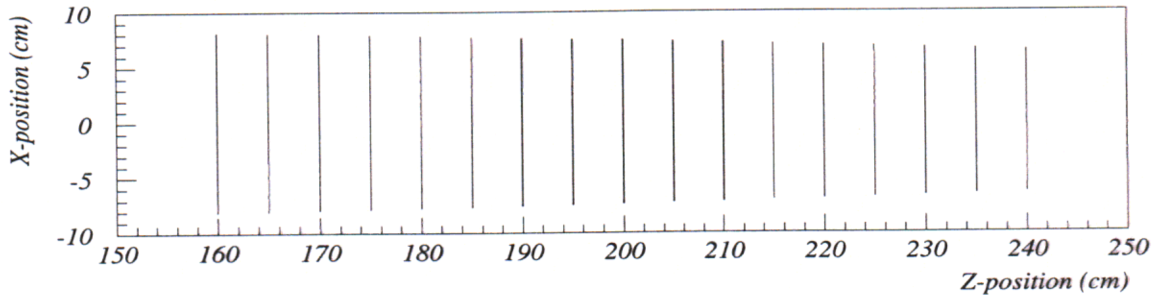
$$\vec{v}_{\text{drift}} = \frac{v_{\|}^2}{\omega R} \frac{\vec{R} \times \vec{B}}{RB} \quad \text{and} \quad \omega = eB/m\gamma(v)\,.$$

1. Each straight section has graded magnetic field, $\sim 0.1\,\text{T/m}$, to prevent particles from getting trapped and arriving late at detector solenoid.
2. Beryllium window at 2nd collimator absorbs anti-protons.
3. Beam particles and $e^-$ from decay at the target with $p_\perp < 90\,\text{MeV}/\text{c}$ pass through detector solenoid undisturbed.
   - $\mu^+$ and $e^+$ in beam all have $p < 40\,\text{MeV}/\text{c}$.
   - Most $e^-$ in beam have $p < 80\,\text{MeV}/\text{c}$; very few survive 80 - 100 MeV/c.

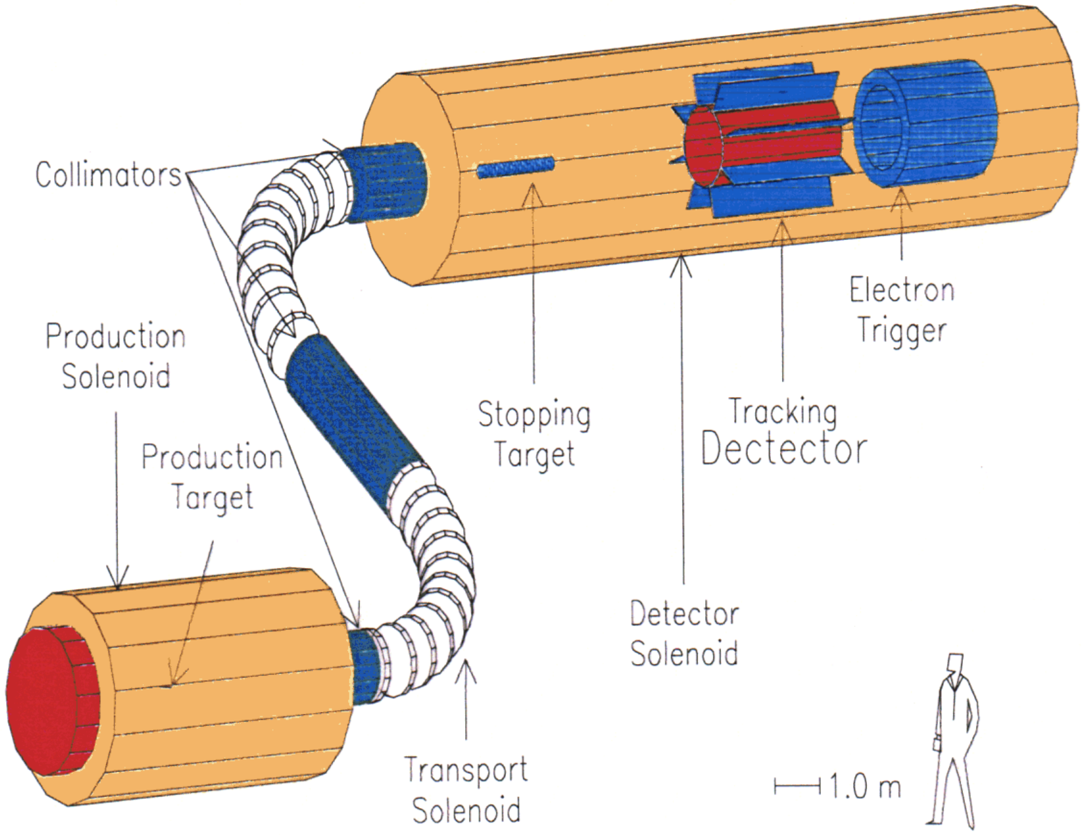
# Detector solenoid: $\mu^-$ stopping target

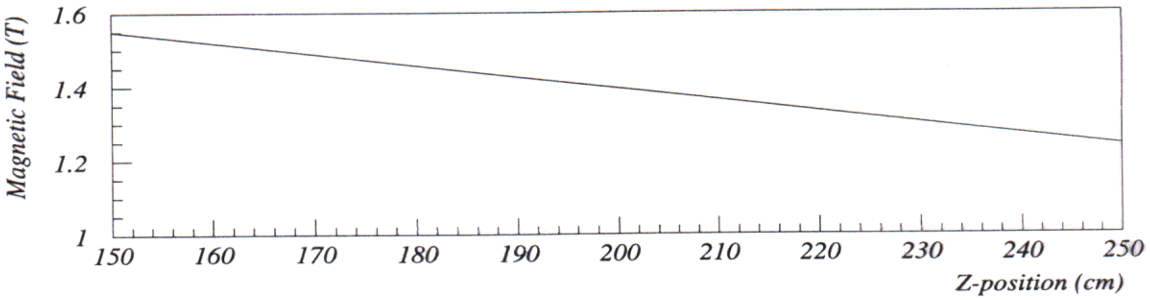


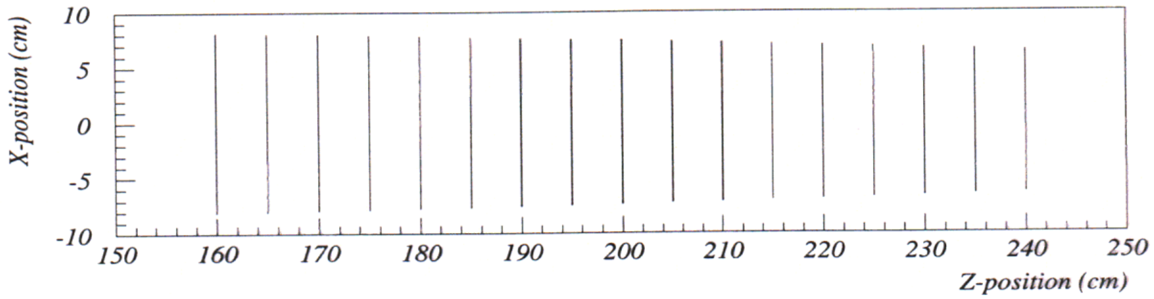




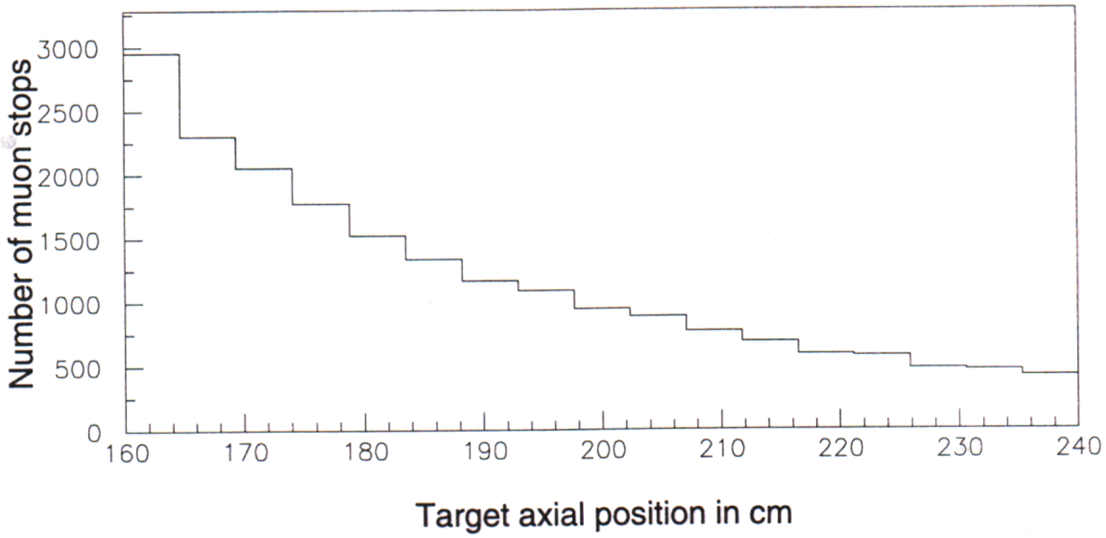
# Detector solenoid: $\mu^-$ stopping target

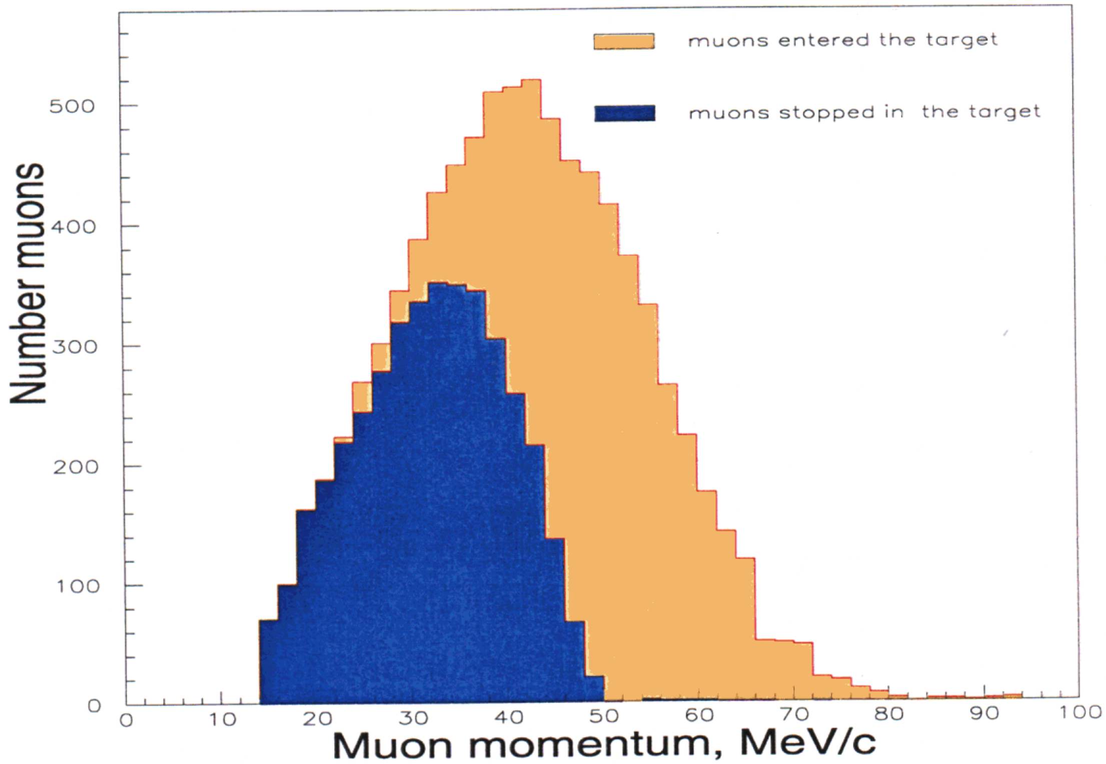




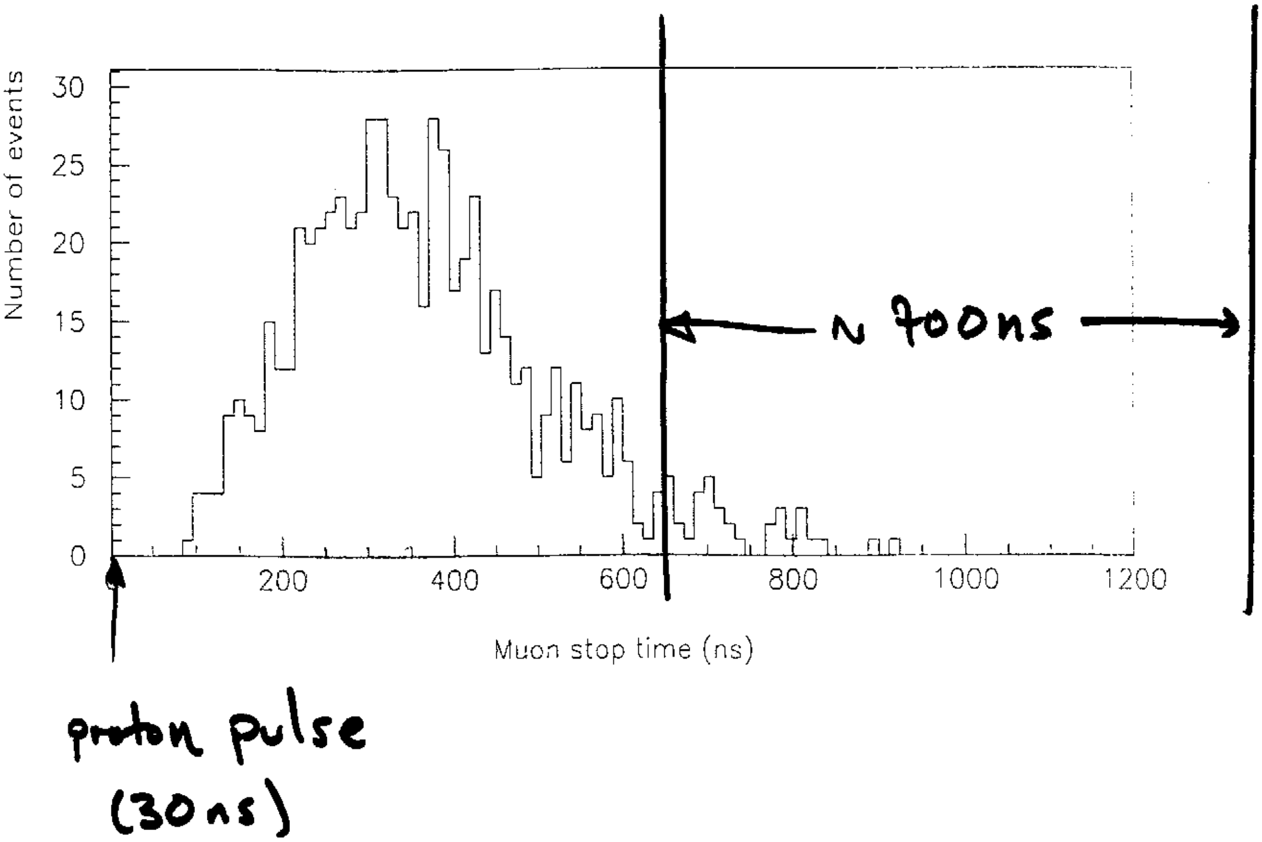


# $\mu^-$ Stopping probability

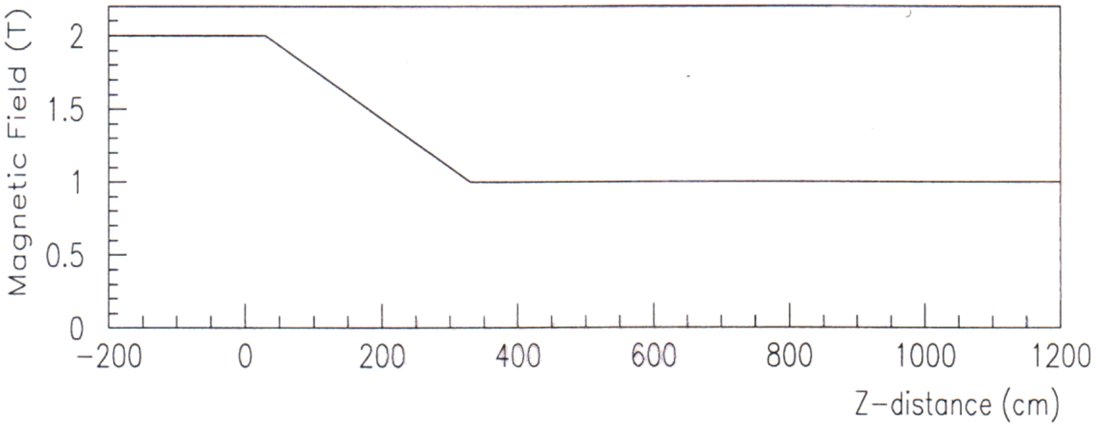


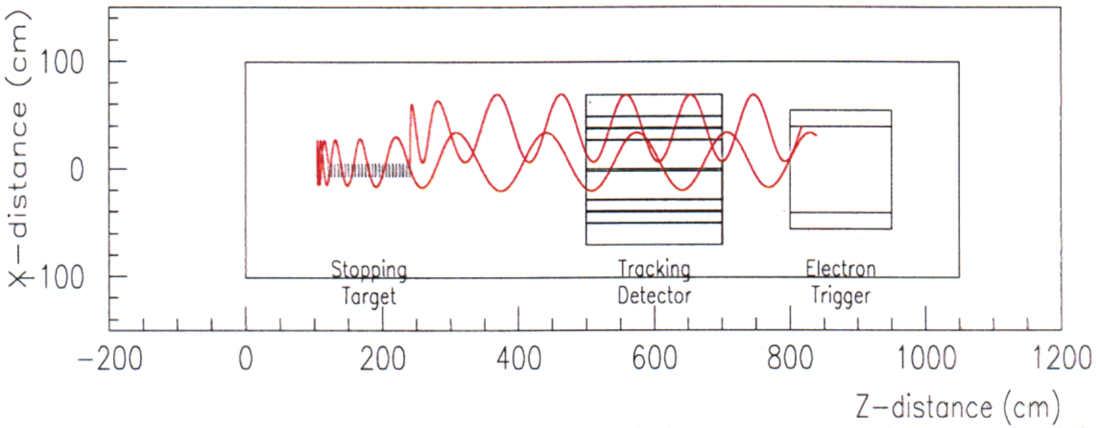


# $\mu^-$ Stopping times



# Decay of stopped muons



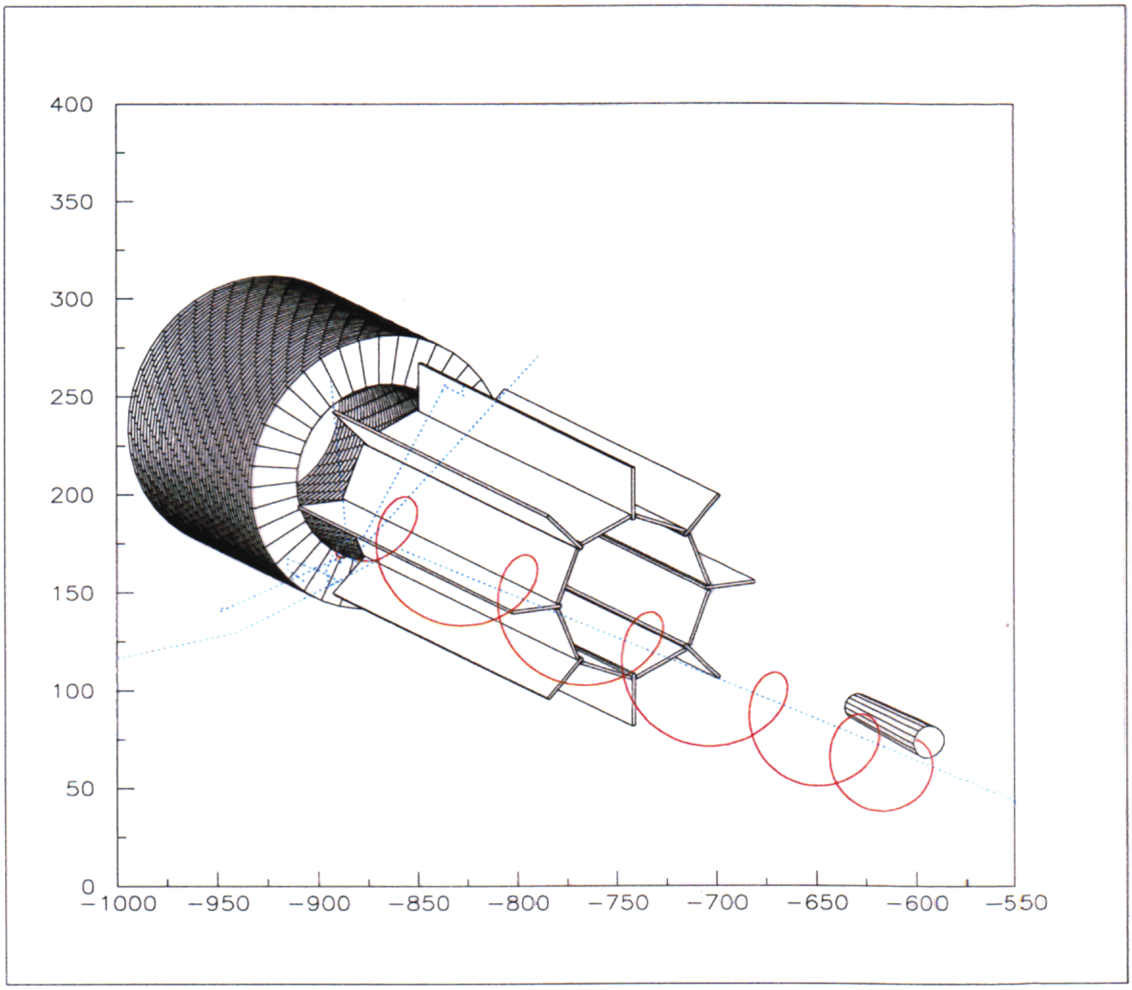


Upstream electron trajectories kicked downstream by graded B-field.

$$\frac{d^2z}{dz^2} \simeq \frac{-v_{\parallel}^2}{2B}\frac{dB}{dz}$$

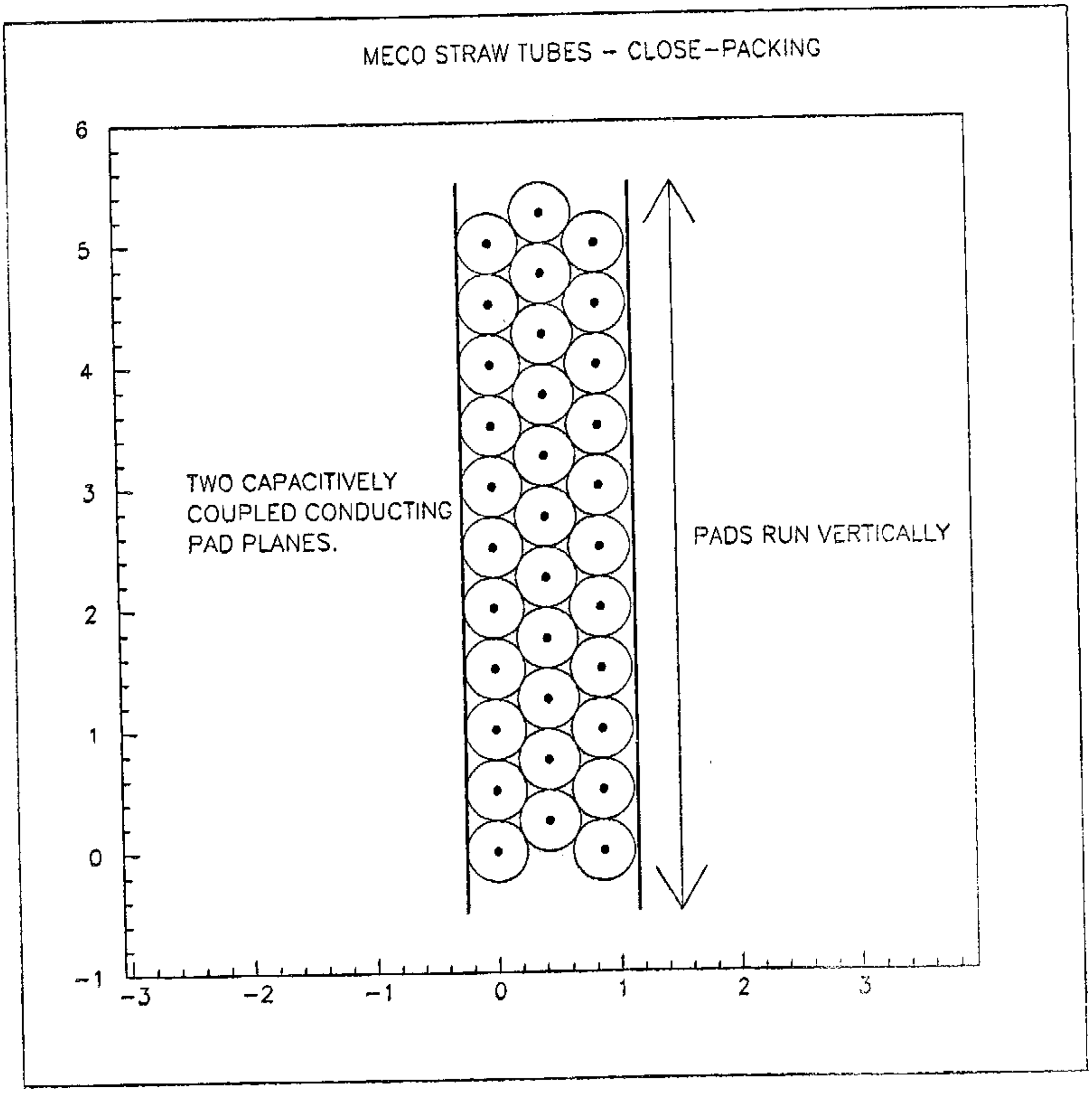
1. 105 MeV $e^-$ upstream of target has $p_\perp < 75\,\mathrm{MeV/c}$ at detector.
2. At the target:
   - Conversion $e^-$ with $60^o \leq \chi \leq 120^o$.
   - Corresponds to $p_\perp > 91\,\mathrm{MeV/c}$.
3. At the tracker:
   - Since $p_\perp^2/B = \mathrm{const.}$, conversion $e^-$ has $45^o \leq \chi \leq 60^o$.
   - Corresponds to $75 \leq p_\perp \leq 91\,\mathrm{MeV/c}$.

# Longitudinal tracker and scintillating calorimeter



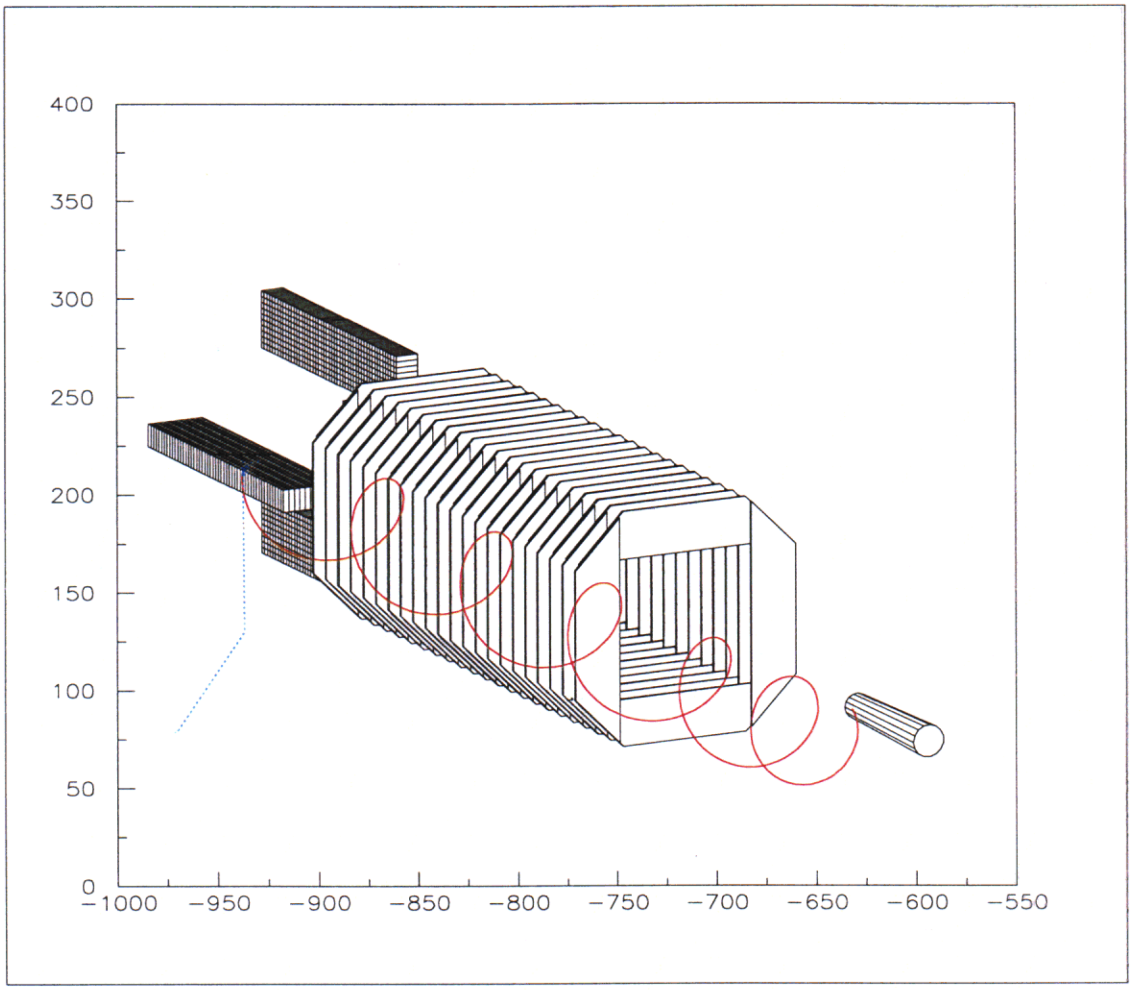
1. Tracker: 16 detector planes, straw tube length 2.5 - 3 m.
   - Inner radius = 39 cm ⇒ cut out low $p_\perp$ bckgrnd.
   - 3 m ⇒ ≥ 2 turns, ≥ 6 plane crossings.
2. Calorimeter: 40 segments azimuth, 40 along axis, length 136 cm.
   - Inner 45 cm. Outer upstream 75 cm, downstream 85 cm.
   - Scintillator plastic, monitored with VLPC's.
   - Position and energy measurement independent of tracker.

# Straw tube detector plane



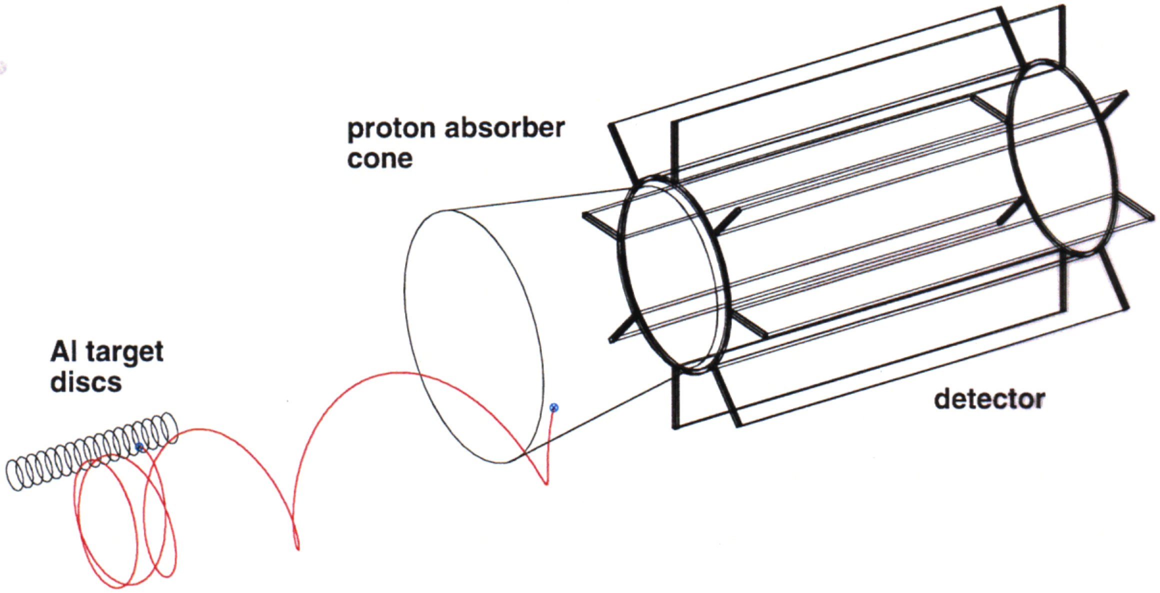
- Kapton, 25 $\mu$m thick, radius = 5 mm, 20 $\mu$m wire.
- Max. electron drift time 30 ns, $CF_4$-isobutane (80/20).
- Drift distance resolution $\sigma \sim 0.2$ mm.
- Resolutions (RMS): position 0.14 mm, angle 1.0°.

# Transverse tracker and crystal calorimeter



1. Tracker: 88 detector planes, straw tube length $< 1.2\,\mathrm{m}$.
    - Plumbing, electronics, supports: out of conversion $e^-$ path.
    - Easier to build and operate.
2. Calorimeter: 500 - $3\,\mathrm{cm} \times 3\,\mathrm{cm} \times 12\,\mathrm{cm}$ cells, length $1.5\,\mathrm{m}$.
    - Crystal type: BGO ($\sim 300\,\mathrm{ns}$), research continues.
    - Resolutions(RMS): Energy $\sim 5\%$,MeV, position $\sim 1.0\,\mathrm{cm}$.
    - Higher energy threshold $85\,\mathrm{MeV}$, with $90\%$ efficiency.

# Event selection



For $e^-$ to be considered a conversion candidate it must at least:

- Signals in 700 ns window delayed from start proton pulse.
- $E_{\text{calorimeter}} \geq E_{\text{trigger}} = 85\,\text{MeV}$.
- Helix $\geq 6$ clusters ($\geq 3 * 6$ straw tubes & pads) in tracker.
- Reconstruct in the tracker with $E_{\text{helix}}$ : 103.6 - 105.1 MeV.
- Transverse momentum $p_\perp$ : 74.0 - 91.0 MeV.
- Helix must extend through graded B-field to stopping target.

# $\mu \rightarrow e$ Possible backgrounds

(Rates for $4 \times 10^{13}$ p/s $\times$ 0.0025 stopped $\mu$/p $\times$ $10^7$ sec)

- Muon Decay in Orbit: $\mu^- + Al \rightarrow e^- + \bar{\nu}_e + \nu_\mu + Al$

  $\frac{\Gamma(E_{elec} > E)}{\Gamma_{Tot}} = 5.6 \times 10^{-18}\, MeV^{-6} \Delta^6 \,|_{\Delta=0}^{\Delta=E_{MAX}-E}$

  Use tracker FWHM ~ 900 KeV

  Resolution ⇒ 0.25 Events, S/N=20 for $R_{\mu e} = 10^{-16}$

  Noise hits superimposed ⇒ < 0.006 Events

- Radiative Muon Capture: $\mu^- + (A, Z) \rightarrow (A, Z-1) + \gamma + \nu$

  $E_\gamma^{max} = 102.5$ MeV

  $P(E_{gamma} > 100.5\text{ MeV}, \gamma \rightarrow e^+e^-, E_{e^-} > 100\text{MeV})$

  Resolution, noise hits ⇒ < 0.005 Events

- Electrons created in production or transport regions

  Graded detector field gives $P_t^{Tracker} = P_t^{Transport}/\sqrt{2}$.

  Transport collimater gives $E_{MAX}$ ~ 120 MeV

  $P(P_t > 90$ MeV/c), extinction $10^{-9}$ ⇒ ~ 0.04 Events

- $\mu^-$, $\pi^-$ decay in flight, $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$, $\pi^- \rightarrow e^- \bar{\nu}_e$

  102 MeV electron implies $P^\mu > 77$ MeV/c, $P^\pi > 54$ MeV/c

  No $e^-$ scatter:

  $P(\text{decay}, 103 < E^e < 105\text{MeV}, P_t^e > 90\text{ MeV/c})$, extinction, ⇒ < 0.03 Events ($\mu$), < 0.001 Events ($\pi$)

  $e^-$ scatter:

  $P(\text{decay}, e^-\text{scatter}, E_{e^-}, P_t^e)$, extinction, ⇒ 0.04 Events ($\mu$), < 0.001 Events ($\pi$)

AM

- Radiative Pion Capture: $\pi^- + (A, Z) \rightarrow (A, Z-1) + \gamma$

  $\mathrm{E}_\gamma^{\mathrm{max}} = 140\,\mathrm{MeV}, \quad \mathrm{E}_\gamma^{\mathrm{peak}} = 110\ \mathrm{MeV}$

  Prompt pions:

  P($\pi$ stop, $\rightarrow \gamma$, $\rightarrow \mathrm{e^+e^-}$, $103 < \mathrm{E_e} < 107$), extinction $\Rightarrow \sim$ 0.07 Events

  Late pions:

  P(late, stop, $\rightarrow \gamma$, $\rightarrow e^+e^-$, $E_{e^-}$) $\Rightarrow \sim$ 0.001 Events

- $\bar{p}$ induced. (low $\beta$ $\rightarrow$ long transit time).

  Transport gives $P^{\bar{p}} < 100\ \mathrm{MeV/c}$

  Using 120 $\mu$m Be window at center of transport solenoid, $\Rightarrow \sim$ 0.007 Events for 8 GeV proton beam, less for lower energy.

- Other late arriving energetic particles:

  Transport drift and collimation in third dimension gives maximum momentum of about 120 MeV/c

  102 MeV electrons give maximum angle between parent and daughter particle.

  Graded magnetic fields give minimum $P_Z$.

  $\Rightarrow$ Negligible rate with 700 ns delay

- Cosmic ray induced $e^-$.

  Scales with exposure time, not $\mu$ flux.

  Active (two 99% efficient) and passive shields to suppress.

  Suppression of $10^{-4} \Rightarrow \sim$ 0.004 Events

AMiller

# Expected MECO backgrounds

1. Running time = $10^7$s, $R_{\mu e} = 10^{-16}$
   - Expect ~ 5 $\mu^- + \mathrm{Al} \to e^- + \mathrm{Al}$ events, in $103.6 \leq E_e \leq 105.1$ MeV.

| Source | Events | Comment |
|---|---|---|
| $\mu$ decay in orbit | 0.3 | S/N = 20 for R = $10^{-16}$ |
| Radiative $\mu$ capture | $<< 0.050$ | |
| ⋆ $\mu$ decay in flight | $< 0.03$ | without scatter in target |
| ⋆ $\mu$ decay in flight | 0.04 | with scatter in target |
| ⋆ Radiative $\pi$ capture | 0.07 | from out of time protons |
| Radiative $\pi$ capture | 0.004 | from late arriving $\pi$ |
| ⋆ $\pi$ decay in flight | $<< 0.01$ | |
| ⋆ Beam electrons | $< 0.02$ | |
| $\bar{p}$ induced | 0.004 | mostly from $\pi^-$ |
| Cosmic ray induced | 0.004 | $10^{-4}$ CR veto inefficiency |
| Total background | $< 0.53$ | assumes $10^{-9}$ extinction |

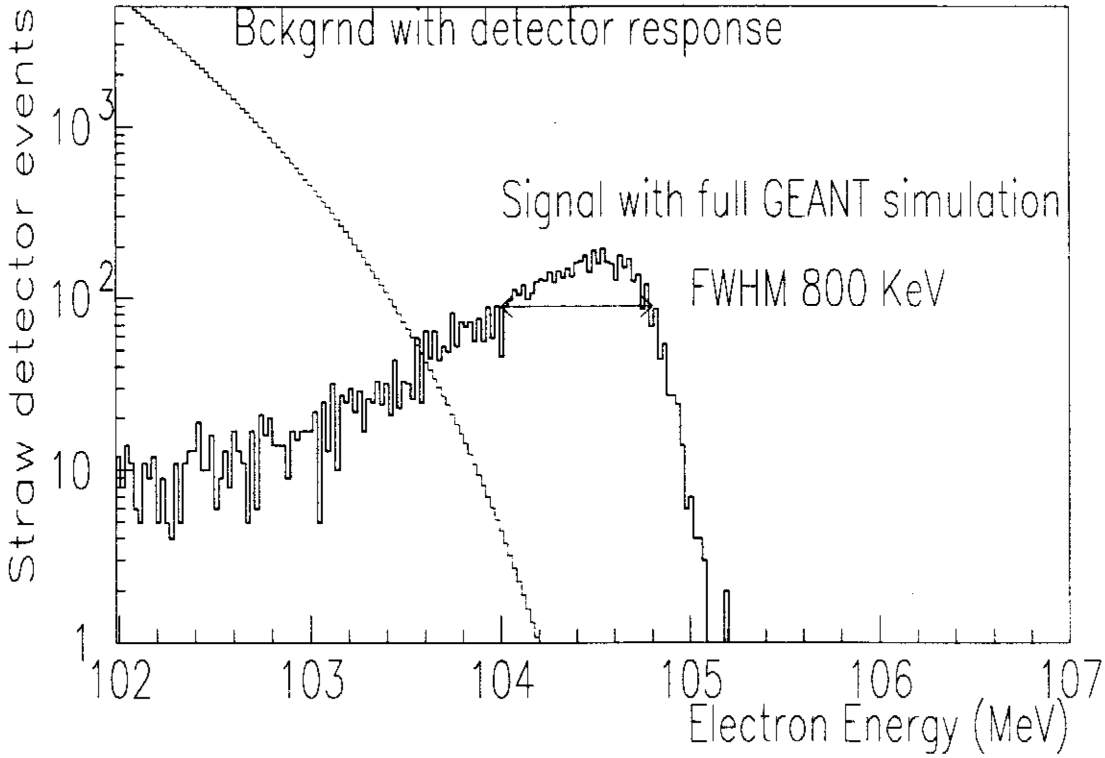
expect $5\times10^6$ DIO

2. Pattern recognition errors:
   - Simulated $10^7$ $e^-$ from muon decay in orbit, $E_e > 95$ MeV.
   - with Random hits at rate expected from muon capture $n$, $\gamma$, and $p$.
   - Misreconstructed 0 events with $E_{\mathrm{reconstructed}} > 103$ MeV.
   - Total muon decay in orbit $e^-$ events above 95 MeV is ~ $5\times10^6$

# Expected MECO sensitivity and detector response

| | |
|---|---|
| Running time (s) | $10^7$ |
| Protons/s (50% DF, 1.35 $\mu$s pulse spacing) | $4 \times 10^{13}$ |
| $\mu^-$ stopped per proton | 0.0025 |
| $\mu^-$ capture probability | 0.60 |
| Fraction of $\mu^-$ capture in time window | 0.49 |
| Electron trigger efficiency | 0.90 |
| Fitting and selection criteria | 0.19 |
| Detected events for $R_{\mu e} = 10^{-16}$ | 5 |

- $R_{\mu e} = 10^{-16}$ expect ~ 15 events in one year of data taking.
- Simulation: MECO detector response.



# Summary and Status

1. Compared to earlier experiments, the proposed MECO experiment is a substantially scaled up search for muon to electron conversion. It will look for * $\mu \to e$ transitions with sensitivity $R_{\mu e} \sim 5 \times 10^{-17}$, tranlates to 15 events in a year of taking data.
2. GEANT simulations indicate, so far, that the background will be dominated by muon decay in orbit, as in earlier experiments. These studies now include background associated with reconstruction errors that result from extra hits in the detector.
3. The MECO Experiment, E940, received scientific approval from the PAC in October of 1997.

   *The search for coherent muon-electron conversion at* $10^{-16}$ *sensitivity is an extremely powerful probe of lepton flavor violation and physics beyond the Standard Model. Such an experiment has the potential to become a flagship effort for AGS-2000 and could make a major discovery.*
4. The National High Field Magnet Laboratory at Florida State "Conceptual Design of the Muon-Electron Conversion Project (MECO) Magnet System Phase II", final report.

*coherent

5. Submitted Proposal for MRE to NSF: Rare Symmetry Violating Processes (RSVP - MECO/K0PI0) Proposal, October 1999. Review Panel Report, January 2000. Recommendations on MECO in Executive Summary:

   > *We recommend that the Foundation proceed with the funding of the MECO proposal. In our view, MECO is in the strongest position, at this time, to make a significant impact on particle physics.*

6. Work on experiment design and preparations for a technical review continue:
   - GEANT studies and detector design are going forward.
   - Neutron background rates are being investigated using MCNP & GEANT.