Status of Studies of Rare Kaon and Muon Processes and Prospects for Improved Experiments

W. Molzon
University of California, Irvine

NuFact′00

Muon Storage Rings for a Neutrino Factory

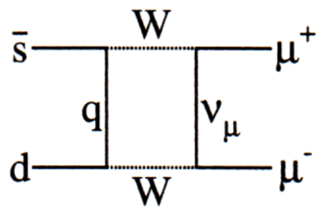
Monterey, California

23 May 2000

- **Physics Issues**
  - Concentrate on rare processes – intense particle beams required
  - Limit this to measurements in which progress is expected
  - Experiments that proton driver for μ collider might benefit
- **Studies of quark mixing matrix using kaons**
- **Muon and electron number violation**

Motivation for Measuring $B(K \to (\pi) l\bar{l})$

- **Standard Model rate small – no tree level FCNC ⇒ decays proceed through box and penguin diagrams.**



zero with degenerate m_q
t quark dominates

- **Study of SM quark mixing matrix**

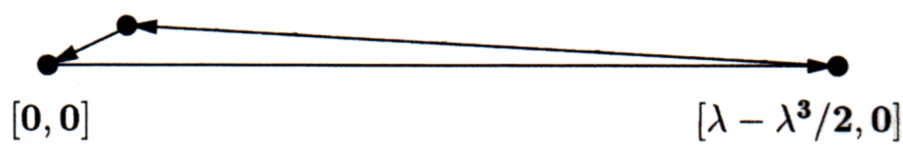
$$\begin{vmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{vmatrix} \qquad \begin{vmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{vmatrix}$$

- **All unitarity triangles have the same area:**

$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0 \quad \text{B triangle}$$
$$V_{ud}V^*_{us} + V_{cd}V^*_{cs} + V_{td}V^*_{ts} = 0 \quad \text{K triangle}$$

Jarlskog invariant $J = \lambda(1-\lambda^2/2) \times A^2\lambda^5\eta$ (2 × area)

$[A^2\lambda^5(1-\rho), A^2\lambda^5\eta]$

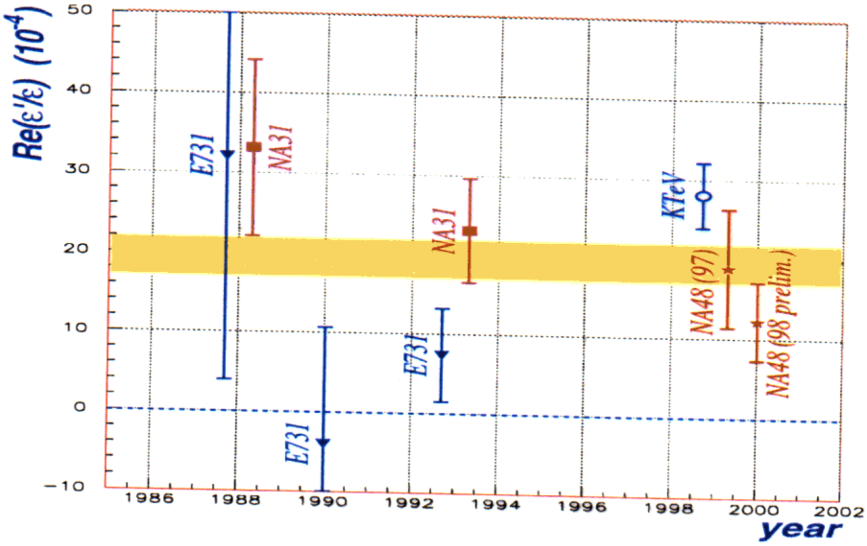


Kaon experiments measure directly Jarlskog invariant:

Experiment	Measured Quantity	
$K^0_L \to \mu^+\mu^-$	$\lvert Re(V_{td}V^*_{ts})\rvert$	$\lvert A^2\lambda^5(1-\rho)\rvert$
$K^0_L \to \pi^0\nu\bar{\nu}$	$\lvert Im(V_{td}V^*_{ts})\rvert$	$\lvert A^2\lambda^5\eta\rvert$
$K^+ \to \pi^+\nu\bar{\nu}$	$\lvert V_{td}V^*_{ts}\rvert$	$\lvert A^2\lambda^5(1-\rho-i\eta)\rvert$

- **Goal of experiments is precise determination of SM parameters and search for deviations that would indicate new physics**
  - **Lack of closure of triangle – matrix not unitary**
  - **Difference in J measured in B and K systems**
  - **Theoretical uncertainties at the level of a few percent**

Implications of ϵ'/ϵ for Rare Decays of Kaons



World average $\epsilon'/\epsilon = (19.3 \pm 2.4) \times 10^{-4}$

Recent work on effective Z_{ds} couplings

- Motivated in part by E787 observation of one $K^+ \to \pi^+ \nu\bar{\nu}$ event at ~ 5 (2) $\times$ SM rate and by large ϵ'/ϵ value
- Z_{DS} couplings would affect both $K \to \pi l \bar{l}$ and ϵ'/ϵ
- Arise naturally in supersymmetry from penguin diagrams

Constraints on $B(K^0_L \to \pi^0 \nu\bar{\nu})$ from ϵ'/ϵ (Bosch, Buras, et al.)

- SM: $1.6 \times 10^{-11} < B(K^0_L \to \pi^0 \nu\bar{\nu}) < 3.9 \times 10^{-11}$
- $\epsilon'/\epsilon < 28 \times 10^{-4} \Rightarrow B(K^0_L \to \pi^0 \nu\bar{\nu}) < 48 \times 10^{-11}$
- Room for new physics above (or below) SM rate

Constraints on $B(K^+ \to \pi^+ \nu\bar{\nu})$ from ϵ'/ϵ and $B(K^0_L \to \mu^+\mu^-)$ (Buras and Silverstrini)

- SM value: $B(K^+ \to \pi^+ \nu\bar{\nu}) = 8.2 \times 10^{-11}$
- $\epsilon'/\epsilon < 28 \times 10^{-4} + B(K^0_L \to \mu^+\mu^-) \Rightarrow B(K^+ \to \pi^+ \nu\bar{\nu}) < 29 \times 10^{-11}$
- Room for new physics above SM rate

Challenges in $K \rightarrow (\pi)l\bar{l}$ Experiments

- **$K_L^0 \rightarrow \mu^+\mu^-$** – lots of data, hard to interpret
  - Short distance rate $\propto (1-\rho)^2$
  - Rate dominated by long distance physics
  - Deduce ReA by subtracting absorptive contribution from measured rate
  - Get A_{SD} from ReA - $ReA_{\gamma^*\gamma}$ (from measurements of radiative decays + theory)
- **$K^+ \rightarrow \pi^+\nu\bar{\nu}$** – easy to interpret, low statistics data
  - Decay rate $\propto |(1-\rho-i\eta)|^2$
  - Standard model rate $\approx 8 \times 10^{-11}$
  - Backgrounds from $K^+ \rightarrow \pi^+\pi^0$ and $K^+ \rightarrow \mu^+\nu$
- **$K_L^0 \rightarrow \pi^0\nu\bar{\nu}$** – easy to interpret, very difficult experiment
  - Decay rate $\propto \eta^2$
  - Standard model rate $\approx 3 \times 10^{-11}$
  - Significant backgrounds from $K_L^0 \rightarrow \pi^0\pi^0$
  - Very few experimental constraints
- **$K_L^0 \rightarrow \pi^0 e^+e^-$** – low rate, significant background
  - Direct CP violating term $\propto \eta^2$ with γ or Z^0 exchange
  - CP conserving term from 2γ intermediate state
  - Indirect CP violating term from $K_1 - K_2$ mixing
  - Standard model rate $\approx 10^{-11}$
  - Many backgrounds – $K_L^0 \rightarrow \gamma e^+e^-$ with radiative γ

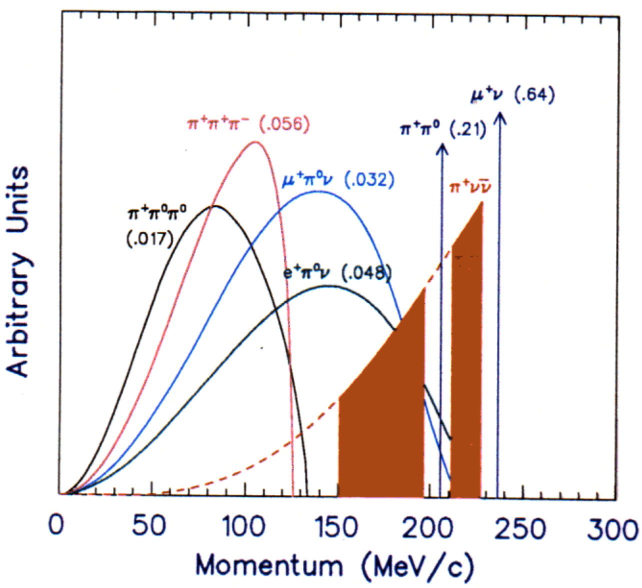
BNL E787 $K^+ \to \pi^+ \nu \bar{\nu}$ Experiment

Alberta, BNL, KEK, Osaka, Princeton, TRIUMF

$B(K^+ \to \pi^+ \nu \bar{\nu}) \Rightarrow |V^*_{td} V_{ts}|$ with small theoretical uncertainty:

$$B(K^+ \to \pi^+ \nu \bar{\nu}) = 4.11 \times 10^{-11} \times A^4 \times X(x_t) \times [(\rho_0 - \rho)^2 + \eta^2]$$

$X(x_t)$ known function of m_t^2/m_W^2, $\rho_0 \simeq 1.4$ due to charm



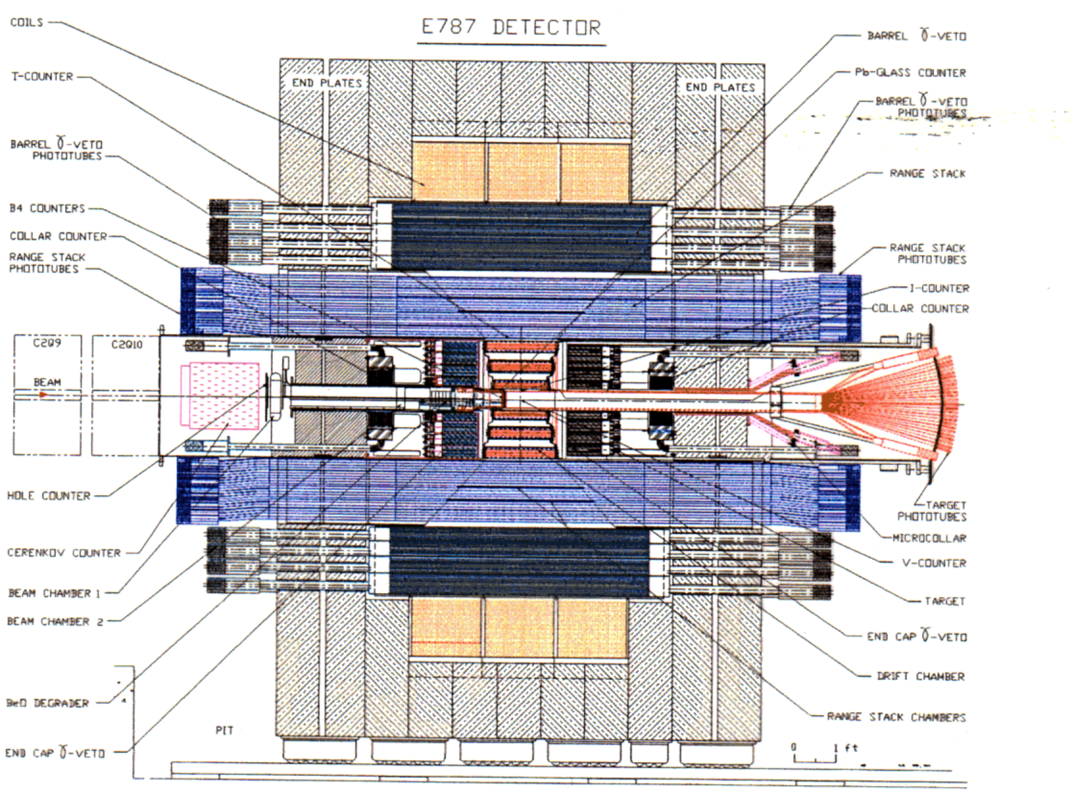
Backgrounds from:

- μ^+ from $K^+ \to \mu^+ \nu$
- π^+ from $K^+ \to \pi^+ \pi^0$

$\Rightarrow$ **Particle identification:**
$K^+ \to \pi^+ \to \mu^+ \to e^+$ decays

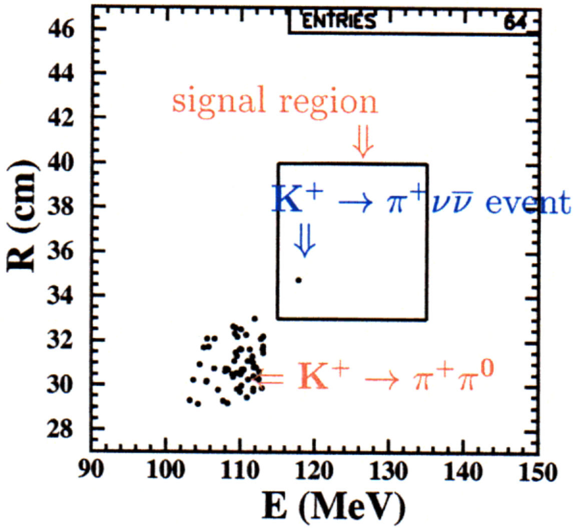
$\Rightarrow$ **Kinematic analysis:**
Measure E, p, R of π^+

$\Rightarrow$ **Veto events with extra γ:**
Pb-scintillator and
CsI hermetic veto

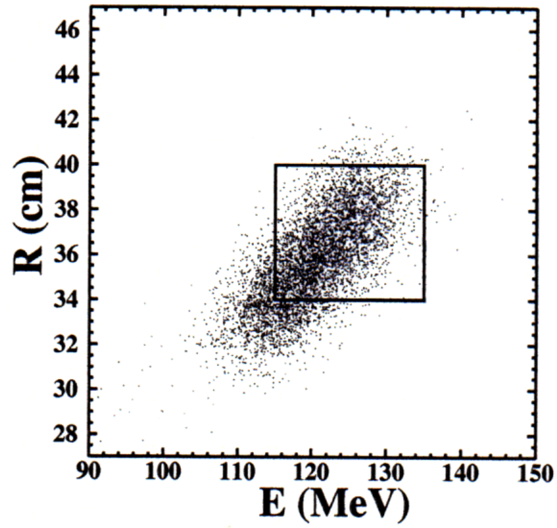


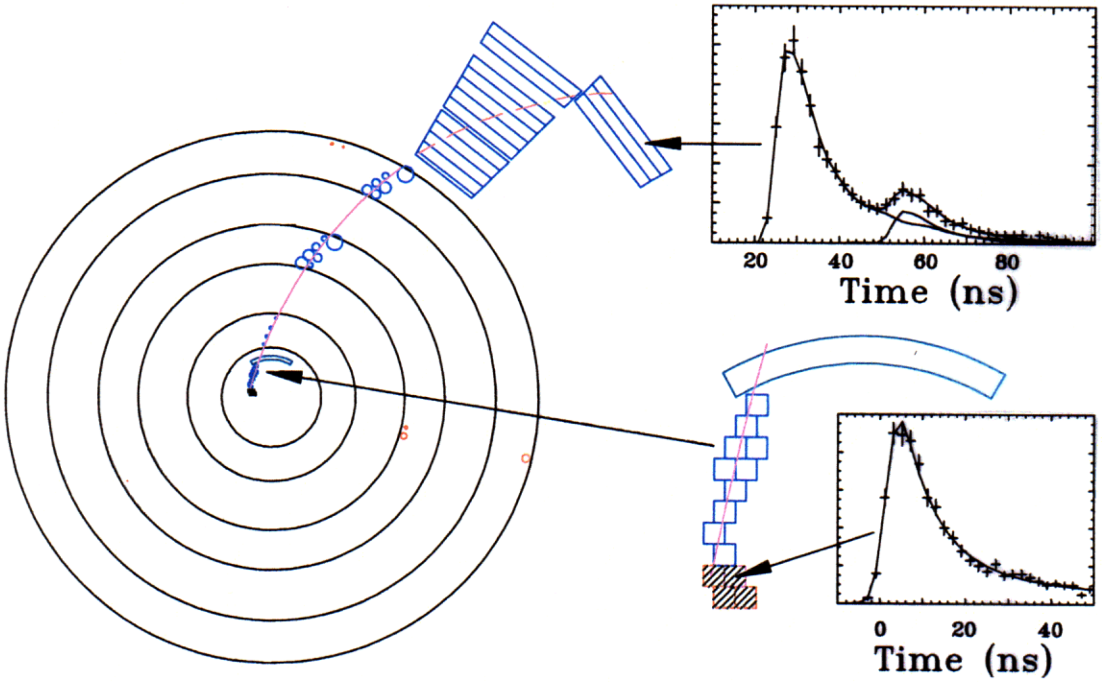
BNL E787 Measurement of $B(K^+ \to \pi^+ \nu\bar{\nu})$

1995-97 Data



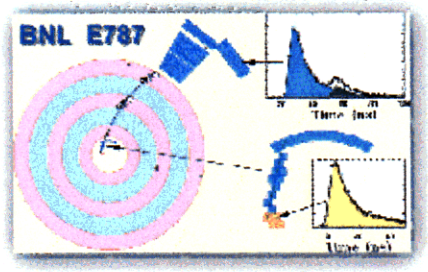
$K^+ \to \pi^+ \nu\bar{\nu}$ Monte Carlo





$$B(K^+ \to \pi^+ \nu\bar{\nu}) = 1.5^{+3.4}_{-1.2} \times 10^{-10} \quad [\mathrm{SM} \sim 0.82 \times 10^{-10}]$$

- Consistent with SM value
- Final E787 data in hand to improve sensitivity $\times 2$



$K^+ \to \pi^+ \nu\bar{\nu}$: E949 & CKM

... the two experiments are stages of a program for studying $K^+ \to \pi^+ \nu\bar{\nu}$, which will eventually reach a sensitivity comparable to the theoretical accuracy at which this process can be calculated in the Standard Model. Stage one would be E949, which seeks to reach a sensitivity of $\sim 10^{-11}$/event and stage two would be CKM, which seeks to reach a sensitivity an order of magnitude beyond this level.

- **Collaboration begun in summer of 1999**
- **E949 approved 8/99**
- **plans for integration of FNAL TDC's into E949 underway (2/00)**
- **system tests planned for 9/00**
- BNL represented at CKM collaboration meeting 9/99
- BNL active in biweekly CKM video meetings
- BNL contribution to PV system under development

- E949
  - FNAL TDC's to instrument the range stack
  - manpower/expertise
- CKM
  - BNL is collaborating on the Photon Veto
  - manpower/expertise

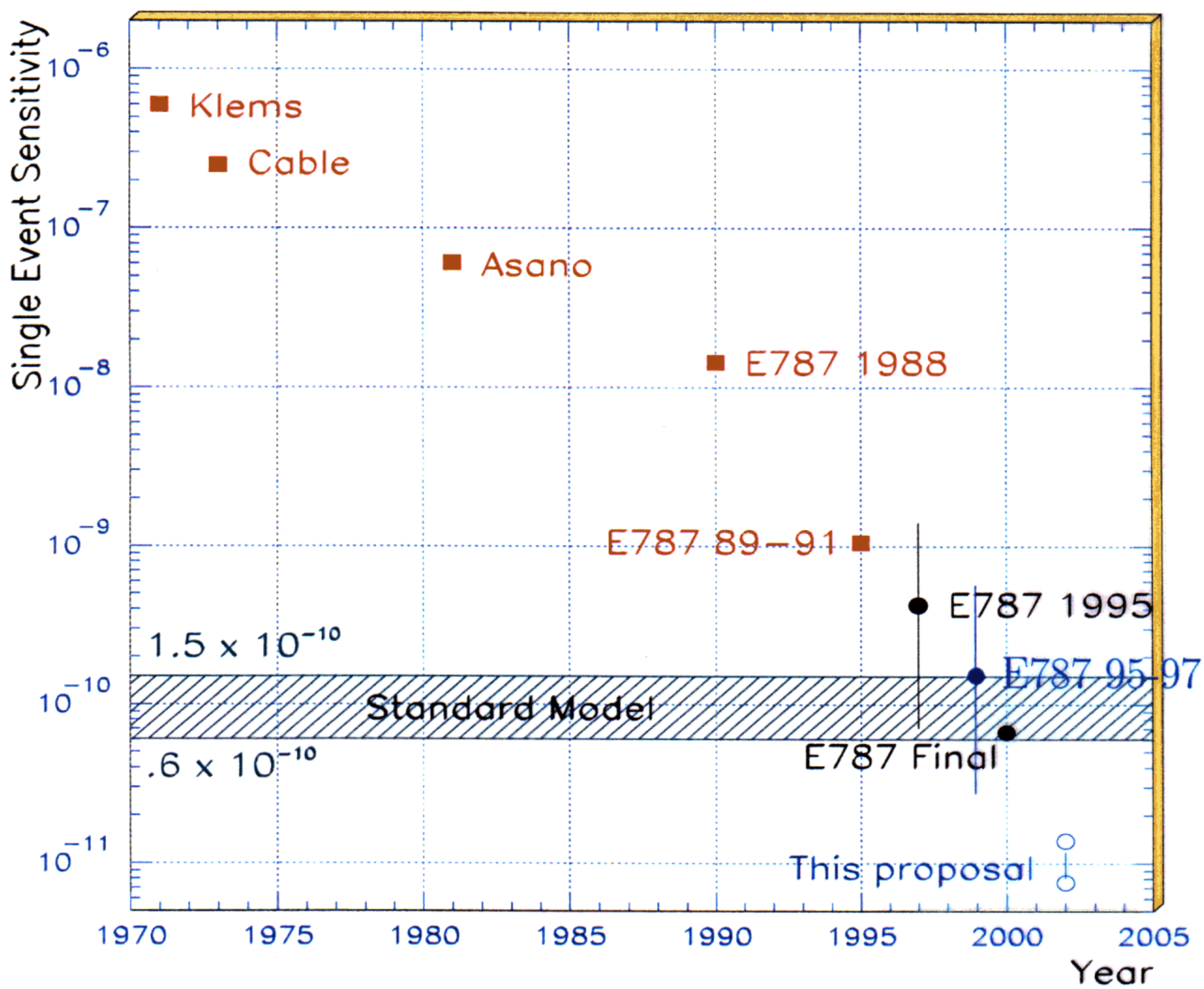
BNL E949 – Improved Measurement of $B(K^+ \to \pi^+ \nu\bar{\nu})$

Alberta, BNL, Fermilab, Fukui, IHEP Moscow
INR Moscow, KEK, Kyoto, UNM, Osaka, TRIUMF

Expected sensitivity, scaled wrt E787 1995 data:

E787 events at SM rate (0.82×10^{-10})	**0.20**
Lower K^+ momentum	**×1.38**
Improved duty factor	**×1.56**
Trigger + other improvements	**×1.54**
Additional detector improvements	**×2.10**
Optimized high-rate analysis	**×2.0**
Running time (6000 hours – 60 weeks)	**×3.6**
Total above $K^+ \to \pi^+\pi^0$ peak at SM	**5 – 10.0 events**
Analyse below $K^+ \to \pi^+\pi^0$ peak	**×2.0**
Best possible sensitivity at SM	**10 – 20 events**

mostly already obtained



CKM at Fermilab – Measurement of $B(K^+ \to \pi^+ \nu \bar{\nu})$

BNL, Fermilab, Serpukhov, San Luis Potosi, Michigan, Texas, Virginia

New technique – decay in flight in separated 12 GeV K^+ beam

- **Momentum analyse K^+ and π^+**
- **Identify K^+ and π^+ with ring imaging Cherenkov**
- **Veto photons with hermetic detector**

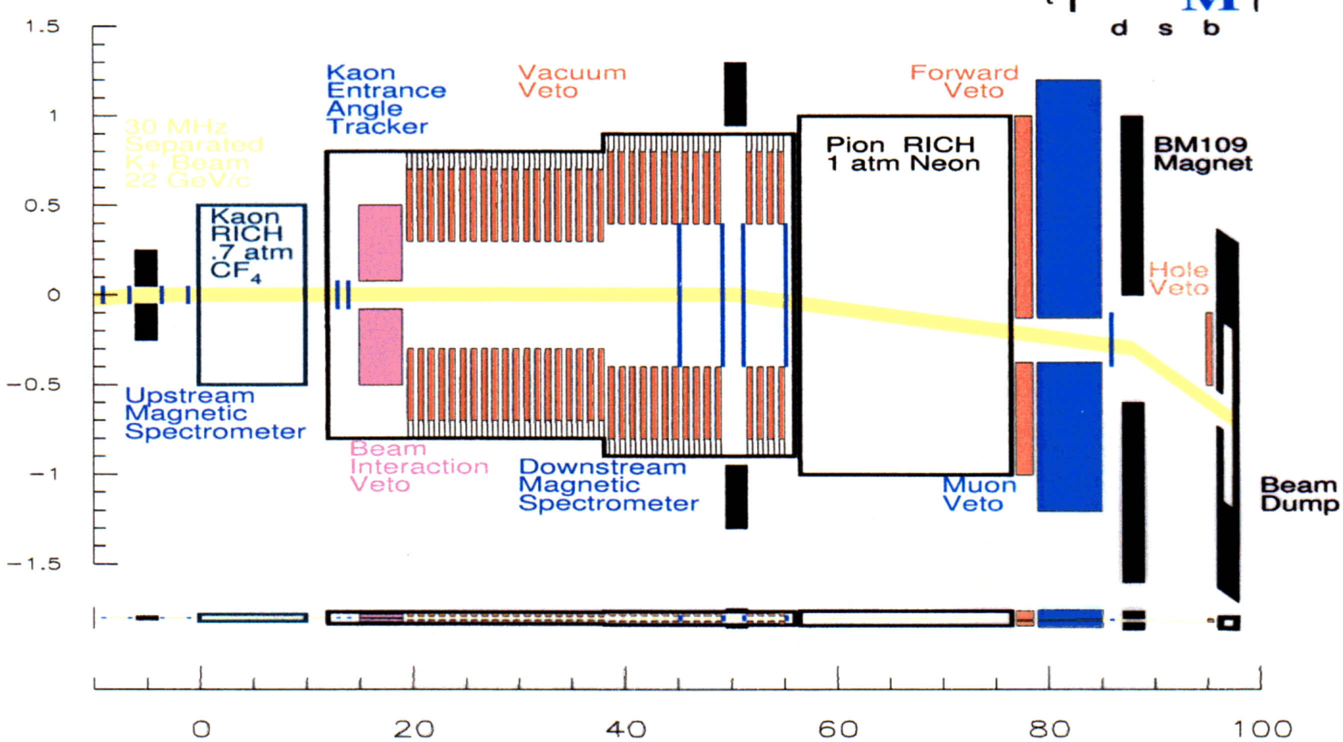
Give up some constraints:

- Don't detect $\pi \to \mu \to$ e decay chain
- Must measure initial state kinematics
- Lose energy and range measurement of π^+

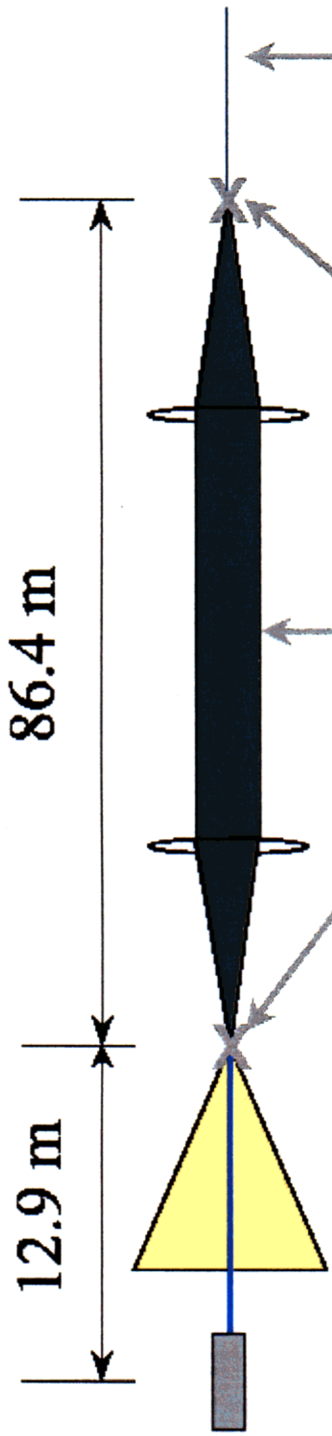
Gain some advantages:

- **Photons from $K^+ \to \pi^+ \pi^0$ decay are higher energy**
- **Much shorter detection time – 300 ns vs. 10 μs**
- **Identify π^+ with RICH**

CKM Apparatus



RF separated K^+ beams



Initial momentum-selected beam $\Delta P/P \sim 2\%$

RF deflection: $A\sin(\omega t)$

$A \sim 15$ MeV/c

Transport $L = (\text{integer})\beta_\pi c/f$

Δt then integer multiple of $2\pi\omega$ for π^+

2nd RF deflection *e.g.* 180° out of phase: $-A\sin(\omega t+\omega\Delta t)$

For π^+, no net deflection

For K^+, deflection is

$2A\sin(n\beta_K c/2f) \bullet \cos(wt+n\beta_K c/2f)$

Stop π^+ with beam plug, collect K^+

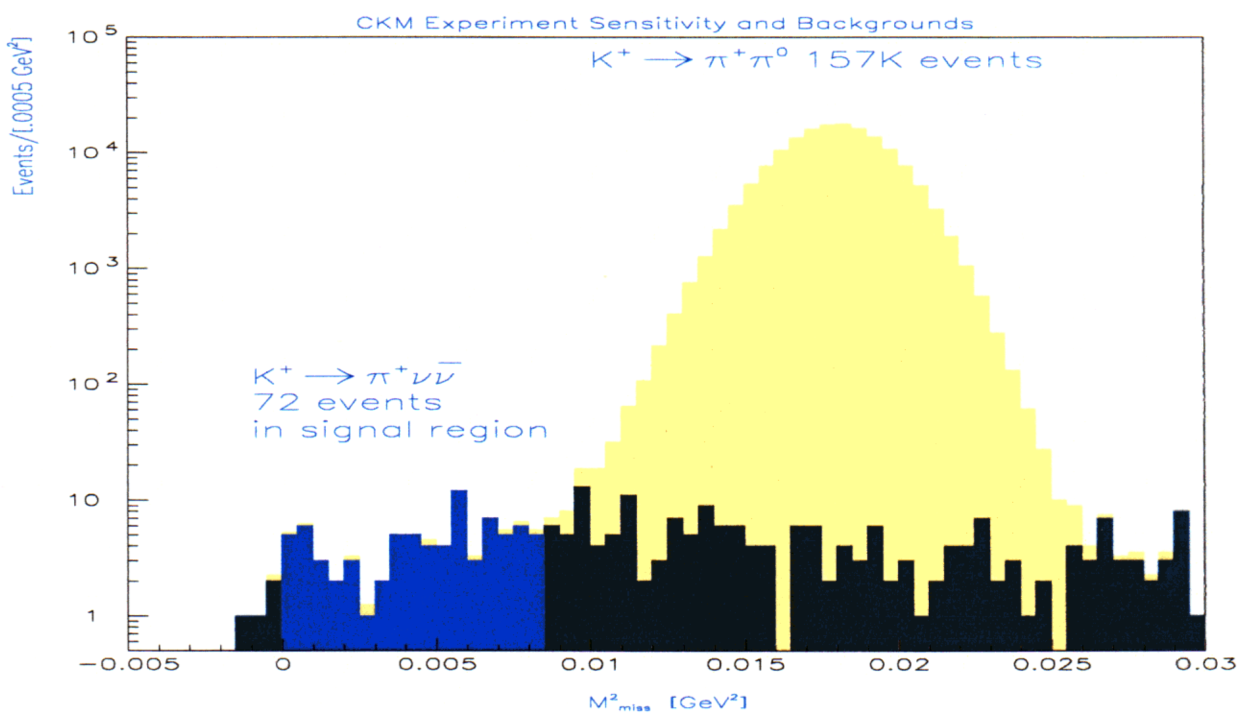
Expected Performance of CKM at Fermilab

Designed to reach a sensitivity of $\sim 10^{-12}$

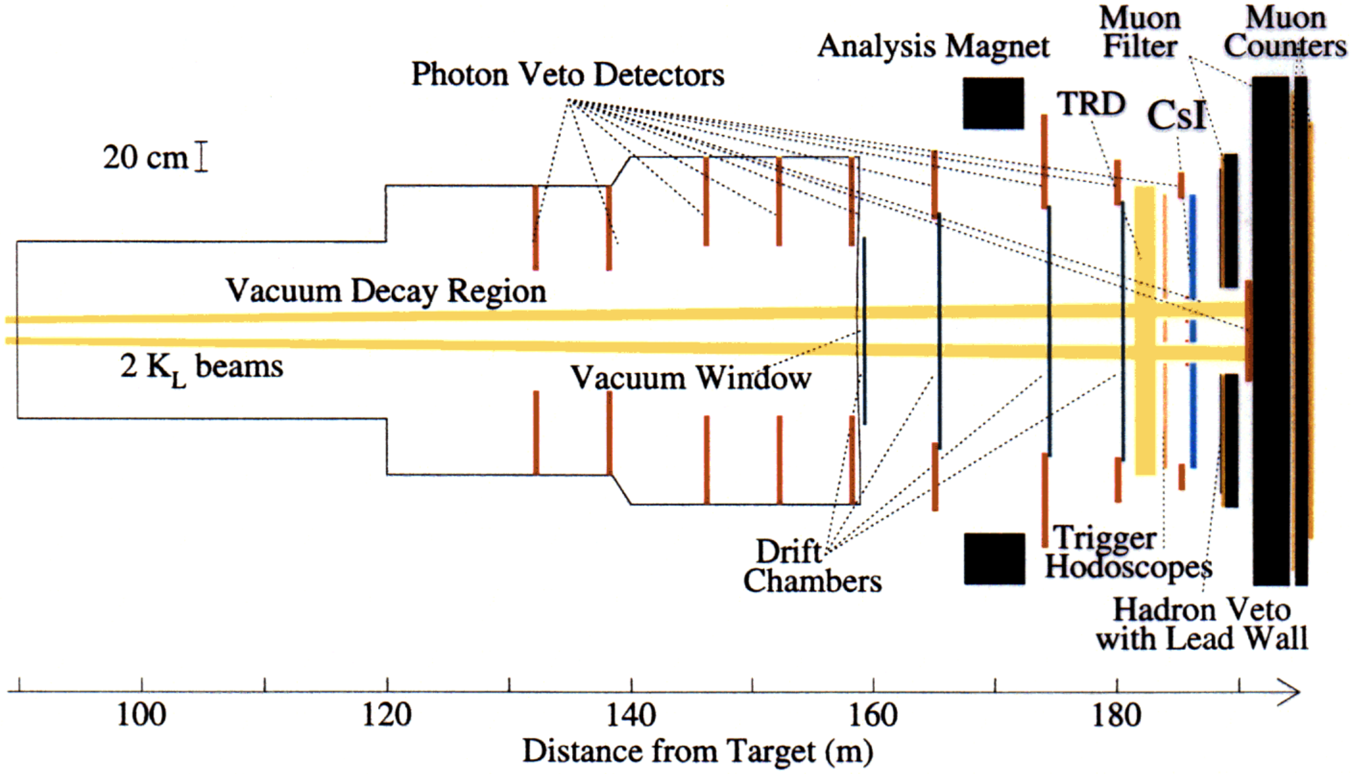
Beam intensity	30 MHz
Decay probability	$\sim 16\%$
Detection efficiency	$\sim 0.7\%$
Running time	2×10^7s

Backgrounds simulated:

Background source	Effective BR ($\times 10^{-12}$)
$K^+ \to \mu^+\nu$	< 0.04
$K^+ \to \pi^+\pi^0$	3.7
$K^+ \to \mu^+\nu\gamma$	< 0.09
$K^+A \to K_LX, K_L \to \pi^+e^-\nu$	< 0.104
$K^+A \to \pi^+X$ in detectors	< 4.0
$K^+A \to \pi^+X$ in residual gas	< 2.1
Accidentals	0.51



Fermilab KTeV E799 Search for $K_L^0 \to \pi^0 l\bar{l}$

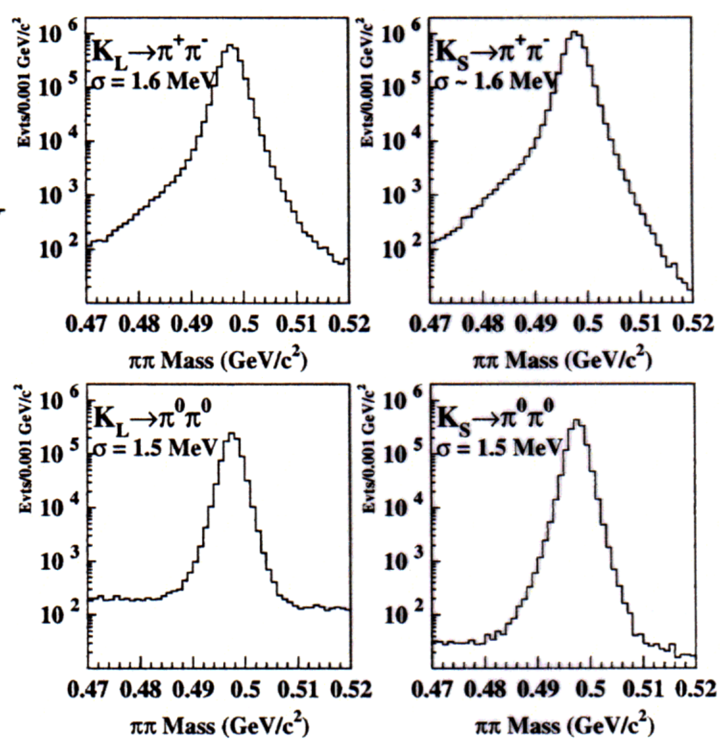


Arizona, Chicago, Colorado, Elmhurst, Fermilab, Osaka, Rice, Rutgers, UCLA, UCSD, Virginia, Wisconsin

Detector and beam highlights

- **Pure CsI calorimeter:**
  $\sigma_E/E = 1\%$ at 10 GeV
  π/e rejection > 700
- **Transition radiation detectors:**
  π/e rejection > 200
- **Clean, intense beam:**
  $\sim 10^8$ per second

Preliminary results from 1996 run shown



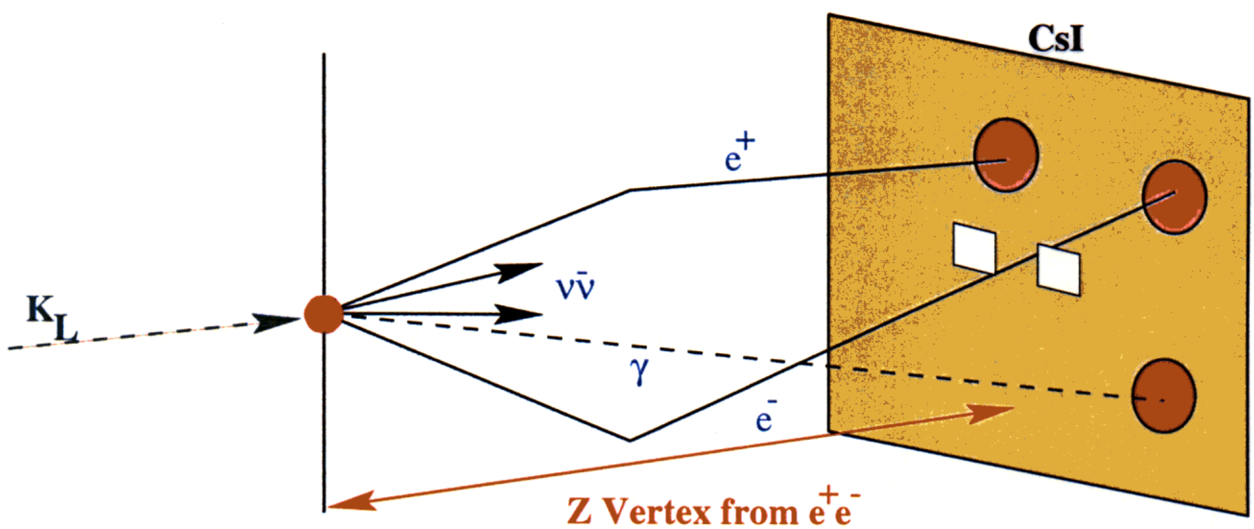
Fermilab KTeV E799 Search for $K_L^0 \to \pi^0 \nu \overline{\nu}$

$B(K_L^0 \to \pi^0 \nu \overline{\nu}) \Rightarrow Im(V_{td}^* V_{ts})$ with small theoretical uncertainty

For $\pi^0 \to \gamma\gamma$ decays, current detectors measure γ position and E

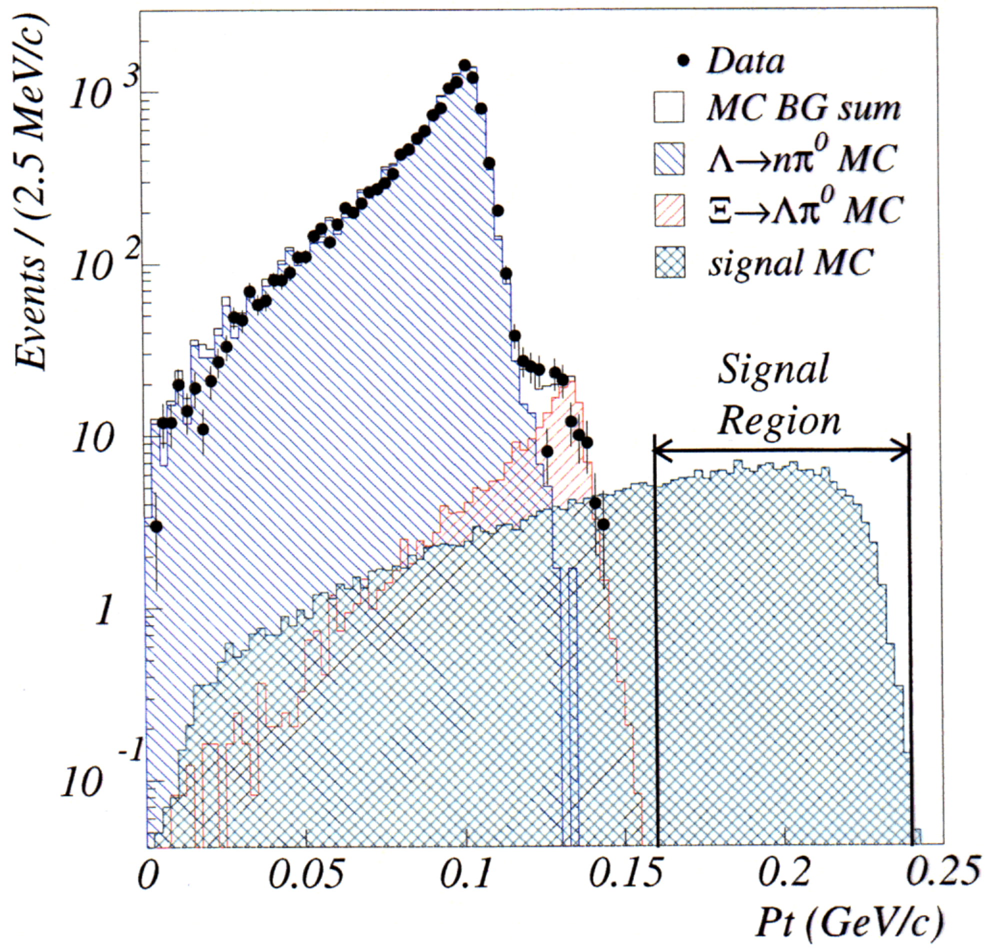
- K_L^0 decay point inferred by constraining $M_{\gamma\gamma}$ to M_{π^0}
- Copious background from $K_L^0 \to \pi^0 \pi^0$
- Rely on γ veto, and cut on p_T of π^0 to reject background
- Requires at least nearly hermetic γ veto with high efficiency

New result uses $\pi^0 \to \gamma e^+ e^-$ to determine K_L^0 decay point



- Insufficient sensitivity to get near Standard Model level
- Allows study of backgrounds other than $B(K_L^0 \to \pi^0 \pi^0)$
  - $\Lambda \to n\pi^0$
  - $\Xi \to \Lambda\pi^0$

New Limit on $B(K^0_L \to \pi^0 \nu \overline{\nu})$ from Fermilab KTeV E799



- Background from hyperon decays at low p_T
- Background from $B(K^0_L \to \pi^0 \pi^0)$ suppressed

$$B(K^0_L \to \pi^0 \nu \overline{\nu}) < 5.9 \times 10^{-7} \; [\mathrm{SM} \sim 3 \times 10^{-11}]$$

One day test of $K^0_L \to \pi^0 \nu \overline{\nu}, \pi^0 \to \gamma\gamma$ done:

- Limit set based on one event consistent with background

$$B(K^0_L \to \pi^0 \nu \overline{\nu}) < 1.6 \times 10^{-6}$$

Fermilab KAMI Experiment to Search for $K^0_L \to \pi^0 \nu\overline{\nu}$

Arizona, Campinas, Chicago, Colorado, Elmhurst
Fermilab, Osaka, Virginia, Wisconsin

KAMI builds on KTeV detector and experience:

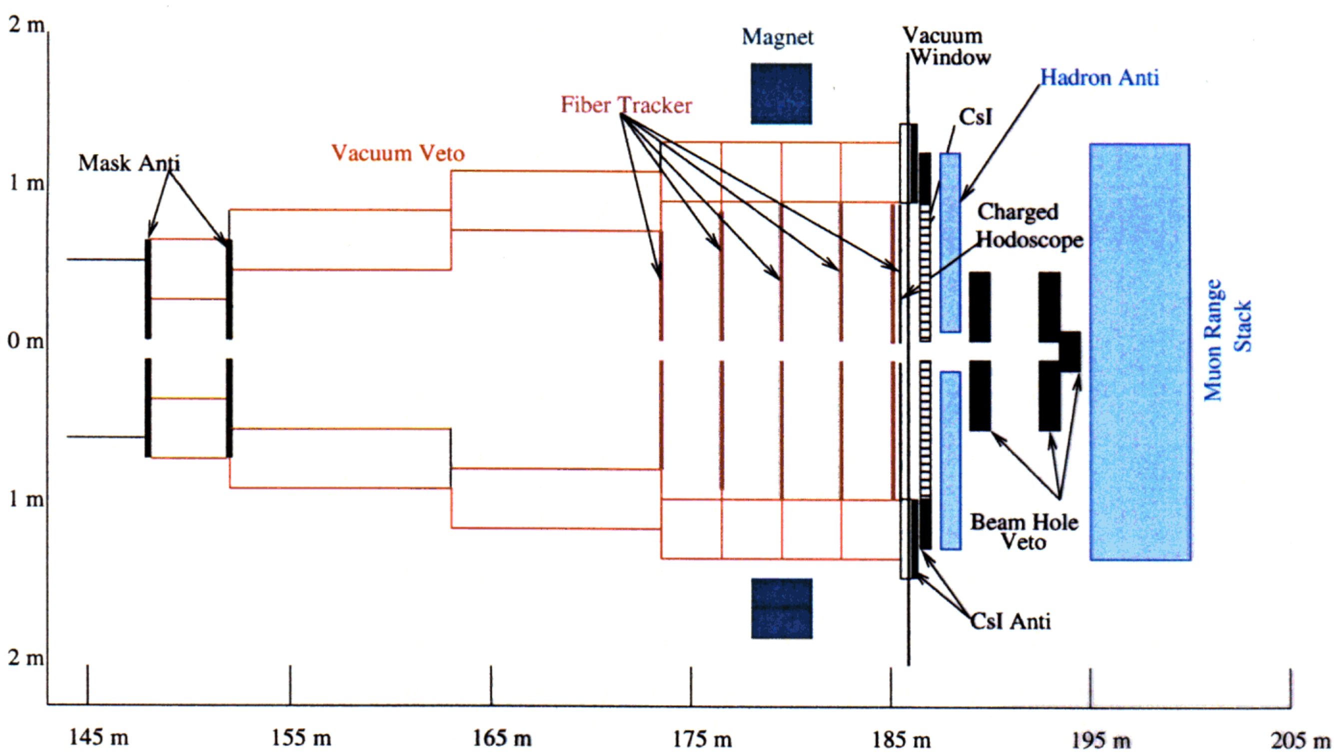
- Superb CsI photon detector
- Long experience in doing experiments with K_L beams

Will use new beam derived from Main Injector:

- 120 GeV beam, debunched, 3×10^{13} protons per pulse
- Transport modified to yield appropriate targeting angle
- Possibility of moving target downstream to increase intensity

Efficient γ veto and kinematics to reject background

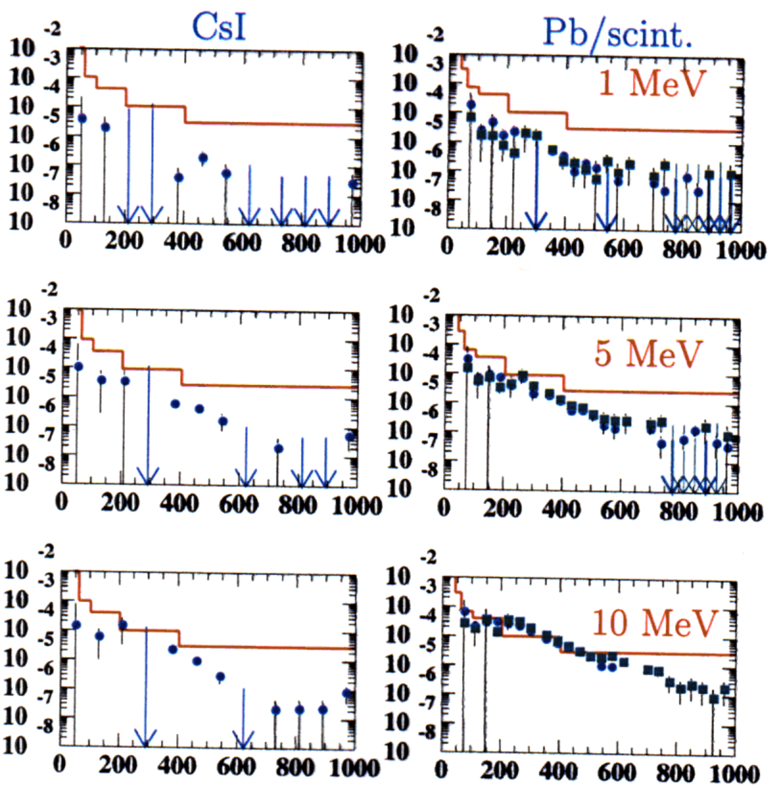
- Hermetic photon veto system, including in the neutral beam
- Energy and position of 2 γ from π^0 decay measured with high precision
- Infer decay location by constraining 2γ mass to π^0 mass
- Require $p_T > 215$ MeV/c to eliminate $2\pi^0$ induced background



Expected Performance of KAMI Search for $K_L^0 \to \pi^0 \nu \overline{\nu}$

Advantages of this technique

- Relatively lower neutron flux and lower solid angle beam
- Higher acceptance, no losses from γ direction measurement
- Extremely good energy resolution from (existing) CsI calorimeter
- Better γ veto by virtue of higher γ energy



γ inefficiency vs. γ energy

$\Leftarrow$ Tests of γ veto at INS in Tokyo

Performance better than EOI assumption

Additional tests of beam hole veto being analysed

Measurements of neutron flux in 150 GeV beam being analysed

Disadvantages of this technique:

- Few kinematic constraints – K_L energy not measured, no γ direction
- Potential for background from π^0 produced by energetic neutrons
- Potential for background from hyperons

3×10^{13} protons/pulse $\Rightarrow$ 15-30 events per year with S:N $\simeq$ 10:1

BNL E926 Experiment to Search for $K_L^0 \to \pi^0 \nu \overline{\nu}$

UBC, BNL, Cincinnati, Kyoto, INR Moscow, New Mexico,
TJNAF, TRIUMF, Virginia Tech, Yale, Zurich

E926 uses novel technique – ⇒ allows full kinematic analysis of event

- Determine K_L energy by time of flight, determine decay point and π^0 momentum by measuring γ energy and direction

Requires microbunched proton beam from AGS

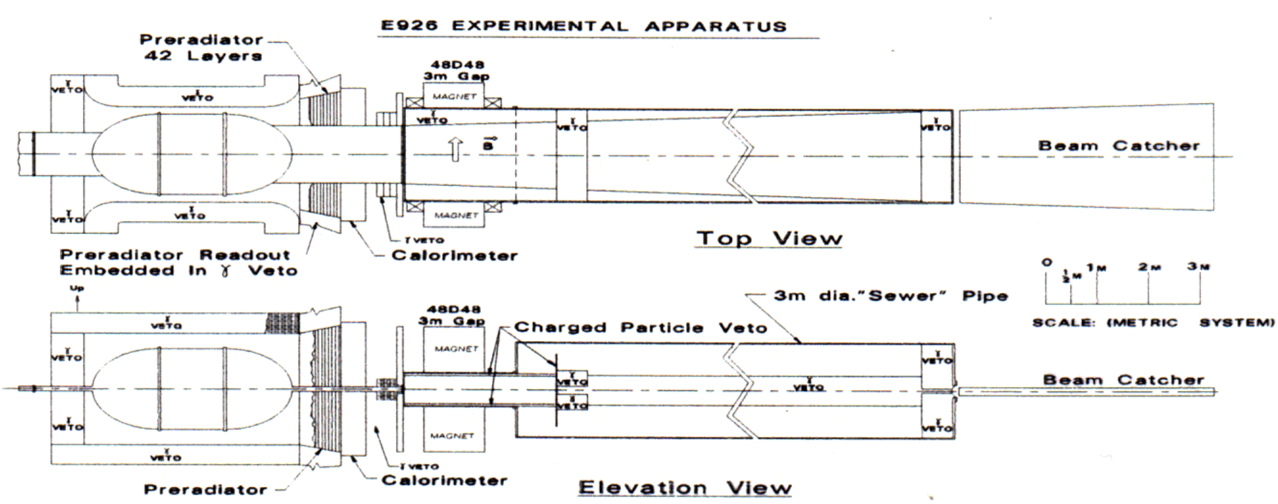
- Unbunched beam extracted between two unfilled RF buckets, bunch spacing determined by RF frequency – 20 MHz
- Bunch width determined by dynamics of extraction – $\sigma_{RMS} = 280$ ps achieved at low intensity in early tests, 150 ps required

Produce low energy beam to allow TOF

- Produce beam at large angle (45°) – low momentum (~ 600 MeV/c) K_L^0
- Run AGS with large duty factor – 10^{14} ppp, 5 s cycle time
- Adjust intensity to maximize events with one K decay per micropulse

Fully measure decay kinematics and reject extra γ

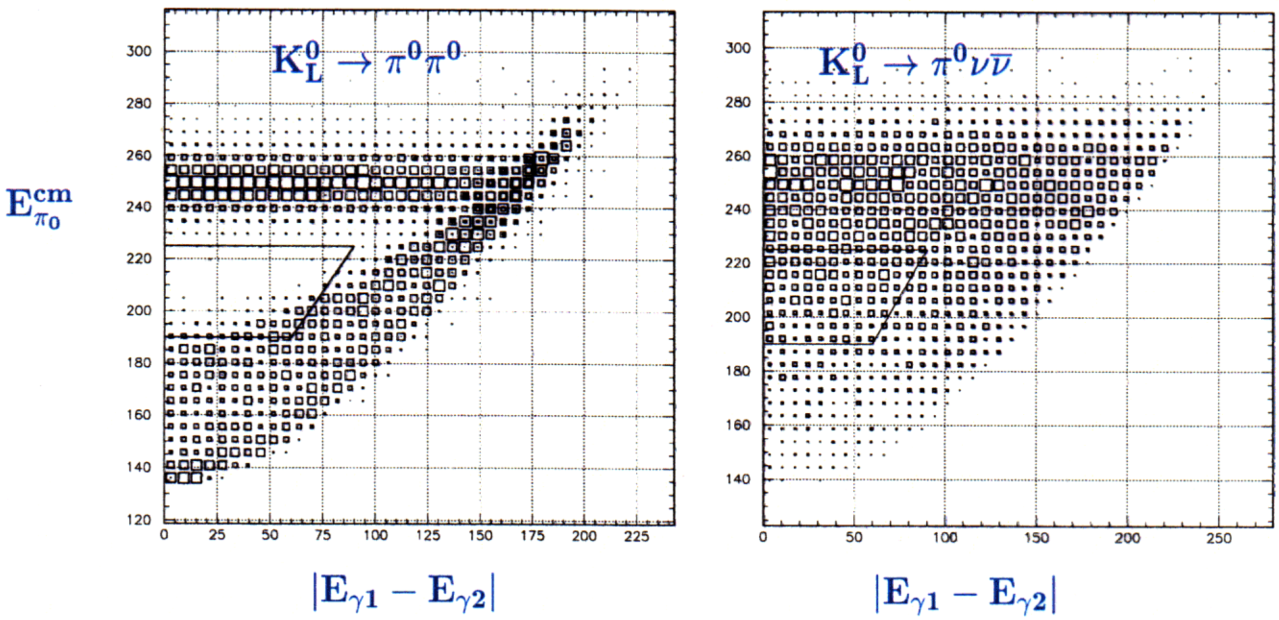
- γ veto performance based on E787 – $\sim 10^{-6}$ inefficiency for $E_\gamma > 20$ MeV
- Deduce $E(K_L^0)$ by TOF – 250 ps γ timing, 150 ps beam timing
- K_L^0 vertex by γ direction – ~ 35 mrad for 200 MeV γ



Expected Performance of BNL E926 Search for $K_L^0 \to \pi^0 \nu \overline{\nu}$

Advantages of this technique:

- No background from hyperons, reduced π^0 production by neutrons
- Accelerator is available at low incremental cost
- Kinematics improves suppression of dominant background ($K_L \to \pi^0\pi^0$)



Disadvantages of this technique:

- Requires vetoing relatively lower energy photons
- Low veto threshholds susceptible to high accidental veto rates
- Low energy secondaries implies complicated trajectories – backward going particles and long event durations
- Low energy neutron fluxes in beam are very high – few [redacted] GHz

Performance calculated based on 9000 hour run:

S/N	Signal events	$B(K_L^0 \to \pi^0\nu\overline{\nu})$ Precision
1	94	0.15
2	65	0.15
3	48	0.17
5	32	0.20

Search for Lepton Flavor Violation

Experimental evidence shows there are nearly conserved additive quantum numbers associated with each *family* of leptons – nonconservation referred to as LFV.

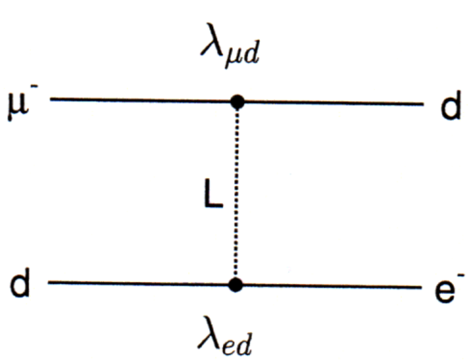
- **These conservation laws are accidental – no known gauge symmetry protects lepton flavor.**
- **Rigorously true in the SM if neutrinos are mass degenerate.**

G=1	e	ν_e	u	d
G=2	μ	ν_μ	c	s
G=3	τ	ν_τ	t	b

- **LFV in extended Standard Model can occur through ν oscillation in loop diagrams.**
- **Information on neutrino mass and mixing ⇒ rate for LFV in charged sector is below any conceivable experiment's sensitivity.**
- **Essentially all extensions to the SM allow LFV.**

⇒ LFV in charged sector would be unambiguous evidence for physics beyond the Standard Model

- **The mass scale probed is very high:**

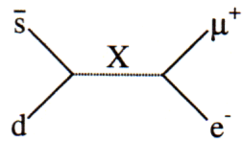
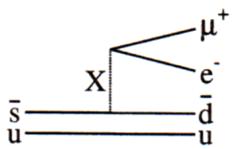
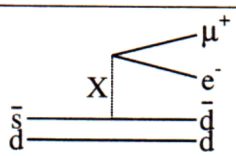


$$R_{\mu e} \equiv \frac{\Gamma(\mu^- N \to e^- N)}{\Gamma(\mu^- N \to \nu_\mu N')} = 10^{-16} \Rightarrow$$

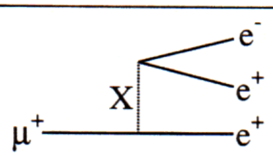
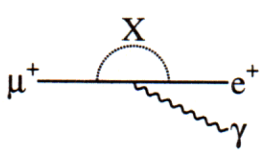
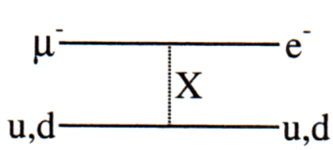
$$M_L = 3000(\lambda_{\mu d}\lambda_{ed})^{1/2}\ \mathrm{TeV}/c^2$$

LFV Searched for in Many Processes

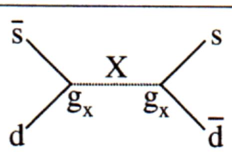
ΔG = 0(2) processes: **M or ΔM Limit**

	**BNL E871** $B(K_L^0 \to \mu^\pm e^\mp) < 4.7 \times 10^{-12}$ AV or PS	$150\ \mathrm{TeV}/c^2$
	**BNL E865** $B(K^+ \to \pi^+\mu^+e^-) < 4.0 \times 10^{-11}$ V or S BNL E865 $\to < 10^{-11}$	$31\ \mathrm{TeV}/c^2$
	**Fermilab E799** $B(K_L^0 \to \pi^0\mu^\pm e^\mp) < 3.2 \times 10^{-10}$ V or S	$37\ \mathrm{TeV}/c^2$

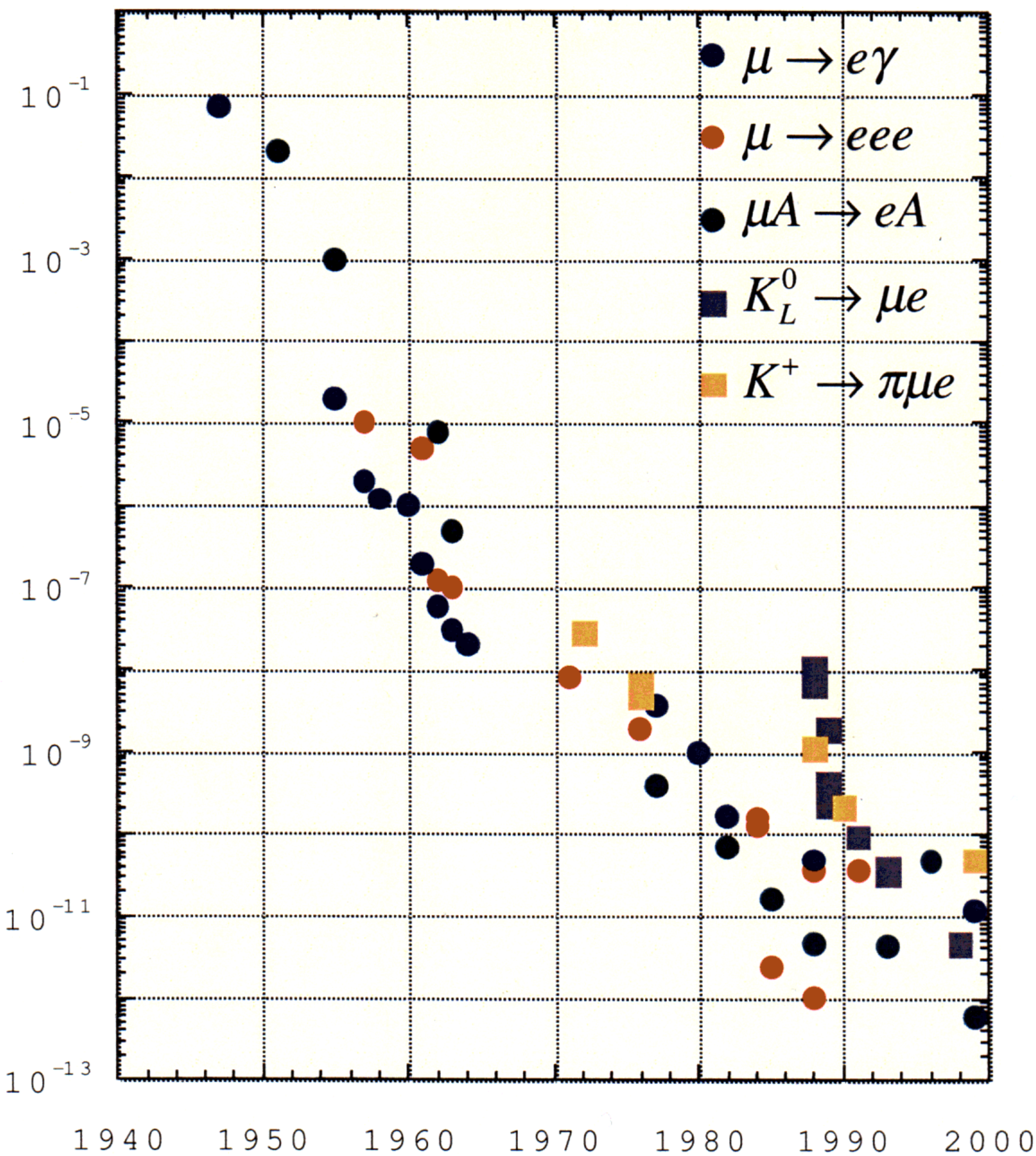
ΔG = ±1 processes:

	$B(\mu \to eee) < 1.0 \times 10^{-12}$	$86\ \mathrm{TeV}/c^2$
	**MEGA** $B(\mu^+ \to e^+\gamma) < 1.2 \times 10^{-11}$ Background limited PSI experiment $\to 10^{-14}$	$21\ \mathrm{TeV}/c^2$
	**PSI SINDRUM2** $\frac{\Gamma(\mu^- A \to e^- A)}{\Gamma(\mu^- A \to \nu A')} < 6.1 \times 10^{-13}$ SINDRUM2 $\to 4 \times 10^{-14}$ MECO at BNL $\to 5 \times 10^{-17}$	$365\ \mathrm{TeV}/c^2$

ΔG = ±2 processes:

	$\Delta M_K < 3.5 \times 10^{-12}\ \mathrm{MeV}/c^2$	$400\ \mathrm{TeV}/c^2$

History of LFV Search Limits

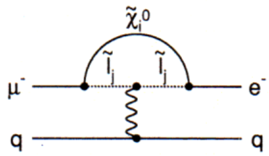


Courtesy Y. Kuno

Examples of Muon Conversion Mechanisms

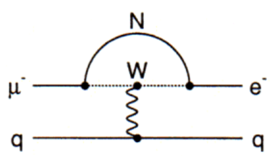
Parameter value for $R_{\mu e} = 10^{-16}$

- Supersymmetry:



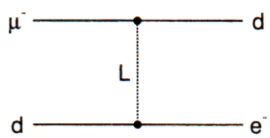
predicitions at 10^{-15} level

- Heavy neutrinos:



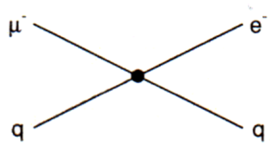
$|U^*_{\mu N} U_{eN}|^2 = 8 \times 10^{-13}$

- Leptoquarks:



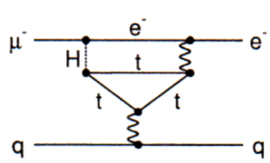
$M_{LQ} = 3000\ (\lambda_{\mu d} \lambda_{ed})^{1/2}\ \mathrm{TeV}/c^2$

- Compositeness:



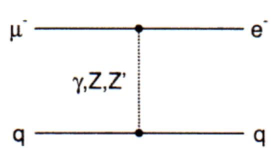
$\Lambda_C = 3000\ \mathrm{TeV}$

- Neutral Higgs:



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

- Heavy Z', anomalous Z coupling:



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

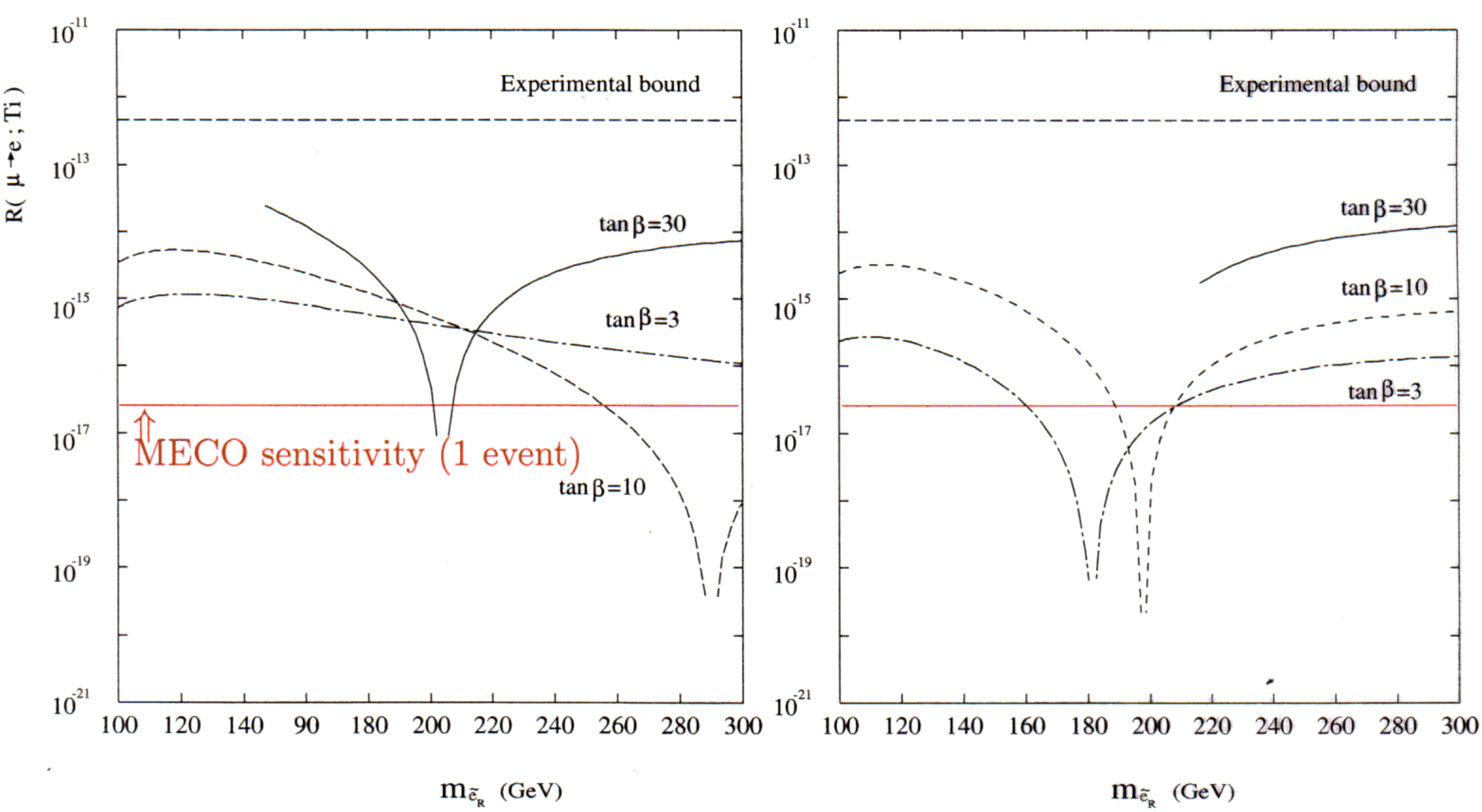
$B(Z \to \mu e) < 10^{-17}$

After W. Marciano

LFV in Supersymmetric Grand Unified Theories

- **Observation of Hall and Barbieri –**
  large t-quark Yukawa couplings ⇒ observable levels of LFV in supersymmetric grand unified theories
- **Degree of LFV in supersymmetric sector related to quark mixing**
- **Interfering diagrams calculated 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^{-6}	10^{-9}



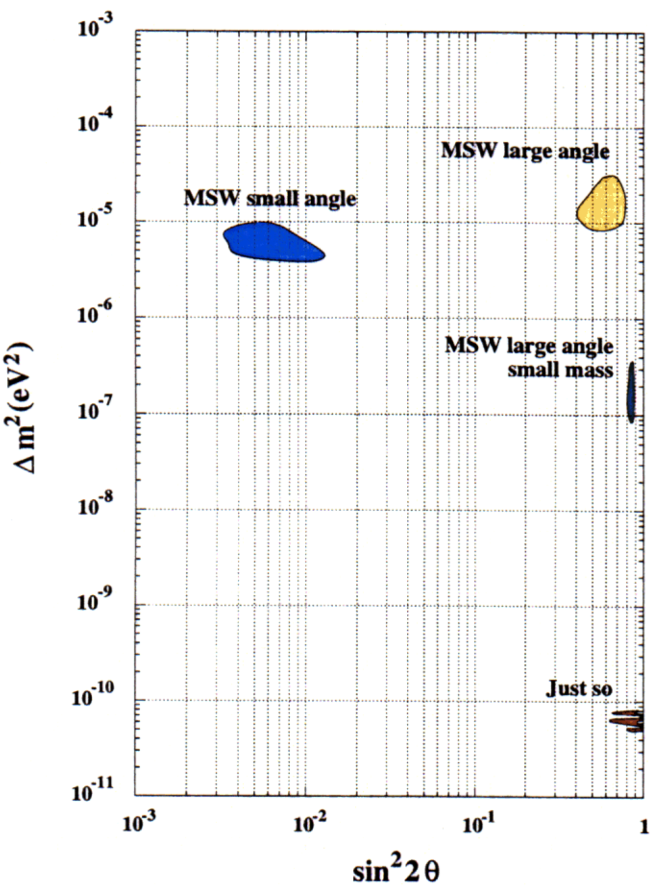
LFV in Supersymmetric Grand Unified Theories

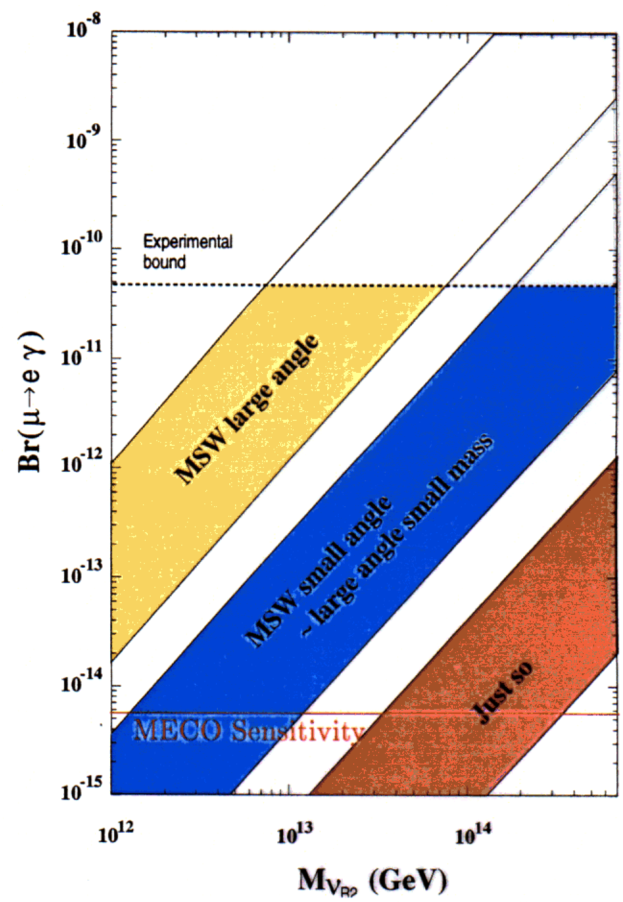
Many recent papers on unified supersymmetric models – an example is Hisano and Nomura, Phys. Rev. D59

Features of the model:

- SU(5) grand unified model
- Heavy right handed neutrinos

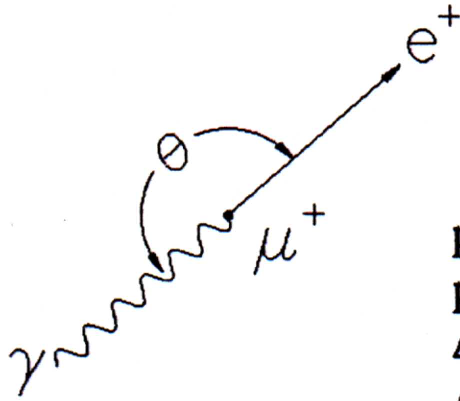
⇒ Solar neutrino results related to LFV





Principles of $\mu^+ \to e^+\gamma$ Search

Stop μ^+ in thin target, detect e^+ and γ



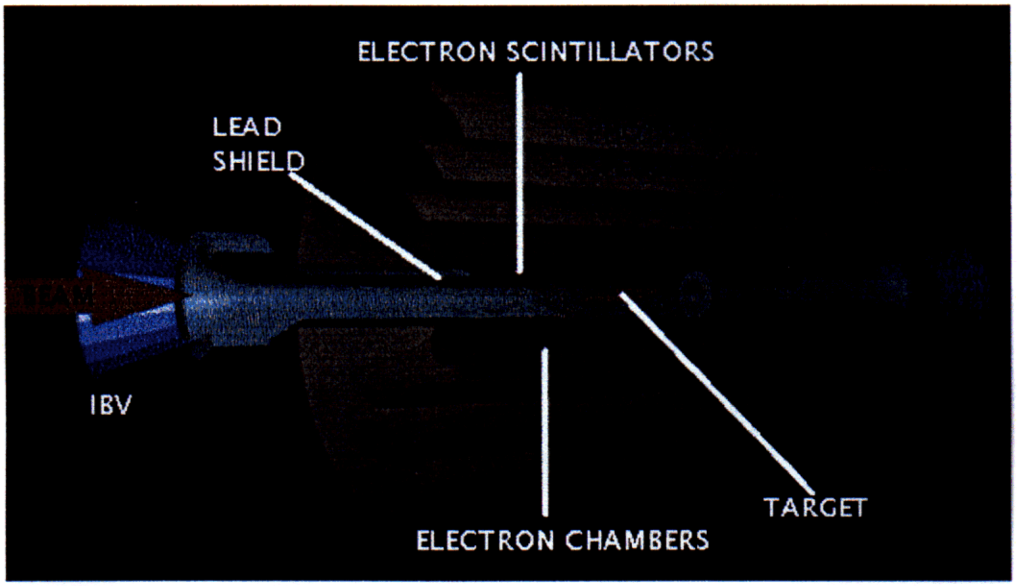
$p_e = 52.83$ MeV/c
$p_\gamma = 52.83$ MeV/c
$\Delta\theta_{e\gamma} = 180°$
$\Delta t_{e\gamma} = 0$ ns

- **Background from radiative decay:**
  $\mu^+ \to e^+\nu_e\overline{\nu}_\mu\gamma$ **suppressed by kinematics**
- **Accidental background from two decays:**
  - $\mu^+ \to e^+\overline{\nu}_\mu\nu_e$
    E_{e^+} **peaked near** $m_\mu/2$**, flat energy dependance**
  - $\mu^+ \to e^+\overline{\nu}_\mu\nu_e\gamma$
    for $y \equiv 2E_\gamma/m_\mu$**, in interval** δy **near** $y = 1$
    $dN_\gamma = \frac{\alpha}{4\pi}\delta y^2(\ln(\delta y) + 7.33)$

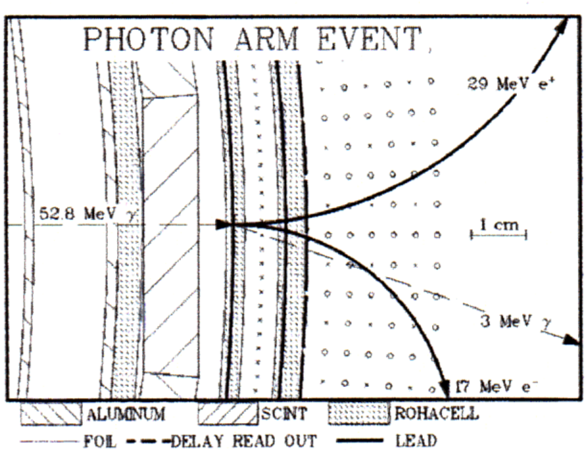
$\Rightarrow$ **Background/Signal** $\propto$

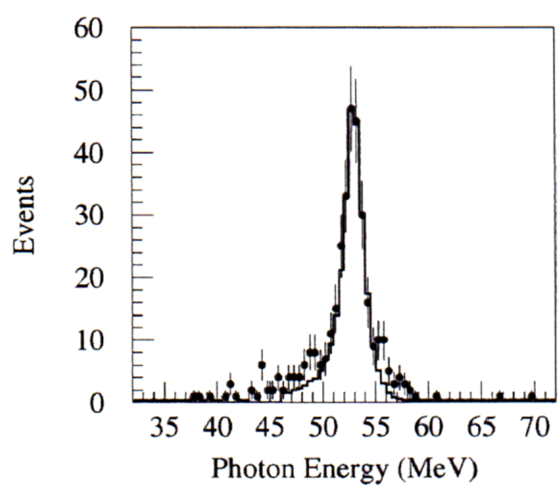
$$\Delta E_e \times (\Delta E_\gamma)^2 \times \Delta t_{e\gamma} \times (\Delta\theta_{e\gamma})^2 \times \text{Rate}$$

The MEGA Search for $\mu^+ \to e^+\gamma$



- Experiment done at LAMPF – 800 MeV linac, 1 mA
  - Duty factor 6-7% – instantaneous μ^+ stop rate 250 MHz
- E_{e^+} and E_γ measured with magnetic spectrometer
  - 1.5 T magnetic field
  - Electron spectrometer – low mass MWPC
  - Photons converted and e^+e^- momenta measured





The MEGA Search for $\mu^+ \to e^+\gamma$

- 1.2×10^{14} μ^+ stopped during 1993-5
- 0.43% $\mu^+ \to e^+\gamma$ detection efficiency
- Require $E_e > 50$ MeV, $E_\gamma > 46$ MeV, $\Delta t < 4$ ns, $\theta_{e\gamma} > 175°$
- Hand scanning of events to eliminate some backgrounds
- $\sim$ 2900 events remain following event selection
  - maximum likelihood analysis used to separate signal and background

$$N(\text{accidental}) = 2870$$

$$N(\mu^+ \to e^+\overline{\nu}_\mu\nu_e\gamma) = 30 \pm 8(\text{stat}) \pm 15(\text{syst})$$

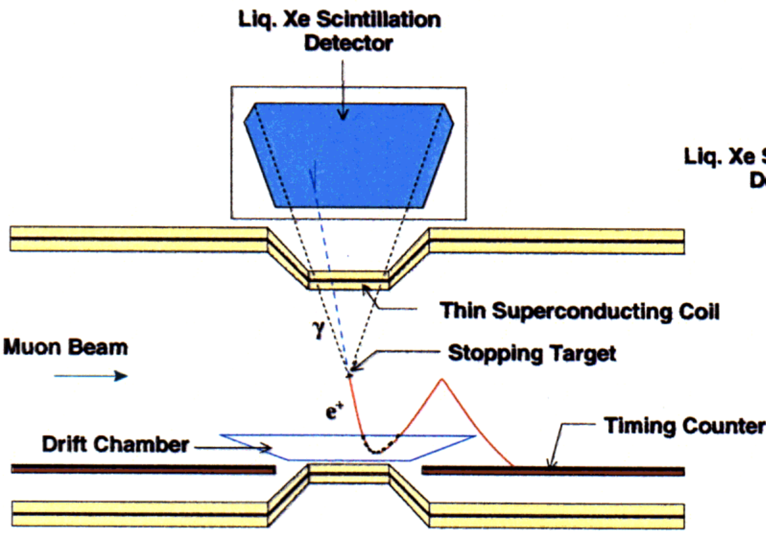
$$N(\mu^+ \to e^+\gamma) < 5.1 \text{ [90\% CL]}$$

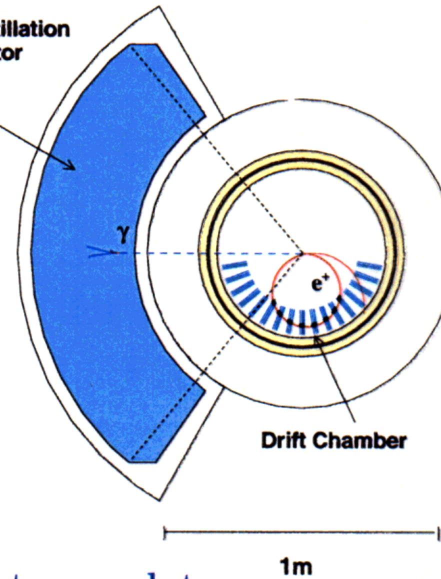
$$B(\mu^+ \to e^+\gamma) < 1.2 \times 10^{-11} \text{ [90\% CL]}$$

MEGA limited by accidental backgrounds

The PSI Search for $\mu^+ \to e^+\gamma$

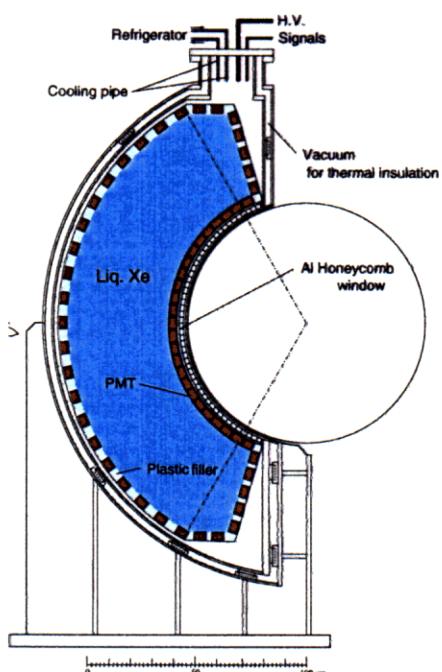
Novosibirsk, Tokyo, KEK, Nagoya, Waseda

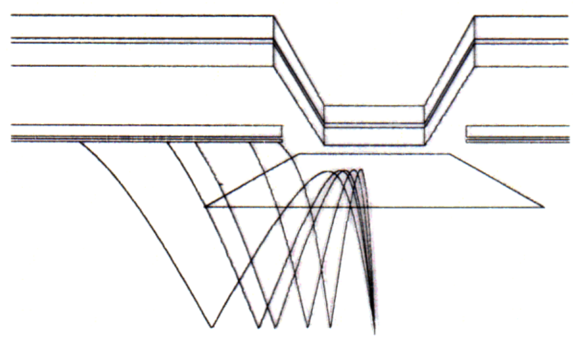




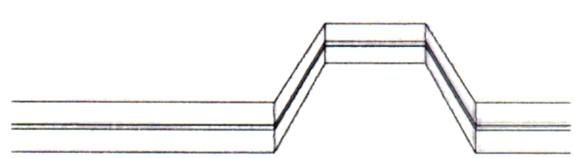
Experiment done at PSI – 1.5 mA 590 MeV proton cyclotron

- 51 MHz pulsed beam – 100% macro duty factor
- E_{e^+} measured with magnetic spectrometer
- E_γ measured with liquid xenon scintillator





graded field ⇒
radius independent of emission angle
no trajectories with many loops



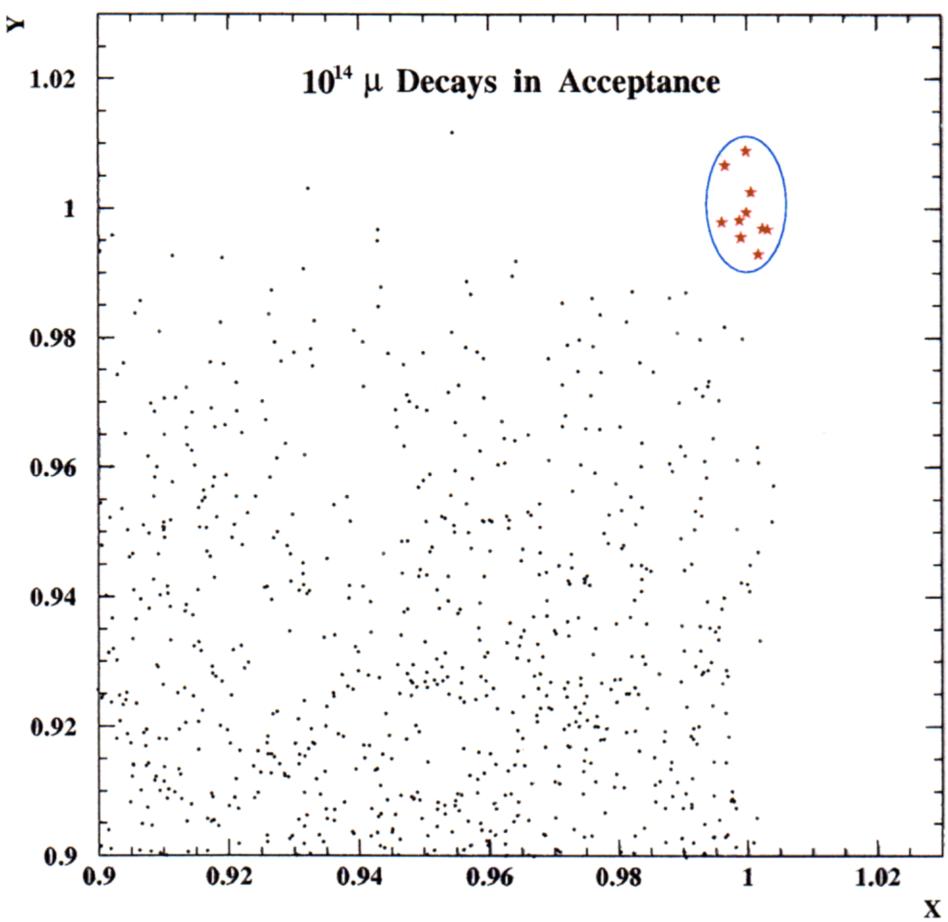
Expected Performance of PSI $\mu^+ \to e^+\gamma$ Search

Simulation of acceptance and background done with conservative but Gaussian error distributions

	FWHM
ΔE_e	0.7 %
ΔE_γ	1.4-2.0 %
$\Delta \theta_{e\gamma}$	12-14 mrad
$\Delta t_{e\gamma}$	0.15 ns

Running time	2.2×10^7 s
μ^+ stop rate	10^8 Hz
$\Omega/4\pi$	0.09
e^+ efficiency	0.95
γ efficiency	0.70
cut efficiency	0.80

$\Rightarrow$ 1 event for $B(\mu^+ \to e^+\gamma) = 0.94 \times 10^{-14}$



$\Rightarrow$ expected background = 0.5 events

Coherent μ^- to e^- Conversion: $\mu^- N \rightarrow e^- N$

- μ^- are brought to rest in a thin target where they form muonic atoms in 1S state.
- Three things may happen to the μ^-:

Nuclear capture	$\mu^- \mathrm{N} \rightarrow \nu_\mu \mathrm{N}'$
Decay in orbit	$\mu^- \mathrm{N} \rightarrow \nu_\mu \mathrm{e}^- \overline{\nu}_\mathrm{e} \mathrm{N}$
Conversion to e$^-$	$\mu^- \mathrm{N} \rightarrow \mathrm{e}^- \mathrm{N}$

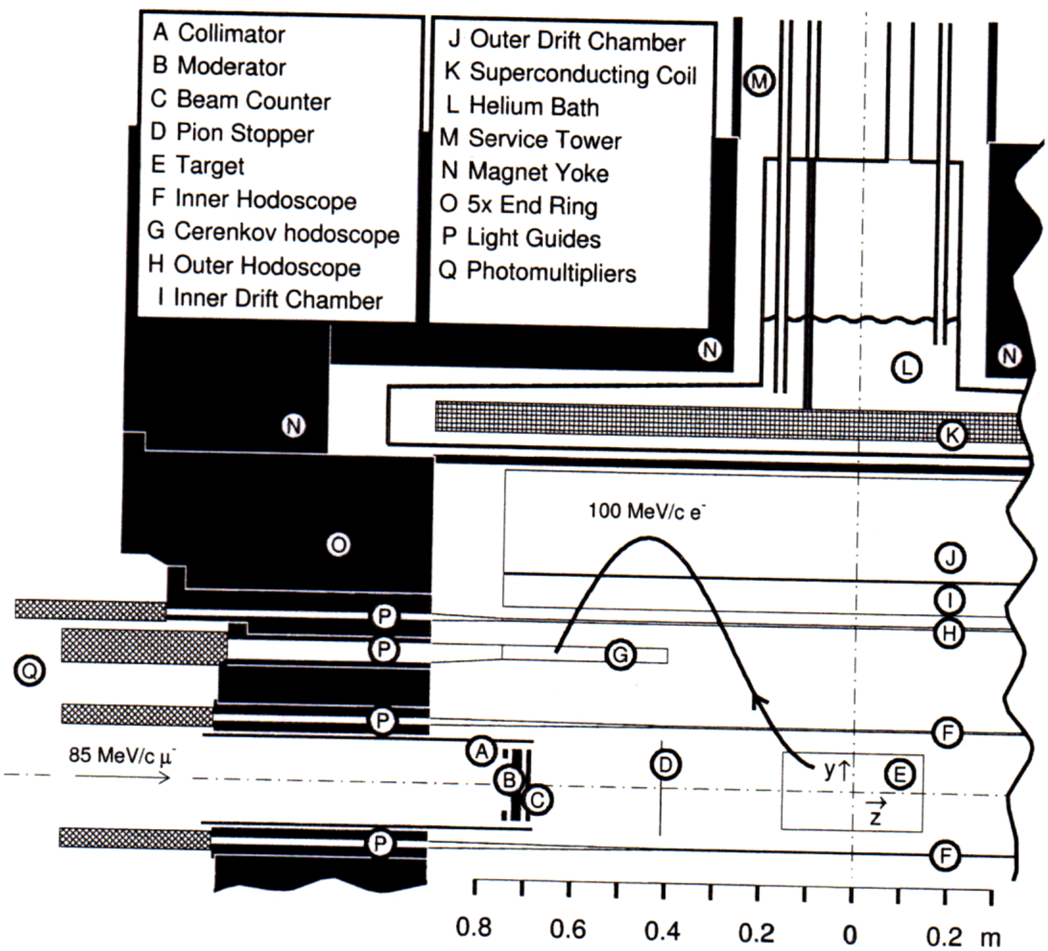
$$\mathrm{R}_{\mu e} \equiv \frac{\Gamma(\mu^- \mathrm{N} \rightarrow \mathrm{e}^- \mathrm{N})}{\Gamma(\mu^- \mathrm{N} \rightarrow \nu_\mu \mathrm{N}')}$$

- This process is coherent if the nucleus left in its ground state.
  - There is an extra factor of Z in the rate.
  - Coherence is reflected in the elastic form factor – it is large at 105 MeV/c momentum transfer.
- Detecting this process is in principle easy.
  - The signature is simple – a 105 MeV electron.
  - The final state is one particle; hence there is no accidental coincidence background at high rates.
  - Other sources of 105 MeV electrons are heavily suppressed.
  - Balance higher sensitivity for large N with less experimental difficulties for small N.

Search for $\mu^- N \to e^- N$ with SINDRUM2 at PSI

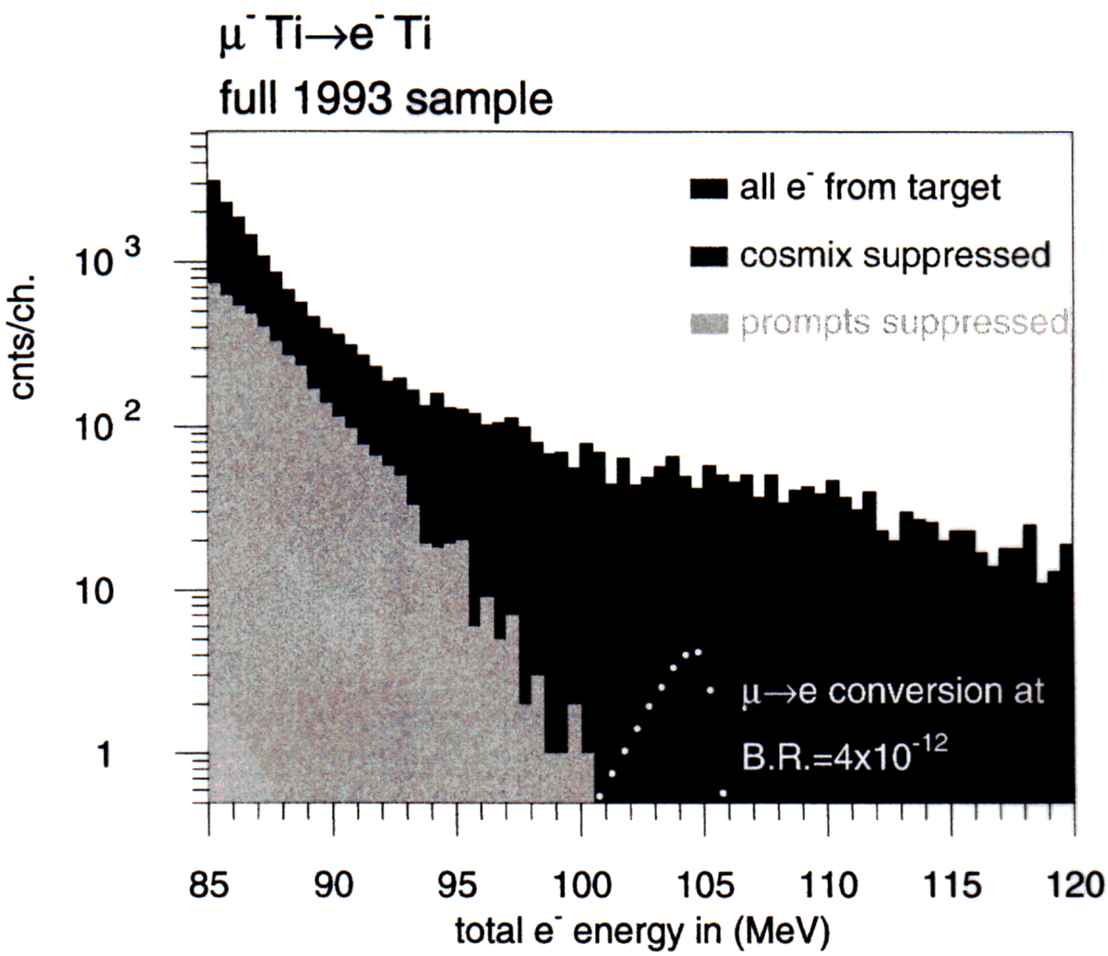
- μ^- beam derived from 1.5 mA, 590 MeV cyclotron (10^{16} protons per second at 1.2 GeV/c)
- Muon beam is a mixed 85 MeV/c π, μ, e beam with total flux $>\sim 10^7\ s^{-1}$
- Data taking complete for first phase

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



Search for $\mu^- N \to e^- N$ with SINDRUM2

- Background from "prompt" π, μ, e processes eliminated with veto counter in beam
- Cosmic ray induced background eliminated by detecting through-going muon in detector
- Electron energy resolution of FWHM ~2.5 MeV, limited by energy loss straggling and spectrometer resolution



Currently running with new beam at higher intensity:

- "Beam blocker" to remove π^- in beam
- Momentum reduced (no μ^- decay in flight background
- Remove beam anti-counter, increase rate

$\Rightarrow$ Sensitivity of 1 event for $\mathbf{R}_{\mu e} = \sim 4 \times 10^{-14}$

BNL MECO Search for $\mu^- N \rightarrow e^- N$

Boston, BNL, UCI, Houston, INR Moscow, NYU, Penn, Purdue, Wm.&Mary

Very intense muon beam – some ideas from Djilkibaev and Lobashev

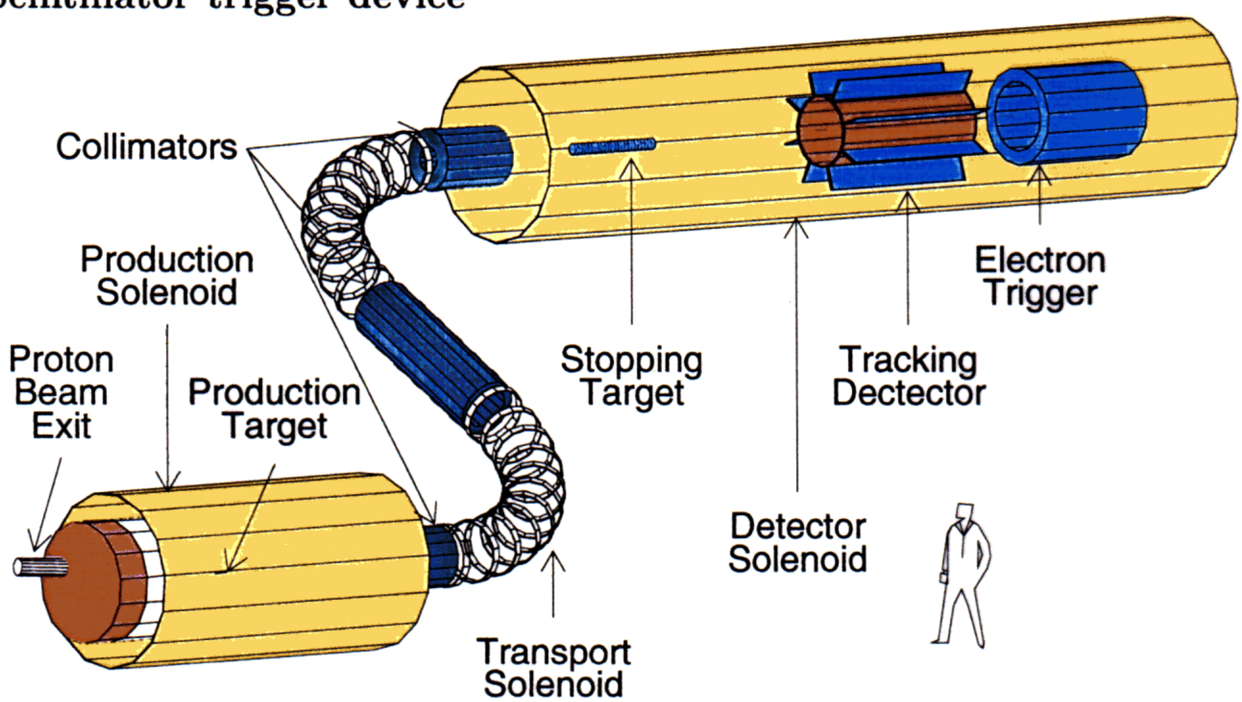
- Produce π^- off heavy target
- Collect π^- and decay μ^- in graded solenoid
- Muon beam transport μ^- in solenoid – sign and momentum select beam
- $\sim 10^{11}$ stopping μ^- for 4×10^{13} 8 GeV protons on target

Pulsed proton and muon beam to reduce "prompt" backgrounds

- Pulse width ~ 50 ns, spacing $\sim 1.35\ \mu$s
- Introduce ~ 600 ns deadtime after proton pulse – electrons pass through apparatus, π^- decay
- Require proton beam suppression during detection time of $\sim 10^{-9}$

Detector with excellent momentum resolution, rate capabilities

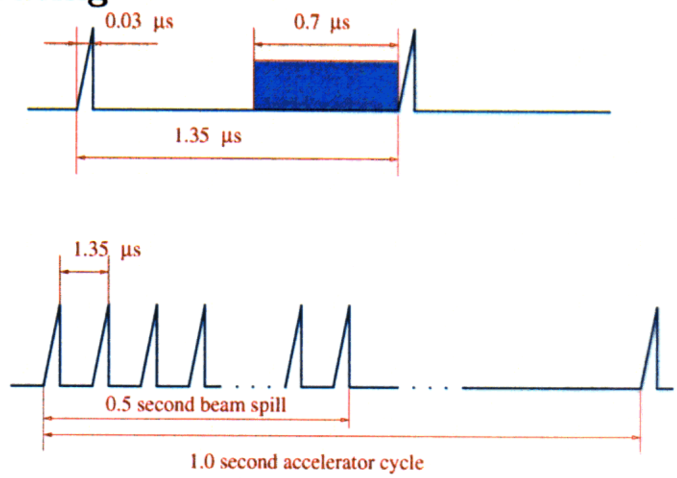
- Stop μ^- in graded field – increase acceptance, reduce rates
- Magnetic spectrometer with straw tube tracking devices in 1 T field
- Scintillator trigger device



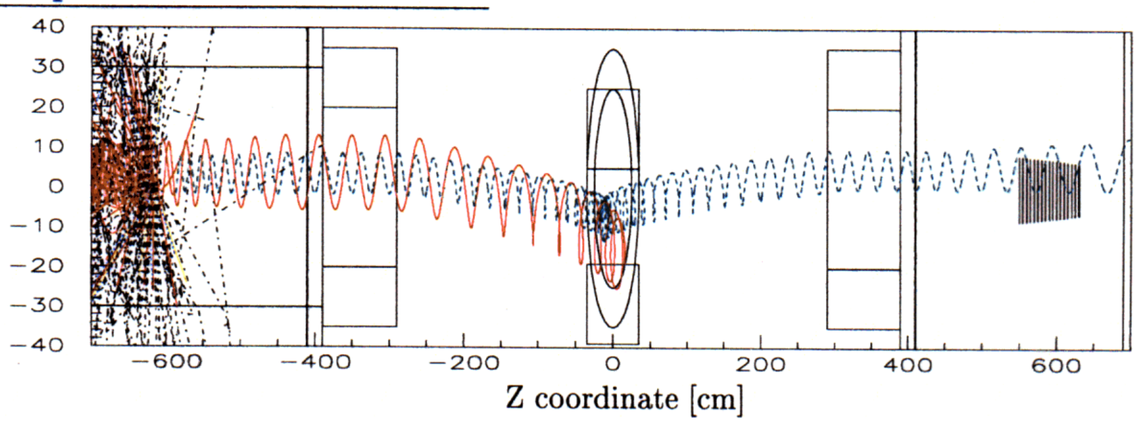
Operation and Performance of MECO μ^- Beam

Beam produced by AGS operating at 8 GeV with RF bunched beam

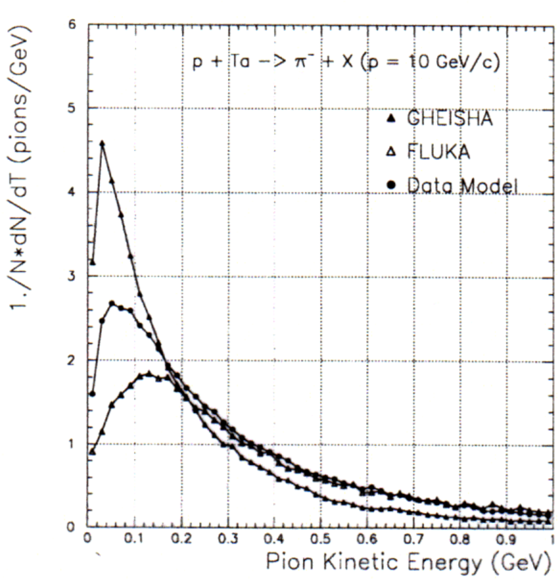
- Revolution time 2.7 μs (6 RF buckets)
- Fill 2 RF buckets 1.35 μs spacing
- Transition at $\Gamma = 8.6$ (p = 7.9 GeV/c)
- 2×10^{13} protons/bucket
  2 × current intensity
- Cycle time 1.0 s
  50% duty factor
- Resonantly extract bunched beam

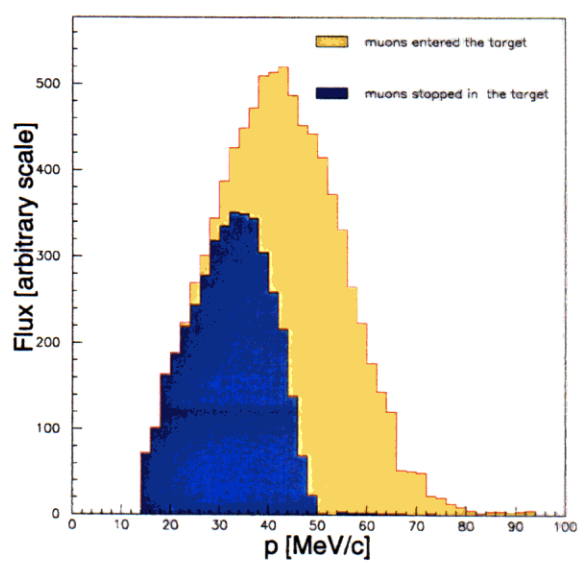


Transport in curved solenoid

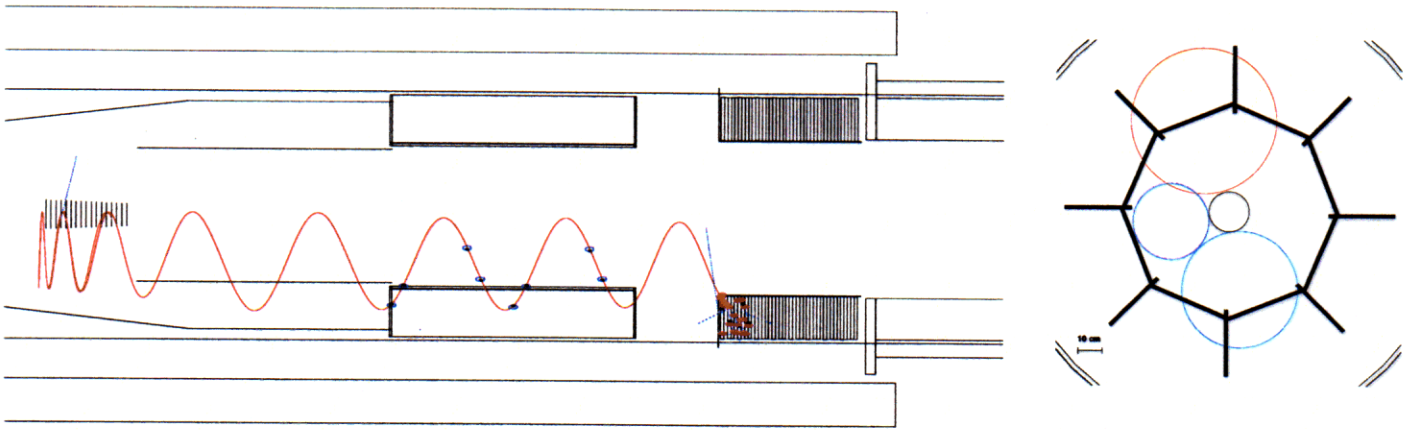


Calculate muon yield based on measured π^- production cross sections

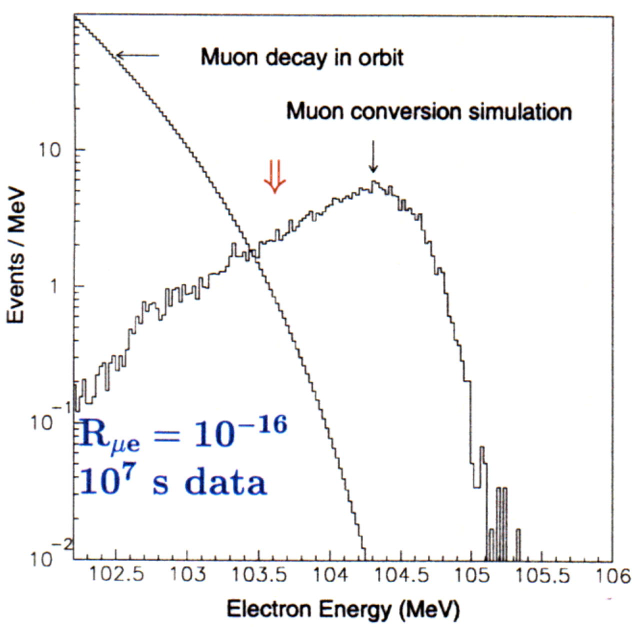


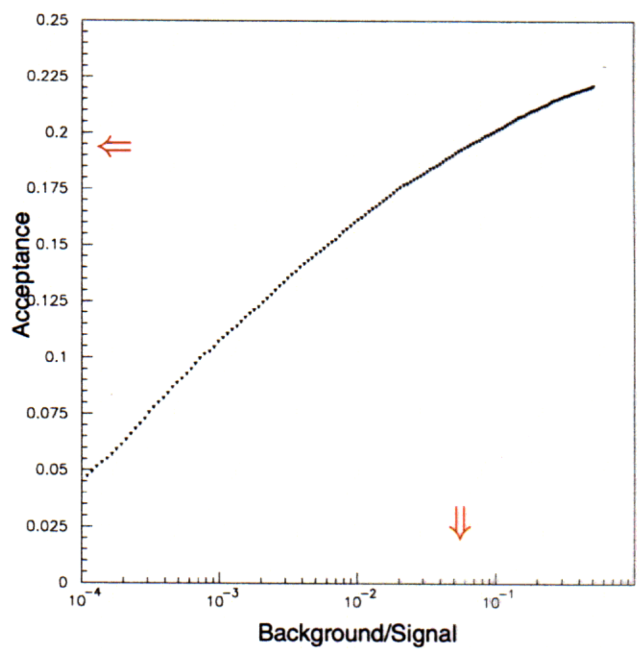


MECO Detector and Resolution Studies



- Tracking detector with nearly axial elements – 3 layers, ~ 2.5 m long
- Electron calorimeter – space and E match with track
- Excellent resolution required to eliminate μ^- DIO background
- Full GEANT simulation of detector response
  - Energy loss in target (large effect, low energy tail)
  - Multiple scattering (dominates intrinsic resolution)
  - Position resolution (small contribution)
- Electron energy fitted by maximum likelihood method
  - FWHM ~ 900 keV, no high energy tail





- Pattern recognition errors simulated at realistic intensities
  – no high energy tails in resolution function

Expected MECO Sensitivity and Backgrounds

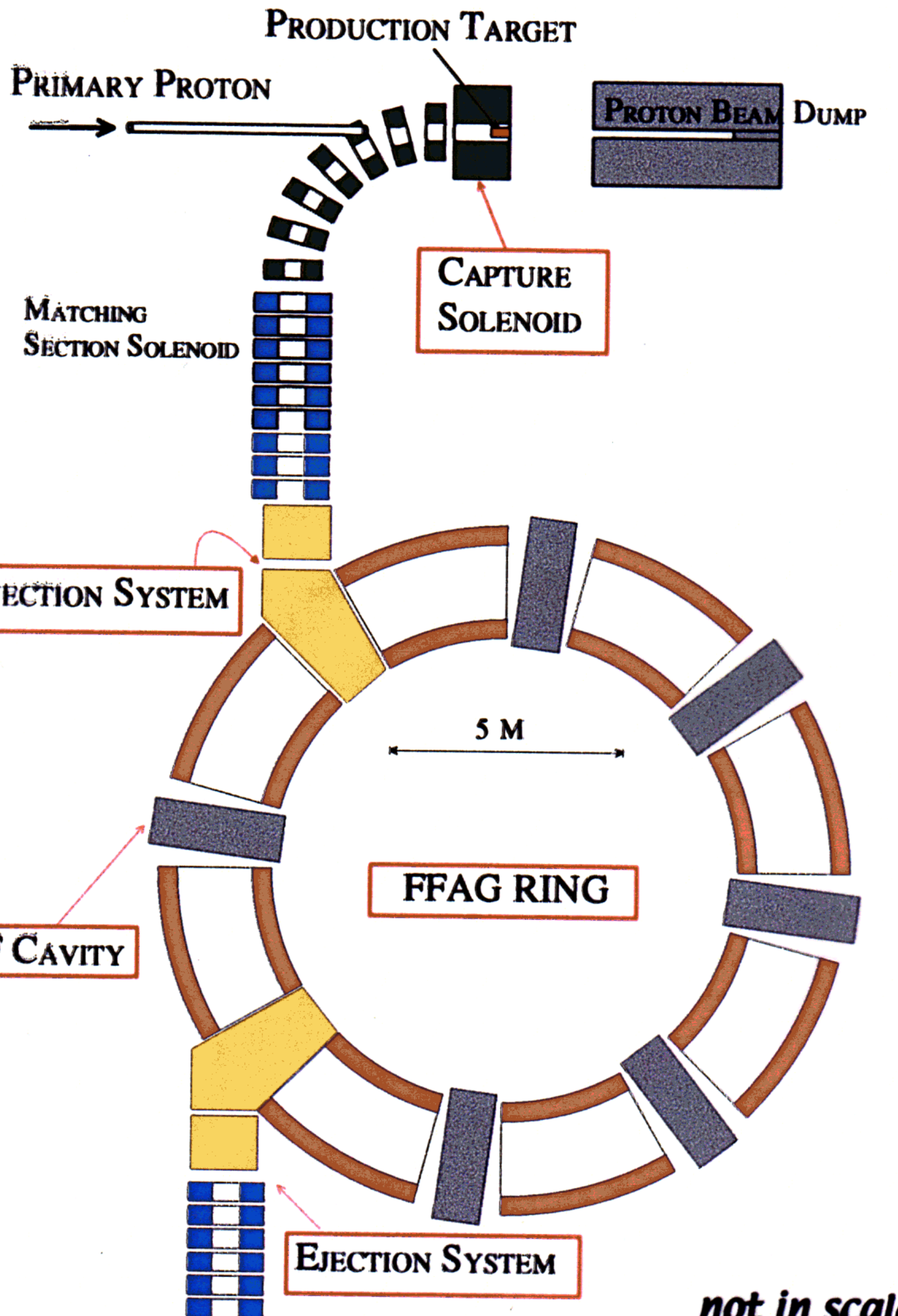
Sensitivity per year of running:

Running time (s)	10^7
Proton flux (Hz) (50% DF, 740 kHz μpulse)	4×10^{13}
μ/p entering solenoid	0.0043
Stopping probability	0.58
μ capture probability	0.60
Fraction of μ capture in time window	0.49
Electron trigger efficiency	0.90
Fitting and selection criteria	0.19
Detected events for $R_{\mu e} = 10^{-16}$	5.0

Expected background:

Source	Events	Comment
μ^- decay in orbit	0.25	S/N = 20 for $R_{\mu e} = 10^{-16}$
Tracking errors	< 0.006	
Radiative μ^- capture	< 0.005	
Beam electrons	< 0.04	
μ^- decay in flight	< 0.03	no scatter in target
μ^- decay in flight	0.04	scatter in target
π^- decay in flight	< 0.001	
Radiative π^- capture	0.07	out of time protons
Radiative π^- capture	0.001	late arriving π^-
Anti-proton induced	0.007	mostly from π^-
Cosmic ray induced	0.004	10^{-4} CR veto ineff.
Total background	0.45	Assumes 10^{-9} extinction

PRISM layout



not in scale

Comments on Use of Muon Storage Ring or Proton Driver for Kaon and Muon Experiments

Some general and not very insightful comments:

- Higher intensity proton beams have almost always resulted in improved experiments – examples of beam improvements:
  - Increased intensity and/or smaller beams
  - Allow for separated charged beams
  - Allow for neutron suppressed neutral beams (absorbers in beam)
  - Allow for the possibility of tertiary beams
- Currently proposed experiments are aiming for very large improvements in sensitivity
  - A great deal will be learned in these experiments
  - They will likely guide where further improvements can be made

Comments on improved CKM matrix studies:

- Proposed experiments aim to reach level of theoretical uncertainty
- Could benefit from better K/n ratio
- Could benefit from smaller solid angle beam
- Low energy technique limited by accidental veto in microbunch
- Will require debunched, slow extracted proton beam

Comments on improved $\mu^+ \to e^+\gamma$ searches:

- Done with very low energy "surface muon beams" – not much room to reduce energy or energy spread
- Goal is to achieve background free experiment – linear increase of sensitivity with running time
- Experiments are limited by accidental backgrounds – cannot afford significantly higher rate without introducing background
- Suggestion of Kuno and Okada to reduce backgrounds using polarized μ^+ beams

Comments on improved $\mu^- N \to e^- N$ searches:

- Intrinsic background is independent of beam rate
- Rate limitations come from detector rates and their effect on things like tracking errors that introduce tails in resolution functions
- Improved acceptance could come from smaller beams, smaller physical extent of stopping target
- Improved energy resolution could come from smaller beam momentum spread – thinner stopping target and less straggling
  need low energy (few MeV) muon beam
- Could imagine $\times 2$ acceptance with smaller, lower energy spread beam, reduction of width of resolution function by factor of 2
- Increasing stopping rate by more than a factor of 5-10 would imply significant detector rate issues – suggestions have been made about detector geometries to deal with this, but no credible calculation has been done
- If extremely pure muon beam of low energy could be made, necessity for pulsed beam would go away – effectively a factor of two in acceptance

Synergism between μ storage ring and rare processes:

- Study option of slow extraction and continuous cooled muon channel
- Maintain contact with ongoing physics efforts using intense μ beams