Physics Potential of Muon Factory and Neutrino Factory Based on FFAGs

Yoshitaka KUNO
Osaka University

TRIUMF FFAG Symposium,
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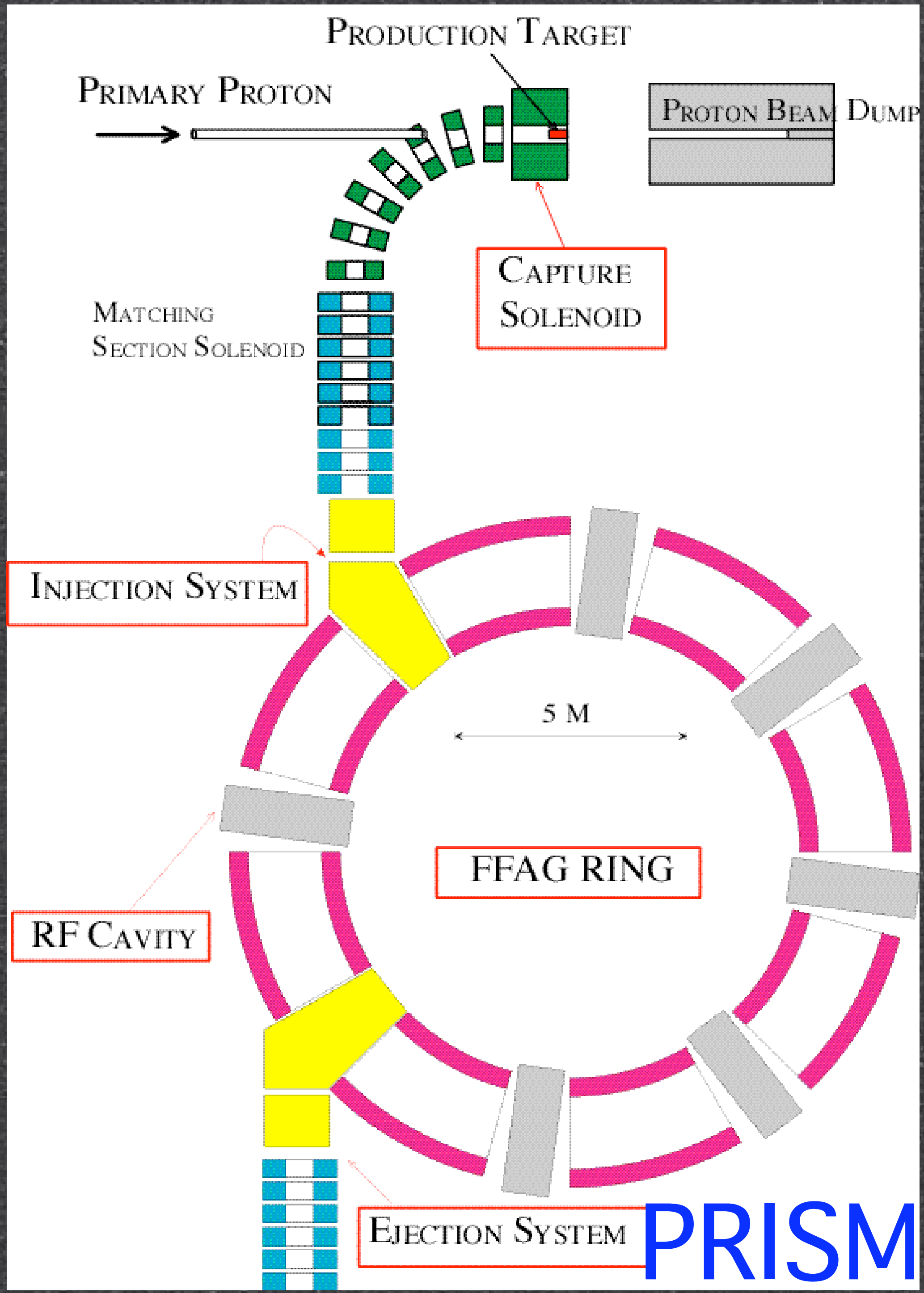
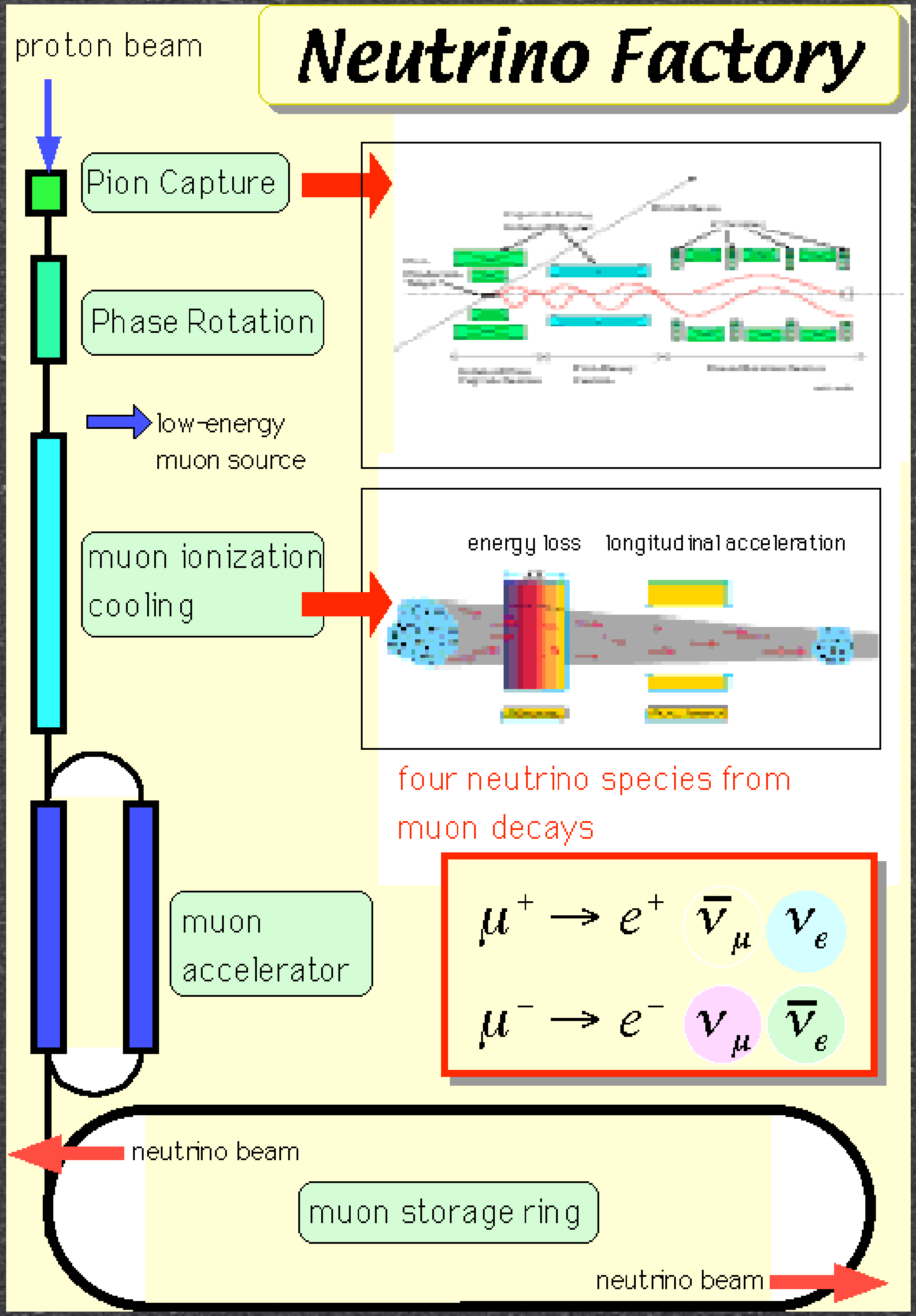
What are Muon and Neutrino Factories ?

- Muon Factory
  - high intensity
    - $10^{12} - 10^{14} \mu^{\pm}/sec$
    - a MW proton machine needed
  - high brightness
    - narrow E width
    - beam treatment (FFAG)
  - high purity (no pions)
  - dedicated to types of experiments?



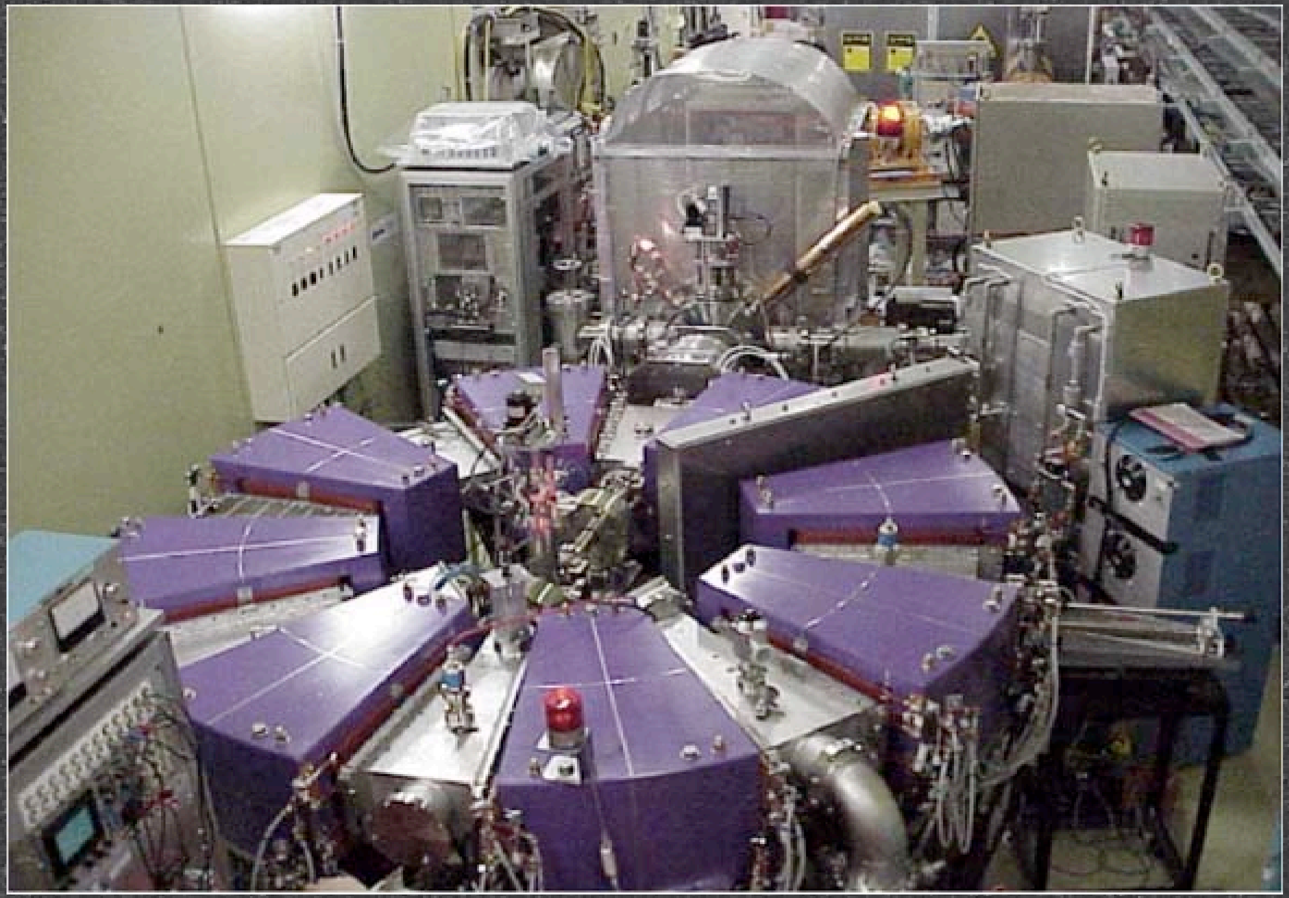
What are Muon and Neutrino Factories ?

- Neutrino Factory
  - high intensity
    - $10^{19} - 10^{21} \nu/year$
    - a MW proton machine needed
  - use decays of muons accelerated to high energy (FFAG) and stored in the ring
  - all four types available
  - high energy neutrinos
  - known beam quality



FFAG Advantages

- Large Acceptance
  - Both Longitudial and Transverse directions
  - strong focusing
- Fast Acceleration
  - due to fixed magnetic field



fast proton FFAG @KEK (2001)

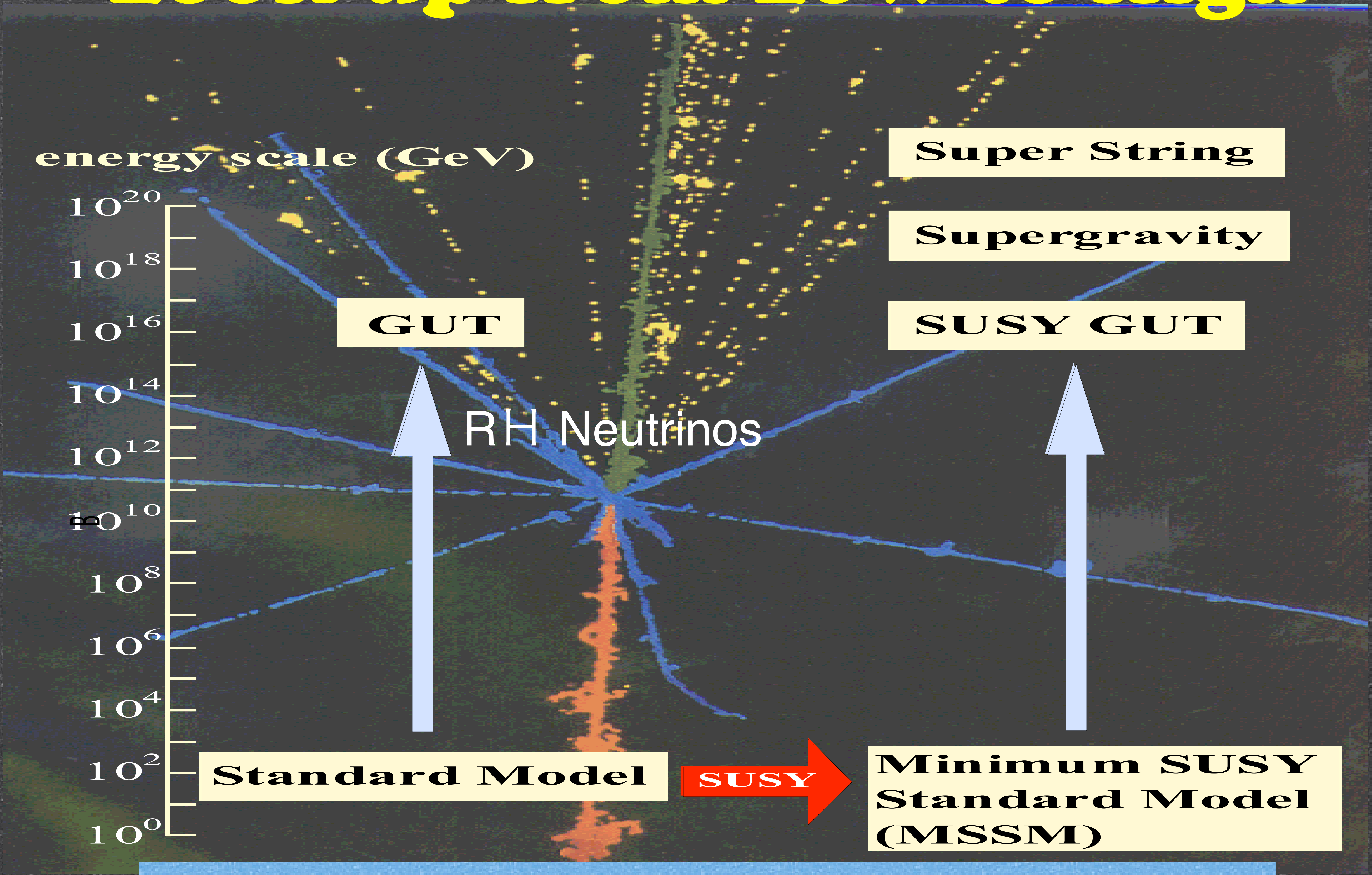
Suitable to Muon Acceleration

Outline

- Introduction to Flavor Particle Physics
- Muon Factory (only specific topics)
  - Muon Lepton Flavor Violation (PRISM)
  - Muon Electric Dipole Moment (PRISM-II)
  - J-PARC Case
- Neutrino Factory
  - Physics Motivation
- PRISM R&D Status
- Conclusion / Announcement

Flavor Particle Physics

Look up from Low to High



Flavor Structure of Quarks and Leptons

Flavor Physics

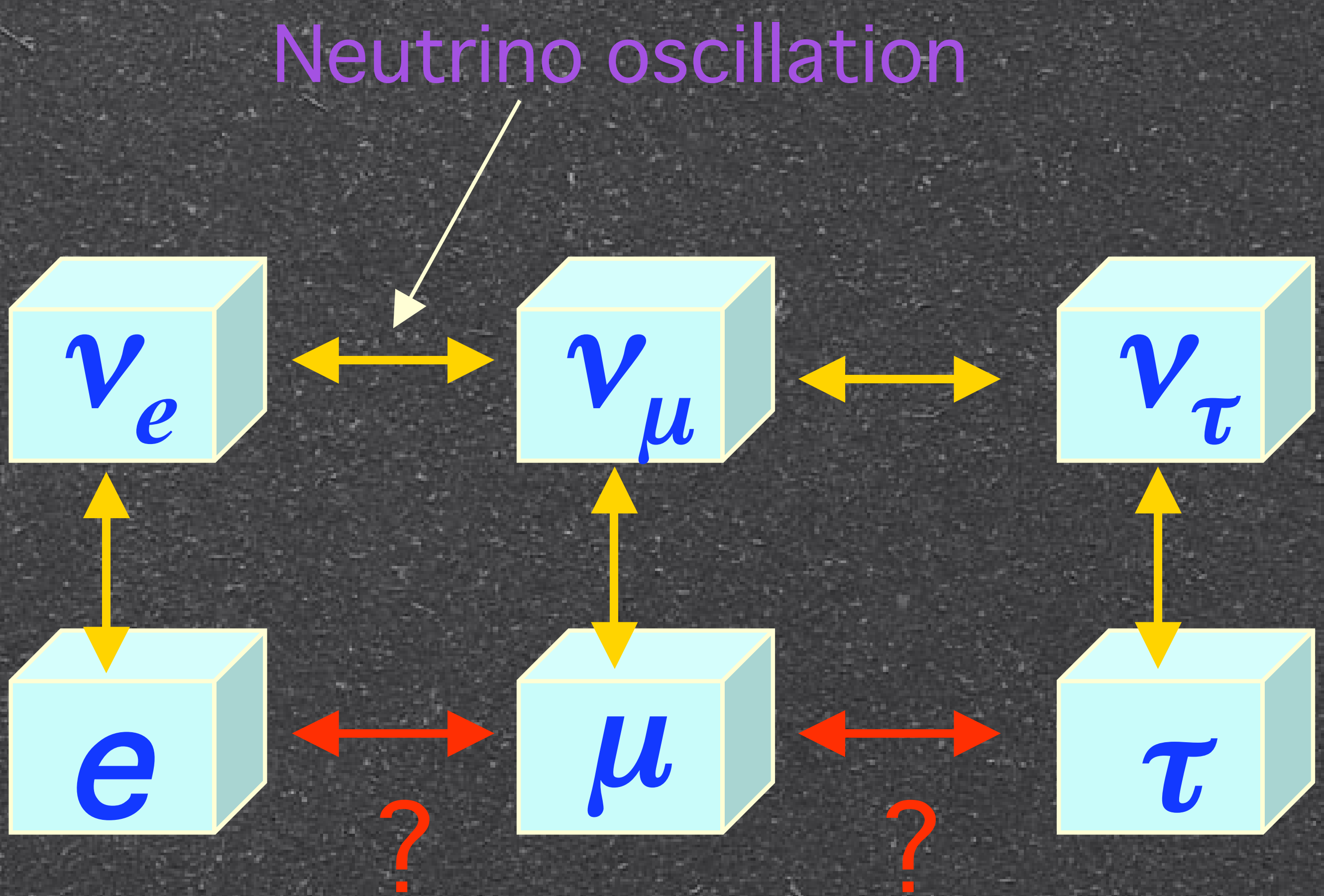
		supersymmetry
Muon Lepton Flavor violation	quarks	squarks
	$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ \dots \end{pmatrix}$	$\begin{pmatrix} \Delta\tilde{m}^2_e & \Delta\tilde{m}^2_{12} & \Delta\tilde{m}^2_{13} \\ \dots \end{pmatrix}$
neut		
$\begin{pmatrix} Y_{11}e^{i\Phi_1} & & \\ & Y_{22}e^{i\Phi_2} & \\ & & Y_{33}e^{i\Phi_3} \end{pmatrix}$	$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} 1 \\ e^{i\phi_1} \\ e^{i\phi_2} \end{pmatrix}$	$\begin{pmatrix} \Delta\tilde{m}^2_e & \Delta\tilde{m}^2_{12} & \Delta\tilde{m}^2_{13} \\ \Delta\tilde{m}^2_{21} & \Delta\tilde{m}^2_{\mu} & \Delta\tilde{m}^2_{23} \\ \Delta\tilde{m}^2_{31} & \Delta\tilde{m}^2_{32} & \Delta\tilde{m}^2_{\tau} \end{pmatrix}$
Leptogensis	Standard Model	New physics

A Muon Factory and a Neutrino Factory are very important

Muon Lepton Flavor Violation

Charged Lepton Flavor Violation (cLFV)

Flavor changing processes in charged lepton ?



- Example: $\mu^+ \rightarrow e^+ \gamma$

	μ^+	$e^+\gamma$
muon flavor	-1	0
electron flavor	0	-1

Not be observed yet !

- Example: $\mu^+ \rightarrow e^+ e^- e^+$

	μ^+	e^+	e^-	e^+
muon flavor	-1	0	0	0
electron flavor	0	-1	+1	-1

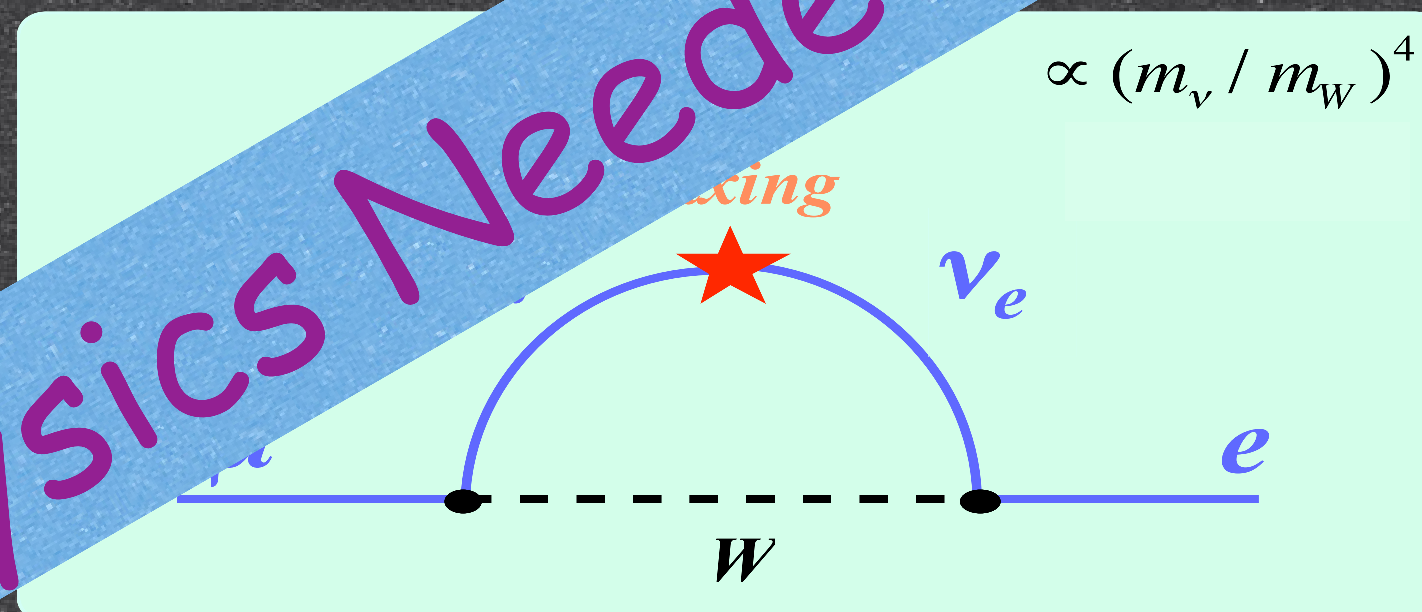
Not be observed yet !

Contribution to LFV from Neutrino Oscillation

Neutrino mixing has been established.

$$\nu_e = \nu_1 \cos\theta + \nu_2 \sin\theta$$

$$\nu_\mu = -\nu_1 \sin\theta + \nu_2 \cos\theta$$



New Physics Needed

Contribution

$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \sin^2\theta \cos^2\theta \frac{(m_1^2 - m_2^2)^2}{m_W^4}$$

Very Small (10^{-50})

High Energy Scale by Rare Decays

Normal Muon Decay

LFV decay

$$\frac{\Gamma(\mu \to eee)}{\Gamma(\mu \to e\nu\nu)} = \frac{G_X^2}{G_F^2} = \left(\frac{m_W}{m_X}\right)^4 \leq 10^{-12}$$

$$m_X \geq 10^3 m_W \approx 100 TeV (= 10^{15} eV)$$

Rare decay searches at low energy could access physics at high energy scale which cannot be reached by accelerators.

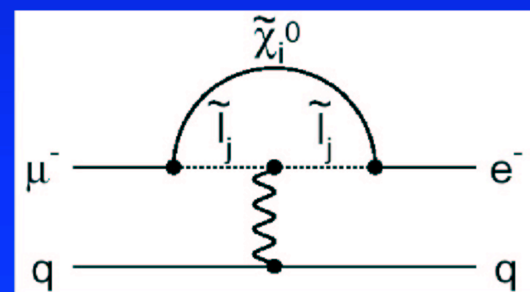
LFV Models beyond SM

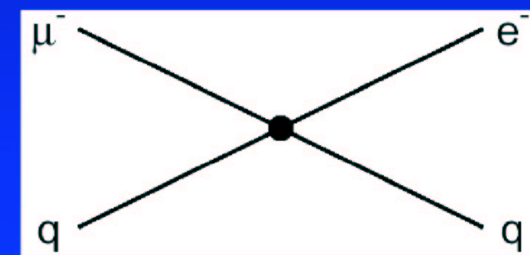
Sensitivity to Different Muon Conversion Mechanisms

MECO

Supersymmetry

Predictions at 10^{-15}





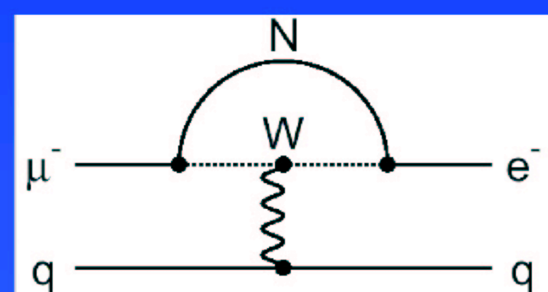
Compositeness

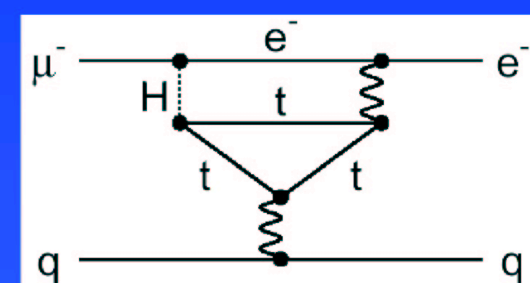
Λ_c = 3000 TeV

Heavy Neutrinos

$|U^*_{\mu N} U_{eN}|^2 =$

8×10^{-13}





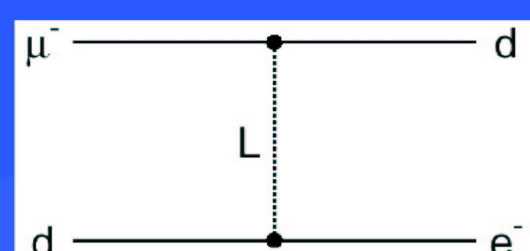
Second Higgs doublet

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

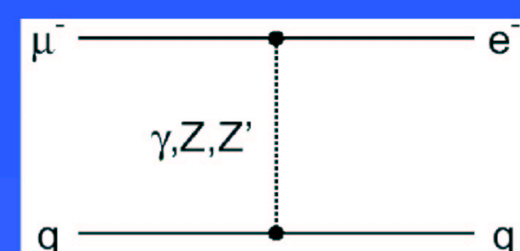
Leptoquarks

$M_L =$

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



After W. Marciano



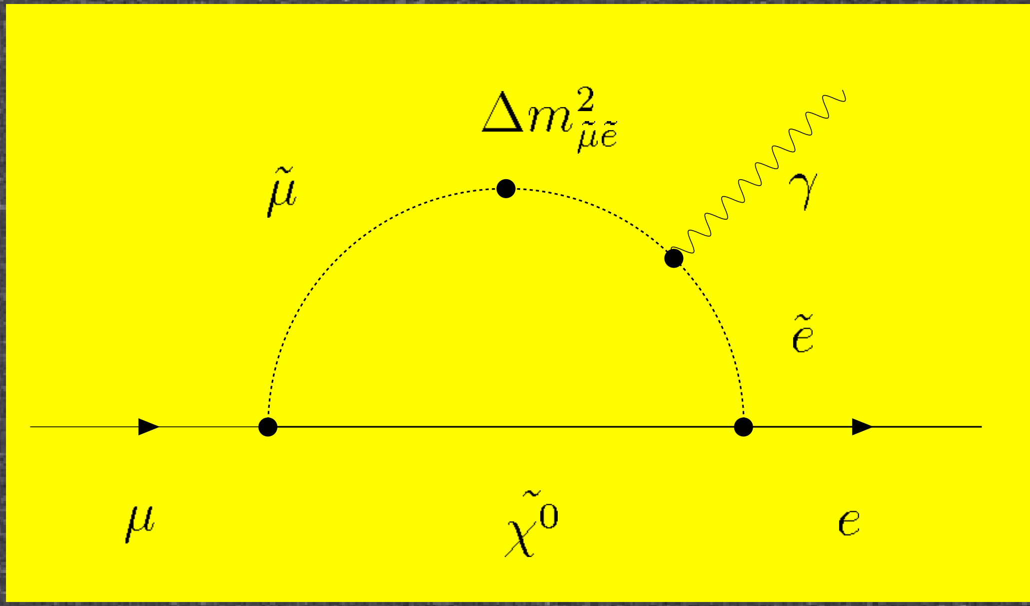
Heavy Z', Anomalous Z coupling

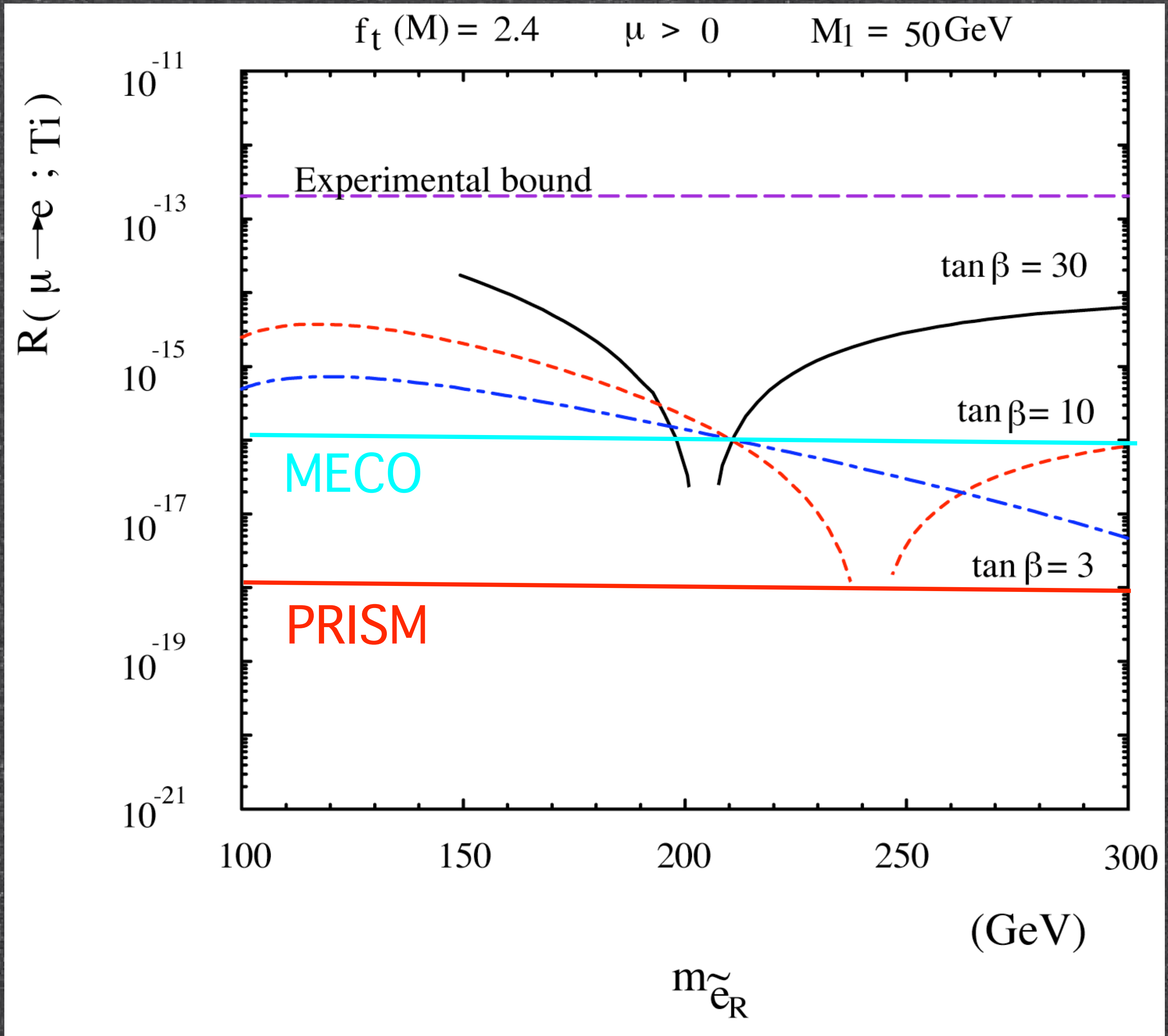
$M_{Z'}$ = 3000 TeV/c^2

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

SUSY-GUT

LFV induced from finite slepton mixing through radiative correction





- SUSY SU(5) predictions

  BR (μ→eγ) ≈ $10^{-14} \div 10^{-13}$

- SUSY SO(10) predictions

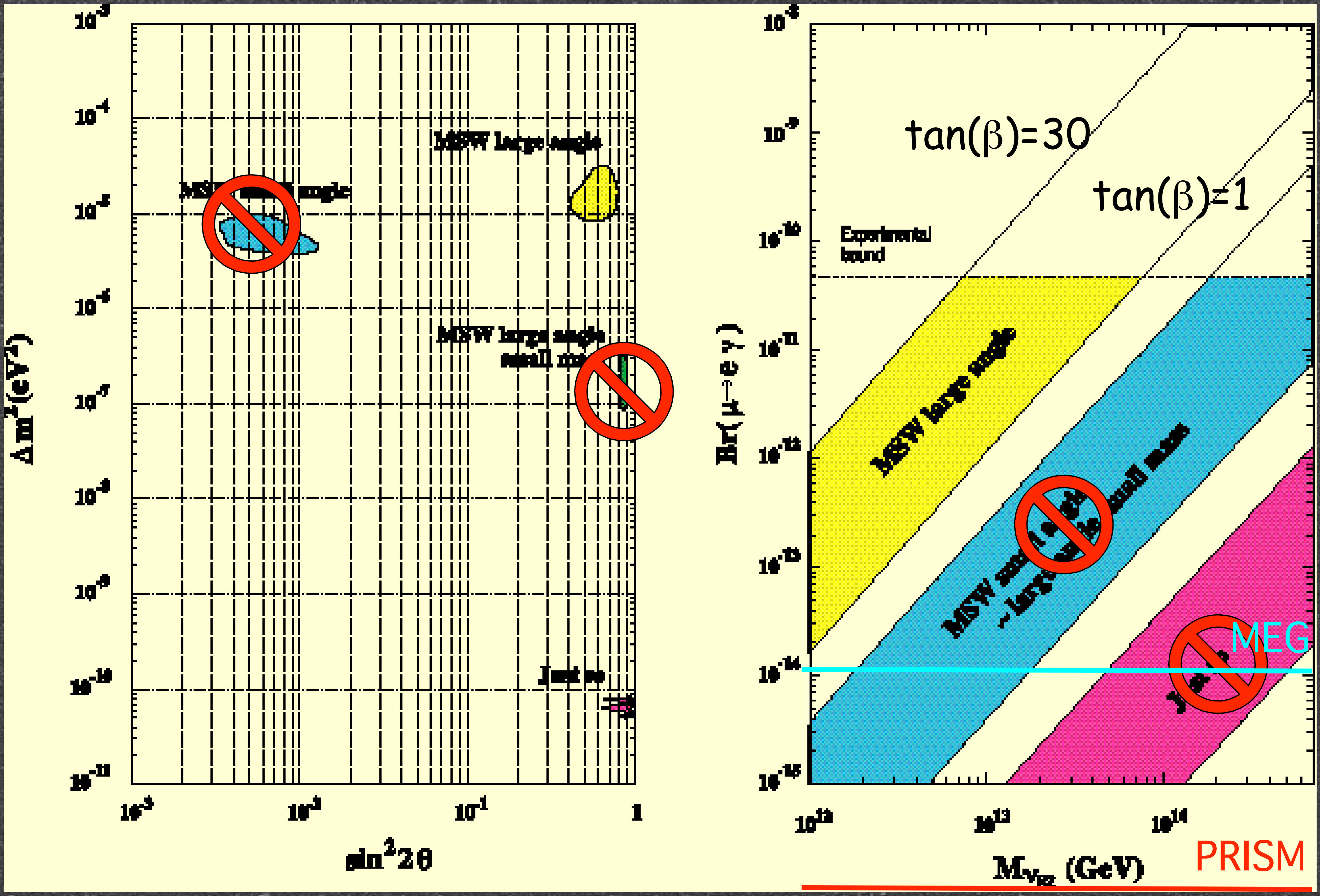
  $BR_{SO(10)} \approx 100\ BR_{SU(5)}$

R. Barbieri *et al.*, Phys. Lett. B338(1994) 212

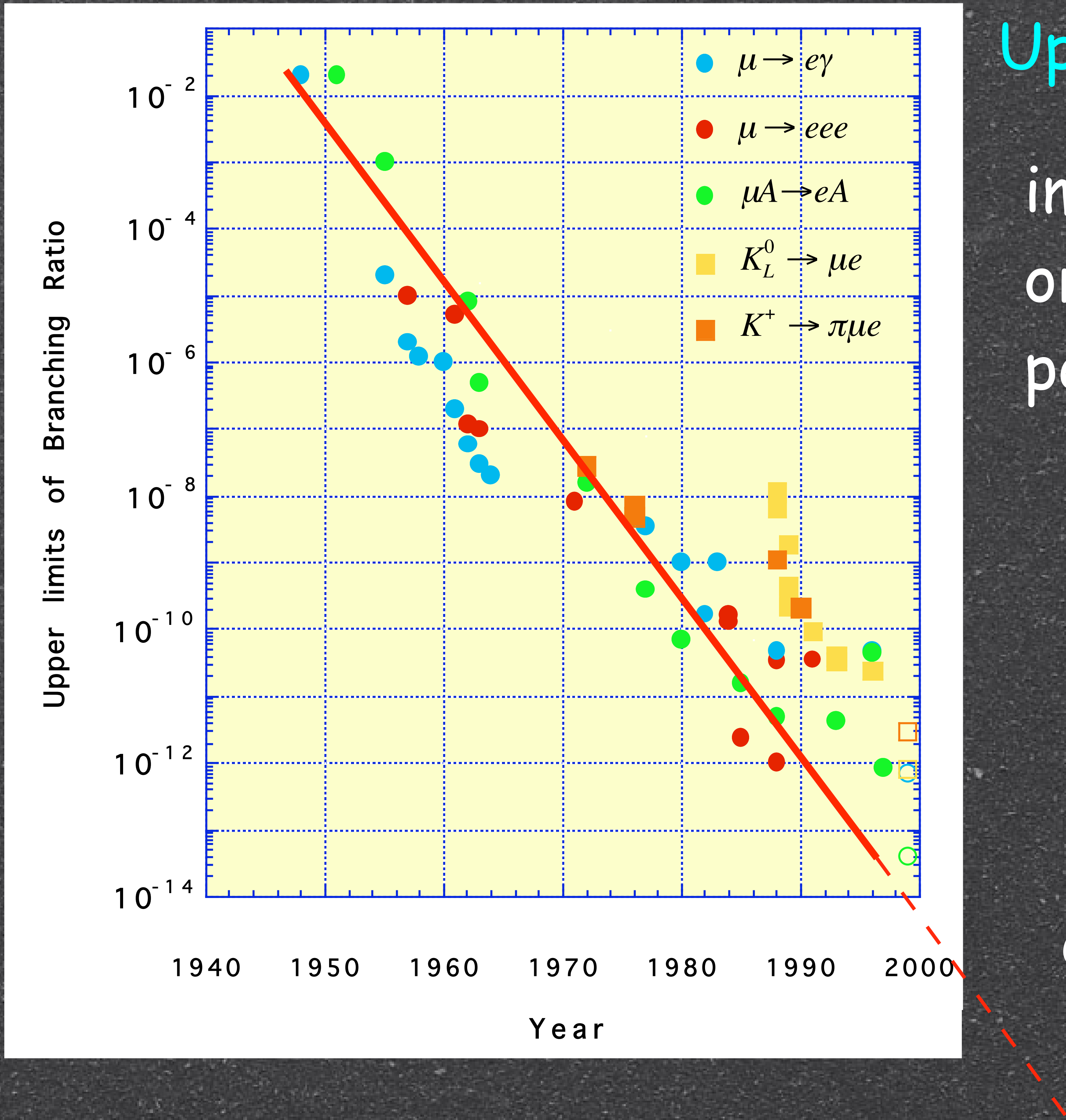
R. Barbieri *et al.*, Nucl. Phys. B445(1995) 215

MSSM with Seesaw Models

Neutrino Mixing→Slepton Mixing→Charged Lepton Mixing



History of LFV Searches



Upper limits of Searches

improved by two orders of magnitude per decade.

coming to

10^{-16} to 10^{-18}

Why Muon LFVs ?

Reaction	90 % CL upper limit
B($\mu^+ \to e\gamma$)	4.2×10^{-11}
B($\mu^+ \to e^+ e^- e^+$)	1.0×10^{-12}
B(μ Ti $\to e^-$Ti)	6.1×10^{-13}
B(μ^-Pb $\to e^-$Pb)	4.6×10^{-11}
B(μ^-Ti $\to e^+$Ca)	1.7×10^{-12}
B($\mu^+ e^- \to \mu^- e^+$)	$G_{MM} < 3 \times 10^{-3} G_F$
B($\tau \to e\gamma$)	2.7×10^{-6}
B($\tau \to \mu\gamma$)	3.0×10^{-6}
B($\tau \to \mu\mu\mu$)	1.9×10^{-6}
B($\tau \to eee$)	3.3×10^{-6}
B($K_L \to \mu e$)	5.0×10^{-11}
B($K^+ \to \pi^+ \mu^+ e^-$)	4.0×10^{-11}
B($K_L \to \pi^+ \mu^+ e^-$)	3.2×10^{-9}
B($D^0 \to \mu e$)	1.9×10^{-5}
B($D^0 \to \tau e$)	5.3×10^{-4}
B($D^0 \to \Phi\mu e$)	3.4×10^{-5}
B($B \to \mu e$)	5.9×10^{-6}
B($B \to K\mu e$)	1.8×10^{-5}
B($Z^0 \to \mu e$)	2.3×10^{-6}
B($Z^0 \to \tau e$)	7.3×10^{-6}
B($Z^0 \to \tau\mu$)	1.0×10^{-5}

beam will increase by 10^4

beam will increase by 10^2

The muon might be the best !

LFV Catalog

For the muons,

ΔL=1

- $\mu^+ \to e^+\gamma$
- $\mu^+ \to e^+e^+e^-$
- $\mu^- + N(A,Z) \to e^- + N(A,Z)$

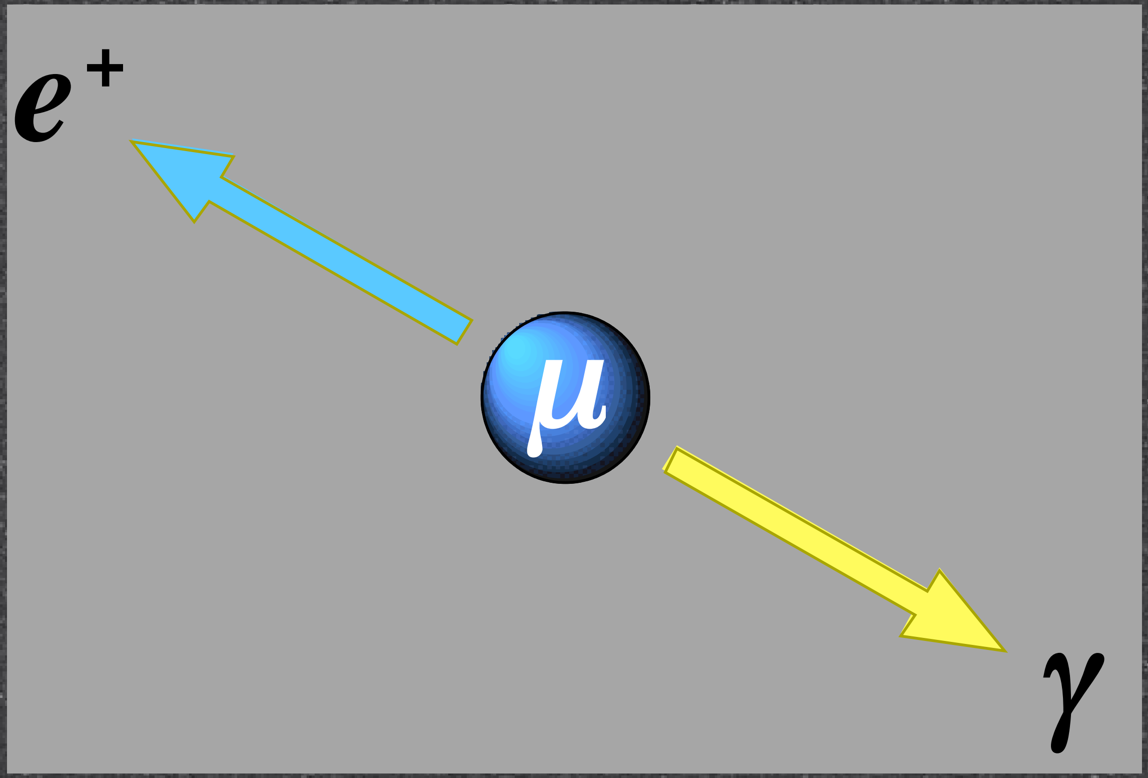
- $\mu^- + N(A,Z) \to e^+ + N(A,Z-2)$

ΔL=2

- $\mu^+e^- \to \mu^-e^+$
- $\mu^- + N(A,Z) \to \mu^+ + N(A,Z-2)$
- $\nu_\mu + N(A,Z) \to \mu^+ + N(A,Z-1)$
- $\nu_\mu + N(A,Z) \to \mu^+\mu^+\mu^- + N(A,Z-1)$

What is $\mu \rightarrow e\gamma$?

- Event Signature
  - $E_e = m_\mu/2$, $E_\gamma = m_\mu/2$ (=52.8 MeV)
  - angle $\theta_{e\gamma}$=180 degrees (back-to-back)
  - time coincidence

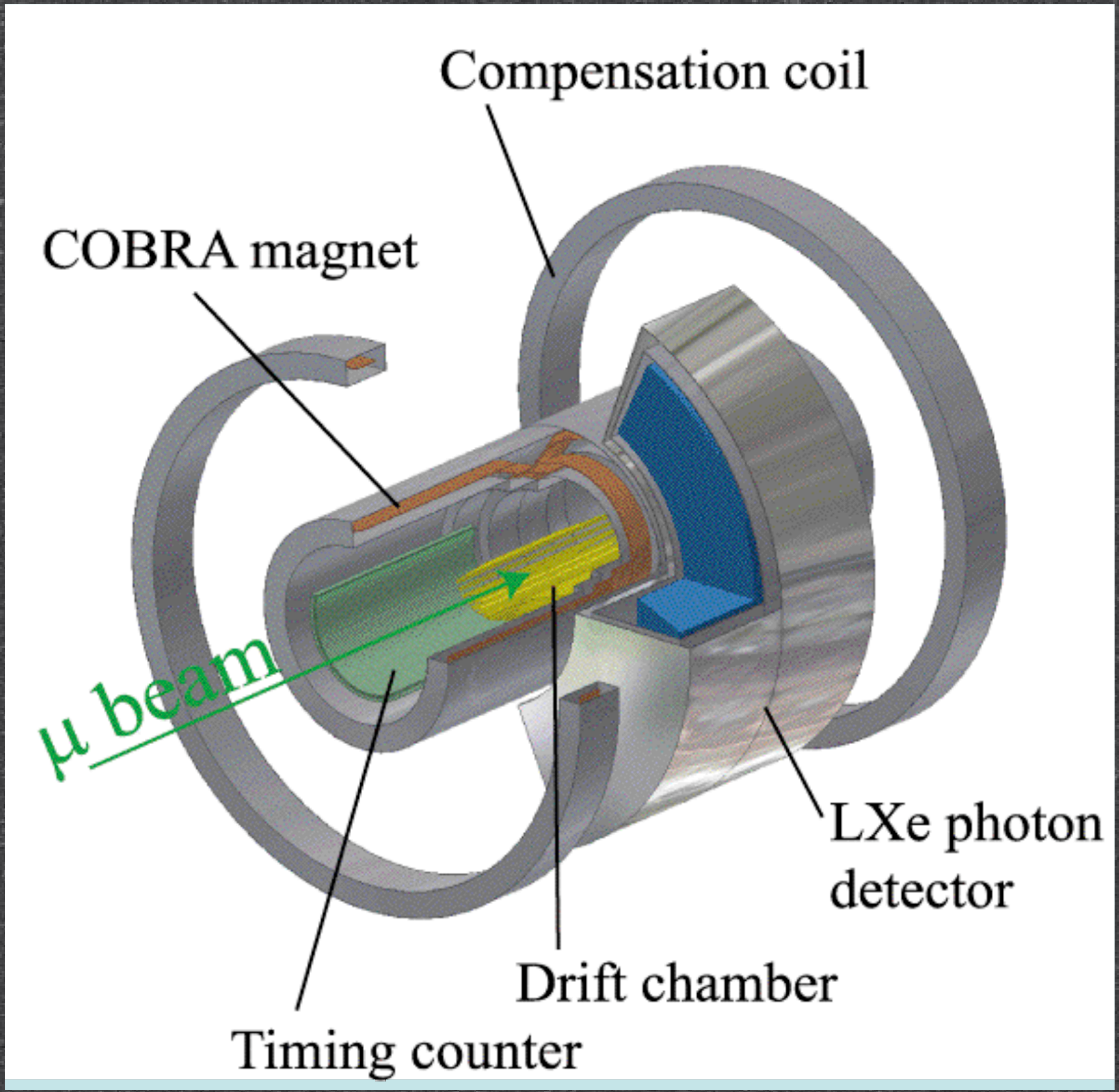


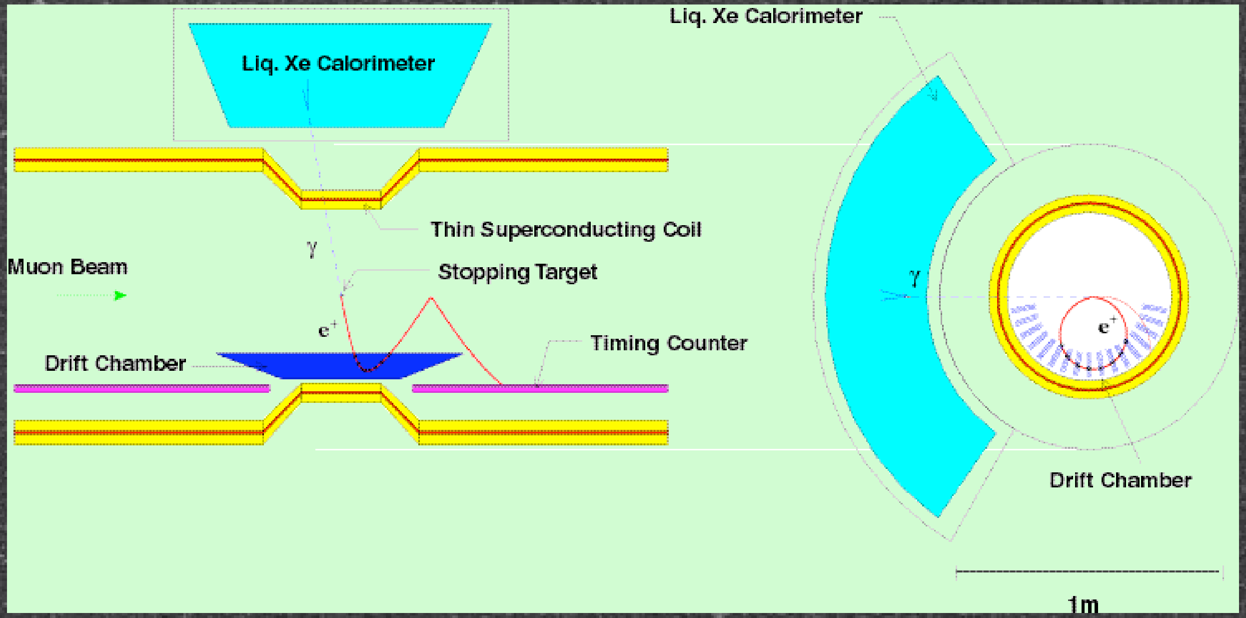
- Backgrounds
  - prompt physics background
    - radiative muon decay $\mu \rightarrow e\nu\nu\gamma$
      - when two neutrinos carry very small energies........
  - accidental background
    - positron e^+ in $\mu \rightarrow e\nu\nu$
    - photon γ in $\mu \rightarrow e\nu\nu\gamma$

      in e^+e^- annihilation in flight

MEG at PSI

- $\mu \rightarrow e\ \gamma$
  - MEG at PSI, 2004~
    - DC beam 10^8 μ/s
    - BR~10^{-13}
  - Accidental background
  - Detector Improvement
  - Polarization





Accidental Background

$$\text{Accidental Background} \propto \left(R_\mu\right)^2 \times \Delta E_e \times \left(\Delta E_\gamma\right)^2 \times \Delta t_{e\gamma} \times \left(\Delta\theta_{e\gamma}\right)^2$$

Place	Year	ΔE_e	ΔE_γ	$\Delta t_{e\gamma}$	$\Delta\theta_{e\gamma}$	R_μ	Upper Limit	References
SIN	1977	8.7%	9.3%	1.4 ns	-	5×10^5	$< 1.0 \times 10^{-9}$	A. Van der Schaaf, *et al.*, NP A340(1980)249
TRIUMF	1977	10%	8.7%	6.7 ns	-	2×10^5	$< 3.6 \times 10^{-9}$	P. Depommier *et al.*, PRL 39(1977)1113
LANL	1979	8.8%	8%	1.9 ns	37 mrad	2.4×10^6	$< 1.7 \times 10^{-10}$	W.W. Kinnison *et al.*, PR D25(1982)2846
Crystal Box	1986	8%	8%	1.8 ns	87 mrad	4×10^5	$< 4.9 \times 10^{-11}$	R.D. Bolton, *et al.*, PR D38(1988)2077
MEGA	1999	1.2%	4.5%	1.6 ns	17 mrad	2.5×10^8	$< 1.2 \times 10^{-11}$	M.L. Brooks, *et al.*, PRL 83(1999)1521
PSI	2004?	0.7%	1.4%	0.15 ns	12 mrad	10^8	$< 10^{-14}$	T. Mori, *et al.*, Research Proposal to PSI (1999)

$B_{\mu\to e\gamma} = 10^{-14}$

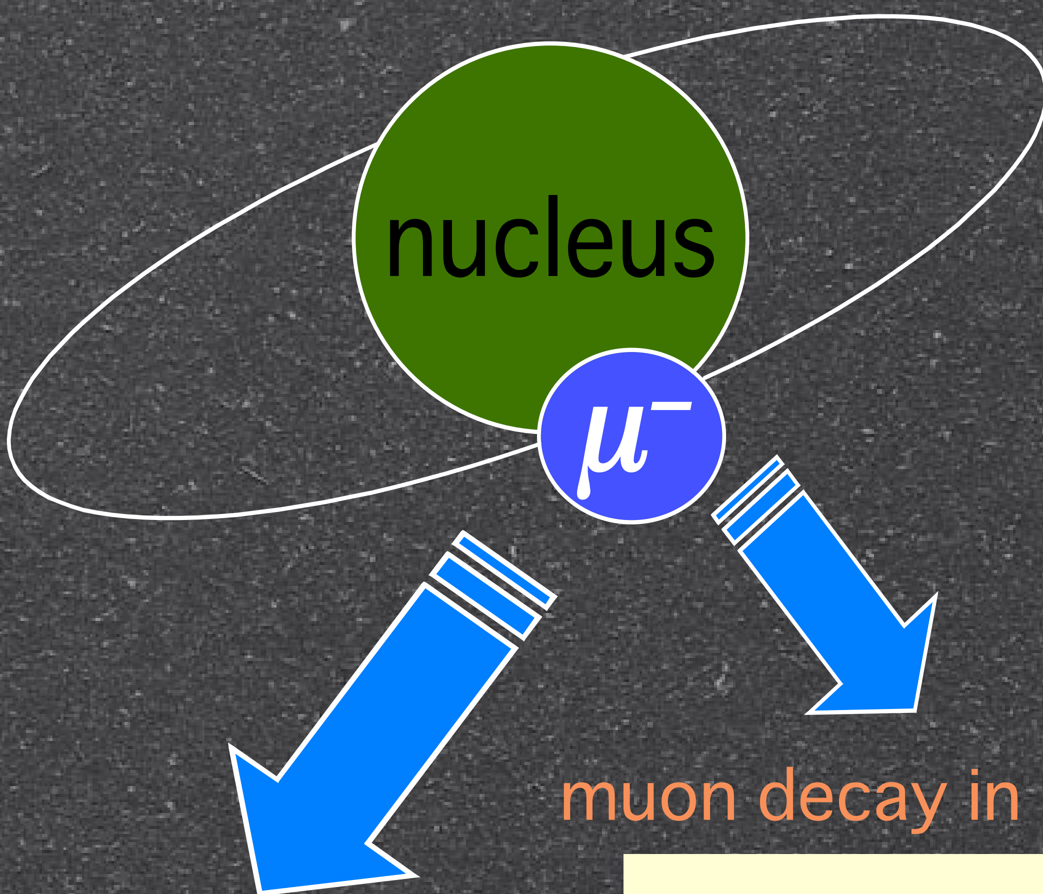
$N_b = 0.5$ events

$B_{\mu\to e\gamma} = 10^{-16}$

- $R_\mu = 10^{10}$ μ/s
- $N_b \sim 10^4$ events?

What is μ-e conversion?

1s state in a muonic atom



muon decay in orbit

$$\mu^- \rightarrow e^- \nu \bar{\nu}$$

nuclear muon capture

$$\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z-1)$$

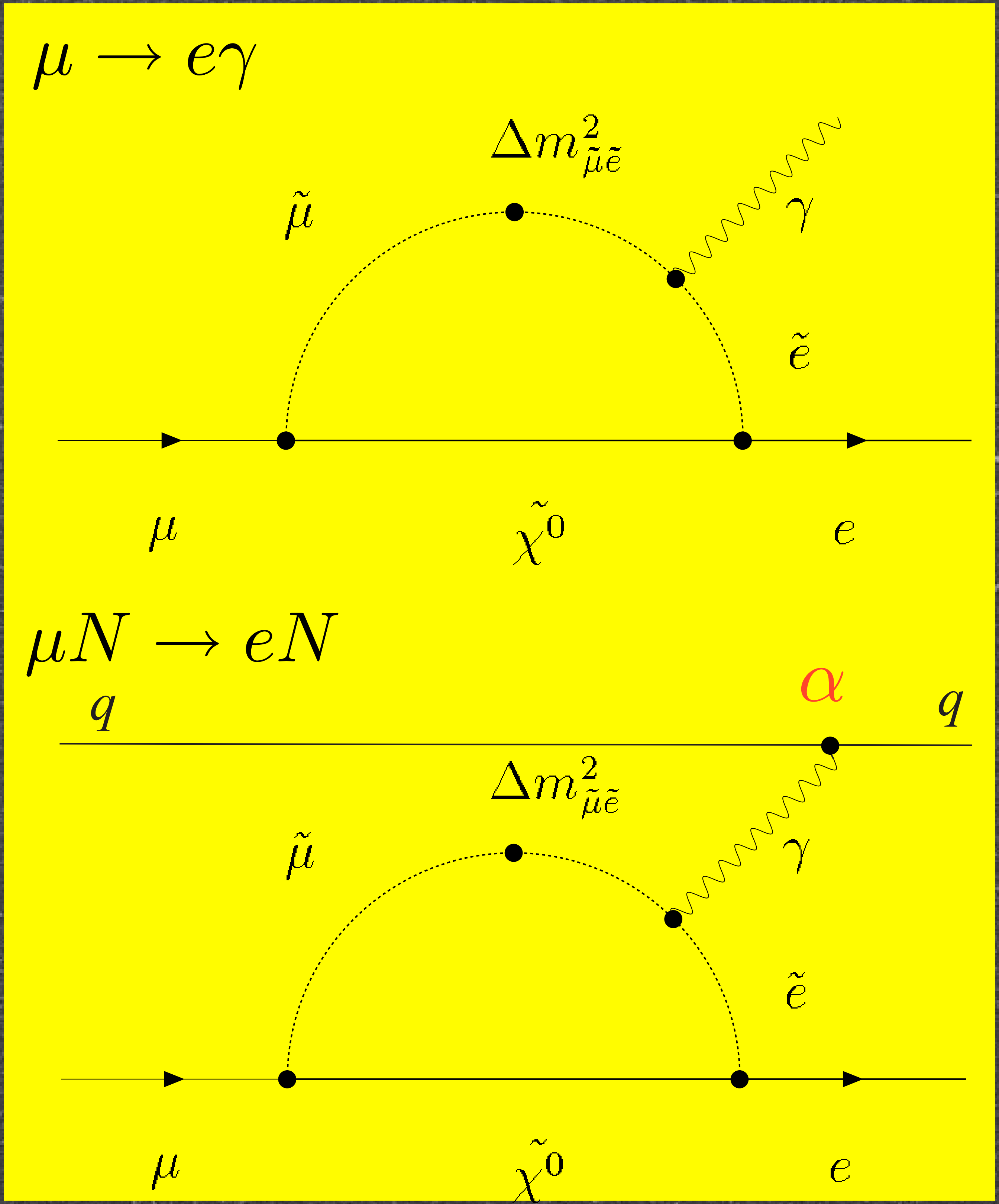
Neutrino-less muon nuclear capture (=μ-e conversion)

$$\mu^- + (A, Z) \rightarrow e^- + (A, Z)$$

lepton flavors changes by one unit.

$$B(\mu^- N \rightarrow e^- N) = \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \nu N')}$$

Photon-mediated LFV



$\mu - e$ conversion vs. $\mu \to e\gamma$

If photon-mediated,

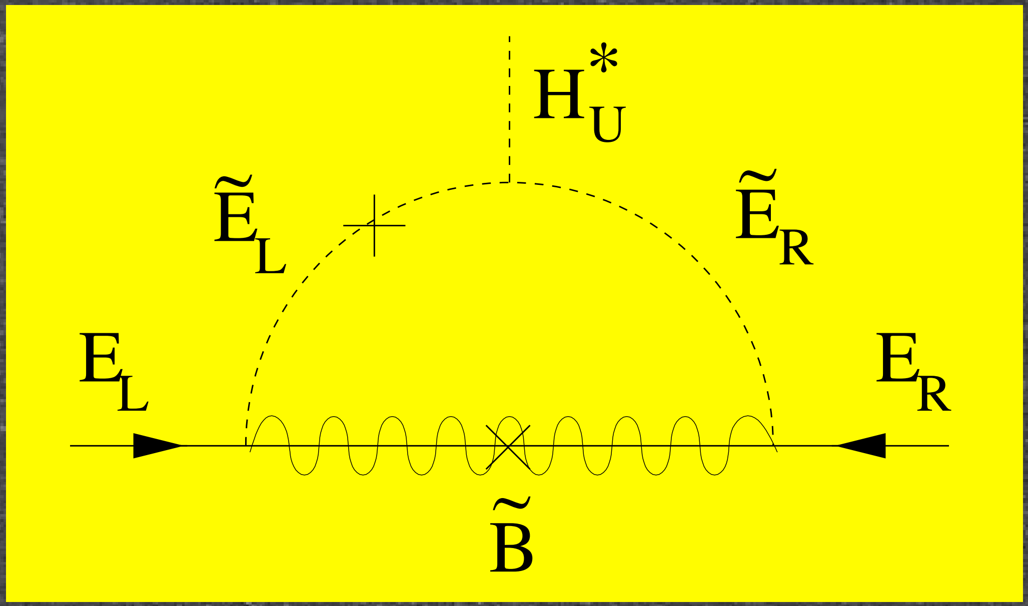
$$\frac{B(\mu N \to eN)}{B(\mu \to e\gamma)} \sim \frac{1}{100}$$

But, experimentally,

$\mu \to e\gamma$	$< 1.2 \times 10^{-11}$
$\mu N \to eN$	$< 6 \times 10^{-13}$

Higgs-mediated SUSY LFV

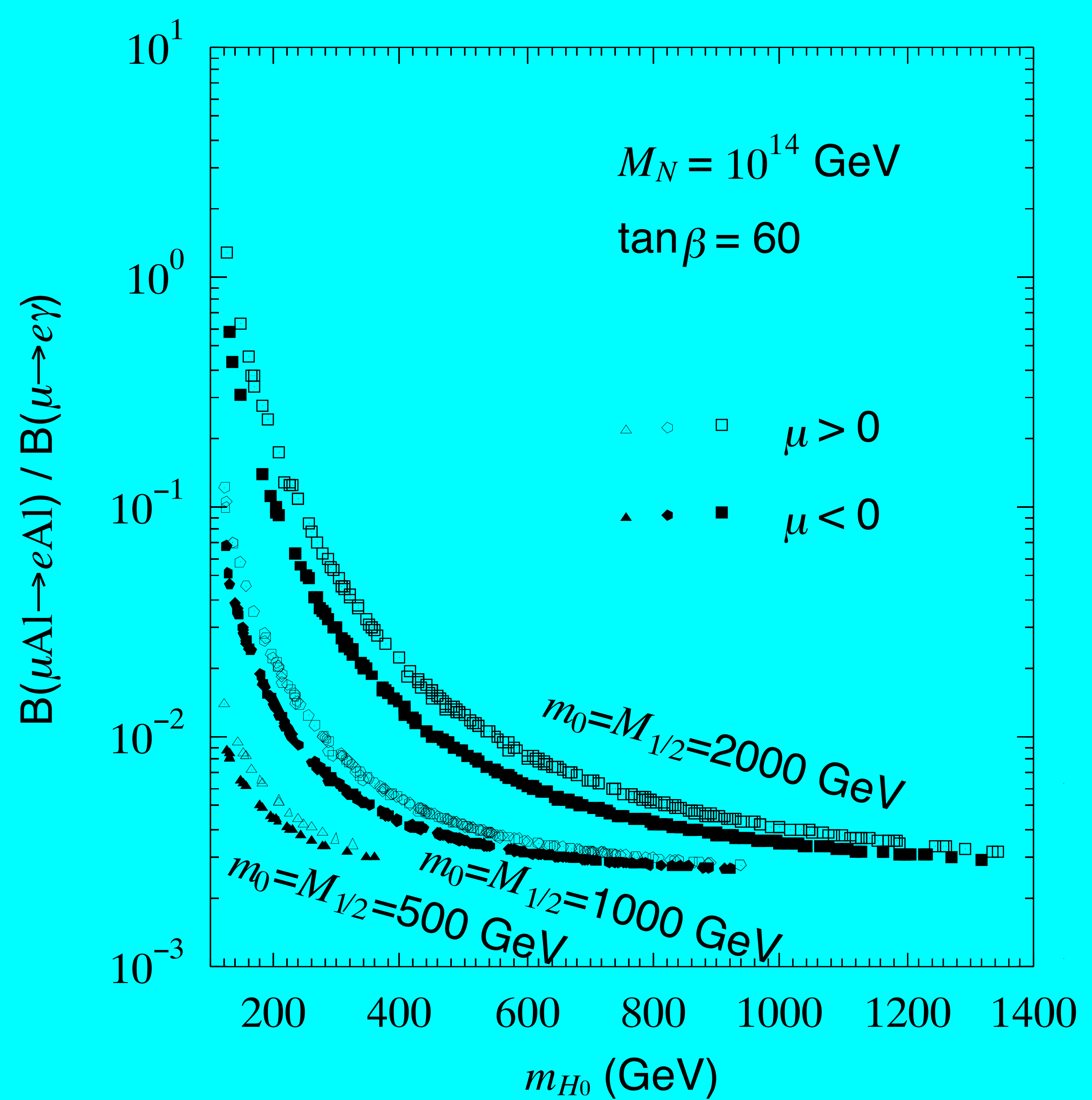
Higgs-exchange for LFV in SUSY Seesaw model



When H_0 mass is small, Higgs-mediated diagram contributes more.

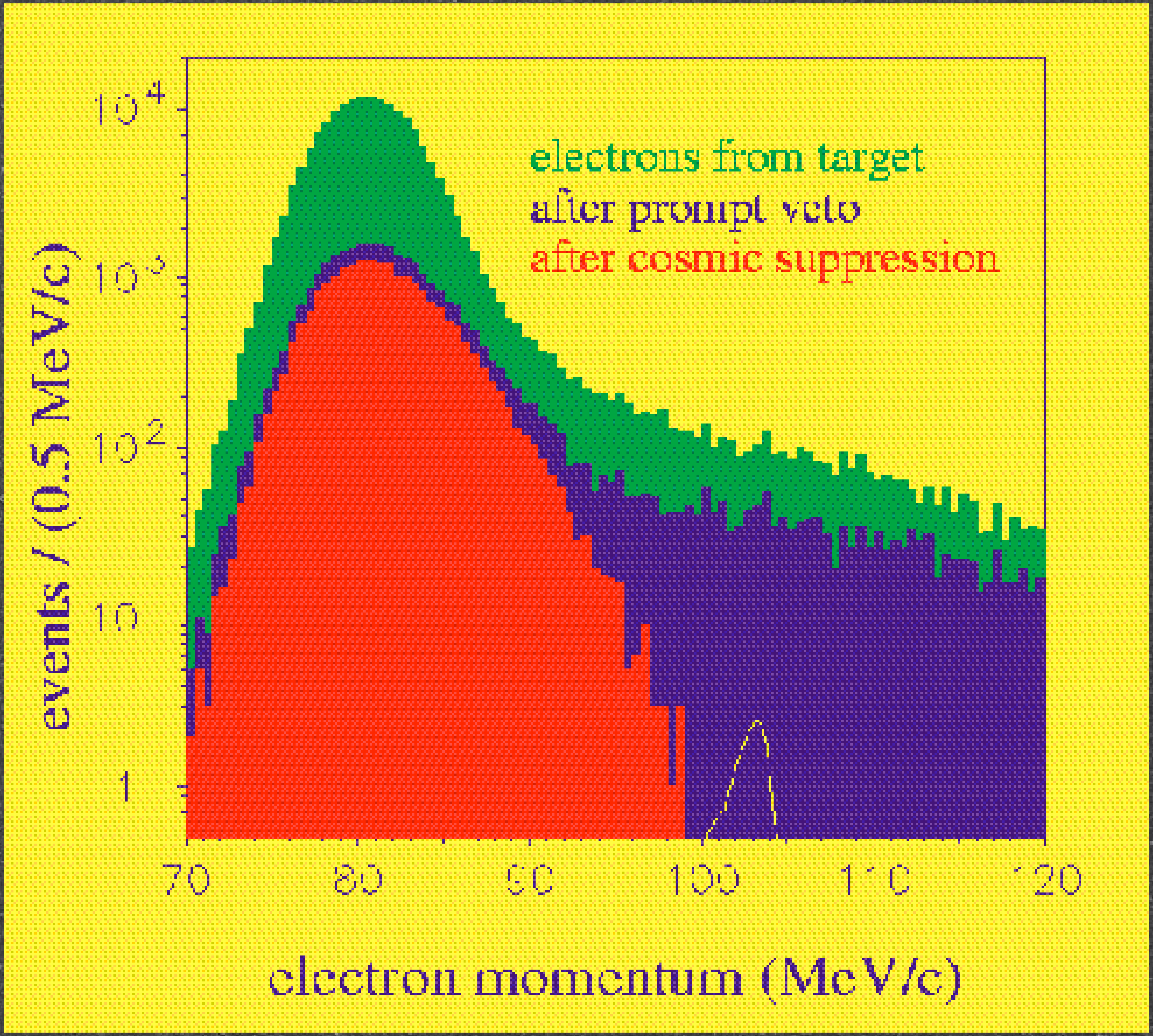
$$\frac{B(\mu N \to eN)}{B(\mu \to e\gamma)} \sim O(1)$$

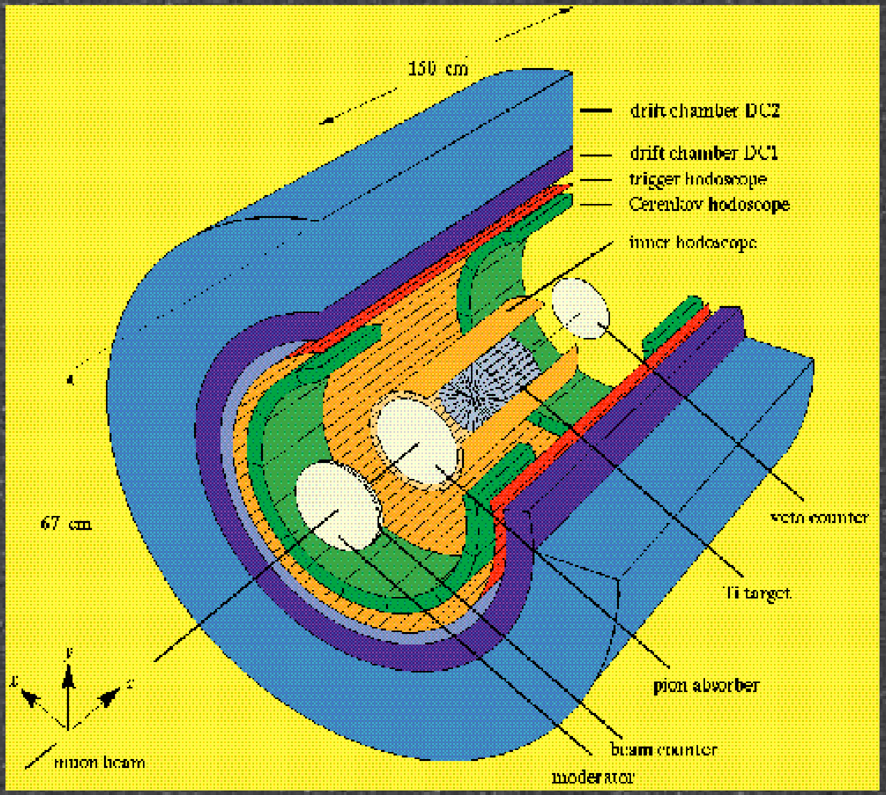
at $H_0 \sim 200$ GeV



Kitano, Koike, Komine, Okada

SINDRUM-II Results





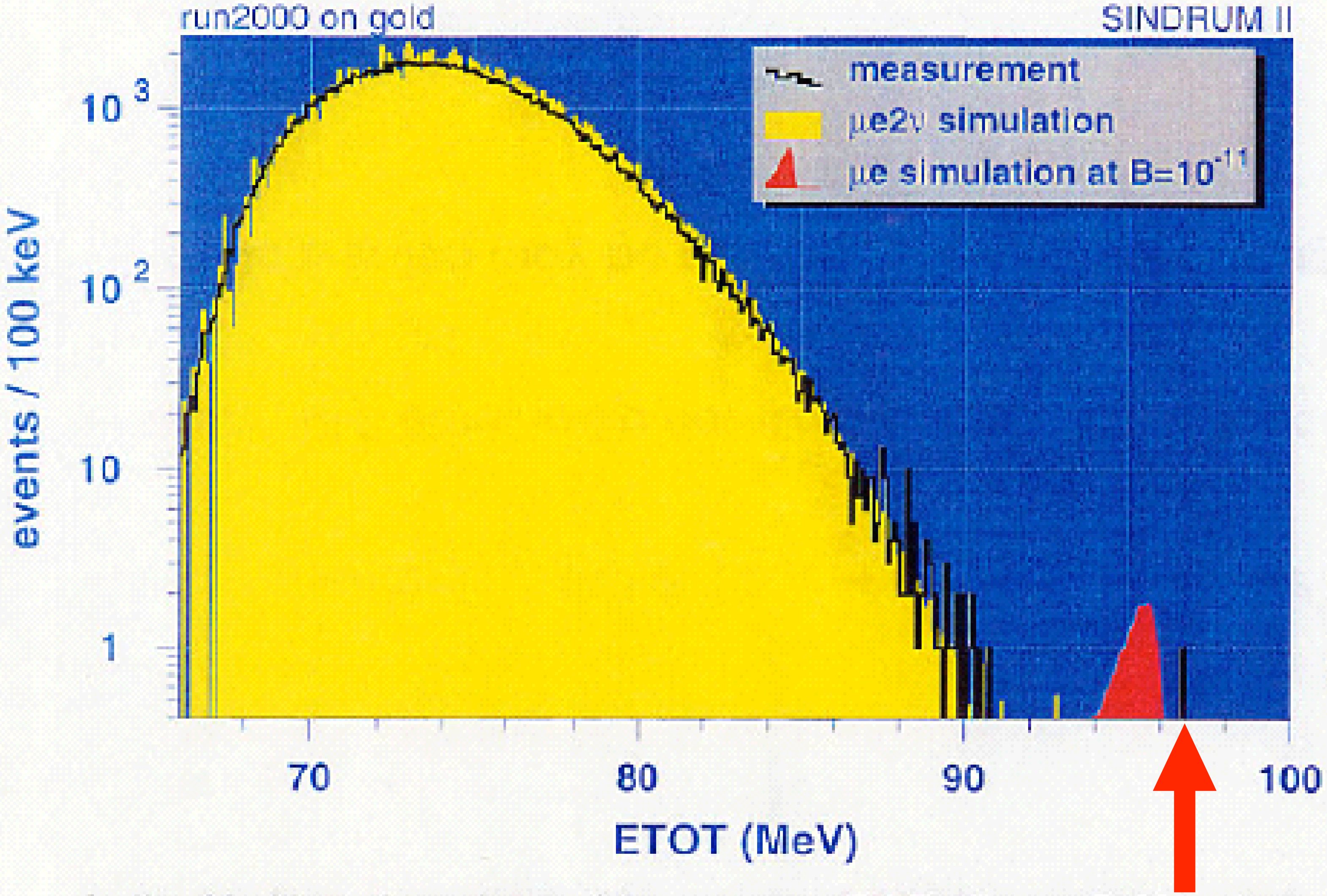
Sindrum-II
1993 result

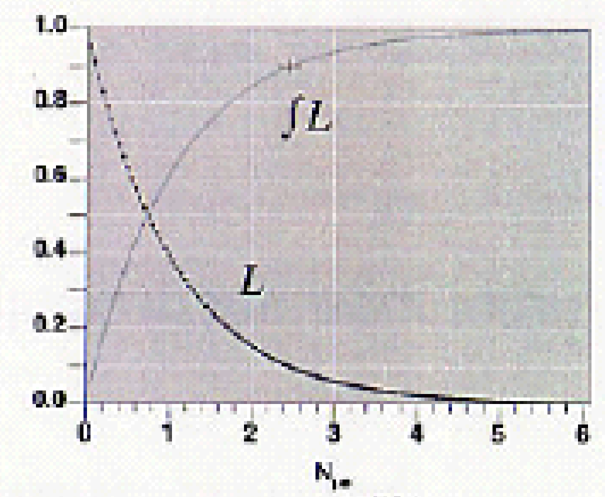
$$B(\mu^- + Ti \rightarrow e^- + Ti) < 6.1 \times 10^{-13}$$

SINDRUM-II Results

Final result

μe Conversion on Gold





$\mathcal{L}(N_{\mu e})$ and $\int_0^{N_{\mu e}^{max}} \mathcal{L}(n)dn.$

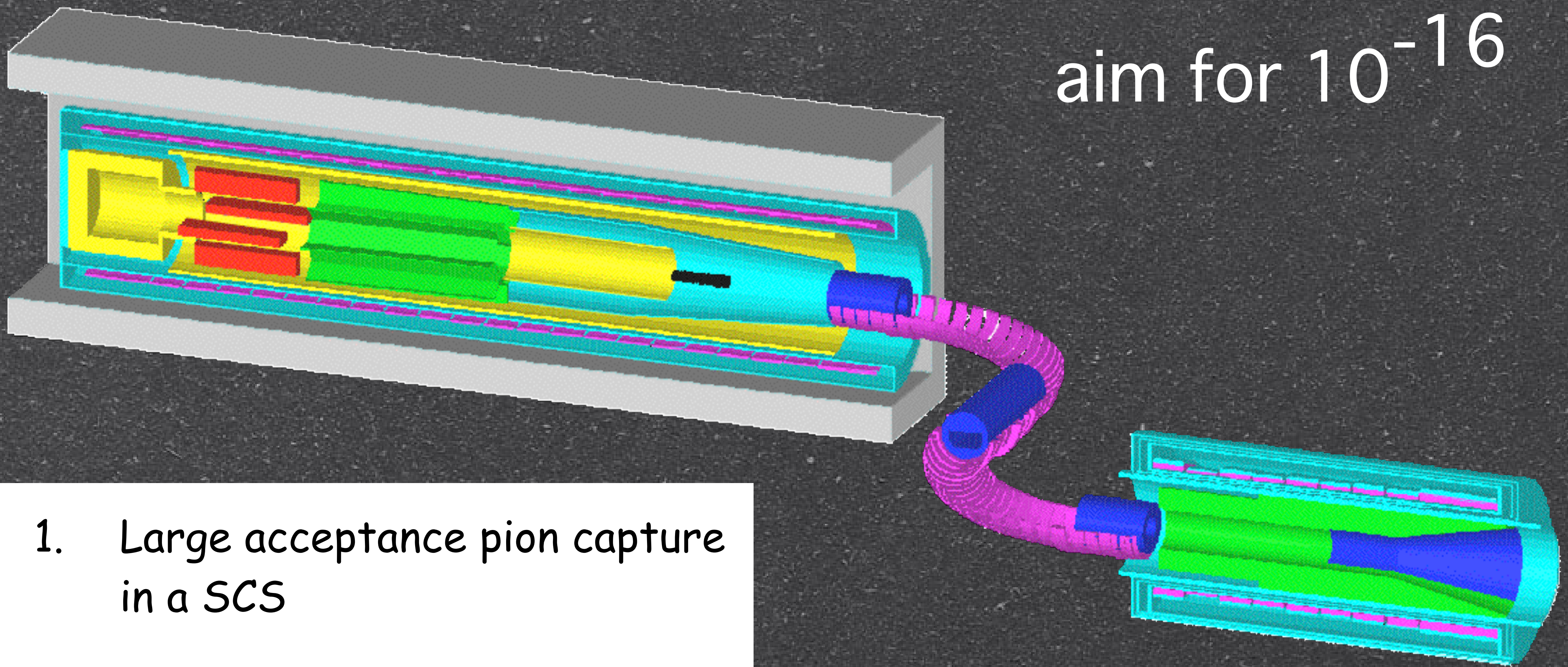
μ^- stops	$4.4 \pm 0.3 \times 10^{13}$
$f_{cap} \times \Omega \times \epsilon_{tot}$	7.0%
single event sensitivity	$3.3 \pm 0.2 \times 10^{-13}$
90% C.L. limit	2.45 events

In the likelihood analysis of the energy distribution a flat background from cosmic rays and radiative pion capture was allowed.

Result: $B_{\mu e}^{\text{gold}} < 8 \times 10^{-13}$ 90% C.L.

MECO at BNL

aim for 10^{-16}



1. Large acceptance pion capture in a SCS
2. Muon transport (60 – 120 MsV/c) in a curved solenoid
3. Long detector solenoid with muon stpping target and tracking system

R&D money in US-FY2004.
Construction money in US-FY2006.

Which Muon LFV Process Next ?

	issue	beam requirement
$\mu \longrightarrow e\gamma$	detector-limited	a continuos beam
$\mu \longrightarrow eee$	detector-limited	a continuos beam
$\mu N \longrightarrow eN$	beam-limited	a pulsed beam