μ-e Conversion and PRISM

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Nufact'00 Workshop
Monterey

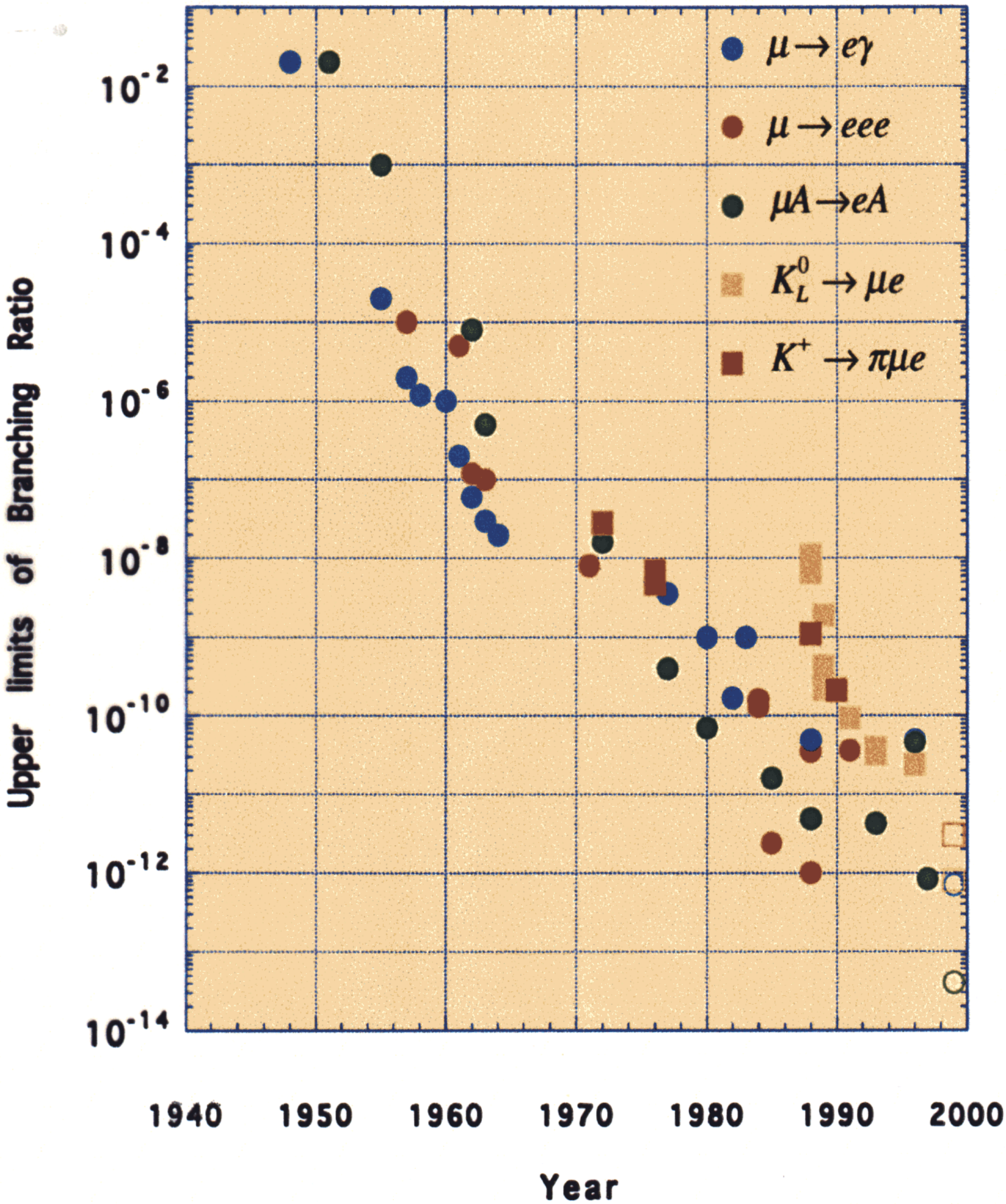
Outline

muon LFV = muon lepton flavor violation

- ***Why, Muon LFV?***
  - *physics motivation*
- ***What is μ-e conversion ?***
- ***PRISM***
  - *a high intensity low-energy muon source*
- ***How, μ-e conversion with PRISM ?***
  - *Basic idea (no detailed simulation yet.)*
- ***Summary***


Why, Muon LFV?

History of LFV Searches

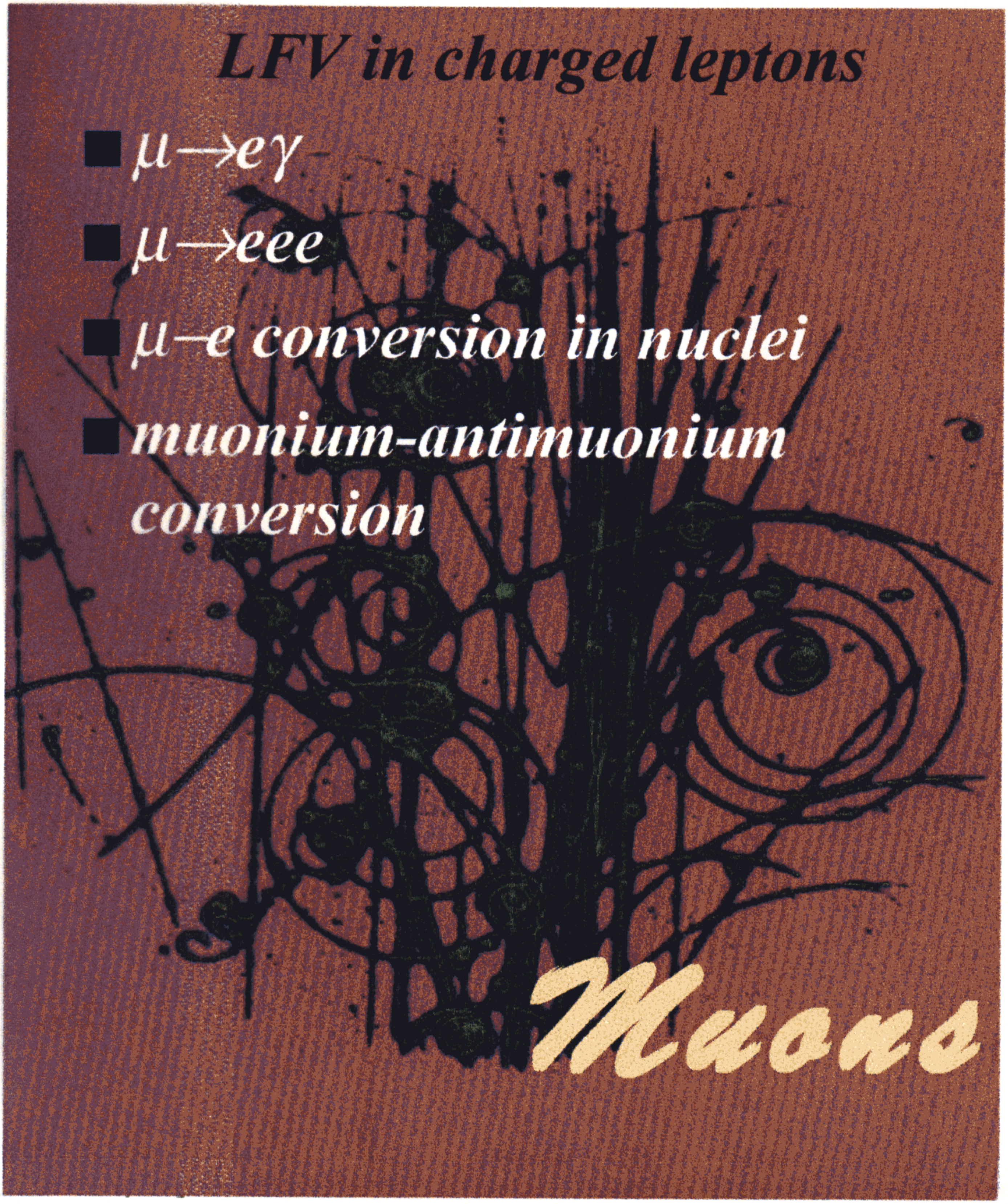


Recent Limits of LFV Searches

Reaction	90 % CL upper limit
$B(\mu^+ \to e\gamma)$	1.2×10^{-11}
$B(\mu^+ \to e^+e^-e^+)$	1.0×10^{-12}
$B(\mu^- Ti \to e^- Ti)$	6.1×10^{-13}
$B(\mu^- Pb \to e^- Pb)$	4.6×10^{-11}
$B(\mu^- Ti \to e^+ Ca)$	1.7×10^{-12}
$B(\mu^+ e^- \to \mu^- e^+)$	8.3×10^{-11}
$B(\tau \to e\gamma)$	2.7×10^{-6}
$B(\tau \to \mu\gamma)$	3.0×10^{-6}
$B(\tau \to \mu\mu\mu)$	1.9×10^{-6}
$B(\tau \to eee)$	2.9×10^{-6}
$B(K_L \to \mu e)$	4.7×10^{-12}
$B(K^+ \to \pi^+\mu^+e^-)$	2.1×10^{-10}
$B(K_L \to \pi^+\mu^+e^-)$	3.1×10^{-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}
$B(Z^0 \to \mu e)$	1.7×10^{-6}
$B(Z^0 \to \tau e)$	9.8×10^{-6}
$B(Z^0 \to \tau\mu)$	1.2×10^{-5}

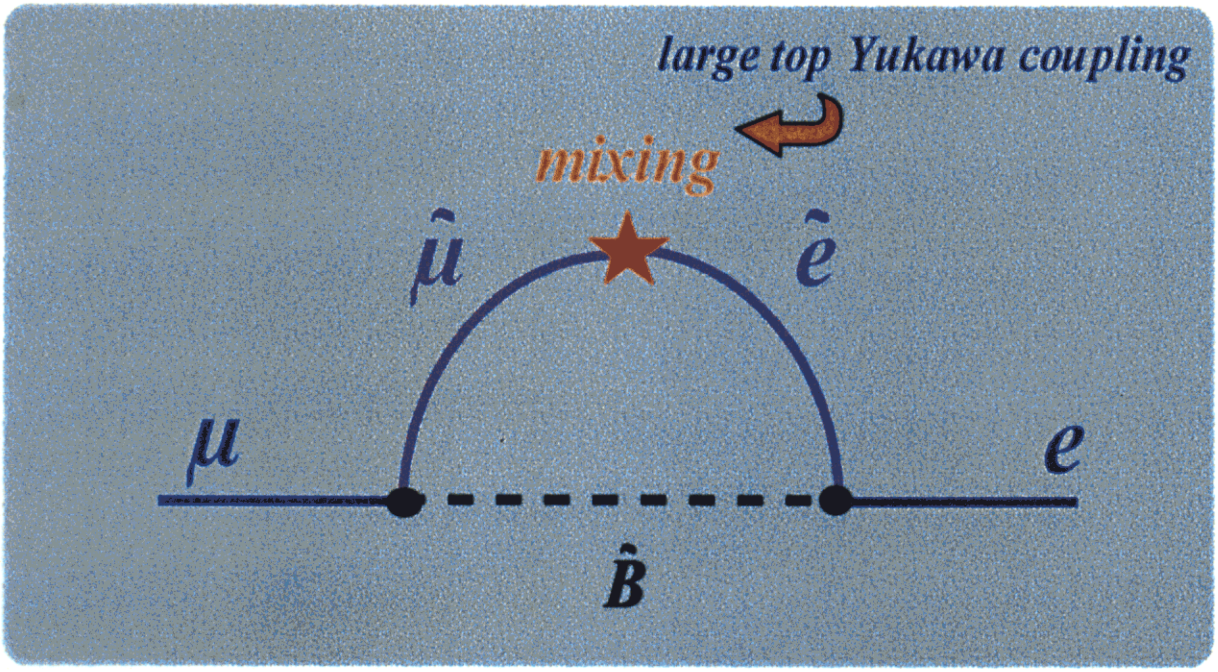
Updated in June, 1999

LFV with low-energy muons



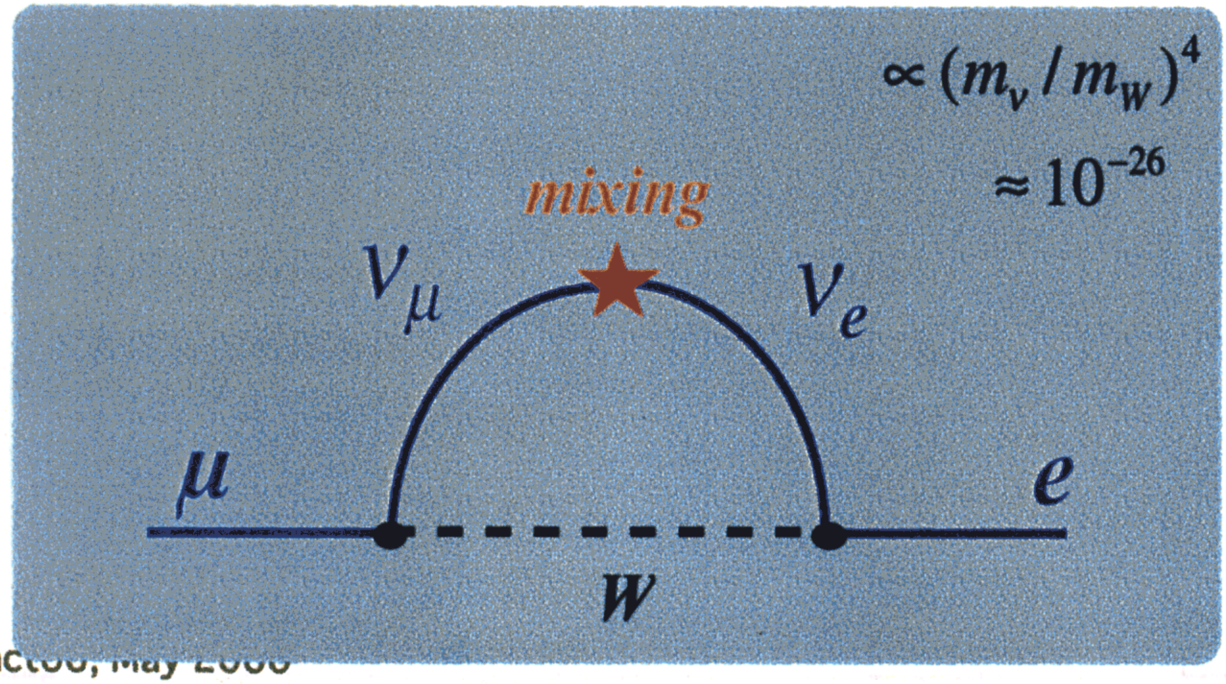
$\mu \rightarrow e\gamma$ at SUSY-GUT

LFV diagram in SUSY-GUT



LFV diagram in Standard Model

mixing in massive neutrinos



$\mu \to e\gamma$ and μ-e conv. in SUSY-GUT

$\mu \to e\gamma$

SU(5) :

$$\Gamma(\mu \to e\gamma) \approx \frac{\alpha}{4} |F_2|^2 \frac{m_\mu^5}{m_{\tilde{\mu}}^4}$$

$$F_2 \propto (\Delta m^2)_{\mu e} \approx -V_{31}^* V_{32} I(y_t)$$

LFV mixing in right-handed sleptons

SO(10) :

$$\Gamma(\mu \to e\gamma)_{SO(10)} \approx \left(\frac{m_\tau}{m_\mu}\right)^2 \Gamma(\mu \to e\gamma)_{SU(5)}$$

LFV mixing in right-handed and left-handed sleptons

$\mu \to e$ conv.

$$\Gamma(\mu \to e) \approx 16\alpha^4 Z^5 |F_3(q)|^2 \, \Gamma(\mu \to e\gamma)$$

$$B(\mu \to e) \approx (1/200) \times B(\mu \to e\gamma)$$

for photonic diagrams

photonic diagram dominates

$\tau \to \mu\gamma$

$$B(\tau \to \mu\gamma) \approx 10^4 \times B(\mu \to e\gamma)$$

R. Barbieri, L. Hall, A.Strumia, Nucl. Phys. B445(1995)219

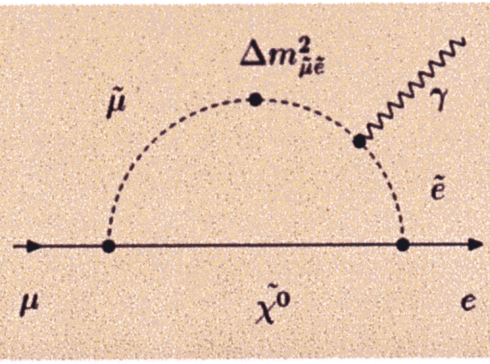
J.Hisano,T.Moroi,K.Tobe,M.Yamaguchi, Phys. Lett. B391 (1997) 341

Flavor Physics at 50-GeV PS

- ***flavor mixing***
  - *nondiagonal elements of the mass matrices*

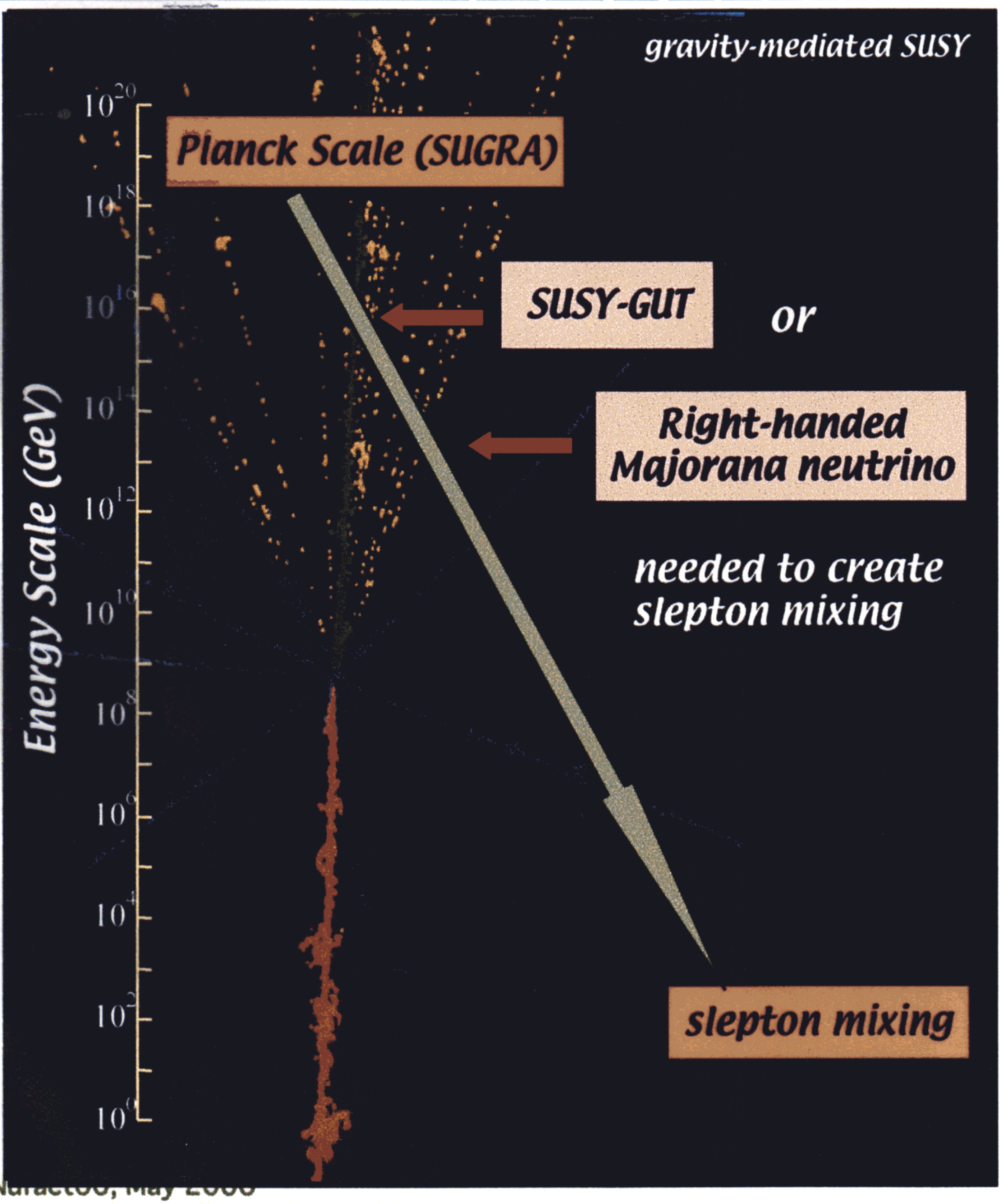
normal particles	SUSY particles
quark	squark
$\begin{pmatrix} m_d & & \\ & m_s & \\ & & m_b \end{pmatrix}$ ex. K-decays, B-decays	$\begin{pmatrix} m_{\tilde d} & & \\ & m_{\tilde s} & \\ & & m_{\tilde b} \end{pmatrix}$
lepton (neutrino)	slepton
$\begin{pmatrix} m_{\nu_e} & & \\ & m_{\nu_\mu} & \\ & & m_{\nu_\tau} \end{pmatrix}$ ex. neutrino oscillation	$\begin{pmatrix} m^2_{\tilde e\tilde e} & \Delta m^2_{\tilde e\tilde\mu} & \Delta m^2_{\tilde e\tilde\tau} \\ \Delta m^2_{\tilde\mu\tilde e} & m^2_{\tilde\mu\tilde\mu} & \Delta m^2_{\tilde\mu\tilde\tau} \\ \Delta m^2_{\tilde\tau\tilde e} & \Delta m^2_{\tilde\tau\tilde\mu} & m^2_{\tilde\tau\tilde\tau} \end{pmatrix}$ ex. charged lepton LFV

μ-e transition diagram



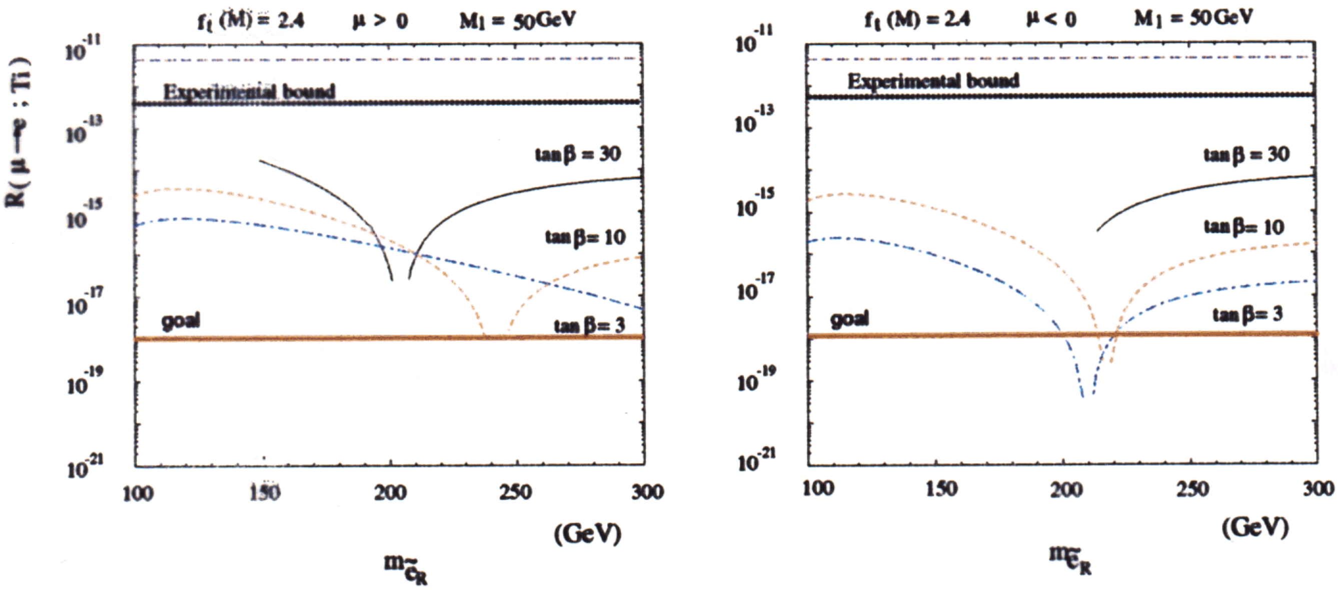
sensitive to slepton mixing

Slepton Mixing and new Physics



SUSY-GUT Prediction on μ-e conversion

- **SU(5) SUSY-GUT prediction**

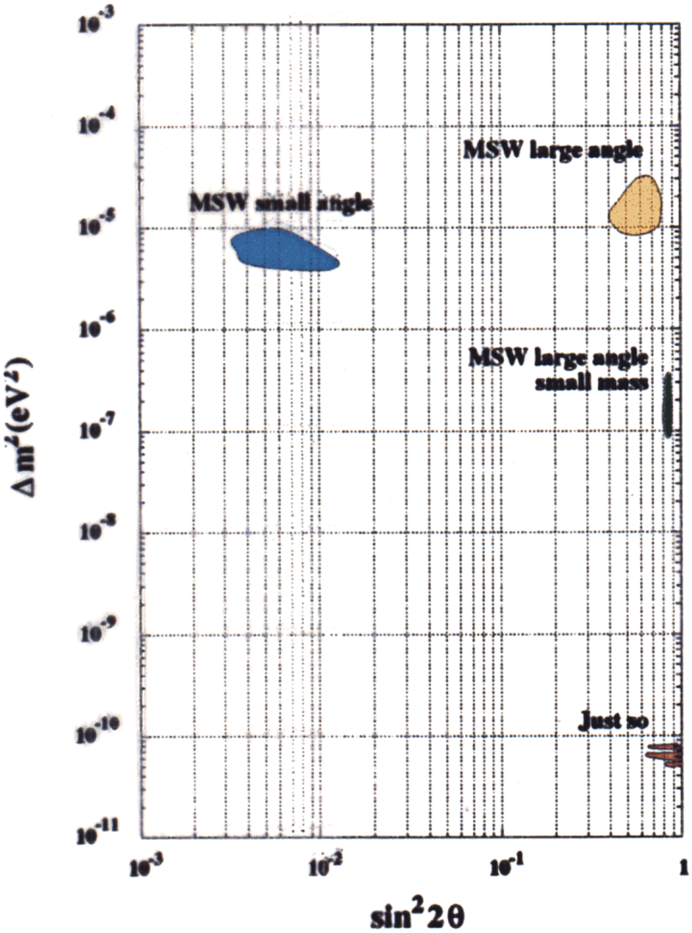


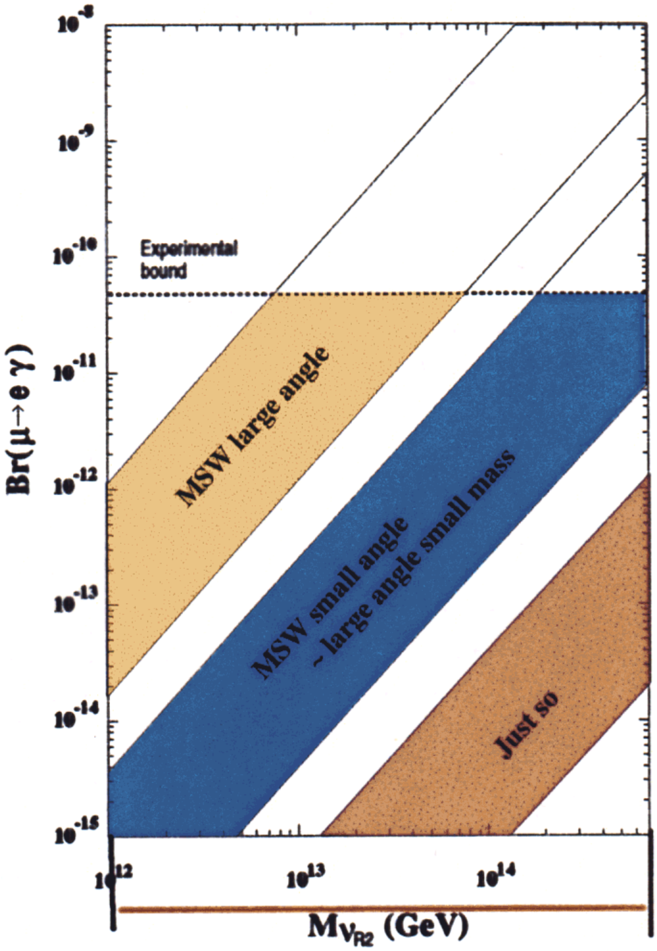
a la J.Hisano

- **SO(10) SUSY-GUT prediction**
  - *enhanced by $(m_\tau/m_\mu)^2$ (=100) from SU(5) prediction*

SUSY with Right-handed Majorana neutrino

- ***MSSM with right-handed*** ν





- $$\frac{B(\mu^- + Ti \to e^- + Ti)}{B(\mu^+ \to e\gamma)} \approx \frac{1}{230}$$

$B(\mu \to e\gamma) \sim 2 \times 10^{-16}$ equivalent

a la Nomura and Hisano

Review on Muon Decay and Muon LFV

KEK preprint 99-69
KEK-TH-639
August 1999
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Muon Decay and Physics Beyond the Standard Model

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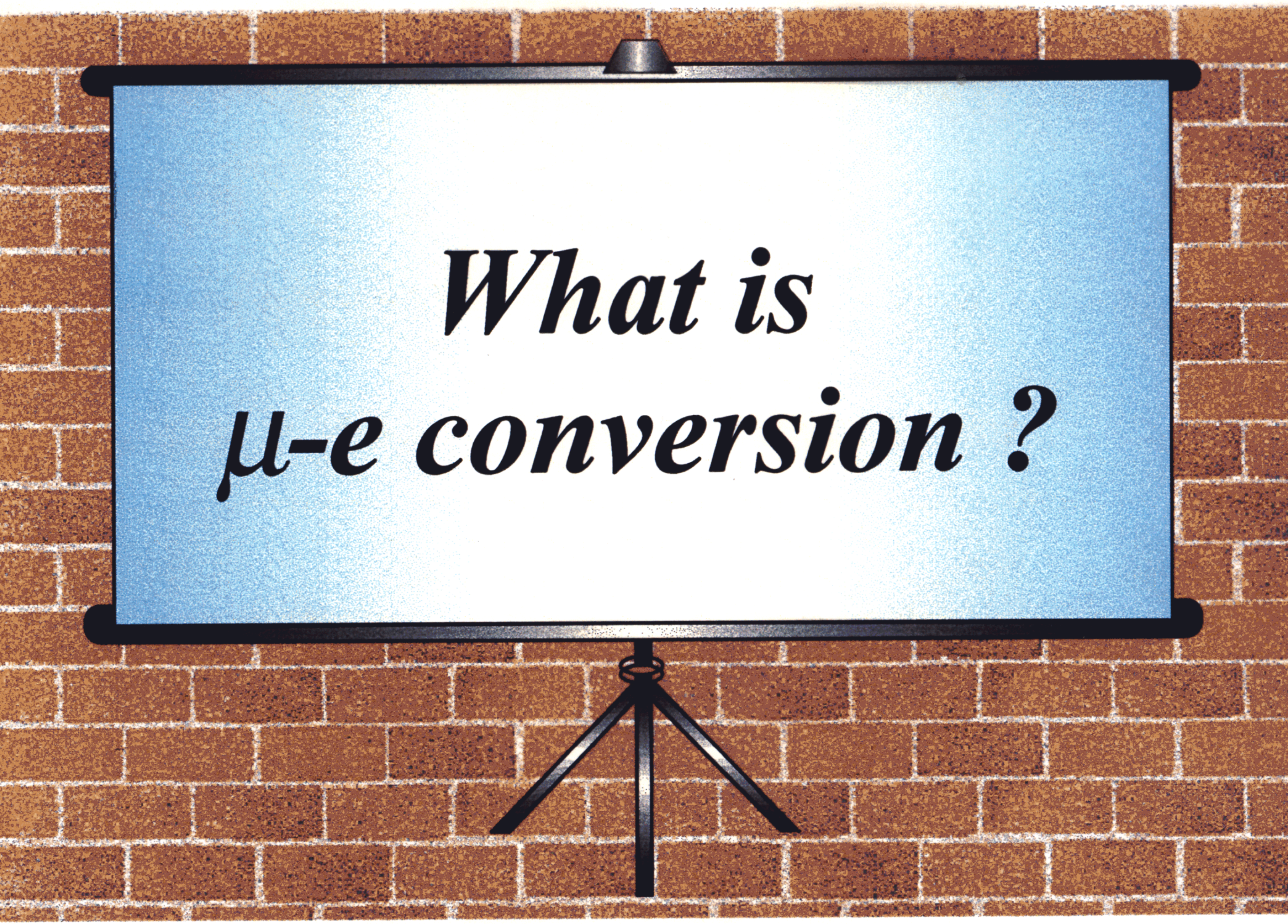
Abstract

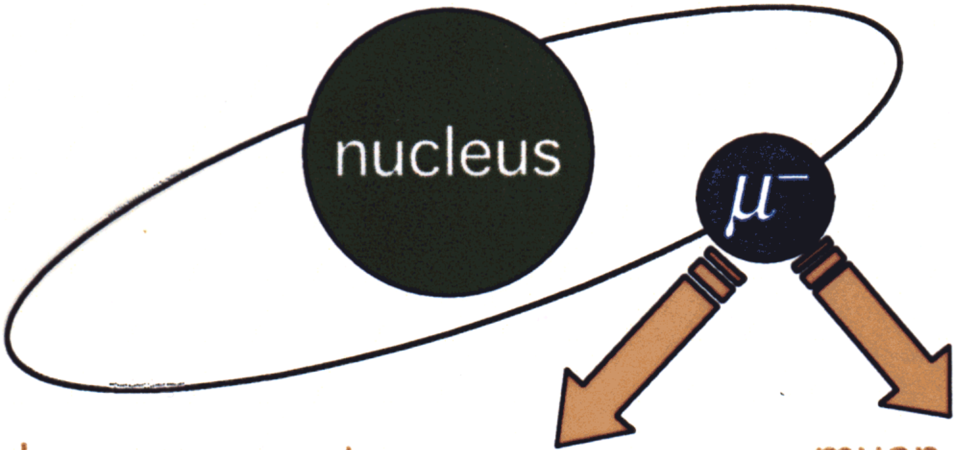
This article reviews the current theoretical and experimental status of the field of muon decay and its potential to search for new physics beyond the Standard Model. The importance of rare muon processes with lepton flavor violation is highly stressed, together with precision measurements of normal muon decay. Recent up-to-date motivations of lepton flavor violation based on supersymmetric models, in particular supersymmetric grand unified theories, are described along with other theoretical models. Future prospects of experiments and muon sources of high intensity for further progress in this field are also discussed.

submitted to Review of Modern Physics.


What is
μ-e conversion ?

μ→e conversion in a Muonic Atom

- ***muonic atom (1s state)***



nuclear muon capture

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

muon decay in orbit

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

- ***neutrinoless muon nuclear capture (= μ-e conversion)***

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

coherent process

lepton flavors changes by one unit.

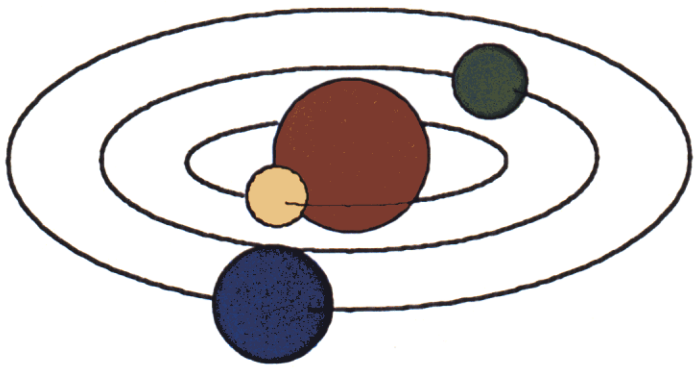
$$B(\mu^- N \rightarrow e^- N) = \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \nu N')}$$

$\mu \to e$ conversion:Signal and Background

- ***coherent conversion*** ($\propto Z^5$)

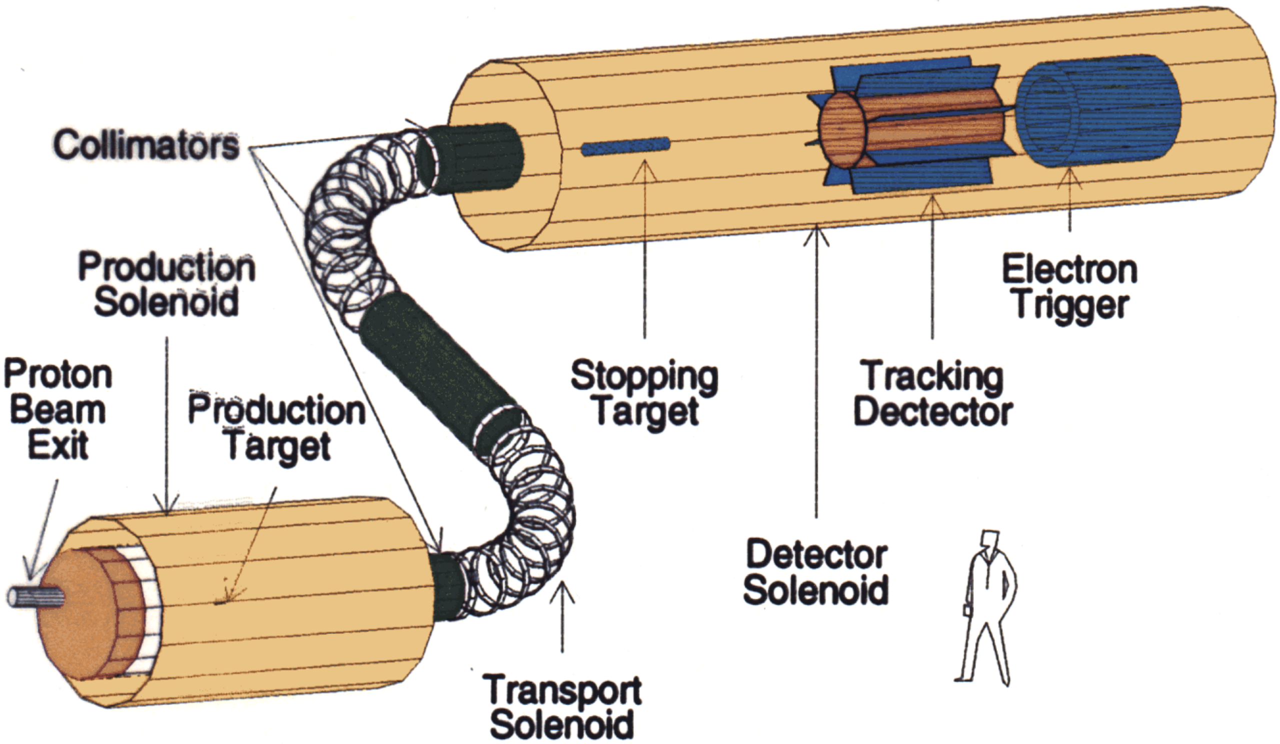
$$\mu^- + (A,Z) \to e^- + (A,Z)$$

- ***Event Signature***
  - *single mono-energetic electron of* $(m_\mu - B_\mu)$ *MeV*
- ***Backgrounds***
  - *no accidental background*
  - *muon decay in orbit* $(\propto(\Delta E)^5)$
    - » *highest endpoint comes to the signal*
  - *radiative muon capture with photon conversion*
  - *pion capture with photon conversion*
    - » *to remove pions in beam, a pulsed beam is useful, where the measurement waits until pions decay.*
  - *cosmic ray*



MECO at BNL/AGS

- ***E940 aim at $B(\mu^- + Al \rightarrow e + Al) < 10^{-16}$ at BNL AGS MECO***



- ***$5x10^{11}\mu^-$/pulse, 1.1MHz pulse***
  - *8GeV proton beam at AGS*
  - *high field capture solenoid of 4T*
- ***schedule : 2003 start ???***

PRISM Beam Requirement for μ-e conversion

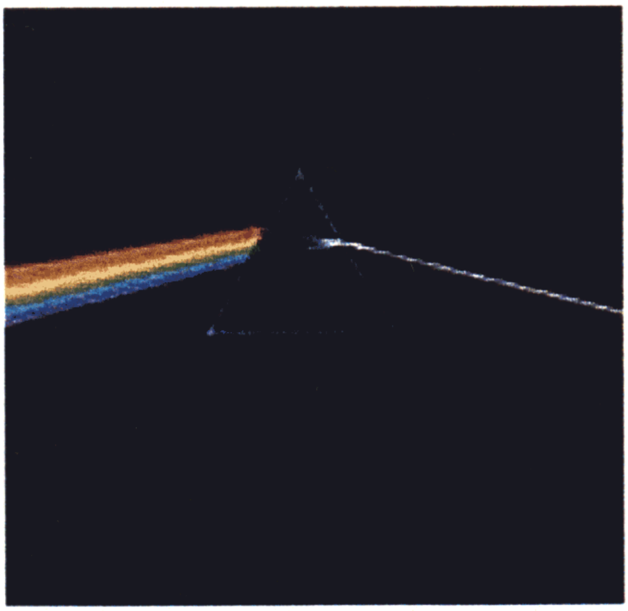
- **higher muon intensity**
  - 10^{12} μ^-/sec
- **pulsed beam**
  - background rejection
- **narrow energy spread**
  - allow a thinner muon-stopping taret
    - » better e^- resolution and acceptance
    - » point source
  - allow a beam blocker behind the target
    - » isolate the target and detector
    - » tracking close to a beam axis
- **less beam contaminations**
  - no pion contamination
    - » long flight path at FFAG (150 m)
  - beam extinction between pulses
    - » kicker magnet at FFAG


PRISM

What is PRISM ?

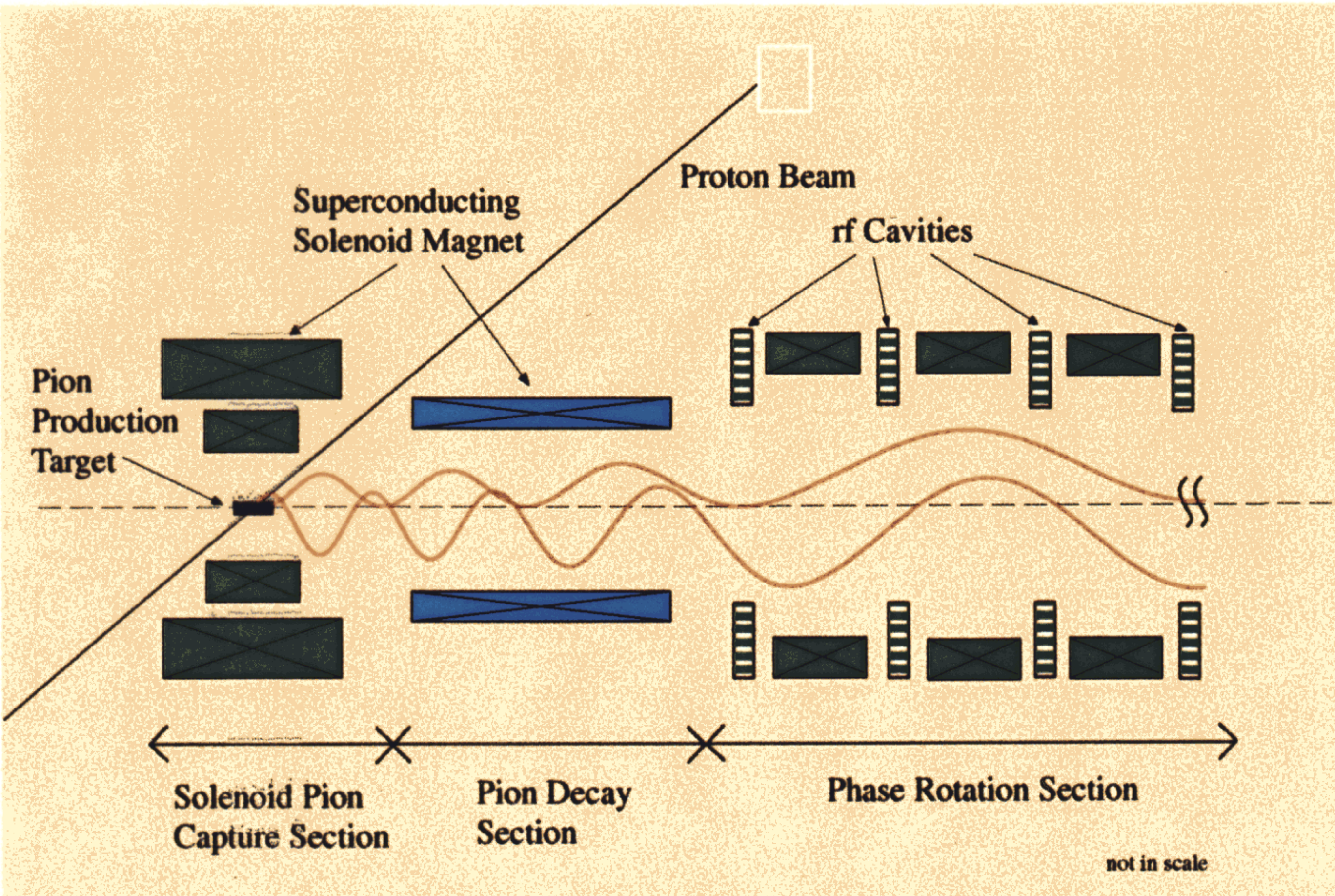
- PRISM (Phase Rotation Intense Slow Muon source)

= a dedicated secondary muon beam channel with high intensity and narrow energy spread for stopped muon experiments.

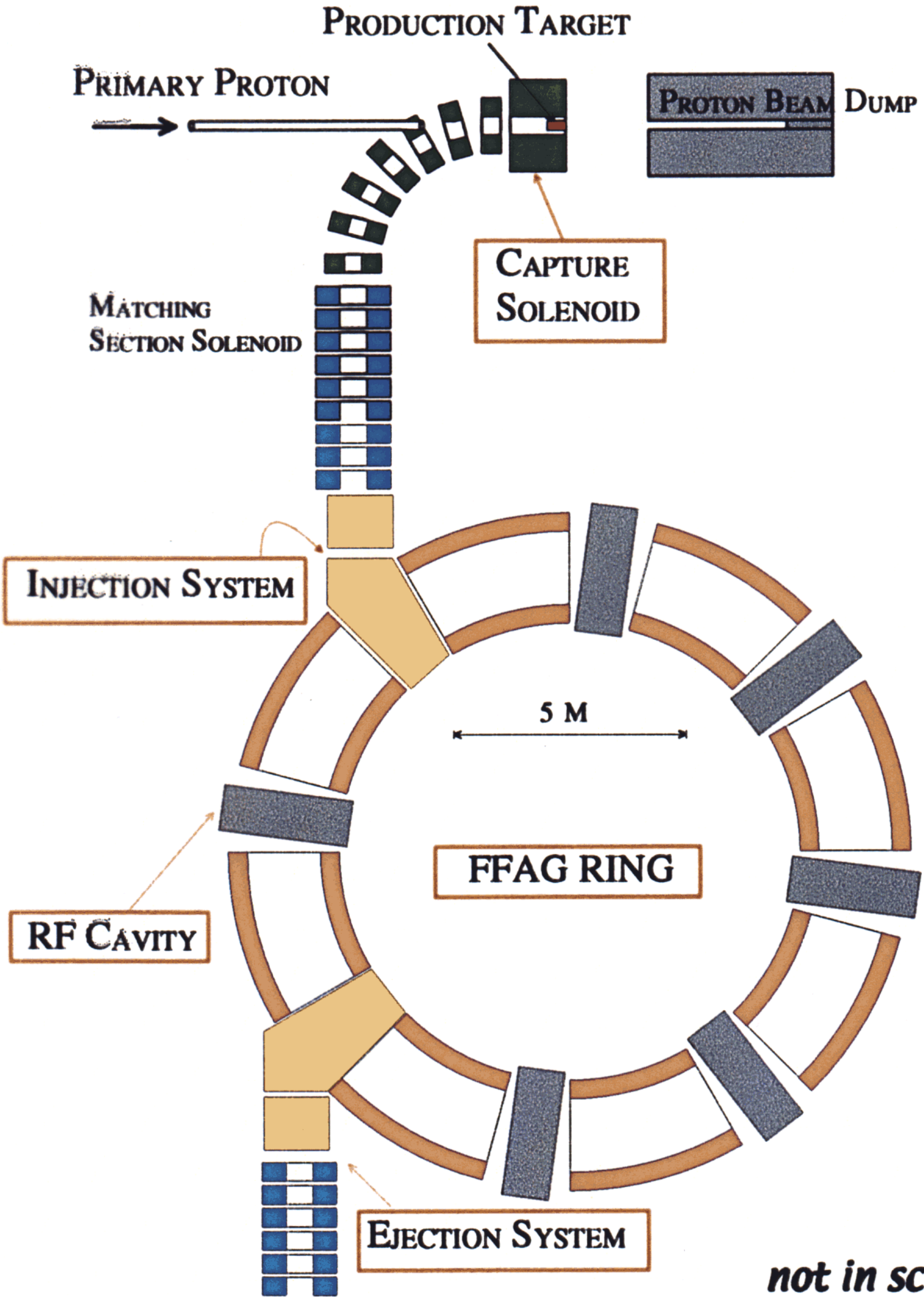


PRISM Scheme

- *pulsed proton beam*
- *pion capture by high solenoid field*
- *pion decay section*
- *phase rotation section*



PRISM layout



not in scale

PRISM
Beam Characteristics

- ***intensity* : 10^{11}-10^{12} $\mu^{\pm}$ /sec**
- ***muon kinetic energy* :**
  20 MeV (=68 MeV/c)
  - range = about 3 g
- ***kinetic energy spread* :**
  $\pm$0.5-1.0 MeV
  - $\pm$a few 100 mg range width
- ***beam repetition* :**
  about 1 kHz
  - in terms of muon lifetime, a 100kHz -1 MHz is ideal.
  - increase in future, if technically possible.

Low Energy Muons

Pion Capture Yield

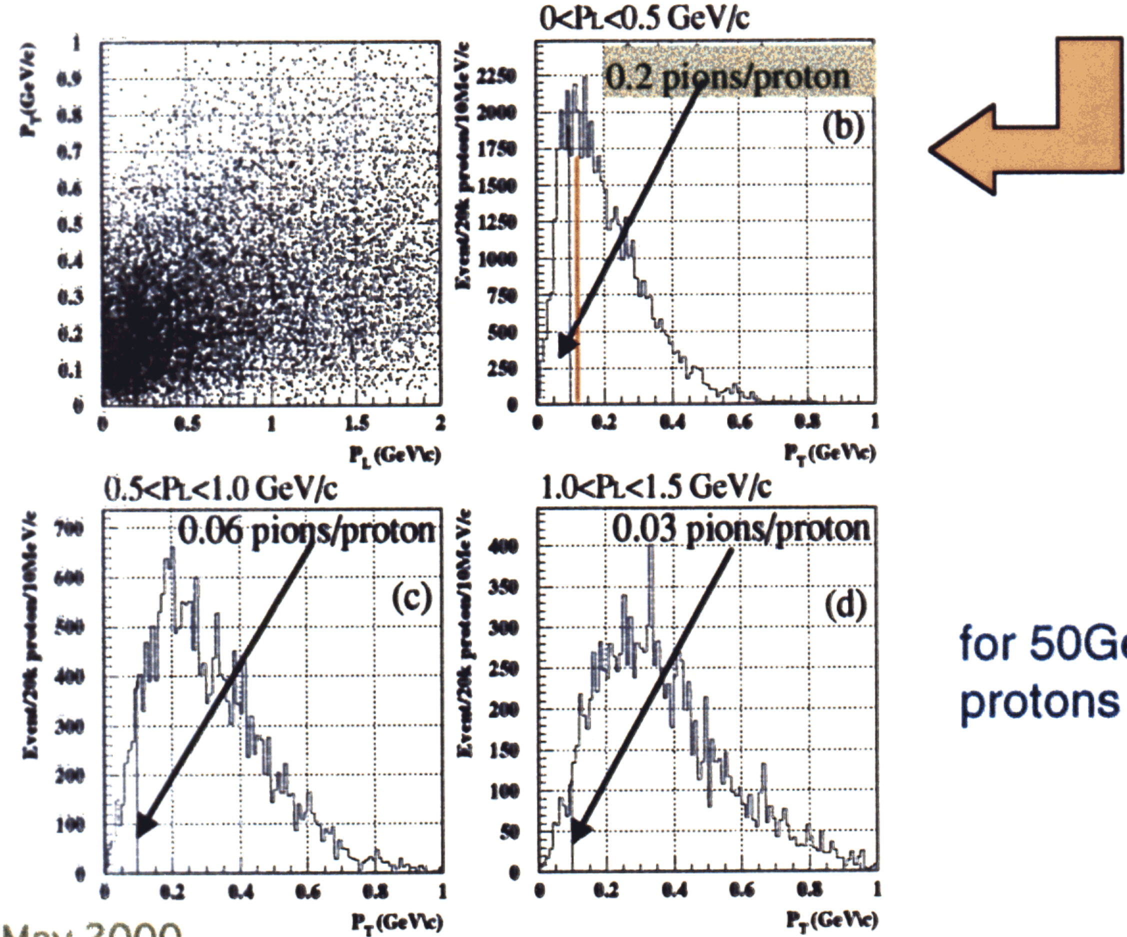
- ***maximum transverse momentum***

$$P_T(MeV/c) = 0.3 \times H(kG) \times \left(\frac{R}{2}\right)(cm)$$

  - R *: radius of magnet*
  - ex: H=*120kG(=12T)*, R=*5cm*
    - » $P_T < 90$ MeV/c

- ***capture yields***

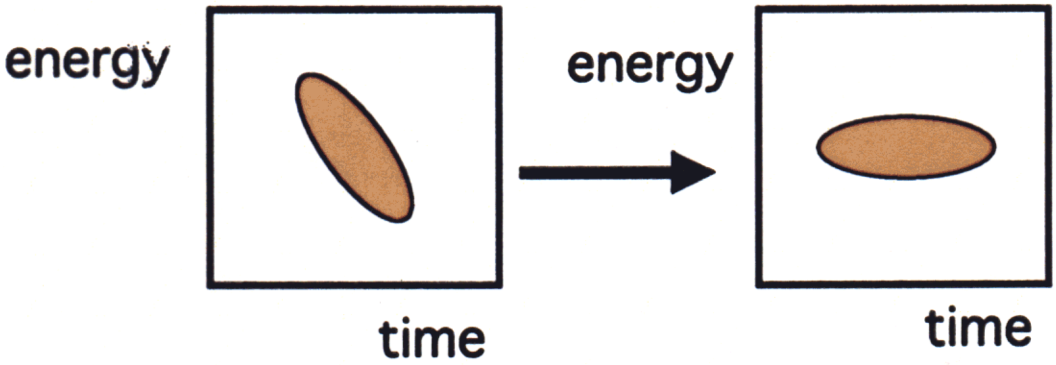
low energy pions



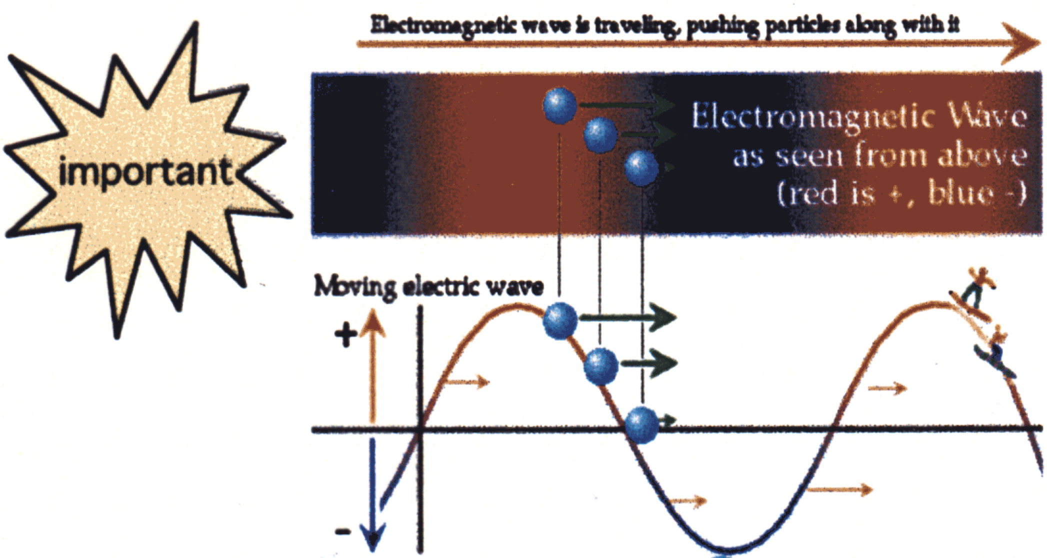
for 50GeV protons

Phase Rotation

- *Phase Rotation = decelerate particles with high energy and accelerate particle with low energy by high-field RF*



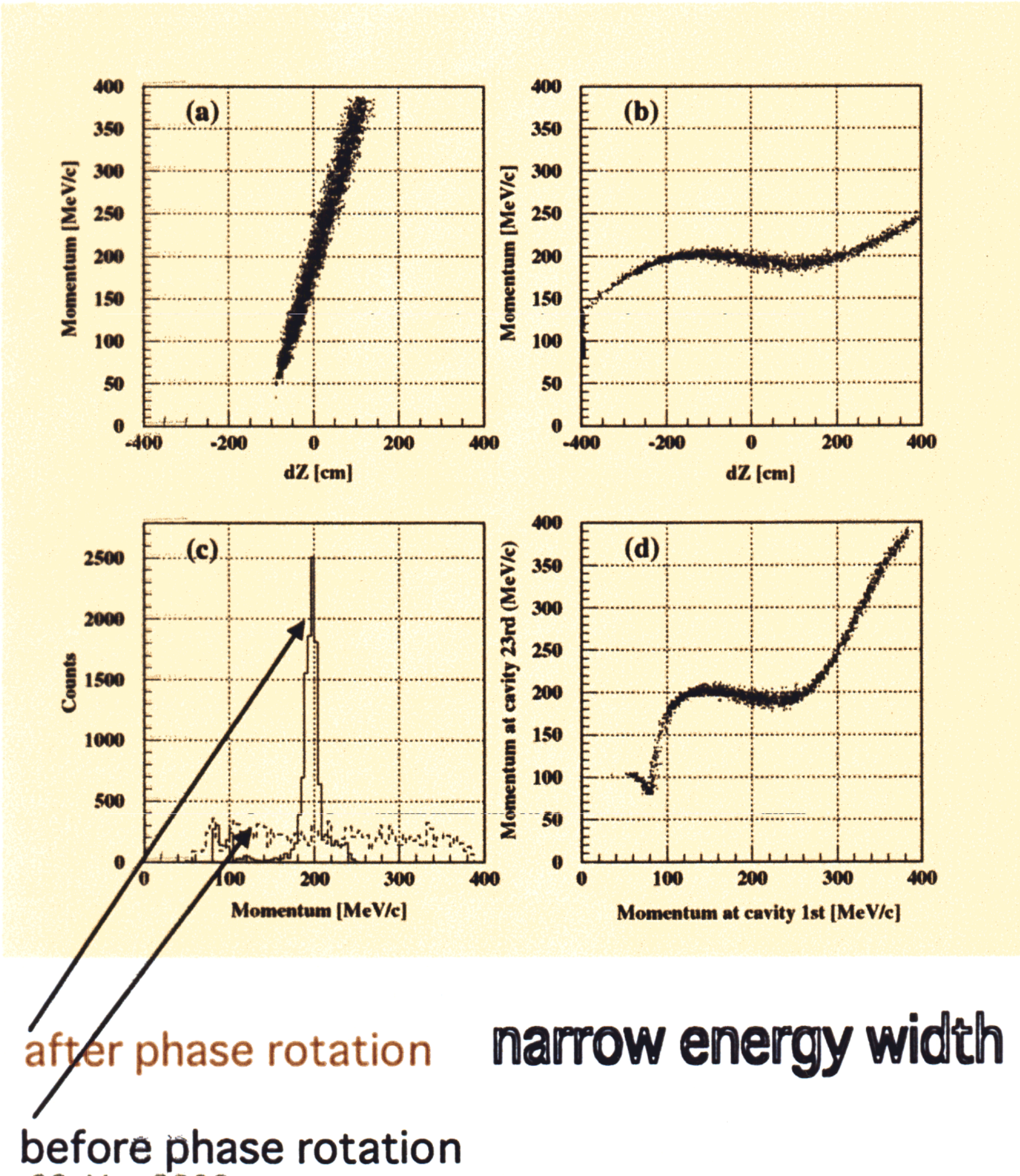
- *A narrow pulse structure (<1 nsec) of proton beam is needed to ensure that high-energy particles come early and low-energy one come late.*



Positively charged particles ( ) close to the crest of the E-M wave experience the most force forward; those closer to the center experience less of a force. The result is that the particles tend to move together with the wave.

Phase Rotation Simulation

- ***simulation with rf kicks***



narrow energy width

FFAG Parameters

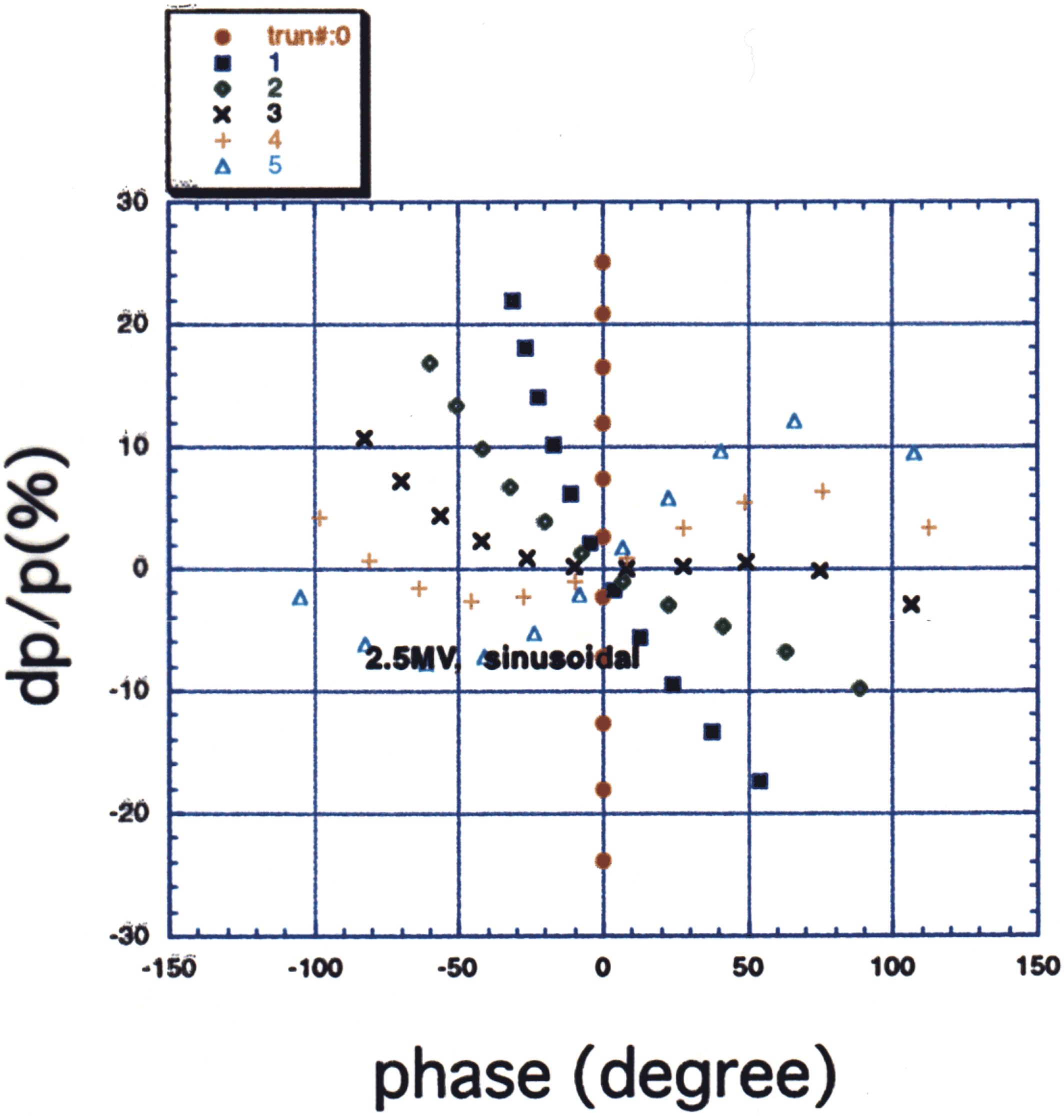
- ***PRISM-FFAG ring parameters***

	parameters
type	FFAG
Diameter	10m
Circumference	31m
Super period	8
Bρ	0.32 Tm
E_K	20 MeV
Δp/p	±0.31
Momentum compaction	0.166
Slippage factor	0.345
Acceptance	3000πmm.mrad
Betatron tunes : νx	3.477
νy	2.238
Max beam size: horizontal	400 mm
Max beam size: vertical	80 mm

under study

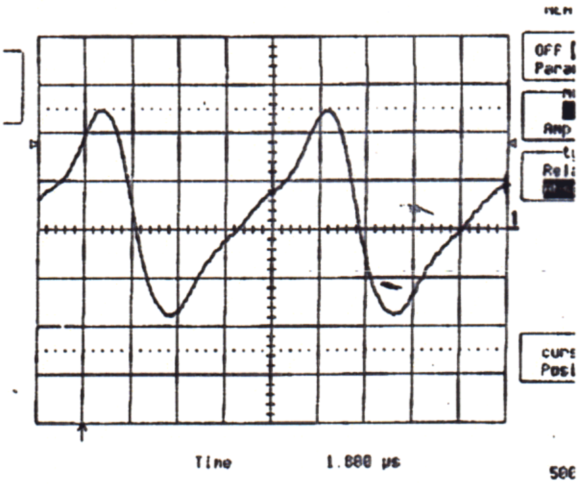
Phase Rotation Simulation at FFAG(1)

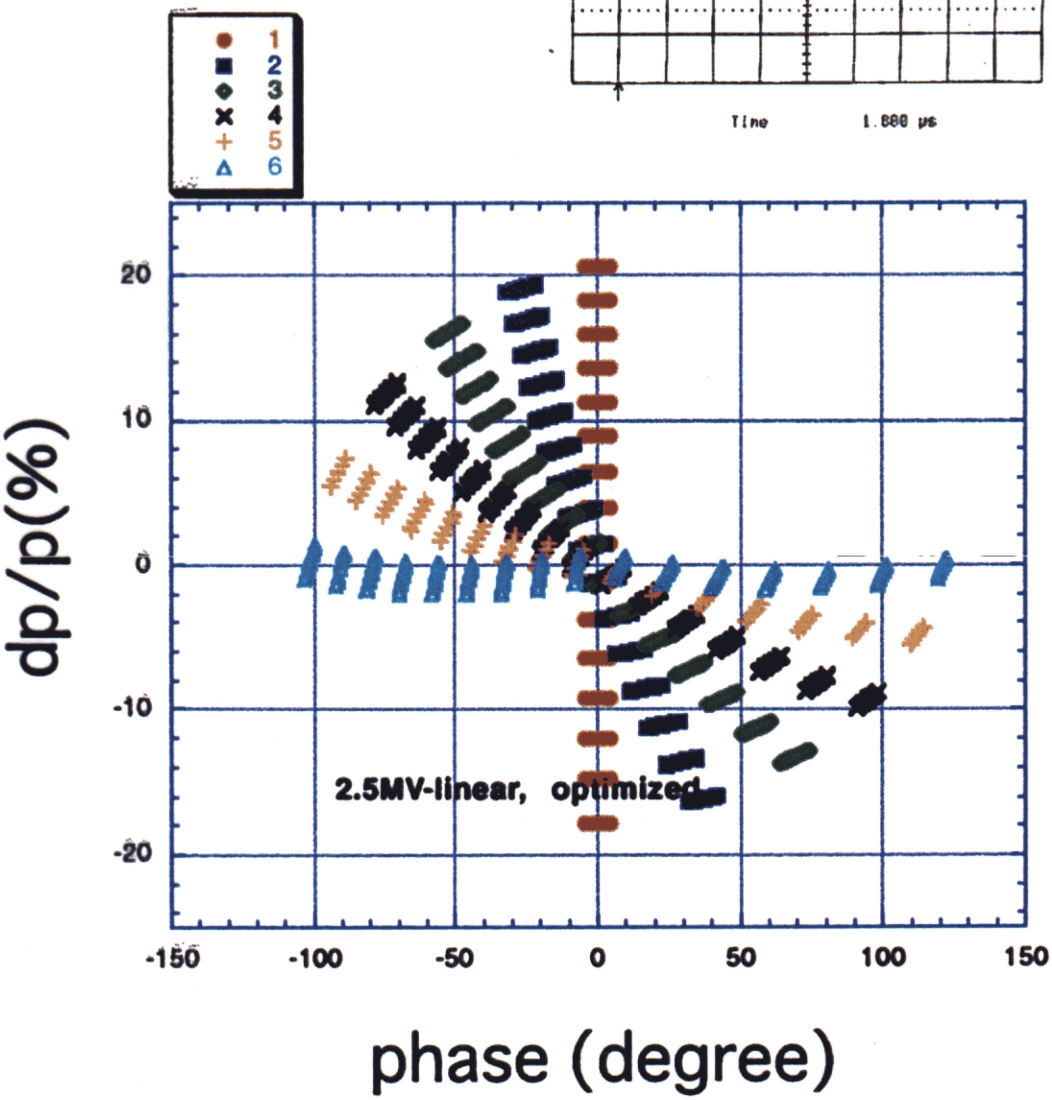
- ***non-linear relation on energy vs. time at low energy***
- ***in case of sin-wave rf***
  - *after 5 turns*



Phase Rotation Simulation at FFAG (2)

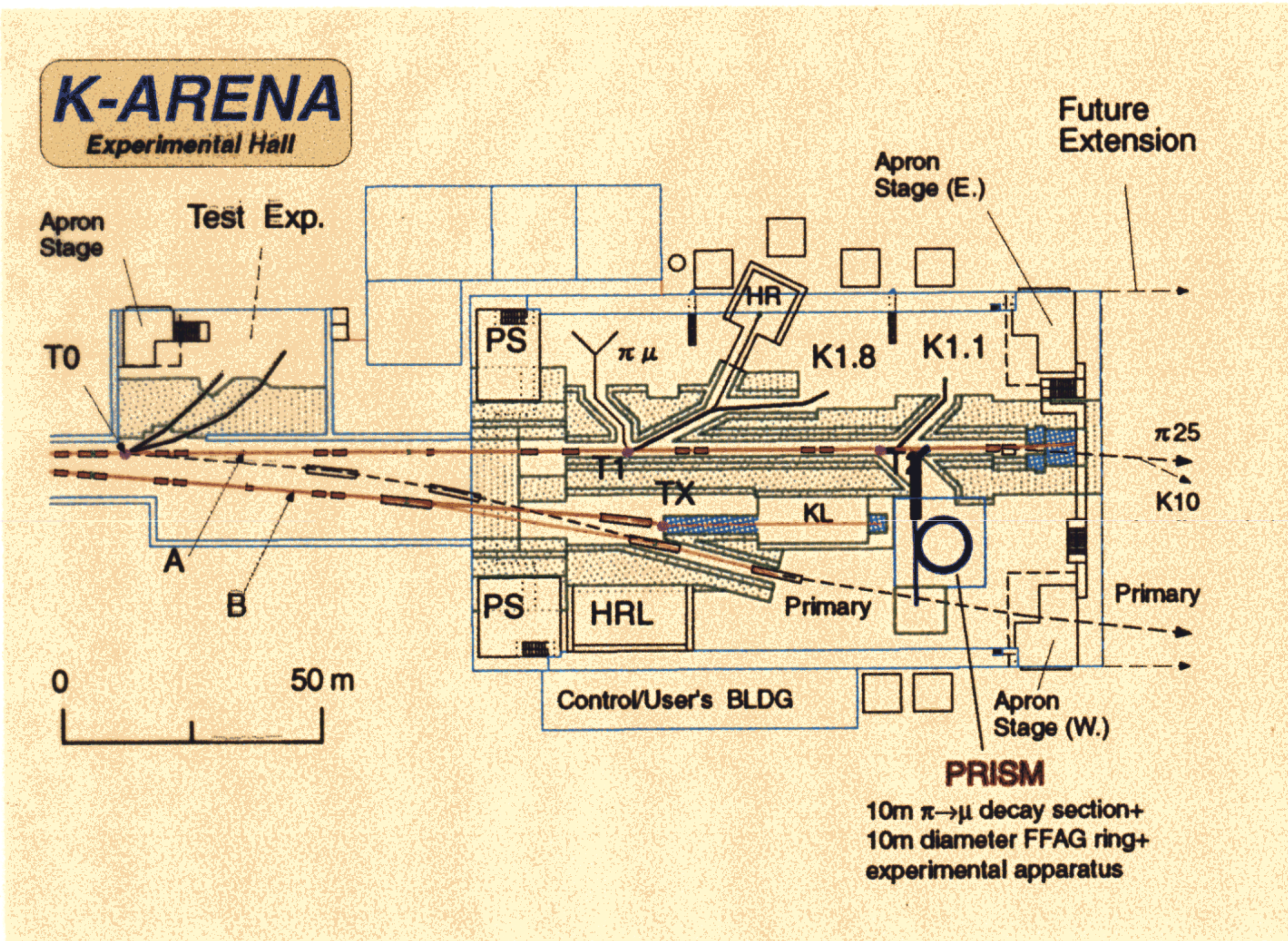
- ***in case of saw-tooth wave rf***





PRISM at the 50-GeV PS

- ***why at the 50-GeV PS?***
  - *a narrow bunched proton beam is needed.*
- ***in the 50-GeV PS experimental hall***



Muon Yield Estimation at PRISM

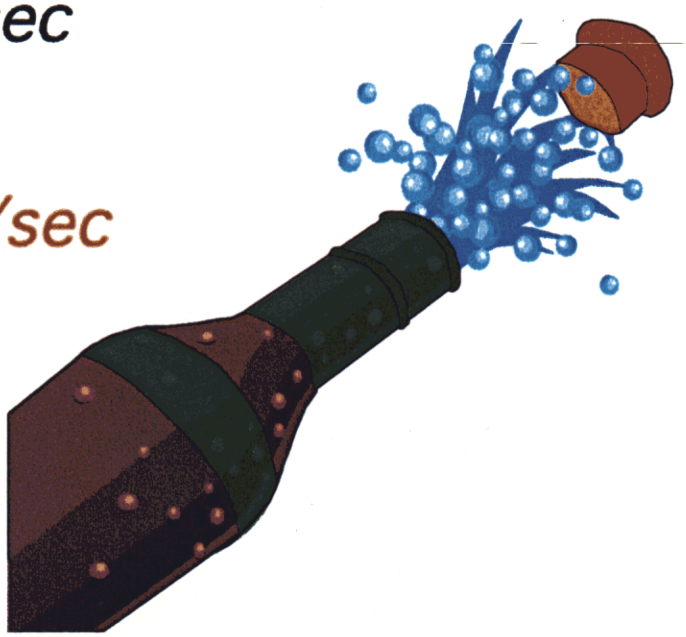
- ***muon yield***
  - P_T<90 MeV/c (12T 5cm radius) at pion capture
  - 3000π mm · mrad vertical acceptance of FFAG

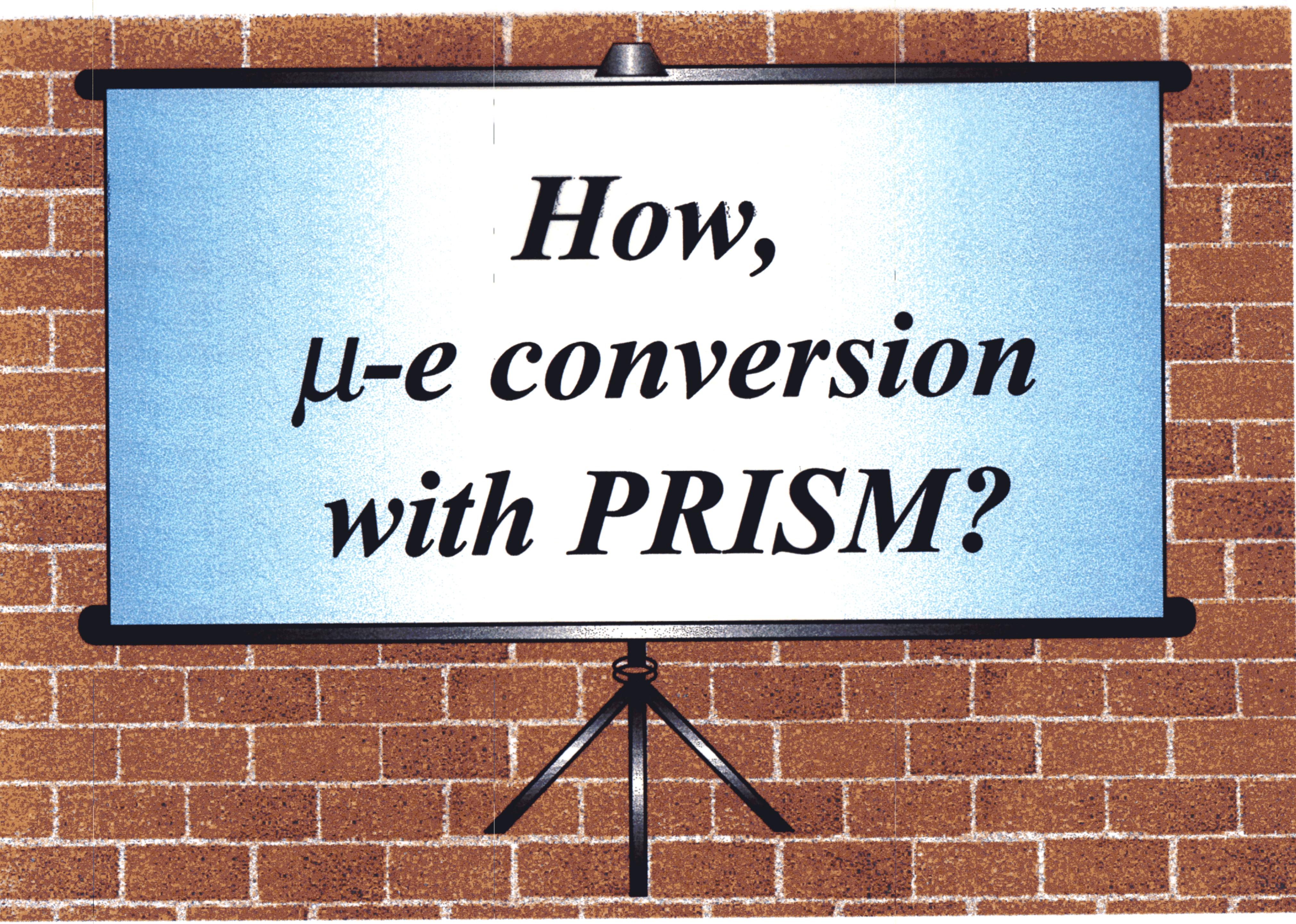
0.005 - 0.01 $\mu^{\pm}$/proton

in 20 MeV±(0.5-1.0)MeV range

- ***proton intensity at the 50-GeV PS***
  - 10^{14} proton/sec
- ***muon yield***
  - 10^{11}-10^{12} $\mu^{\pm}$/sec

OK!




How,
μ-e conversion
with PRISM?

Backgrounds to μ-e conversion (1)

- ***muon decay in orbit***
  - $(E_0\text{-}E)^5$
  - *better* e^+ *momentum resolution*
    - » *a thin muon stopping target is helpful. (=several 100 g)*
- ***radiative muon capture***
  - *endpoint for Ti = 89.7MeV*
    - » *signal = 104.3 MeV*
  - *better* e^+ *momentum resolution*
    - » *a thin muon stopping target*
- ***radiavtive*** π ***capture***

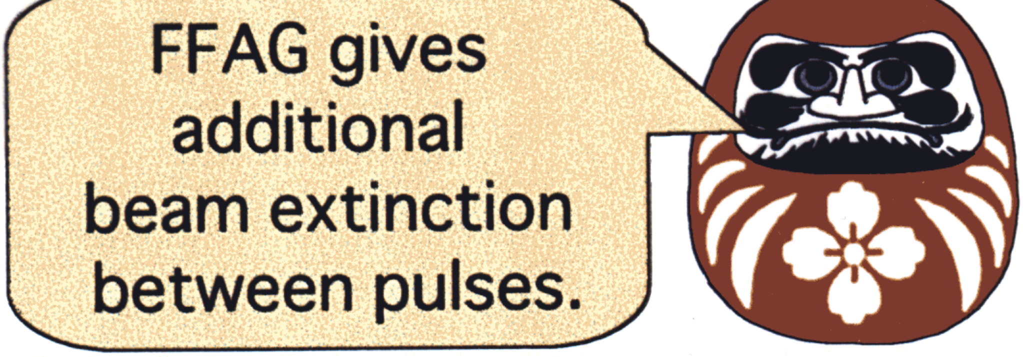
most dangerous in the past

  - *long flight length (150m)*
    - » *30 m FFAG circumference x 5 turns*
  - π *surviving rate:* 10^{-18} *at 68 MeV/c*

absolutely no pions

Backgrounds to μ-e conversion (2)

- ***cosmic ray backgrounds***
  - *1kHz (duty factor: 1/1000)*
- ***long transit time backgrounds***
  - *FFAG timing (kicker)*
- ***anti-proton***
  - *absorber before FFAG*
- ***beam electrons, electrons from muon decay in flight***
  - *FFAG's momentum accpetance:*
  - *different β (→out of time)*
  - *not bunched at FFAG ?*



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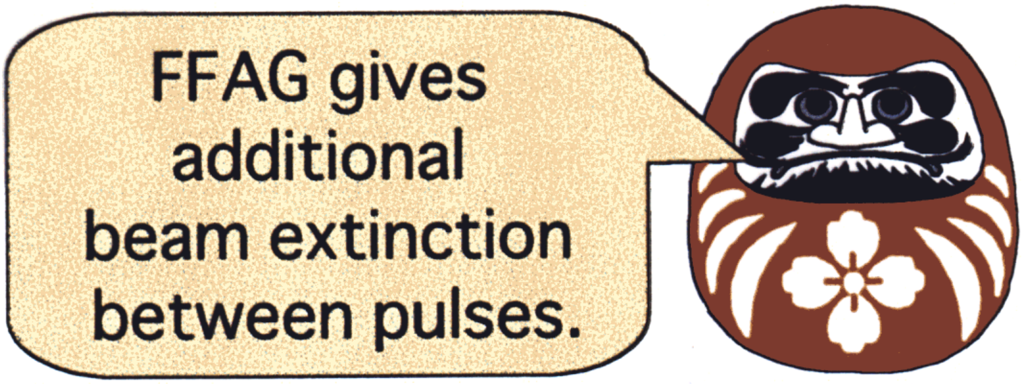
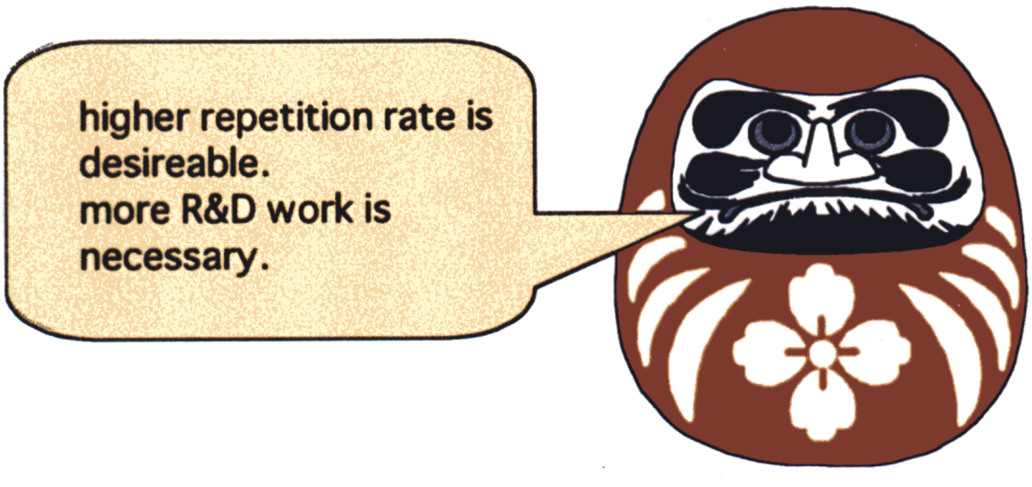
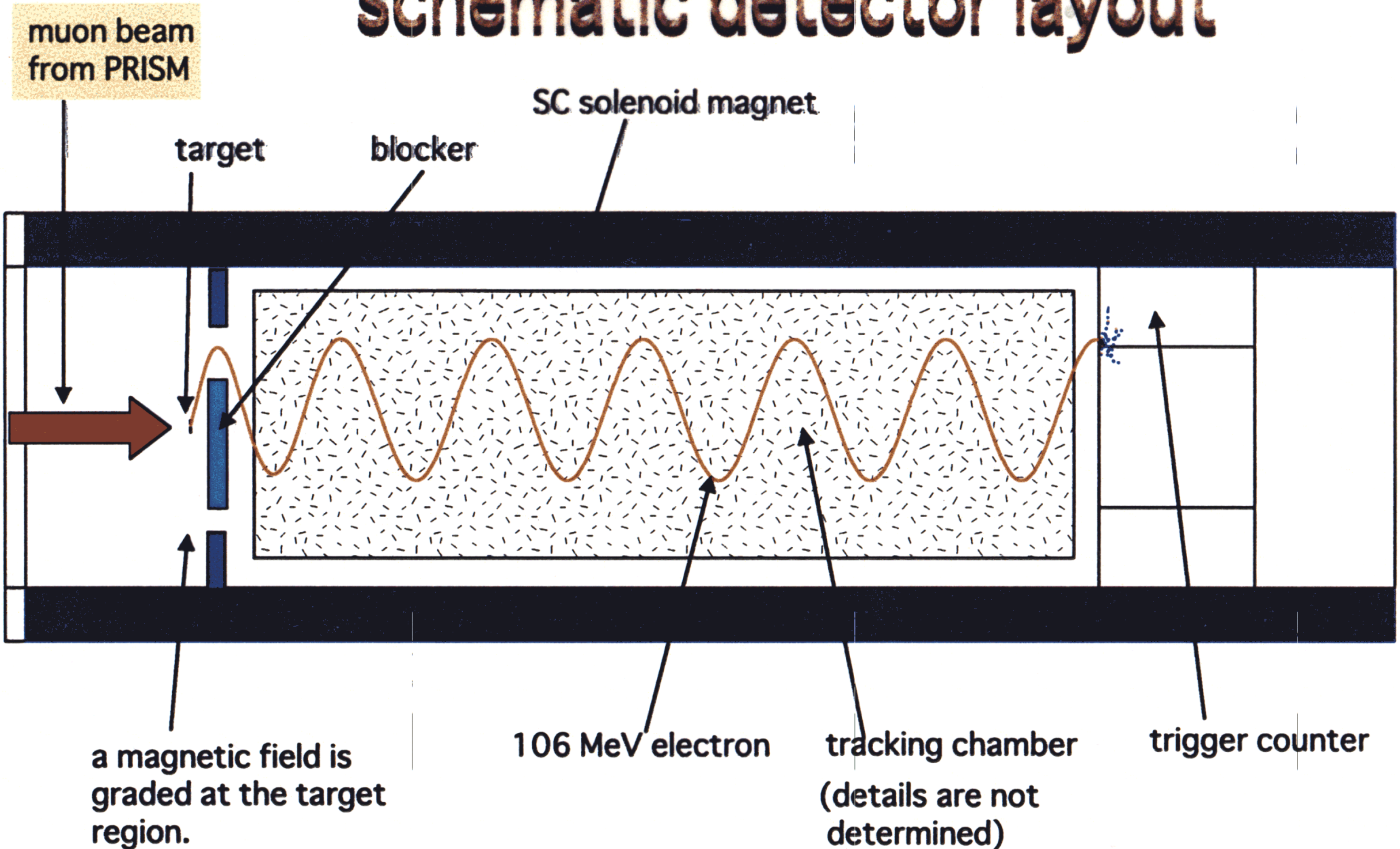


Rates in μ-e conversion

- **A *beam blocker* between the target and detection regions**
  - *reduce single rates at the tracking chambers, even if 1 kHz pulse beam operation.*
  - *no muon beam hits directly the beam blocker (due to narrow beam energy width).*
  - *rates come from muon decay in orbit, and muon capture.*
  - *no pions in a beam.*



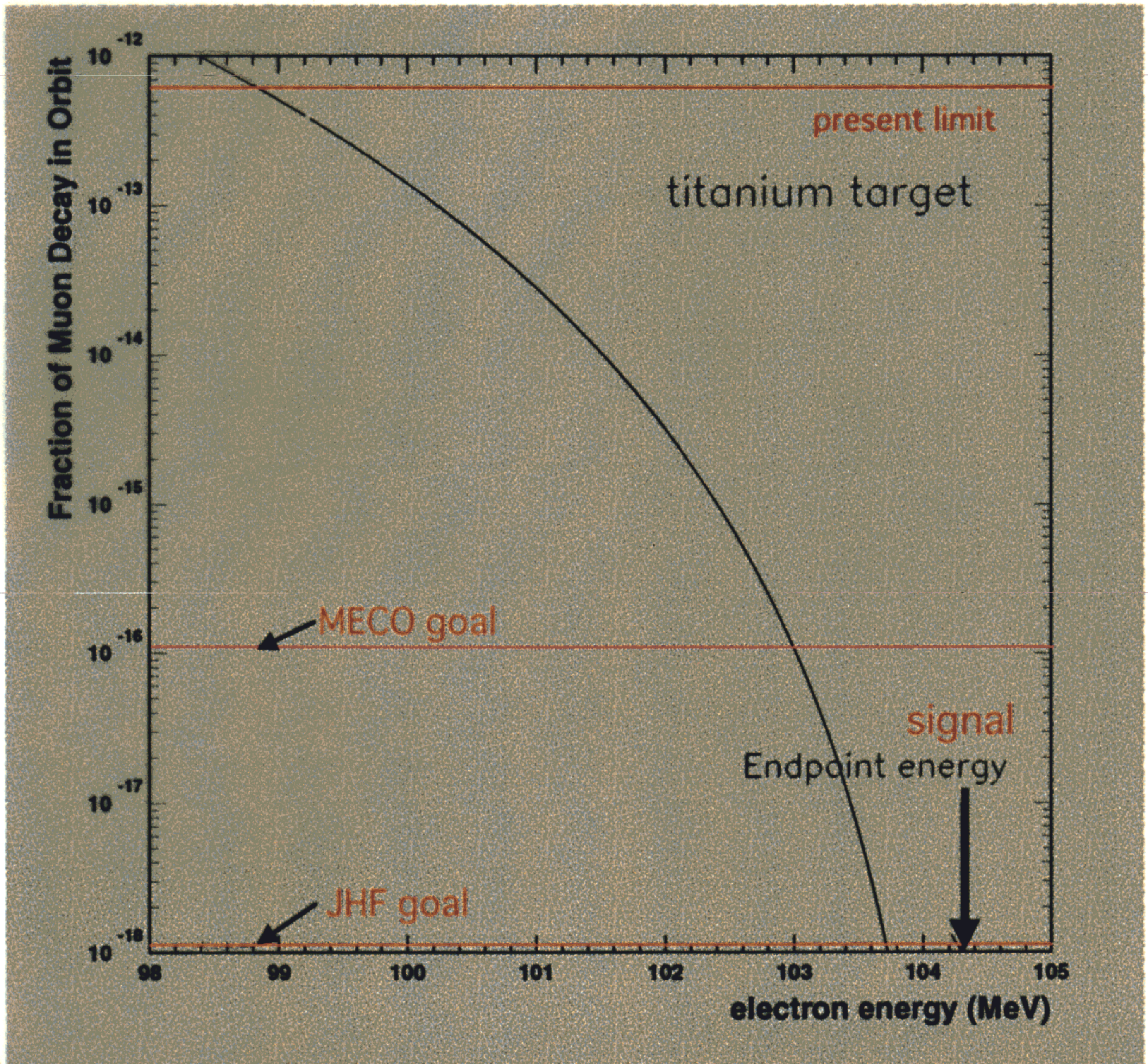
schematic detector layout



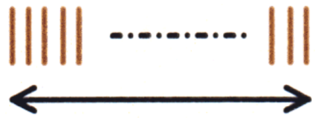
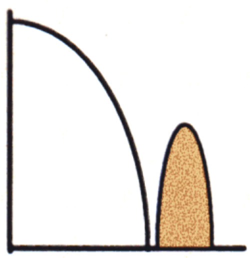
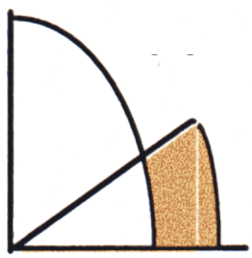
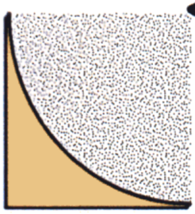
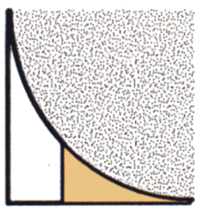
not in scale

$\mu \rightarrow e$ conversion: Muon Decay in Orbit

- ***Muon decay in orbit*** $(\propto (E_{\mu e} - E_e)^5)$
  - *required* e^+ *momentum resolution is determined (100-200 keV) at* 10^{-18} *sensitivity*



Improvement of Signal Sensitivity

	PRISM	*MECO*
Stopped muons/sec	10^{12}/sec (x4 times protons in future) ←	10^{11}/sec
Target material	Ti $B(\mu A \to eA)/B(\mu \to e\gamma) \approx 1/238$	Al $B(\mu A \to eA)/B(\mu \to e\gamma) \approx 1/389$
Target arrangement	Single 0.005 cm plate or 10 layers of 5 μm plates	(17-25) layers of 0.05 cm plate 
e^- momentum resolution	σ_{RMS} = 100 keV	σ_{RMS} = 150 keV
e^- detection solid angle	40 % ←	<20 % (45<θ<62)
e^- signal acceptance (response function)	No tails 100 % ←  energy	Tail due to energy loss <50 %  energy
Time window	Full time window 100 % ←  time	Delayed window 50 %  time

Summary

- Muon lepton flavor violation (LFV) is important to search for physics beyond SM, such as SUSY-GUT and SUSY with right-handed neutrino.
- PRISM (=phase rotation intense slow muon source) is a high-intensity muon source with narrow energy spread and less contamination.
- μ-e conversion has potential to be improved with PRISM, aiming at 10^{-18}.