Rare Muon Decay Experiments

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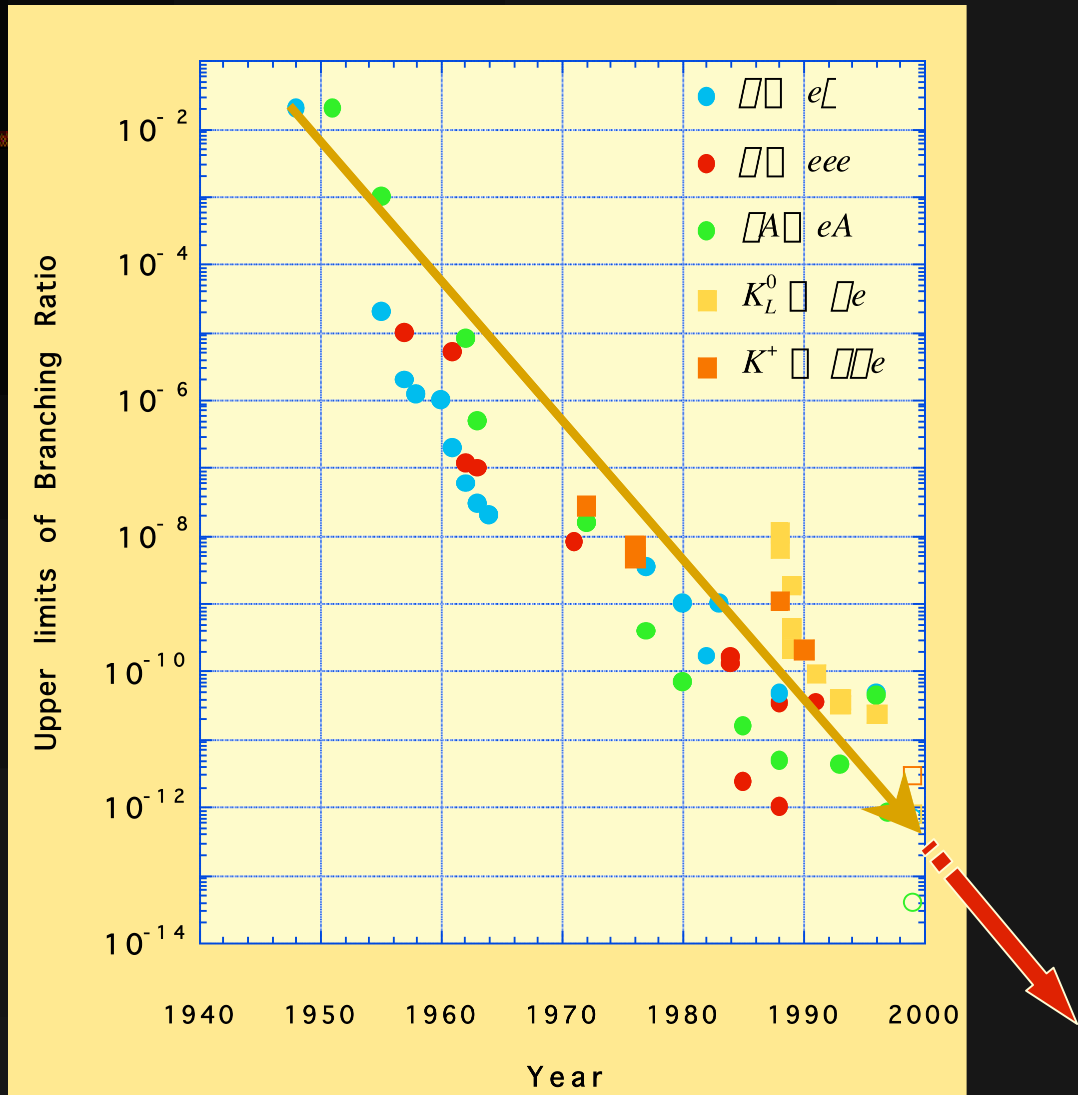
話の内容

- Rare Muon Decaysの物理意義
- 統合計画でのRare Muon Decay Experiments
  - 大強度高輝度ミューオン源 - PRISM
  - □-e conversion探索実験
- Future Extension
- まとめ

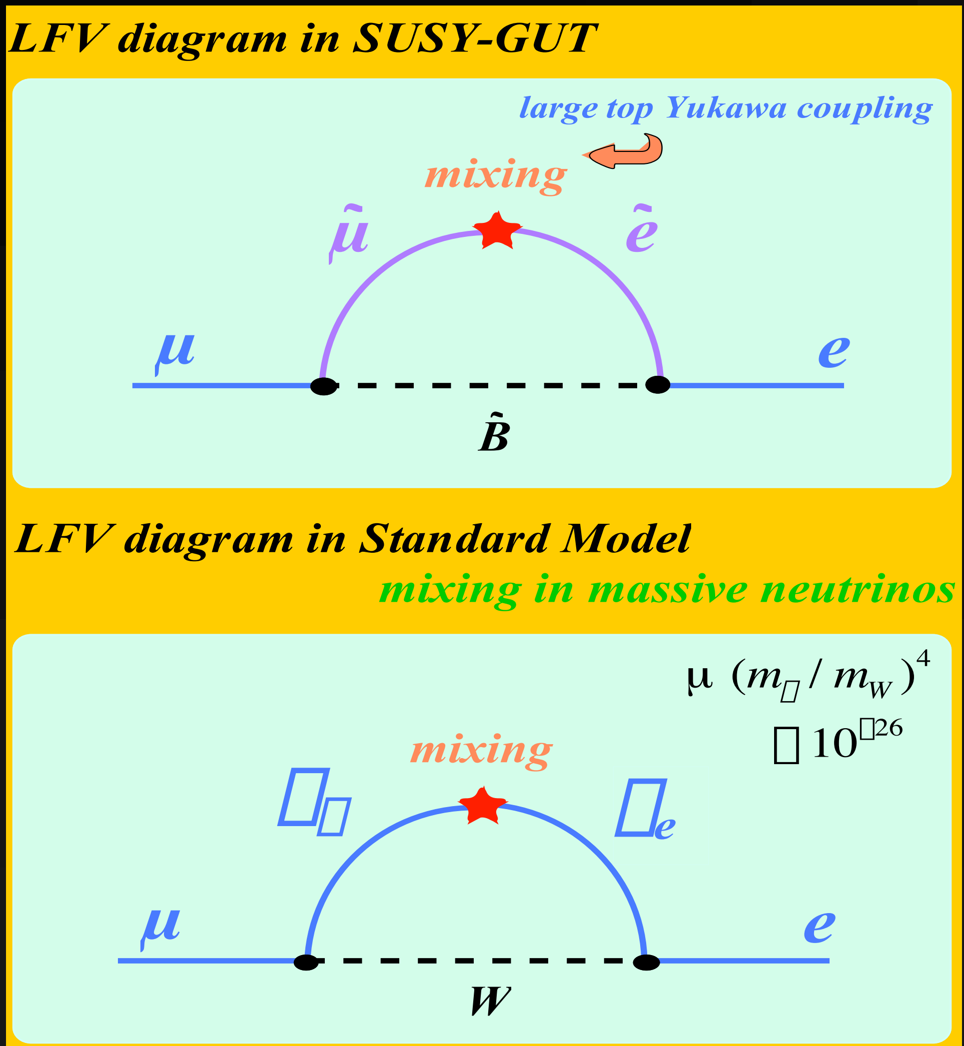
Charged Lepton Flavor Violation (LFV)

Muon Lepton Flavor Violation

- ミューオン稀崩壊
- $|\Delta L_i| = 1$
  - $\mu \to e\gamma$
  - $\mu \to eee$
  - $\mu^- A \to e^- A$ 変換
- $|\Delta L_i| = 2$
  - $\mu^+ e^- \to \mu^- e^+$ 変換
  - $\mu^- A \to e^+ A$ 変換
  - $\mu^- A \to \mu^+ A$ 変換



□□ *e* Transition in SUSY



SUSY Contribution

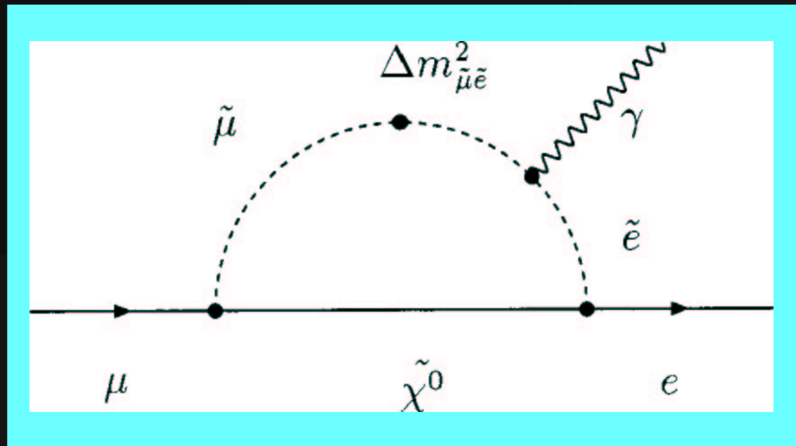
Contribution from Neutrino oscillation is small.

Lepton Flavor Violation and SUSY

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

μ-e transition diagram

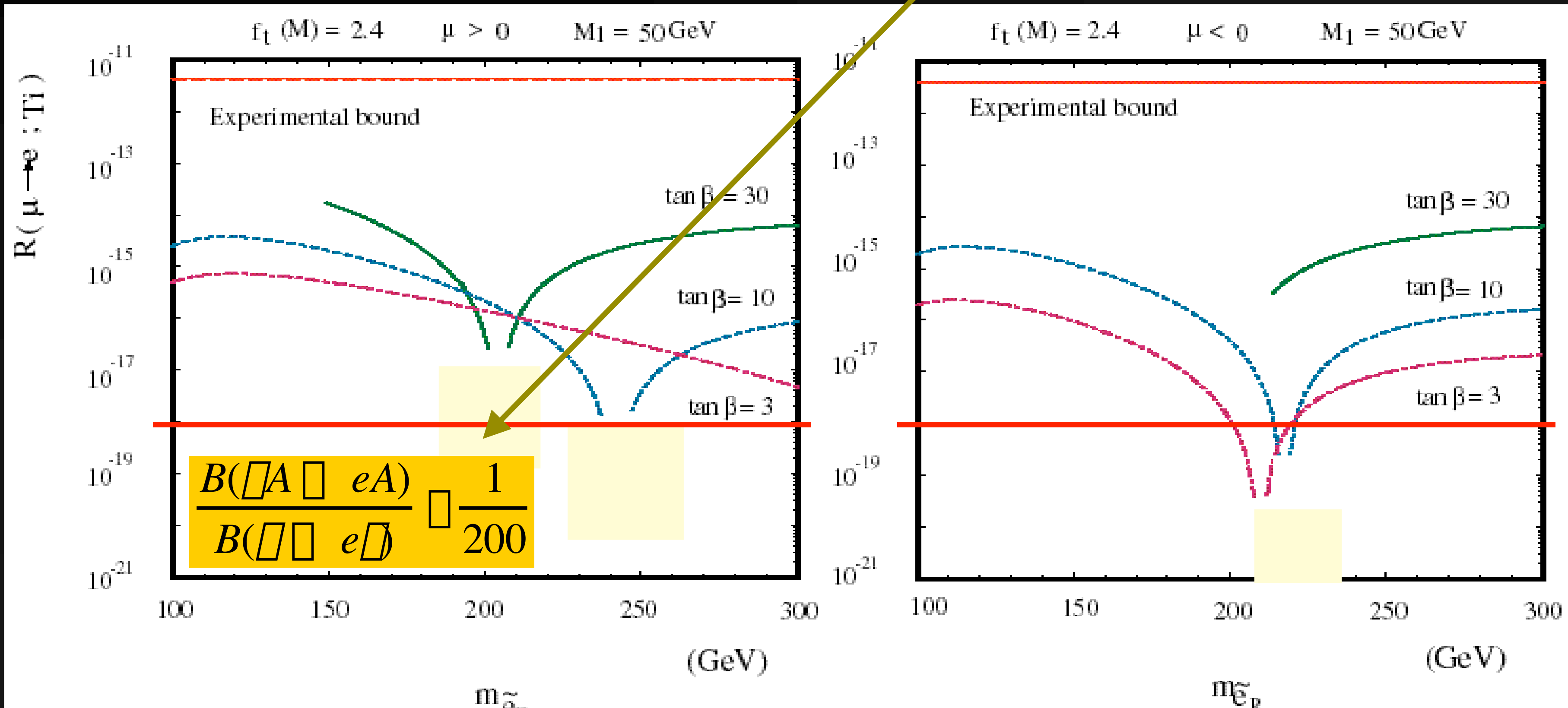
sensitive to slepton mixing



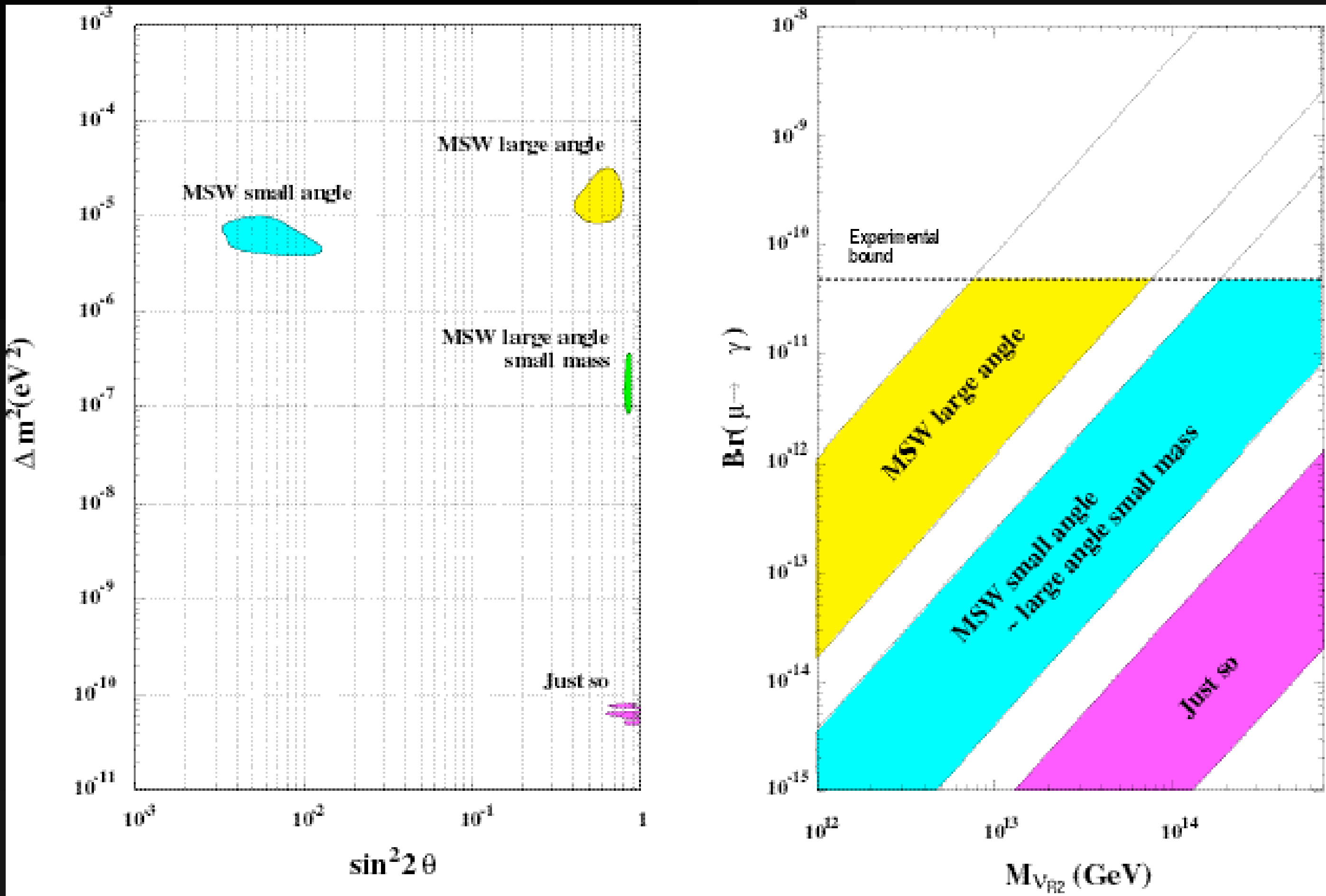
Muon g-2, EDM

□□ e conversion in SU(5) SUSY GUT

- gravity-mediated SUSY-breaking
- □□ *e* conversion



SUSY with Right-handed Majorana Neutrino



Related to Neutrino oscillation

A la Hisano and Nomura

LFV 探索の現状

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(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}
P($\mu^+e^- \to \mu^-e^+$)	8.3×10^{-11}
B($\tau \to e\gamma$)	2.7×10^{-6}
B($\tau \to \mu\gamma$)	1.1×10^{-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($K_L \to \pi^0\mu^{\pm}e^{\mp}$)	6.2×10^{-9}
B($D^0 \to \mu e$)	8.1×10^{-6}
B($D^0 \to$ □e)	5.3×10^{-4}
B($D^0 \to$ □□e)	3.4×10^{-5}
B($B \to \mu e$)	3.5×10^{-6}
B($B \to K\mu e$)	1.8×10^{-5}
B($Z \to \mu e$)	1.7×10^{-6}
B($Z \to \tau e$)	9.8×10^{-6}
B($Z \to \tau\mu$)	1.2×10^{-5}

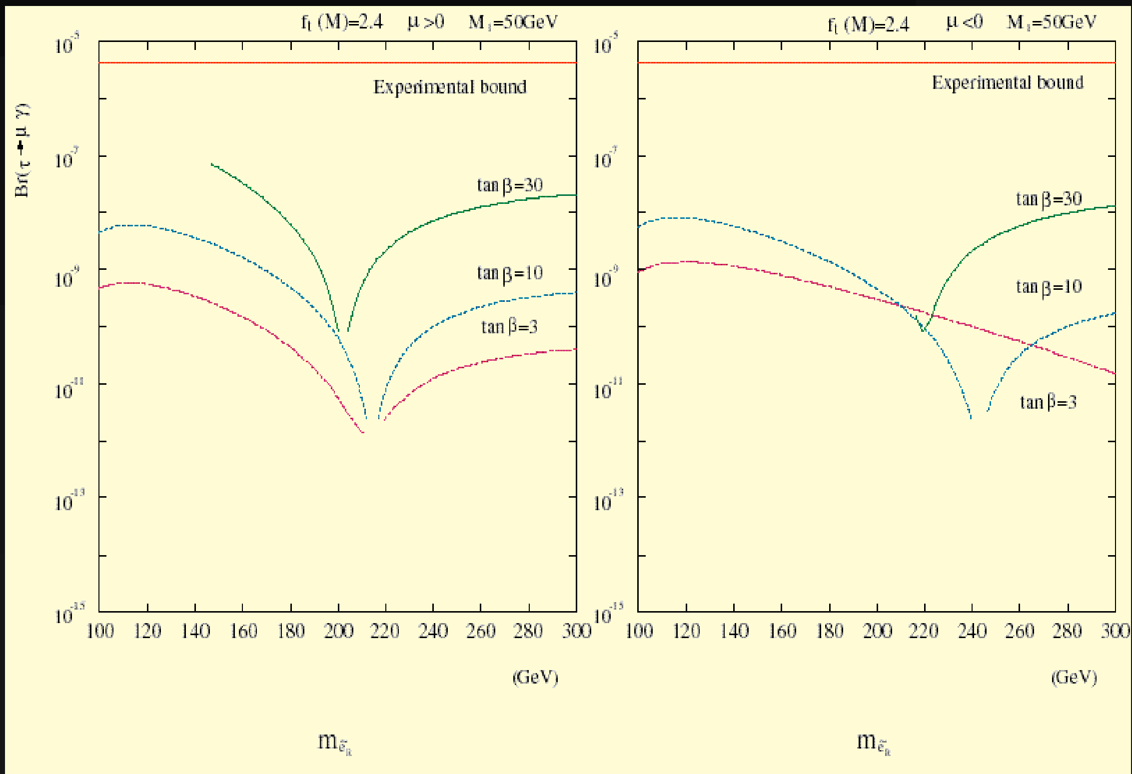
Based on a table written by Y. Kuno
Updated in August, 2000

ミュオンが
大変健闘し
ている

- 質量が比較的小さい為、大量に生成可能
    - 統計を上げやすい
- 寿命が比較的長い
    - 実験しやすい

□□w compared with □□ □□?

- SUSY SU(5) GUT gravity-mediated SUSY-breaking
  - Universal scalar mass matrix at Plank scale, and LFV occurs at GUT scale.
- □□ □□



$$\frac{B(\square\square\ \square\square)}{B(\square\square\ e\square)} = \frac{|V_{33}^{*}\cdot V_{32}|^2}{|V_{31}^{*}\cdot V_{32}|^2} \square 10^4$$

$B<10^{-16}$ for muons/

$B<10^{-8}$ for taus

Much better sensitivity in muons.

μ → eγ: Accidental Background

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

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)

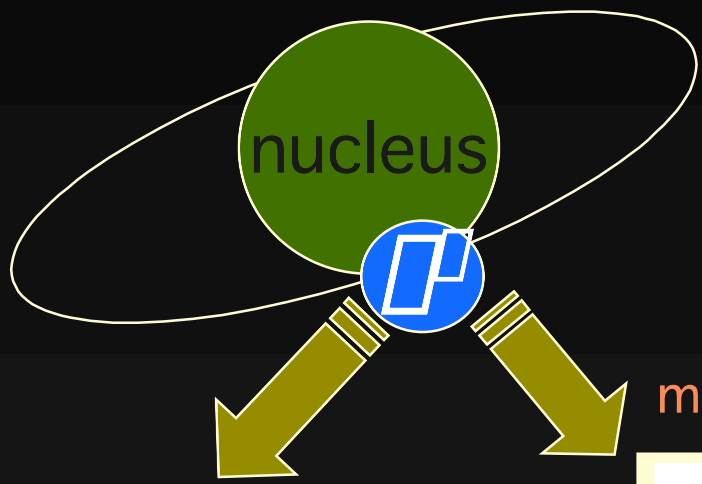
$B_{\mu\to e\gamma} = 10^{-14}$
$N_b = 0.5$ events

$B_{\mu\to e\gamma} = 10^{-16}$
- $R_\mu = 10^{10}$ μ/s
- $N_b \sim 10^4$ events?

Need detector improvement

μ⁻– e conversion in a Muonic Atom

- muonic atom (1s state)



muon decay in orbit

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

nuclear muon capture

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

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

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

lepton flavors changes by one unit.

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

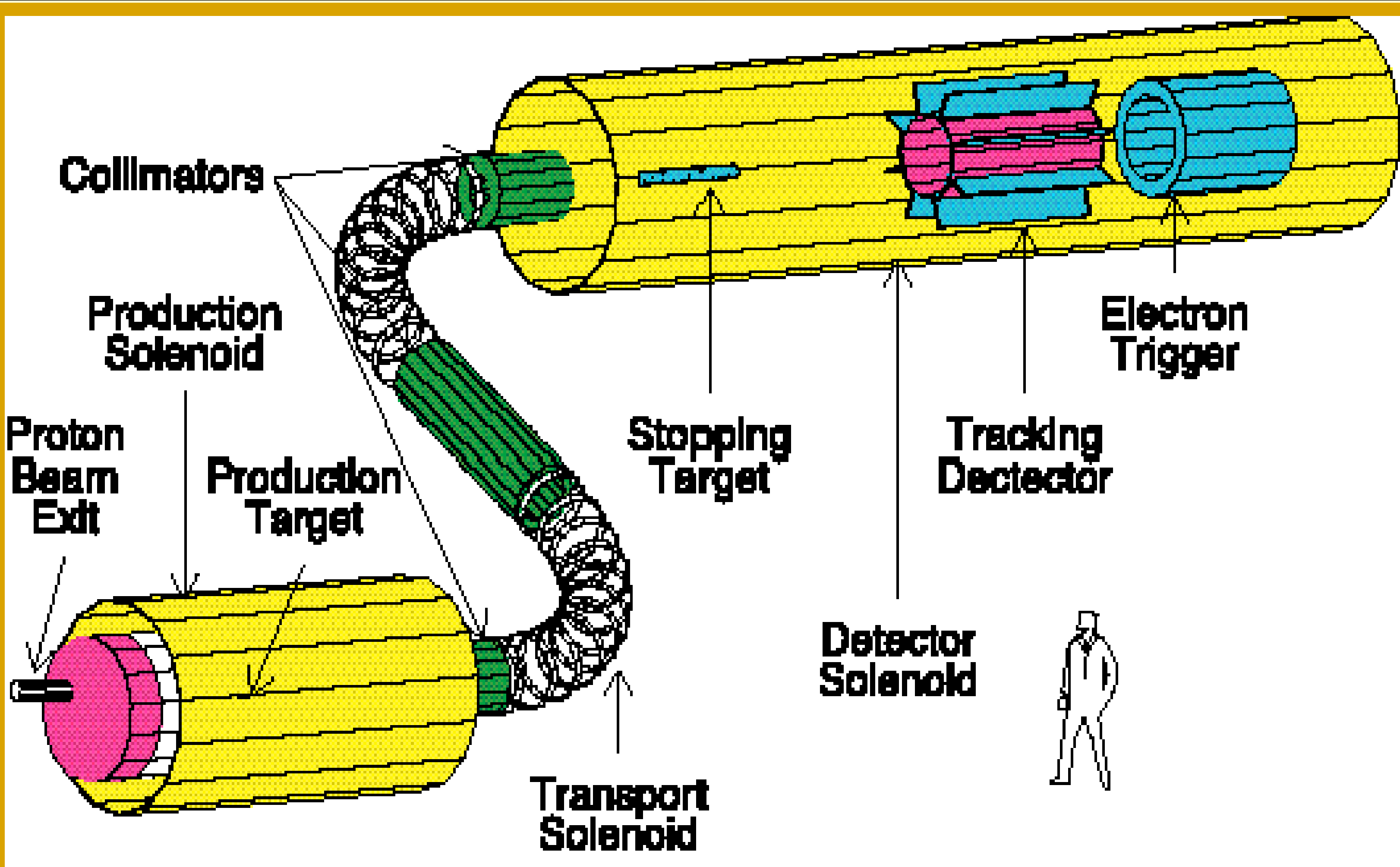
□□ e conversion : Signal and Background

- Event Signature

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

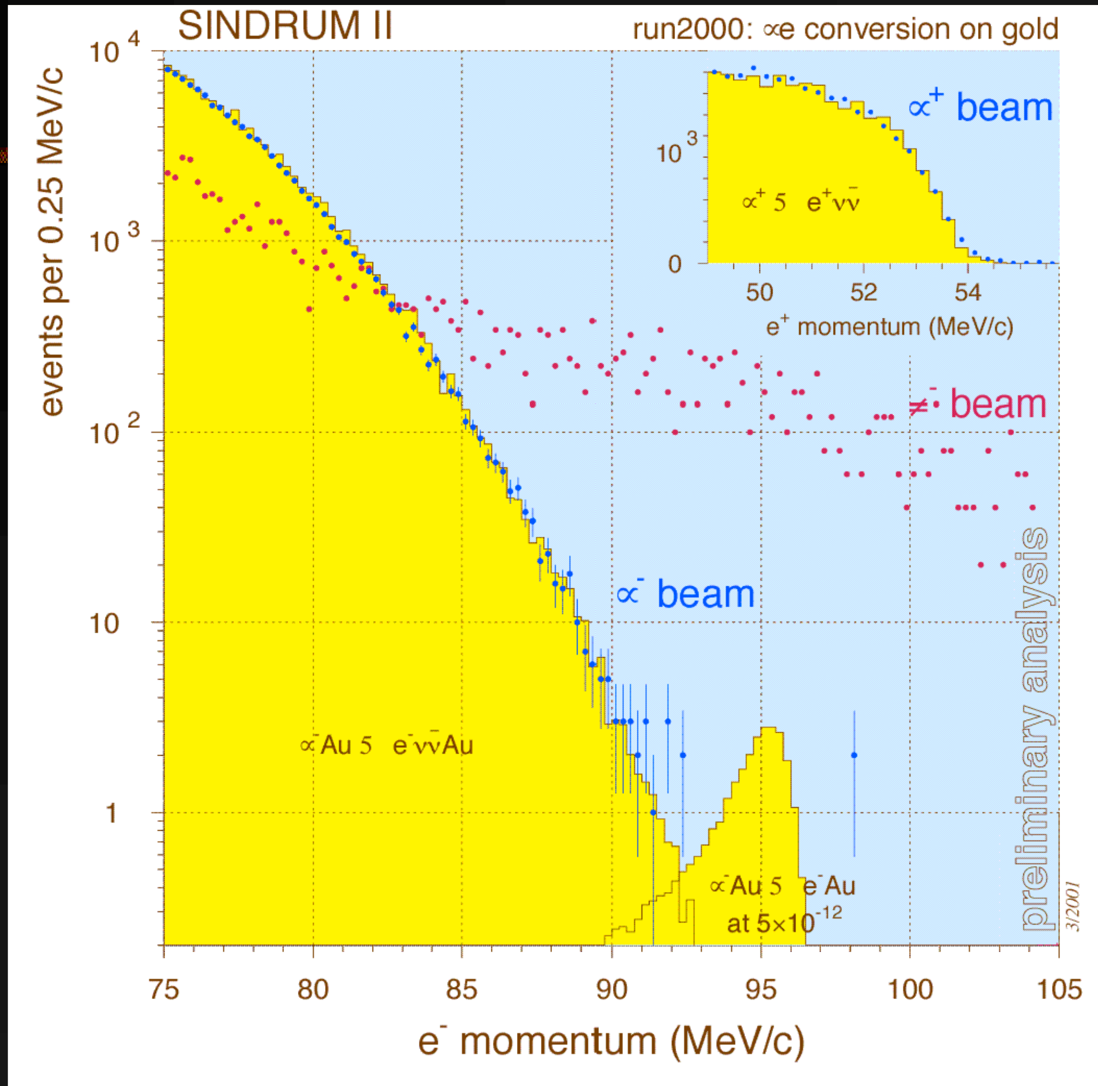
  - single mono-energetic electron of ($m_□$-$B_□$) MeV
  - Coherent process (∝Z5)
- Backgrounds
  - muon decay in orbit (μ(□E)^5)
    - highest endpoint comes to the signal
  - radiative muon capture with photon conversion
  - pion capture with photon conversion
    - to remove pions in beam, a pulsed beam is useful, where the measurement waits until pions decay.
  - cosmic ray

MECO (BNL-E940) Detector



SINDRUM-II Results

- 60g Au target
- 2.5 months



After A. van der Schaaf

μ-e conversion探索実験に必要なビーム条件

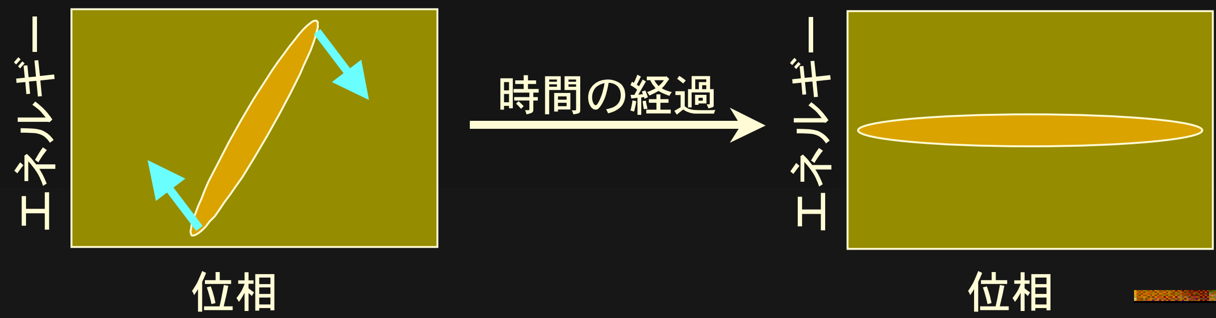
- higher muon intensity
  - 10^{11} - 10^{12} μ^-/sec
- pulsed beam
  - background rejection
- narrow energy spread
  - allow a thinner muon-stopping target
    - better e- resolution and acceptance
    - point source
  - allow a beam blocker behind the target
    - isolate the target and detector
    - tracking close to a beam axis
- less beam contamination
  - no pion contamination
    - long flight path at FFAG (150 m)
  - beam extinction between pulses
    - kicker magnet at FFAG

PRISM

What is PRISM ?

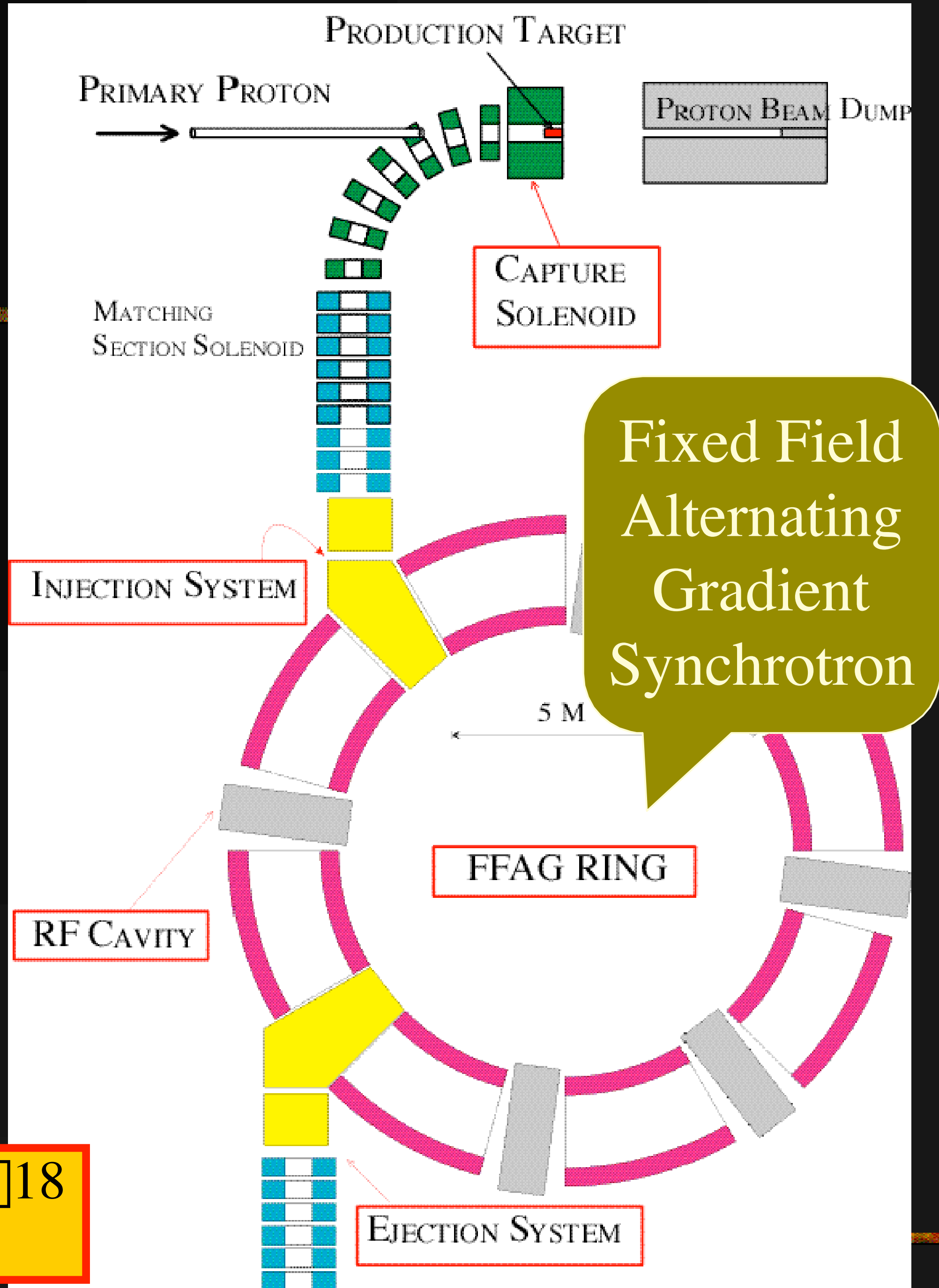
- PRISM (Phase Rotated Intense Slow Muon source)

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



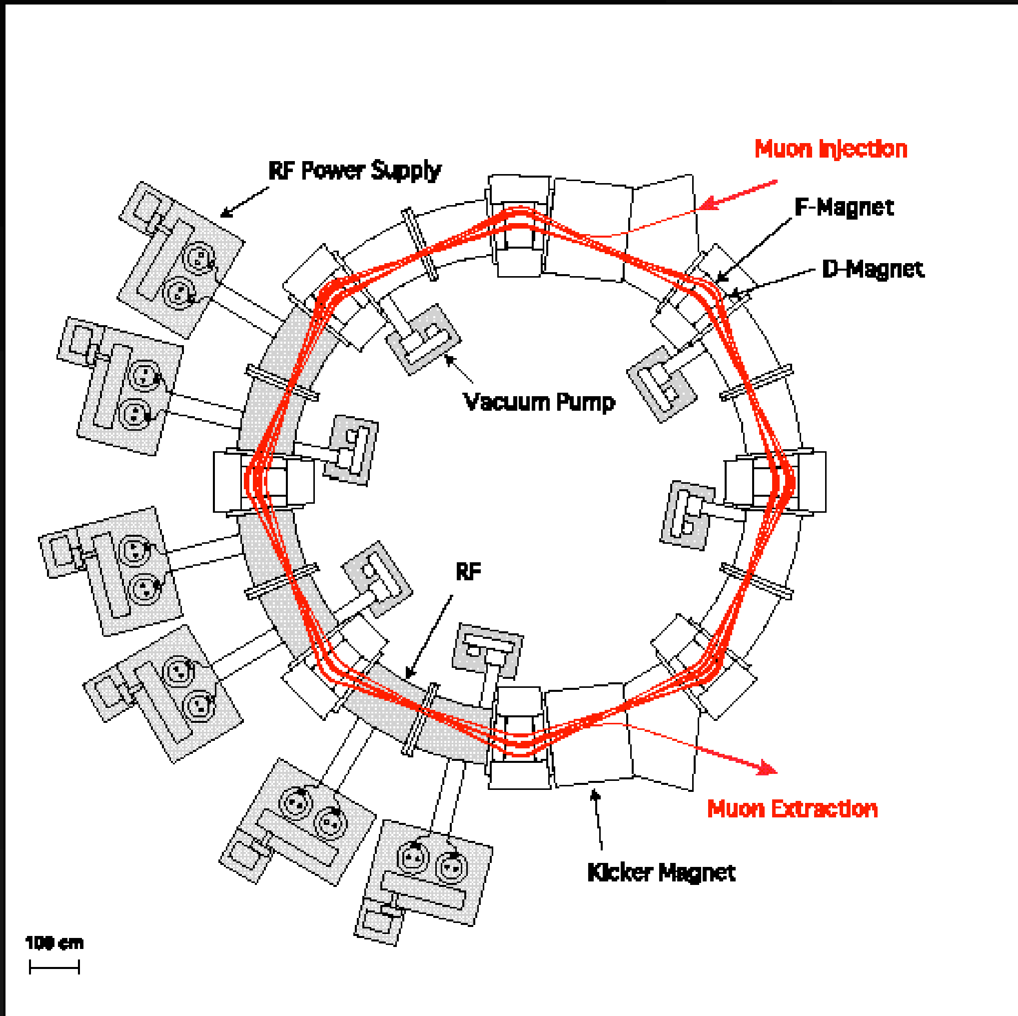
PRISM

- PRISM = Phase-Rotated Intense Slow Muon source
  - Phase rotation at PRISM-FFAG
  - P_μ=68 MeV/c (KE=20 MeV)
  - 10^{19} muons/(10^7sec) in the ring
  - Based on 0.8-MW 50-GeV PS



$$B(\mu^- N \to e^- N) < 10^{-18}$$

PRISM FFAG 加速器リング



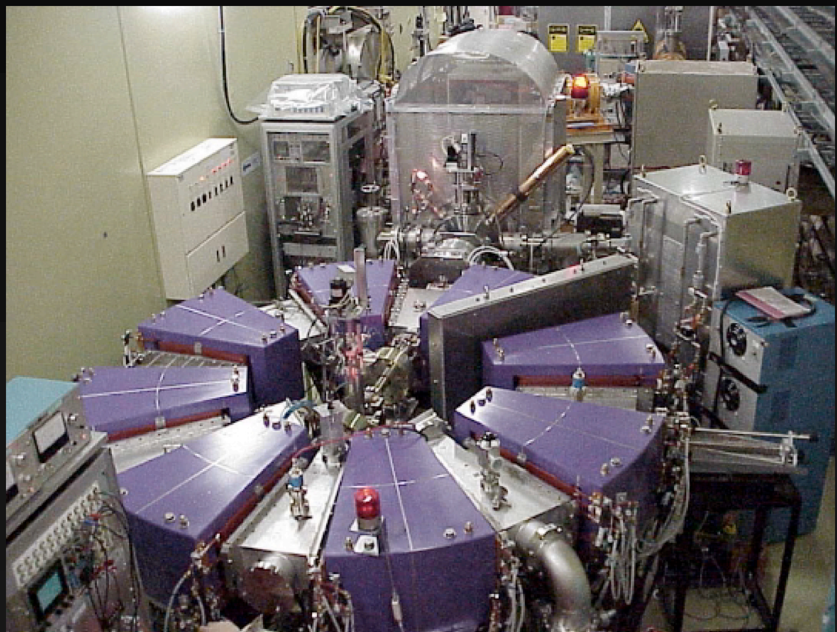
3-dimensional beam Simulation is studied.

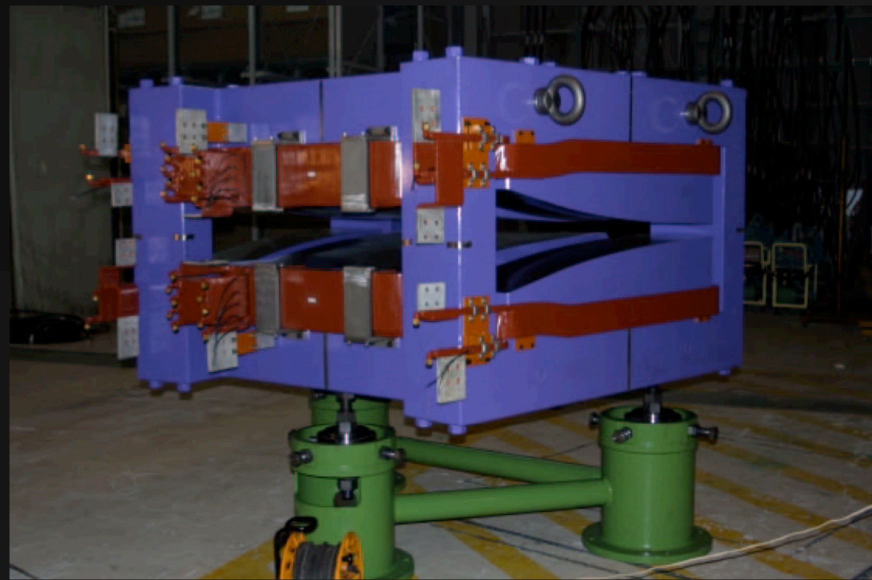
Realistic layout is studied.

Budget request has been made with 6 RFs.

FFAG R&D

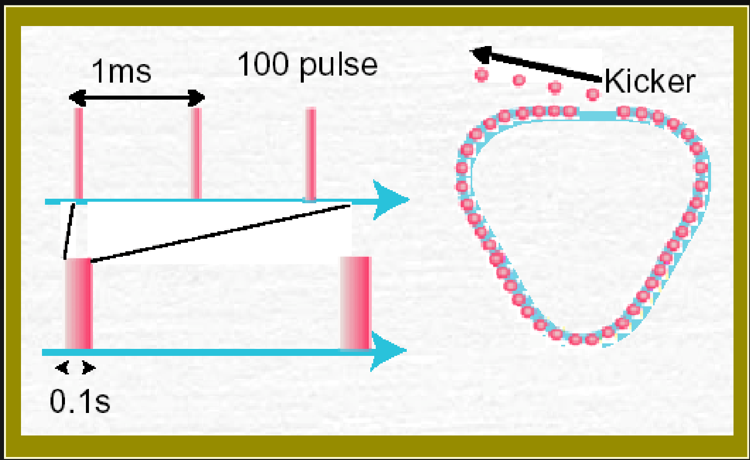
- 0.5-MeV Proton FFAG at KEK
- 150 MeV Proton FFAG at KEK
  - Under construction





Fast Extractionと実験室

- Fast Extraction of bunched proton beam
  - パルス幅< 10ns
  - 繰り返し=100Hz

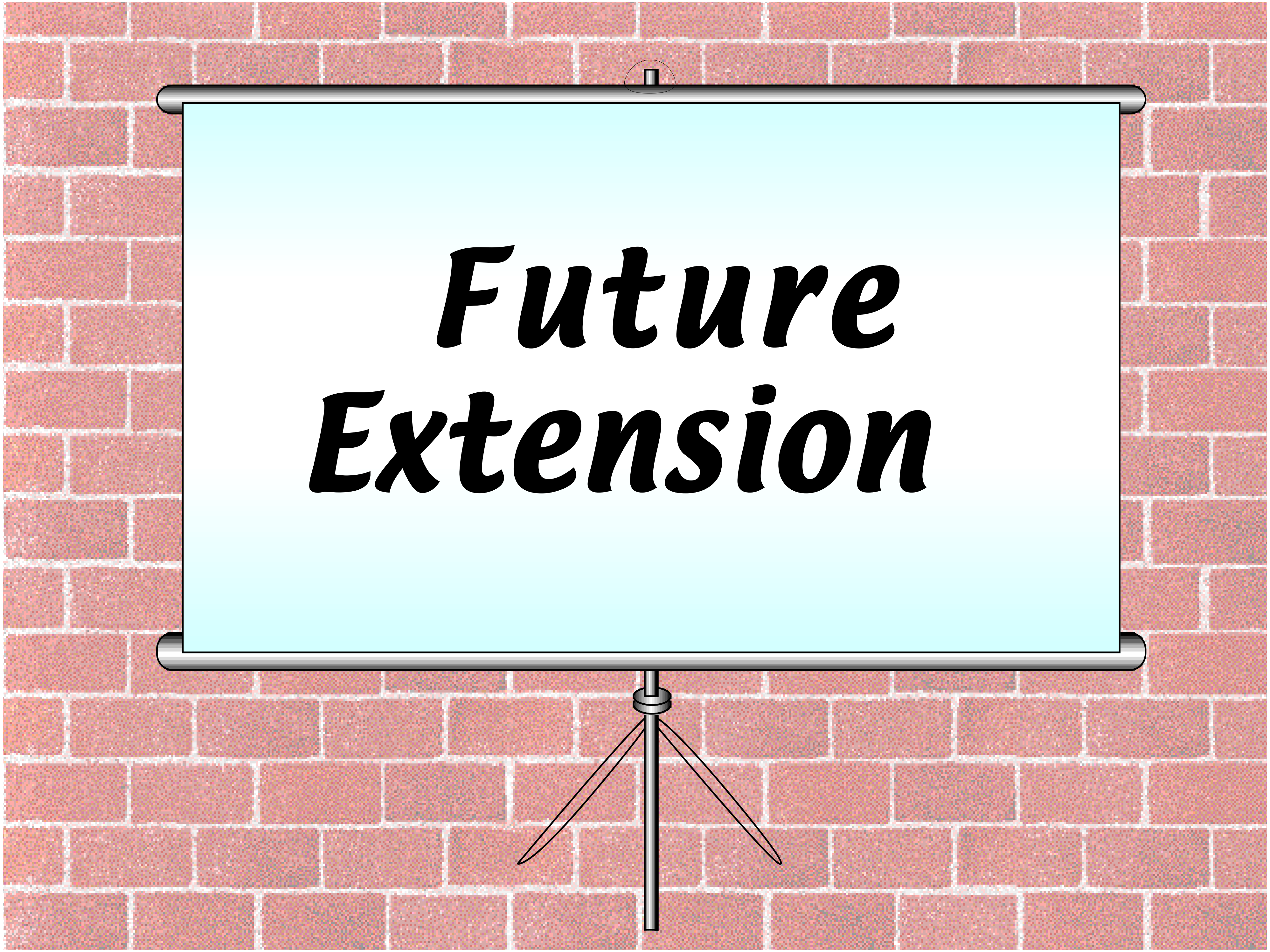


- Fast Extraction Exp. Hall（要求検討）

PRIME (=PRISM Mu E conversion)

- Advantages from PRISM
  - Pure muon beam
    - 10^{-18} pion survival
  - A thinner target
    - Better e^{+} energy resolution
- Lower repetition rate (100 - 1000 Hz)
  - High instantaneous rate

Solutions:
(1) A longer distance
a) Curved (spiral) solenoid
(2) A longer time delay
b) electron storage ring


Future
Extension

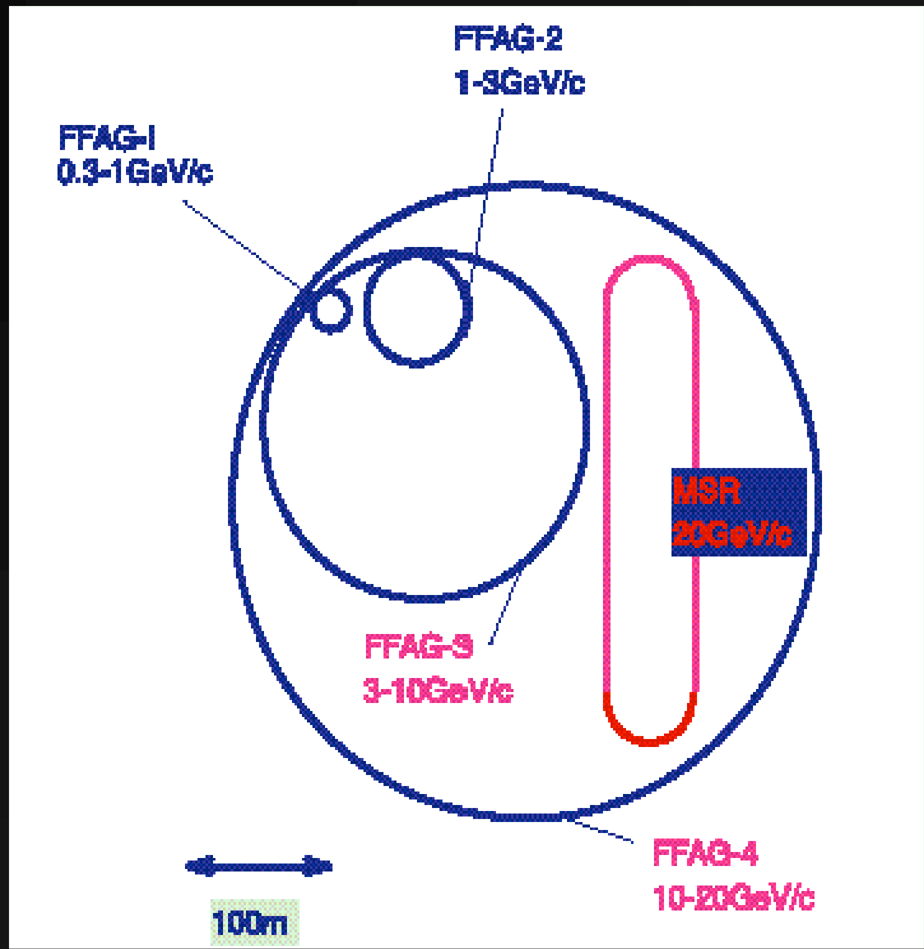
Future Extensions

- Muon Factory (PRISM)
  - Stopped muon experiments
- Muon Factory-II (PRISM-II)
  - Muon moments
- Neutrino Factory
  - Based on 1 MW proton beam
- Neutrino Factory-II
  - Based on 4.4 MW proton beam
- (Muon Collider)

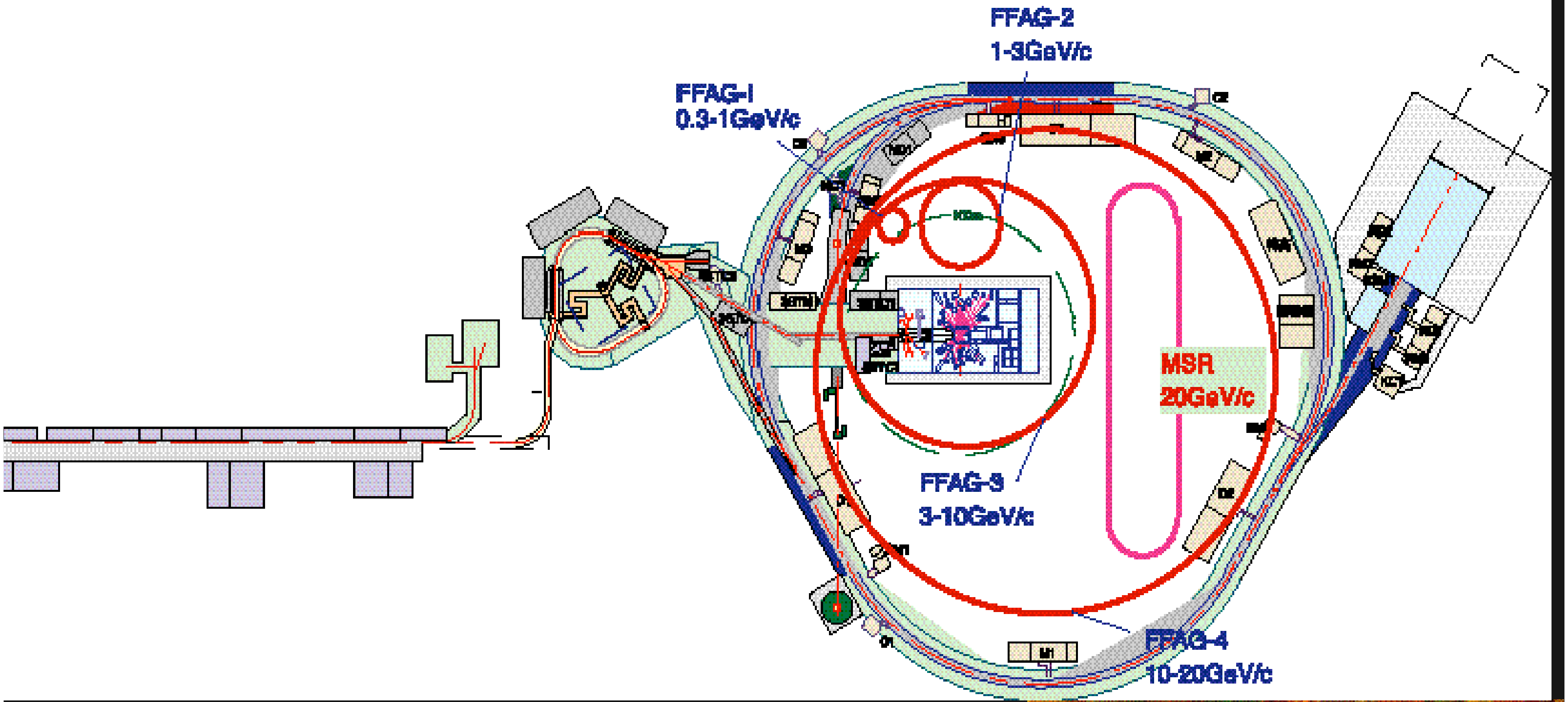
Physics outcome at each stage

FFAG-based Neutrino Factory

- FFAG acceleration
  - No muon ionization cooling
- Advantages
  - Costs saving
  - Simple, compact
  - Earlier readiness



FFAG-based Neutrino Factory



Flavor Physics

	quarks	squarks
	$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & [illegible] & V_{tb} \end{pmatrix}$	$\begin{pmatrix} \tilde{m}_e^2 & \tilde{m}_{12}^2 & \tilde{m}_{13}^2 \\ [illegible] & \tilde{m}_{\mu}^2 & \tilde{m}_{23}^2 \\ [illegible] & [illegible] & \tilde{m}_{\tau}^2 \end{pmatrix}$
neutrinos (RH)	**neutrinos (LH)**	**sleptons**
$\begin{pmatrix} Y_{11}e^{i\phi_1} & & \\ & Y_{22}e^{i\phi_2} & \\ & & Y_{33}e^{i\phi_3} \end{pmatrix}$	$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} 1 \\ e^{i\phi_1} \\ e^{i\phi_2} \end{pmatrix}$	$\begin{pmatrix} \tilde{m}_e^2 & \tilde{m}_{12}^2 & \tilde{m}_{13}^2 \\ \tilde{m}_{21}^2 & \tilde{m}_{\mu}^2 & \tilde{m}_{23}^2 \\ \tilde{m}_{31}^2 & \tilde{m}_{32}^2 & \tilde{m}_{\tau}^2 \end{pmatrix}$

Neutrino oscillation

?
CPV in LFV /EDM?

Muon Lepton Flavor violation

Leptogensis

まとめ

- Muon Lepton Flavor Violation, in particular □-e conversion, has large discovery potential.
- Highly intense proton beam at the 50-GeV PS will provide good opportinity.
- Highly intense muon source, PRISM, (our original idea) is needed to construct.
- PRISM could be extended to a future neutrino factory.