Lepton Flavor Violation
- Experimental -

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Overview

- Introduction
- $|\Delta L_i|=1$
  - $\mu \rightarrow e\,\gamma$ (MEG)
  - $\mu \rightarrow e$ conversion (MECO)
  - PRISM
- $|\Delta L_i|=2$
- Muon Factory
- Summary

Introduction

Lepton Flavor Violation

Obviously LF is Violated for neutrinos.
LFV referes to LFV for charged leptons.

- $|\Delta L_i| = 1$
  - $\mu \to e\,\gamma$, $\mu \to 3e$, $\mu^- A \to e^- A$
  - $\tau \to \mu\,\gamma$, $\mu A \to \tau A'$
  - $K_L \to e\,\mu$, $K_L \to \pi^0\, e\,\mu$, $K^+ \to \pi^+\, e\,\mu$
  - $e\,e \to e\,\mu\,\tilde{\chi}^0\,\tilde{\chi}^0$
- $|\Delta L_i| = 2$
  - $\mu^+ e^- \to \mu^- e^+$ $|\Delta L| = 0$
  - $A \to e\,e\,A'$, $\mu^- A \to e^+ A'$, $\mu^- A \to \mu^+ A'$ $|\Delta L| = 2$

Recent Limits

Reaction	90% CL Upper Limit
$\mu^+ \to e^+ \gamma$	1.2×10^{-11}
$\mu^+ \to e^+ e^- e^+$	1.0×10^{-12}
$\mu^- Ti \to e^- Ti$	4.3×10^{-12}
$\mu^- Pb \to e^- Pb$	4.6×10^{-11}
$\mu^- Au \to e^- Au$	$4.4 \sim 6.8 \times 10^{-13}$
$\mu^- Ti \to e^+ Ca$	3.6×10^{-11}
$\mu^- e^+ \to \mu^+ e^-$	8.3×10^{-11}
$\tau \to e \gamma$	2.7×10^{-6}
$\tau \to \mu \gamma$	1.1×10^{-6}
$\tau \to e\, e\, e$	2.9×10^{-6}
$\tau \to \mu\, \mu\, \mu$	1.9×10^{-6}
$K_L \to \mu e$	4.7×10^{-12}
$K_L \to \pi^0 \mu e$	6.2×10^{-9}
$K^+ \to \pi^+ \mu e$	2.8×10^{-11}
$D^0 \to \mu e, \varphi \mu e$	8.1×10^{-6}, 3.4×10^{-5}
$B \to \mu e, K \mu e$	1.5×10^{-6}, 8×10^{-7}
$Z \to \mu e, \tau e, \tau\mu$	1.7×10^{-6}, 9.8×10^{-6}, 1.2×10^{-5}
$J/\psi \to \mu \tau, e \tau$	2.0×10^{-6}, 8.3×10^{-6}

- **Muon provides most sensitive limits**
  - **Large number of muons available at Meson Factories**
  - **Relatively longer muon life time**

    $\tau_\mu = 2.2\ \mu s$

    $\tau_K = 12\ ns$

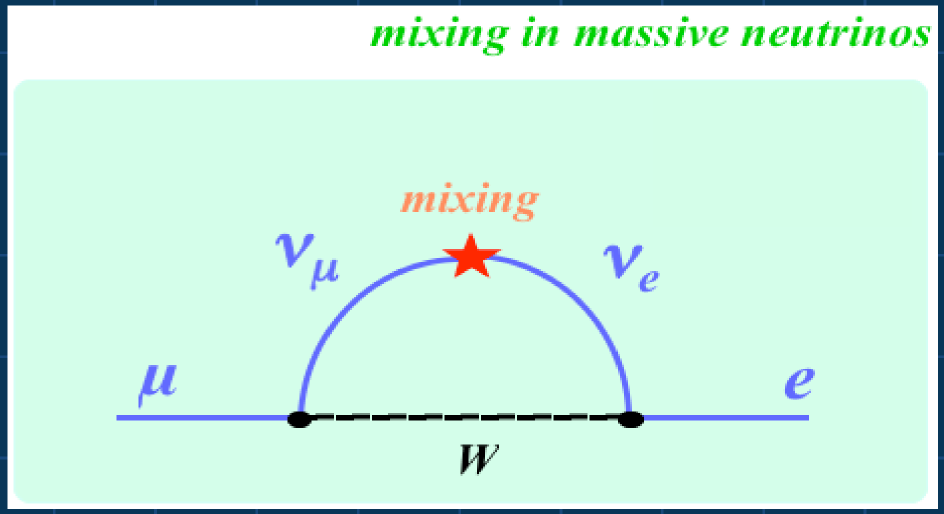
Muon
Lepton Flavor Violation
- Experimental -

$$|\Delta L_i| = 1$$

ν Oscillation & Muon LFV

Lepton Flavor is already **VIOLATED** at ν sector.

- **ν contribution to muon LFV process**



- **GIM suppression**

$$B(\mu \to e\gamma) =$$

$$\frac{3\alpha}{32\pi}\sum_i \left| U_{\mu i} U^*_{ei} \frac{m^2_{\nu_i}}{M^2_W} \right|^2 \simeq 16^{-60} \left(\frac{m_\nu}{10^{-2}\,\mathrm{eV}} \right)^4$$

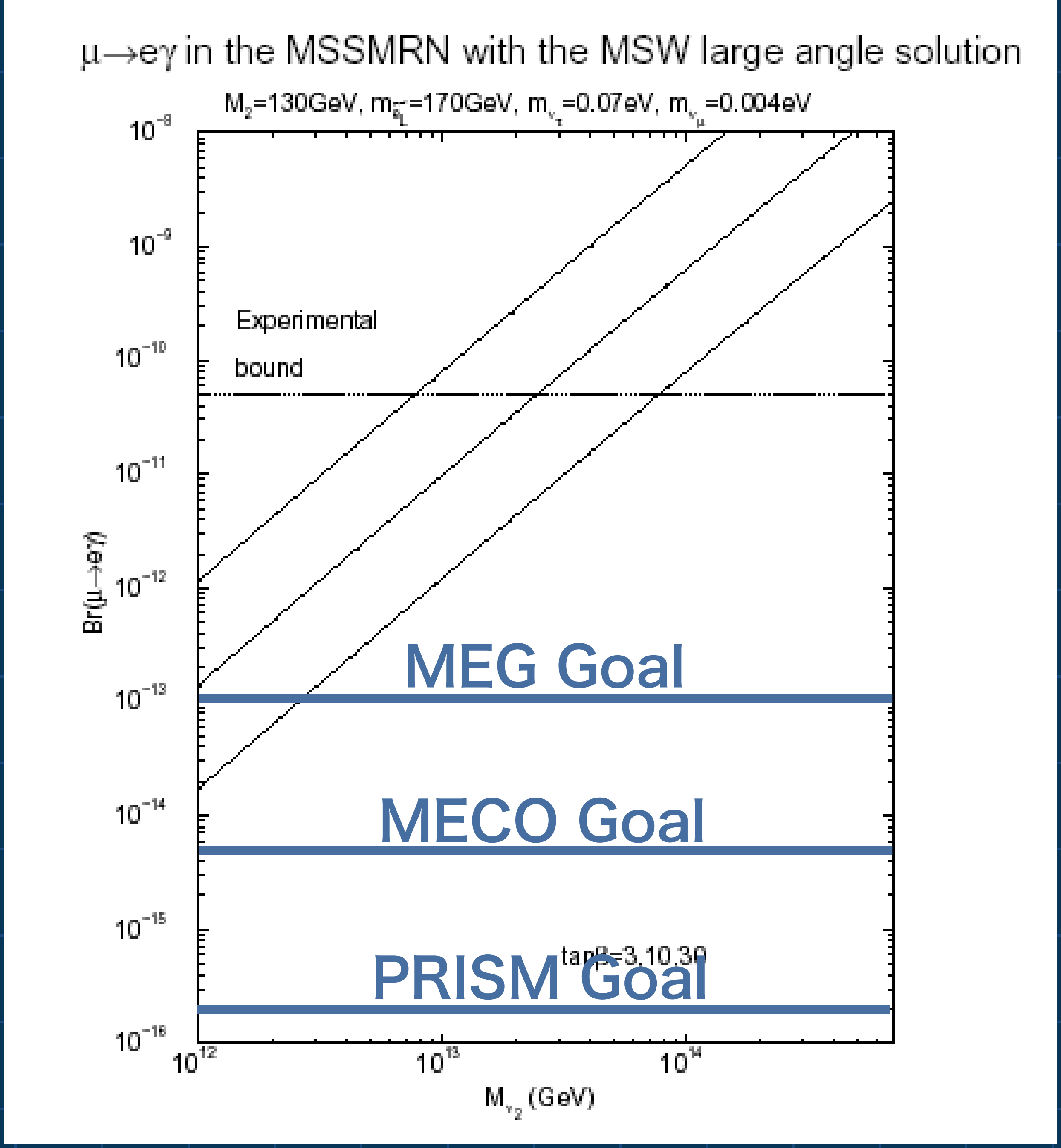
Very small

Muon LFV indicates a physics beyond the simple ν oscillation

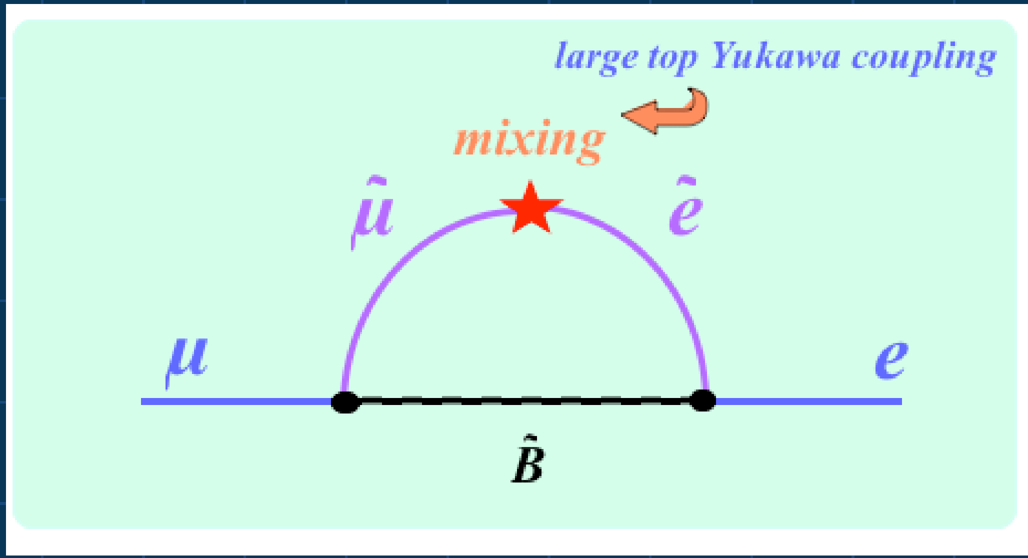
SUSY with RH Majorana neutrino

- **SUSY + See-Saw**
- **Solar neutrino**
  MSW large angle

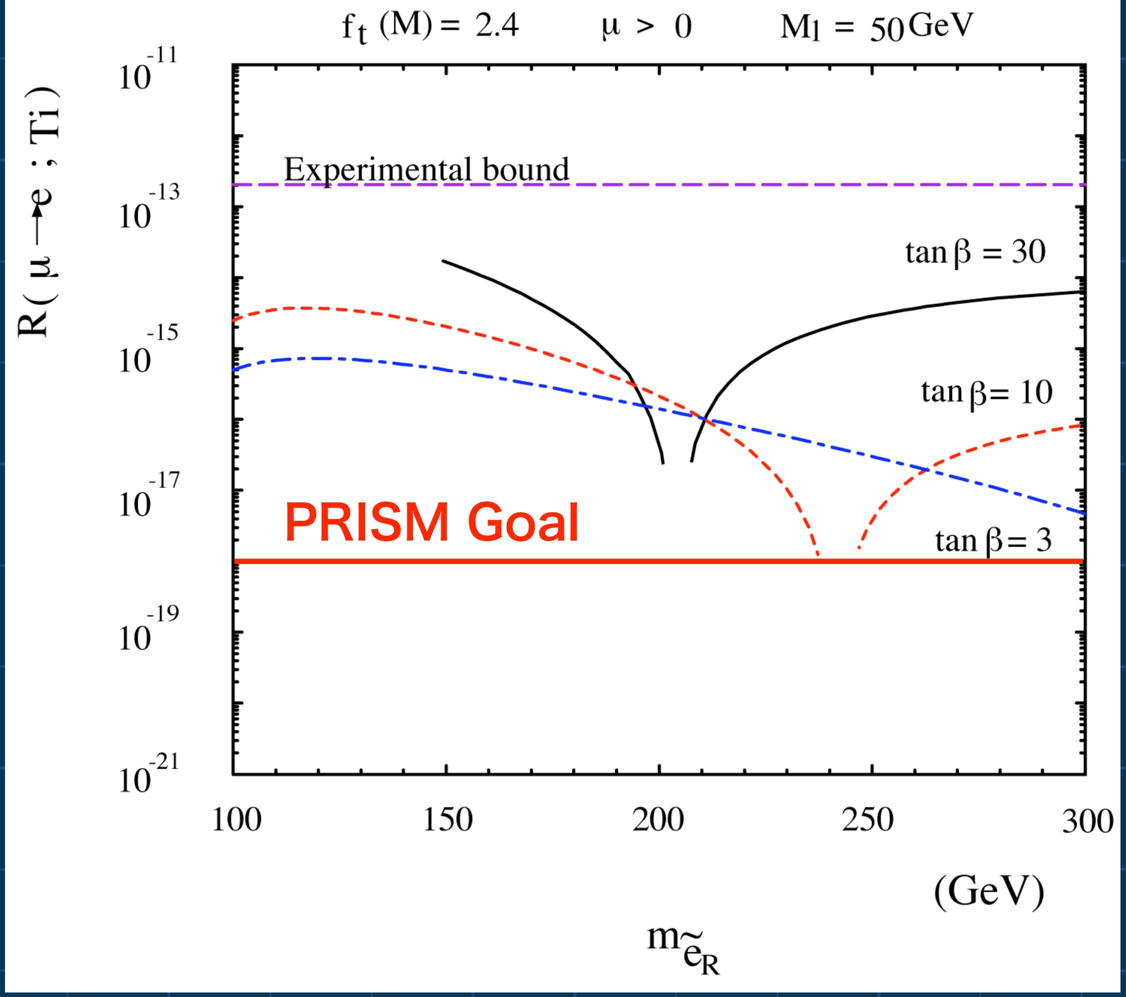
μ-LFV provides a clue to the ν oscillation



SUSY-GUT Prediction

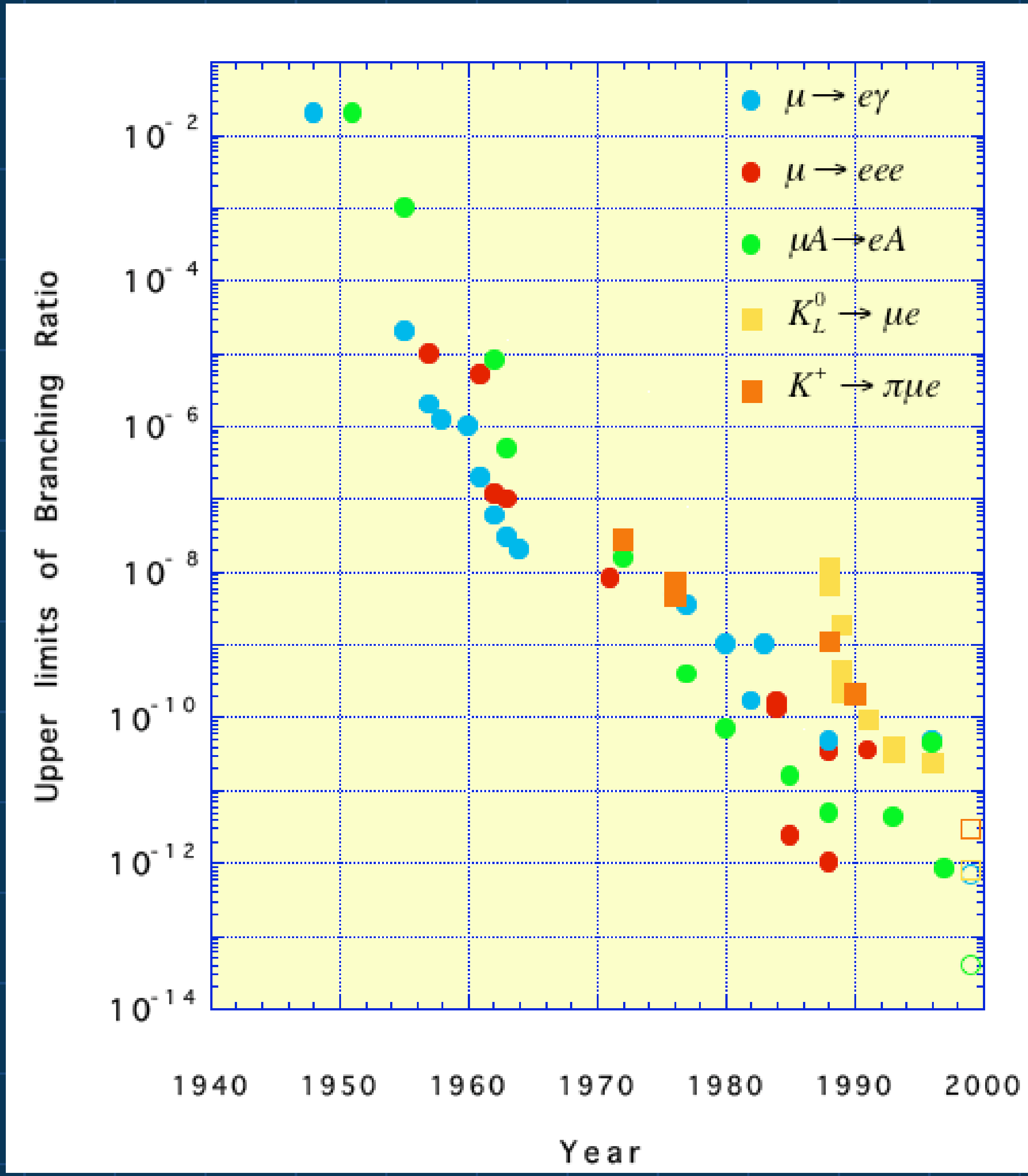


Process ~	Current Limit	SUSY-GUT level	Future Exp.
μ N → e N	10^{-13}	10^{-16}	10^{-18}(1)
μ → e γ	10^{-11}	10^{-14}	10^{-13}(2)
τ → μ γ	10^{-6}	10^{-9}	10^{-8} (3)
e e → τ μ 2χ⁰	-	1 ab	$1\ ab^{-1}$(4)



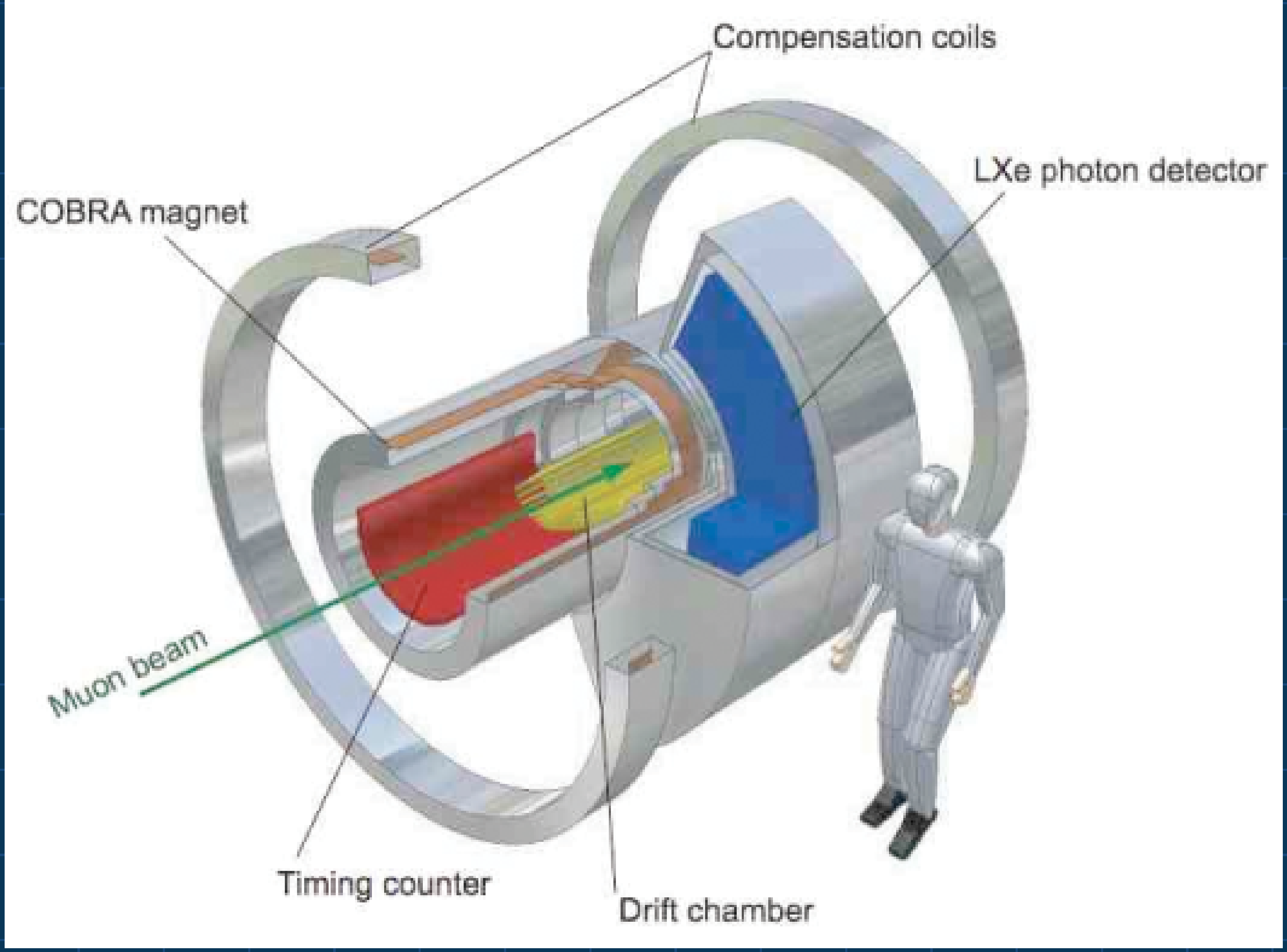
(1) PRISM
(2) MEG
(3) Super-B
(4) LC

New Generation of μ-LFV Experiments



- **MEG**
  - **BR($\mu^+ \to e^+ \gamma$) < 10^{-13}**
- **MECO**
  - **BR($\mu^- N \to e^- N$) < 10^{-16}**
- **PRISM**
  - **BR($\mu^- N \to e^- N$) < 10^{-18}**

MEG @ PSI

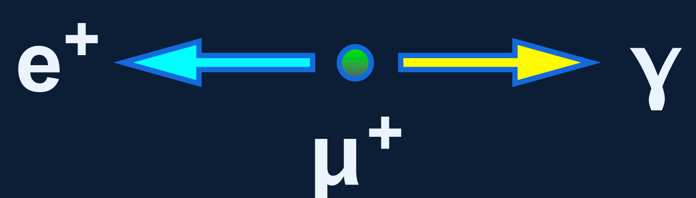


- $\mu^+ \to e^+ \gamma$
  - ICEPP, KEK, Waseda U., INFN, PSI, Budker Inst.
  - PSI-πE5 Beam Line
  - R_μ: 0.2-0.3 x 10^8 /s
  - Run: 2006-
  - Running Time: 4 x 10^7 s
  - S.E.S.: 4 x 10^{-14}

Signal and Background

signal

$\mu^+ \rightarrow e^+ \gamma$



$\theta_{e\gamma} = 180°$

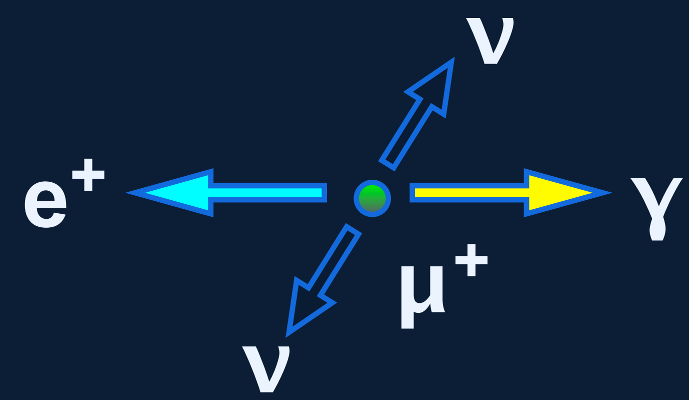
$E_e = E_\gamma = 52.8$ MeV

$T_e = T_\gamma$

background

correlated

$\mu \rightarrow e \gamma \nu \nu$



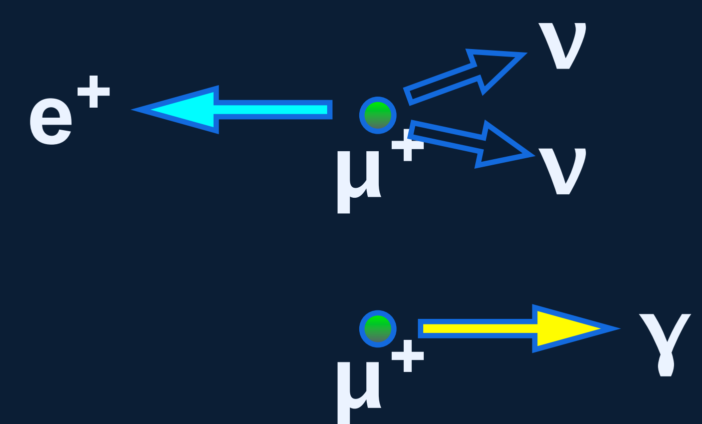
accidental

$\mu \rightarrow e \nu \nu$

$\mu \rightarrow e \gamma \nu \nu$

$ee \rightarrow \gamma \gamma$

$eZ \rightarrow eZ \gamma$



Required Performances

Accidental Background Limited

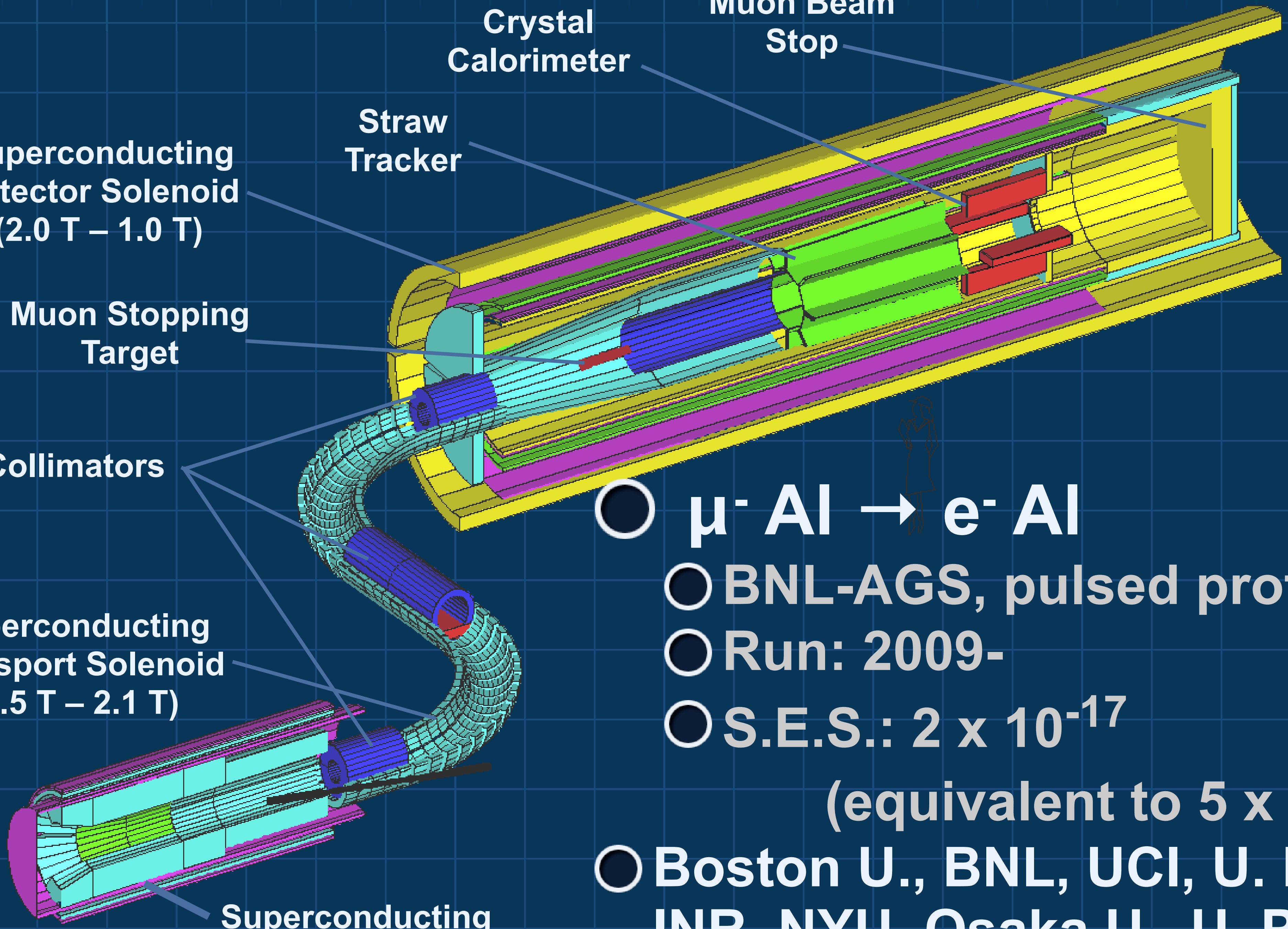
$$BR_{\mathrm{acc}} \propto R_\mu \times \Delta E_e \times \Delta E_\gamma^2 \times \Delta\theta_{e\gamma}^2 \times \Delta t_{e\gamma}$$

FWHM

Exp./Lab	Year	ΔEe/Ee (%)	ΔEγ /Eγ (%)	Δteγ (ns)	Δθeγ (mrad)	Stop rate (s-1)	Duty cyc.(%)	BR (90% CL)
SIN	1977	8.7	9.3	1.4	-	5×10^5	100	3.6×10^{-9}
TRIUMF	1977	10	8.7	6.7	-	2×10^5	100	1×10^{-9}
LANL	1979	8.8	8	1.9	37	2.4×10^5	6.4	1.7×10^{-10}
Crystal Box	1986	8	8	1.3	87	4×10^5	(6..9)	4.9×10^{-11}
MEGA	1999	1.2	4.5	1.6	17	2.5×10^8	(6..7)	1.2×10^{-11}
MEG	2007	0.7	4.5	0.1	19	2.5×10^7	100	1×10^{-13}

- **Liquid Xenon calorimeter** (scintillation)
- DC beam @PSI

MECO @ BNL-AGS

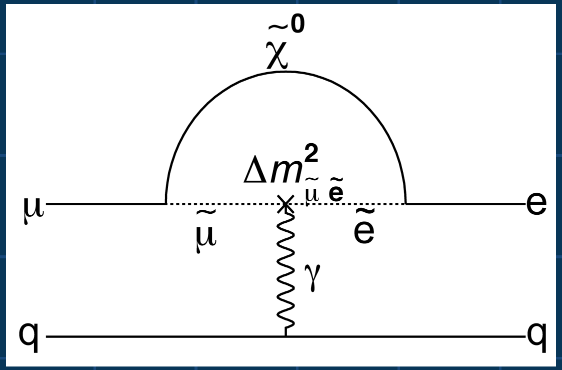


- $\mu^- Al \rightarrow e^- Al$
  - BNL-AGS, pulsed proton beam
  - Run: 2009-
  - S.E.S.: 2×10^{-17}

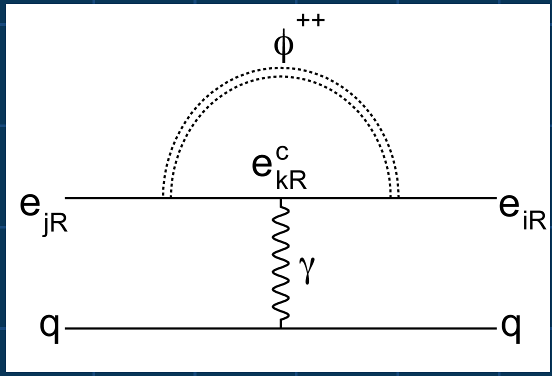
    (equivalent to 5×10^{-15} of $\mu \rightarrow e\gamma$)
- Boston U., BNL, UCI, U. Houston, UMA, INR, NYU, Osaka U., U. Pennsylvania, Syracuse U., CWM

Models: $\mu^- N \rightarrow e^- N$

- **SUSY-GUT (photonic process)**
  - **BR ~ 10^{-15}**

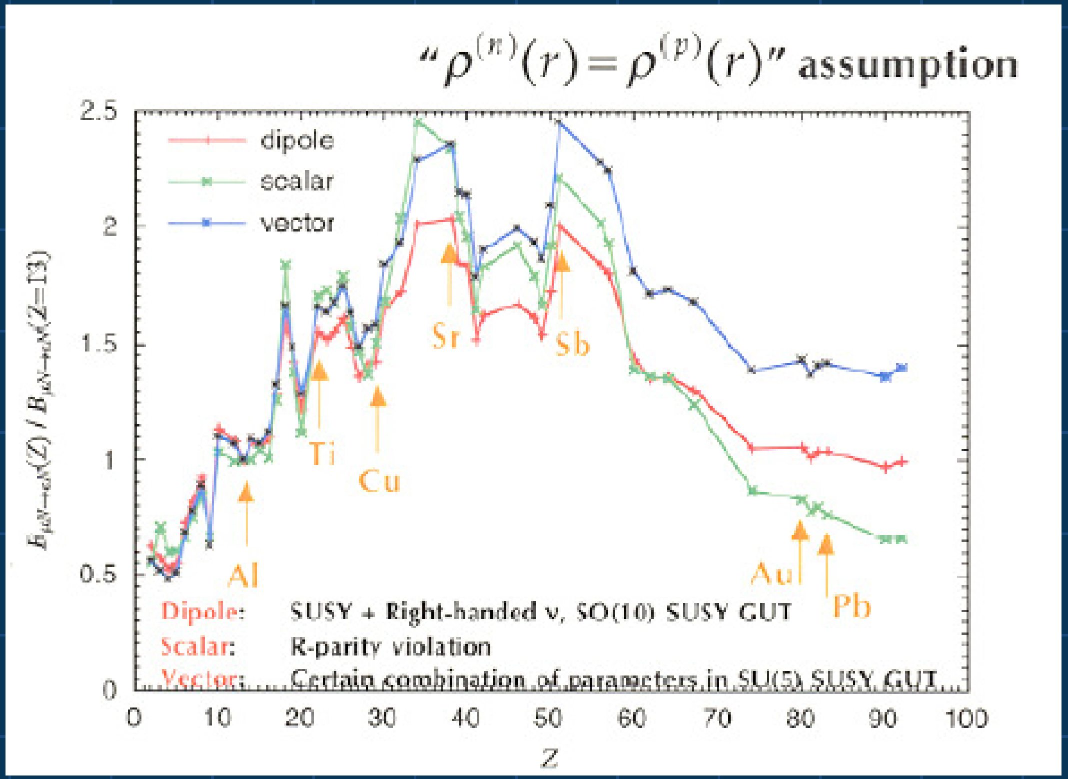


- **Doubly Charged Higgs Boson**



  - **Logarithmic enhancement in a loop diagram for $\mu^- N \rightarrow e^- N$, not for $\mu \rightarrow e\gamma$**
    - M. Raidal and A. Santamaria, PLB 421 (1998) 250

- **SUSY with R-parity Violation**
- **Leptquarks**
- **Heavy Z'**
  - $M_{Z'} > (5\text{-}100)$ TeV for $R_{\mu e} \sim 10^{-16}$
    - J. Bernabeu et al., NPB 409 (1993)69-86
- **Compositeness**
- **Multi-Higgs Models**
- **Higgs-Mediated**



Signal

- Muonic atom (1s state)

- Neutrinoless muon nuclear capture

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

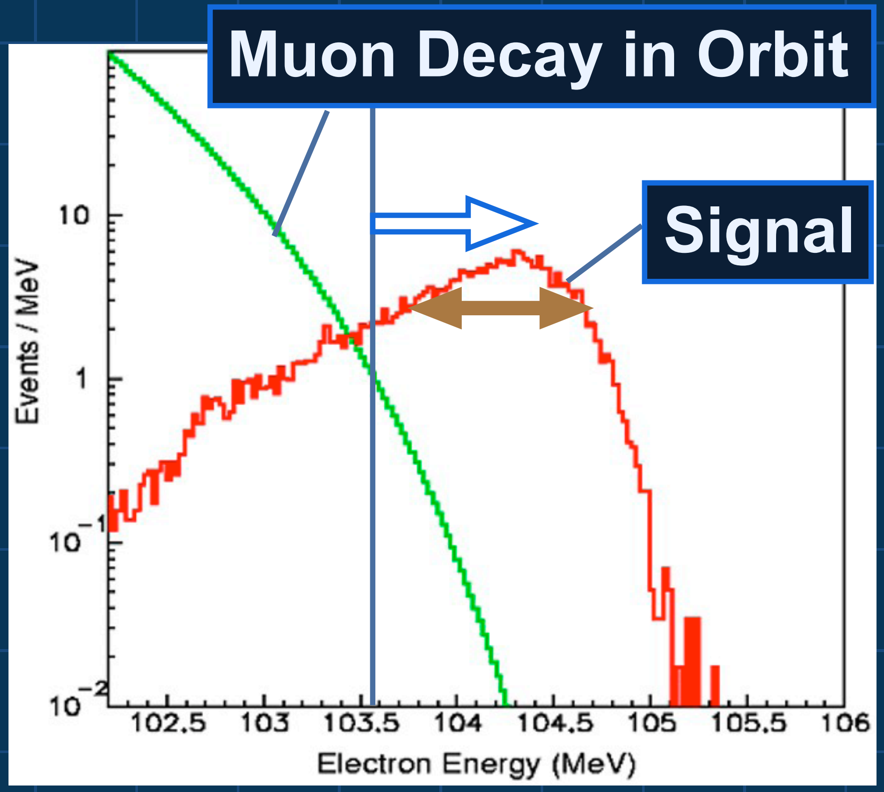
  - Single mono-energetic e^-: $E_e = (M_\mu - B_\mu)$ MeV (~105 MeV)
  - Rate is normalized to the kinematically similar weak capture process:

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

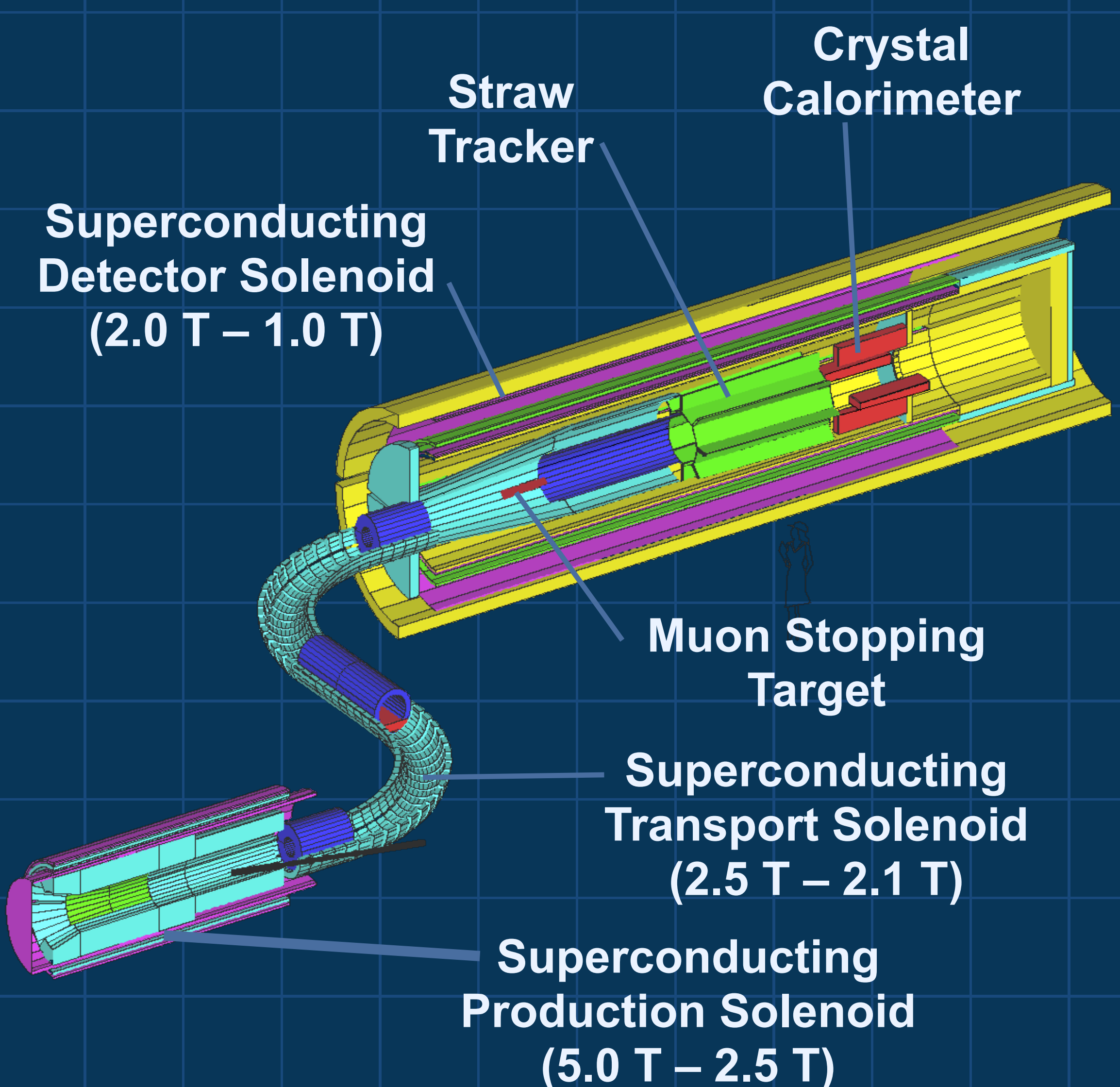
Potential Backgrounds

- **No Accidental Background**
-
- **Muon Decay in Orbit**
  - $E_{max} = E_e$, $dN/dE_e \propto (E_{max} - E_e)^5$
  - ΔE_e=900 keV FWHM

    N_{bg} = 0.25 for $R_{\mu e}=2 \times 10^{-17}$
  -
- **Radiative Pion Capture**
  - Limits allowed pion contamination in beam during detection time window.
- **Radiative Muon Capture**



Detector Outline



- **Solenoid Pion Capture**
  - 1000 fold increase of muon rate
- **Pulsed Proton Beam**
  - Eliminate prompt background.
- **Good Detector Resolution and Large Acceptance**
  - Graded field around target
  - Long detector solenoid
  - Straw Tracker
- **Optimized target thickness**
  - Energy loss uncertainty
  - Muon stopping power

$\mu^- N \rightarrow e^- N$ vs. $\mu \rightarrow e\gamma$

$\mu^- N \rightarrow e^- N$

• Sensitive to non-photonic process

• Require new beam line
• No accidental background.

$\mu \rightarrow e\gamma$

• $B(\mu \rightarrow e\gamma) = 200 \times B(\mu^- N \rightarrow e^- N)$
for photonic process

Strong physics motivation for both

• Existing surface muon beam
• Rate-limited due to accidental background.

Possibly different systematics,
thus complementary each others.
Both should be done to maximize discovery potential

New muon beam will boost the experiment further more.

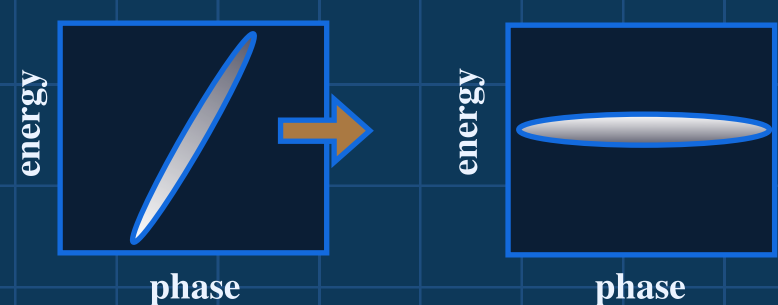
- narrow p_μ spread
- thiner target

PRISM

Phase-Rotated Intense Slow Muon source

Accelerator Technology

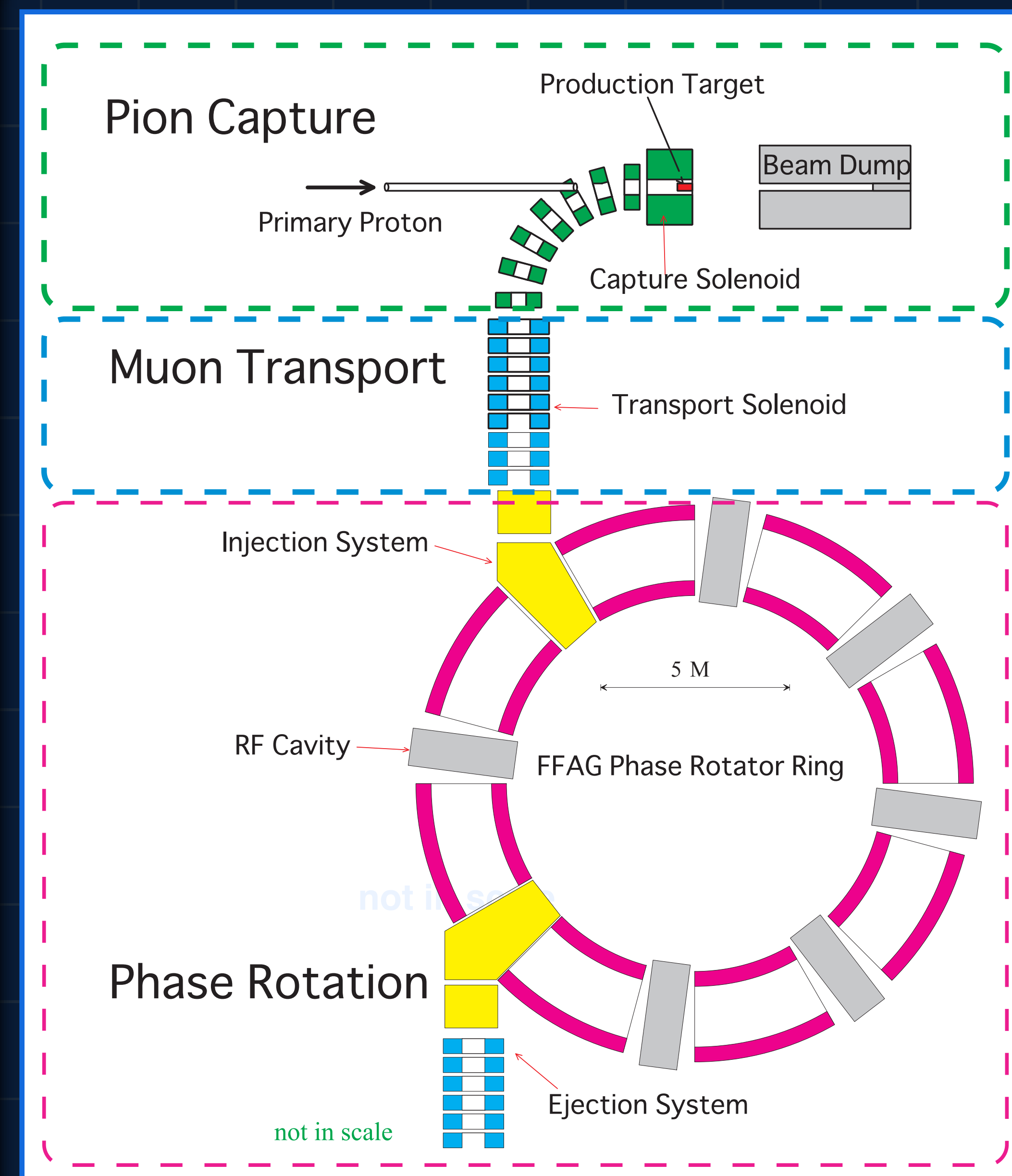
- **High Intensity**
  - 10^{11} - 10^{12} $\mu^{\pm}$ / sec
- **High Brightness**
  - Phase Rotation
    dp/p:±20% → ±2%



- **High Purity**

BR(μ N → e N) < 10^{-16}

→ BR(μ N → e N) < 10^{-18}

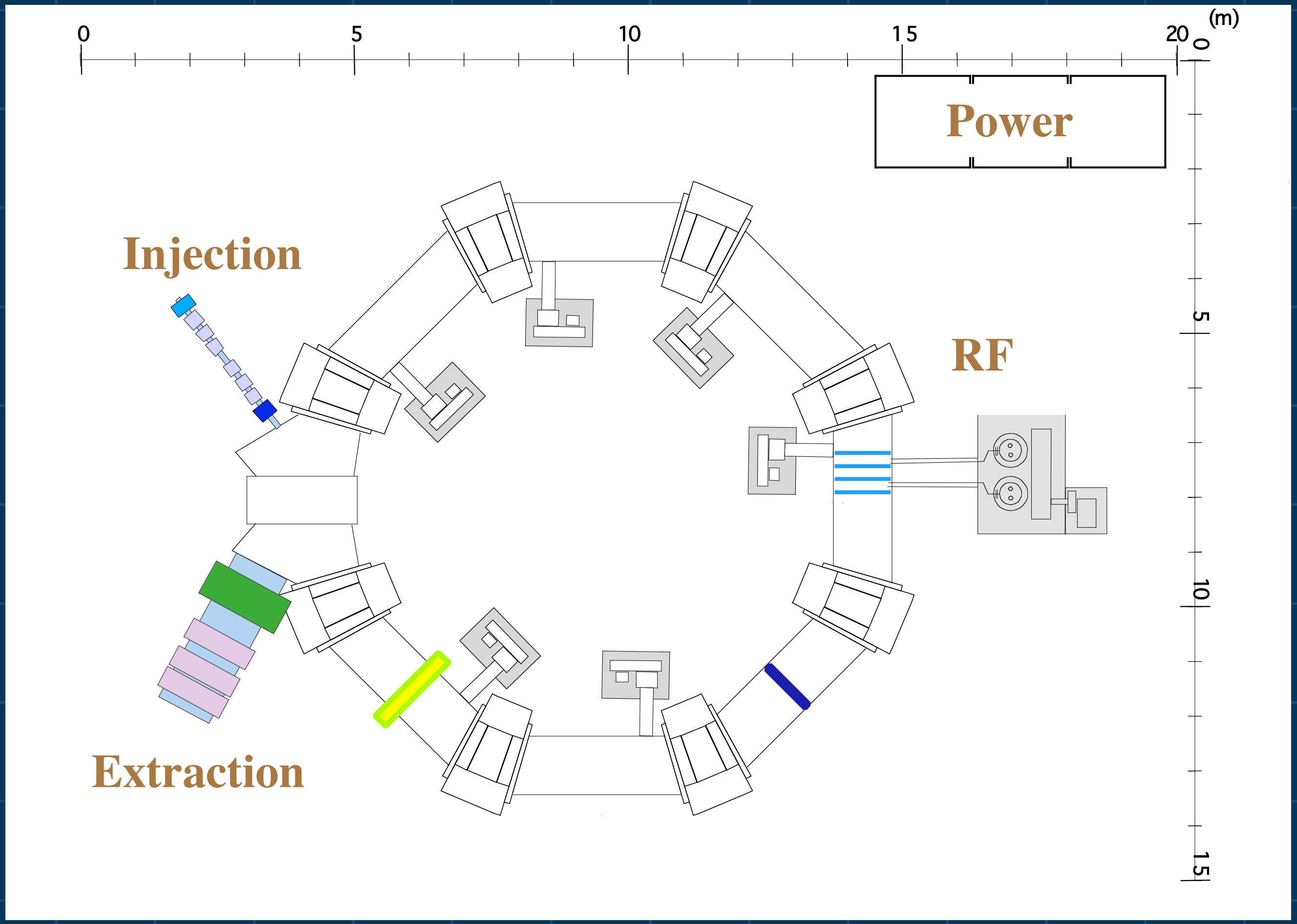


PRISM-Phase-Rotator Development

AWARDED Grant-in-Aid for Creative Scientific Research
A Study of A Super Muon Beam for New initiative on Muon Physics
Five-years termed JFY2003 ~ JFY2007

- **Prove**
  - **Phase Rotation**
  - **Ionization Cooling**
  -
- **Schedule**
  - **2003 : RF-PS development**
    Mag. design
  - **2004 : RF test**
    Mag. prototyping
  - **2005 : Mag. construction**
    Ring construction
  - **2006 : Commissioning**
  - **2007 : Phase Rotation Test**
    Cooling Test

Install to J-PARC



$$|\Delta L_i| = 2$$

$|\Delta L|=2$

Majorana nature of ν

- $N \to e\, e\, N'$
- $\mu^- N \to e^+ N'$ Conversion
  - MECO by-product: $BR(\mu^- N \to e^+ N') \sim 10^{-17}$
  - Correponding Kaon Process: $K^+ \to \pi^- \mu^+ e^+$
    BNL-E865 result: $BR(K^+ \to \pi^- \mu^+ e^+) = 5.0 \times 10^{-10}$
    equivalents to $BR(\mu^- N \to e^+ N') \sim 3 \times 10^{-11}$

L.S. Littenberg and R. Shrock, PLB 491(2000)285-290

- $\mu^- N \to \mu^+ N'$ Conversion J.H.Missimer *et al.* PRD50(1994)2067-2070
  - BNL-E865 result: $BR(K^+ \to \pi^- \mu^+ \mu^+) = 3.0 \times 10^{-9}$
  - No direct measurements yet.
  - R-parity violating SUSY: 5×10^{-9} y ($BR \sim 10^{-24}$)
  - Need radioact

    high inte   tness μ^- beam

PRISM

Muon
Lepton Flavor Violation
- Experimental -

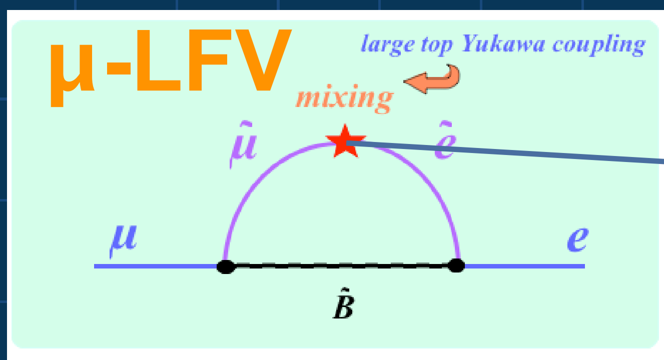
Muon
Lepton Flavor Violation
and
Other Muon Physics
- Experimental -

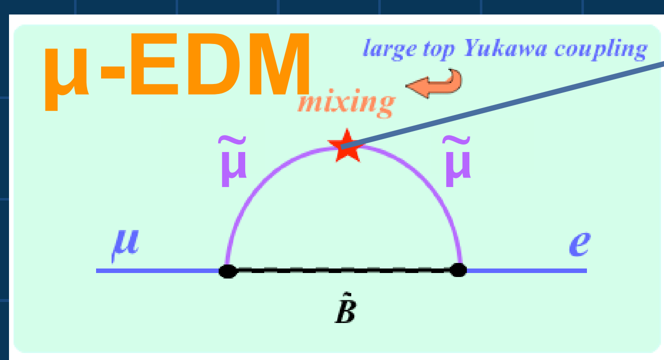
Leptogenesis

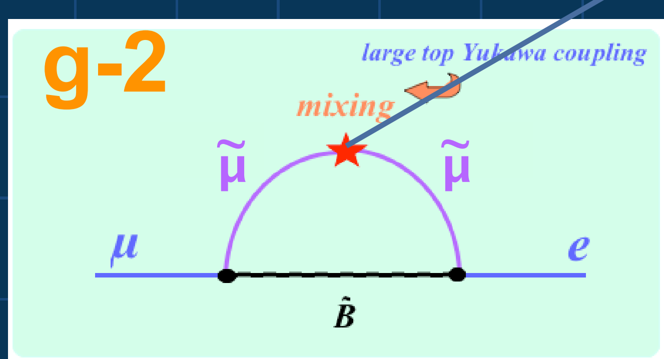
- CPV in CKM is not enough to explain Baryon Asymmetry
  → New sources of CPV beyond the SM
- ν Oscillation + CPV in lepton sector
  → leptogenesis (Fukugida & Yanagida '86)
- AND if SUSY exists →
  - T-violation in muon LFV
  - muon EDM

⇒ Imaginary part slepton mass matrix

SUSY Mass Matrix



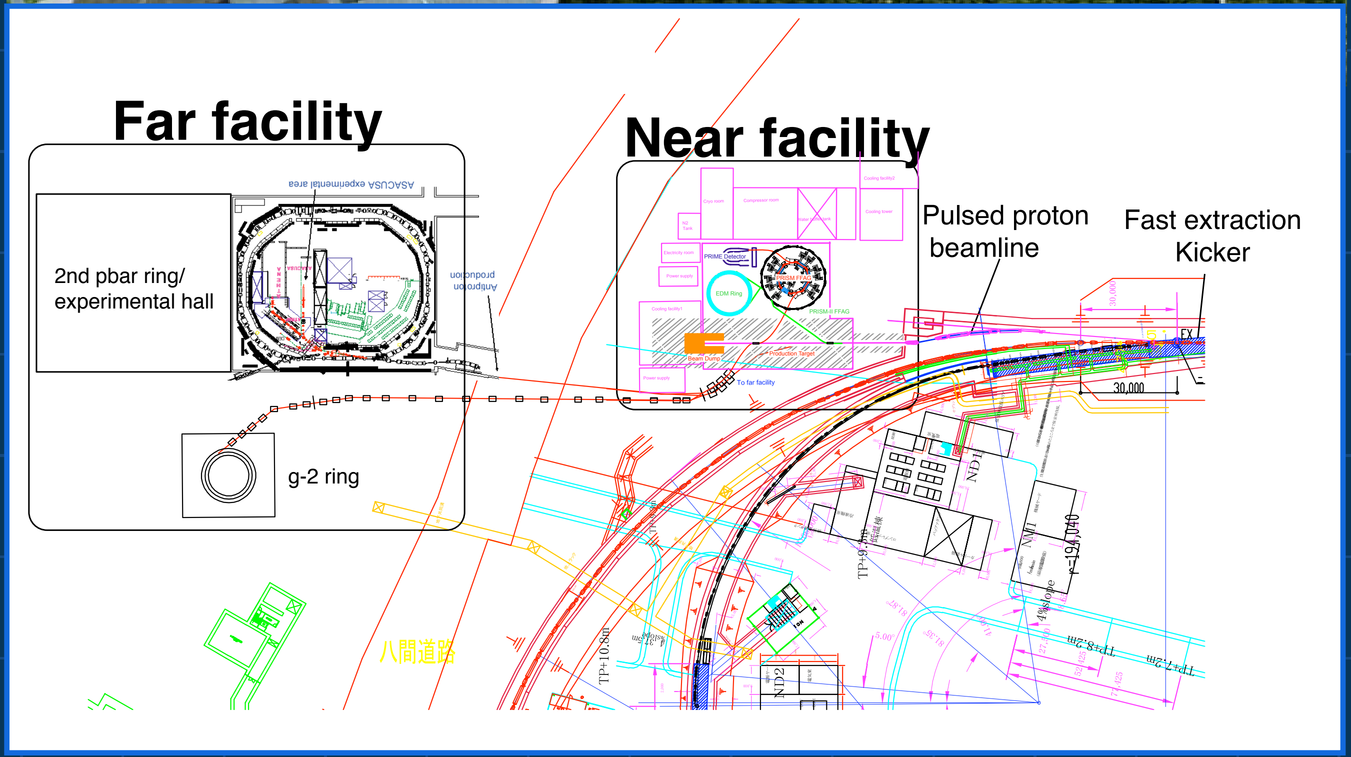




$$\begin{pmatrix} m^2_{\tilde{e}\tilde{e}} & \Delta m^2_{\tilde{e}\tilde{\mu}} & \Delta m^2_{\tilde{e}\tilde{\tau}} \\ \Delta m^2_{\tilde{\mu}\tilde{e}} & m^2_{\tilde{\mu}\tilde{\mu}} & \Delta m^2_{\tilde{\mu}\tilde{\tau}} \\ \Delta m^2_{\tilde{\tau}\tilde{e}} & \Delta m^2_{\tilde{\tau}\tilde{\mu}} & m^2_{\tilde{\tau}\tilde{\tau}} \end{pmatrix}$$

- $a_\mu(\mathrm{Exp})-a_\mu(e^-e^+) = 2.7\sigma$ off
  - $d_\mu < 10^{-20}$ e.cm
- PRISM-II @ J-PARC
  - PRISM for 500 MeV/*c* muon
  - $d_\mu < 10^{-24}$ e.cm (LoI to J-PARC)

Muon Factory



- 1 MW 50 GeV PS
  - g-2: 0.05 ppm
- PRISM
  - $\mu^- N \to e^- N$: 10^{-18}
- PRISM-II
  - μ-EDM: 10^{-24} e.cm

Muon Beam Manipulation

Phase Rotation

Ionization Cooling

Muon Acceleration

- **Neutrino Factory**
  - θ_{13}, CPV, sign of δm^2
- **μ N → τ N' Conversion**

  S.N. Gninenko et al., Mod. Phys. Lett. A 17(2002) 1407-1417
  M. Sher et al., Phys. Rev. D 69(2004)017302

  - Yet another LFV
  - E_μ > 20 GeV, 10^{20} μ/year
  - 10^7 events for $B(\tau \rightarrow \mu\gamma)=10^{-7}$
    - Super-B: 10^{-8}, LHC: 10^{-7} (@100 fb^{-1})
  - Substantial background, though.

Summary

- Lepton Flavor Violation is interesting.
  - Relevant to ν oscillation physics
  - Predictions from SUSY-GUT
- Muon is a key for LFV
  - Stringent limits
  - Muon Trio (μ−LFV, μ−EDM, g−2)
  - Muon Acceleration: Load to Neutrino Factory
- PRISM, as a pathfinder toward the era of muon/neutrino factory

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