WG4: Slow Muon Physics

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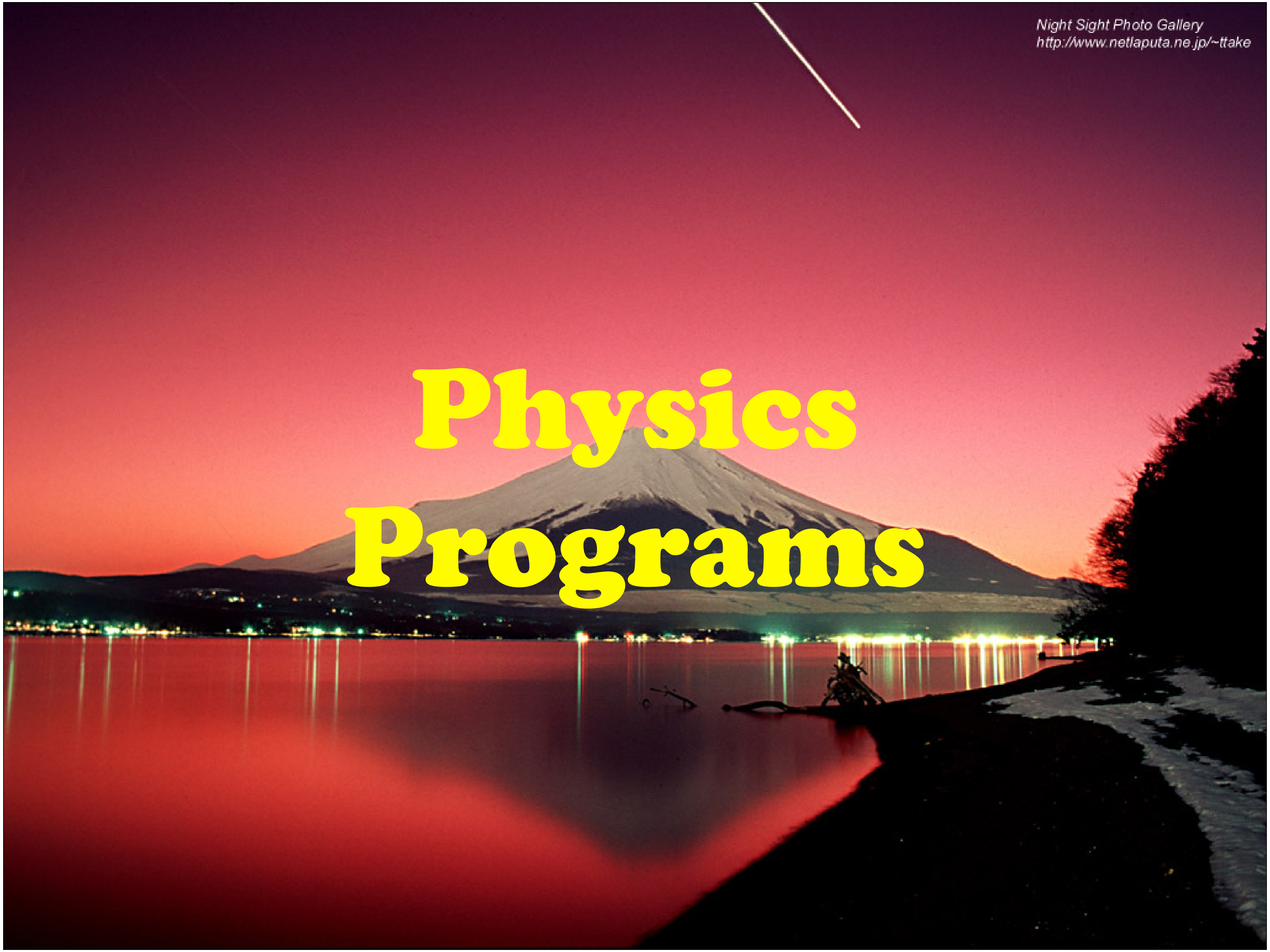
WG4 : Slow Muon Physics

- Outline
  - Physics Programs
  - Muon Trio
    - (Particle) Physics Motivation
    - Experimental
  - Muon Beams
  - Other topics

WG4: Conveners
Lee Roberts (Boston)
Marco Grassi (Pisa)
AKira Sato (Osaka)


Night Sight Photo Gallery
http://www.netlaputa.ne.jp/~ttake
Physics
Programs

Slow Muon Physics

Categories	Topics	Comments	Beams
Precision measurements	Muon lifetime	G_F	pulsed
	Muon g-2	New physics search	pulsed
Rare Muon processes	Muon EDM	SM suppressed	pulsed
	Charged lepton mixing	SM forbiden	pulsed / DC
Applications	Catalyzed fusion	Break even ?	pulsed
	Materials science		DC

Slow Muon Physics

Muon Trio

		Comments	Beams
	ne	G_F	pulsed
measurements	Muon g-2	New physics search	pulsed
Rare Muon processes	Muon EDM	SM suppressed	pulsed
	Charged lepton mixing	SM forbiden	pulsed / DC
Applications	Catalyzed fusion	Break even ?	pulsed
	Materials science		DC

Physics Motivation

Future Extrapolation

Muon g-2

$$0.7\text{ppm} \rightarrow 0.05 \text{ ppm}$$

Muon LFV

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

Muon EDM

$$d_\mu < 10^{-19} e \cdot cm \rightarrow d_\mu < 10^{-24} e \cdot cm$$

The Physics Case

... following the discussions at the FNAL proton driver workshop (a la Lee Roberts)

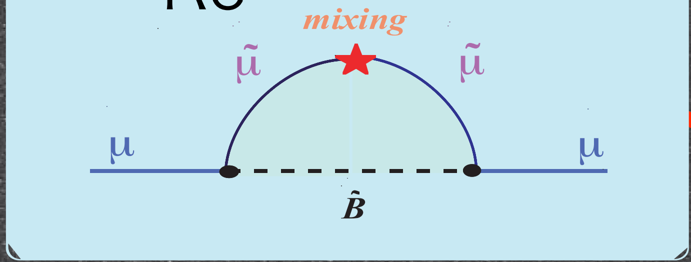
Scenario 1 :
LHC finds SUSY

All three in the trio have significant contributions from SUSY.

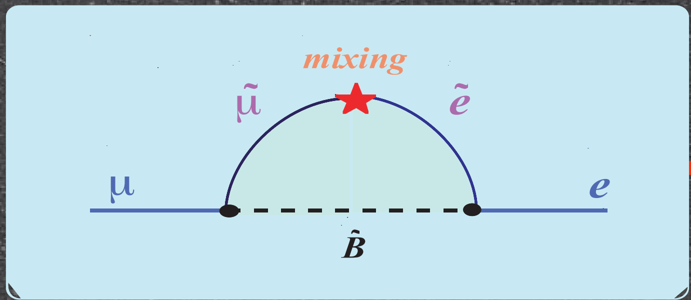
The Muon Trio

Muon g-2

Re

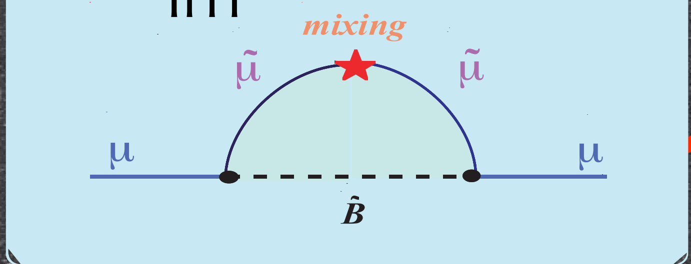


Muon LFV



Muon EDM

Im



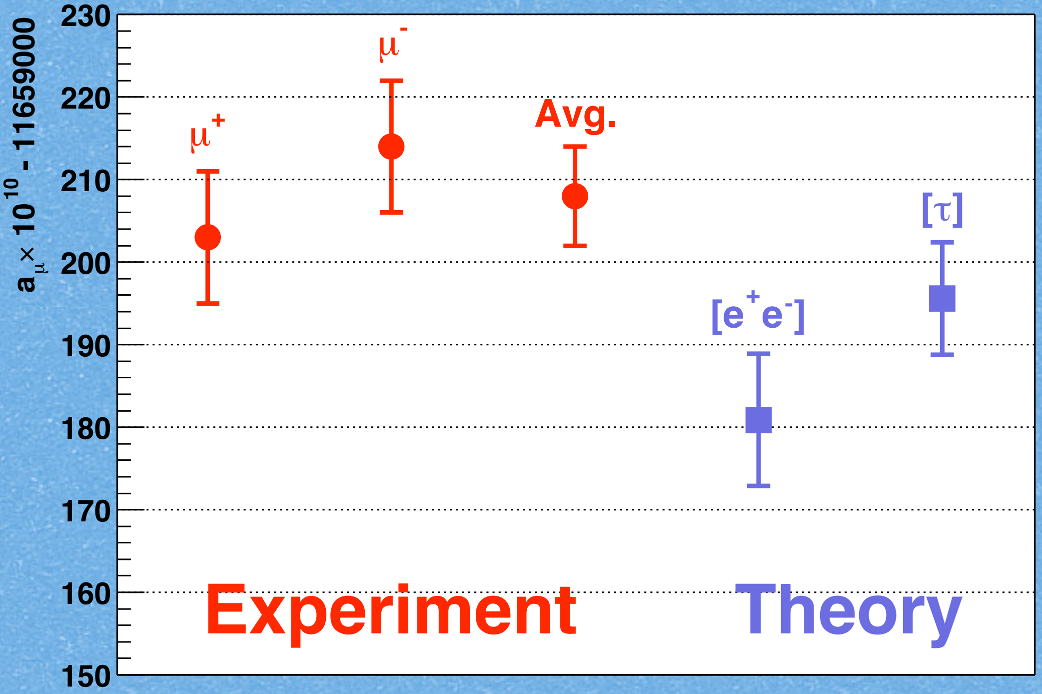
in SUSY case

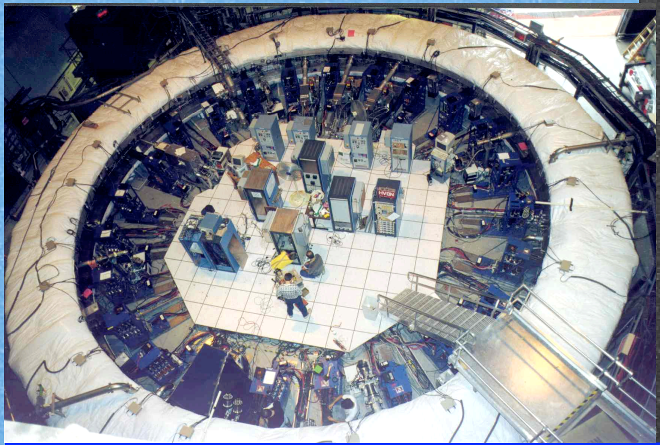
Slepton mixing matrix

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

Hints for SUSY breaking

BNL Muon g-2 Result



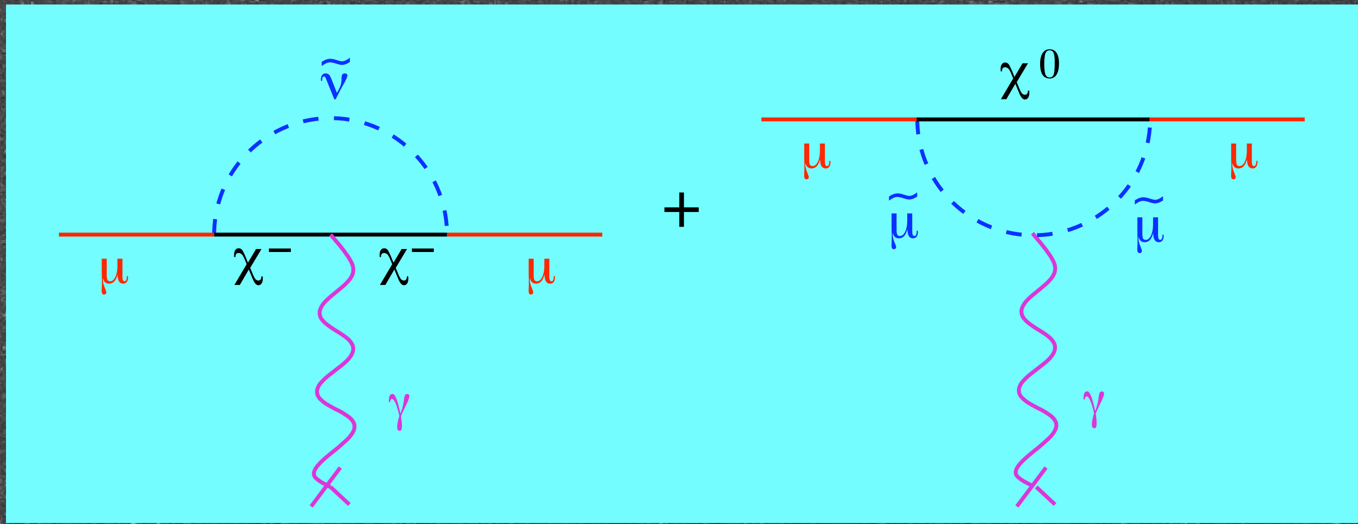


$a_\mu = 11659208(6)$
$\mu^\pm$ combined

$$\Delta a_\mu(ee) = (23.9 \pm 9.9) \times 10^{-10} \quad 2.7 \text{ s.d.}$$

$$\Delta a_\mu(\tau) = (7.6 \pm 8.9) \times 10^{-10} \quad 0.9 \text{ s.d.}$$

g-2 sensitivity to SUSY



$$a_\mu(SUSY) \sim \frac{\alpha(M_Z)}{8\pi \sin^2\theta_W} \cdot \frac{m_\mu^2}{\tilde{m}^2} \cdot \tan\beta(1 - \frac{4\alpha}{\pi}\ln\frac{\tilde{m}}{m_\mu})$$

$$\sim 13 \times 10^{-10} \tan\beta \left(\frac{100\mathrm{GeV}}{\tilde{m}_\mu}\right)^2$$

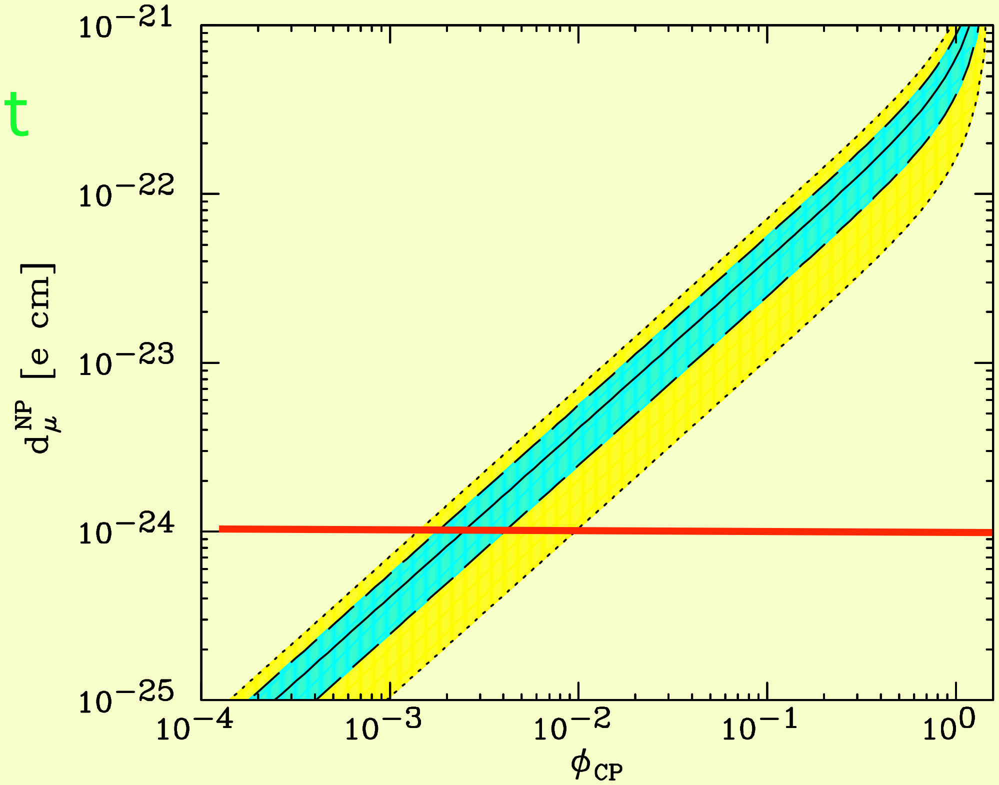
Significant for large $\tan\beta$ and $\tilde{m}$ in the LHC range

Muon EDM

SUSY contribution to muon EDM

Muon (g-2) and EDM might be related.

hints for leptogenesis

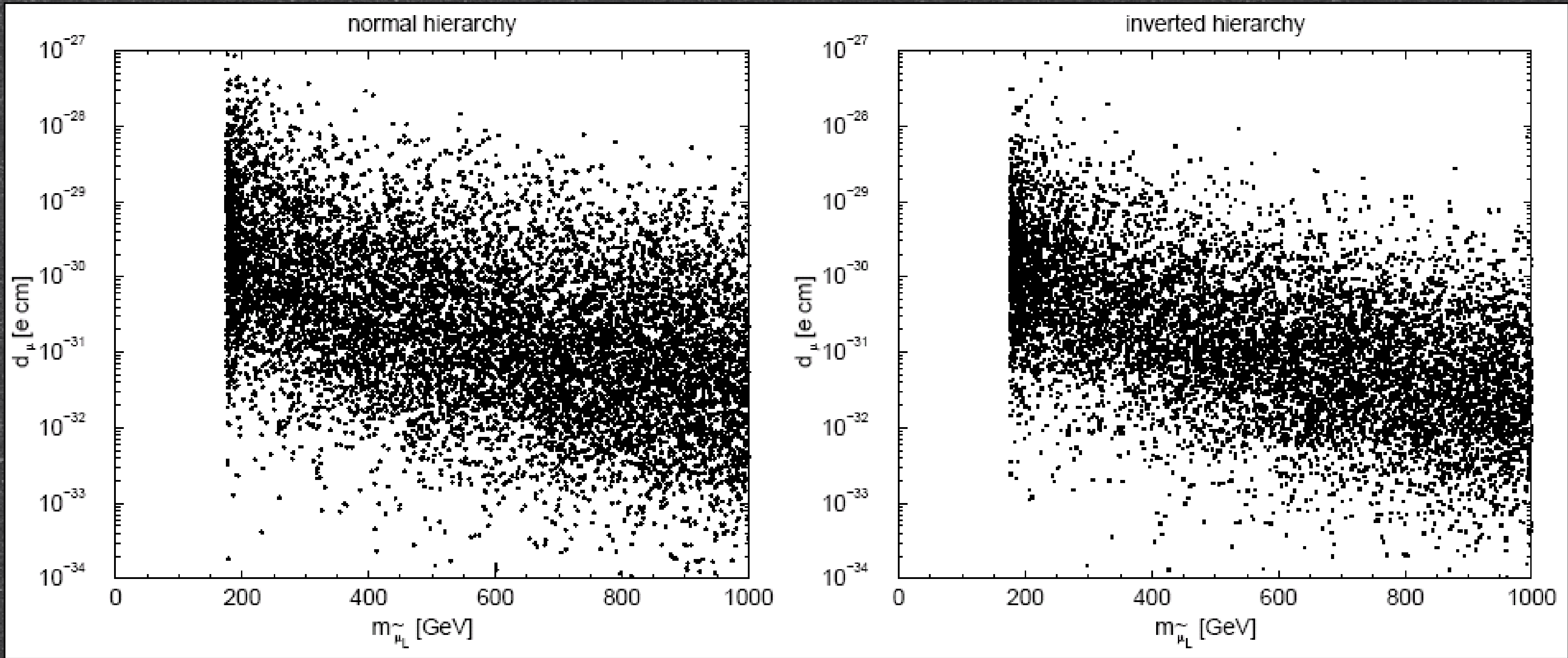


$d_\mu^{NP} \approx 3\times10^{-22}(\frac{a_\mu^{NP}}{3\times10^{-9}}) \tan\phi_{CP}\, e\cdot cm,\ a_{NP} = a_\mu^{exp} - a_\mu^{SM} \approx 3(1)\times10^{-9}$

Feng, Matchev, Shadmi, NP B613, 366(2001)

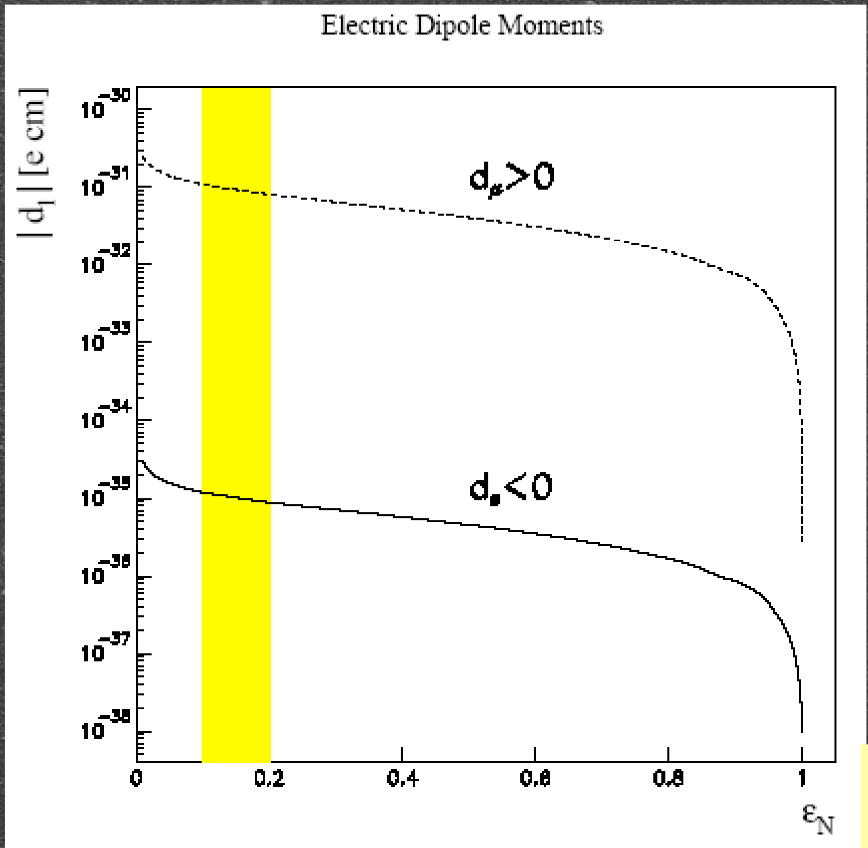
Muon EDM from SUSY

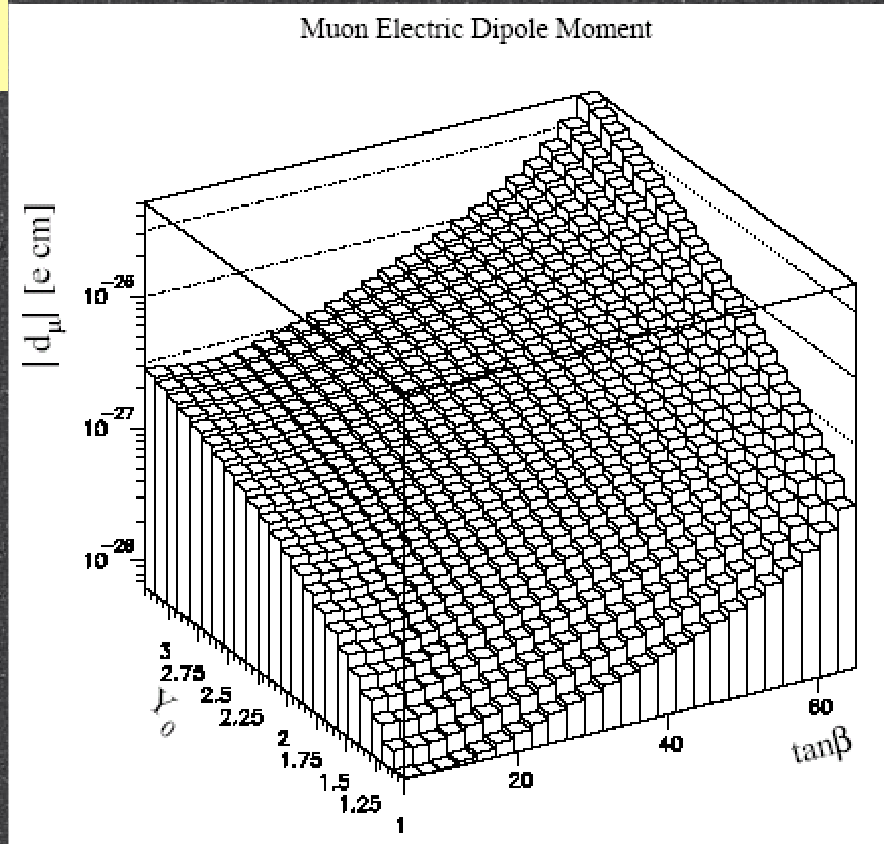
In minimal supersymmetric seesaw models consistent with neutrino oscillation data : assuming CP violation in soft supersymmetry-breaking parameters induced neutrino Yukawa couplings.



SUSY to Muon EDM

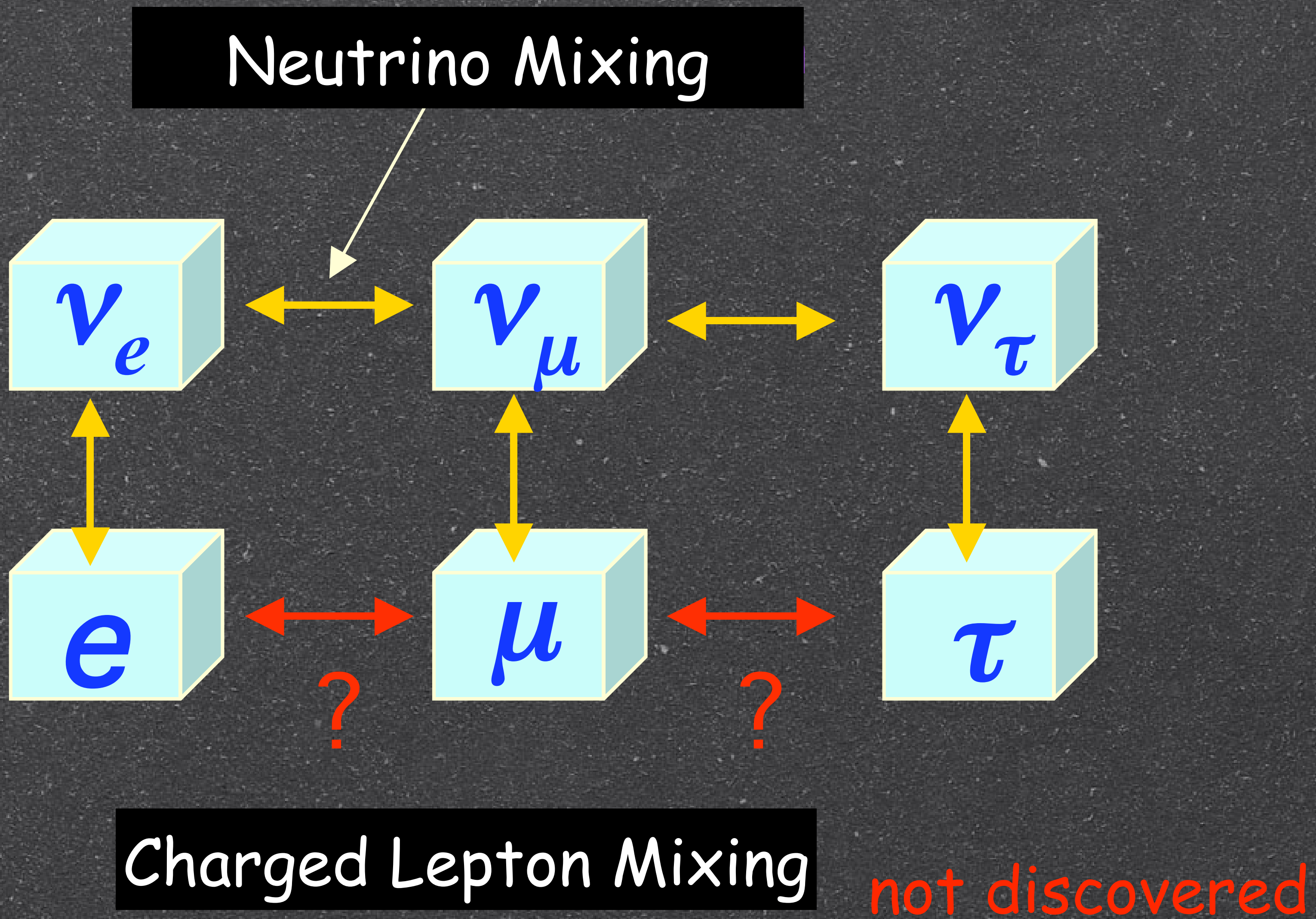
muon EDM may be enhanced by more than m(mu)/m(e)





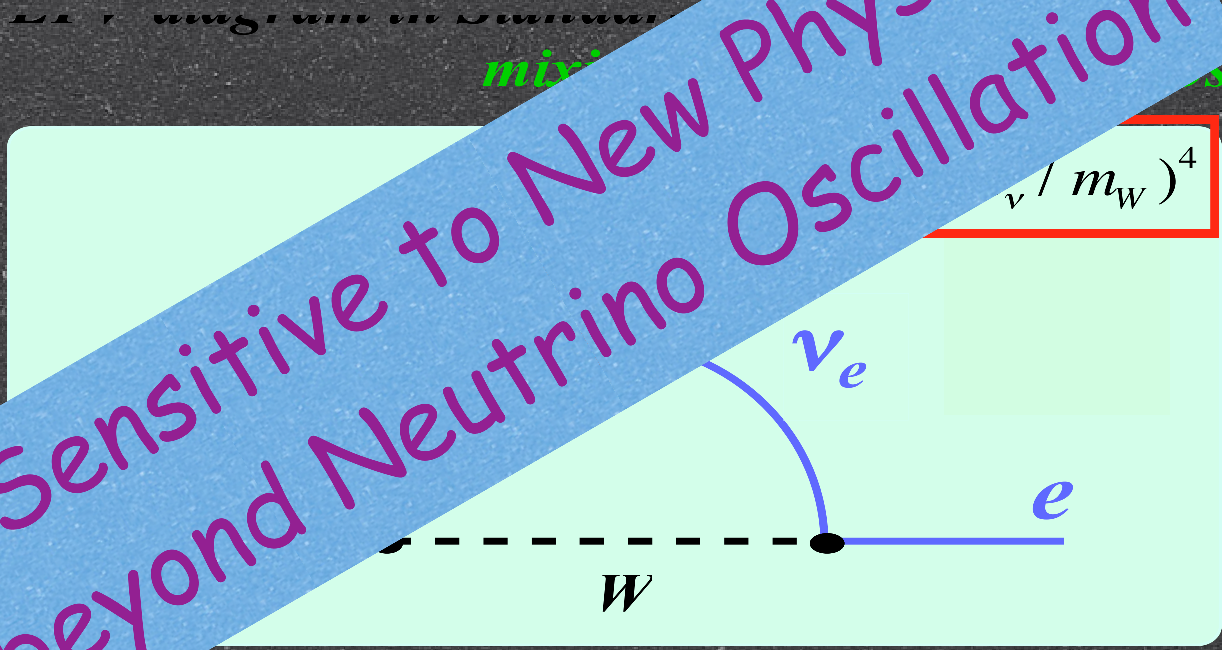
muon EDM greatly enhanced when heavy neutrino non-degerate

Charged Lepton Mixing (CLM)



Neutrino Mixing for CLM

- Observed neutrino oscillation (mixing) implies lepton flavor violation in the neutrin... ...or. How does it contribute to char...

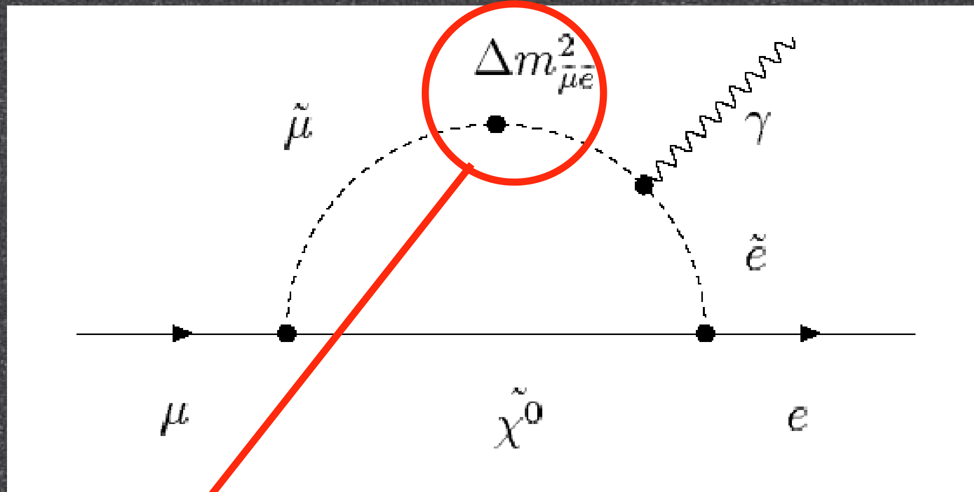


Sensitive to New Physics beyond Neutrino Oscillation

Very Small (10^{-50})

SUSY for LFV

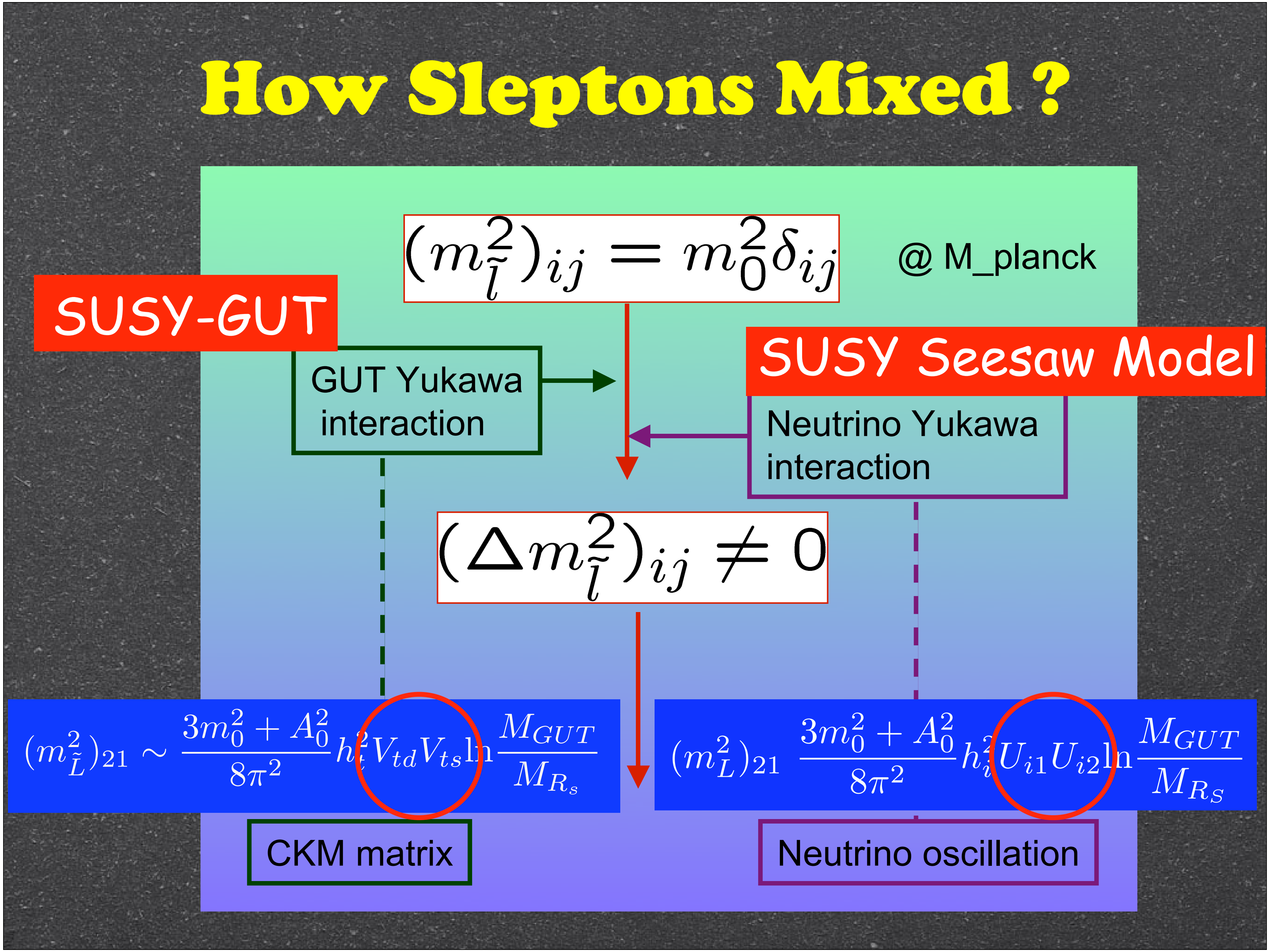
$$\mu^+ \to e^+\gamma$$



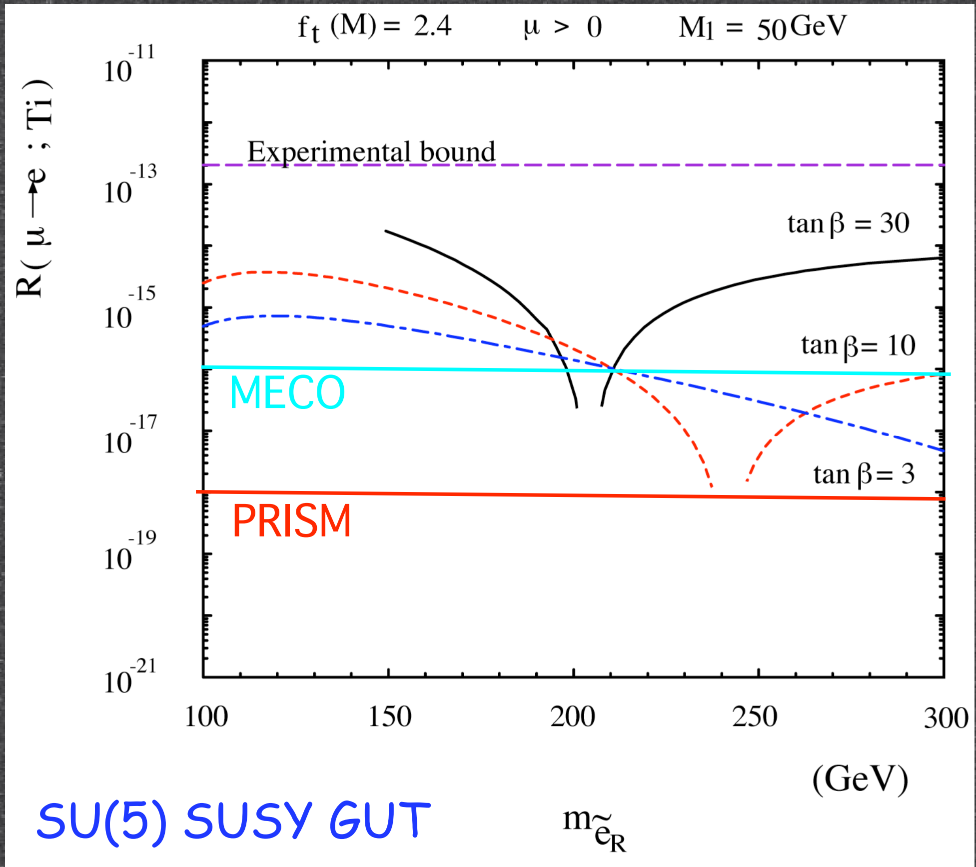
$$m^2_{\tilde l} = \begin{pmatrix} m^2_{11} & m^2_{12} & m^2_{13} \\ m^2_{21} & m^2_{22} & m^2_{23} \\ m^2_{31} & m^2_{32} & m^2_{33} \end{pmatrix}$$

In SUSY, LFV processes are induced by the off-diagonal terms in the slepton mass matrix. In MSSM, no off-diagonal terms exist @Planck, and need more.

How ?


How Sleptons Mixed ?
$(m^2_{\tilde{l}})_{ij} = m^2_0 \delta_{ij}$
@ M_planck
SUSY-GUT
GUT Yukawa interaction
SUSY Seesaw Model
Neutrino Yukawa interaction
$(\Delta m^2_{\tilde{l}})_{ij} \neq 0$
$(m^2_{\tilde{L}})_{21} \sim \frac{3m_0^2 + A_0^2}{8\pi^2} h_t^2 V_{td} V_{ts} \ln \frac{M_{GUT}}{M_{R_s}}$
$(m^2_{\tilde{L}})_{21} \frac{3m_0^2 + A_0^2}{8\pi^2} h_i^2 U_{i1} U_{i2} \ln \frac{M_{GUT}}{M_{R_S}}$
CKM matrix
Neutrino oscillation

SUSY-GUT



right-handed slepton mass

Slepton mixing is induced through radiative correction from GUT (where quarks and leptons are in the same multiplet) to weak scale.

- SUSY SU(5) predictions

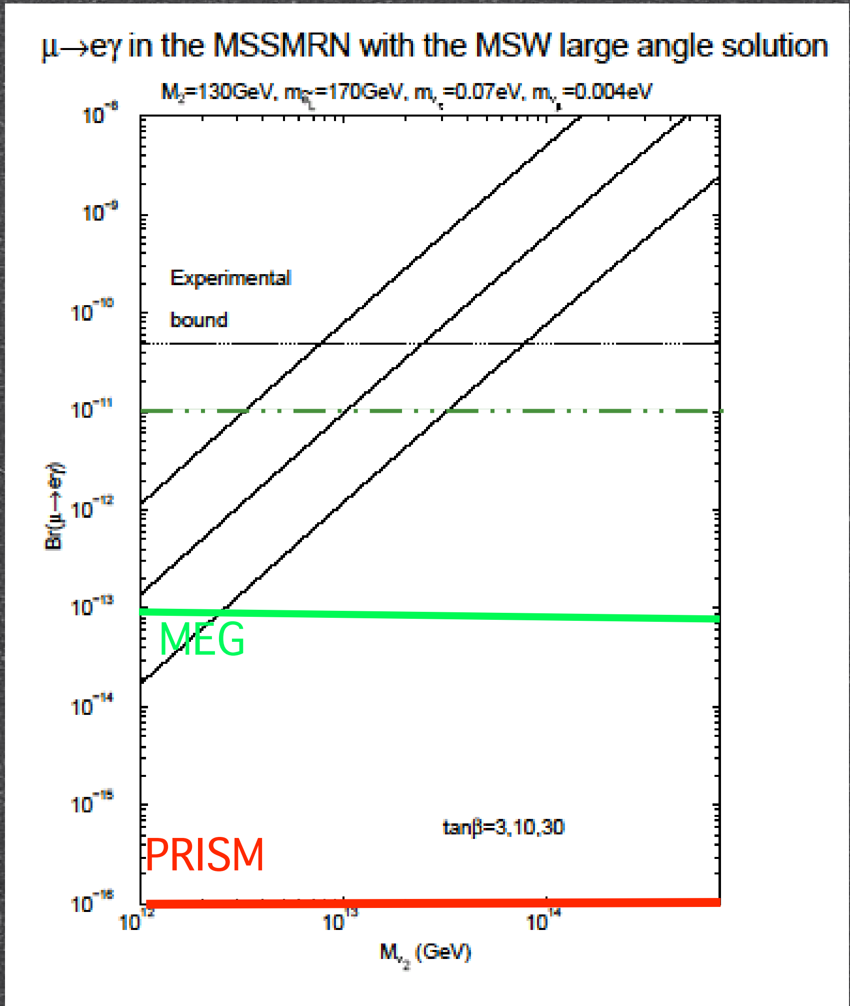
  BR (μ→eγ) ≈ 10^{-14} ÷ 10^{-13}

- SUSY SO(10) predictions

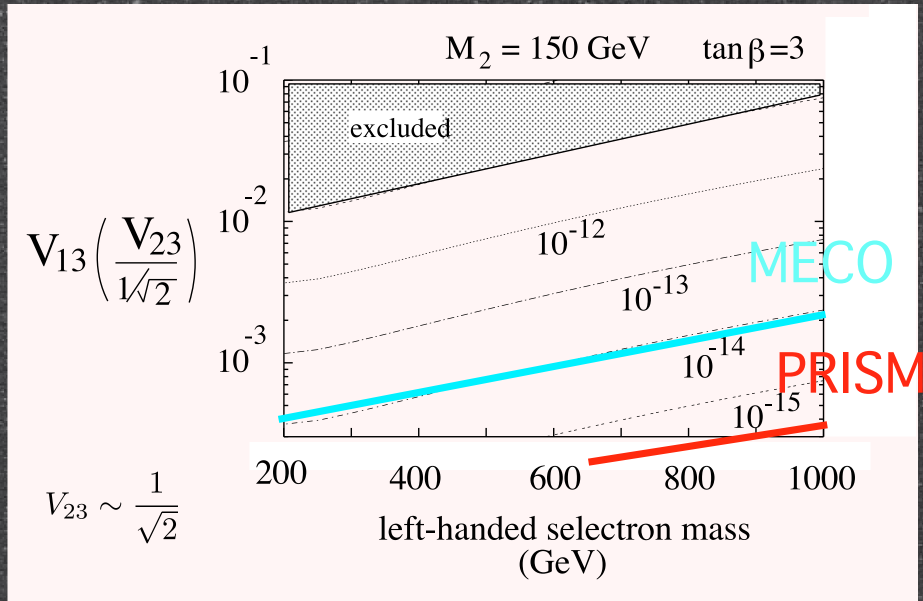
  $BR_{SO(10)} \approx 100\ BR_{SU(5)}$

Predictions are just a few orders of magnitude smaller than the present limit. Future experiments might cover.

SUSY Seesaw Model



right-handed neutrino mass



Through SUSY, only way to access heavy right-handed neutrinos in seesaw models.

CLM : SUSY after LHC

If LHC finds SUSY

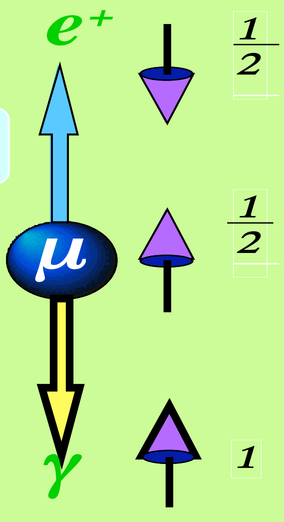
- ☑ Search for charged lepton mixing becomes more important, with less risk
- ☑ Search for charged lepton mixing is sensitive to SUSY-GUT and/or SUSY-Seesaw (not just MSSM).

after observation

Polarized $\mu \rightarrow e\gamma$

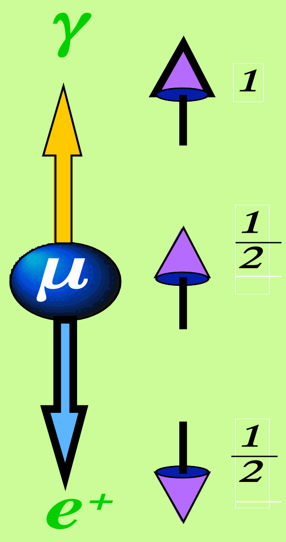
Left handed e^+

$1+\cos\vartheta_e$



Right handed e^+

$1-\cos\vartheta_e$



useful to distinguish different theoretical models

SU(5) SUSY-GUT

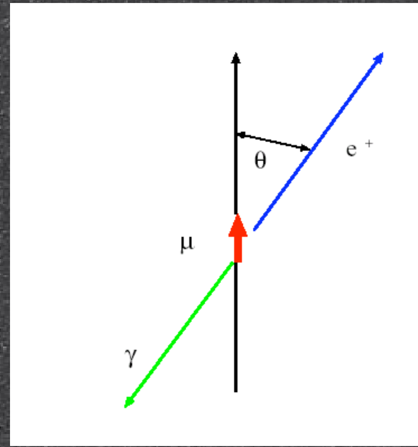
non-unified SUSY with heavy neutrino

Left-right symmetric model

SO(10) SUSY-GUT

Y.Kuno and Y. Okada, Physical Review Letters 77 (1996) 434

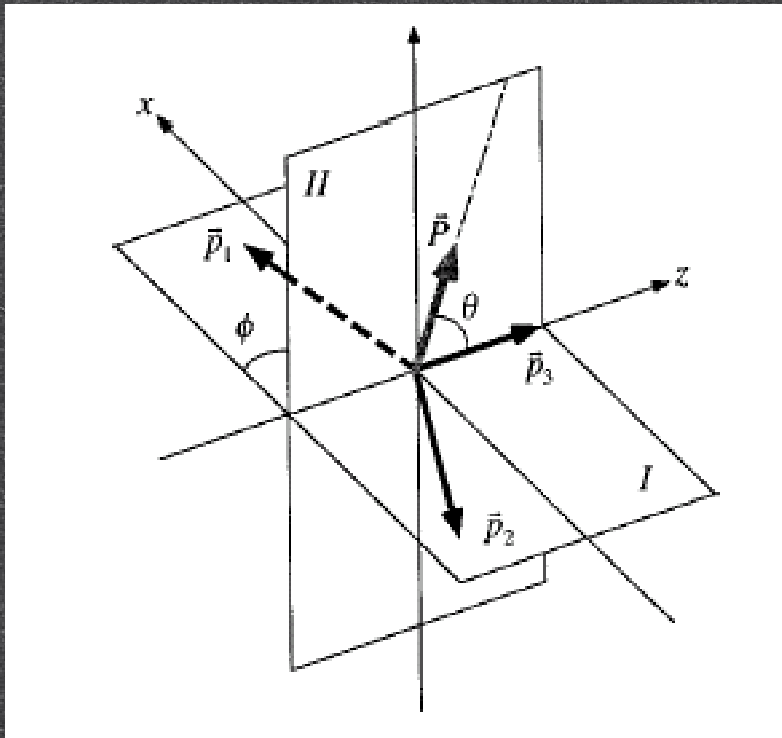
Y.Kuno, A. Maki and Y. Okada, Physical Reviews D55 (1997) R2517-2520



P-odd asymmetry reflects whether right or left-handed slepton have flavor mixing, after observation

T-odd (CPV) in CLM

$$\mu^+ \to e^+ e^+ e^-$$



Two P-odd and one T-odd asymmetry

$$\vec{P}_\mu \cdot (\vec{p}_{e^+} \times \vec{p}_{e^-})$$

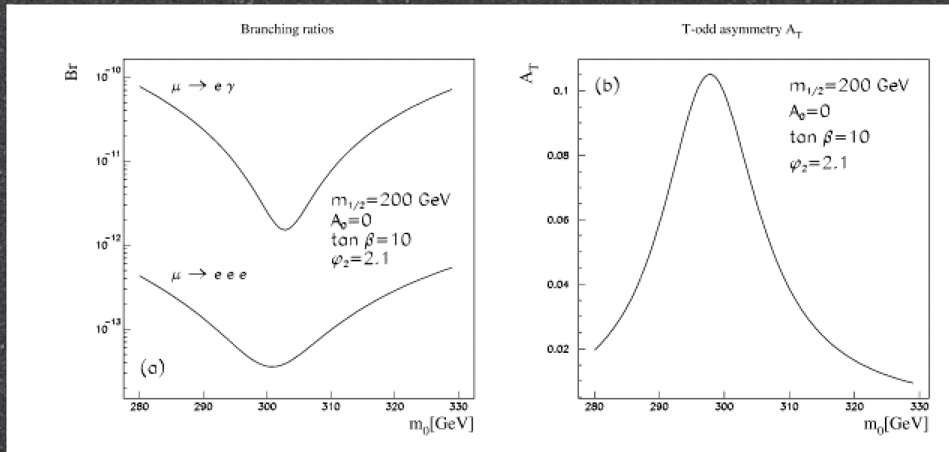
P and T-odd asymmetries in SUSY GUT models

	SU (5)	SO (10)
$A_{\mu\to e\gamma}$	+100%	-100% – +100%
A_{P_1}	-30% – +40 %	$\simeq -A_{\mu\to e\gamma}/10$
A_{P_2}	-20% – +20 %	$\simeq -A_{\mu\to e\gamma}/6$
$\lvert A_T\rvert$	$\lesssim$15%	$\lesssim$ 0.01%

Y.Okada, K.Okumura and Y.Shimizu, 2000

Y.Okada,K.Okumura,and Y.Shimizu, 2000

T-odd asymmetry in the SUSY seesaw model



Leptogenesis

J.Ellis,J.Hisano,S.Lola, and M.Raidal, 2001

The Physics Case

Scenario 2 : LHC not find SUSY

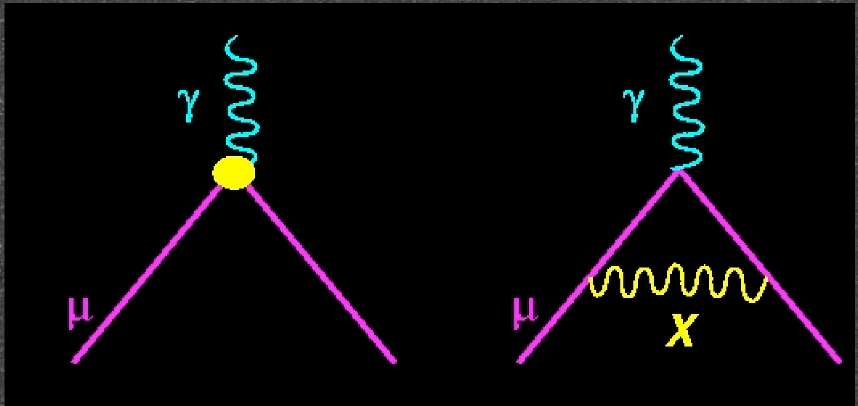
Either no SUSY or heavy SUSY ?

High intensity frontier (precision measurements and searches for rare process) comes to the forefront, since it is sensitive to heavier mass scale.

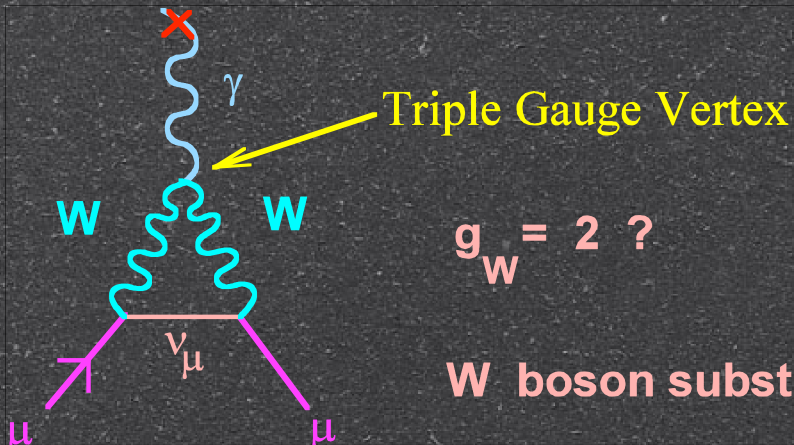
g-2 sensitivity to NP

Muon substructure

$$\delta a_\mu(\Lambda_\mu) \simeq \frac{m_\mu^2}{\Lambda_\mu^2}$$



Anomoulous $W\gamma\gamma$ Couplings



$g_W = 2$?

W boson substructure?

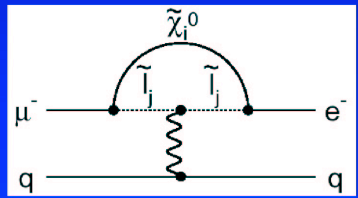
CLM Models beyond SM

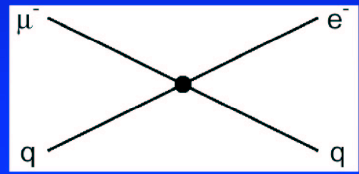
Sensitivity to Different Muon Conversion Mechanisms

MECO

Supersymmetry

Predictions at 10^{-15}





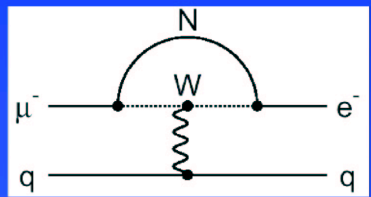
Compositeness

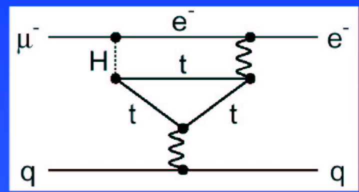
$\Lambda_c = 3000$ TeV

Heavy Neutrinos

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

8×10^{-13}





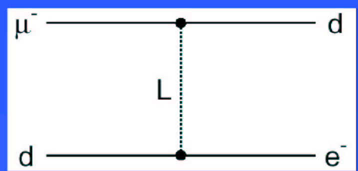
Second Higgs doublet

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

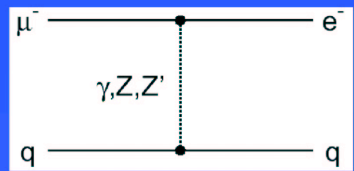
Leptoquarks

$M_L =$

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



After W. Marciano



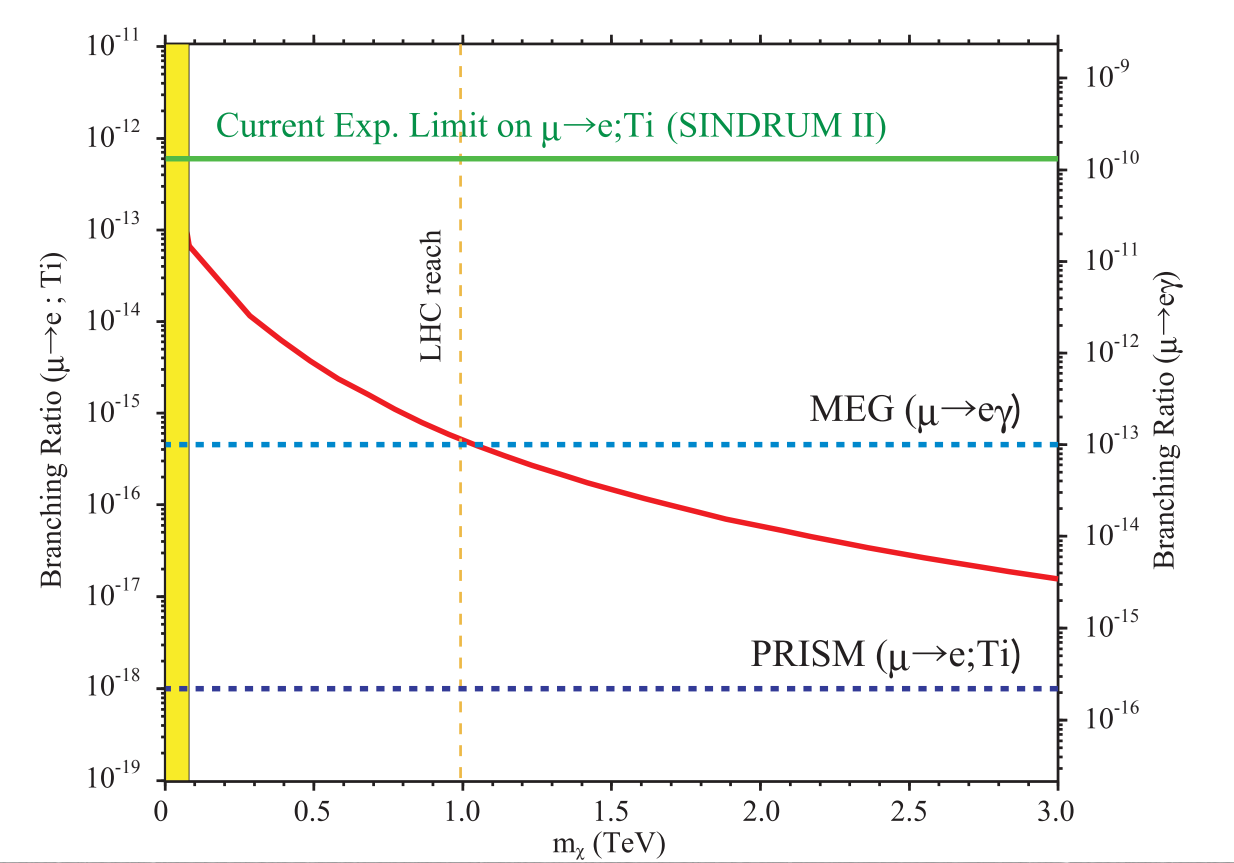
Heavy Z', Anomalous Z coupling

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

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

CLM : SUSY beyond LHC

If LHC not finds SUSY



from A.Masiero et al.

... if suffienct sensitivity is achieved.


Night Sight Photo Gallery
http://www.netlaputa.ne.jp/~ttake
Experimental

Muon EDM

$$\vec{\omega} = -\frac{e}{m}\left[a\vec{B} + \left(\frac{1}{\gamma^2 - 1} - a\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right]$$

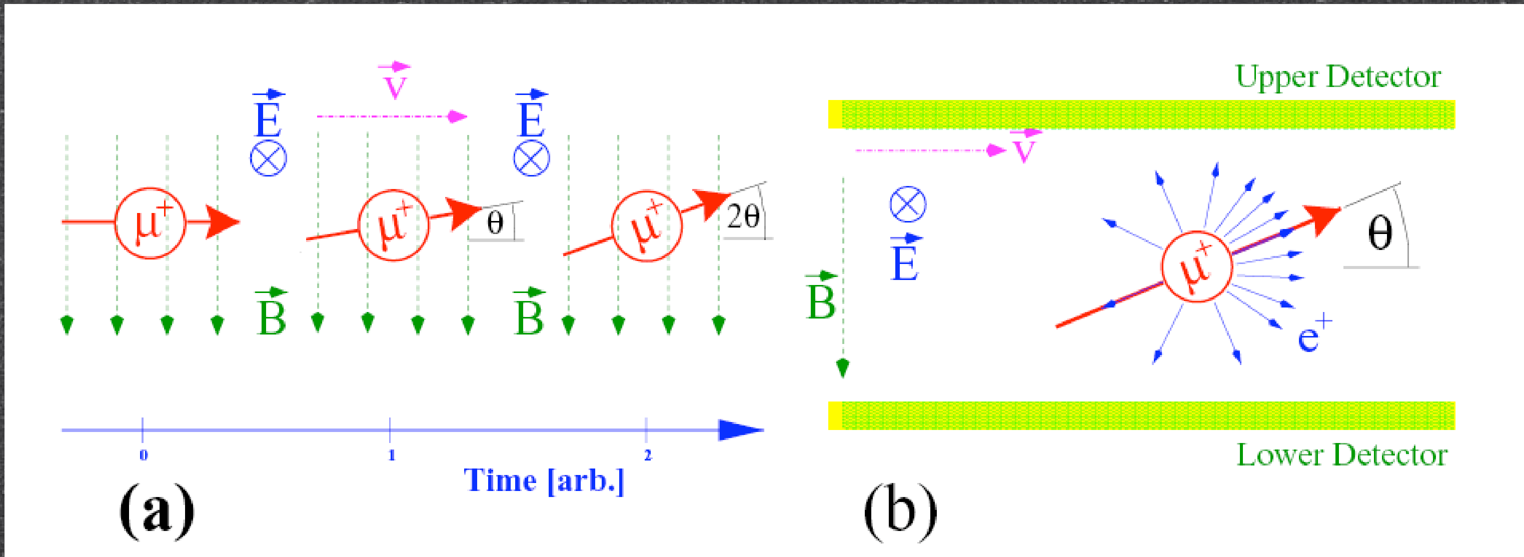
=0

Cancellation E field

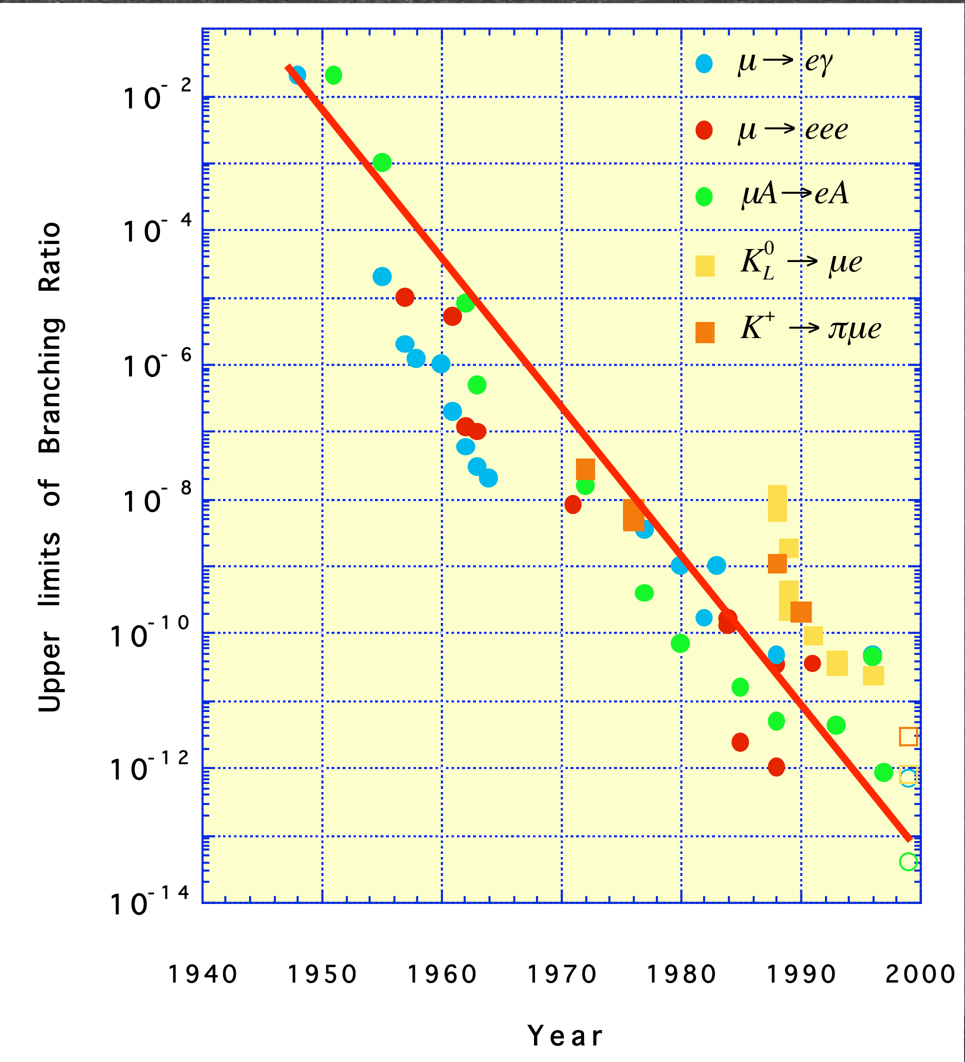
$$E = \frac{aBc(\gamma^2 - 1)}{\beta}$$

E field for EDM rotation

$$E = Bc\beta$$



History of LFV Searches



Lepton Flavor Violation (LFV)

No (charged) LFV in the Standard Model

Upper limits improved by two orders of magnitude per decade.

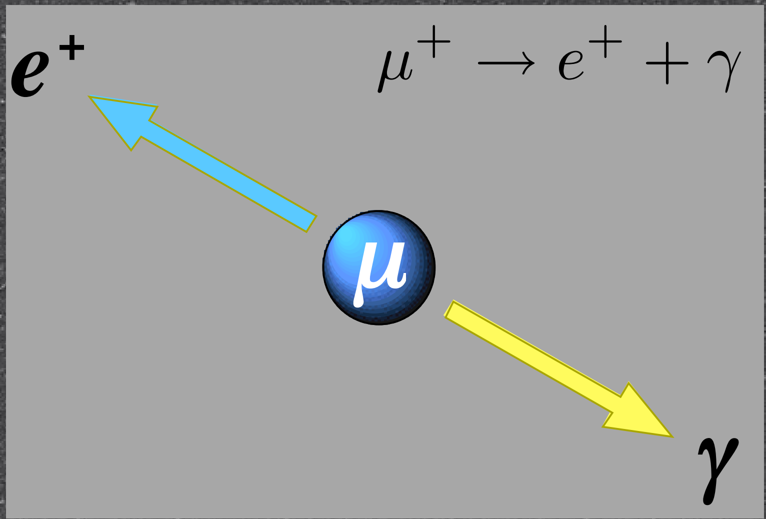
Why the Muon for CLM ?

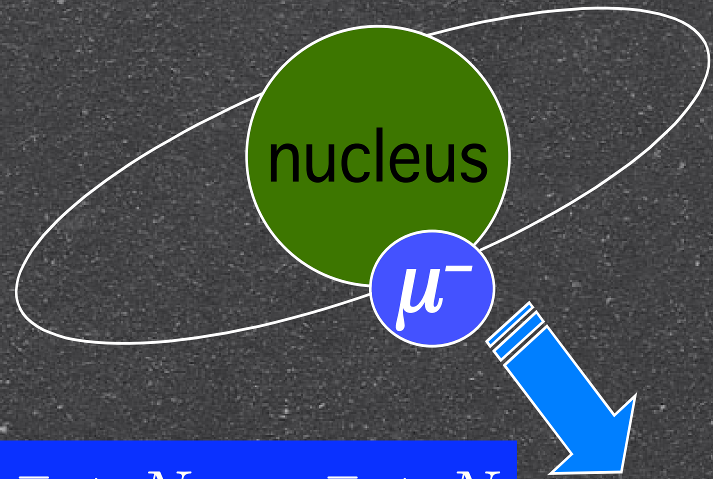
- CLM Sensitivity in the muon will be the highest over the other systems because of enormous beam intensity (~10^{-12}/sec) thanks to R&D studies of neutrino factory front-end.
- The muon provides a clean test ground, on the contrast to hadrons where QCD corrections needed introduces sensitivity limits,

Upper Limits for CLM

Process	Current	Future
$\mu^+ \to e^+\gamma$	1.2×10^{-11}	$<10^{-13}$(MEG)
$\mu^+ \to e^+e^+e^-$	1.0×10^{-12}	
$\mu^- A \to e^- A$ (Ti)	6.1×10^{-13}	$<10^{-18}$(PRISM)
$\mu^- A \to e^- A$ (Al)		$<10^{-16}$(MECO)
$\tau \to \mu\gamma$	3.2×10^{-7}	
$\tau \to lll$	$1.4 - 3.1 \times 10^{-7}$	
$G_{Mu\overline{Mu}}/G_F$	3×10^{-3} ←	$\Delta L_f = 2$

μ→eγ & μ-e conversion





$$\mu^- + N \to e^- + N$$

Signature

$$E_e = E_\gamma = m_\mu/2$$

back-to-back, same time

Background

(1) radiative decay

(2) accidentals

Signature: $E_e = m_\mu - B_\mu$

monoenergetic electron

Background:

(1) bound muon decay

(2) radiative pion/muon catpure

(3) cosmic rays, etc.

Photon-mediated SUSY LFV

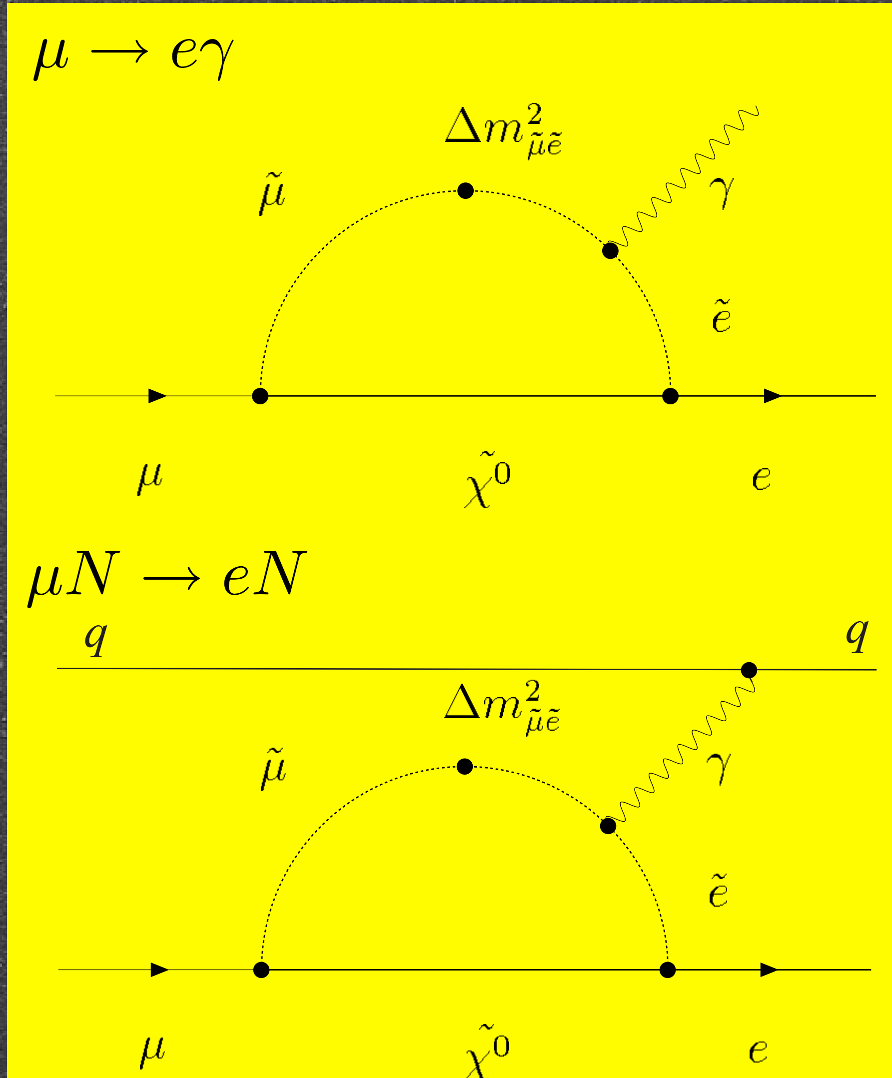
$\mu - e$ conversion vs. $\mu \to e\gamma$

If photon-mediated,

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

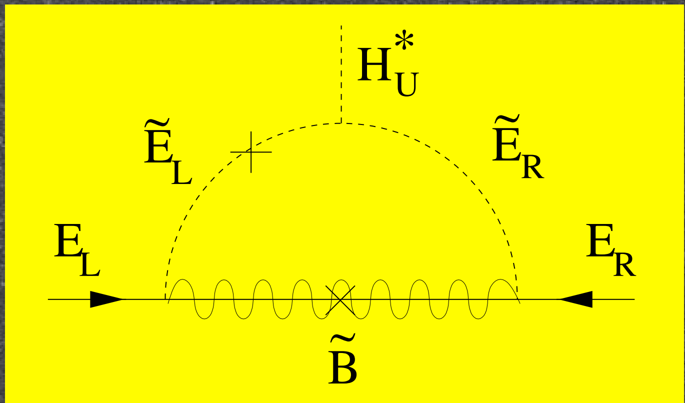
But, experimentally,

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



Higgs-mediated SUSY LFV

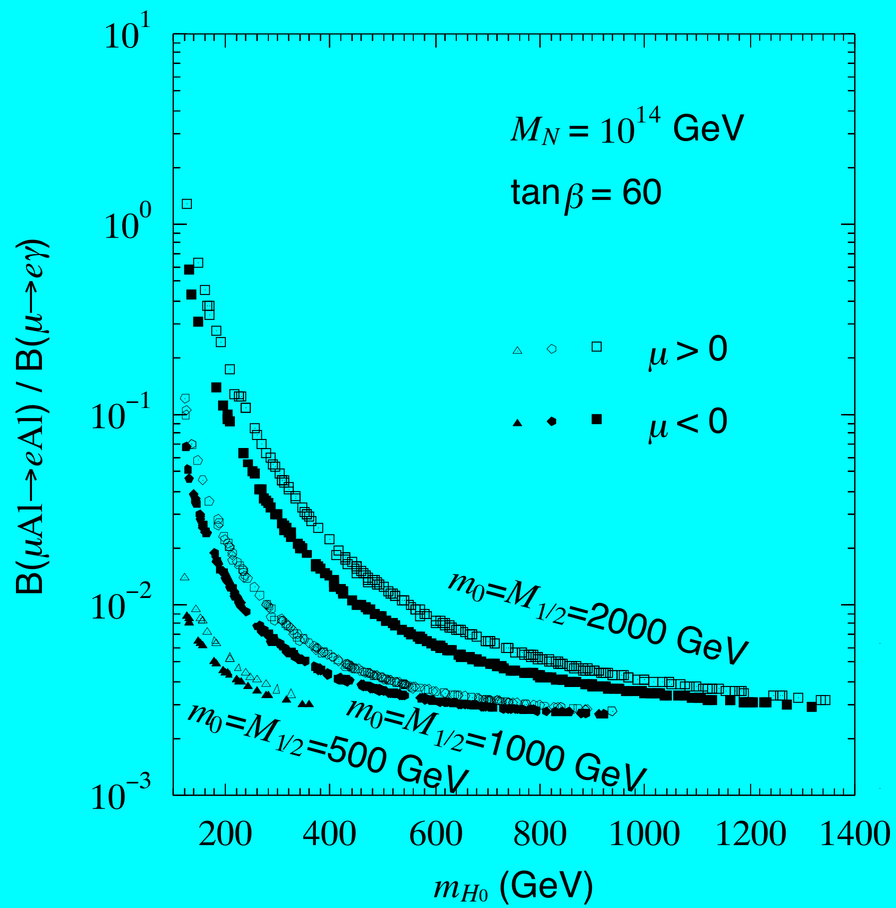
Higgs-exchange for LFV in SUSY Seesaw model



As the H_0 mass is light, the contribution of the Higgs-mediated diagram becomes larger.

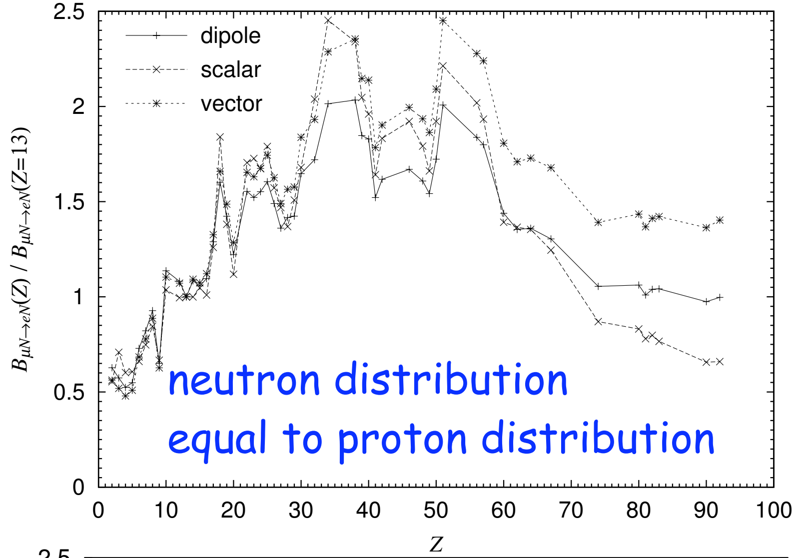
$$\frac{B(\mu N \to eN)}{B(\mu \to e\gamma)} \sim O(1)$$

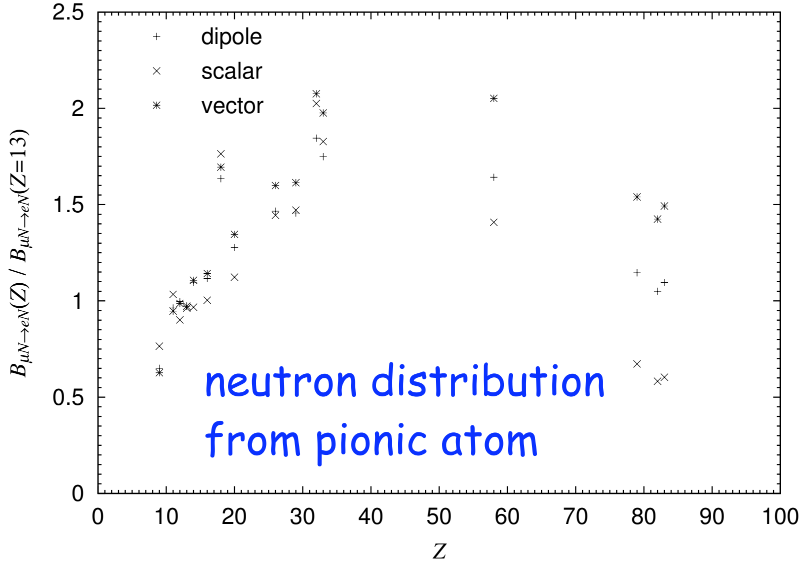
at $H_0 \sim 200$ GeV

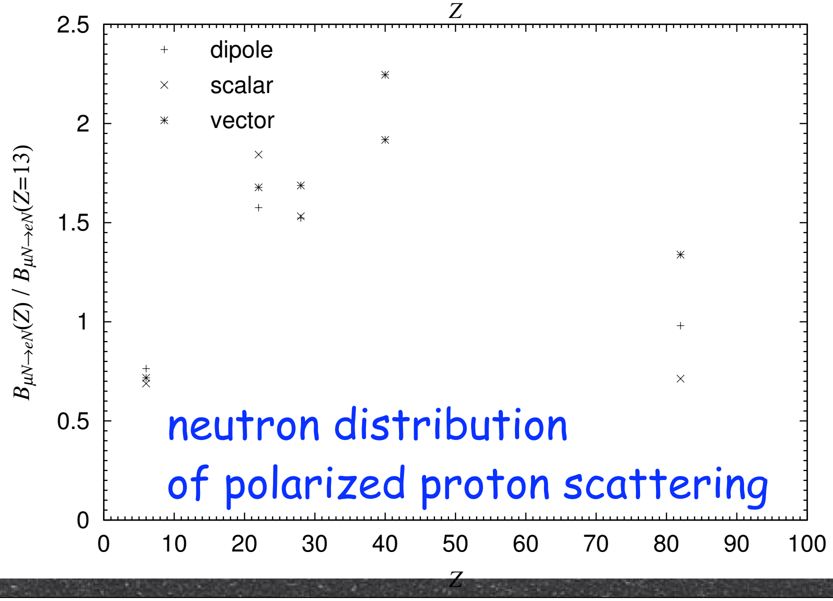


Kitano, Koike, Komine, Okada

μ-e conversion : Z dependence







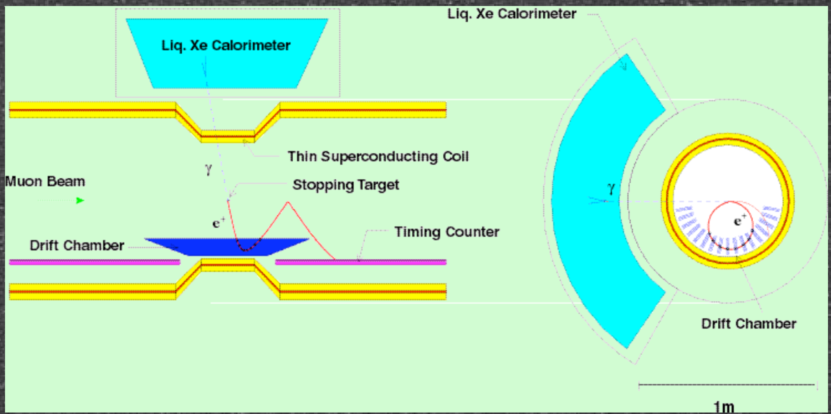
normalized at Al target.

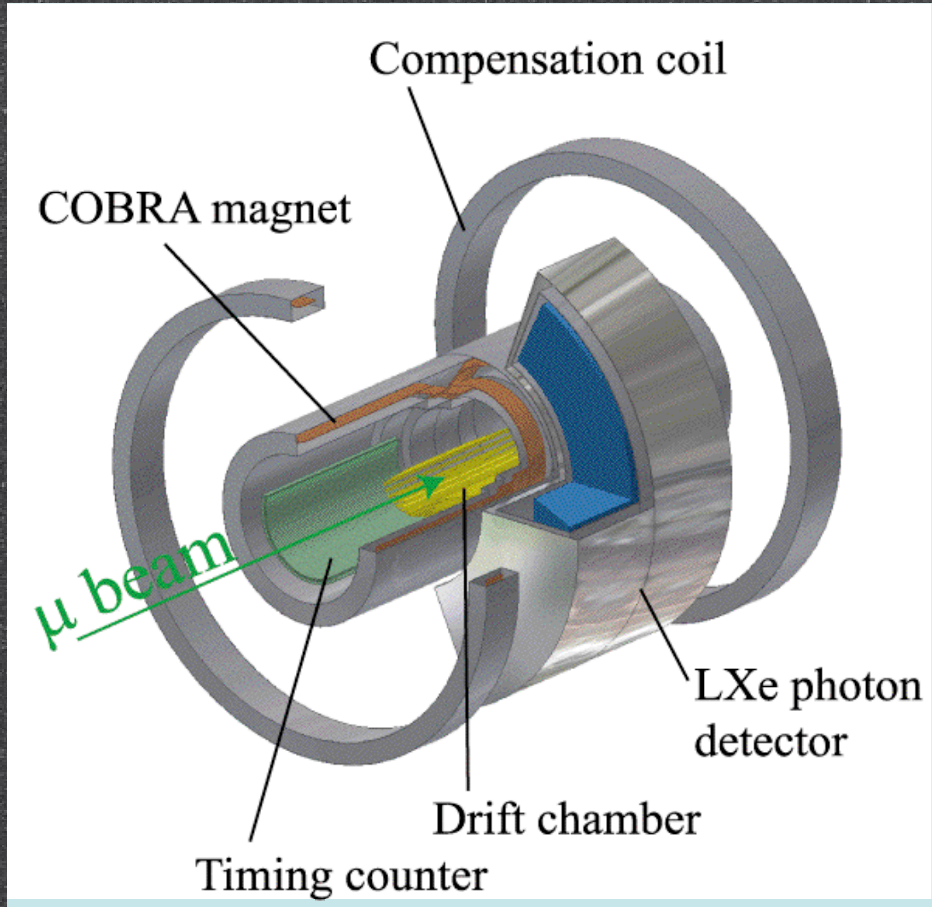
For heavy target, difference of the interactions might be seen ?

R. Kitano, M. Koike, and Y. Okada, 2002

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



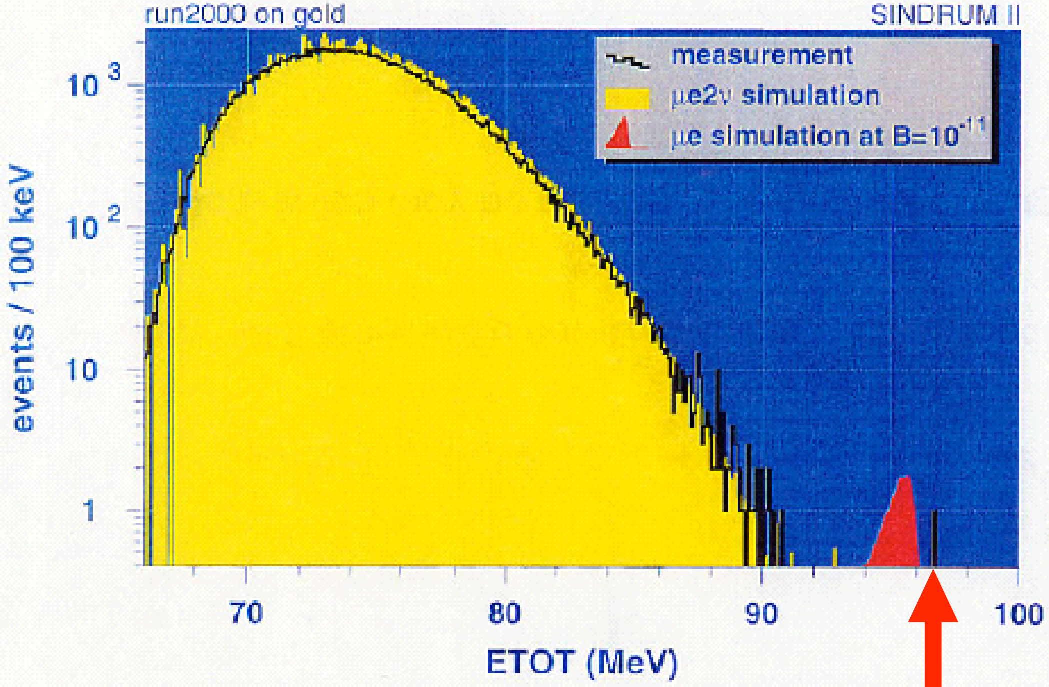


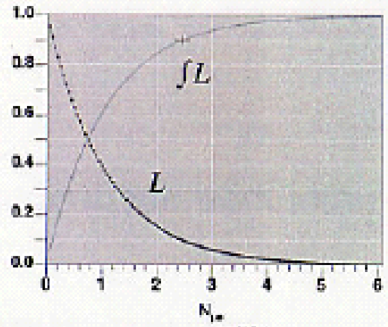
start engineering in 2006

SINDRUM-II μ-e conversion

Final result

μe Conversion on Gold





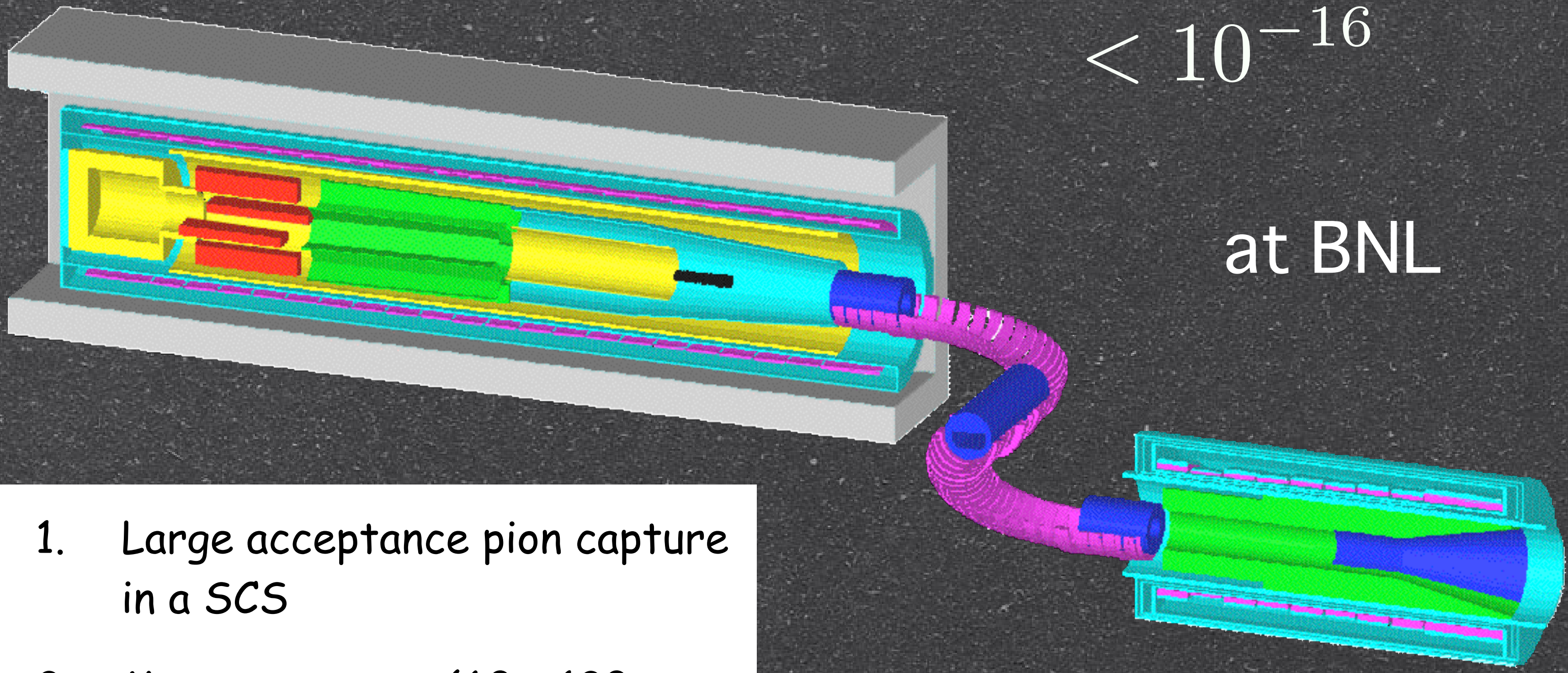
$\mathcal{L}(N_{\mu e})$ and $\int_0^{N_{\mu e}^{max}} \mathcal{L}(n)dn$.

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

MECO μ-e conversion



$< 10^{-16}$

at BNL

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

start in 2011 ?

NSF Review, 2005

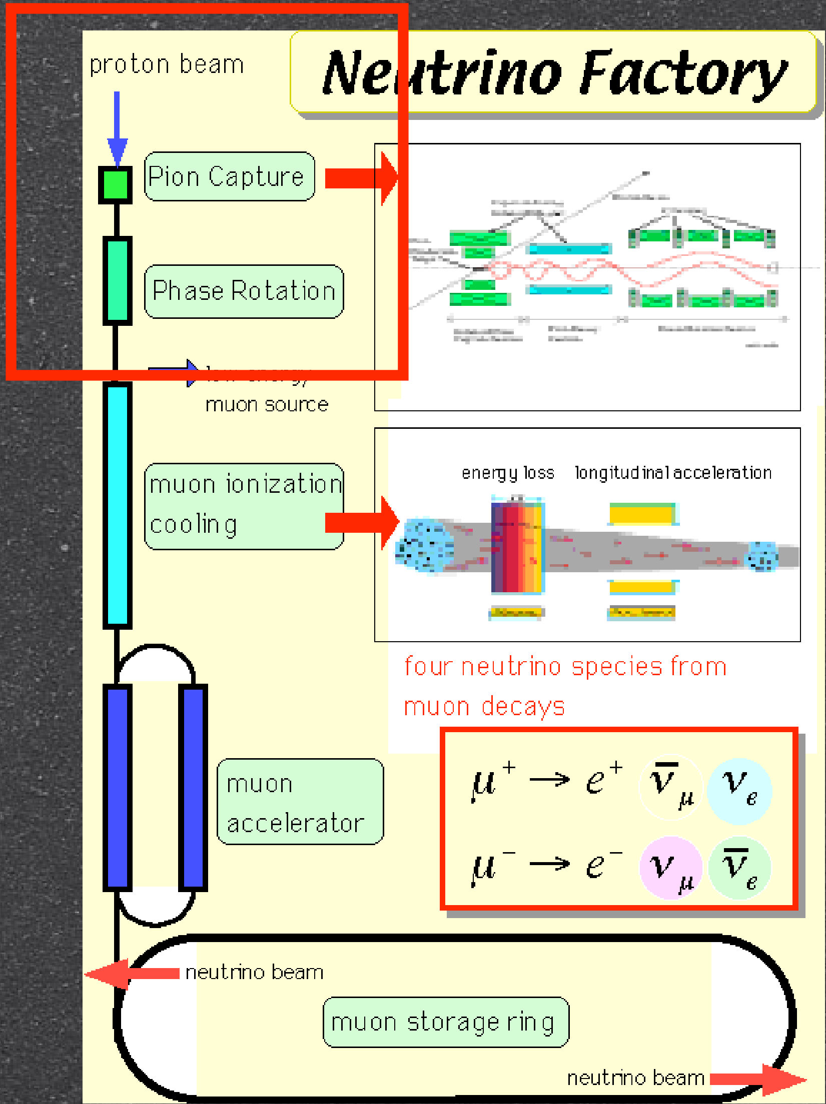

Night Sight Photo Gallery
http://www.netlaputa.ne.jp/~ttake
Muon Beams

Muon Statistics

- Meson Factory (PSI, TRIUMF, LAMPF)
  - proton energy ~ 500 MeV
  - beam current ~ 10^{15} - 10^{16} protons/sec
  - 10^{6} - 10^{8} muons /secs
  - about 10^{-8} muons/proton
- Neutrino Factory
  - proton energy ~ a few to several 10 GeV
  - beam current ~ a few 10^{14} protons/sec
  - 10^{13} - 10^{14} muons /sec
  - about 0.1 - 0.3 muons/proton

NuFACT or Proton Driver

- The front end of Neutrino Factory aims to produce about 10^{14} muons/sec with given time structure.
- The proton driver associated with neutrino factory would produce high intensity muon beam with more variety of beam specifications.



Muon Beam Requirements

Table 6: Beam requirements for new muon experiments. Given are required sign of charge q_μ and the minimum of the total usable number of muons $\int I_\mu dt$ above which significant progress can be expected in the physical interpretation. The experiments which require pulsed beams (see Fig. 27) are sensitive to the muon suppression I_0/I_m between pulses of length δT and separation ΔT. This does not apply (n/a) for continuous beams. Most experiments require energies below 4 MeV corresponding to 29 MeV/c momentum. Thin targets and storage ring acceptances, demand rather small momentum bites $\Delta p_\mu/p_\mu$.

Experiment	q_μ	$\int I_\mu dt$	I_0/I_m	δT [ns]	ΔT [μs]	E_μ [MeV]	$\Delta p_\mu/p_\mu$ [%]
$\mu^- N \to e^- N^\dagger$	$-$	10^{21}	$< 10^{-10}$	≤ 100	≥ 1	< 20	< 10
$\mu^- N \to e^- N^\ddagger$	$-$	10^{20}	n/a	n/a	n/a	< 20	< 10
$\mu \to e\gamma$	$+$	10^{17}	n/a	n/a	n/a	1...4	< 10
$\mu \to eee$	$+$	10^{17}	n/a	n/a	n/a	1...4	< 10
$\mu^+ e^- \to \mu^- e^+$	$+$	10^{16}	$< 10^{-4}$	< 1000	≥ 20	1...4	1...2
τ_μ	$+$	10^{14}	$< 10^{-4}$	< 100	≥ 20	4	1...10
transvers. polariz.	$+$	10^{16}	$< 10^{-4}$	< 0.5	> 0.02	30-40	1...3
$g_\mu - 2$	$\pm$	10^{15}	$< 10^{-7}$	≤ 50	$\geq 10^3$	3100	10^{-2}
edm_μ	$\pm$	10^{16}	$< 10^{-6}$	≤ 50	$\geq 10^3$	$\leq$1000	$\leq 10^{-3}$
M_{HFS}	$+$	10^{15}	$< 10^{-4}$	≤ 1000	≥ 20	4	1...3
M_{1s2s}	$+$	10^{14}	$< 10^{-3}$	≤ 500	$\geq 10^3$	1...4	1...2
μ^-atoms	$-$	10^{14}	$< 10^{-3}$	≤ 500	≥ 20	1...4	1...5
condensed matter (incl. bio sciences)	$\pm$	10^{14}	$< 10^{-3}$	< 50	≥ 20	1...4	1...5

† Scenario in which a pulsed beam is utilized.

‡ Scenario in which a continuous beam after the muon cooling stage is employed.

Muon Factory

- Use of the Front End of NuFACT
  - sharing a beam ?
- Use of parts of of the proton machine complex for NuFACT and construct dedicated facility (muon factory)
  - Accumulator ring needed to change beam time structure as demanded from muon experiment
  - ex. 50 GeV + 3 GeV @J-PARC, FNAL, MI (120 GeV) + 8 GeV (recycler) @FNAL

Which Muon Programs ?

- Not all the muon programs need high intensity muon beams. High quality beam is obtained from high intensity beam. Need studies.

Topics	high intensity needed ?	high quality needed ?
muon g-2		
muon EDM		
muon mixing (LFV)		
muon lifetime		
catalyzed fusion		
muSR		

For CLM Processes ?

	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

Beam Requirements for μ-e conversion

Beam is critical element for μ-e conversion

MECO

- Higher muon intensity
  - more than 10^{12} μ^-/sec
- pulsed beam
  - rejection of background from proton beam

- Less beam contamination
  - no pion contamination
    - ⇛ long flight path
  - beam extinction between pulses
    - ⇛ kicker magnet

- Narrow energy spread
  - allow a thinner muon-stopping target
    - ⇛ better e^- resolution and acceptance

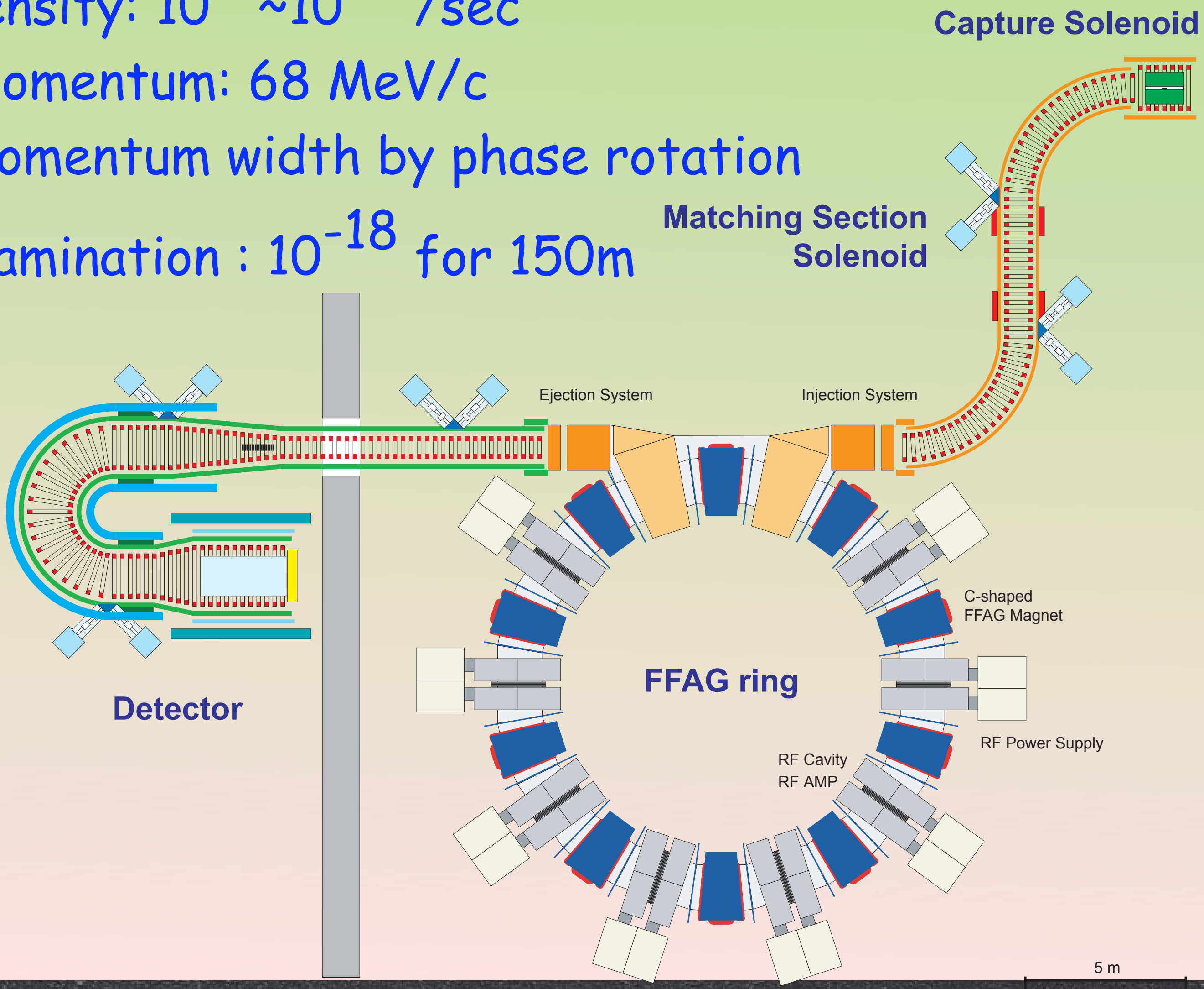
- Point Source
  - allow a beam blocker behind the target
    - ⇛ isolate the target and detector
    - ⇛ tracking close to a beam axis

PRISM

PRISM

PRISM=Phase Rotated Intense Slow Muon source

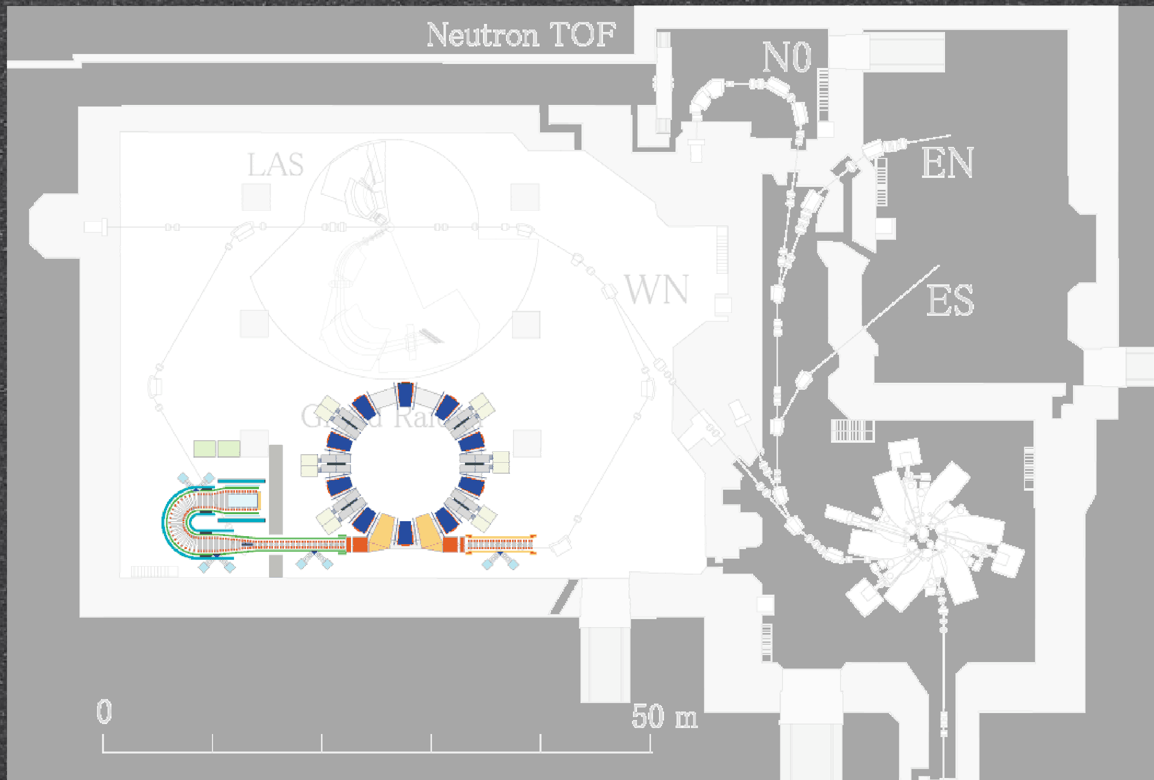
- muon intensity: $10^{11} \sim 10^{12}$ /sec
- central momentum: 68 MeV/c
- narrow momentum width by phase rotation
- pion contamination : 10^{-18} for 150m



PRISM -Phase I @ RNCP

- Research Center for Nuclear Physics (RCNP), Osaka University
  - 400 MeV proton (above pion production threshold)
  - upto 5 micro A

Purpose : Test of fundamental performance of PRISM with muons.




Night Sight Photo Gallery
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Other Topics

Other Topics

- Muon Lifetime Measurements
  - Determination of G_F
- CLM Deep Inelastic Reaction (tau appearance)
  - $\mu + N \to \tau + X, e + N \to \tau + X$
- Proposal on Enhanced Lepton Number Non-conservation
- Muon Catalyzed Fusion
- MuSR
- Slow-Muon Production by Laser
- and others......

End of My Slides