Lepton Flavor Violation of Charged Leptons

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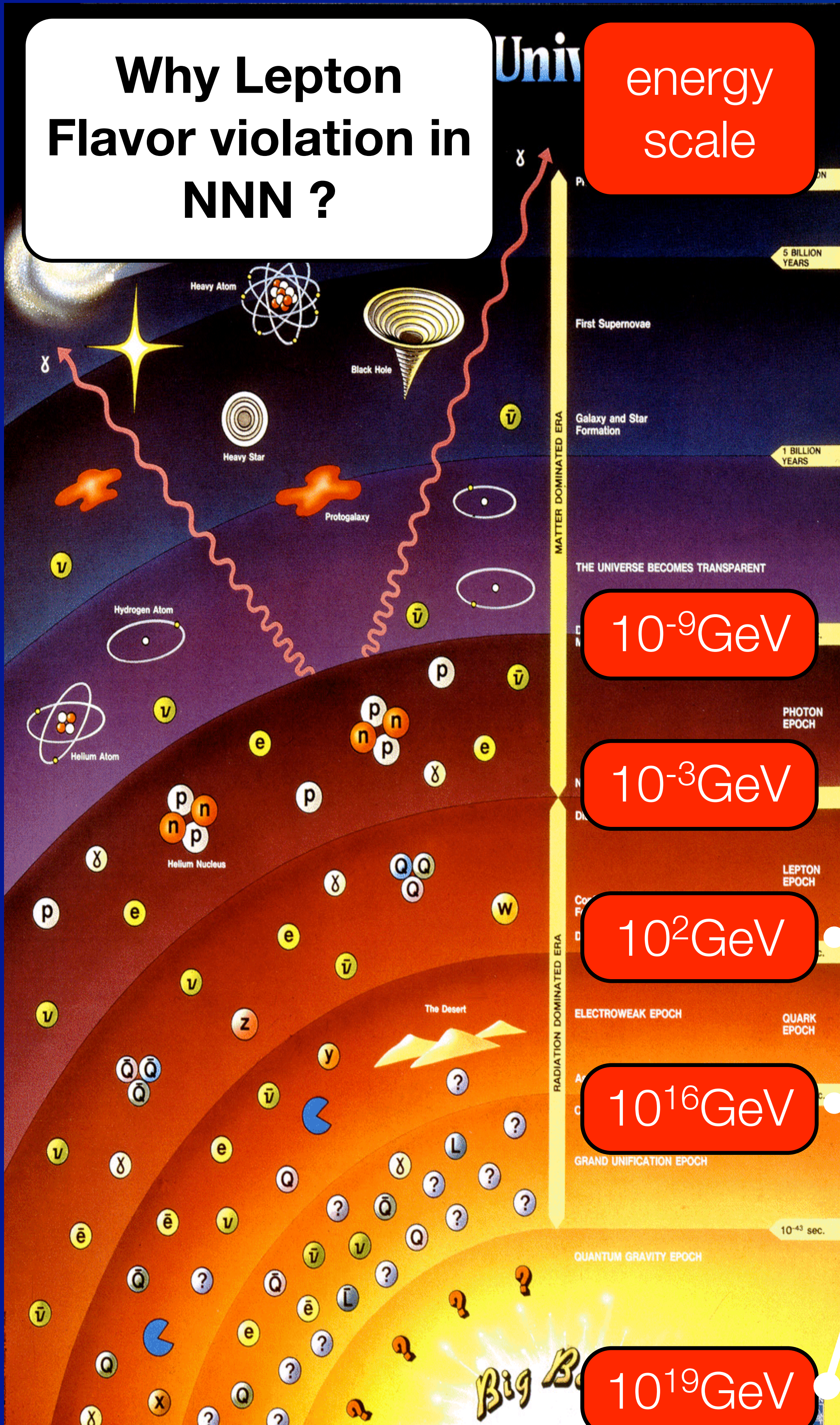
Why Lepton Flavor violation in NNN ?



energy scale

- 10^{-9}GeV
- 10^{-3}GeV
- 10^{2}GeV
- 10^{16}GeV
- 10^{19}GeV

Electroweak Epoch

- Higgs particles
- Supersymmetry

Unification Epoch

- Grand unification of fundamental forces
- Origin of Neutrino mass
- Leptogenesis (baryogenesis)

Nucleon decays

Neutrino physics

Lepton Flavor Violation

Quantum Gravity Epoch

- Superstrings

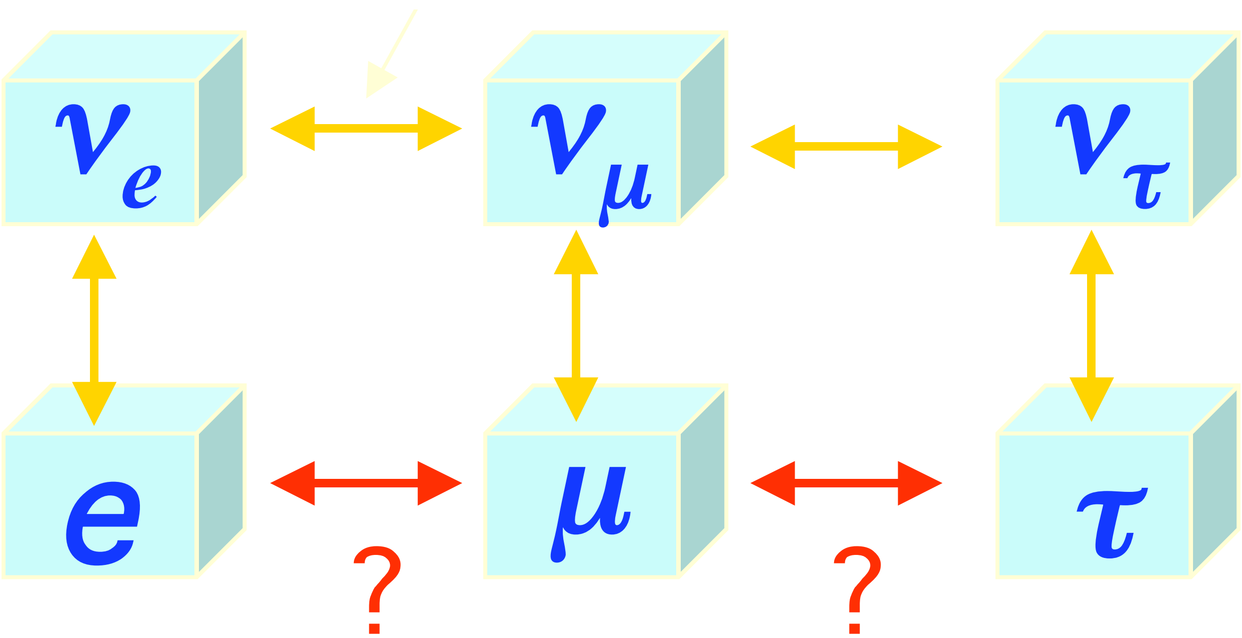
Outline

- Physics Motivation
    - Contributions in the Standard Model
    - New physics contributions - Supersymmetry (SUSY)
- Phenomenology
    - $\mu \to e\gamma$
    - μ-e conversion
    - Comparison and Next steps
- Experiments
    - MEG
    - Mu2E
    - COMET and PRISM/PRIME
- Summary

Physics Motivation

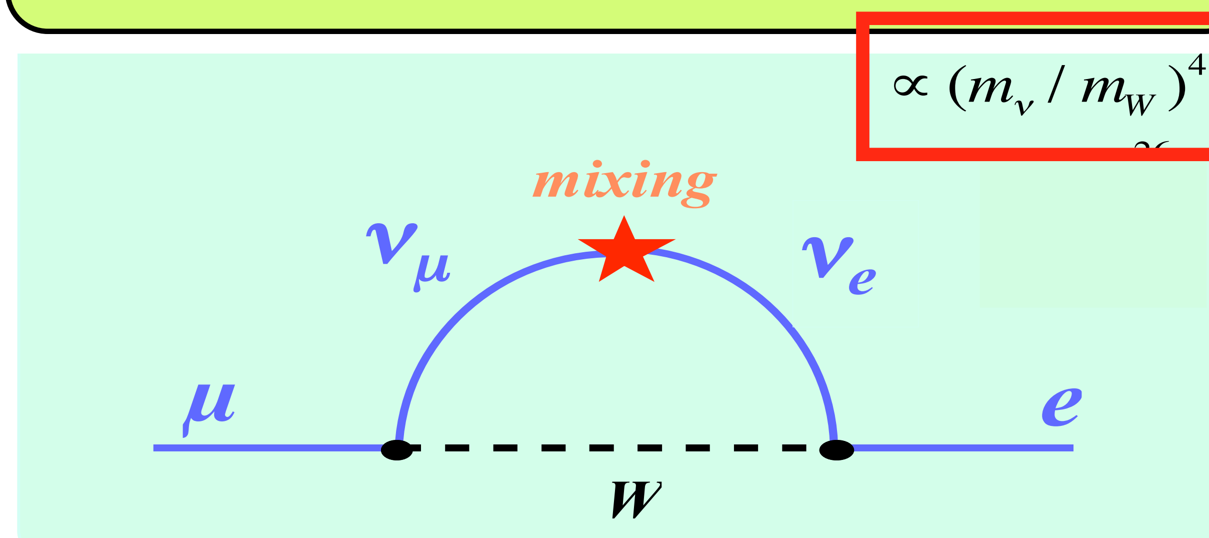
Lepton Flavor Violation (LFV) of Charged Leptons

LFV of neutrinos
(confirmed)



LFV of charged leptons
(not observed yet)

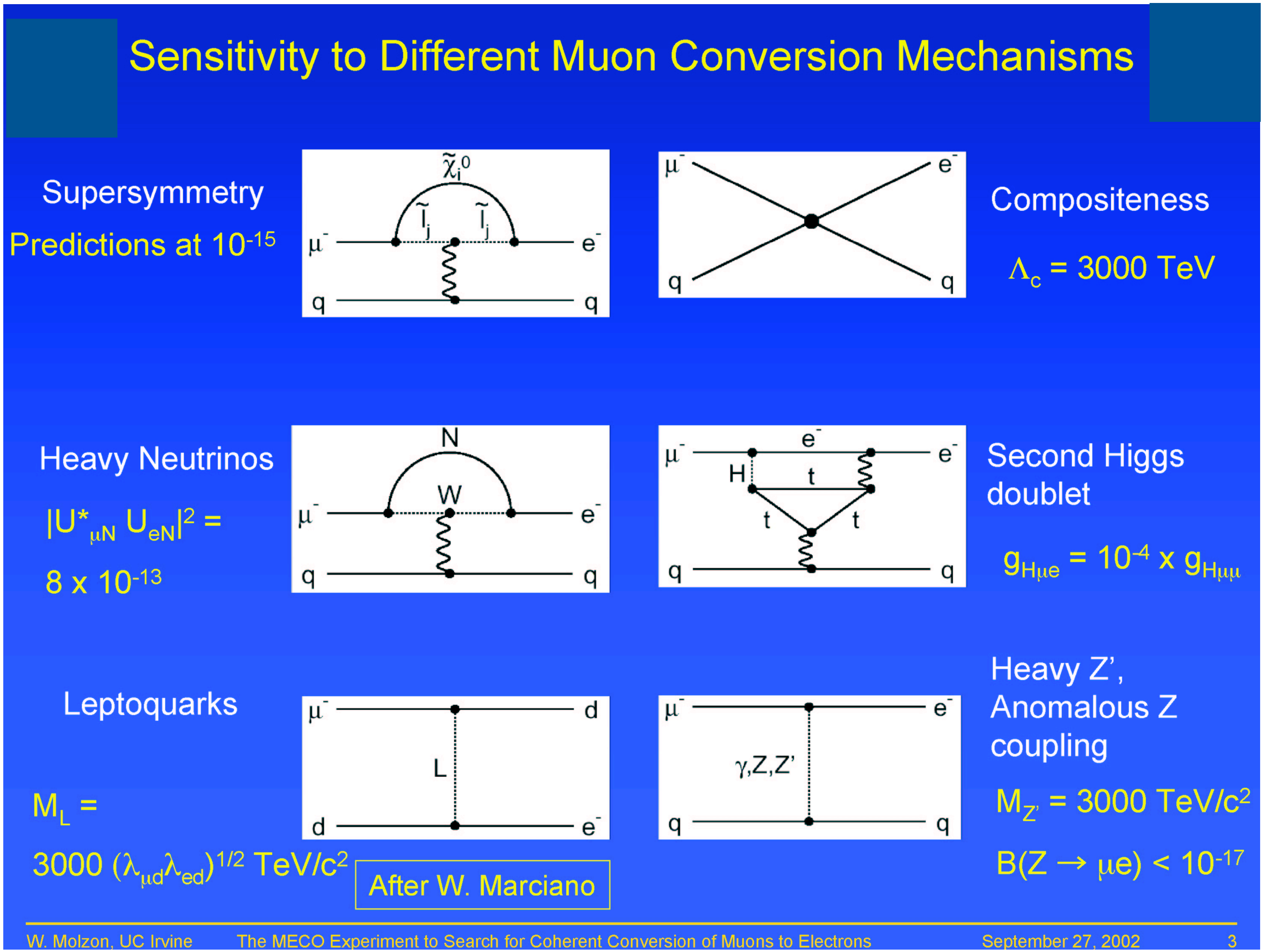
What is the contribution from
neutrino mixing
in the Standard Model?



Very Small (10^{-52})

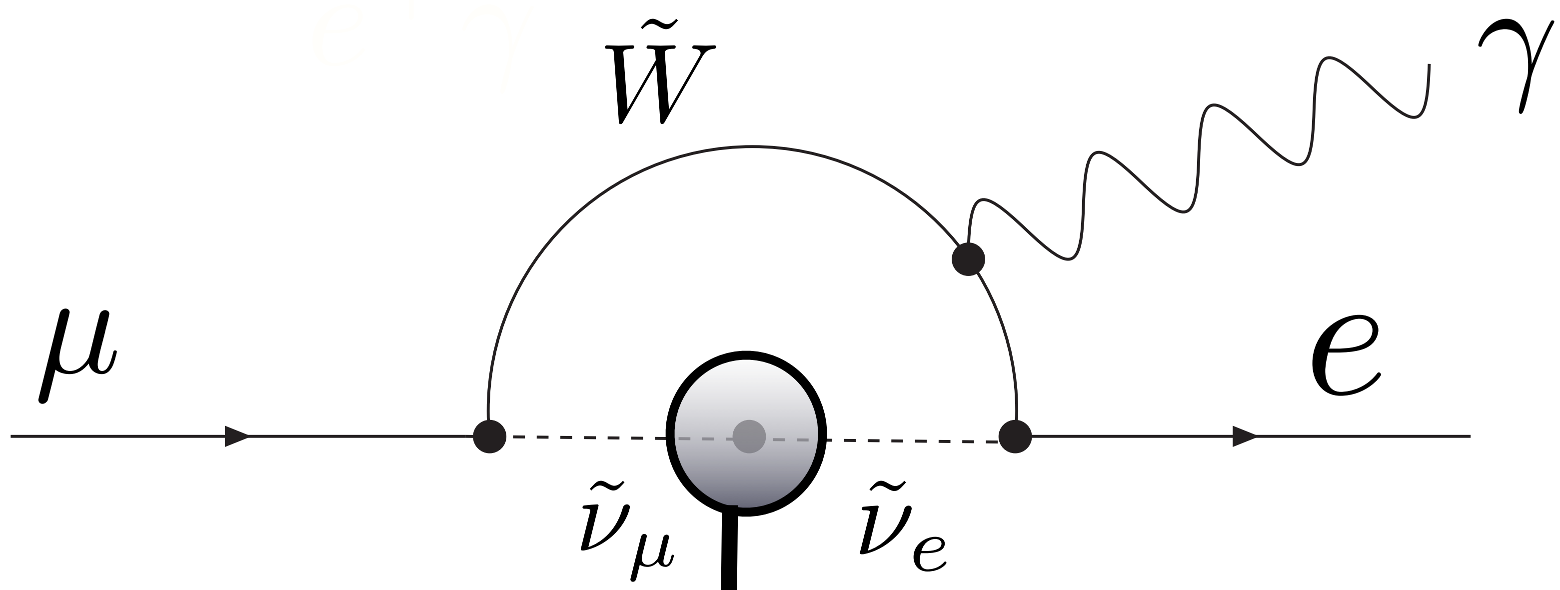
Sensitive to new Physics
beyond the Standard Model

Various Models Predict Charged Lepton Mixing.

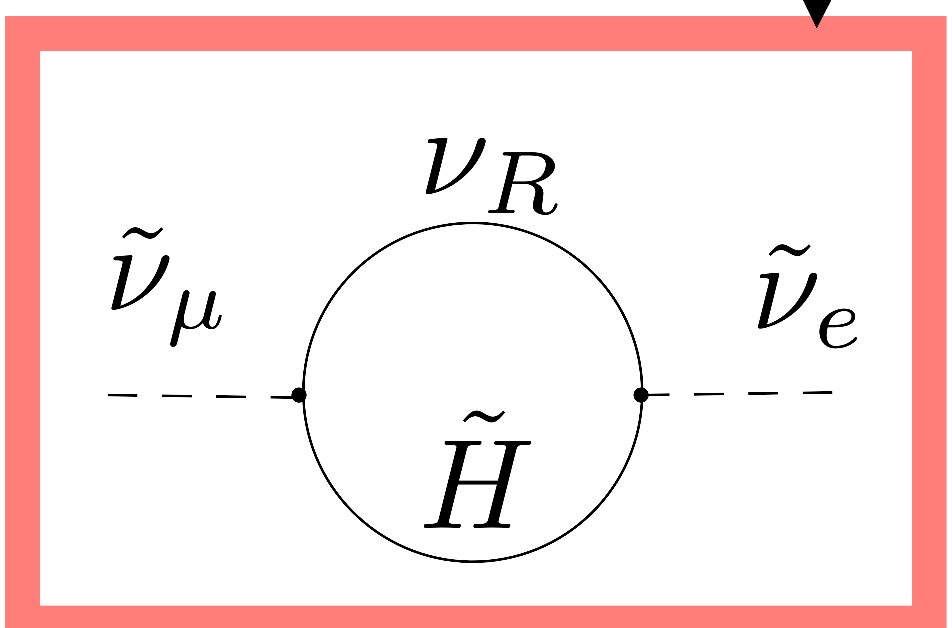


LFV in SUSY Models

an example diagram



Slepton Mixing



Features

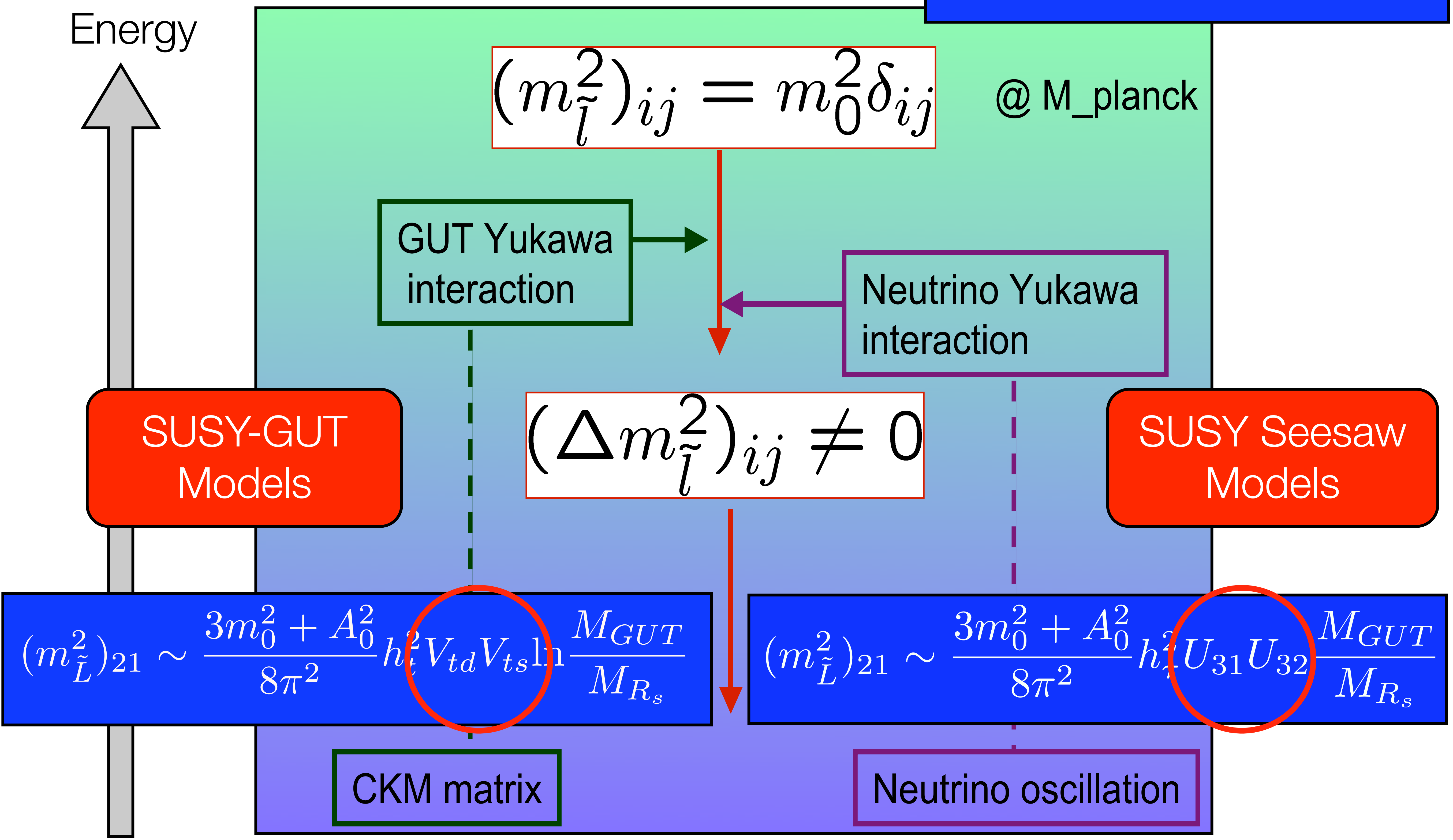
- The decay rate is not too small, because it is determined by the SUSY mass scale.
- But, it contains the information at 10^{16} GeV through the slepton mixing.
- It is in contract to proton decays or double beta decays which need many particles.

Through quantum corrections, LFV could access ultra-heavy particles such as ν_R ($\sim 10^{12}$-10^{14} GeV/c^2) and GUT that cannot be produced directly by any accelerators.

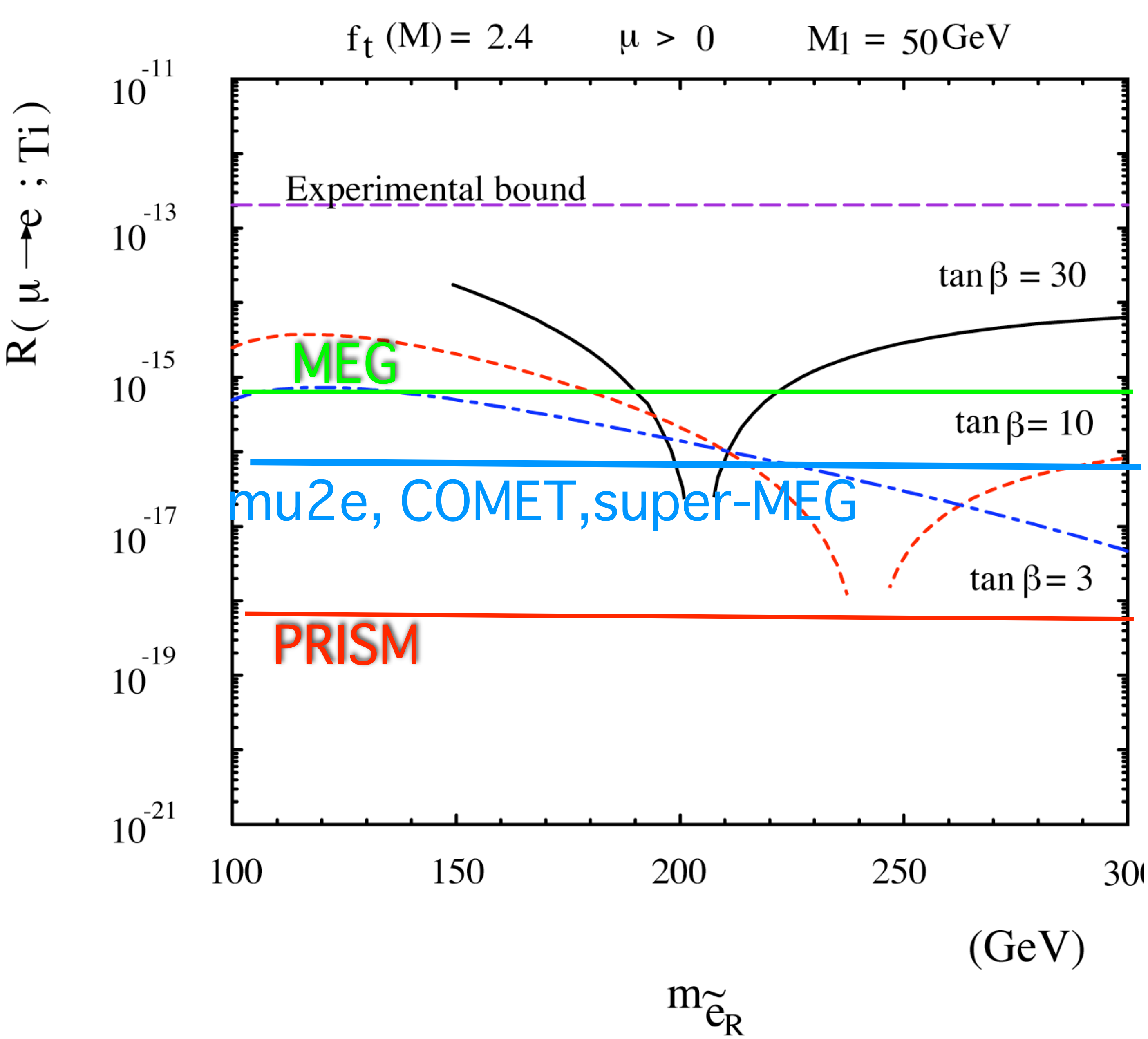
SUSY GUT and SUSY Seesaw

Slepton Mixing in mSUGRA Models

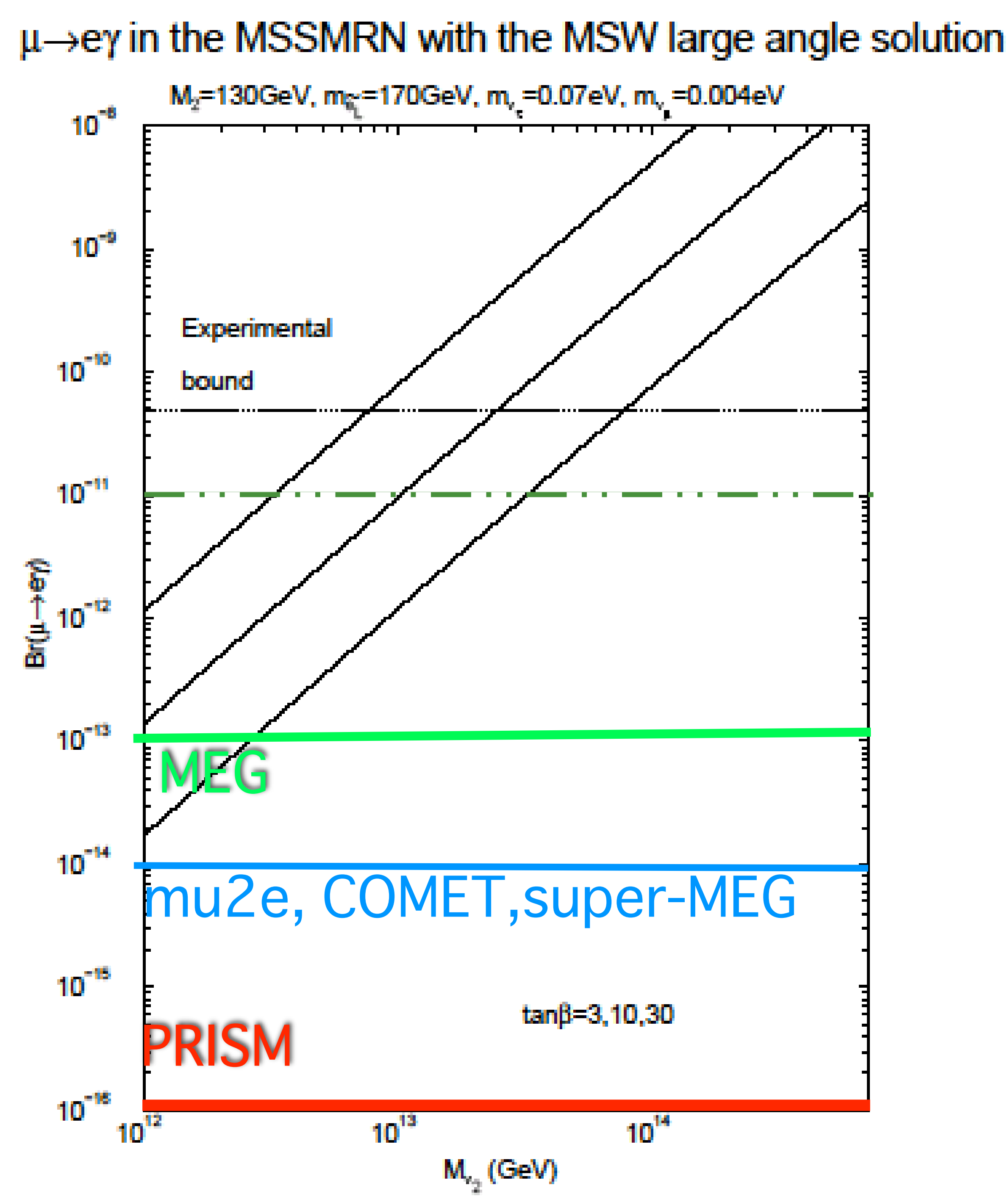
$$m^2_{\tilde{l}} = \begin{pmatrix} m^2_{11} & m^2_{12} & m^2_{13} \\ m^2_{21} & m^2_{22} & m^2_{23} \\ m^2_{31} & m^2_{32} & m^2_{33} \end{pmatrix}$$



SUSY (mSUGRA) Predictions for Muon LFV



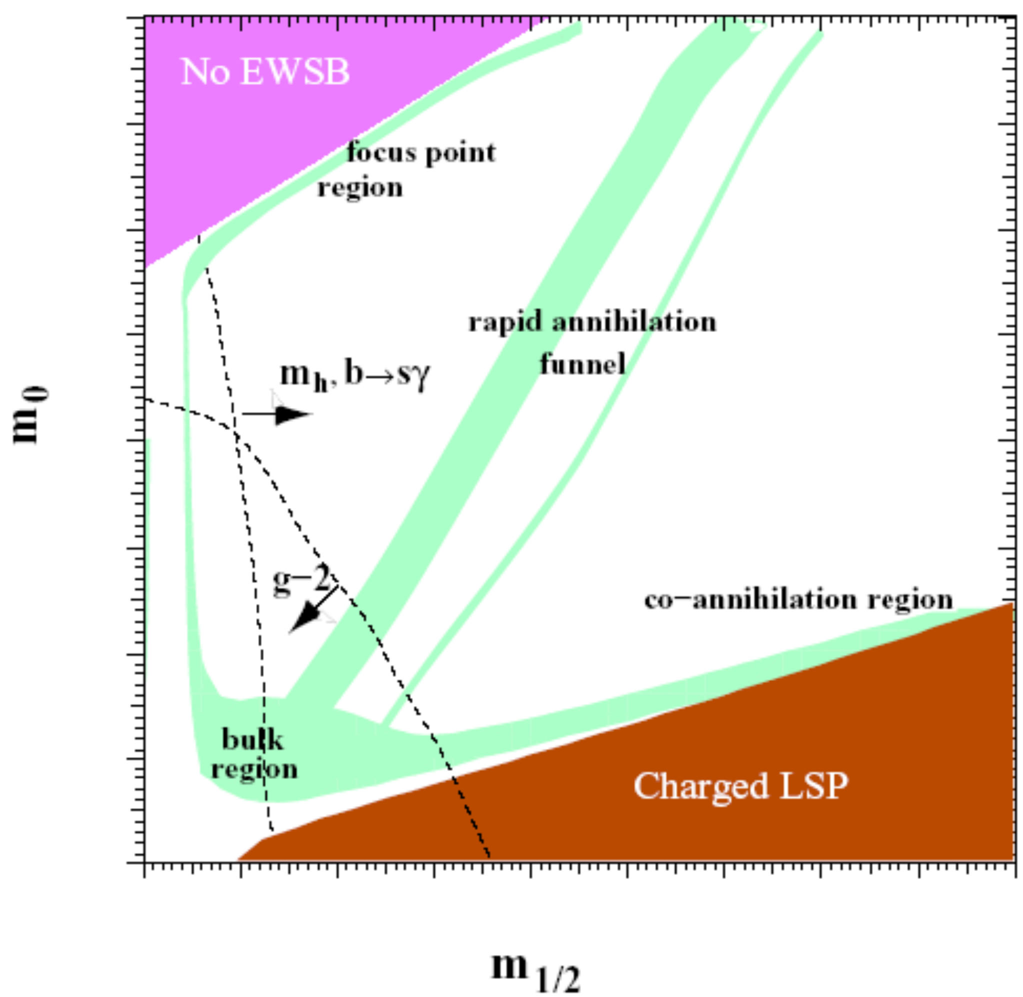
SU(5) SUSY GUT



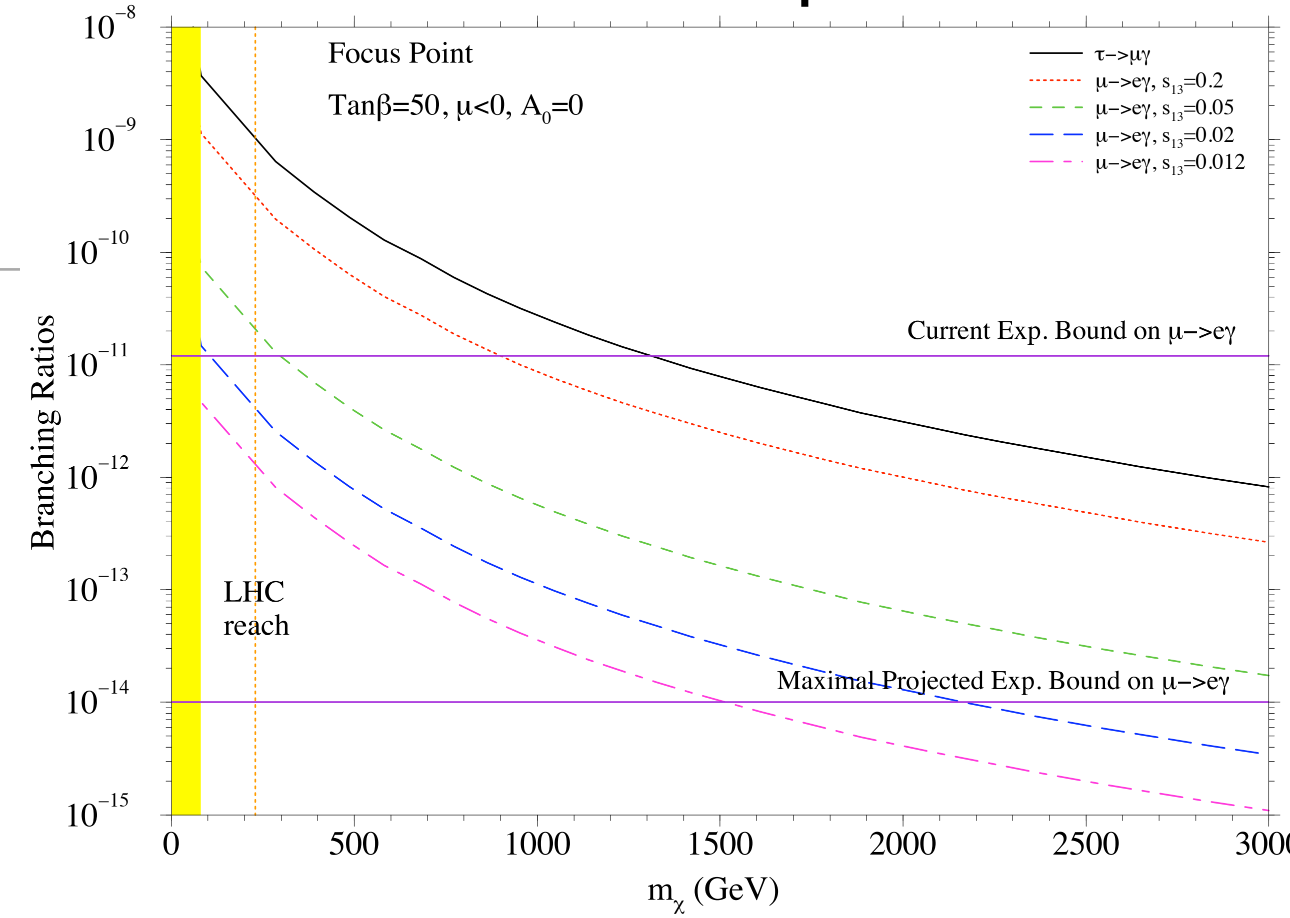
SUSY Seesaw Model

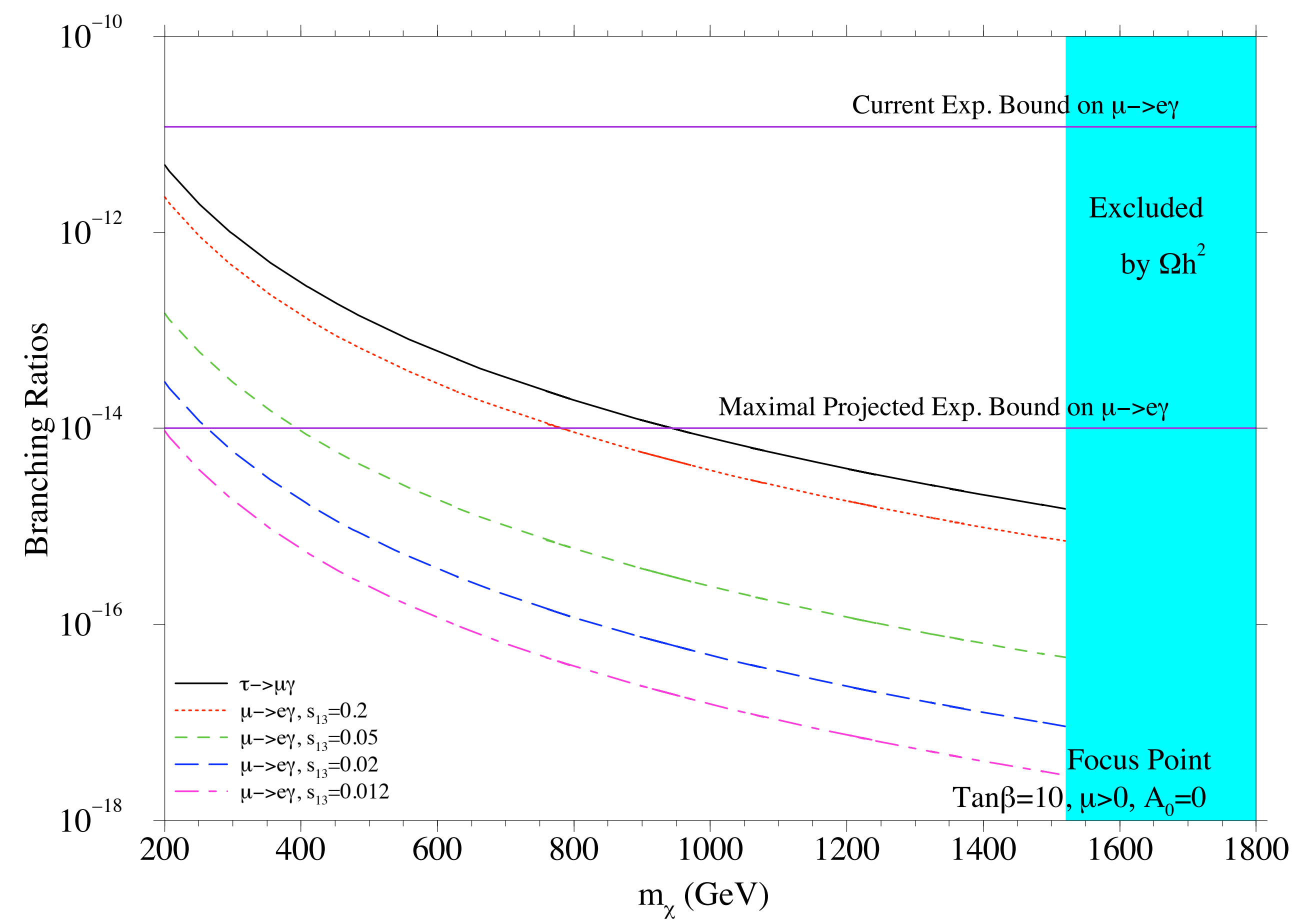
Complementarity to LHC (mSUGRA)

- In mSUGRA, some of the parameter regions, where LHC does not have sensitivity to SUSY, can be explored by LFV.
- Bench mark points



focus point





Complementarity to High Energy Frontier (LHC)

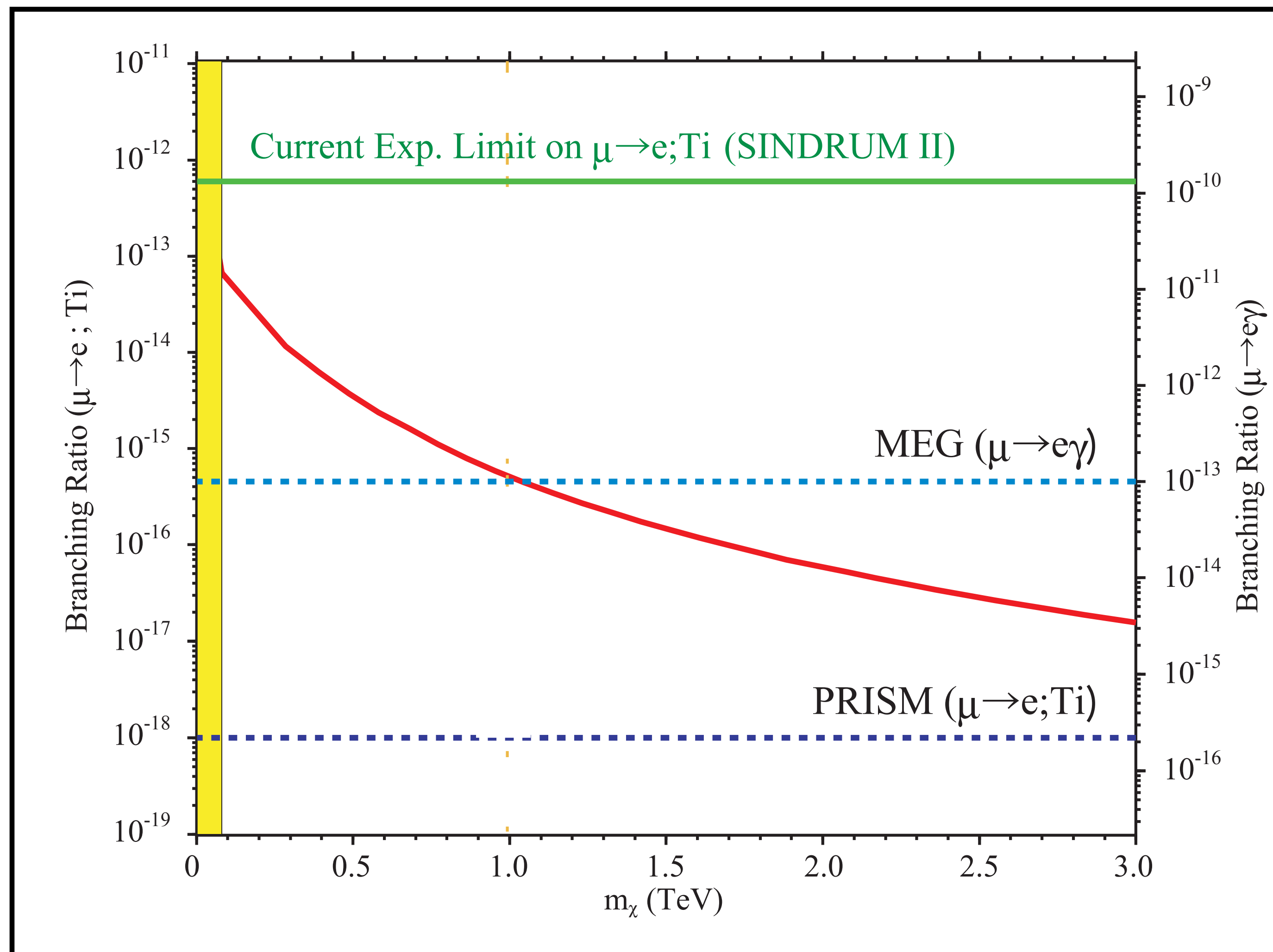
If LHC finds SUSY

LFV search would become important, since the slepton mixing matrix should be studied.
- SUSY-GUT
- SUSY Seesaw models.

And, slepton mixing is hard to study at the LHC and the ILC.

If LHC not find SUSY

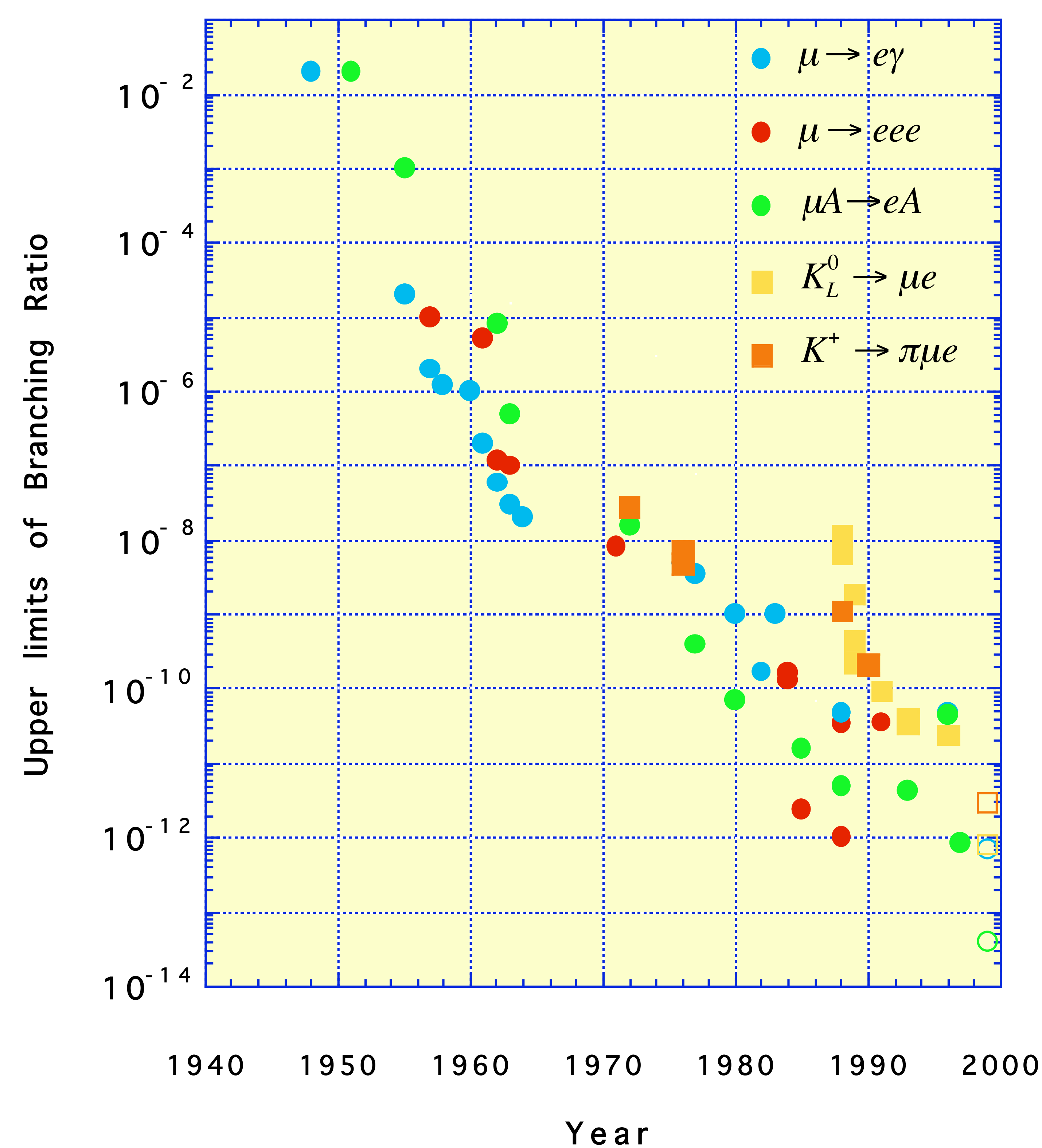
LFV might be sensitive to multi-TeV SUSY if $B<10^{-18}$



Phenomenology

Searches in the Past

- A long history of the LFV search, which started from the experiment with cosmic rays by Pontecorvo et al. in 1947. They believed the muon is an excited state of the electron, and went to the ground state by emitting a photon.
- Since then, the upper limits have been improved by two orders of magnitude with muons that are created by accelerators.

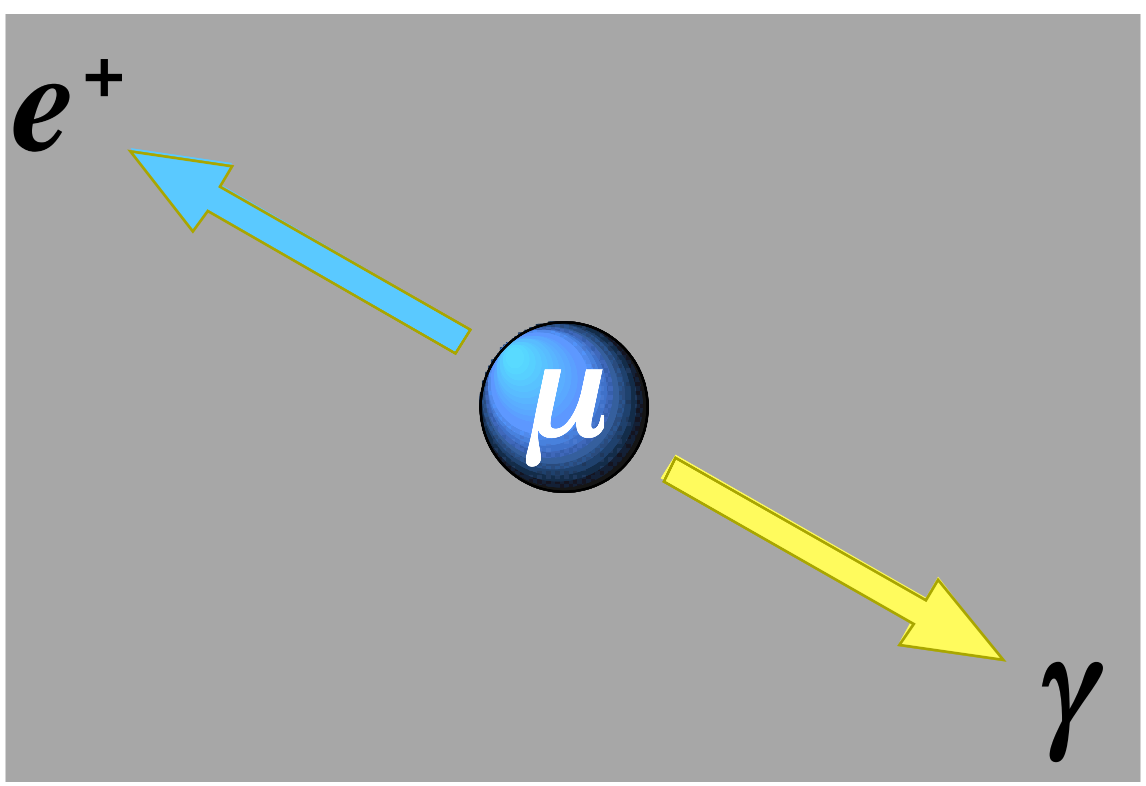


Present Limits and Expectations in Future

process	present limit	near future	comments
$\mu \to e\gamma$	1.2×10^{-11}	10^{-13}	MEG at PSI
$\mu \to eee$	1.0×10^{-12}	10^{-13} - 10^{-14}	?
$\mu N \to eN$ (in Tl)	4.3×10^{-12}	10^{-18}	PRISM
$\mu N \to eN$ (in Al)	none	10^{-16}	COMET and Mu2e
$\tau \to e\gamma$	1.1×10^{-7}	10^{-8} - 10^{-9}	super B factory
$\tau \to eee$	2.7×10^{-7}	10^{-8} - 10^{-9}	super B factory
$\tau \to \mu\gamma$	6.8×10^{-8}	10^{-8} - 10^{-9}	super B factory
$\tau \to \mu\mu\mu$	2×10^{-7}	10^{-8} - 10^{-9}	super B factory

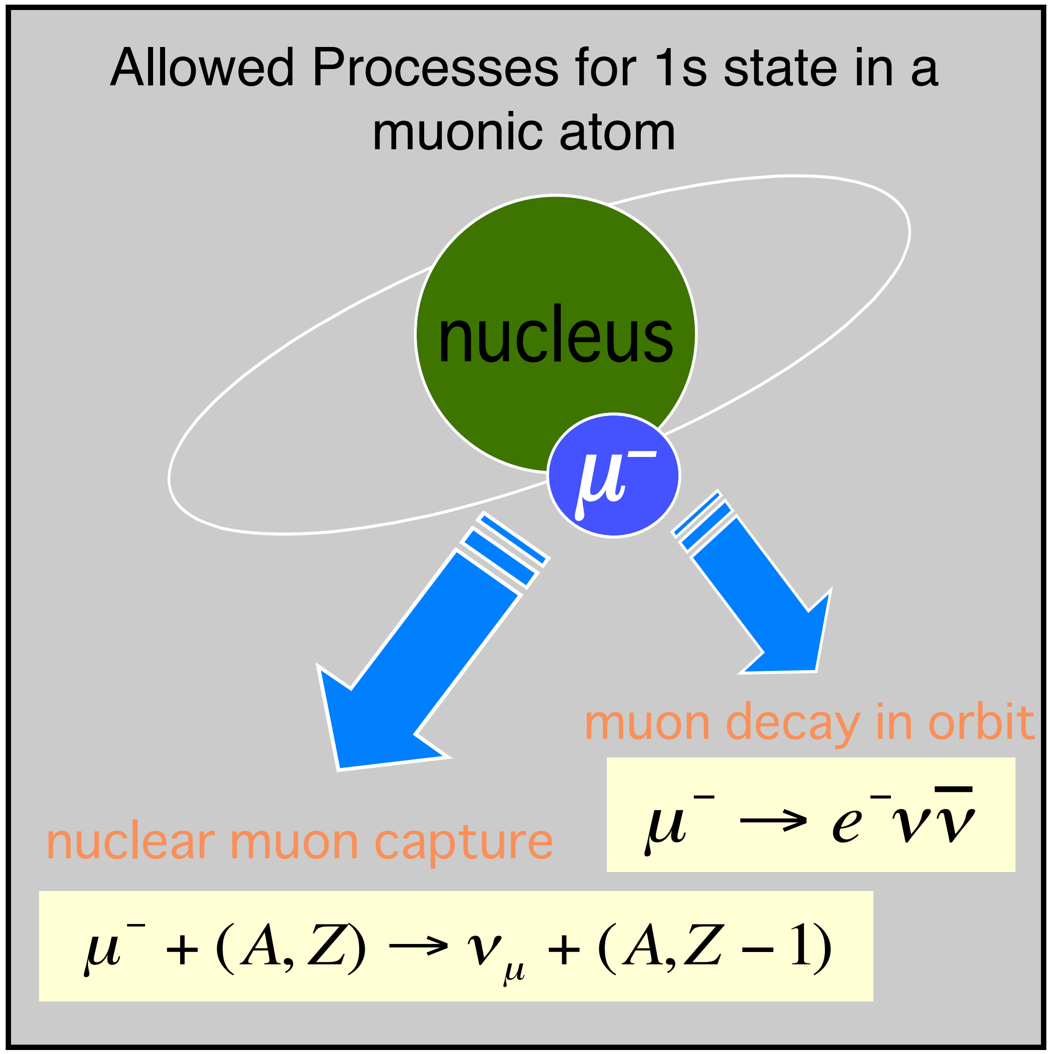
What is $\mu \to e\gamma$?

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



- Backgrounds
  - prompt physics backgrounds
    - radiative muon decay $\mu \to e\nu\nu\gamma$ when two neutrinos carry very small energies.
  - accidental backgrounds
    - positron in $\mu \to e\nu\nu$
    - photon in $\mu \to e\nu\nu\gamma$ or photon from e^+e^- annihilation in flight.

What is Muon to Electron Conversion in a muonic atom ?



μ-e conversion = Neutrino-less muon nuclear capture

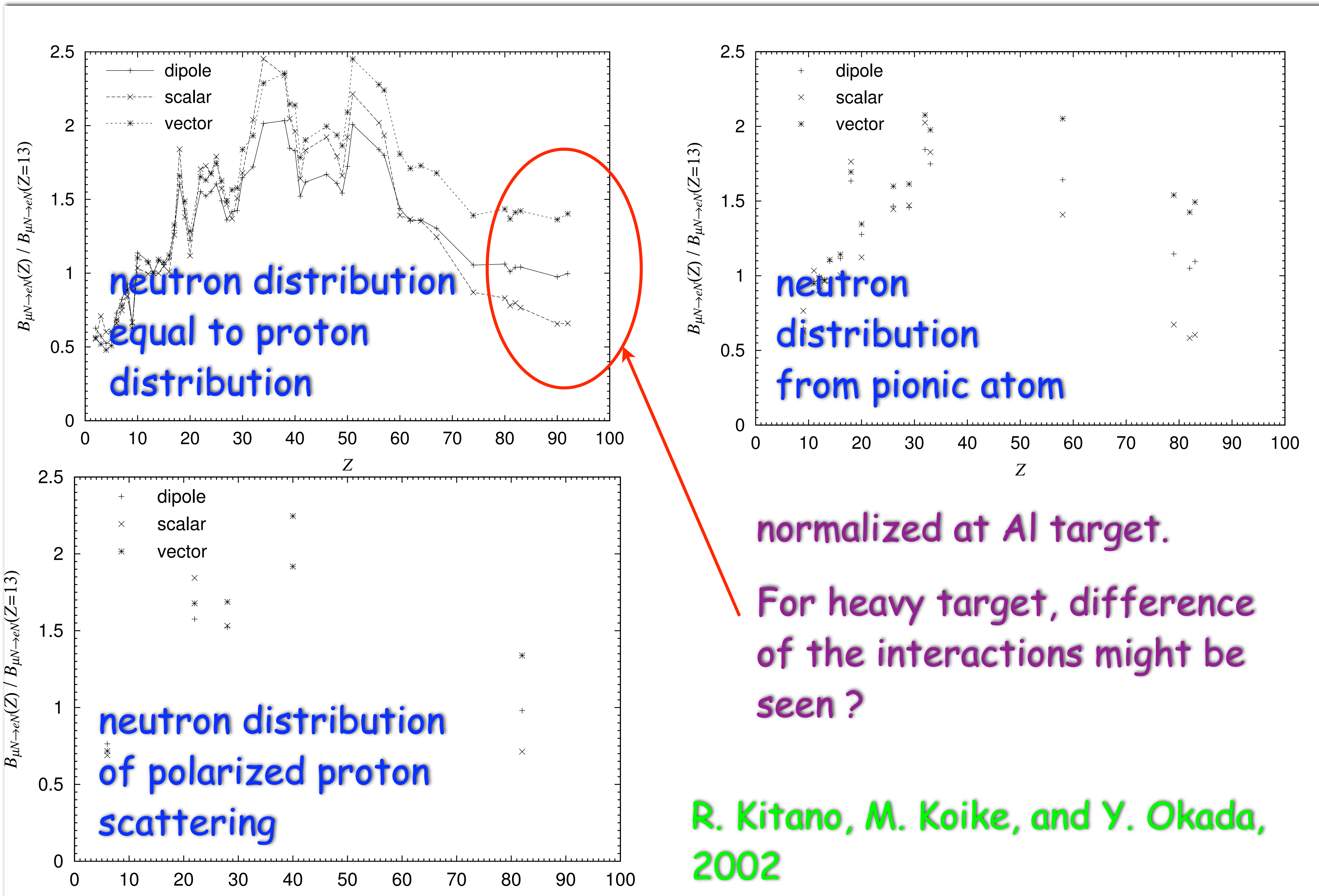
$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$

- Event Signature
  - single mono-energetic electron of 100 MeV/c

$$m_\mu - B_\mu \sim 105 MeV$$

  - coherent process
- Backgrounds
  - Muon decay in orbit
  - Radiative muon capture
  - Radiative pion capture
  - Muon decays in flight
  - Cosmic rays
  - and many others

μ-e Conversion : Target dependence (discriminating effective interaction)

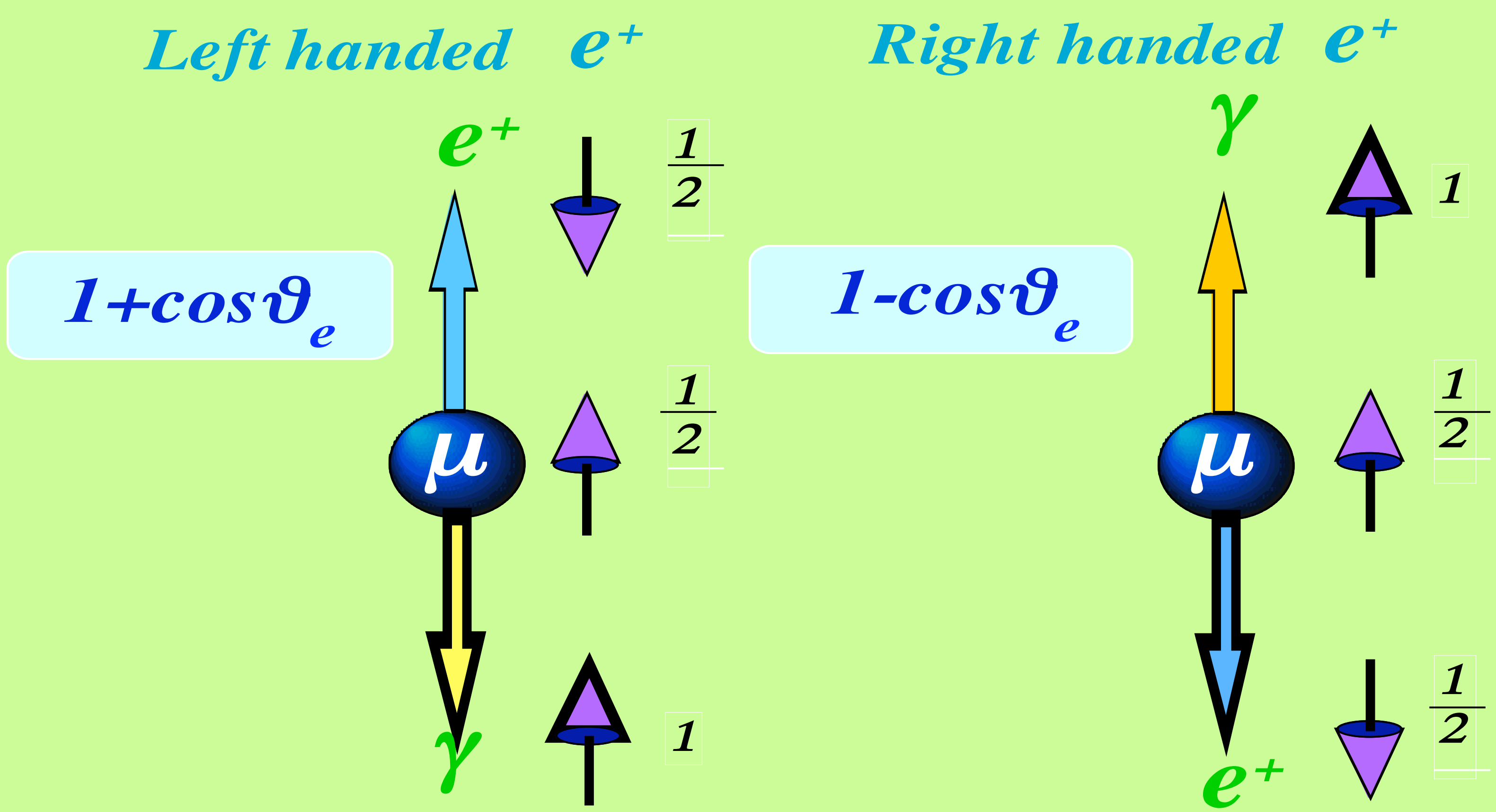


normalized at Al target.

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

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

P-Odd Angular Distribution of Polarized $\mu \rightarrow e\gamma$ Decay (after its observation)

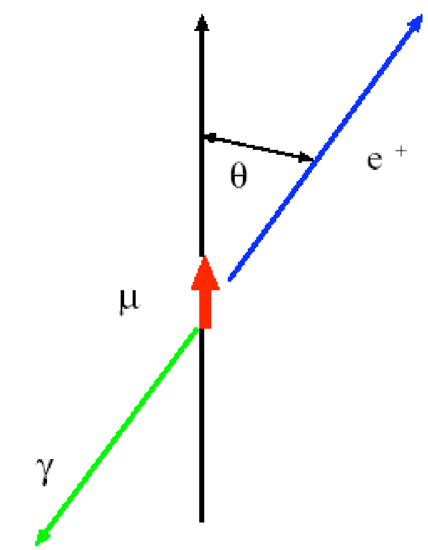


useful to distinguish different theoretical models

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



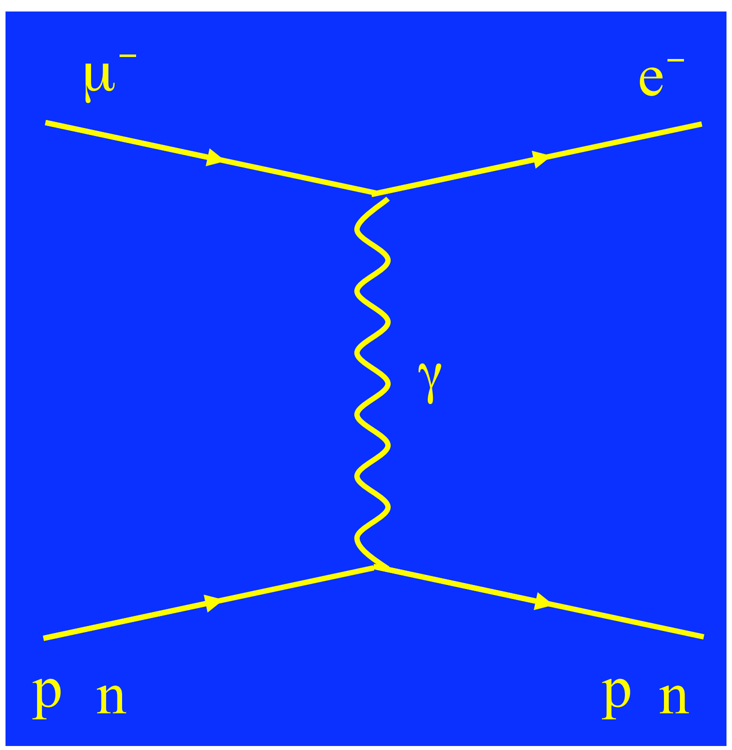
P-odd asymmetry reflects whether right or left-handed slepton have flavor mixing,

Discriminate theoretical models

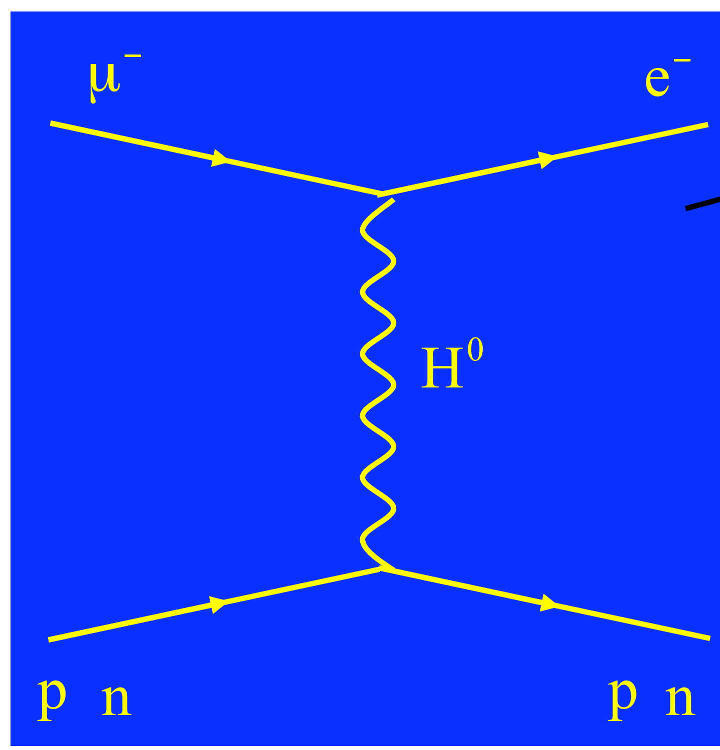
Physics Comparison between μ→eγ and Muon to Electron Conversion

Photonic and non-photonic (SUSY) diagrams

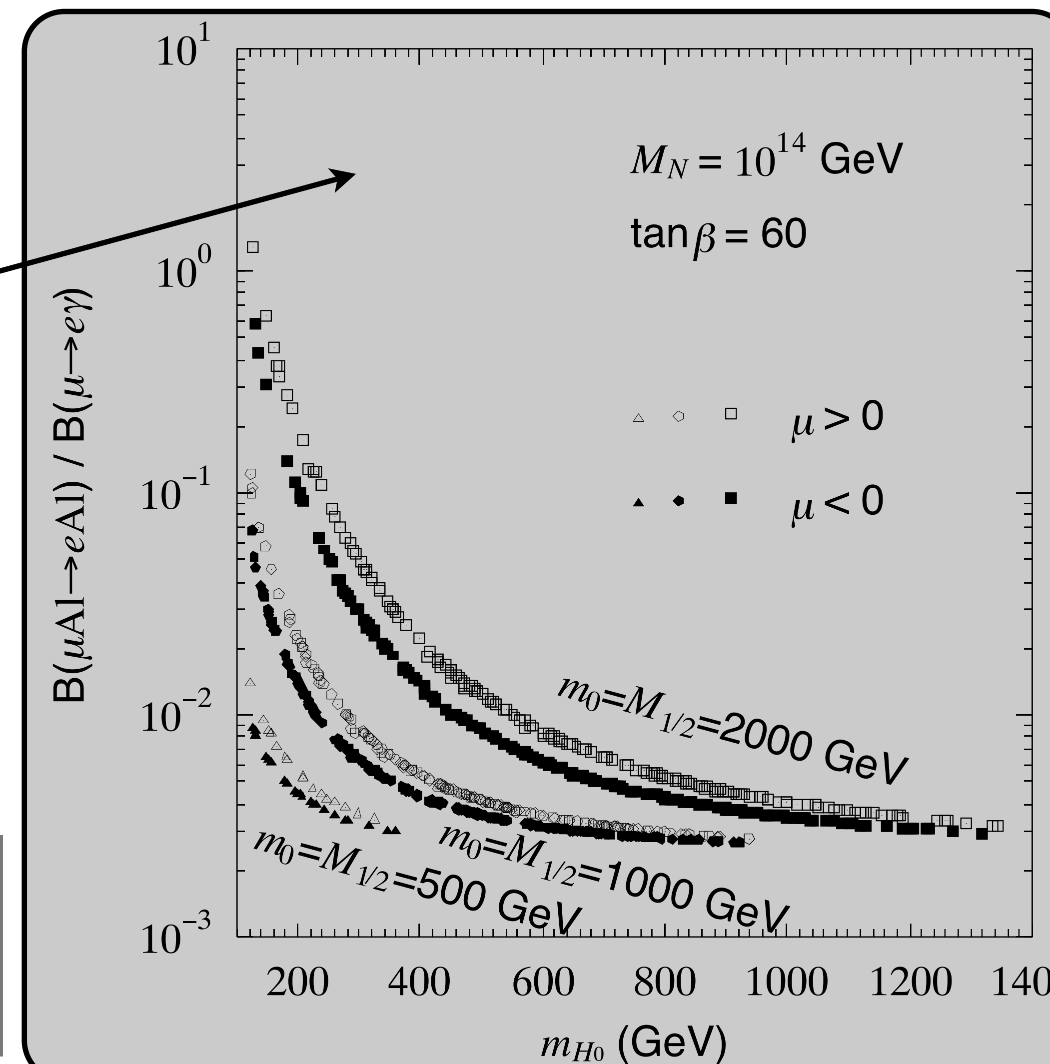
	photonic	non-photonic
• μ→eγ	yes (on-shell)	no
• μ-e conversion	yes (off-shell)	yes



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



$$\frac{B(\mu N \rightarrow eN)}{B(\mu \rightarrow e\gamma)} \leq 1$$



Experimental Comparison between $\mu \to e\gamma$ and μ-e Conversion

	background	challenge	beam intensity
• $\mu \to e\gamma$	accidentals	detector resolution	limited
• μ-e conversion	beam	beam background	no limitation

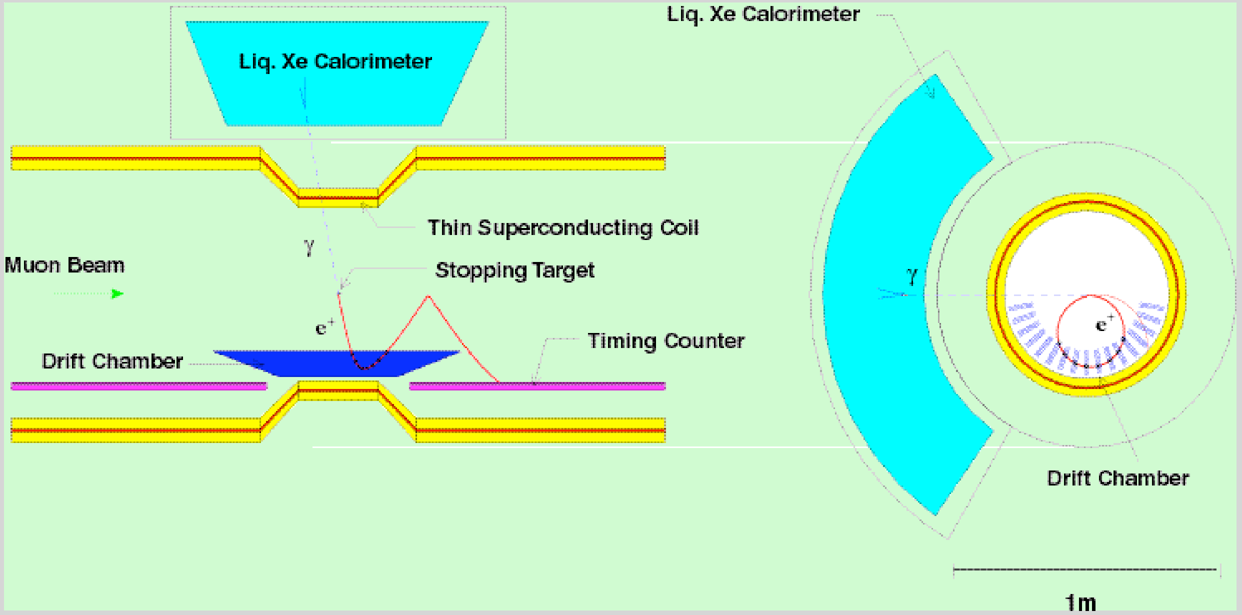
- $\mu \to e\gamma$: Accidental background is given by $(\text{rate})^2$. The detector resolutions have to be improved, but they (in particular, photon) would be hard to go beyond MEG from present technology. The ultimate sensitivity would be about 10^{-14} (with about 10^8/sec) unless the detector resolution is radically improved.
- μ-e conversion : Improvement of a muon beam can be possible, both in purity (no pions) and in intensity (thanks to muon collider R&D). A higher beam intensity can be taken because of no accidentals.

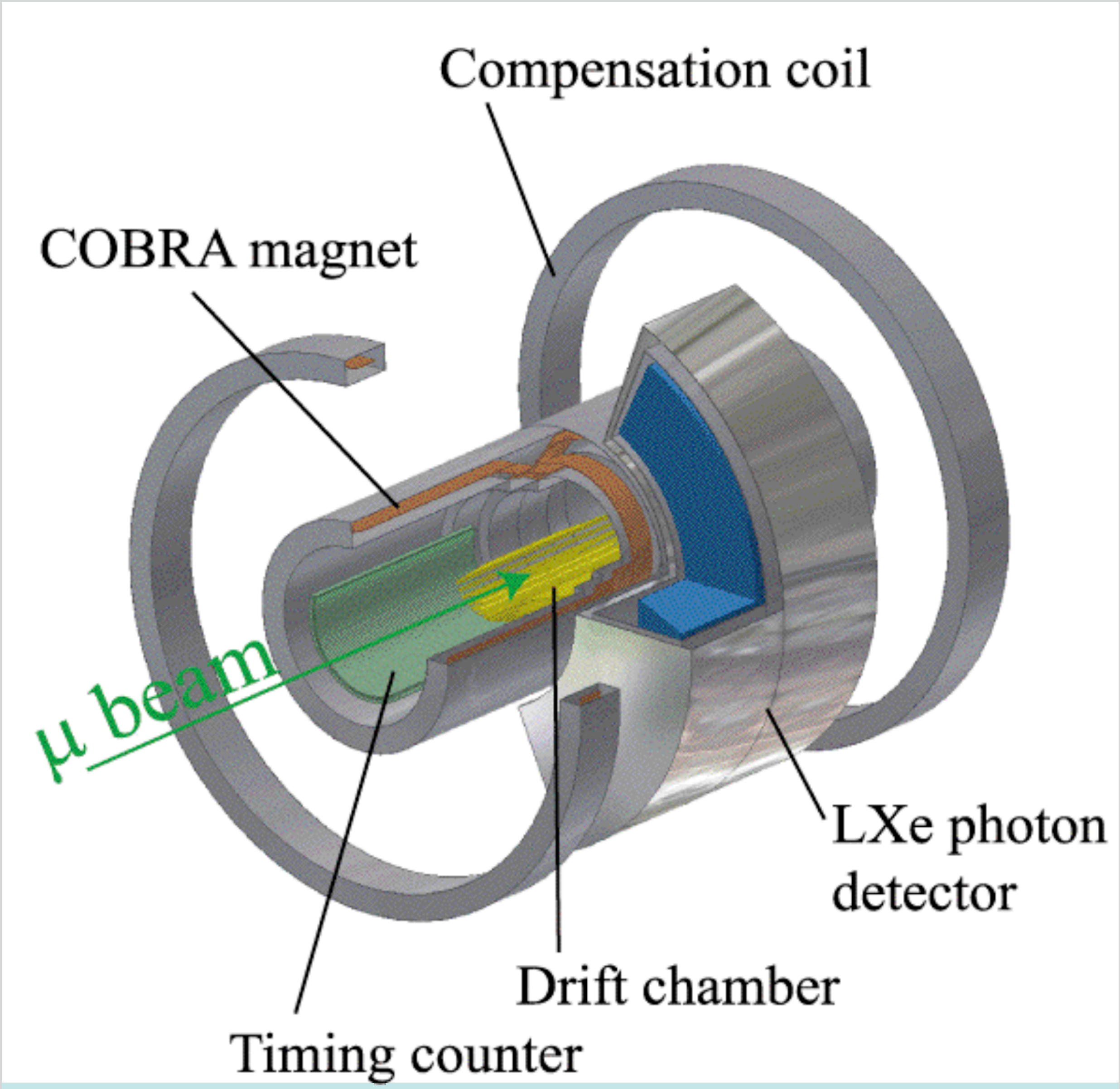
μ-e conversion might be a next step.

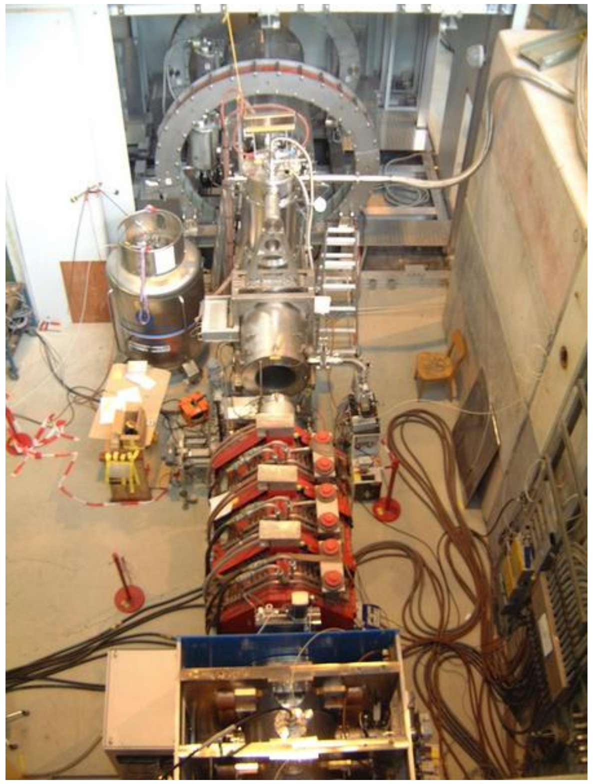
Experiments

MEG at PSI

- DC beam 10^7 muons/sec.
- Goal : B < 10^{-13}
- COBRA : spectrometer for e^+ detection.
- Liquid Xenon detector for photon detection.
- running since 2007.



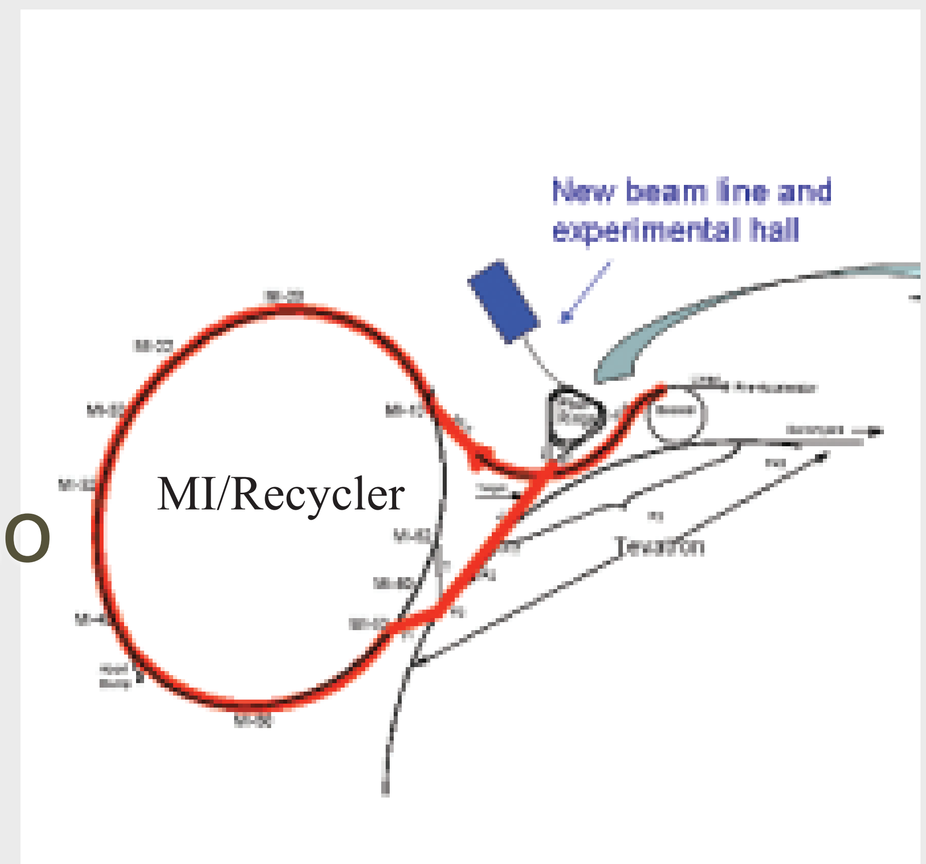


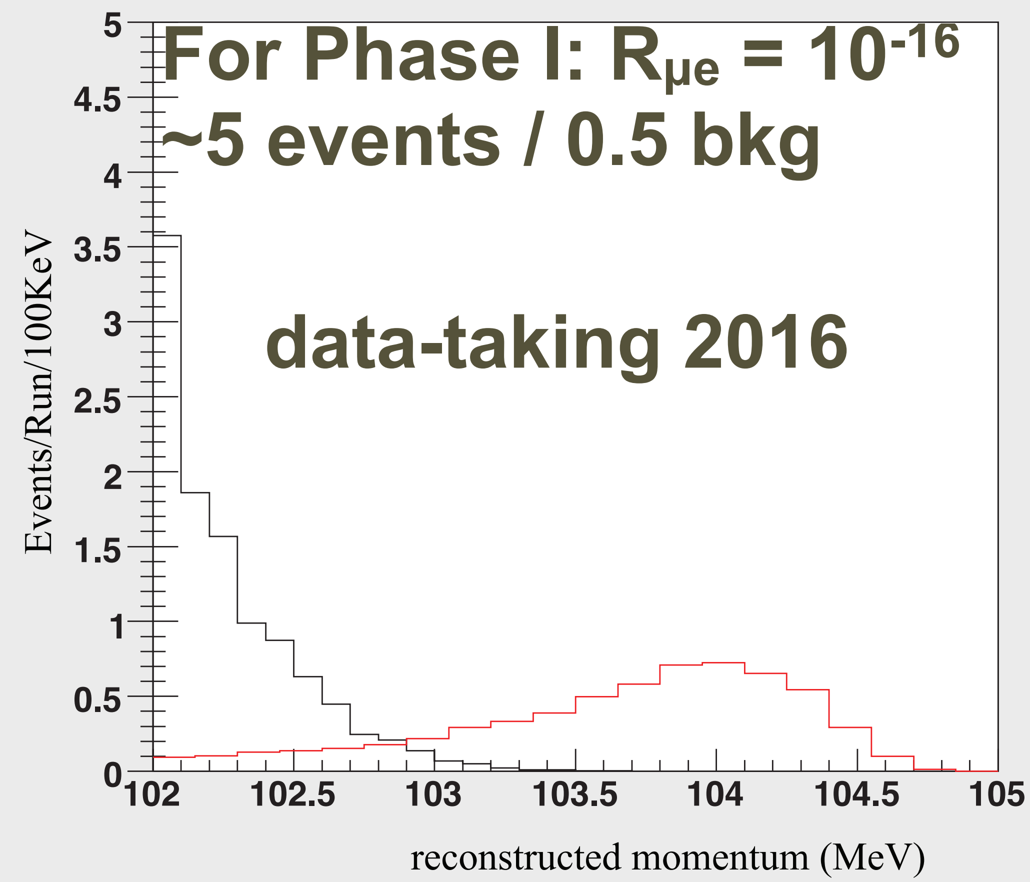


Mu2e: Muon-Electron Conversion at Fermilab

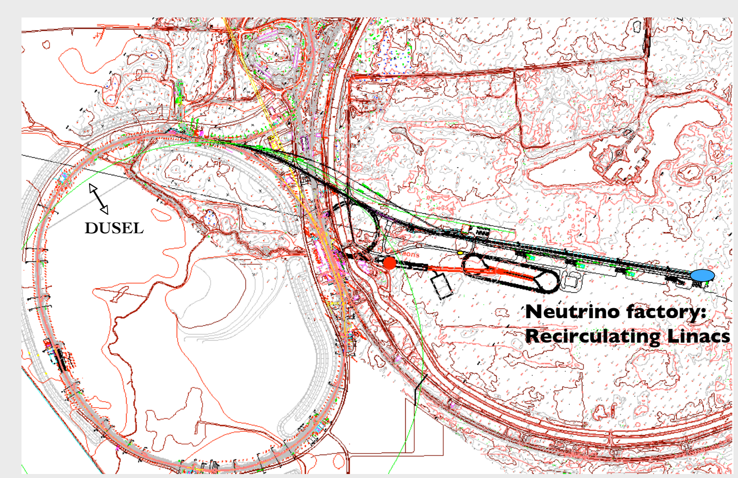
starts with advanced MECO design

uses existing rings with minor changes: no effect on NOvA





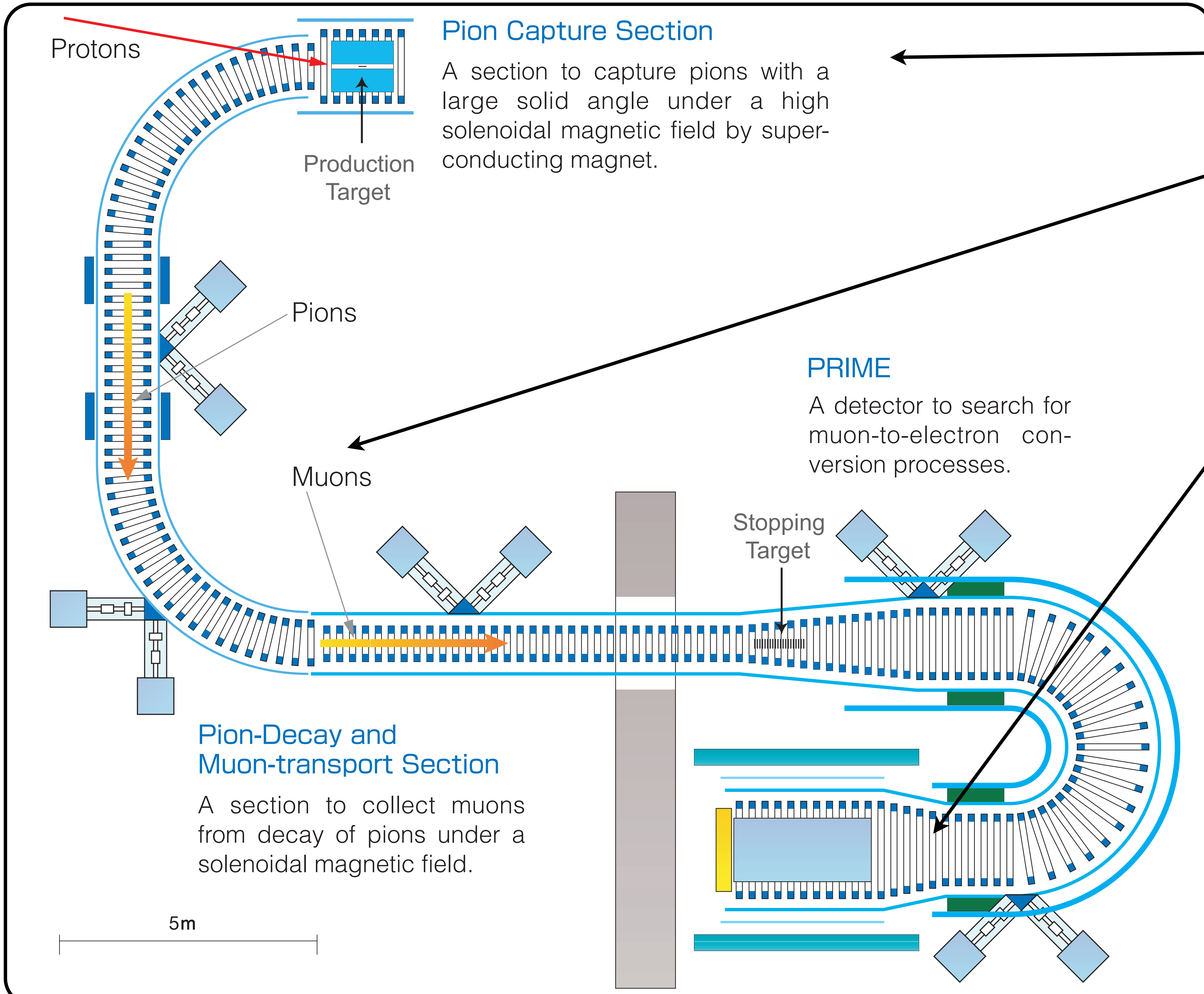
$R_{\mu e}$ ~10^{-18} at Project X



with DUSEL (and kaons, g-2,...?)

COMET (COherent Muon to Electron Transition) in J-PARC (Japan)

$B(\mu^- + Al \rightarrow e^- + Al) < 10^{-16}$



Proton Beam

The Muon Source
- Proton Target
- Pion Capture
- Muon Transport

The Detector
- Muon Stopping Target
- Electron Transport
- Electron Detection

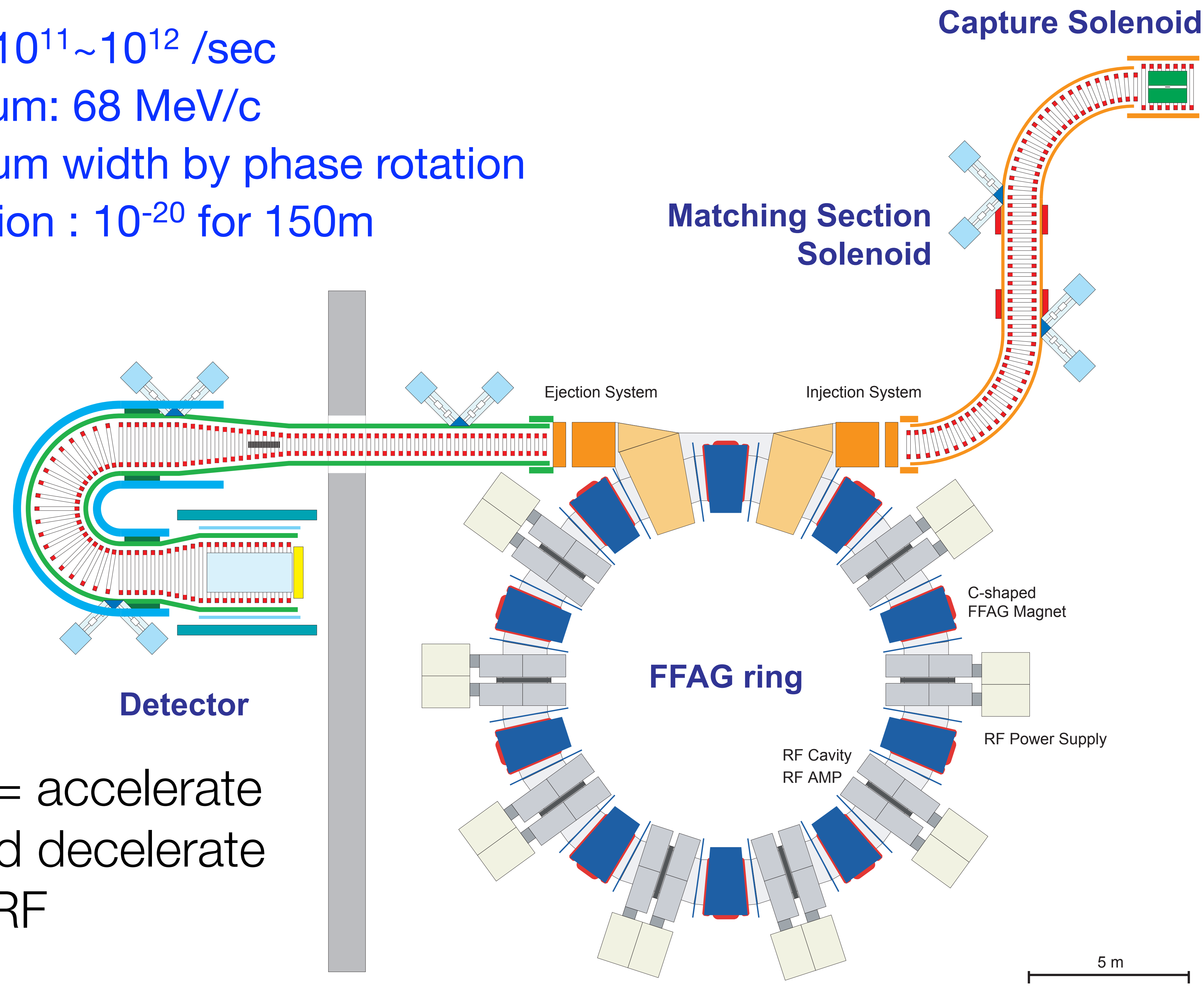
proposed to J-PARC

PRISM=Phase Rotated Intense Slow Muon source

PRISM

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

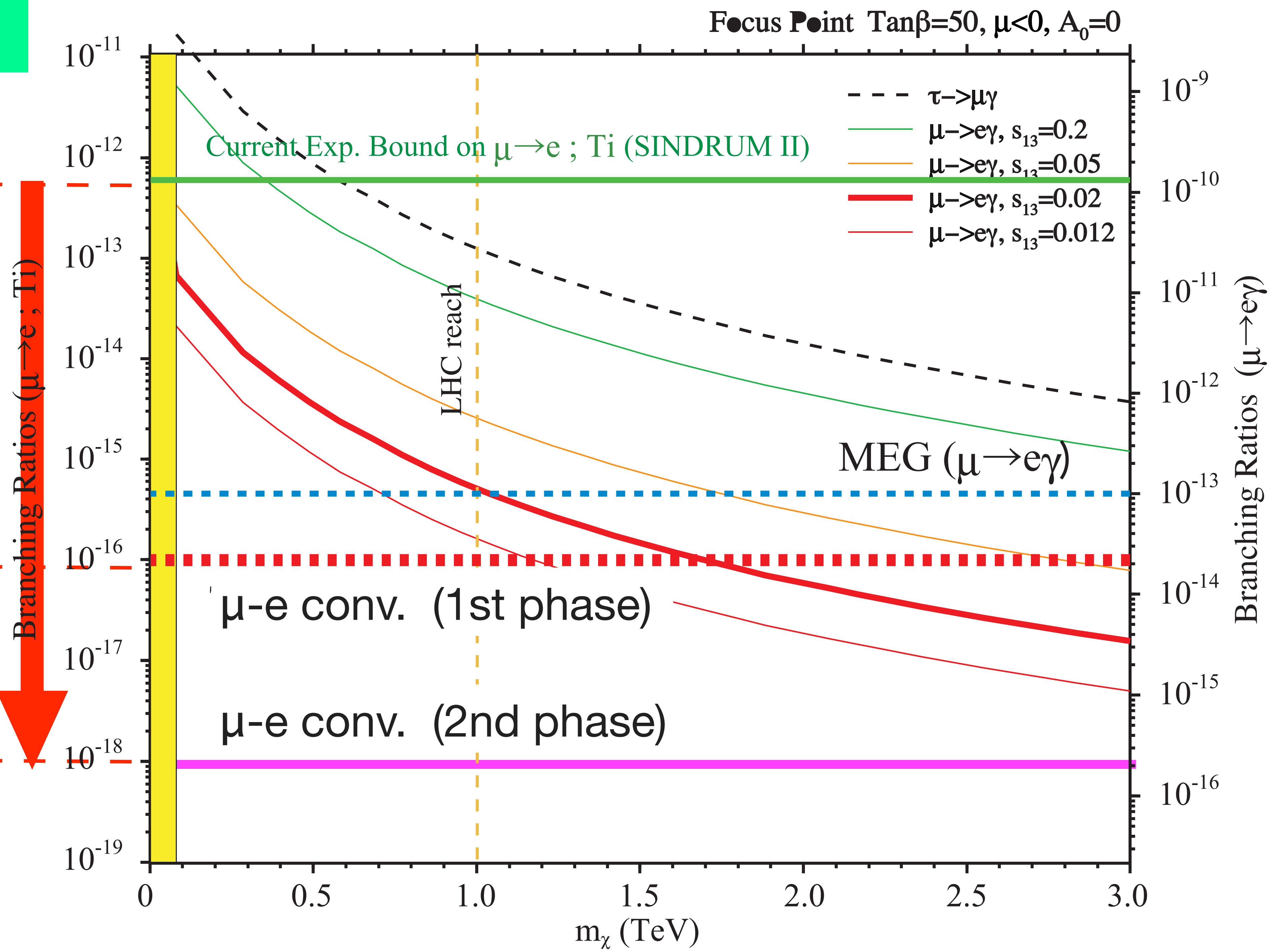
- muon intensity: 10^{11}~10^{12} /sec
- central momentum: 68 MeV/c
- narrow momentum width by phase rotation
- pion contamination : 10^{-20} for 150m



Phase rotation = accelerate slow muons and decelerate fast muons by RF mSUGRA with right-handed neutrinos

will be improved by a factor of 10,000.

will be improved by a factor of 1000,000.



Sensitivity Goals

$$B(\mu^- + Al \to e^- + Al) < 10^{-16}$$

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

Conclusion and Outlook

- Physics motivation of charged lepton flavor violation (LFV) with muons is very strong and robust, even in the LHC era.
- LFV of charged leptons is sensitive to new physics beyond the Standard Model, in particular SUSY models (SUSY-GUT and SUSY-Seesaw), which are related to proton decay studies and neutrino physics respectively.
- For $\mu \rightarrow e\gamma$ decay, the MEG experiment at PSI is running.
- For μ-e conversion, the mu2e experiment at FNAL and the COMET experiment at J-PARC with sensitivity of $B<10^{-16}$ is under preparation.
- In the second stage of μ-e conversion, experiments with $B<10^{-18}$ will be aimed.
- Collaborators are welcome !

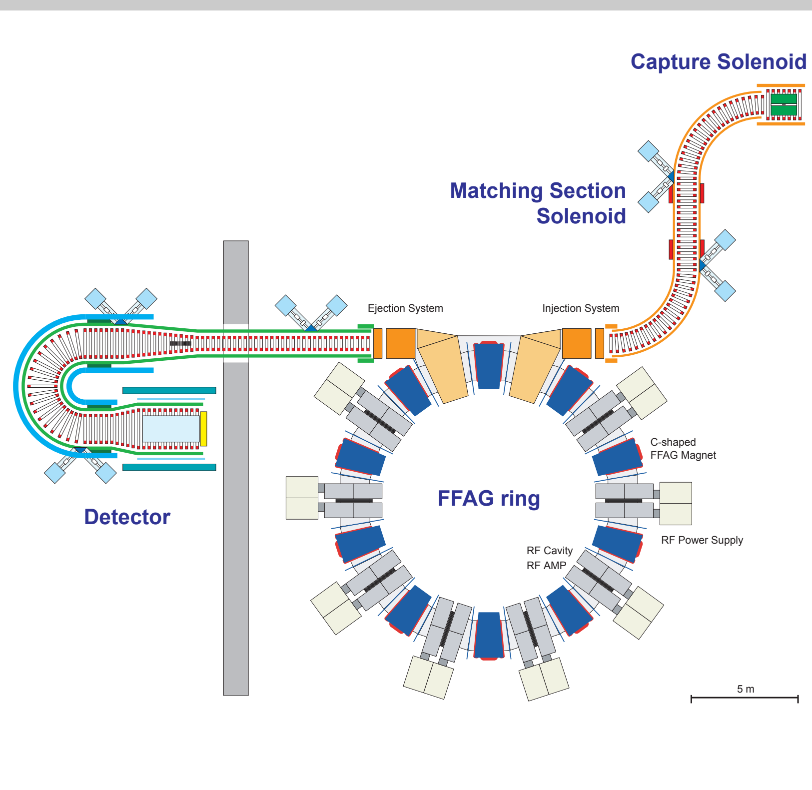
Backups

Roadmap of Particle Physics based on muons

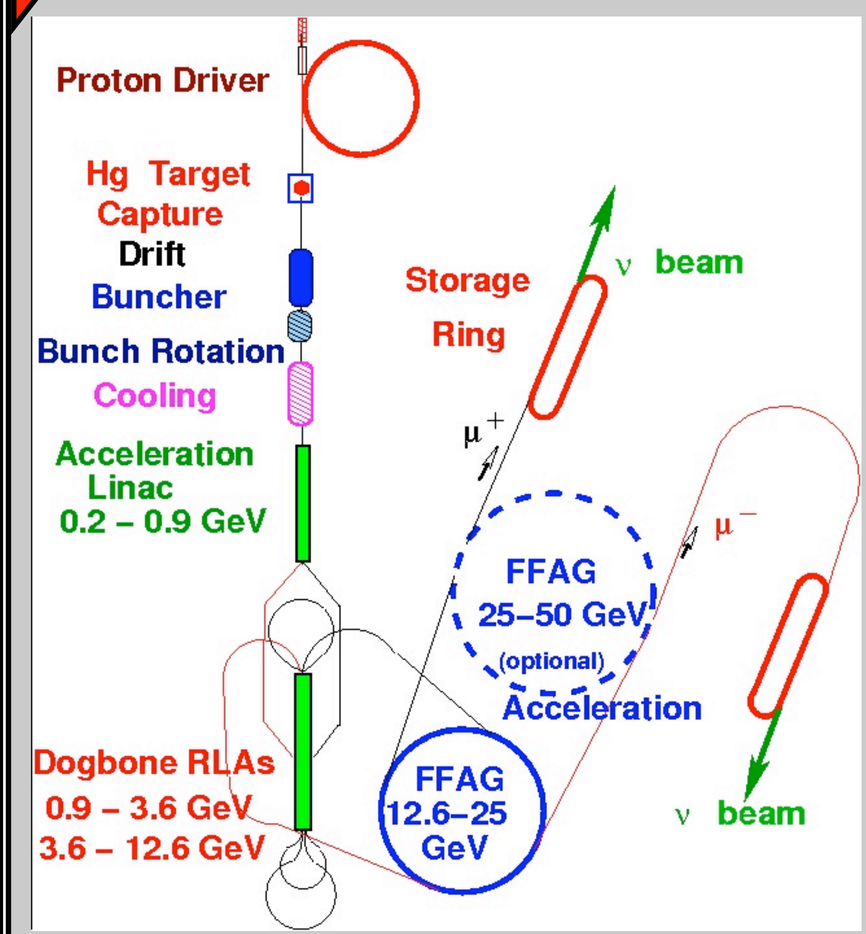
Based on common technologies

Muon Factory

muon LFV,
muon g-2,
muon EDM
muon application



Neutrino Factory



Energy frontier Muon Collider - 2~4 TeV