Muon Experiments in Project X

Yoshitaka Kuno
Department of Physics
Osaka University

DOE Briefing
November 17th, 2010

OSAKA UNIVERSITY

Outline

- Why Intensity Frontier with Muons?
- Project X Muon Source: Comparison in the World
- Muon Experiments at Project X
- Why Charged Lepton Flavor Violation (CLFV) ?
- Why μ-e Conversion, not $\mu \rightarrow e\gamma$?
- Why 10^{-18} for μ-e Conversion ?
- Planned μ-e Conversion Experiment at Fermilab (Mu2e)
- μ-e Conversion Experiment at Project X
- Summary

Why Intensity Frontier with Muons ?

Electroweak Epoch

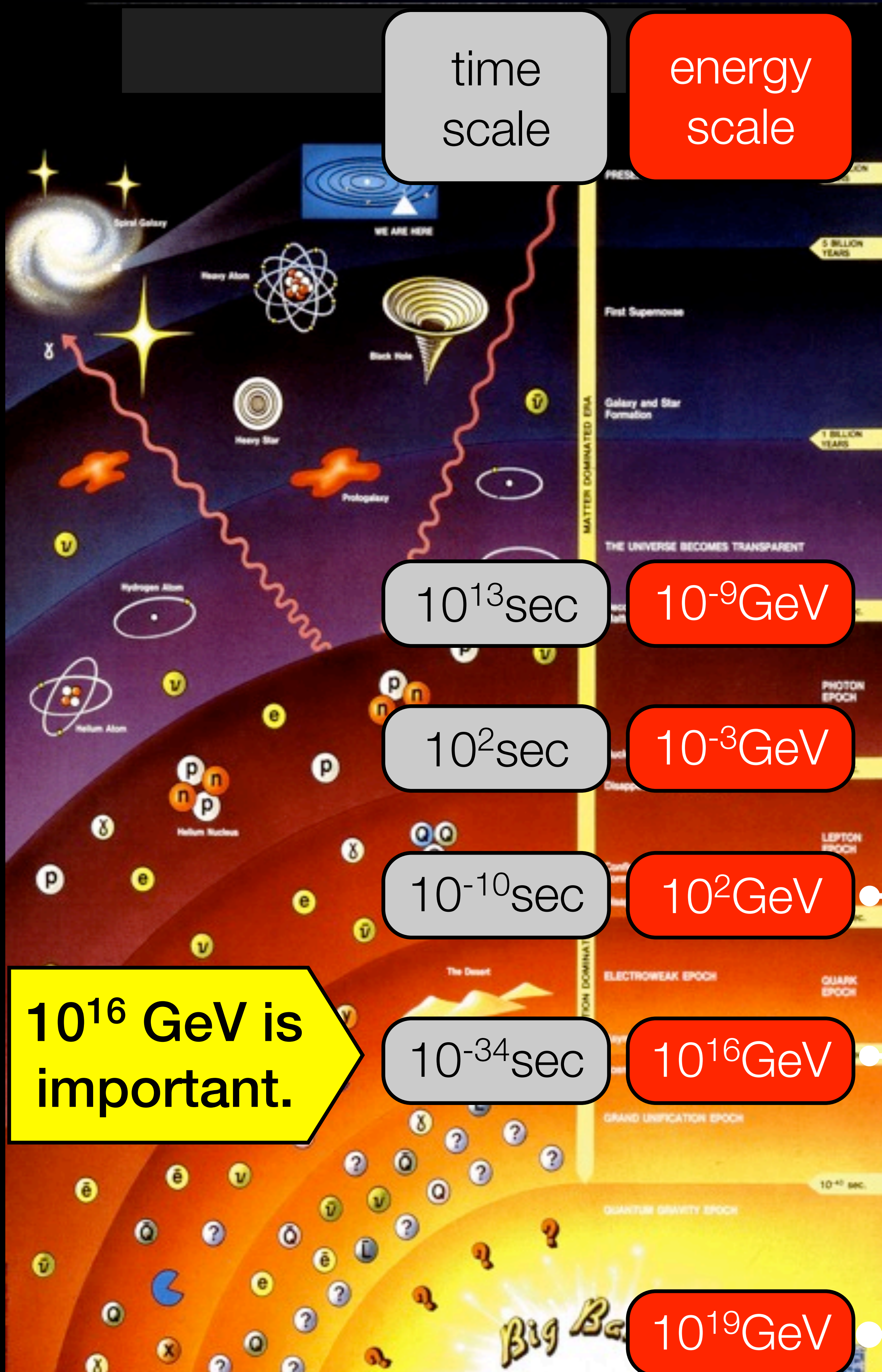
- Origin of Mass (Higgs Particle)
- New Symmetry (Supersymmetry)

Unification Epoch

- Unification of Fundamental Forces (GUT)
- Origin of Neutrino mass (Right-handed Neutrinos)
- Our Existence in the Universe (Leptogenesis)

Quantum Gravity Epoch

- Superstrings



Electroweak Epoch

- Origin of Mass (Higgs Particle)
- New Symmetry (Supersymmetry)

Unification Epoch

- Unification of Fundamental Forces (GUT)
- Origin of Neutrino mass (Right-handed Neutrinos)
- Our Existence in the Universe (Leptogenesis)

Quantum Gravity Epoch

- Superstrings

The Intensity Frontier is.....

- Energy scale reached by the intensity frontier would be much higher than that of accelerators of O(1 TeV) through quantum radiative corrections (renormalization group equation = RGE).

Quantum Corrections

- Effects are small.
  - Rare process searches
  - High precision measurements
- High intensity machine is needed.
- Indirect searches

$$\Delta E \sim \frac{\hbar}{2\Delta t}$$

Uncertainty principle

Why Muons for the Intensity Frontier ?

Guidelines for Rare Process Searches

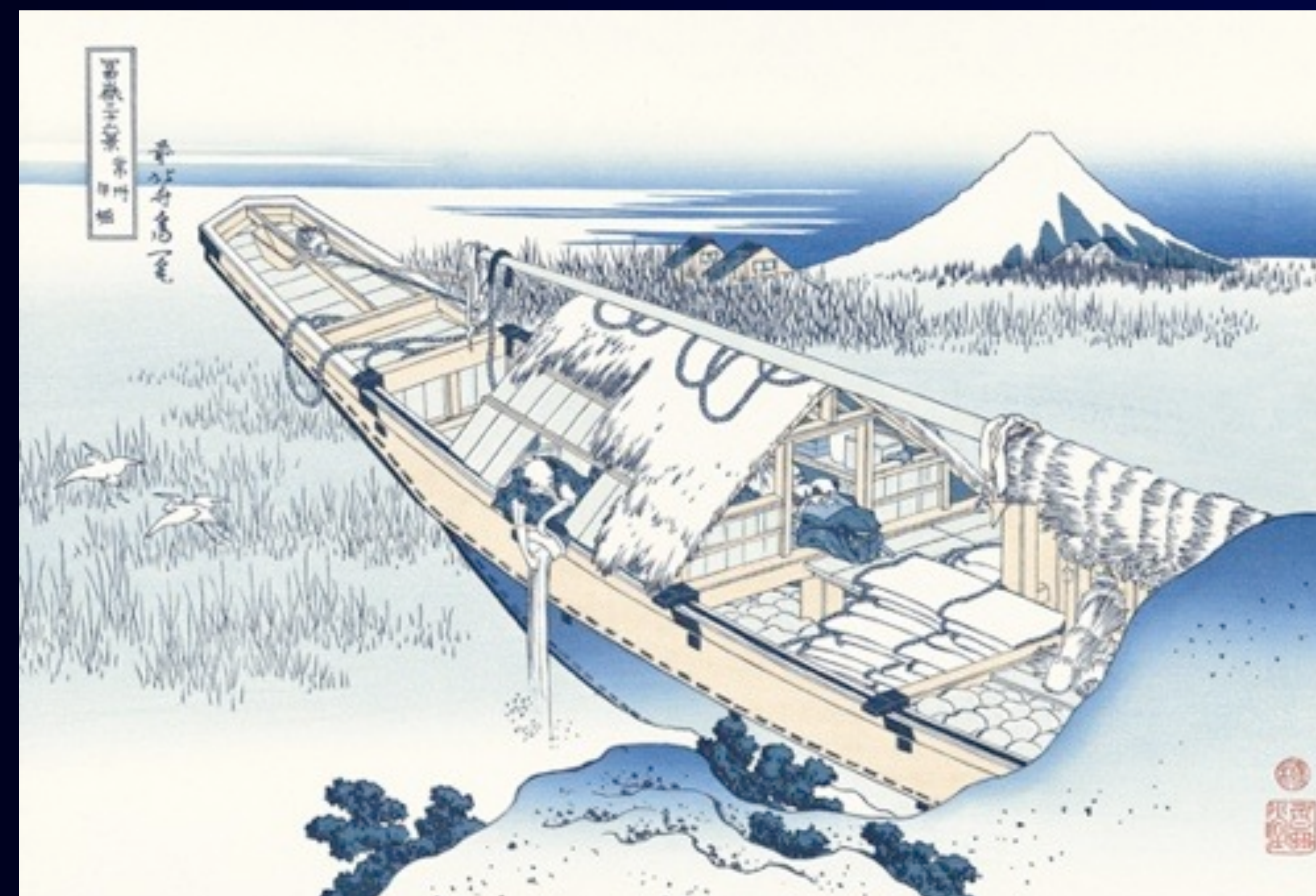
(1) Many particles are needed

The muon is the lightest unstable particle and therefore given energy, more muons can be produced.

(2) Theoretical uncertainty should be small.

The muon does not have strong interaction, and therefore the processes with muons are theoretically clean.

Project X Muon Source: Comparison



Comparison : Muon Beam Sources

	beam power	time structure	muon yield
PSI	1.2 MW	DC	10^{8}/sec
TRIUMF	75 kW	DC	10^{5}/sec
MuSIC	400 W	DC	$10^{7\text{-}8}$/sec
RAL	200 kW	pulsed (50 Hz)	$2\mathrm{x}10^{5}$/sec
J-PARC (MLF)	1 MW	pulsed (25 Hz)	$2\mathrm{x}10^{7}$/sec
Project X Muon	1-2 MW	DC & pulsed	$10^{8\text{-}12}$/sec

Comparison : Muon Beam Sources

	beam power	time structure	muon yield
PSI	1.2 MW	DC	10^{8}/sec
TRIUMF	75 kW	DC	10^{5}/sec
MuSIC	400 W	DC	10^{7-8}/sec
RAL	200 kW	pulsed (50 Hz)	2×10^{5}/sec
J-PARC (MLF)	1 MW	pulsed (25 Hz)	2×10^{7}/sec
Project X Muon	1-2 MW	DC & pulsed	10^{8-12}/sec

adjustable

Comparison : Muon Beam Sources

	beam power	time structure	muon yield
PSI	1.2 MW	DC	[illegible]/sec
TRIUMF	75 kW	[illegible]	[illegible]ec
MuSIC	400 W	[illegible]	10^{7-8}/sec
RAL	[illegible]	[illegible] (50 Hz)	$2x10^5$/sec
J-PA[illegible]	[illegible]	pulsed (25 Hz)	$2x10^7$/sec
P[illegible]	1-2 MW	DC & pulsed	10^{8-12}/sec

Capability of pulsed muon beams would make “Muons at Project X” unique.

adjustable

Muon Experiments at Project X

Muon Particle Physics Programs at Project X

Mode	Beam	Current limit	planned goal	Project X goal	Priority
$\mu^- N \to e^- N$	pulsed	$<10^{-12}$	3×10^{-17}	3×10^{-19}	
$\mu^+ \to e^+ \gamma$	DC	$<1.1\times10^{-12}$	2×10^{-13}	2×10^{-14}	
$\mu^{*} \to e^+ e^+ e^-$	DC	$<10^{-12}$	-	1×10^{-16}	
$\mu^- e^- N \to e^- e^- N$	DC	-		1×10^{-16}	
Mu to $\overline{\text{Mu}}$ conv	pulsed	$<8\times10^{-11}$		$<5\times10^{-15}$	
muon EDM	pulsed	$<1.8\times10^{-19}$		$<5\times10^{-25}$	
muon lifetime	pulsed	1ppm		0.1ppm	

Muon Particle Physics Programs at Project X

Mode	Beam	Current limit	planned goal	Project X goal	Priority
$\mu^- N \to e^- N$	pulsed	$<10^{-12}$	$3\text{x}10^{-17}$	$3\text{x}10^{-19}$	★★★
$\mu^+ \to e^+ \gamma$	DC	$<1.1\text{x}10^{-12}$	$2\text{x}10^{-13}$	$2\text{x}10^{-14}$	★★
$\mu^* \to e^+ e^+ e^-$	DC	$<10^{-12}$	-	$1\text{x}10^{-16}$	★★
$\mu^- e^- N \to e^- e^- N$	DC	-		$1\text{x}10^{-16}$	★★
Mu to $\overline{\text{Mu}}$ conv	pulsed	$<8\text{x}10^{-11}$		$<5\text{x}10^{-15}$	★★
muon EDM	pulsed	$<1.8\text{x}10^{-19}$		$<5\text{x}10^{-25}$	★★½
muon lifetime	pulsed	1ppm		0.1ppm	★

Muon Particle Physics Programs at Project X

Mode	Beam	Current limit	planned goal	Project X goal	Priority
$\mu^- N \to e^- N$	pulsed	$<10^{-12}$	$3x10^{-17}$	$3x10^{-19}$	★★★
$\mu^+ \to e^+ \gamma$	DC	$<1.1x10^{-12}$	$2x10^{-13}$	[illegible]	★★
$\mu^* \to e^+ e^+ e^-$	DC	$<10^{-12}$	[illegible]	$1x10^{-16}$	★★
$\mu^- e^- N \to e^- e^- N$	DC	[illegible]	[illegible]	$1x10^{-16}$	★★
Mu to $\overline{\text{Mu}}$	[illegible]	$<8x10^{-11}$		$<5x10^{-15}$	★★
[illegible]	pulsed	$<1.8x10^{-19}$		$<5x10^{-25}$	★★½
muon lifetime	pulsed	1ppm		0.1ppm	★

μ-e conversion is a flagship experiment.

Why CLFV ?

What is Charged Lepton Flavor Violation ?

Quarks

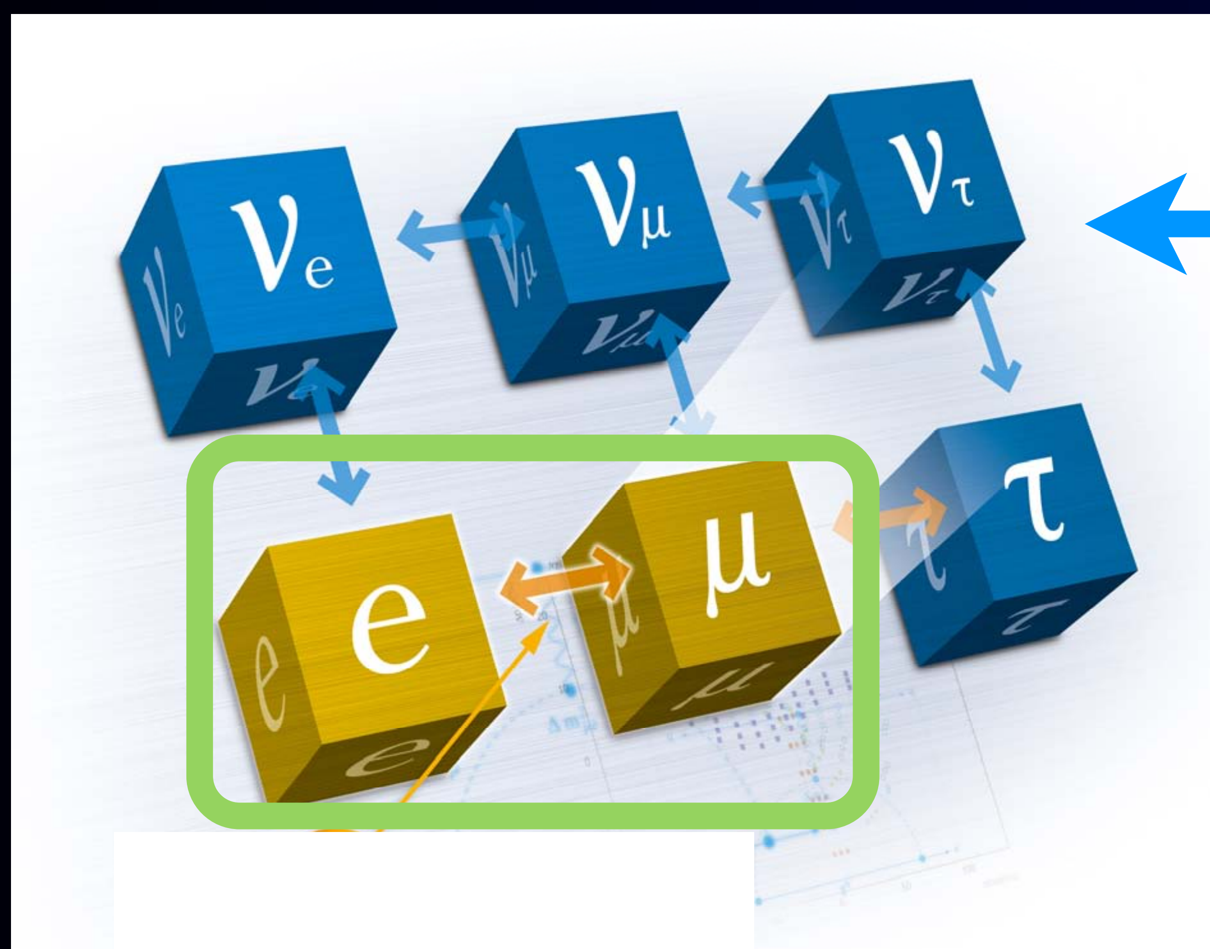
Quark mixing observed

What is Charged Lepton Flavor Violation ?

Quarks

Quark mixing observed

Leptons



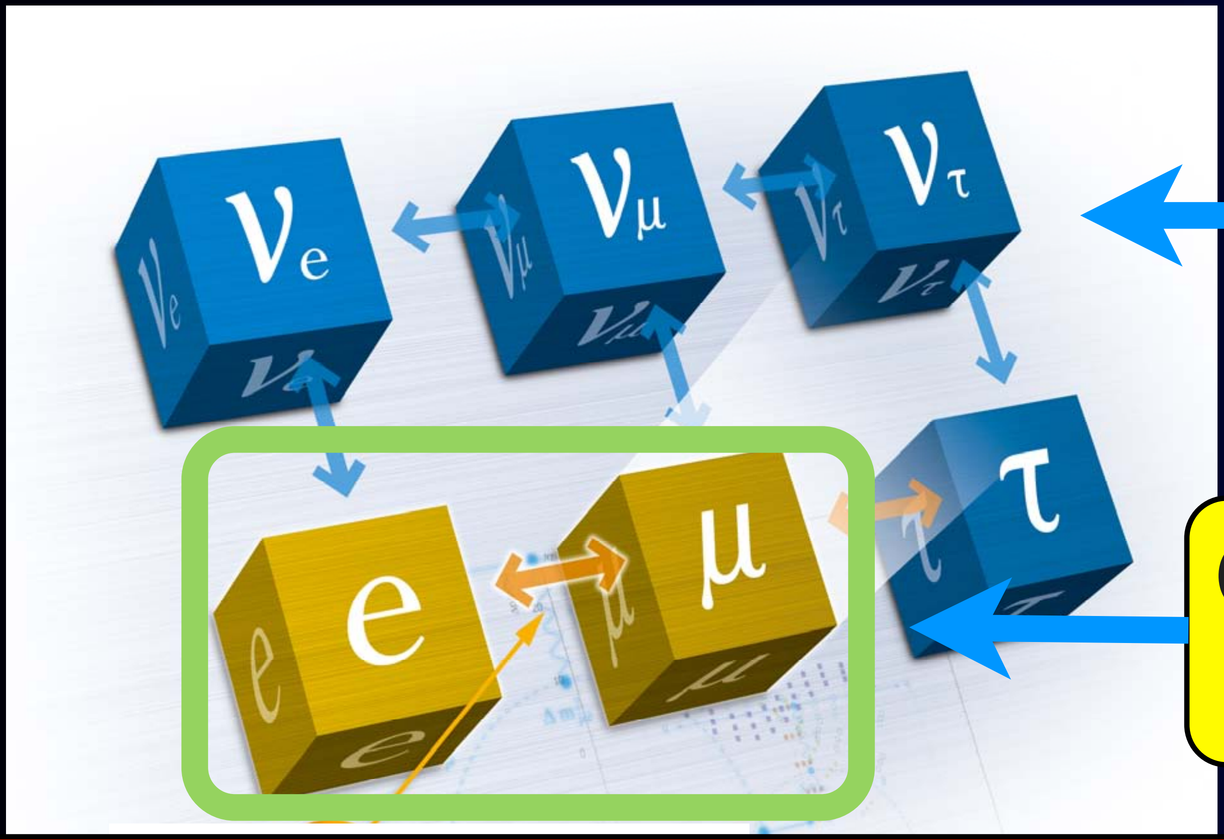
Neutrino mixing observed

What is Charged Lepton Flavor Violation ?

Quarks

Quark mixing observed

Leptons



Neutrino mixing observed

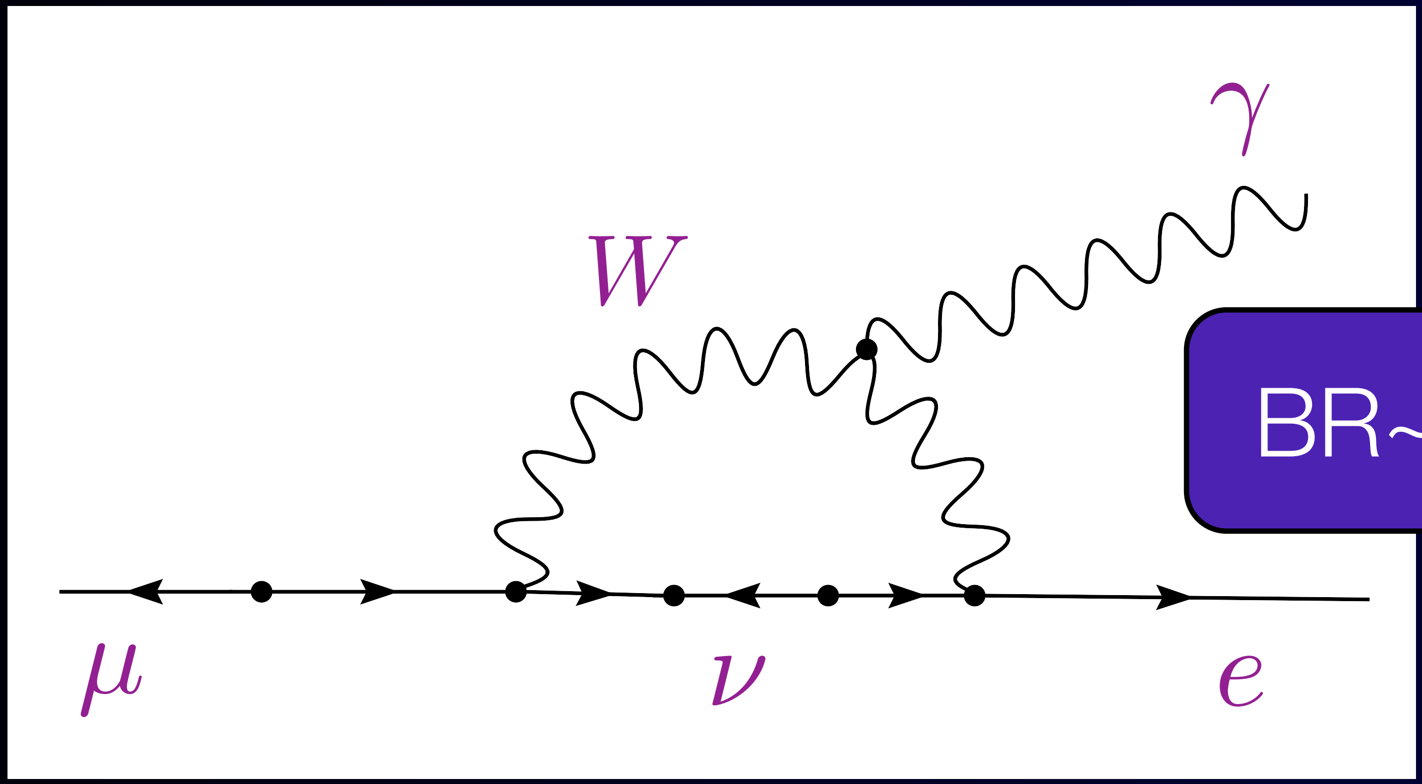
Charged lepton mixing not observed.

Charged Lepton Flavor Violation (CLFV)

Nobel Prize-wining class research

cLFV in the SM with massive neutrinos

$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_l (V_{MNS})^*_{\mu l} (V_{MNS})_{el} \frac{m^2_{\nu_l}}{M^2_W} \right|^2$$



BR~O(10^{-54})

Observation of CLFV would indicate a clear signal of physics beyond the SM with massive neutrinos.

Comparison of Sensitivity to New Physics Models (a la Prof. Dr. A. Buras at TUM)

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0-\bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}(B\to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B\to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B\to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B\to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s\to\mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+\to\pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L\to\pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu\to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau\to\mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu+N\to e+N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

Different theoretical models

W. Altmannshofer, A.J. Buras, S. Gori, P. Paradisi, D.M. Straub, . **Nucl.Phys.B830:17-94 ,2010**.

Comparison of Sensitivity to New Physics Models (a la Prof. Dr. A. Buras)

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\mathrm{CP}}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

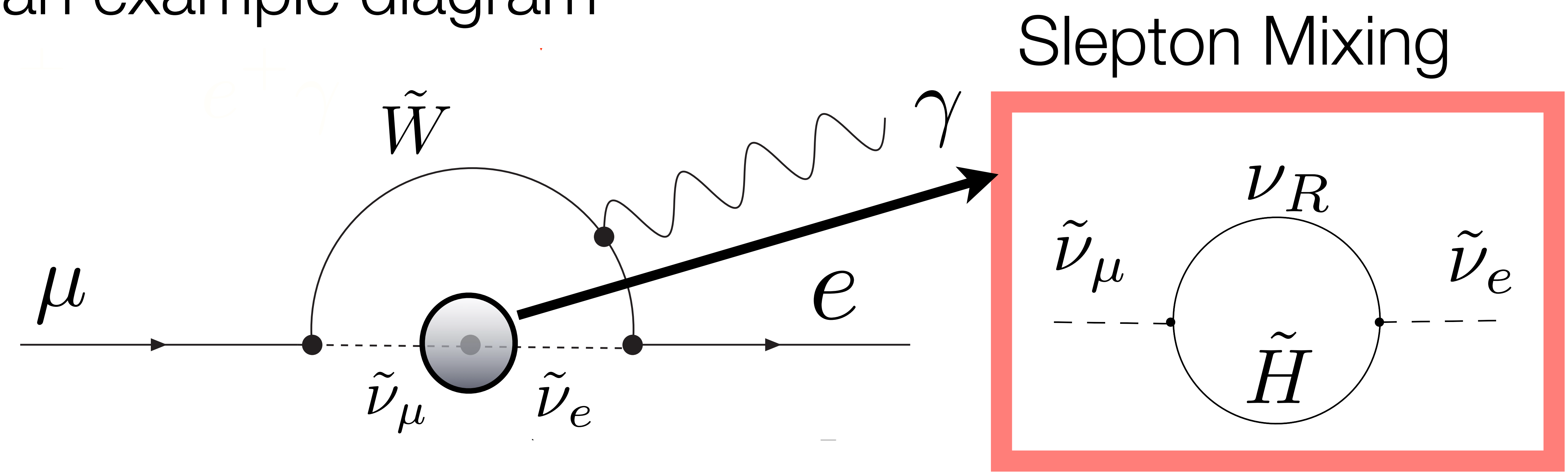
Different theoretical models

All three stars for μ-e conversion

W. Altmannshofer, A.J. Buras, S. Gori, P. Paradisi, D.M. Straub, . **Nucl.Phys.B830:17-94 ,2010**.

CLFV in SUSY Models

an example diagram

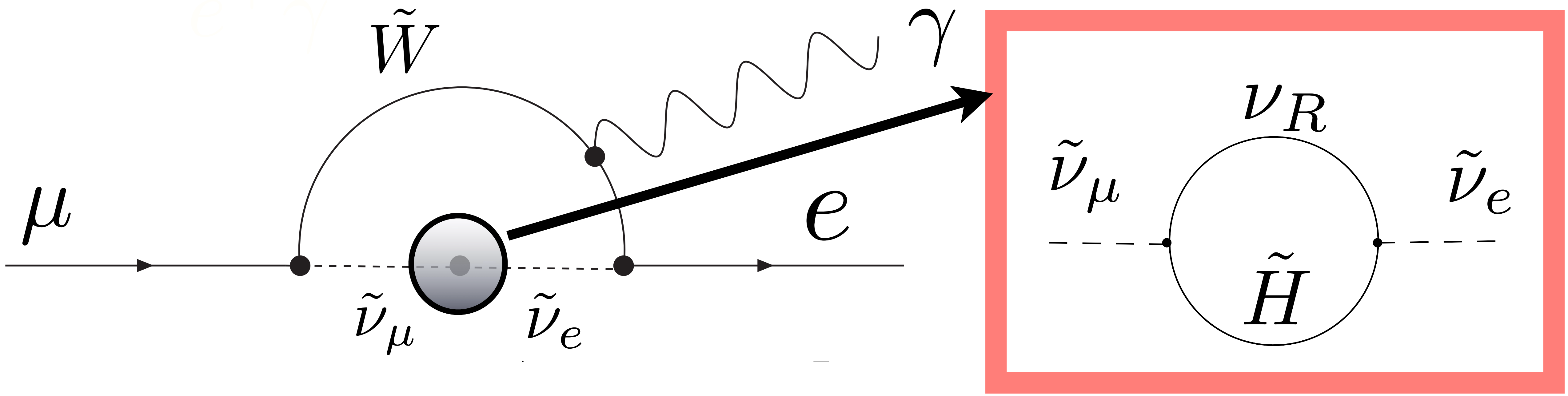


- Through quantum corrections (RGE), slepton mixing is sensitive to physics at very high energy scale (such as GUT and neutrino seesaw models).
- In contrast to proton decay (~1M tons) and double beta decays (~0.1-1 ton), CLFV need only $10^{19\text{-}21}$ muons.

CLFV in SUSY Models

an example diagram

Slepton Mixing



- By using SUSY, CLFV can provide hints of physics at very high energy scale that accelerator cannot directly reach.
- SUSY plays a role of a bridge between physics at high (10^{16} GeV) and low energy (102 GeV) scales.

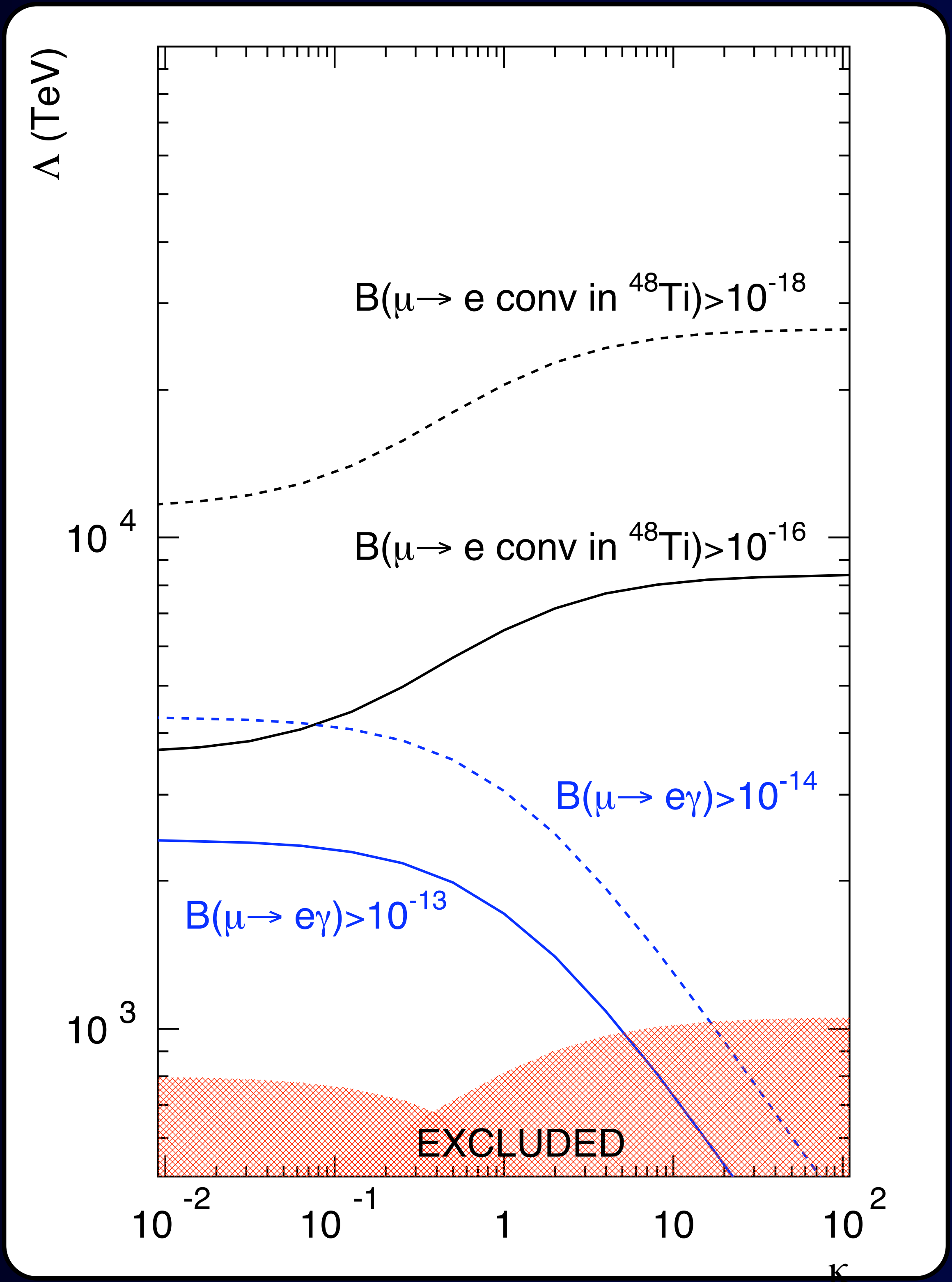
Why μ-e Conversion, not $\mu \to e\gamma$?

Physics Sensitivity Comparison between μ→eγ and μ-e Conversion

Photonic (dipole) and non-photonic contributions

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

more sensitive to new physics



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

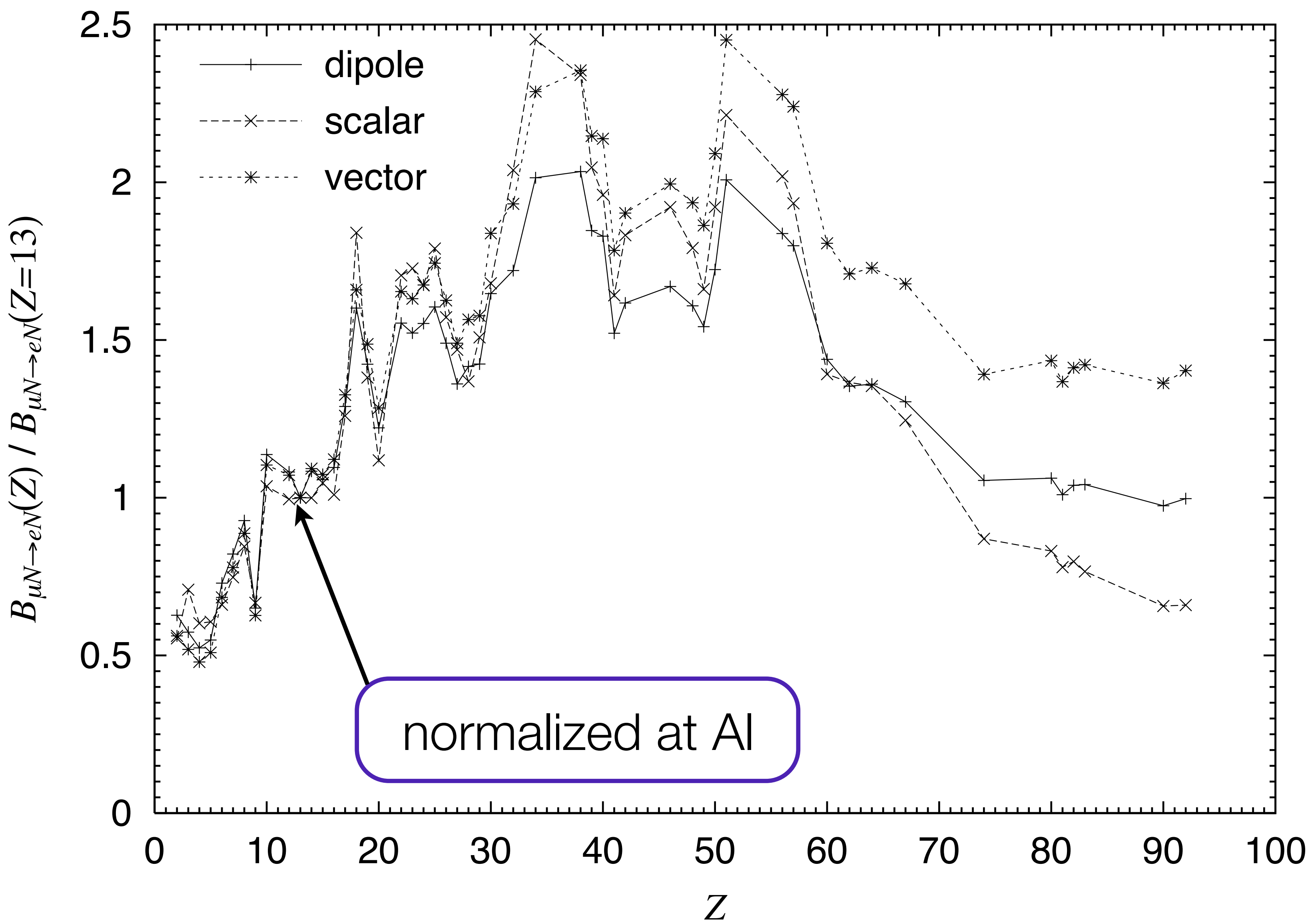
- $\mu \to e\gamma$:
  - Accidental background is given by $(\text{rate})^2$.
  - The detector resolutions have to be improved, but difficult.
  - The ultimate sensitivity would be about 10^{-14}.
- μ-e conversion :
  - A higher beam intensity can be taken because of no accidentals.
  - Improvement of a muon beam can be possible.
    - high intensity and high purity

μ-e conversion might be a next step.

Why $<10^{-18}$ Sensitivity for μ-e conversion ?

μ-e Conversion : Target dependence

If signal is seen at 10^{-16},



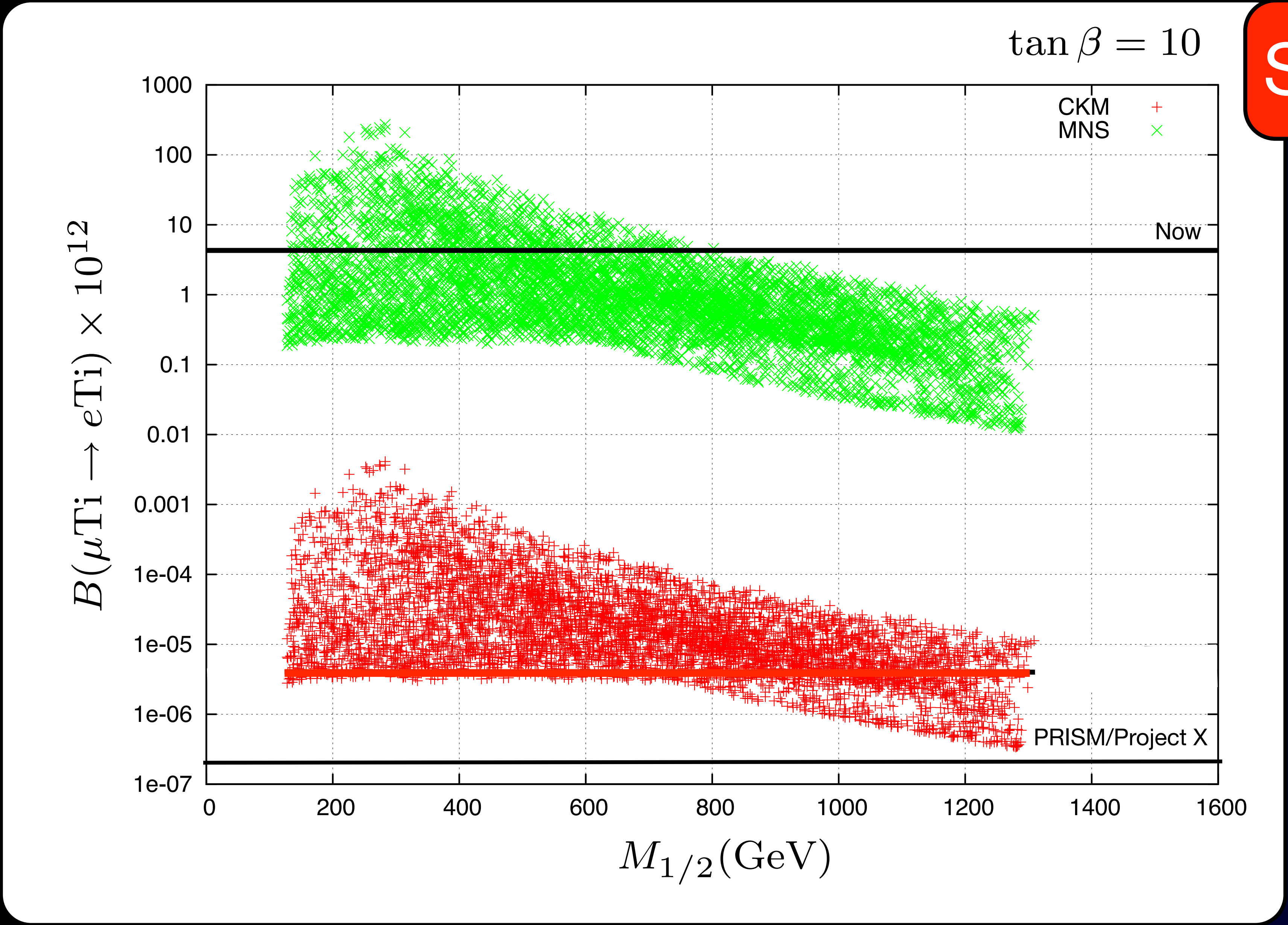
R. Kitano, M. Koike and Y. Okada, Phys. Rev. D66, 096002 (2002)

By changing muon-stopping target materials, effective interaction of new physics can be discriminated.

Aiming at Single Event Sensitivity of 2×10^{-19}

If signal is not seen at 10^{-16},

SUSY predictions



BR~10^{-12}

Project X

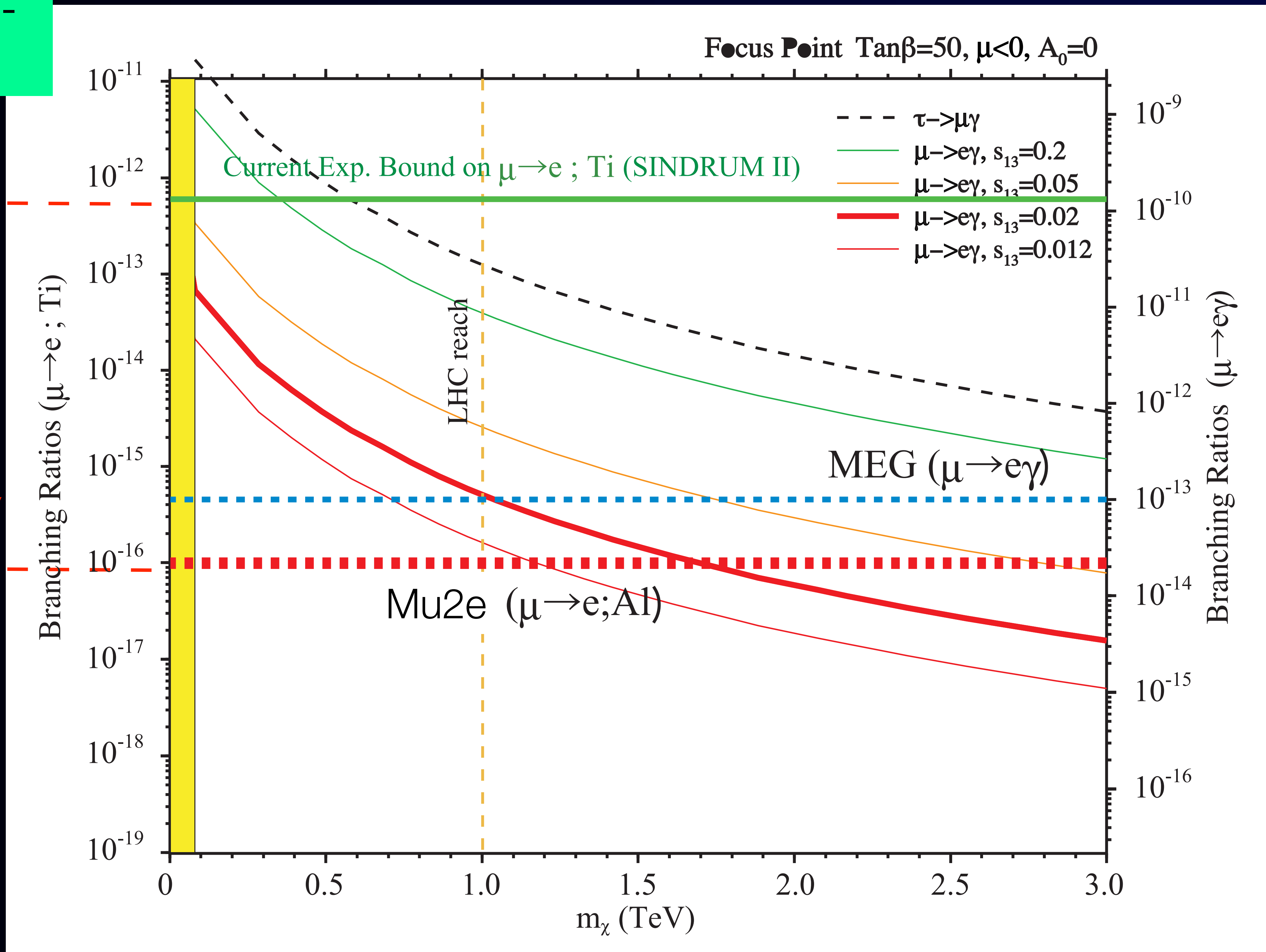
BR~10^{-19}

Calibbi, Faccia, Masiero, Vempati, hep-ph/0605139

BR~10^{-19} covers the whole SUSY-parameter space for LHC.
When SUSY is found at LHC, CLFV should be observed.

mSUGRA with right-handed neutrinos

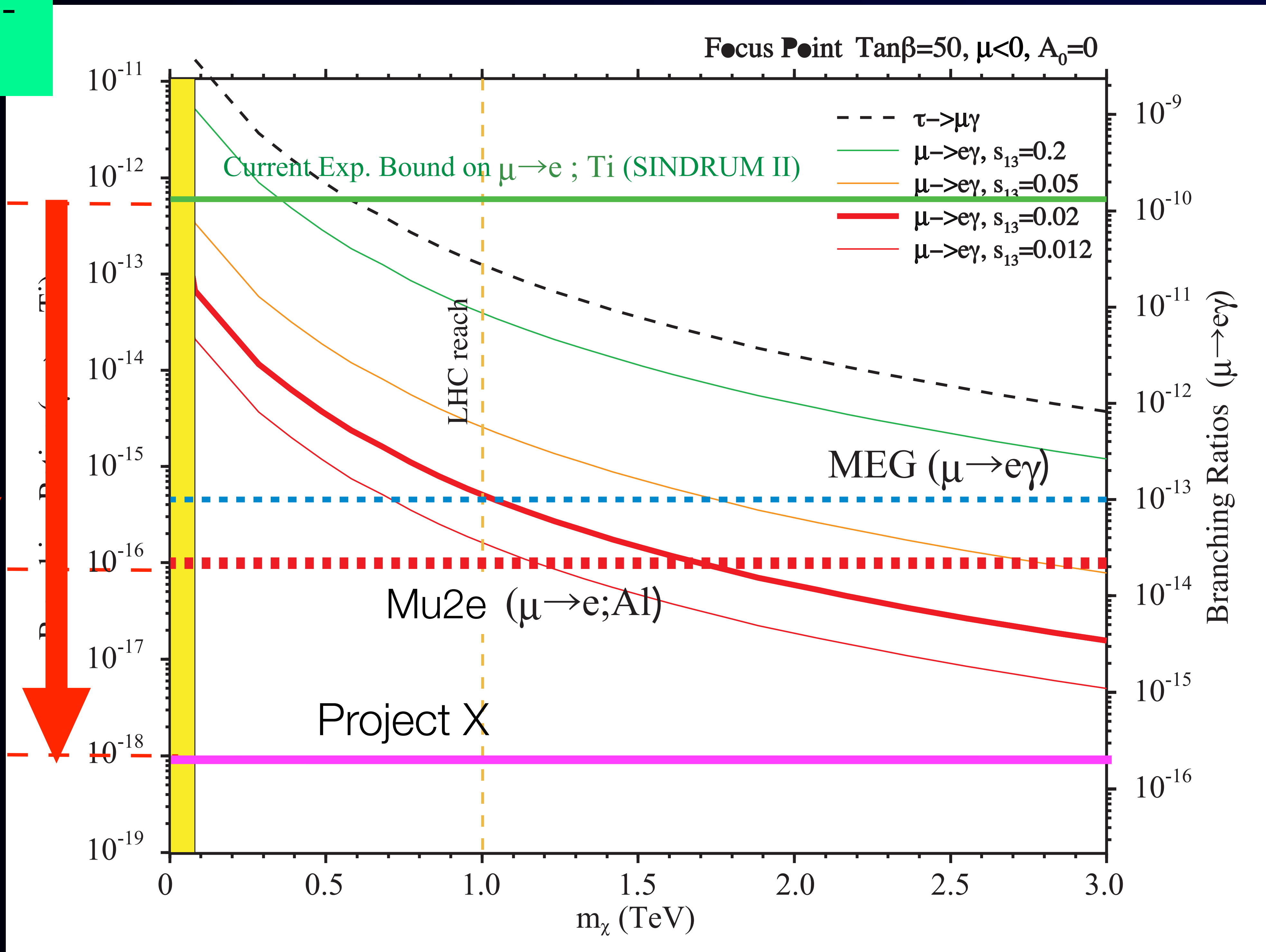
will be improved by a factor of 10,000.



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

Sensitivity of $<10^{-18}$

mSUGRA with right-handed neutrinos



will be improved by a factor of 10,000.

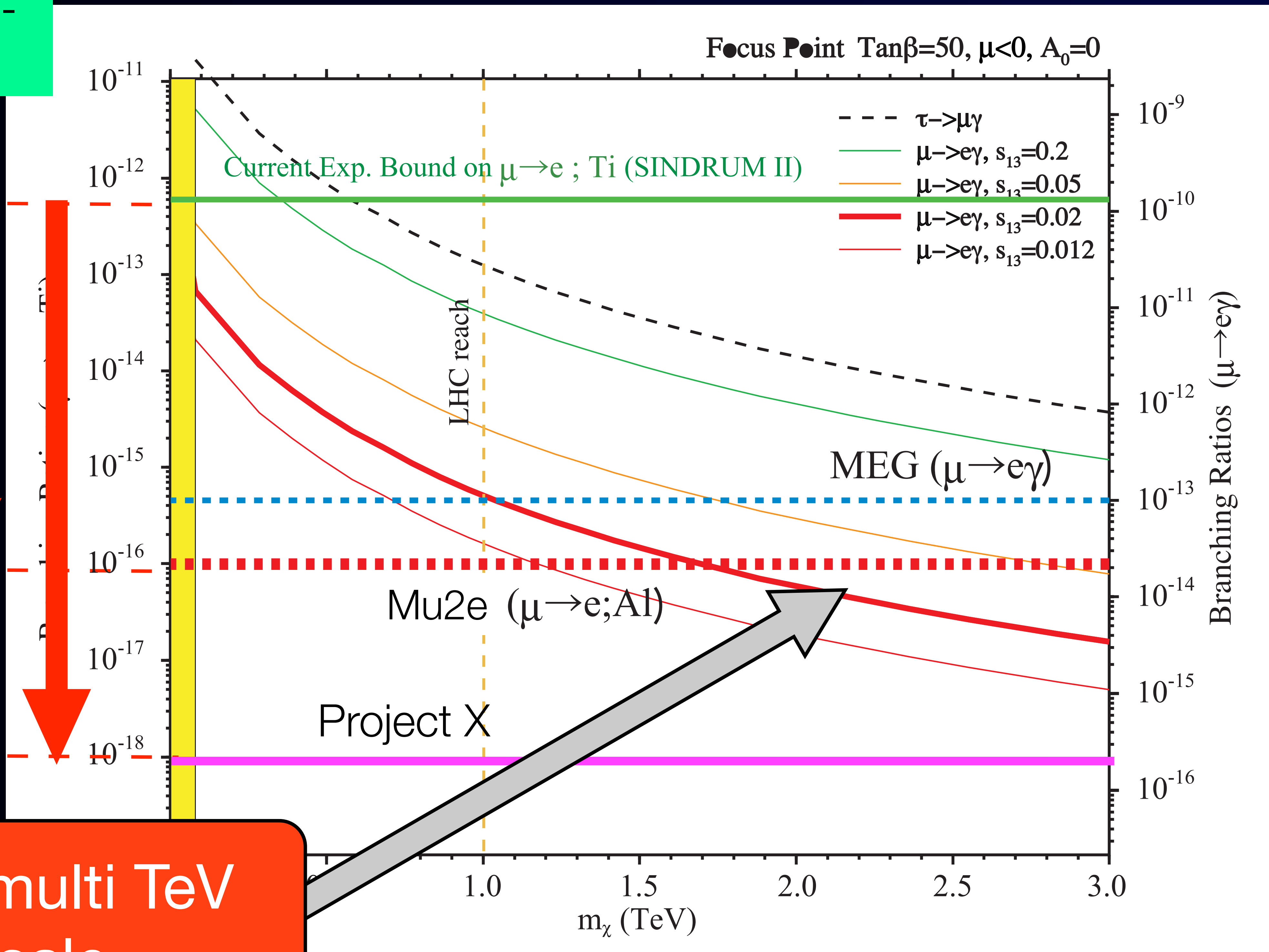
will be improved by a factor of 1000,000.

Sensitivity of <10^{-18}

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

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

mSUGRA with right-handed neutrinos



will be improved by a factor of 10,000.

will be improved by a factor of 1000,000.

sensitive to multi TeV energy scale.

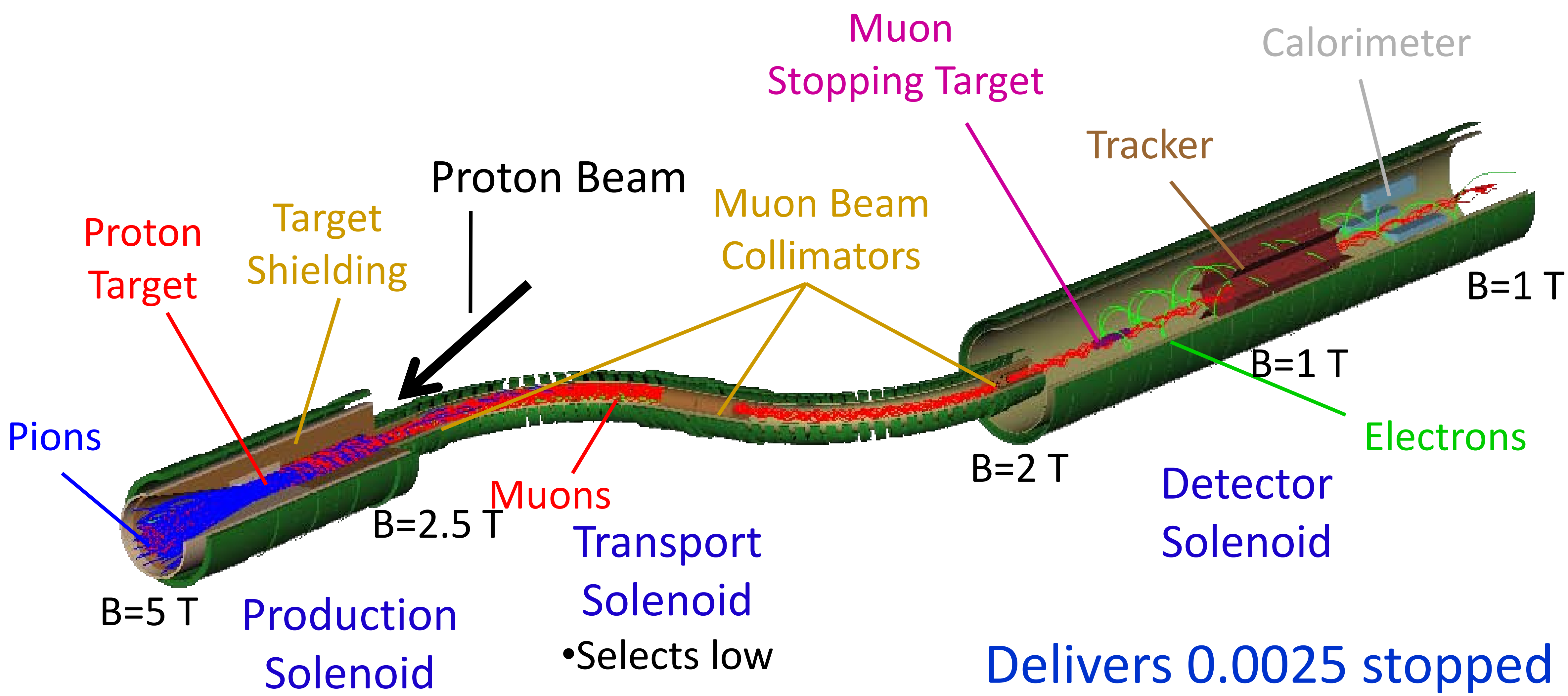
Sensitivity of $<10^{-18}$

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

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

Planned
μ-e conversion
Experiment (Mu2e)

Mu2e at Fermilab
(for single event sensitivity of 3×10^{-17})



- Selects low momentum μ^-
- Avoids straight line from production target to detectors

Delivers 0.0025 stopped muons per 8 GeV proton

Muon Intensity for Mu2e

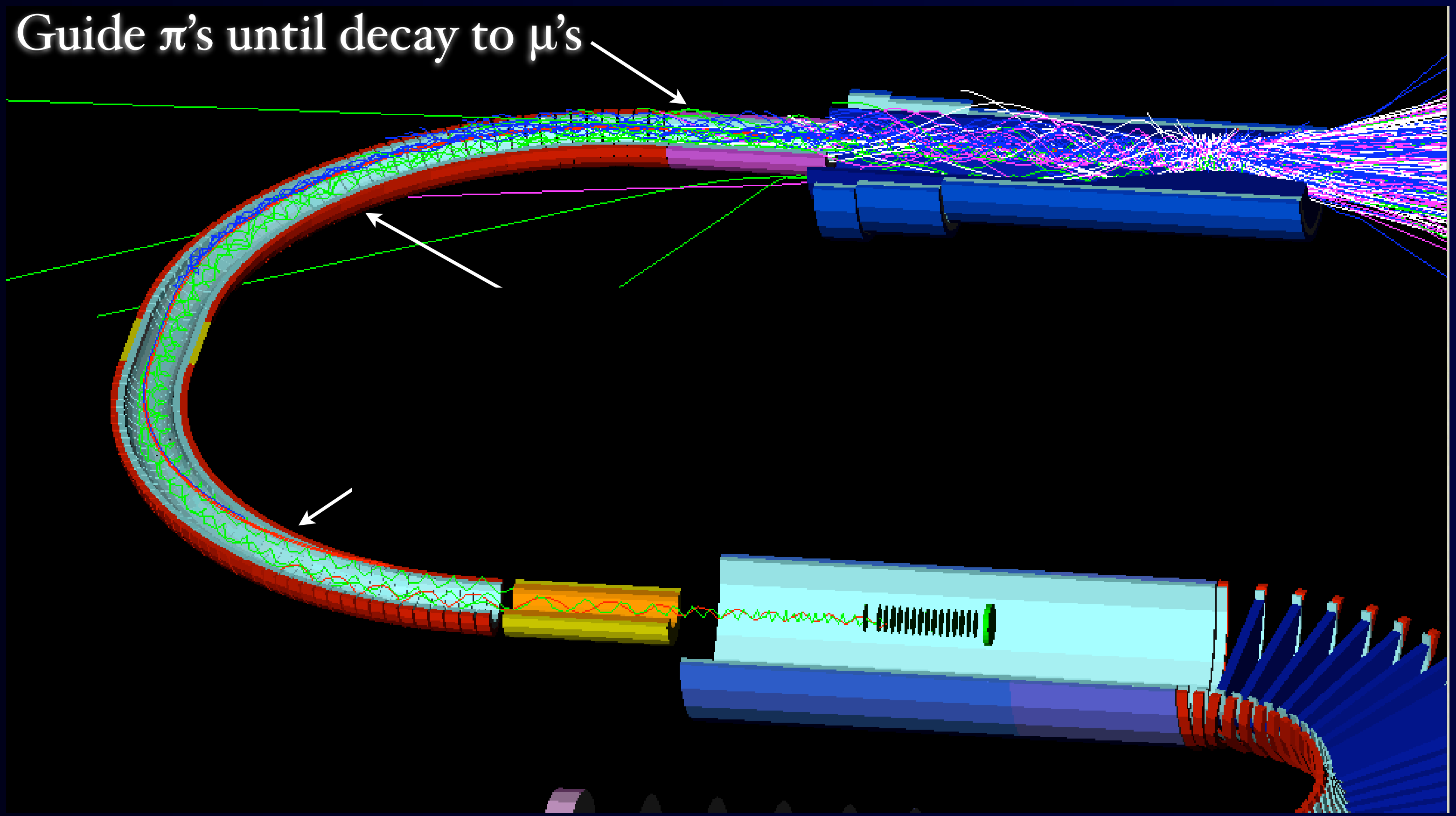
To achieve a single sensitivity of 10^{-17}, we need

10^{11} muons/sec (with 10^{7} sec running)

whereas the current highest intensity is 10^{8}/sec at PSI.

Pion Capture by Superconducting Solenoid System

only 20 kW beam power needed



Background Rejection Methods for Mu2e

Beam-related backgrounds → **Beam pulsing with separation of 1μsec**

measured between beam pulses

proton extinction = #protons between pulses/#protons in a pulse $< 10^{-9}$

Muon DIO background → **low-mass trackers in vacuum & thin target**

improve electron energy resolution

Muon DIF background → **curved solenoids for momentum selection**

eliminate energetic muons (>75 MeV/c)

μ-e Conversion Experiment at Project X

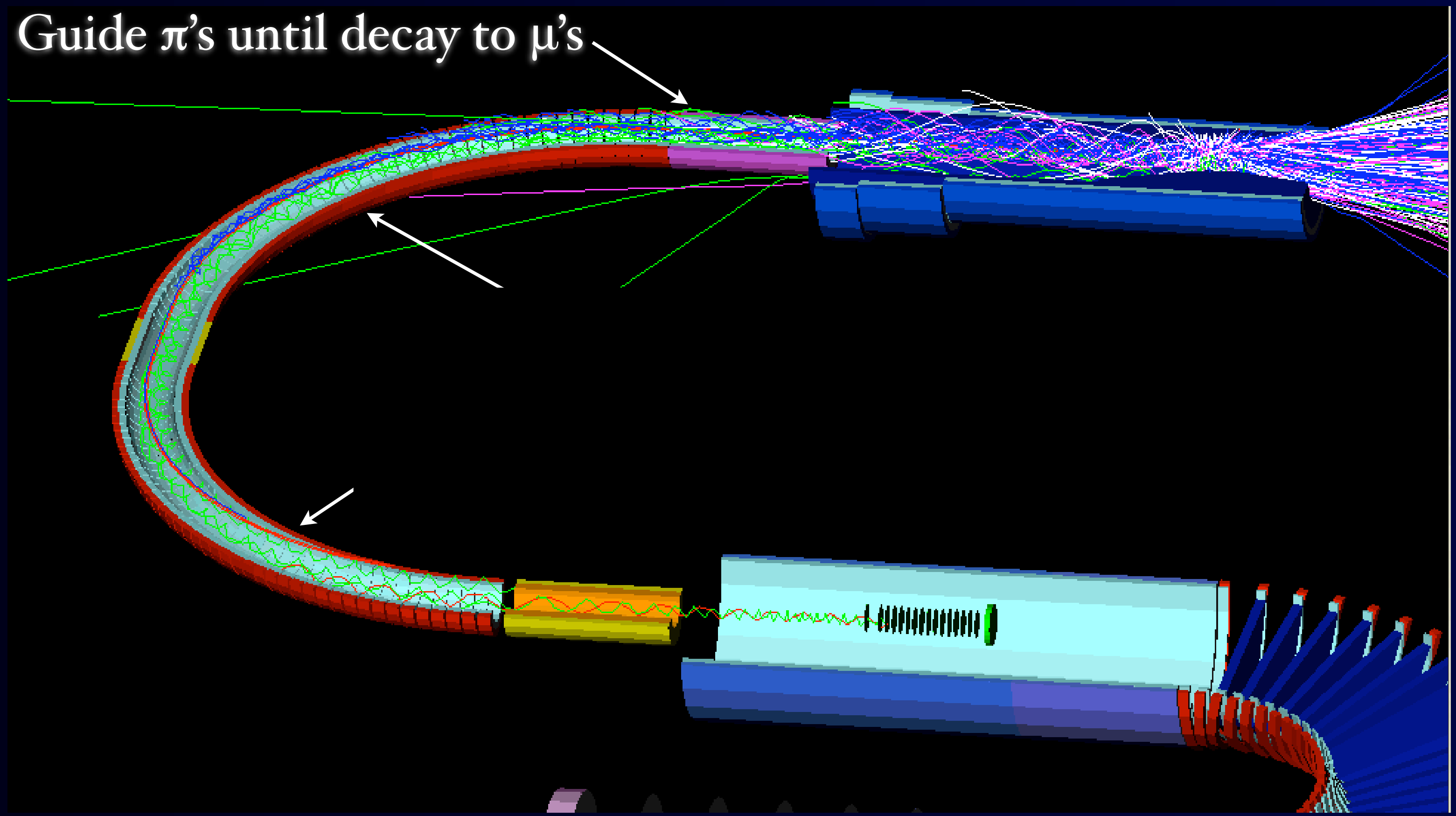
Muon Intensity for Sensitivity < 3×10^{-19} at Project X

To achieve a single sensitivity of 10^{-19}, we need

$>10^{12}$ muons/sec (with 10^{7} sec running)

whereas the current highest intensity is 10^{8}/sec at PSI.

Pion Capture by Superconducting Solenoid System



Muon Intensity for Sensitivity < 3×10^{-19} at Project X

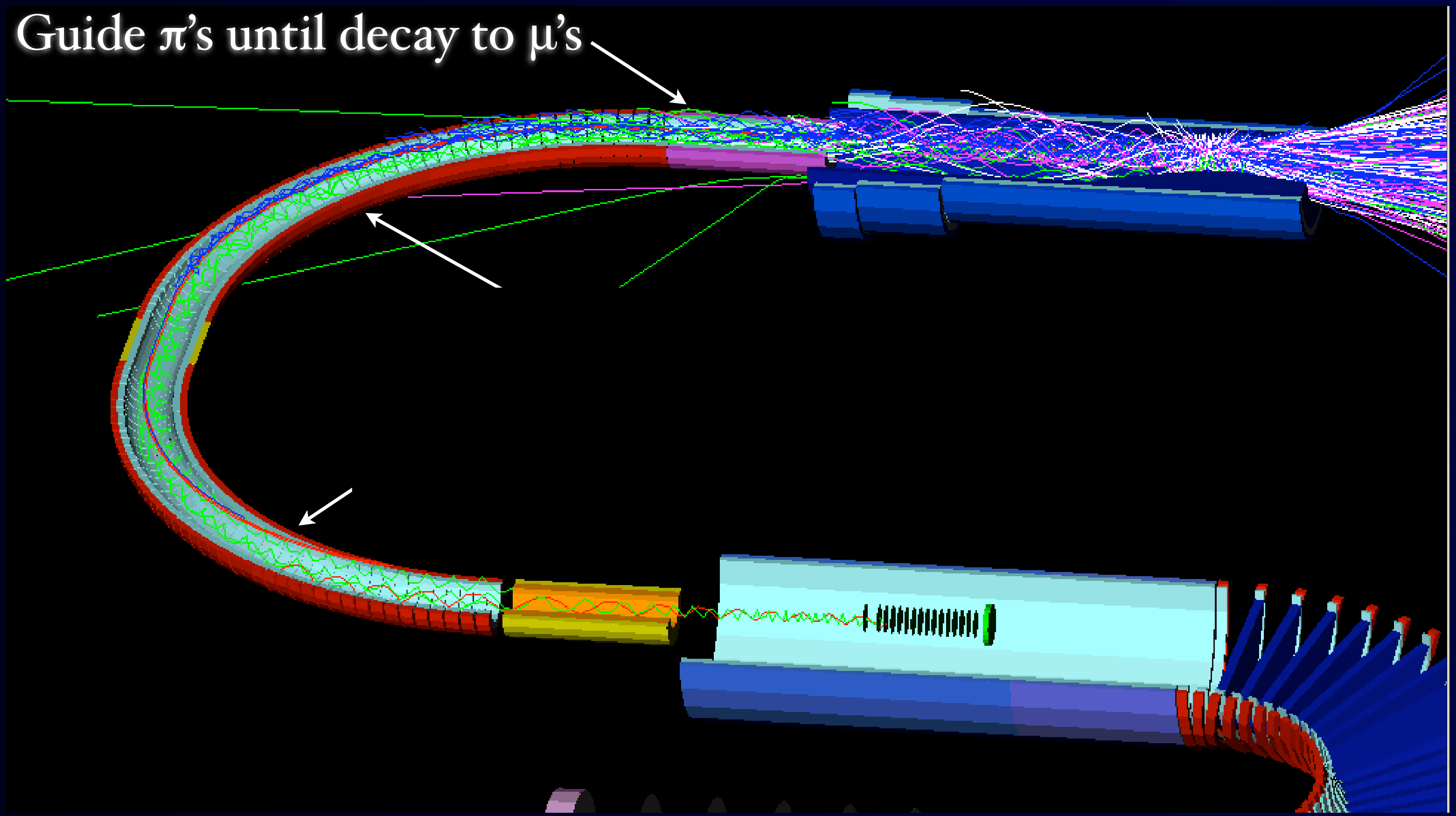
To achieve a single sensitivity of 10^{-19}, we need

$>10^{12}$ muons/sec (with 10^7 sec running)

whereas the current highest intensity is 10^8/sec at PSI.

Pion Capture by Superconducting Solenoid System

Multi MW beam power at Project X needed



Additional Background Rejection Methods for Sensitivity < 3×10^{-19} at Project X

pion free beam

Pion background → long muon beam-line

long solenoid or a muon storage ring

mono-energetic muon beam

Muon DIO background → narrow muon beam spread

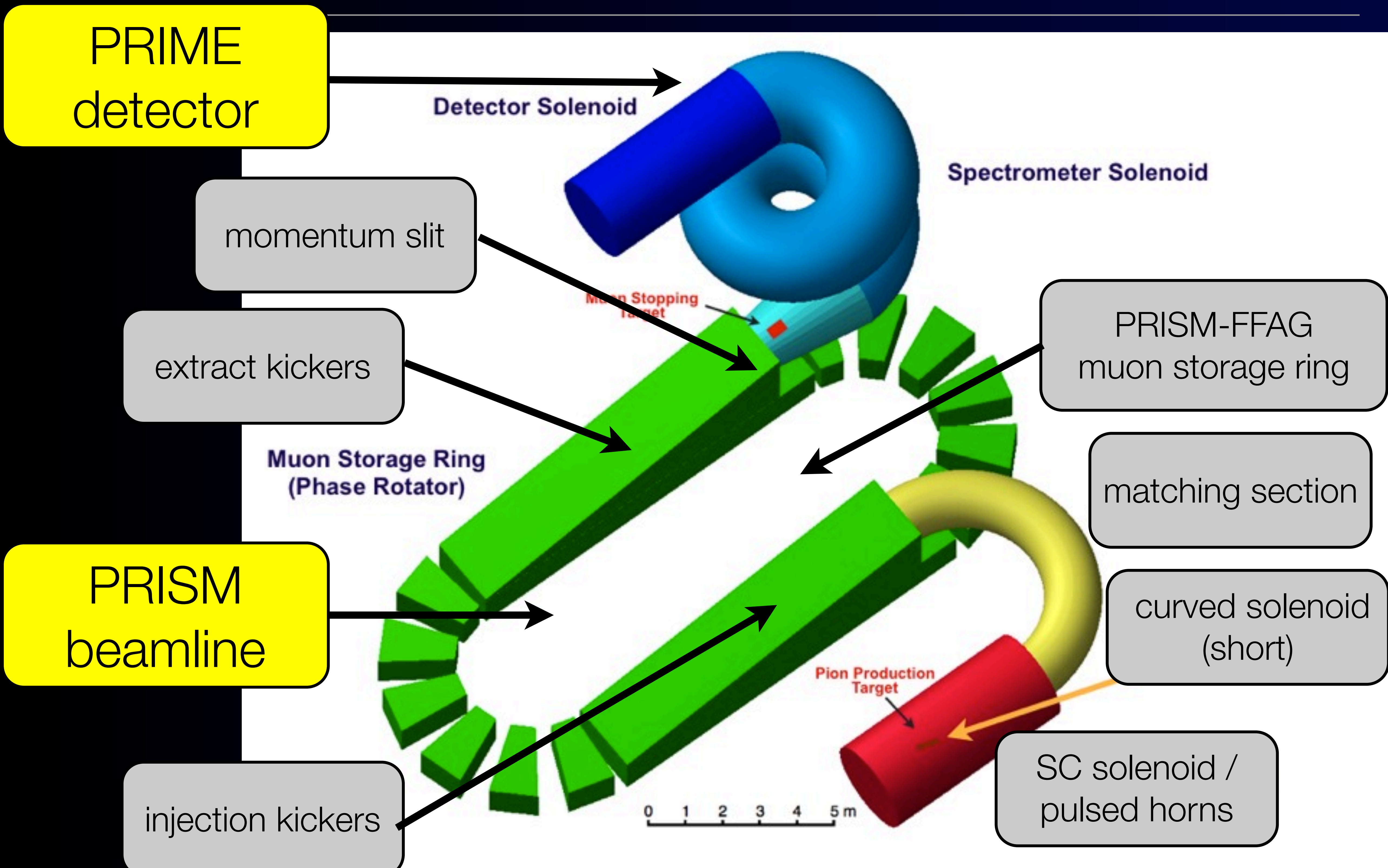
1/10 thickness muon stopping target

options:

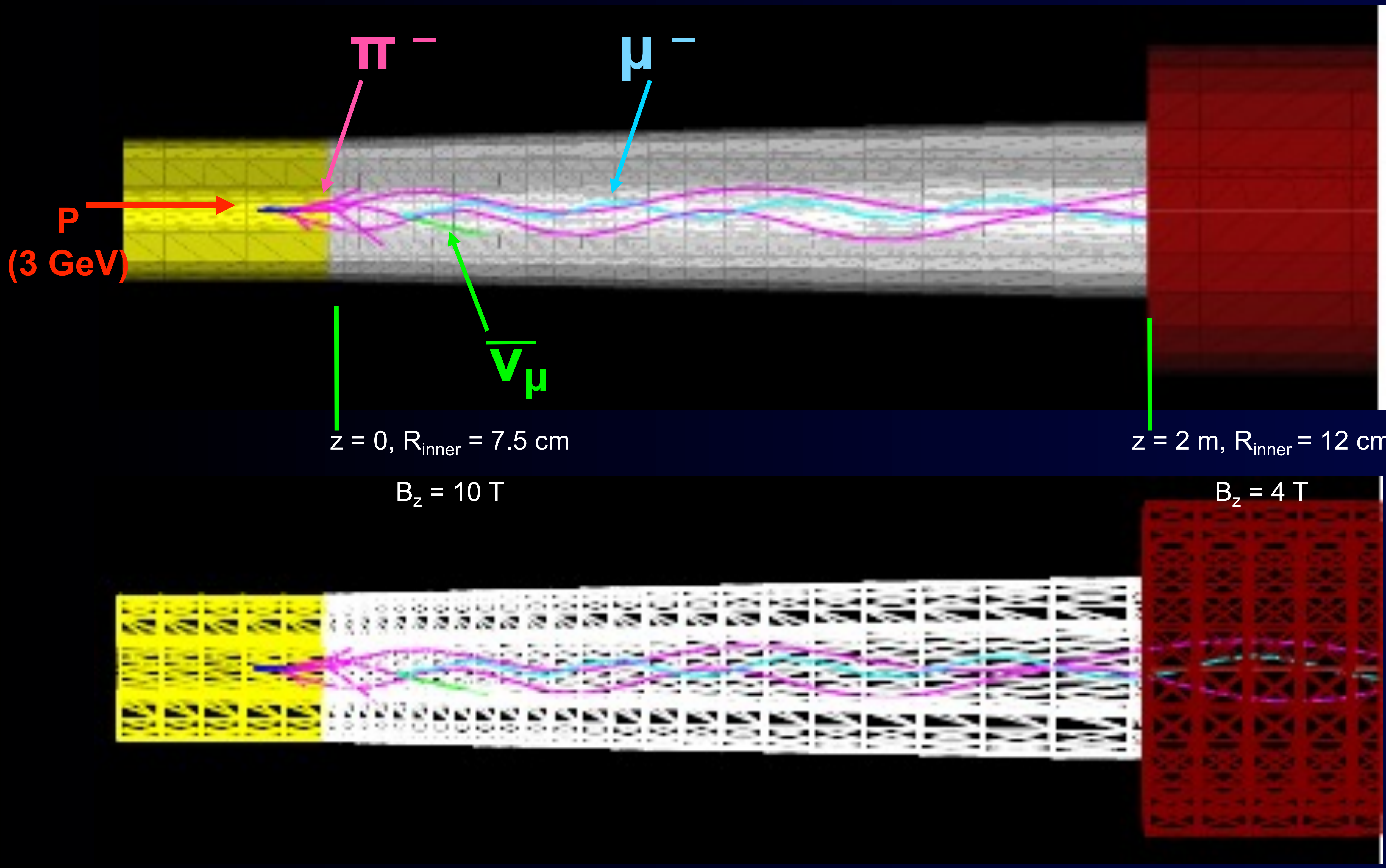
- phase rotation
- or
- muon beam cooling

beam handling technique developed for muon collider and Nufact.

Phase Rotation Option: PRISM/Project X



Muon Beam Cooling Option:
Geant4 Simulation of Ionization Cooling



Sensitivity and Background (preliminary) at Project X

Sensitivity

- muon beam intensity = 2×10^{12}/sec
- detector acceptance = 0.2
- single event sensitivity = 2×10^{-19}
- 90% C.L. upper limit = 5×10^{-19}

Background estimation

Item	rate	Comments
Muon decay in orbit	0.05	350 keV (FWHM) resolution
Radiative muon capture	0.01	
Pion related backgrounds	~0	No pions
Muon decay in flight	~0	Momentum cut at extraction
Cosmic rays	0.002	
Total	0.06	

Muon Particle Physics Programs at Project X

Mode	Beam	Current limit	planned goal	Project X goal	Priority
$\mu^- N \to e^- N$	pulsed	$<10^{-12}$	$3x10^{-17}$	$3x10^{-19}$	★★★
$\mu^+ \to e^+ \gamma$	DC	$<1.1x10^{-12}$	$2x10^{-13}$	$2x10^{-14}$	★★
$\mu^{*} \to e^+ e^+ e^-$	DC	$<10^{-12}$	-	$1x10^{-16}$	★★
$\mu^- e^- N \to e^- e^- N$	DC	-		$1x10^{-16}$	★★
Mu to $\overline{\text{Mu}}$ conv	pulsed	$<8x10^{-11}$		$<5x10^{-15}$	★★
muon EDM	pulsed	$<1.8x10^{-19}$		$<5x10^{-25}$	★★
muon lifetime	pulsed	1ppm		0.1ppm	★

Muon Particle Physics Programs at Project X

Mode	Beam	Current limit	planned goal	Project X goal	Priority
$\mu^- N \to e^- N$	pulsed	$<10^{-12}$	$3\text{x}10^{-17}$	$3\text{x}10^{-19}$	[illegible]
$\mu^+ \to e^+ \gamma$	DC	$<1.1\text{x}10^{-12}$	$2\text{x}10^{-13}$	[illegible]	★★
$\mu^* \to e^+ e^+ e^-$	DC	$<10^{-12}$	[illegible]	$1\text{x}10^{-16}$	★★
$\mu^- e^- N \to e^- e^- N$	DC	[illegible]	[illegible]	$1\text{x}10^{-16}$	★★
Mu to $\overline{\text{Mu}}$	[illegible]	$<8\text{x}10^{-11}$		$<5\text{x}10^{-15}$	★★
[illegible]	pulsed	$<1.8\text{x}10^{-19}$		$<5\text{x}10^{-25}$	★★½
muon lifetime	pulsed	1ppm		0.1ppm	★

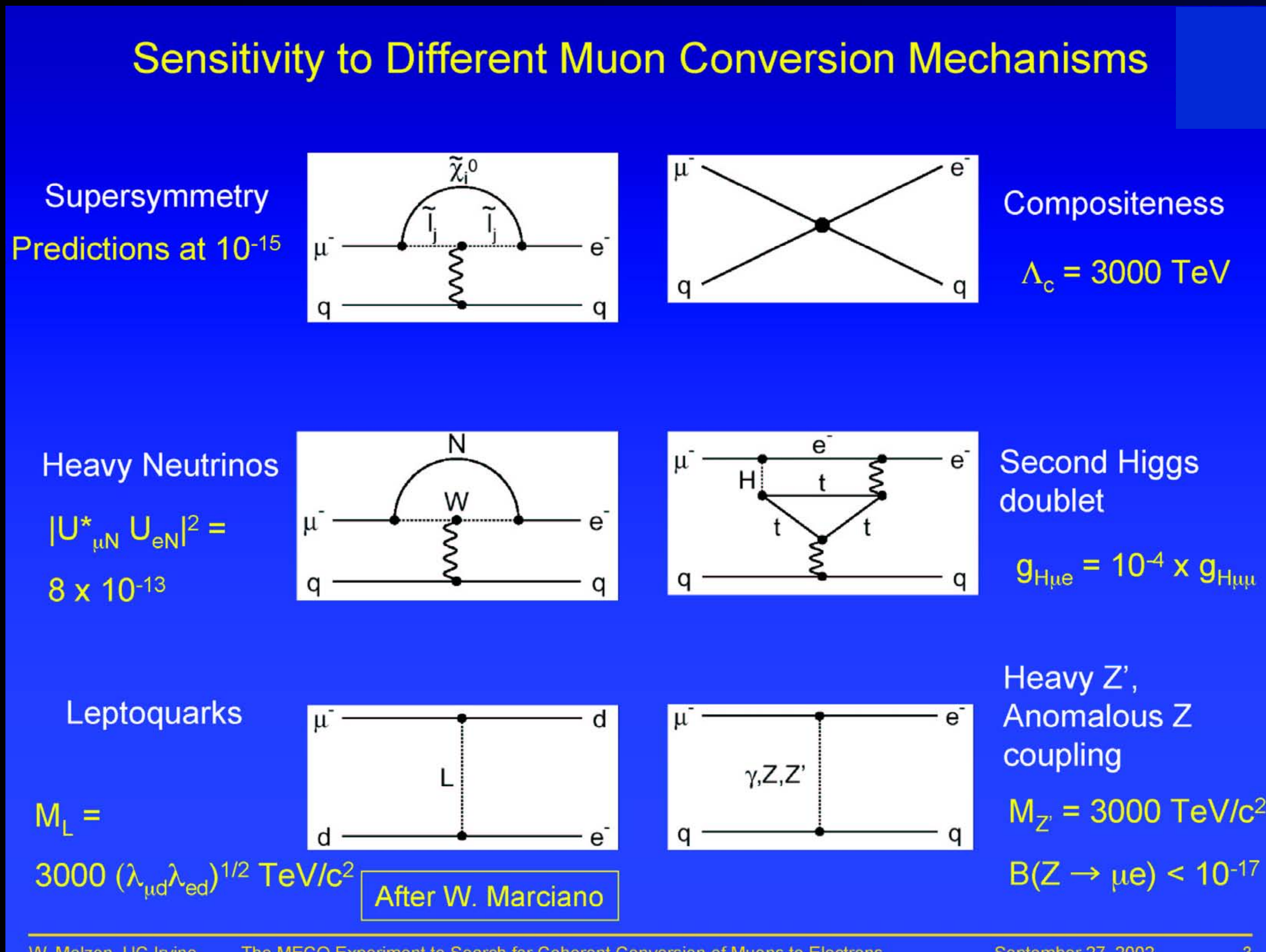
Rich muon physics programs at Project X

Summary

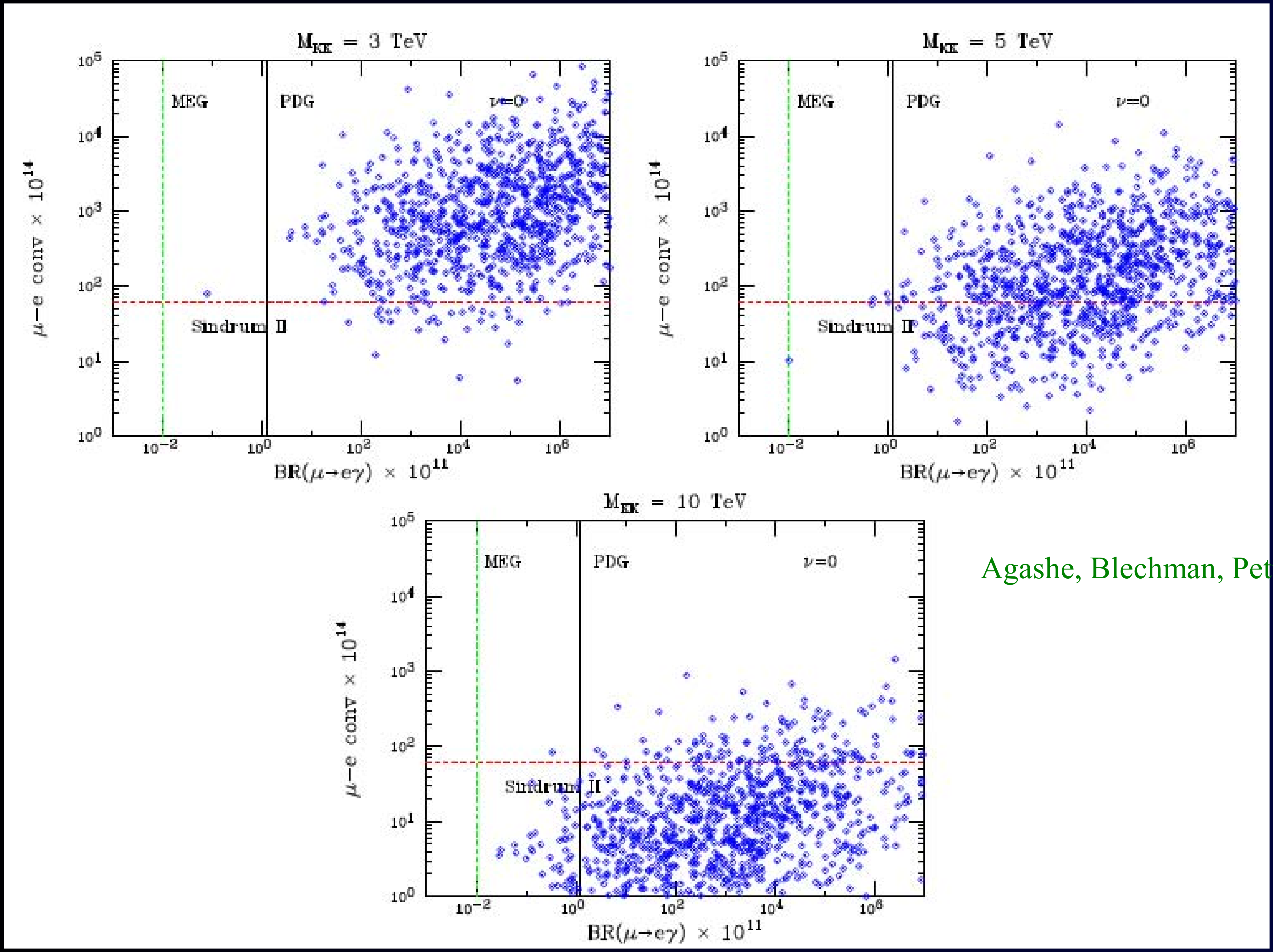
- Physics motivation of CLFV processes would be significant and robust at the LHC era. The CLFV would have sensitivity to study physics at high energy scale, in particular with SUSY,
- Among various muon programs at Project X, μ-e conversion would be a flagship experiment. The aimed single event sensitivity is 2×10^{-19}.
- μ-e conversion experiment needs a pulsed muon beam of 1-2 MW. Project X would provide such a beam, but PSI cannot.
- Muon fundamental physics programs at Project X is rich and would have high discovery potentials.

Backup Slides

Various Models Predict Charged Lepton Mixing.



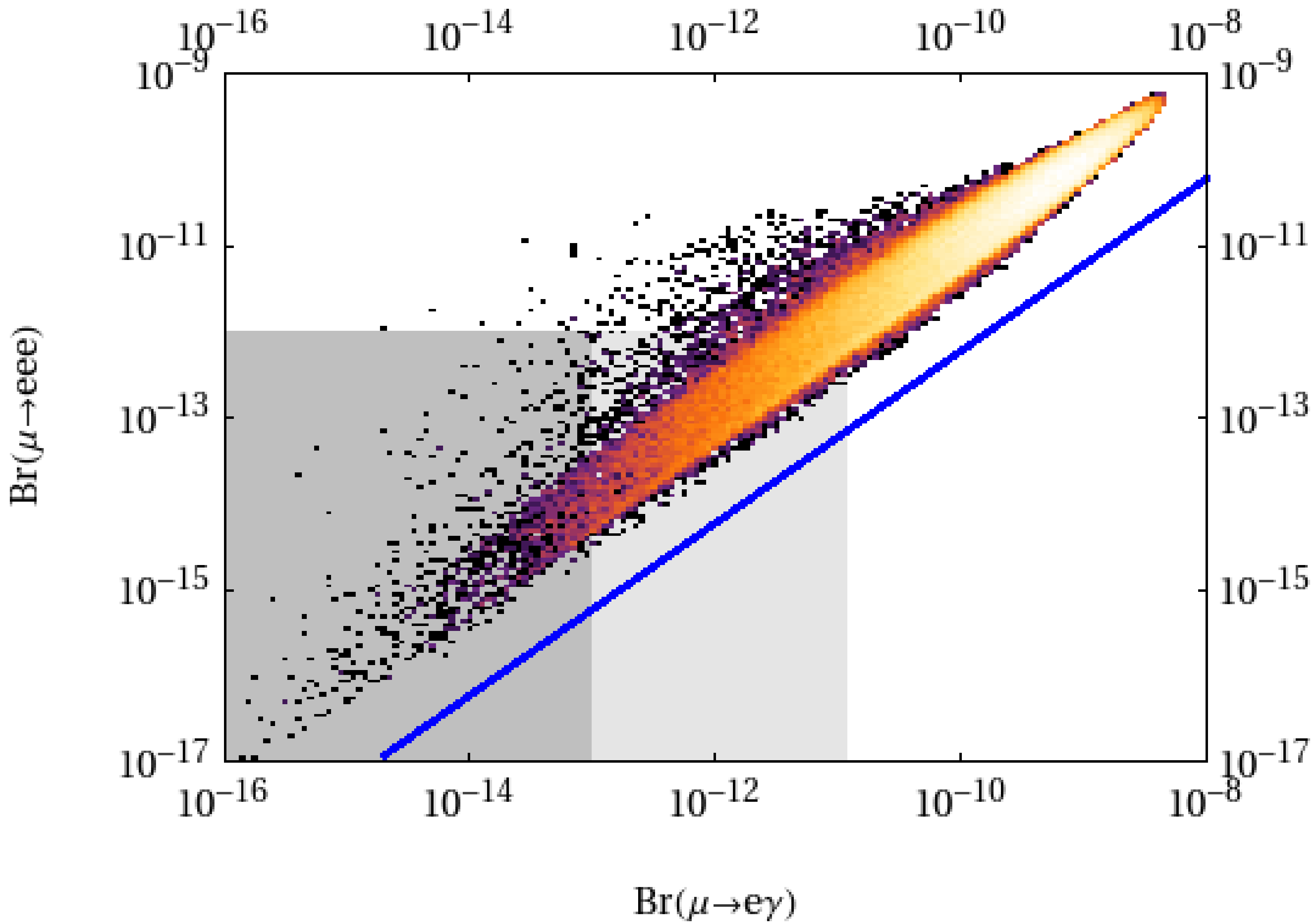
CLFV Predictions by Extra Dimension Models



Agashe, Blechman, Petriello

"Anarchic" Randall-Sundrum model

CLFV Predictions by Little Higgs Model (with T parity)



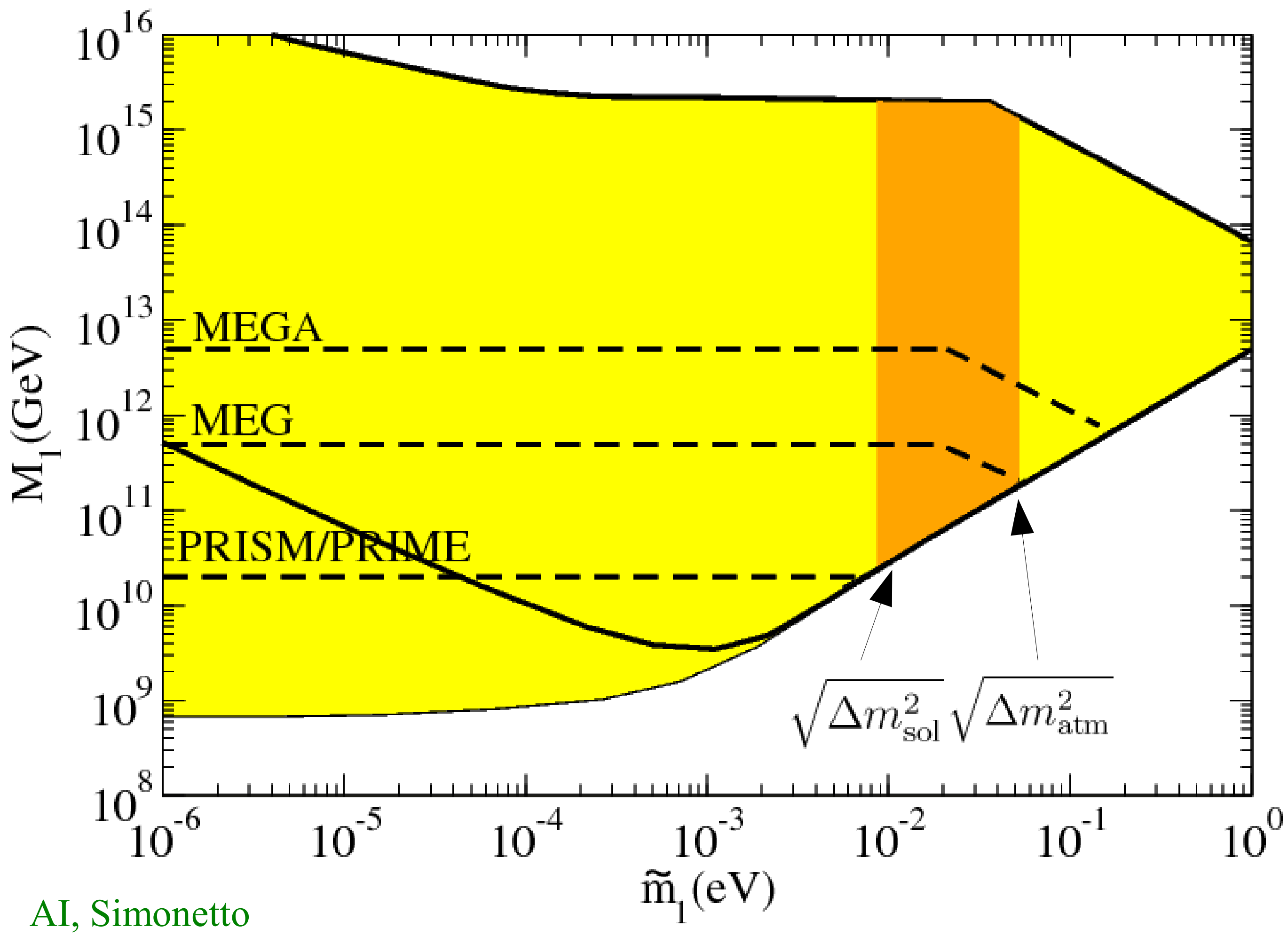
Blanke et al.

Mirror lepton masses between 300 GeV-1.5 TeV
Generic angles and phases

SUSY Leptogenesis with CLFV (1)

Assumptions:
- No cancellations
- hierarchical neutrino Yukawa eigenvalues: $y_1 \ll y_2 \ll y_3$

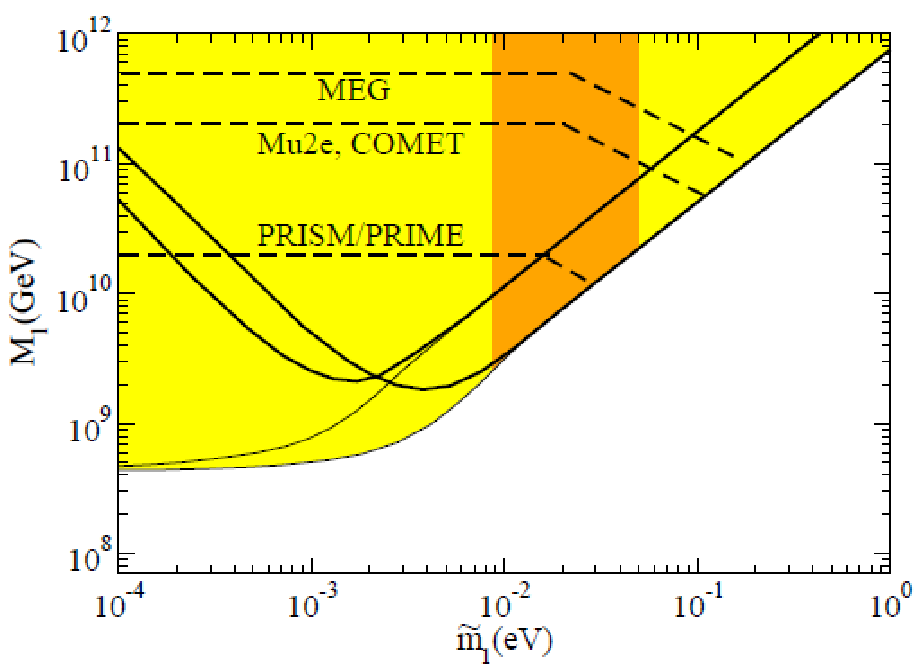
(Leptogenesis requires $\Lambda > 10^{16}$ GeV, so no need to assume a large cut-off)



AI, Simonetto

m_S=200 GeV, tanβ=10

Including flavour effects in leptogenesis



SUSY Leptogenesis with CLFV (2)

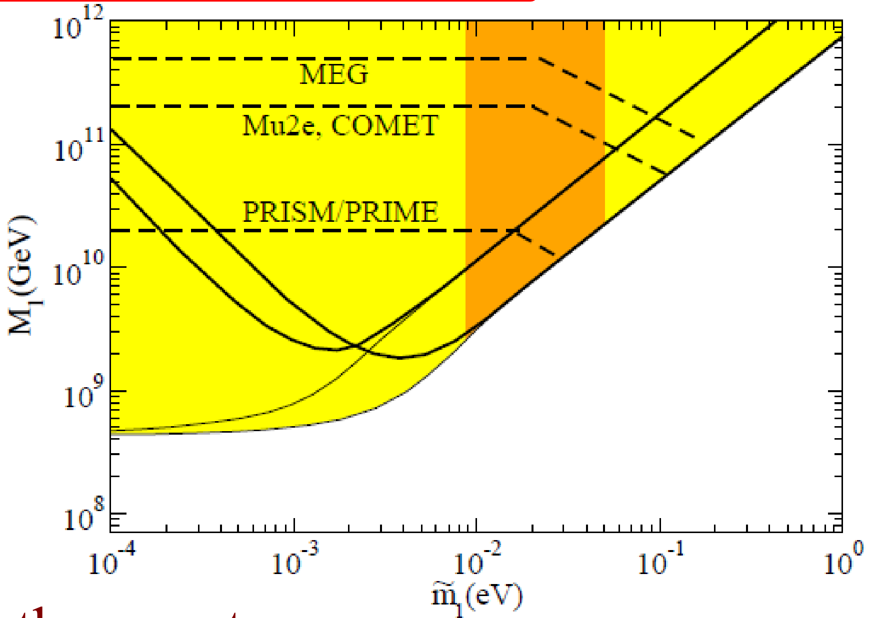
μ-e conversion at 10^{-18}??

$$R(\mu \mathrm{Ti} \to e\mathrm{Ti}) \gtrsim 10^{-18} \left(\frac{M_1}{2\times 10^{10}\ \mathrm{GeV}}\right)^2 \left(\frac{m_S}{200\ \mathrm{GeV}}\right)^{-4} \left(\frac{\tan\beta}{10\ \mathrm{GeV}}\right)^2$$

Expectations from leptogenesis,
(for m_S=200 GeV, $\tan\beta$=10)

Natural region for $\tilde{m}_1$:

No flavour effects: $R \gtrsim 10^{-18}$
"typical" flavour effects: $R \gtrsim 2\times 10^{-19}$
"extreme" flavour effects: $R \gtrsim 2\times 10^{-20}$

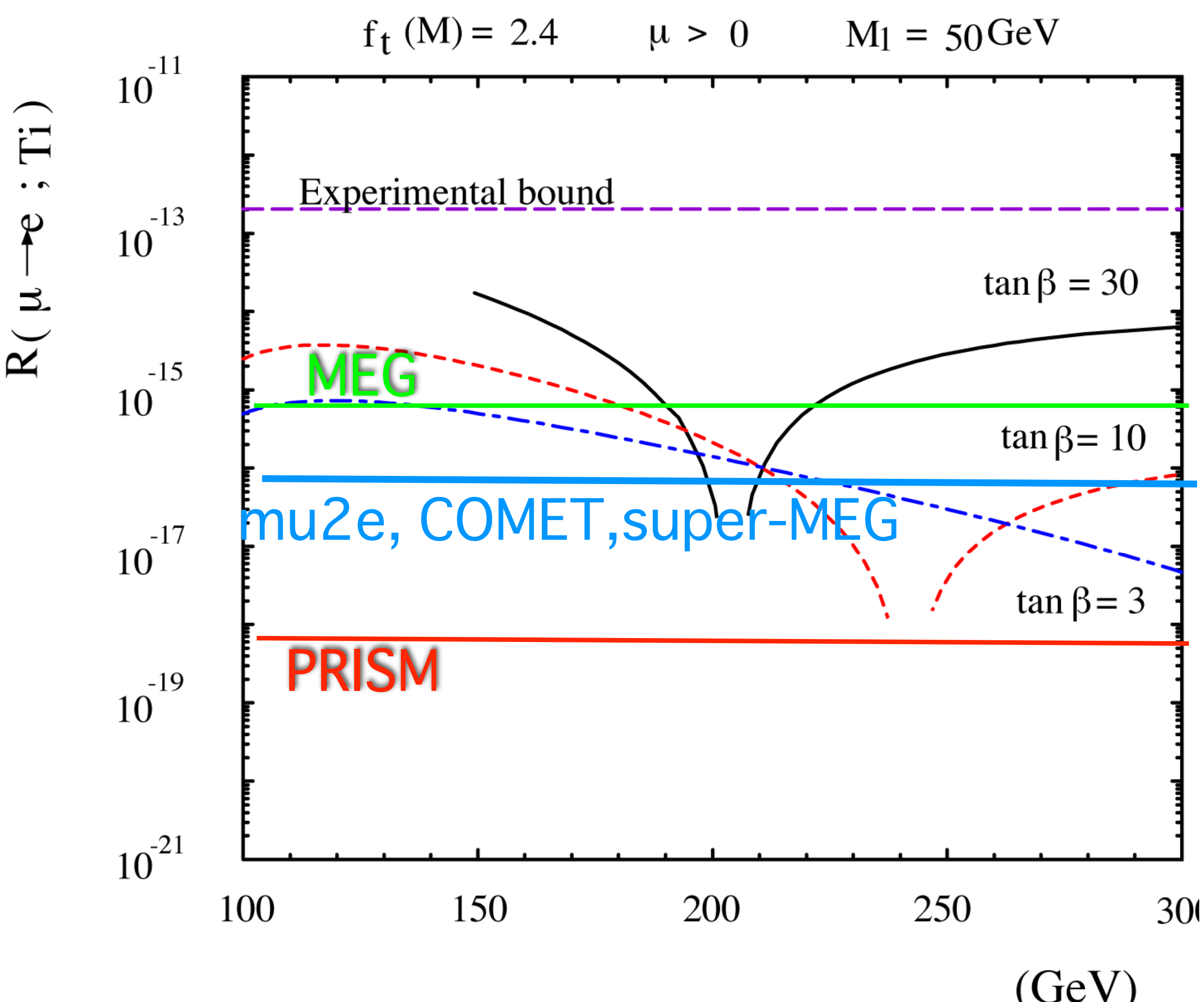


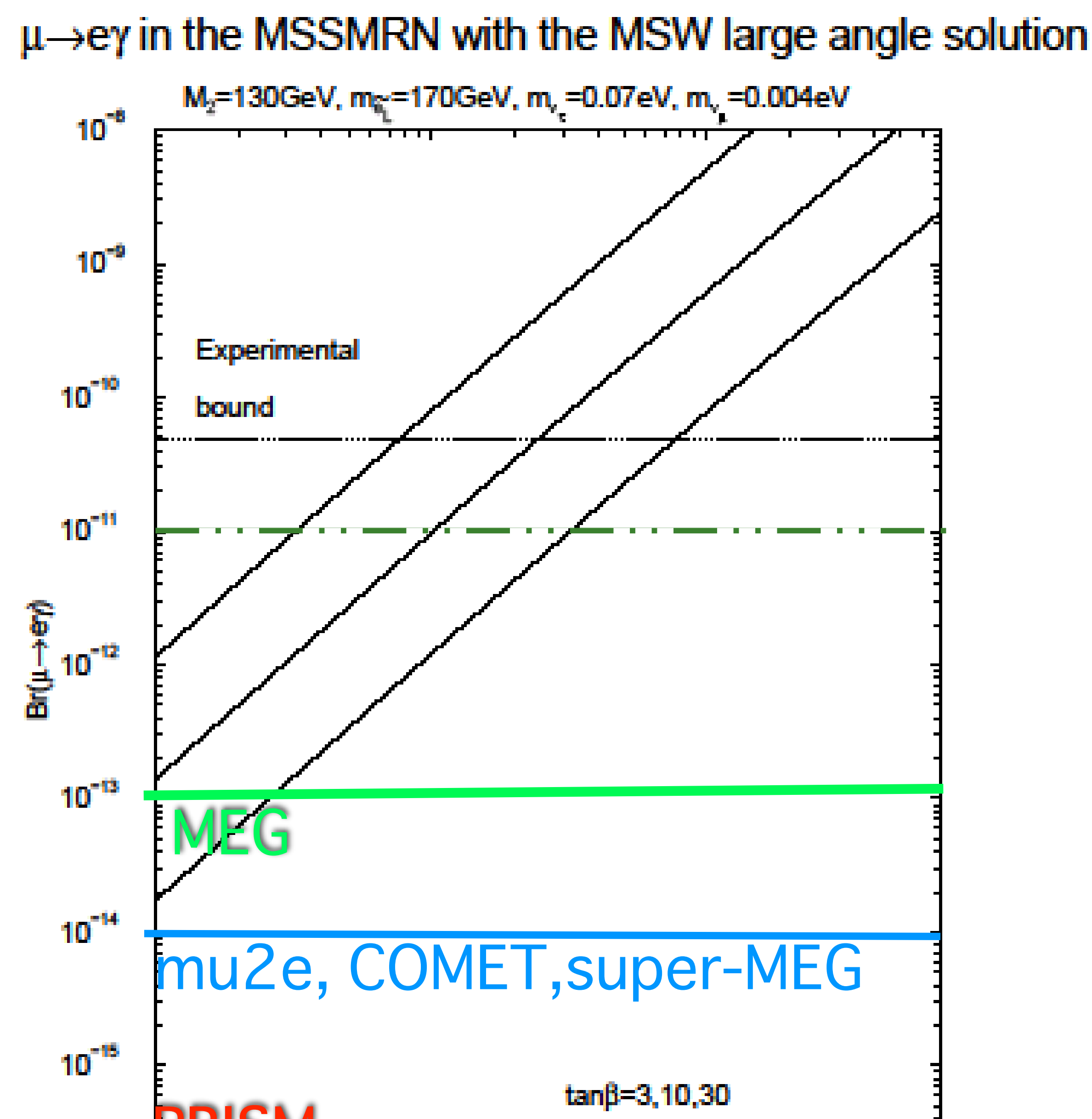
Note that in deriving this result we have assumed the worst case scenario for the detection of μ – e flavour violation:

- R-parity conserved.
- Universal soft terms at the cut-off scale.
- Yukawa textures that minimize the flavour violation: $(Y_\nu^\dagger Y_\nu)$ diagonal.
- Also, it is unlikely that M_1 saturates the lower bound (this requires optimal CP phases).

→ in general, much larger rates expected

SUSY Predictions for cLFV





Theoretical predictions are just below the present experimental bound.

Minimal SUSY Scenario

slepton mass matrix

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

$\Delta m^2_{ij} = 0$ @ Planck energy scale

New physics at high energy scale would introduce off-diagonal mass matrix elements, resulting in slepton mixing.

neutrino seesaw mechanism (~10^{15}GeV)

grand unification (GUT) (~10^{16}GeV)

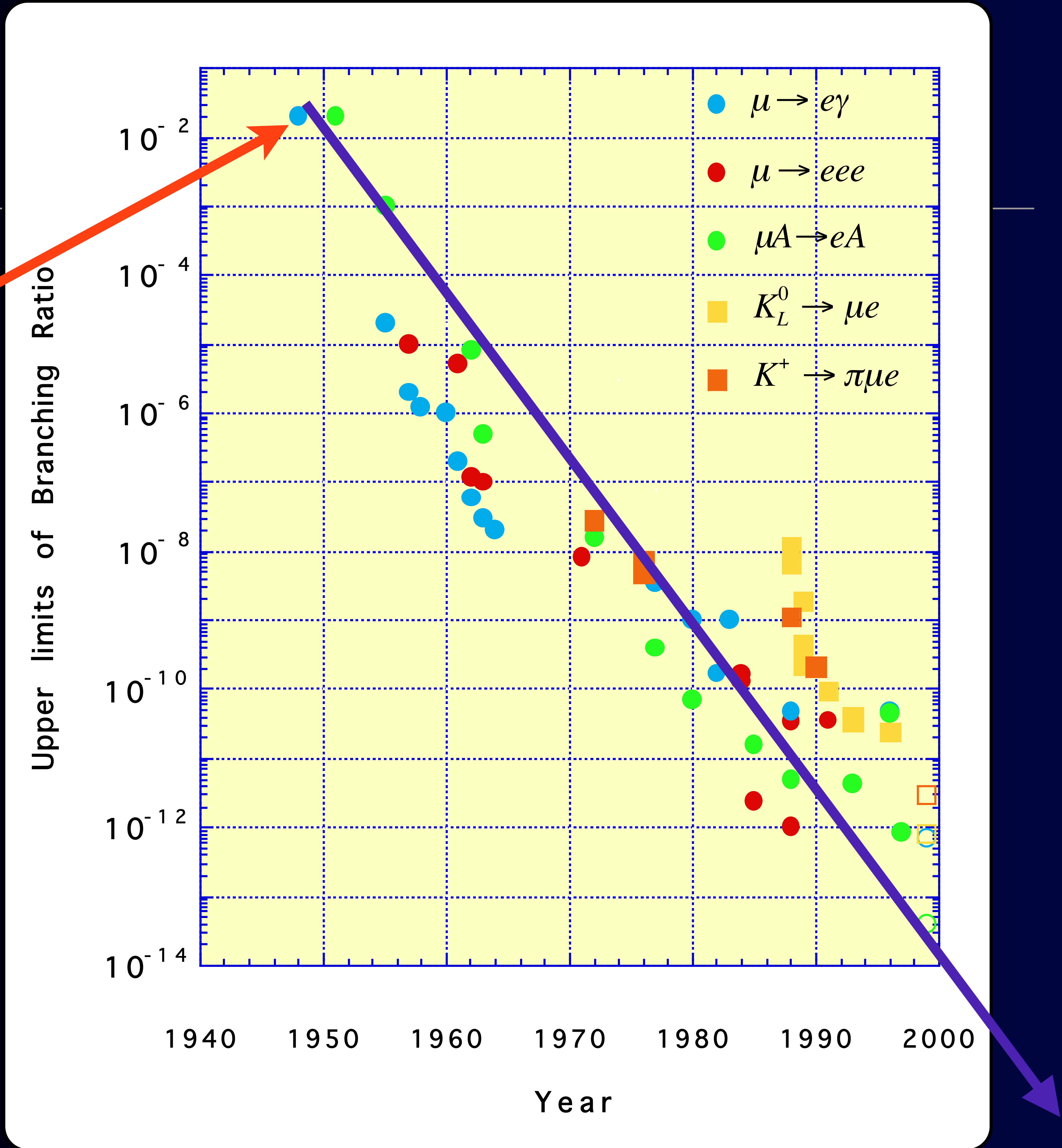
$\Delta m^2_{ij} \neq 0$ @ Weak energy scale (100 GeV)

cLFV have potential to study physics at very high energy scale like 10^{16} GeV.

cLFV History

First cLFV search

Pontecorvo in 1947

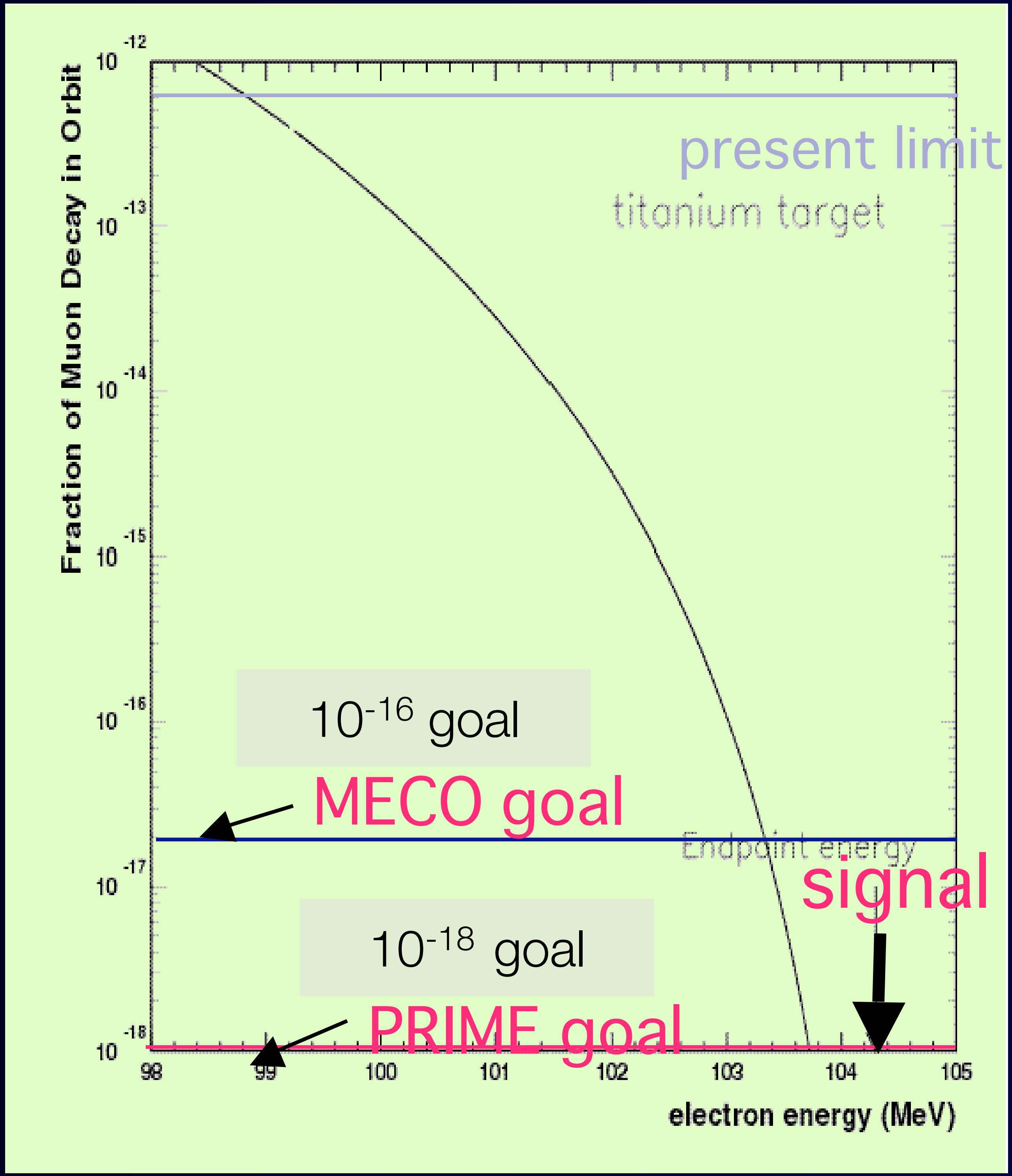


Muon Decay In Orbit (DIO) in a Muonic Atom

- Normal muon decay has an endpoint of 52.8 MeV, whereas the end point of muon decay in orbit comes to the signal region.
- good resolution of electron energy (momentum) is needed.

$$\propto (\Delta E)^5$$

- 150 keV energy resolution of electron detection is sufficient for $<10^{-18}$ sensitivity.



COMET at J-PARC (for single event sensitivity of 3×10^{-17})