Experimental Searches for Muon to Electron Conversion

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FJPPL, EPOCHAL, Tsukuba

Outline

- Overview of Our Proposal to FJPPL
- Physics Motivation of Lepton Flavor Violation of Charged Leptons (cLFV)
- What is μ-e conversion in a muonic atom ?
- Experimental searches for μ-e conversion at J-PARC (COMET)
- Summary

New Proposal

Overview of Our Proposal to FJPPL

- The objective of this year's proposal is to hold a mini-workshop in France to increase collaborators in France. And then we will invite the people who are interested to Japan for further discussions.

- Funding Requests
  - from France : 10,000 Euro for travel, organization of LFV mini-workshop
  - from KEK : none
- Additional funding
  - from Osaka University (including Kakenhi) :
    - 5,000 Euro for travel

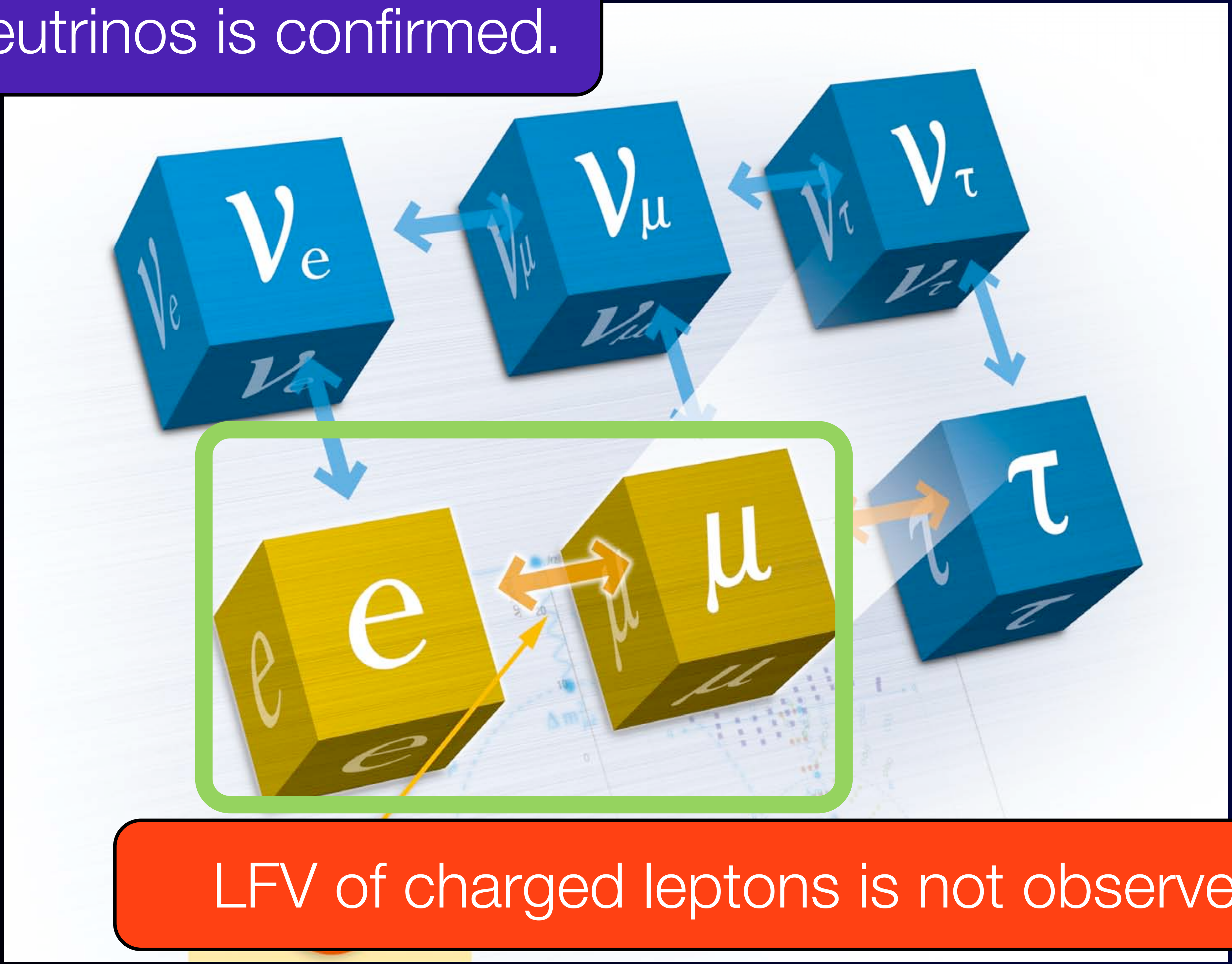
    - about 50,000 Euro for postdoc
    - about 50,000 Euro for equipments

Apology for my mistakes!

Physics Motivation of cLFV

Lepton Flavor Violation of Charged Leptons (cLFV)

LFV of neutrinos is confirmed.

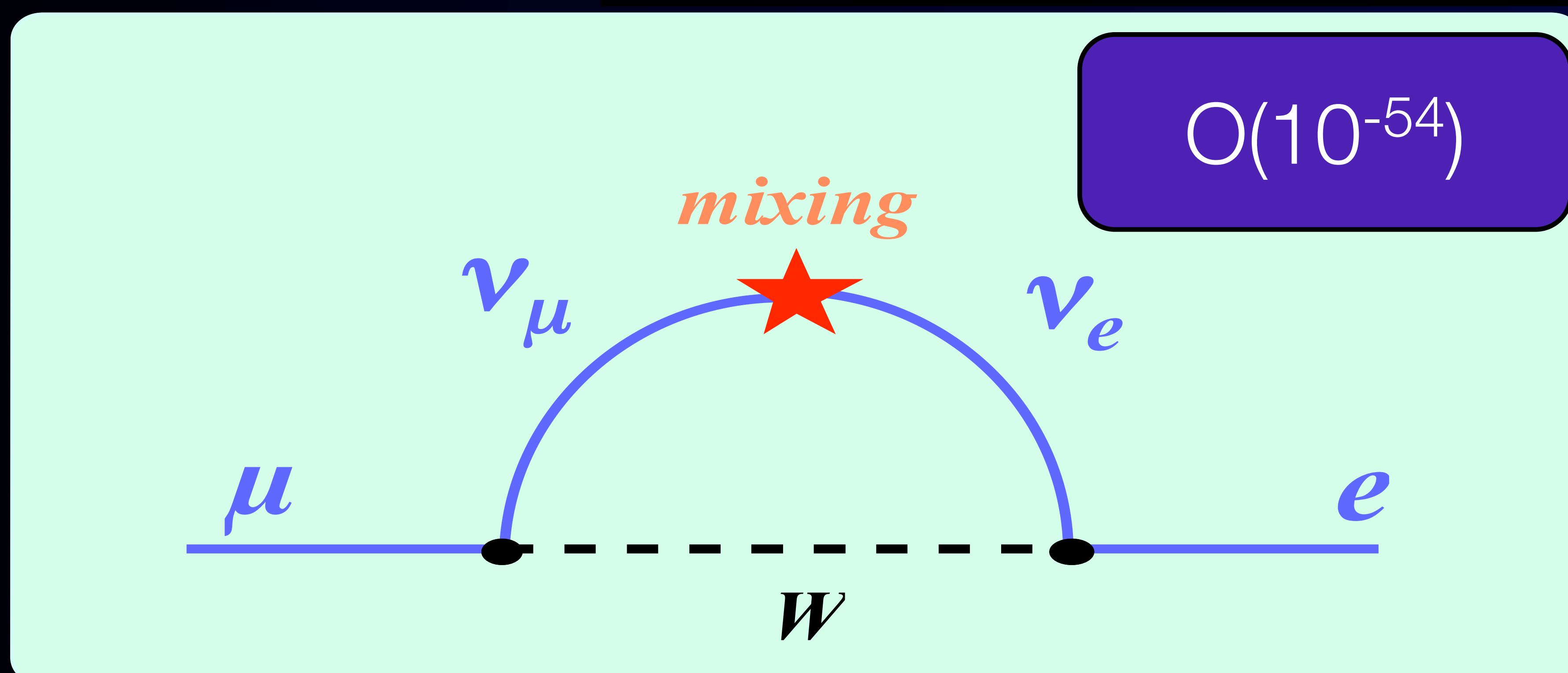


LFV of charged leptons is not observed.

Standard Model Contribution from Neutrino Mixing (GIM mechanism)

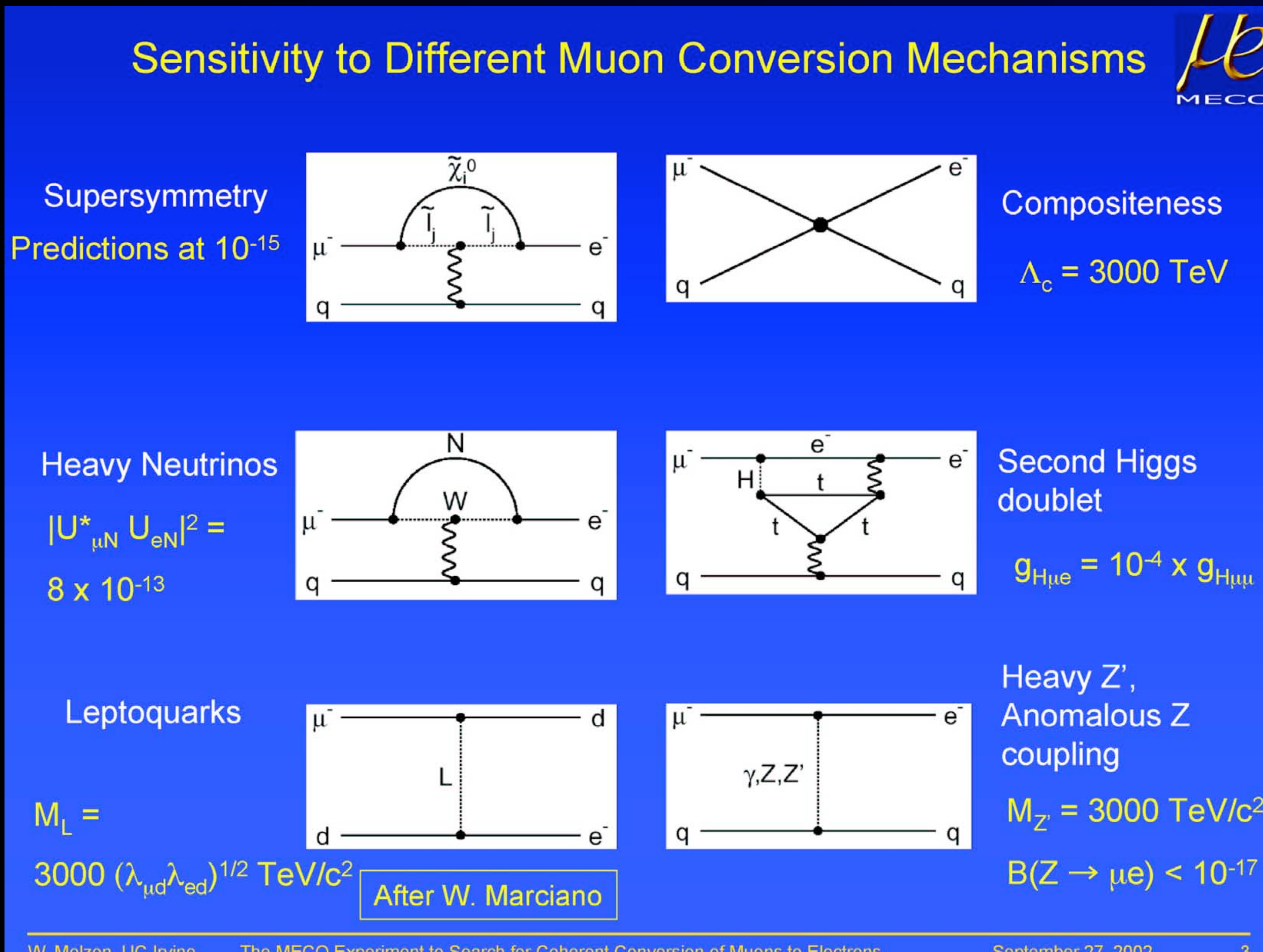
$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_l (V_{MNS})^*_{\mu l}(V_{MNS})_{el}\frac{m^2_{\nu_l}}{M^2_W}\right|^2$$

[redacted]



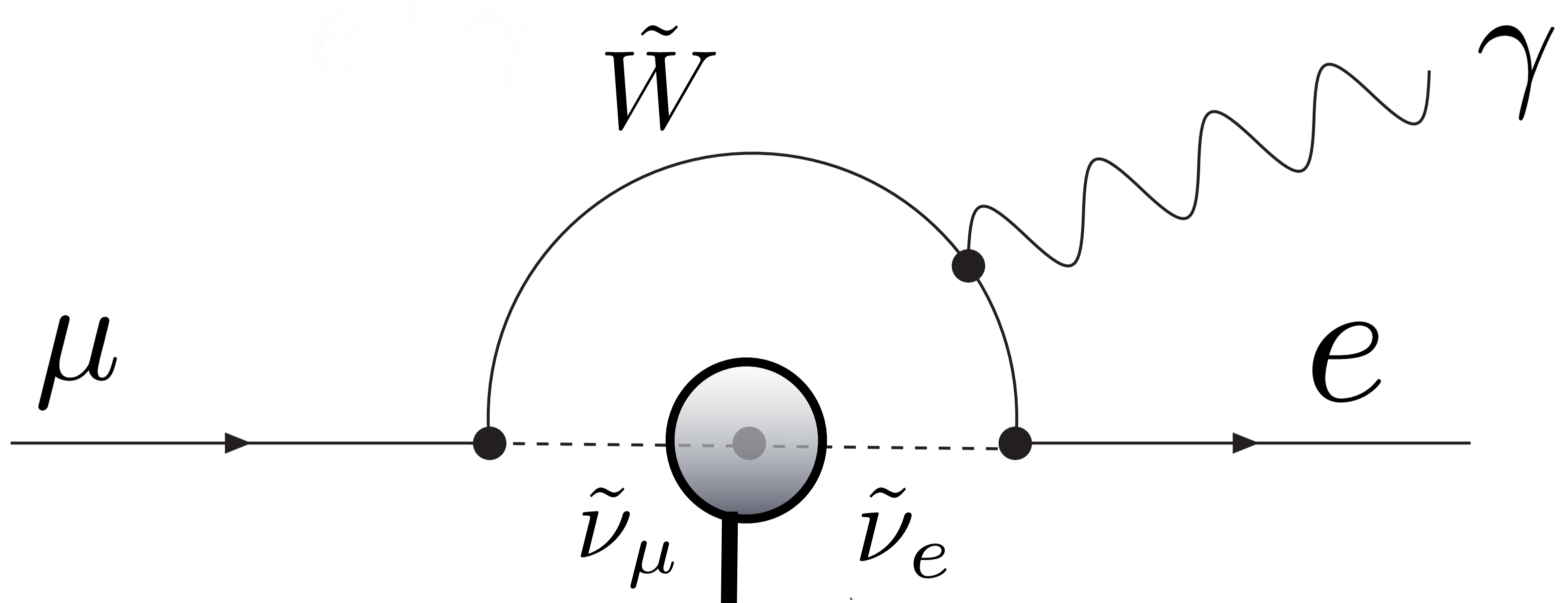
A Large Window for New Physics beyond the Standard Model

Various Models Predict cLFV....

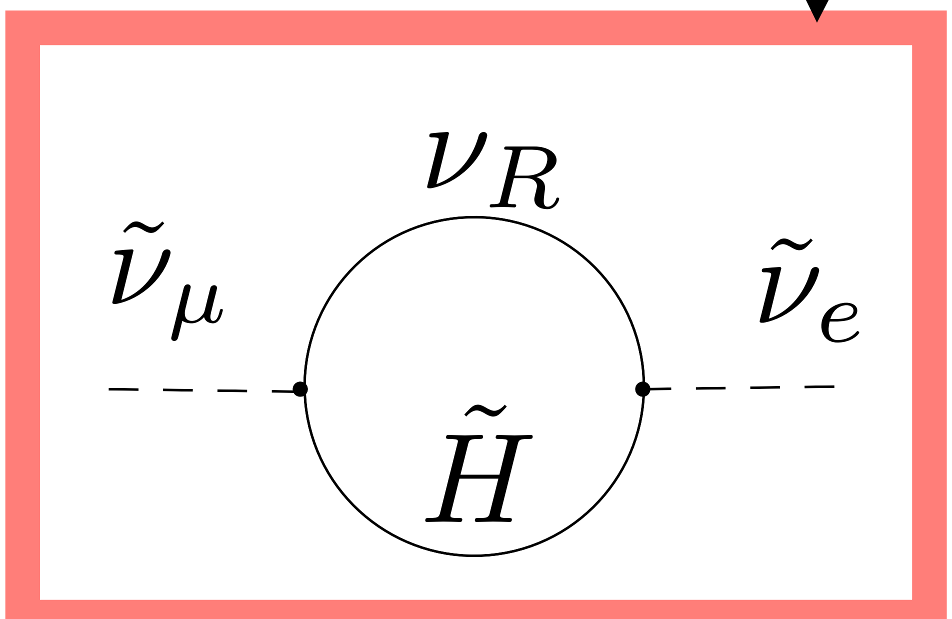


cLFV in SUSY Models

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 (~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

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

$$(m^2_{\tilde{l}})_{ij} = m_0^2 \delta_{ij}$$ @ M_planck

GUT Yukawa interaction

Neutrino Yukawa interaction

$$(\Delta m^2_{\tilde{l}})_{ij} \neq 0$$

SUSY-GUT Models

$$(m^2_{\tilde{L}})_{21} \sim \frac{3m_0^2 + A_0^2}{8\pi^2} h_t^2 V_{td} V_{ts} \ln \frac{M_{GUT}}{M_{R_s}}$$

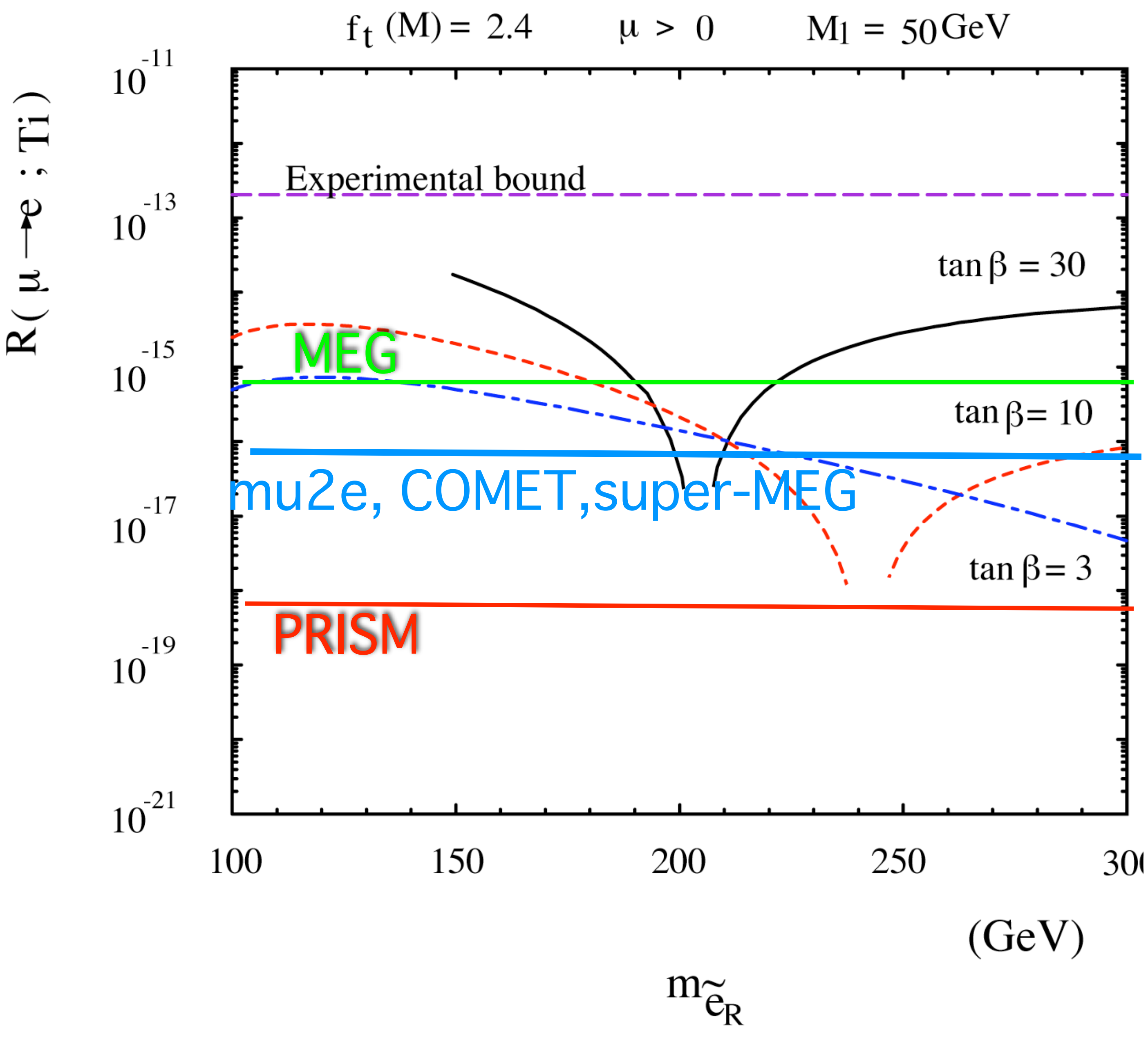
CKM matrix

SUSY Seesaw Models

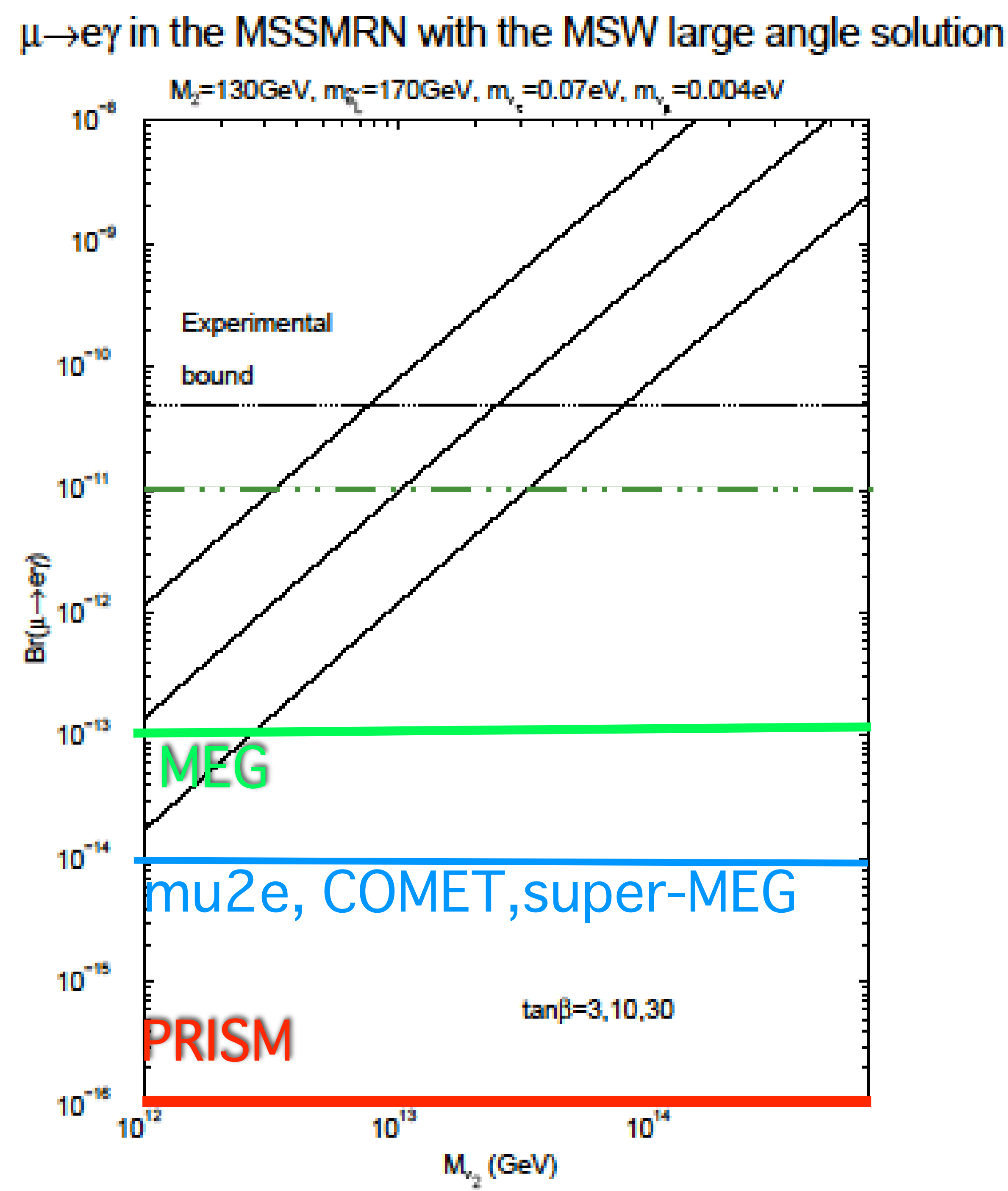
$$(m^2_{\tilde{L}})_{21} \sim \frac{3m_0^2 + A_0^2}{8\pi^2} h_t^2 U_{31} U_{32} \frac{M_{GUT}}{M_{R_s}}$$

Neutrino oscillation

SUSY Predictions for cLFV



SU(5) SUSY GUT



SUSY Seesaw Model

Short Summary of Physics Motivation : cLFV, Energy Frontier and SUSY

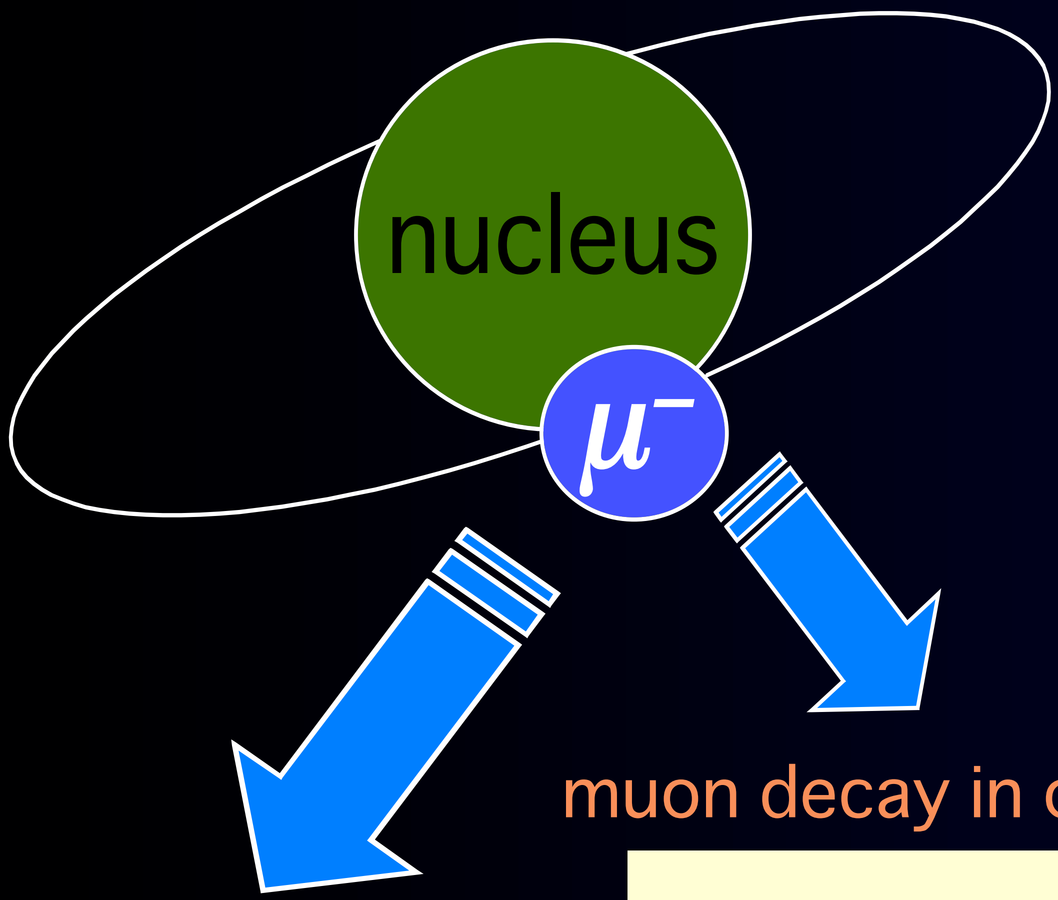
- In SUSY models, cLFV is sensitive to slepton mixing.
- LHC would have potentials to see SUSY particles. However, at LHC nor even ILC, slepton mixing would be difficult to study in such a high precision as proposed here.

- Slepton mixing is sensitive to either (or both) Grand Unified Theories (SUSY-GUT models) or neutrino seesaw mechanism (SUSY-Seesaw models).
- If cLFV sensitivity is extremely high, it might be able to explore multi-TeV SUSY which LHC cannot reach, in particular SUSY parameters.


$\mu \rightarrow e$ conversion
in
a muonic atom

What is a Muon to Electron Conversion ?

1s state in a muonic atom



muon decay in orbit

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

nuclear muon capture

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

Neutrino-less muon nuclear capture (=μ-e conversion)

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

lepton flavors changes by one unit.

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

μ-e Conversion
Signal and Backgrounds

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

- Signal
  - single mono-energetic electron

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

- The transition to the ground state is a coherent process, and enhanced by a number of neuclus.

$$\propto Z^5$$

- The ratio of excited states versus the ground state is about 1:9 for Ti.

Backgrounds

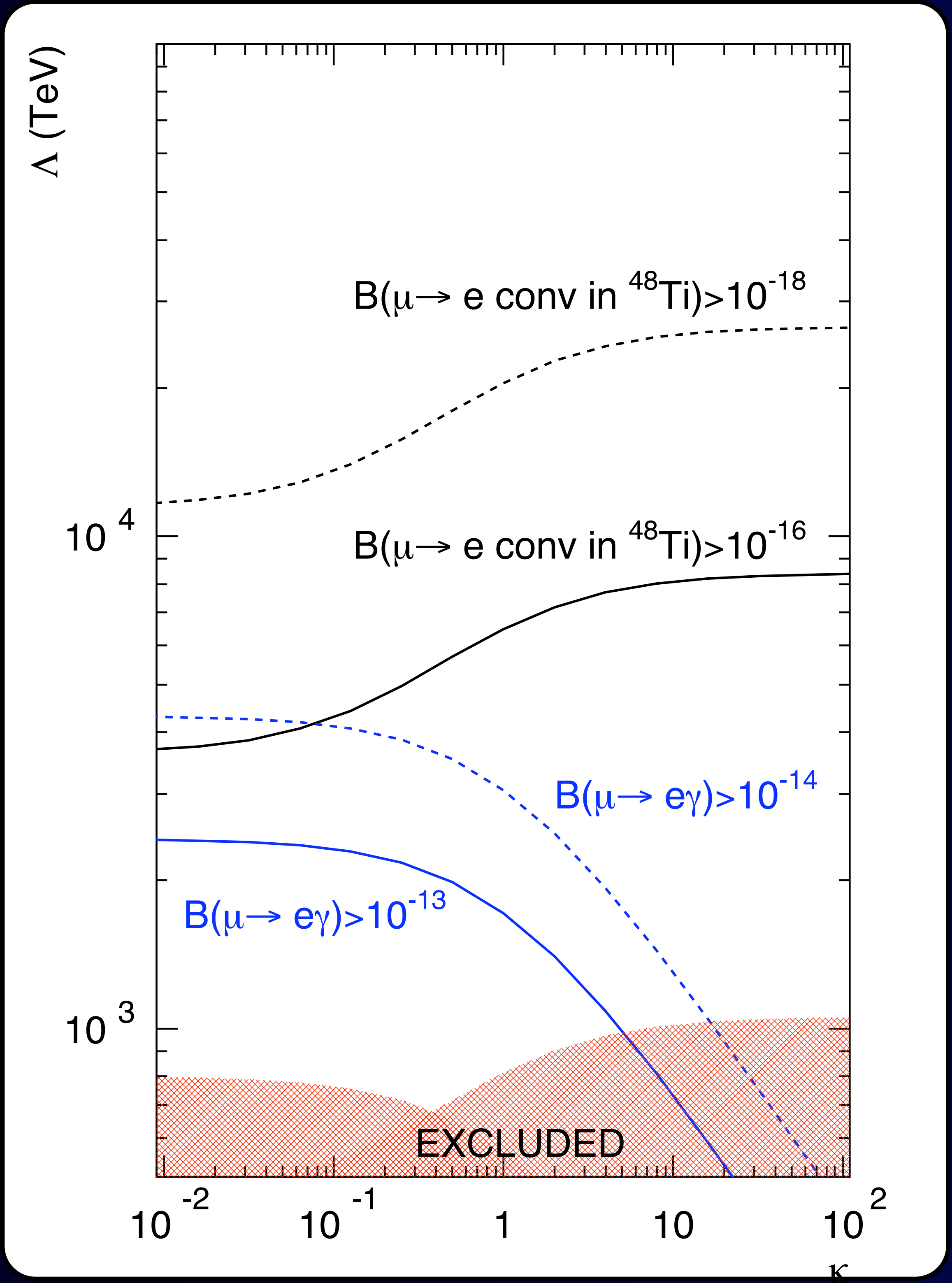
Category	Examples of backgrounds
Intrinsic Physics Backgrounds	muon decay in orbit (DIO)
	particle emissions from nuclear muon capture
	radiative muon capture (RMC)
Beam-related backgrounds	radiative pion capture (RPC)
	muon decay in flight
	neutrons, kaons, and anti-protons
Other Backgrounds	cosmic rays
	miss-tracking events

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

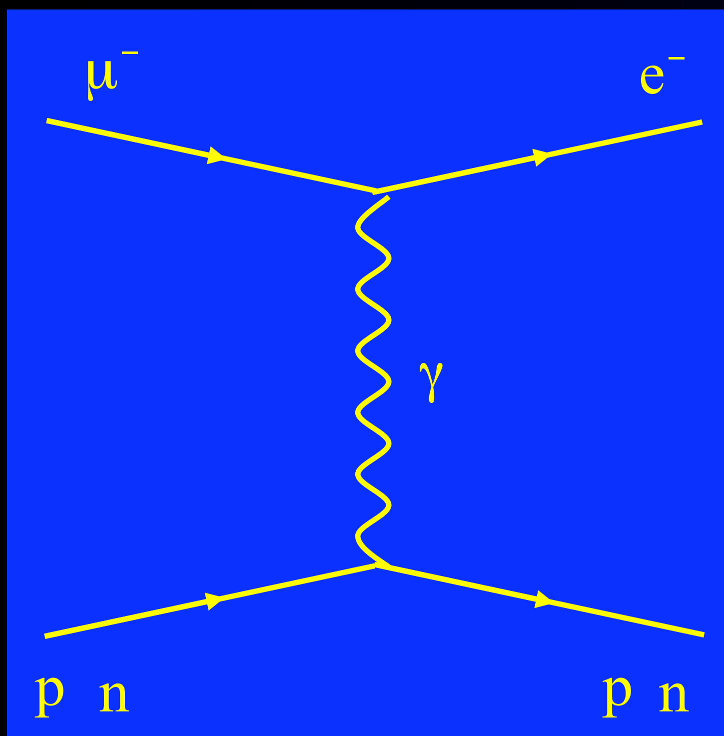
Photonic (dipole) and non-photonic contributions

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

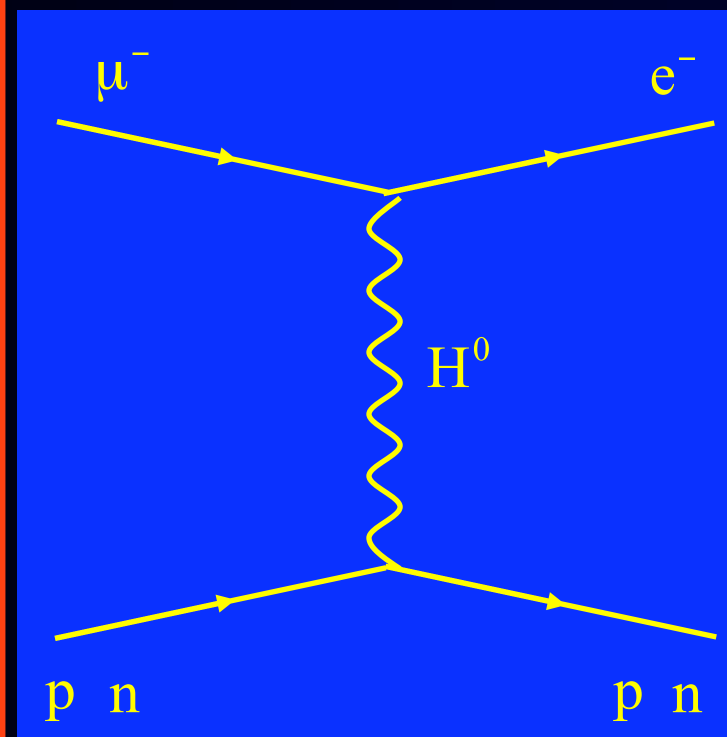
more sensitive to new physics



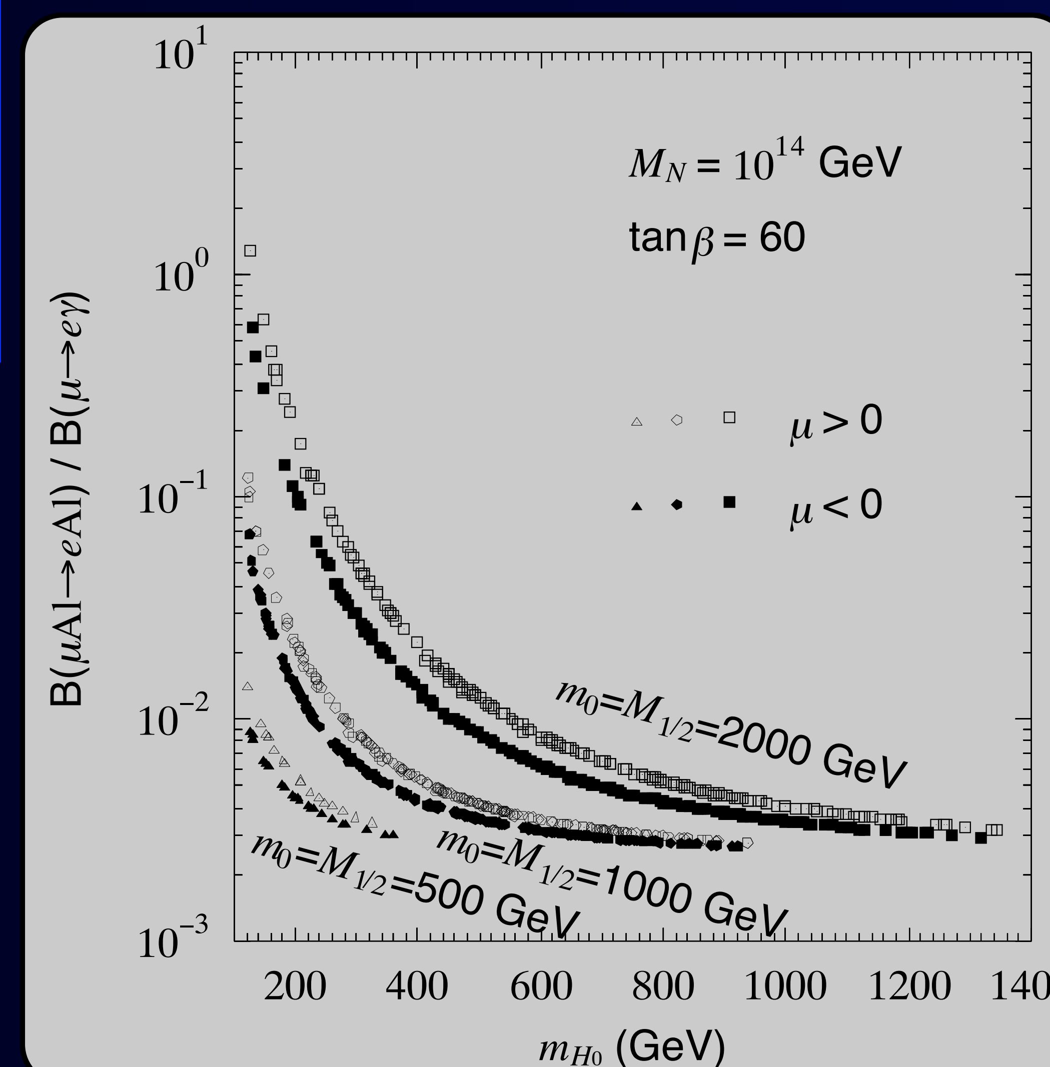
SUSY Higgs Mediated Contribution (large tanβ)



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



R. Kitano, M. Koike, S. Komine and Y. Okada, Phys. Lett. B575, 300 (2003)



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

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

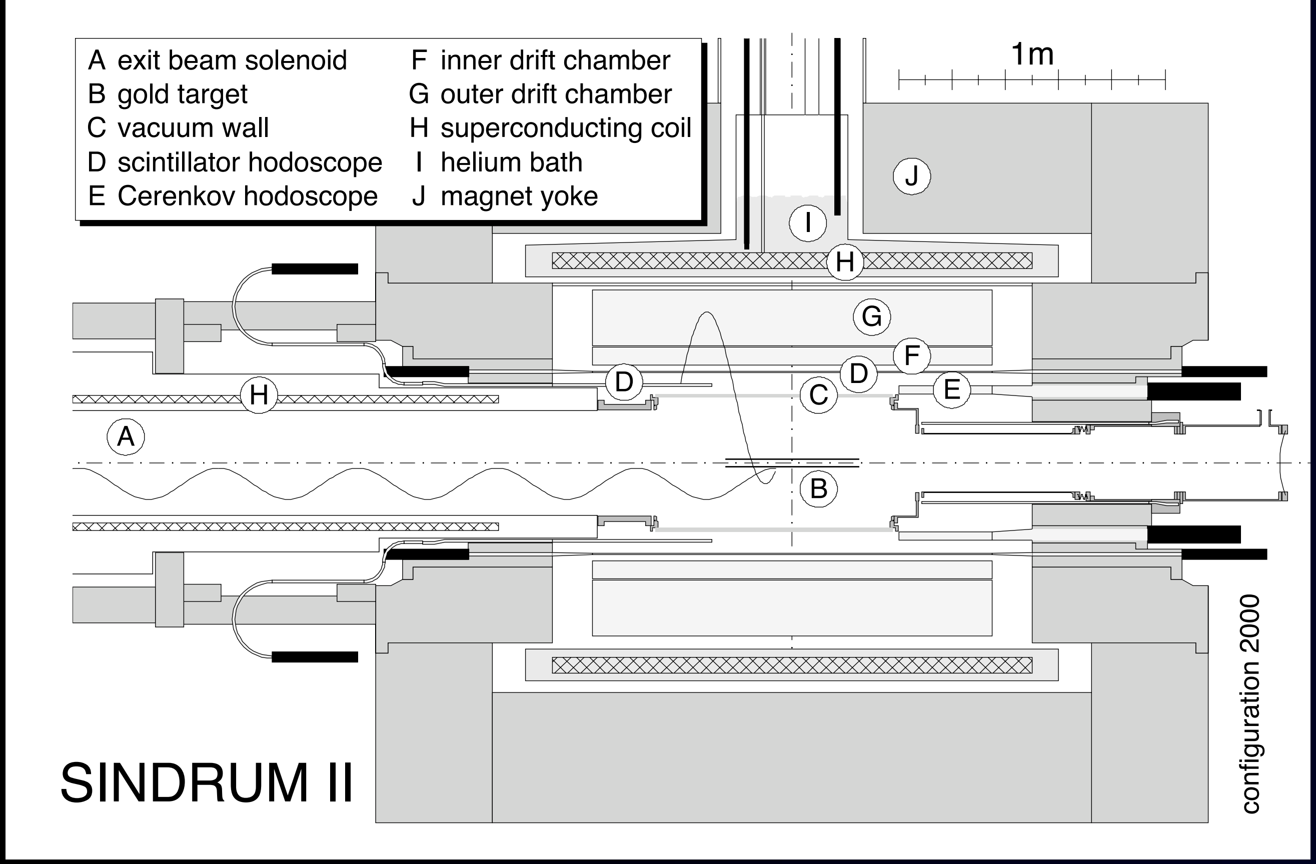
- $\mu \to e\gamma$: Accidental background is given by $(\text{rate})^2$. The detector resolutions have to be improved, but they (in particular, photon) would be hard to go beyond MEG from present technology. The ultimate sensitivity would be about 10^{-14} (with about 10^8/sec) unless the detector resolution 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.

Experimental Search for Muon to Electron Conversion

Previous Measurements

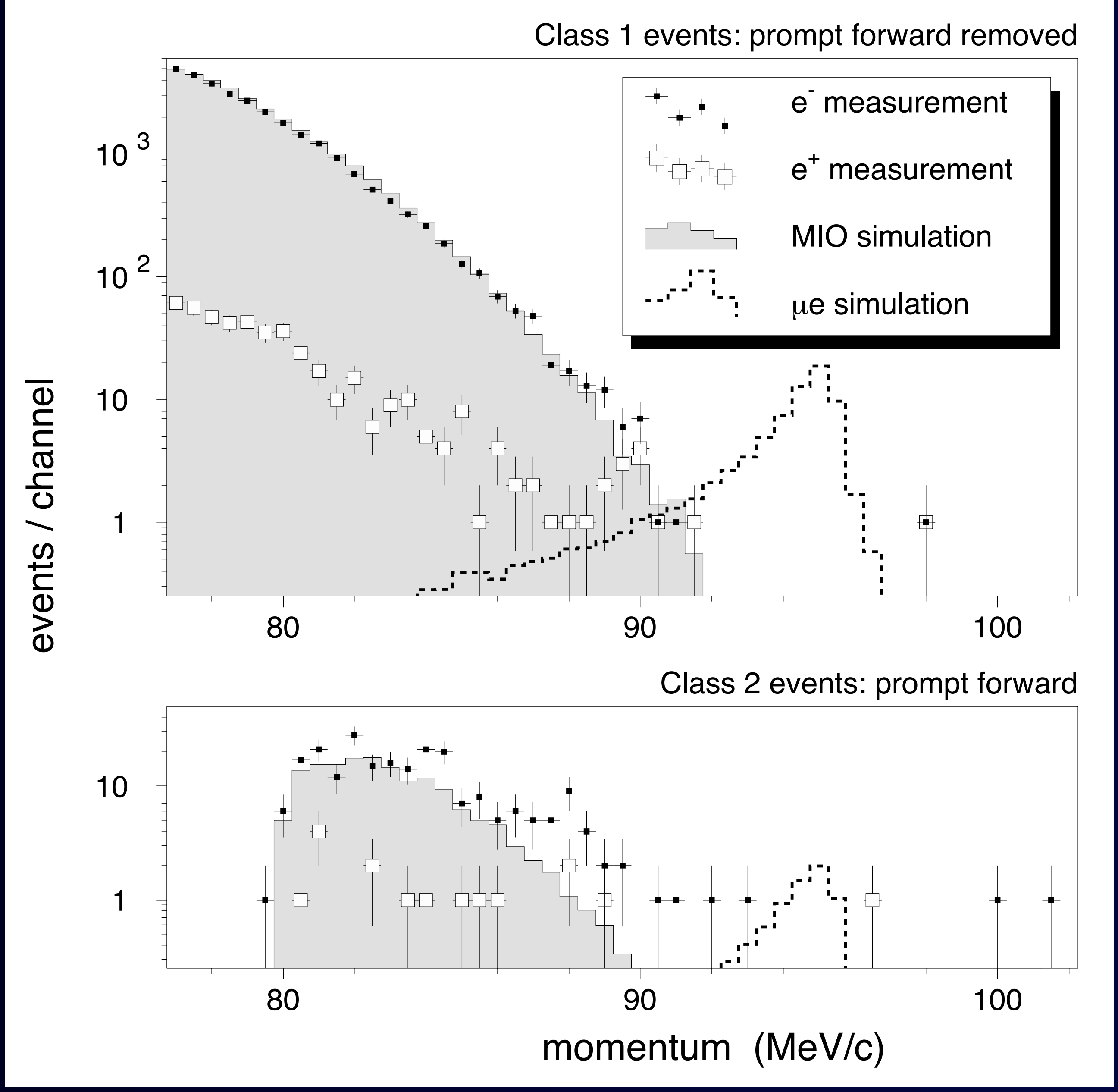
SINDRUM-II (PSI)



PSI muon beam intensity ~ $10^{7\text{-}8}$/sec beam from the PSI cyclotron. To eliminate beam related background from a beam, a beam veto counter was placed. But, it could not work at a high rate.

Published Results (2004)

$$B(\mu^- + Au \rightarrow e^- + Au) < 7 \times 10^{-13}$$



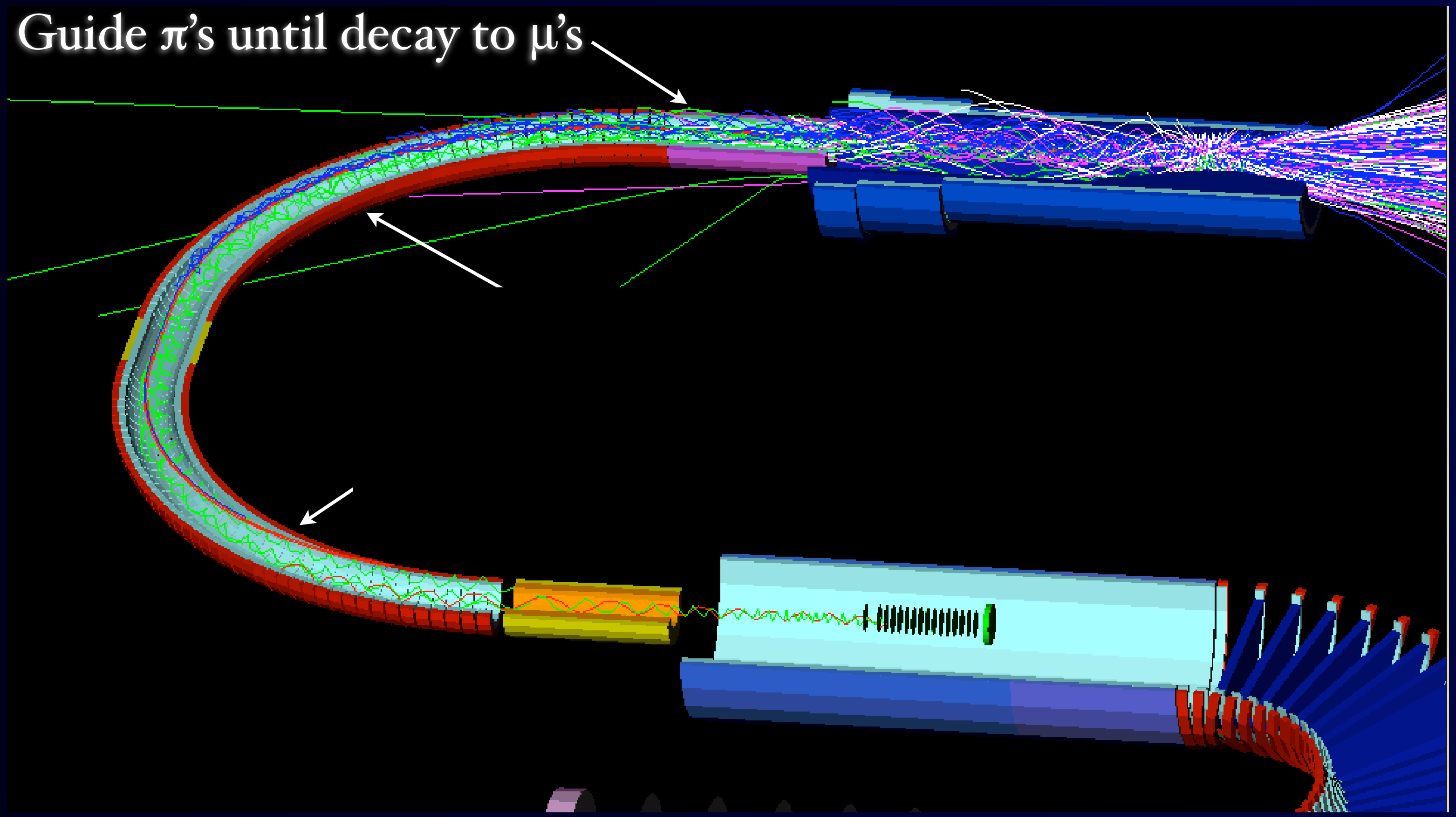
Improvements for Signal Sensitivity

To achieve a single sensitivity of 10^{-16}, we need

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

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

Pion Capture and Muon Transport by Superconducting Solenoid System

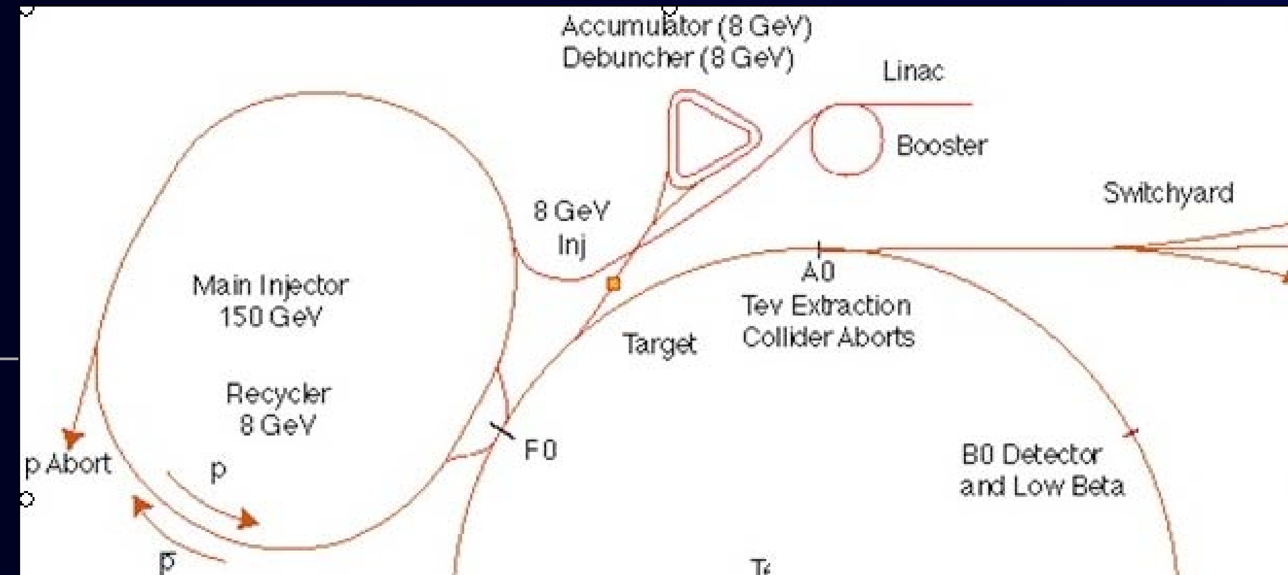


Improvements for Background Rejection

Beam-related backgrounds	→ Beam pulsing with separation of 1 μsec	measured between beam pulses
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)

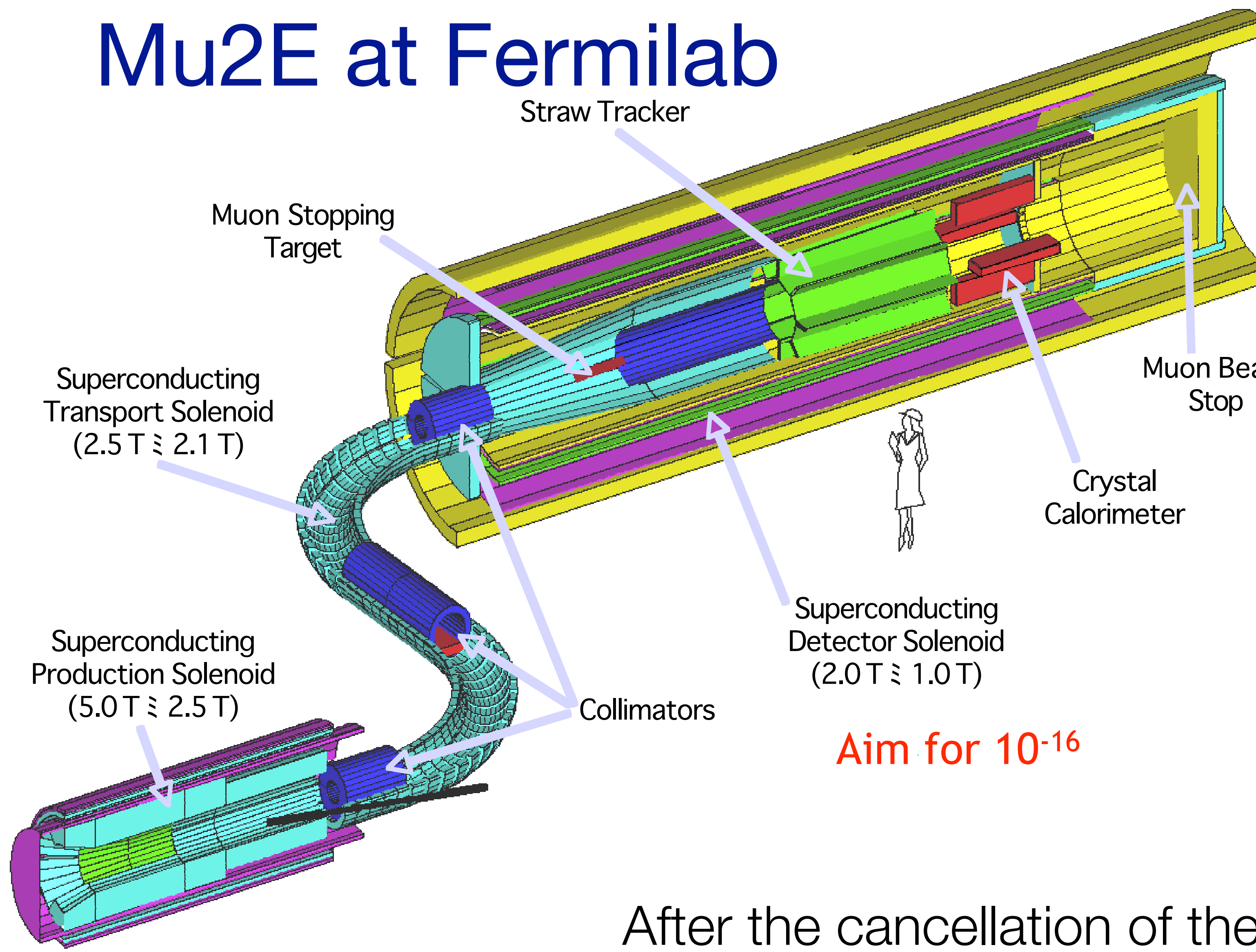
base on the MELC proposal at Moscow Meson Factory

Mu2E at Fermilab



- After Tevatron shutdown, use the antiproton accumulator ring and debuncher ring for beam pulsing.
- Proton beam power is 20 kW and 200 kW for pre and post Project-X.

Mu2E at Fermilab

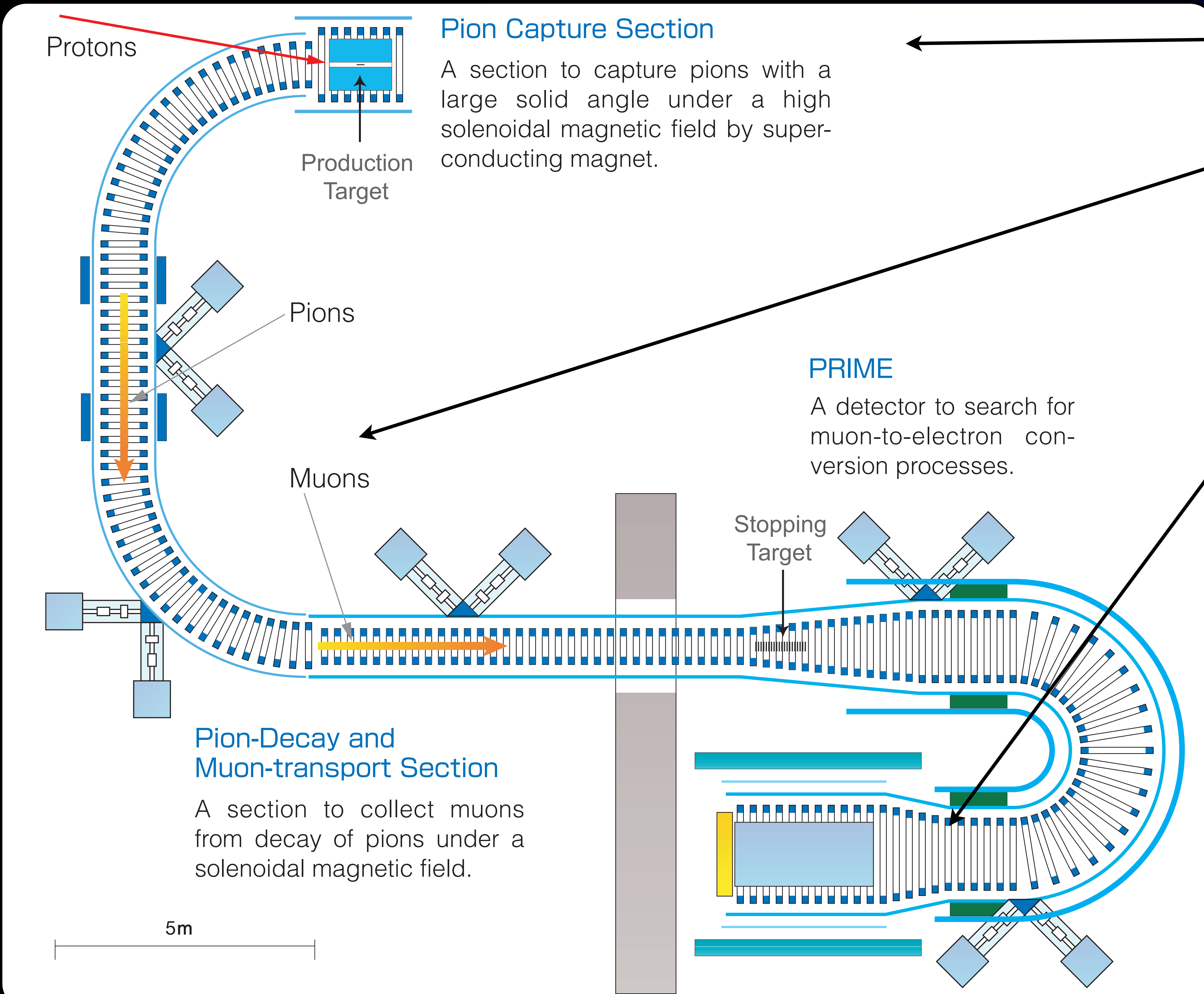


Aim for 10^{-16}

After the cancellation of the MECO experiment in 2005

COMET (COherent Muon to Electron Transition) in Japan

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



Proton Beam

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

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

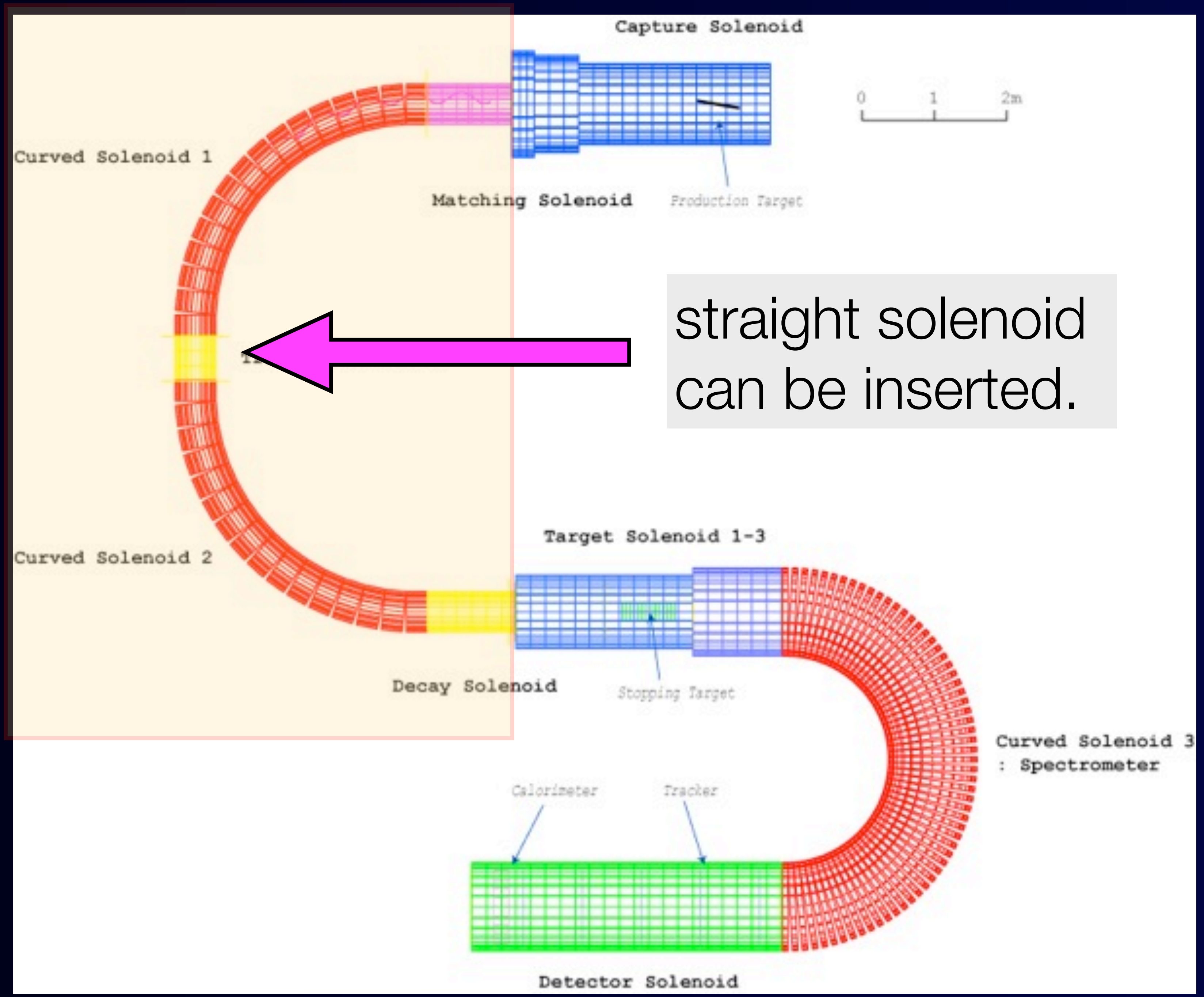
proposed to J-PARC

Design Difference Between Mu2e and COMET

	Mu2e	COMET
Muon Beam-line	S-shape	C-shape
Electron Spectrometer	Straight solenoid	Curved solenoid

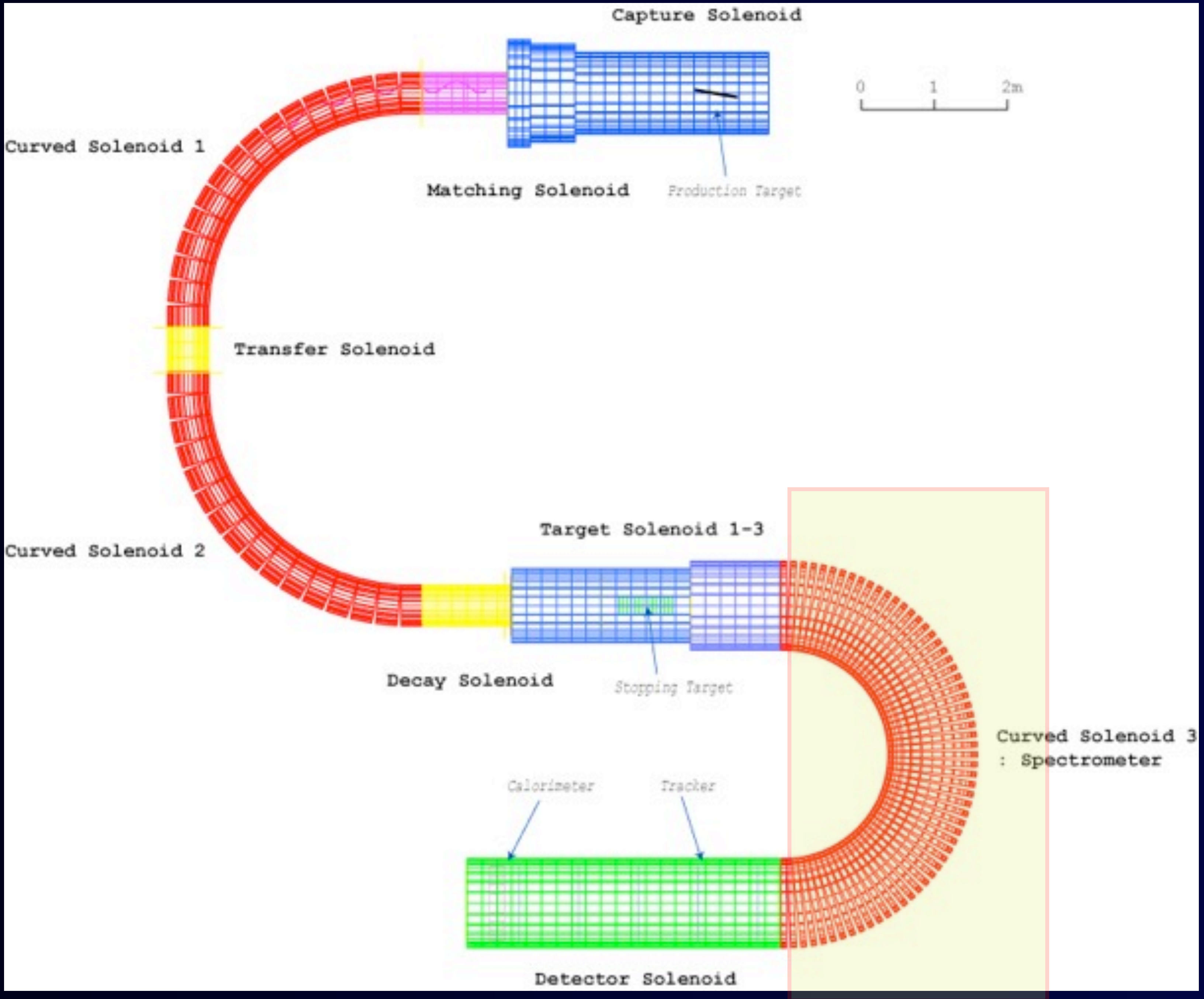
Muon Transport Solenoid Beam-line for COMET

- C-shape beam line :
  - better beam momentum separation
  - collimators can be placed anywhere.
- Radius of curvature is about 3 meters.
- A straight solenoid section can be inserted between the two toroids.
- Reference momentum is 35 MeV/c for 1st bend and 47 MeV/c for 2nd bend.



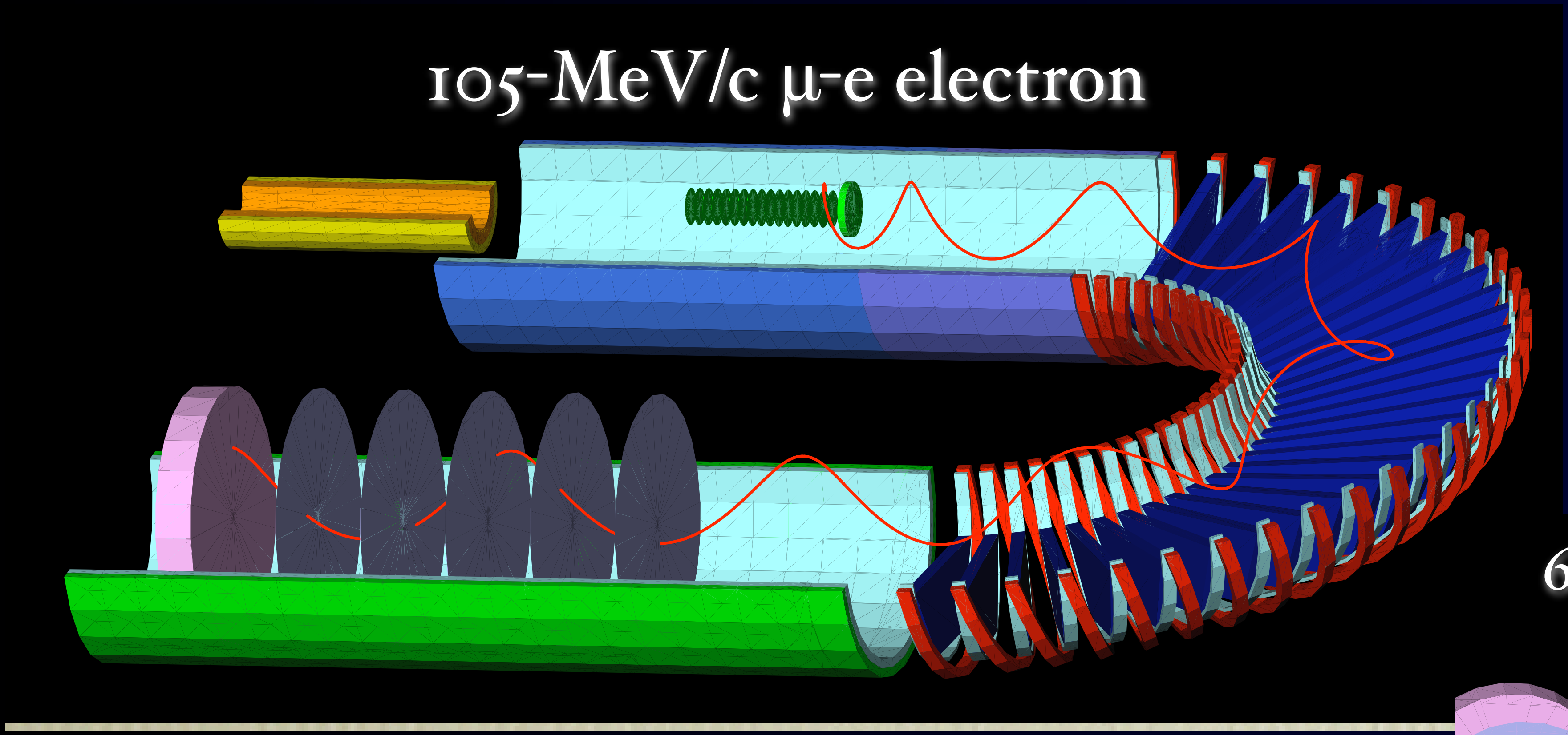
Curved Solenoid Spectrometer for COMET

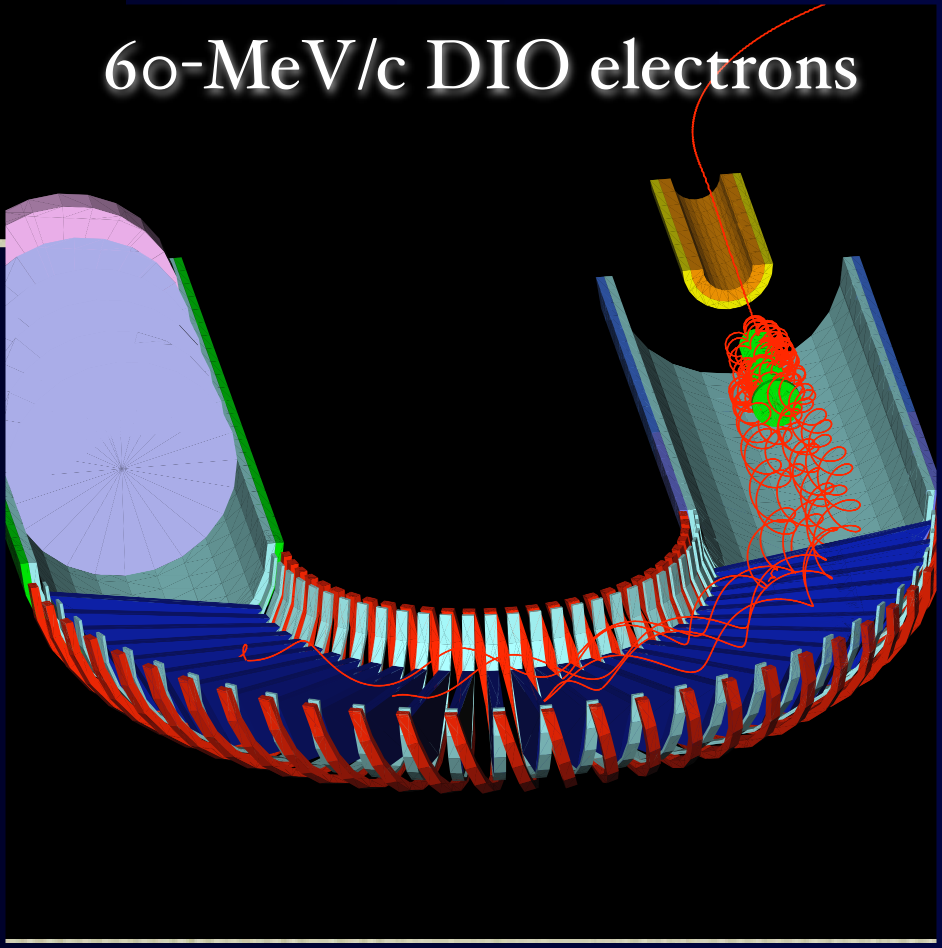
- 180 degree curved
  - Bore radius : 50 cm
  - Magnetic field : 1T
  - Bending angle : 180 degrees
- reference momentum ~ 104 MeV/c
- elimination of particles less than 80 MeV/c for rate issues
- a straight solenoid where detectors are placed follows the curved spectrometer.



schematic

Event Displays for Curved Solenoid Spectrometer





Signal Sensitivity (preliminary) - 1 SSC years

- Single event sensitivity

$$B(\mu^- + Al \to e^- + Al) \sim \frac{1}{N_\mu \cdot f_{cap} \cdot A_e},$$

  - N_μ is a number of stopping muons in the muon stopping target. It is 1.1×10^{18} muons.
  - f_{cap} is a fraction of muon capture, which is 0.6 for aluminum.
  - A_e is the detector acceptance, which is 0.04.

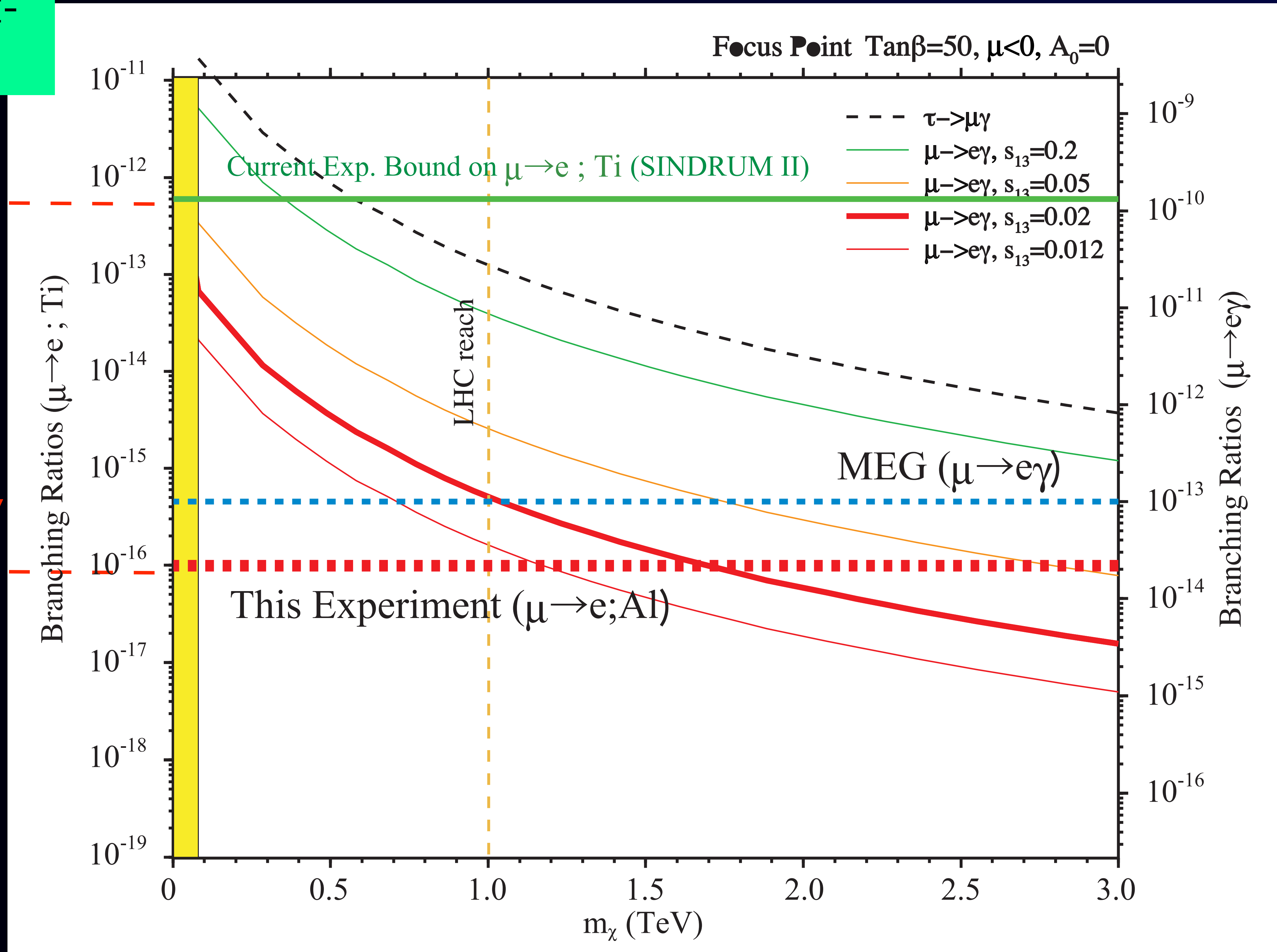
total protons	4×10^{20}
muon transport efficiency	0.009
muon stopping efficiency	0.3
# of stopped muons	1.1×10^{18}

$$B(\mu^- + Al \to e^- + Al) = 3.3 \times 10^{-17}$$

$$B(\mu^- + Al \to e^- + Al) < 7 \times 10^{-17} \quad (90\% C.L.)$$

mSUGRA with right-handed neutrinos

will be improved by a factor of 10,000.



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

Sensitivity Goal

BG with asterisk needs beam extinction.

Background Rejection Summary (preliminary)

Backgrounds	Events	Comments
Muon decay in orbit	0.05	230 keV resolution
Radiative muon capture	<0.001	
Muon capture with neutron emission	<0.001	
Muon capture with charged particle emission	<0.001	
Radiative pion capture*	0.12	prompt
Radiative pion capture	0.002	late arriving pions
Muon decay in flight*	<0.02	
Pion decay in flight*	<0.001	
Beam electrons*	0.08	
Neutron induced*	0.024	for high energy neutrons
Antiproton induced	0.007	for 8 GeV protons
Cosmic-ray induced	0.10	10^{-4} veto & 2×10^{7}sec run
Pattern recognition errors	<0.001	
Total	0.4	

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End of
My Slides