J-PARC Experimental Proposal P21 :

An Experimental Search For Lepton Flavor Violating μ^- - e^- Conversion at Sensitivity of 10^{-16} with a Slow-Extracted Bunched Beam

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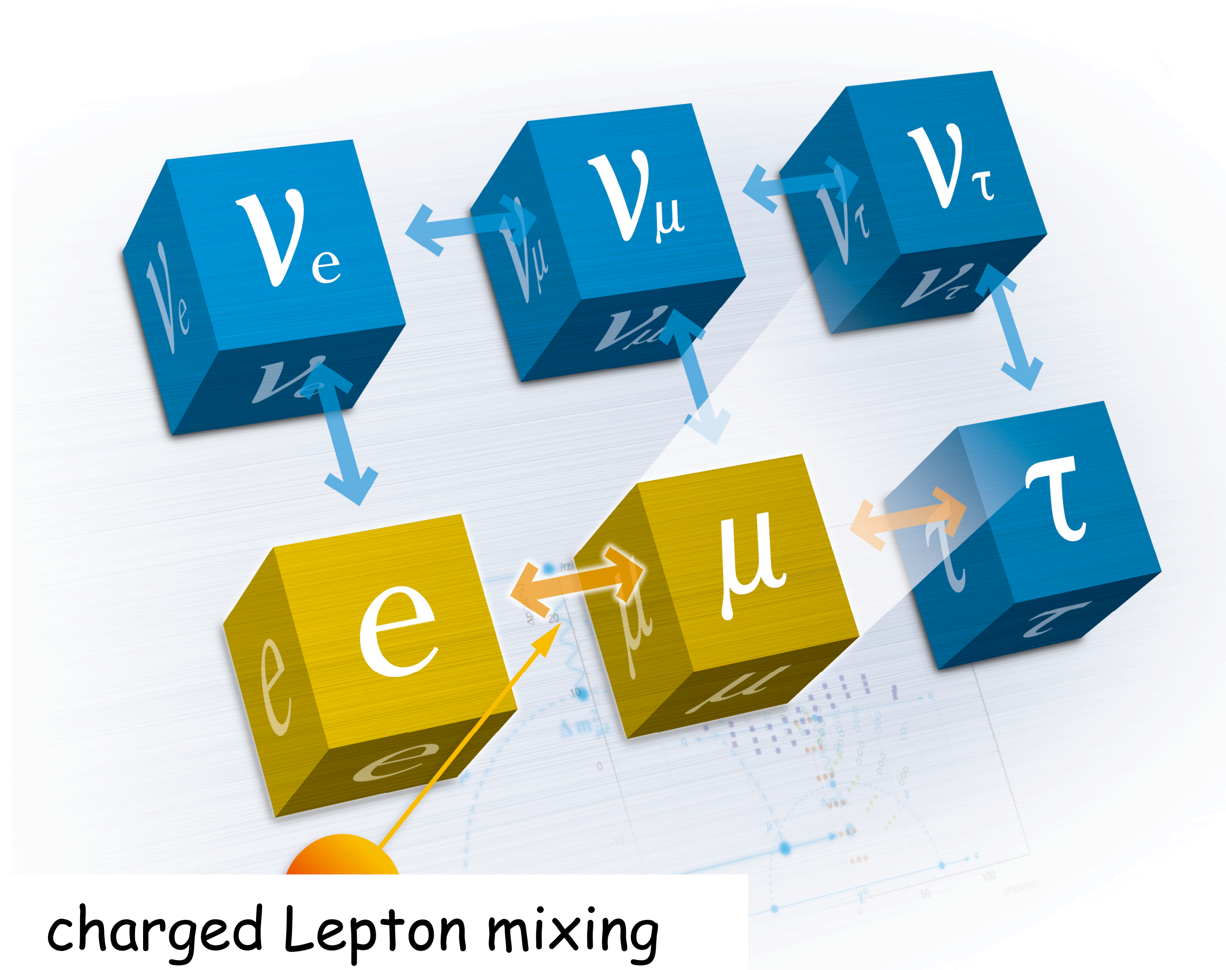
January 7th, 2008
J-PARC PAC Meeting



charged Lepton mixing

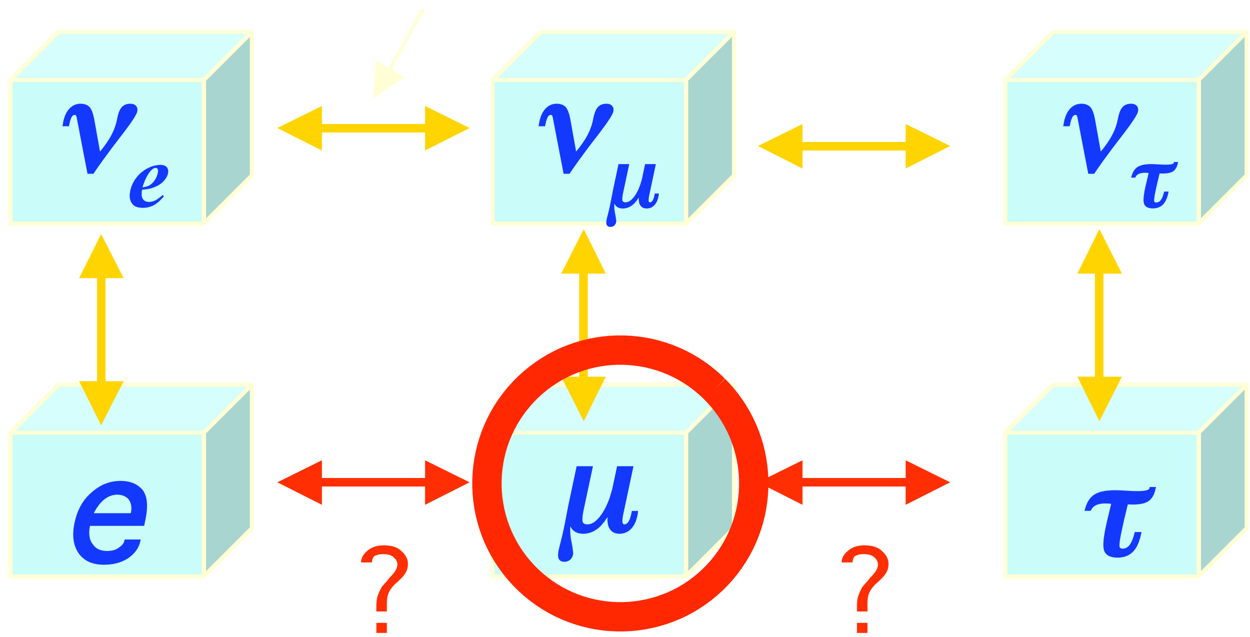
Outline

- Physics Motivation of Lepton Flavor Violation (LFV) for Charged Leptons
- μ-e conversion and Experiments
  - What is a μ-e conversion ?
  - Experimental Status
- A New Experiment at J-PARC
  - Overview
  - The Muon Beam
  - The Detector
  - Signal Sensitivity and Backgrounds
  - Possible Layout and Plan
- Summary

Physics Motivation of
Lepton Flavor Violation
for Charged Leptons

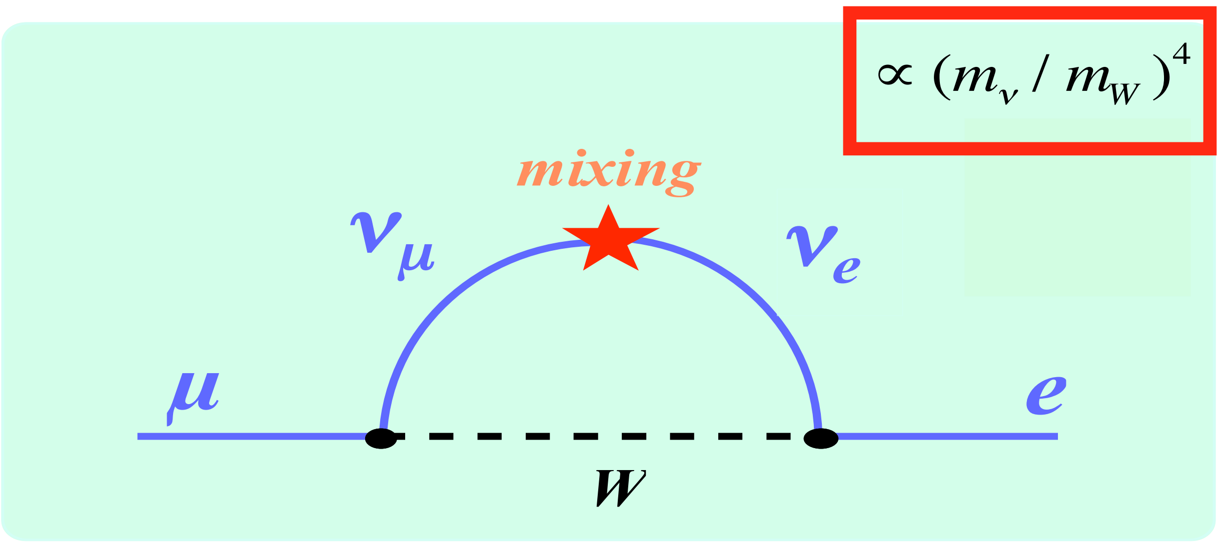
Lepton Flavor Violation of Charged Leptons (Charged Lepton Mixing)

Neutrino Mixing
(confirmed)



Charged Lepton Mixing
(not observed yet)

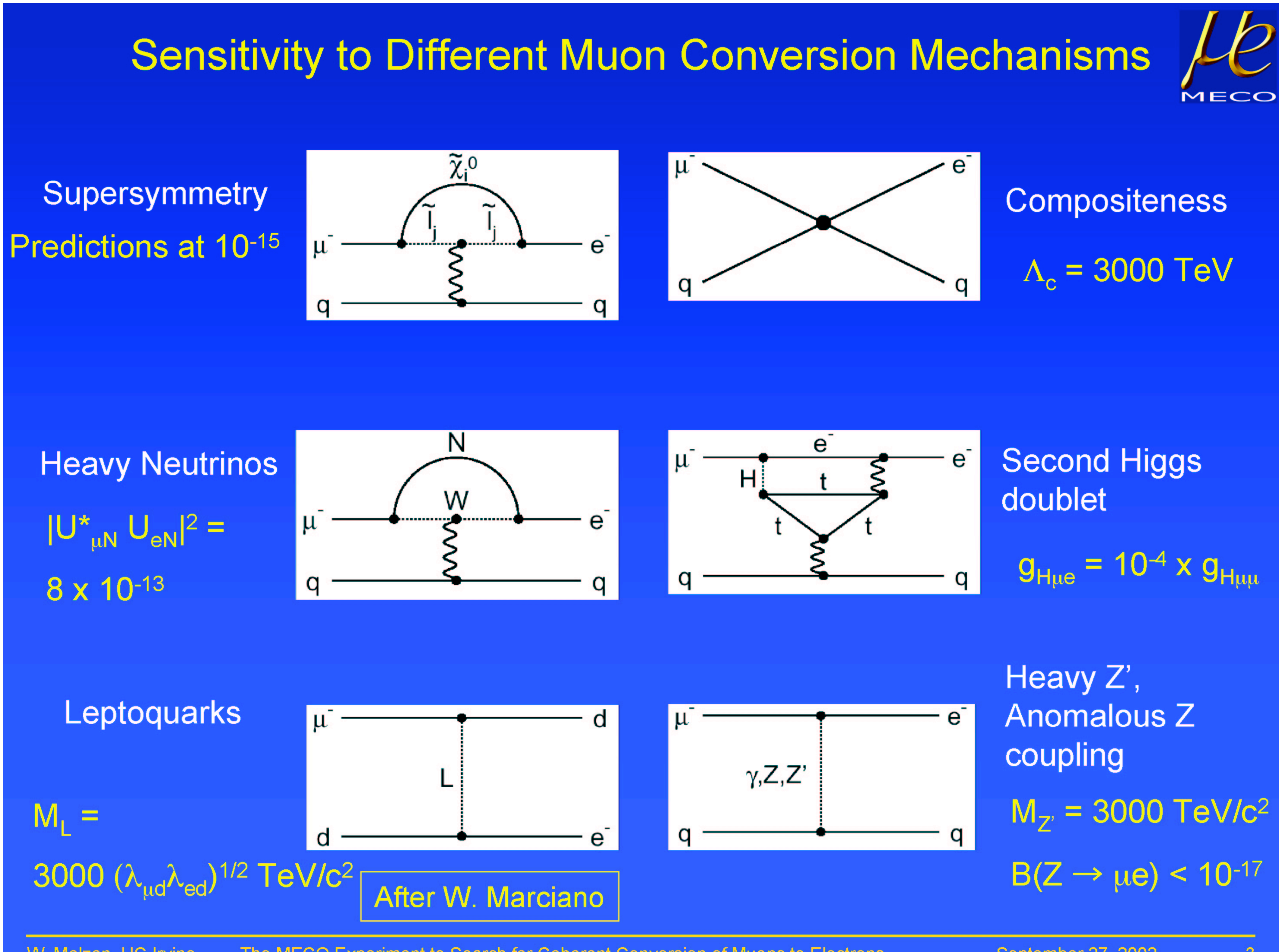
- What is The Contribution to Charged Lepton Mixing from Neutrino Mixing ?



Very Small (10^{-52})

Sensitive to new Physics beyond the Standard Model

Various Models Predict Charged Lepton Mixing.

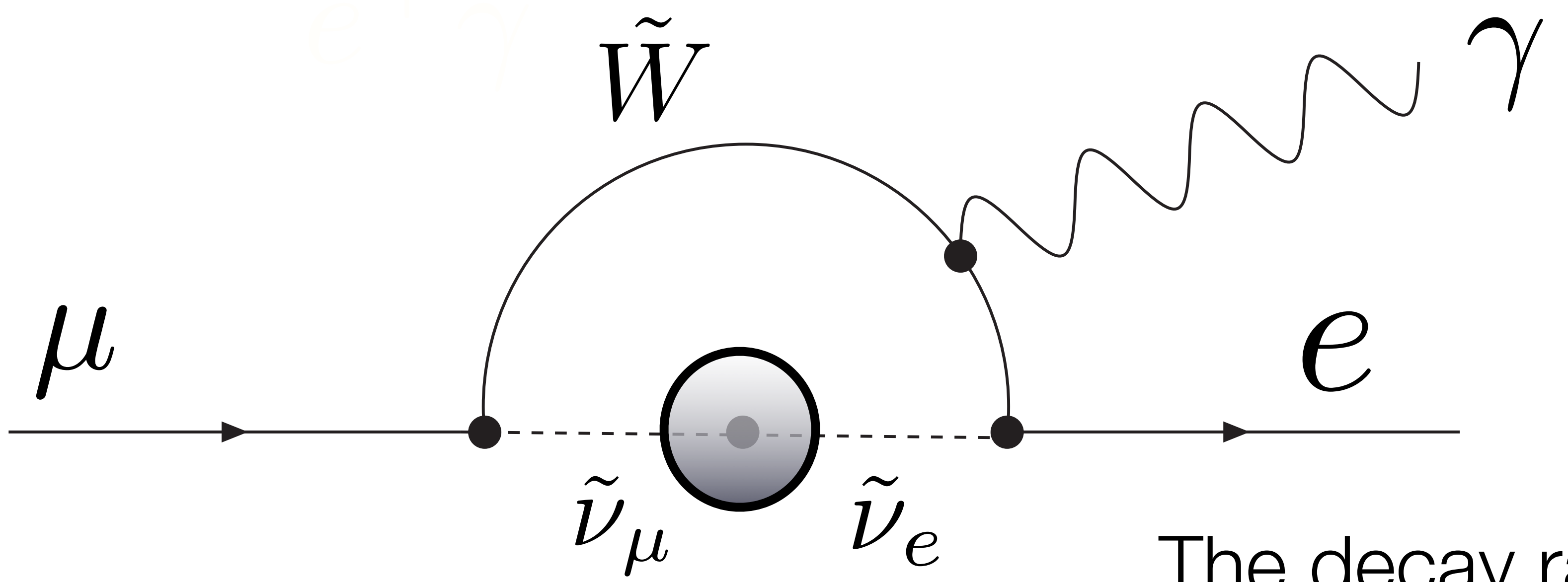


LFV in SUSY Models

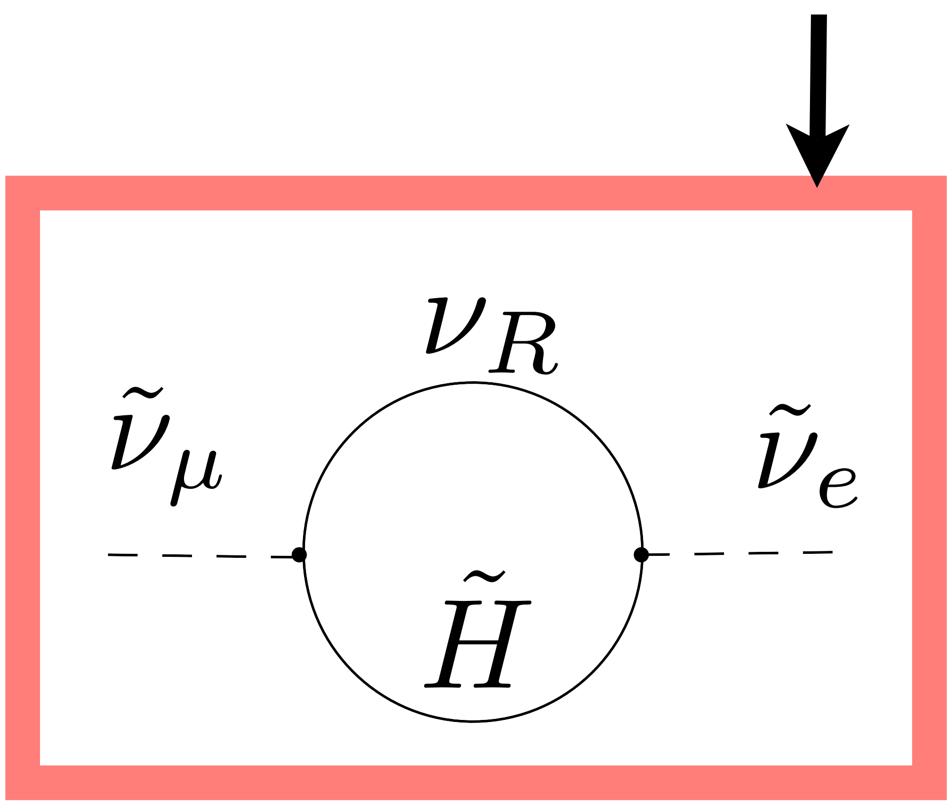
$$\frac{B(\mu N \to eN)}{B(\mu \to e\gamma)} \sim \frac{1}{200}$$

(photon being attached to quarks in nucleons)

an example diagram



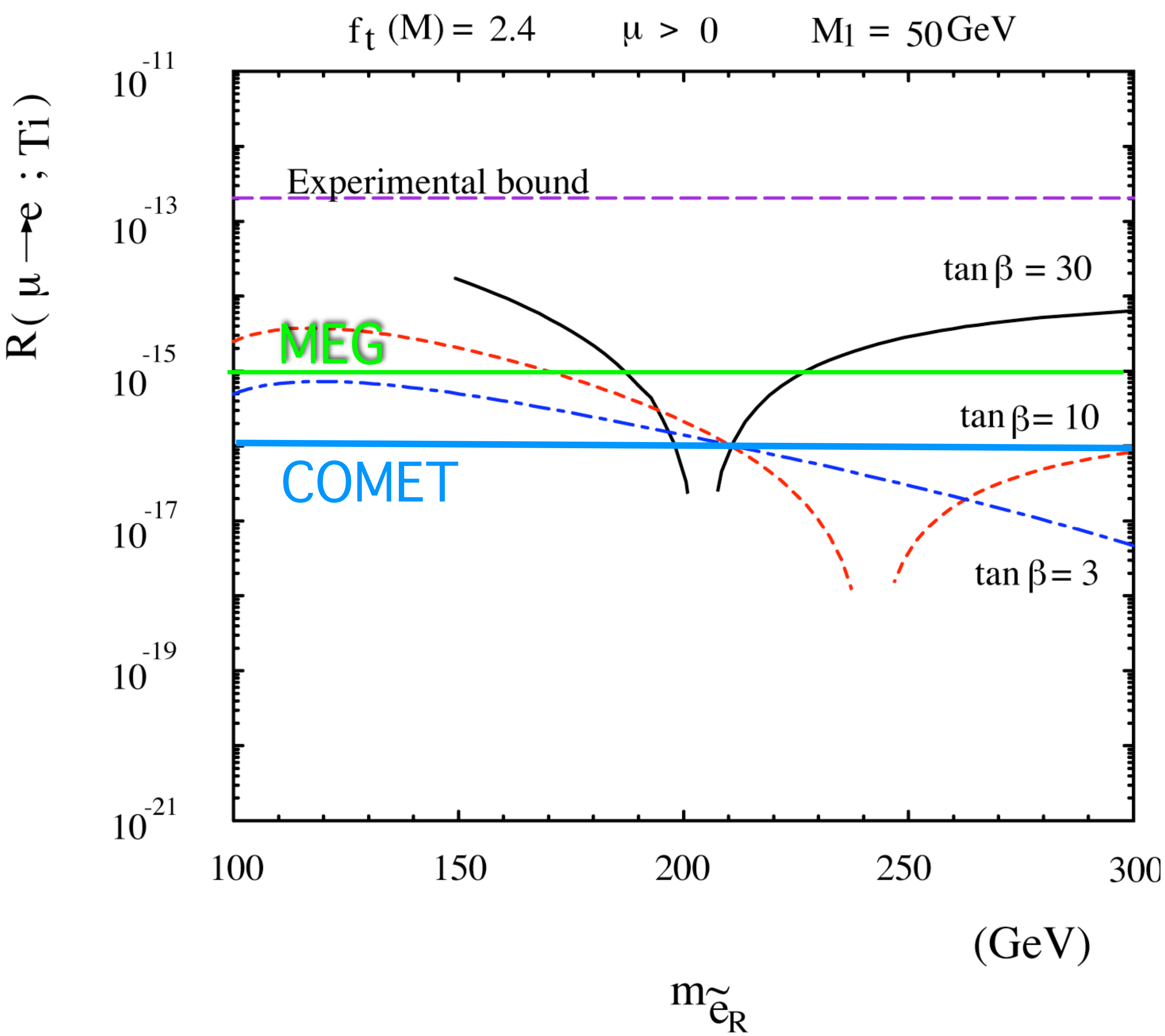
The decay rates is determined by SUSY-mass scale but the dot includes higher energy information.



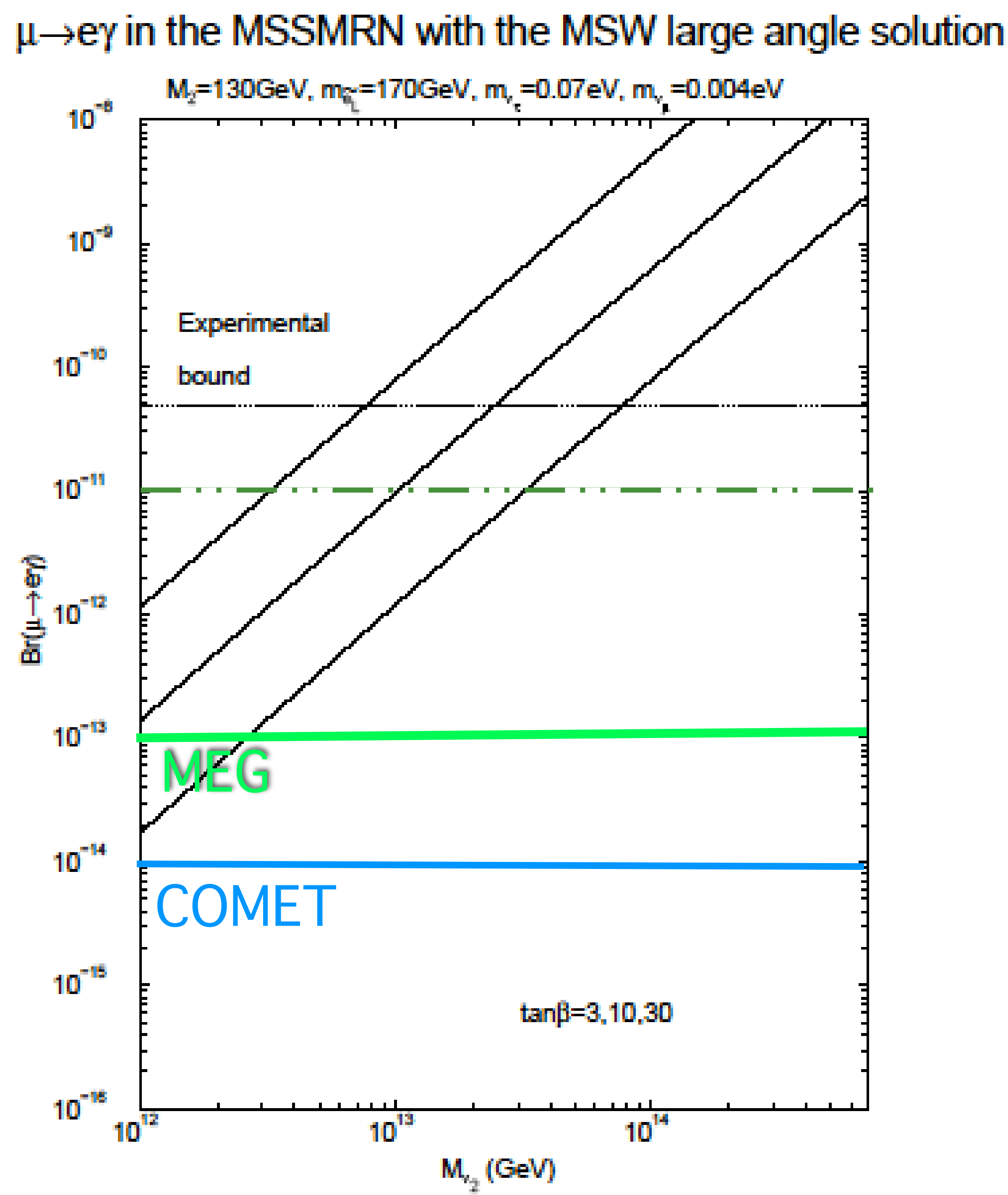
Through quantum corrections, LFV could access ultra-heavy particles such as ν_R (~10^{12}-10^{14} GeV/c^2) and GUT that cannot be produced directly by any accelerators.

SUSY GUT and SUSY Seesaw

SUSY Predictions for LFV with Muons



SU(5) SUSY GUT



SUSY Seesaw Model

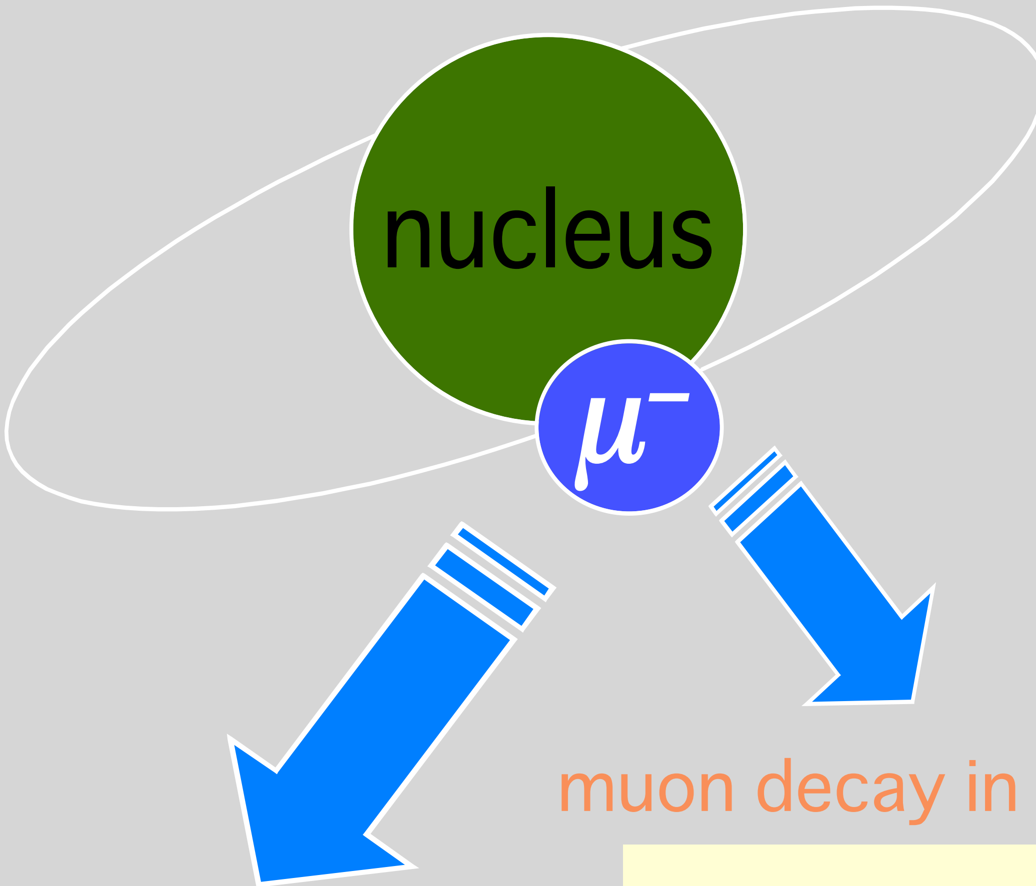
Energy Frontier, SUSY, and Charged Lepton Mixing

- In SUSY models, charged lepton mixing is sensitive to slepton mixing.
- LHC would have potentials to see SUSY particles. However, at LHC nor even ILC, slepton mixing would be hard 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 LFV sensitivity is extremely high, it might be sensitive to multi-TeV SUSY which LHC cannot reach, in particular SUSY models.

μ-e Conversion and Experiments

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.

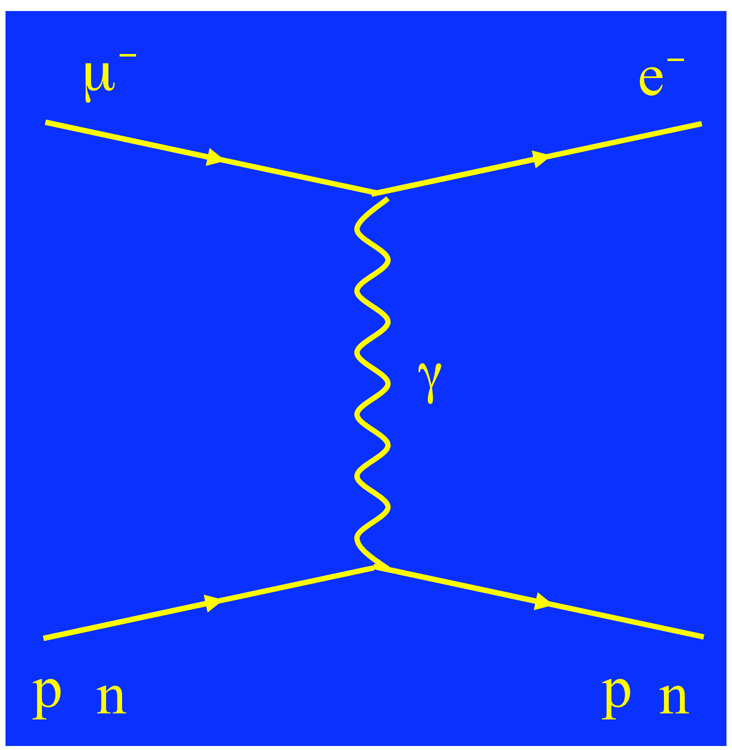
$$B(\mu^- N \rightarrow e^- N) = \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \nu N')}$$

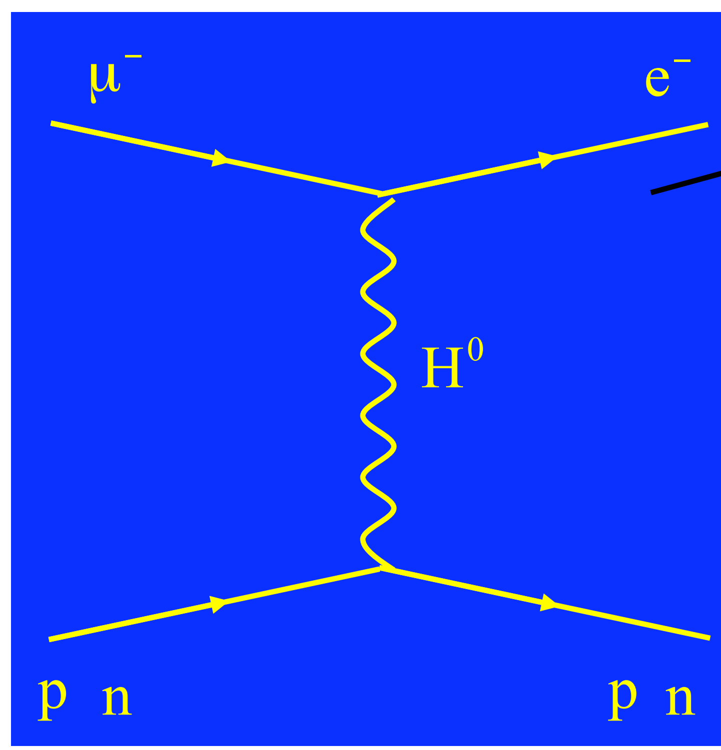
What is a μ-e Conversion ?

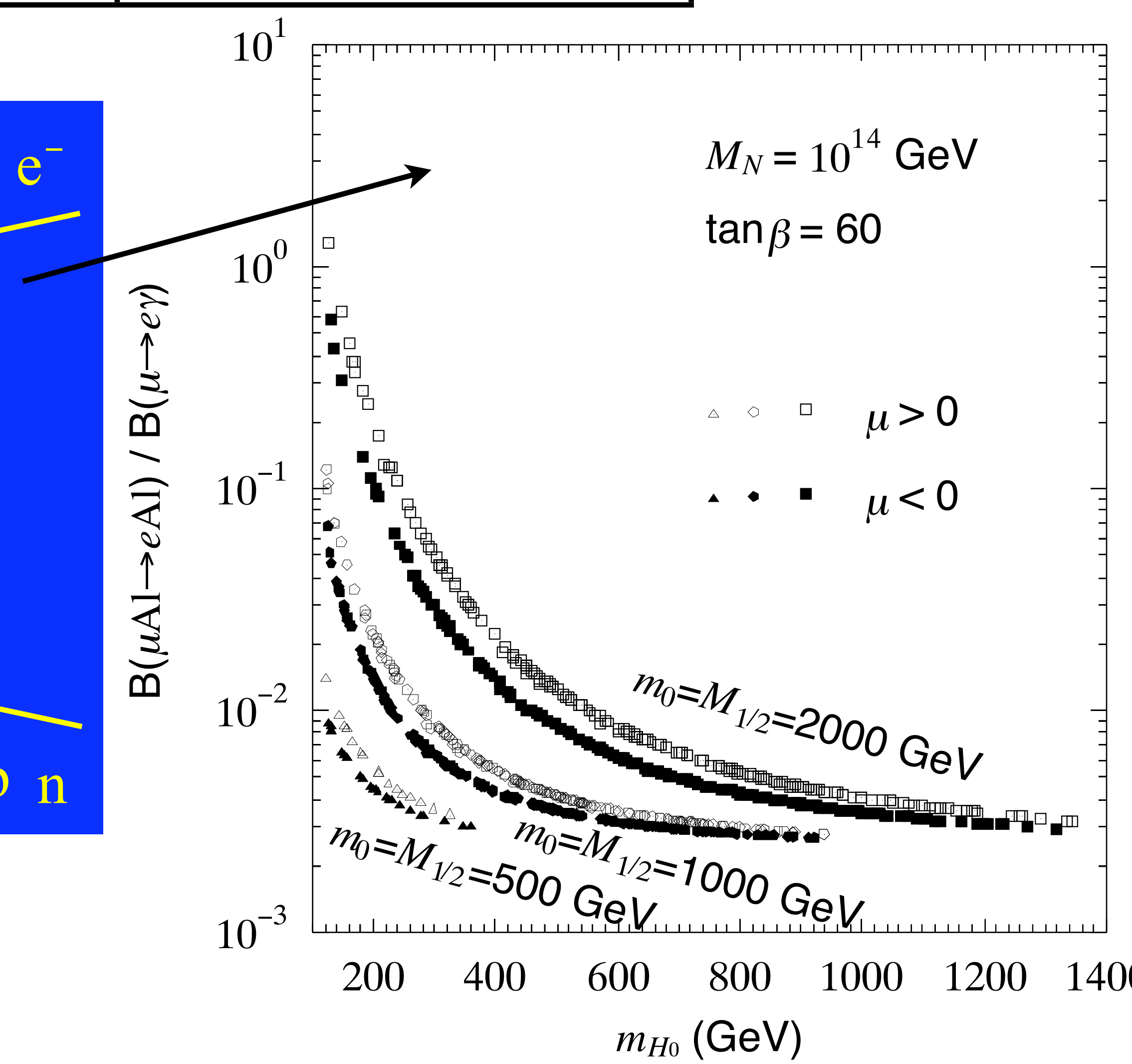
Comparison between
μ→eγ and μ-e Conversion (Physics sensitivity)

Photonic and non-photonic (SUSY) diagrams

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







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

μ-e Conversion
Signal and Backgrounds

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

- Signal
  - single mono-energetic electron

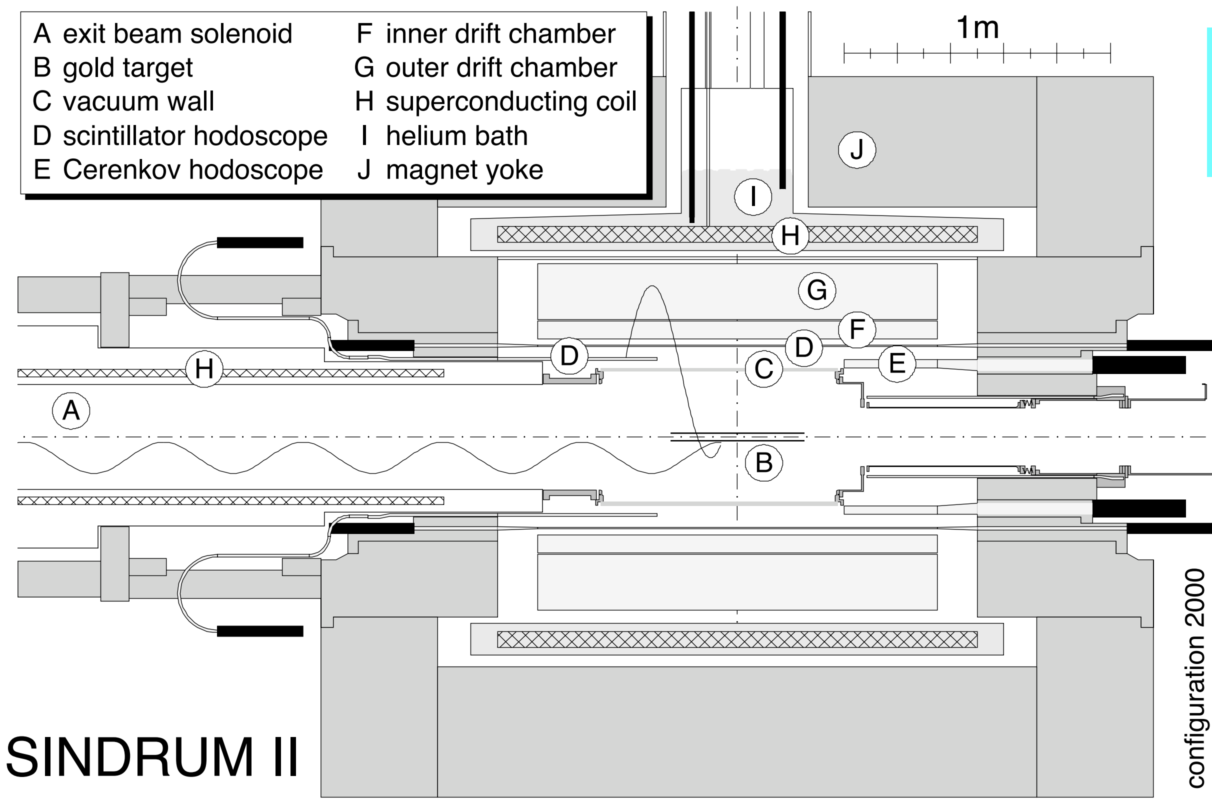
    $$m_\mu - B_\mu \sim 105 MeV$$

  - coherent process (the same initial and final nucleus)

    $$\propto Z^5$$

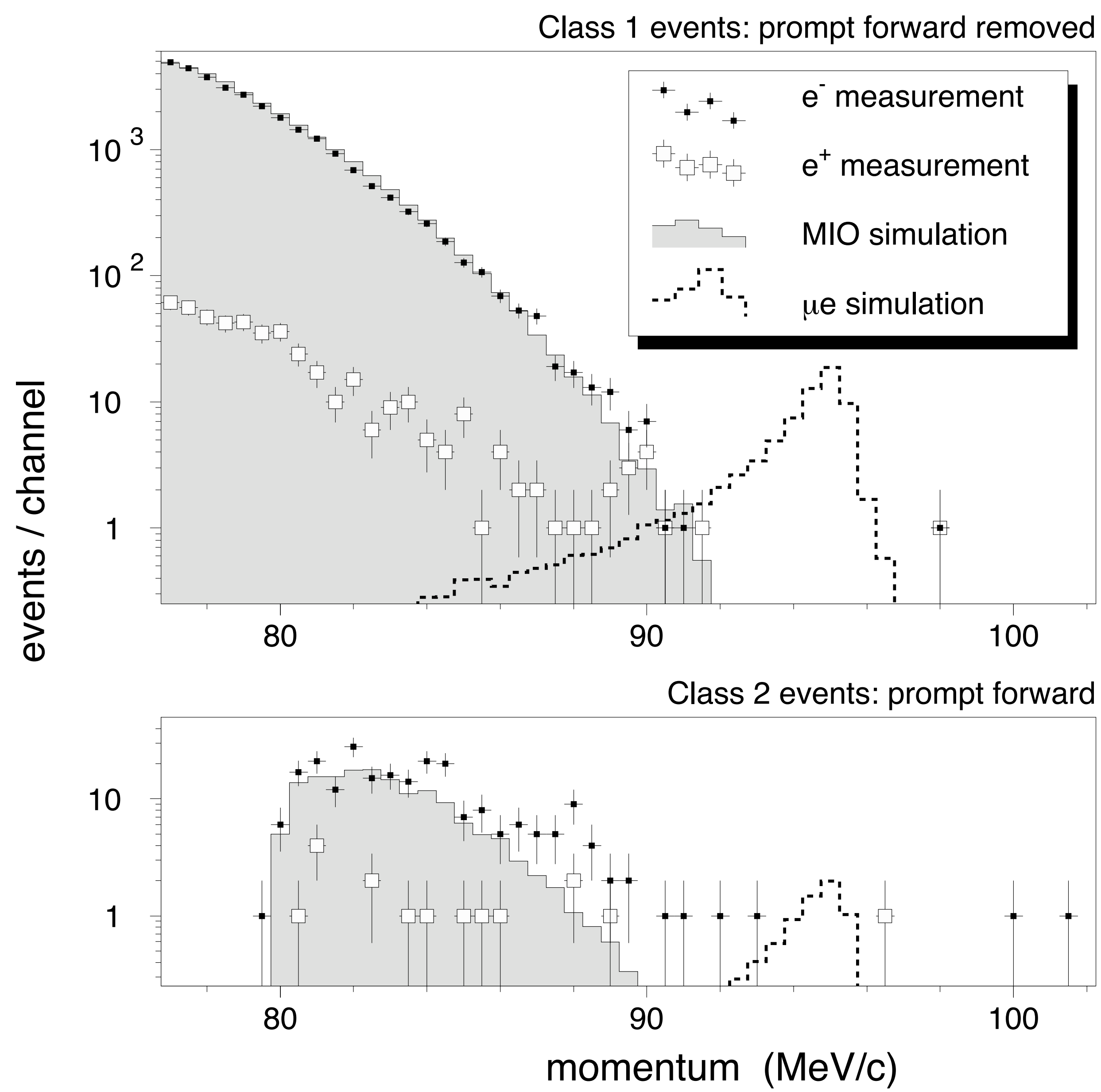
- Backgrounds
  - Muon decay in orbit
    - Endpoint comes to the signal region $\propto (\Delta E)^5$
  - Radiative muon capture
  - Radiative pion capture
    - pulsed beam required
    - wait until pions decay.
  - Electrons from muon decays in flight
  - Cosmic rays
  - and many others

The SINDRUM-II Experiment (at PSI)



Published Results

$$B(\mu^- + Ti \to e^- + Ti) < 4.3 \times 10^{-12}$$



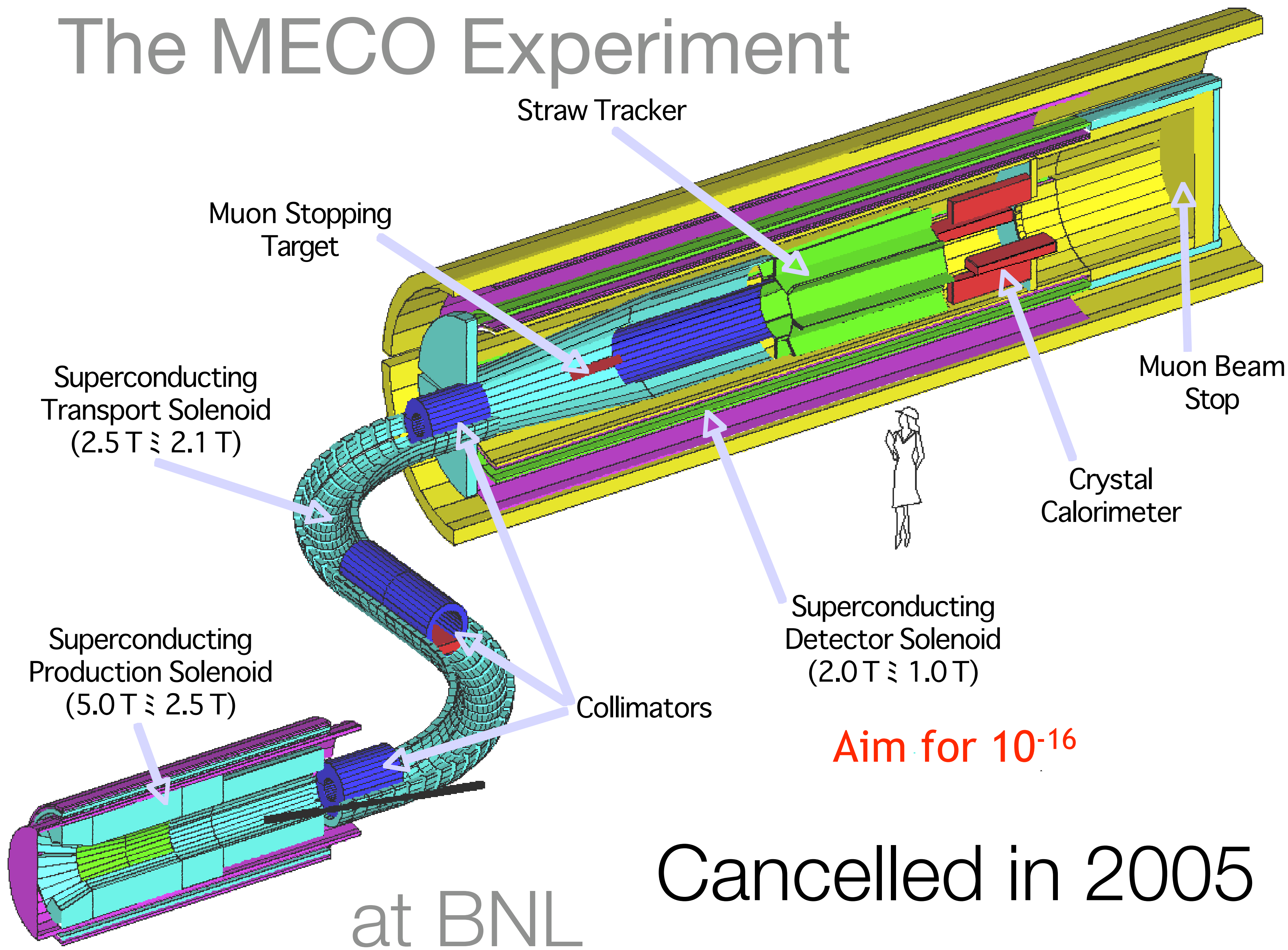
SINDRUM-II used a continuous muon beam from the PSI cyclotron. To eliminate beam related background from a beam, a beam veto counter was placed. But, it could not work at a high rate.

The MELC and MECO Proposals

MELC (Russia) and then MECO (the US)

- To eliminate beam related background, beam pulsing was adopted (with delayed measurement).
- To increase a number of muons available, pion capture with a high solenoidal field was adopted.
- For momentum selection, curved solenoid was adopted.

The MECO Experiment



at BNL

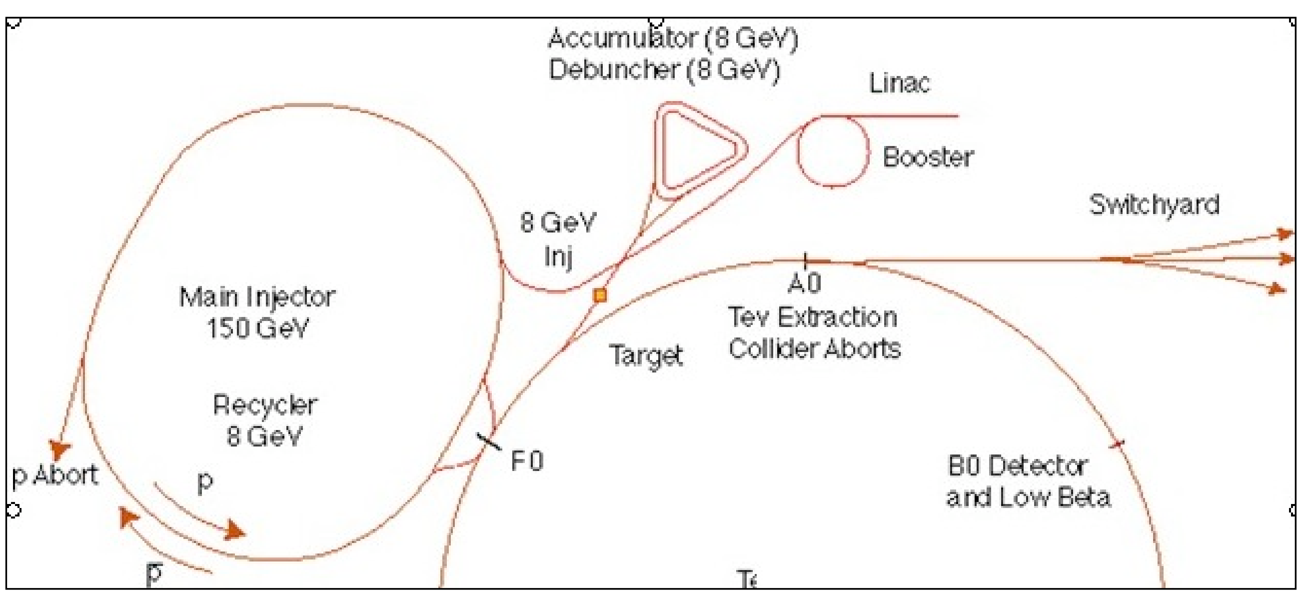
Aim for 10^{-16}

Cancelled in 2005

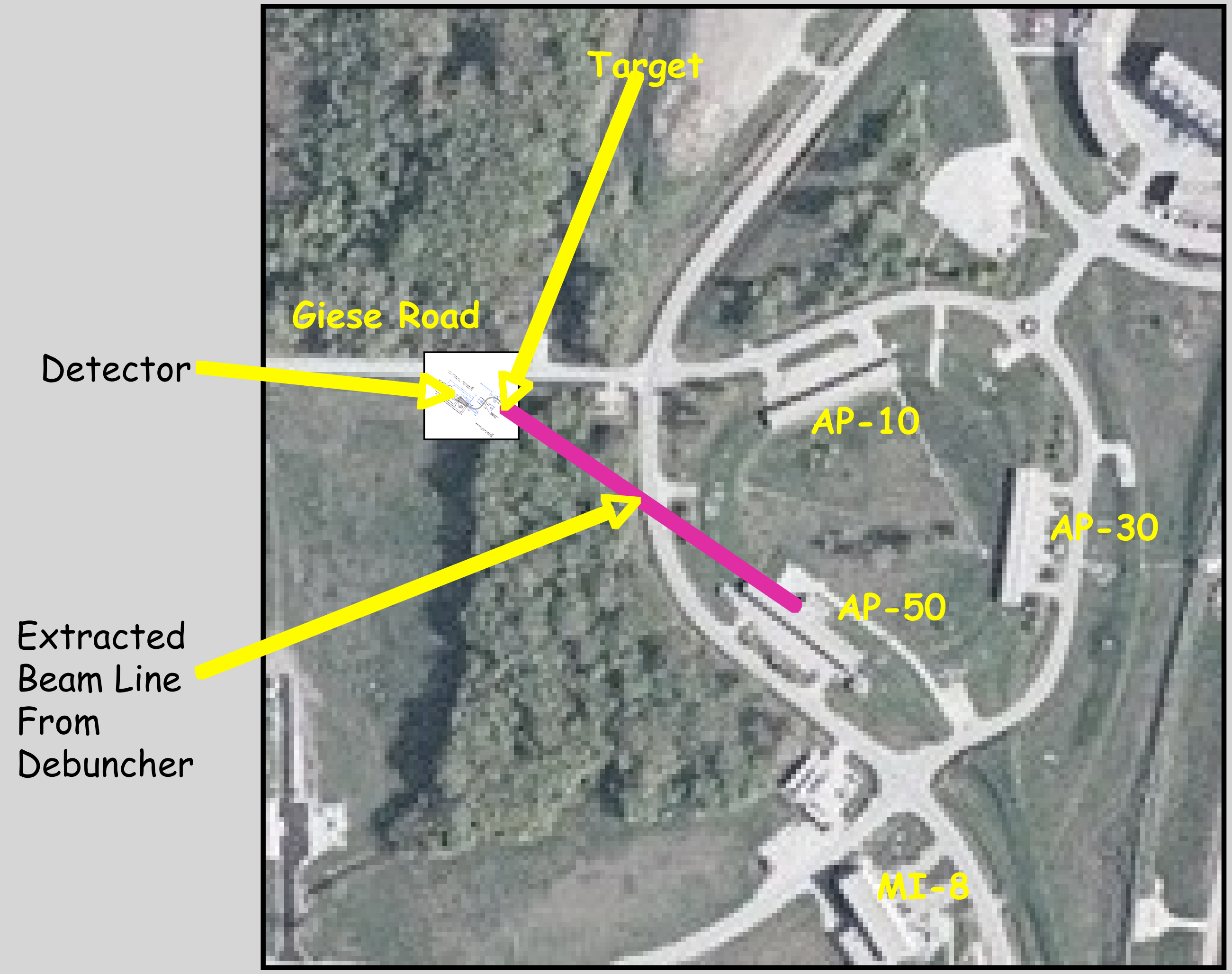
→mu2e @ Fermilab

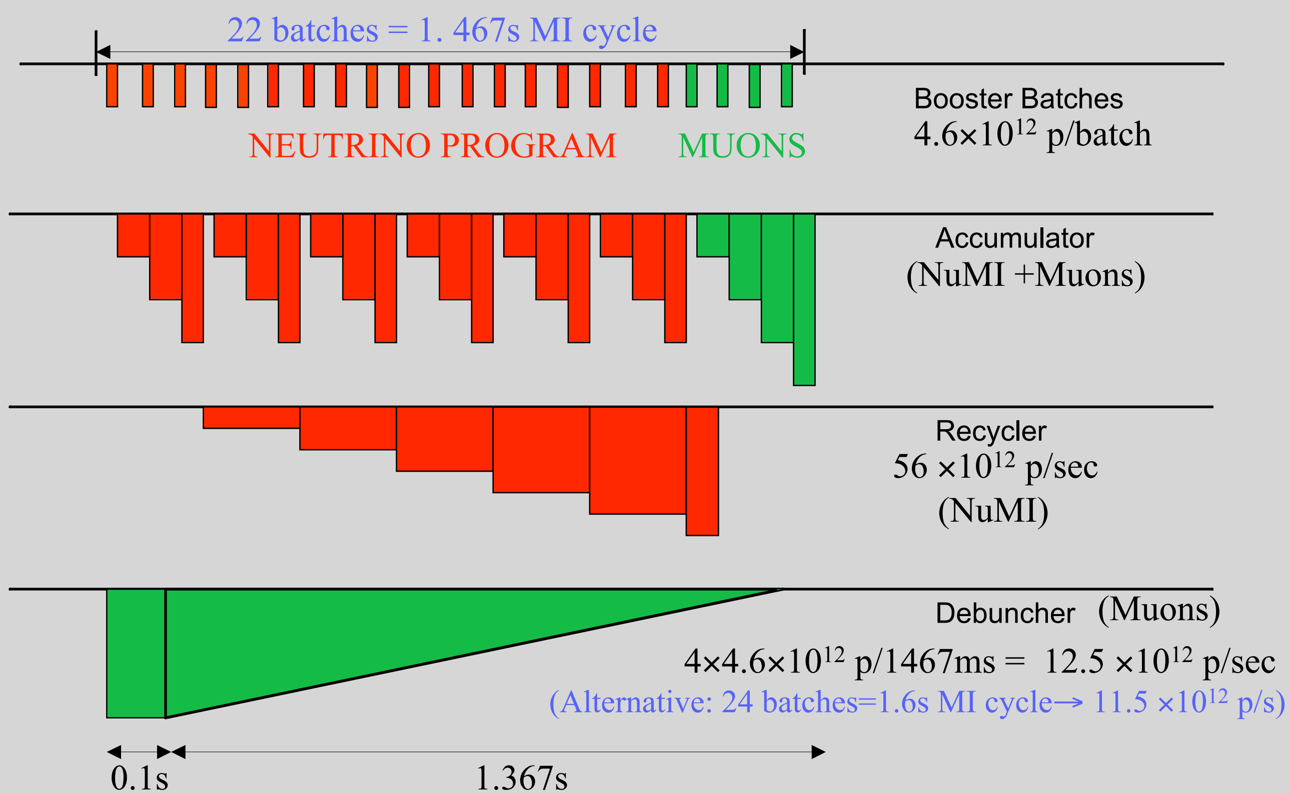
Mu2E @ Fermilab

- The mu2e Experiment at Fermilab.
  - EOI and LOI have been submitted. It is well accepted.
  - After the Tevatron shut-down.
  - use the antiproton accumulator ring and the debuncher ring to manipulate proton beam bunches.
  - running with Nova.
  - with Project-X in future.

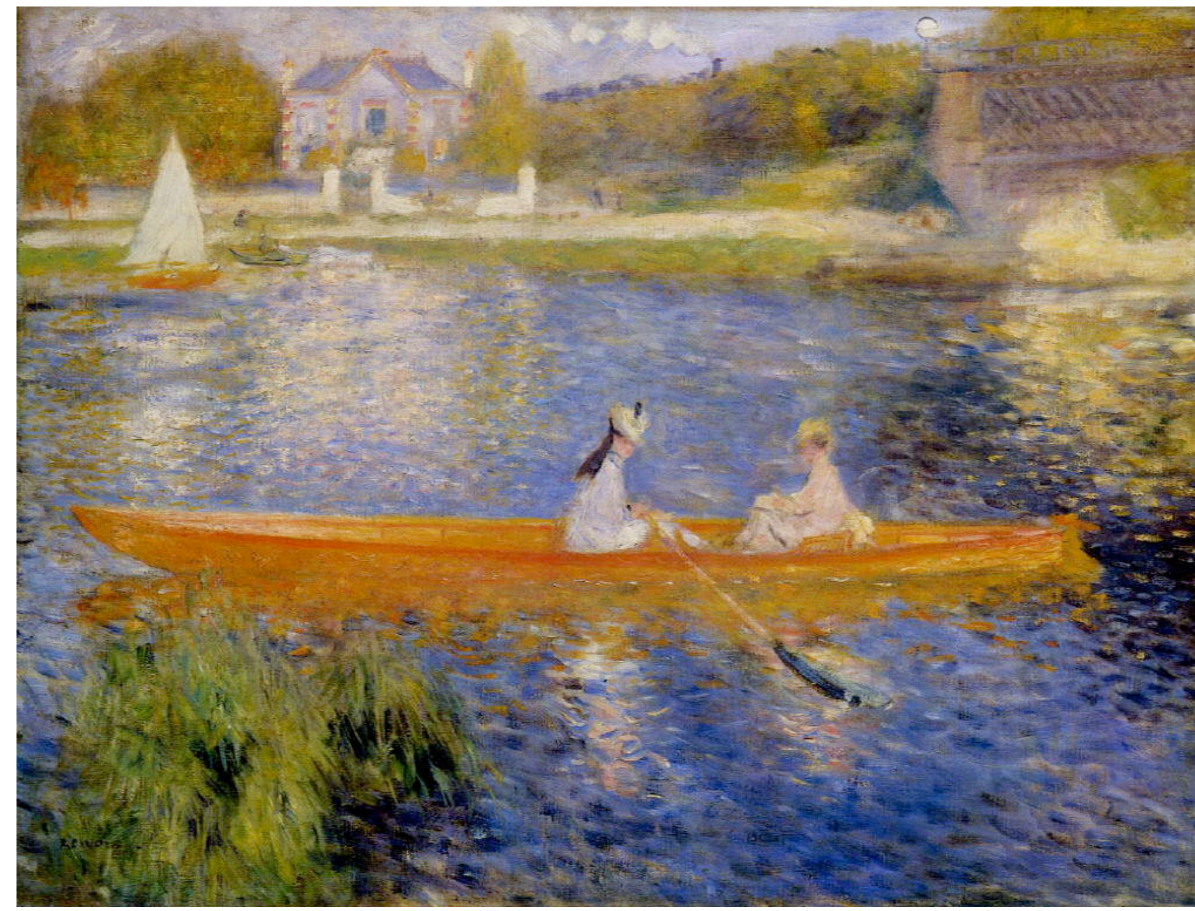


Fermilab Accelerators

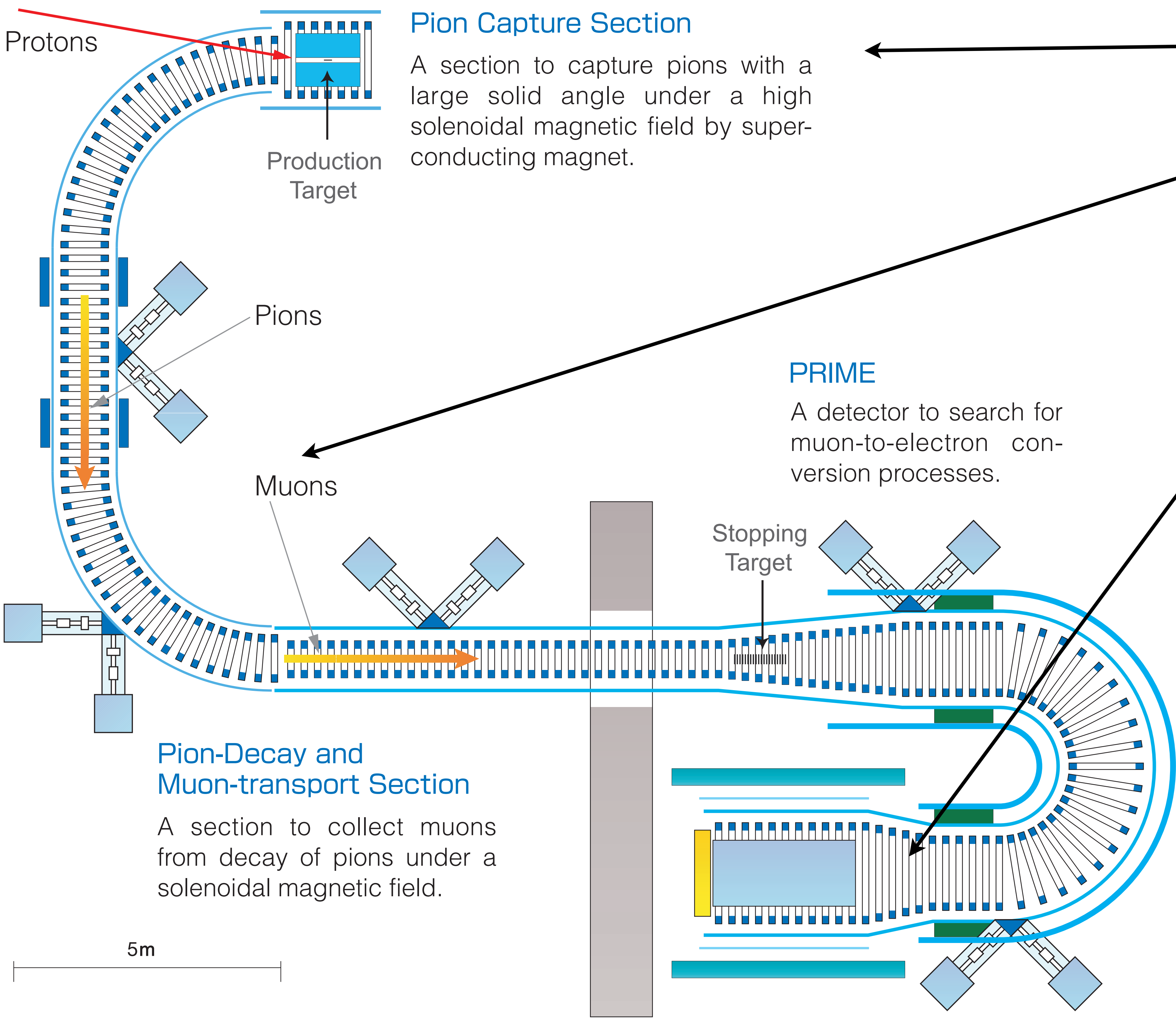




New Experimental Proposal at J-PARC



Overview of the COMET Experiment (COherent Muon to Electron Transition)



Proton Beam

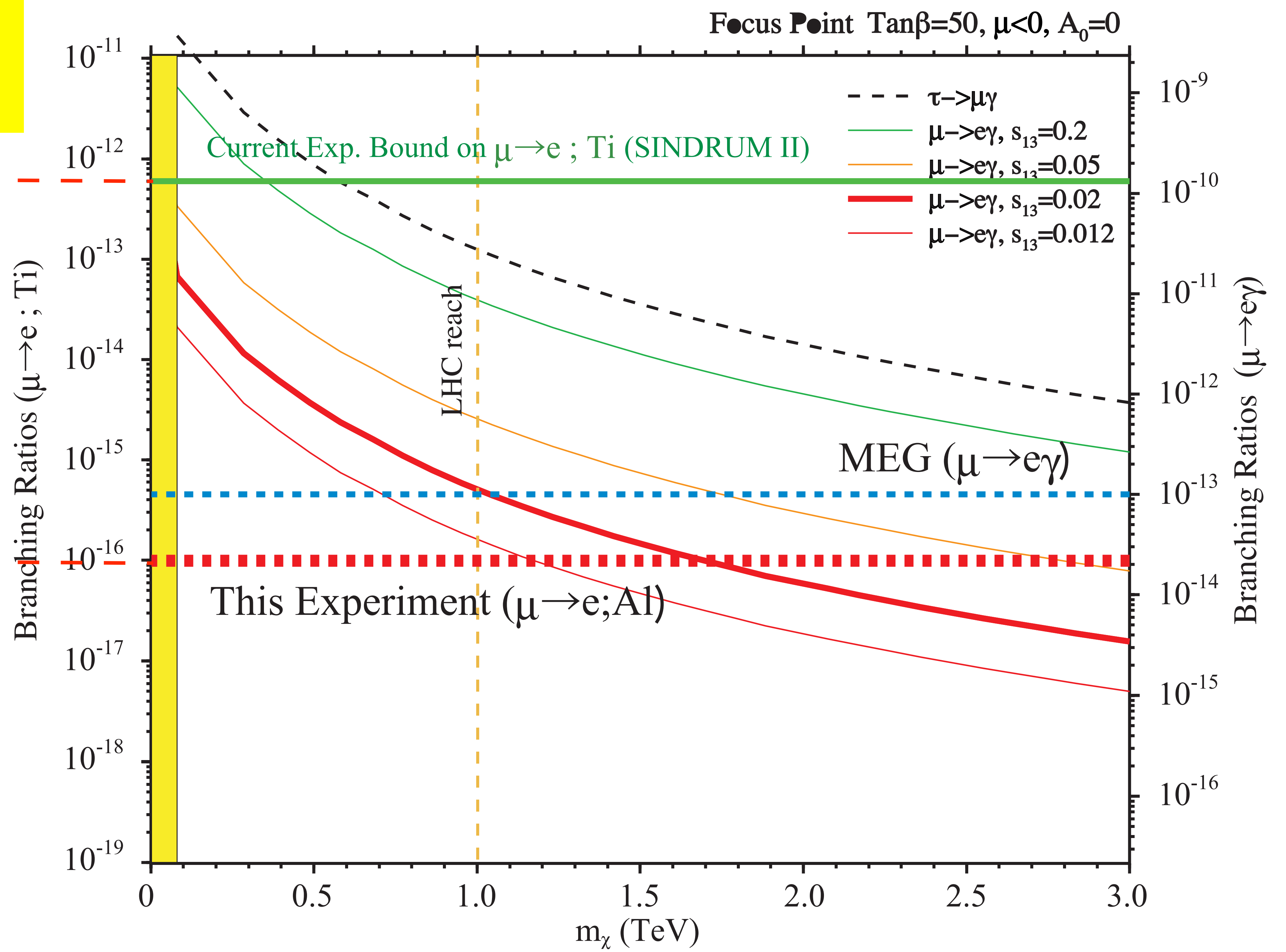
The Muon Source
- Proton Target
- Pion Capture
- Muon Transport

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

The beamline design is very important.

SUSY-Seesaw Model
(SUSY-GUT SO(10))
Prediction

will be improved by a factor of 10,000.



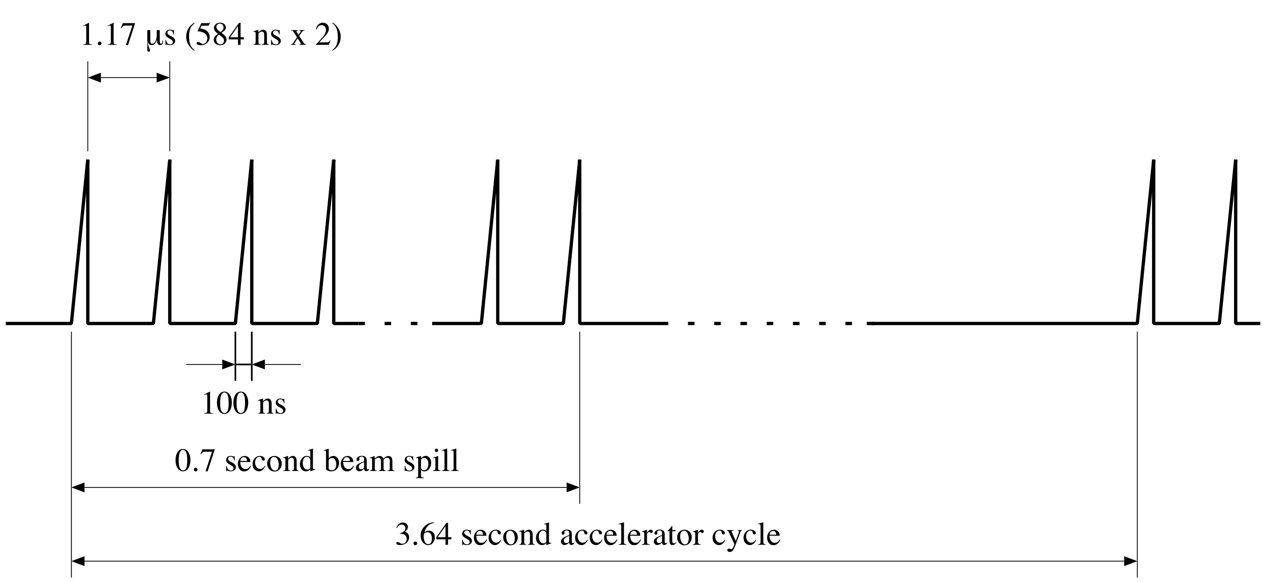
Sensitivity Goal

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

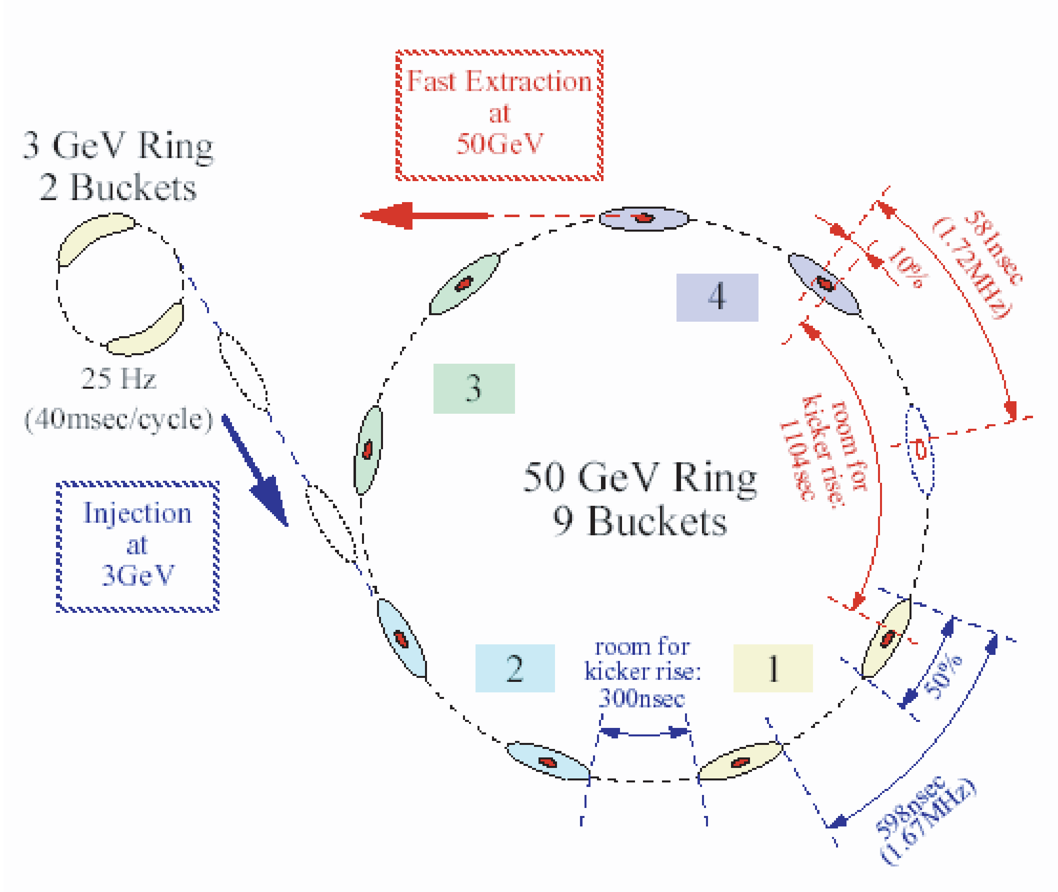
The Muon Source

Proton Beam (1)

- A pulsed proton beam is needed to reject beam-related prompt background.
  - Detection will be made between pulses (delayed measurement).
- Time structure required for proton beams.
  - Pulse separation is ~ 1μsec or more (muon lifetime).
  - Narrow pulse width (<100 nsec)

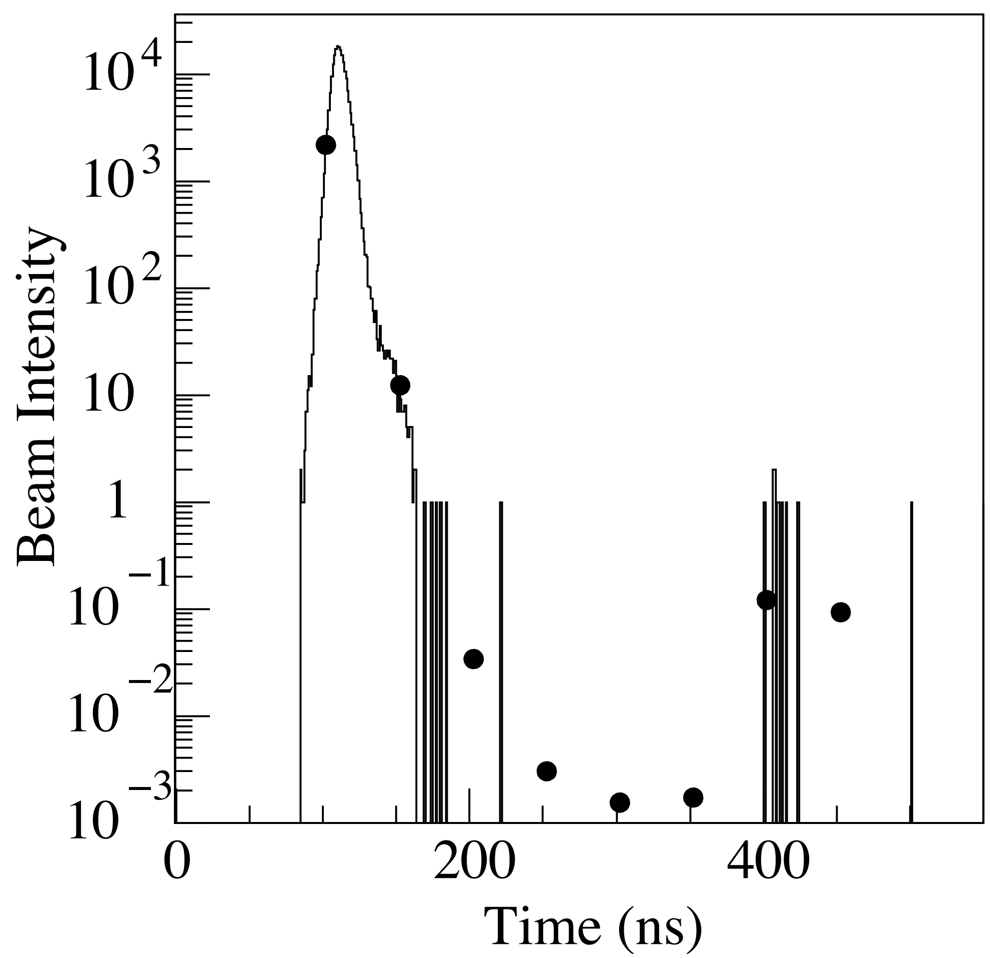


- Pulsed beam from slow extraction.
  - fill every other rf buckets with protons and make slow extraction with keeping bunches
  - spill length (flat top) ~ 0.7 sec
    - good to be shorter for cosmic-ray backgrounds.



Proton Beam (2) - 2 SSC years

- Proton Extinction :
  - (delayed)/(prompt)<10^{-9}
  - Test done at BNL-AGS gave 10^{-7} (shown below).
  - Extra extinction devices are needed.

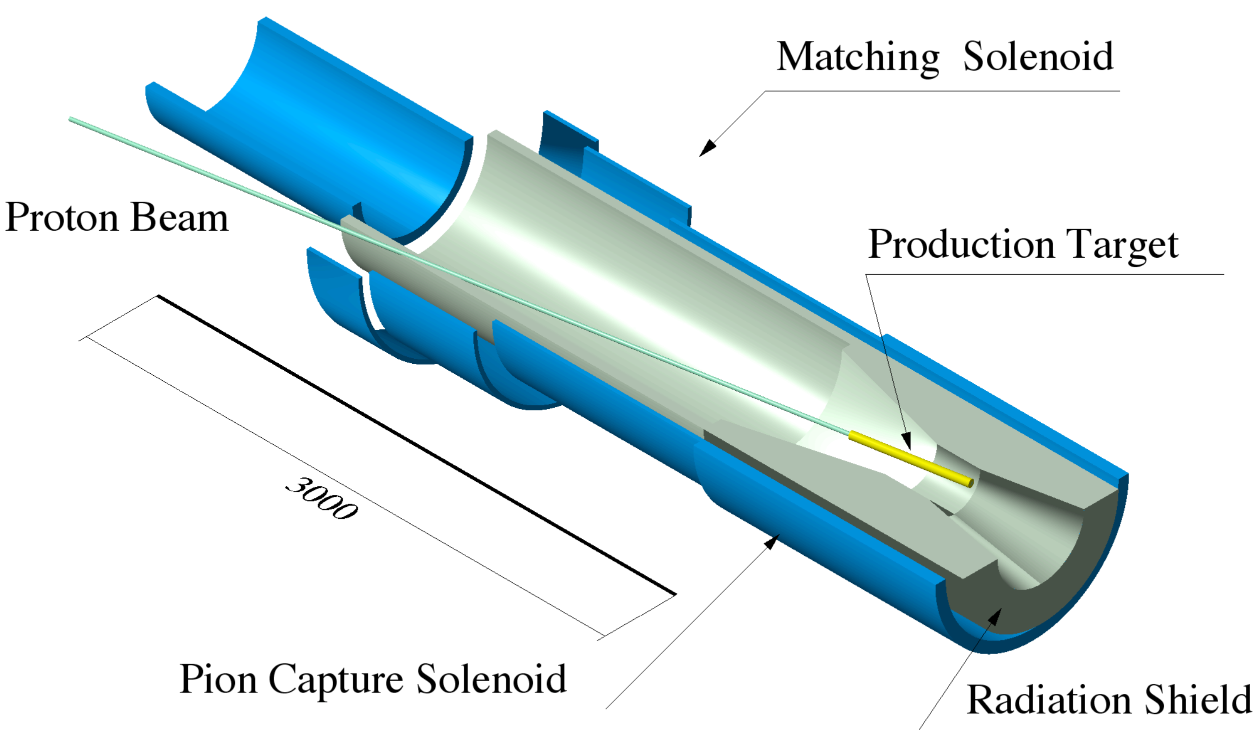


Test of Extinction at BNL-AGS

- Required Protons :
  - 8 x 10^{20} protons of 8 GeV in total for a single event sensitivity of about 0.3 x 10^{-16}.
  - For 2 x 10^7 sec running, 4 x 10^{13} protons /sec (= 7 μA).
  - A total beam power is 56 kW, which is about 1/8 of the J-PARC full beam power of 450 kW (30 GeV x 15μA).

Pion Capture

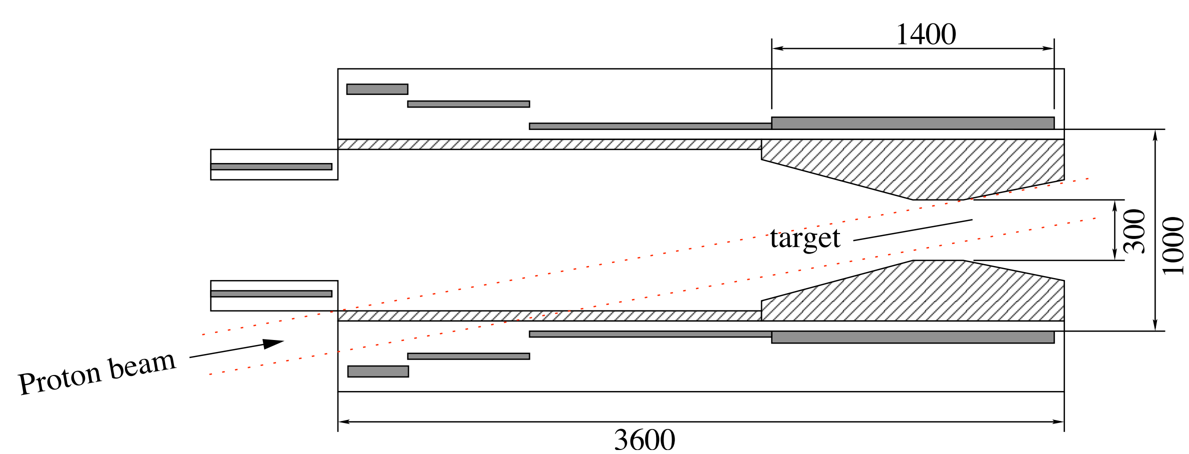
- A large muon yield can be achieved by large solid angle pion capture by a high solenoid field, which is produced by solenoid magnets surrounding the proton target.



$$P_T(GeV/c) = 0.3 \times B(T) \times (\frac{R(m)}{2})$$

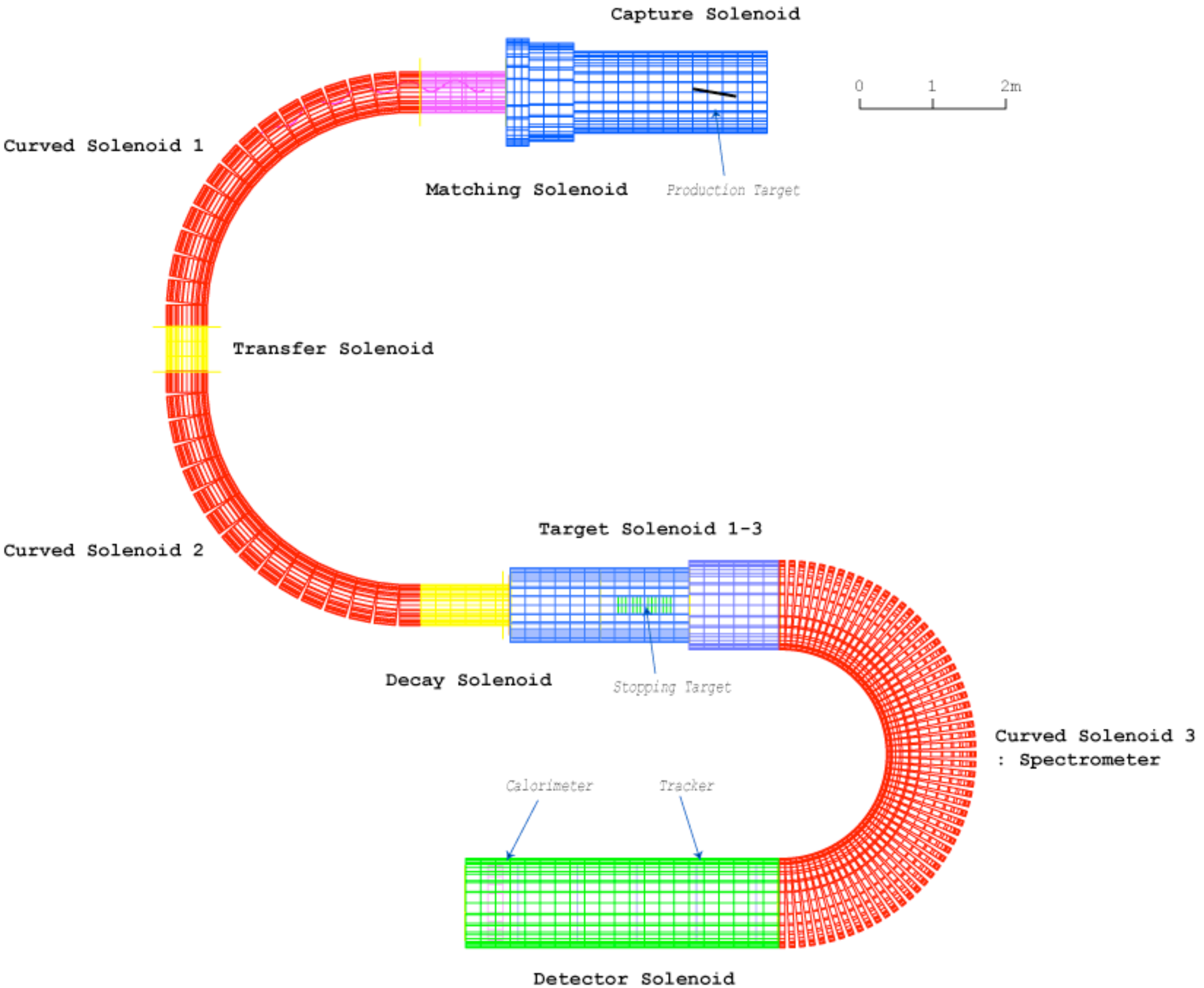
  - B=5T,R=0.2m, P_T=150MeV/c.

- Superconducting Solenoid Magnet for pion capture
  - 15 cm radius bore
  - a 5 tesla solenoidal field
  - 30 cm thick tungsten radiation shield
  - heat load from radiation
  - a large stored energy



Muon Transport Beamline

- Muons are transported from the capture section to the detector by the muon transport beamline.
- Requirements :
  - long enough for pions to decay to muons (> 20 meters ≈ 2×10^{-3}).
  - high transport efficiency (P_μ~40 MeV/c)
  - negative charge selection
  - low momentum selection (P_μ<75 MeV/c)
- Straight + curved solenoid transport system is adopted.



Charged Particle Trajectory in Curved Solenoids

- A center of helical trajectory of charged particles in a curved solenoidal field is drifted by

$$D = \frac{p}{qB}\theta_{bend}\frac{1}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$

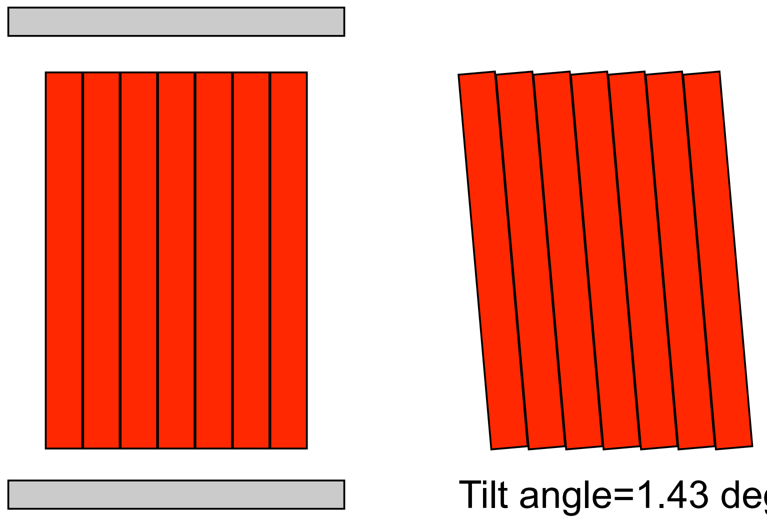
D : drift distance
B : Solenoid field
θ_{bend} : Bending angle of the solenoid channel
p : Momentum of the particle
q : Charge of the particle
θ : atan(P_T/P_L)

  - This effect can be used for charge and momentum selection.

- This drift can be compensated by an auxiliary field parallel to the drift direction given by

$$B_{comp} = \frac{p}{qr}\frac{1}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$

p : Momentum of the particle
q : Charge of the particle
r : Major radius of the solenoid
θ : atan(P_T/P_L)



Tilt angle=1.43 deg.

Spectra at the End of the Muon Transport

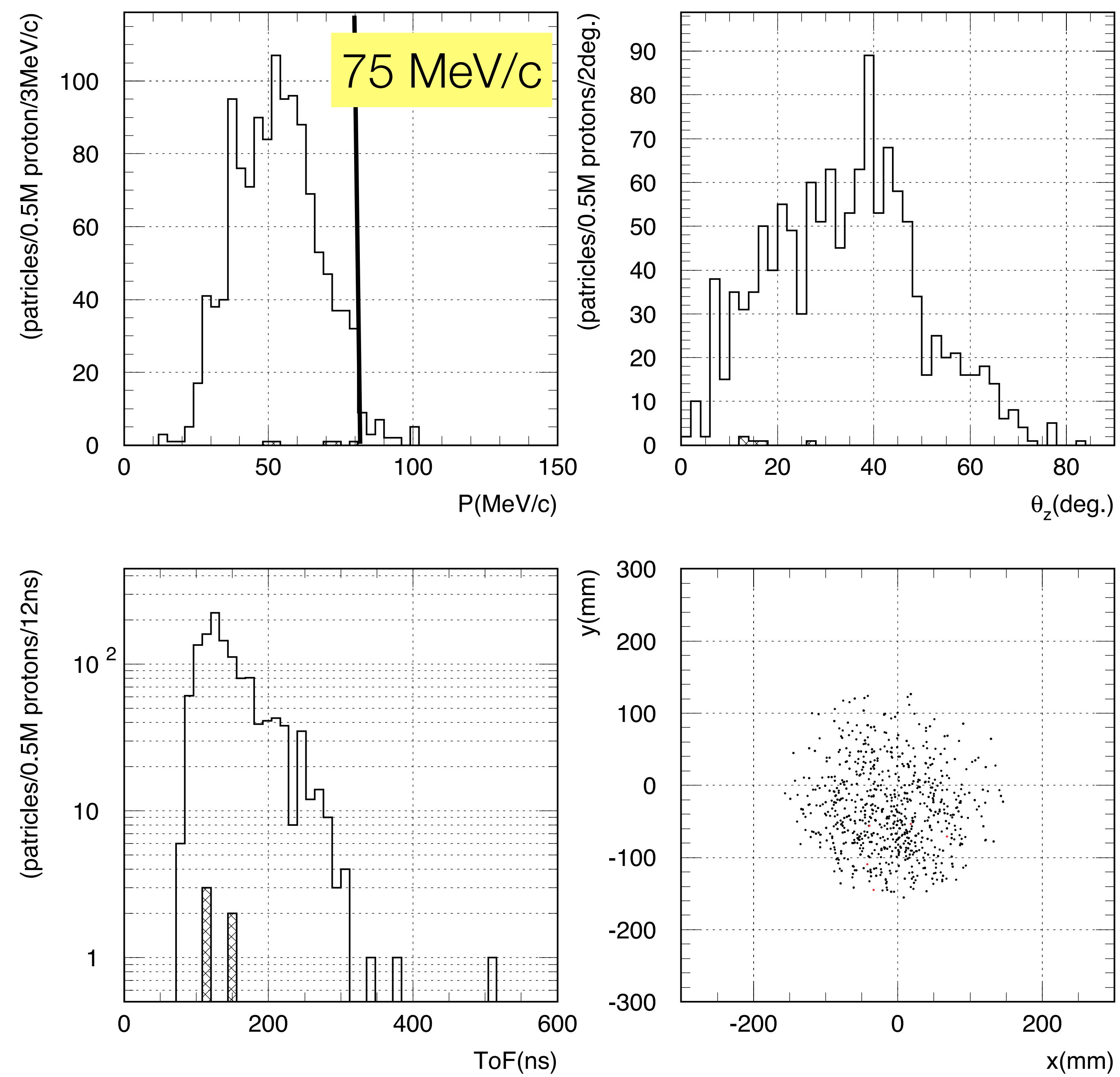
- Preliminary beamline design
  - main magnetic field
  - compensation field
  - radius of magnets (200 mm)

- Transport Efficiency

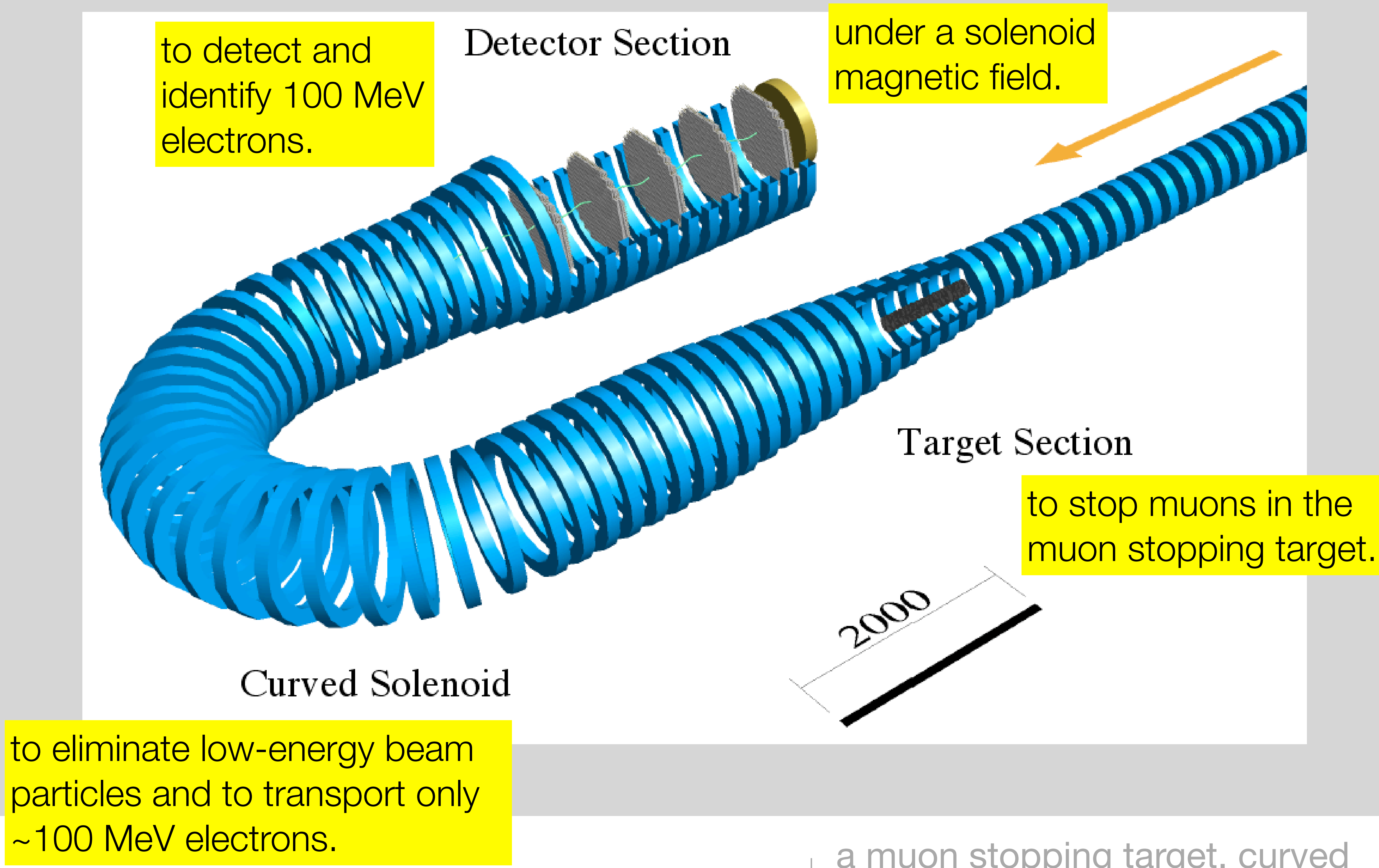
# of muons /proton	0.0071
# of stopped muons /proton	0.0018
# of muons of p_μ >75 MeV/c /proton	2×10^{-4}

Spectra at the end of the beamline

(top left) total momentum
(top right) direction angles to beam axis
(bottom left) time of flight
(bottom right) beam profile
muons for open histograms, pions for hatched histograms.



The Detector



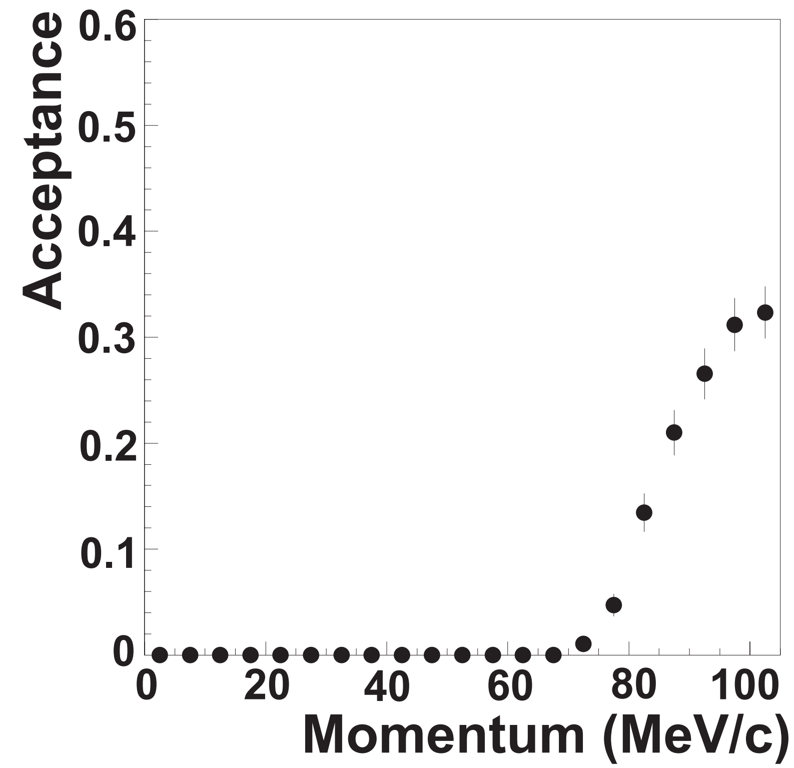
Detector Components

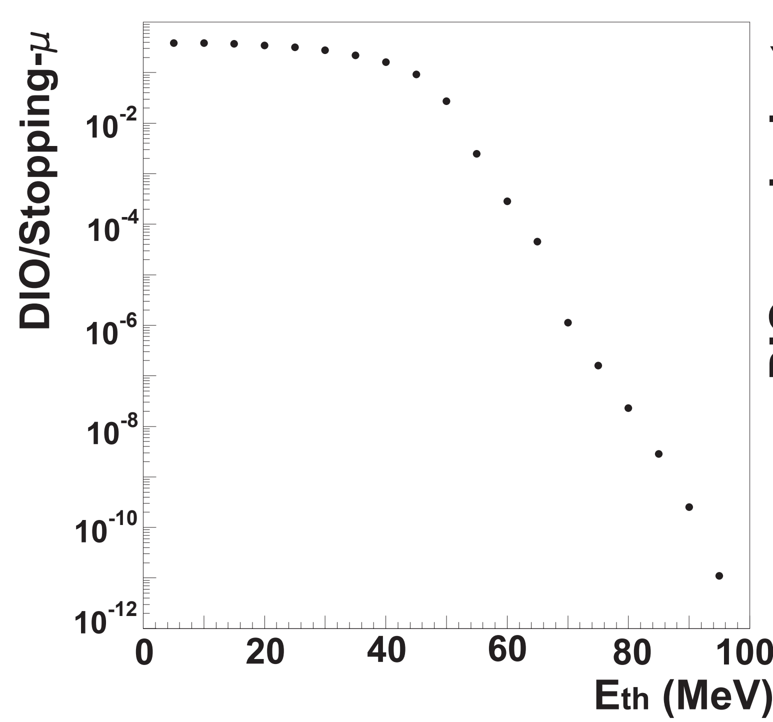
a muon stopping target, curved solenoid,tracking chambers, and a calorimeter/trigger and cosmic-ray shields.

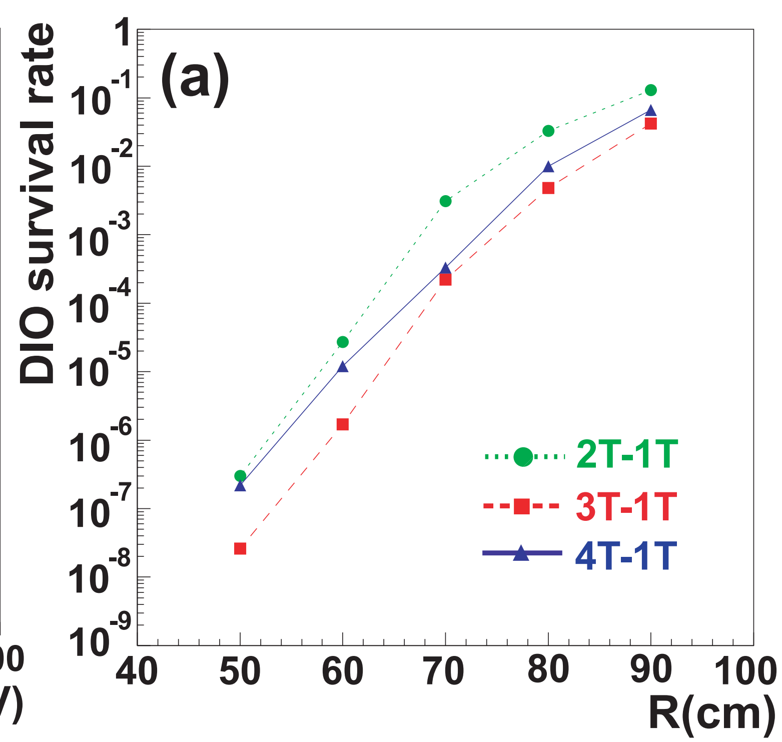
Transmission of the Electron Transport

- Electron Transport System Parameters (preliminary)
  - Radius : 50 cm
  - Magnetic field : 1 Tesla
  - Bending angle : 180 degrees
- Geometrical Acceptance
  - Solid angel at the target : 0.73
    - mirror effect at a graded field
  - Transport efficiency : 0.44
  - Total : 0.32
- Suppression of electrons from decay in orbit.
  - about 10^{-8} suppression
  - about 1000 tracks / sec for 10^{11} stopping muons.

Ratio of a number of electrons reaching the end of transport to all electrons emitted in 4π.





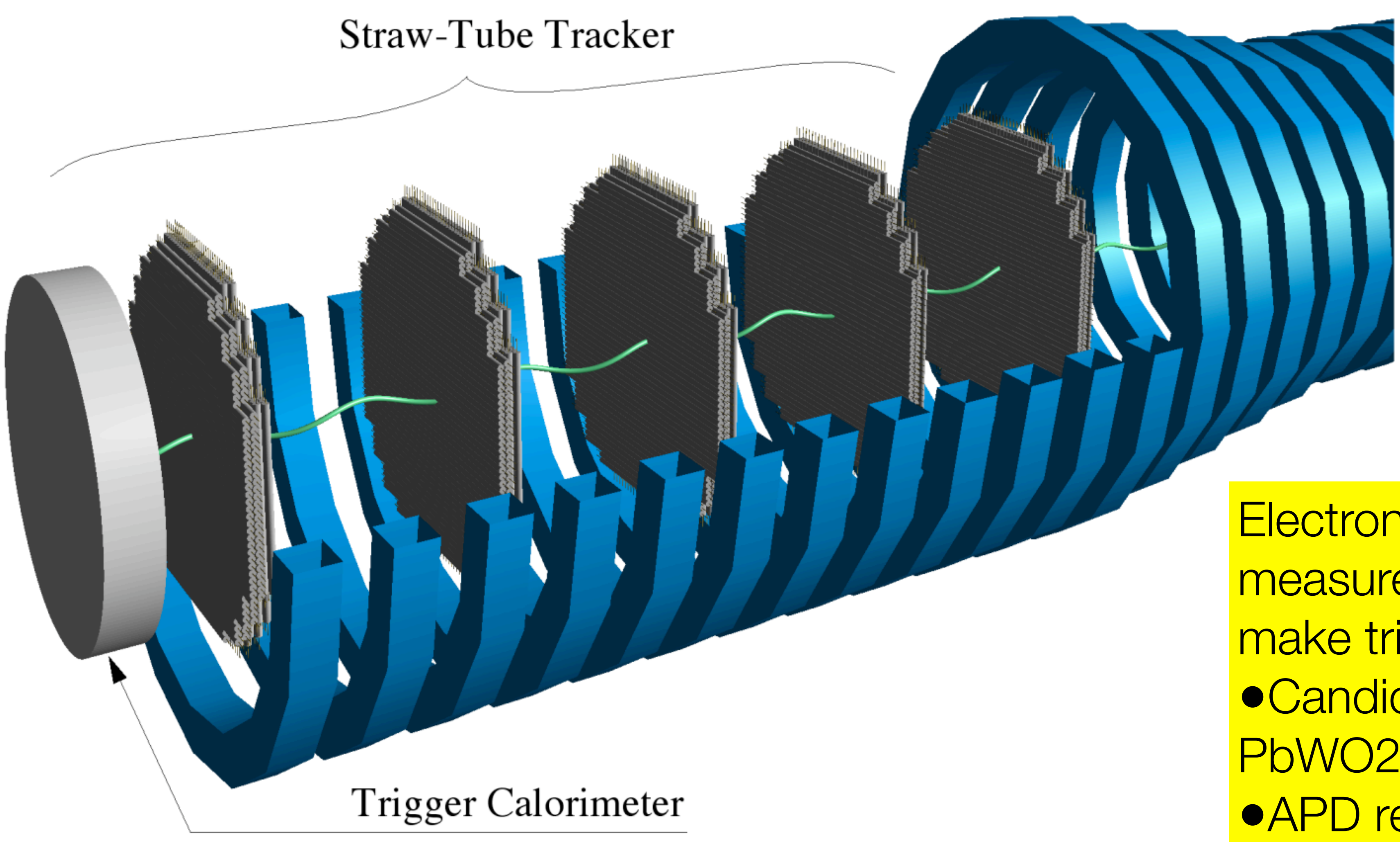


Electron Detection (preliminary)

Straw-tube Trackers to measure electron momentum.
- should work in vacuum and under a magnetic field.
- A straw tube has 25μm thick, 5 mm diameter.
- One plane has 2 views (x and y) with 2 layers per view.
- Five planes are placed with 48 cm distance.
- 250μm position resolution.

Under a solenoidal magnetic field of 1 Tesla.

In vacuum to reduce multiple scattering.

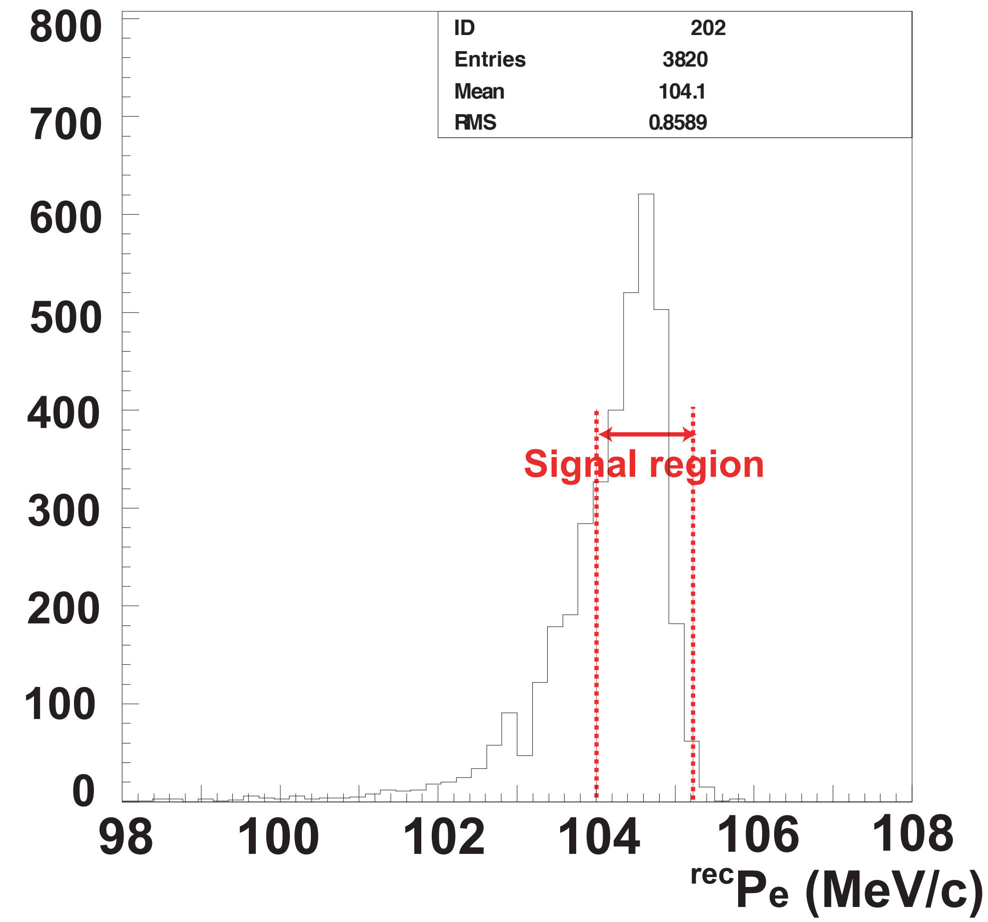


Electron calorimeter to measure electron energy and make triggers.
- Candidate are GSO or PbWO2.
- APD readout (no PMT).

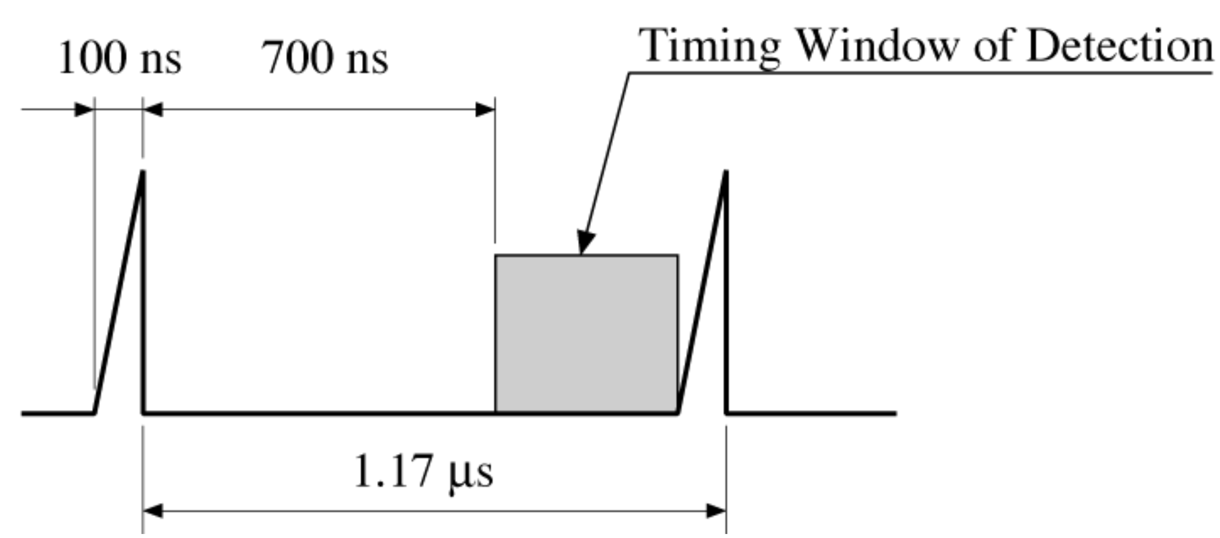
Signal Acceptance

- The signal acceptance is given by the geometrical acceptance of the detector and the analysis (cut) acceptance.

Items	Acceptance
geometrical	
solid angle at target	0.73
transport efficiency	0.44
analysis	
p_t > 52 MeV/c cut	0.67
chi2 cut	0.86
energy cut	0.56
time window cut	0.38
total	0.04



signal energy window (104.0-105.2 MeV in uncorrected energy scale)



Sensitivity and Backgrounds

Signal Sensitivity (preliminary) - 2 SSC years

- Single event sensitivity

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

Tungsten target &
beam line optimzation
→ improvement of x2.7

  - N_μ is a number of stopping muons in the muon stopping target. It is $1.5\text{x}10^{18}$ 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	$8\text{x}10^{20}$
muon transport efficiency	0.0071
muon stopping efficiency	0.26
# of stopped muons	$1.5\text{x}10^{18}$

$$B(\mu^- + Al \to e^- + Al) = \frac{1}{1.5 \times 10^{18} \times 0.6 \times 0.04} = 2.8 \times 10^{-17}$$

$$B(\mu^- + Al \to e^- + Al) < 5 \times 10^{-17} \quad (90\% \text{ C.L.})$$

Potential Background Events

- Background rejection is the most important in searches for rare decays.
- Types of backgrounds for $\mu^- + N \rightarrow e^- + N$ are,

Intrinsic backgrounds	originate from muons stopping in the muon stopping target.	•muon decay in orbit •radiative muon capture •muon capture with particle emission
Beam-related backgrounds	caused by beam particles, such as electrons, pions, muons, and anti-protons in a beam	•radiative pion capture •muon decay in flight •pion decay in flight •beam electrons •neutron induced •antiproton induced
Other backgrounds	caused by cosmic rays	•cosmic-ray induced •pattern recognition error

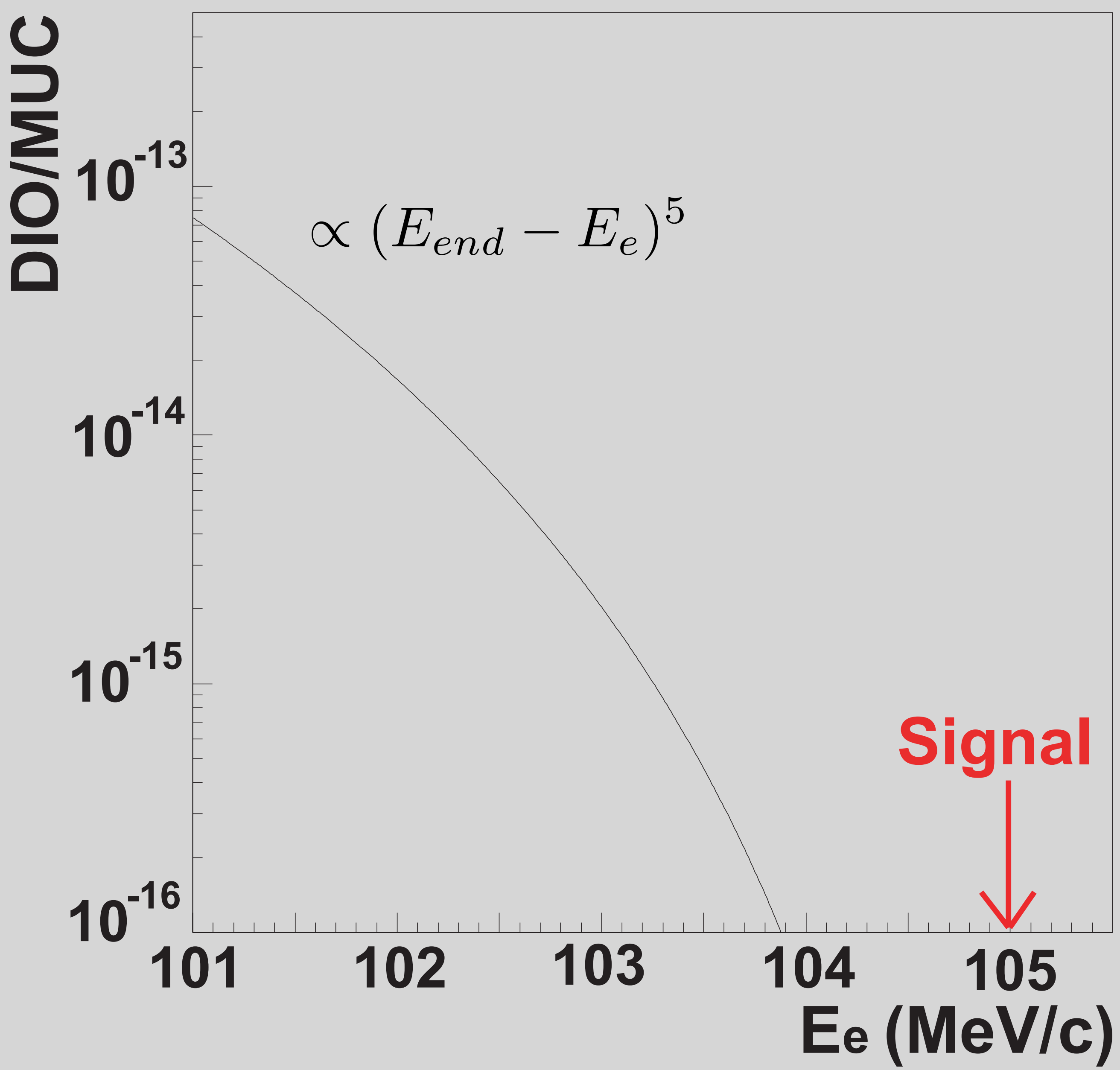
Intrinsic Background (from muons)

- Muon Decay in Orbit
  - Electron spectrum from muon decay in orbit
  - Response function of the spectrometer included.
  - 0.05 events in the signal region of 104.0 - 105.2 MeV (uncorrected).
- Radiative Muon Capture with Photon Conversion

$$\mu^- + Al \rightarrow \nu_\mu + Mg + \gamma$$

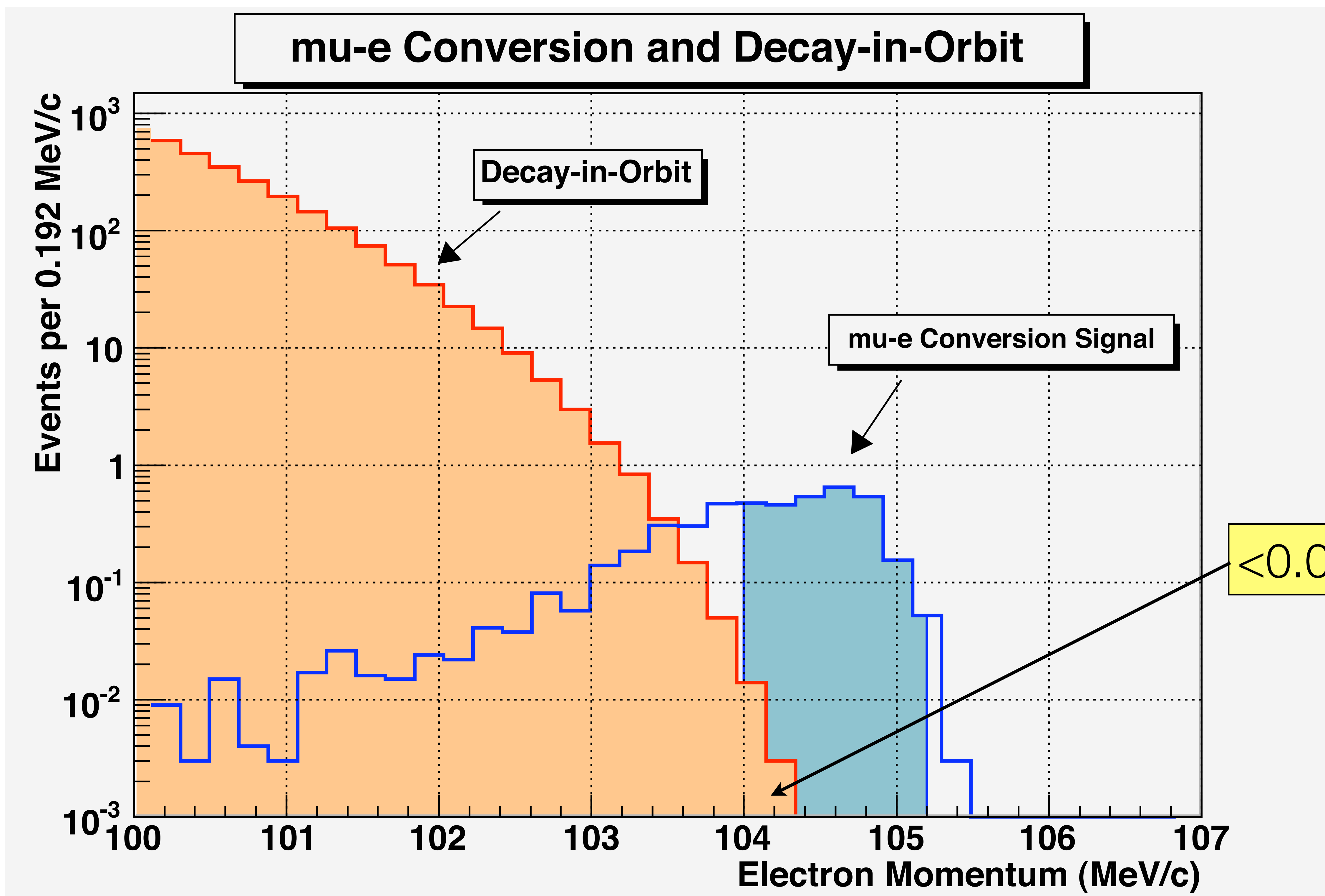
  - Max photon energy 102.5 MeV
  - < 0.001 events
- Muon Capture with Neutron Emission
- Muon Capture with Charged Particle Emission
  - <0.001 events for both.

Energy spectrum of electrons from decays in orbit in a muonic atom of aluminum, as a function of electron energy. The vertical axis shows the effective branching ratio of μ-e conversion.



DIO Background

a number of events for
1.1 x10^{18} stopped muons.



Beam Related Background Rejection

Rejection of beam related (prompt) backgrounds can be done by a combination of the following components.

Momentum Selection at the Muon Transport
($p_\mu < 75$ MeV/c)

Electron Energy Cut
(104.0 - 105.2 MeV uncorrected)

Electron Transverse Momentum Cut
($p_T > 52$ MeV/c)

Timing Cut and Beam Extinction
(10^{-9})

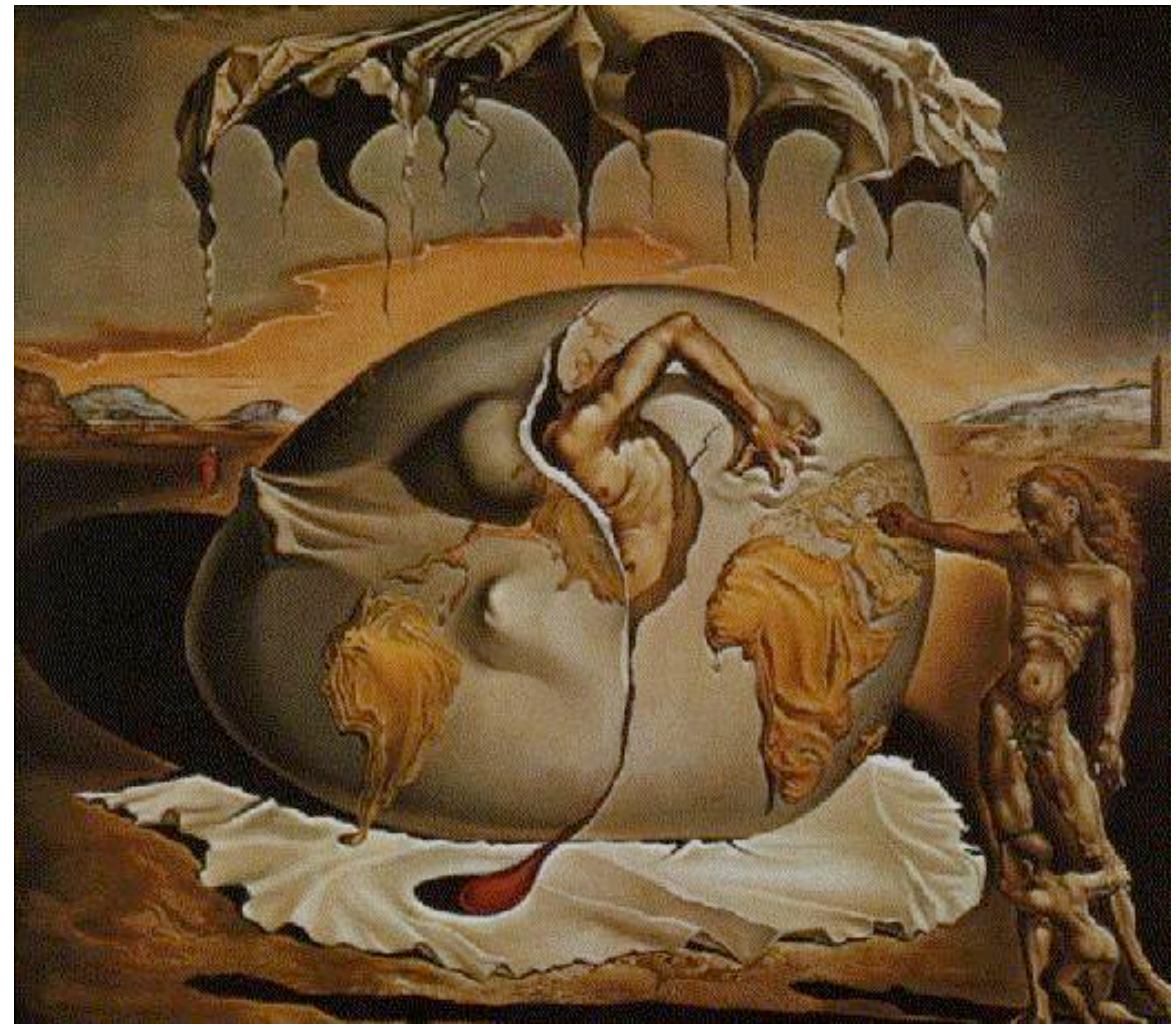
Beam Channel Length
(pion decay)

BG with asterisk needs beam extinction.

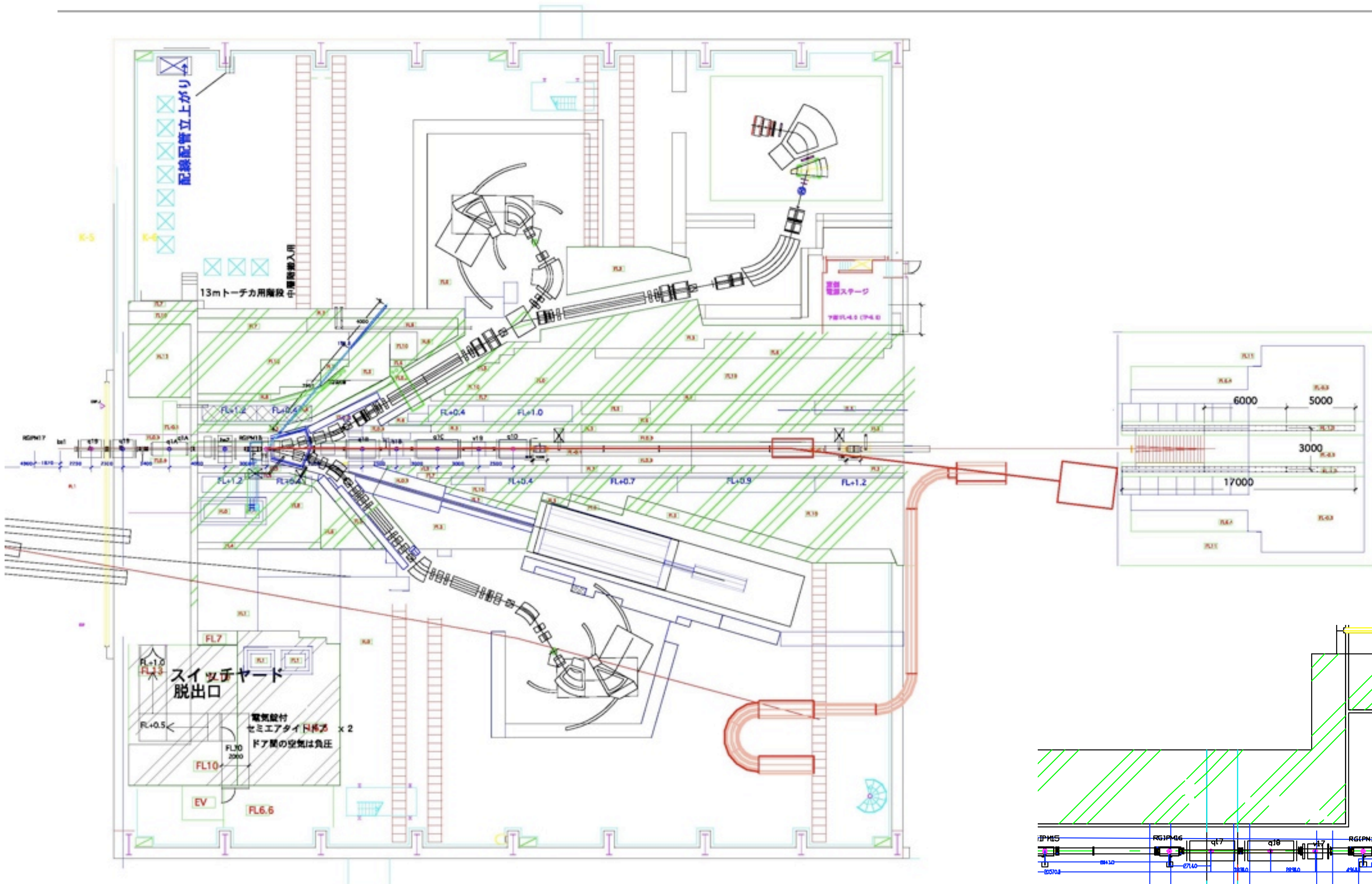
Background Rejection Summary (preliminary)

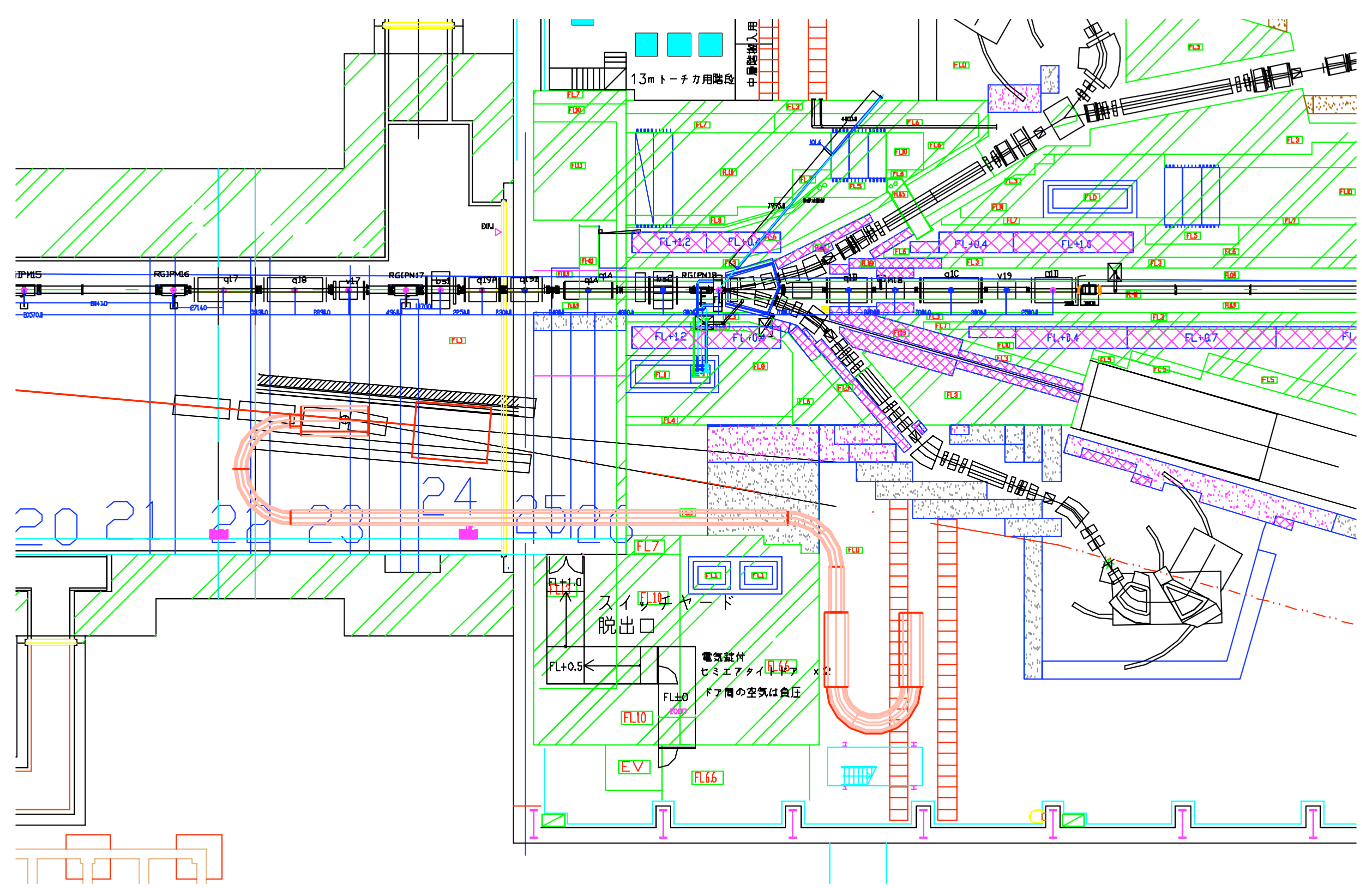
	Backgrounds	Events	Comments
(1)	Muon decay in orbit	0.05	230 keV resolution
	Radiative muon capture	<0.001	
	Muon capture with neutron emission	<0.001	
	Muon capture with charged particle emission	<0.001	
(2)	Radiative pion capture*	0.12	prompt
	Radiative pion capture	0.002	late arriving pions
	Muon 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
(3)	Cosmic-ray induced	0.10	10^{-4} veto & $2\text{x}10^{7}$sec run
	Pattern recognition errors	<0.001	
	Total	0.4	

Layout
at J-PARC NP Hall



Possible Layout at the NP Hall





Cost Estimation

Item	Cost (MJPY)
MR modification[1)]	130
External Extinction Device	230
Production Target & Shield	190
Superconducting Solenoid[2)]	2,420
Pion Capture Solenoid	(870)
Curved Muon Transport Solenoid	(360)
Muon-Stopping Target Solenoid	(530)
Curved Solenoid Spectrometer	(370)
Detector Solenoid	(290)
SC Solenoid Extension (20 m)[3)]	380
Tracking Detector	110
Electron Calorimeter	160
Cosmic Ray Shield	570
Data Acquisition and Trigger	50
Installation and Integration	200
Total	4,440

Schedule (preliminary)

Funding starting

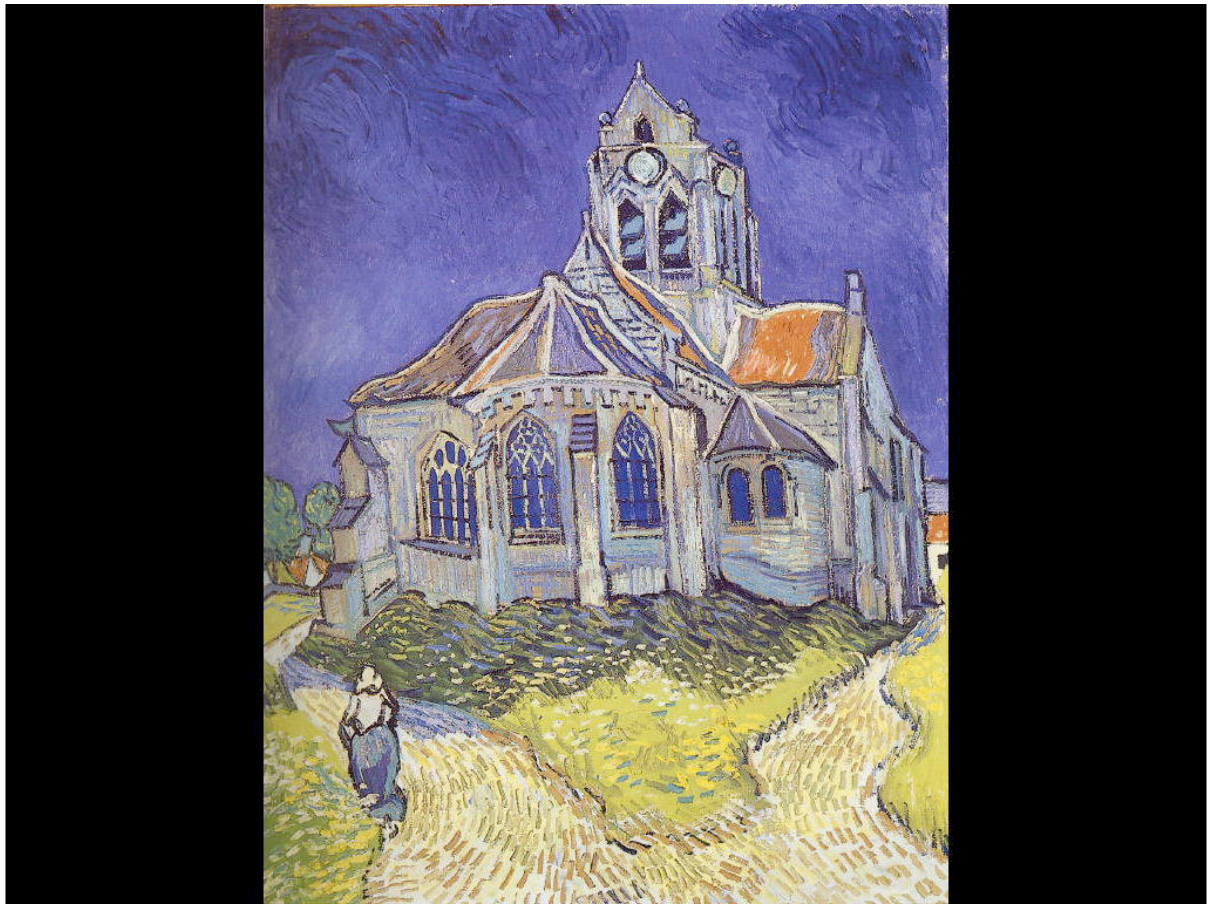
1st year	2nd year	3rd year	4th year	5th year	6th year
design & order of SC wires	construction			engineering run	physics run

Summary

- We propose a new experiment of searching for coherent neutrino-less conversion of muons to electron (μ-e conversion) at a sensitivity of 10^{-16}. This sensitivity is a factor of 10,000 better than the current experimental limit.
- The experiment COMET (COherent Muon to Electron Transition) would offer powerful opportunity for new physics phenomena beyond the Standard Model.
- The experiment is planned to carry out in the J-PARC NP Hall by using a bunched proton beam slowly-extracted from the J-PARC main ring.
- This initiative has been taken to achieve an early and timely start of the searches in terms of international competition.

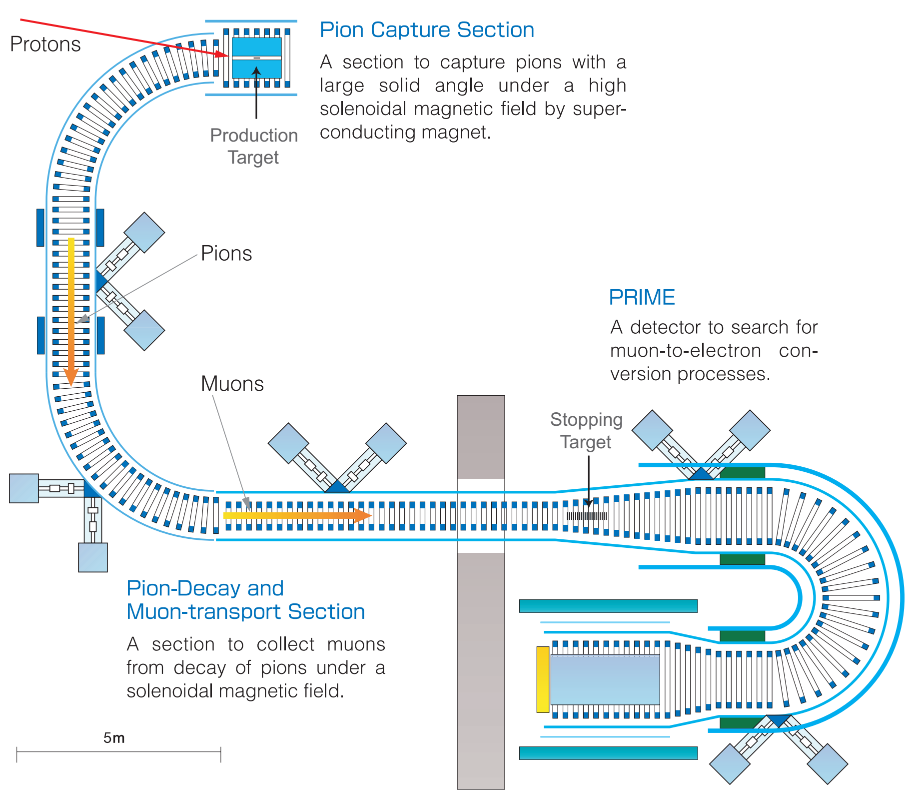
End of My Talk

Backup Slides

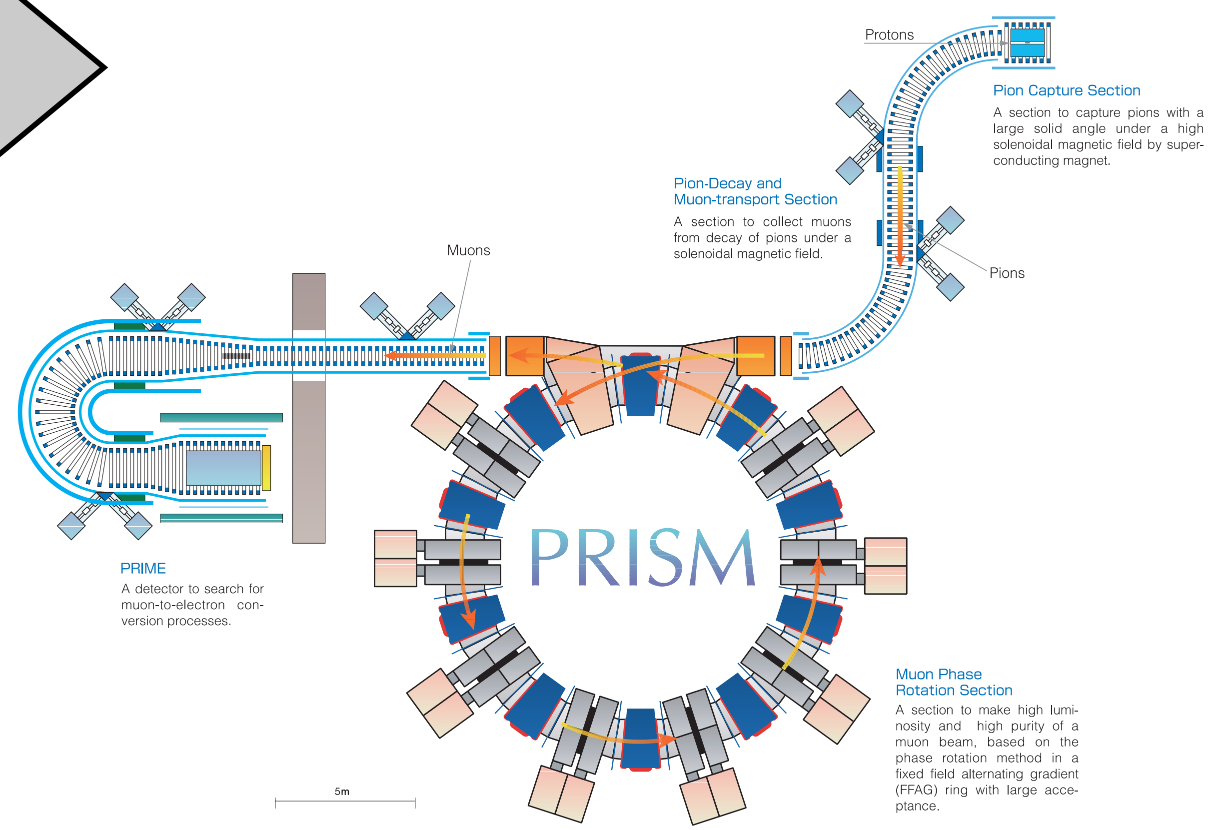


PRISM Project in Japan

Phase 1 (P1)



PRISM



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

- without a muon storage ring.
- with a slowly-extracted pulsed proton beam.
- doable at the J-PARC NP Hall.
- regarded as the first phase / MECO type
- Early realization

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

- with a muon storage ring.
- with a fast-extracted pulsed proton beam.
- need a new beamline and experimental hall.
- regarded as the second phase.
- Ultimate search