# Introduction to Physics of Muon to Electron Conversion and PRISM/COMET Experiments

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# Outline

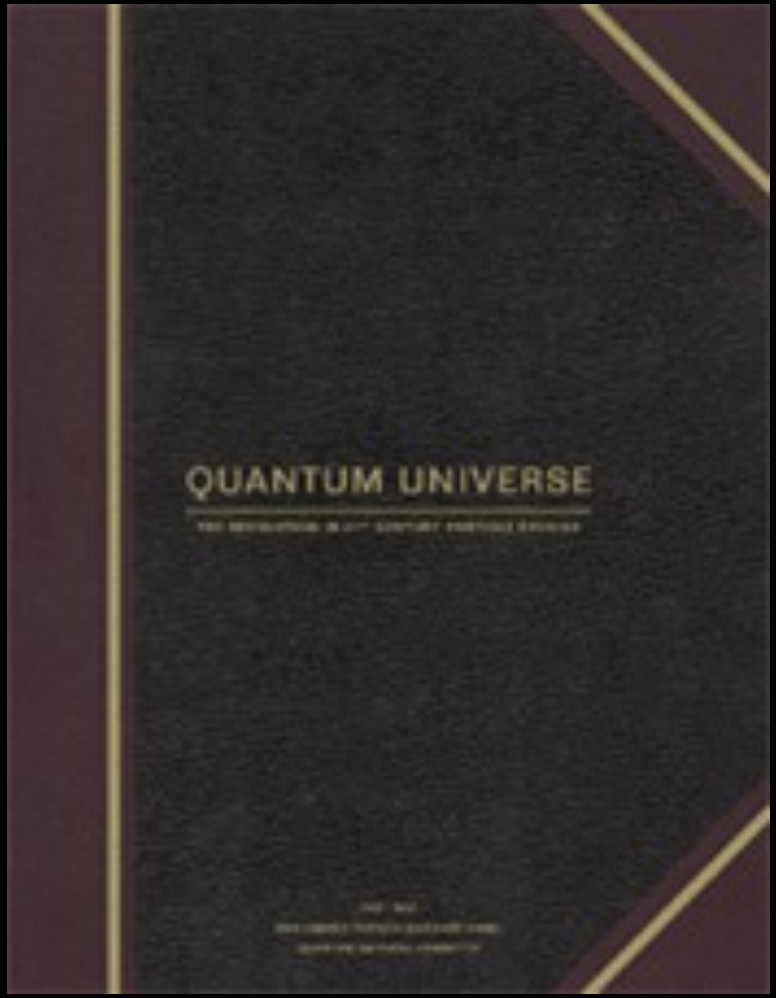
- Intensity Frontier and Charged Lepton Flavor Violation (cLFV)
- cLFV Physics Motivation with Muons
- Overview of cLFV Experiments with Muons
  - $\mu \to e\gamma$
  - $\mu$-e conversion
- Experimental searches for $\mu$-e conversion
- cLFV of taus with neutrinos (if a time allows)
- Summary

# Intensity Frontier and Charged Lepton Flavor Violation (cLFV)

From “Quantum Universe”

# The Big Questions
# to explore the mysteries of the Universe

1. What is the origin of mass for fundamental particles?
2. Are there undiscovered principles of nature?
3. Are there extra dimensions of space?
4. Do all the forces becomes one?
5. Why are there so many kinds of particles?
6. What happened to the antimatter?
7. What is dark matter?
   How can we make it in the laboratory?
8. How can we solve the mystery of dark energy?
9. How did the universe come to be?
10. What are neutrinos telling us?



DOE/NSF high
energy physics advisory panel

From “Quantum Universe”

# The Big Questions
# to explore the mysteries of the Universe

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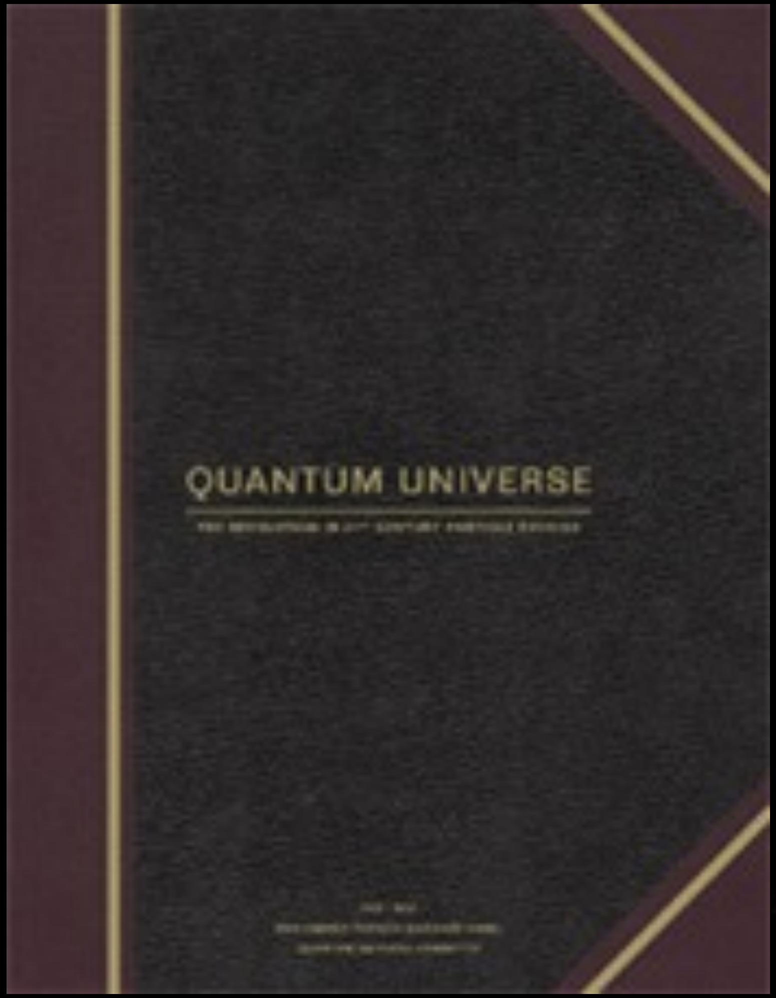

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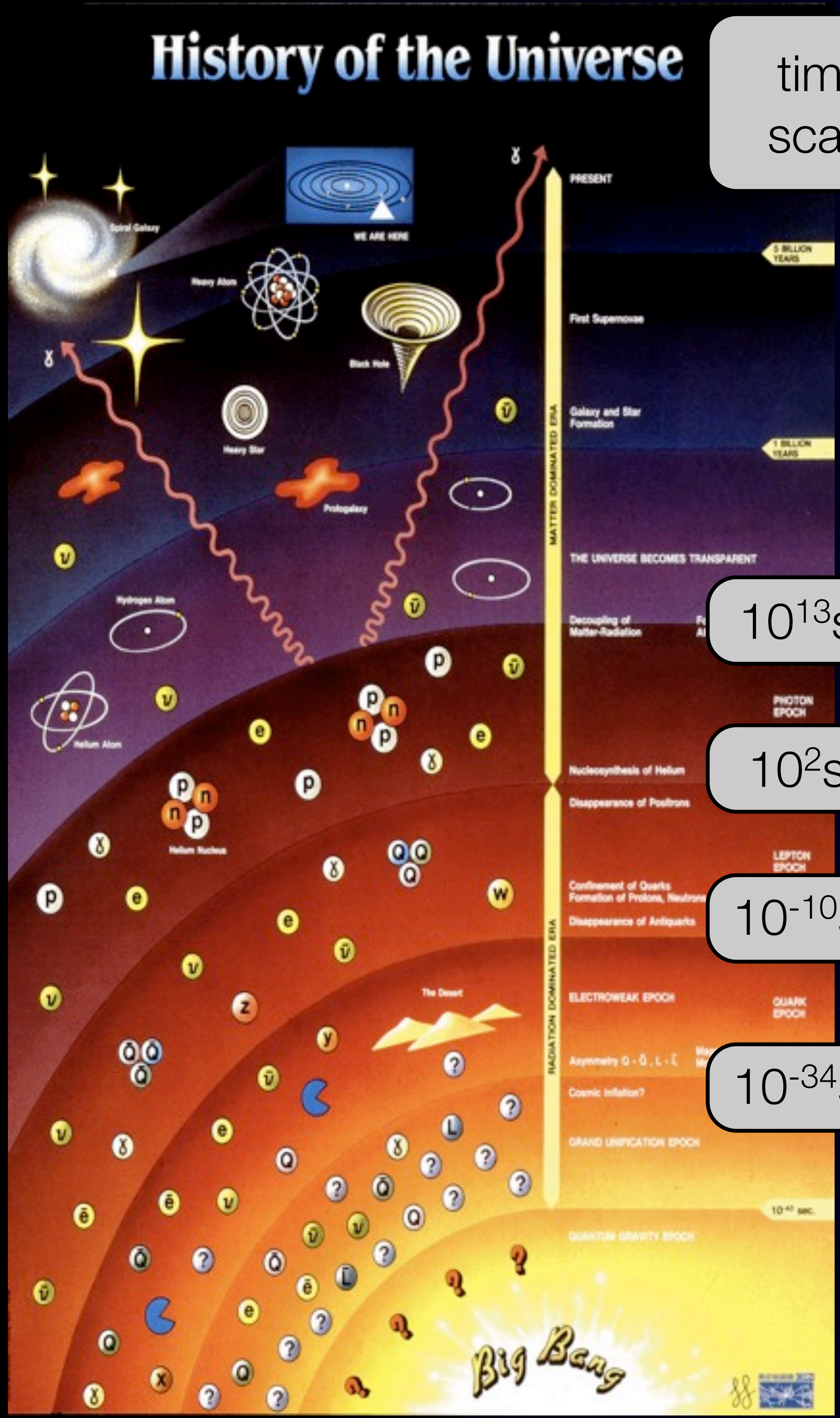
The Standard Model continues working well, but cannot answer these fundamental questions.

Search for new physics at higher energy scale!



time scale

energy scale

$10^{13}$sec

$10^{-9}$GeV

$10^{2}$sec

$10^{-3}$GeV

$10^{-10}$sec

$10^{2}$GeV

$10^{-34}$sec

$10^{16}$GeV

$10^{19}$GeV

Electroweak Epoch

Higgs particles

Supersymmetry

Unification Epoch

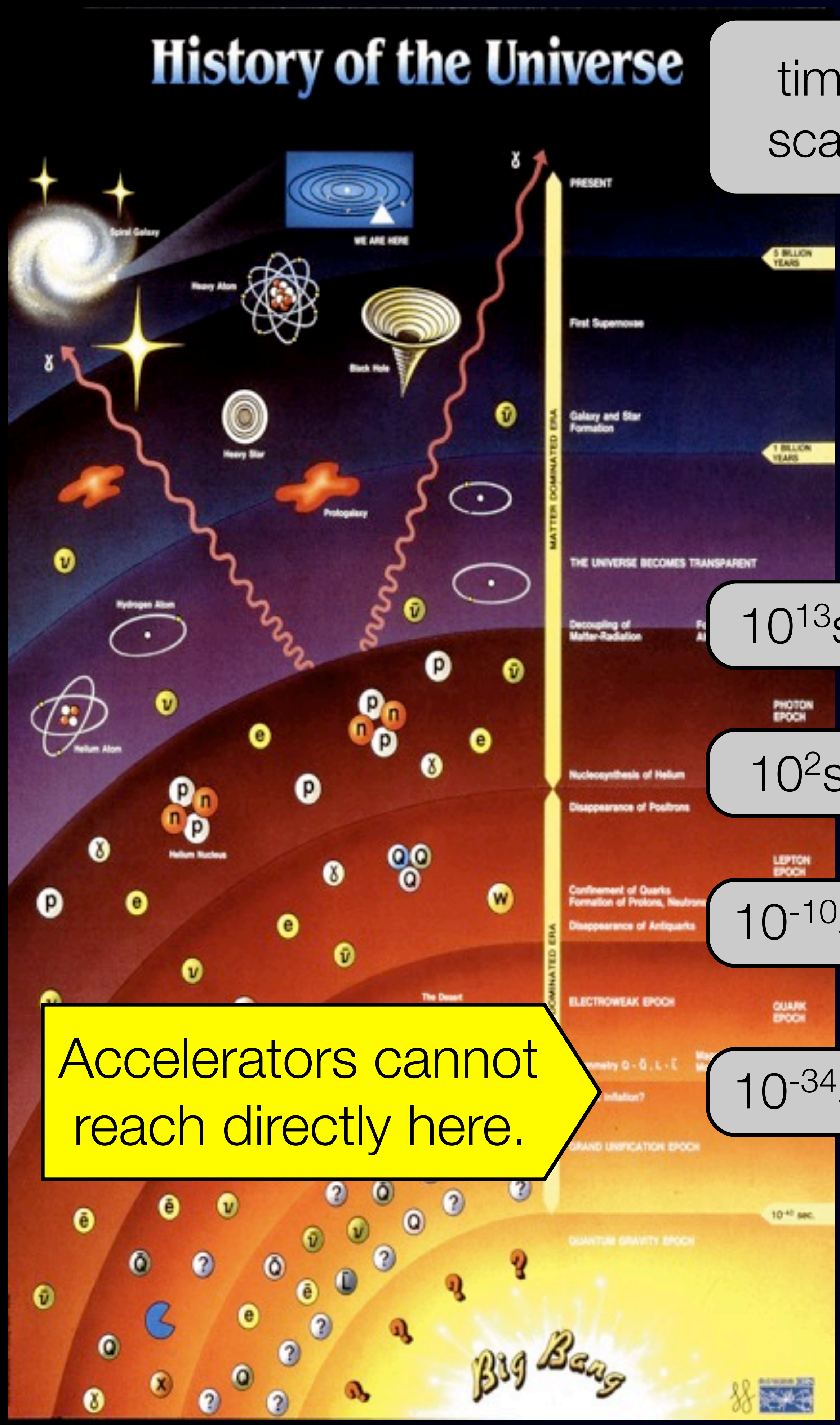
Grand unification of fundamental forces

Origin of Neutrino mass (RH neutrino)

Leptogenesis (baryogenesis)

Quantum Gravity Epoch

Superstrings



Accelerators cannot reach directly here.

| time scale | energy scale |
|---|---|
| $10^{13}$sec | $10^{-9}$GeV |
| $10^{2}$sec | $10^{-3}$GeV |
| $10^{-10}$sec | $10^{2}$GeV |
| $10^{-34}$sec | $10^{16}$GeV |
| | $10^{19}$GeV |

**Electroweak Epoch**

- Higgs particles
- Supersymmetry

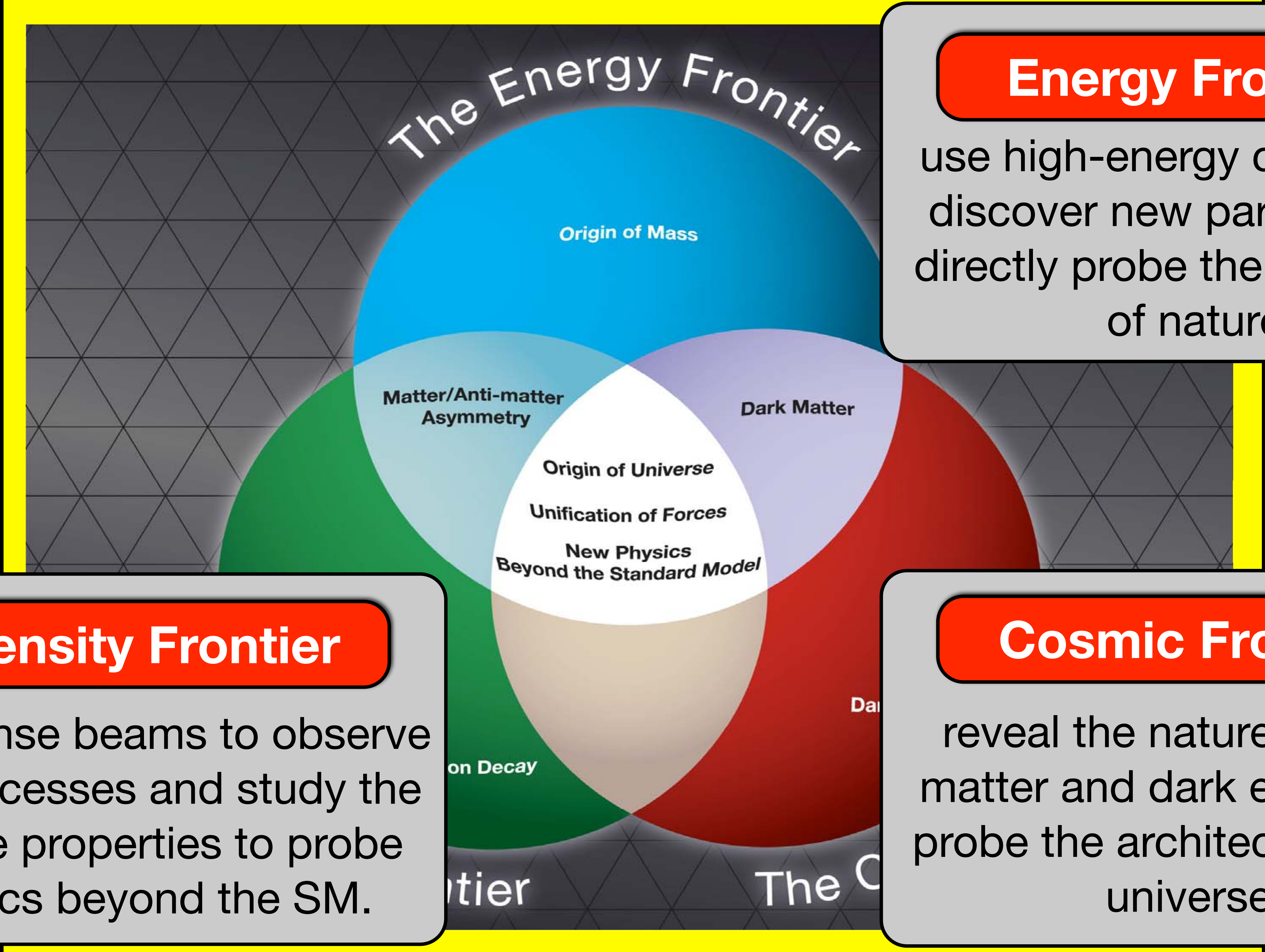
**Unification Epoch**

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

**Quantum Gravity Epoch**

- Superstrings

# Tools :
# The Three Frontiers of Particle Physics



**Energy Frontier**

use high-energy colliders to discover new particles and directly probe the properties of nature

**Intensity Frontier**

use intense beams to observe rare processes and study the particle properties to probe physics beyond the SM.

**Cosmic Frontier**

reveal the natures of dark matter and dark energy and probe the architecture of the universe.

from C. Baltay's talk at the P5 meeting, 29 May 2008

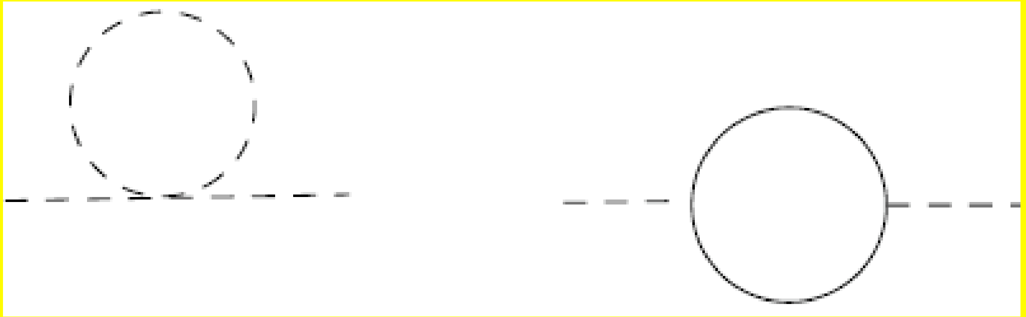
# Precision Measurements in The European Strategy

“Flavour physics and precision measurements at the high-luminosity frontier at lower energies complement our understanding of particle physics and allow for a more accurate interpretation of the results at the high-energy frontier.” (2006)

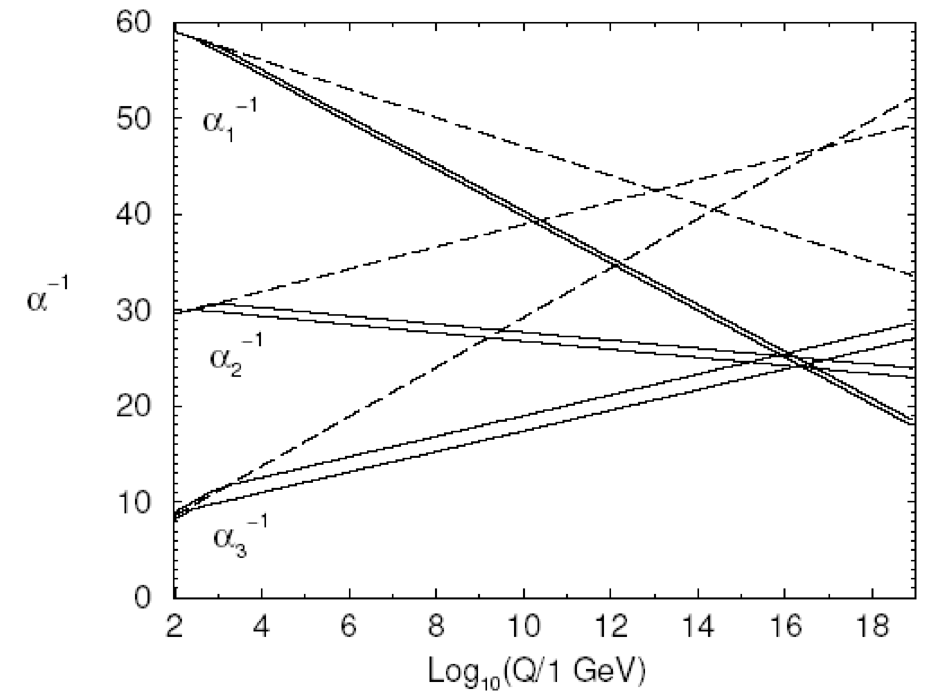
# The Intensity Frontier

- The Intensity Frontier is
  - an indirect search, but
  - energy scale that could be studied would be much higher than that of accelerators of O(1 TeV).
- Through quantum radiative corrections
  - renormalization group equations

Quantum Corrections



usefulness of renormalization equations



- Effects are small.
  - High precision measurements
  - High intensity beams

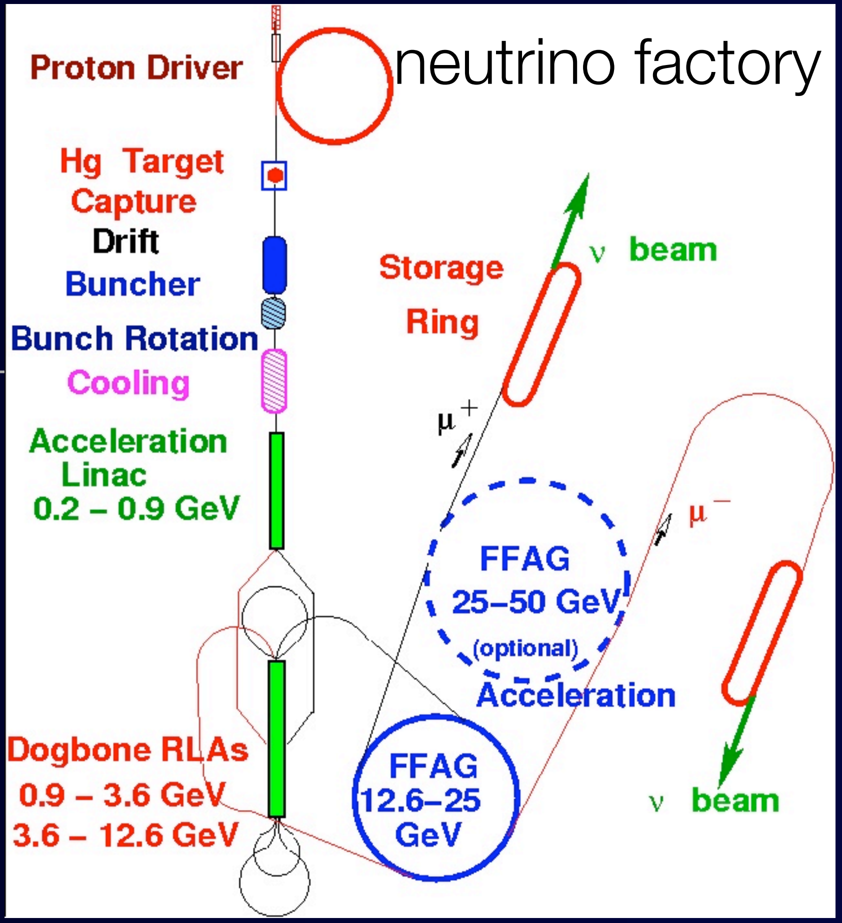
# Which Rare Processes at Low Energy ?

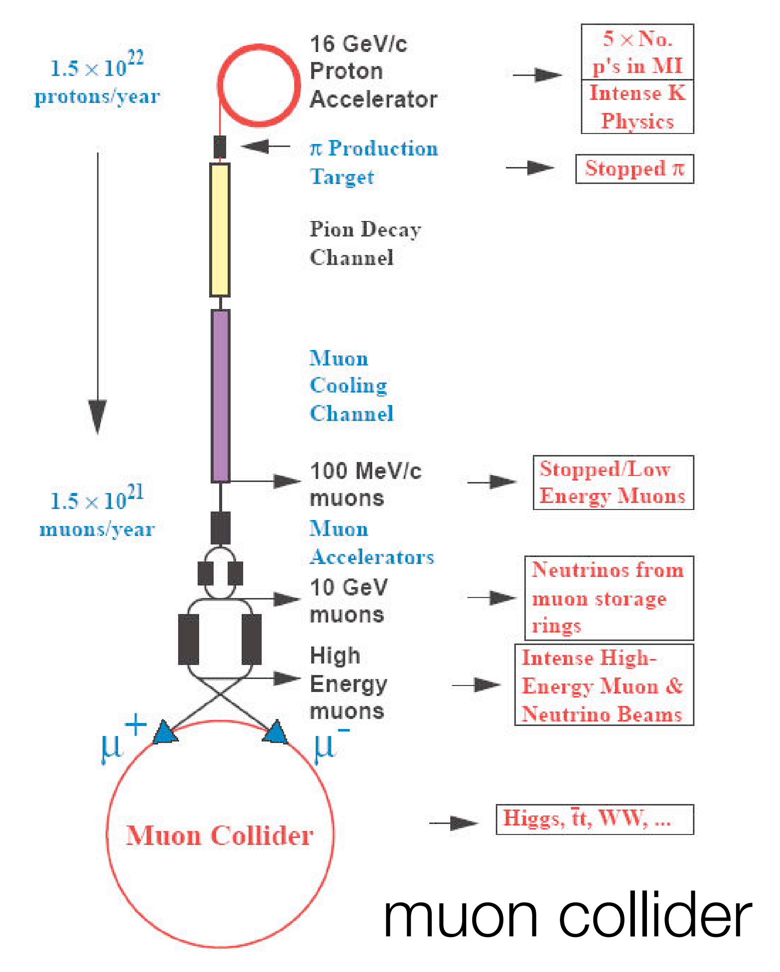
- Processes which are forbidden or highly suppressed in the Standard Model would be the best ones to search for new physics beyond the Standard Model.
- Flavor Changing Neutral Current Process (FCNC)
- FCNC in the quark sector
  - $b \to s\gamma$, $K \to \pi\nu\nu$, etc.
  - Allowed in the Standard Model.
  - Need to study deviations from the SM predictions.
    - Uncertainty of more than a few % (from QCD) exists.
- FCNC in the lepton sector
  - $\mu \to e\gamma$, $\mu + N \to e + N$, etc. ( Lepton Flavor Violation = LFV)
  - Not allowed in the Standard Model ($\sim 10^{-50}$ with neutrino mixing)
  - Need to study deviations from none
    - clear signature and high sensitivity

# Why Muons, not Taus ?

- Taus at B factories is not large enough, like about 10 taus/sec.
  - At future super-B factories, intensity increase of O(10-100) is expected. Also some of the decay modes are already background-limited.
- Muons at PSI is about $10^8$ /sec.
  - Intensity increase of $10^{11}$-$10^{14}$ /sec with the technology developed for the front end R&D of muon colliders and/or neutrino factories, where intensity improvement factor of up to about O(1,000,000).

A larger window for new physics !

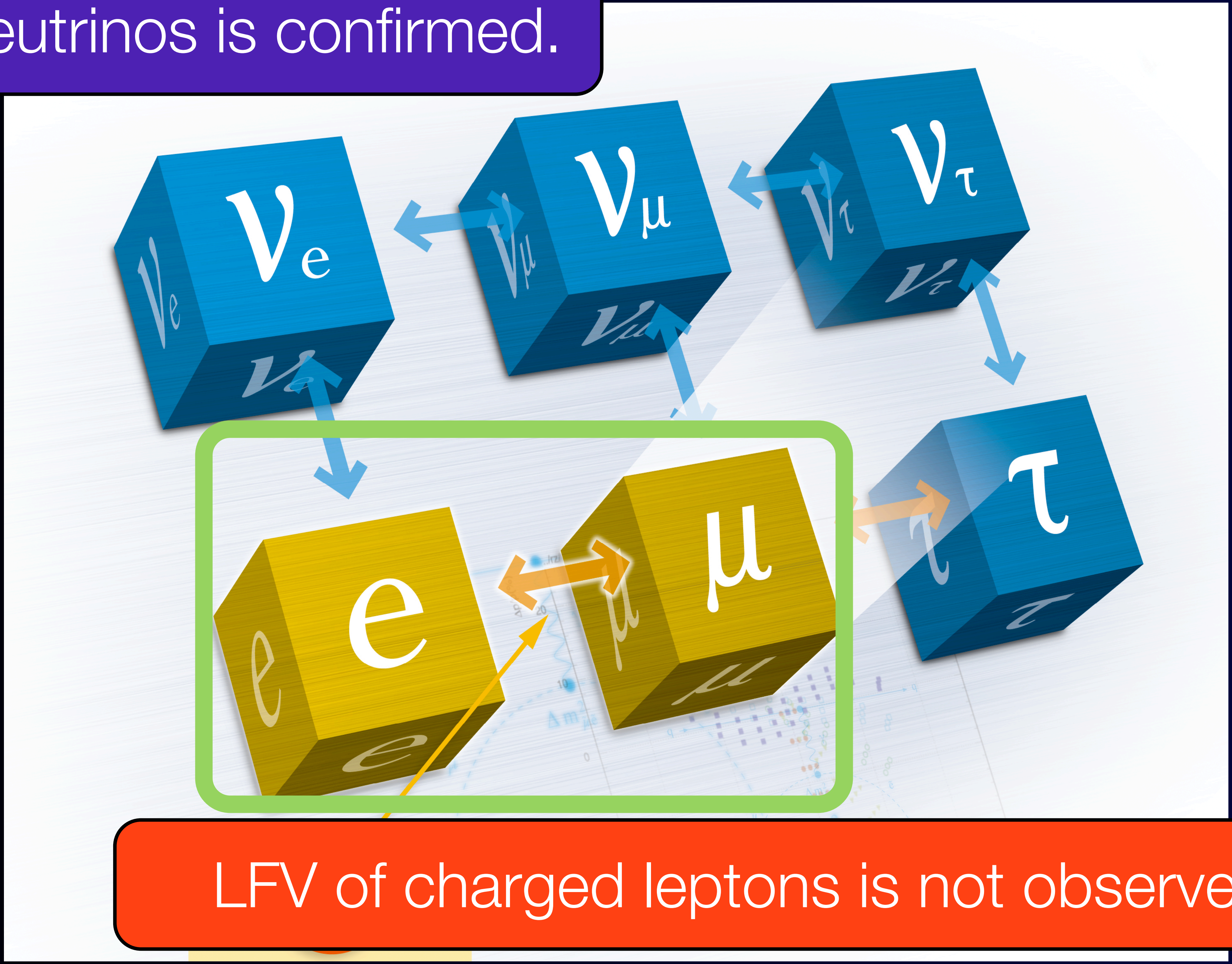




# Physics Motivation of cLFV

# Lepton Flavor Violation of Charged Leptons (cLFV)

LFV of neutrinos is confirmed.



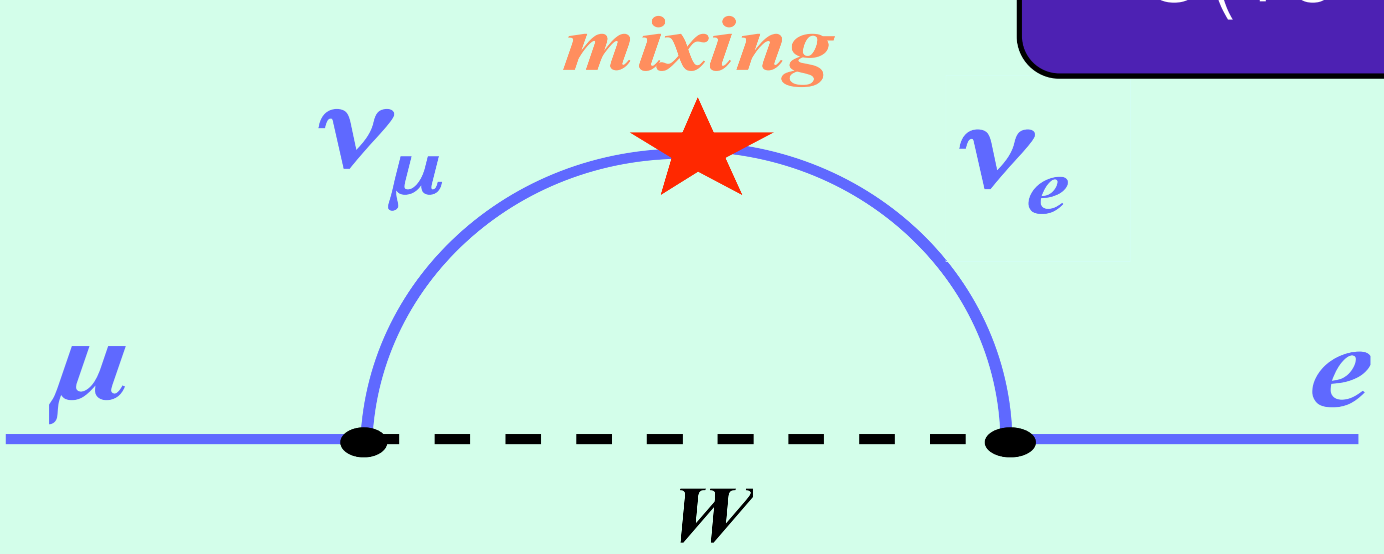
LFV of charged leptons is not observed.

# Standard Model Contribution from Neutrino Mixing (GIM mechanism)

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

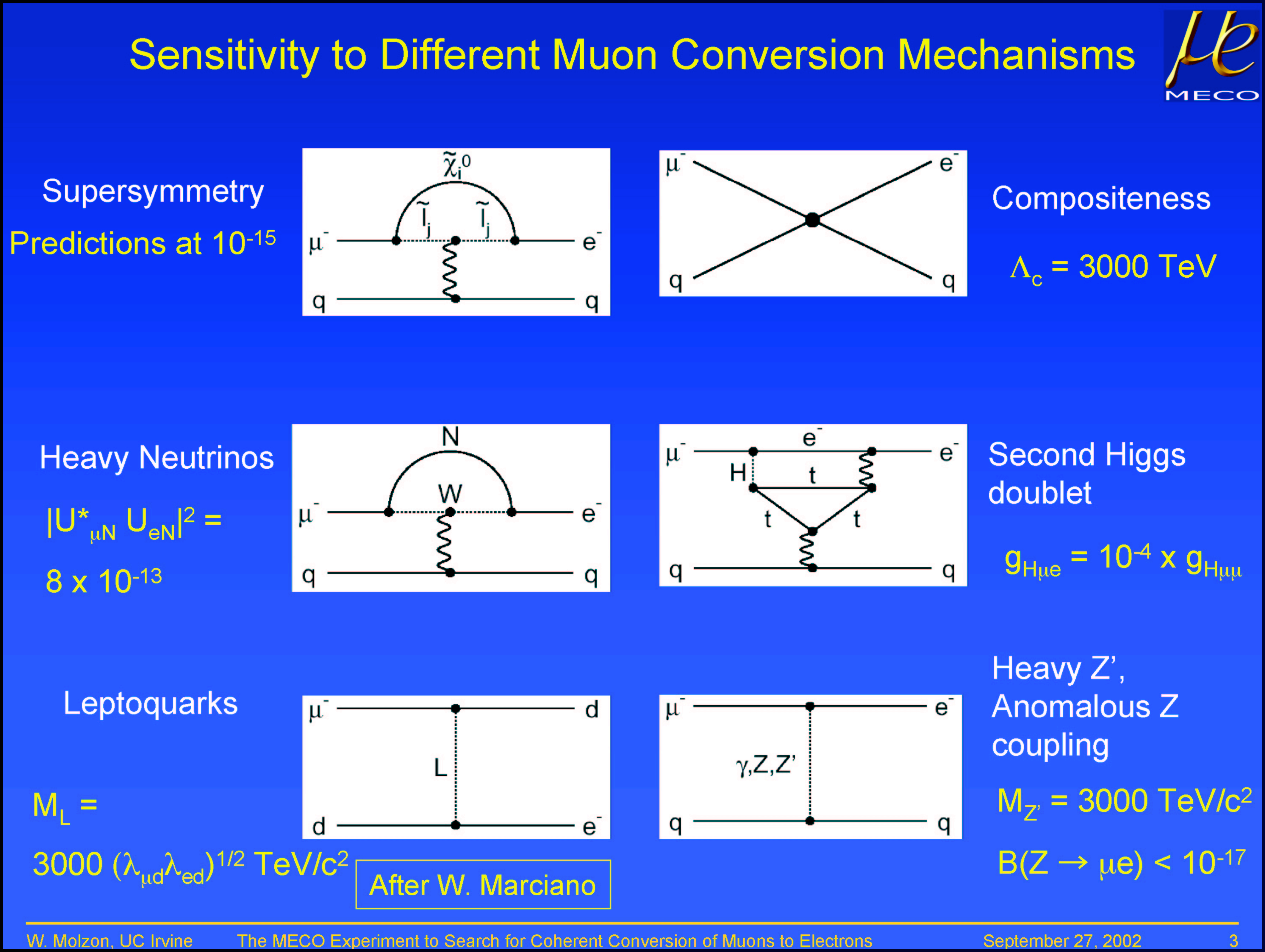
[redacted]

O($10^{-54}$)



A Large Window for New Physics beyond the Standard Model

# Various Models Predict Charged Lepton Mixing.



## Sensitivity to Different Muon Conversion Mechanisms

Supersymmetry

Predictions at $10^{-15}$

Compositeness

$\Lambda_c = 3000$ TeV

Heavy Neutrinos

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

$8 \times 10^{-13}$

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

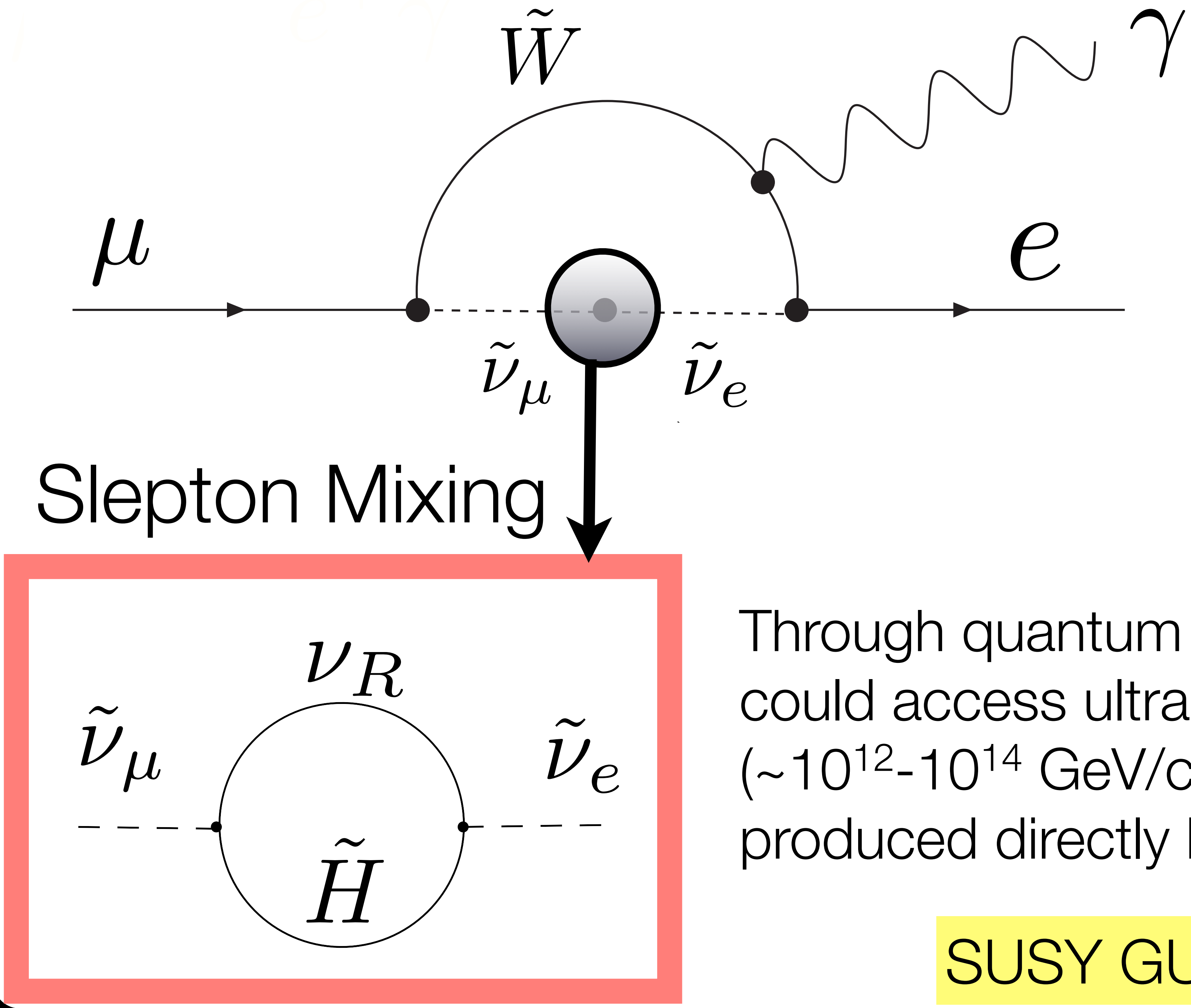
Heavy Z', Anomalous Z coupling

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

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

# LFV in SUSY Models

an example diagram



Slepton Mixing

Features

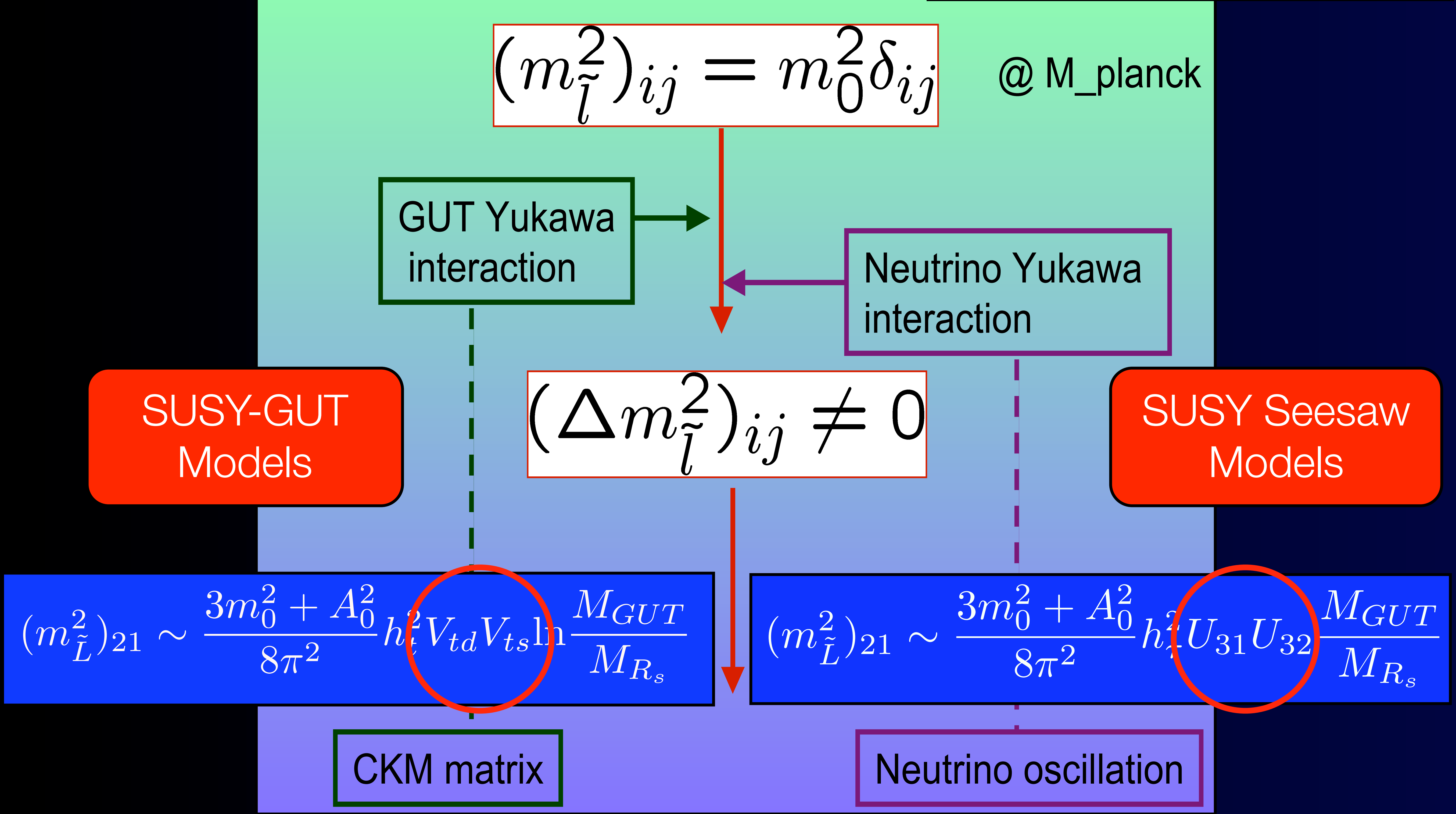
- The decay rate is not too small, because it is determined by the SUSY mass scale.
- But, it contains the information at $10^{16}$ GeV through the slepton mixing.
- It is in contract to proton decays or double beta decays which need many particles.

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

SUSY GUT and SUSY Seesaw

# Slepton Mixing in mSUGRA Models

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



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

@ M_planck

GUT Yukawa interaction

Neutrino Yukawa interaction

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

SUSY-GUT Models

SUSY Seesaw Models

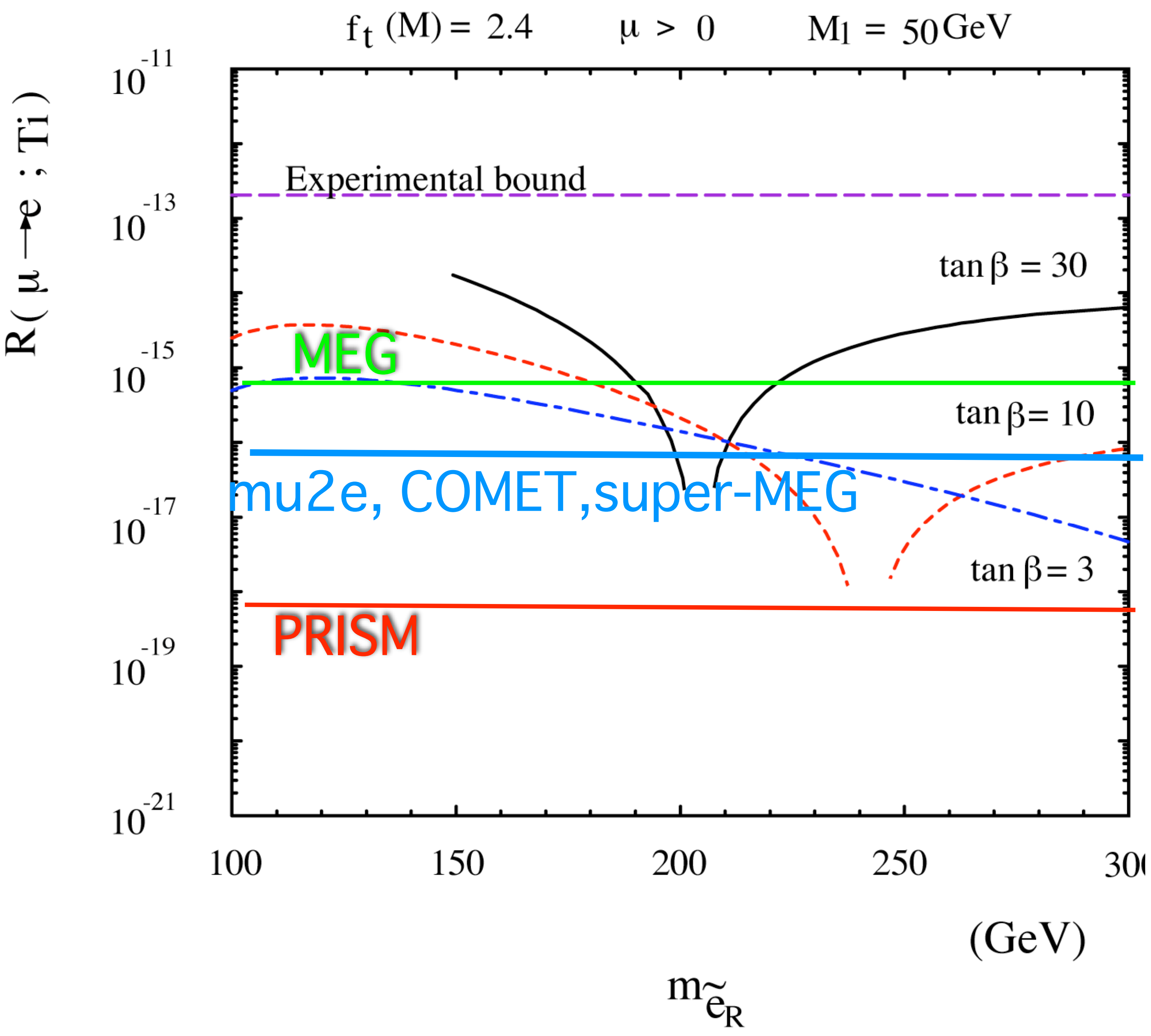
$$(m^2_{\tilde L})_{21} \sim \frac{3m_0^2 + A_0^2}{8\pi^2} h_t^2 V_{td} V_{ts} \ln \frac{M_{GUT}}{M_{R_s}}$$

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

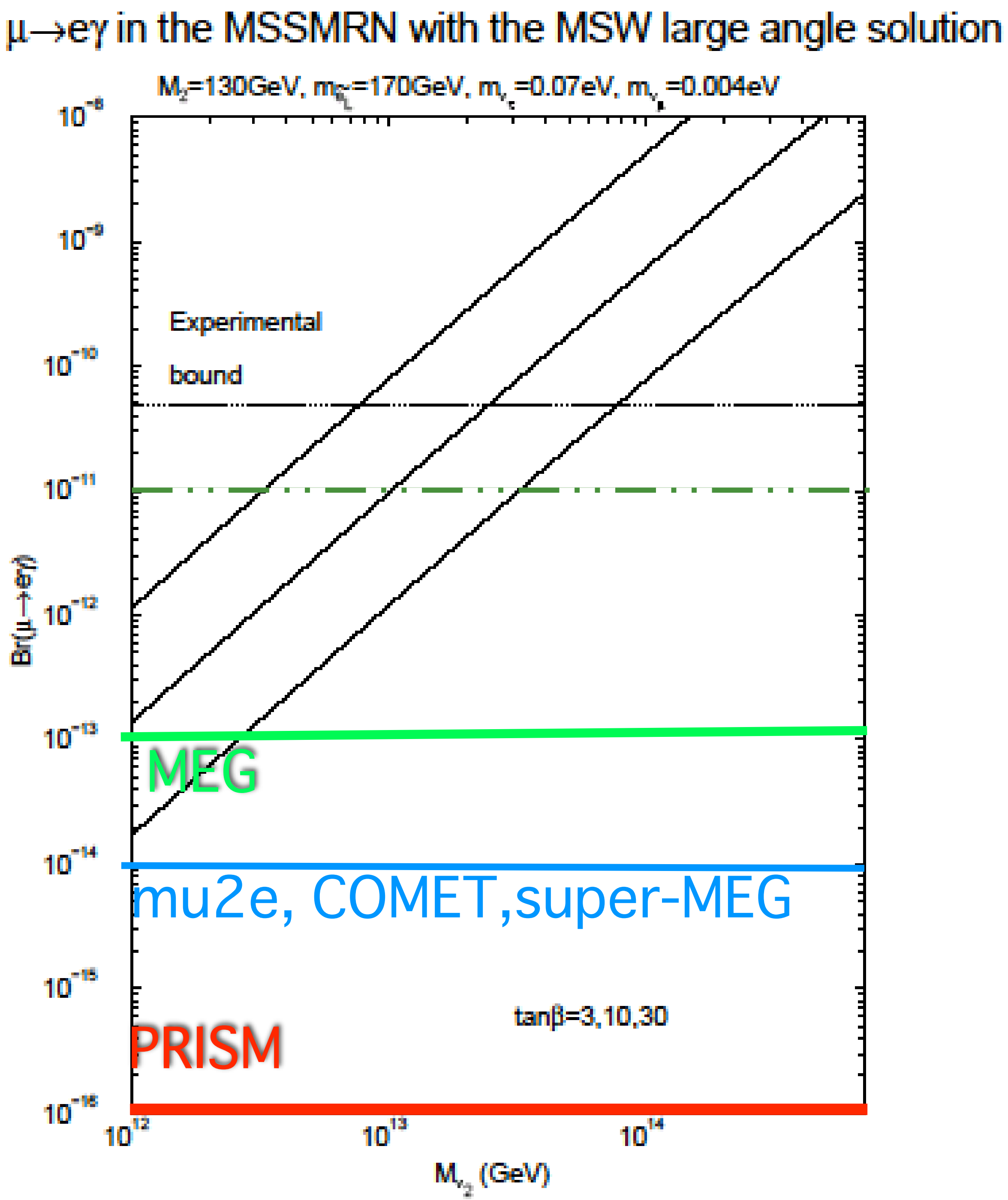
CKM matrix

Neutrino oscillation

# SUSY Predictions for cLFV



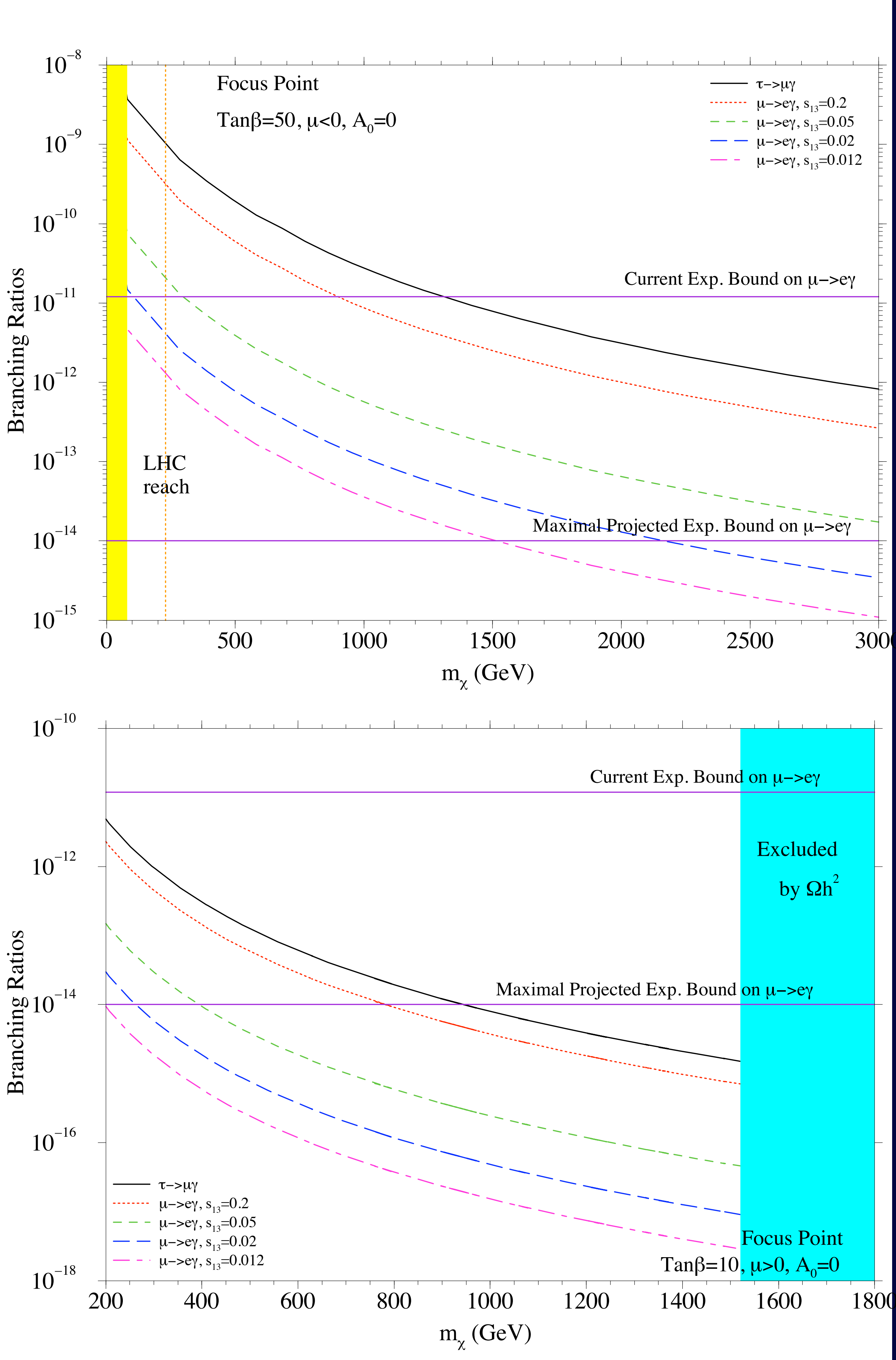
SU(5) SUSY GUT



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 cLFV.
- Bench mark points
  - Focus point
    - LHC can not cover and cLFV can cover.



cLFV is complementary to LHC, and in some case has much better sensitivity than LHC.

# 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.

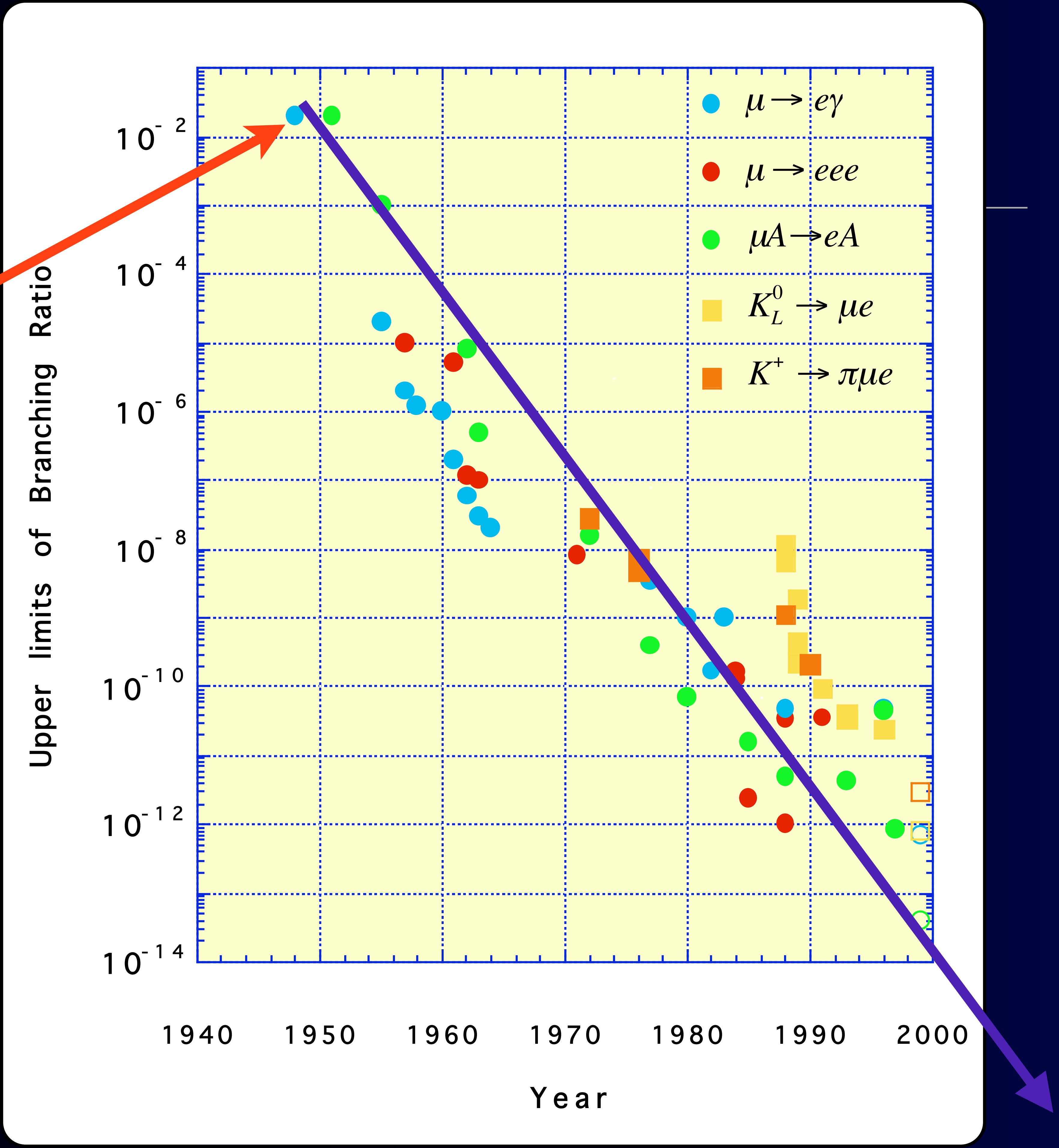
- Slepton mixing is sensitive to either (or both) Grand Unified Theories (SUSY-GUT models) or neutrino seesaw mechanism (SUSY-Seesaw models).
- If cLFV sensitivity is extremely high, it might be able to explore multi-TeV SUSY which LHC cannot reach, in particular SUSY parameters.

# cLFV Experiments

# cLFV History

First cLFV search

Pontecorvo in 1947



# Present Limits and Expectations in Future

| process | present limit | future | |
|---|---|---|---|
| $\mu \rightarrow e\gamma$ | $<1.2 \times 10^{-11}$ | $<10^{-13}$ | MEG at PSI |
| $\mu \rightarrow eee$ | $<1.0 \times 10^{-12}$ | $<10^{-13} - 10^{-14}$ | ? |
| $\mu N \rightarrow eN$ *(in Al)* | none | $<10^{-16}$ | Mu2e / COMET |
| $\mu N \rightarrow eN$ *(in Ti)* | $<4.3 \times 10^{-12}$ | $<10^{-18}$ | PRISM |
| $\tau \rightarrow e\gamma$ | $<1.1 \times 10^{-7}$ | $<10^{-9} - 10^{-10}$ | super B factory |
| $\tau \rightarrow eee$ | $<3.6 \times 10^{-8}$ | $<10^{-9} - 10^{-10}$ | super B factory |
| $\tau \rightarrow \mu\gamma$ | $<4.5 \times 10^{-8}$ | $<10^{-9} - 10^{-10}$ | super B factory |
| $\tau \rightarrow \mu\mu\mu$ | $<3.2 \times 10^{-8}$ | $<10^{-9} - 10^{-10}$ | super B factory |

# List of cLFV Processes with Muons

## ΔL=1

- $\mu^+ \rightarrow e^+\gamma$
- $\mu^+ \rightarrow e^+e^+e^-$
- $\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$
- $\mu^- + N(A,Z) \rightarrow e^+ + N(A,Z-2)$

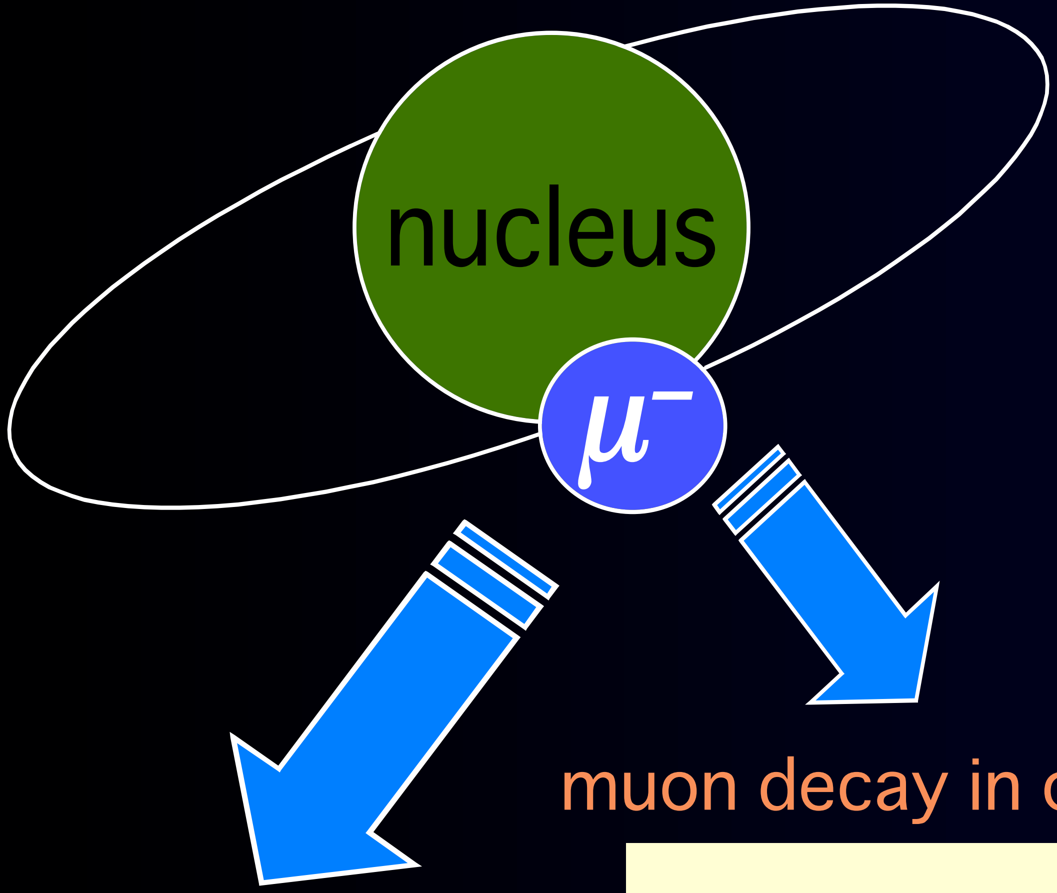
## ΔL=2

- $\mu^+e^- \rightarrow \mu^-e^+$
- $\mu^- + N(A,Z) \rightarrow \mu^+ + N(A,Z-2)$
- $\nu_\mu + N(A,Z) \rightarrow \mu^+ + N(A,Z-1)$
- $\nu_\mu + N(A,Z) \rightarrow \mu^+\mu^+\mu^- + N(A,Z-1)$

# $\mu \to e$ conversion in a muonic atom

# What is a Muon to Electron Conversion ?

1s state in a muonic atom



muon decay in orbit

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

nuclear muon capture

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

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

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

lepton flavors changes by one unit.

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

# μ-e Conversion
# Signal and Backgrounds

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

- Signal
  - single mono-energetic electron

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

- 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.

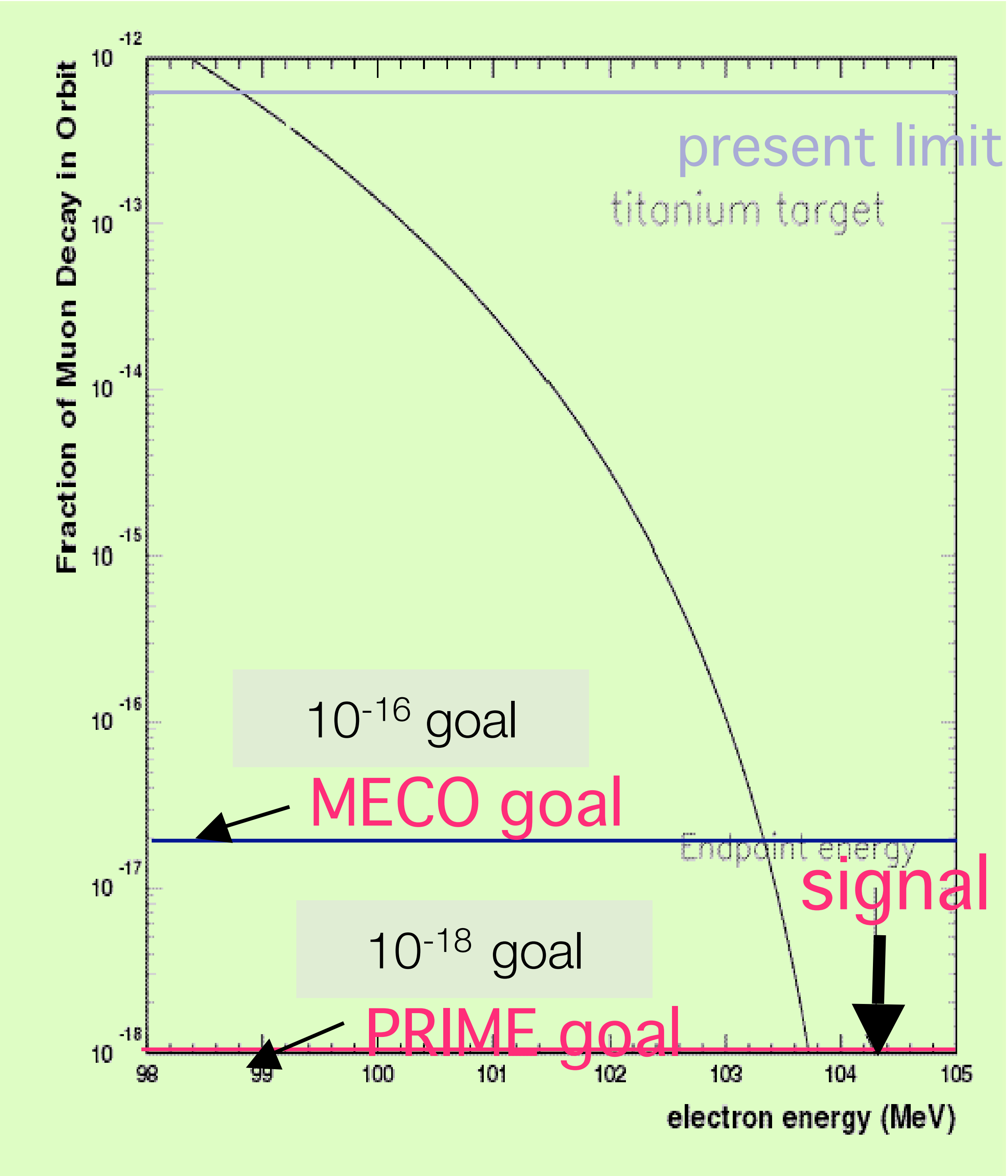
# Backgrounds

| 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 |

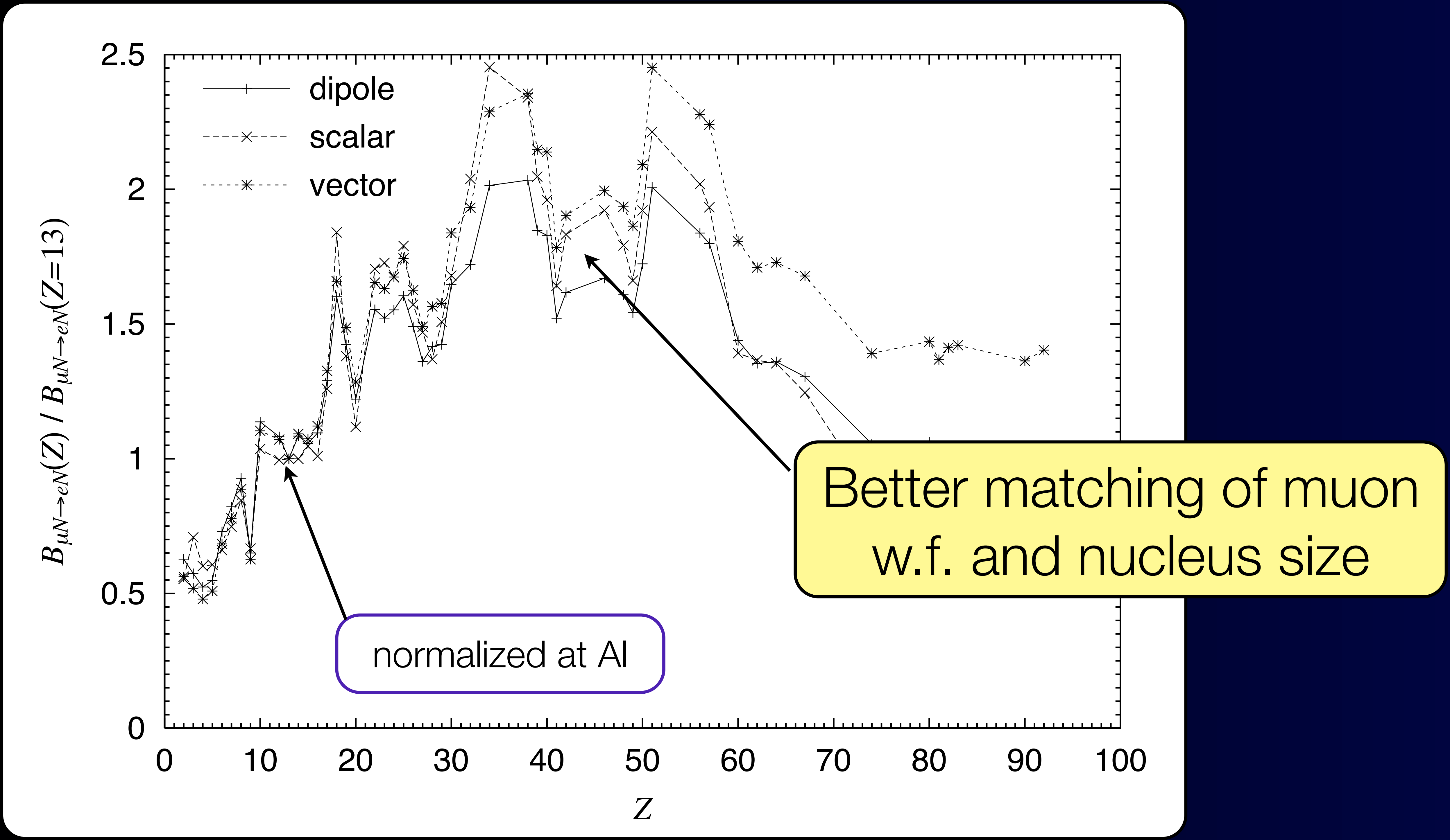
# Muon Decay In Orbit (DIO) in a Muonic Atom

- 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.

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



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



Better matching of muon w.f. and nucleus size

normalized at Al

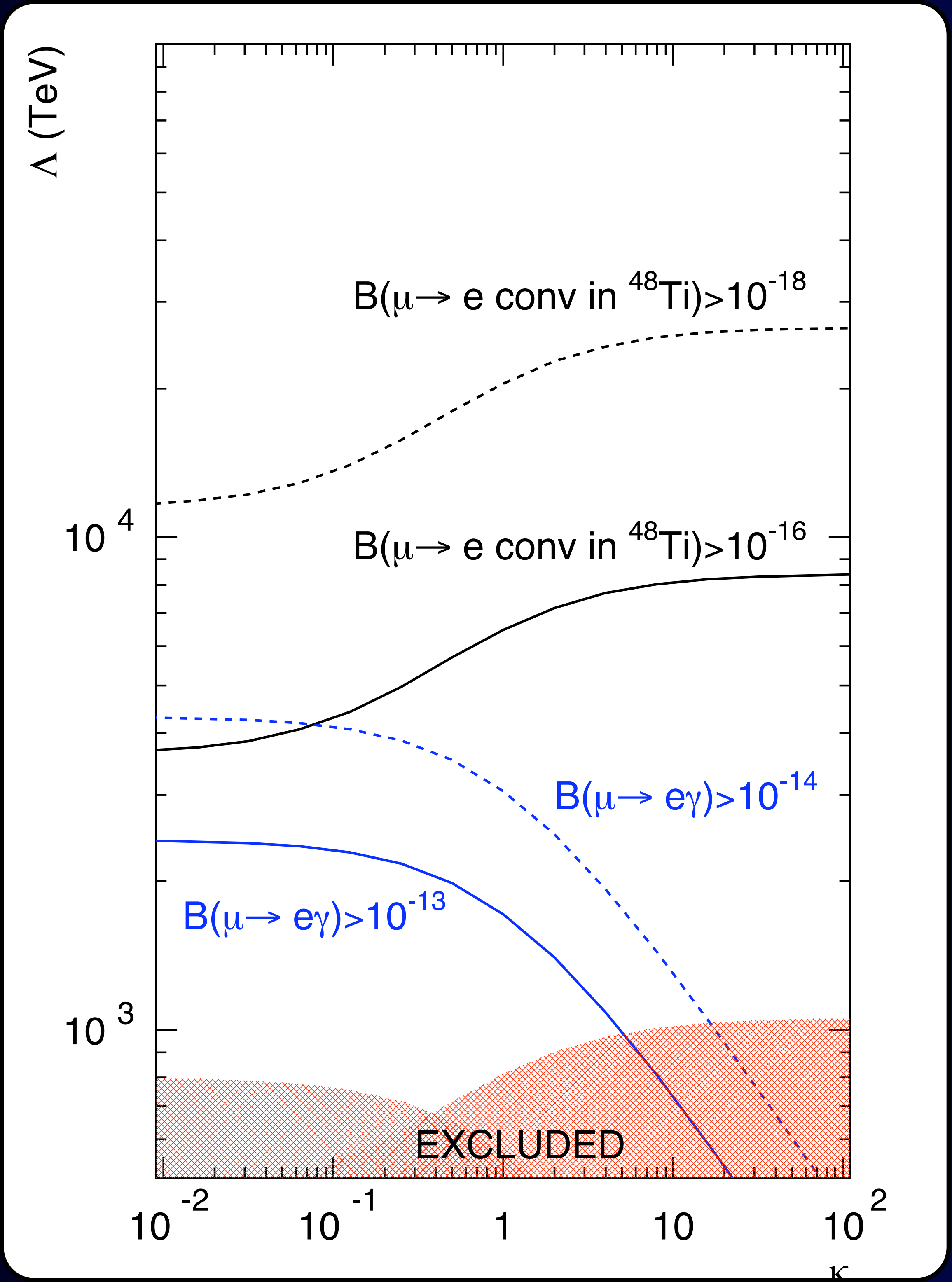
R. Kitano, M. Koike and Y. Okada, Phys. Rev. D66, 096002 (2002)

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

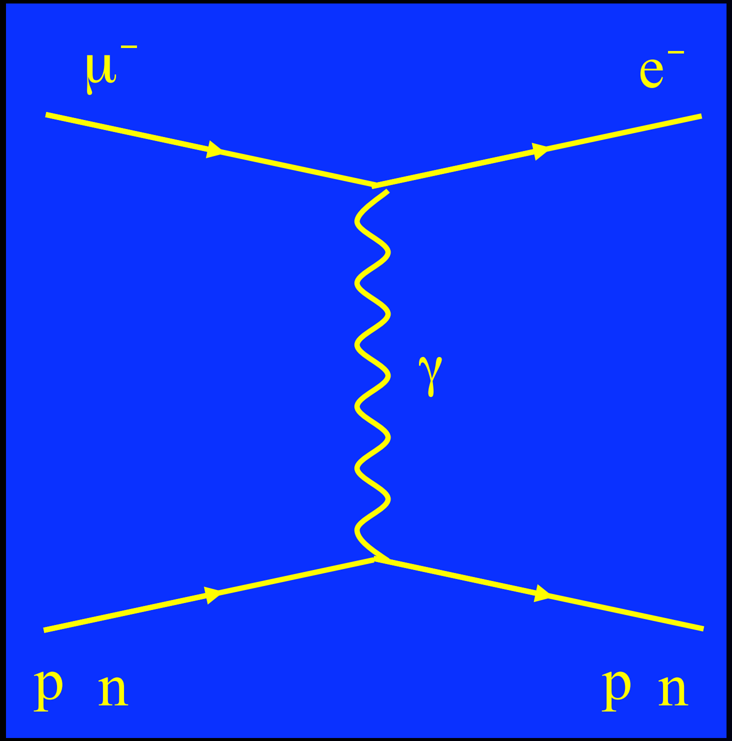
Photonic (dipole) and non-photonic contributions

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

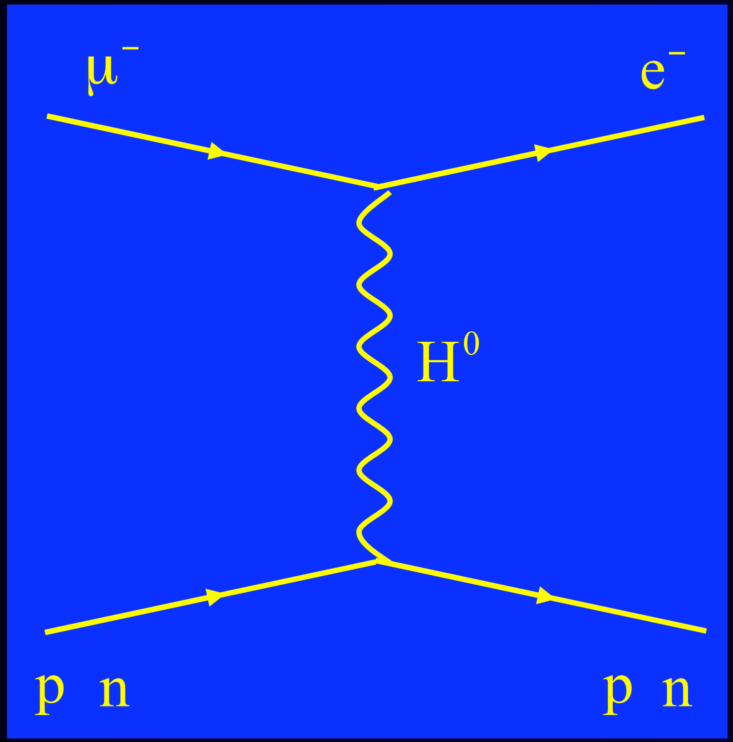
more sensitive to new physics



# SUSY Higgs Mediated Contribution (large tanβ)

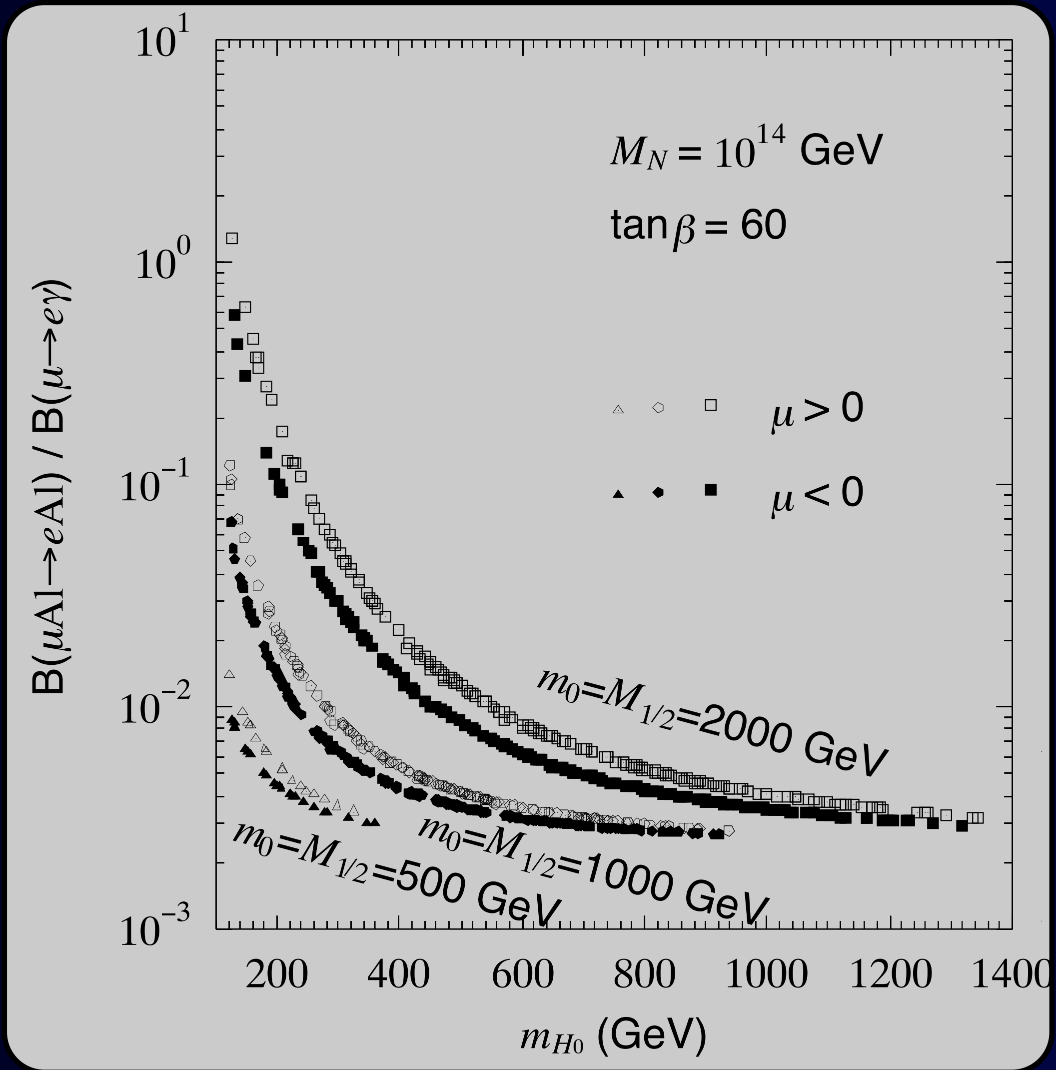


$$\frac{B(\mu N \to eN)}{B(\mu \to e\gamma)} \sim \frac{1}{100}$$



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

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



# Experimental Comparison between μ→eγ and μ-e Conversion

| | background | challenge | beam intensity |
|---|---|---|---|
| • μ→eγ | accidentals | detector resolution | limited |
| • μ-e conversion | beam | beam background | no limitation |

- μ→eγ : 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.

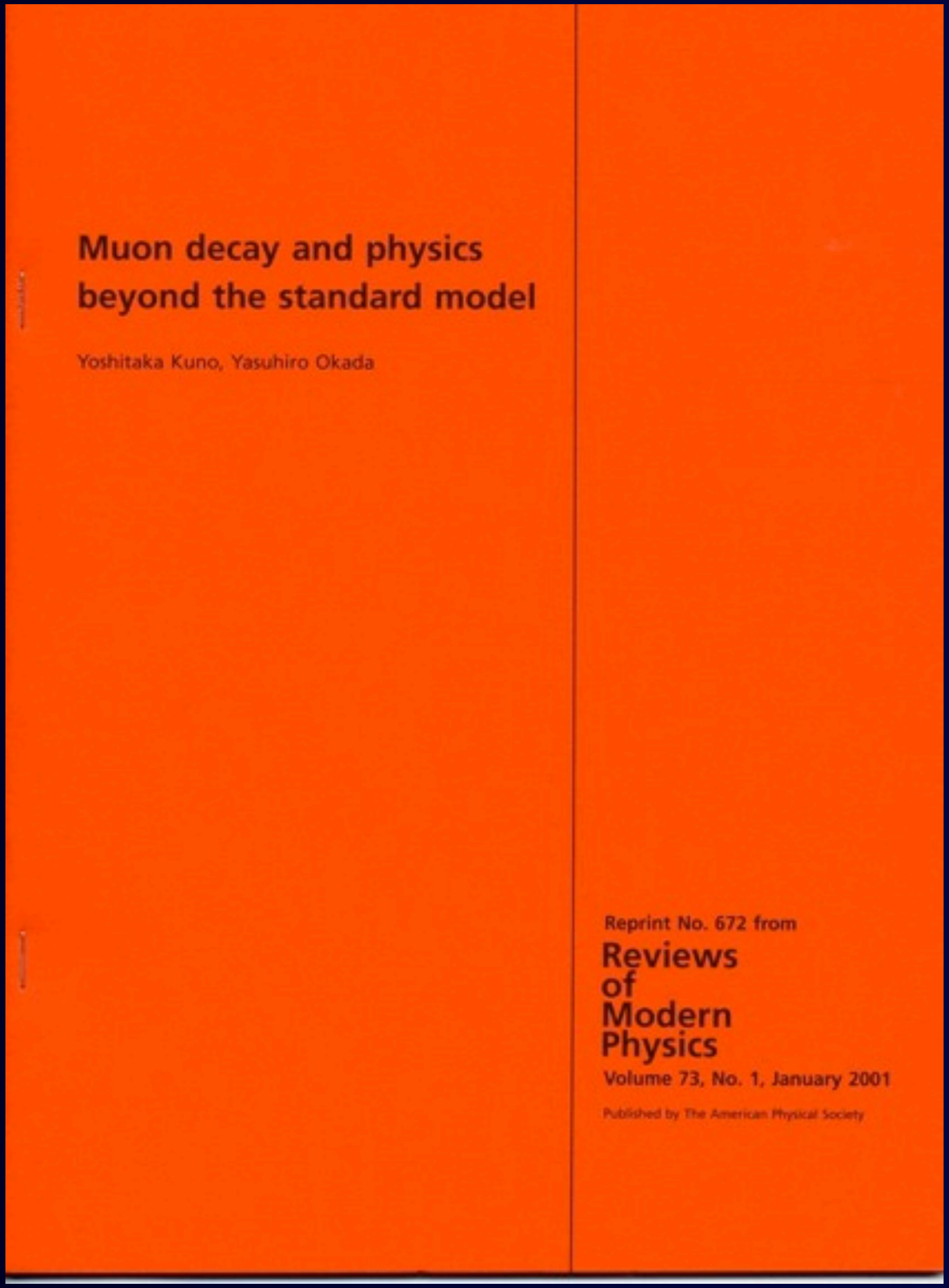
μ-e conversion might be a next step.

# For Further References

## Muon decay and physics beyond the standard model

Yoshitaka Kuno and Yasuhiro Okada

Review of Modern Physics 73 (2001)



Muon decay and physics beyond the standard model

Yoshitaka Kuno, Yasuhiro Okada

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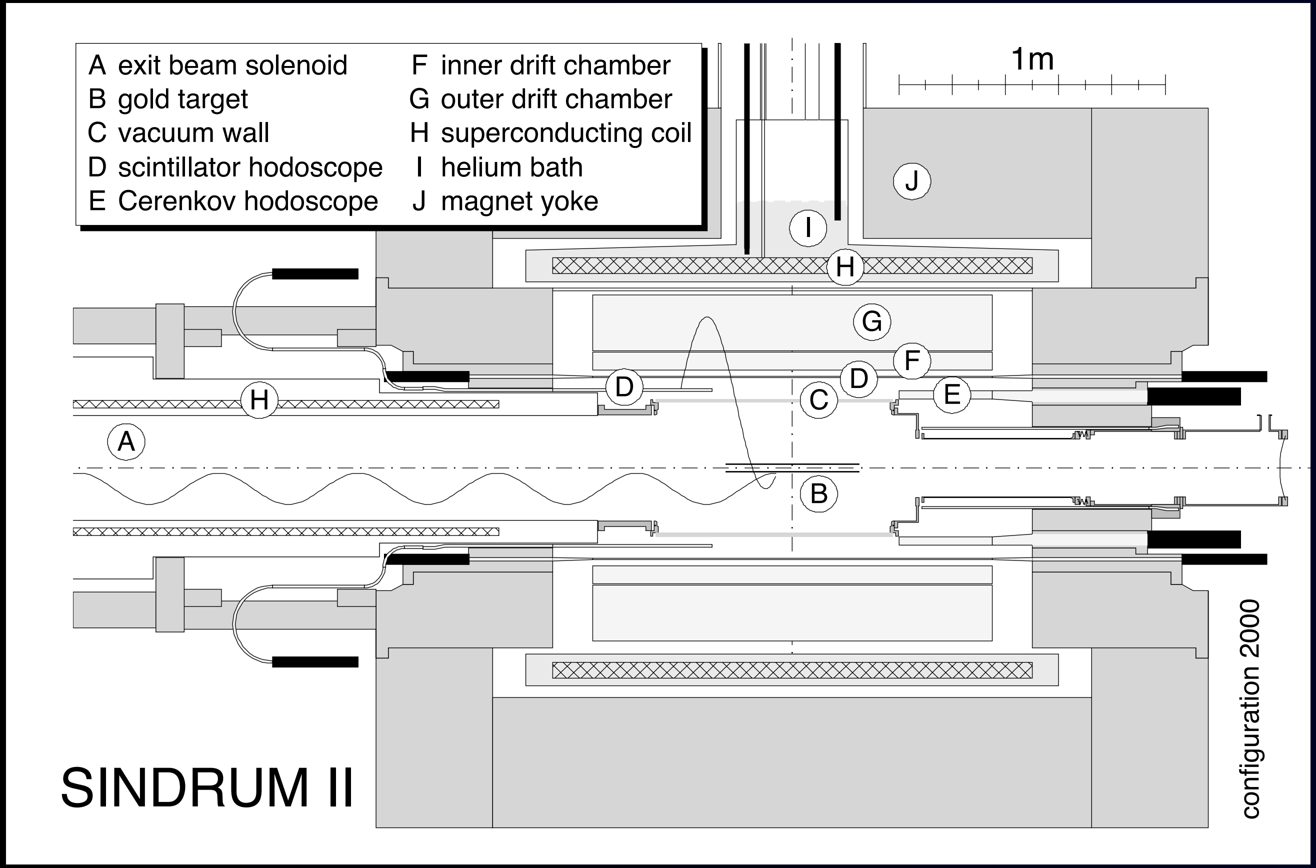
Reviews
of
Modern
Physics
Volume 73, No. 1, January 2001

Published by The American Physical Society

# Experimental Design for Muon to Electron Conversion - $10^{-16}$

# Previous Measurements

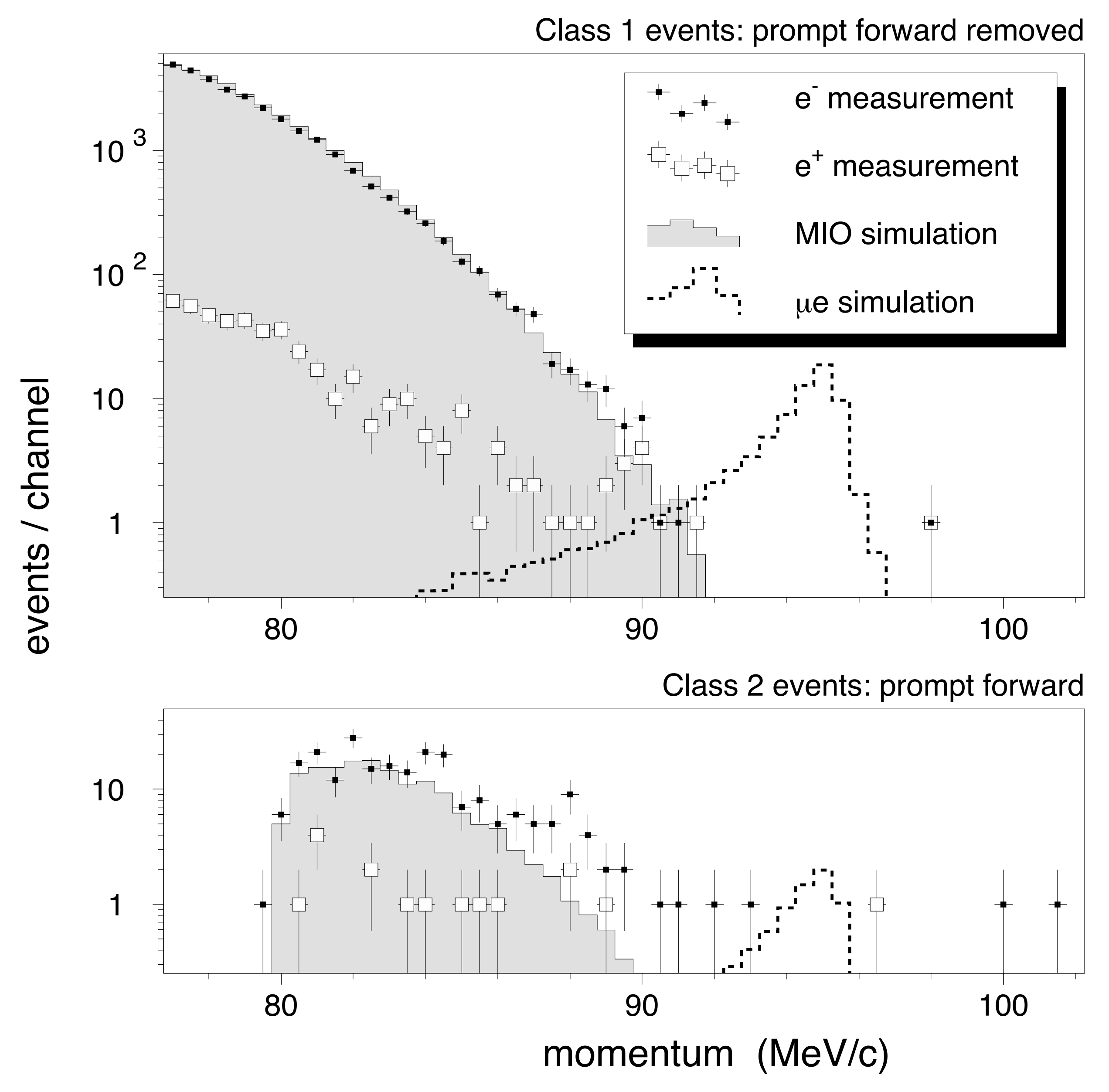
## SINDRUM-II (PSI)



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)

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



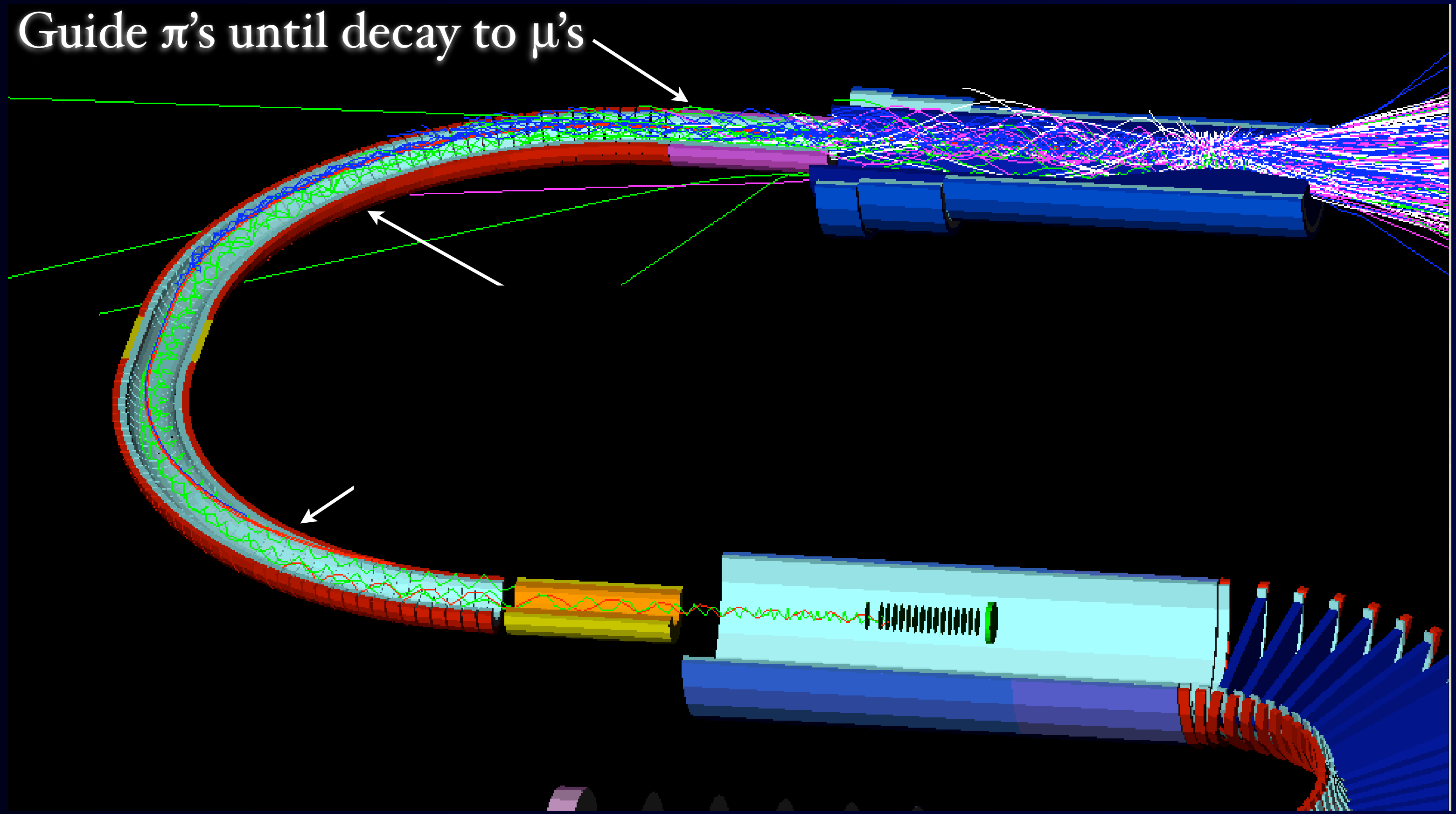
# Improvements for Signal Sensitivity

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

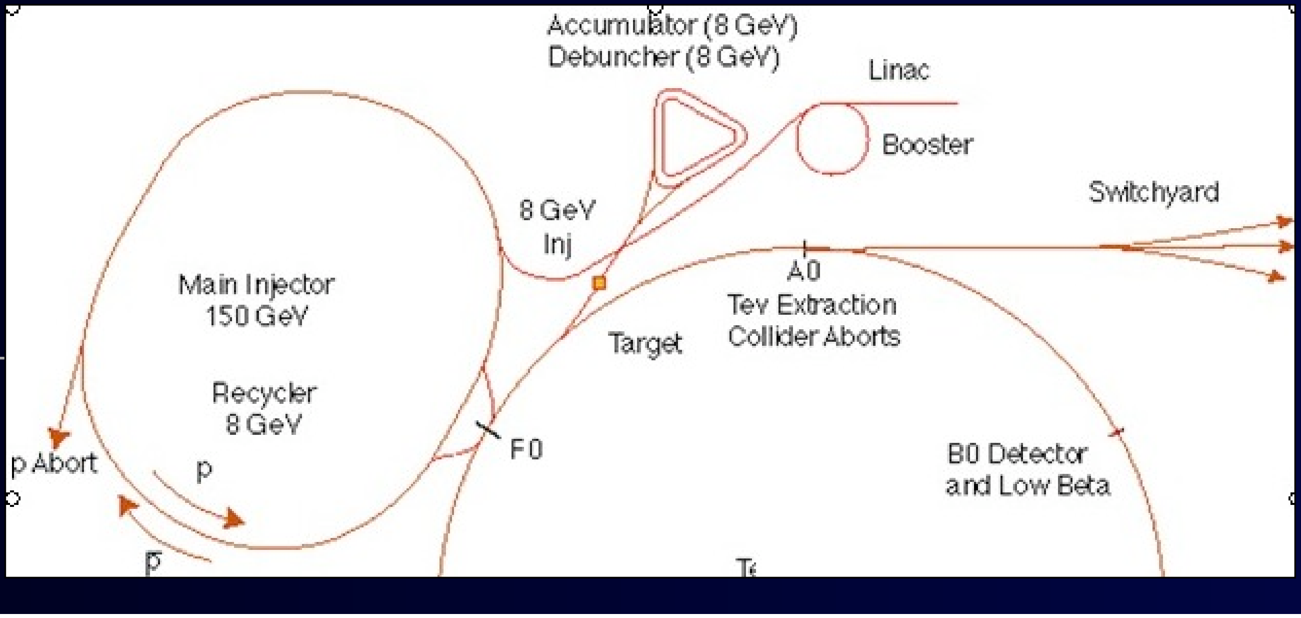


# Improvements for Background Rejection

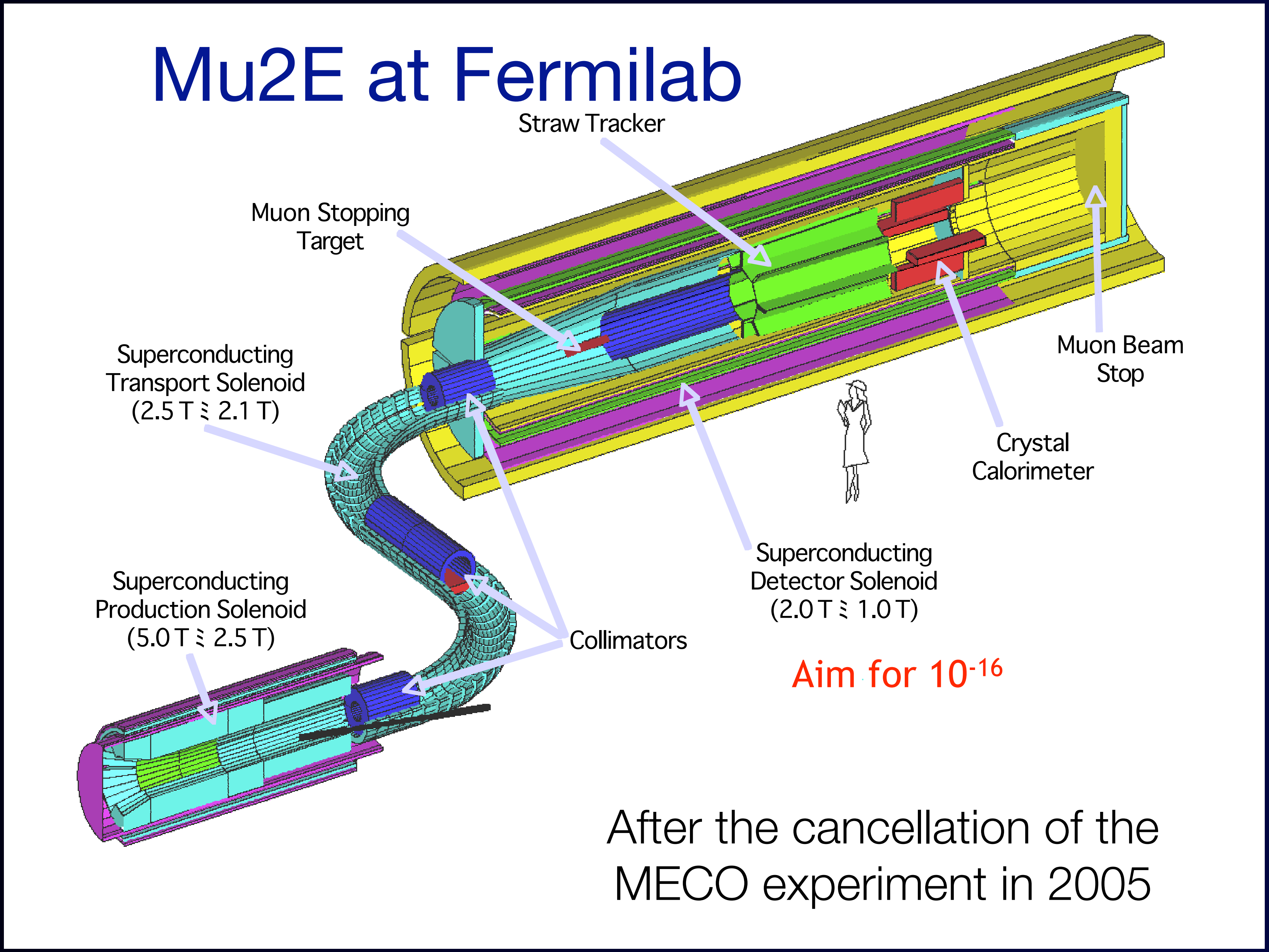
| | | |
|---|---|---|
| Beam-related backgrounds | Beam pulsing with separation of 1µsec | measured between beam pulses |
| Muon DIO background | low-mass trackers in vacuum & thin target | improve electron energy resolution |
| Muon DIF background | curved solenoids for momentum selection | eliminate 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.



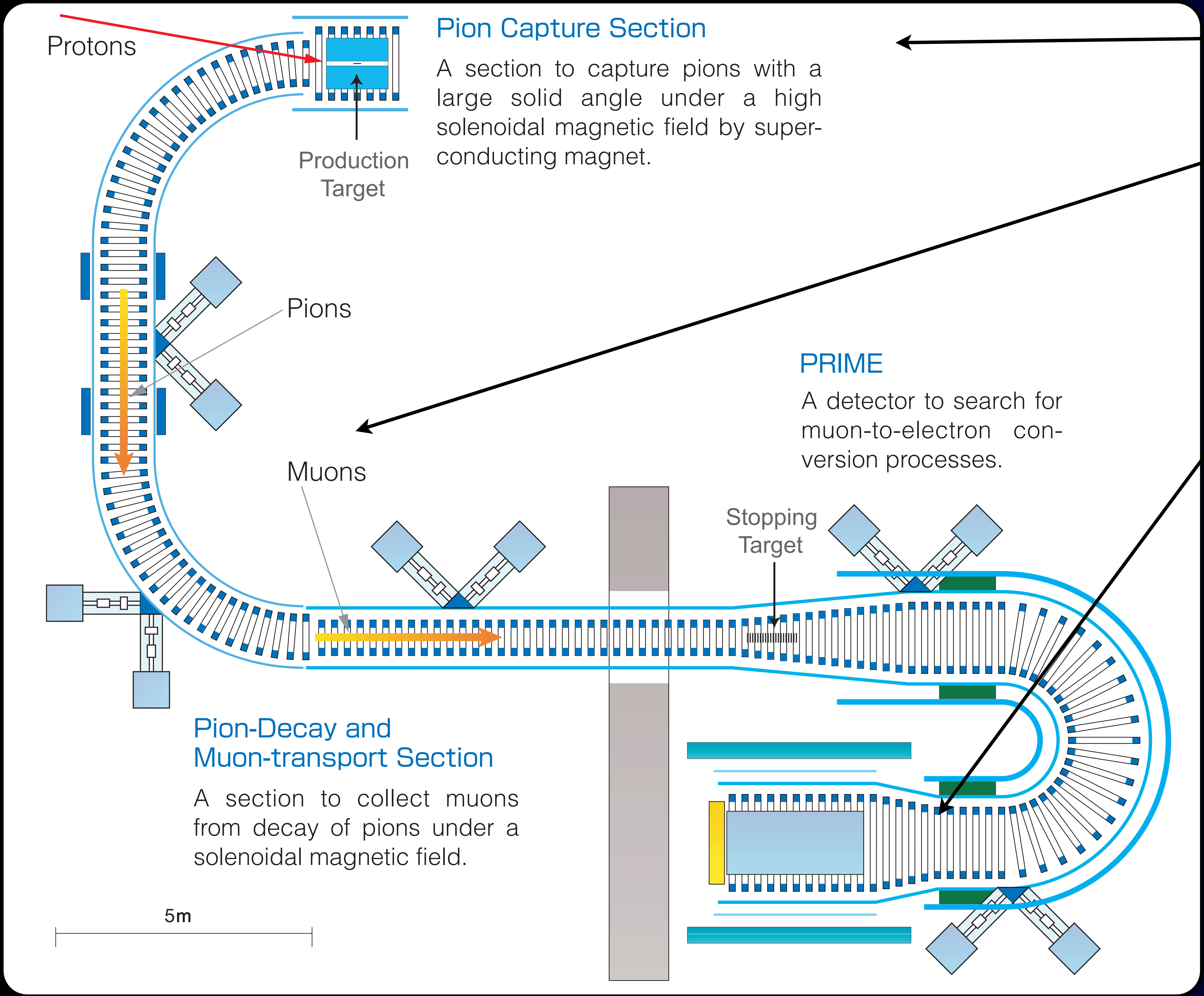
## Mu2E at Fermilab

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 |

# Charged Particle Trajectory in Curved Solenoids

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

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

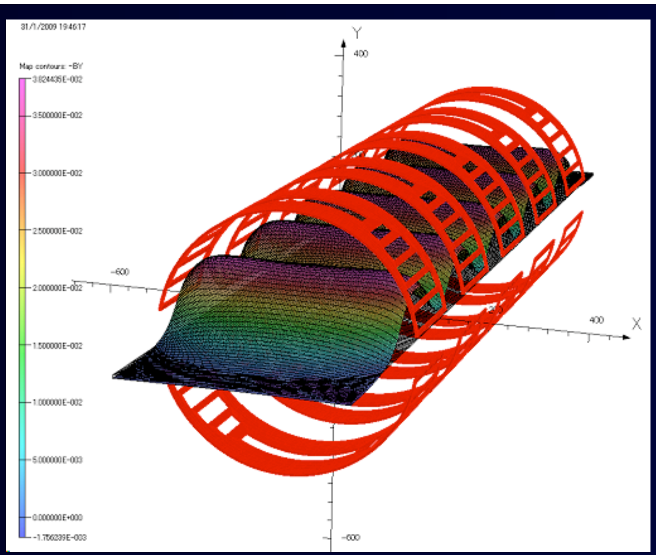
$D$ : *drift distance*
$B$ : *Solenoid field*
$\theta_{bend}$ : *Bending angle of the solenoid channel*
$p$ : *Momentum of the particle*
$q$ : *Charge of the particle*
$\theta$ : *atan*$(P_T/P_L)$

  - This can be used for charge and momentum selection.

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

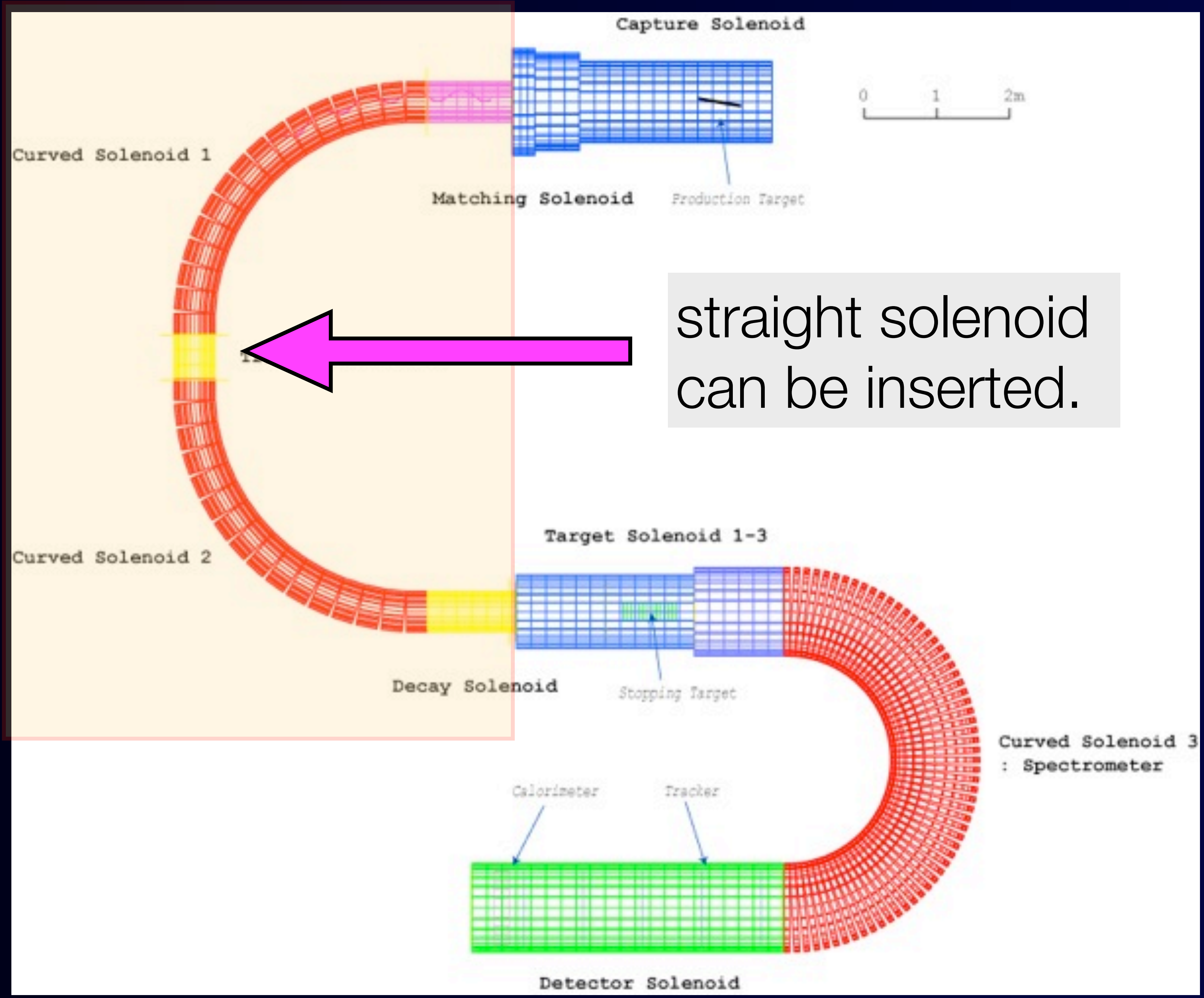
$$B_{comp} = \frac{p}{qr}\frac{1}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$

$p$ : *Momentum of the particle*
$q$ : *Charge of the particle*
$r$ : *Major radius of the solenoid*
$\theta$ : *atan*$(P_T/P_L)$



# Muon Transport Solenoid Beam-line for COMET

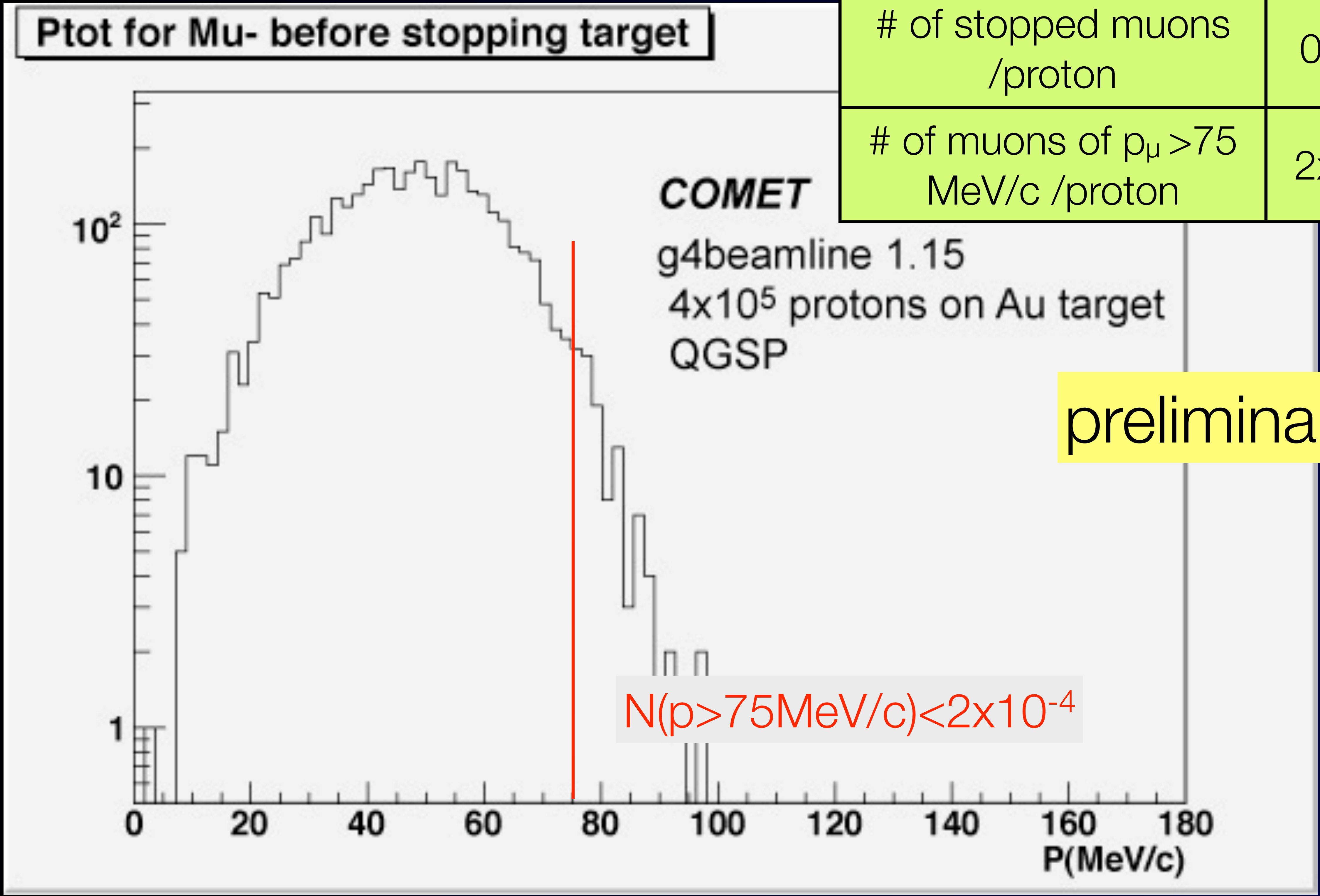
- C-shape beam line :
  - better beam momentum separation
  - collimators can be placed anywhere.
- Radius of curvature is about 3 meters.
- A straight solenoid section can be inserted between the two toroids.
- Reference momentum is 35 MeV/c for 1st bend and 47 MeV/c for 2nd bend.



straight solenoid can be inserted.

# Muon Momentum Spectrum at the End of the Transport Beam Line

| | |
|---|---|
| # of muons /proton | 0.009 |
| # of stopped muons /proton | 0.003 |
| # of muons of $p_\mu > 75$ MeV/c /proton | $2\times10^{-4}$ |

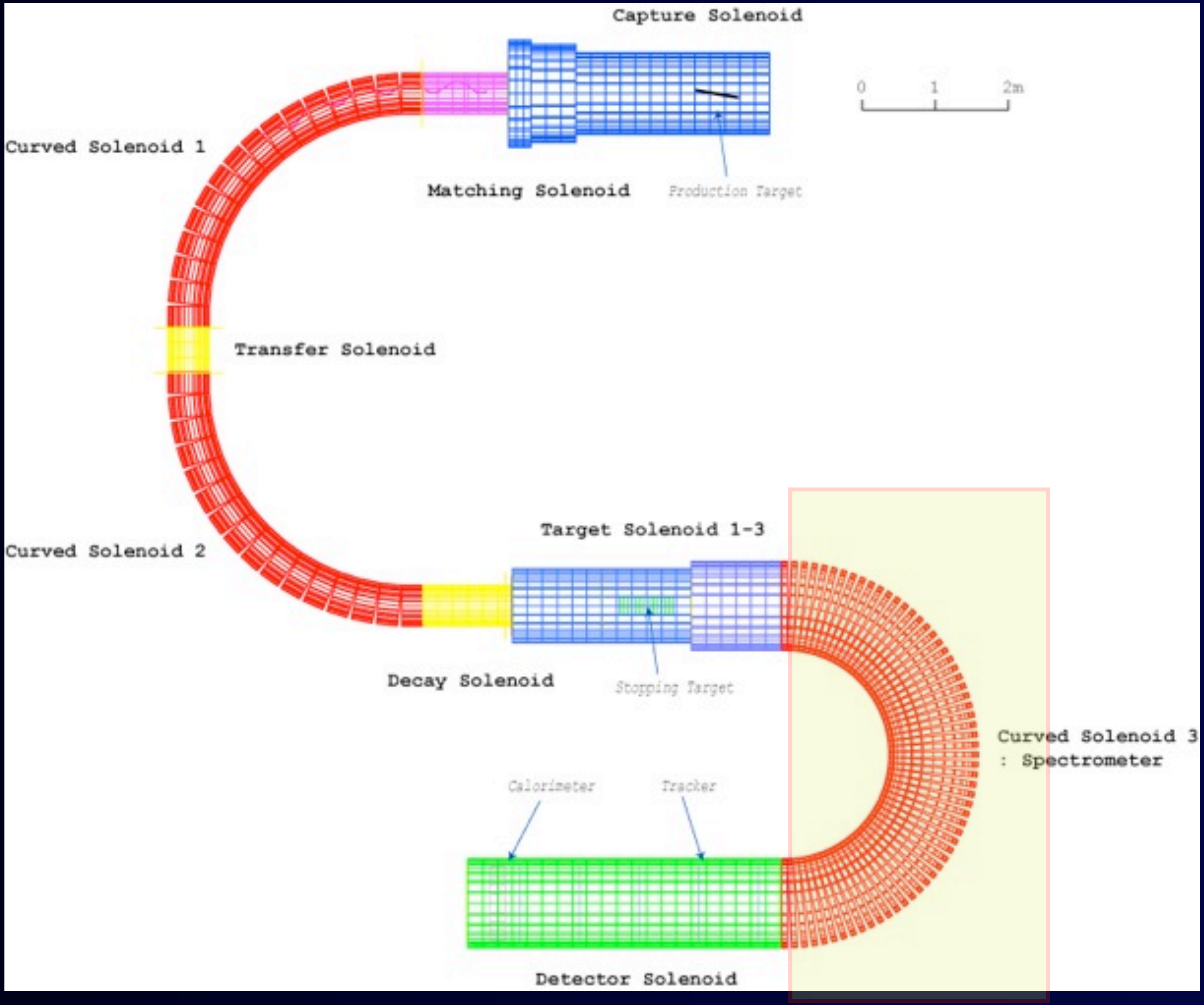


$N(p > 75\text{MeV/c}) < 2\times10^{-4}$

preliminary

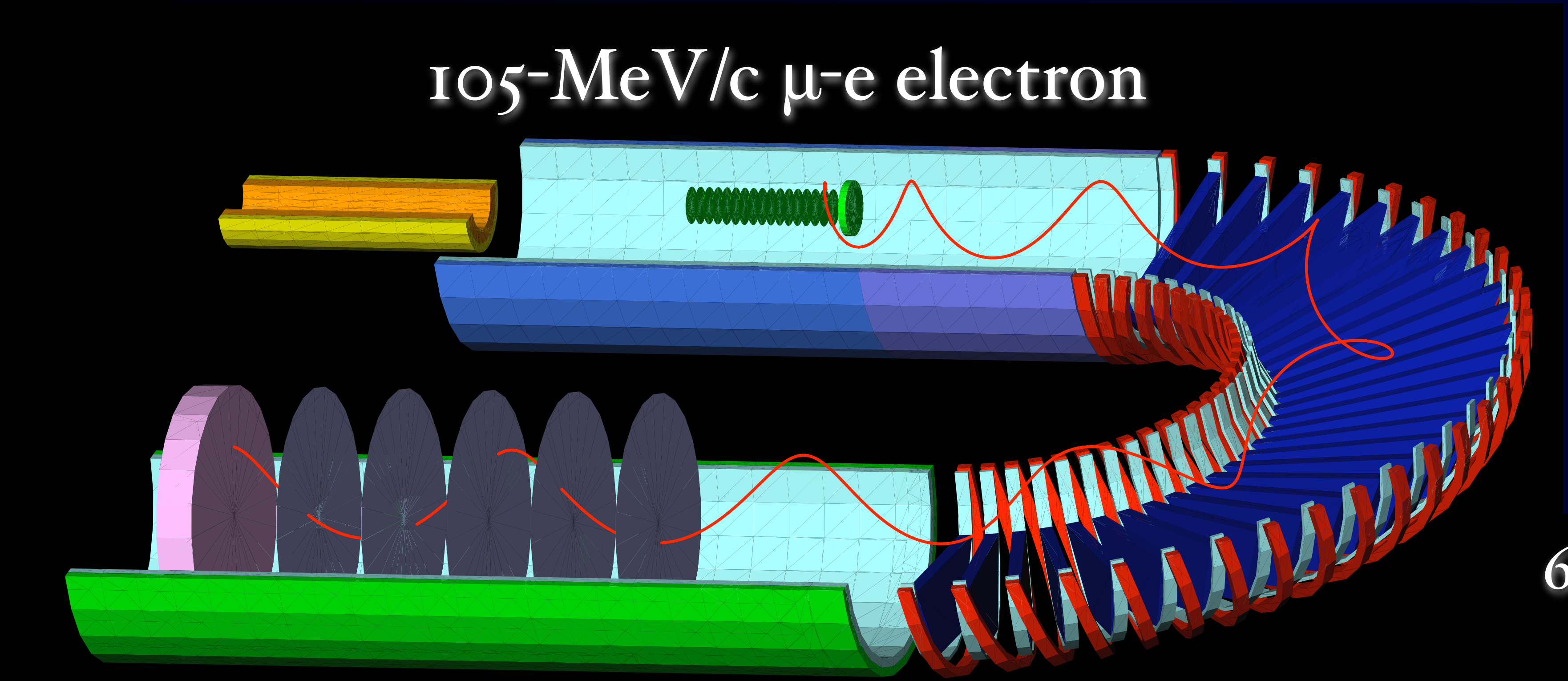
# Curved Solenoid Spectrometer for COMET

- 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.

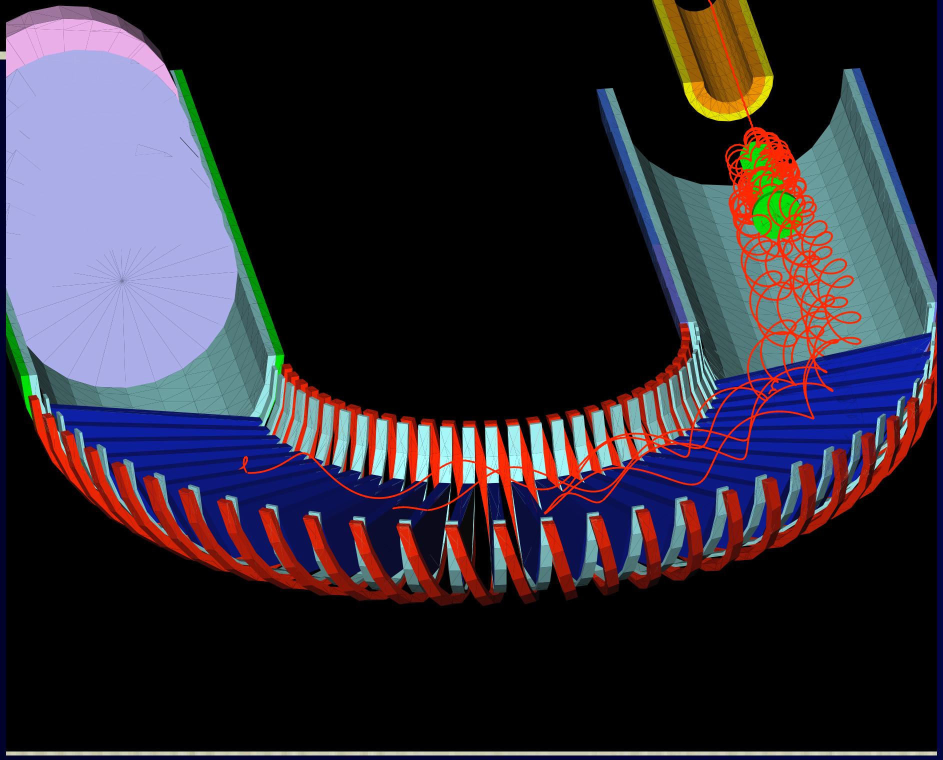


schematic

# Event Displays for Curved Solenoid Spectrometer



105-MeV/c μ-e electron



60-MeV/c DIO electrons

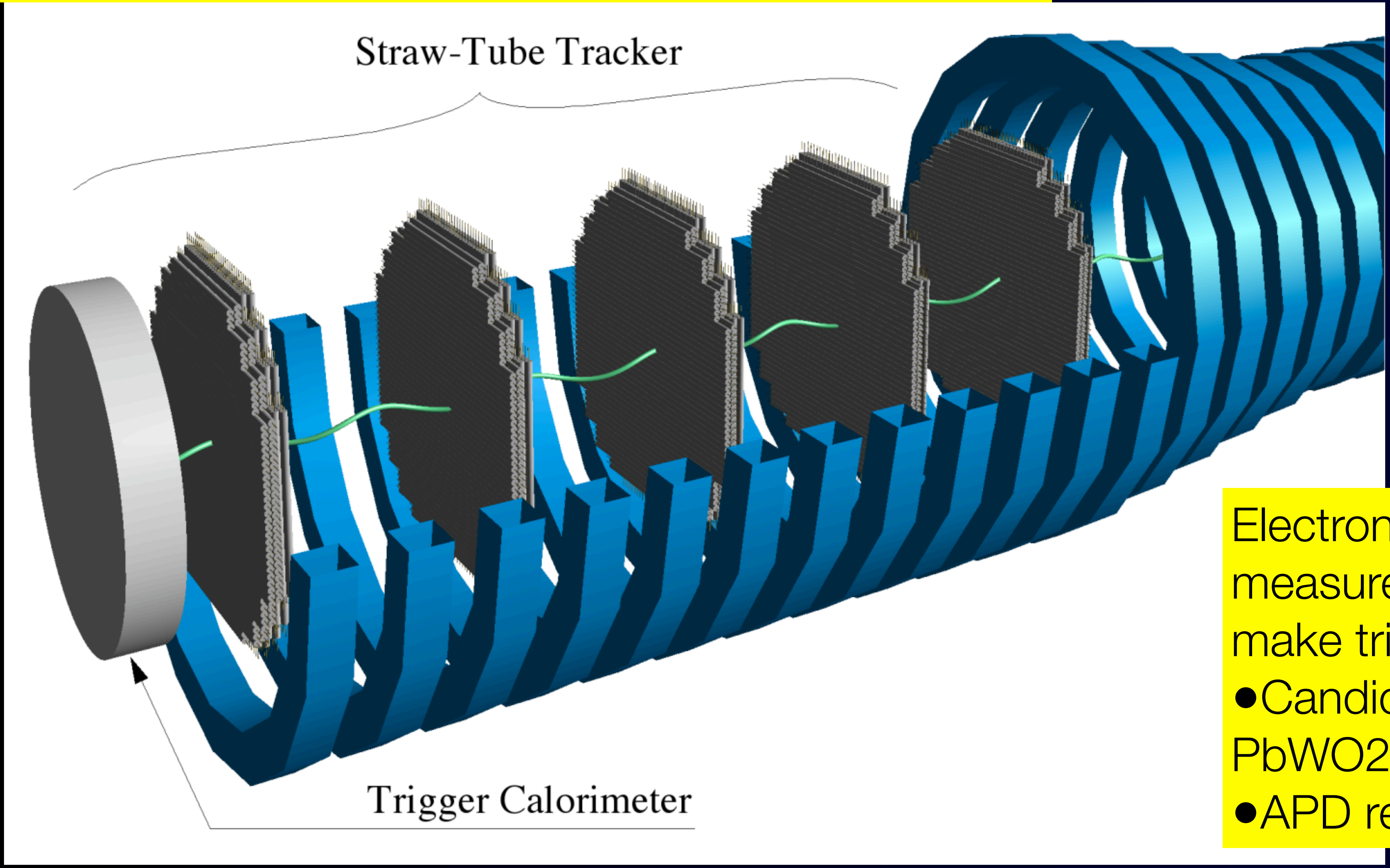
# Electron Detection (preliminary)

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.

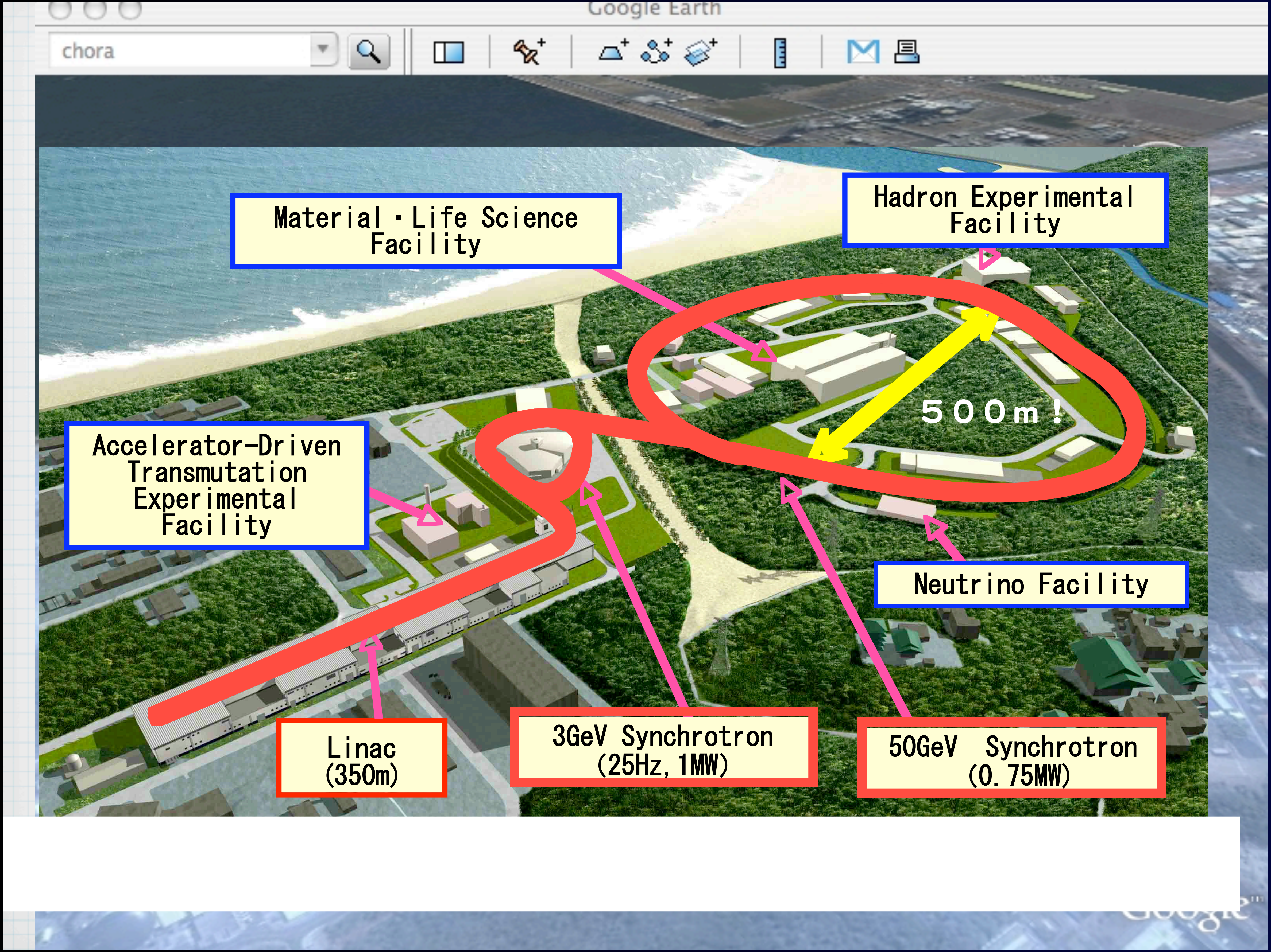
In vacuum to reduce multiple scattering.



Electron calorimeter to measure electron energy and make triggers.

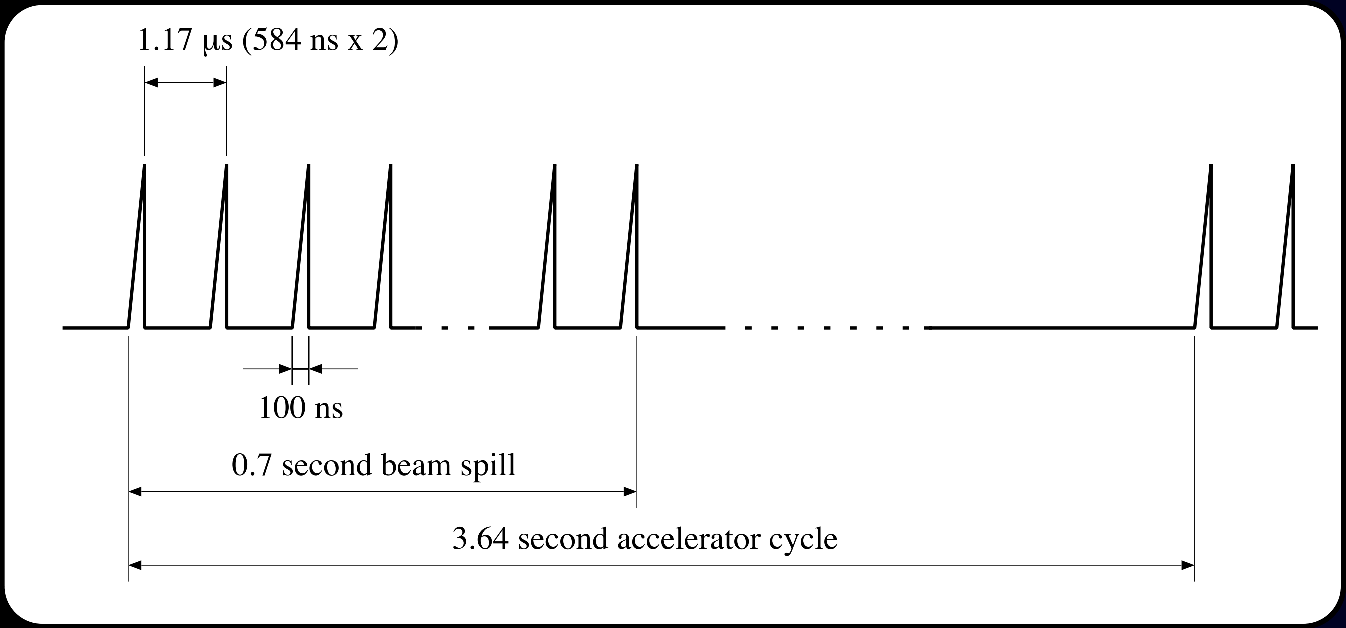
- Candidate are GSO or PbWO2.
- APD readout (no PMT).

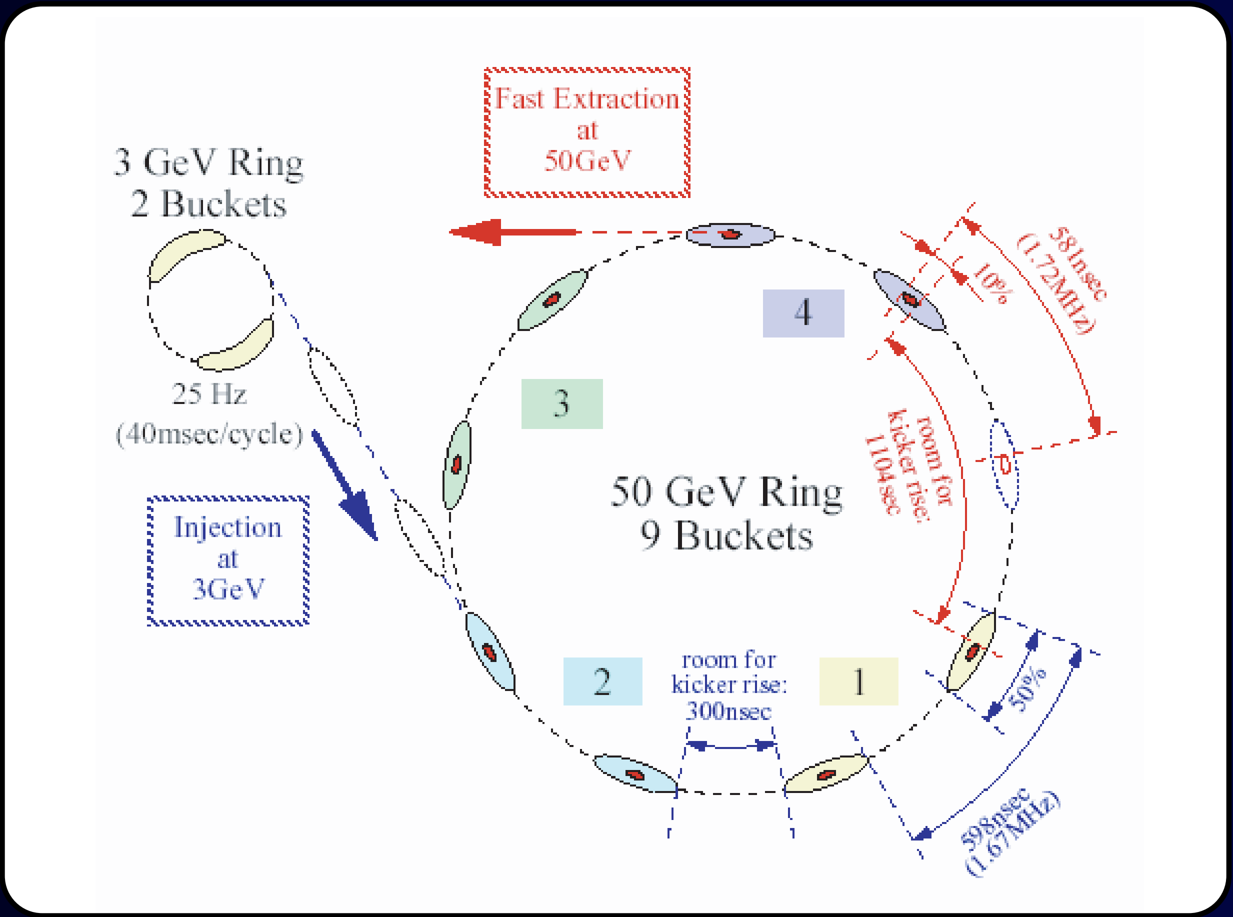
# J-PARC at Tokai, Japan



# Proton Beam at J-PARC (1)

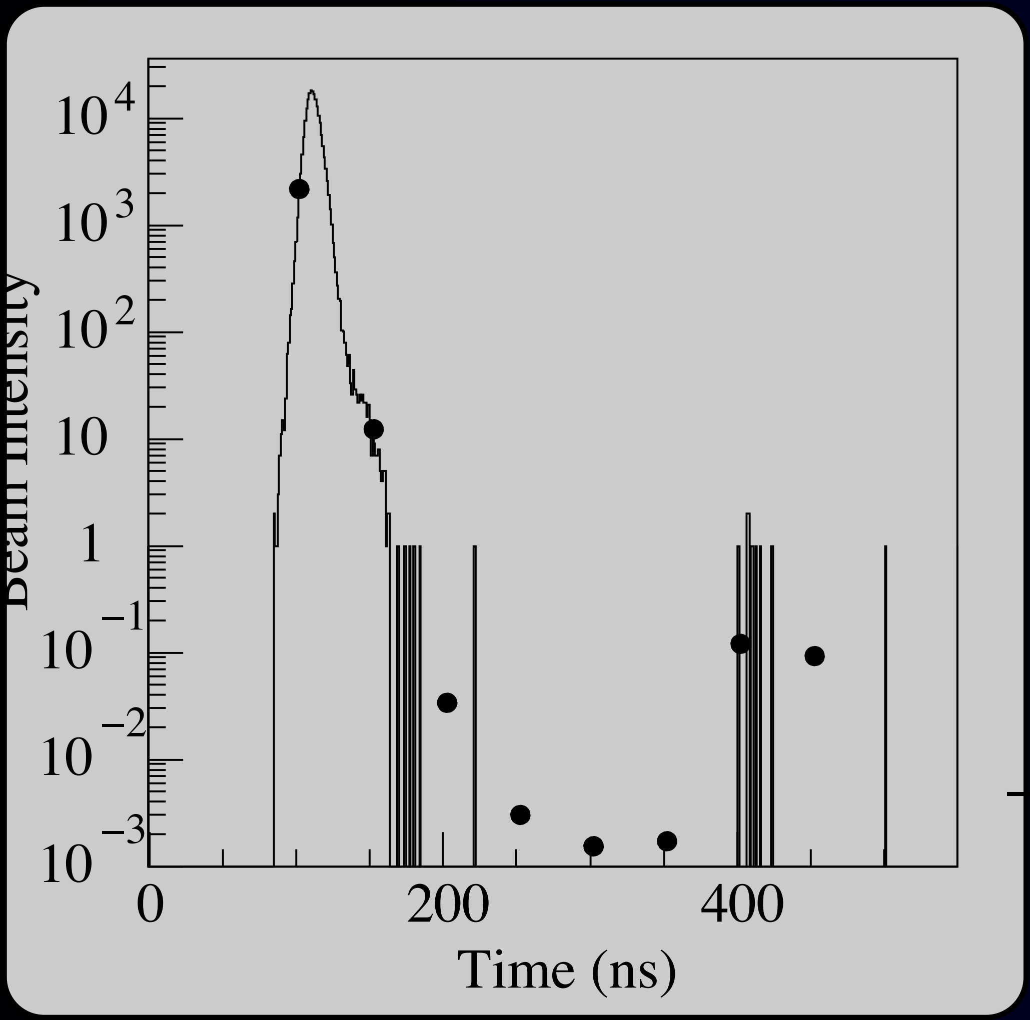
- A pulsed proton beam is needed to reject beam-related prompt background.
- Time structure required for proton beams.
  - Pulse separation is ~ 1µsec or more (muon lifetime).
  - Narrow pulse width (<100 nsec)
- Pulsed beam from slow extraction.
  - fill every other rf buckets with protons and make slow extraction
  - spill length (flat top) ~ 0.7





# Proton Beam at J-PARC (2)

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

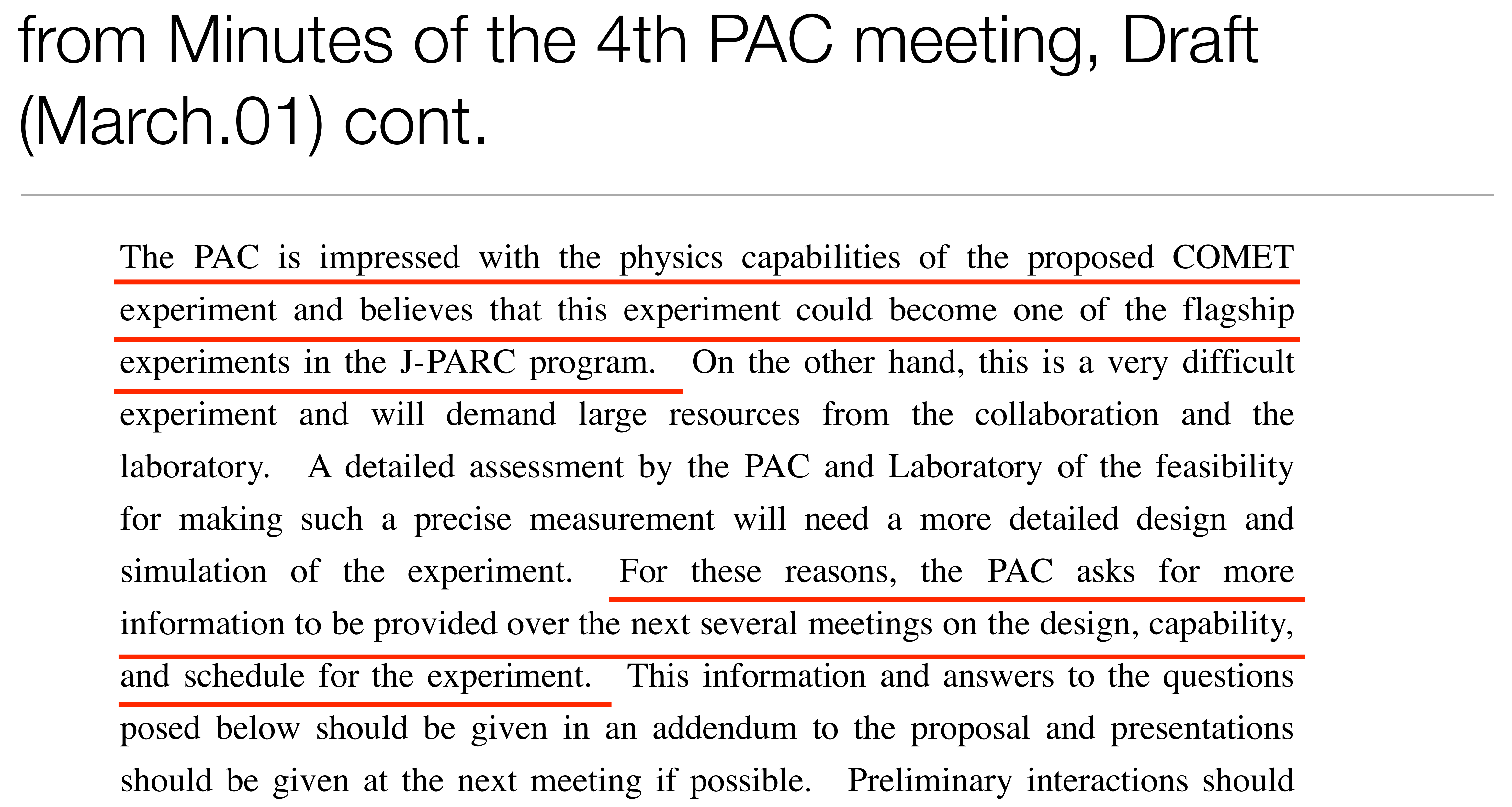


Test of Extinction at BNL-AGS

- Required Protons :
  - 4 x $10^{20}$ protons of 8 GeV in total for a single event sensitivity of about 0.33 x $10^{-17}$.
  - For 1 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).

# Report from the J-PARC PAC Meeting Jan. 2008

One of the flagship experiments in the J-PARC programs.



from Minutes of the 4th PAC meeting, Draft (March.01) cont.

The PAC is impressed with the physics capabilities of the proposed COMET experiment and believes that this experiment could become one of the flagship experiments in the J-PARC program. On the other hand, this is a very difficult experiment and will demand large resources from the collaboration and the laboratory. A detailed assessment by the PAC and Laboratory of the feasibility for making such a precise measurement will need a more detailed design and simulation of the experiment. For these reasons, the PAC asks for more information to be provided over the next several meetings on the design, capability, and schedule for the experiment. This information and answers to the questions posed below should be given in an addendum to the proposal and presentations should be given at the next meeting if possible. Preliminary interactions should

# Signal Sensitivity (preliminary) - 2 x $10^7$ sec

- Single event sensitivity

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

  - $N_\mu$ is a number of stopping muons in the muon stopping target. It is $1.1\times10^{18}$ 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<br>muon transport efficiency<br>muon stopping efficiency | $4\times10^{20}$<br>0.009<br>0.3 |
| # of stopped muons | $1.1\times10^{18}$ |

$$B(\mu^- + Al \to e^- + Al) = 3.3 \times 10^{-17}$$
$$B(\mu^- + Al \to e^- + Al) < 7 \times 10^{-17} \quad (90\% C.L.)$$

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 & $2\times10^{7}$sec run |
| Pattern recognition errors | <0.001 | |
| Total | 0.4 | |

# $10^{-18}$ Sensitivity with PRISM

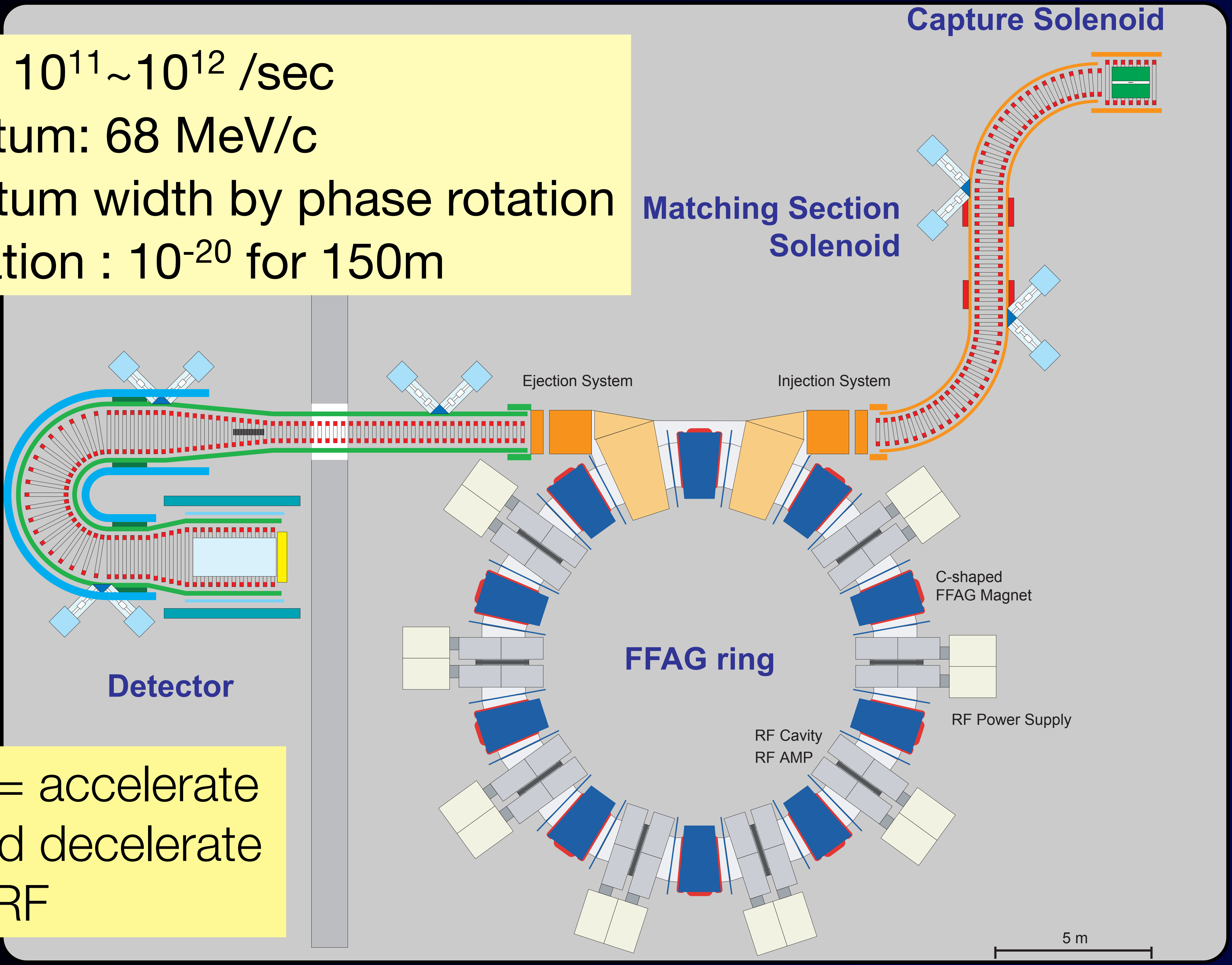
# Further Background Rejection to $< 10^{-18}$

| | | |
|---|---|---|
| Pion background | long muon beam-line | muon storage ring |
| Muon DIO & Beam flush | narrow muon beam spread | 1/10 thickness muon stopping target |
| Beam-related Background | Extinction at muon beam | fast kickers |
| Cosmic-ray background | low-duty running | 100 Hz rather than 1 MHz |

# PRISM Muon Beam

PRISM=Phase Rotated Intense Slow Muon source

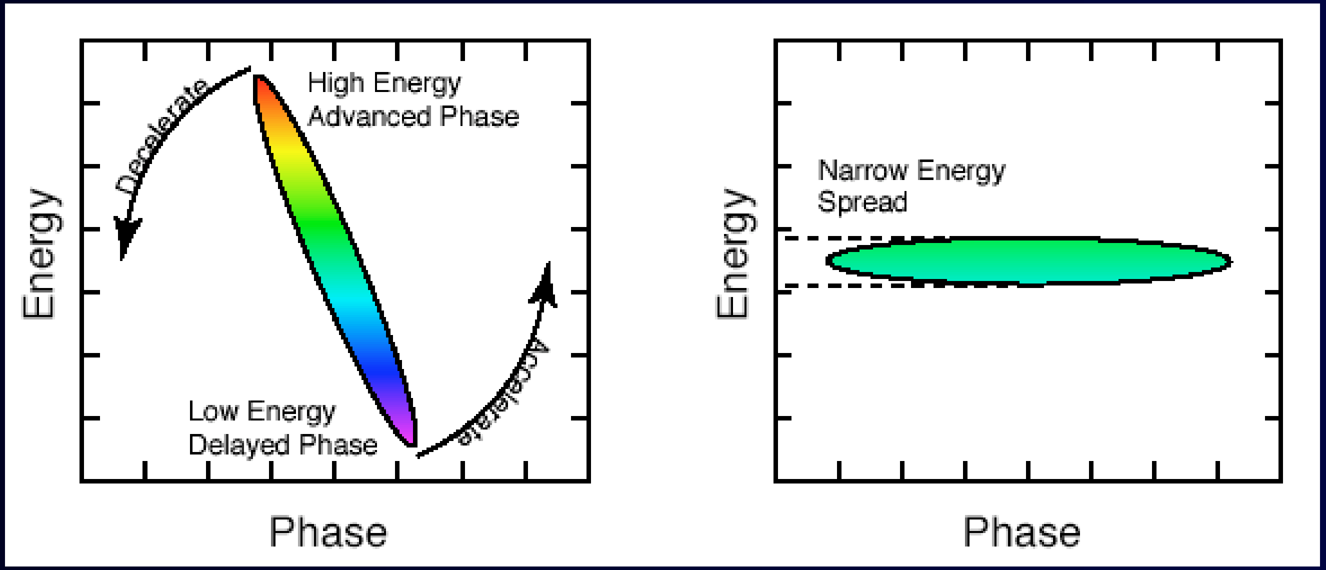
muon intensity: $10^{11}$~$10^{12}$ /sec
central momentum: 68 MeV/c
narrow momentum width by phase rotation
pion contamination : $10^{-20}$ for 150m



Phase rotation = accelerate slow muons and decelerate fast muons by RF

# ... To Make Narrow Beam Energy Spread

- A technique of phase rotation is adopted.
- The phase rotation is to decelerate fast beam particles and accelerate slow beam particles.
- To identify energy of beam particles, a time of flight (TOF) from the proton bunch is used.
  - Fast particle comes earlier and slow particle comes late.
- Proton beam pulse should be narrow (< 10 nsec).
- Phase rotation is a well-established technique, but how to apply a tertiary beam like muons (broad emittance) ?



# Phase Rotation for a Muon Beam

## Use a muon storage ring ?

(1) Use a muon Storage Ring :

A muon storage ring would be better and realistic than a linac option because of reduction of # of cavities and rf power.

(2) Rejection of pions in a beam :

At the same time, pions in a beam would decay out owing to long flight length.

## Which type of a storage ring ?

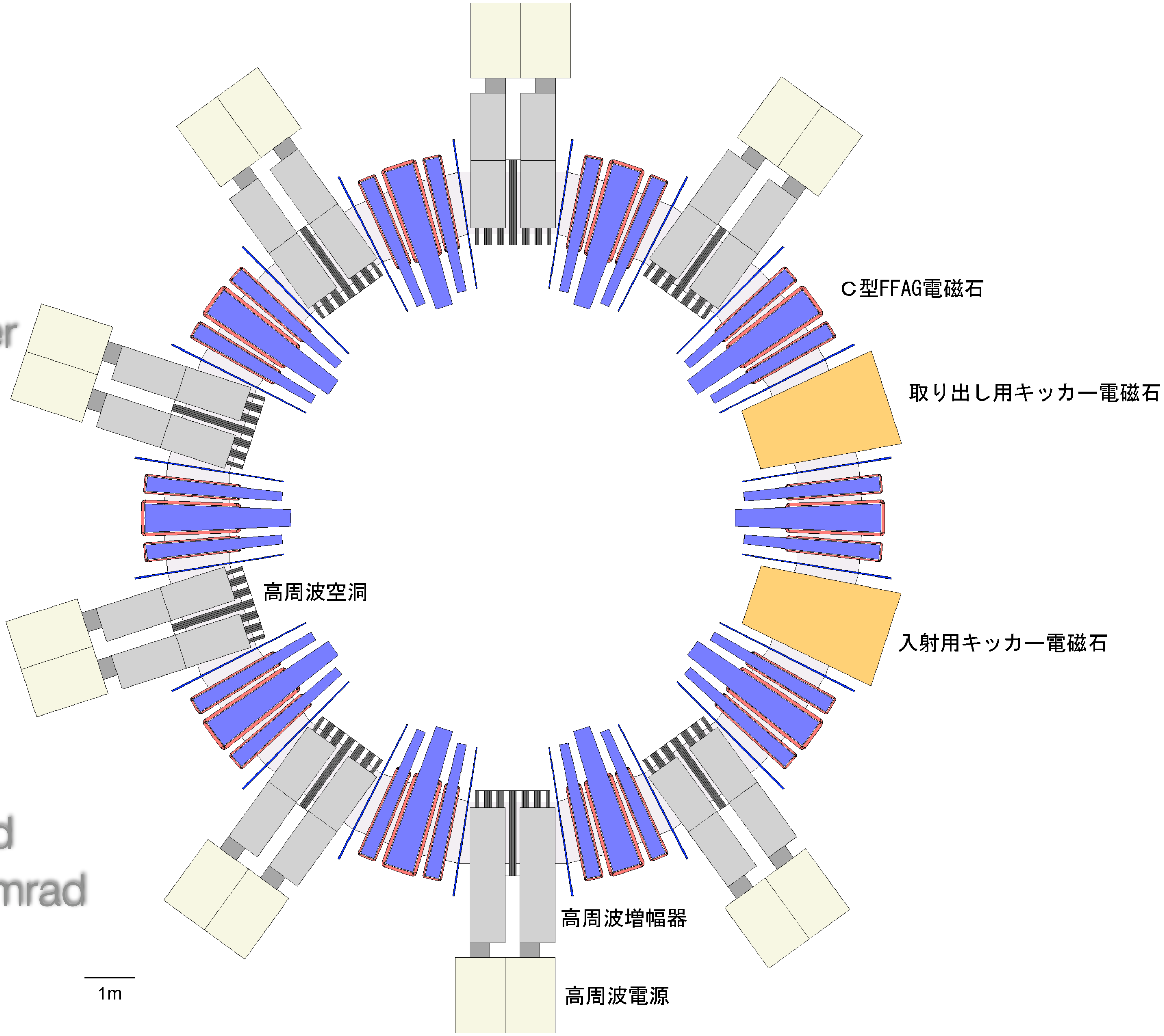
(1) cannot be cyclotron, because of no synchrotron oscillation.

(2) cannot be synchrotron, because of small acceptance and slow acceleration.

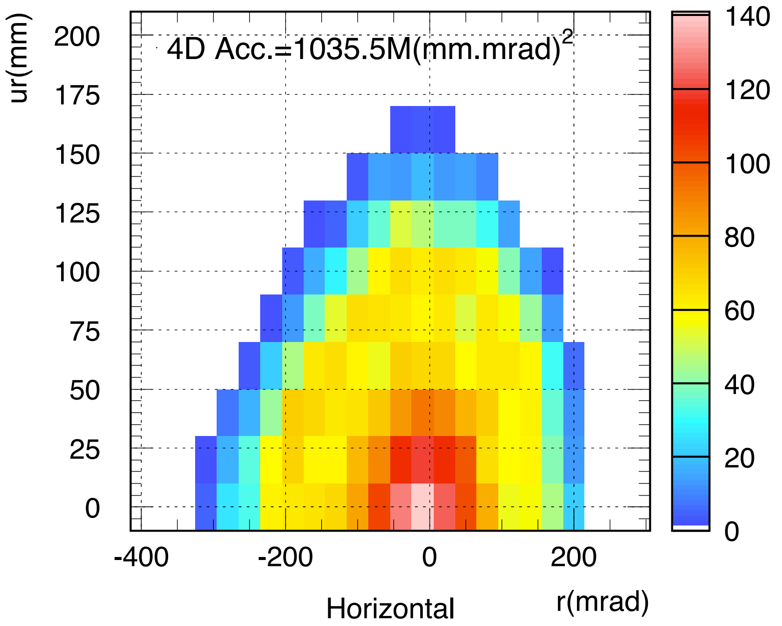
**Fixed field Alternating Gradient Ring (FFAG)**

# PRISM FFAG Lattice Design

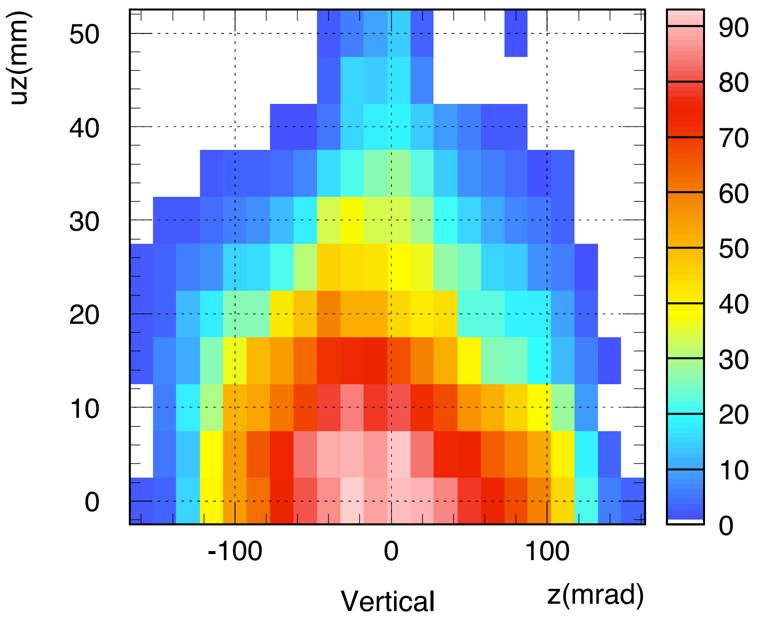
- 10 cells
- k=5(4.6-5.2)
- F/D(BL)=8
- r0=6.5m for 68MeV/c
- half gap = 15cm
- mag. size 110cm @ F center
- Triplet
  - $\theta_F$=4.40deg
  - $\theta_D$=1.86deg
- tune
  - h : 2.86
  - v : 1.44
- acceptance
  - h : 140000 π mm mrad
    - --> 40000 π mm mrad
  - v :   6500 π mm mrad



# PRISM-FFAG Acceptance

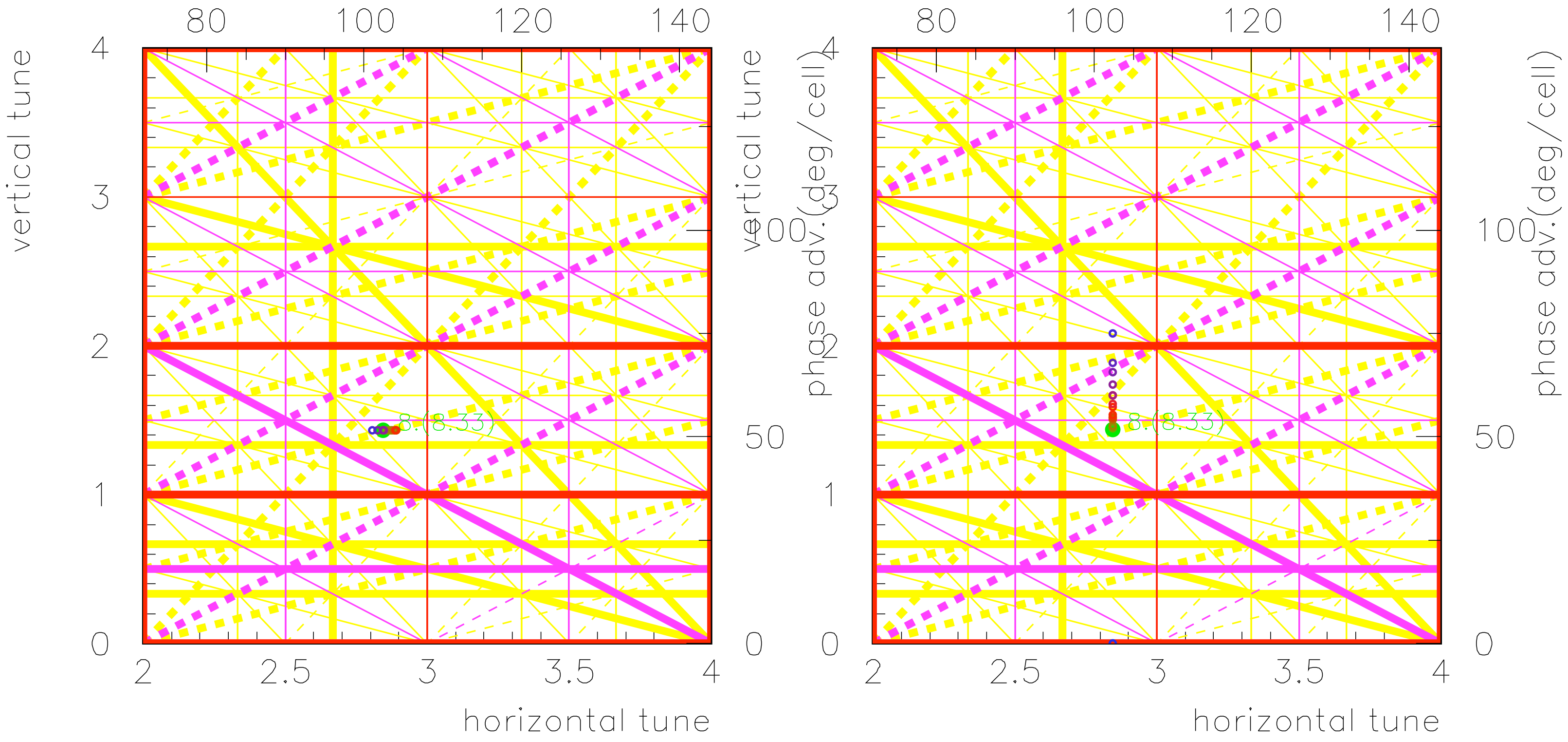


**Horizontal Acceptance**
**40000$\pi$ mm mrad**



**Vertical Acceptance**
**6500$\pi$ mm mrad**

N=10
F/D=8
k=5
r0=6.5m
H:2.86
V:144

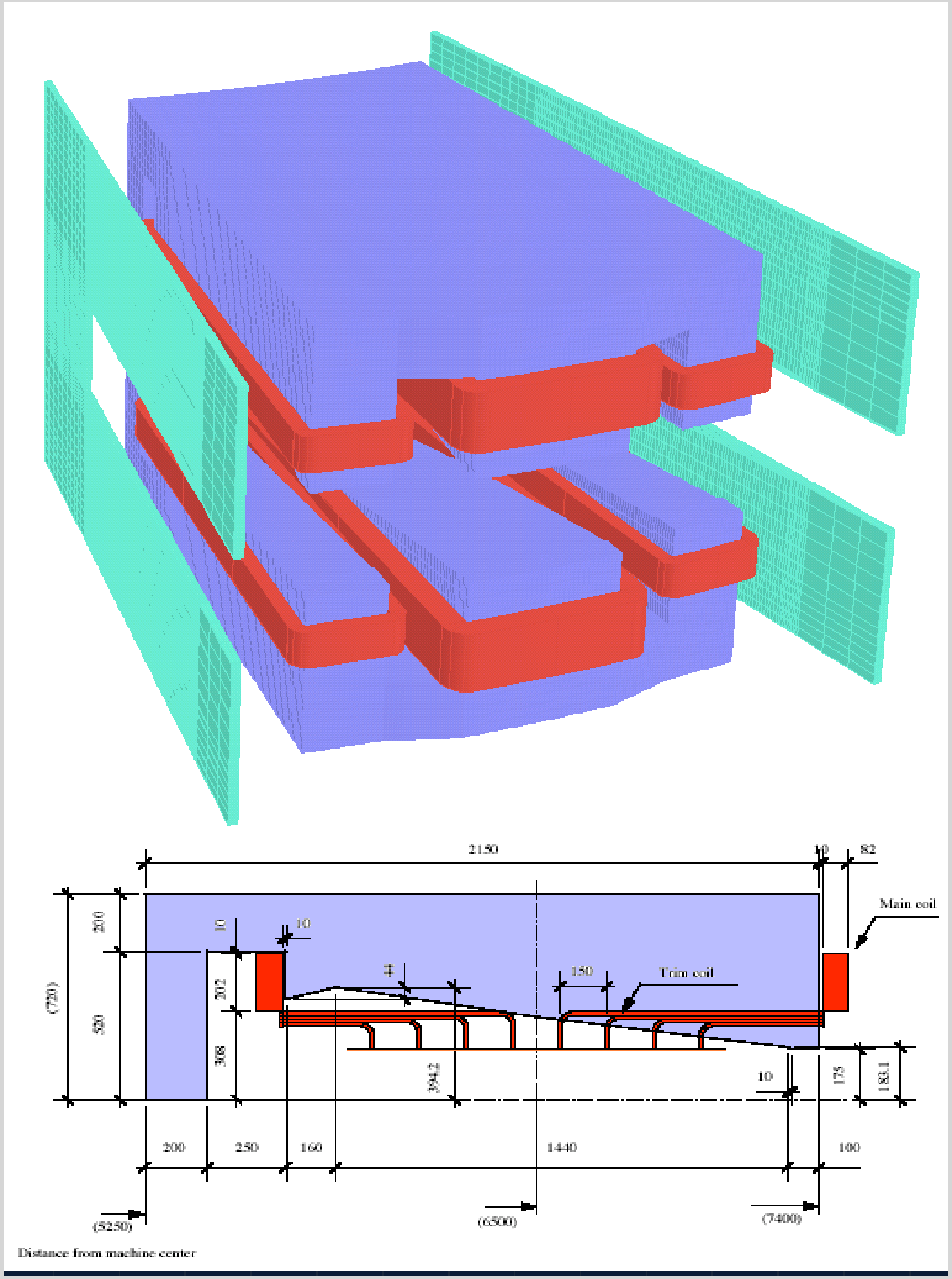


# PRISM FFAG Magnets

- radial sector with C-type yoke
  - D-F-D triplet

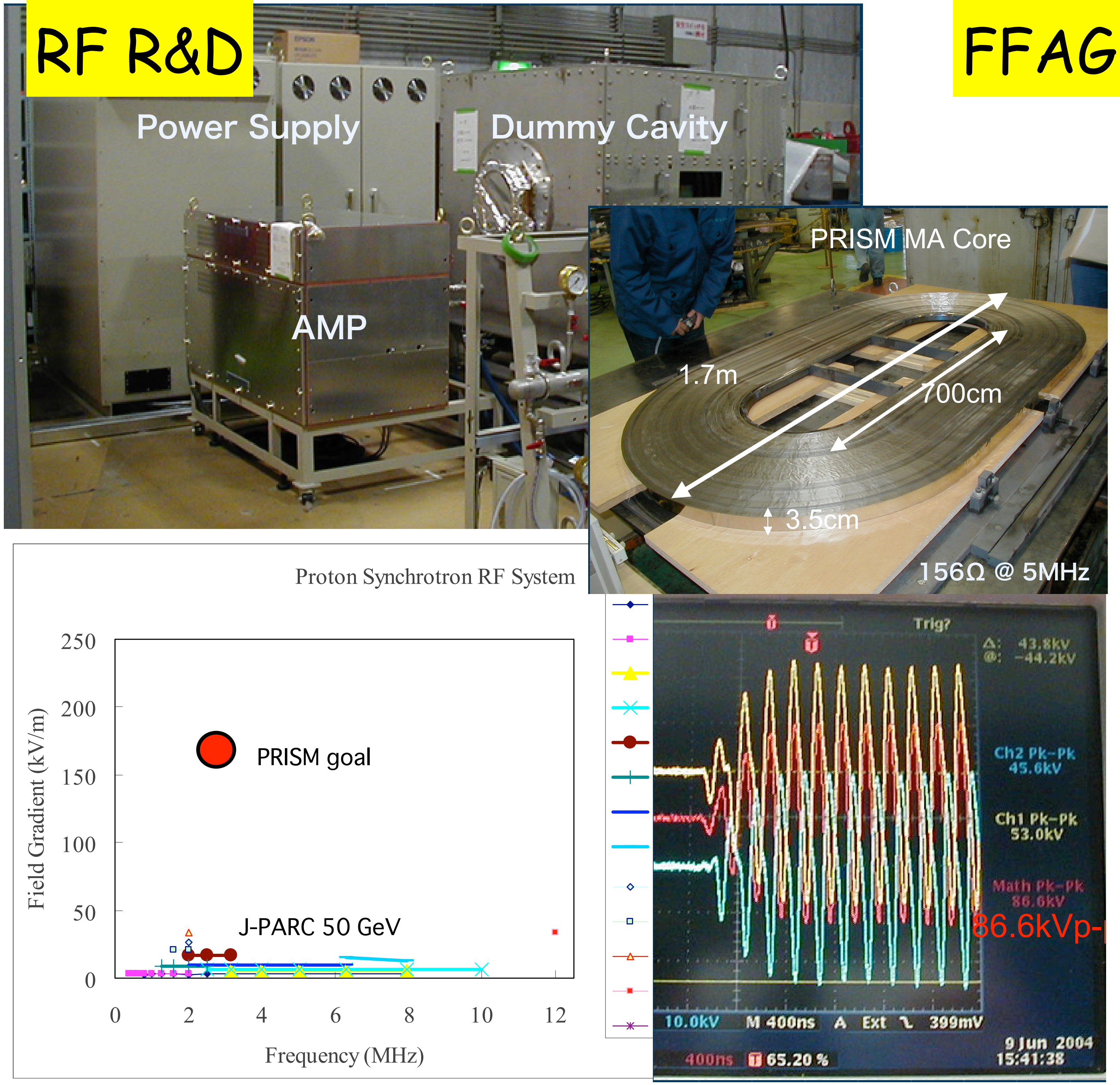
$$B(r) = B_0 \times (\frac{r}{r_0})^k$$

- machined pole shape to create field gradient (k)
- trim coils for variable k values (future)
- vertical tune : F/D
- horizontal tune : k value
- magnetic field design : TOSCA

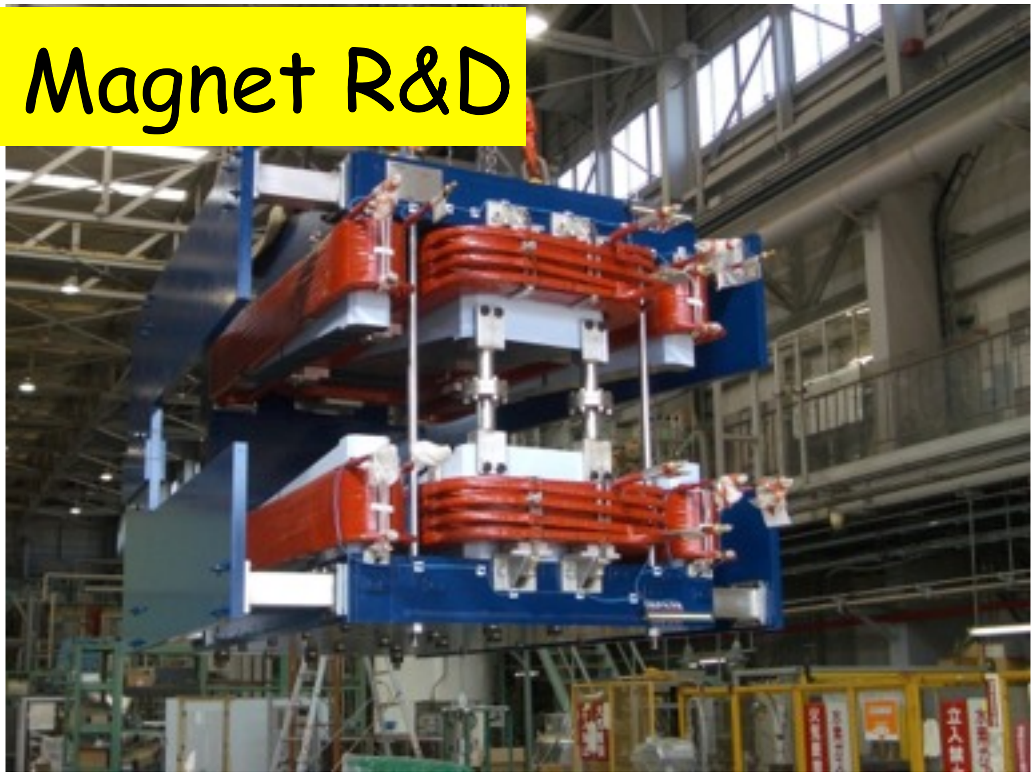


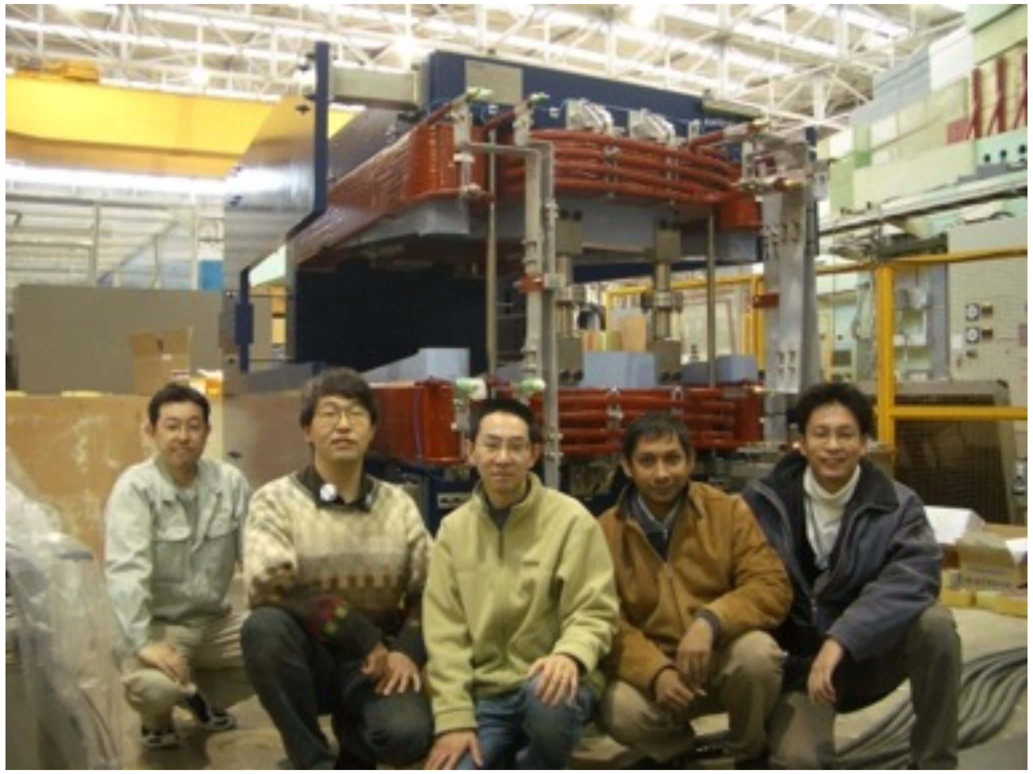
# PRISM FFAG R&D is Going...

**RF R&D**



**FFAG Magnet R&D**

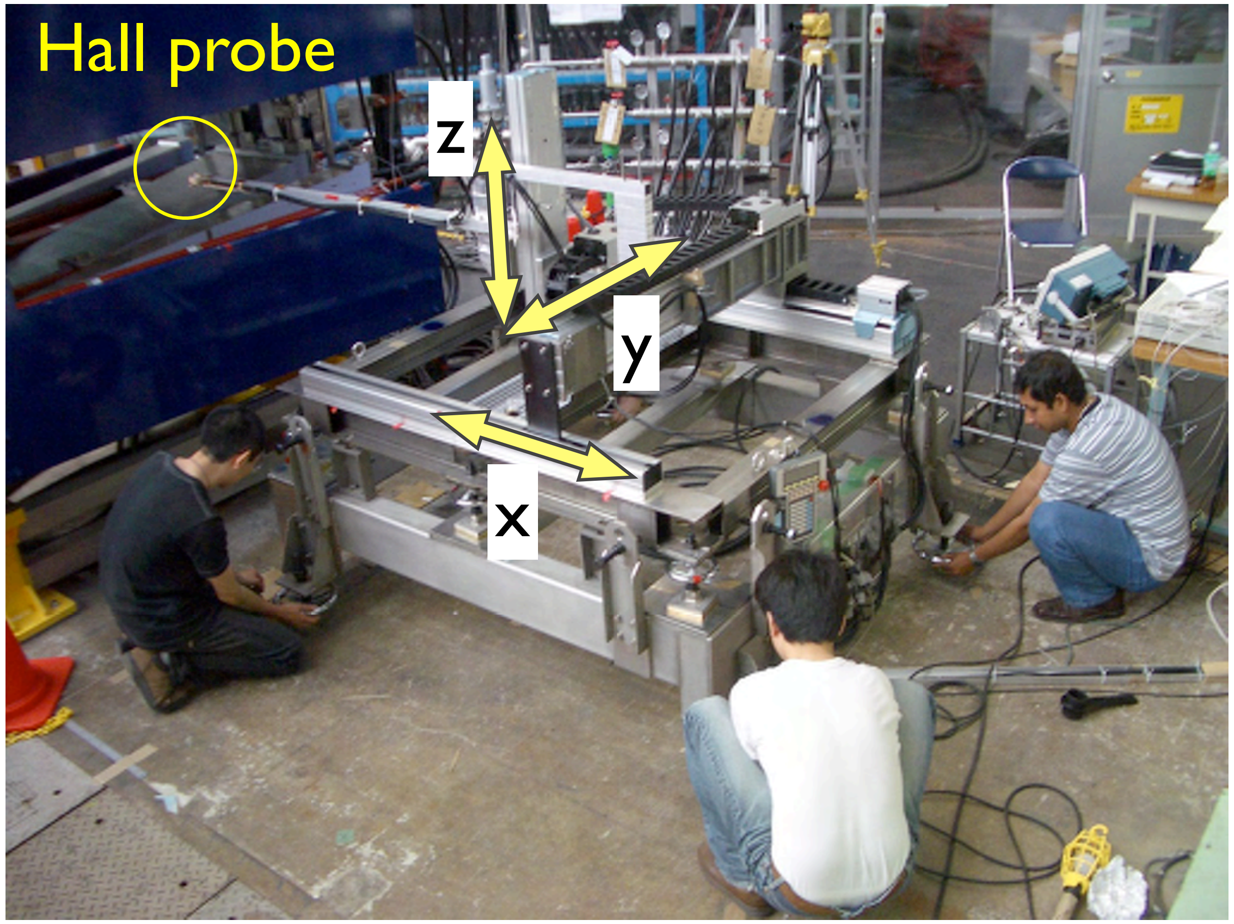


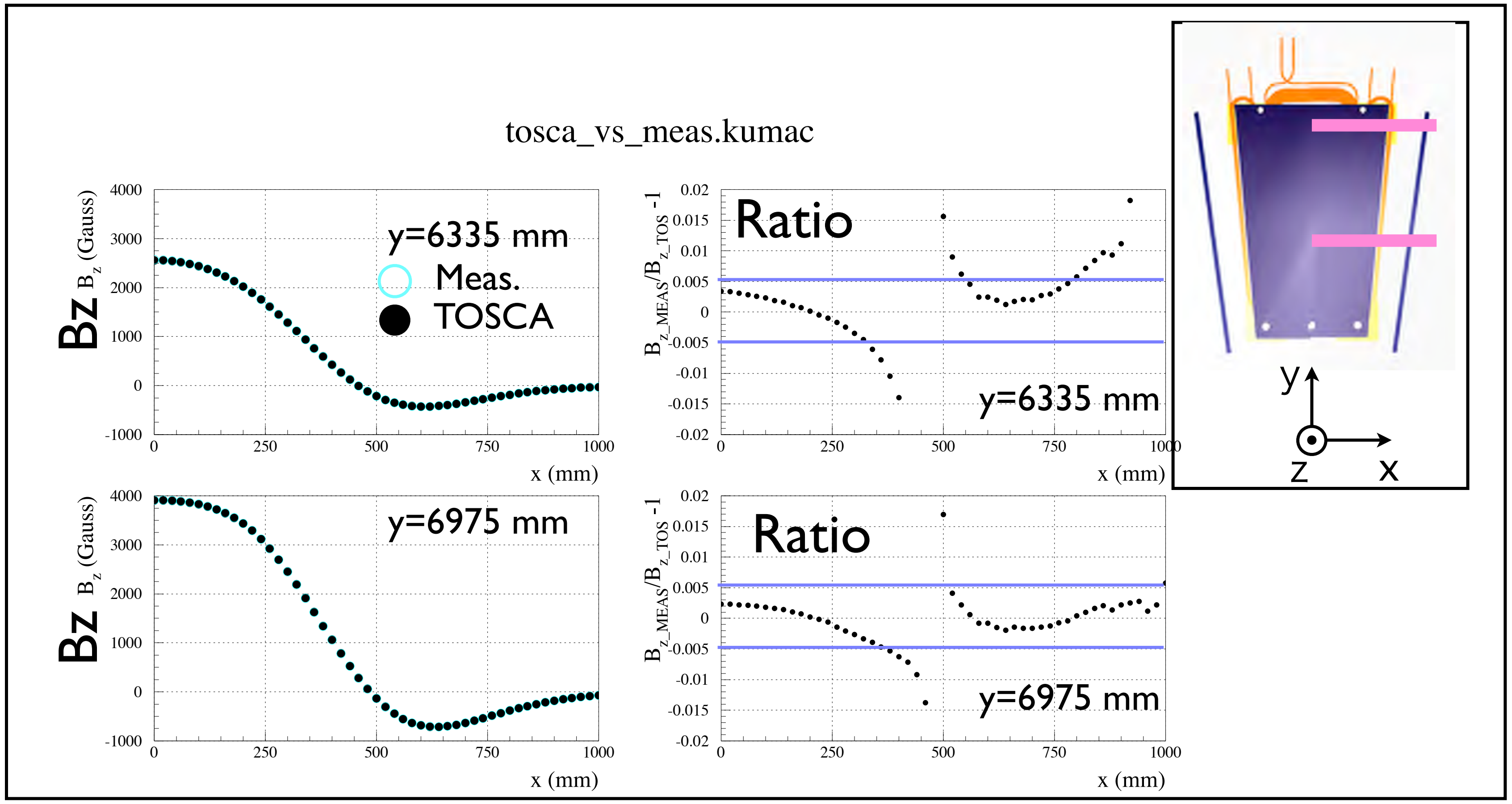


# Magnetic Field Measurements

---

- Magnetic field measurements for PRISM FFAG magnet has been made in spring, 2006.
- The measured field distribution has been compared with TOSCA calculation.
- Differences between them are less than 0,5%. It is within tolerance.



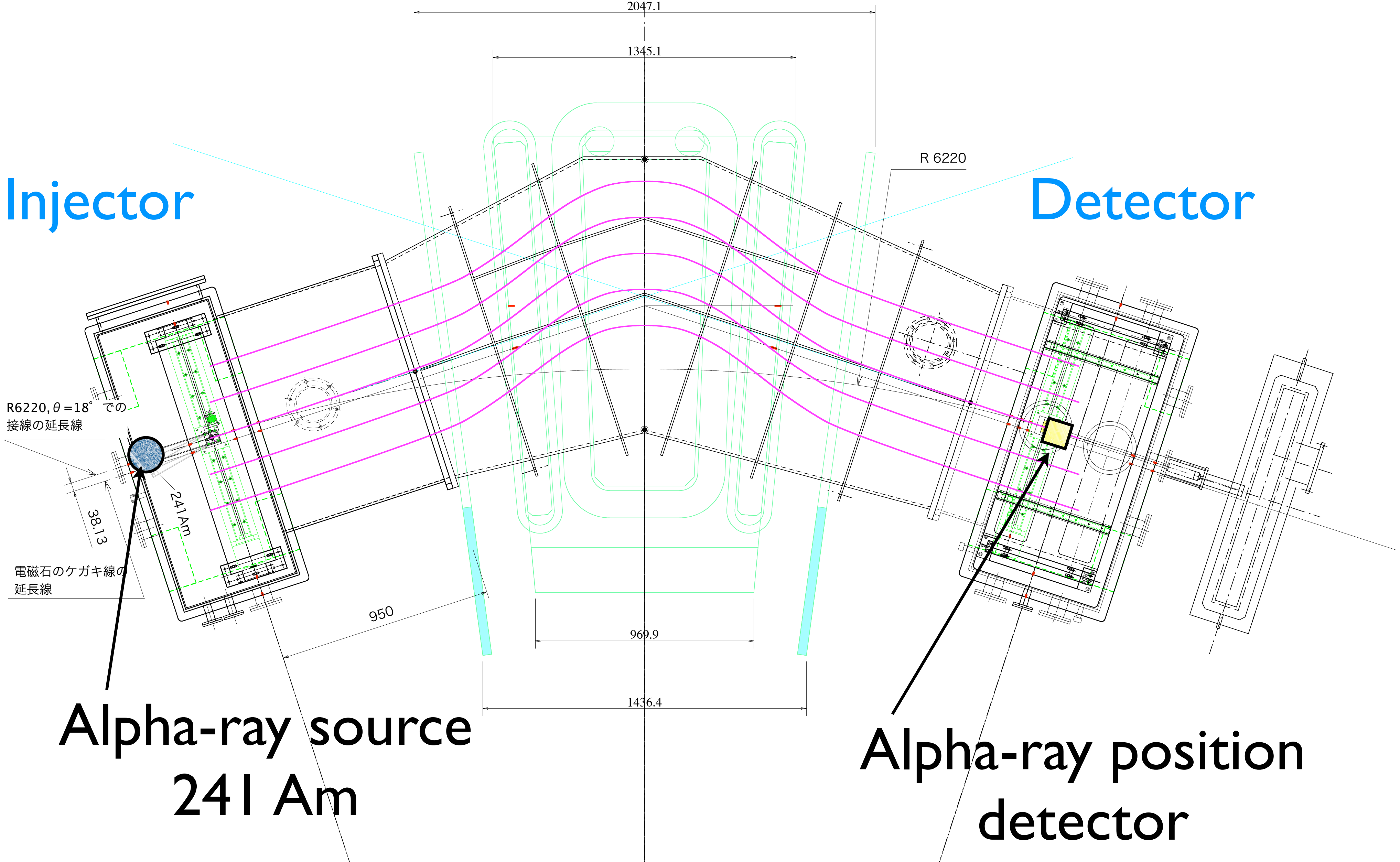


# Alpha Particle Tracking with One Magnet Cell

Purpose: study beam dynamics at large amplitudes (non-linearity) by determining a transfer mapping between in and out.

muon 68 MeV/c = alpha particle 2.5 MeV.

2007/02/06 Y. Arimoto



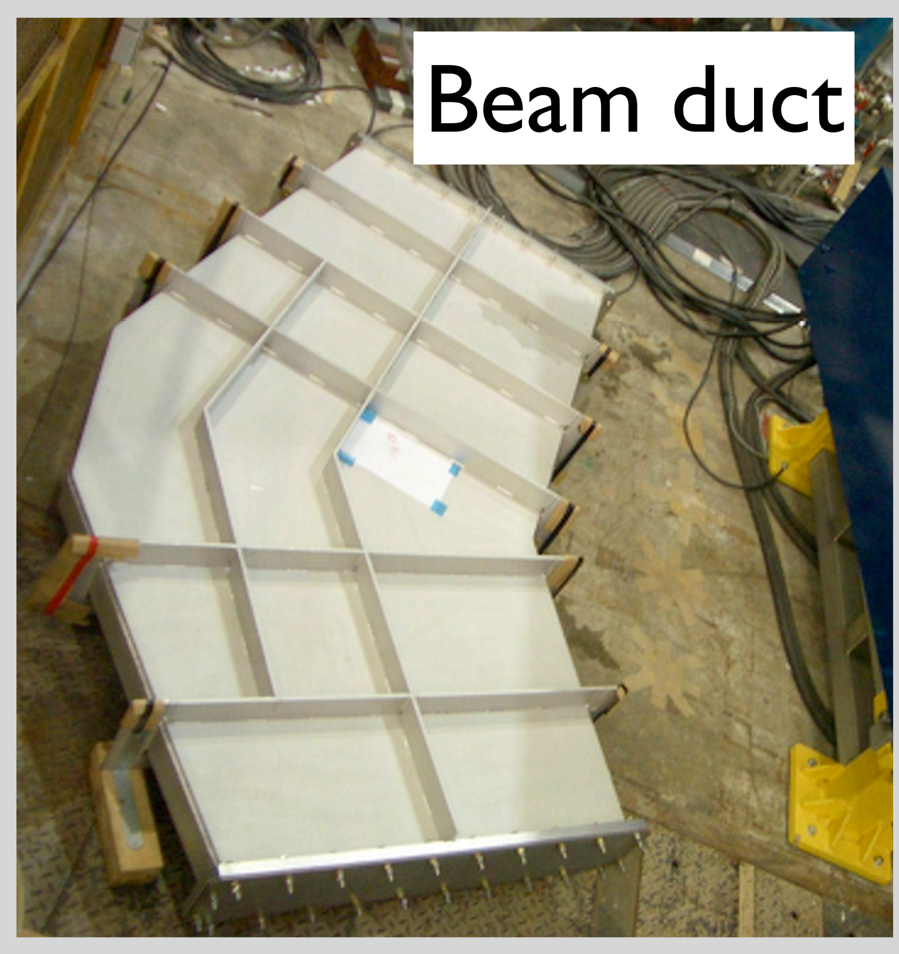
Injector

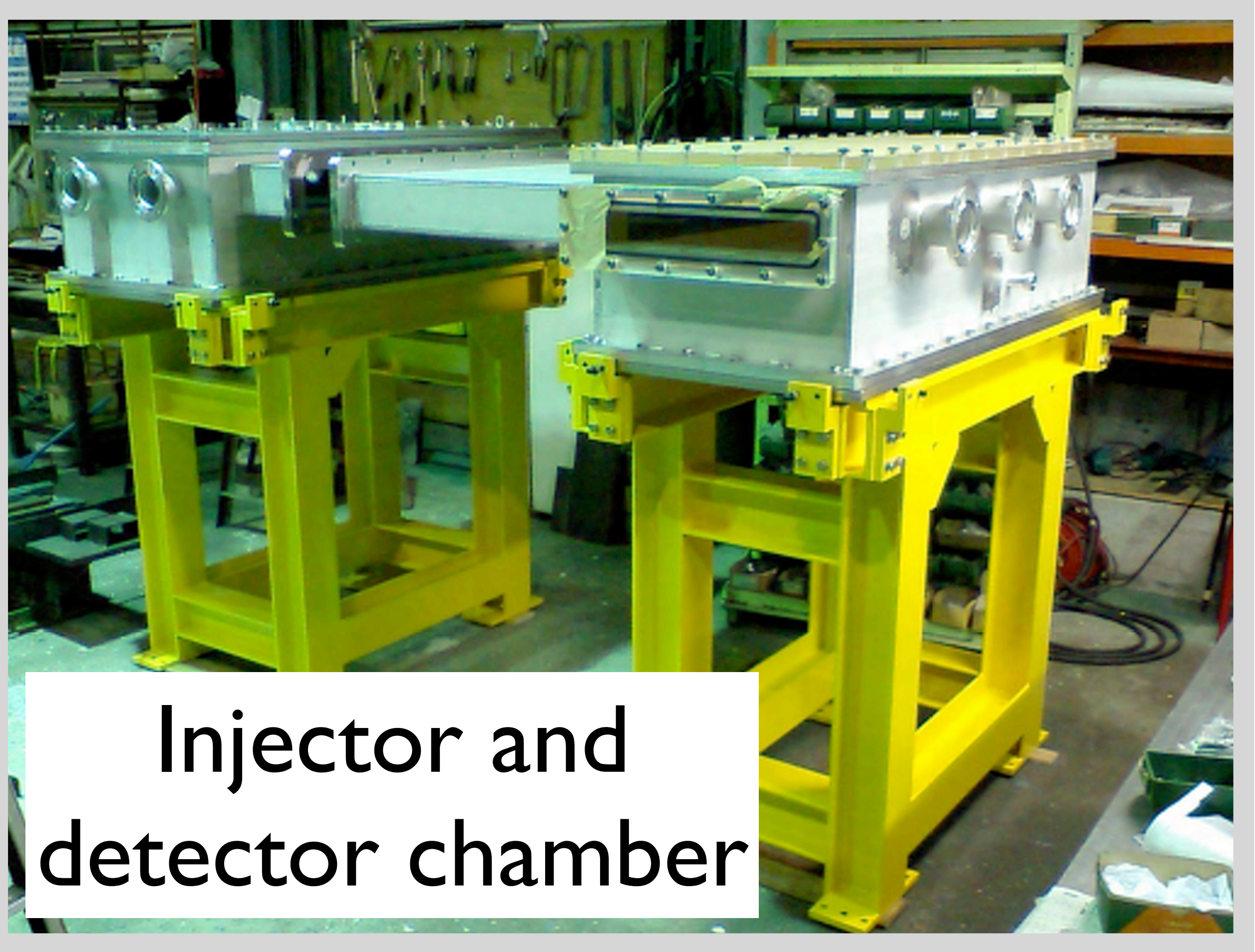
Detector

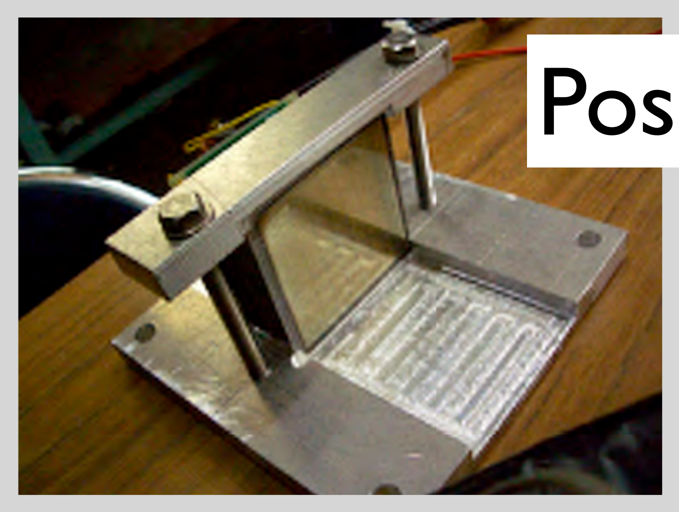
Alpha-ray source
241 Am

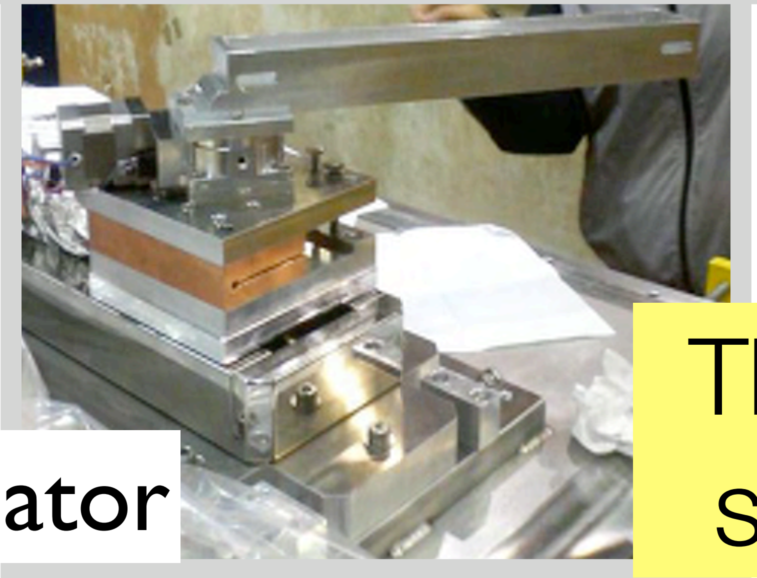
Alpha-ray position
detector

# One-cell Test Stand under Preparation


Beam duct


Injector and detector chamber

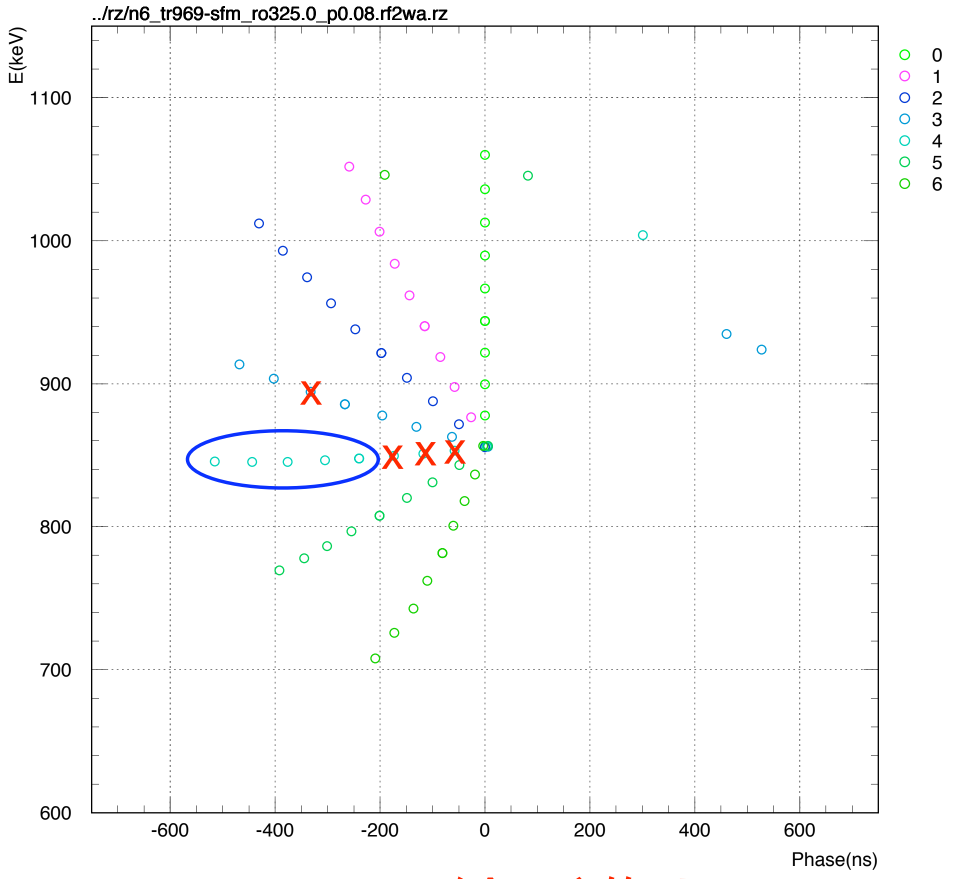

Position detector

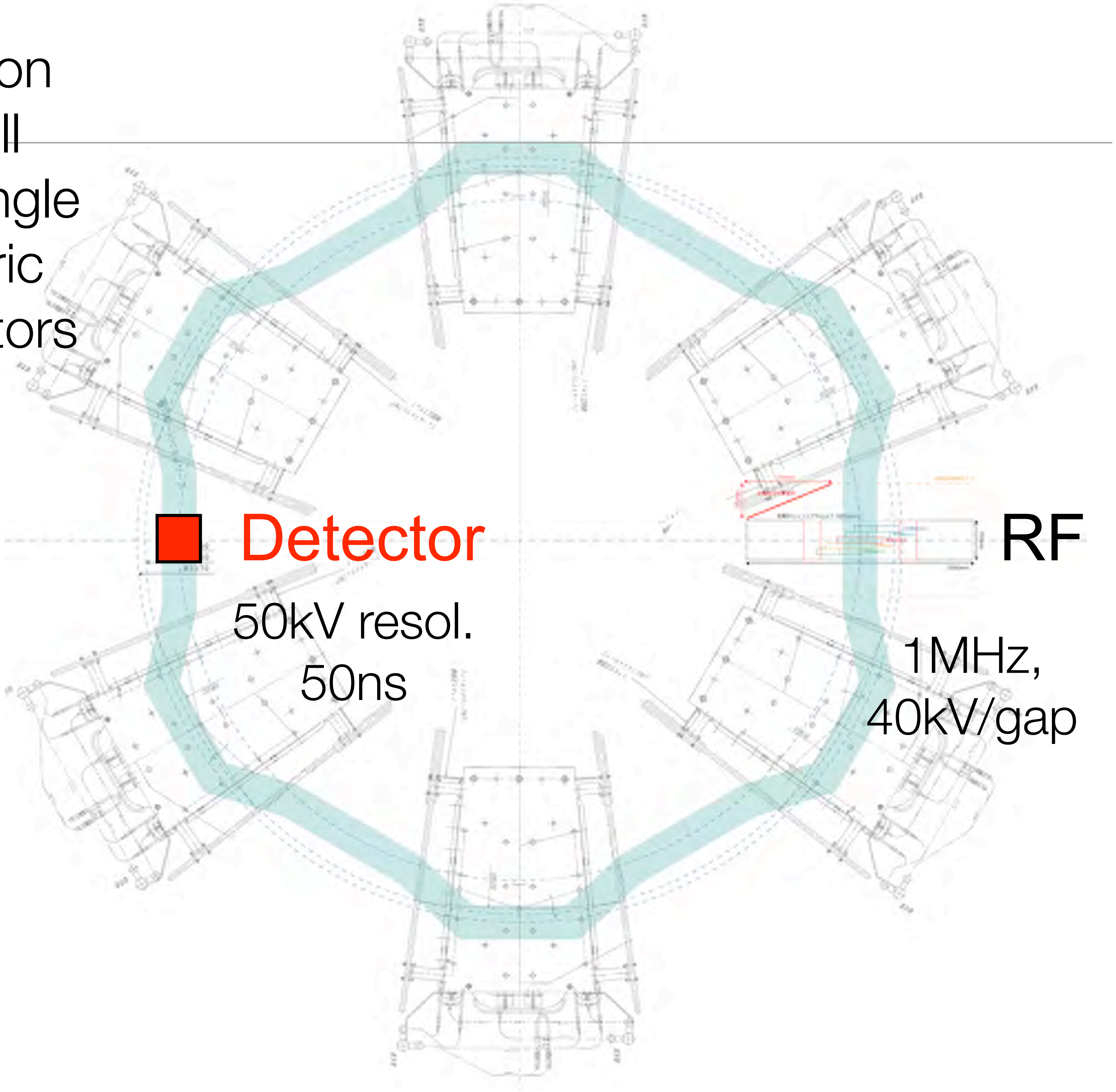

Injector collimator

The test will start soon.

# Alpha Particle Tracking with 6 Magnet Cells

Purpose: study demonstration of phase rotation with a 6-cell ring with one RF cavity by single alpha particle tracking. Electric static kicker plus SSD detectors are needed.





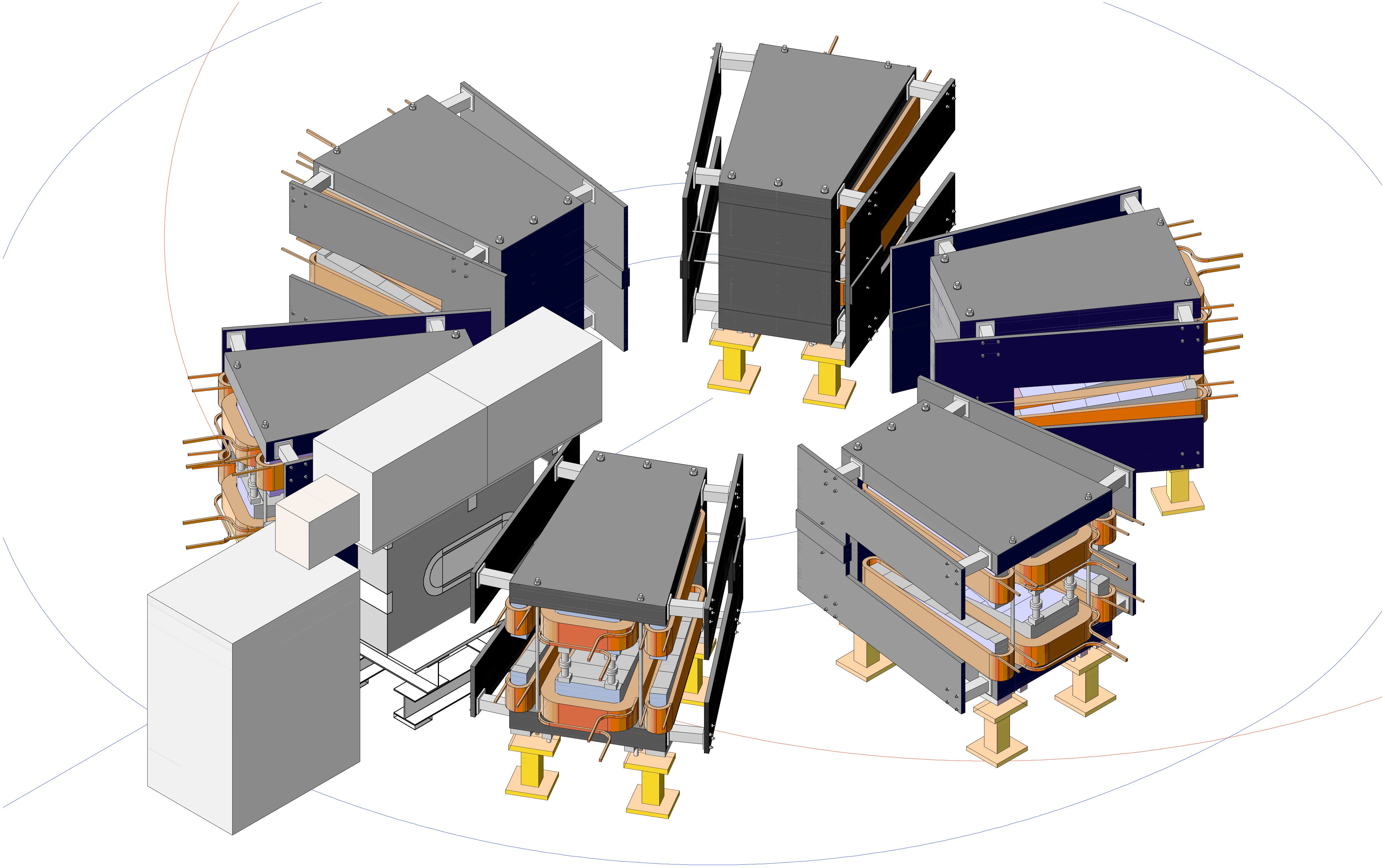
Detector

50kV resol.
50ns

RF

1MHz,
40kV/gap

# PRISM-FFAG 6 Cell Ring Layout



# R&D on the PRISM Muon Storage (FFAG) Ring at Osaka University

***PRISM-FFAG (6 sectors) in RCNP, Osaka***

Ready to demo. phase rotation

# Technical Challenges for PRISM FFAG

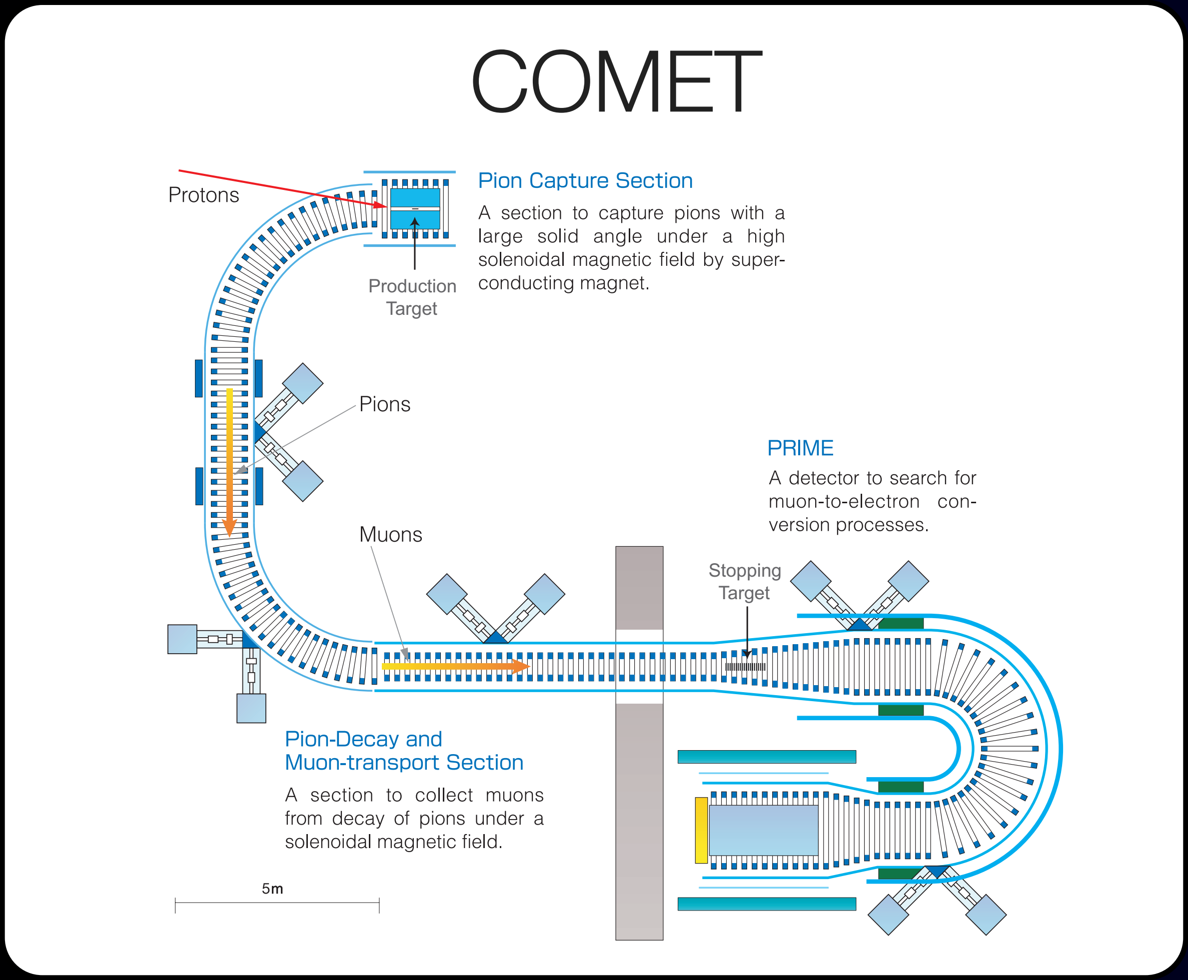
- Injection & Extraction Scheme
  - longer straight line ?
- Fast kicker magnet for muon FFAG
  - extinction of a pulsed muon beam
  - momentum selection
    - dispersive beam with momentum slit
- Larger acceptance
  - more muon intensity

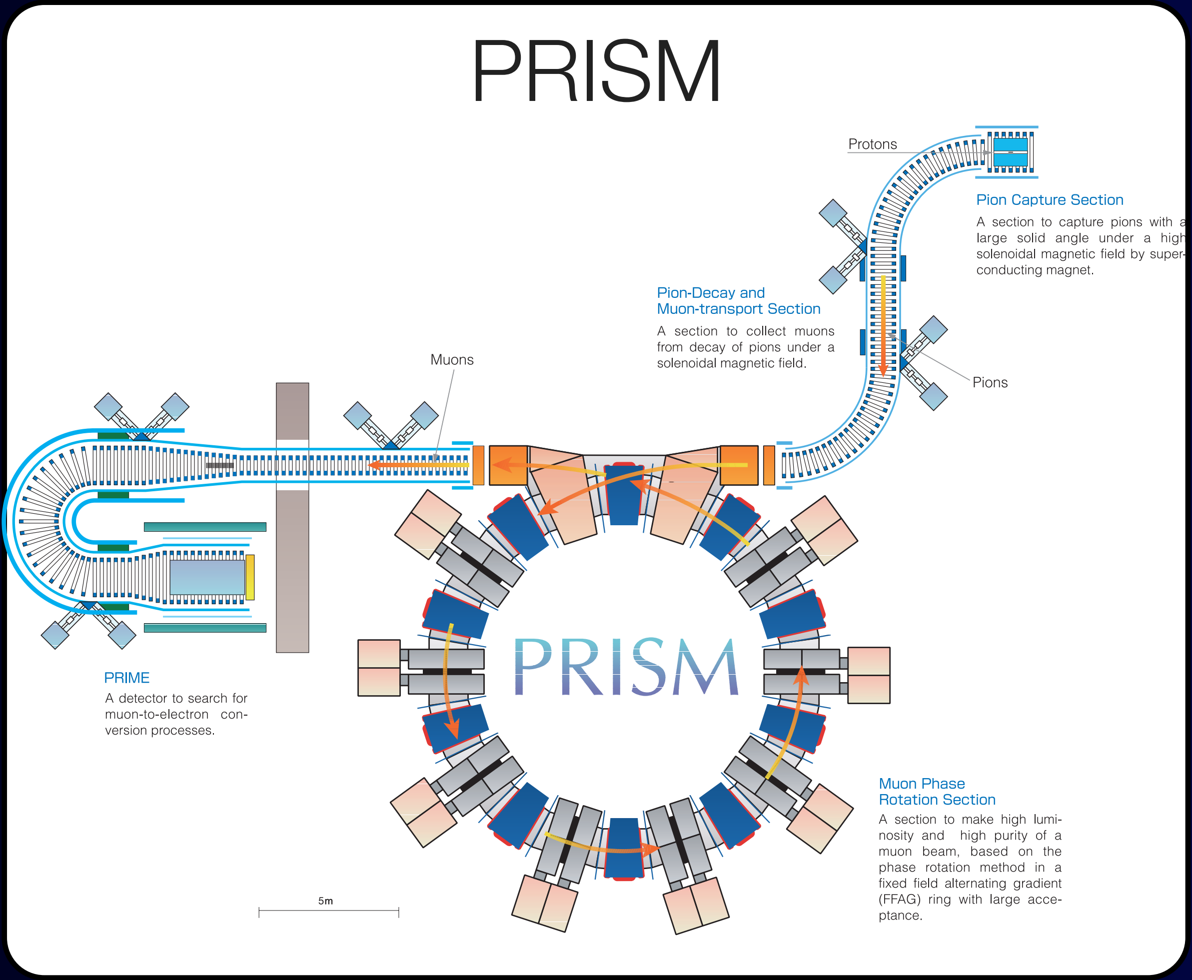
# Requirements for a Proton Beam for PRISM FFAG

- Requirements
  - Narrow pulse width
    - ~ 10 nano seconds
  - Repetition rate
    - same as the PRISM kicker magnet
    - 100 Hz ~ 1kHz (or faster)
  - Energy
    - 2 GeV ~ 10 GeV

# Road Map

# Long Future Prospects : From COMET to PRISM





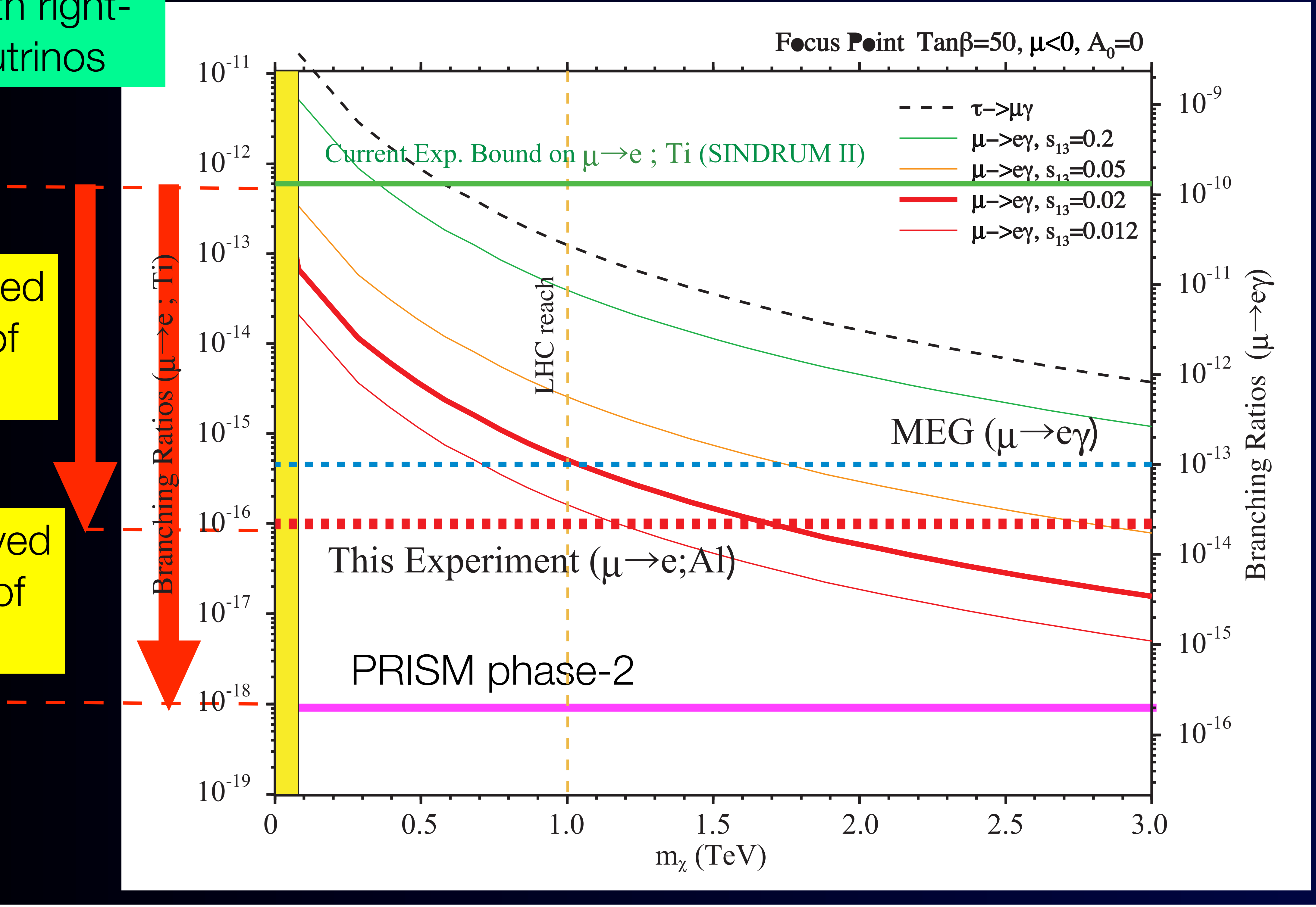
$$B(\mu^- + Al \rightarrow e^- + Al) < 10^{-16}$$

- 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 beam-line and experimental hall.
- regarded as the second phase.
- Ultimate search

mSUGRA with right-handed neutrinos



will be improved by a factor of 10,000.

will be improved by a factor of 1000,000.

Sensitivity Goal

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

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

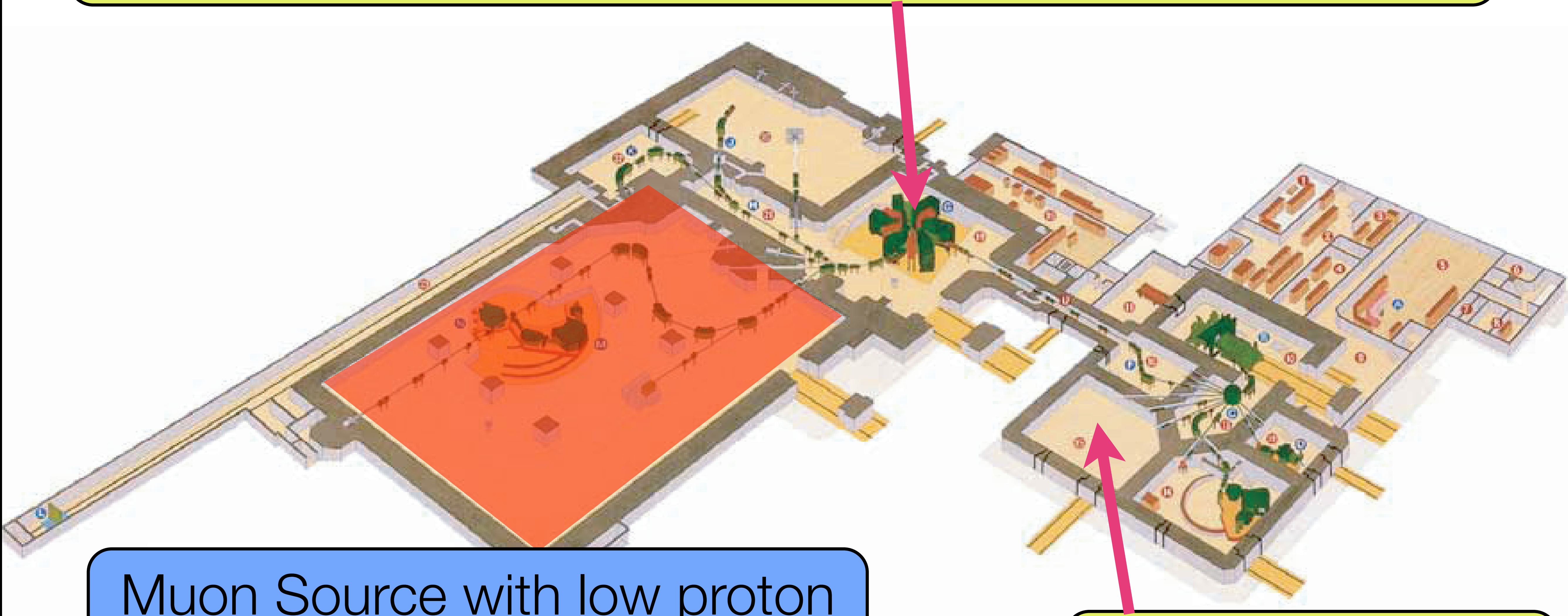
# Summary

- Physics motivation of cLFV processes is robust and strong.
- The cLFV processes with muons are, for example, $\mu \to e\gamma$ and μ-e conversion.
- The MEG experiment to search for $\mu \to e\gamma$ with sensitivity of $10^{-13}$ is running.
- The future next step would be μ-e conversion, where Mu2E (for $10^{-16}$ sensitivity) in Fermilab and COMET (for $10^{-16}$ sensitivity) in Japan are being planned. For further development, PRISM/PRIME (for $10^{-18}$ sensitivity) are considered.

End of
My Slides

# Research Center for Nuclear Physics (RCNP), Osaka University

Research Center for Nuclear Physics (RCNP), Osaka University has a cyclotron of 400 MeV with 1 microA. The energy is above pion threshold.



Muon Source with low proton power at Osaka U.?

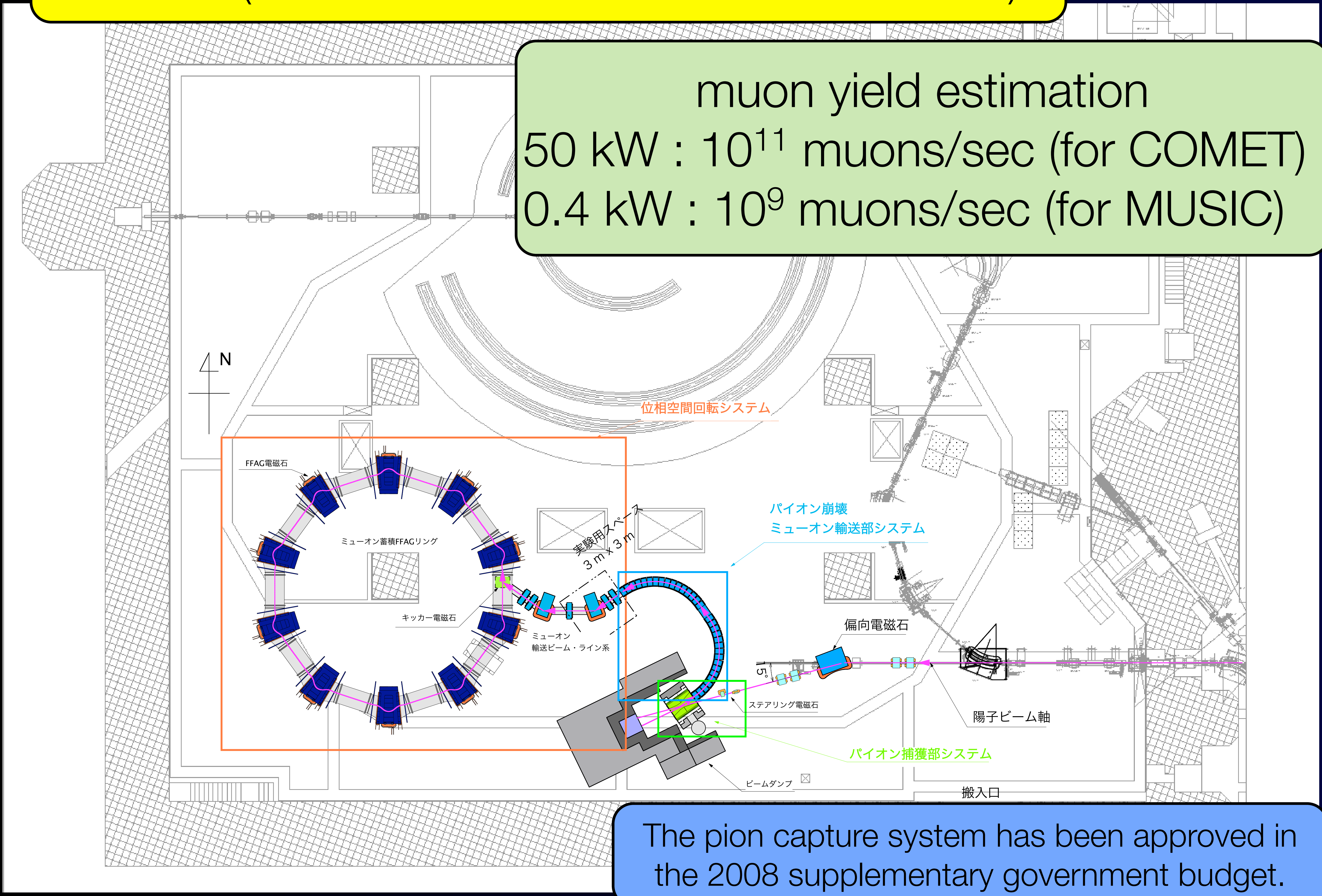
PRISM-FFAG R&D

# MUSIC (=MUon Science International Center)

muon yield estimation

50 kW : $10^{11}$ muons/sec (for COMET)

0.4 kW : $10^{9}$ muons/sec (for MUSIC)



The pion capture system has been approved in the 2008 supplementary government budget.

# Technology-Limited Schedule

Funding starting

| 2011 | 2nd year | 3rd year | 4th year | 5th year | 6th year |
|---|---|---|---|---|---|
| design & order of SC wires | construction | | | engineering run | physics run |