Future LFV Experiments

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Flavor Physics and CP Violation

Outline

- Introduction to charged lepton flavor violation (cLFV)
- cLFV with muons
  - $\mu \rightarrow e\gamma$
  - μ-e conversion
    - Searches for μ-e conversion at Sensitivity of $<10^{-16}$
    - Searches for μ-e conversion at Sensitivity of $<10^{-18}$
  - MuSIC project at Osaka University
- cLFV with taus
- LFV charged currents with neutrinos
- Summary

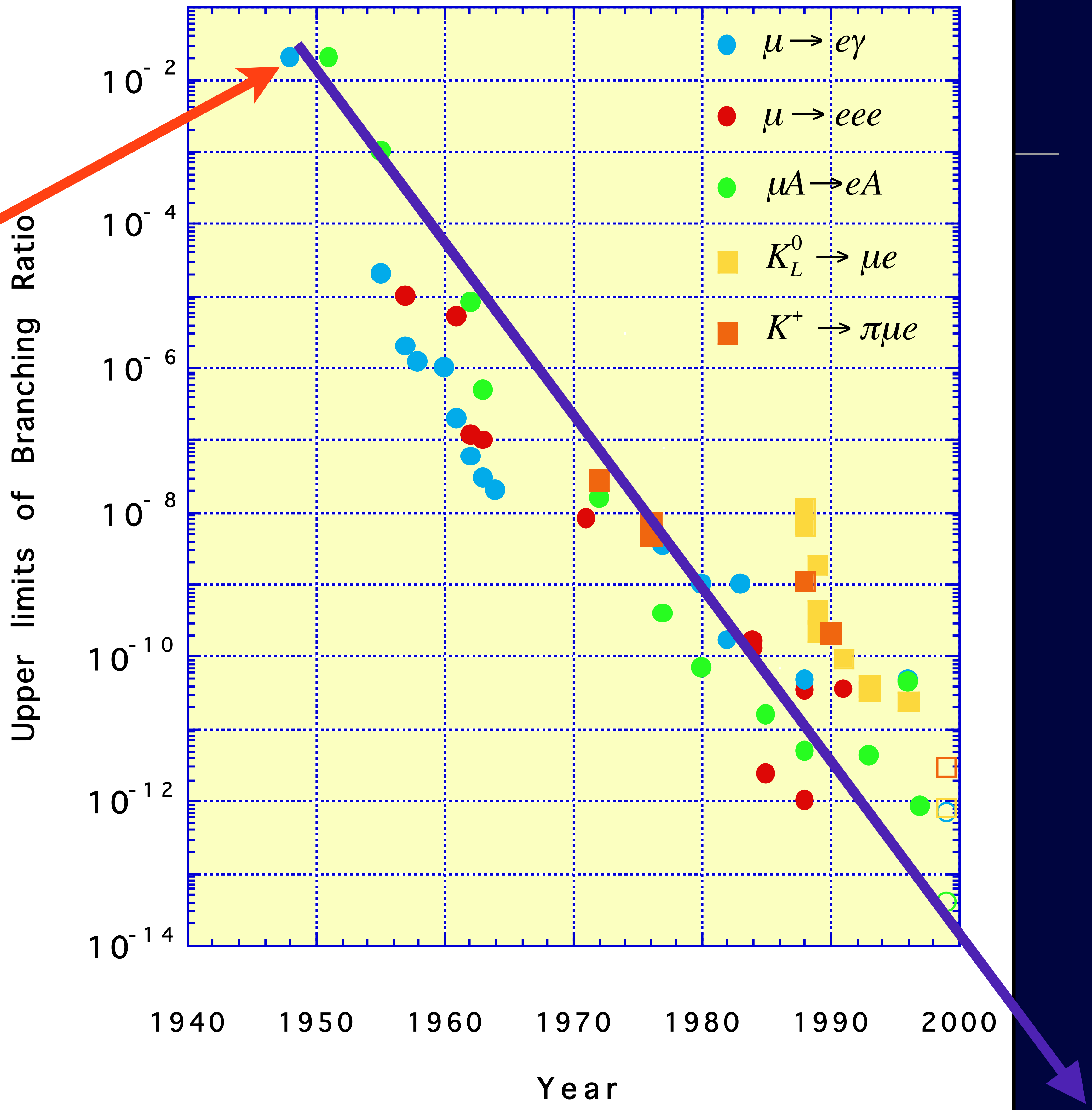
Introduction

at Kawasaki

cLFV History

First cLFV search

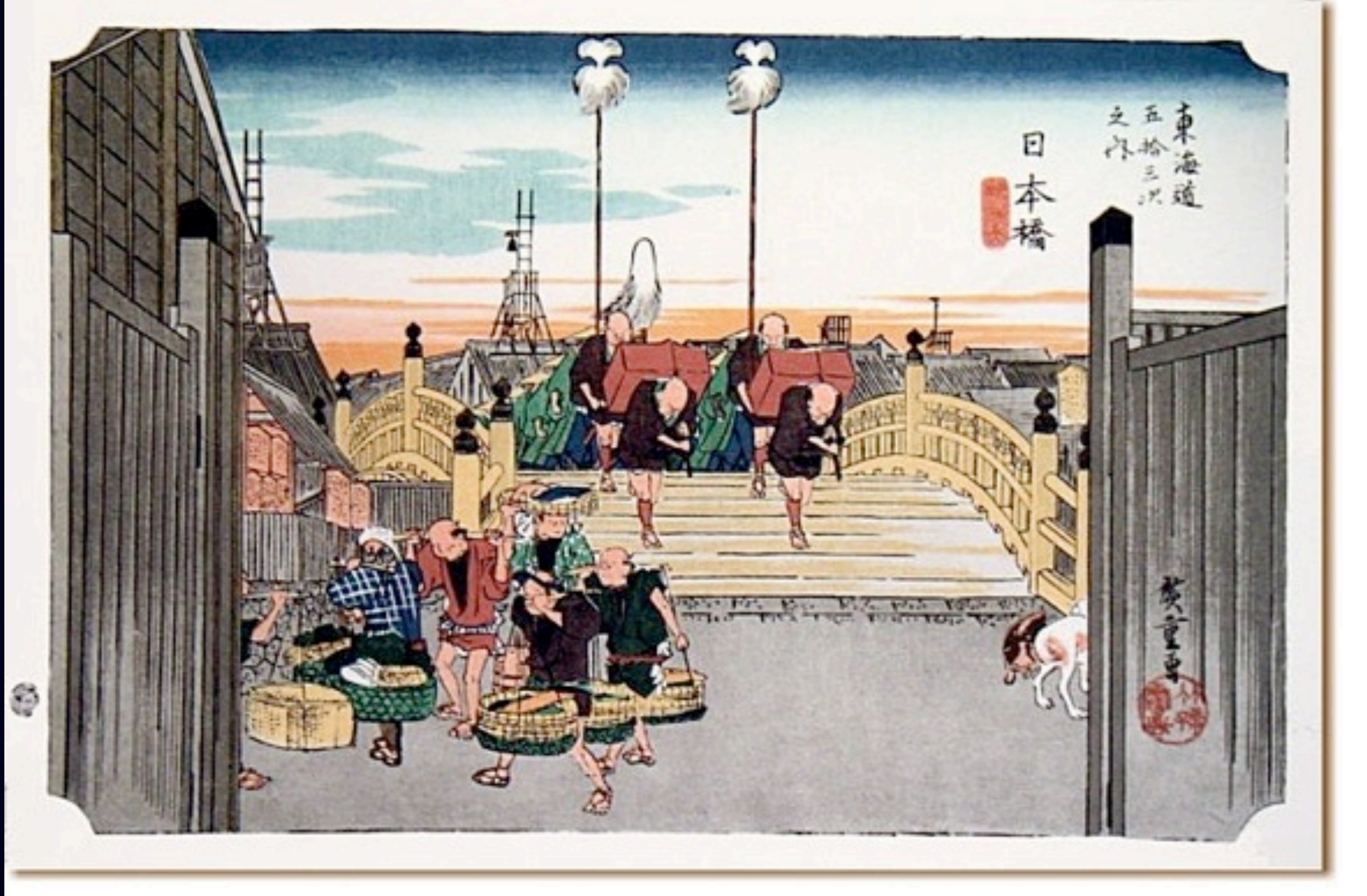
Pontecorvo in 1947



Present Limits and Expectations in Future

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

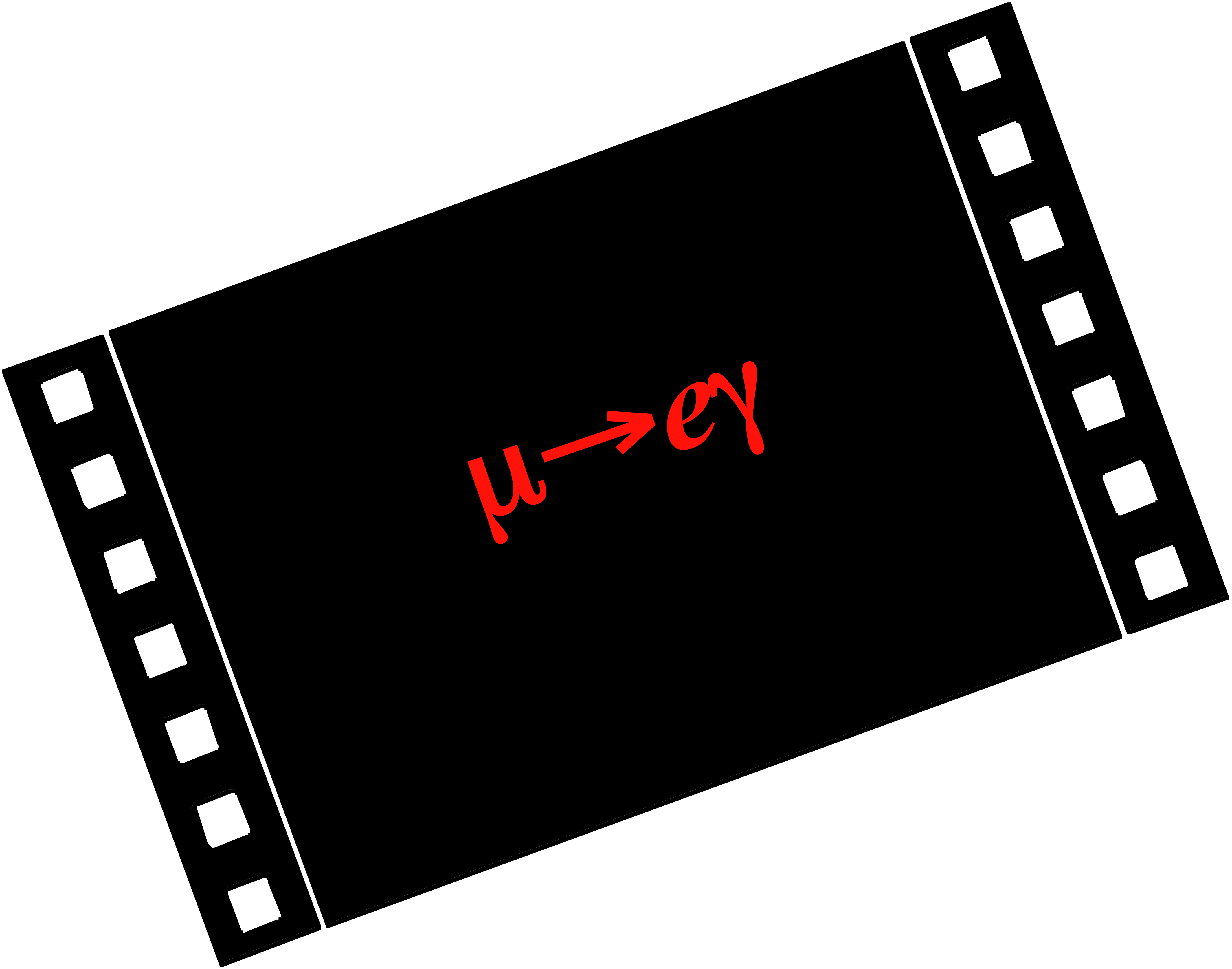
cLFV with Muons



starting from Nihonbashi, Tokyo

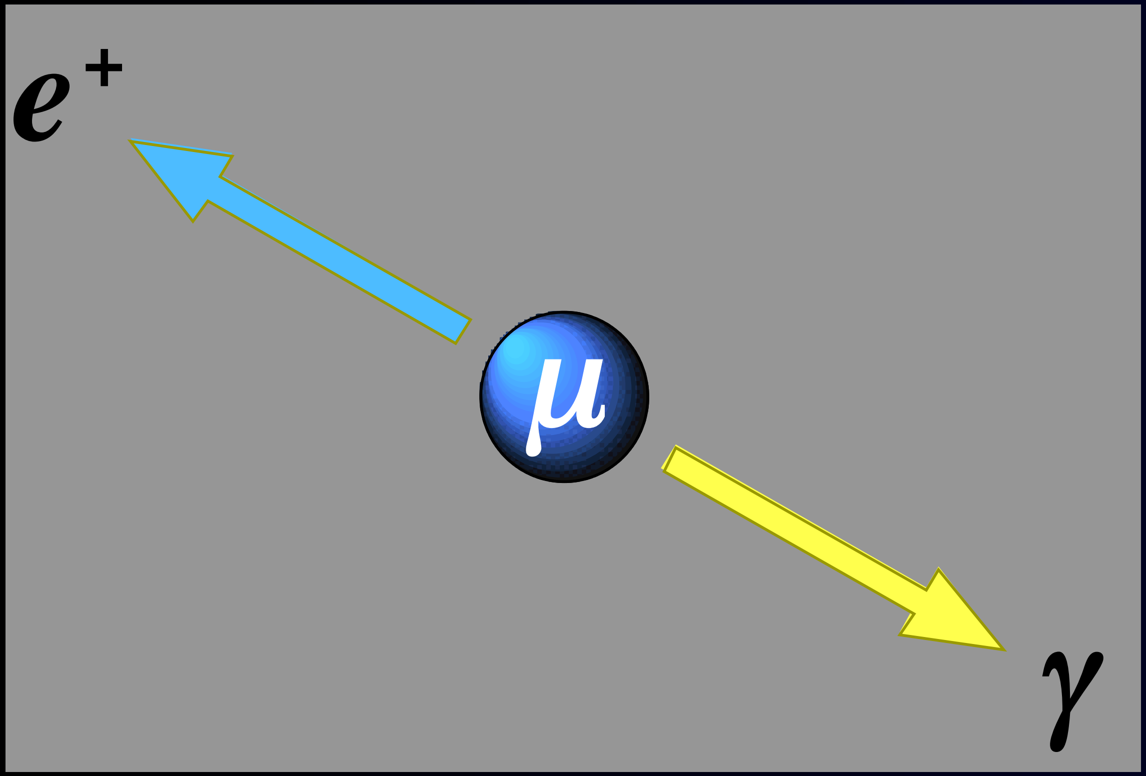
Charged Lepton Flavor Violation with Muons

ΔL=1	current	future
$\bullet \mu^+ \to e^+\gamma$	$<10^{-11}$	$<10^{-14}$
$\bullet \mu^+ \to e^+e^+e^-$	$<10^{-12}$	$<10^{-14}$
$\bullet \mu^- + N(A,Z) \to e^- + N(A,Z)$	$<10^{-12}$	$<10^{-18}$
$\bullet \mu^- + N(A,Z) \to e^+ + N(A,Z-2)$		
ΔL=2		
$\bullet \mu^+e^- \to \mu^-e^+$	$<10^{-3}G_F$	$<10^{-4}G_F$
$\bullet \mu^- + N(A,Z) \to \mu^+ + N(A,Z-2)$		
$\bullet \nu_\mu + N(A,Z) \to \mu^+ + N(A,Z-1)$		
$\bullet \nu_\mu + N(A,Z) \to \mu^+\mu^+\mu^- + N(A,Z-1)$		


$\mu \to e\gamma$

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

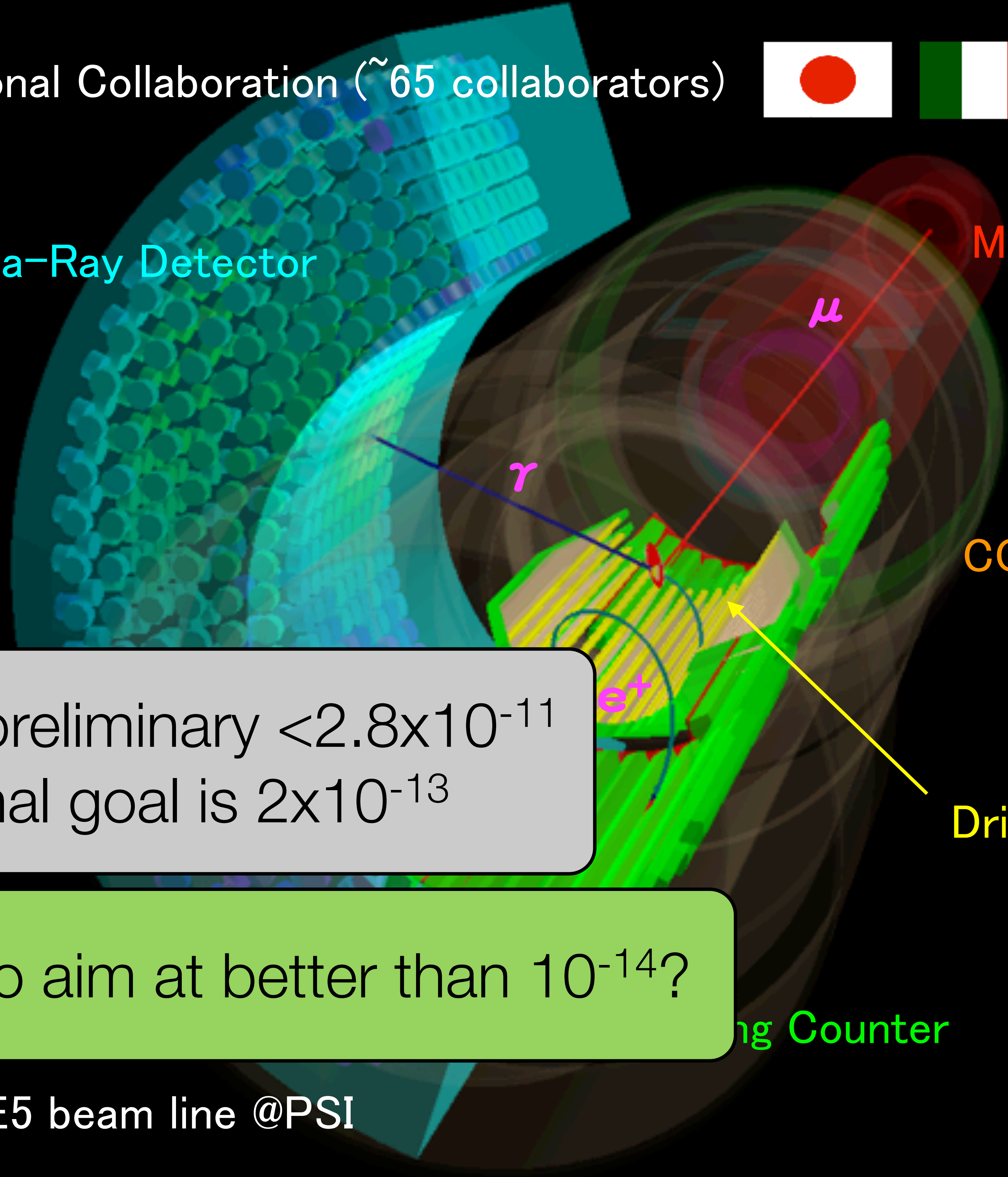
- Event Signature
  - $E_e = m_\mu/2$, $E_\gamma = m_\mu/2$ (=52.8 MeV)
  - angle $\theta_{\mu e}$=180 degrees (back-to-back)
  - time coincidence



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

The MEG Experiment

International Collaboration (~65 collaborators)

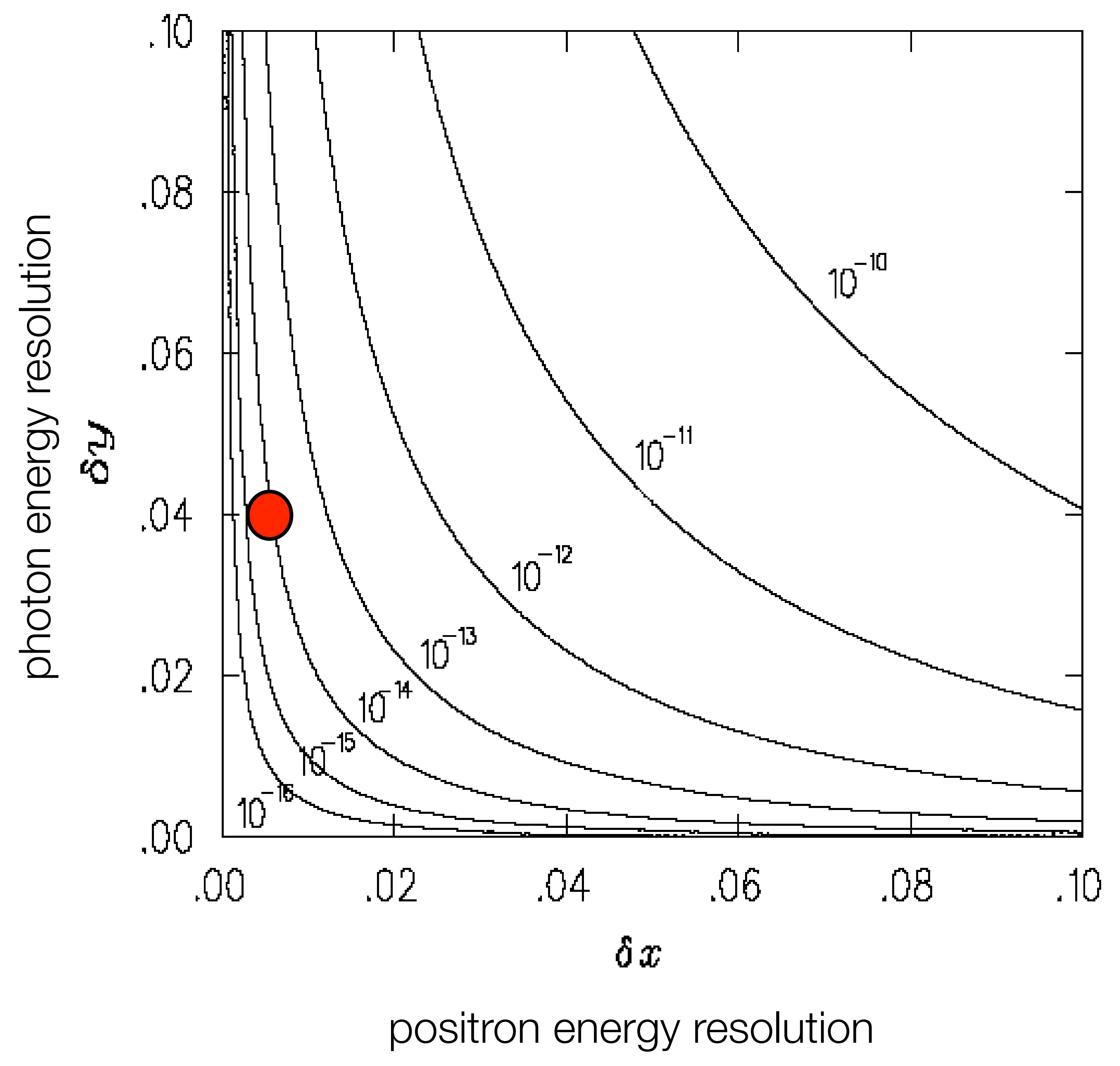


2009 preliminary <2.8x10^{-11}
Final goal is 2x10^{-13}

How to aim at better than 10^{-14}?

π E5 beam line @PSI

Physics Background for μ→eγ Decay



$$\mu^+ \longrightarrow e^+\nu_e\overline{\nu}_\mu\gamma$$

Effective branching ratio is a function of the resolution of electron detection (**δ**x) and that of photon detection (**δ**y).

Background level is about 10^{-14} for **δ**x~1% and **δ**y=5%.

Accidental Backgrounds for μ→eγ

Place	Year	ΔE_e	ΔE_γ	$\Delta t_{e\gamma}$	$\Delta\theta_{e\gamma}$	Upper limit
TRIUMF	1977	10%	8.7%	6.7ns	–	$< 3.6 \times 10^{-9}$
SIN	1980	8.7%	9.3%	1.4ns	–	$< 1.0 \times 10^{-9}$
LANL	1982	8.8%	8%	1.9ns	37mrad	$< 1.7 \times 10^{-10}$
LANL	1988	8%	8%	1.8ns	87mrad	$< 4.9 \times 10^{-11}$
LANL	1999	1.2%	4.5%	1.6ns	15mrad	$< 1.2 \times 10^{-11}$
PSI (MEG)	2007	0.9%	5 %	0.1 ns	23mrad	$< 10^{-13}$

states of arts

$$\text{Accidental Background} \propto \left(R_\mu\right)^2 \times \Delta E_e \times \left(\Delta E_\gamma\right)^2 \times \Delta t_{e\gamma} \times \left(\Delta\theta_{e\gamma}\right)^2$$

N_B=0.5 events at B(μ→eγ)~10^{-13}

With the same resolutions, $N_\mu=10^8$μ/s,
N_B=50 events at B(μ→eγ)~10^{-14}

Improvements of detector resolutions are critical.

Suppression of Physics Background with Polarized μ→eγ Decay

radiative muon decay

at end-point of spectrum when neutrinos have small energy

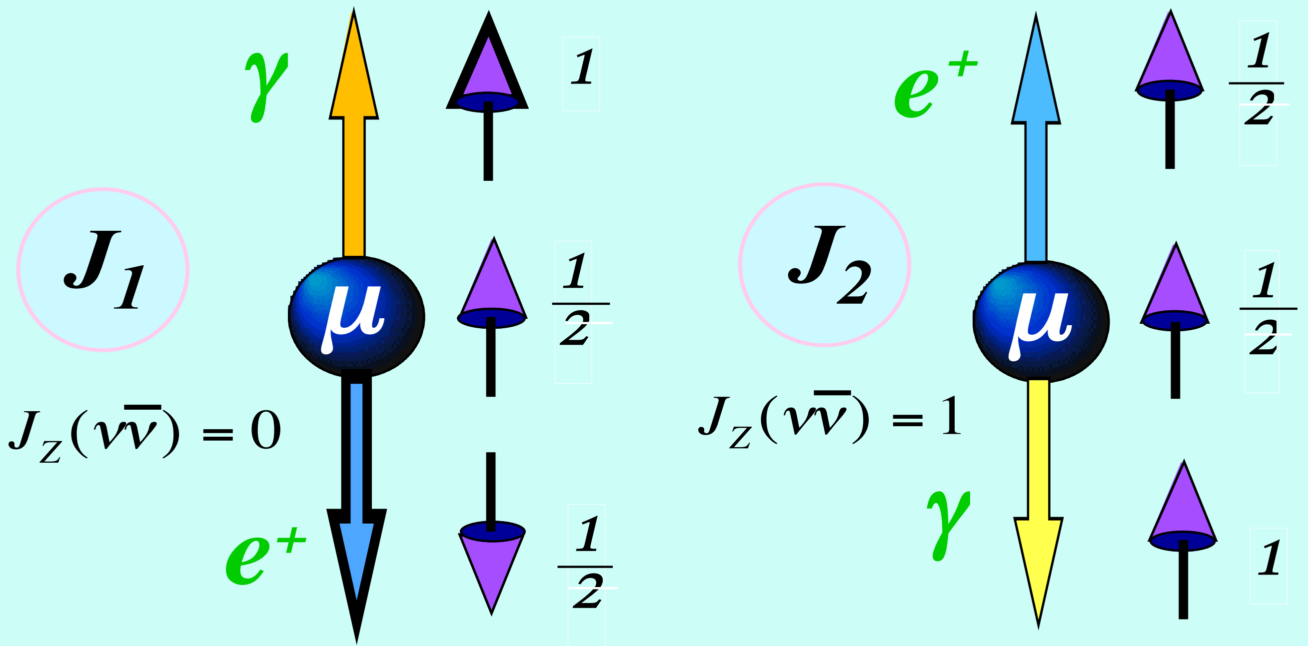
integrate the decay width

$1-\delta x < x < 1$ $\quad$ δx : *e energy*

$1-\delta y < y < 1$ $\quad$ δy : *γ energy*

$0 < z < \delta z$ $\quad$ δz : *angle*

$$dB = \frac{\alpha}{16\pi}\left[J_1(1-P_\mu\cos\theta_{e\gamma}) + J_2(1+P_\mu\cos\theta_{e\gamma})\right]$$

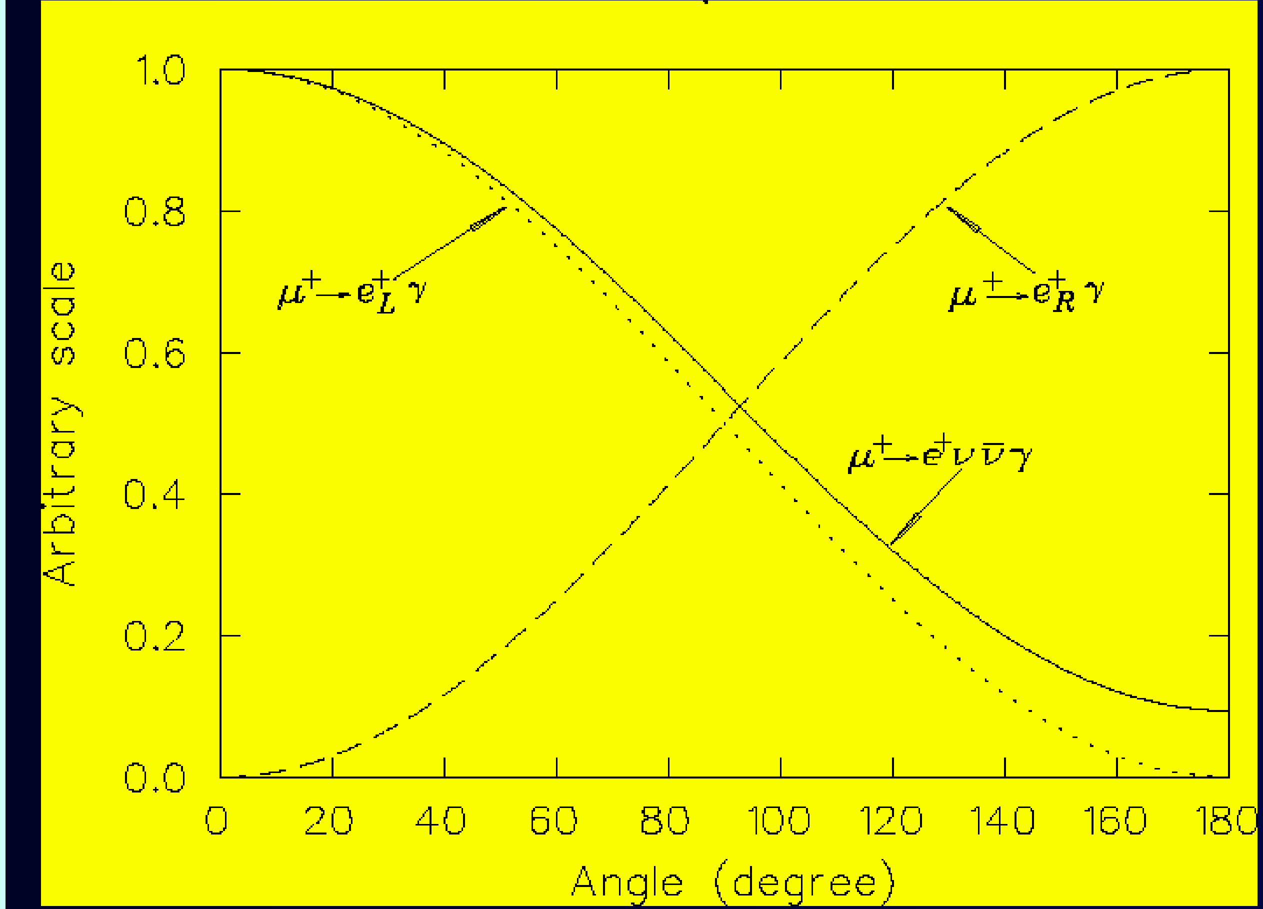


$$J_1 = (\delta x)^4(\delta y)^2 \qquad J_2 = \frac{8}{3}(\delta x)^3(\delta y)^3$$

if $(\delta y) > (\delta x)$, *then* $J_2 > J_1$, *following a* $(1+P_\mu\cos\vartheta)$

Improve a S/B ratio for $\mu^+ \to e_R\gamma$

Angular distribution of Physics Background with polarized muon decays

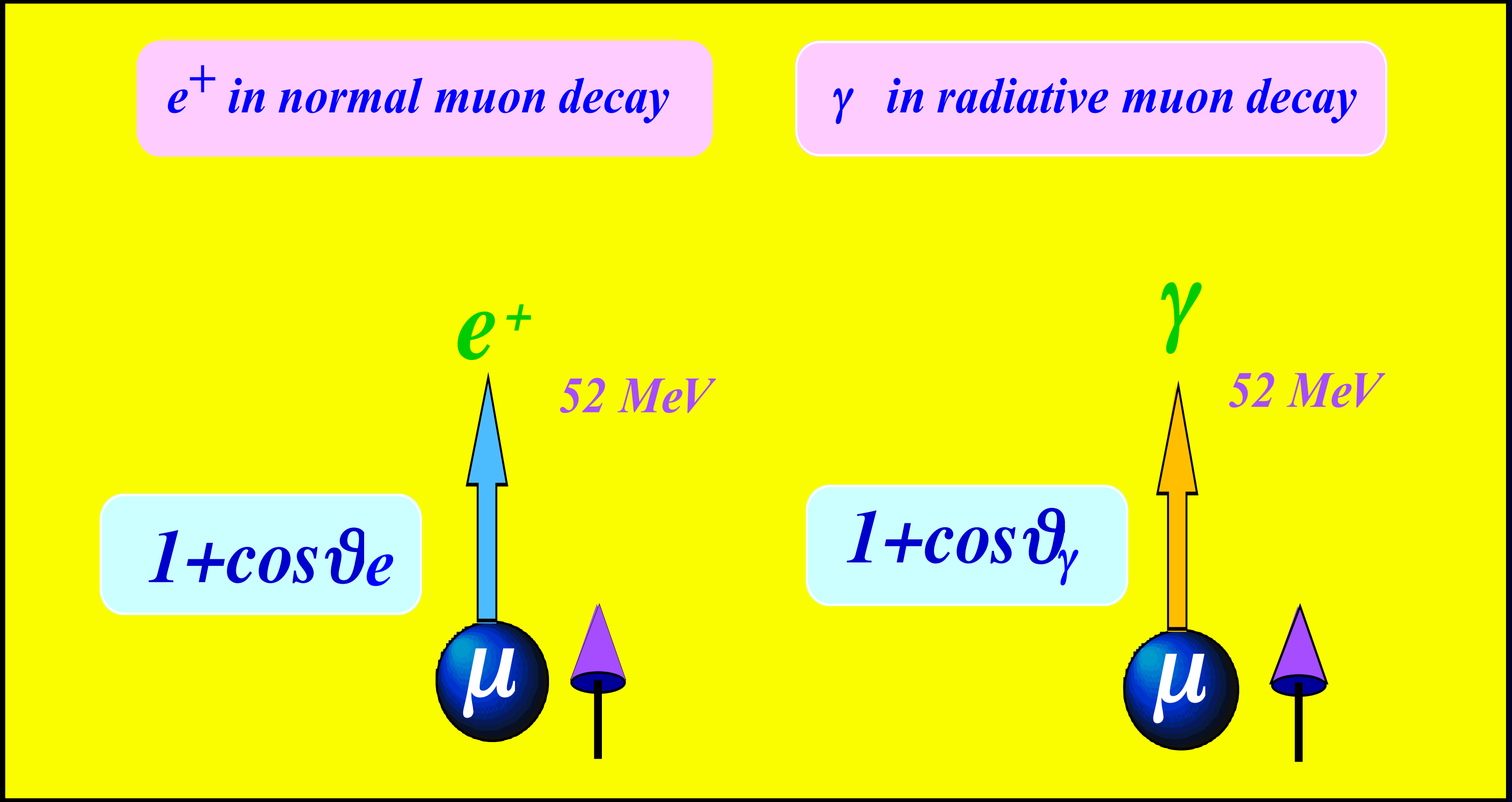


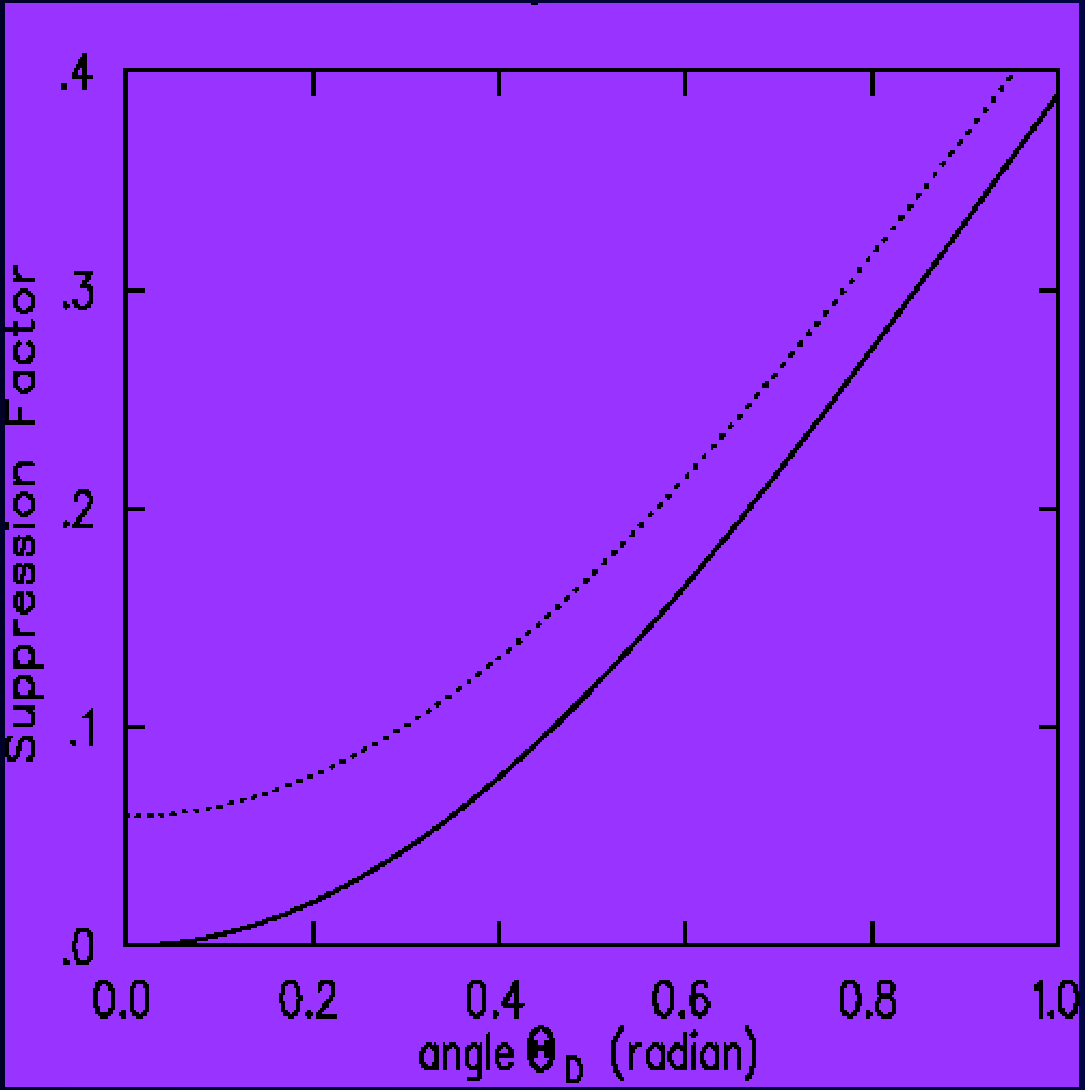
Y. Kuno and Y. Okada, Phys. Rev. Lett. 77 (1996) 434

Suppression of Accidental Background with Polarized μ→eγ Decay

accidental coincidence between 52.8 MeV e^+ and 52.8 MeV photon.

In a high-intensity beam, it becomes more serious.





suppressed if e^+ going opposite to muon spin is measured

→ $\mu^+ \to e^+_L \gamma$

suppressed if photons going opposite to muon spin is measured.

→ $\mu^+ \to e^+_L \gamma$

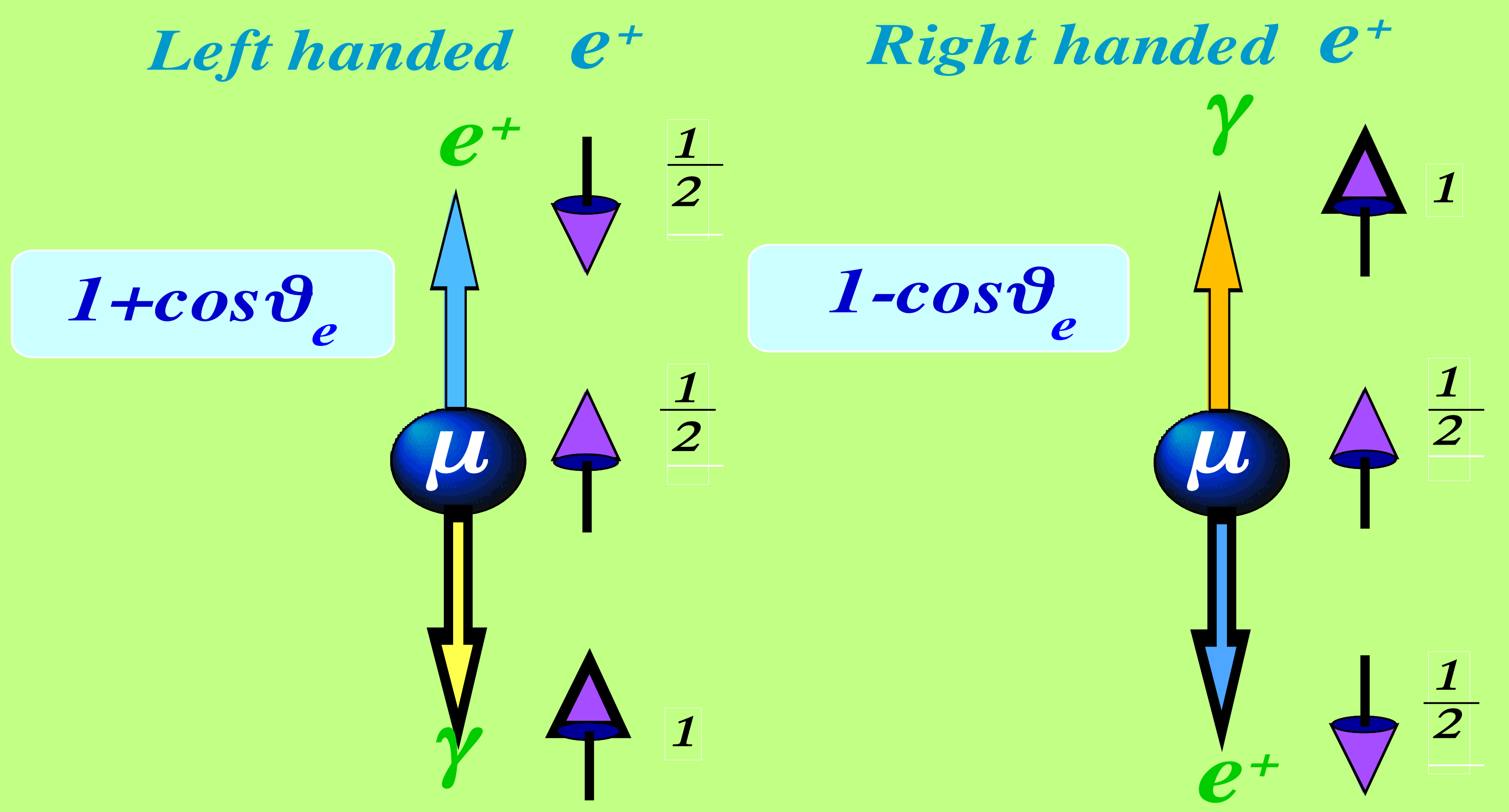
$$\eta = \frac{\int_{\cos\theta_D}^{1} d(\cos\theta)(1+P_\mu\cos\theta)(1-P_\mu\cos\theta)}{\int_{\cos\theta_D}^{1} d(\cos\theta_D)}$$

$$= (1-P_\mu^2) + \frac{1}{3}P_\mu^2(1-\cos\theta_D)(2+\cos\theta_D)$$

Both helicities are OK !

Y. Kuno, A. Maki, and Y. Okada, Phys. Rev. D55 (1997) R2517

P-Odd Angular Distribution of Polarized μ→eγ Decay (after its observation)



Left handed e^+

$1+\cos\vartheta_e$

Right handed e^+

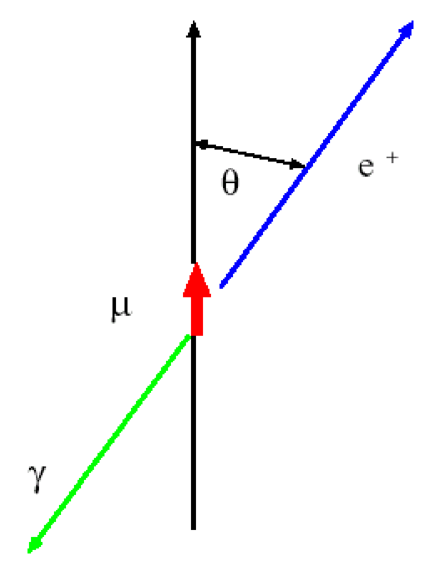
$1-\cos\vartheta_e$

useful to distinguish different theoretical models

SU(5) SUSY-GUT	*non-unified SUSY with heavy neutrino* *Left-right symmetric model*

SO(10) SUSY-GUT

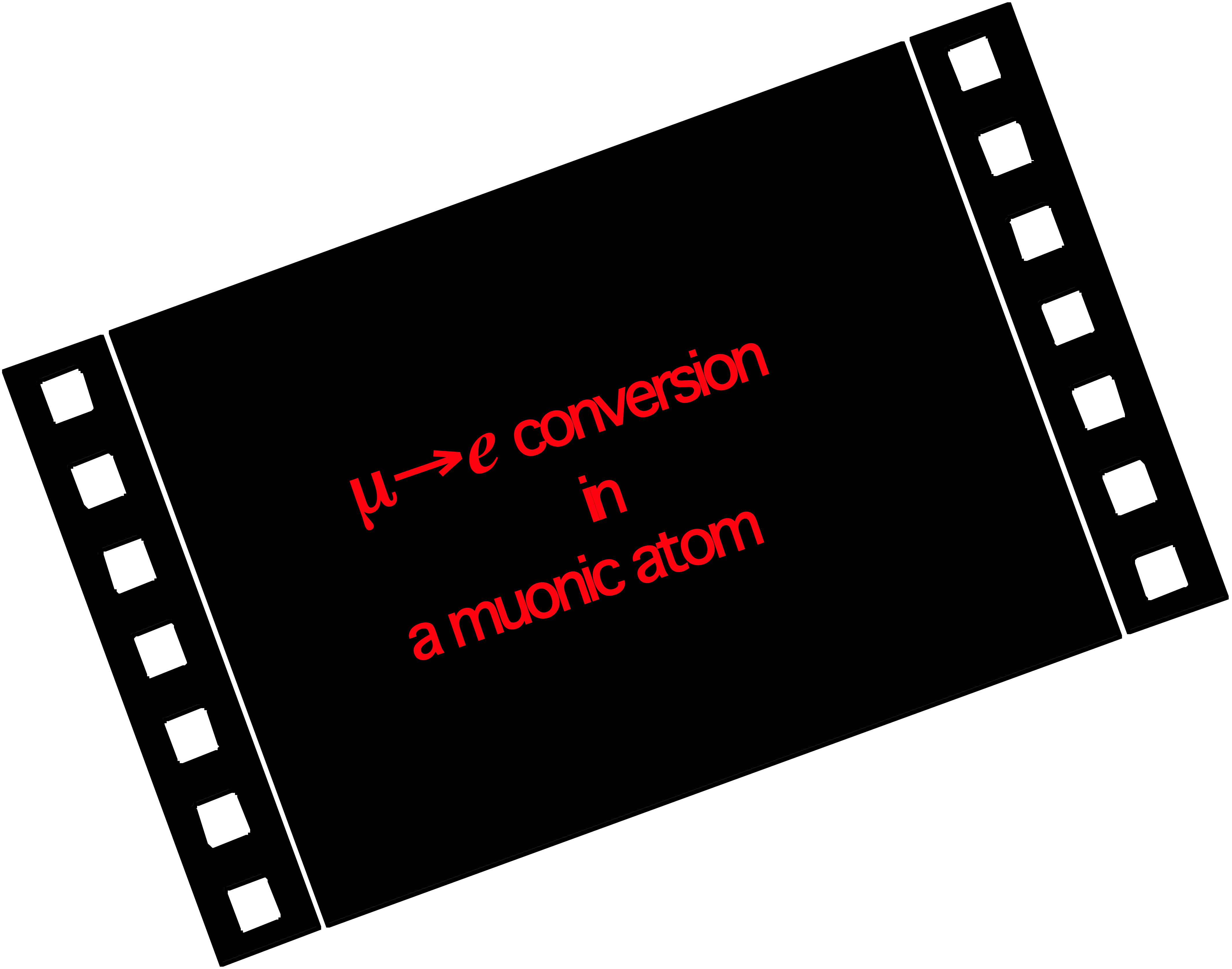
Y.Kuno and Y. Okada, Physical Review Letters 77 (1996) 434
Y.Kuno, A. Maki and Y. Okada, Physical Reviews D55 (1997) R2517-2520



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

Discriminate theoretical models

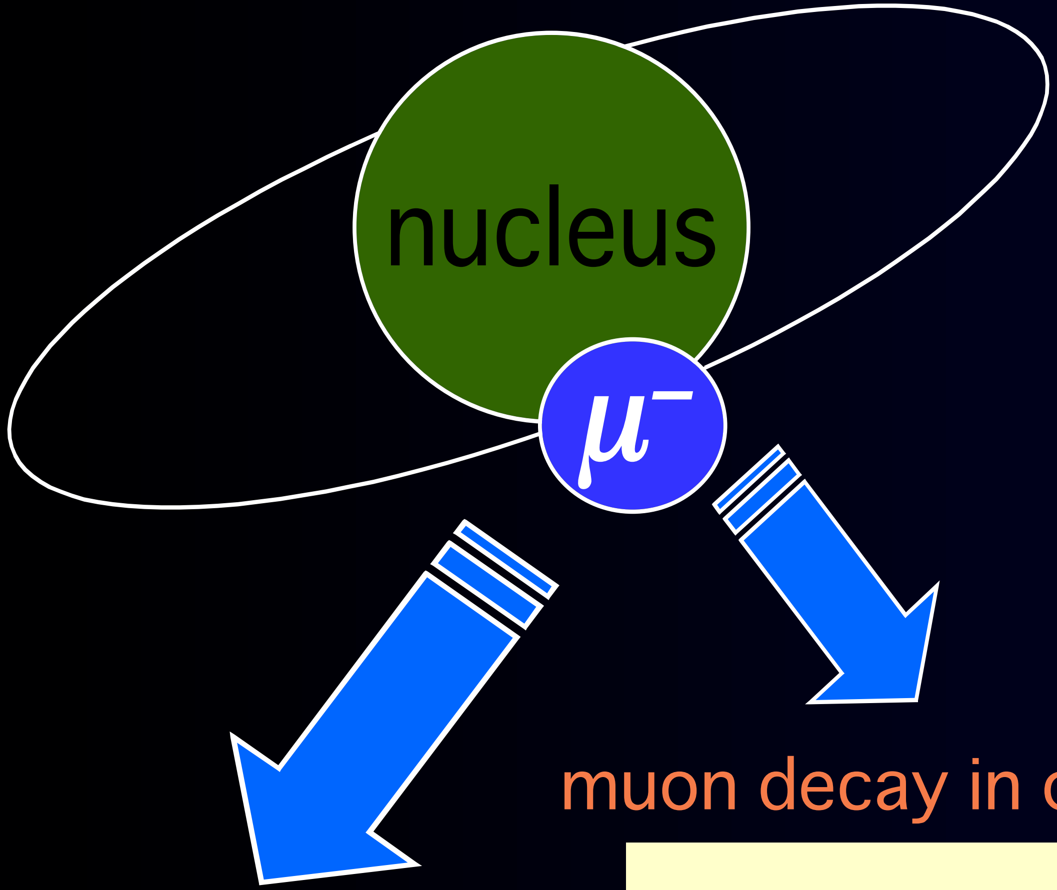
surface muons



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

What is a Muon to Electron Conversion ?

1s state in a muonic atom



muon decay in orbit

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

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

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

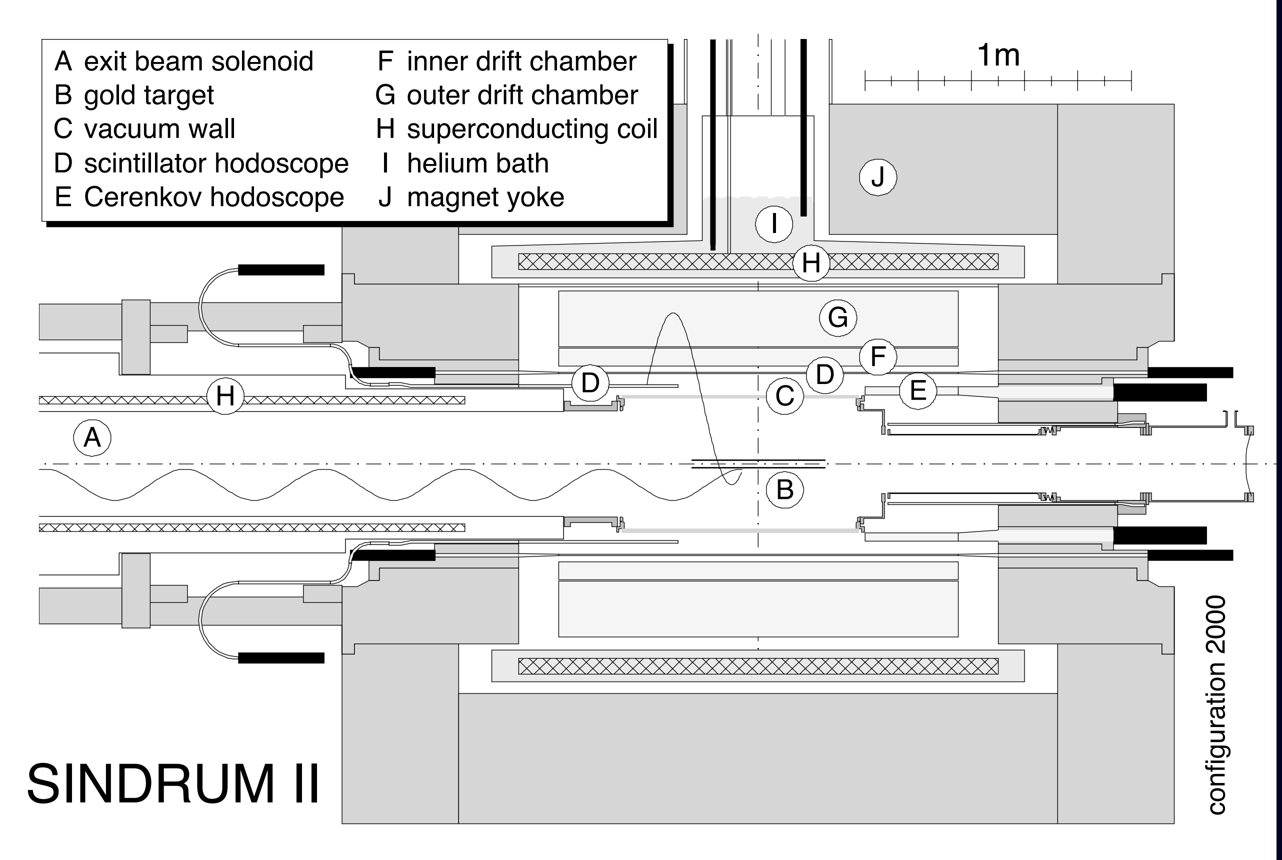
- The transition to the ground state is a coherent process, and enhanced by a number of nucleus.

$$\propto Z^5$$

- Backgrounds
  - Intrinsic physics background
    - muon decay in orbit (DIO)
  - beam-related background
    - radiative pion capture
    - muon decay in flight (DIF)
  - cosmic-ray background
  - tracking failure
  - etc....

Previous Measurements

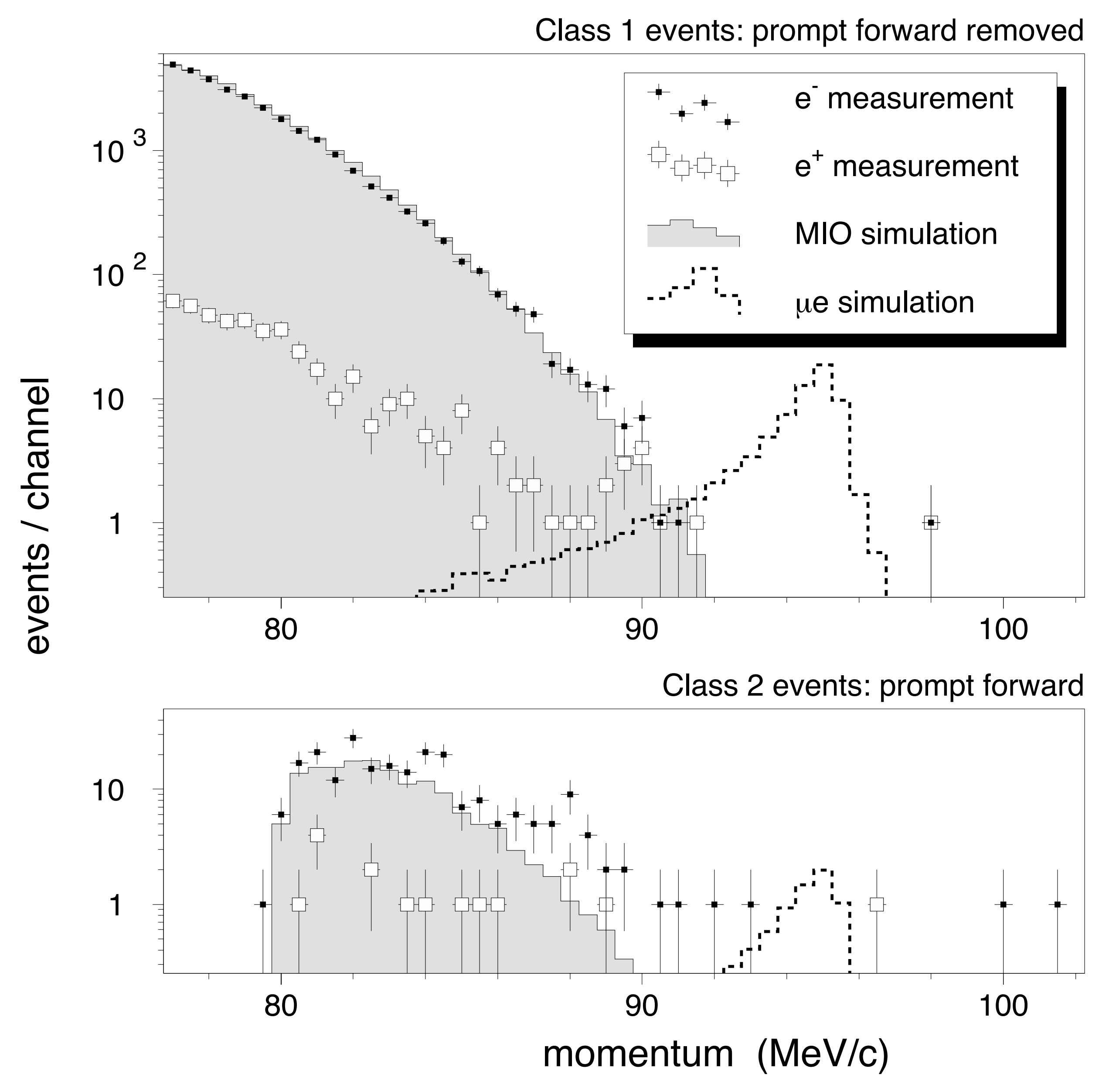
SINDRUM-II (PSI)



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)

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

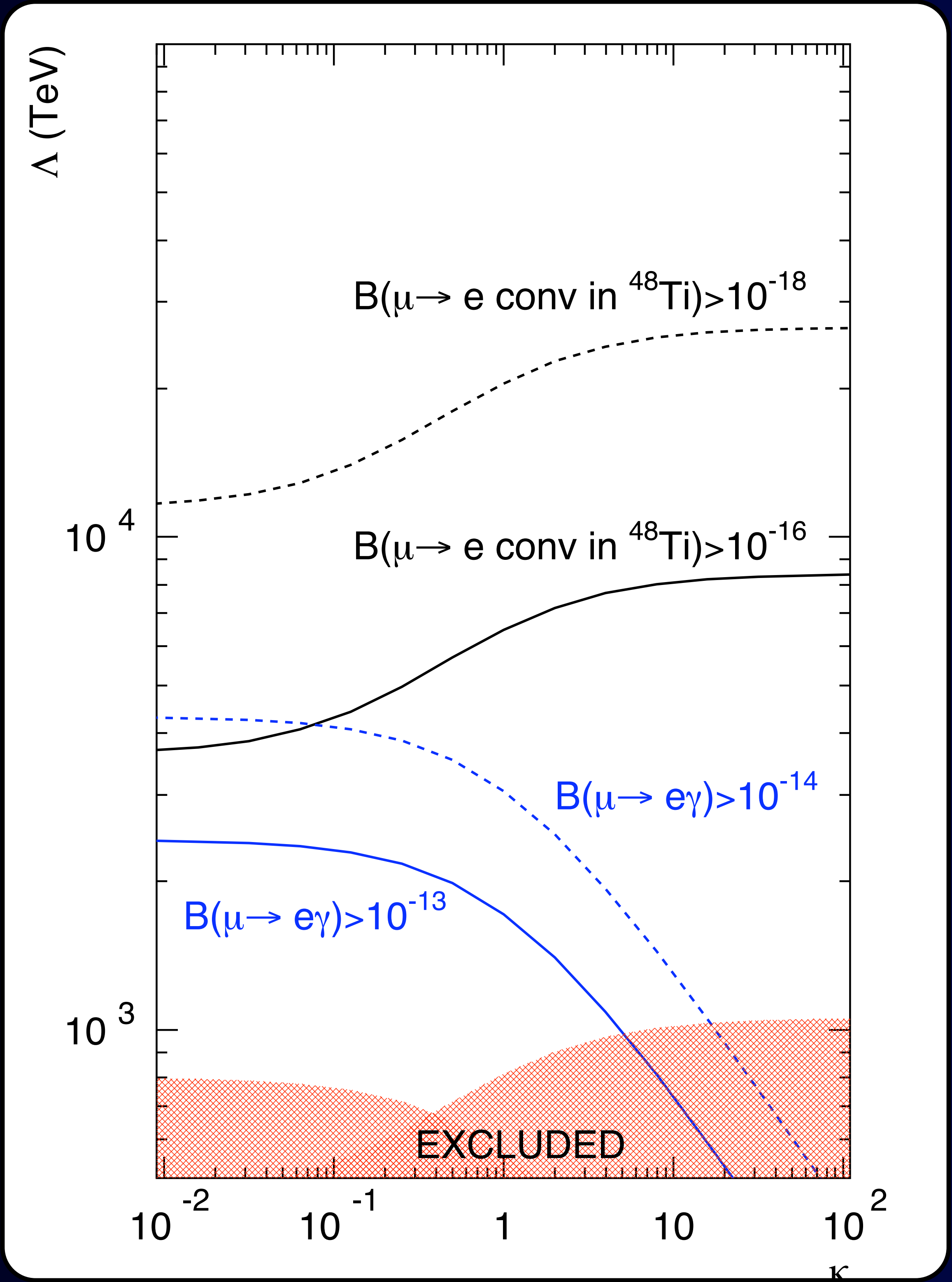


Physics Sensitivity Comparison between μ→eγ and μ-e Conversion

Photonic (dipole) and four Fermion contributions

	photonic (dipole)	Four Fermi interaction
μ→eγ	yes (on-shell)	no
μ-e conversion	yes (off-shell)	yes

μ-e conversion is sensitive to more new physics



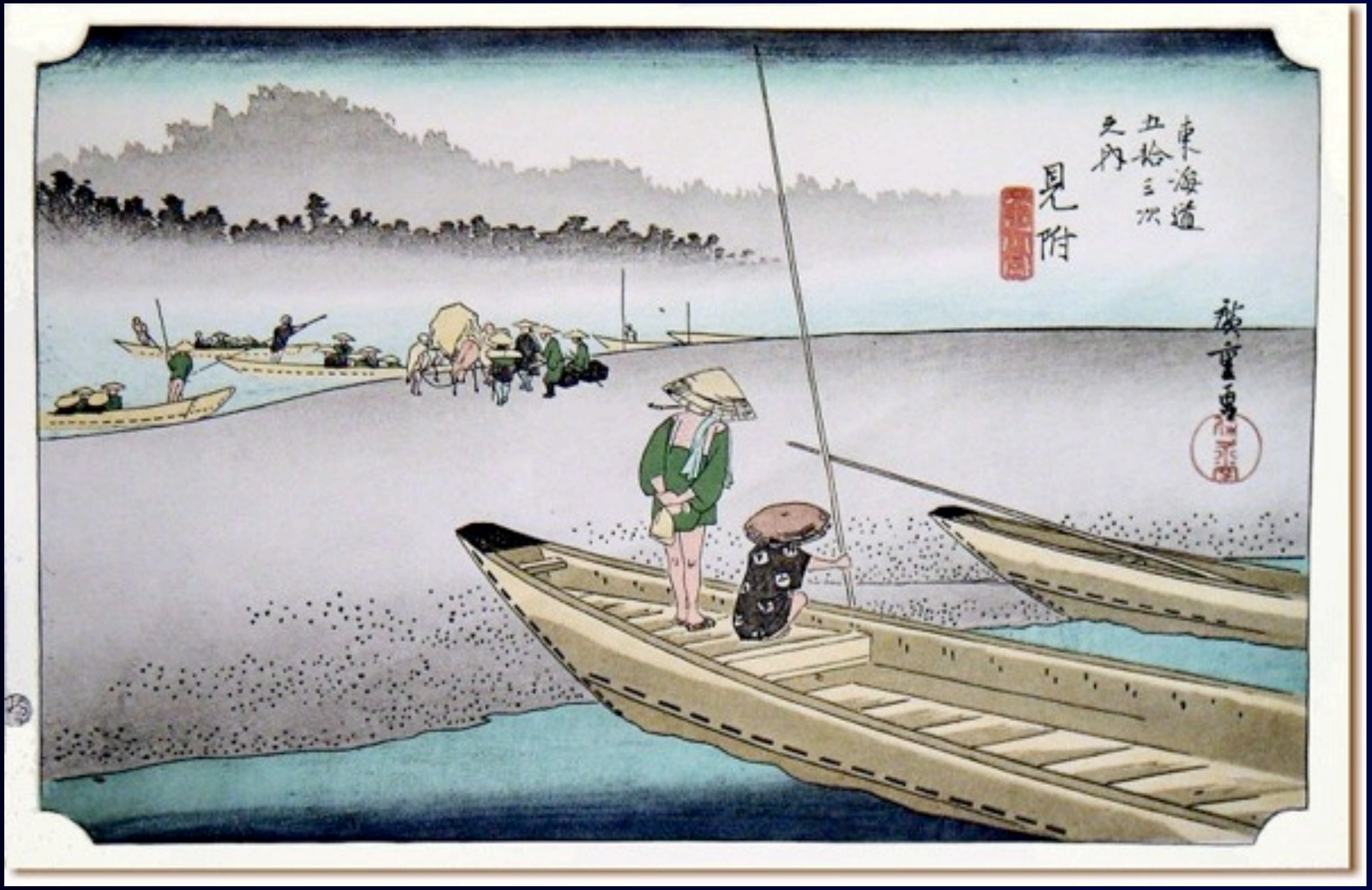
Experimental Comparison between μ→eγ and μ-e Conversion

	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.

Experimental Design for Muon to Electron Conversion



at Tenryu river, Shizuoka

Improvements for Signal Sensitivity

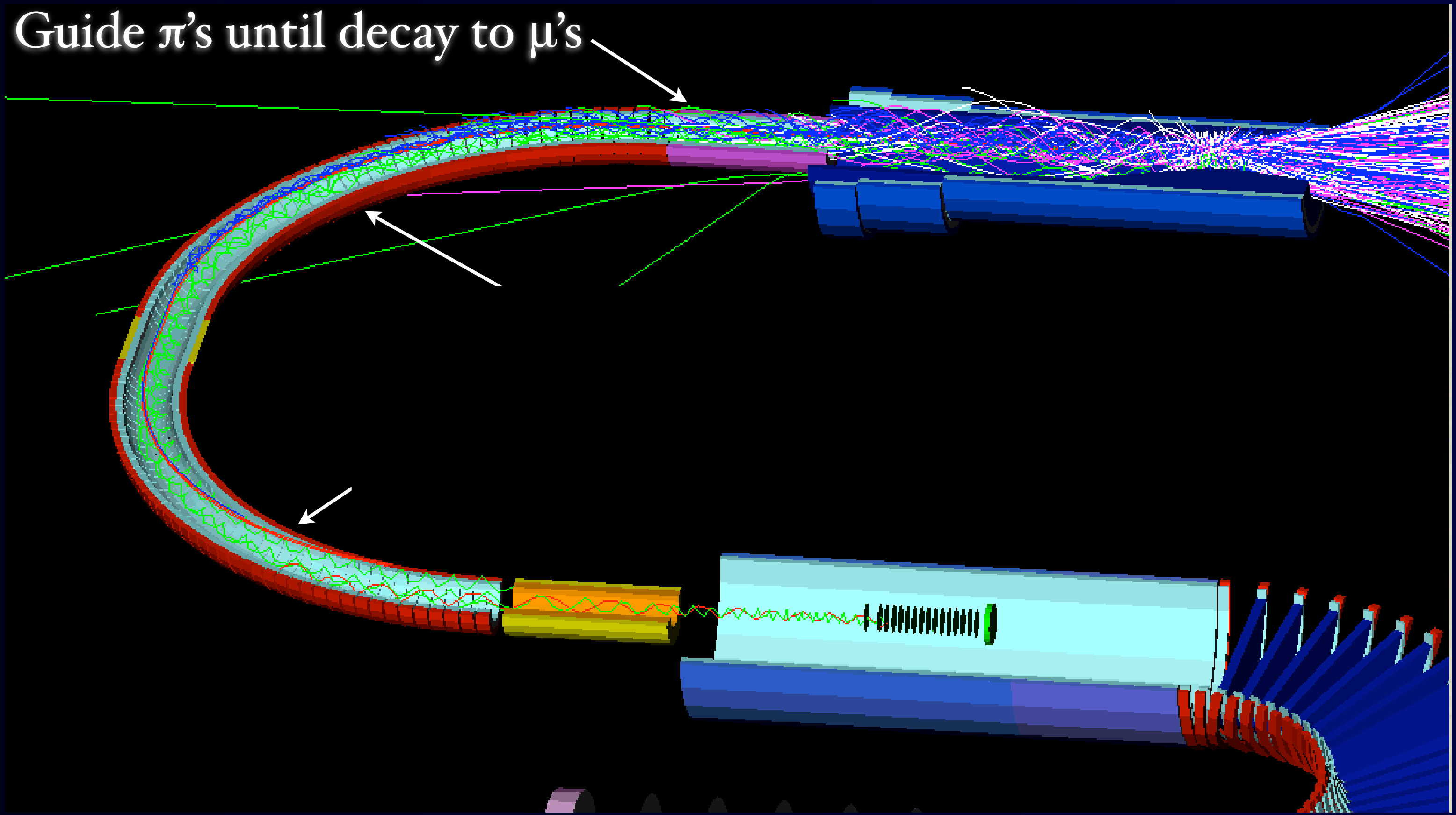
To achieve a single sensitivity of 10^{-16}, we need

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

(10^{11} muons for 50 kW beam power)



Improvements for Background Rejection

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

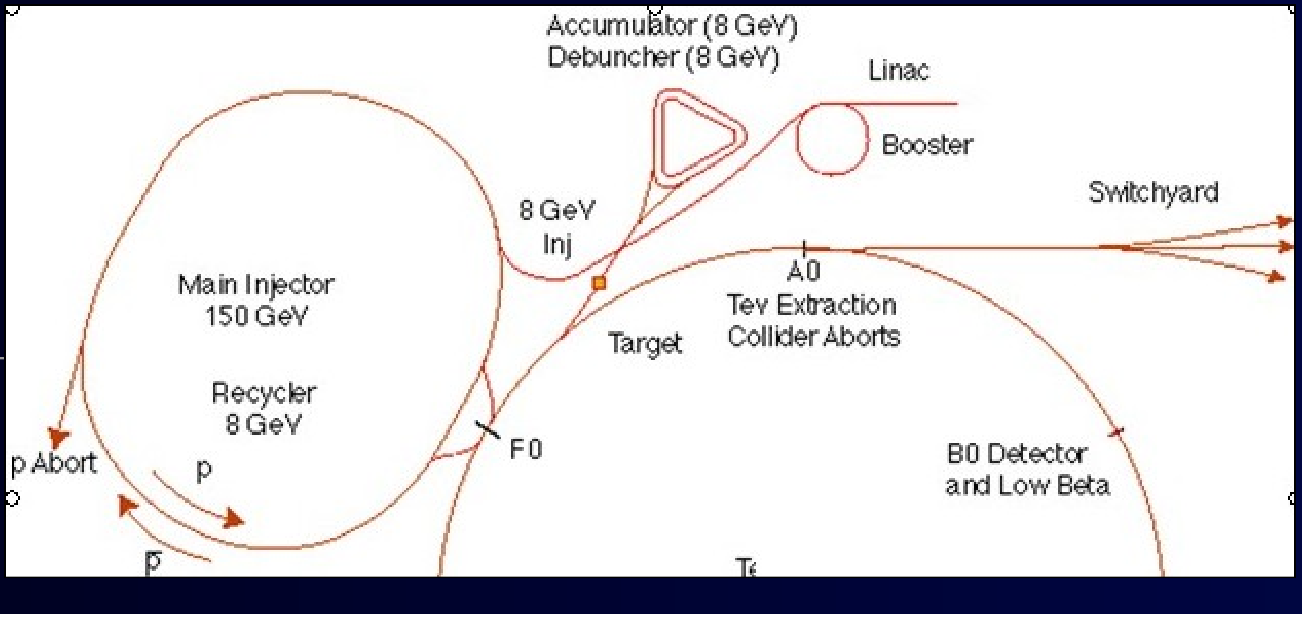
improve electron energy resolution

Muon DIF background → curved solenoids for momentum selection

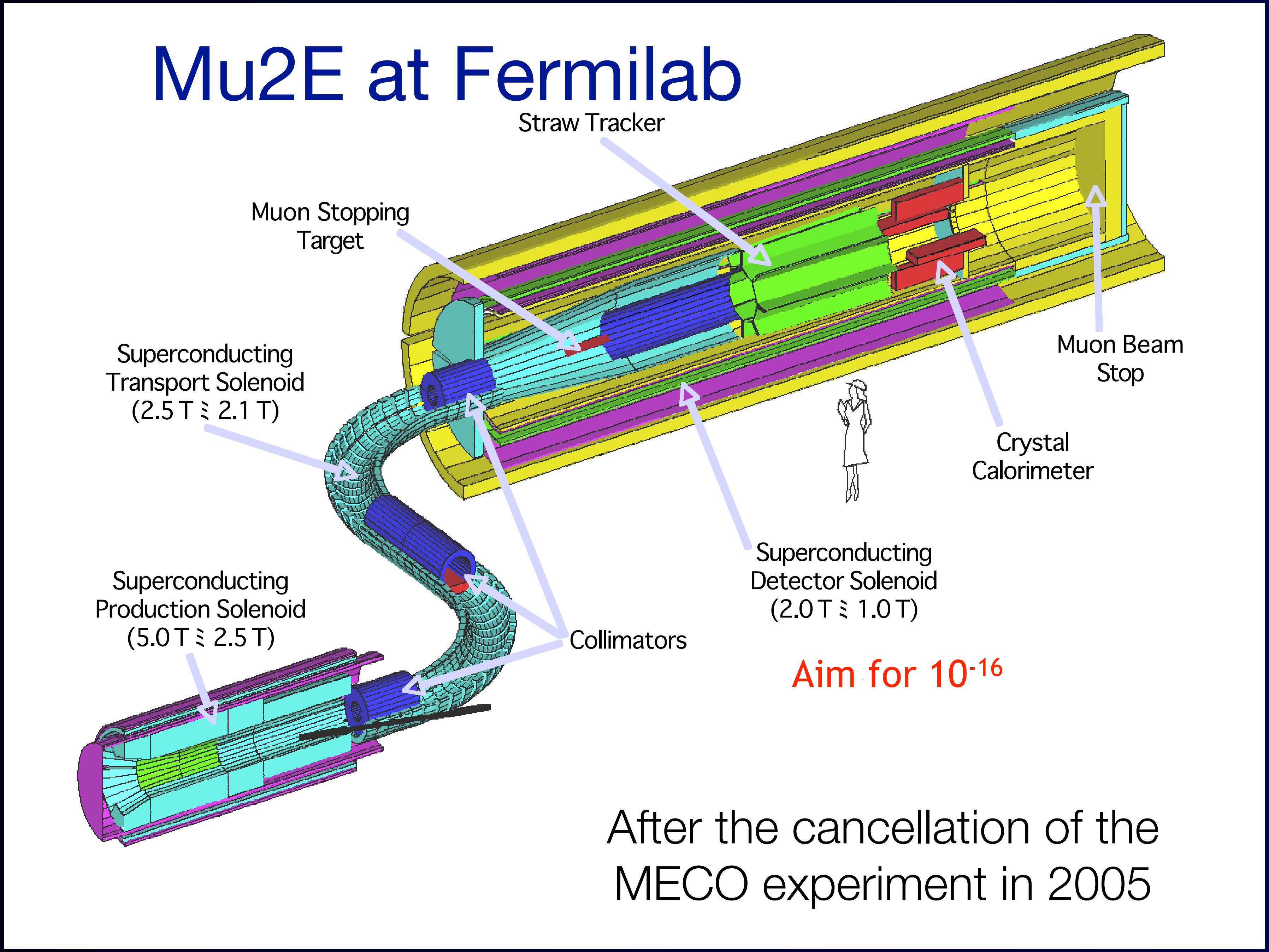
eliminate energetic muons (>75 MeV/c)

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, respectively.

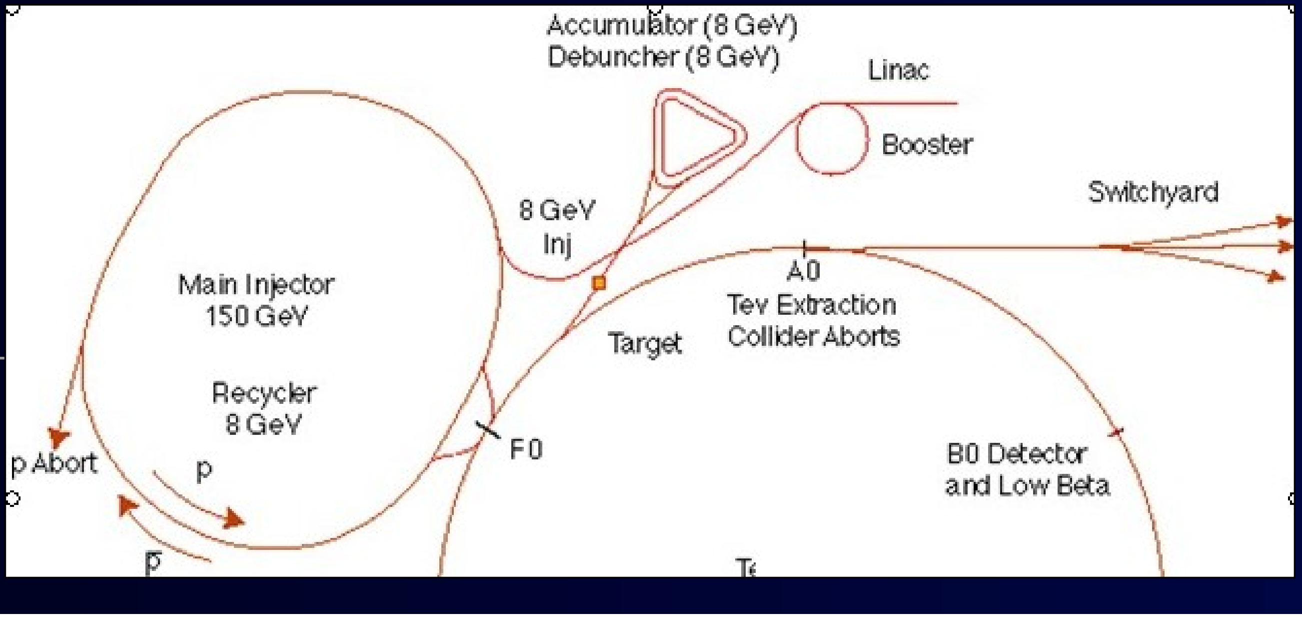


Mu2E at Fermilab

Aim for 10^{-16}

After the cancellation of the MECO experiment in 2005

Mu2E
at Fermilab



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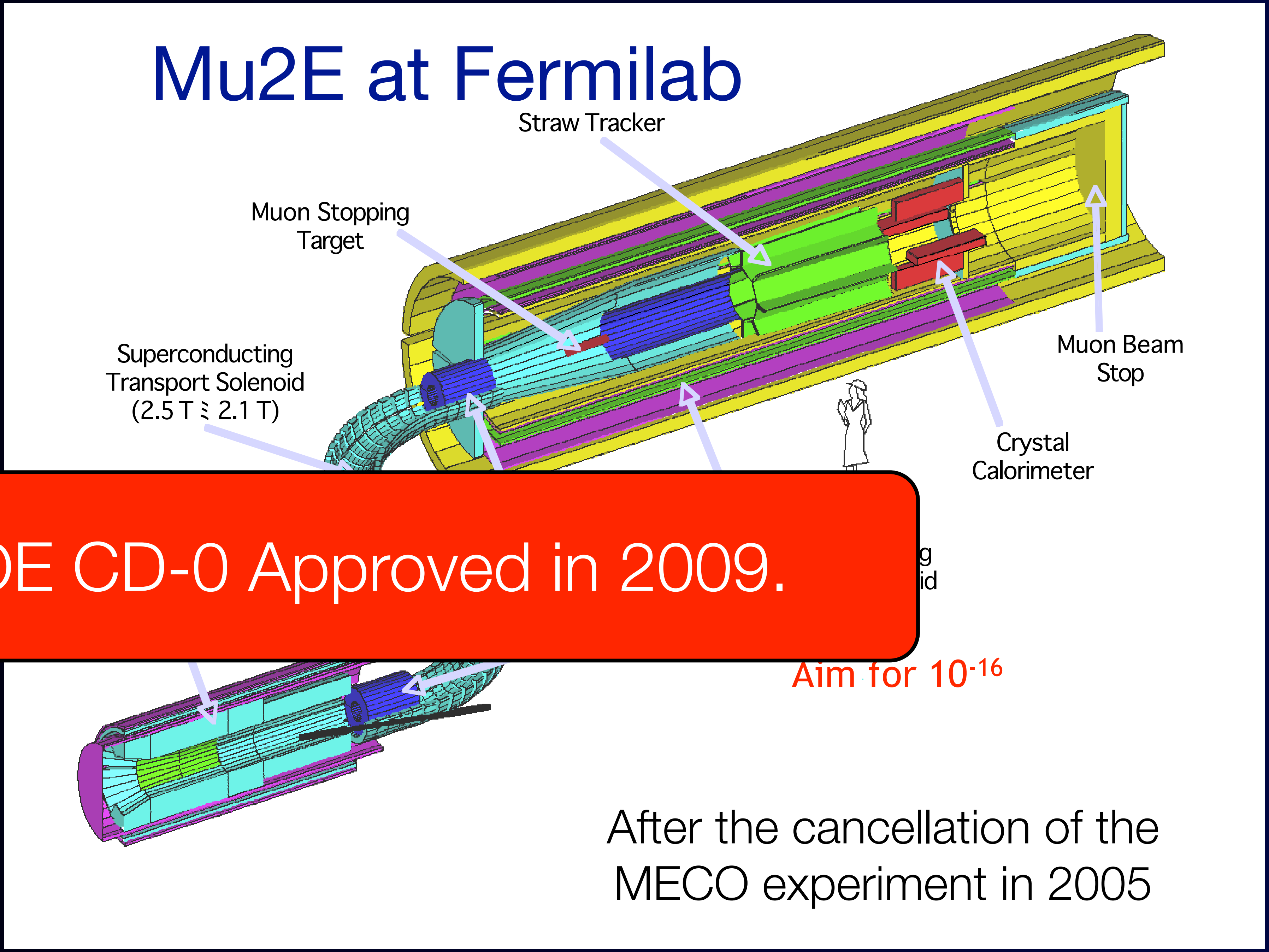


Mu2E at Fermilab

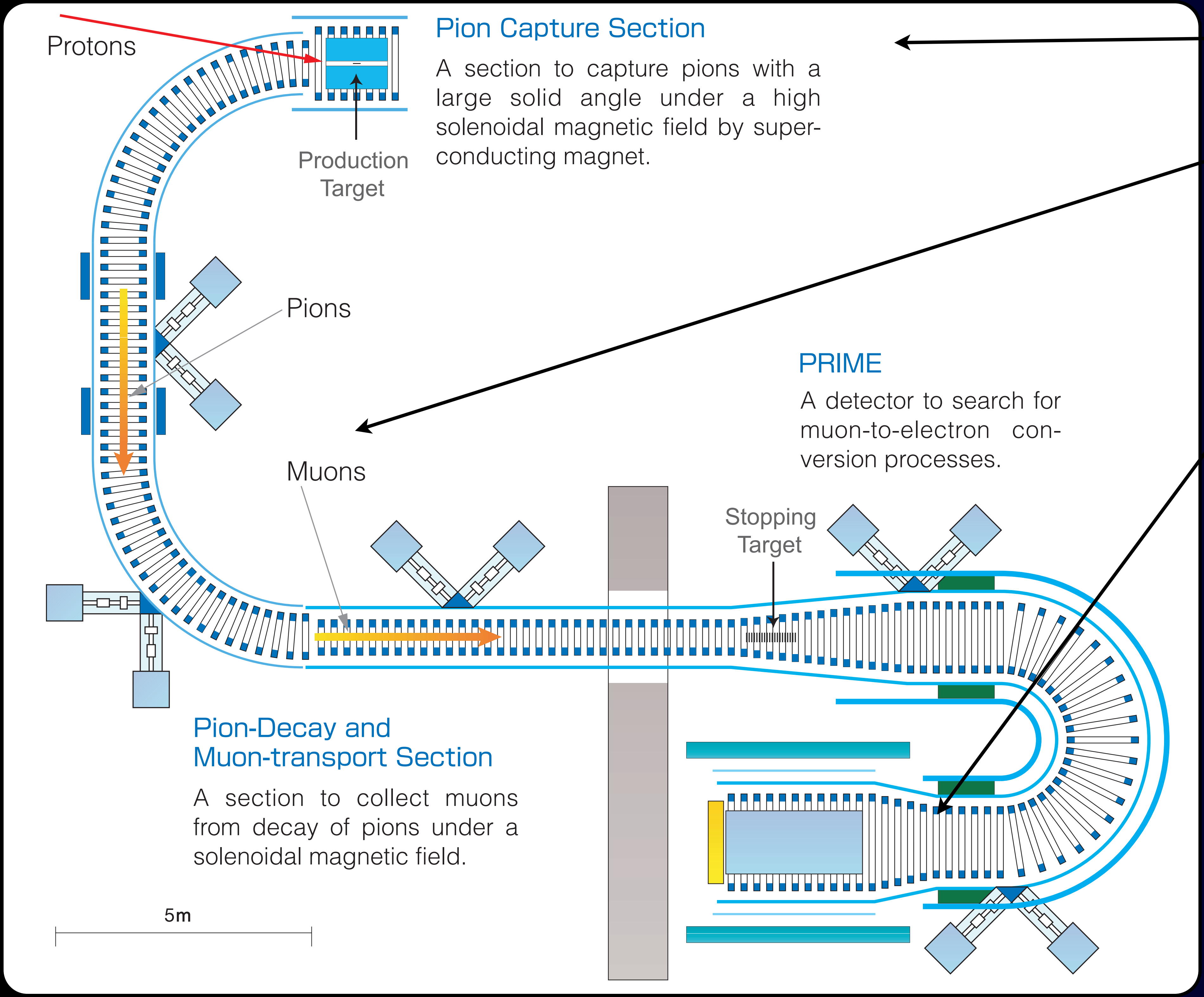
Aim for 10^{-16}

After the cancellation of the MECO experiment in 2005

DOE CD-0 Approved in 2009.

COMET (COherent Muon to Electron Transition) in Japan

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



Proton Beam

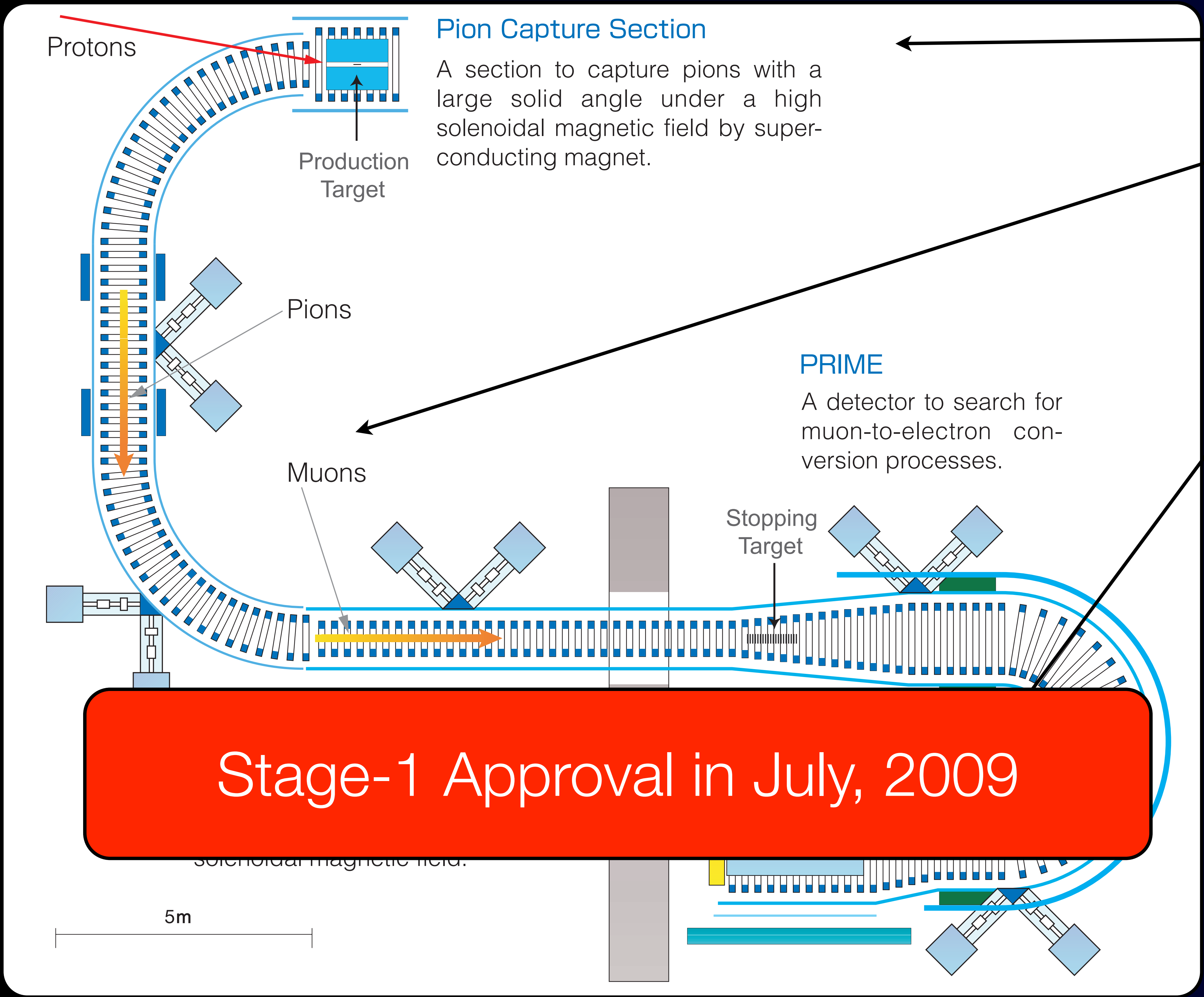
The Muon Source
- Proton Target
- Pion Capture
- Muon Transport

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

proposed to
J-PARC

COMET (COherent Muon to Electron Transition) in Japan

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



Pion Capture Section

A section to capture pions with a large solid angle under a high solenoidal magnetic field by superconducting magnet.

PRIME

A detector to search for muon-to-electron conversion processes.

Proton Beam

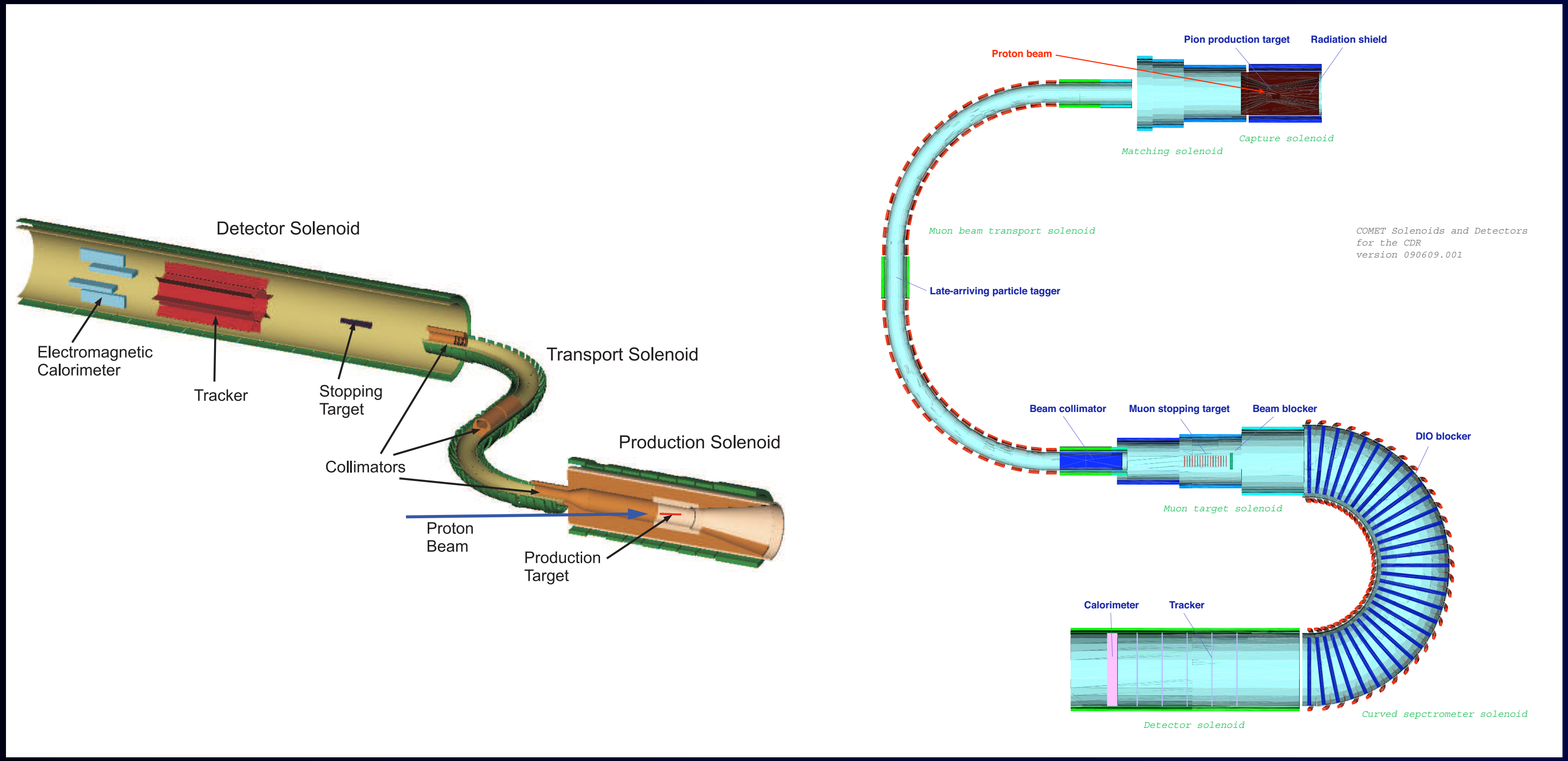
The Muon Source
- Proton Target
- Pion Capture
- Muon Transport

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

Stage-1 Approval in July, 2009

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

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

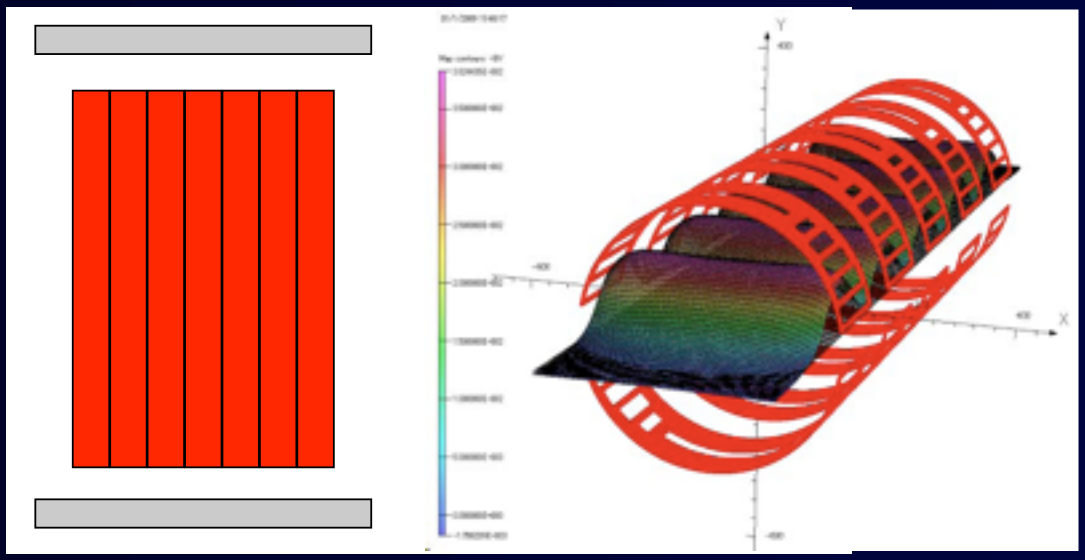
D : drift distance
B : Solenoid field
θ_{bend} : Bending angle of the solenoid channel
p : Momentum of the particle
q : Charge of the particle
θ : $\mathrm{atan}(P_T/P_L)$

  - This can be used for charge and momentum selection.

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

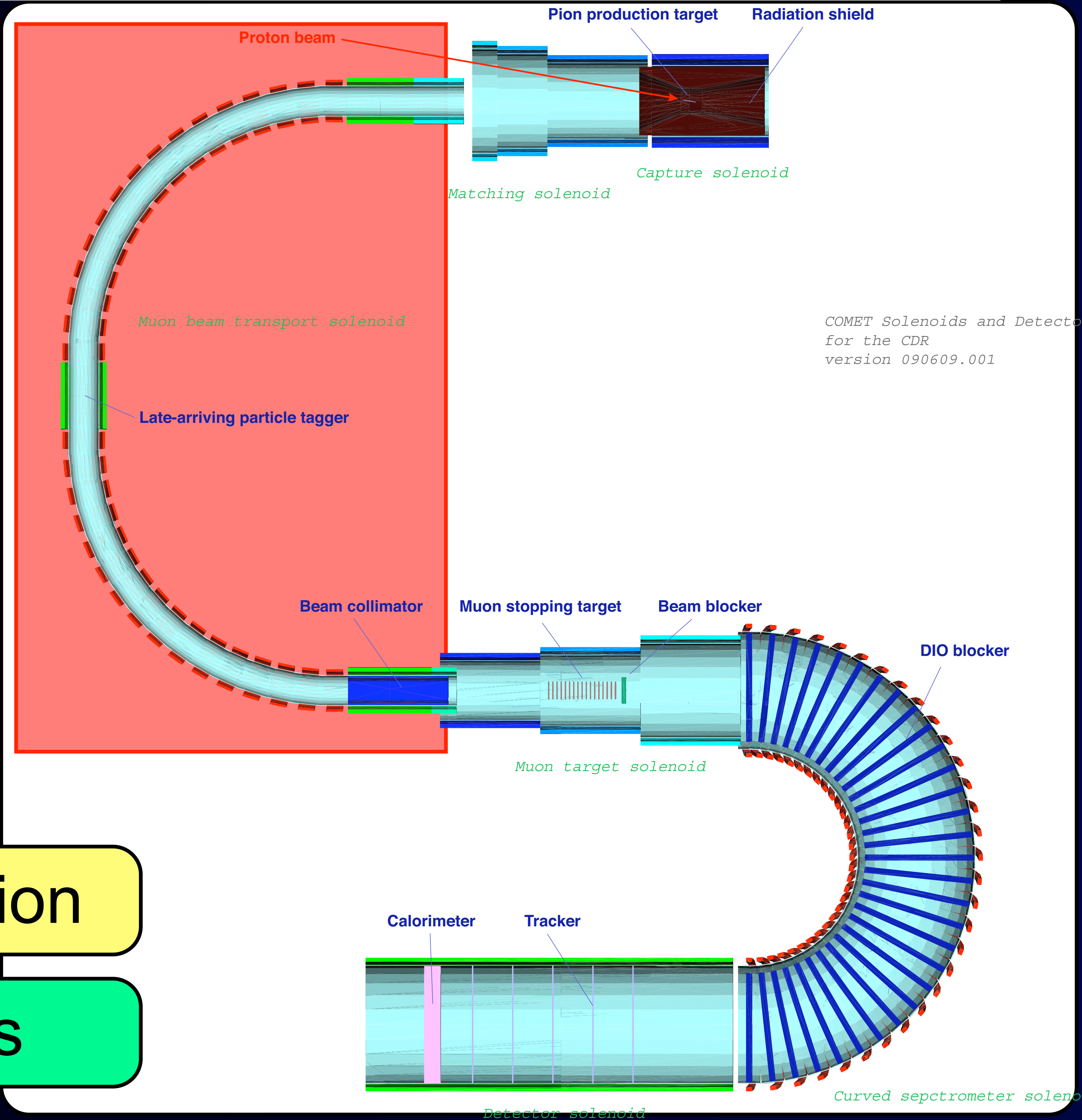
$$B_{comp} = \frac{p}{qr}\frac{1}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$

p : Momentum of the particle
q : Charge of the particle
r : Major radius of the solenoid
θ : $\mathrm{atan}(P_T/P_L)$



Muon Transport System for COMET

- The muon transport system consists of curved solenoids.
  - bore radius : 175 mm
  - magnetic field : 2 T
  - bending angle : 180 degrees
  - radius of curvature : 3 m
- Dispersion is proportional to a bending angle.
- muon collimator after 180 degree bending.
- Elimination of muon momentum > 70 MeV/c

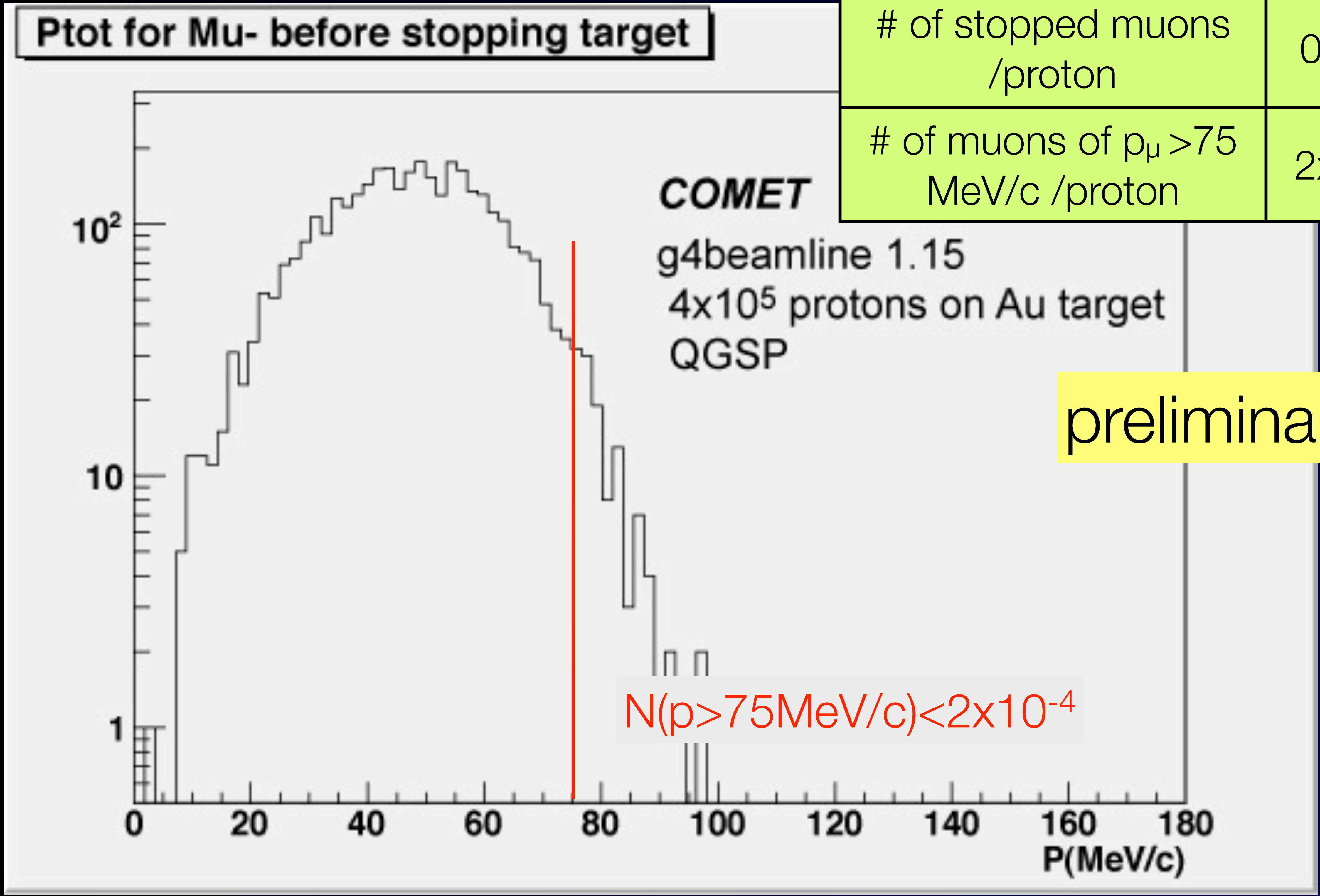


good momentum selection

no high-energy muons

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	2×10^{-4}



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

preliminary

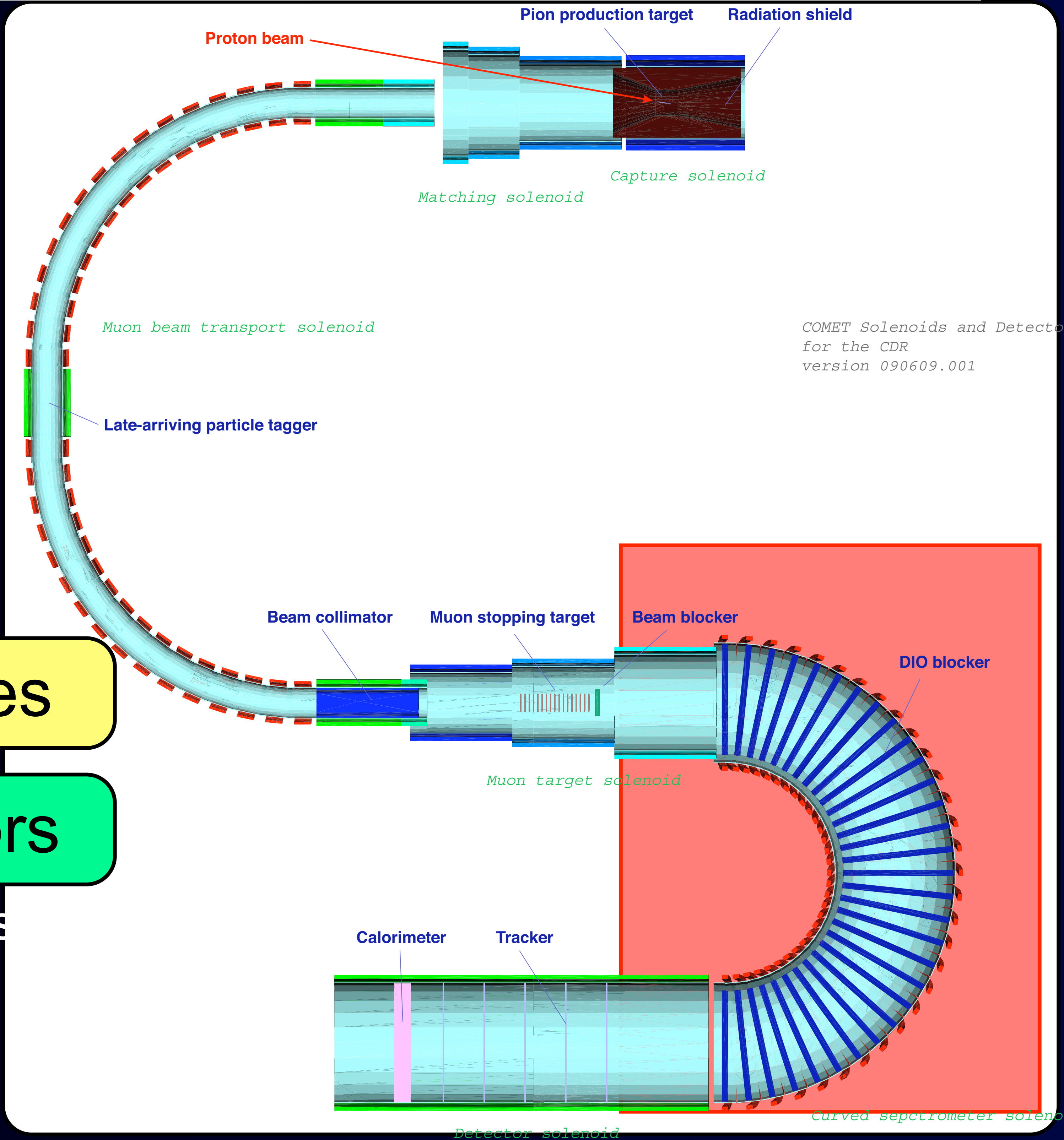
Electron Transport System for COMET

- The electron transport
  - bore : 700 mm
  - magnetic field : 1T
  - bending angle : 180 degrees
- Electron momentum ~ 104 MeV/c
- Elimination of negatively-charged particles less than 80 MeV/c
- Elimination of positively-charged particles (like protons from muon capture)

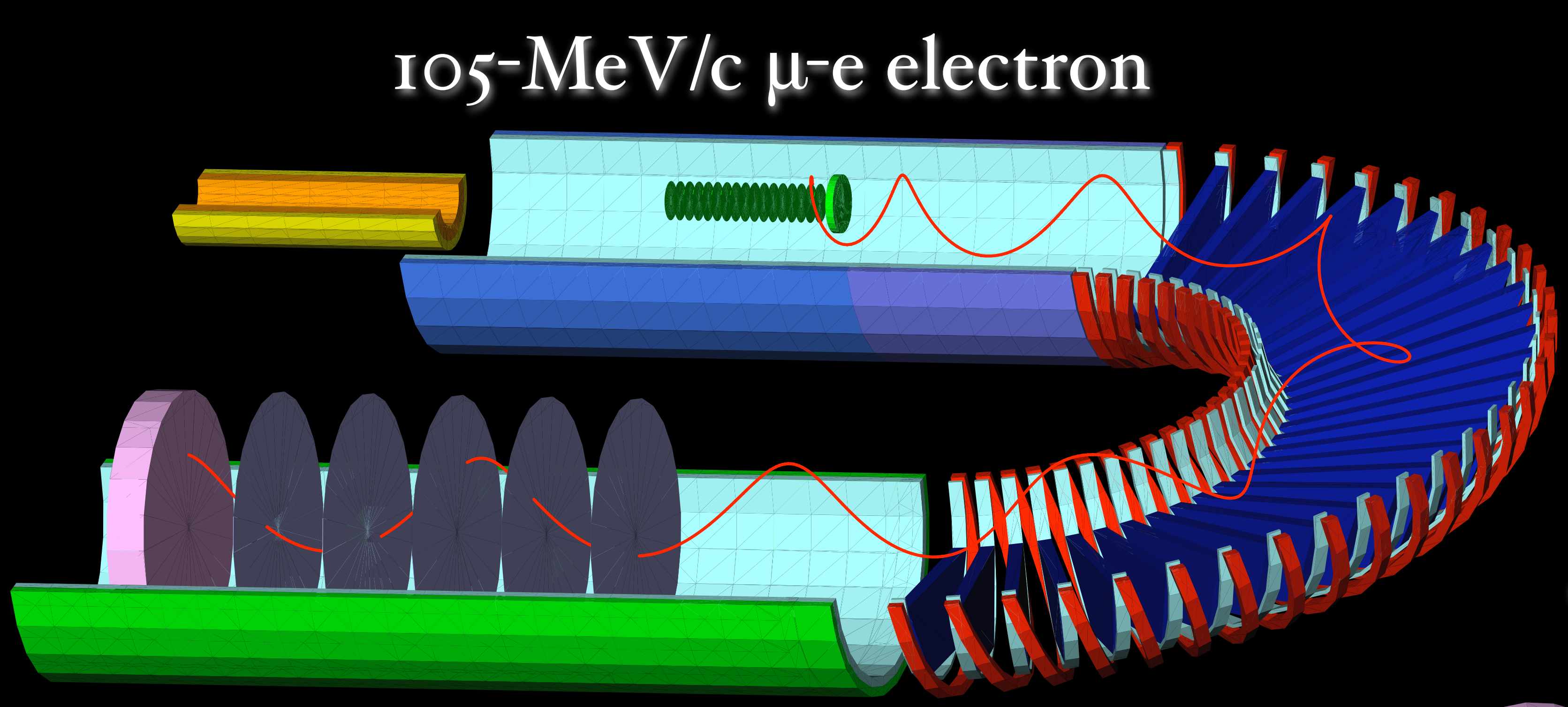
reduction of detector rates

no protons in the detectors

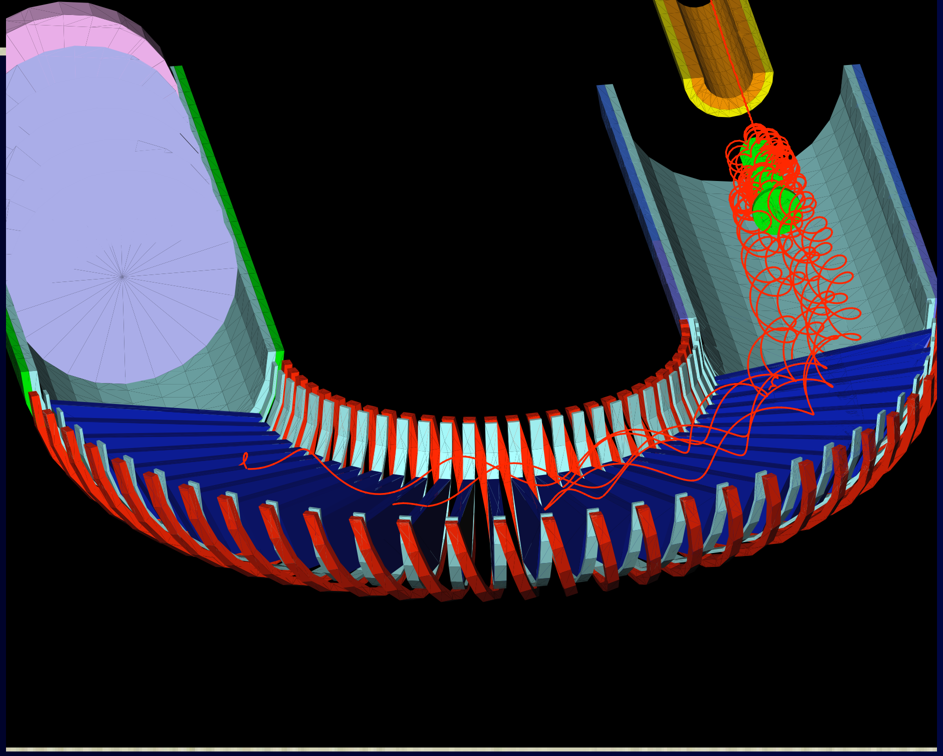
- a straight solenoid where detectors are placed follows the curved spectrometer.



Event Displays for Curved Solenoid Spectrometer

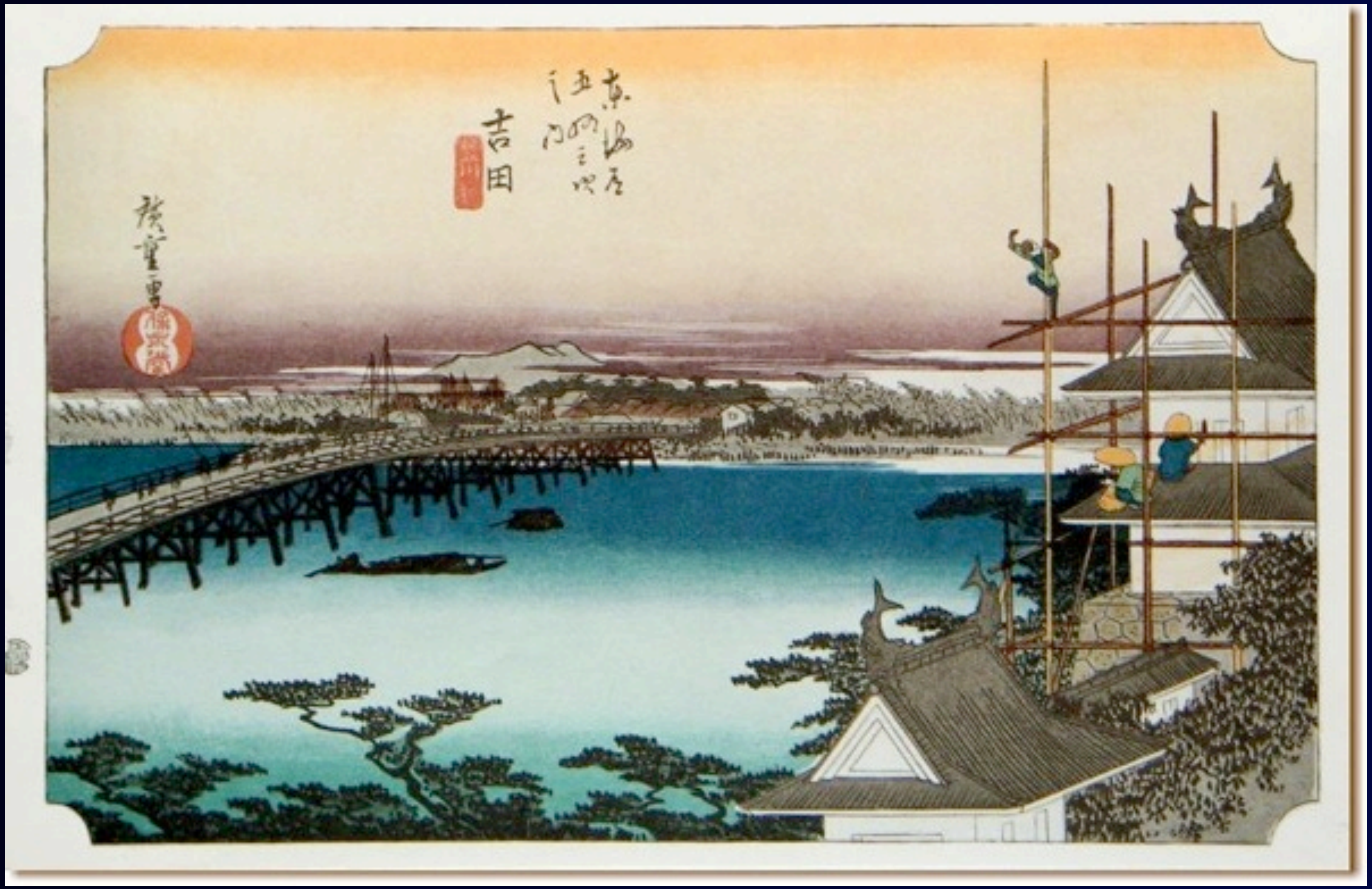


105-MeV/c μ-e electron



60-MeV/c DIO electrons

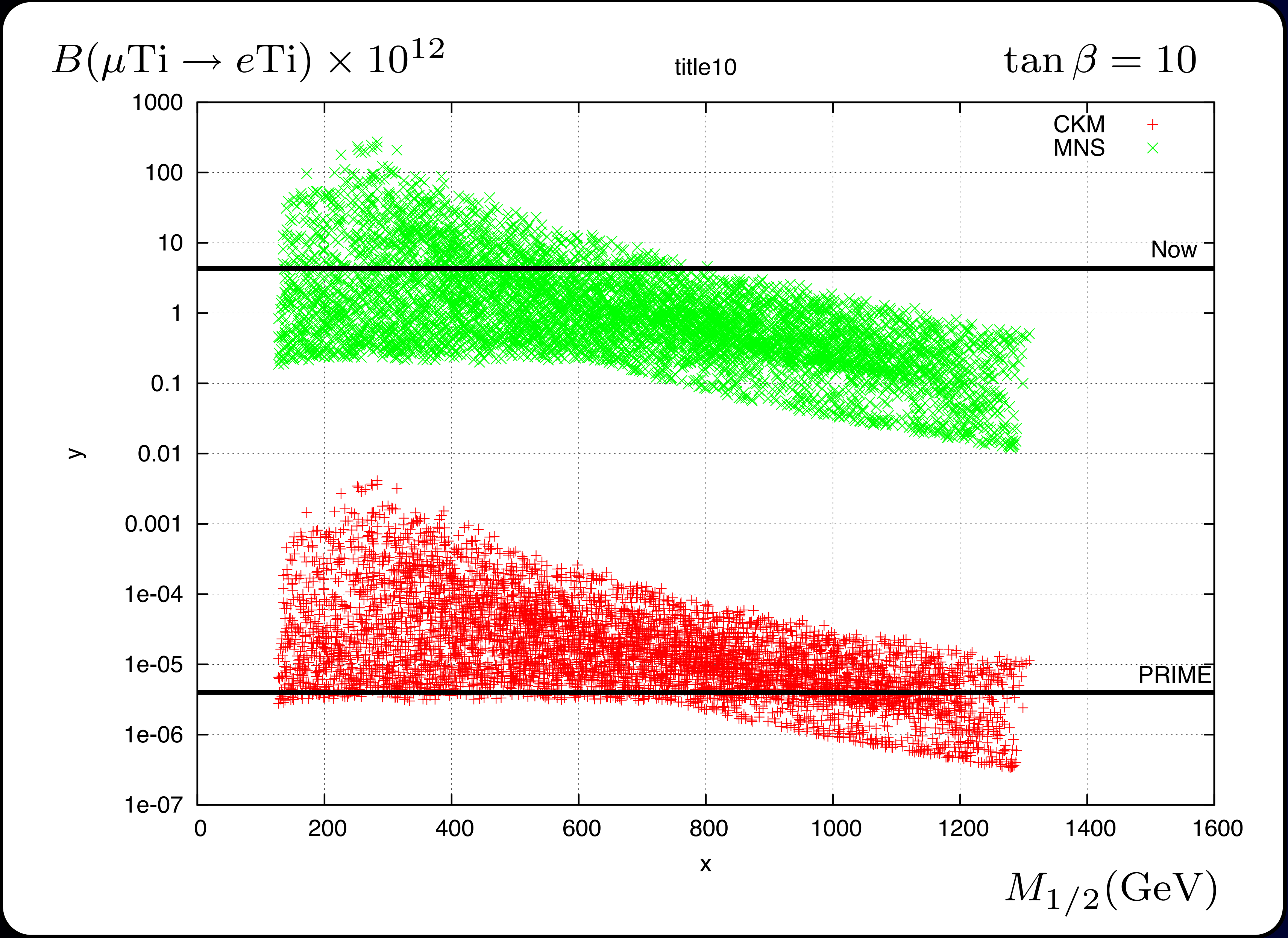
10^{-18} Sensitivity with PRISM/PRIME



at Yoshida (Toyohashi), Aichi

PRISM

Why Sensitivity of <10^{-18} ?



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

BR~10^{-18}

Full coverage of SUSY parameter space can be made.

Improvement on Signal Sensitivity of $< 10^{-18}$

Multi MW beam power is essential.

+

Time structure of a beam is very important.

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

mono-energetic muon beam

Muon DIO background → narrow muon beam spread

1/10 thickness muon stopping target

pure muon beam

Pion background → long muon beam-line

muon storage ring

Beam-related Background → Extinction at muon beam

fast kickers

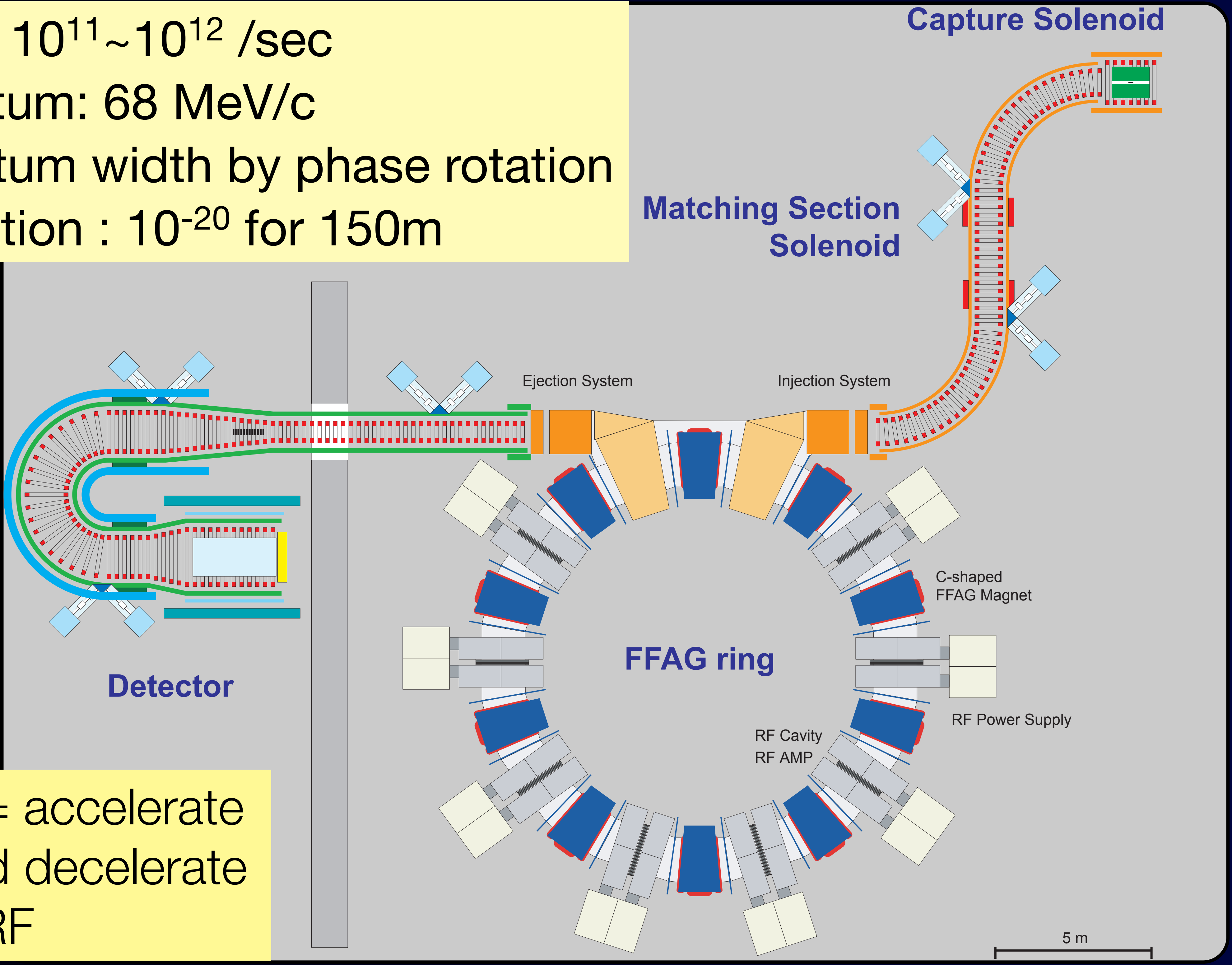
Cosmic-ray background → low-duty running

100 Hz rather than 1 MHz

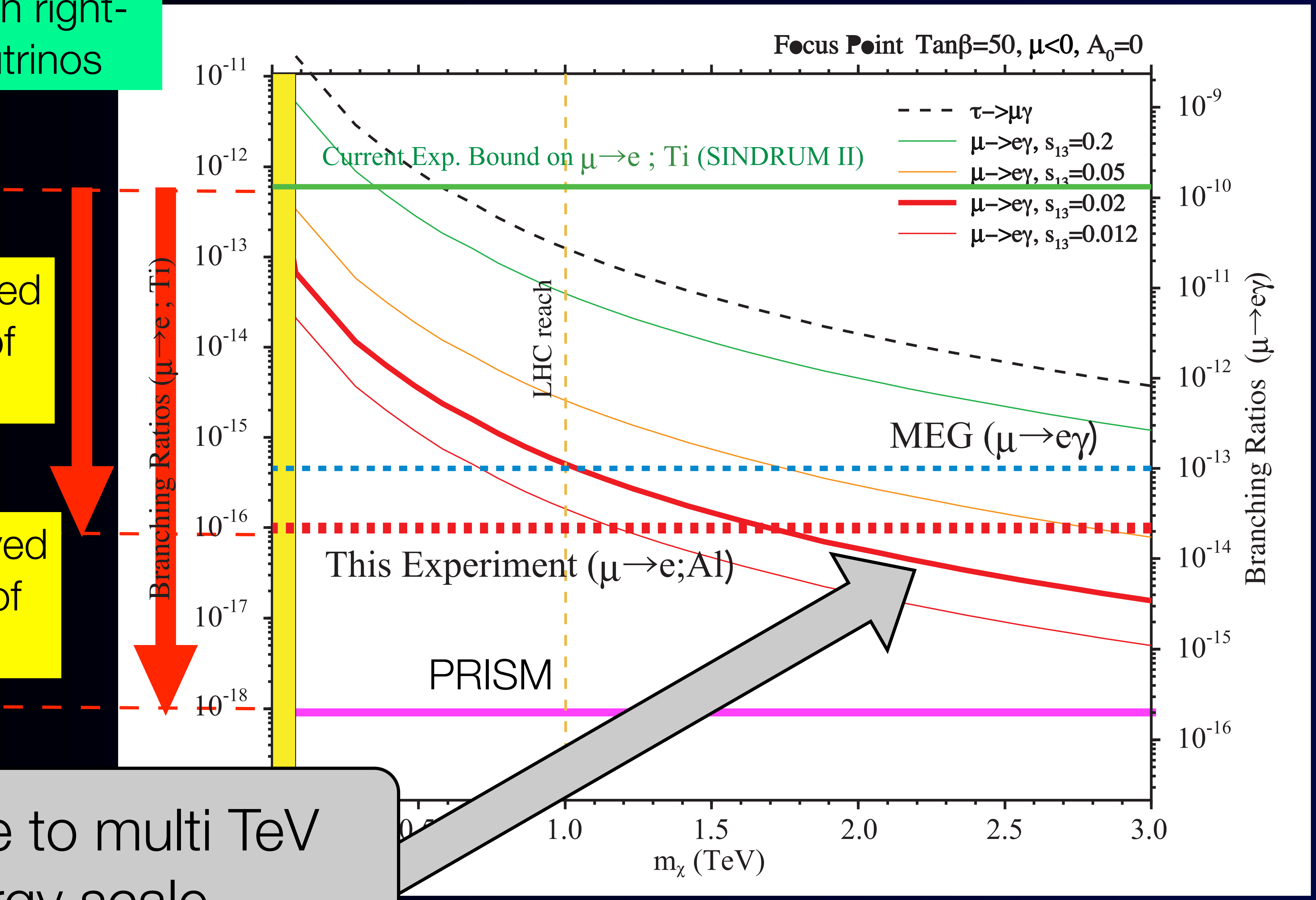
PRISM Muon Beam
PRIME Detector

PRISM=Phase Rotated Intense Slow Muon source

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



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



will be improved by a factor of 10,000.

will be improved by a factor of 1000,000.

sensitive to multi TeV energy scale.

Sensitivity Goals

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

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

R&D on the PRISM-FFAG Muon Storage Ring at Osaka University

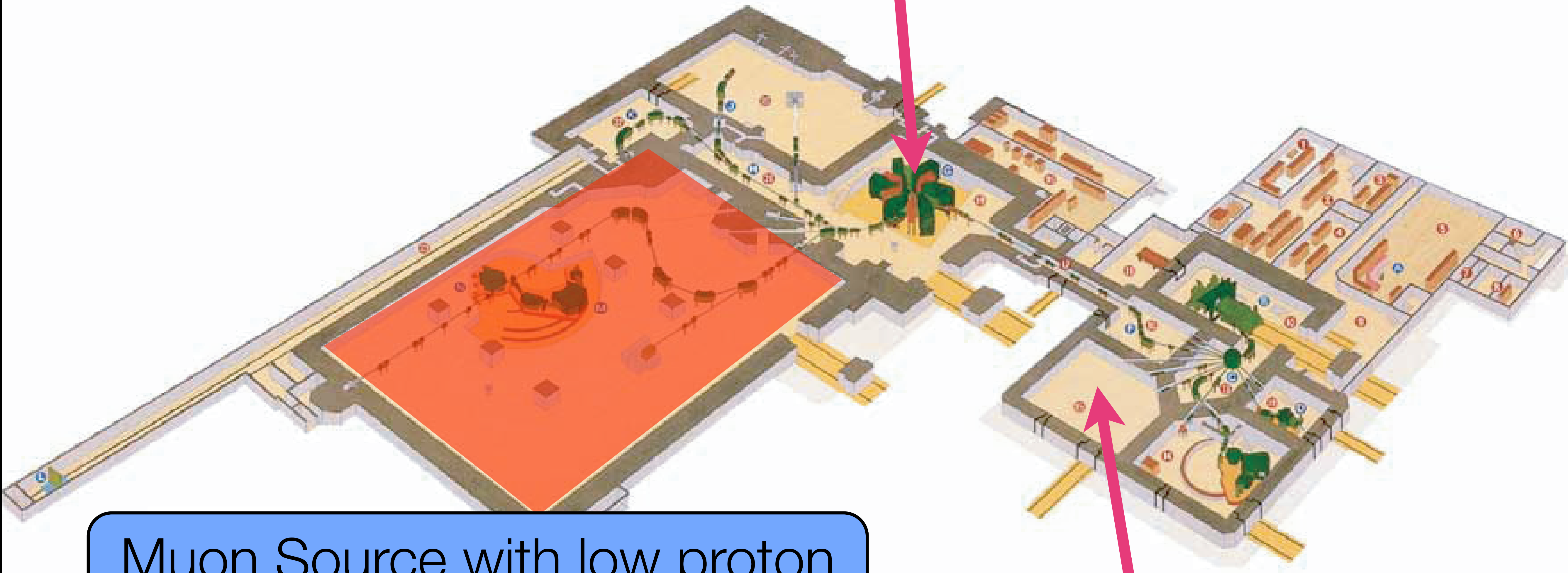
PRISM-FFAG (6 sectors) in RCNP, Osaka

Ready to demo. phase rotation

R&D at
Osaka University

at Okazaki, Aichi

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.

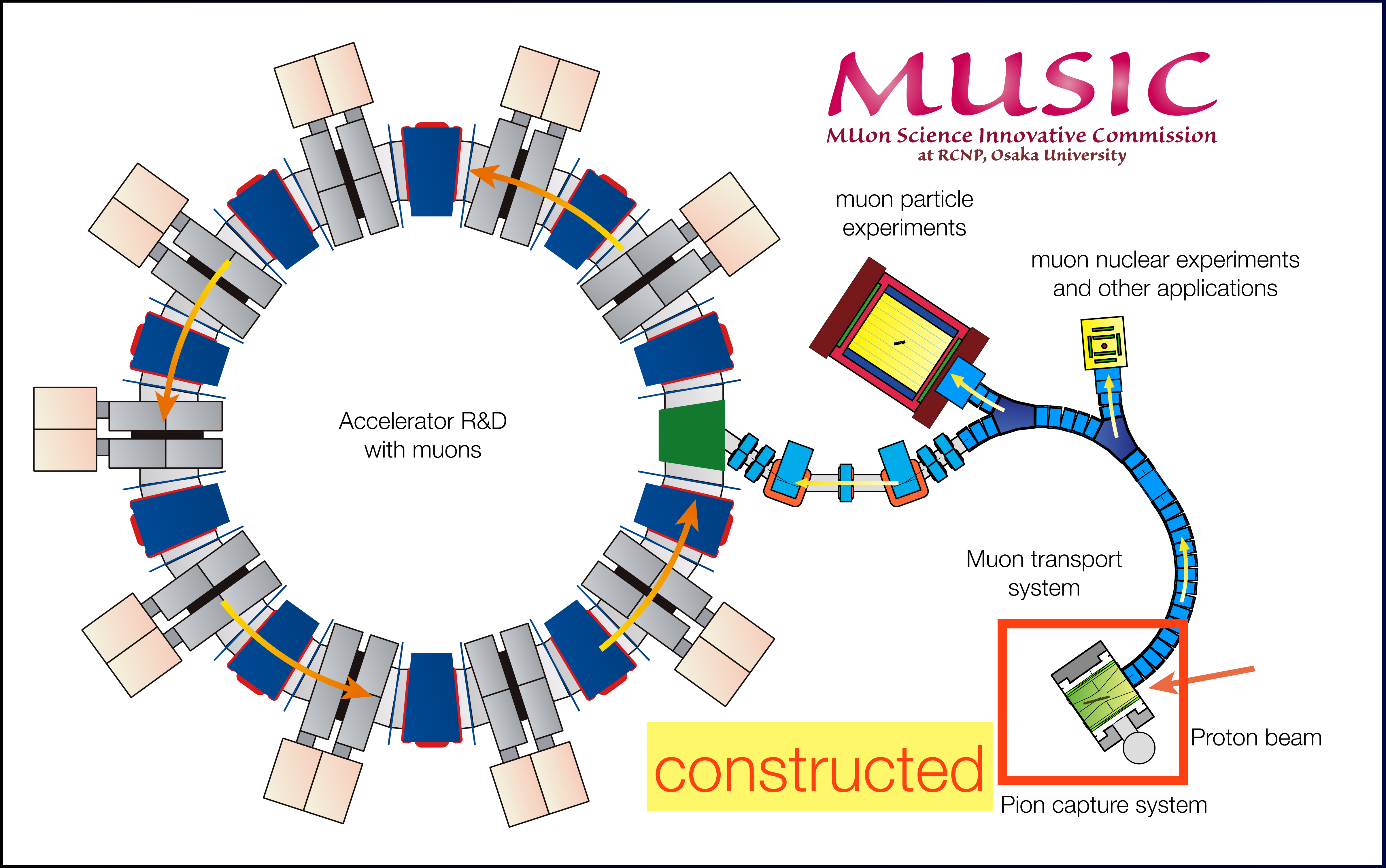
Muon Source with low proton power at Osaka U.?

PRISM-FFAG R&D

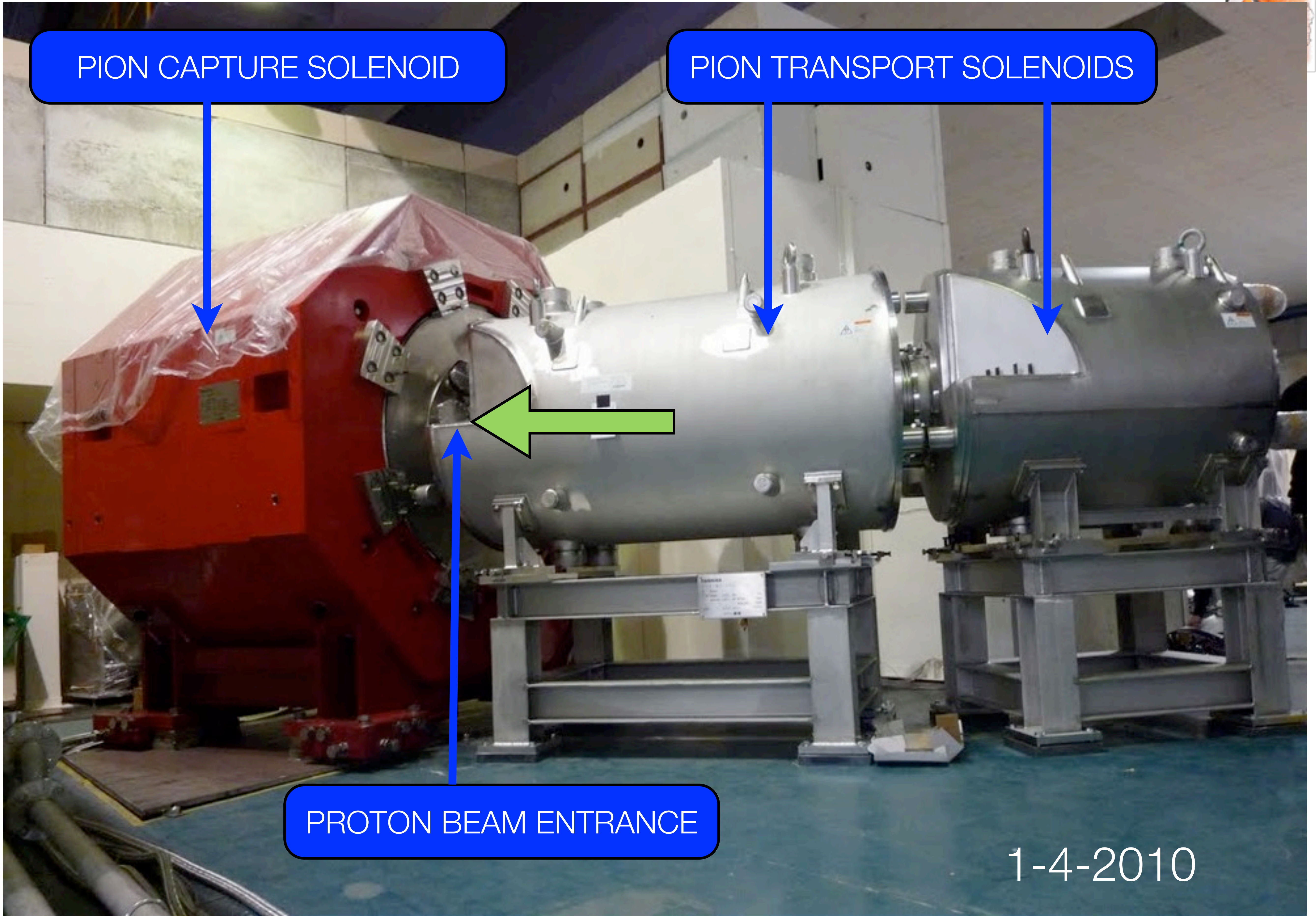
muon yield estimation

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

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



constructed



PION CAPTURE SOLENOID

PION TRANSPORT SOLENOIDS

PROTON BEAM ENTRANCE

1-4-2010

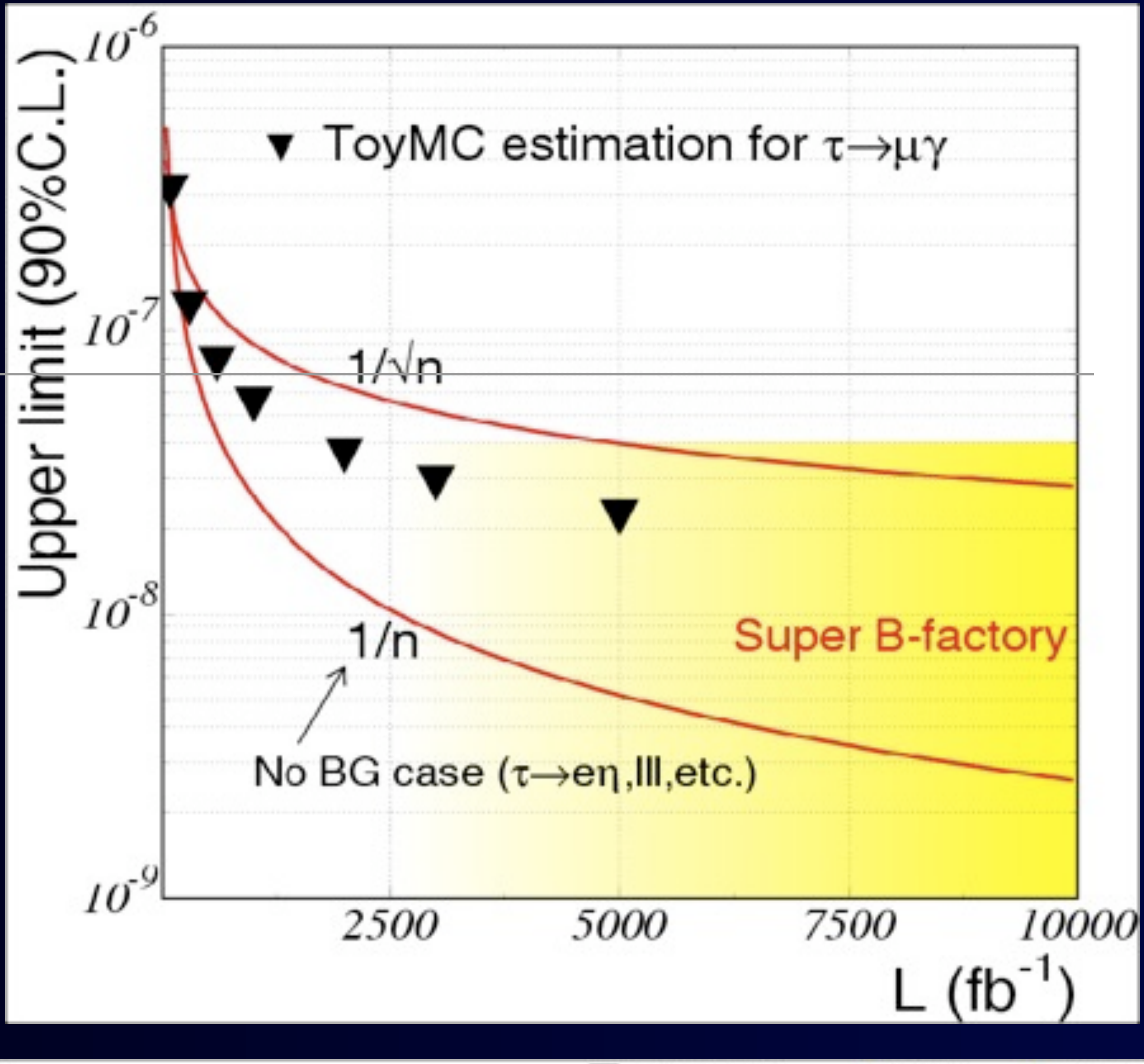
cLFV with taus

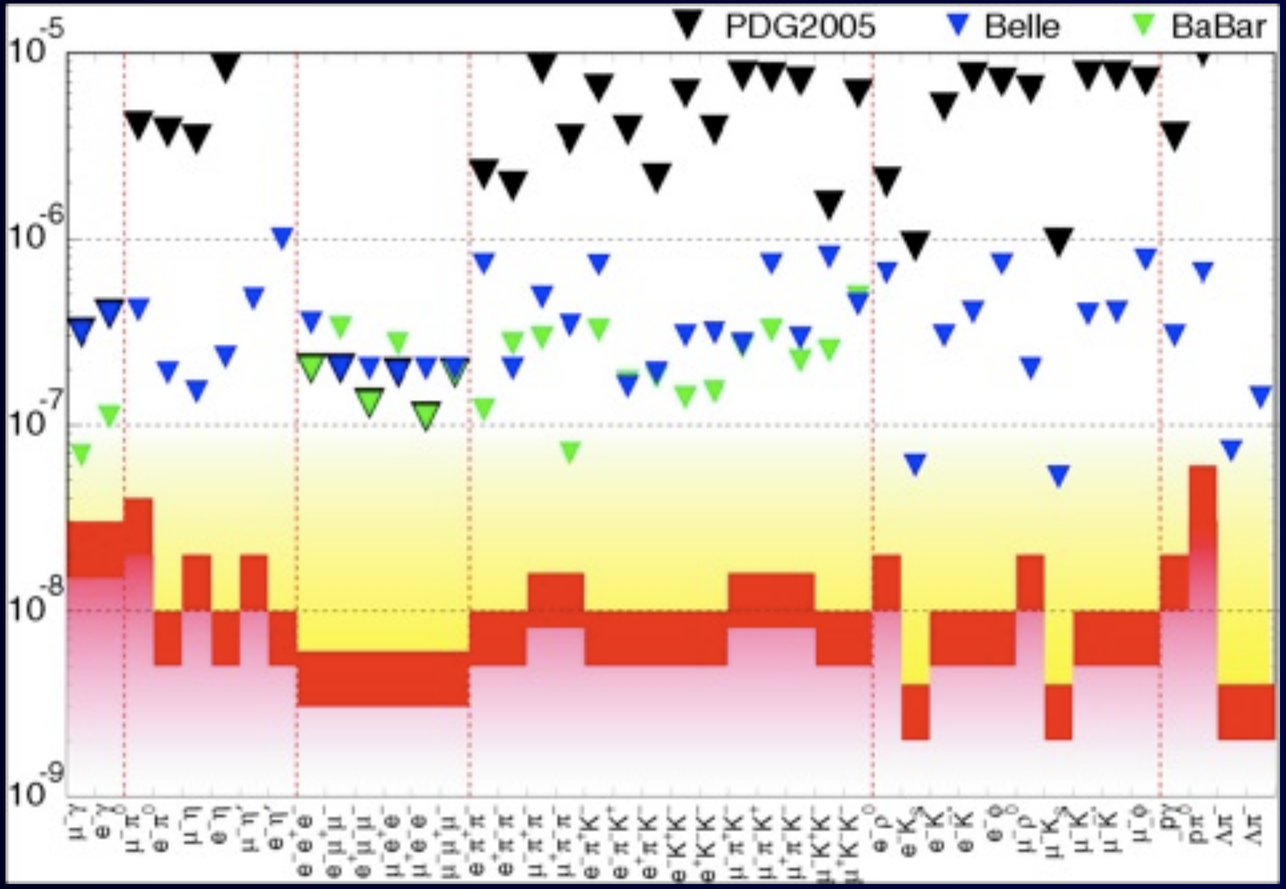
Shinagawa

CLFV with Taus

- B factories produce many taus of more than 10^8 in total ($\sigma \sim 0.9$nb).
- $\tau \rightarrow l\gamma$ is background-limited, and improved by $1/\sqrt{N}$.
- Super B factories will produce a factor of 10-100 times taus.
- The red bands (in right plot) having sensitivities of 10^{-9} are expected with 5 - 10 ab^{-1}.

SuperB and SuperKEKB

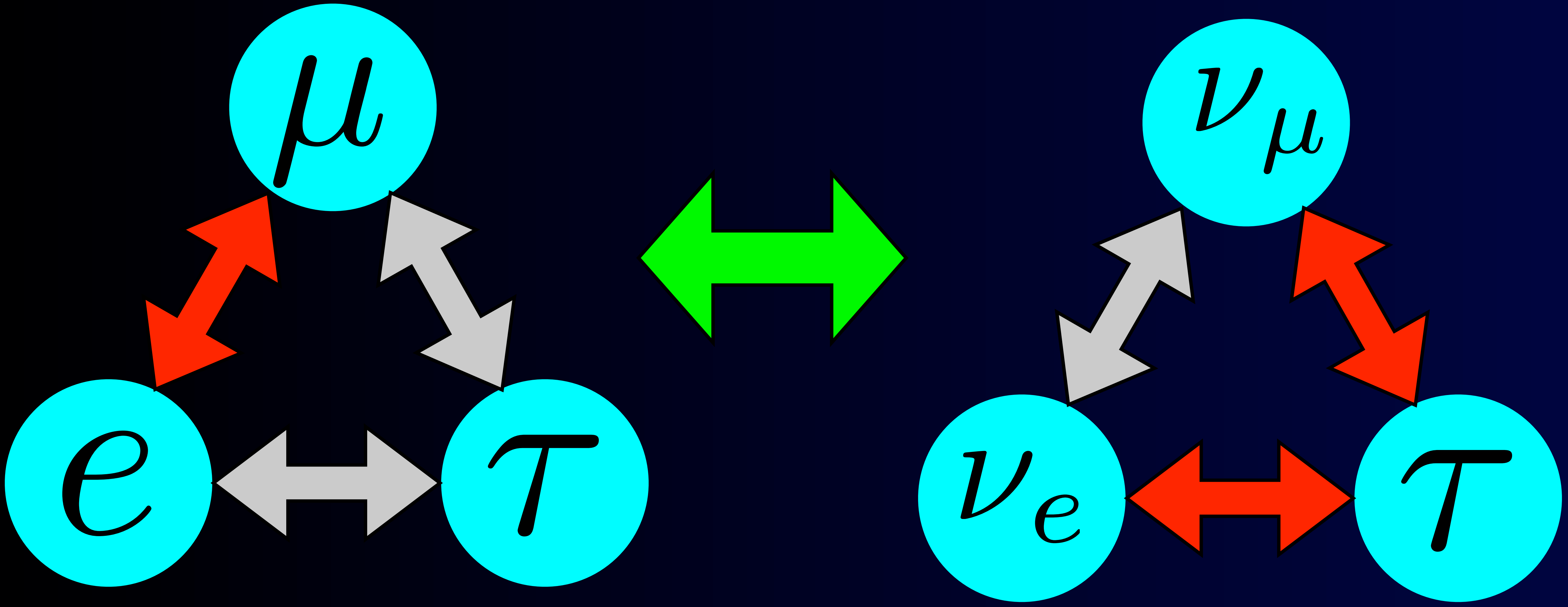




LFV charged
current process

cLFV with Tau Leptons

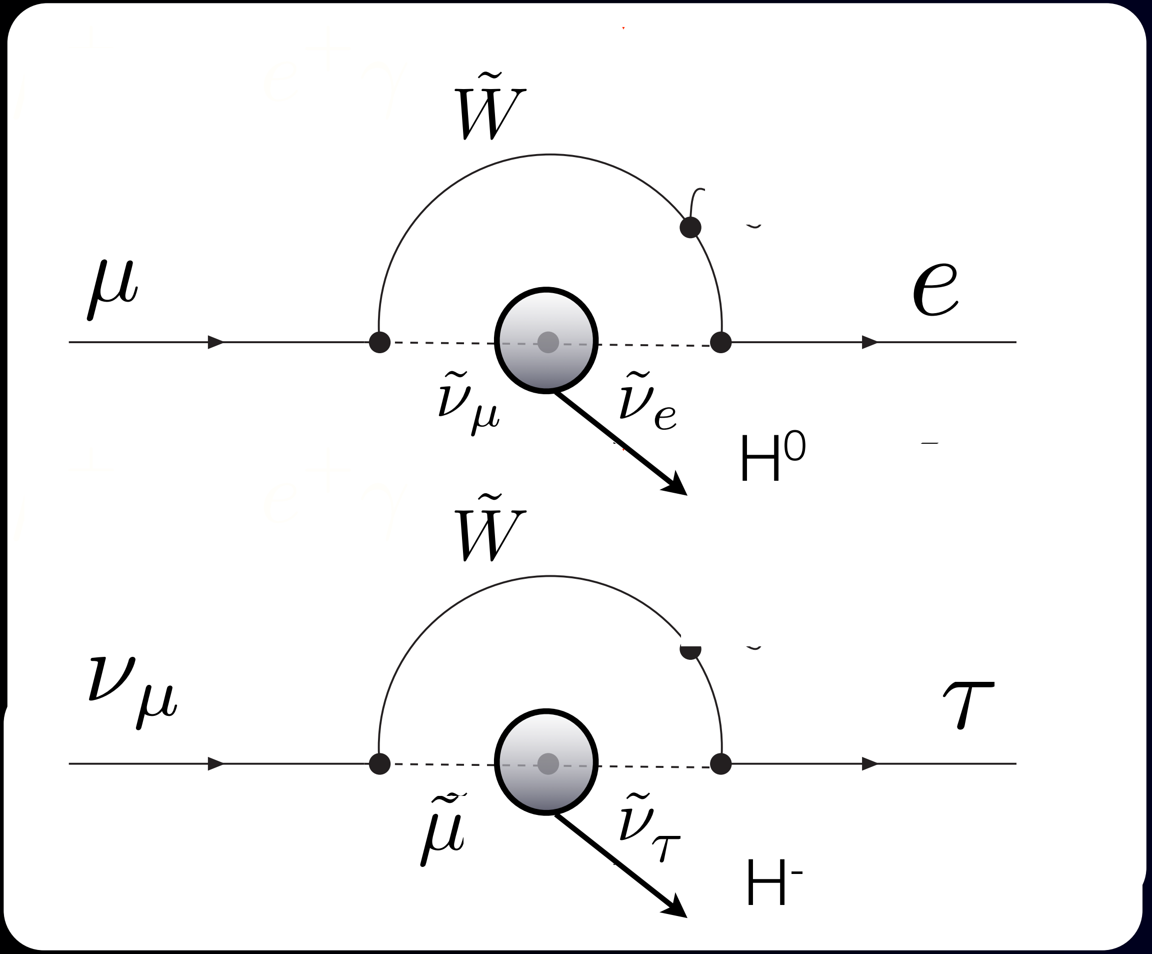
- How can we improve the limits between tau and muon (electron) ?
  - The Super B factory will aim at about 10-100 times luminosity.



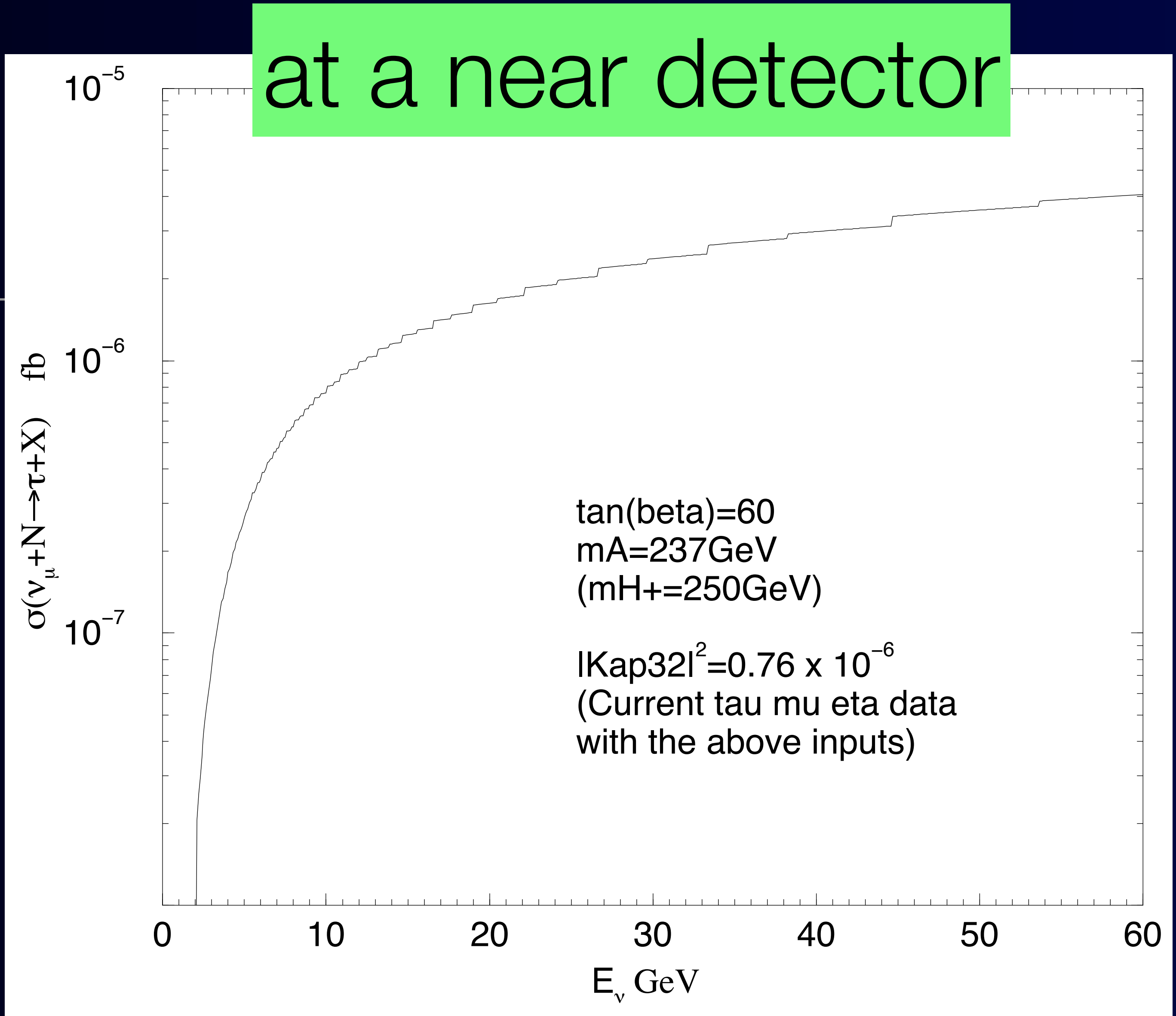
If SU(2) symmetry in the weak doublet holds

Neutrino-induced Charged LFV Current

$$\nu_{\mu(e)} + N \to \tau + X$$



If SU(2) is valid in new physics, the two are related (constrained) one another.


at a near detector

- The present upper limit is obtained by tau rare decays at B factories.
- When E_ν =30 GeV, the upper limit of the cross section is about 10^{-6} fb.
- 10^{20} νs/year at a neutrino factory, a 100 kg (1 ton) detector, 10^5 (10^6) events are expected.

Summary

- Physics motivation of cLFV processes would be significant and robust in 10-15 years from now.
- For muon cLFV processes, μ-e conversion may be the next step.
  - The Mu2e at Fermilab and the COMET experiment at J-PARC are aiming at a search for μ-e conversion at $<10^{-16}$ (10,000 improvement).
  - R&D for the PRISM/PRIME, aiming at $<10^{-18}$ sensitivity (1,000,000 improvement), is being carried out.
  - The MUSIC project at Osaka University is undertaken.
- Tau cLFV processes will be explored by SuperB or SuperKEKB,
- Charged LFV process with neutrinos is being considered.