Experimental Searches for Charged Lepton Flavor Violation with Muons

A Fermilab lecture series on
Physics at the Intensity Frontier
throughout 2009

extreme
BEAM

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Outline

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

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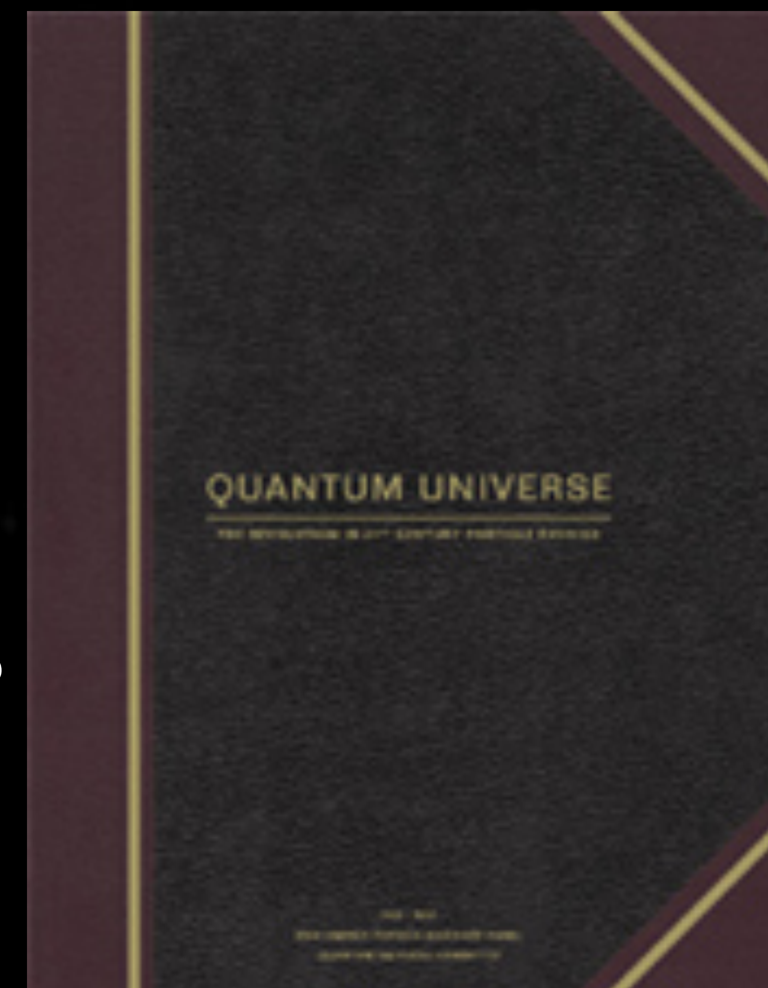
Intensity Frontier and
Charged Lepton Flavor Violation (cLFV)

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

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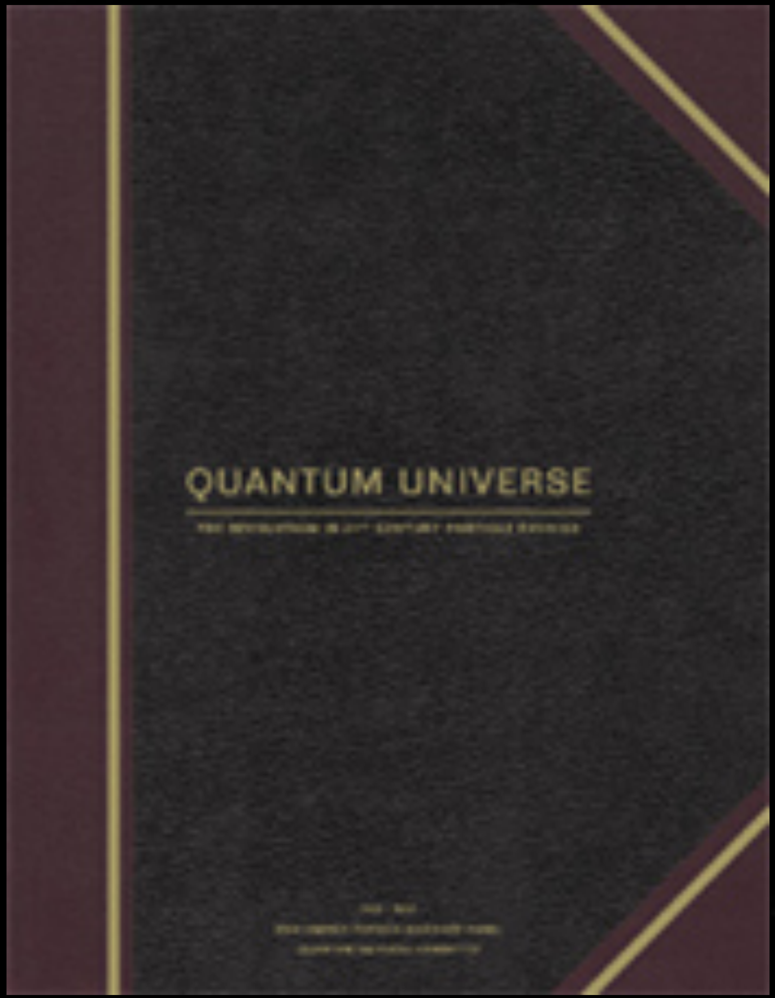

DOE/NSF high
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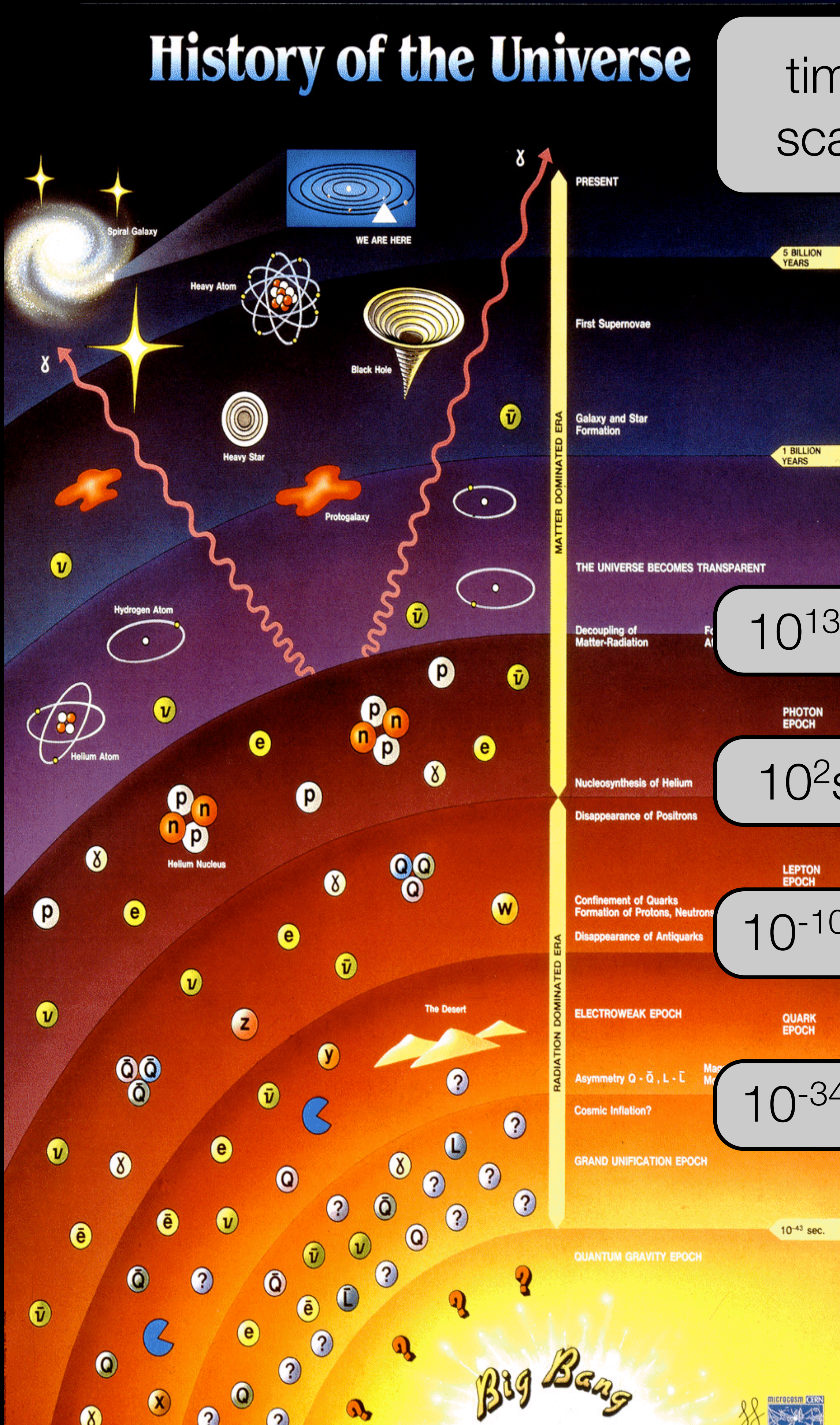
The Standard Model continues working well, but cannot answer these fundamental questions.

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 (10^{2}GeV)

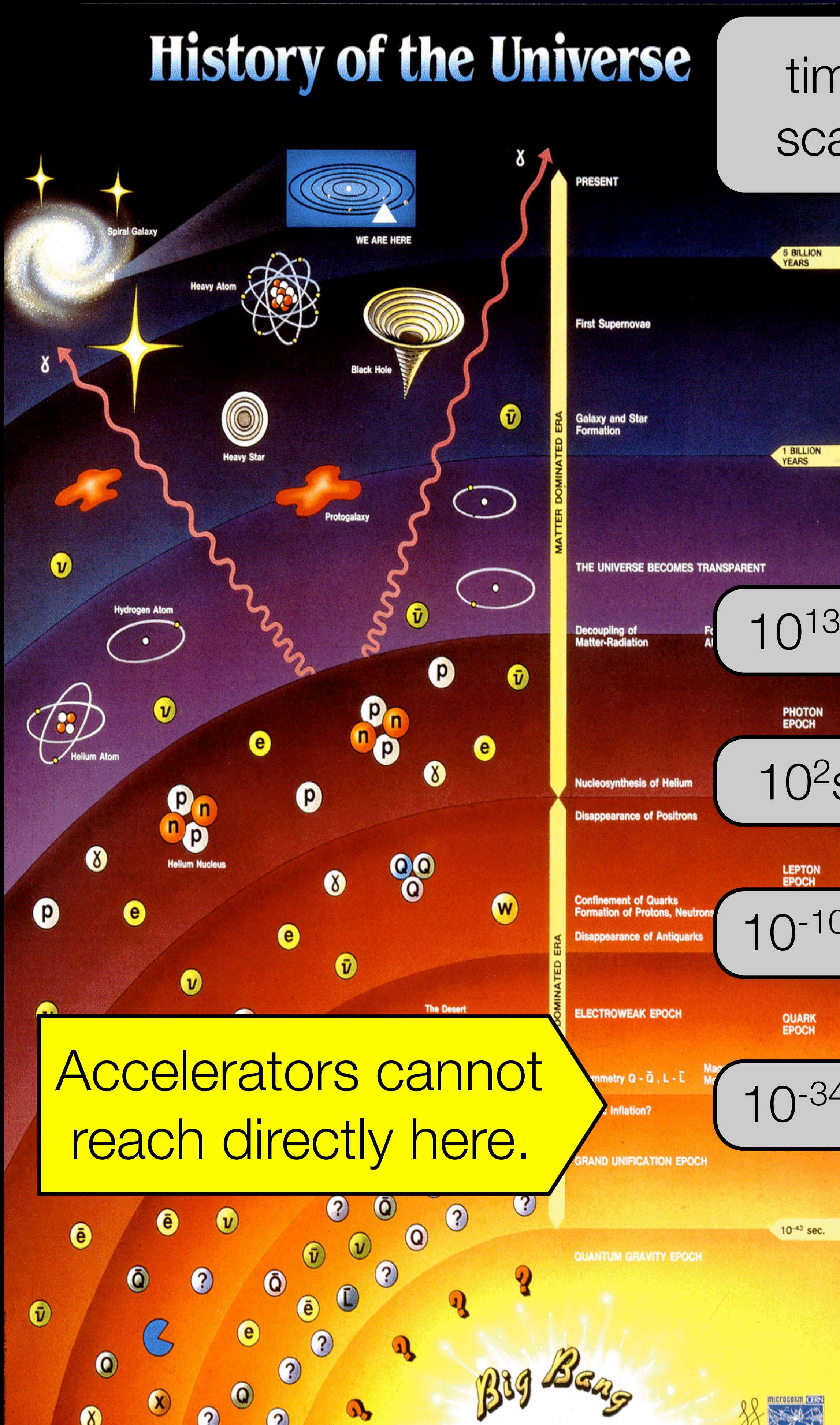
- Higgs particles
- Supersymmetry

Unification Epoch (10^{16}GeV)

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

Quantum Gravity Epoch (10^{19}GeV)

- Superstrings



Accelerators cannot reach directly here.

time scale	energy scale
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10^{-34}sec	10^{16}GeV
	10^{19}GeV

Electroweak Epoch

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- Supersymmetry

Unification Epoch

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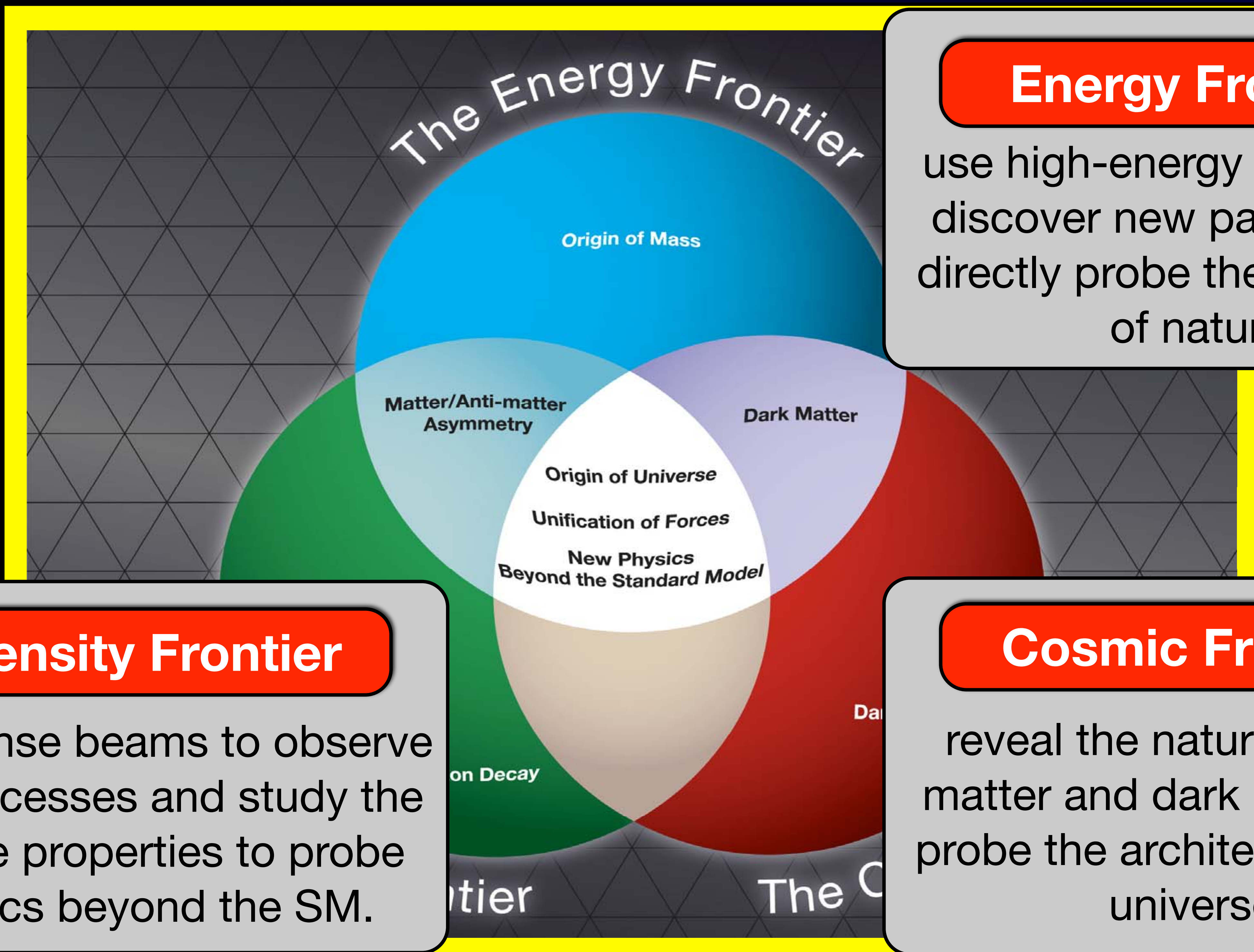
Quantum Gravity Epoch

- 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.

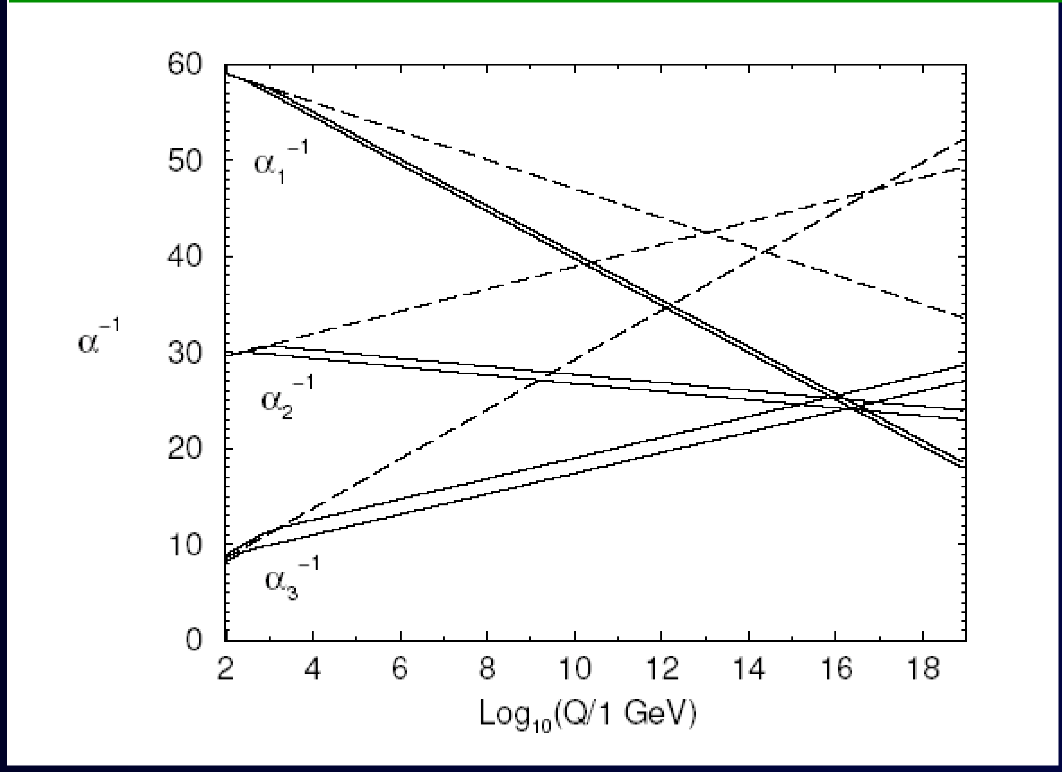
from C. Baltay's talk at the P5 meeting, 29 May 2008

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

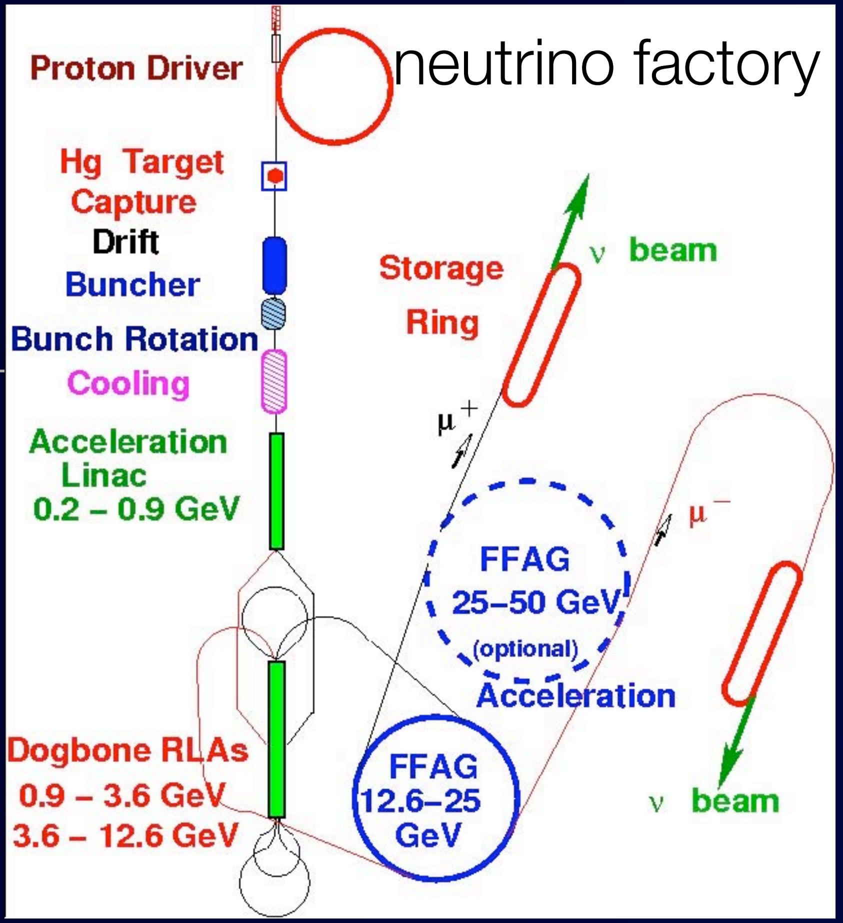
Which Rare Processes at Low Energy ?

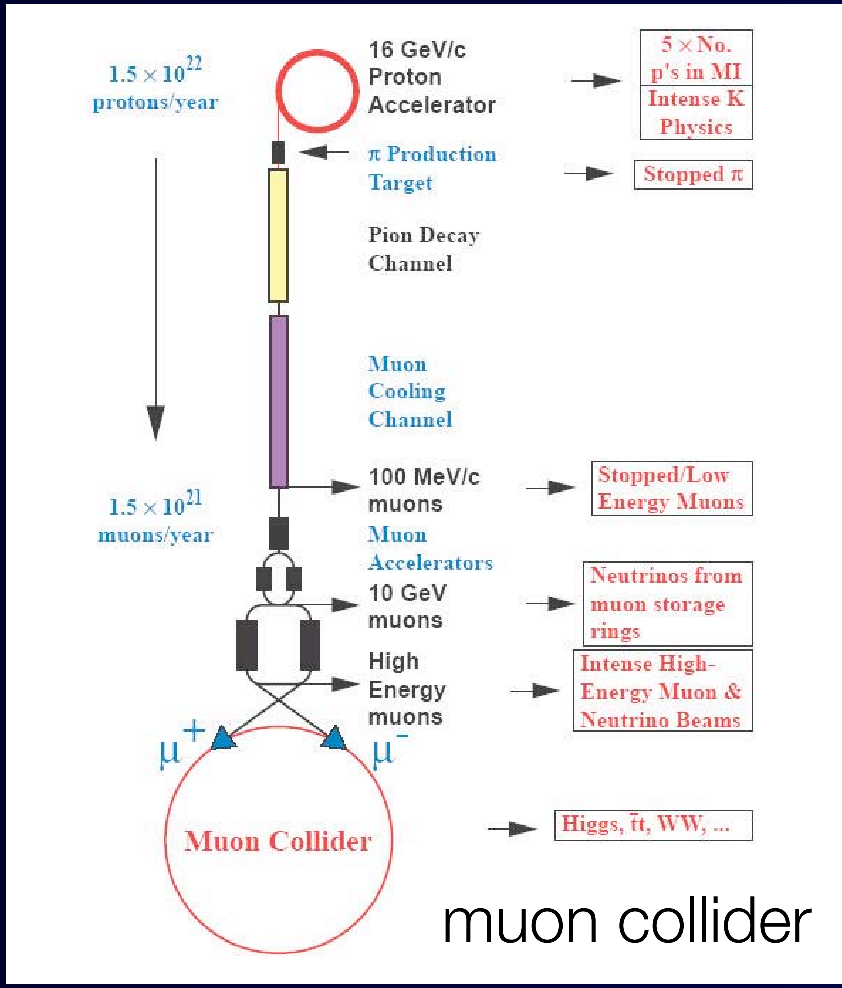
- Processes which are forbidden or highly suppressed in the Standard Model would be the best ones to search for new physics beyond the Standard Model.
- Flavor Changing Neutral Current Process (FCNC)
- FCNC in the quark sector
  - $b \rightarrow s\gamma$, $K \rightarrow \pi\nu\nu$, etc.
  - Allowed in 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
  - $\mu \rightarrow e\gamma$, $\mu + N \rightarrow e + N$, 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 !





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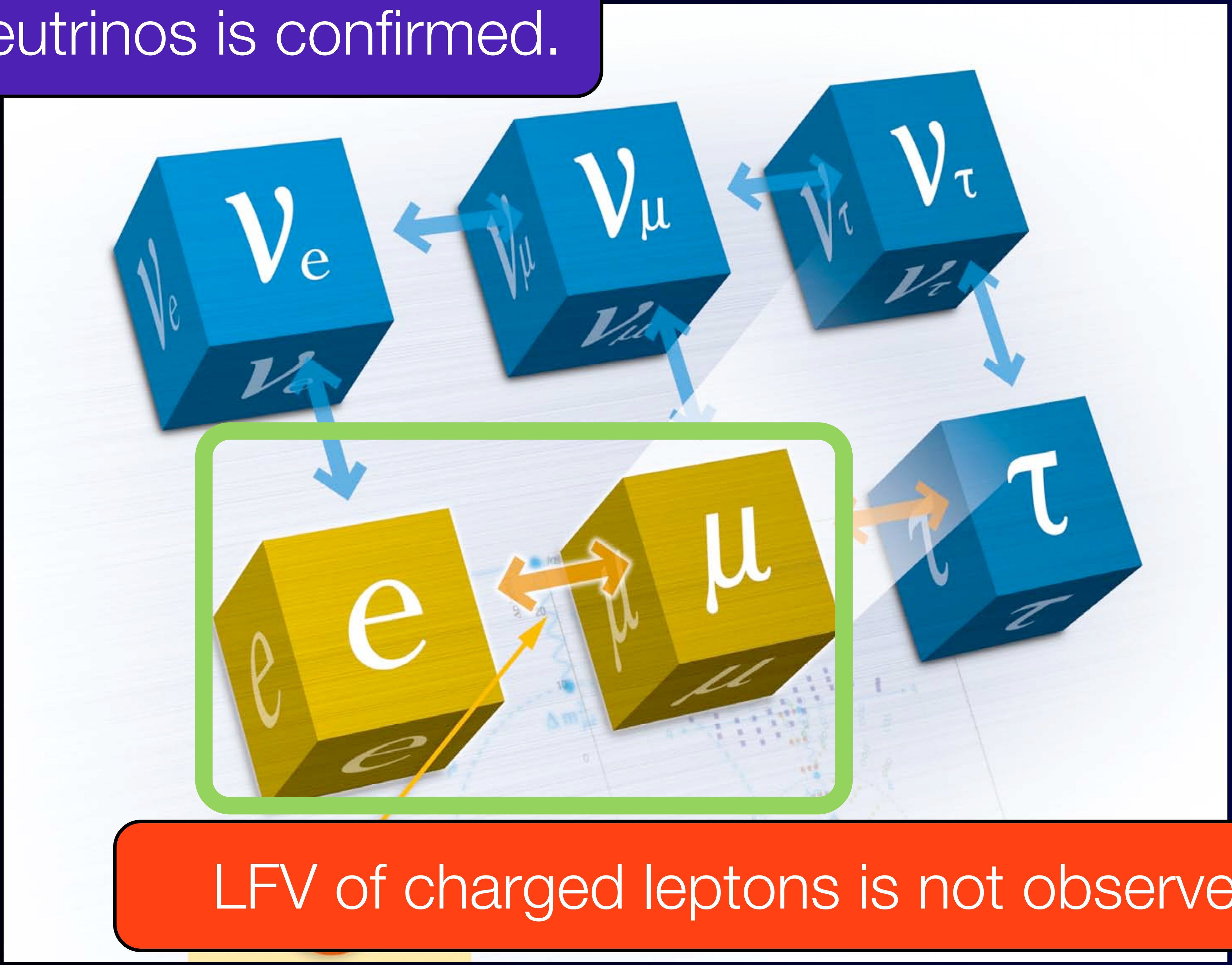
Physics Motivation of cLFV

Lepton Flavor Violation of Charged Leptons (cLFV)

LFV of neutrinos is confirmed.



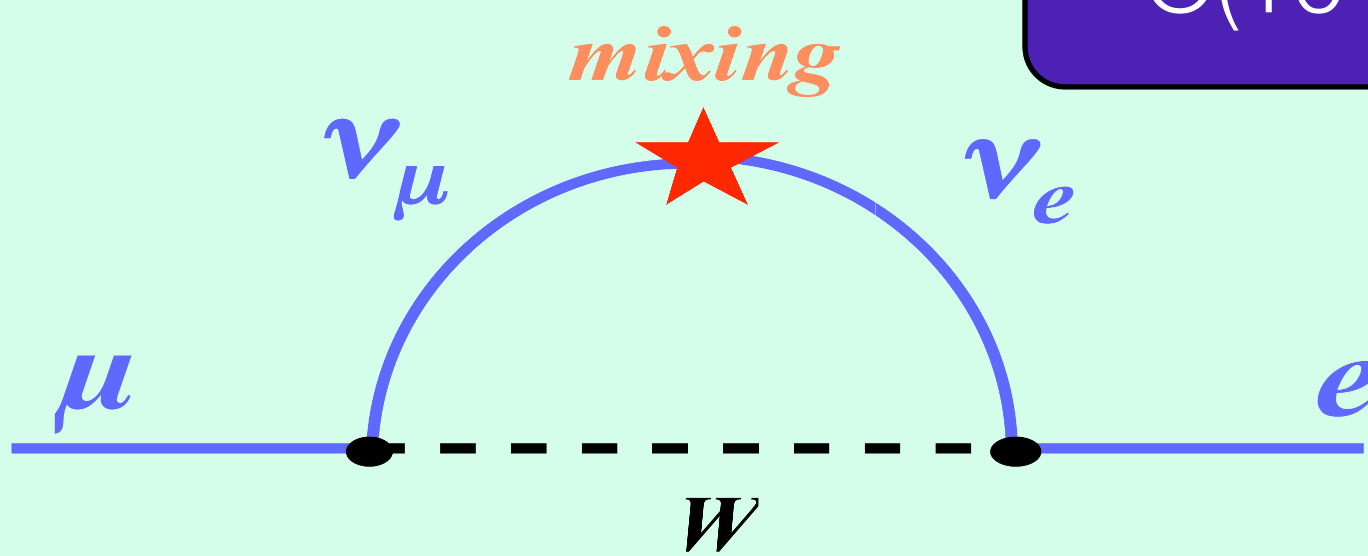
LFV of charged leptons is not observed.

Standard Model Contribution from Neutrino Mixing (GIM mechanism)

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

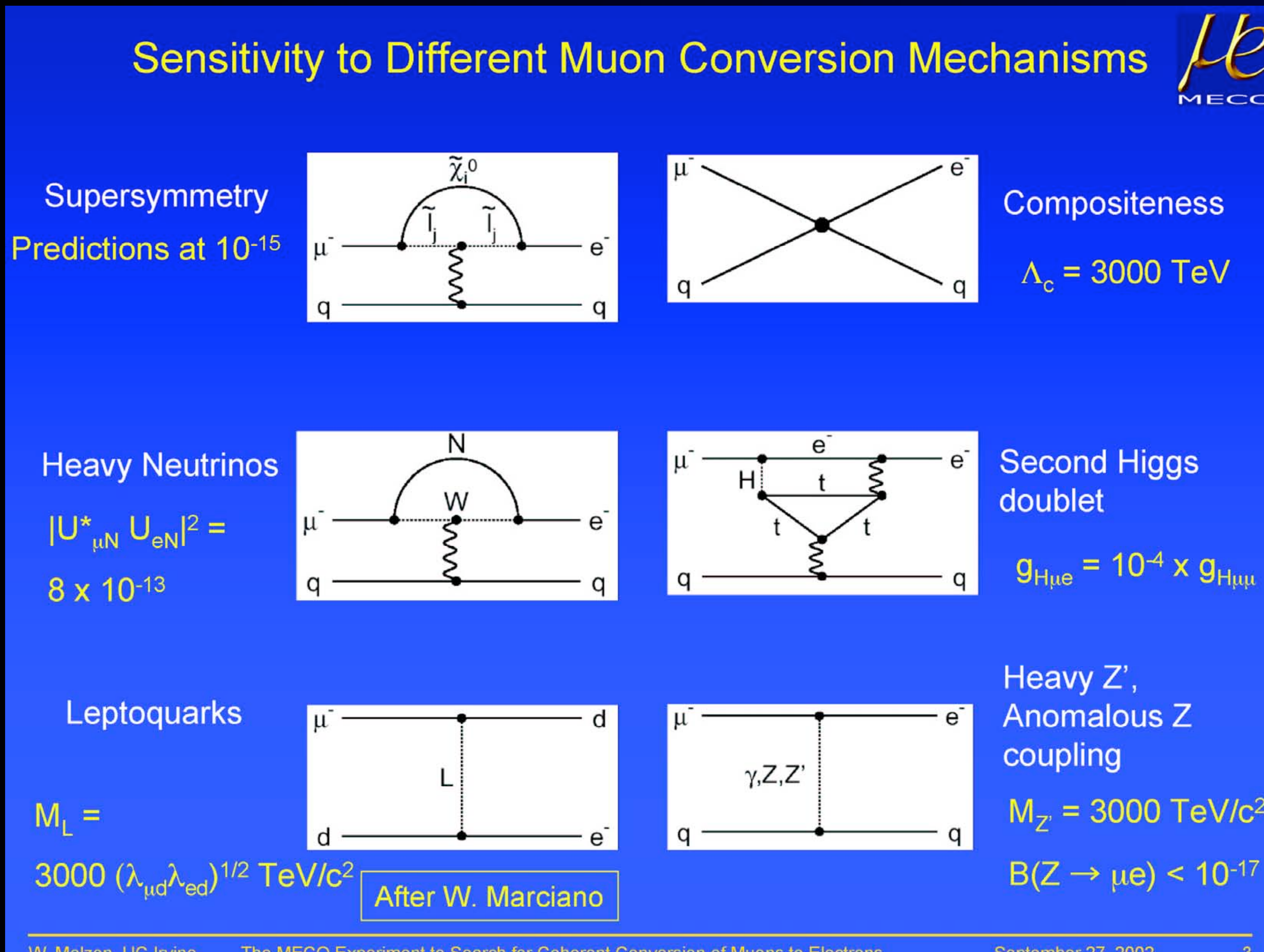
[redacted]

O(10^{-54})



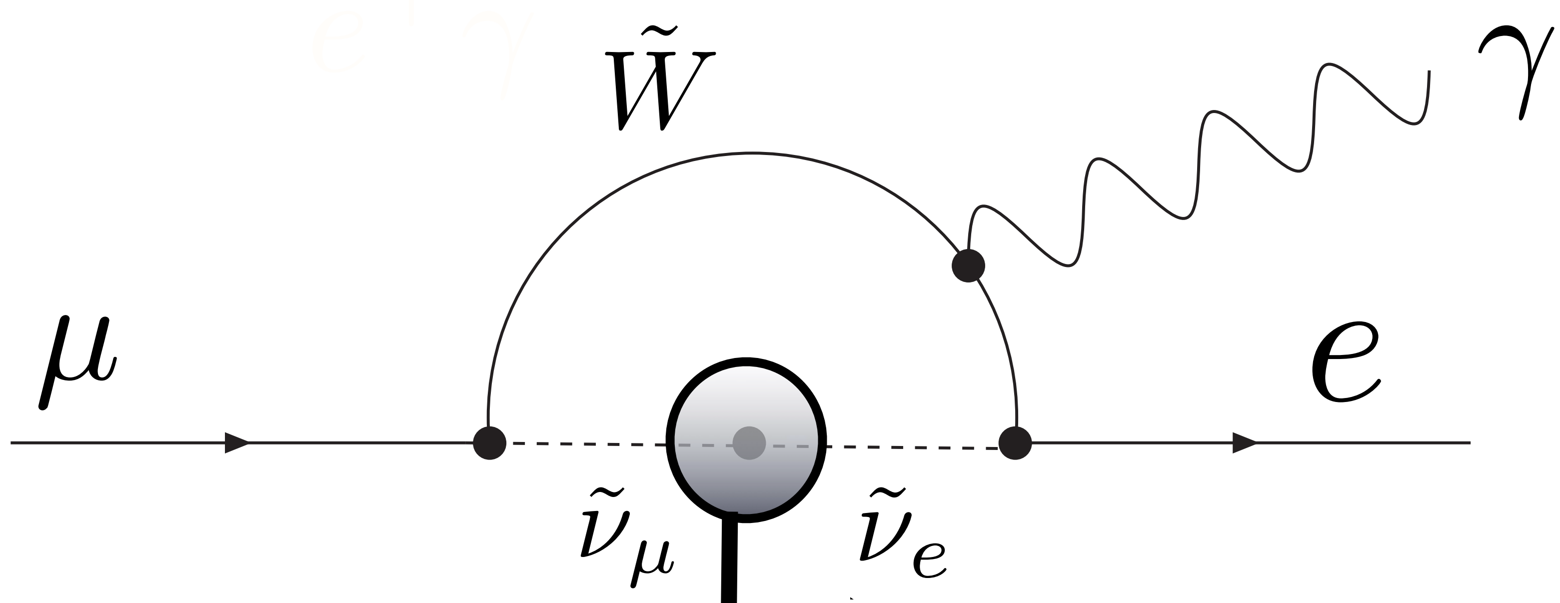
A Large Window for New Physics beyond the Standard Model

Various Models Predict Charged Lepton Mixing.

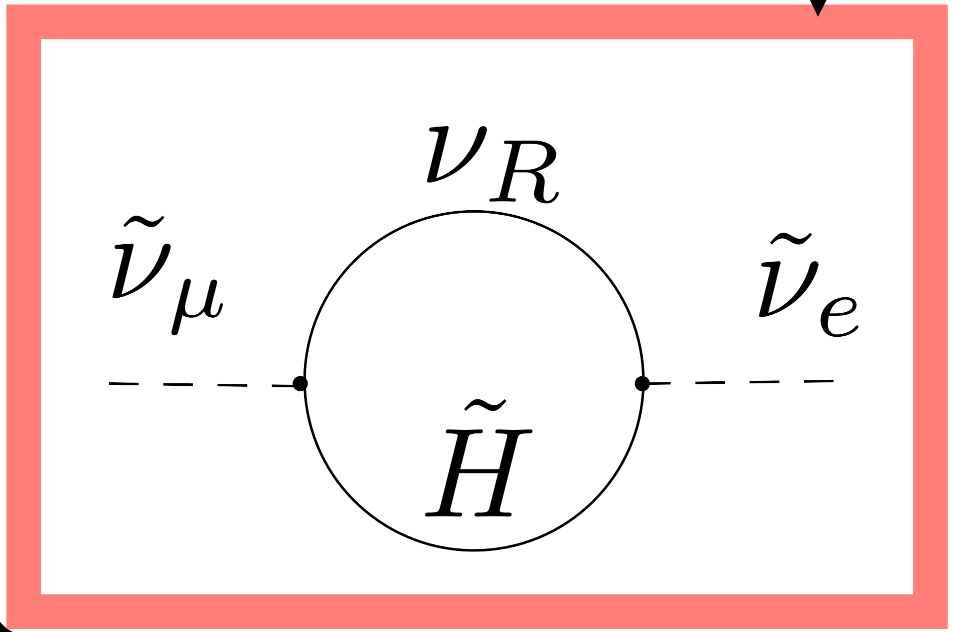


LFV in SUSY Models

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 ν_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

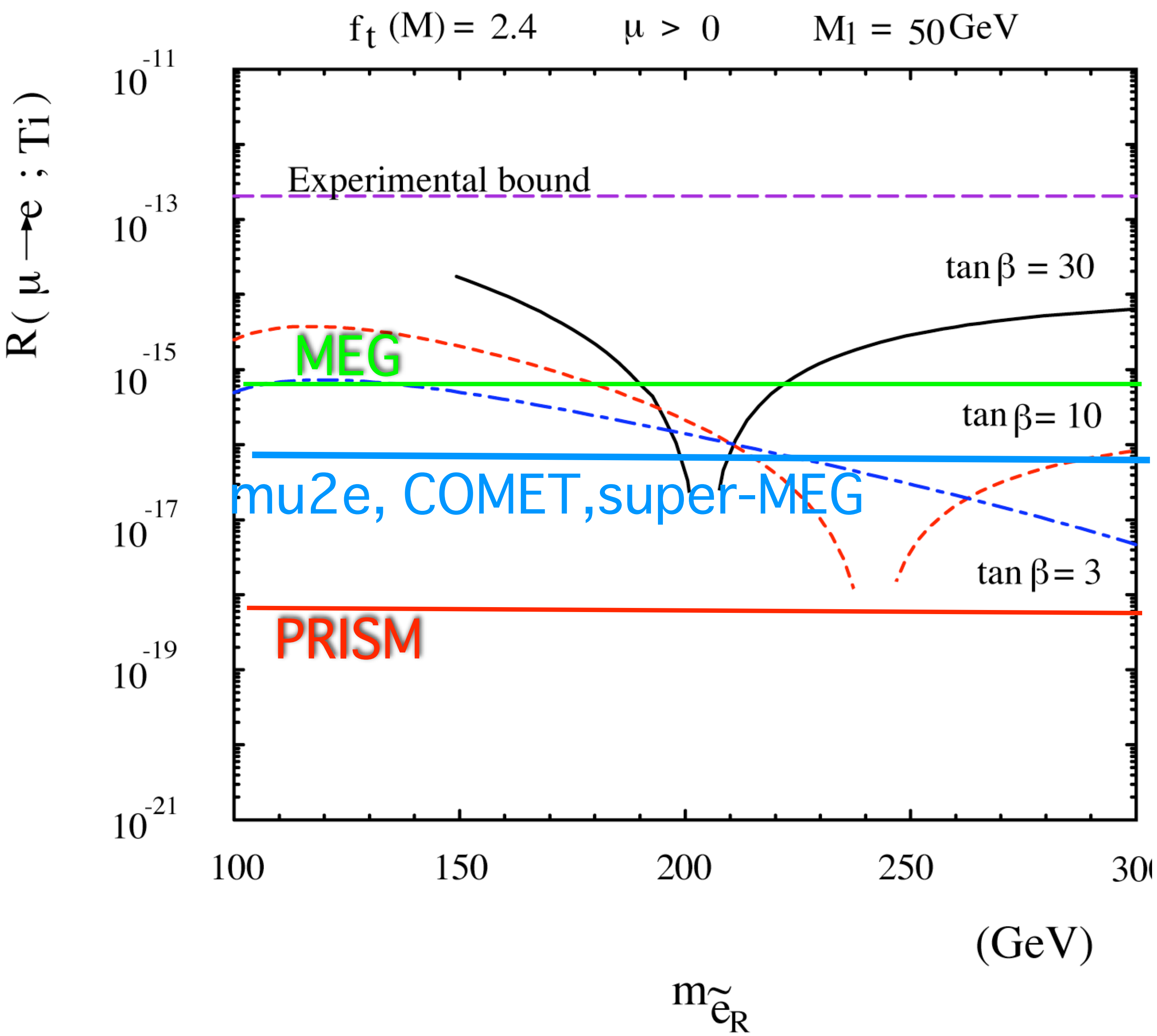
$$(m^2_{\tilde{L}})_{21} \sim \frac{3m_0^2 + A_0^2}{8\pi^2} h_t^2 V_{td} V_{ts} \ln \frac{M_{GUT}}{M_{R_s}}$$

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

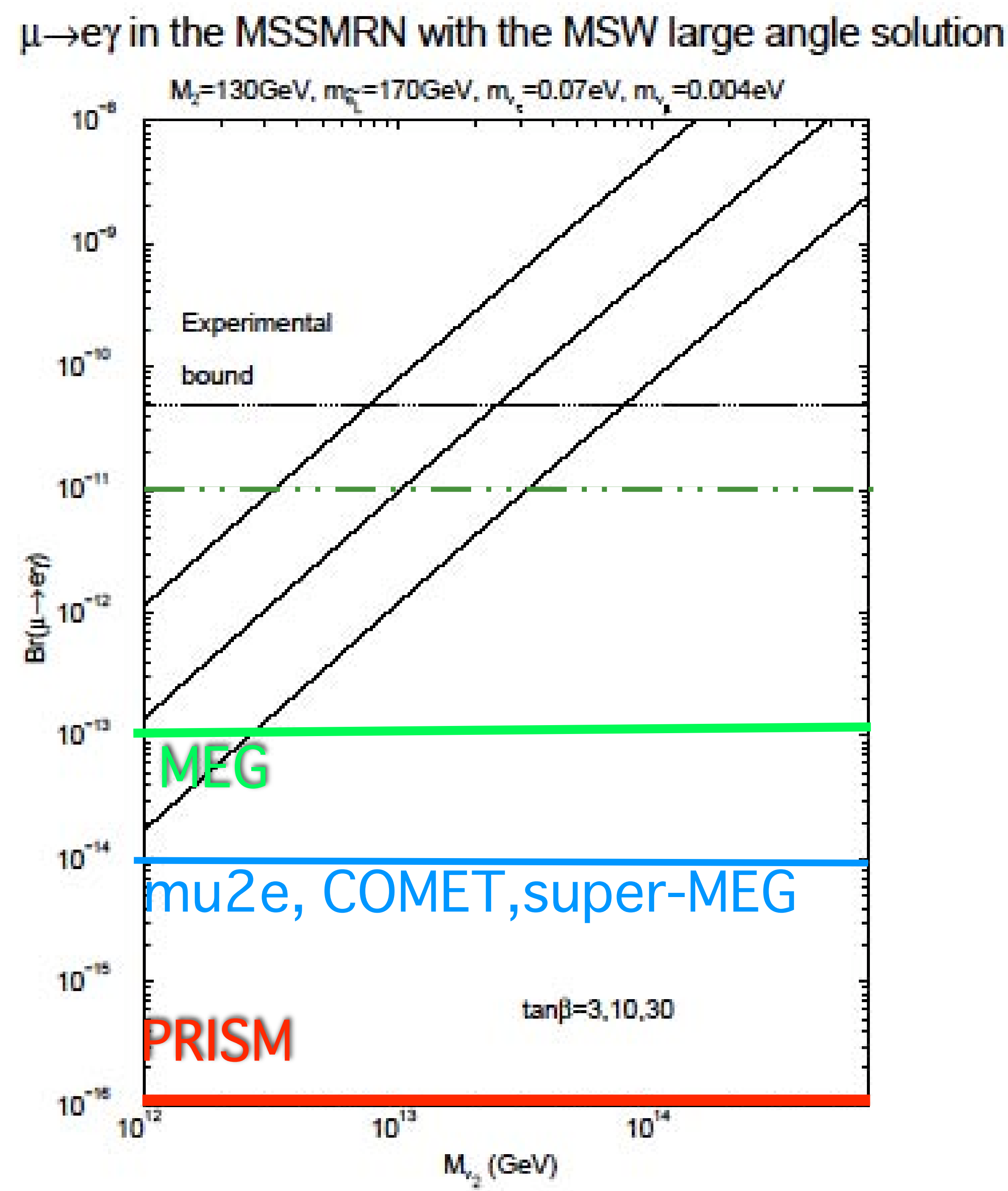
CKM matrix

Neutrino oscillation

SUSY Predictions for cLFV



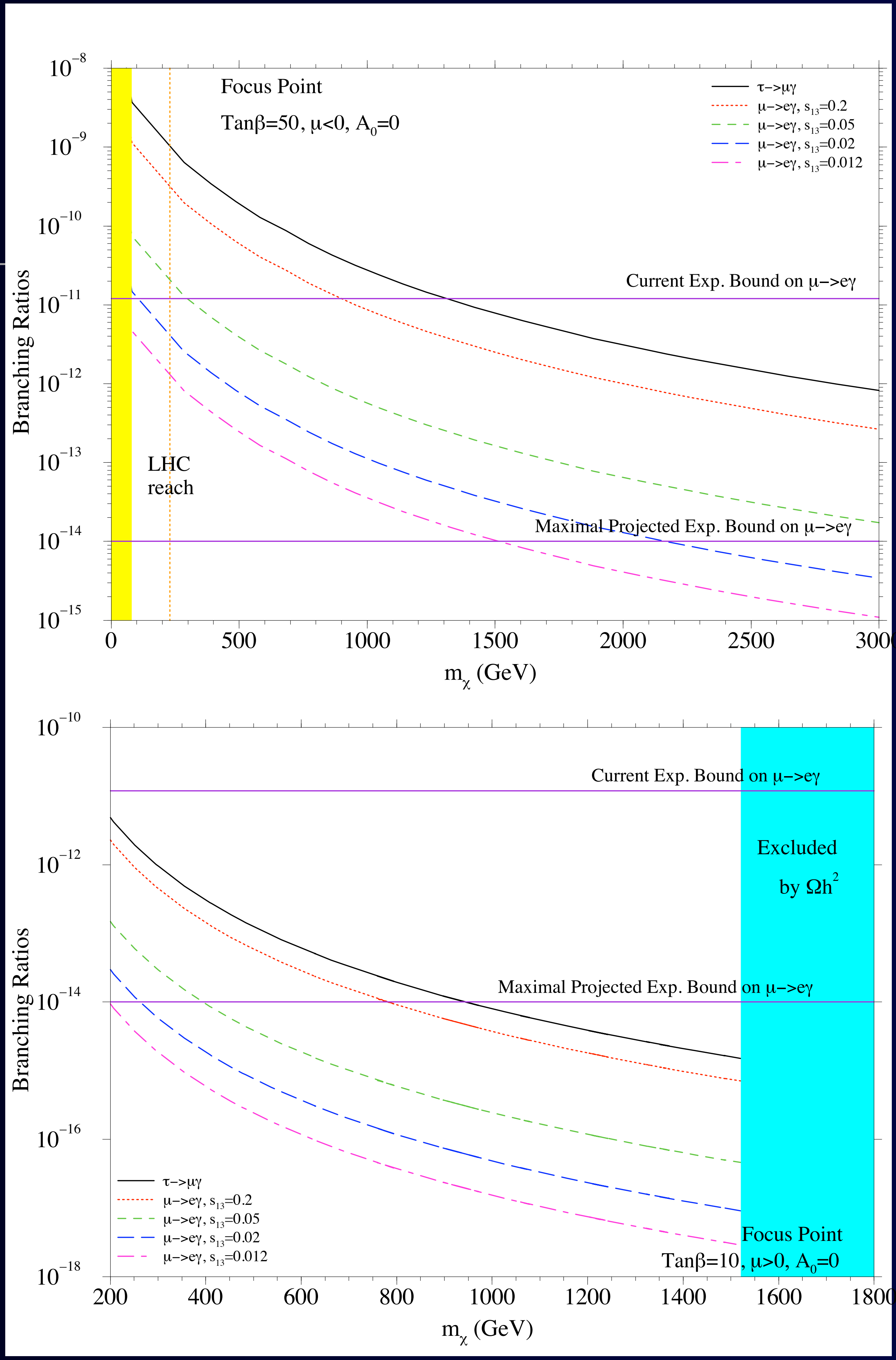
SU(5) SUSY GUT



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.

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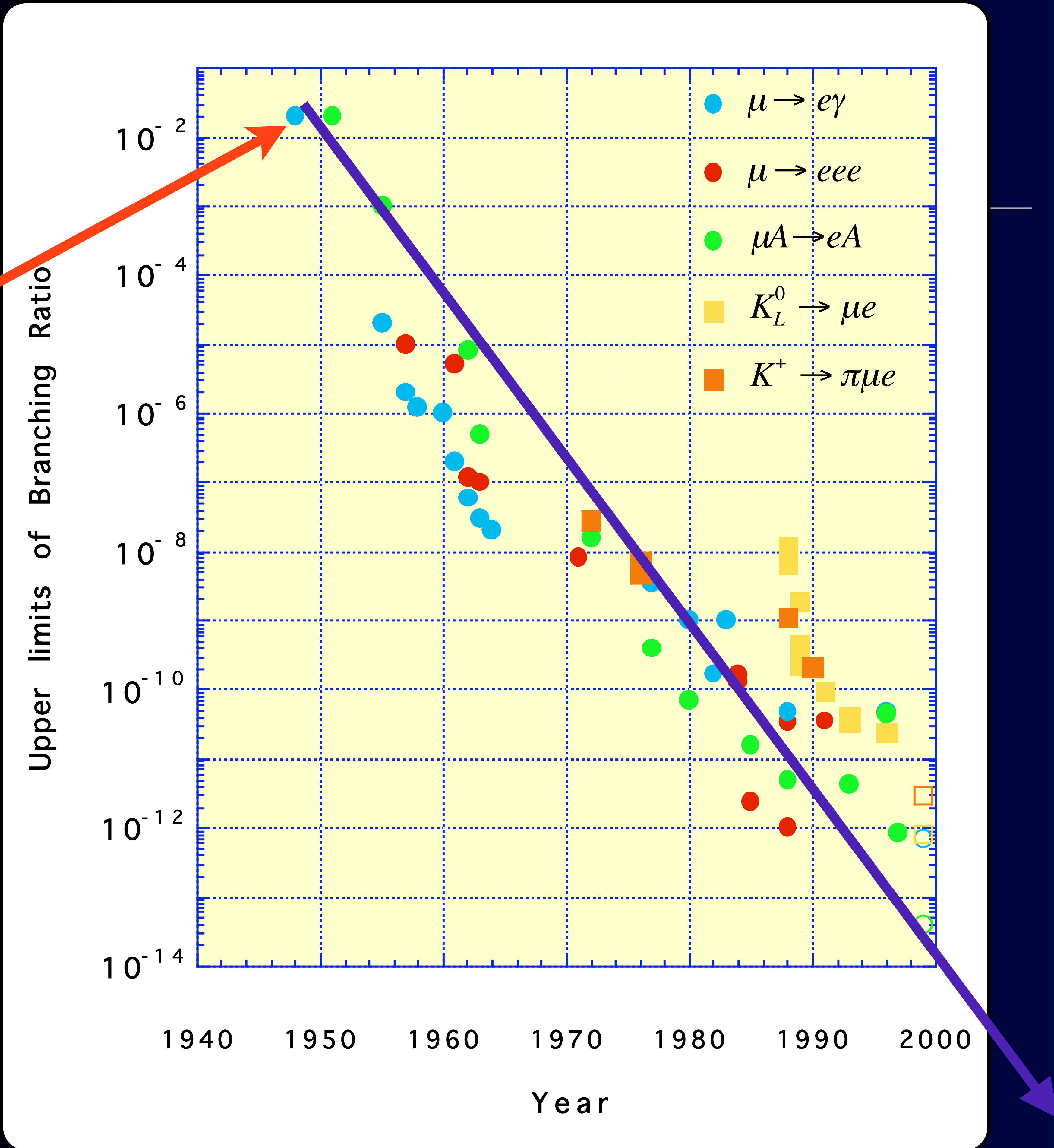
LFV Experiments

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
$\mu \to eee$	$<1.0 \times 10^{-12}$	$<10^{-13}$ - 10^{-14}	?
$\mu N \to eN$ (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 B factory
$\tau \to eee$	$<3.6 \times 10^{-8}$	$<10^{-9}$ - 10^{-10}	super B factory
$\tau \to \mu\gamma$	$<4.5 \times 10^{-8}$	$<10^{-9}$ - 10^{-10}	super B factory
$\tau \to \mu\mu\mu$	$<3.2 \times 10^{-8}$	$<10^{-9}$ - 10^{-10}	super B factory

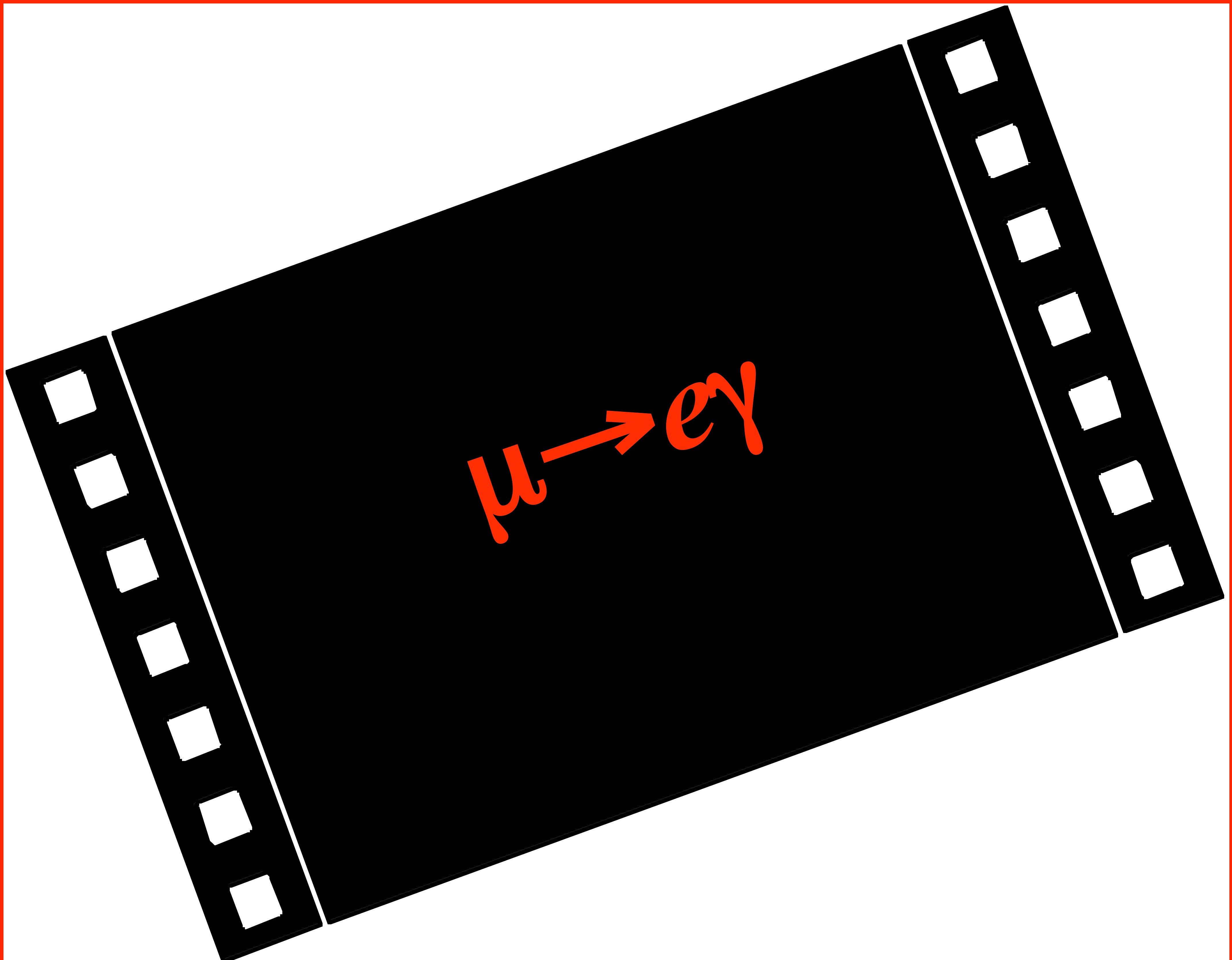
List of cLFV Processes with Muons

ΔL=1

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

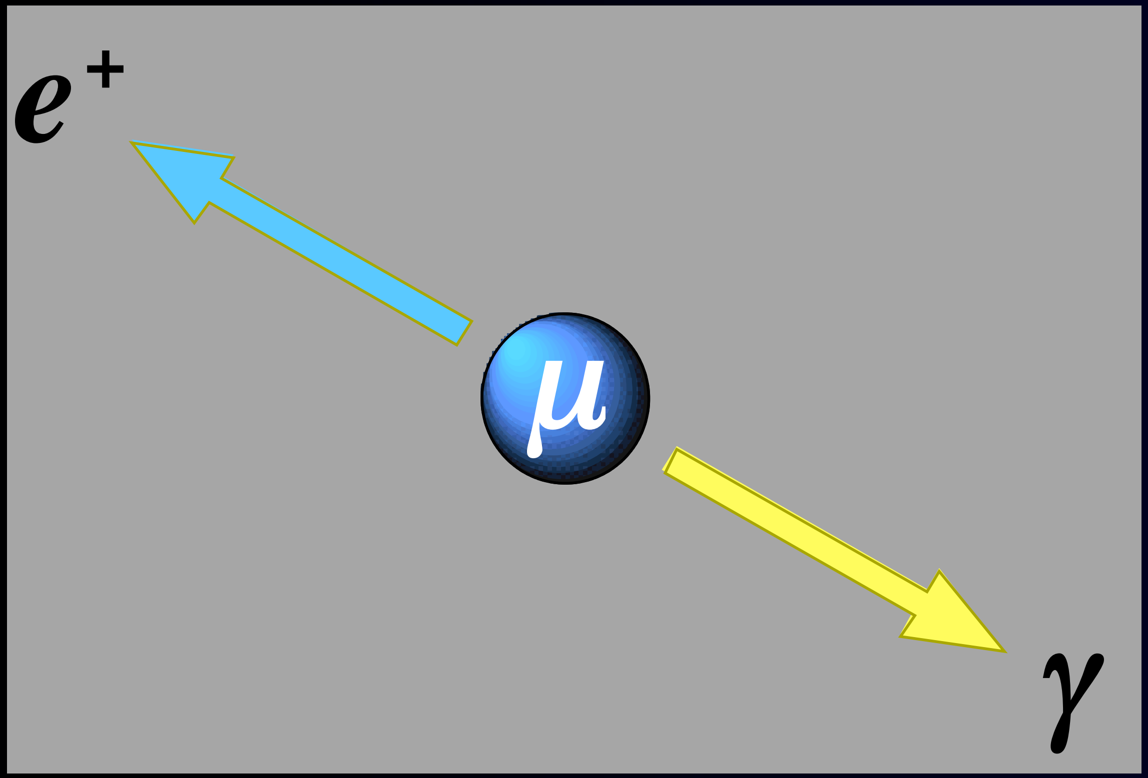
ΔL=2

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


μ→eγ

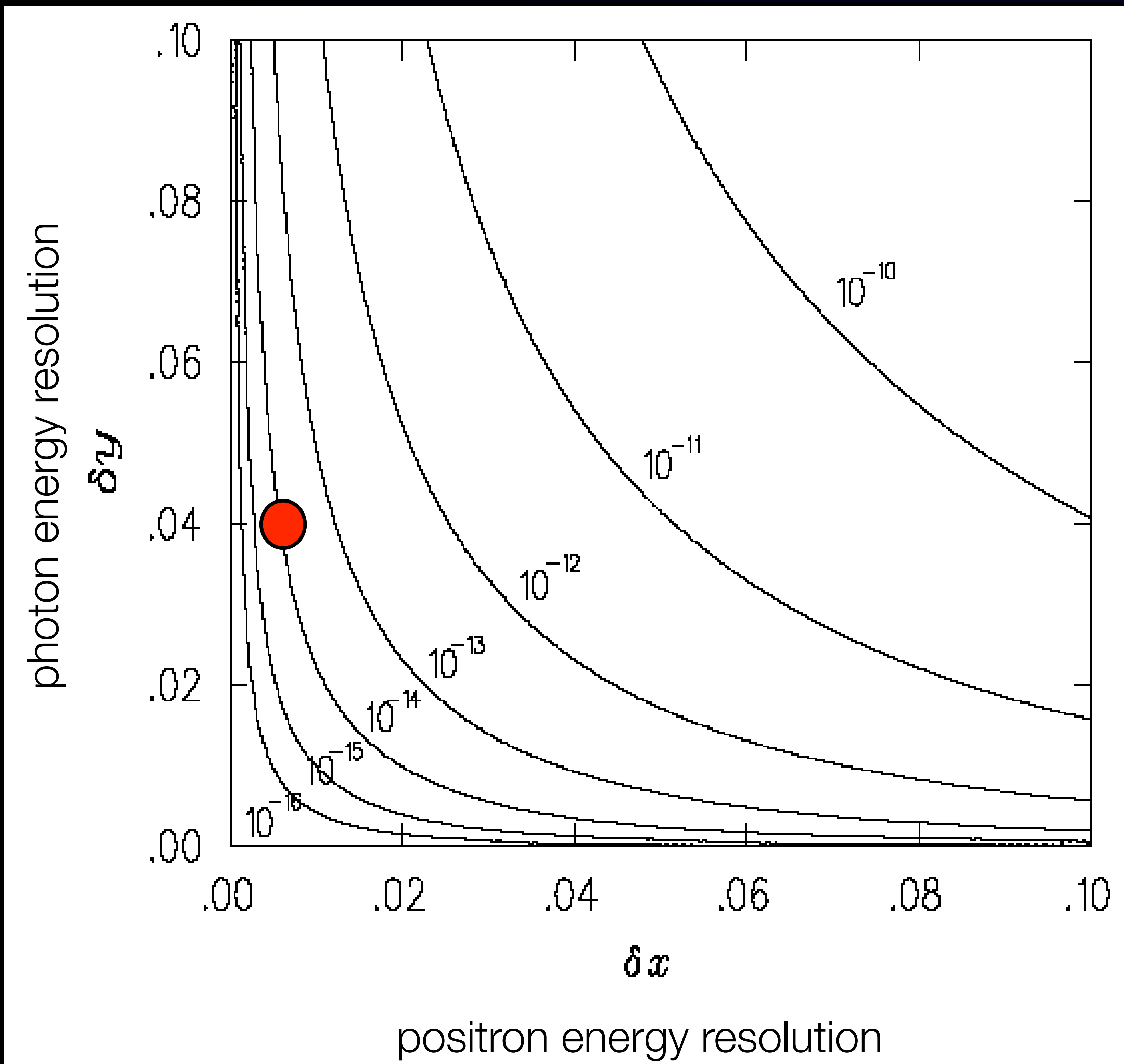
What is $\mu \to e\gamma$?

- 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 $\mu \to e\nu\nu\gamma$ when two neutrinos carry very small energies.
  - accidental backgrounds
    - positron in $\mu \to e\nu\nu$
    - photon in $\mu \to e\nu\nu\gamma$ or photon from e^+e^- annihilation in flight.

Physics Background for μ→eγ Decay



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

Effective branching ratio is a function of the resolution of electron detection (δx) and that of photon detection (δy).

Background level is about 10^{-14} for δx~1% and δy=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

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

N_B=0.5 events at B(μ→eγ)~10^{-13}

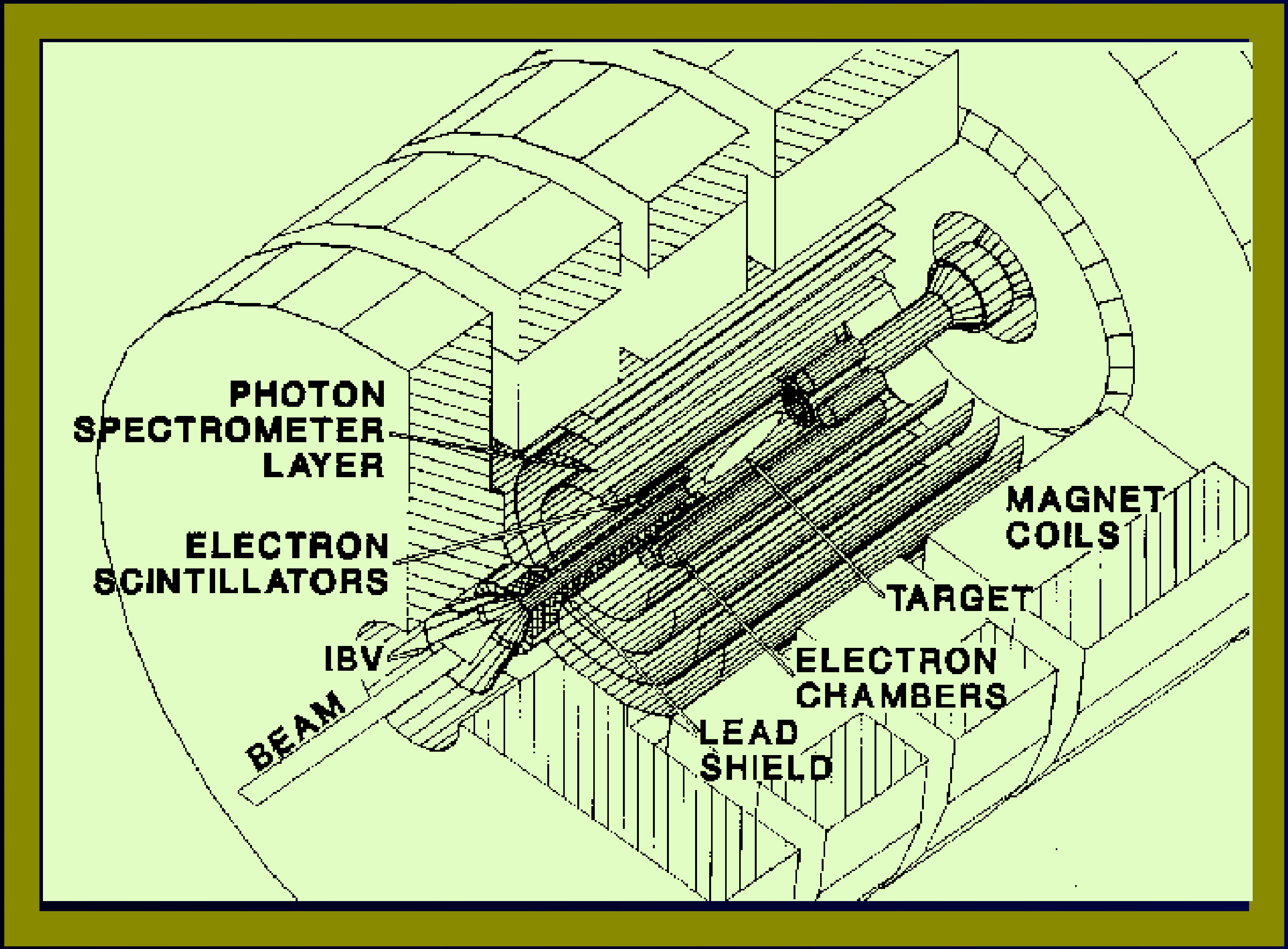
With the same resolutions, $N_\mu=10^{10}$μ/s,
N_B=5000 events at B(μ→eγ)~10^{-16}

Improvements of detector resolutions are critical.

MEGA at Los Alamos

- MEGA at Los Alamos (~1999)

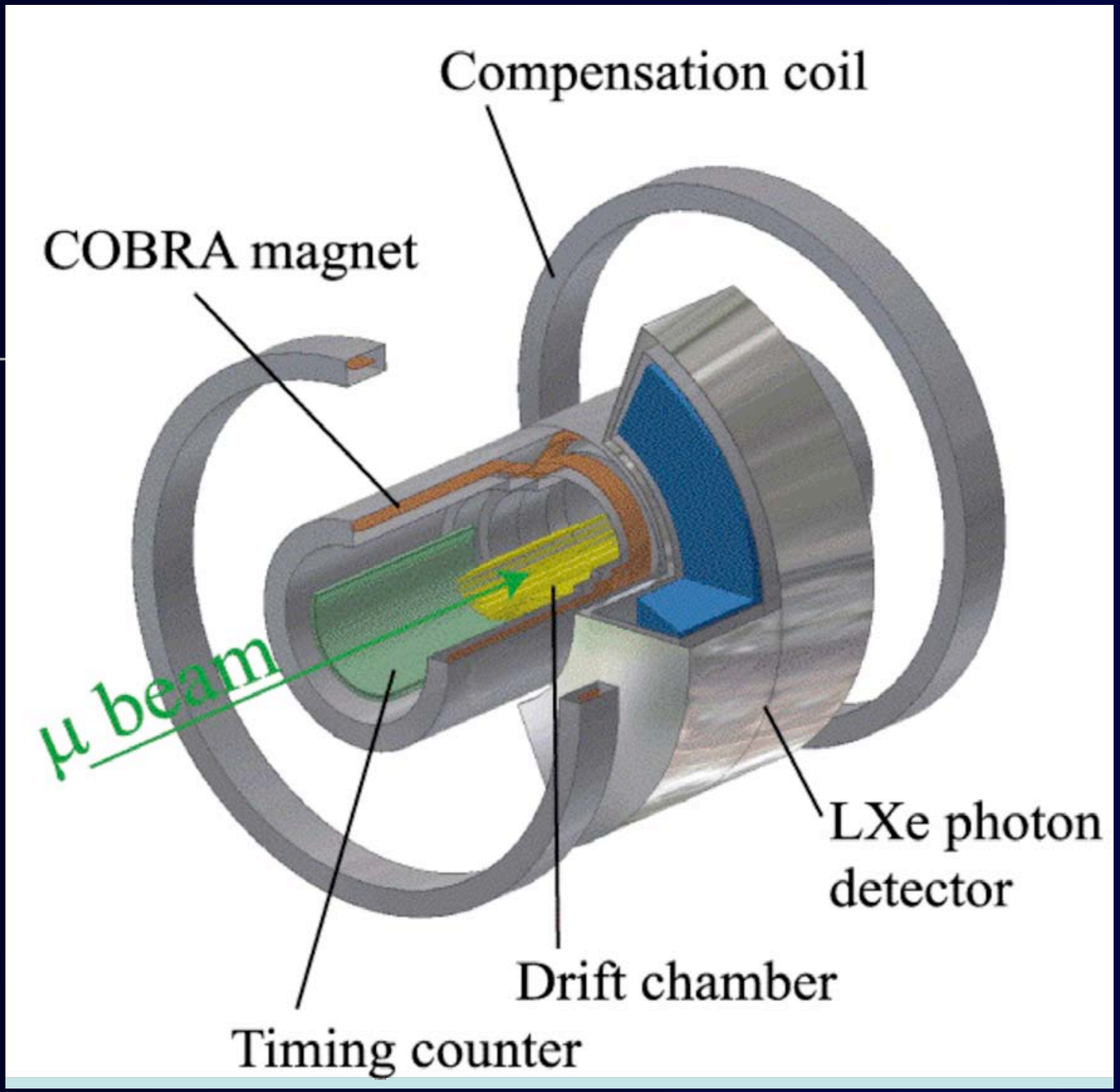
- A thin slanted target.
- 1.5 T solenoid magnetic field
- 7 dwarf chambers for e^+ tracking
- pair spectrometer for gamma detection

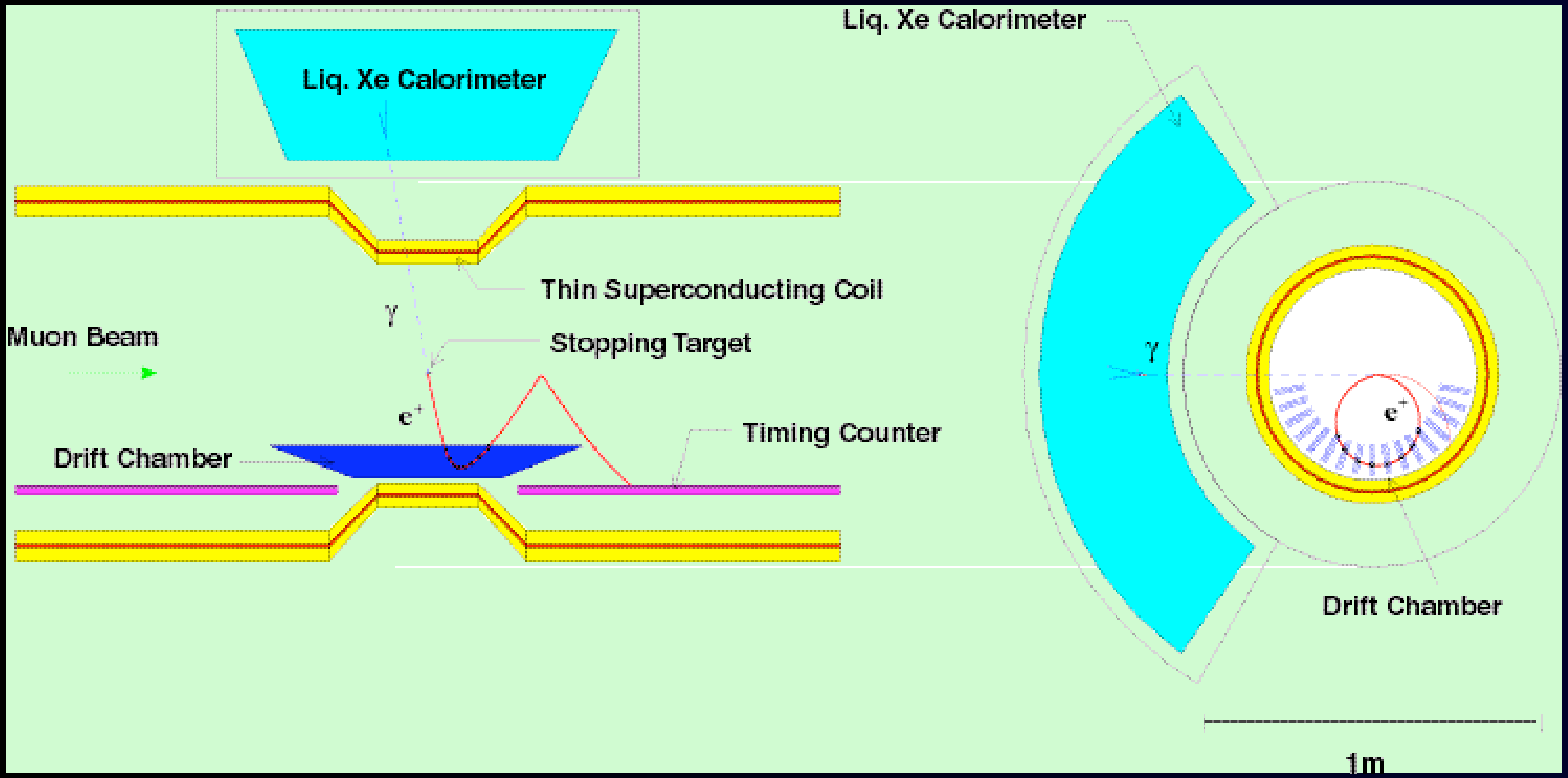


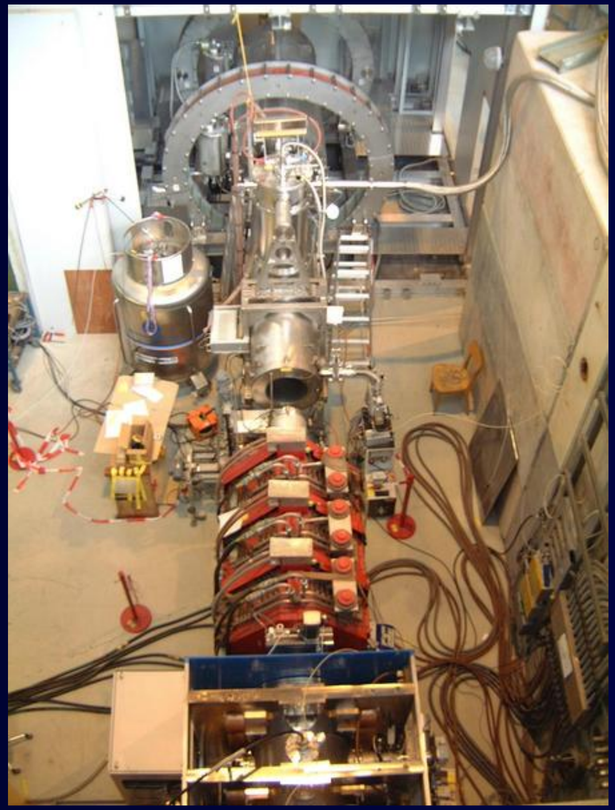
$$B(\mu^+ \to e^+\gamma) < 1.2 \times 10^{-11}$$

MEG at PSI

- DC beam 10^7 muons/sec.
- Goal : $B < 2 \times 10^{-13}$
- COBRA : spectrometer for e^+ detection.
- Liquid Xenon detector for photon detection.



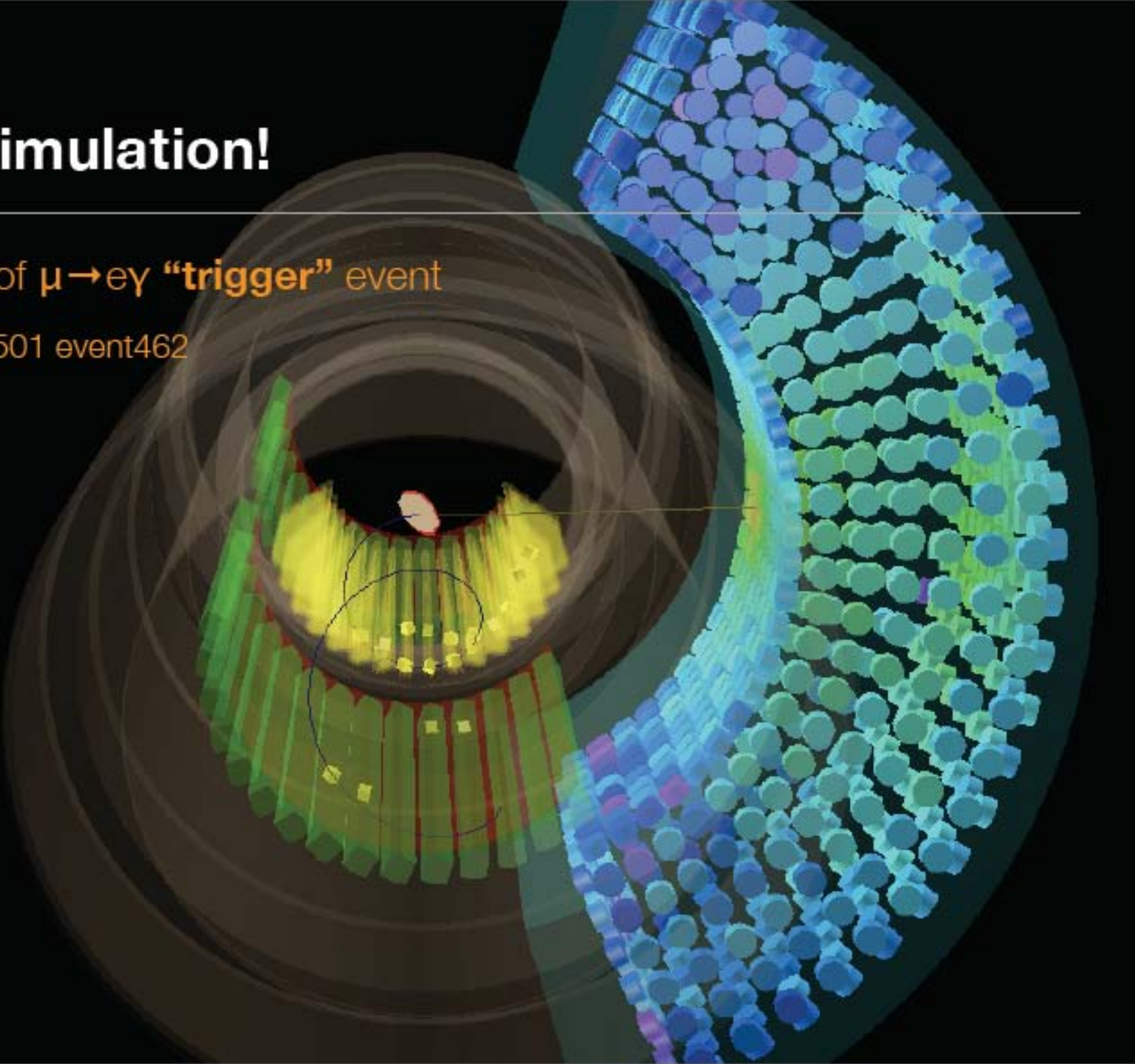




Not a Simulation!

Example of $\mu \to e\gamma$ **"trigger"** event

Run#24501 event462



- Preliminary
- Calibration is in progress for 2008 data

- Blue numbers likely to change - Grey numbers may vanish

(%)	"Goal"	2008 Provisional Lower Limits	2009 Provisional Prospects
Gamma	> 40	> 50 x (65 x 85) (depth, pileup)	> 50 x 90
e+	65	30 x 40 (DC, DC-TC)	85 x 50
Trigger	100	100 x 99 x 80 (energy, time, direction)	> 99
Selection	$90^4 = 66$	$90^3 \times 95 = 69$	69
DAQ	(> 90)	> 80 x 93 (live, run transition)	> 90 x 99
Calibration Run etc	(> 95)	~70	90
Running Time (week)	100*	11.5**	11.5
Single Event Sensitivity (10^{-13})	0.5	< 30 - 50	< 3 - 5

* 1 week = 4×10^5 sec (66%) ** CEX runs not included

Efficiencies Summary

S. Mihara, 5/March/2009 KEK

- All 2008 numbers are provisional

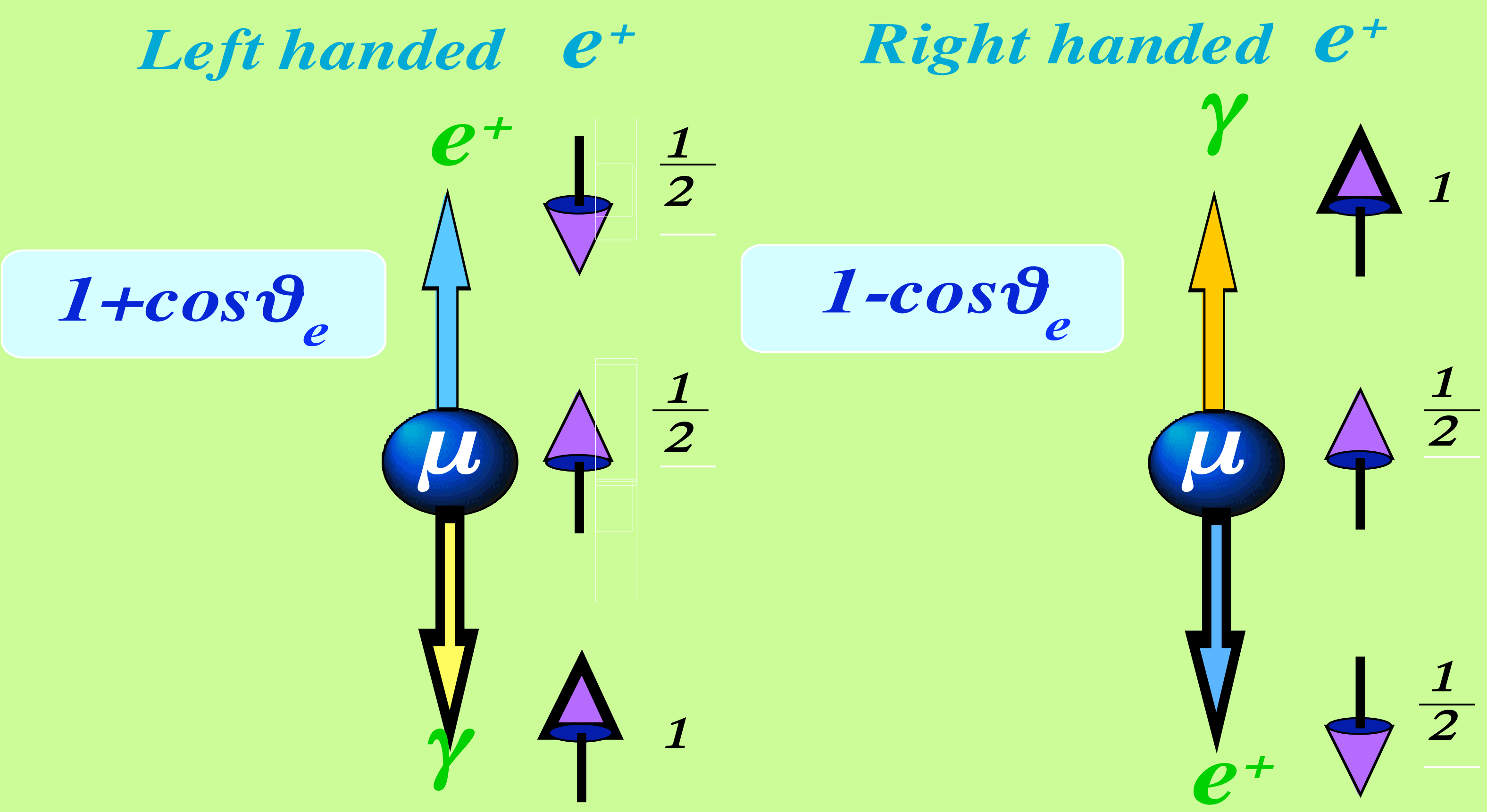
(in sigma)	"Goal"	2008 Provisional	2009 Provisional Prospects
Gamma Energy (%)	1.2 - 1.5	< 2.3	< 1.7
Gamma Timing (ps)	65	< 100*	< 80
Gamma Position (mm)	2 - 4	5 - 6.5	5
e+ Momentum (%)	0.35	1.5 - 2.0	0.7 - 0.8
e+ Timing (ps)	45	< 60 - 90	60
e+ Angle (mrad)	4.5	9 - 18	11
mu Decay Point (mm)	0.9	3 - 4	2
Gamma - e+ Timing (ps)	80	150	100
Background (10^{-13})	0.1 - 0.3	-	< 0.6 - 3

* clock error of ~60ps included

Resolutions

S. Mihara, 5/March/2009 KEK

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

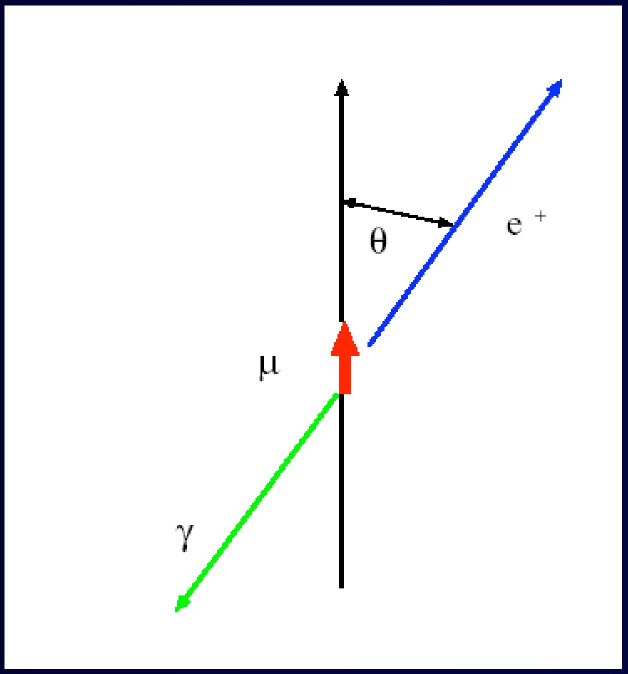


useful to distinguish different theoretical models

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

Suppression of Physics Background with Polarized μ→eγ Decay

radiative muon decay

at end-point of spectrum when neutrinos have small energy

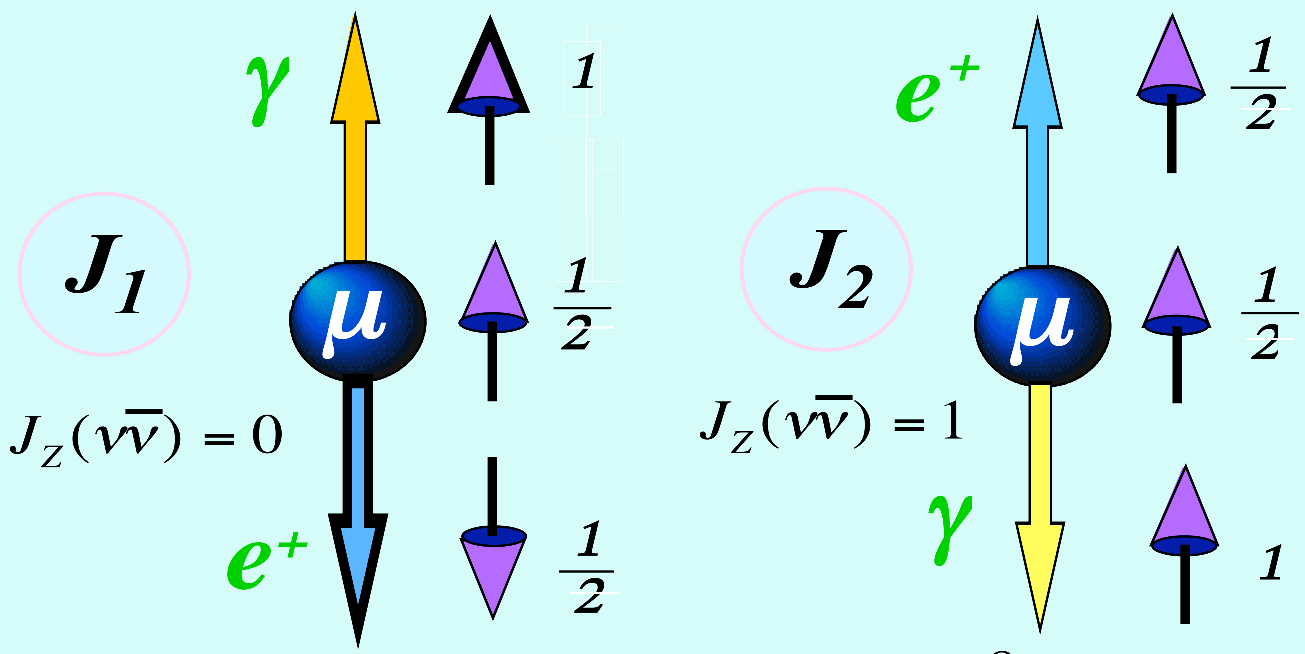
integrate the decay width

$1-\delta x < x < 1$ δx : e energy

$1-\delta y < y < 1$ δy : γ energy

$0 < z < \delta z$ δz : angle

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



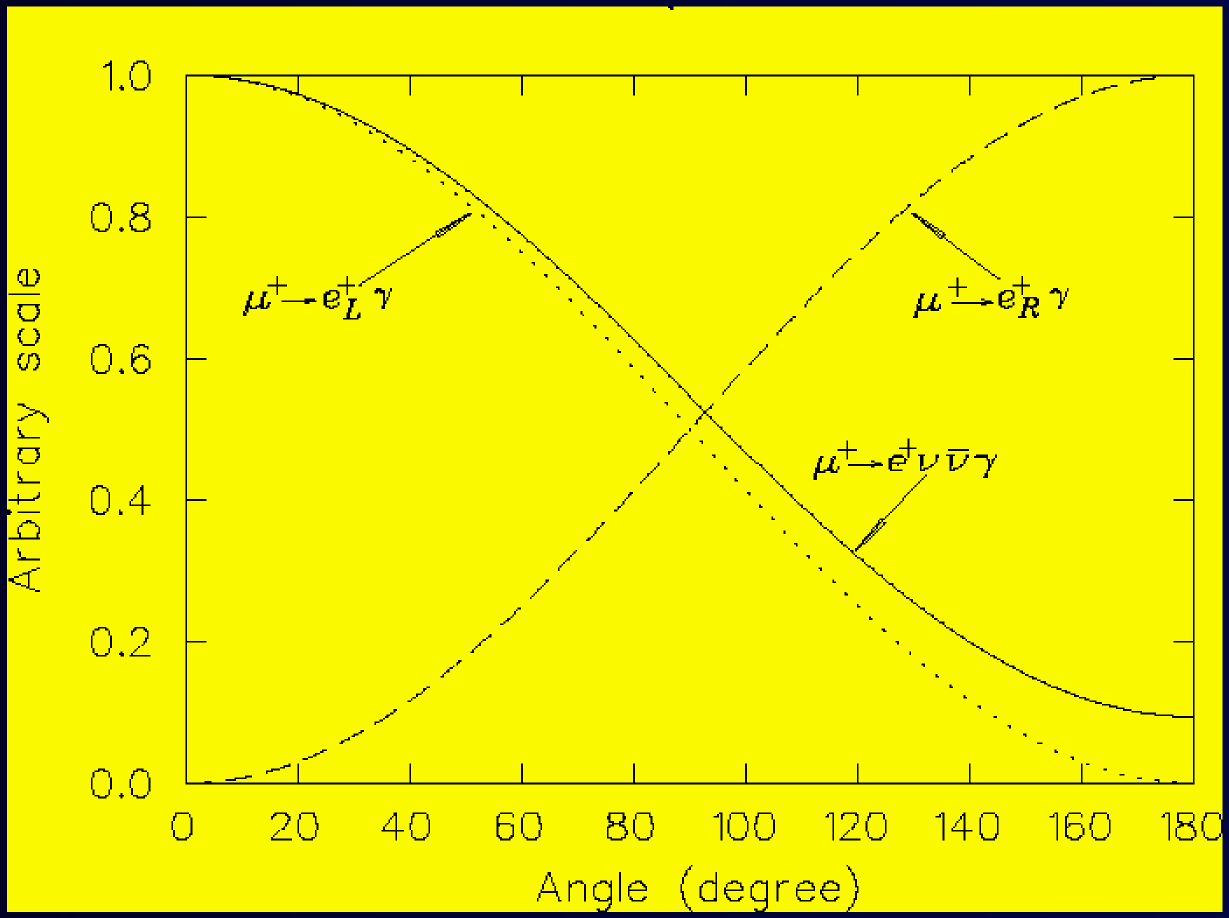
$J_z(\nu\bar{\nu}) = 0$ $J_z(\nu\bar{\nu}) = 1$

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

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

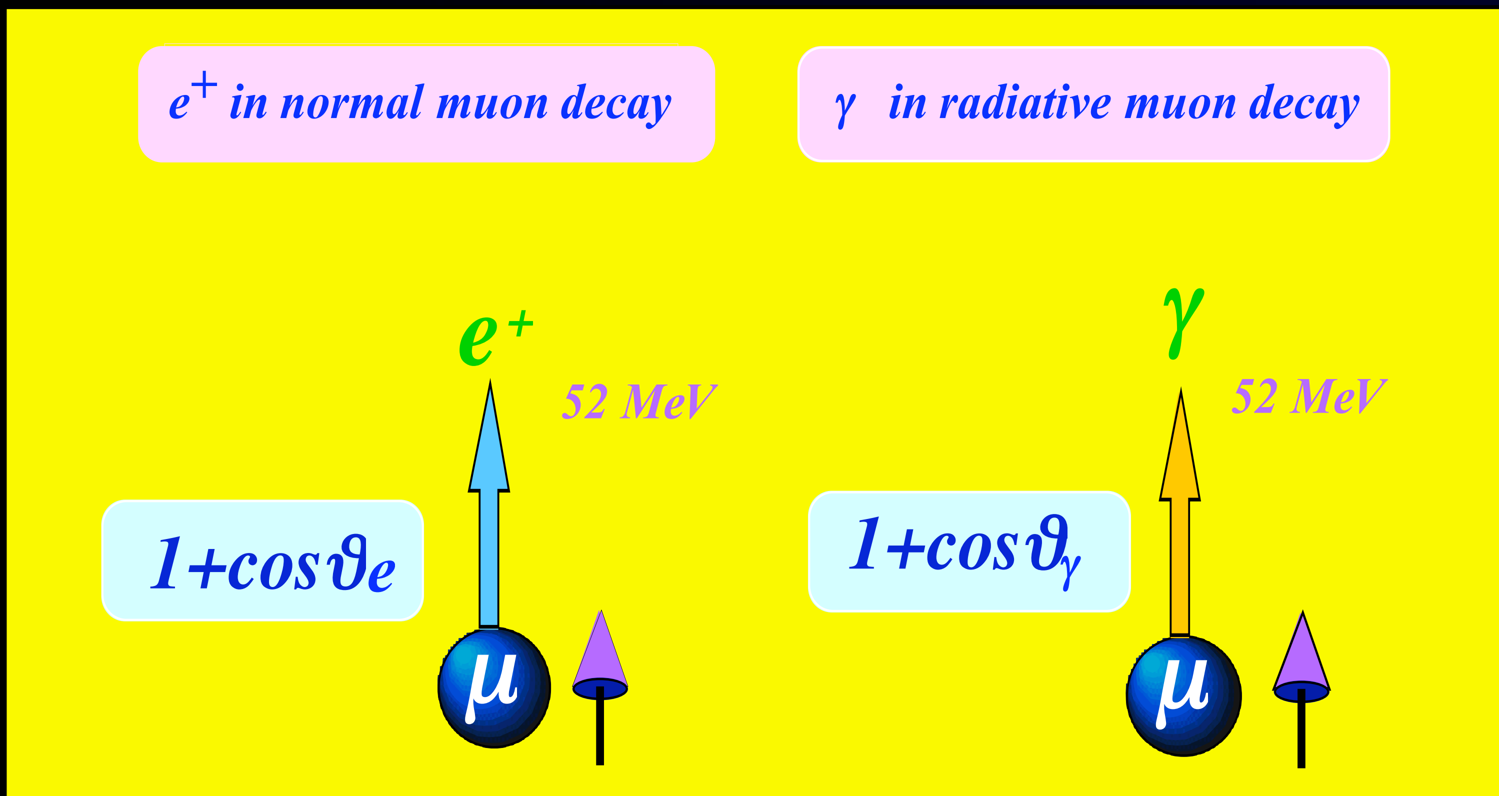


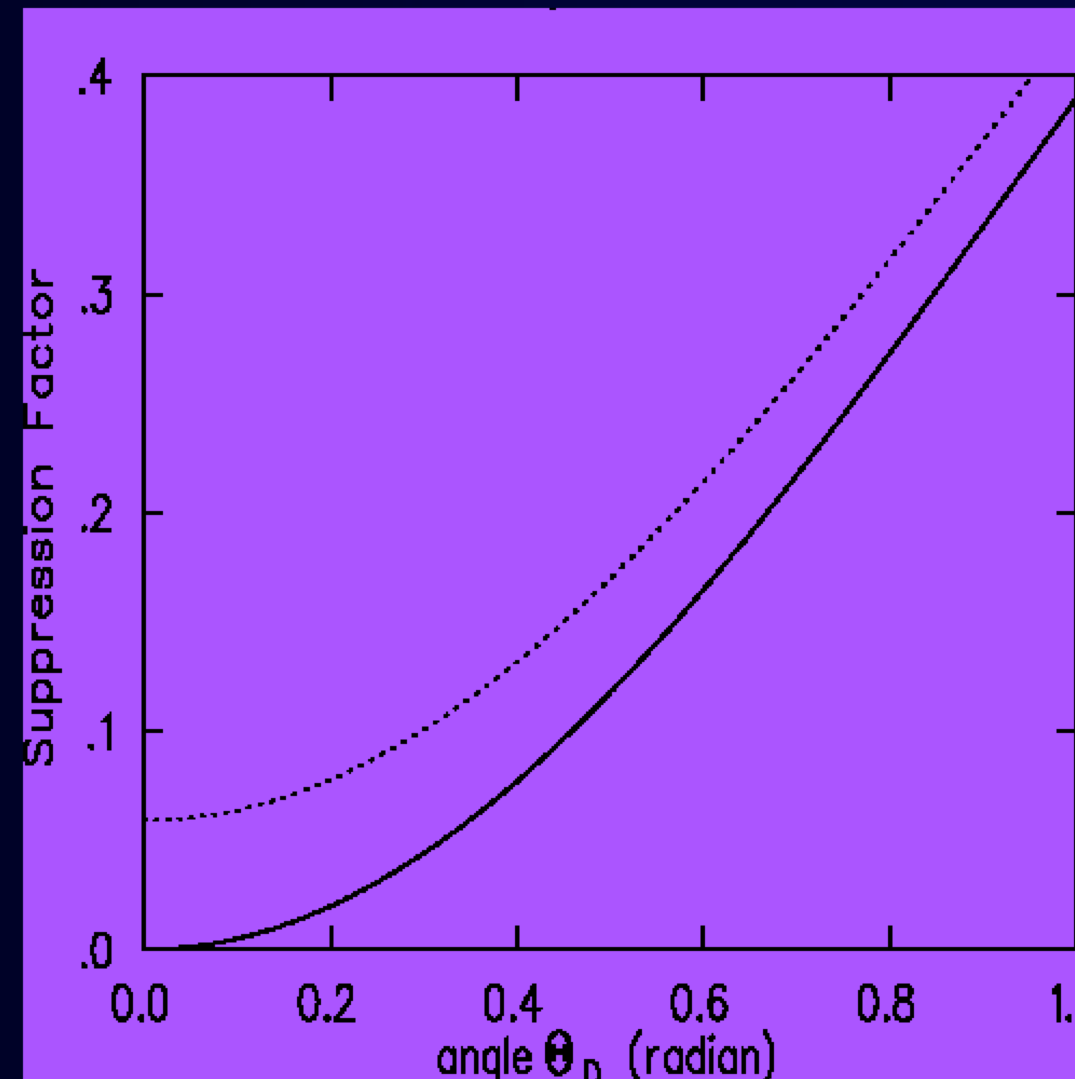
Y. Kuno and Y. Okada, Phys. Rev. Lett. 77 (1996) 434

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

$\rightarrow$ $\mu^+ \rightarrow e^+_L \gamma$

suppressed if photons going opposite to muon spin is measured.

$\rightarrow$ $\mu^+ \rightarrow e^+_L \gamma$

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

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

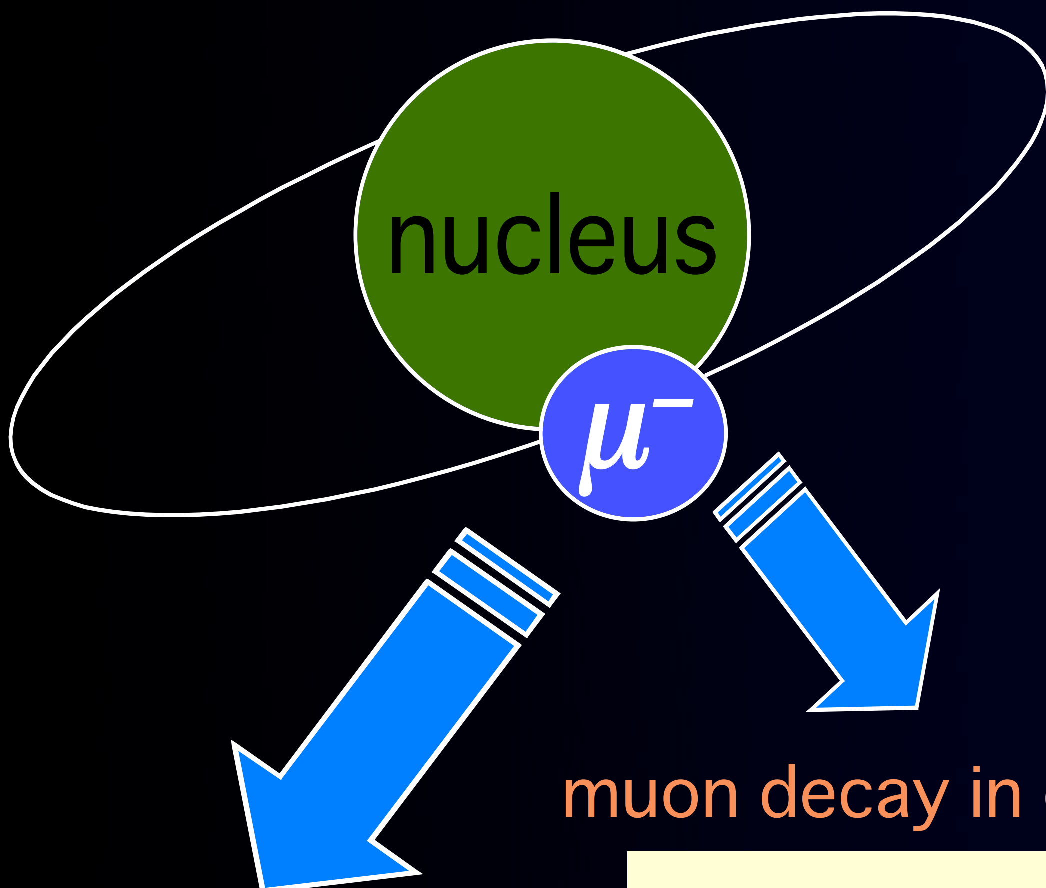
Both helicities are OK !

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

$\mu \rightarrow e$ 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

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

- 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.

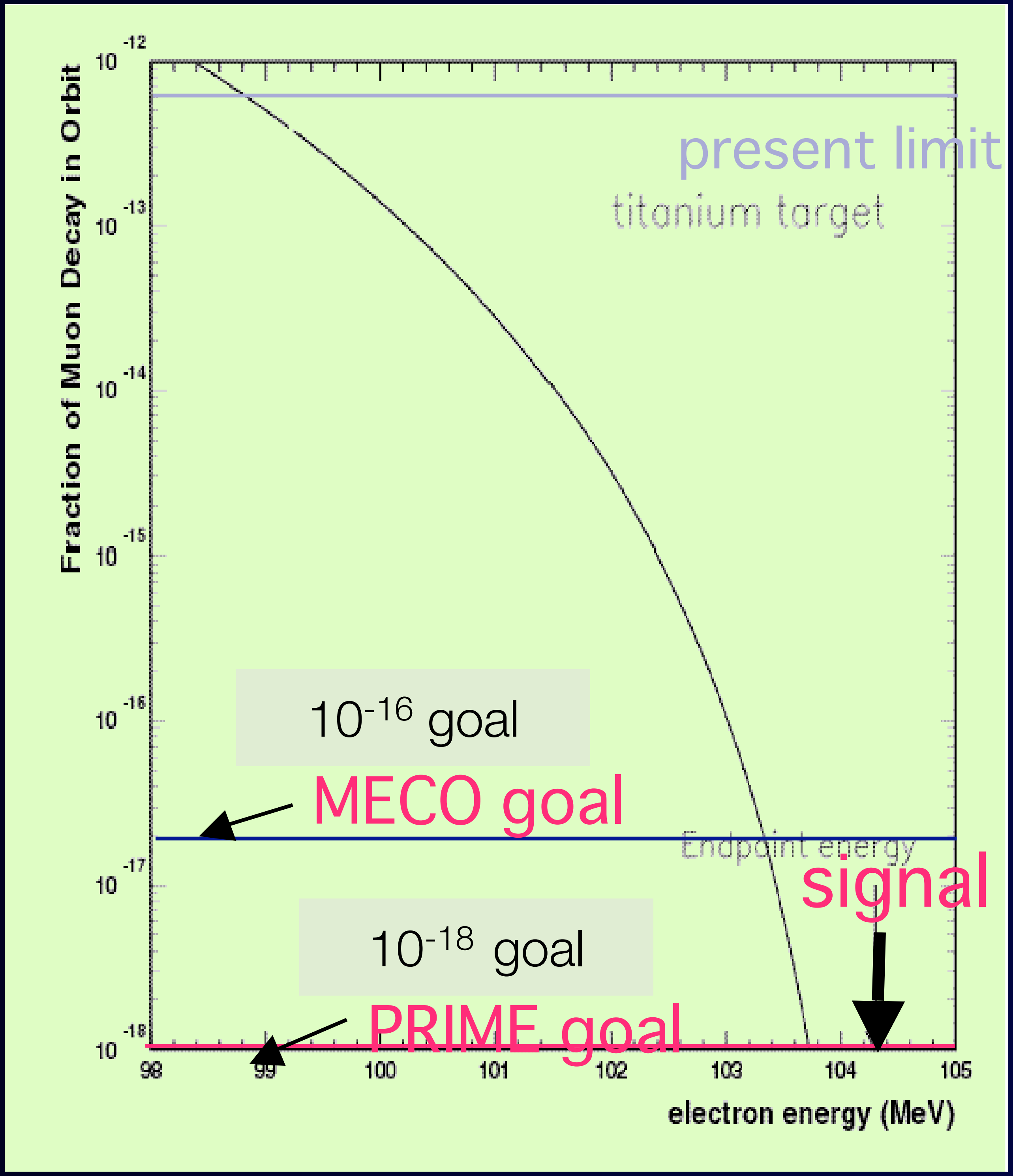
Backgrounds

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

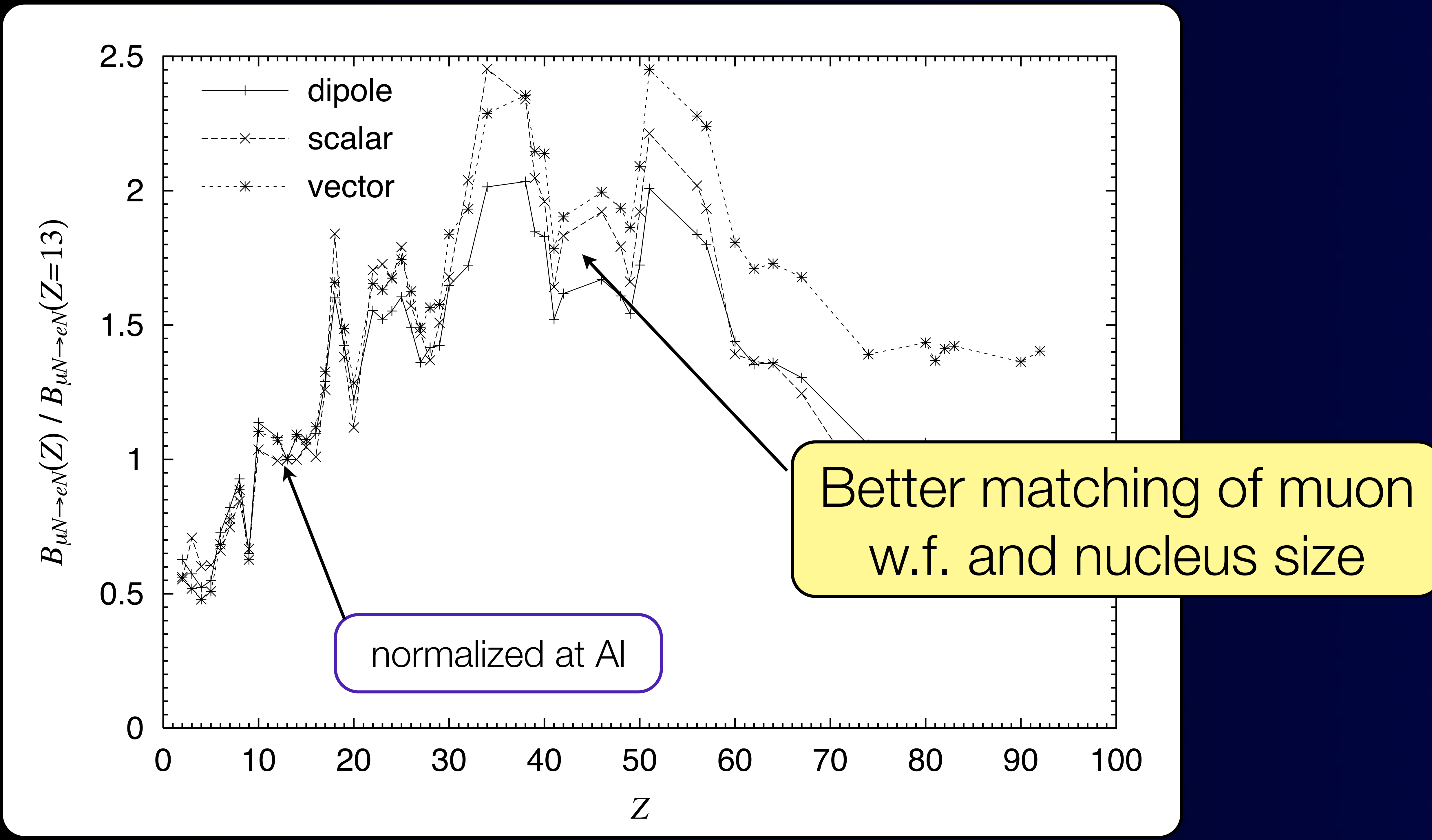
Muon Decay In Orbit (DIO) in a Muonic Atom

- 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)

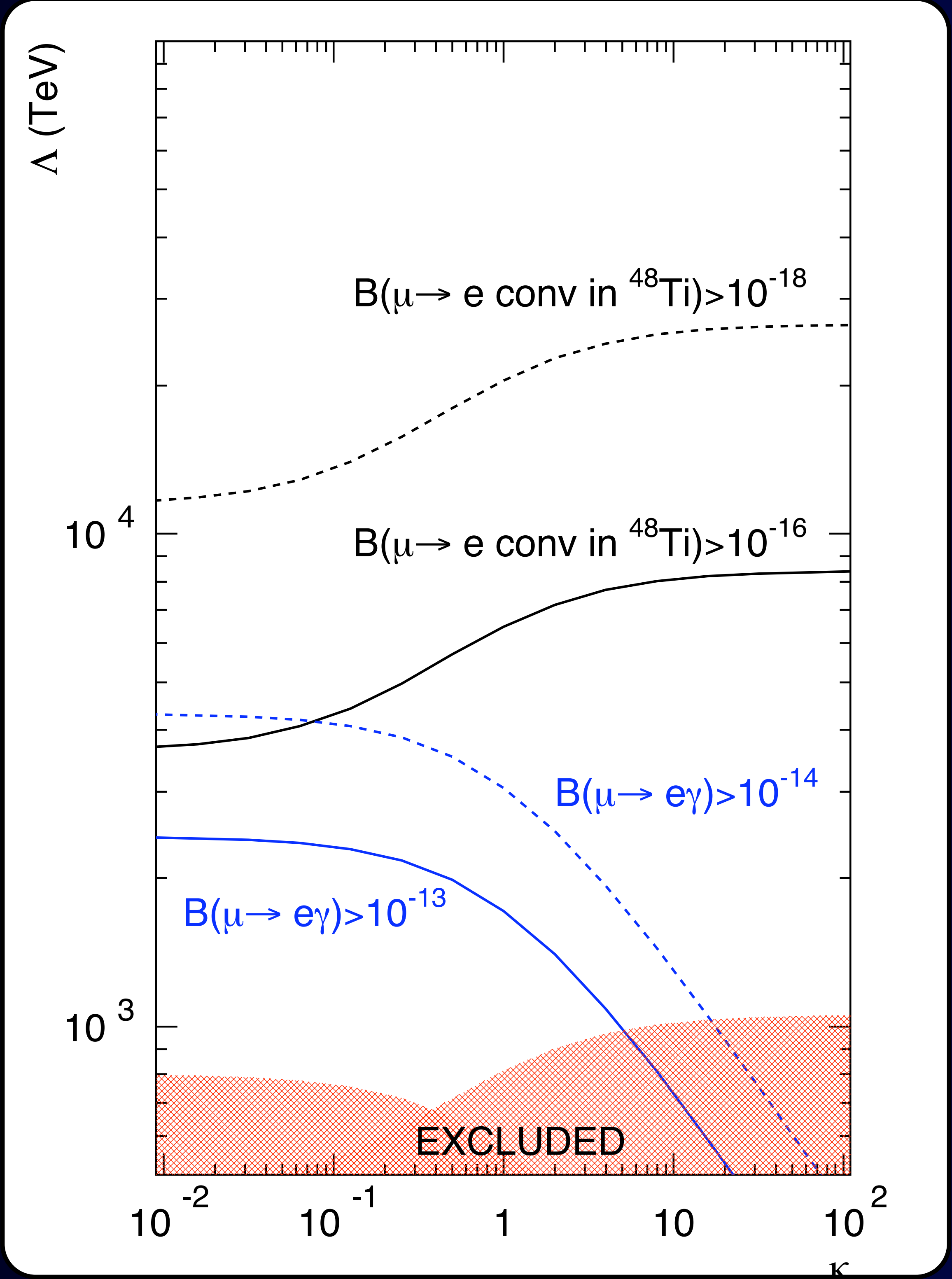


R. Kitano, M. Koike and Y. Okada, Phys. Rev. D66, 096002 (2002)

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

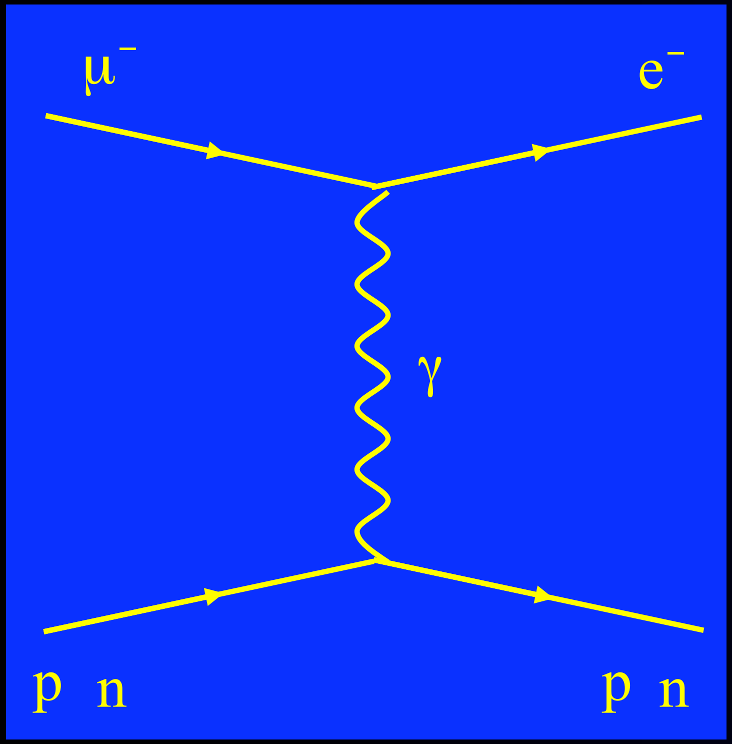
Photonic (dipole) and non-photonic contributions

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

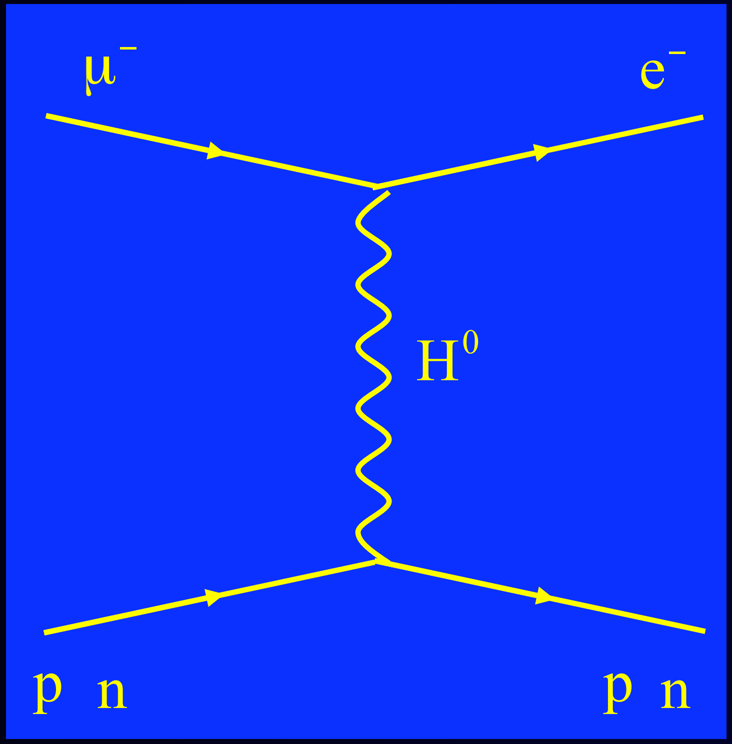


more sensitive to new physics

SUSY Higgs Mediated Contribution (large tanβ)

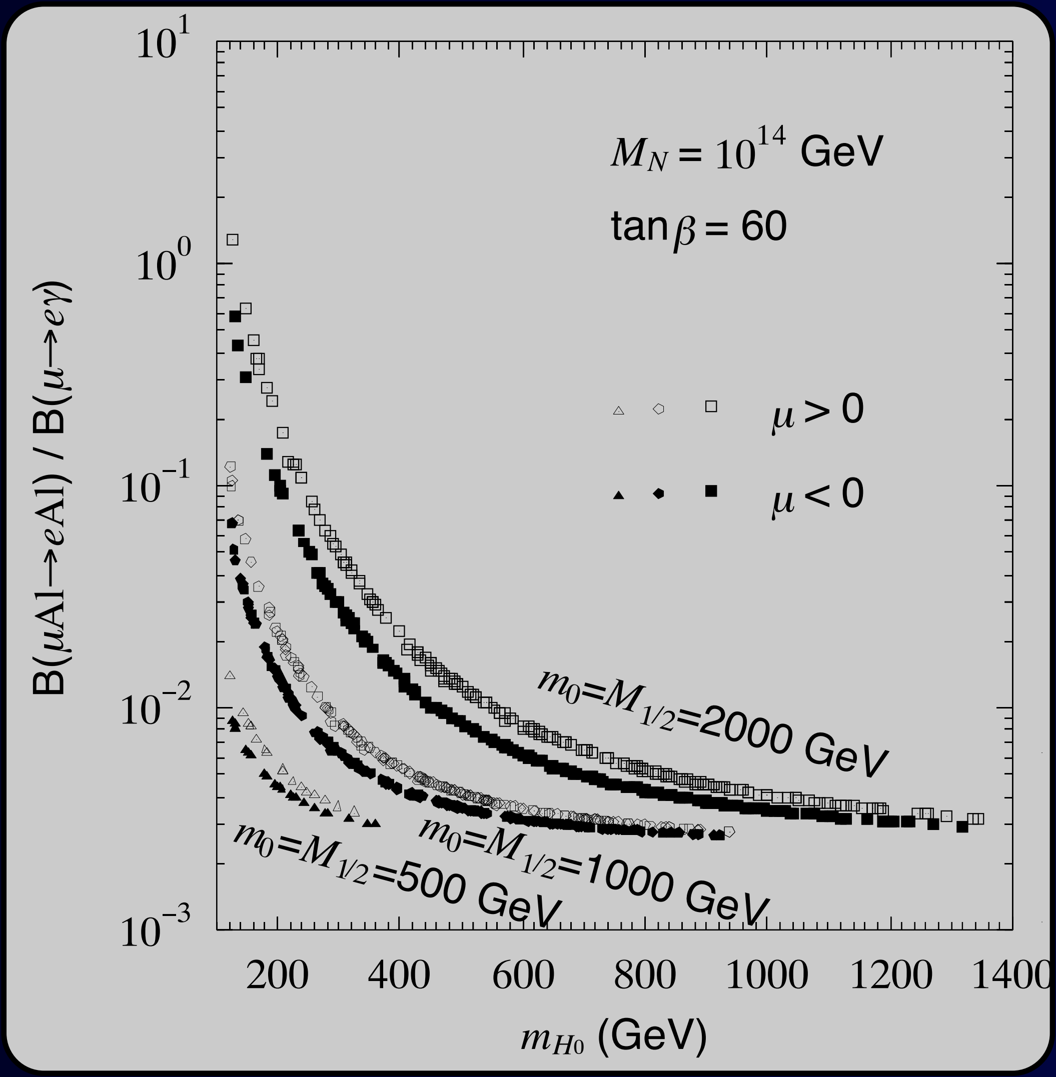


$$\frac{B(\mu N \to eN)}{B(\mu \to e\gamma)} \sim \frac{1}{100}$$



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

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



Experimental Comparison between $\mu \to e\gamma$ 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.

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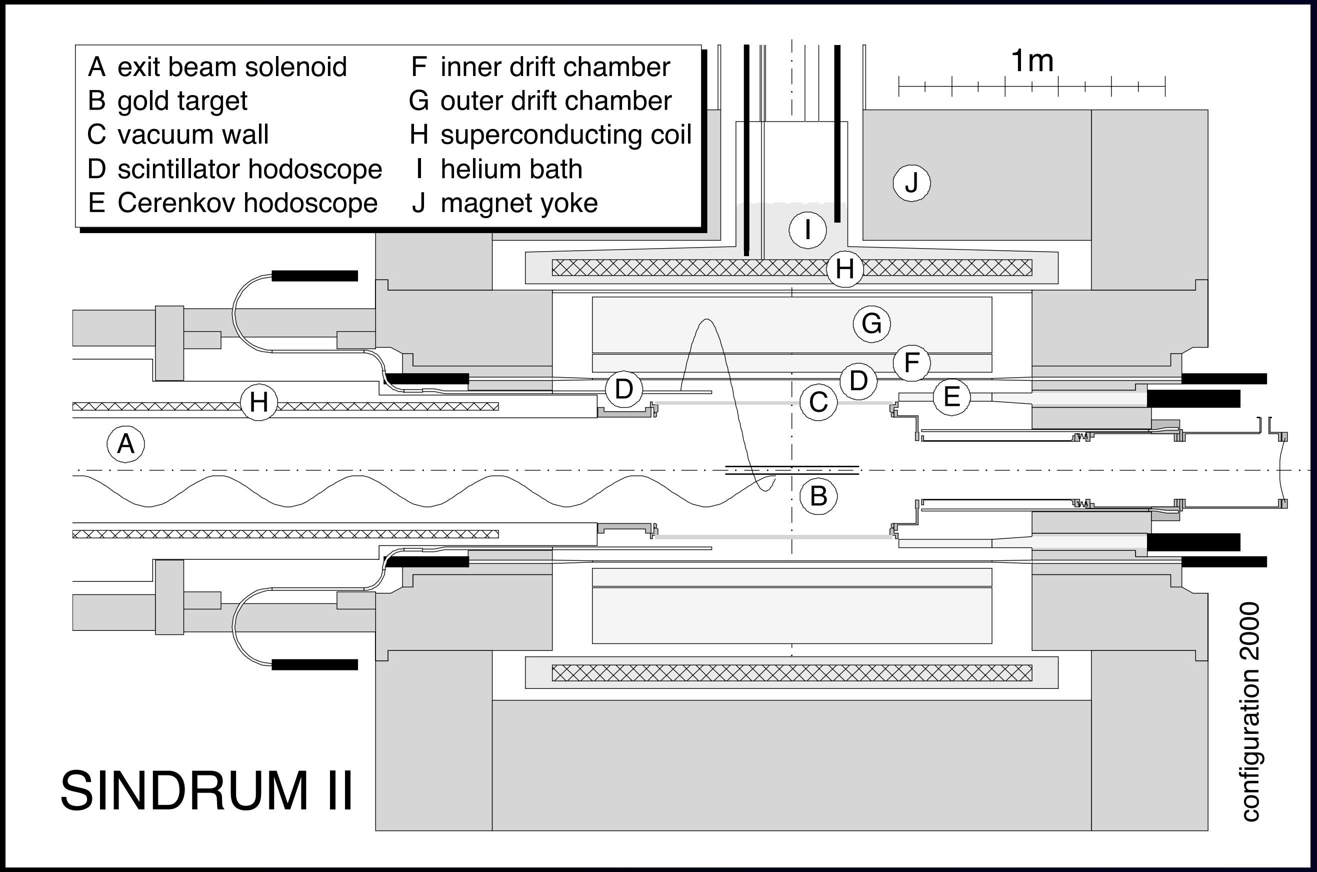
Experimental Design for Muon to Electron Conversion

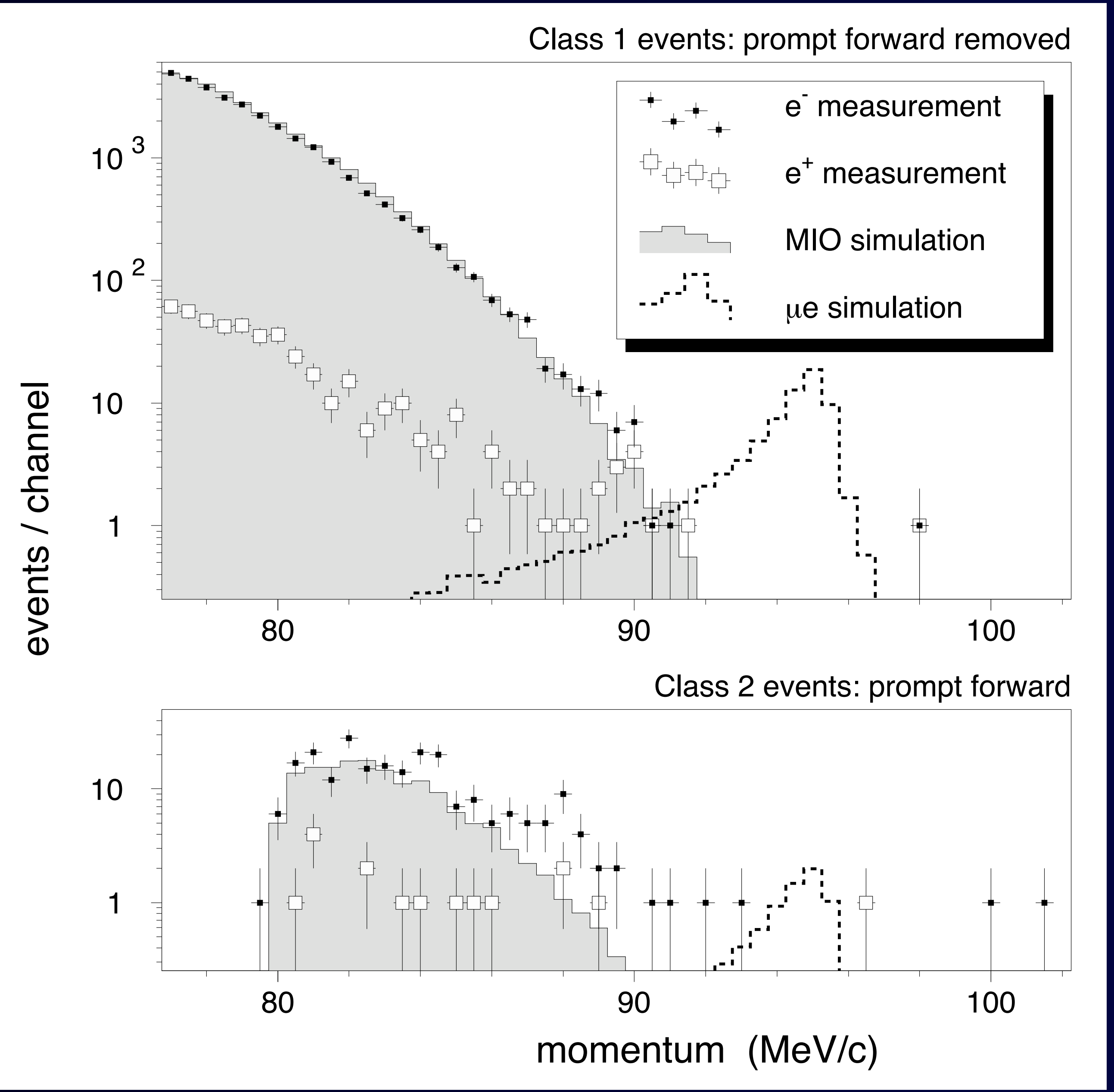
Previous Measurements

SINDRUM-II (PSI)



Published Results (2004)

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



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.

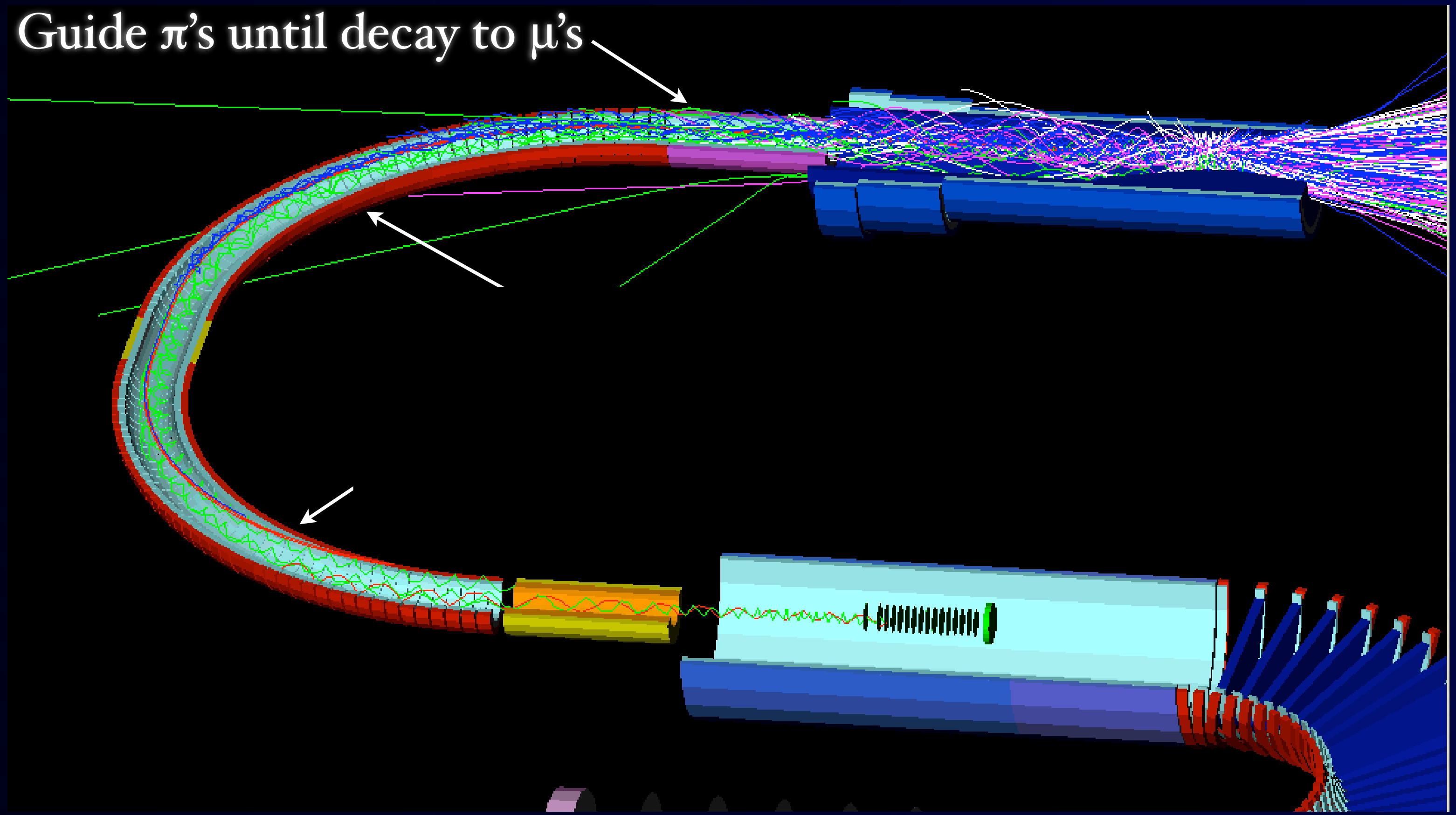
Improvements for Signal Sensitivity

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

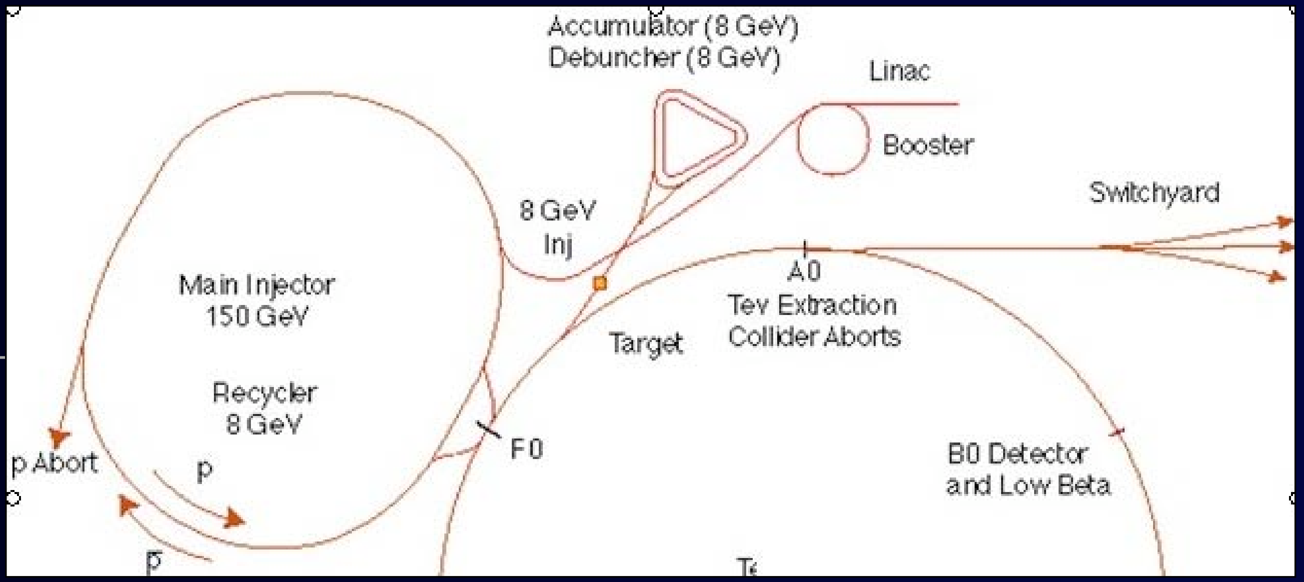


Improvements for Background Rejection

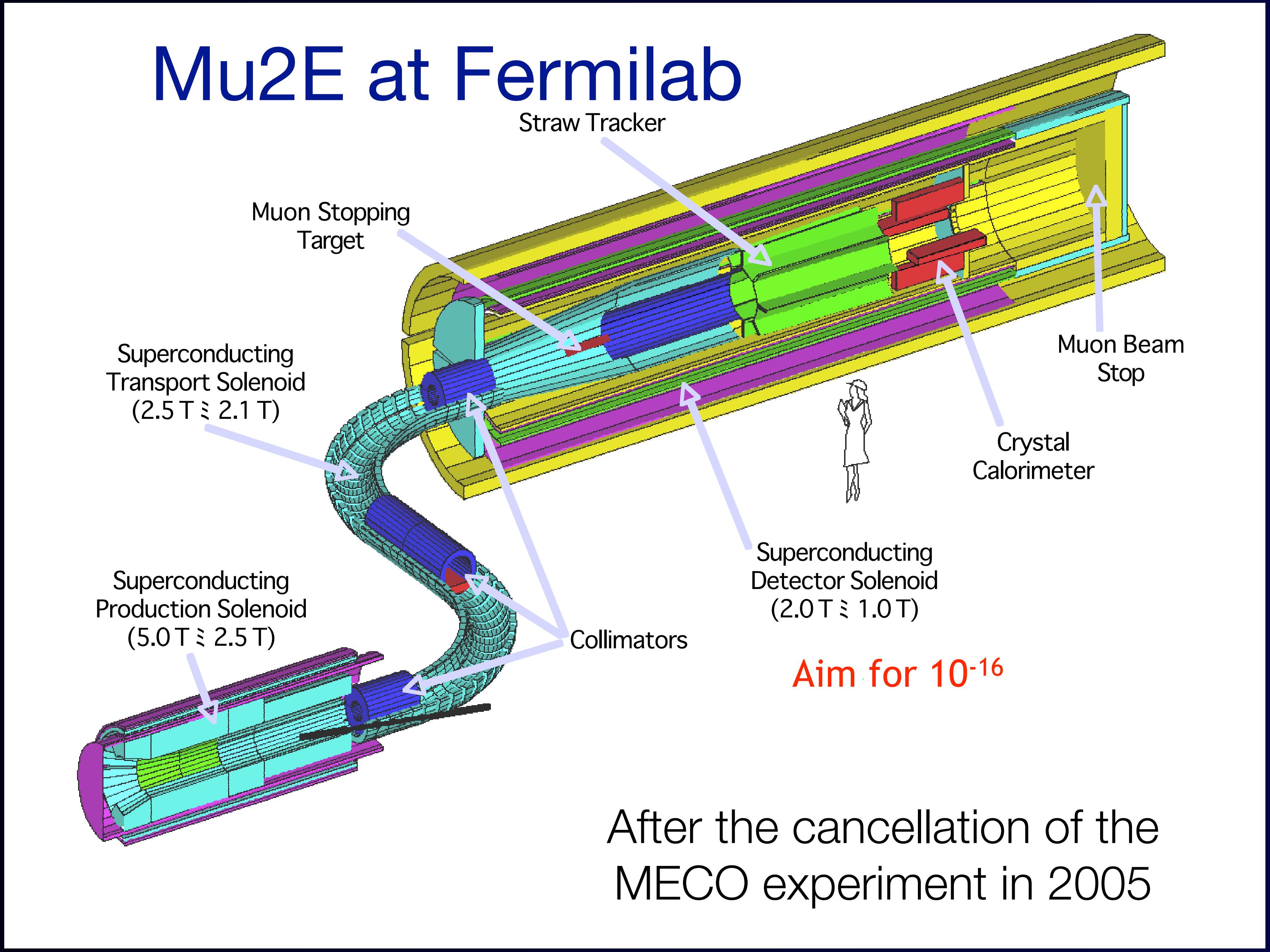
Beam-related backgrounds	Beam pulsing with separation of 1μsec	measured between beam pulses
Muon DIO background	low-mass trackers in vacuum & thin target	improve electron energy resolution
Muon DIF background	curved solenoids for momentum selection	eliminate energetic muons (>75 MeV/c)

base on the MELC proposal at Moscow Meson Factory

Mu2E
at Fermilab

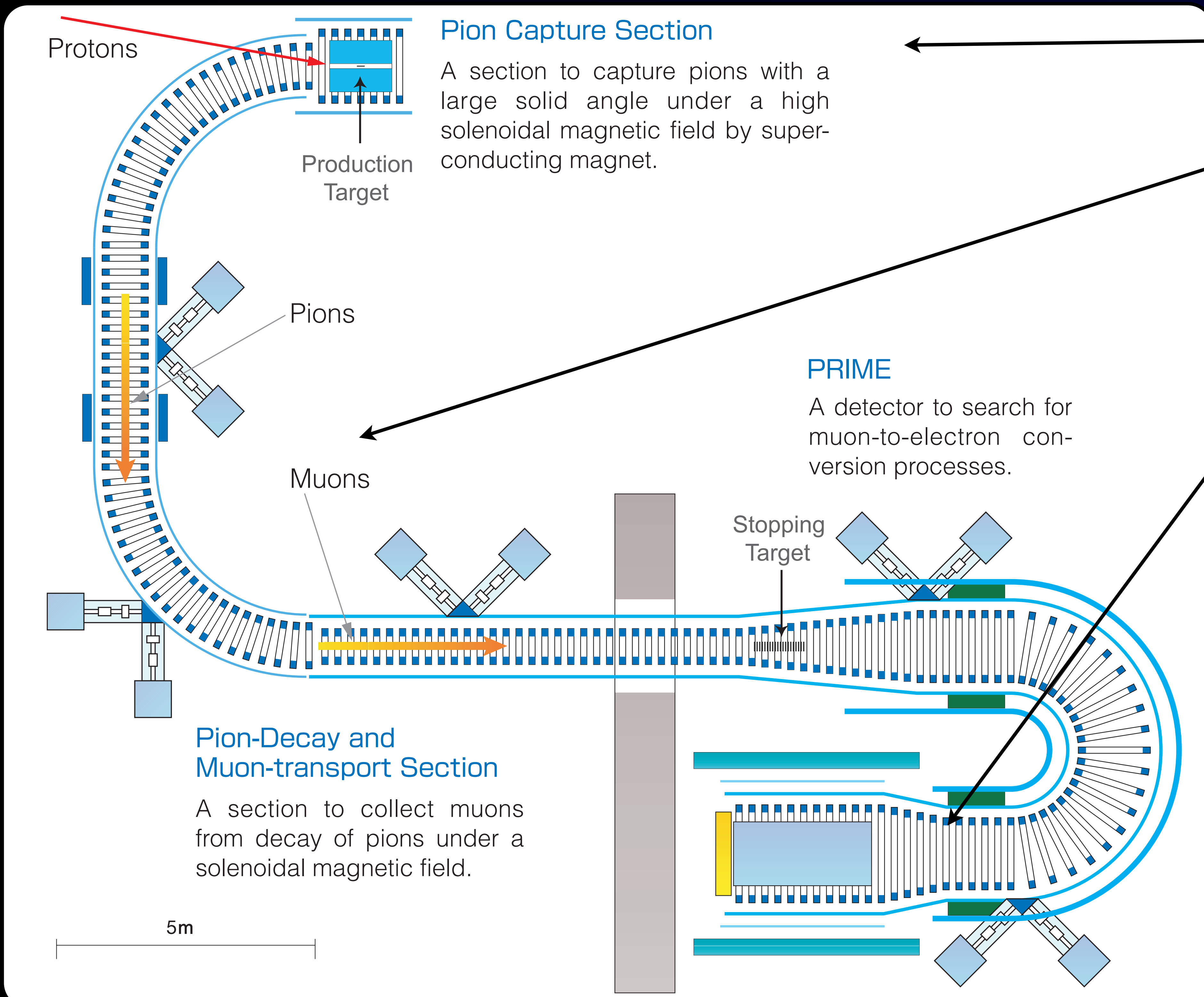


- After Tevatron shutdown, use the antiproton accumulator ring and debuncher ring for beam pulsing.
- Proton beam power is 20 kW and 200 kW for pre and post Project-X.



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

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

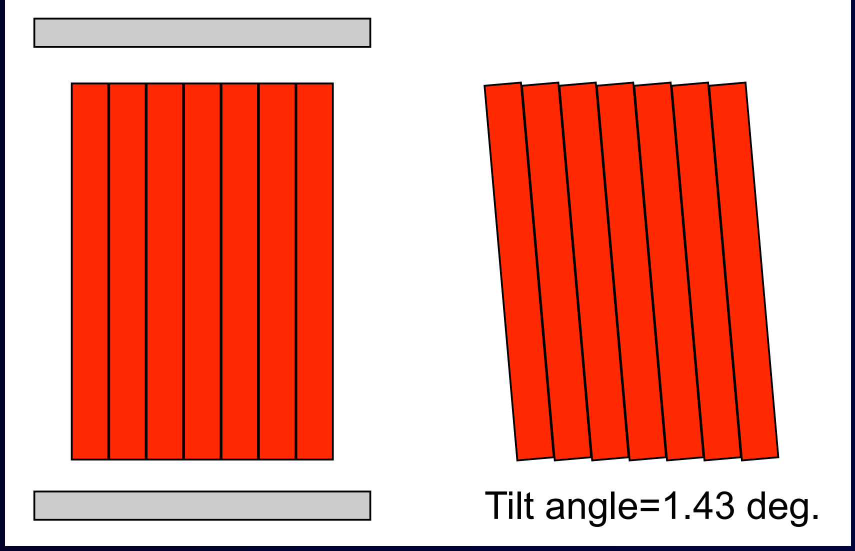
D : drift distance
B : Solenoid field
θ_{bend} *: Bending angle of the solenoid channel*
p : Momentum of the particle
q : Charge of the particle
θ *: atan(*P_T/P_L*)*

  - This can be used for charge and momentum selection.

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

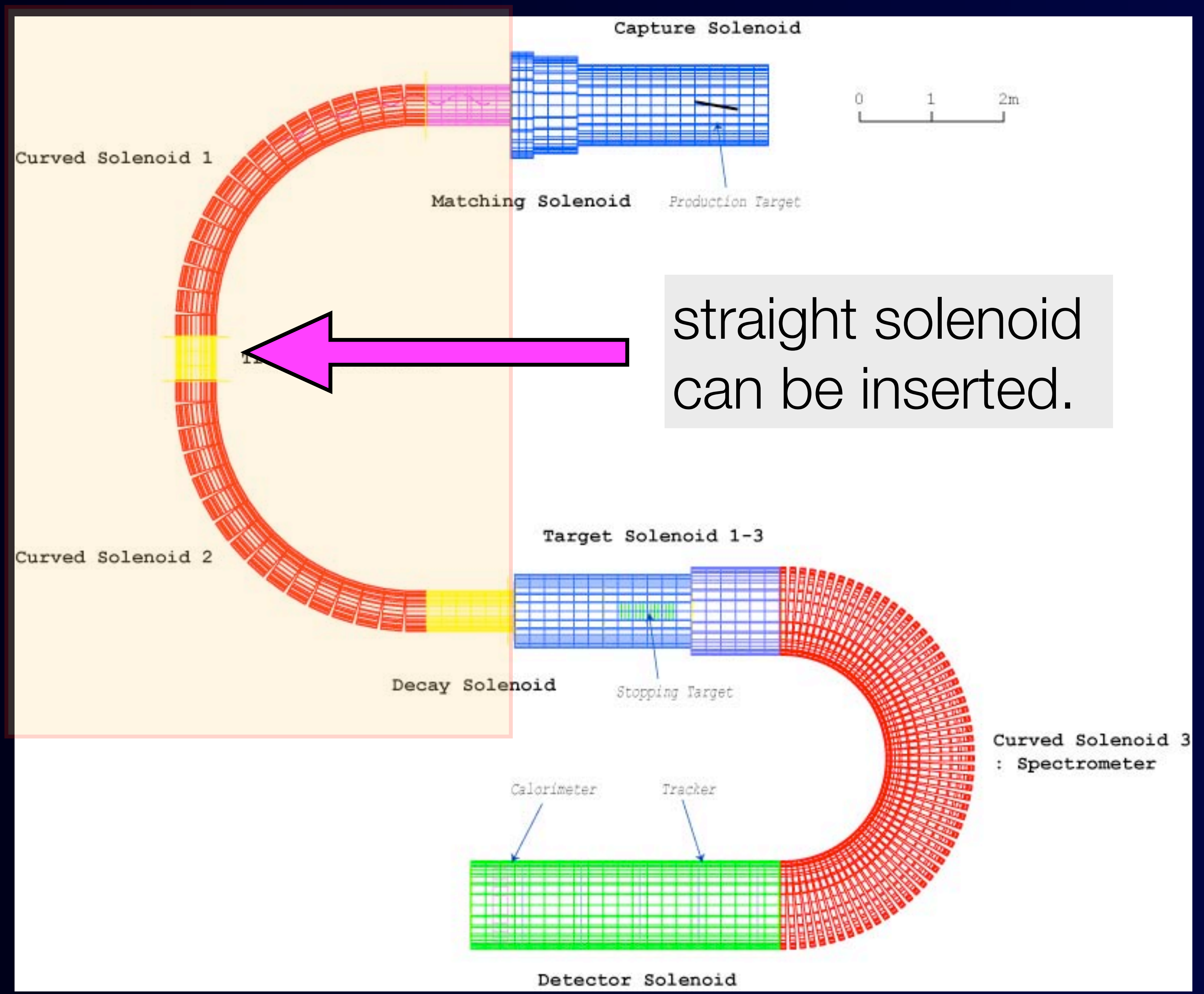
$$B_{comp} = \frac{p}{qr}\frac{1}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$

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



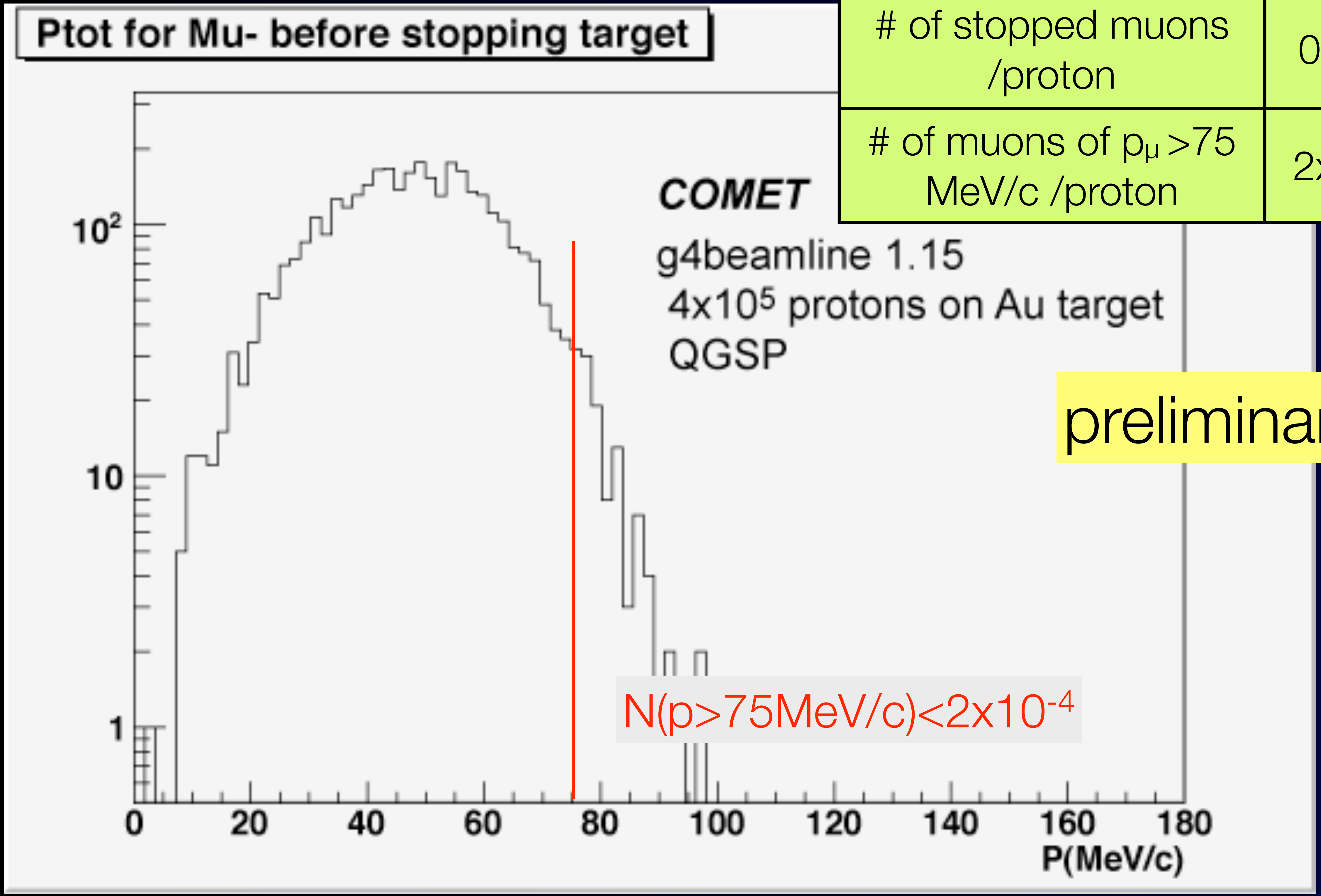
Muon Transport Solenoid Beam-line for COMET

- 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.



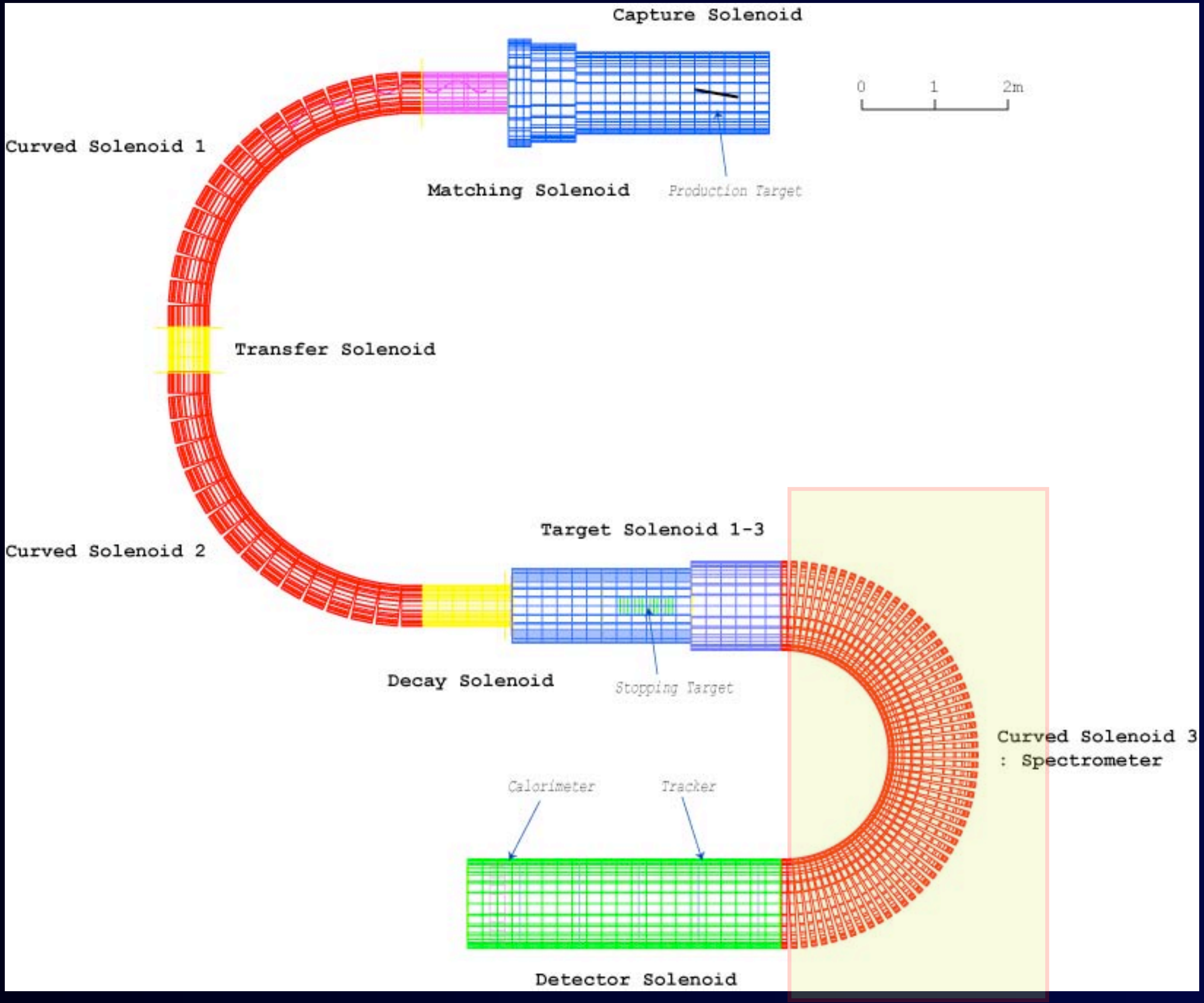
Muon Momentum Spectrum at the End of the Transport Beam Line

# of muons /proton	0.009
# of stopped muons /proton	0.003
# of muons of $p_{\mu} > 75$ MeV/c /proton	2×10^{-4}



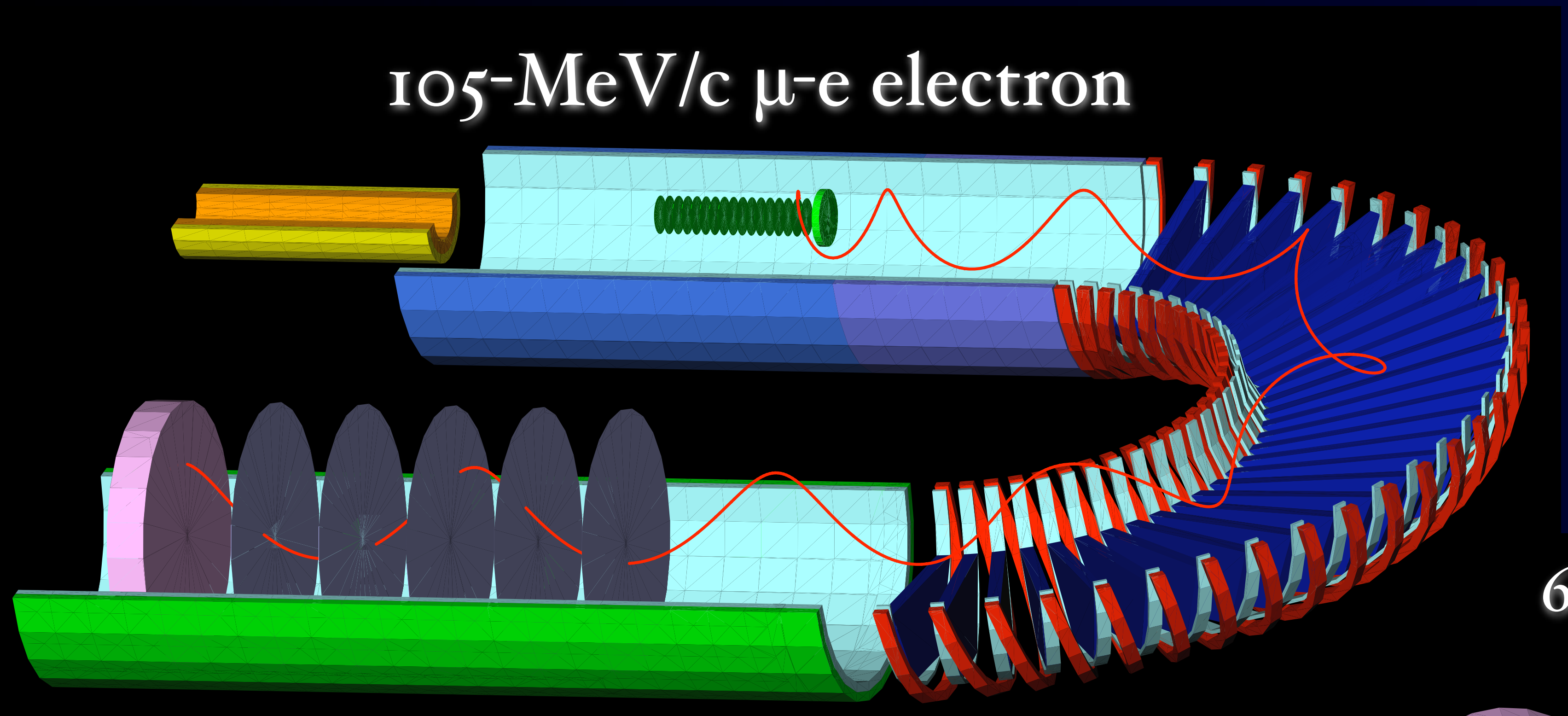
Curved Solenoid Spectrometer for COMET

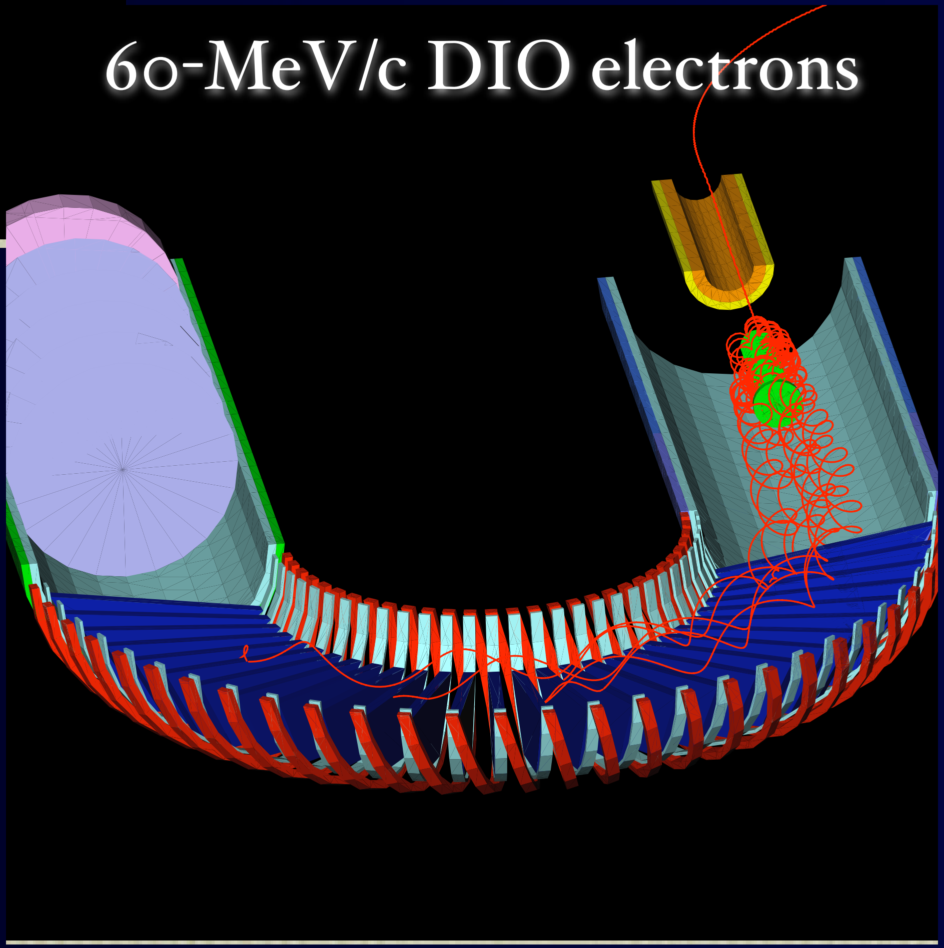
- 180 degree curved
  - Bore radius : 50 cm
  - Magnetic field : 1T
  - Bending angle : 180 degrees
- reference momentum ~ 104 MeV/c
- elimination of particles less than 80 MeV/c for rate issues
- a straight solenoid where detectors are placed follows the curved spectrometer.



schematic

Event Displays for Curved Solenoid Spectrometer



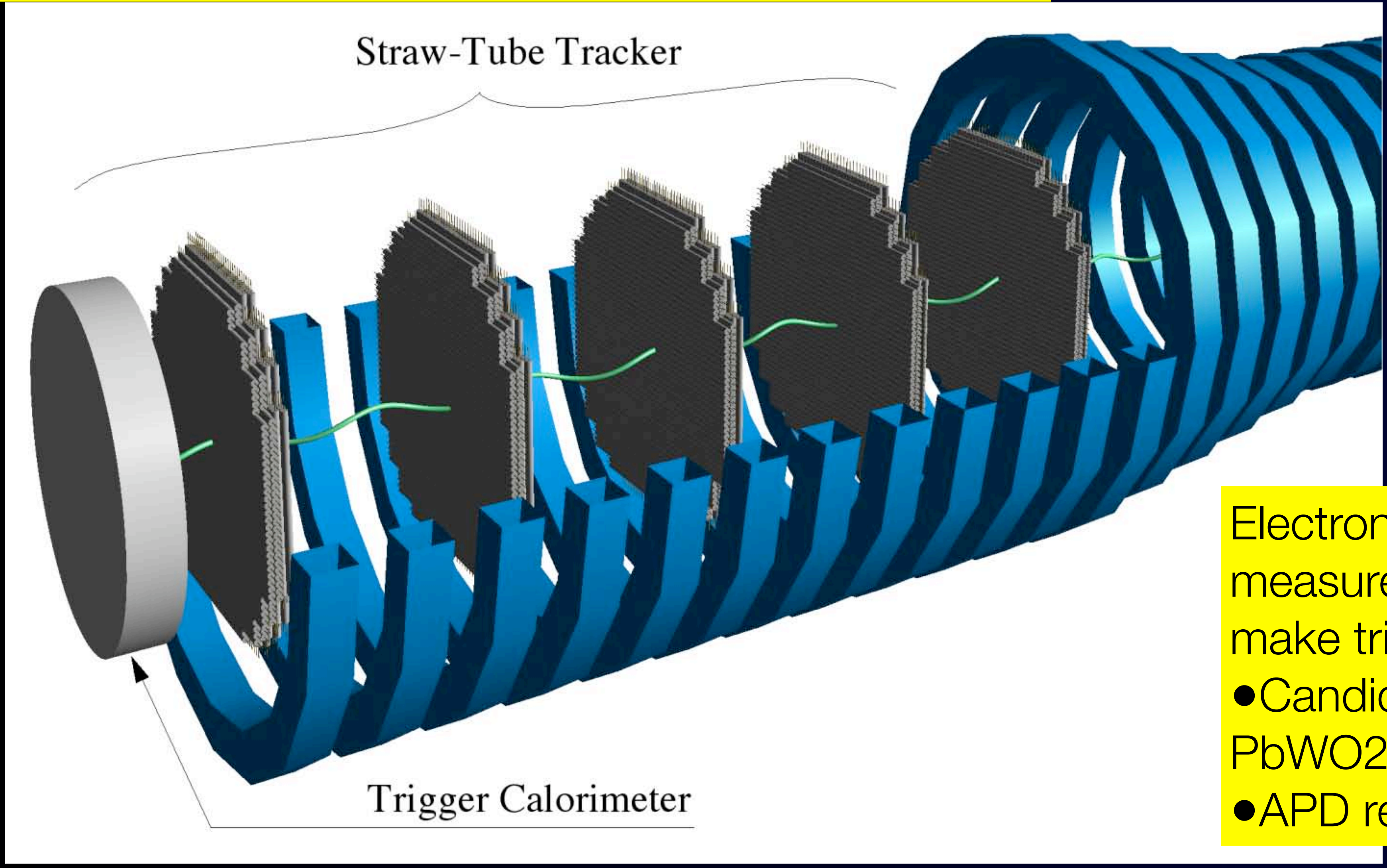


Electron Detection (preliminary)

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.

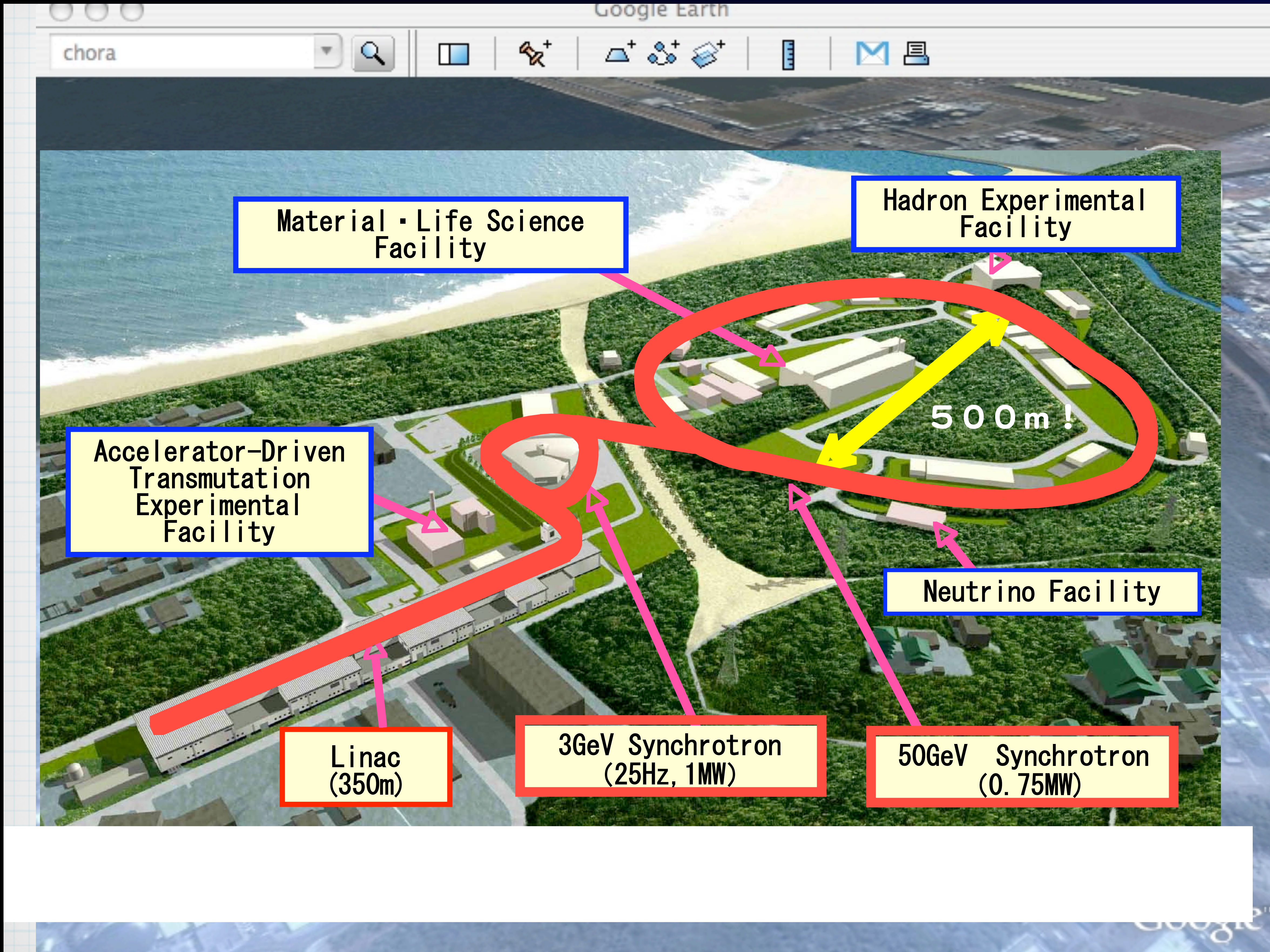
Under a solenoidal magnetic field of 1 Tesla.

In vacuum to reduce multiple scattering.



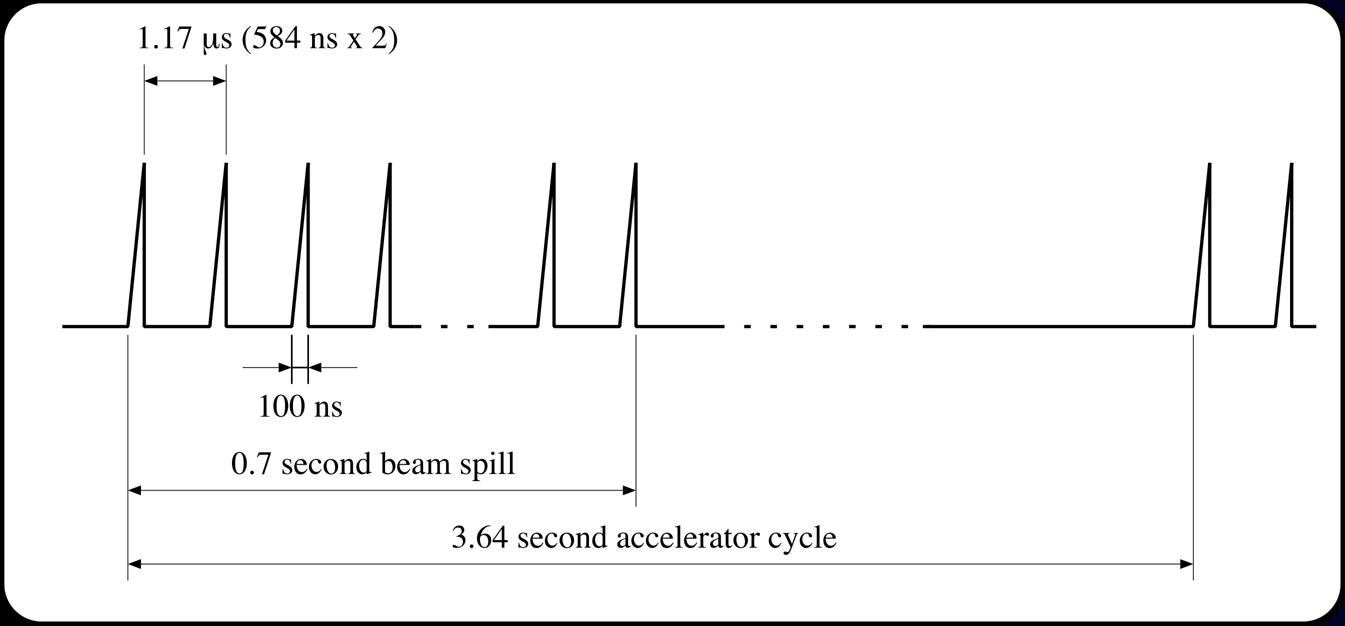
Electron calorimeter to measure electron energy and make triggers.
- Candidate are GSO or PbWO2.
- APD readout (no PMT).

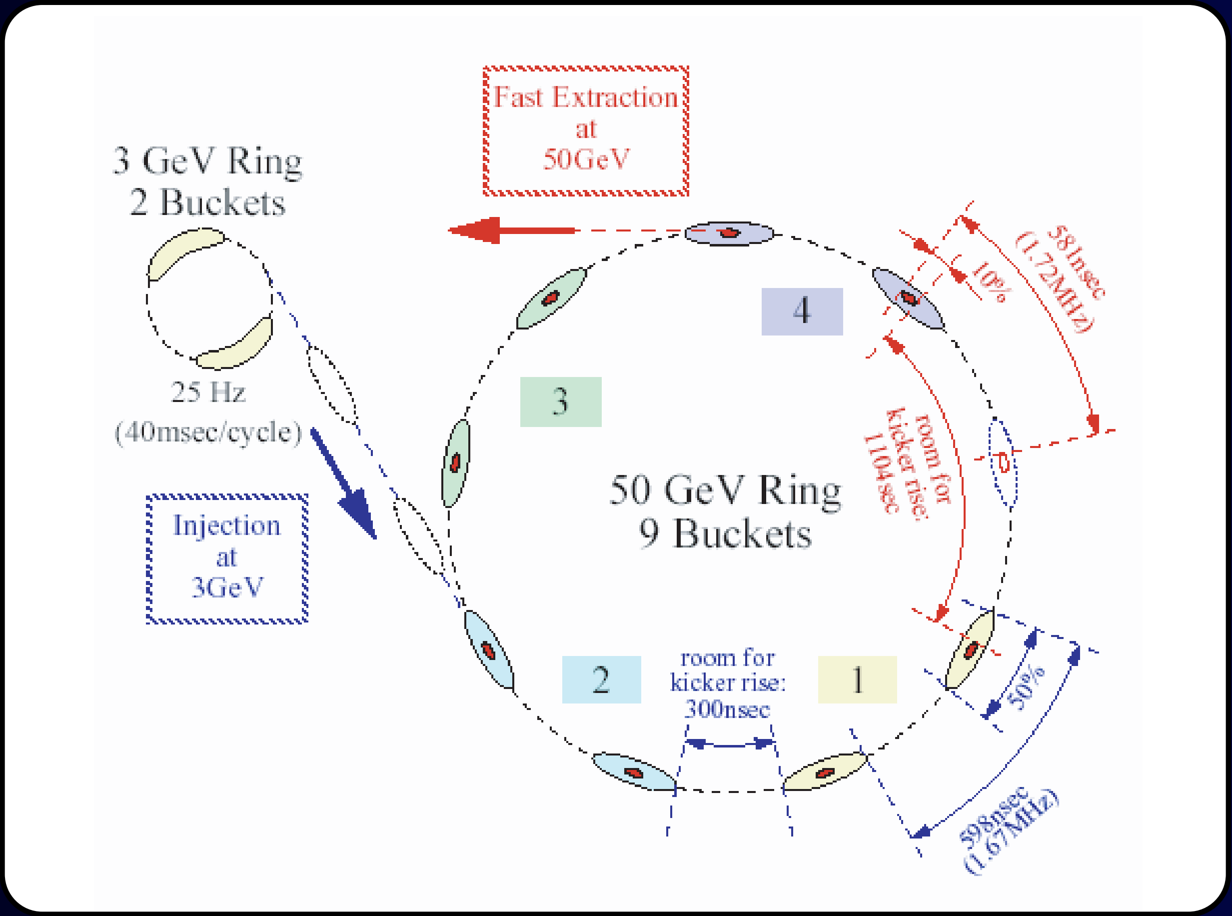
J-PARC at Tokai, Japan



Proton Beam at J-PARC (1)

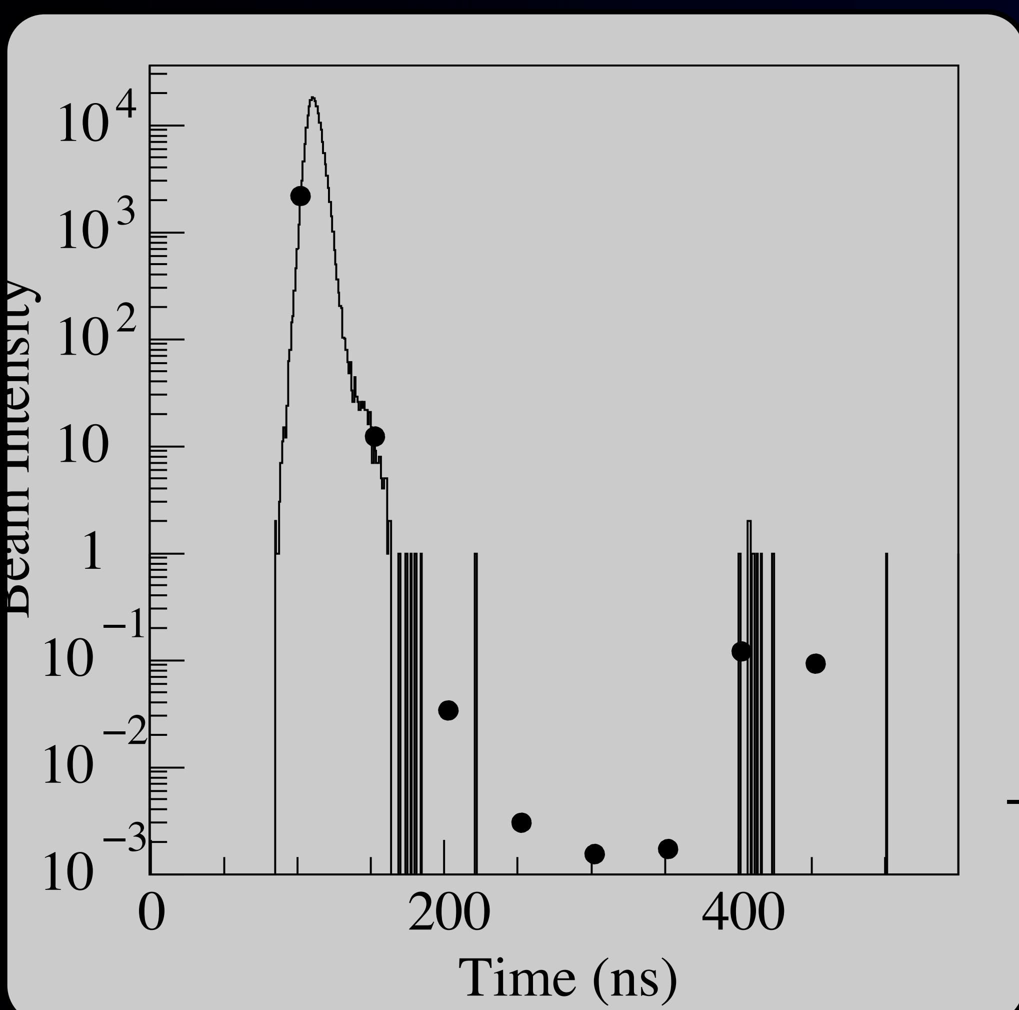
- A pulsed proton beam is needed to reject beam-related prompt background.
- Time structure required for proton beams.
  - Pulse separation is ~ 1μsec or more (muon lifetime).
  - Narrow pulse width (<100 nsec)
- Pulsed beam from slow extraction.
  - fill every other rf buckets with protons and make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

Signal Sensitivity (preliminary) - 1 SSC years

- Single event sensitivity

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

- 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}

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

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

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 & 2×10^{7} sec run
Pattern recognition errors	<0.001	
Total	0.4	

PRISM

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10^{-18} Sensitivity with PRISM

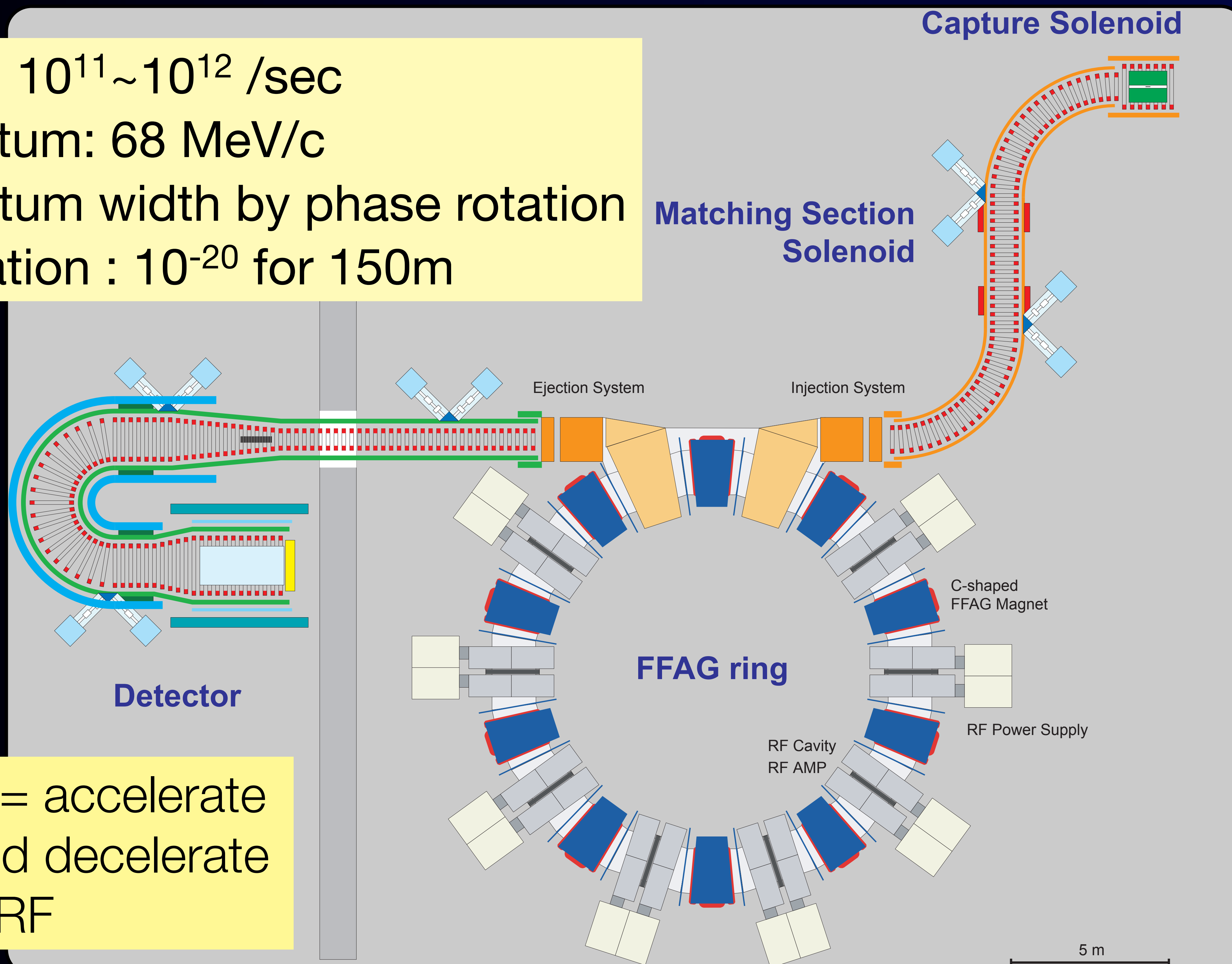
Further Background Rejection to < 10^{-18}

Background	Solution	
Pion background	long muon beam-line	muon storage ring
Muon DIO background	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

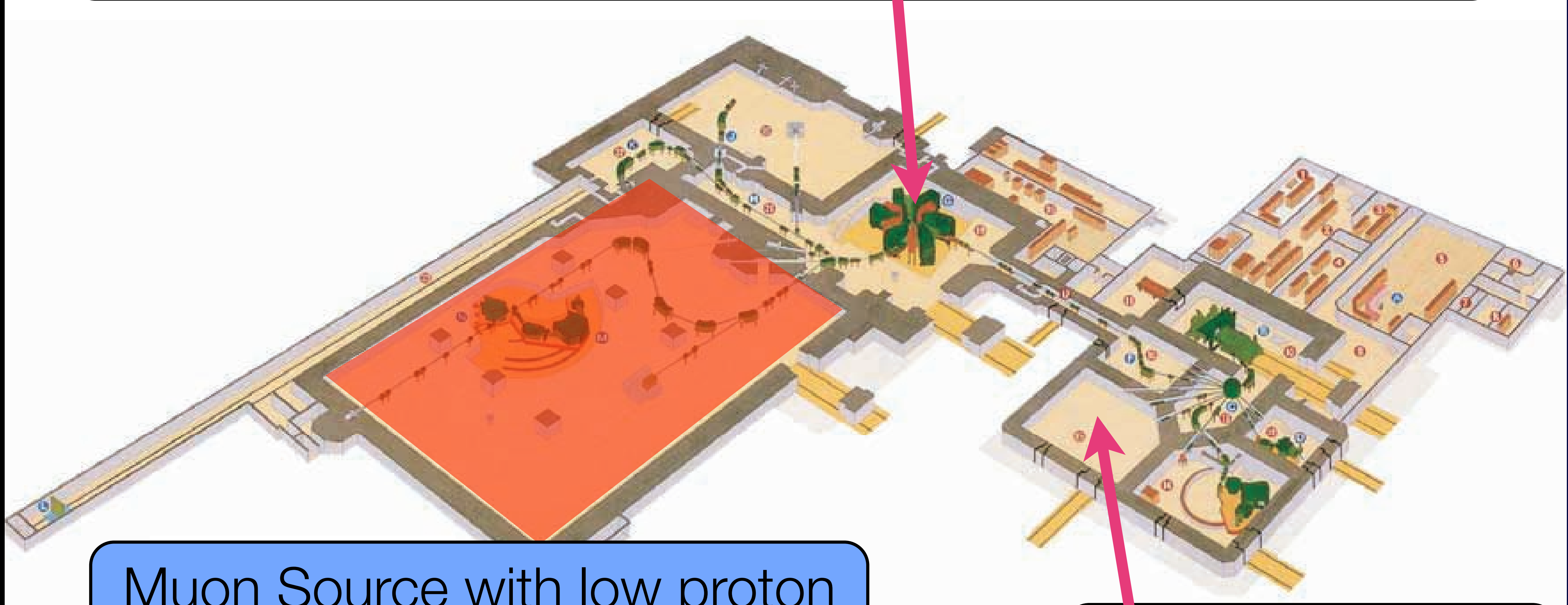


Phase rotation = accelerate slow muons and decelerate fast muons by RF

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

Research Center for Nuclear Physics (RCNP), Osaka University

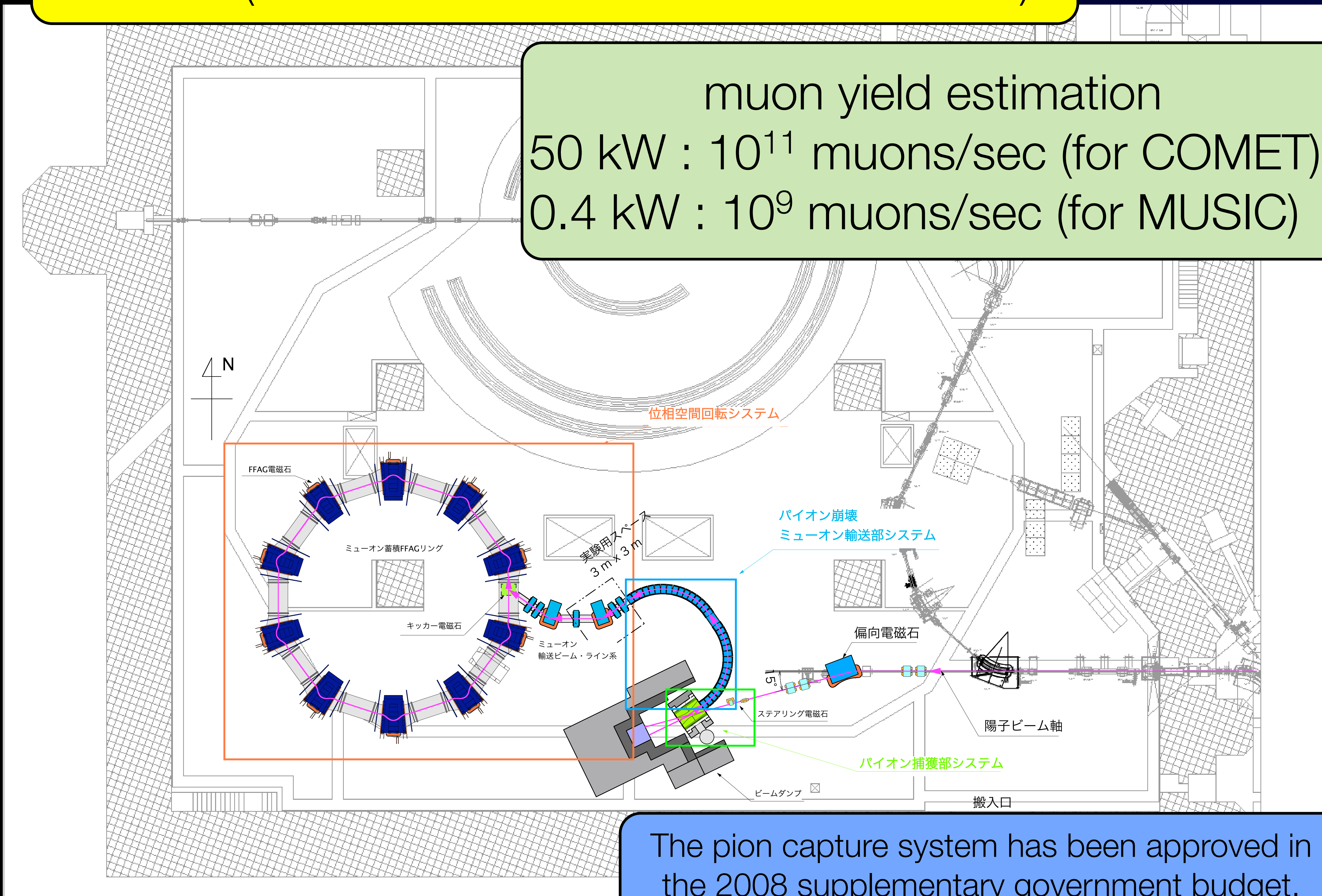
Research Center for Nuclear Physics (RCNP), Osaka University has a cyclotron of 400 MeV with 1 microA. The energy is above pion threshold.



Muon Source with low proton power at Osaka U.?

PRISM-FFAG R&D

MUSIC (=MUon Science International Center)



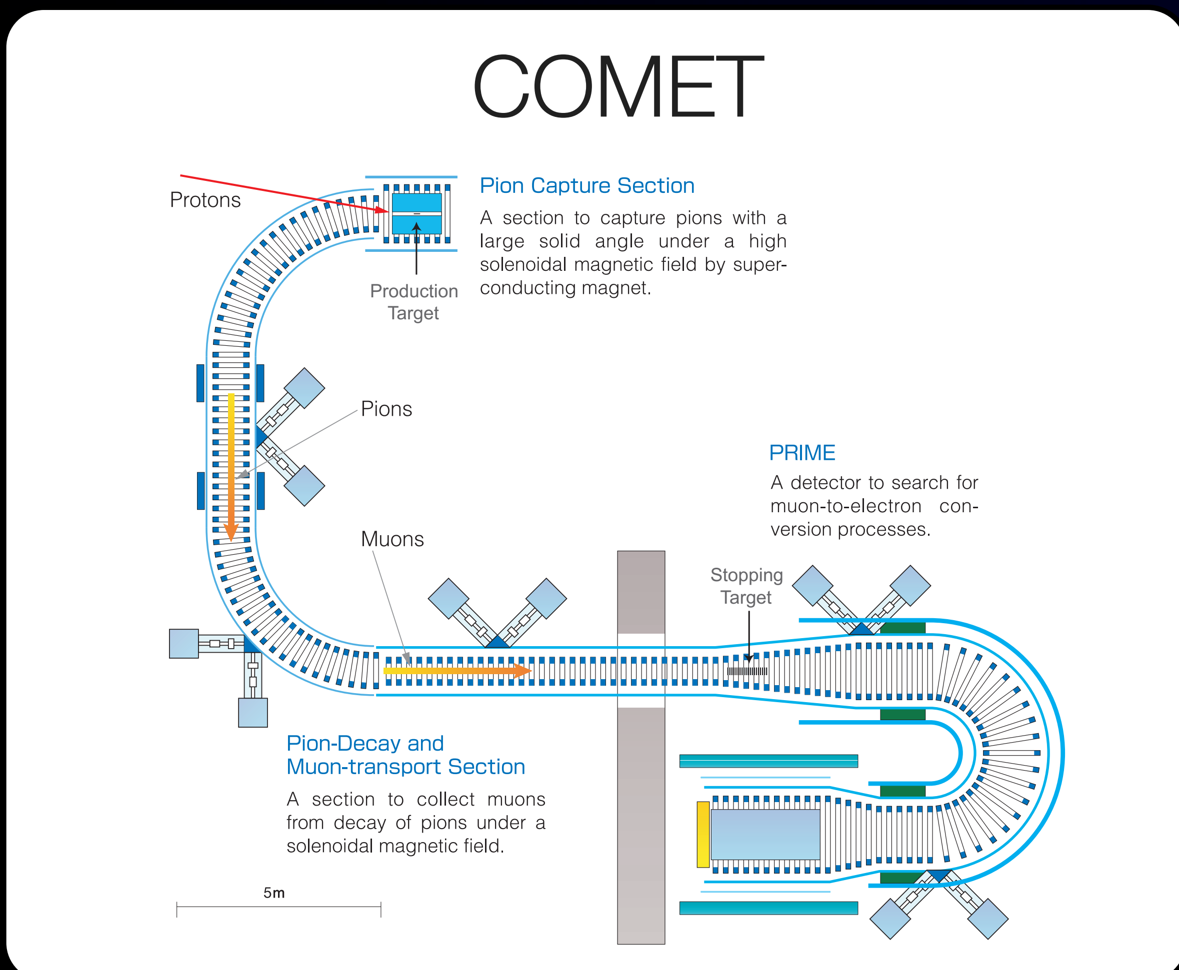
muon yield estimation

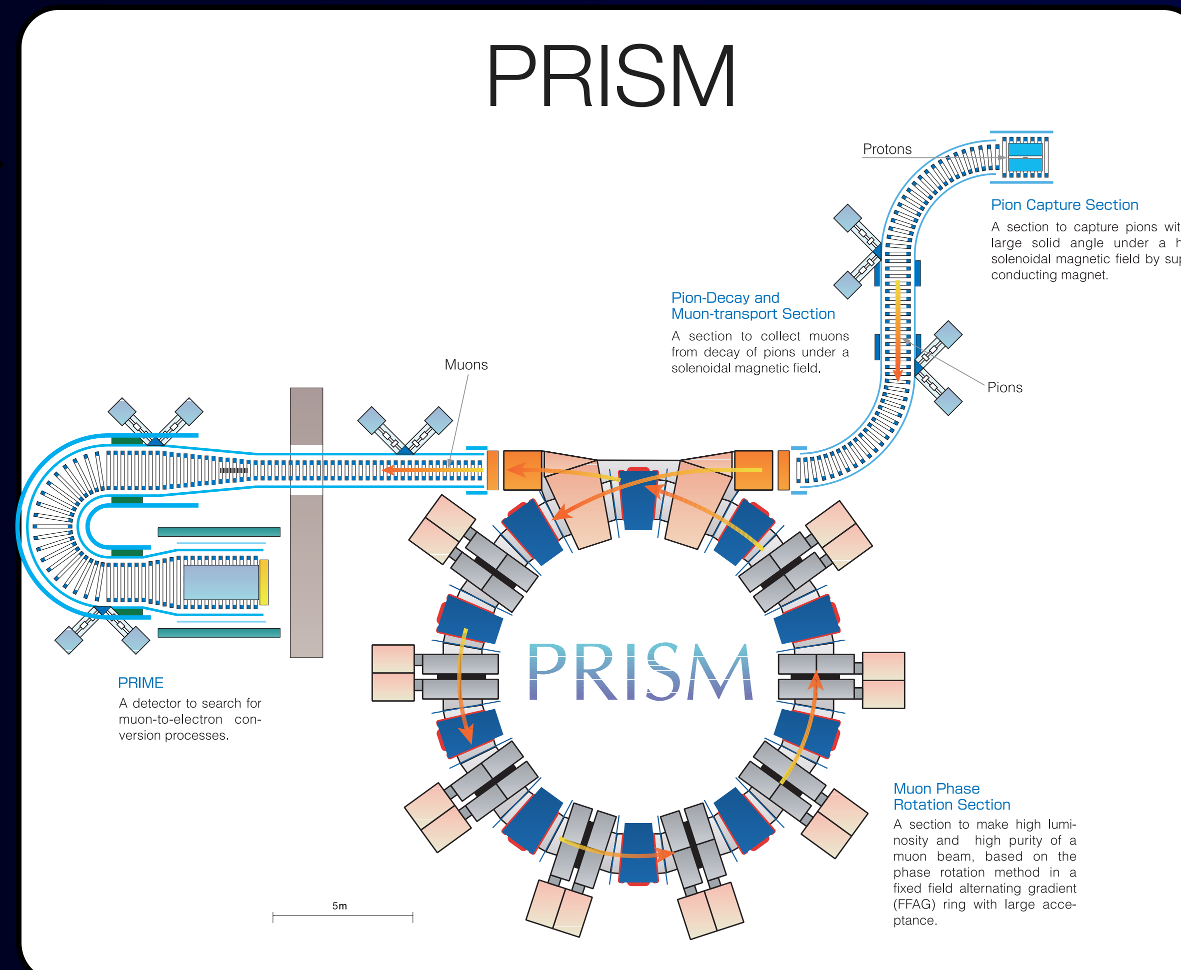
50 kW : 10^{11} muons/sec (for COMET)

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

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

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

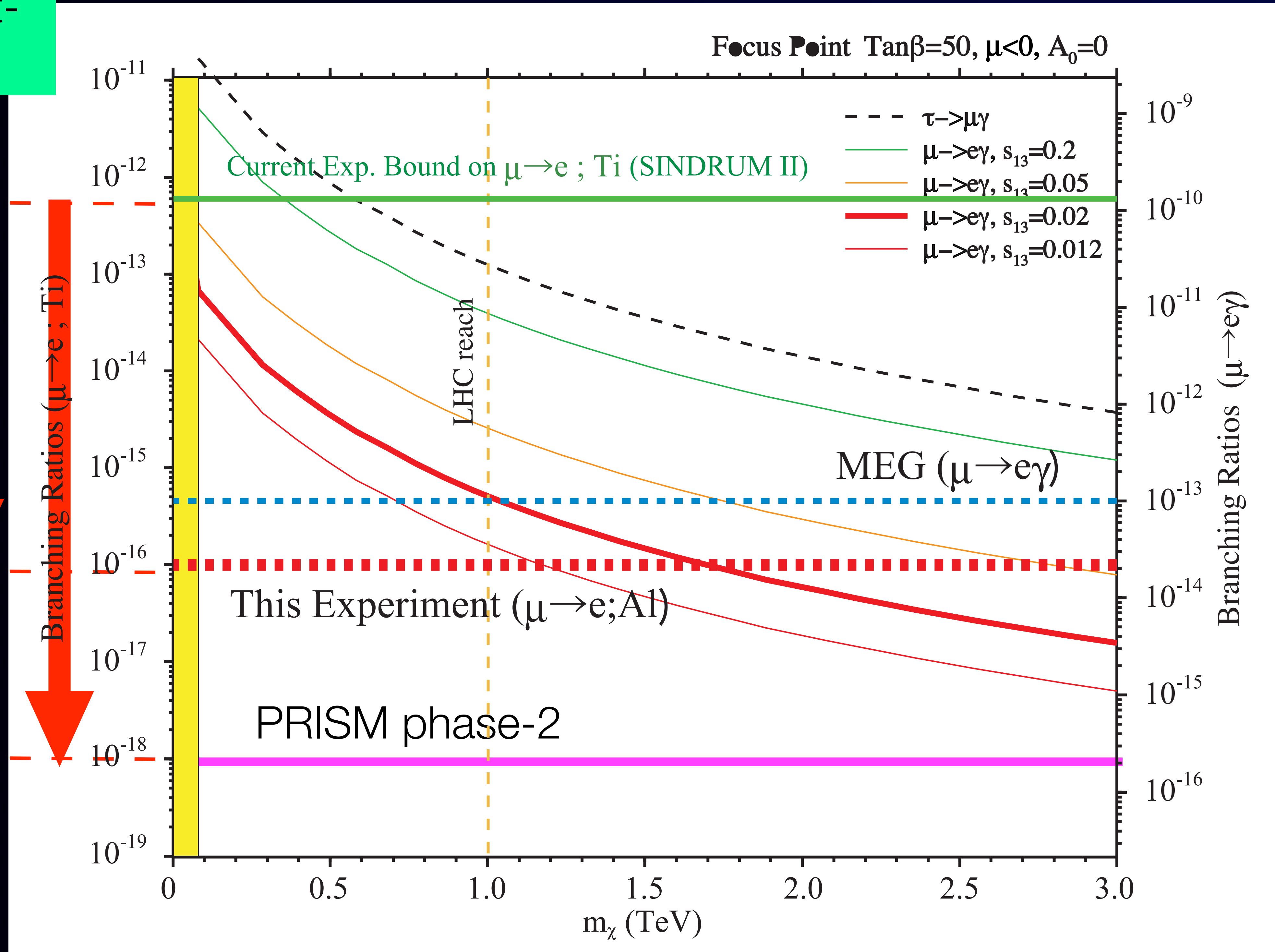
$$B(\mu^- + Ti \rightarrow e^- + Ti) < 10^{-18}$$

- 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

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

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

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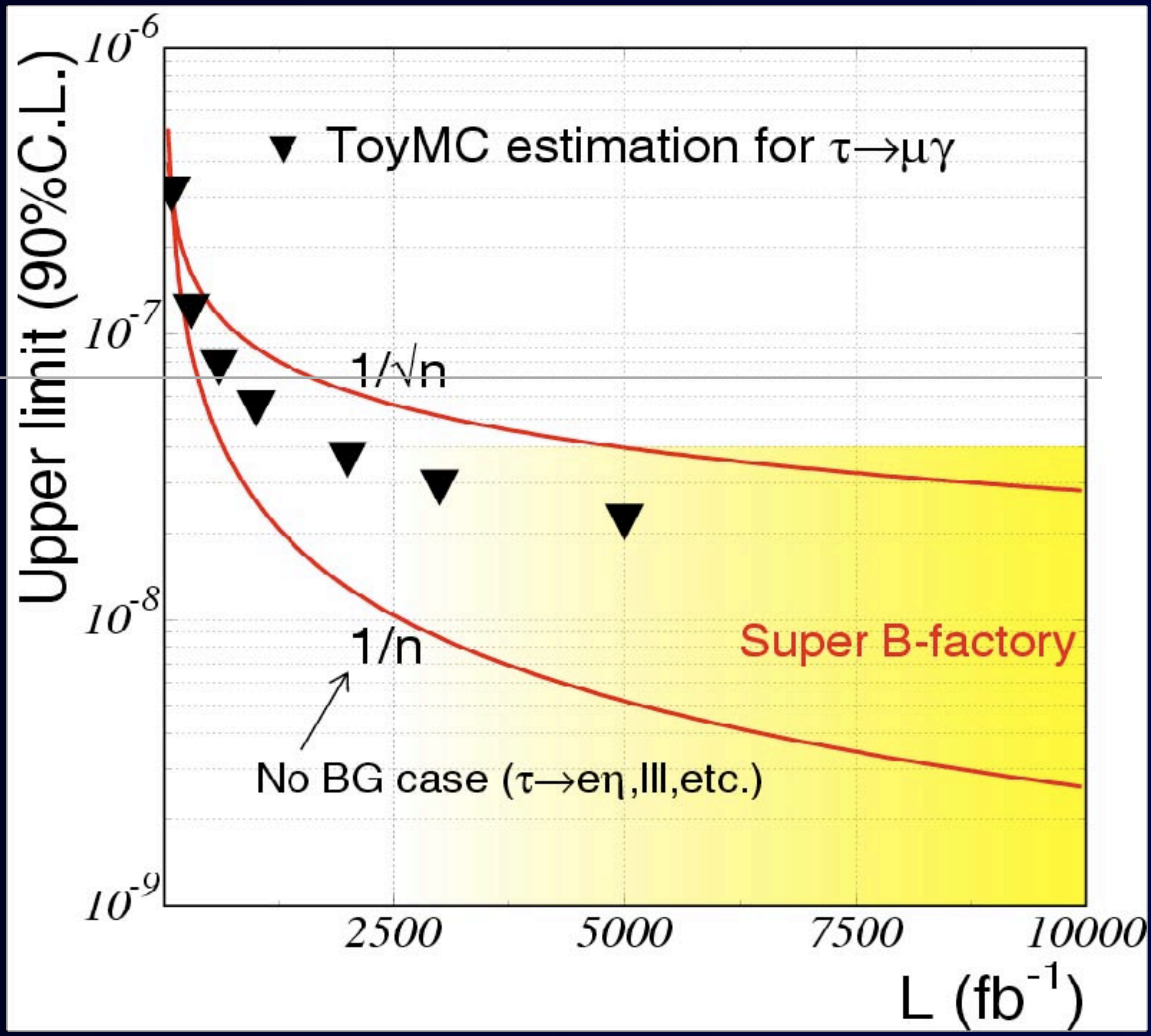
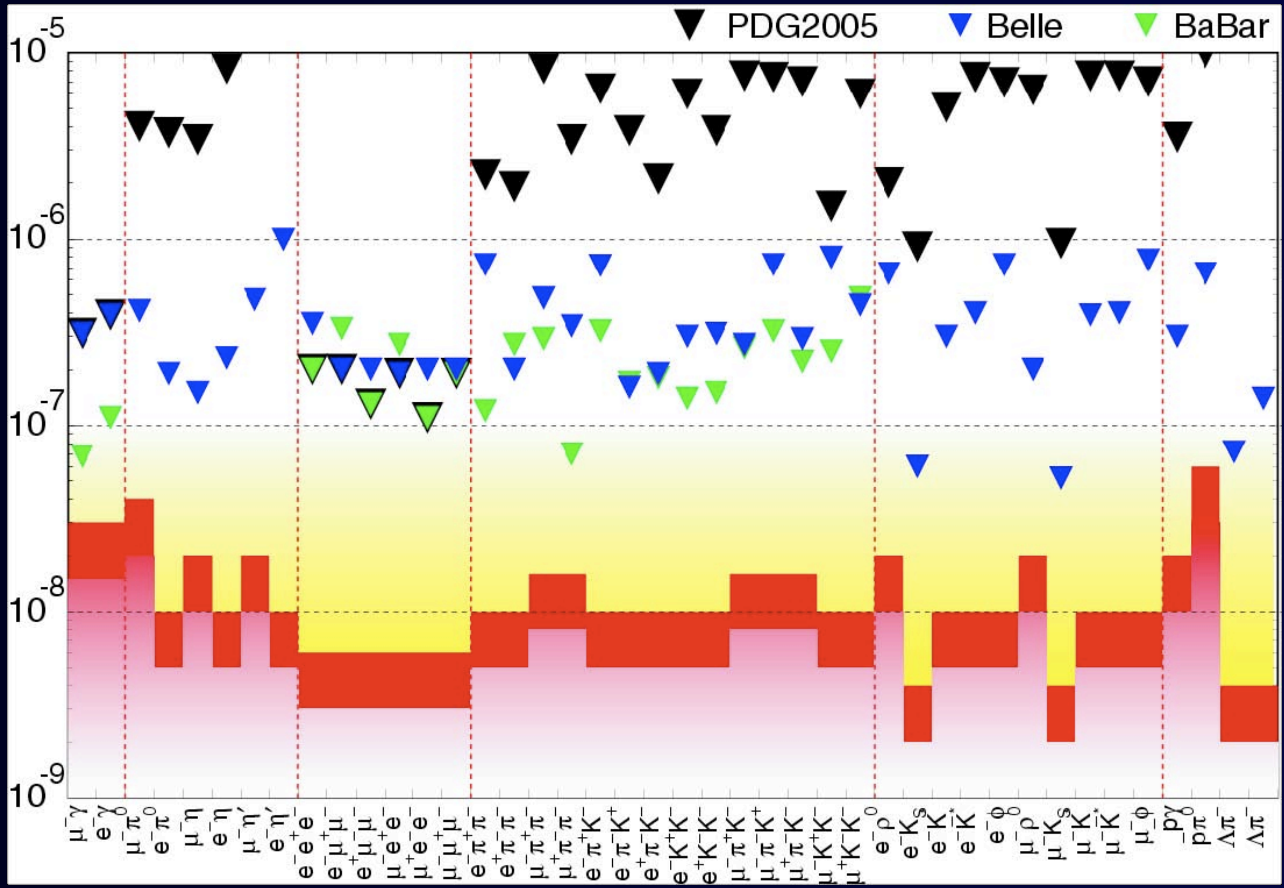
cLFV with Tau Leptons

CLFV with Taus at e^+e^- colliders

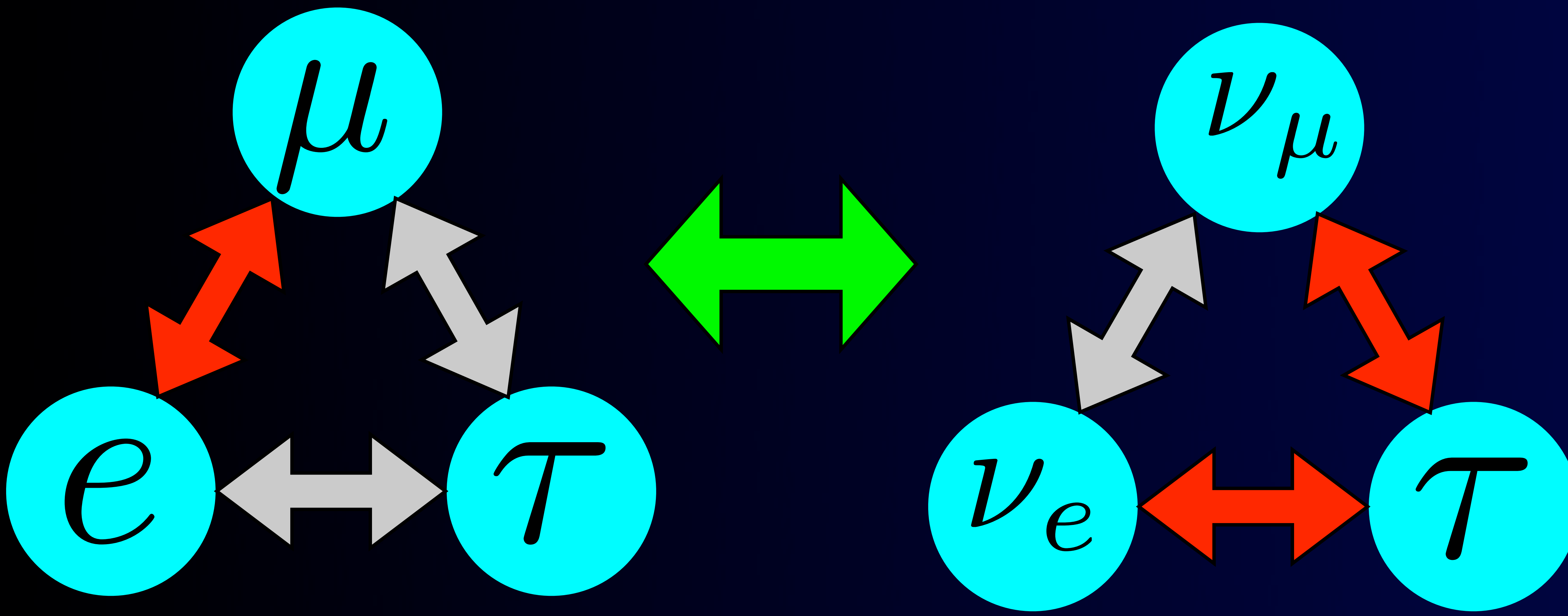
- B factories produce many taus of more than 10^8 in total (σ~0.9nb).
- $\tau \rightarrow l\gamma$ is background-limited, and improved by $1/\sqrt{N}$.
- Super B factories will produce a factor of 10-100 times taus.
- The red bands (in right plot) having sensitivities of 10^{-9} are expected with 5 -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





cLFV with Tau Leptons

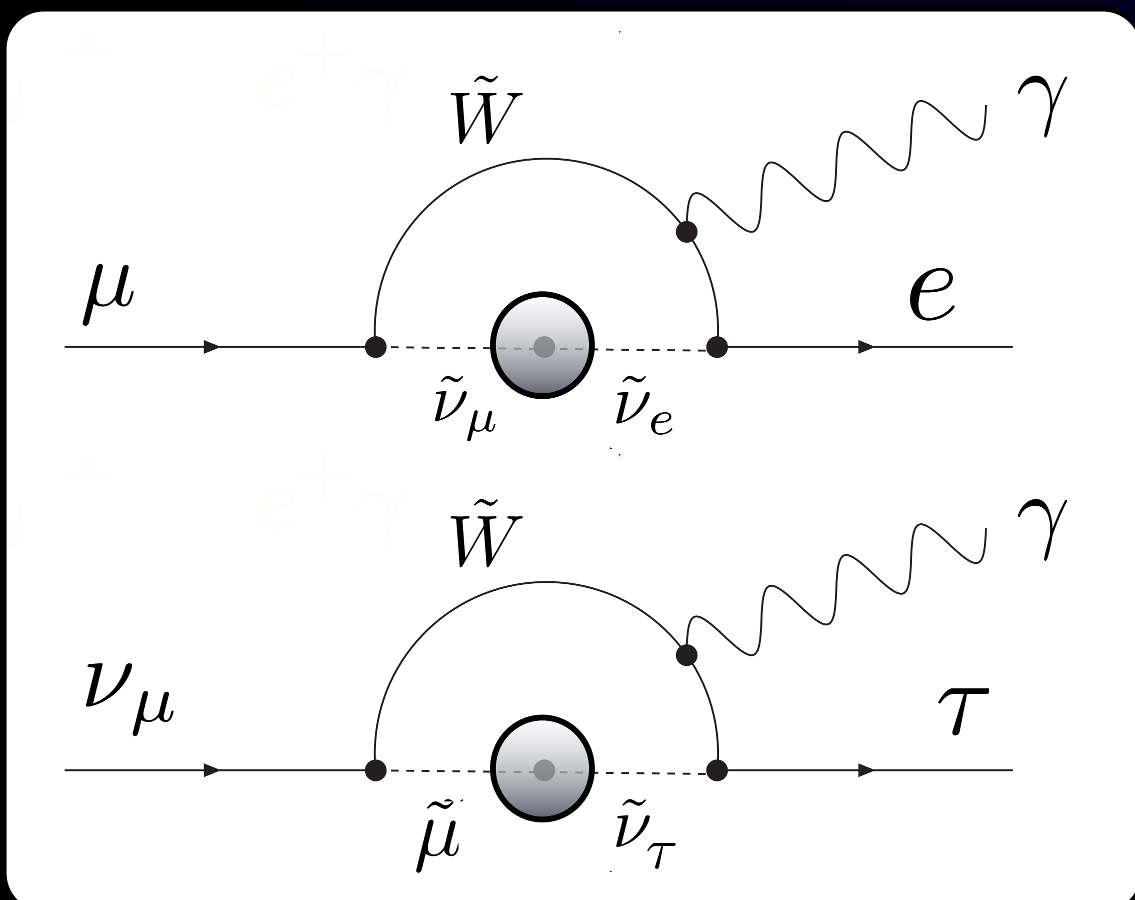
- How can we improve the limits between tau and muon (electron) ?
  - The Super B factory will aim at about 10-100 times luminosity.



If SU(2) symmetry in the weak doublet holds

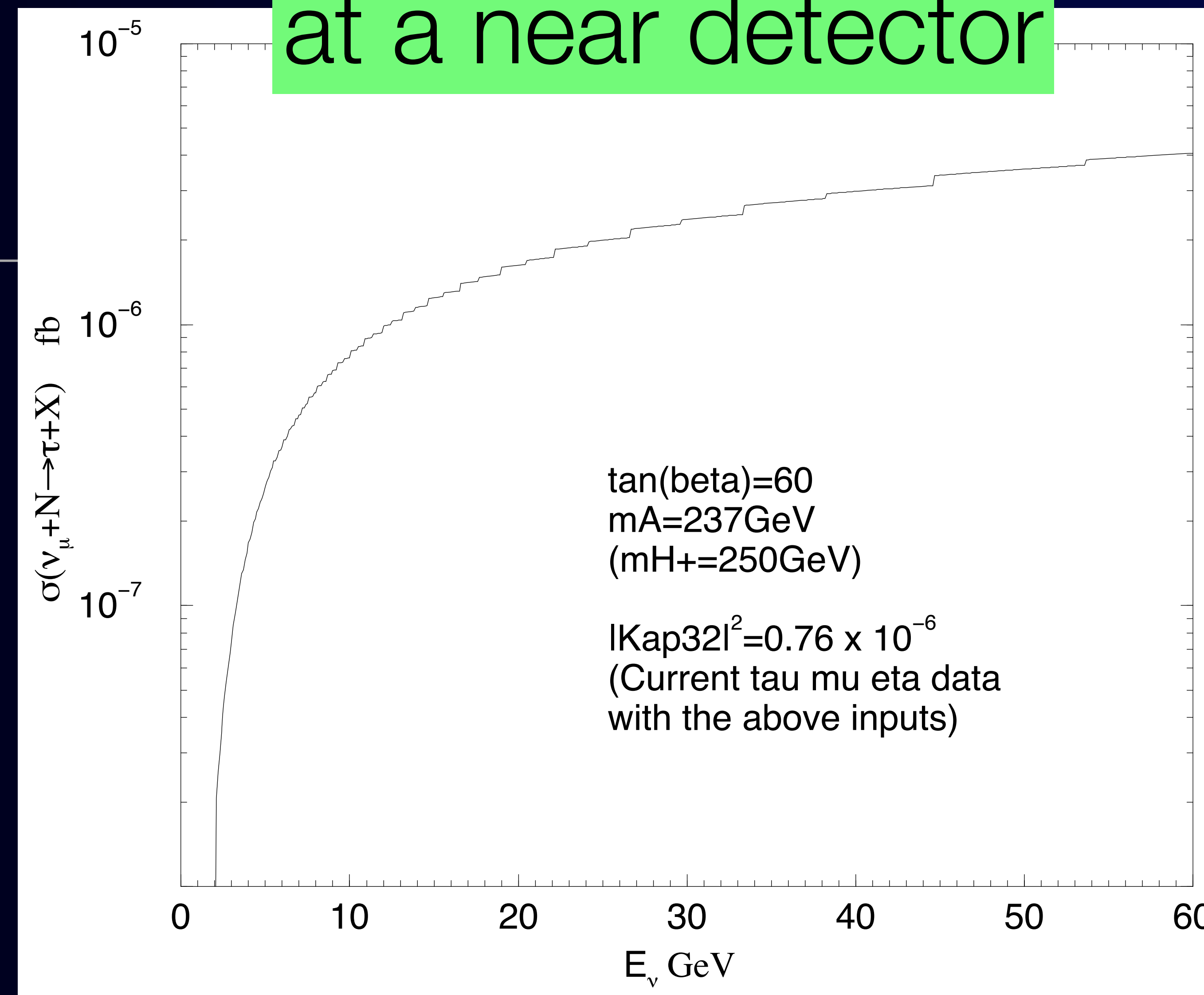
Neutrino-induced Charged LFV Current

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



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

at a near detector



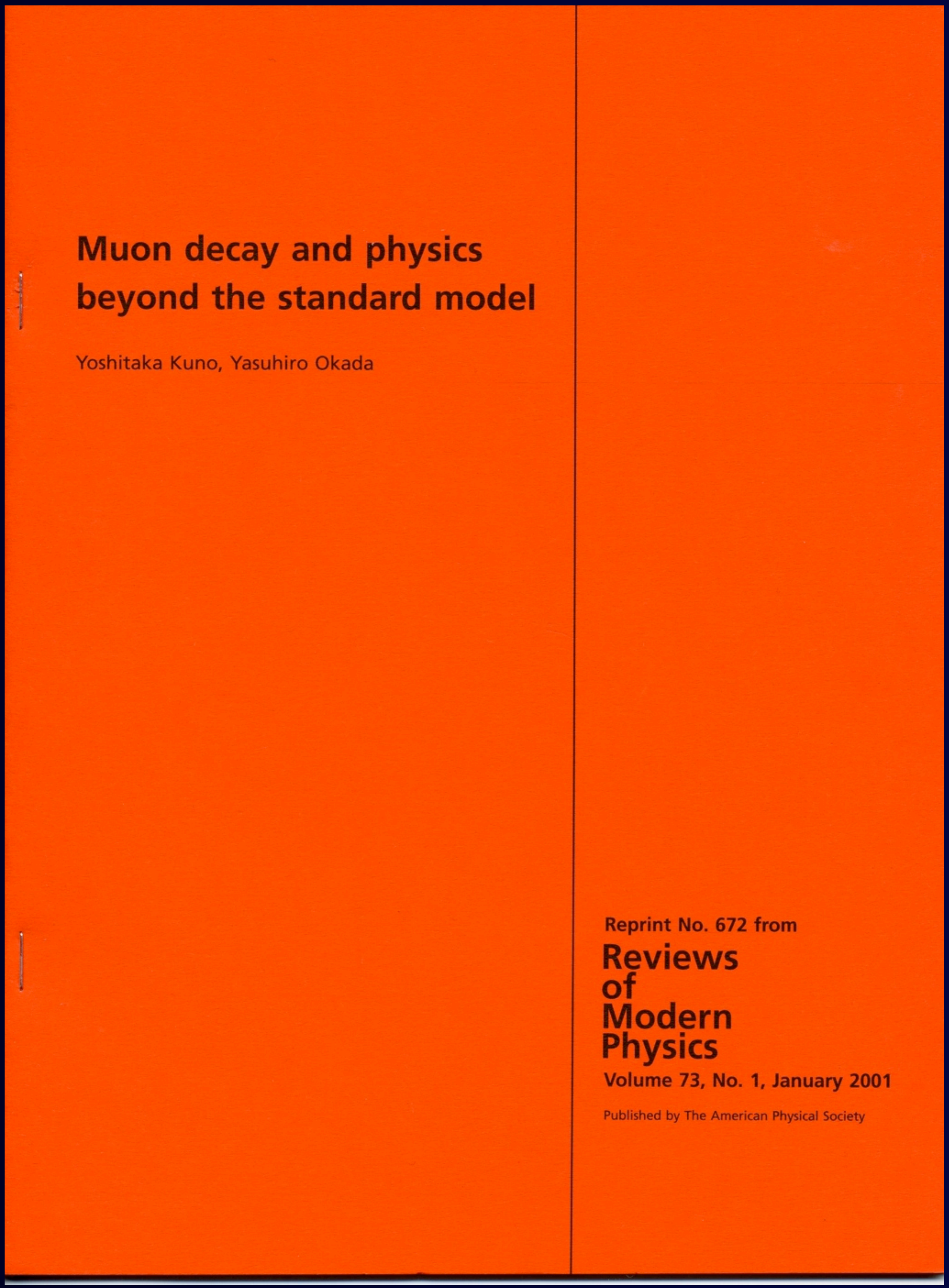
- The present upper limit is obtained by tau rare decays at B factories.
- When E_ν =30 GeV, the upper limit of the cross section is about 10^{-6} fb.
- 10^{20} νs/year at a neutrino factory, a 100 kg (1 ton) detector, 10^5 (10^6) events are expected.

For Further References

Muon decay and physics beyond the standard model

Yoshitaka Kuno and Yasuhiro Okada

Review of Modern Physics 73 (2001)



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