Future Prospect of Searches for Lepton Flavor Violation with Muons

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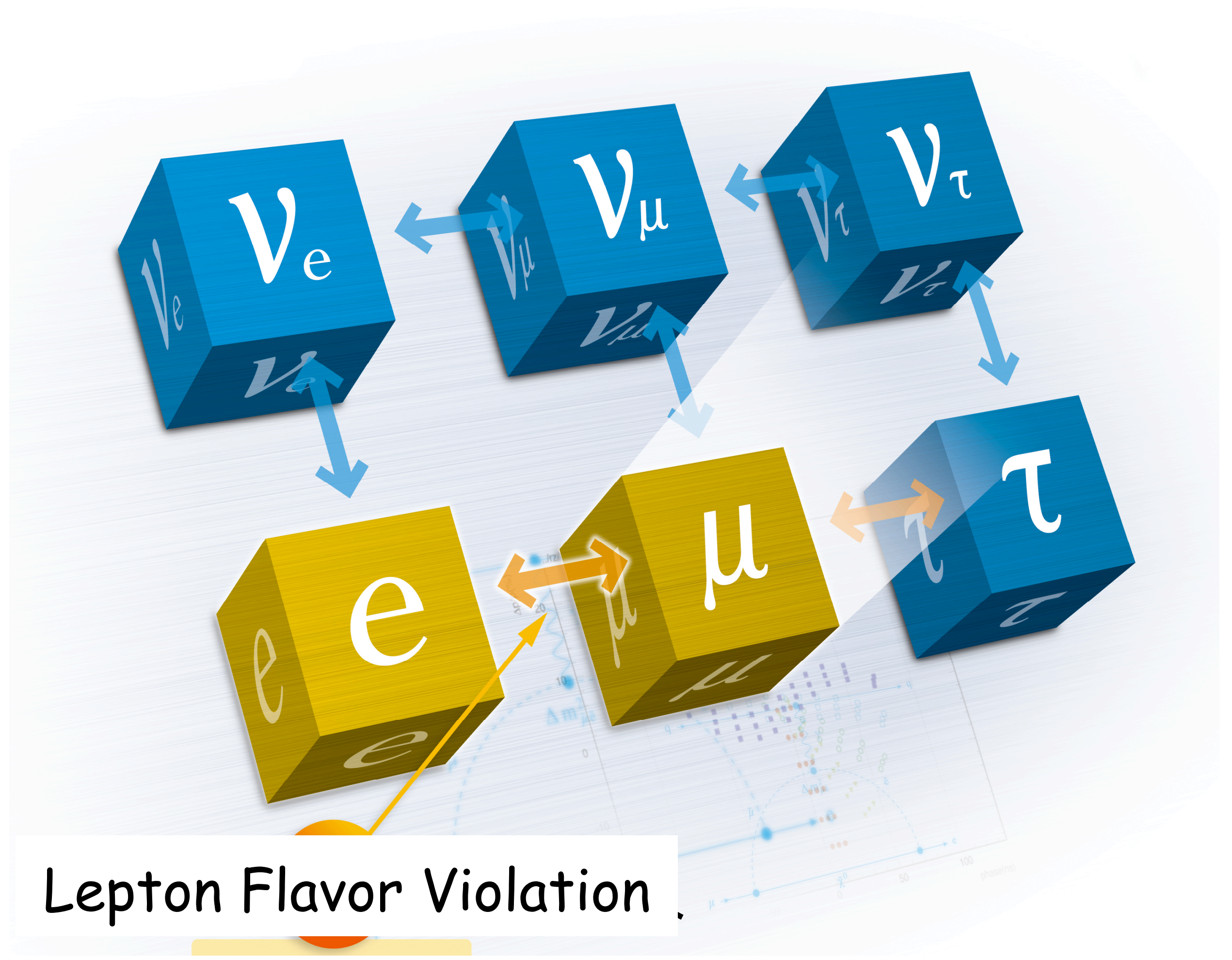
January 19th, 2007
"Precision Measurements at Low Energy" Workshop at PSI

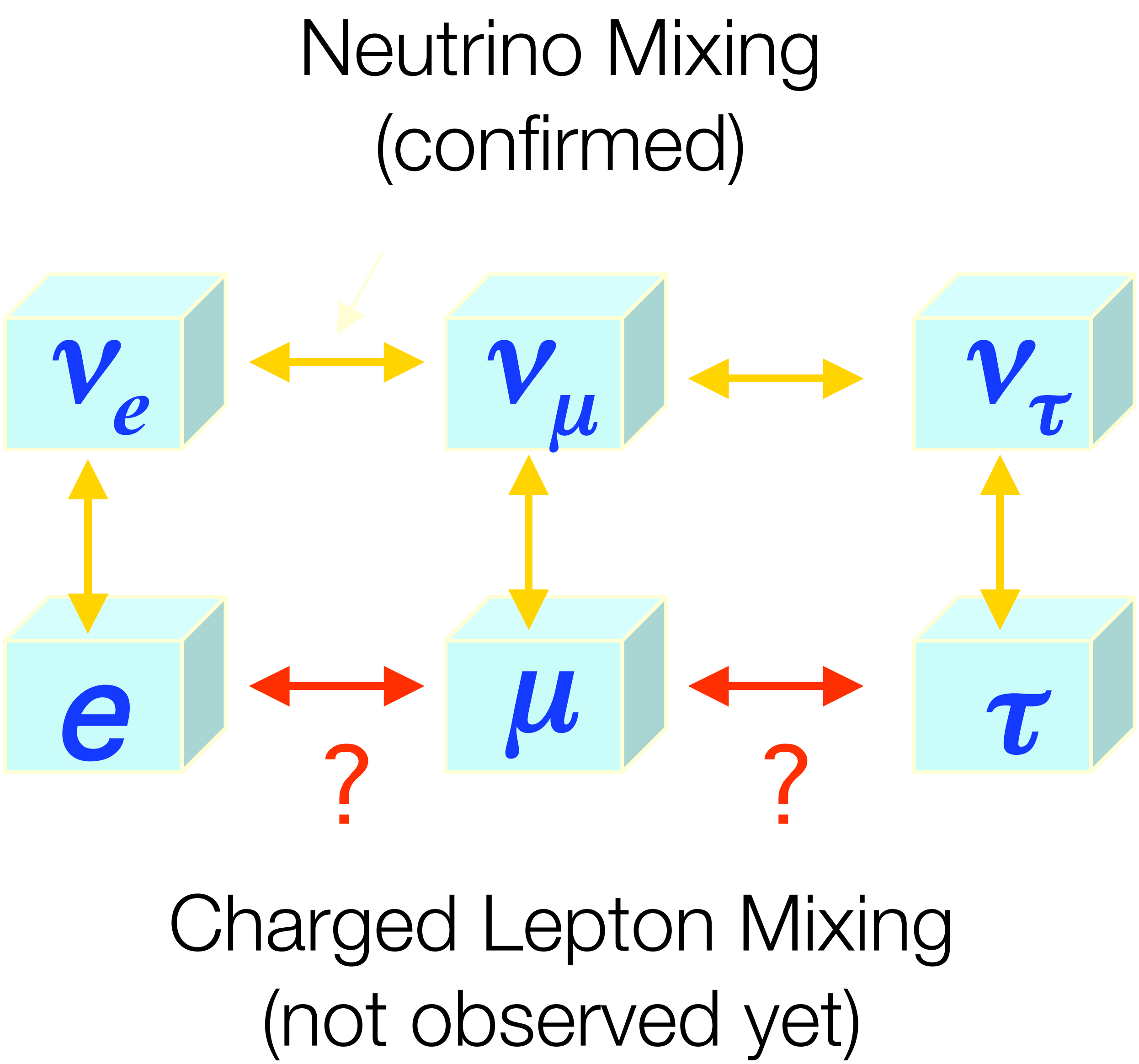


Outline

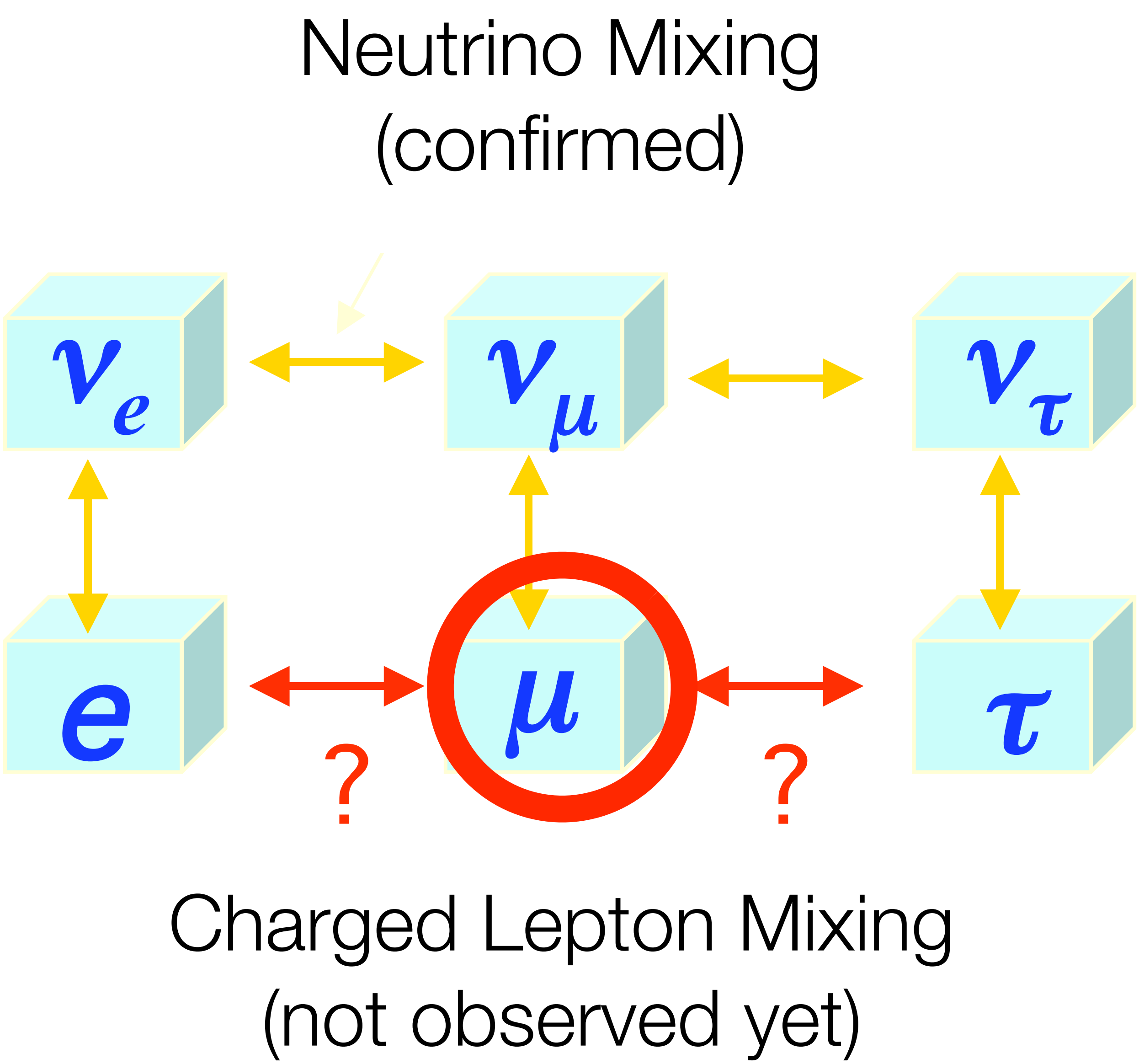
- Physics Motivation of Lepton Flavor Vioation (LFV)
- Phenomenology of LFV
- Comparison - Theoretical
- Comparison - Experimental
  - $\mu \to e\gamma$
  - $\mu \to eee$
  - μ - e conversion
- Roadmap
- at J-PARC
- at PSI
- Summary

Physics Motivation

Lepton Flavor Violation (LFV) of Charged Leptons - Charged Lepton Mixing

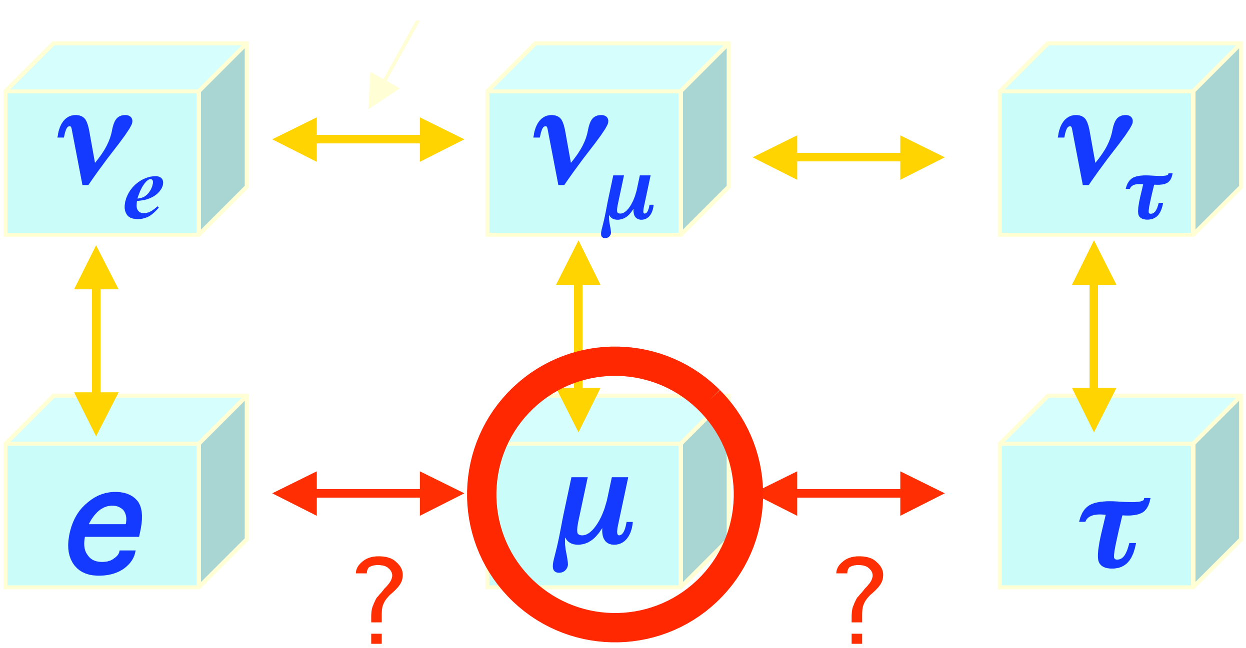


Lepton Flavor Violation (LFV) of Charged Leptons
- Charged Lepton Mixing



Lepton Flavor Violation (LFV) of Charged Leptons - Charged Lepton Mixing

Neutrino Mixing
(confirmed)

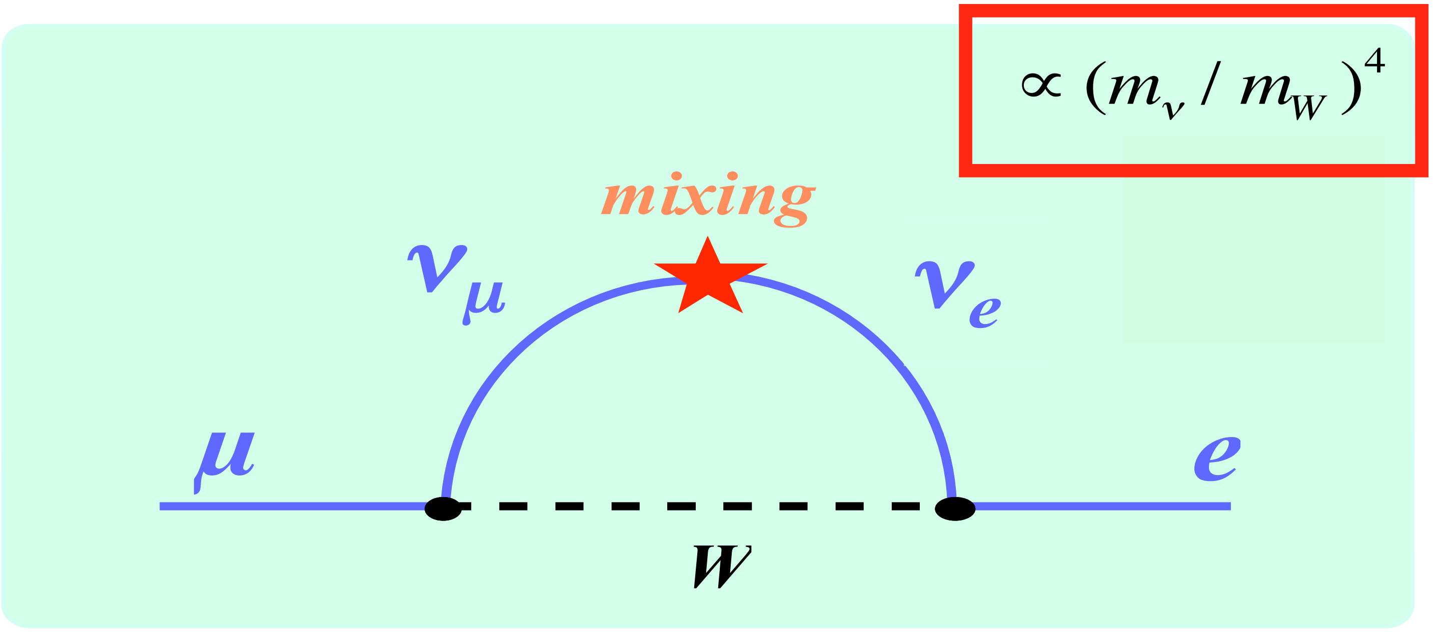


Charged Lepton Mixing
(not observed yet)

- Lepton flavor is exactly conserved in the Standard Model with massless neutrinos.
- Non-zero (although tiny!) neutrino masses are confirmed by the observation of neutrino oscillation, which indicates lepton flavor violation.
- Then, naively, one can ask what would happen for lepton flavor conservation for charged leptons, whether they are mixed (charged lepton mixing).

Contribution to Charged Lepton Mixing from Neutrino Mixing

- In the Standard Model with neutrino mixing, charged lepton mixing (flavor changing neutral current) can occur through loop diagrams.
- From the GIM mechanism, the diagrams are suppressed by $(m_\nu/m_W)^4$.
- It is about $O(10^{-54})$ and no chance to observe LFV in the Standard Model.
- LFV of charged leptons would have a large window to search for new physics beyond the Standard Model at high energy scale.



very small (10^{-54})

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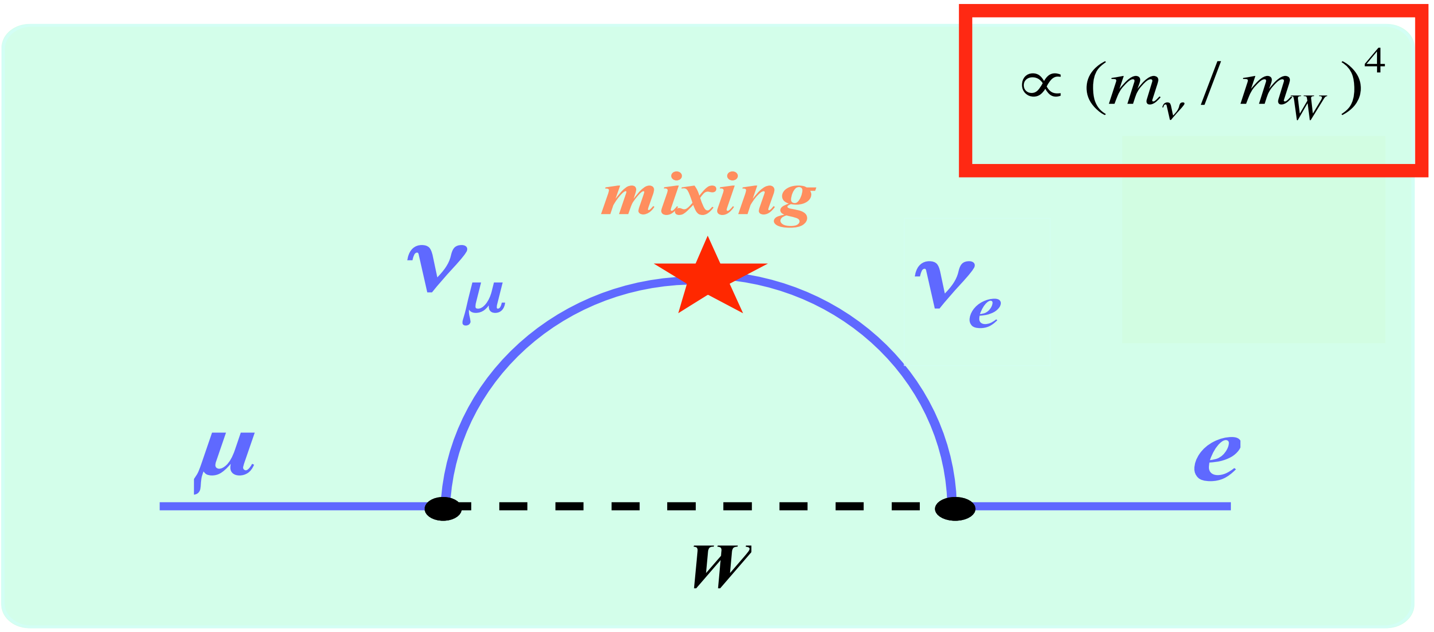
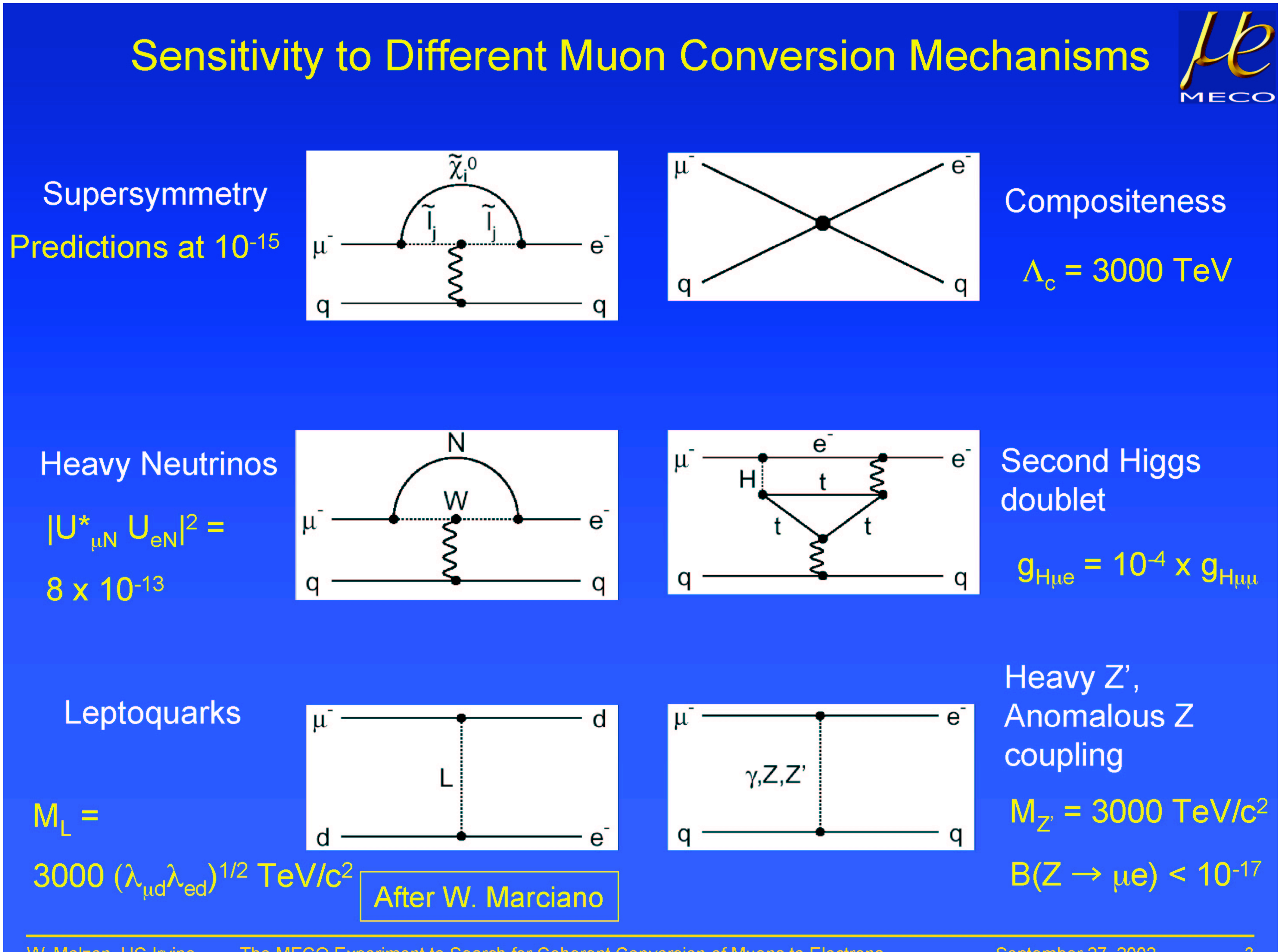


very small (10^{-54})

Sensitive to new Physics beyond the Standard Neutrino Oscillation Physics

Various Models Predict Charged Lepton Mixing.



Charged Lepton Mixing in SUSY (mSUGRA)

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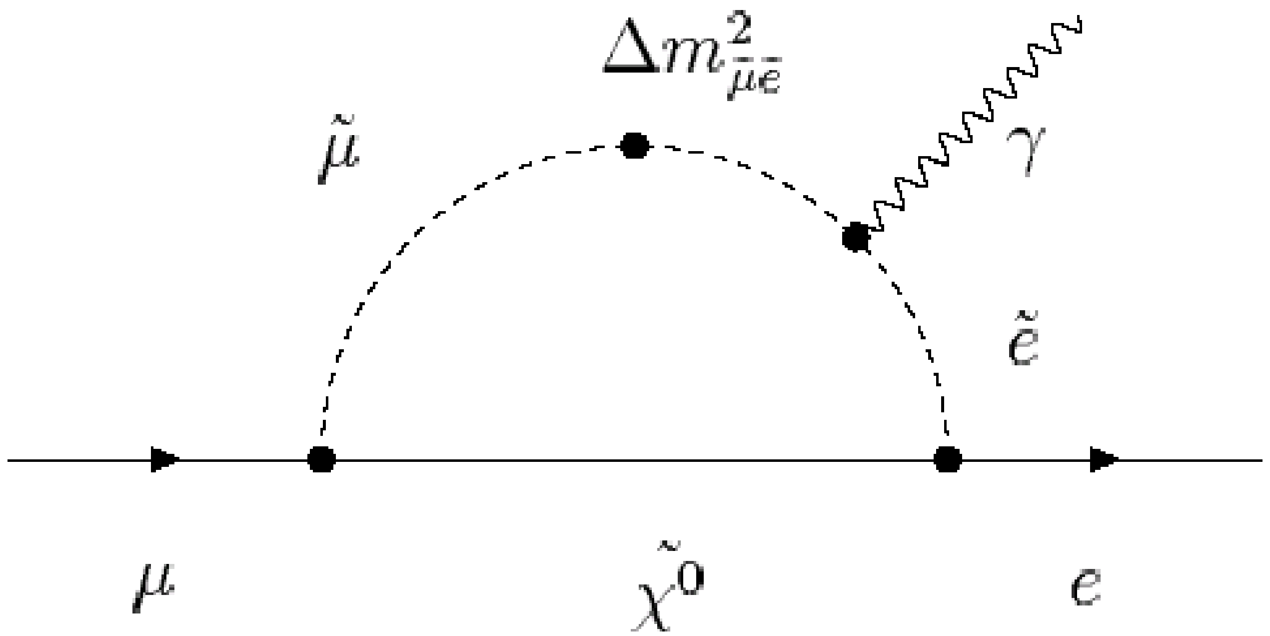
$$\mu^+ \rightarrow e^+\gamma$$



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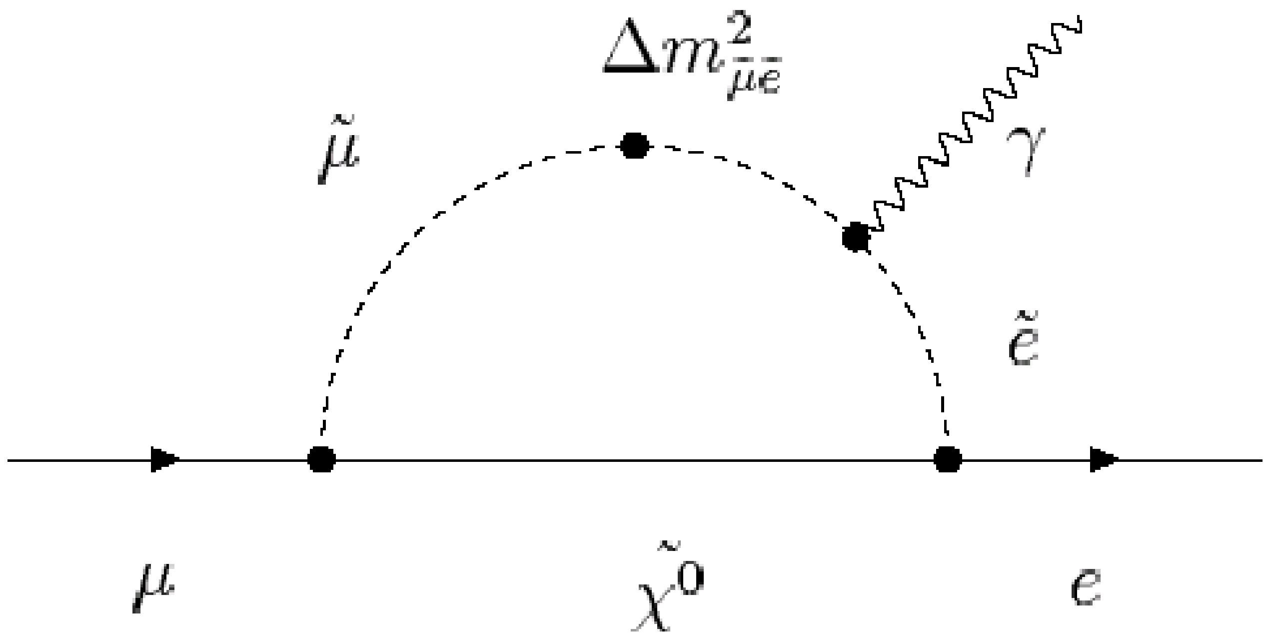
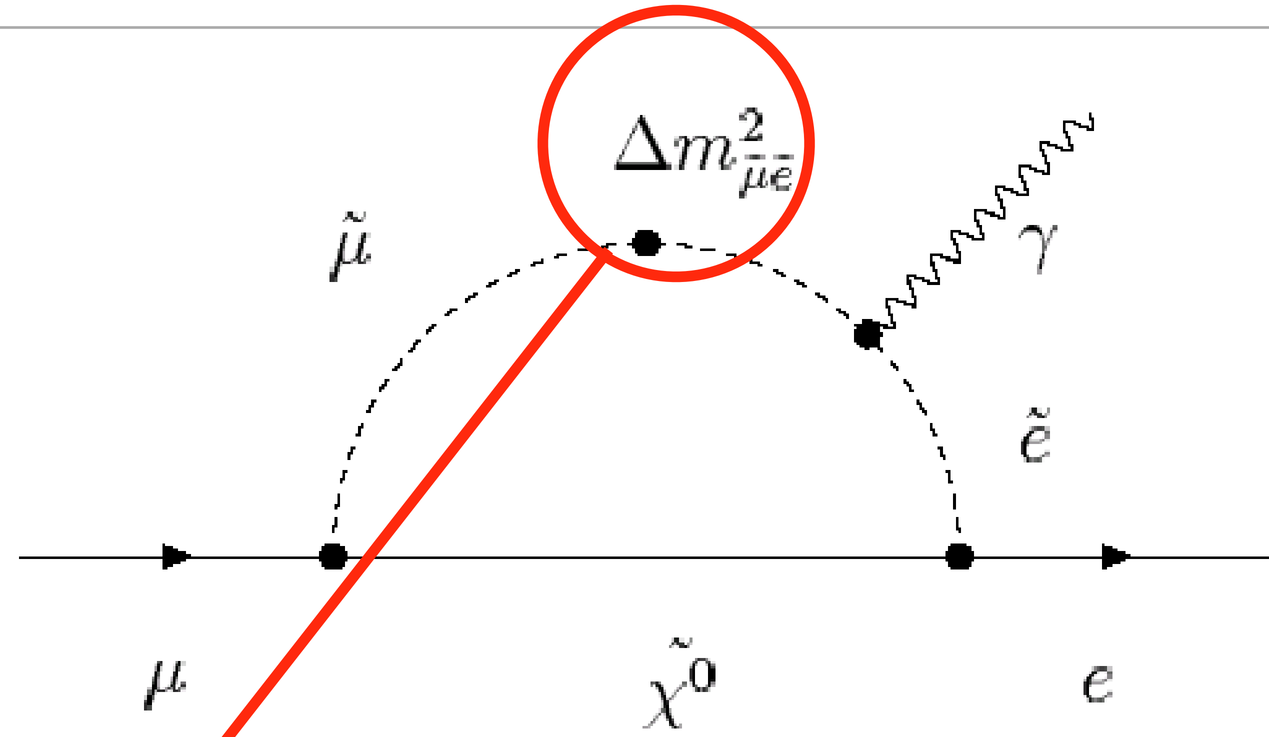


$$m^2_{\tilde{l}} = \begin{pmatrix} m^2_{11} m^2_{12} m^2_{13} \\ m^2_{21} m^2_{22} m^2_{23} \\ m^2_{31} m^2_{32} m^2_{33} \end{pmatrix}$$

In SUSY, LFV processes are induced by the off-diagonal terms in the slepton mass matrix. In MSSM, no off-diagonal terms exist @Planck, and need other mechanisms.

Charged Lepton Mixing in SUSY (mSUGRA)

$$\mu^+ \to e^+\gamma$$



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From Planck Scale to Weak

In the mSUGRA frame work

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

@ M_planck

SUSY-GUT

GUT Yukawa interaction

SUSY Seesaw Model

Neutrino Yukawa interaction

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

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

CKM matrix

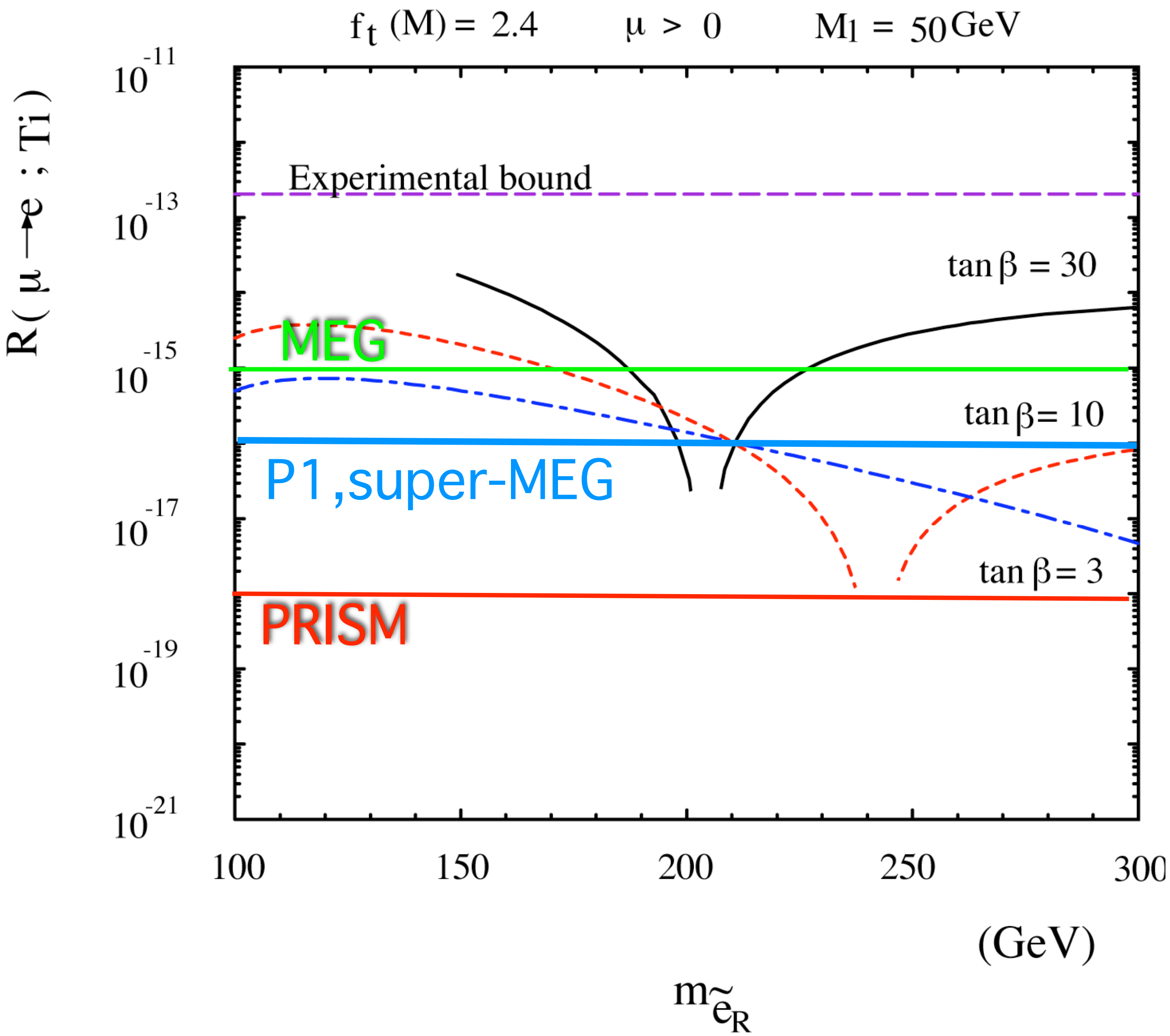
$$(m^2_{\tilde{L}})_{21} \sim \frac{3m_0^2 + A_0^2}{8\pi^2} h_t^2 U_{31} U_{32} \ln \frac{M_{GUT}}{M_{R_s}}$$

Neutrino oscillation

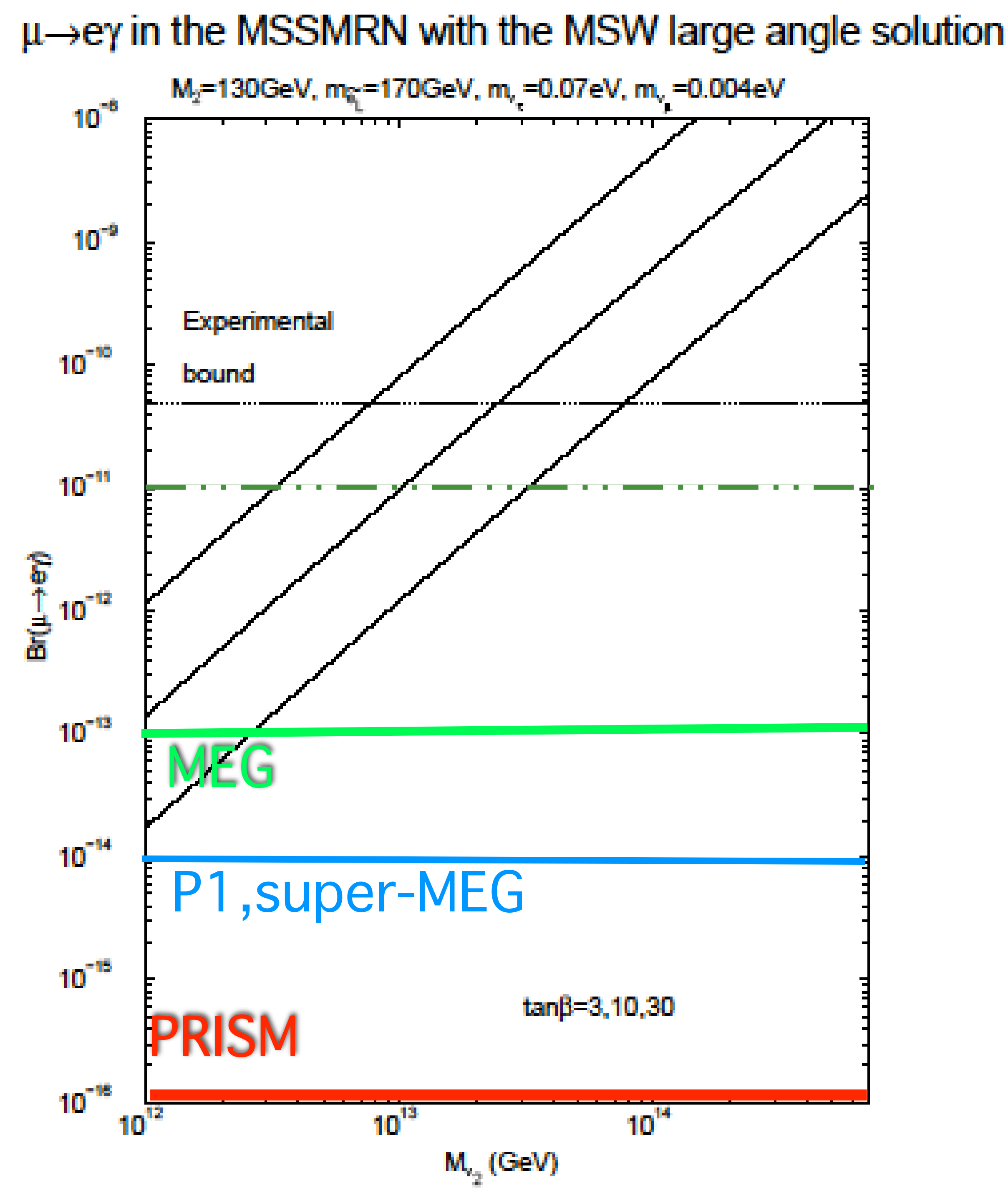
From Planck Scale to Weak

In the mSUGRA frame work

SUSY Predictions for LFV with Muons



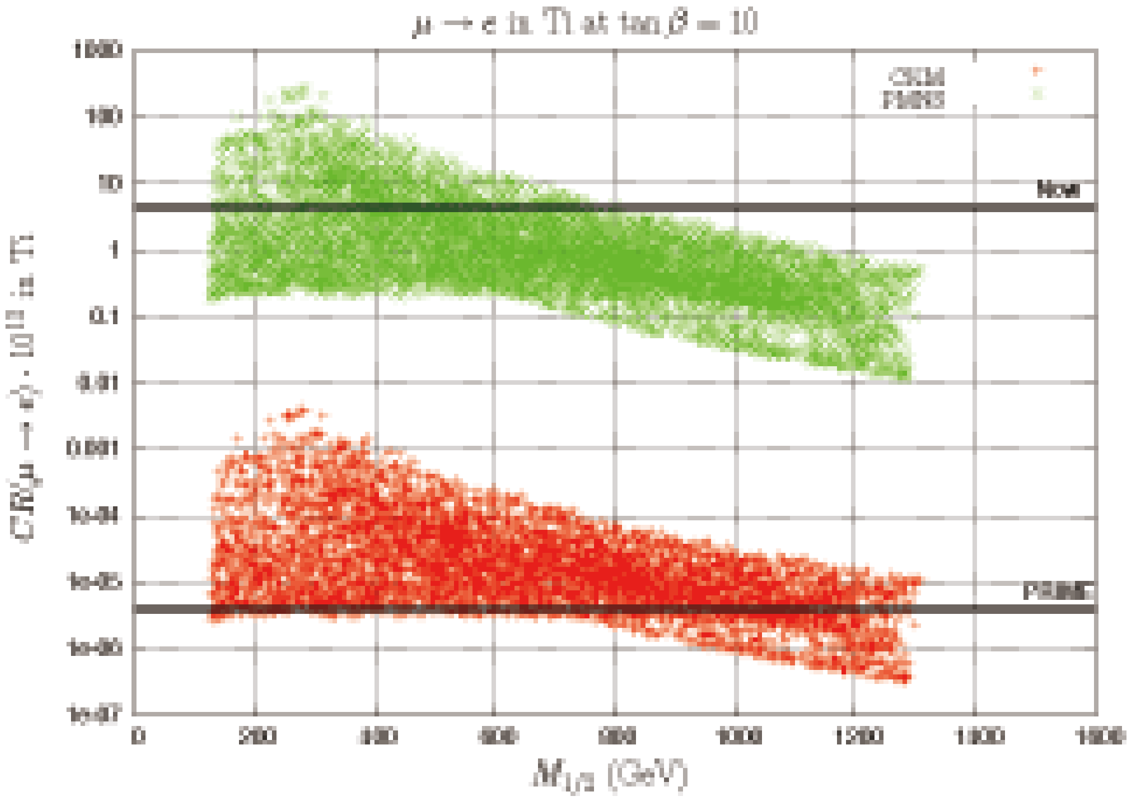
SU(5) SUSY GUT



SUSY Seesaw Model

SUSY-Seesaw Predictions for μ-e Conversion

low tanβ

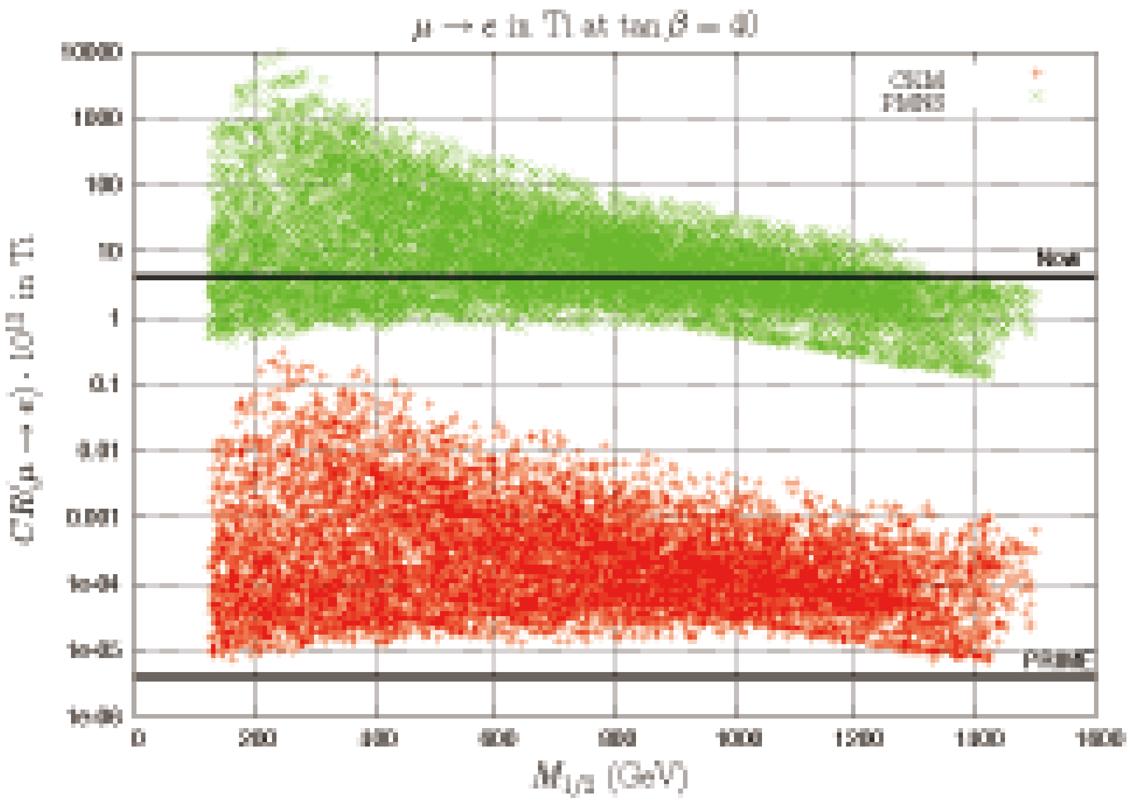


10^{-12}

10^{-18}

A. Masiero et al.

high tanβ



10^{-12}

10^{-18}

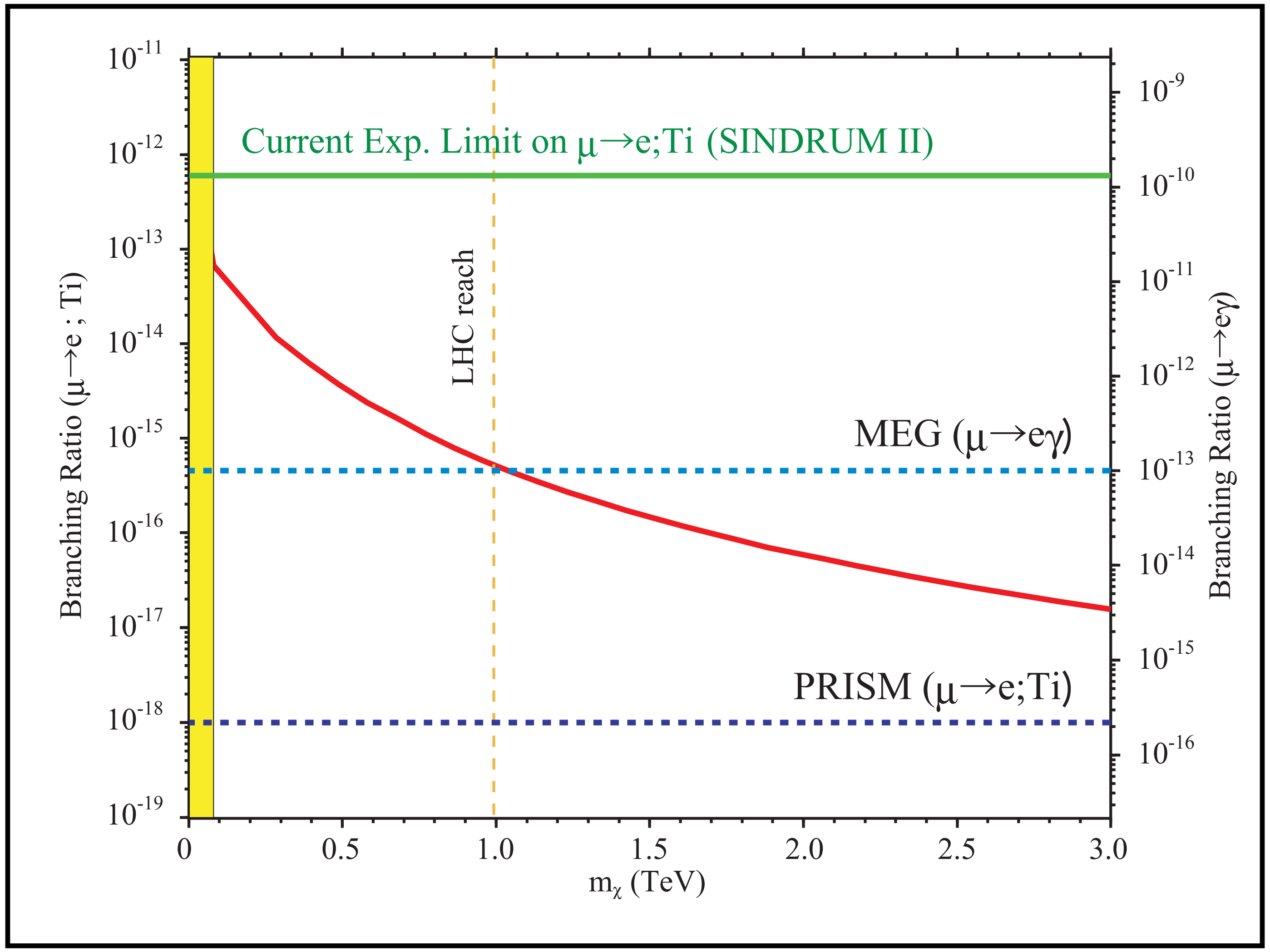
Energy Frontier and LFV

If LHC finds SUSY

LFV search would become important, since the slepton mixing matrix should be studied.
- SUSY-GUT
- SUSY Seesaw models.

If LHC not find SUSY

LFV search would become more important, since

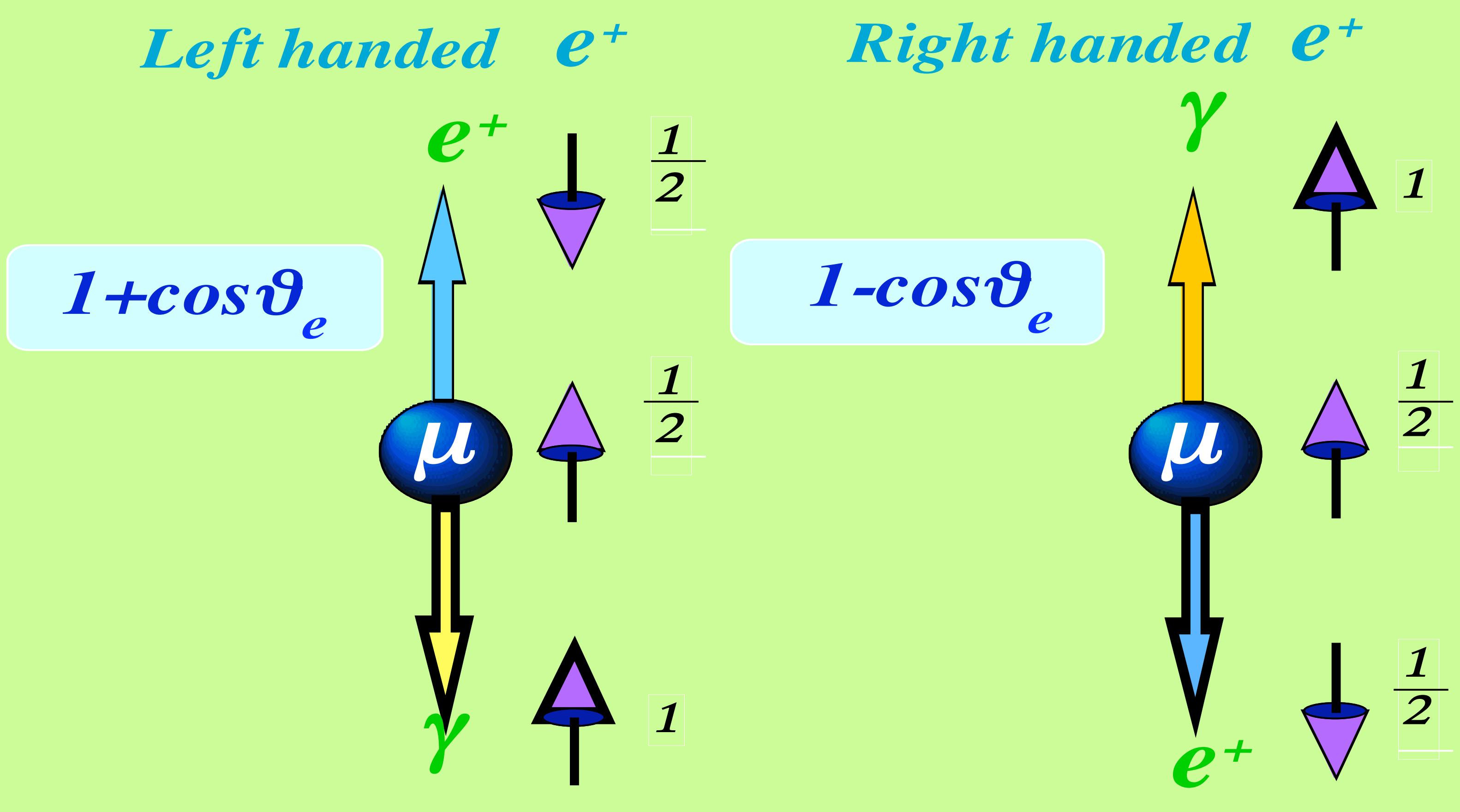


from A.Masiero et al.

Energy Frontier, SUSY, and Charged Lepton Mixing

- In SUSY models, charged lepton mixing is sensitive to slepton mixing.
- LHC would have potentials to see SUSY particles, however, at LHC nor even ILC, slepton mixing would be hard to study in such a high precision as proposed here.
- Slepton mixing is sensitive to either (or both) Grand Unified Theories (SUSY-GUT models) or neutrino seesaw mechanism (SUSY-Seesaw models).

P-Odd Angular Distribution of Polarized $\mu \to e\gamma$ Decay (after its observation)



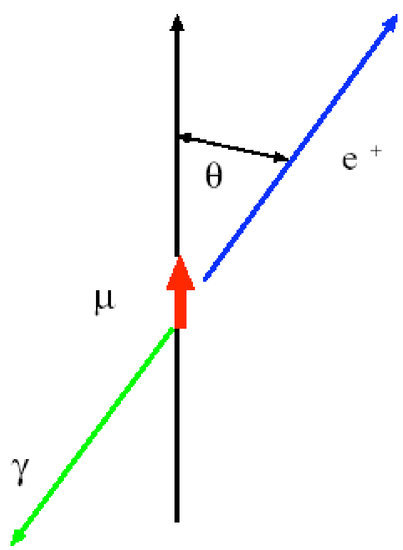
useful to distinguish different theoretical models

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

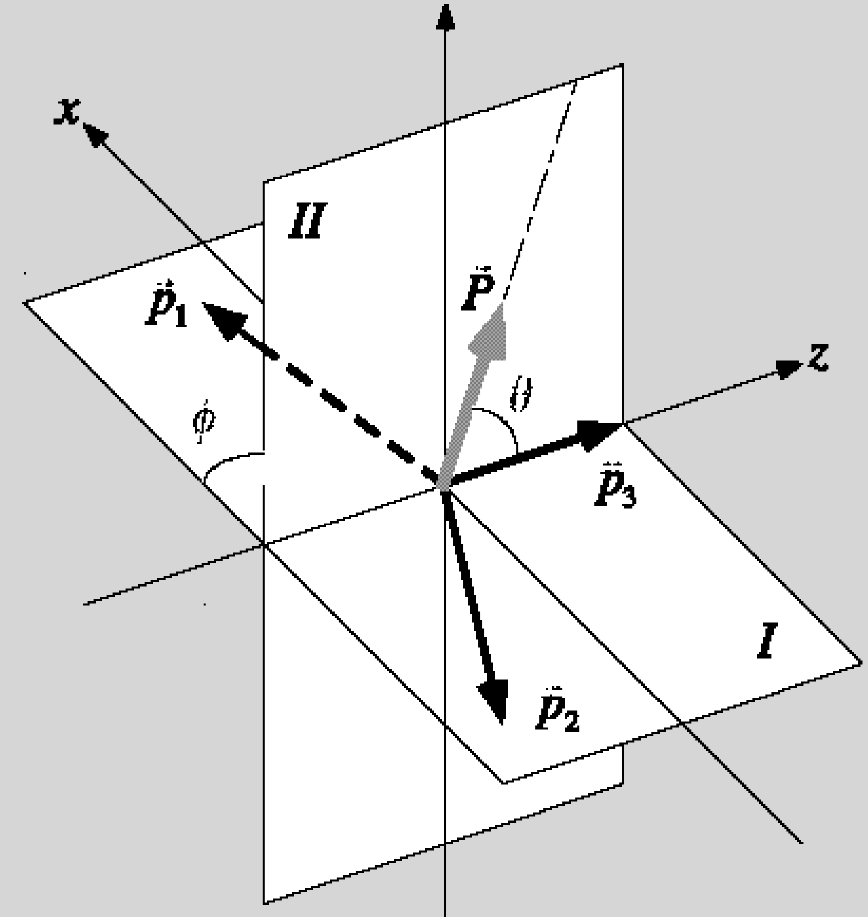


P-odd asymmetry reflects whether right or left-handed slepton have flavor mixing,

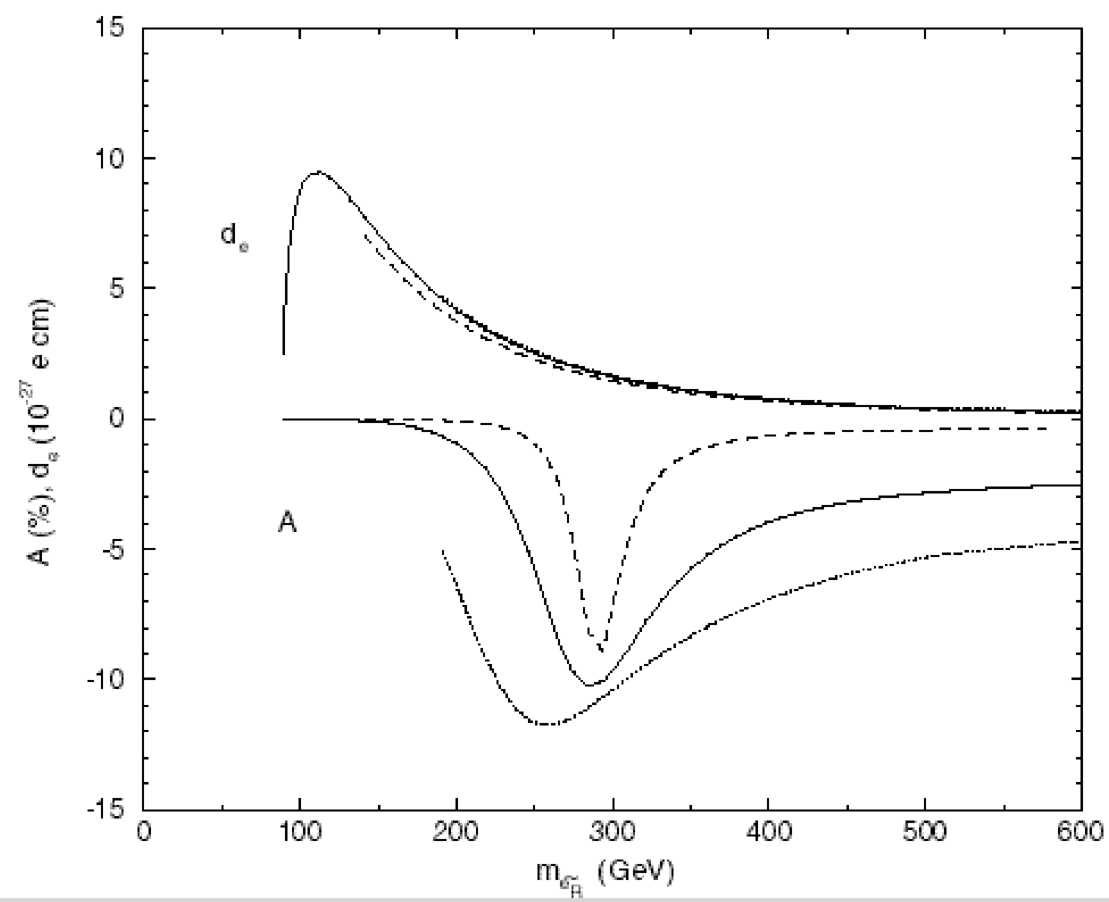
Discriminate theoretical models

T-odd Correlation in $\mu^+ \rightarrow e^+ e^+ e^-$

- In SUSY, T-odd (or CP-odd) in LFV processes and the muon EDM are interested in terms of the Majorana phase of the heavy right-handed neutrinos (model dependent).
- T-odd correlation can be studied, where the correlation can be formed by the muon spin and the two positron momenta.



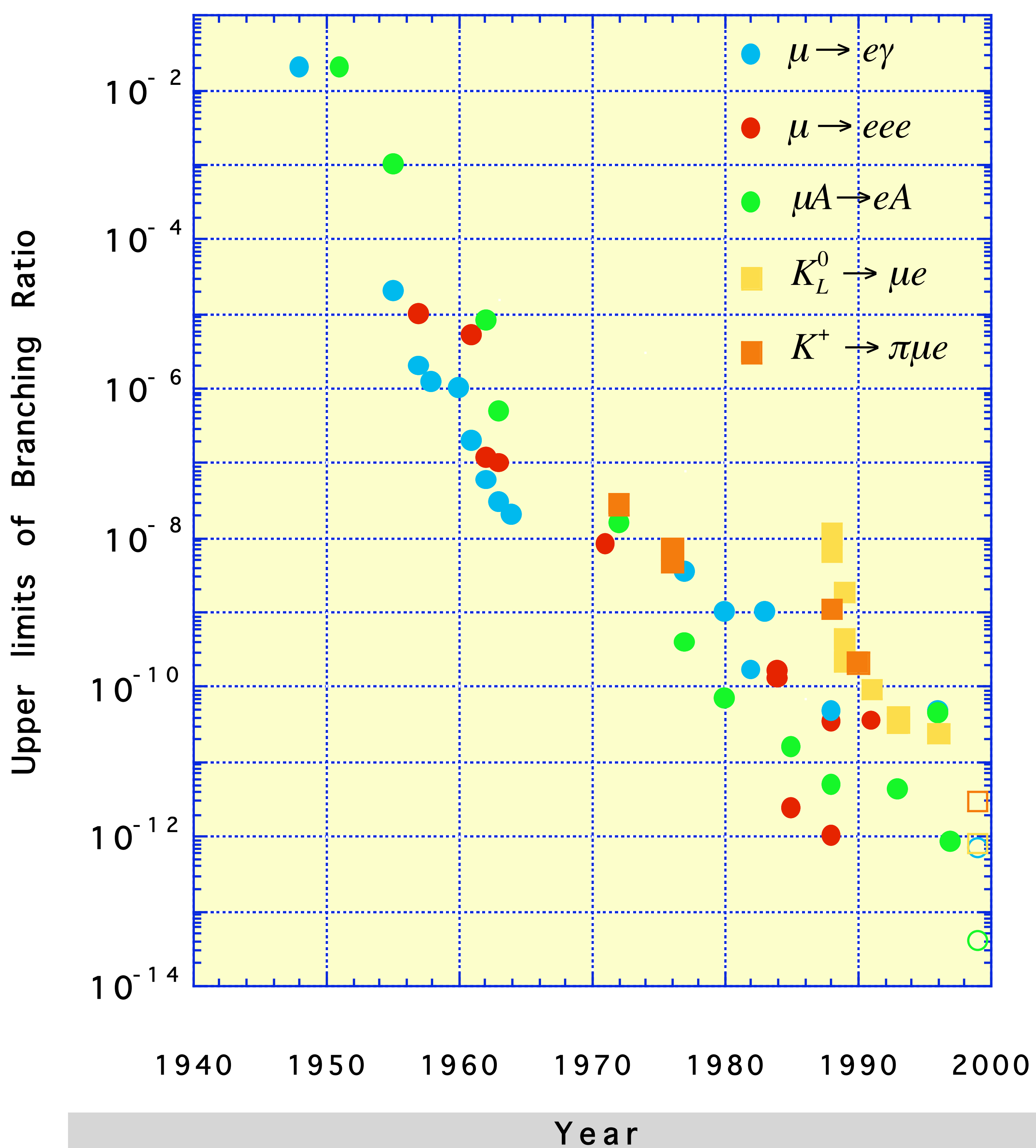
$$\vec{s}_\mu \cdot (\vec{p}_1 \times \vec{p}_2)$$



Phenomenology

Searches in the Past

- No lepton flavor violation in the Standard Model.
- No lepton flavor violation in the charged lepton sector has been observed, although it in the neutrino sector has been observed.
- Upper limit improved by two orders of magnitude

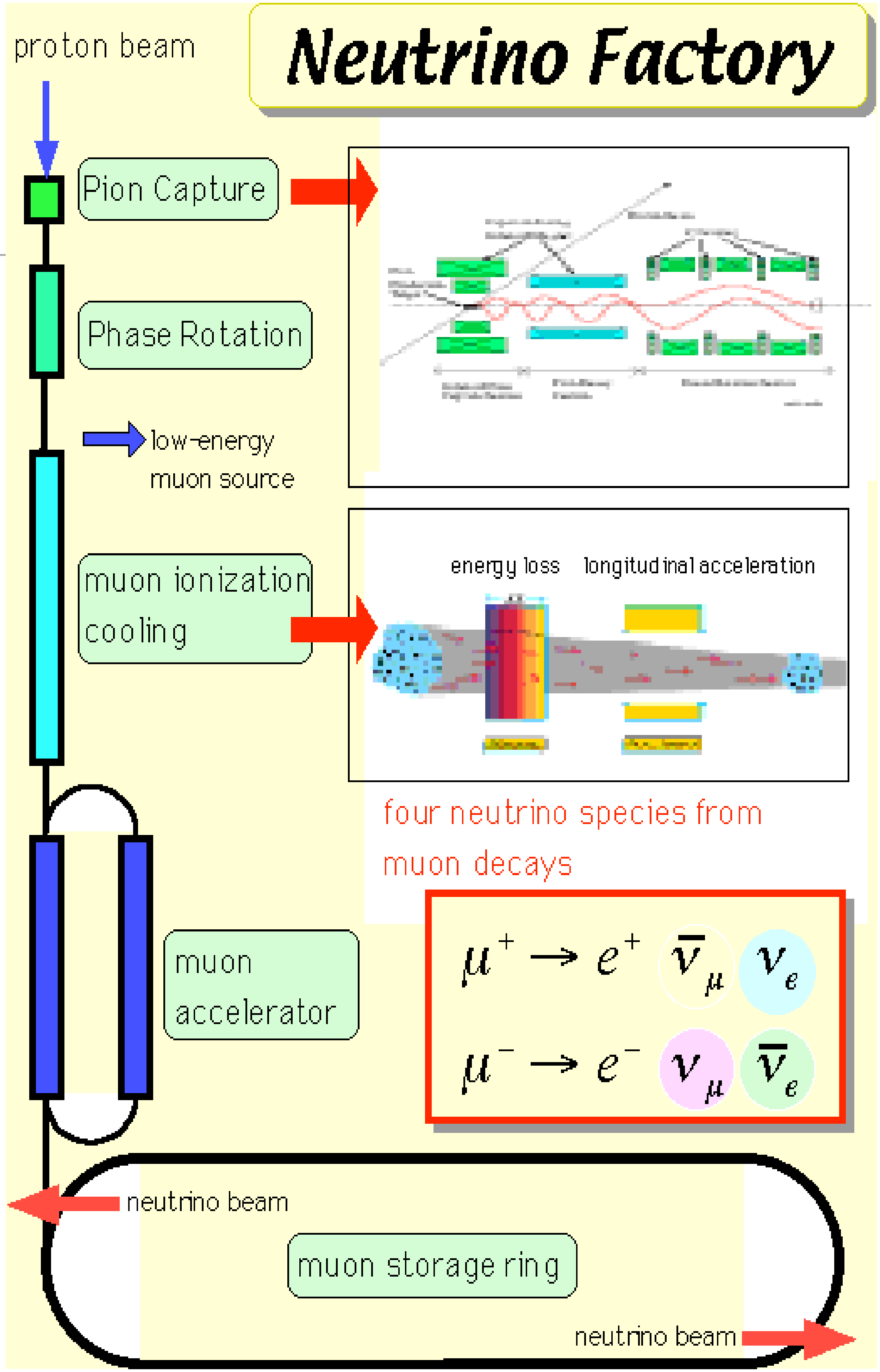


Present Limits and Expected Sensitivities of LFV Processes

process	Present limit	Future sensitivity
$\mu \to e\gamma$	1.2×10^{-11}	10^{-13} (MEG)
$\mu \to eee$	1.0×10^{-12}	10^{-13} - 10^{-14}
$\mu N \to eN$ *(in Tl)*	4.3×10^{-12}	10^{-18} (PRISM)
$\mu N \to eN$ *(in Al)*	none	10^{-16} (P1@J-PARC)
$\tau \to e\gamma$	1.1×10^{-7}	10^{-8} - 10^{-9}
$\tau \to eee$	2.7×10^{-7}	10^{-8} - 10^{-9}
$\tau \to \mu\gamma$	6.8×10^{-8}	10^{-8} - 10^{-9}
$\tau \to \mu\mu\mu$	2×10^{-7}	10^{-8} - 10^{-9}

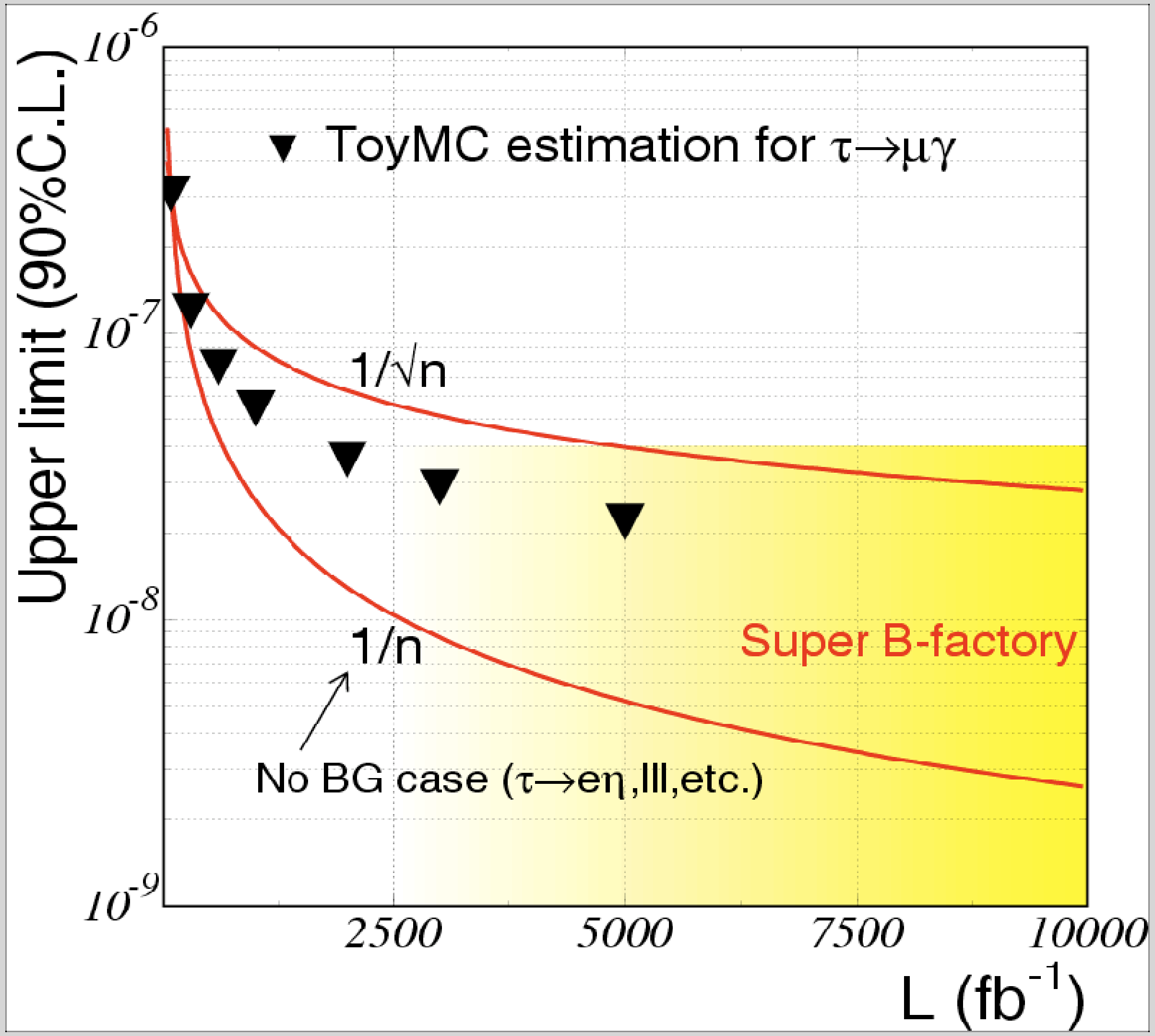
Why is the Muon ?

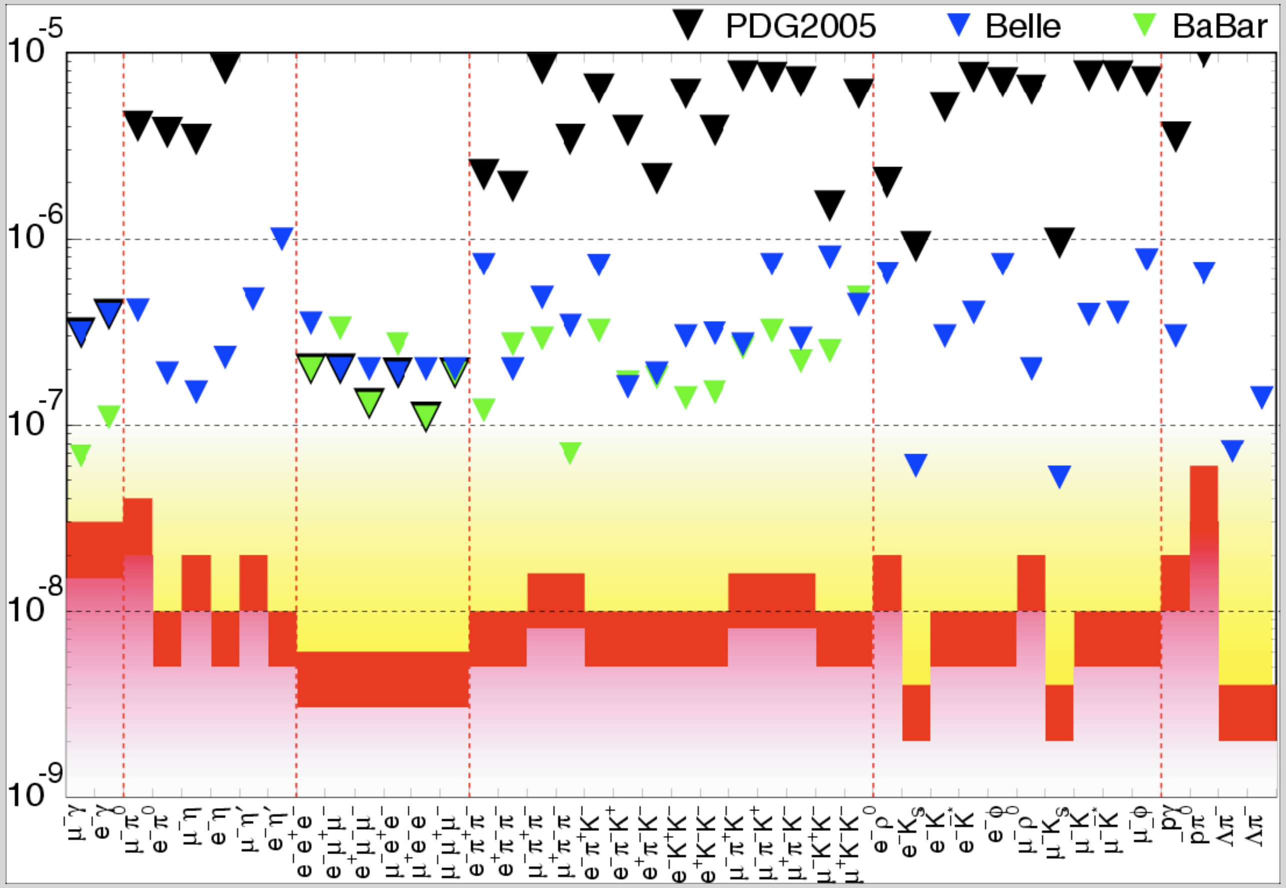
- A number of muons available now is the highest (10^8/sec at PSI).
- High power (M Watt) proton drivers (for neutrino physics) will be available.
- In future, by using the ideas and R&D on muon colliders and neutrino factories, a number of muons of 10^{12}-10^{14}/sec will be possible. (4-6 orders of magnitude).
  - solenoid pion capture
  - phase rotation
  - ionization cooling
- The future prospect for muons is better than taus at super-B factory.



Lepton Flavor Violation with Taus

- 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 20 more taus.
- The red bands (right) having sensitivities of 10^{-9} are expected with 5 - 10 ab^{-1}.





List of Lepton Flavor Violating Processes with Muons

ΔL=1

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

SUSY

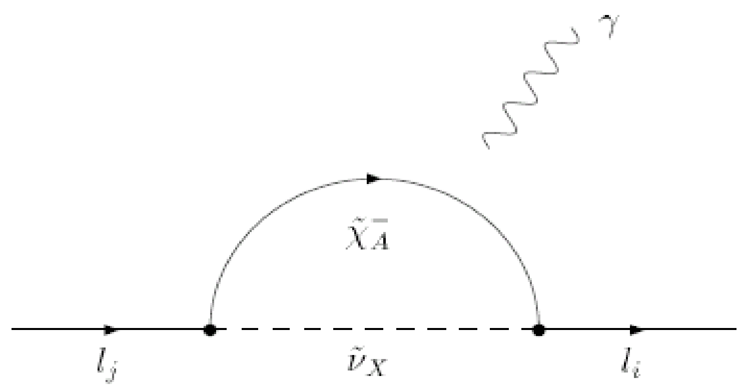
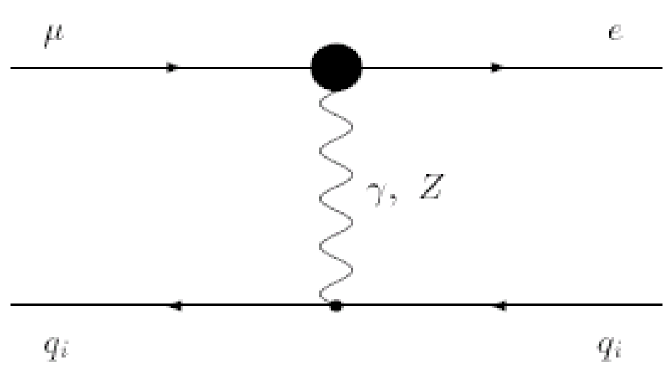
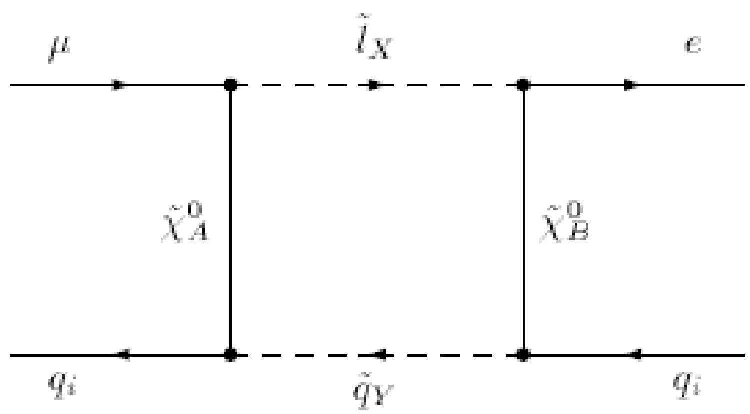
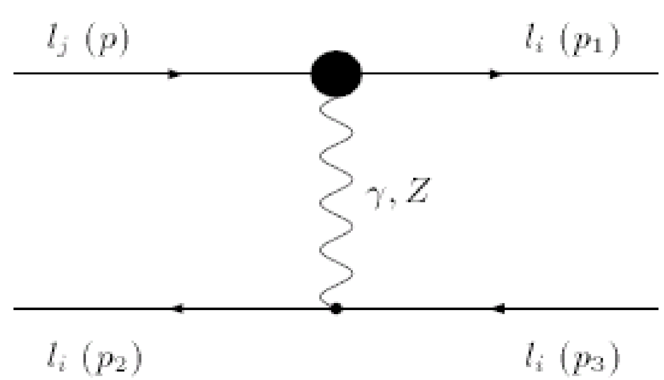
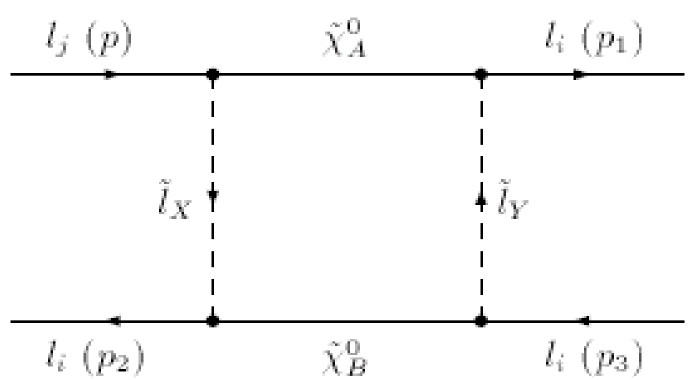
Majorana neutrinos

ΔL=2

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

Comparison
- Theoretical

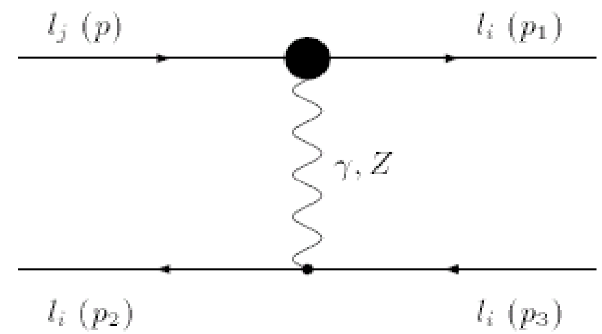
New Physics Diagrams (SUSY) of μ→eγ, μ→eee, μ-e conversion

	photonic	non-photonic
• μ→eγ		absent
• μ-e conversion		
• μ→eee		

Physics Sensitivities :
- Photonic Penguin Diagram Dominated

- μ→eee

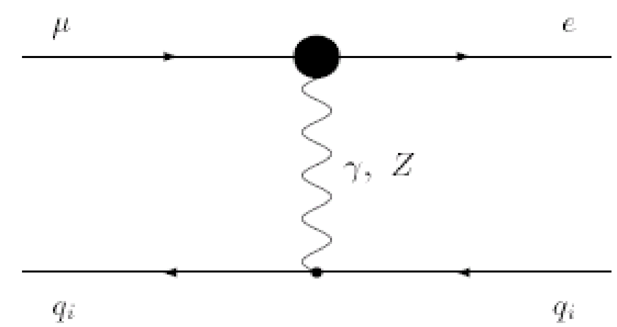
$$\frac{B(\mu \to eee)}{B(\mu \to e\gamma)} \sim 6 \times 10^{-3}$$



- μ-e conversion

$$\frac{B(\mu N \to eN)}{B(\mu \to e\gamma)} = \frac{G_F^2 m_\mu^4}{96\pi^3\alpha} \times 3 \times 10^{12} B(A,Z)$$

$$\sim \frac{B(A,Z)}{428}$$



  - for Al muon target, about 1/380.
  - for Ti muon target, about 1/230.

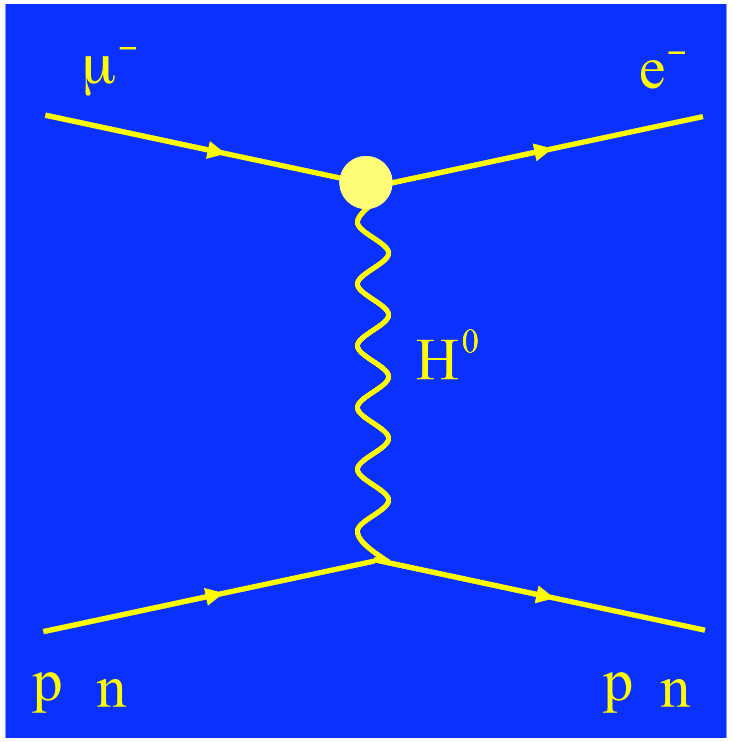
	Al	Ti	Pb
(1)	1.2	2.0	1.6
(2)	1.3	2.2	2.2
(3)	1.1	1.8	1.3
(4)	Increasing as Z		

B(A,Z)

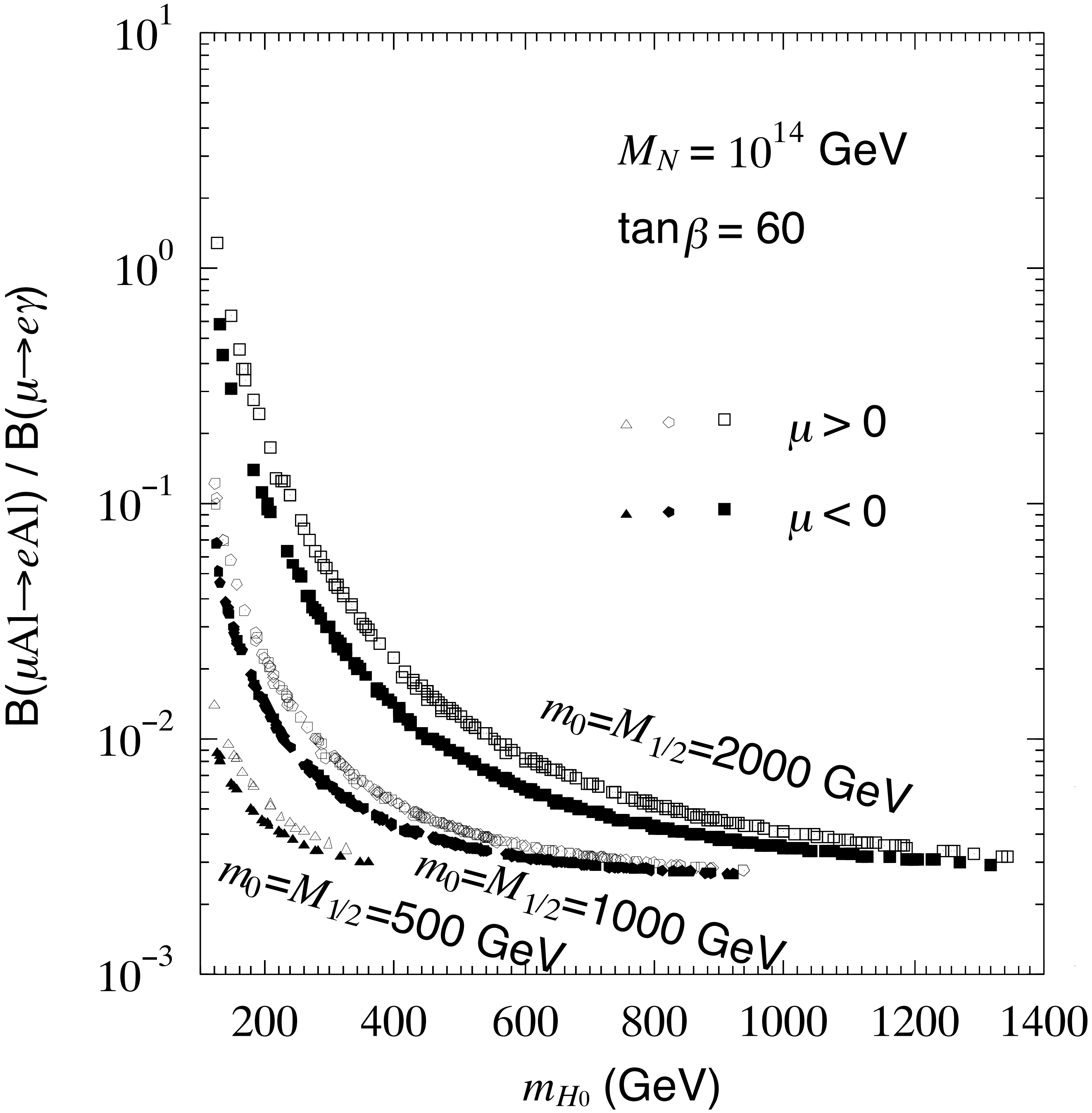
(1) S.Weinberg and G.Feinberg, PRL, 3 (1959)111
(2) O.Shanker, PR D20 (1979) 1608.
(3) A.Czarnecki et al., Workshop of FMC, 1997
(4) T.S. Kosmas et al., PR 264 (1996)

Physics Sensitivities : Non-photonic Cases for μ-e Conversion

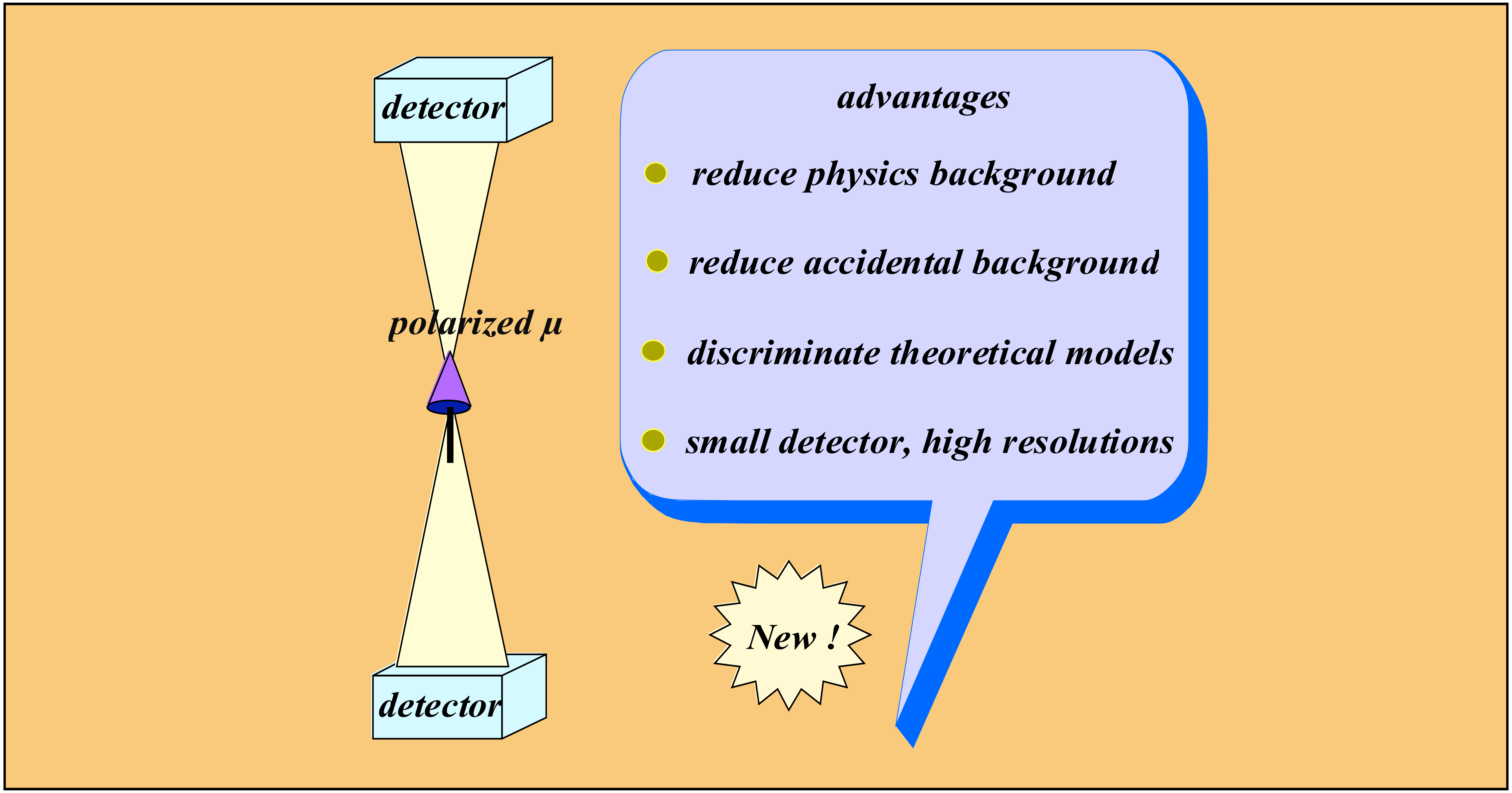
- Higgs Mediated Diagrams



- When SUSY Higgs is light, then the ratio comes to O(1).



Idea of The Use of Muon Polarization



Y.Kuno and Y.Okada, Physical Review Letters 77 (1996) 434

Y.Kuno, A.Maki and Y.Okada, Physical Review D55 (1997) R2517-R2520

Suppression of Physics Background with Polarized μ→eγ Decay

radiative muon decay

at end-point of spectrum when neutrinos have small energy

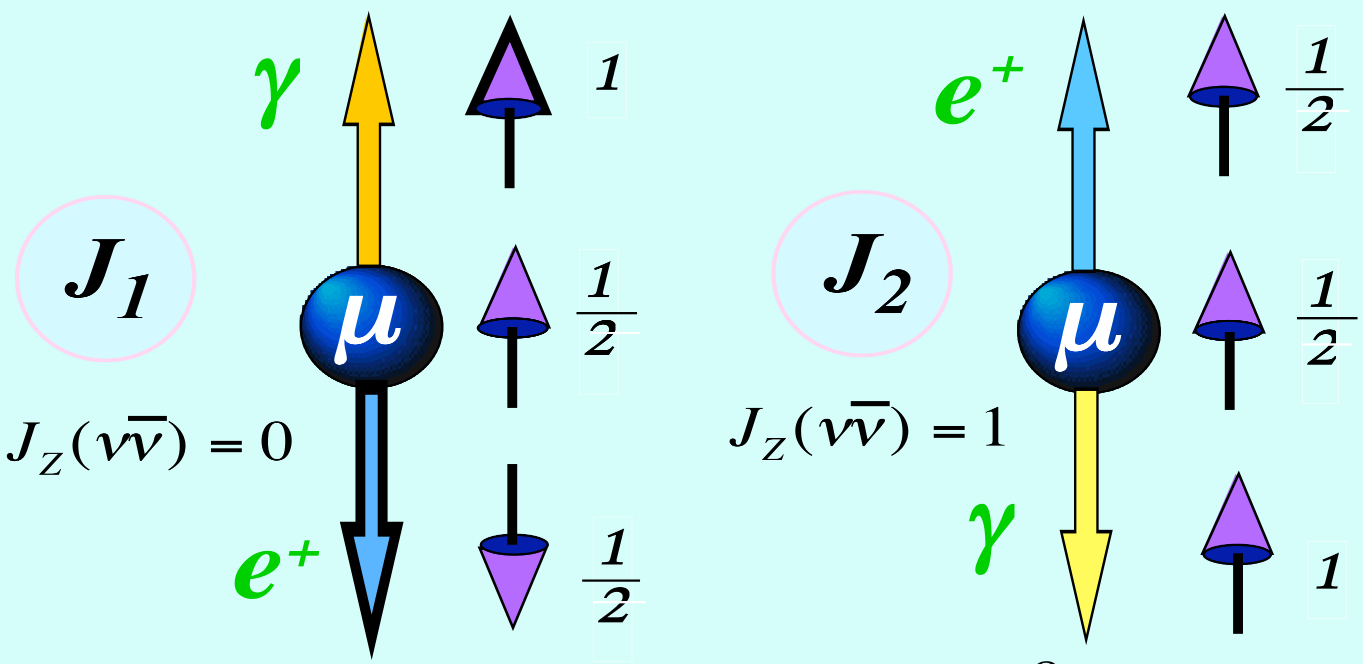
integrate the decay width

$1-\delta x < x < 1$ δx : *e energy*

$1-\delta y < y < 1$ δy : *γ energy*

$0 < z < \delta z$ δz : *angle*

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

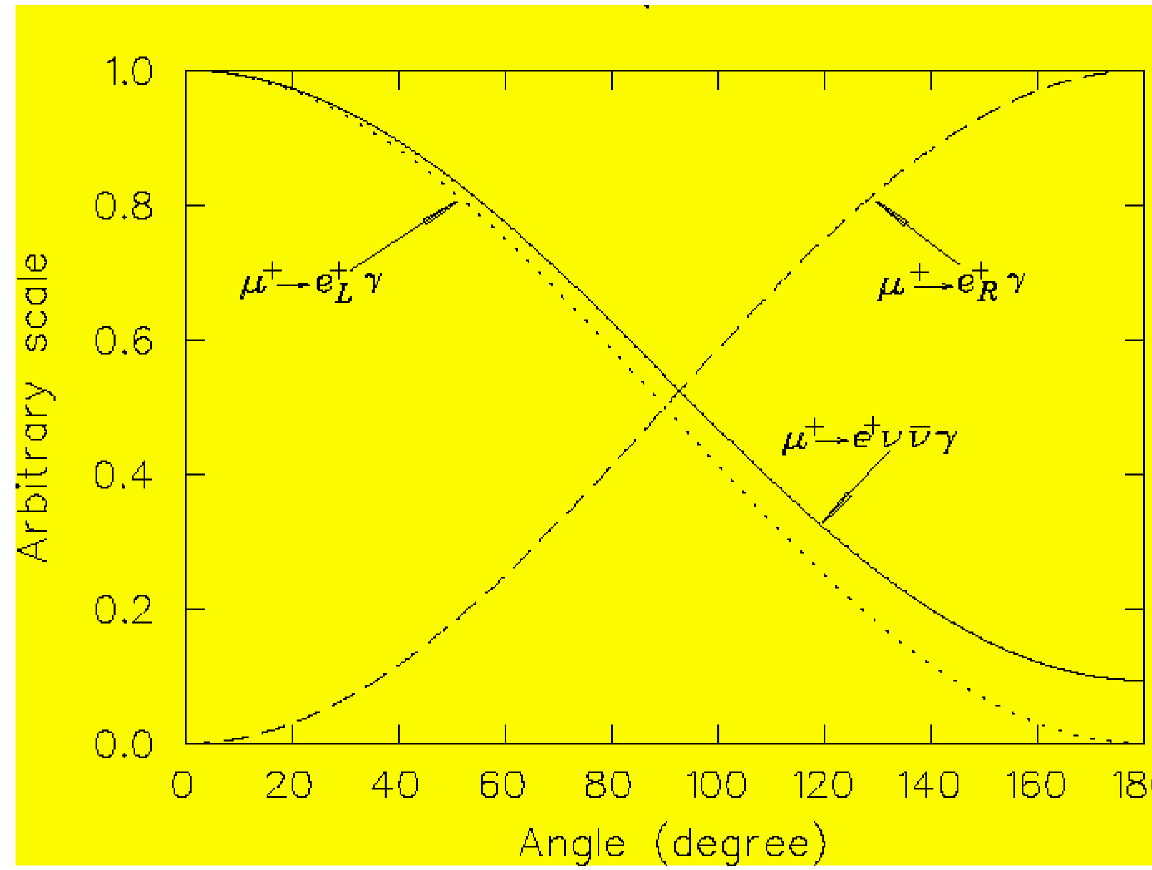


$J_Z(\nu\bar{\nu}) = 0$ $J_Z(\nu\bar{\nu}) = 1$

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

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

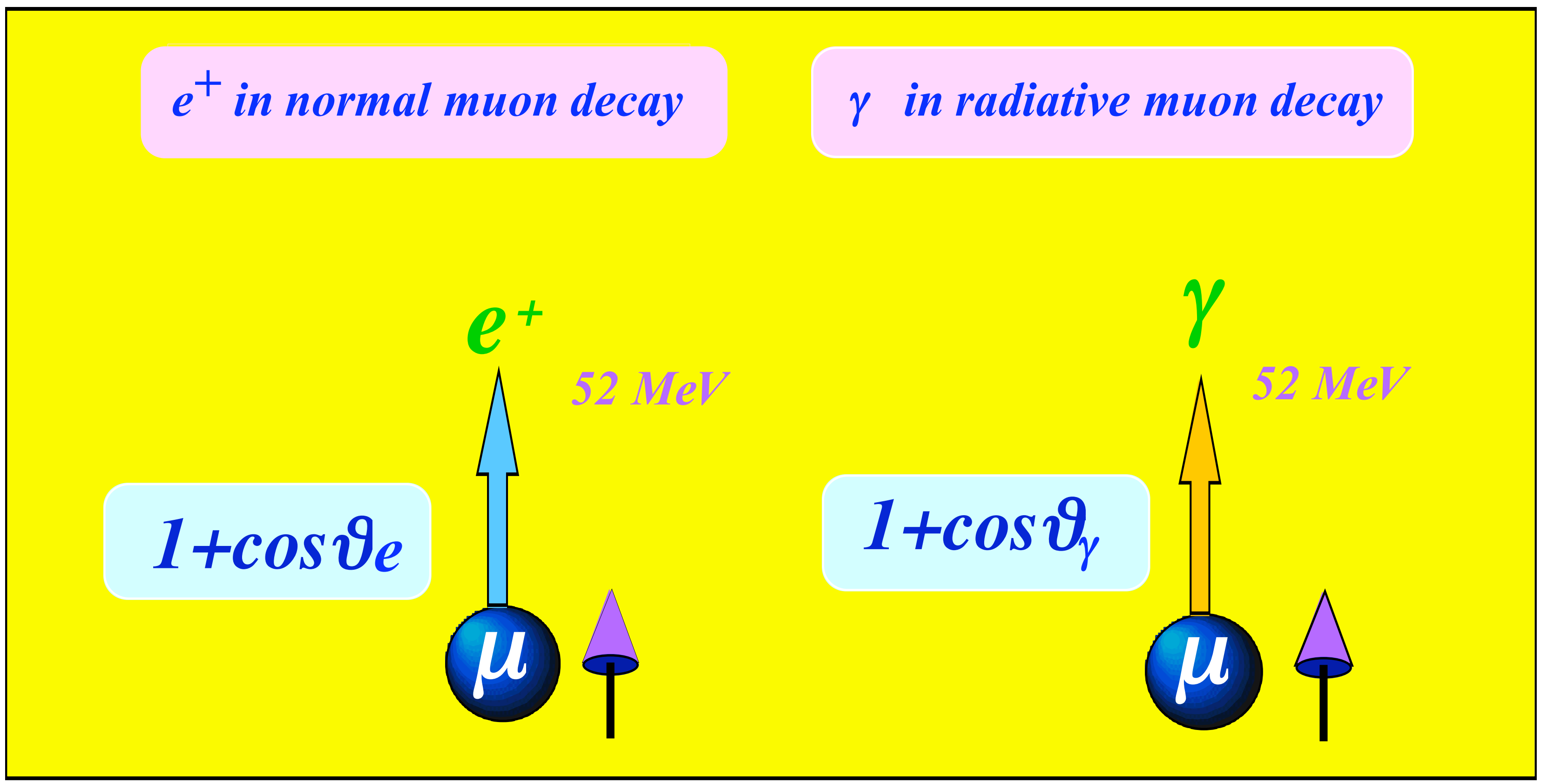
Improve a S/B ratio for $\mu^+ \to e_R\gamma$



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

$\mu^+ \to e_L^+ \gamma$

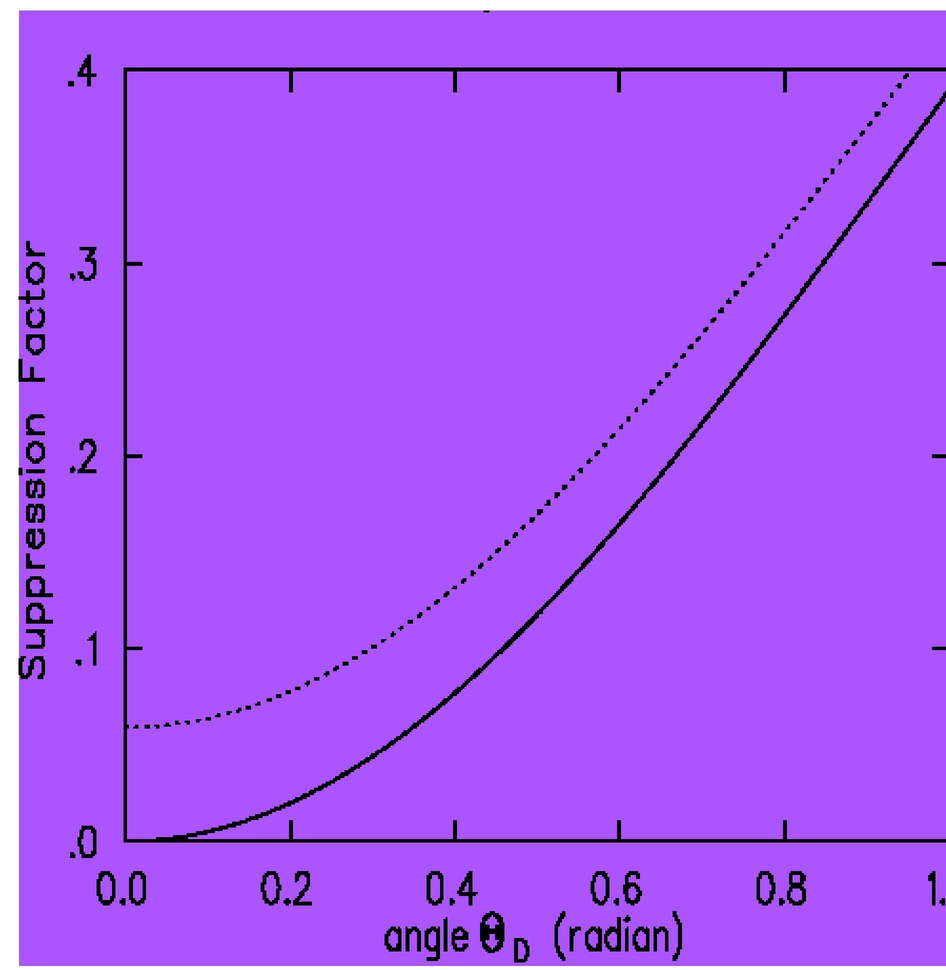
suppressed if photons going opposite to muon spin is measured.

$\mu^+ \to e_L^+ \gamma$

Both helicities are OK !

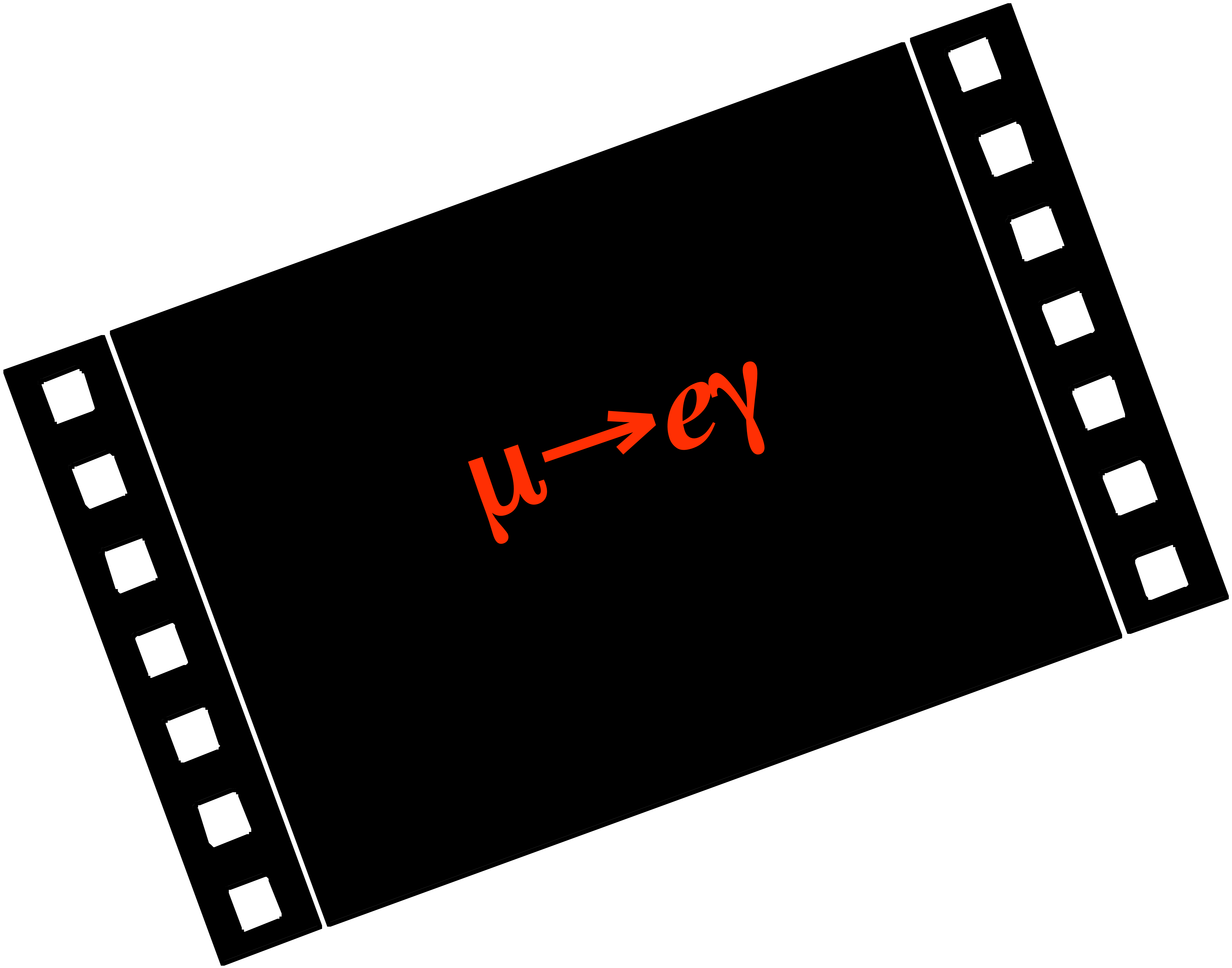
$$\eta = \frac{\int_{\cos\theta_D}^{1} d(\cos\theta)(1+P_\mu\cos\theta)(1-P_\mu\cos\theta)}{\int_{\cos\theta_D}^{1} d(\cos\theta_D)}$$

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



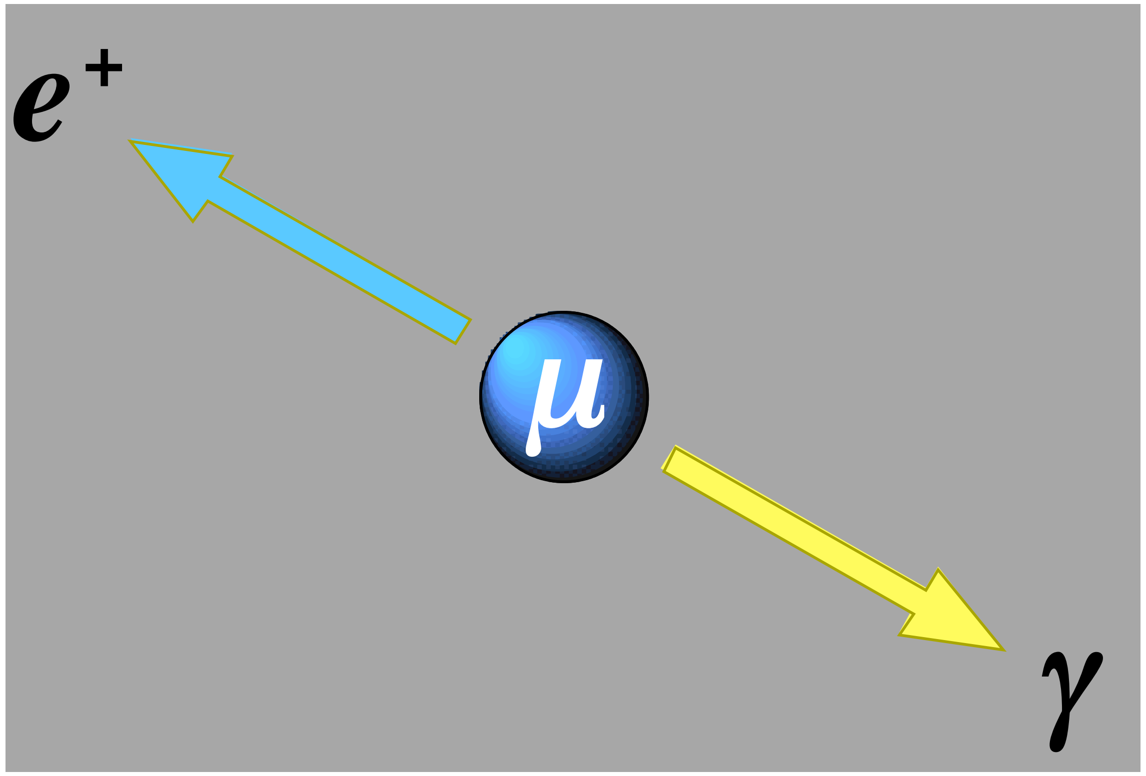
A solid line is P=100% and a dotted line is P=97%.

Comparison
- Experimental


μ→eγ

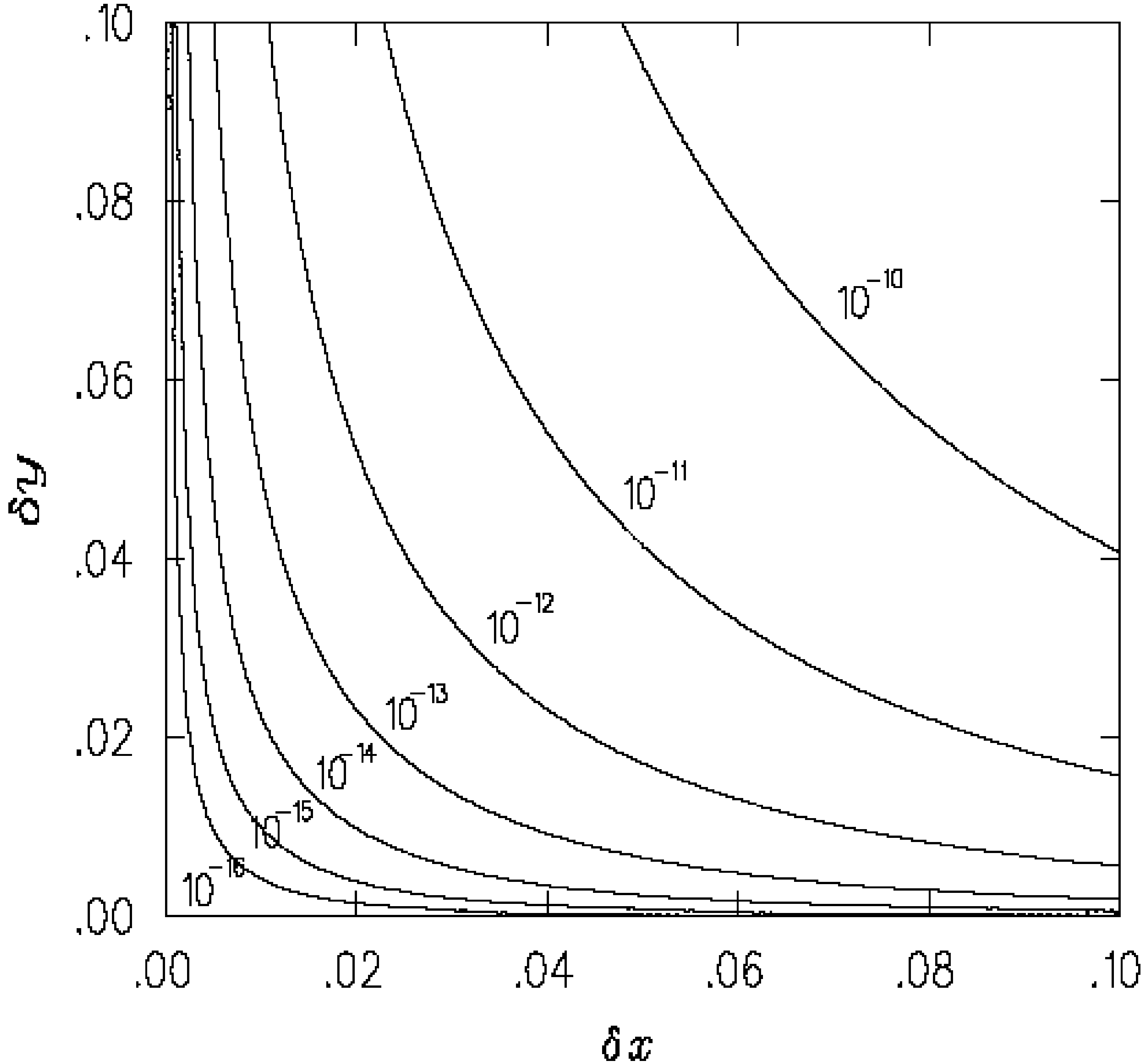
What is $\mu \to e\gamma$?

- 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 (3)



Effective branching ratio is a function of δx and δy.

Radiative correction of physics background can be done.

$$\delta z > 2\sqrt{(\delta x)(\delta y)}$$

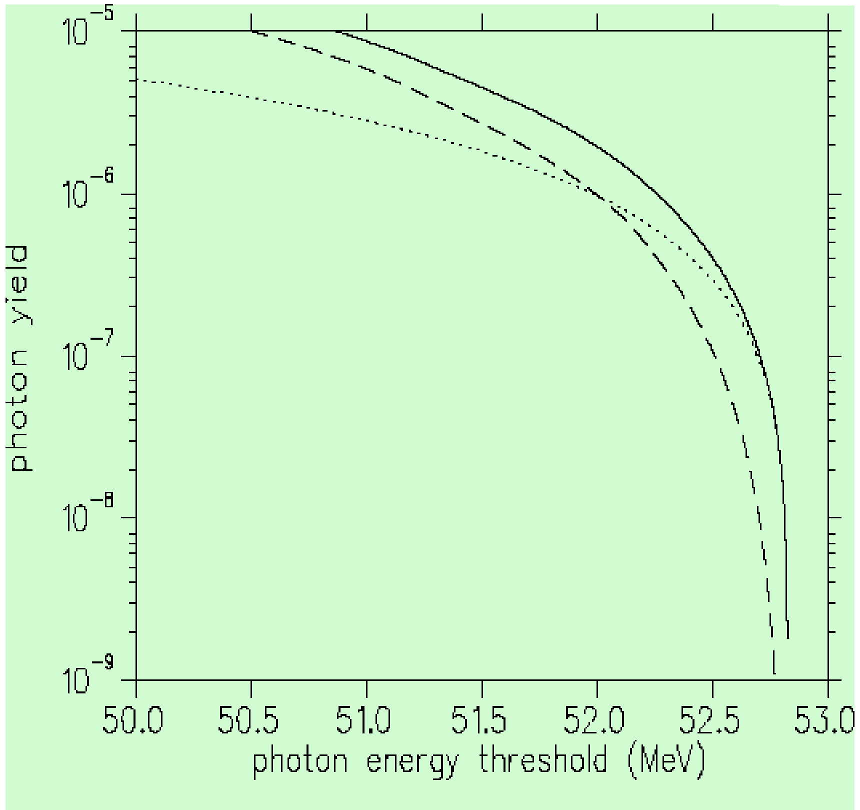
Accidental Background for μ→eγ Decay

- With a very high rate, accidental background becomes most serious.
- Event rate of accidentals is given by

$$B_{acc} = R_\mu \cdot f_e^{\,0} \cdot f_\gamma^{\,0} \cdot (\Delta t_{e\gamma}) \cdot \left(\frac{\Delta\omega_{e\gamma}}{4\pi}\right)$$

  - R_μ: instantaneous muon intensity.
  - $f_e^{\,0}$ integrated fraction of positron spectrum
  - $f_\gamma^{\,0}$: integrated fraction of gamma spectrum

  - $\Delta t_{e\gamma}$: time coincidence width
  - $\Delta\omega_{e\gamma}$: back-to-back kinematics
- 50-MeV photon yield $f_\gamma^{\,0}$



  - dotted line: annihilation
  - dashed line: radiative decay
  - solid line: total

Accidental Background for μ→eγ Decay

- Integrated Fractions

$$f_e^0 \approx 2(\delta x)$$

$$f_\gamma^0 \approx \int_{1-\delta y}^{1} dy \int d(\cos\theta_\gamma) \frac{dB(\mu \to e\nu\bar{\nu}\gamma)}{dy\,d(\cos\theta_\gamma)}$$

$$= \left(\frac{\alpha}{2\pi}\right)(\delta y)^2[\ln(\delta y) + 7.33]$$

$$\left(\frac{\Delta\omega_{e\gamma}}{4\pi}\right) = \frac{(\delta\theta_{e\gamma})^2}{4}$$

- Effective Branching Ratio of Accidental Background

$$B_{acc} = R_\mu \cdot (2\delta x) \cdot \left[\frac{\alpha}{2\pi}(\delta y)^2[\ln(\delta y) + 7.33]\right] \times \left(\frac{\delta\theta_{e\gamma}^2}{4}\right) \cdot (2\delta t_{e\gamma})$$

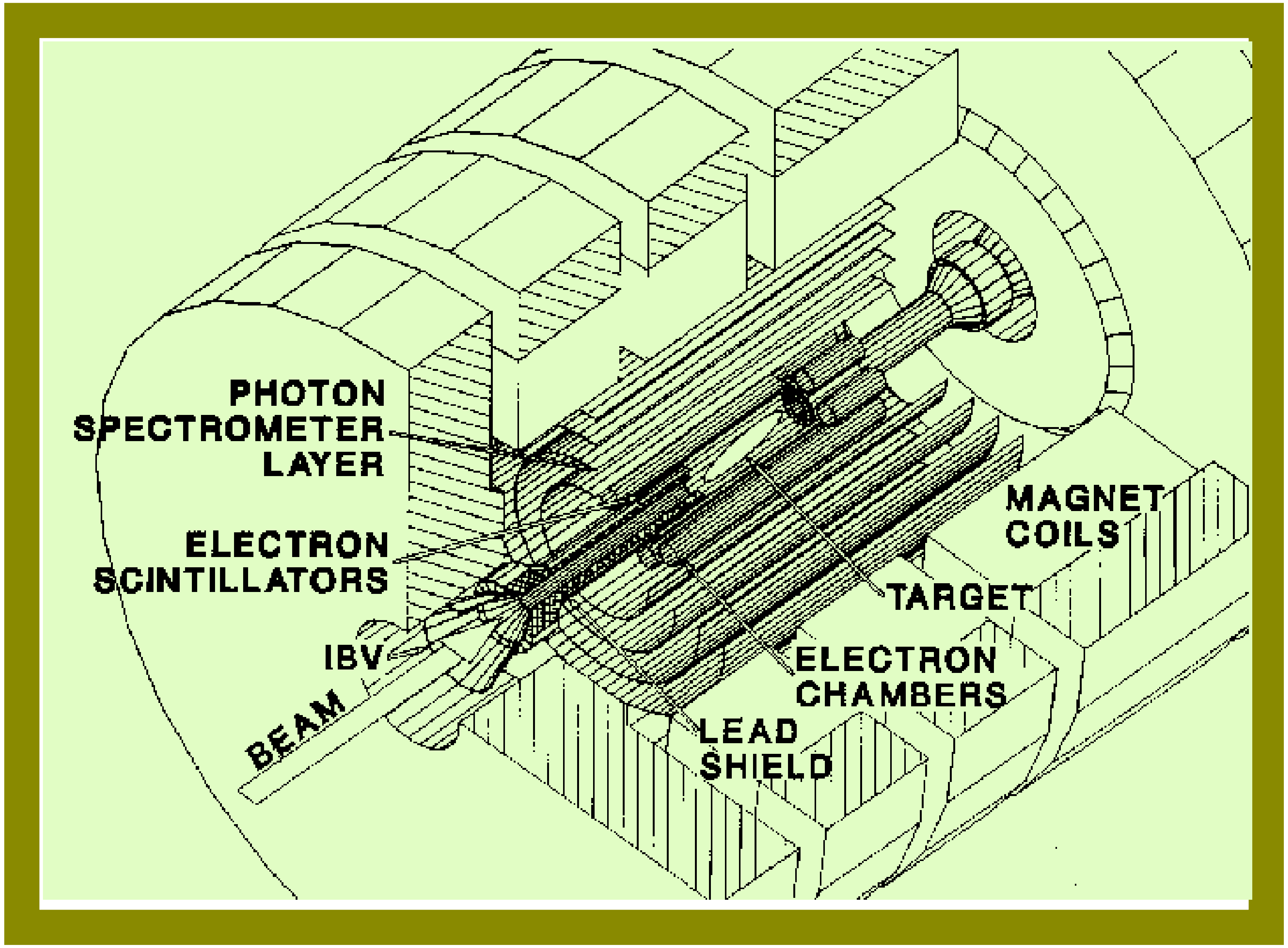
$$\delta x = 1\%,\ \delta y = 6\%,\ \Delta\omega_{e\gamma} = 3\times 10^{-4},$$

$$\Delta t_{e\gamma} = 1ns,\ R_\mu = 3\times 10^{8}\,\mu^+/s \ \Rightarrow\ B_{acc} = 3\times 10^{-13}$$

MEGA at Los Alamos

- MEGA at Los Alamos (~1999)

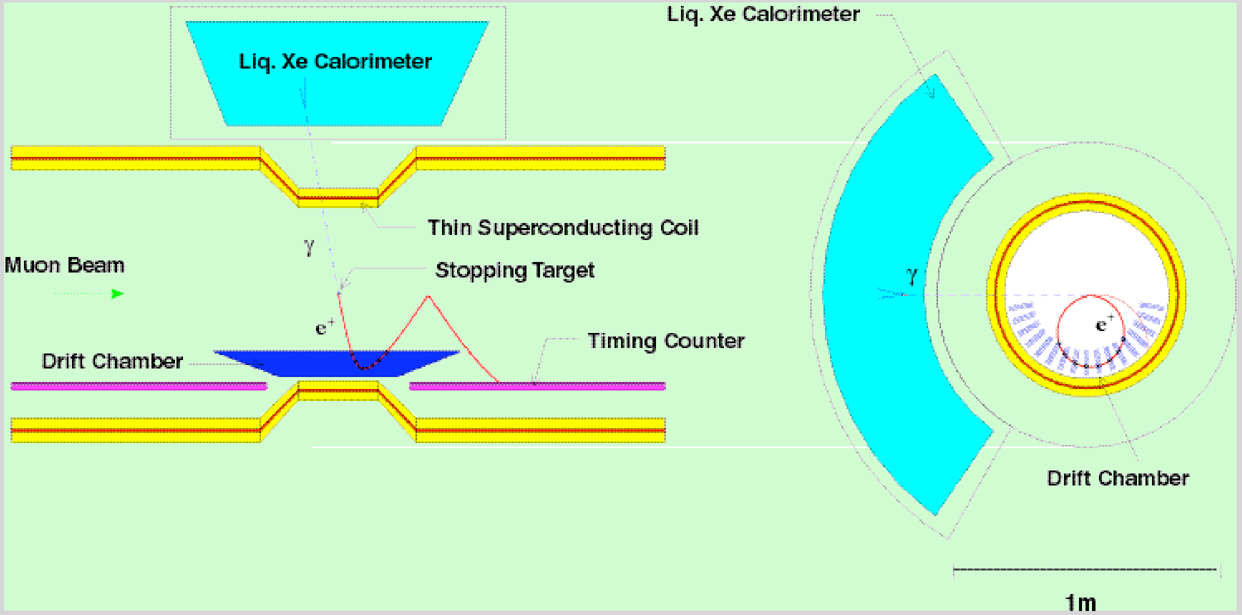
- A thin slanted target.
- 1.5 T solenoid magnetic field
- 7 dwarf chambers for e^+ tracking
- pair spectrometer for gamma detection

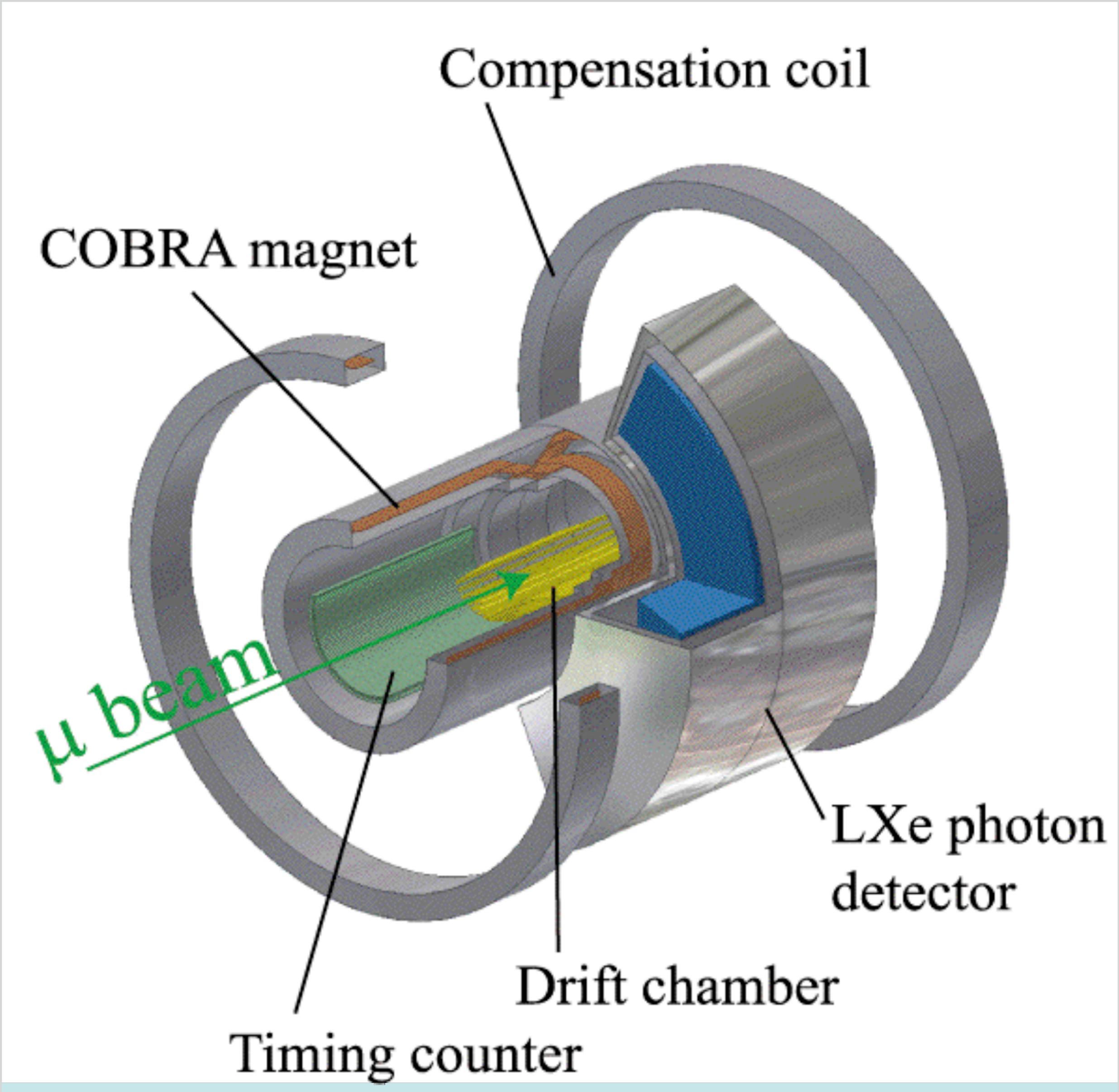


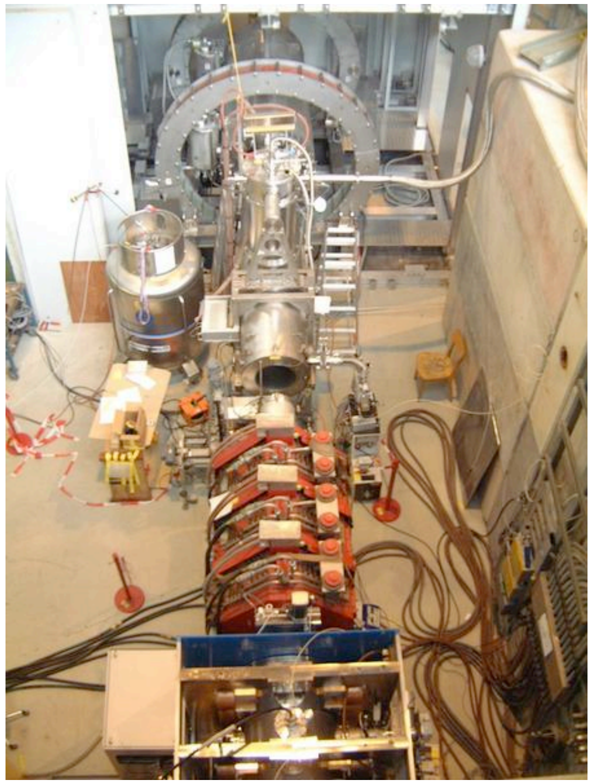
$$B(\mu^+ \to e^+\gamma) < 1.2 \times 10^{-11}$$

MEG at PSI

- DC beam 10^7 muons/sec.
- Goal : $B < 10^{-13}$
- COBRA : spectrometer for e^+ detection.
- Liquid Xenon detector for photon detection.
- start engineering run in 2007.



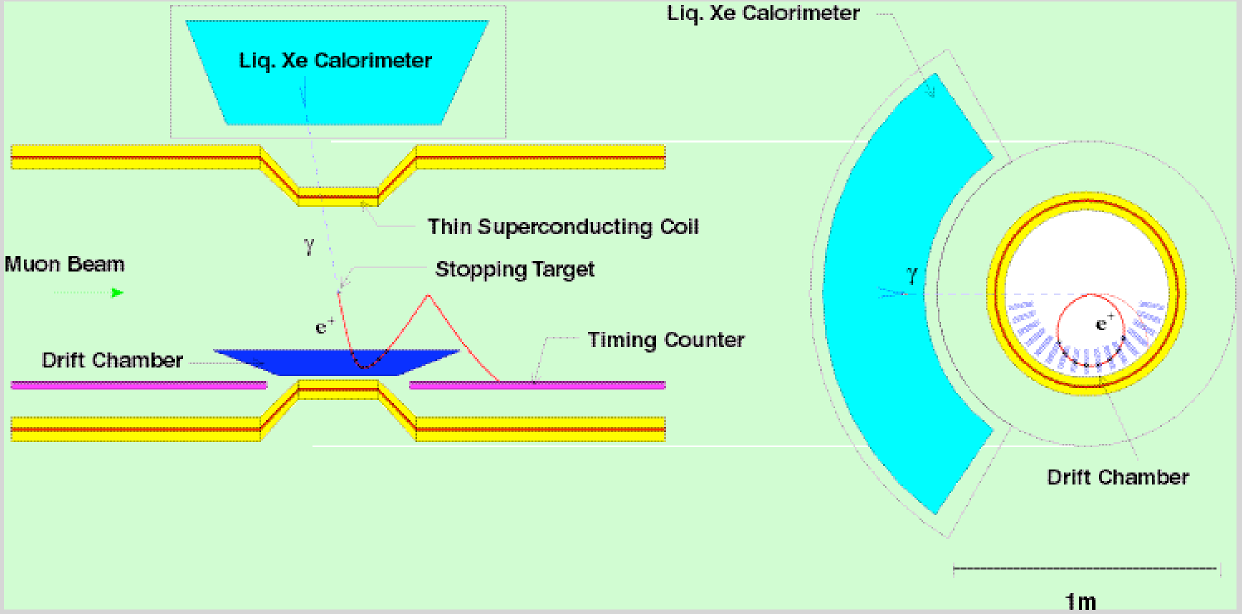


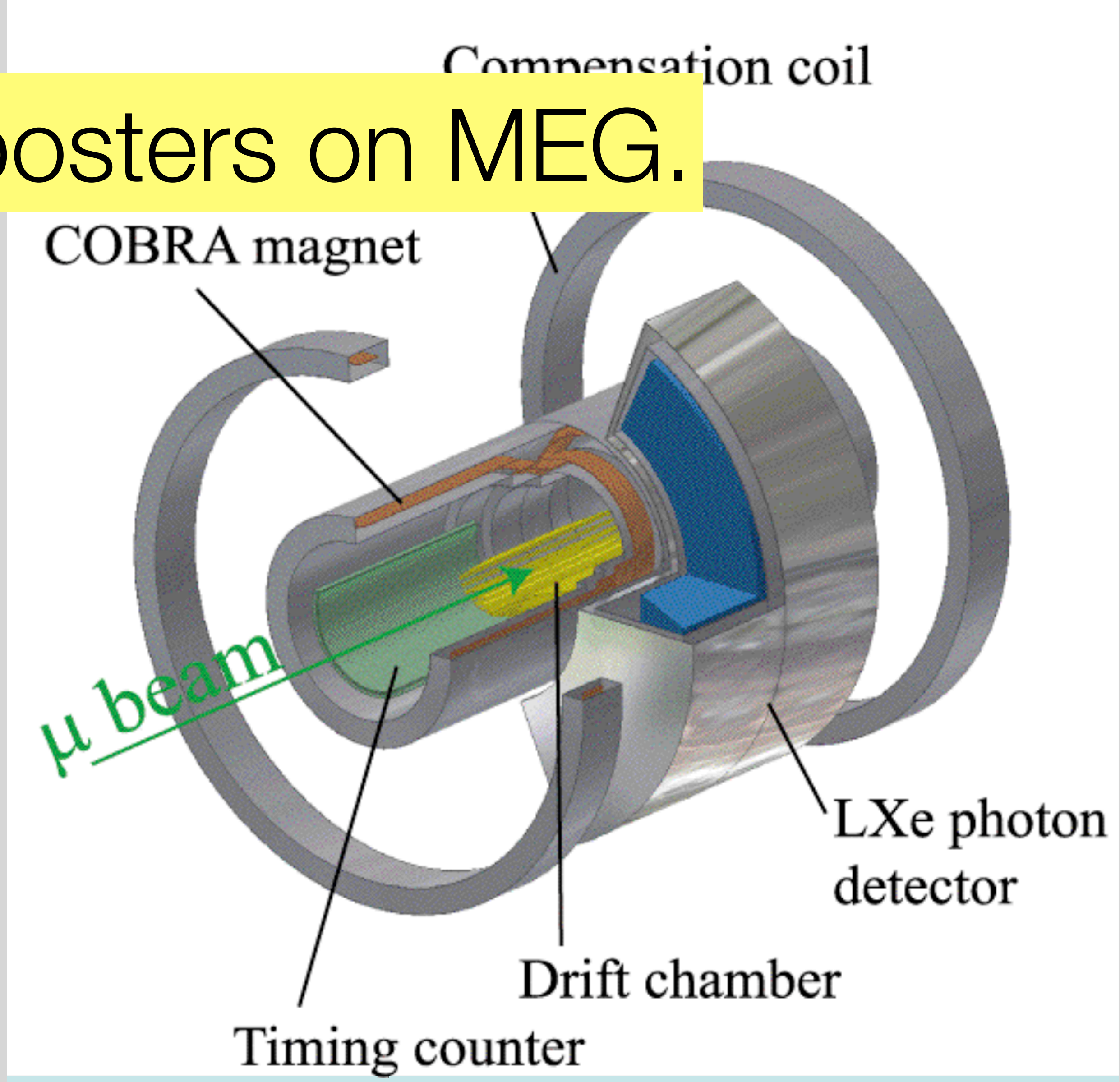


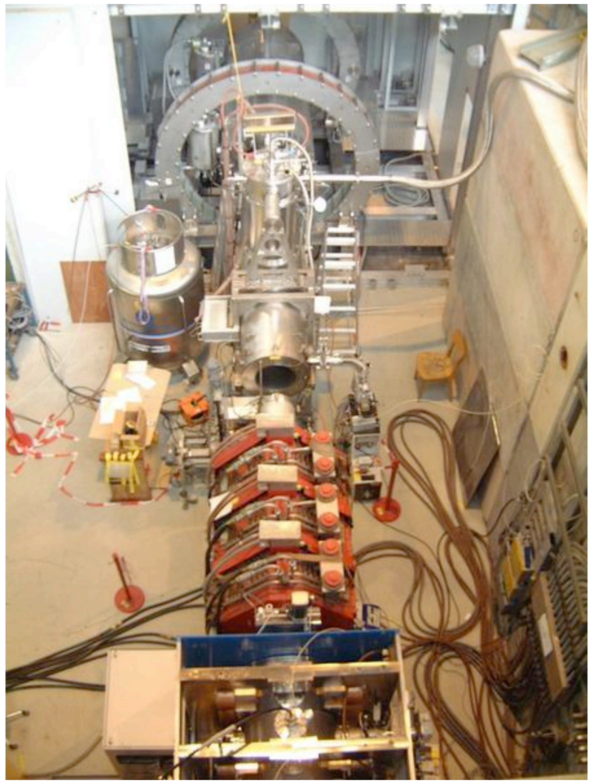
MEG at PSI

- DC beam 10^7 muons/sec.
- Goal : $B < 10^{-13}$
- COBRA : spectrometer for e^+ detection.
- Liquid X[illegible] photon detection.
- start engineering run in 2007.

Please look at the posters on MEG.







Detector Resolutions in the Past $\mu \to e\gamma$ Experiments

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	$< 10^{-13}$

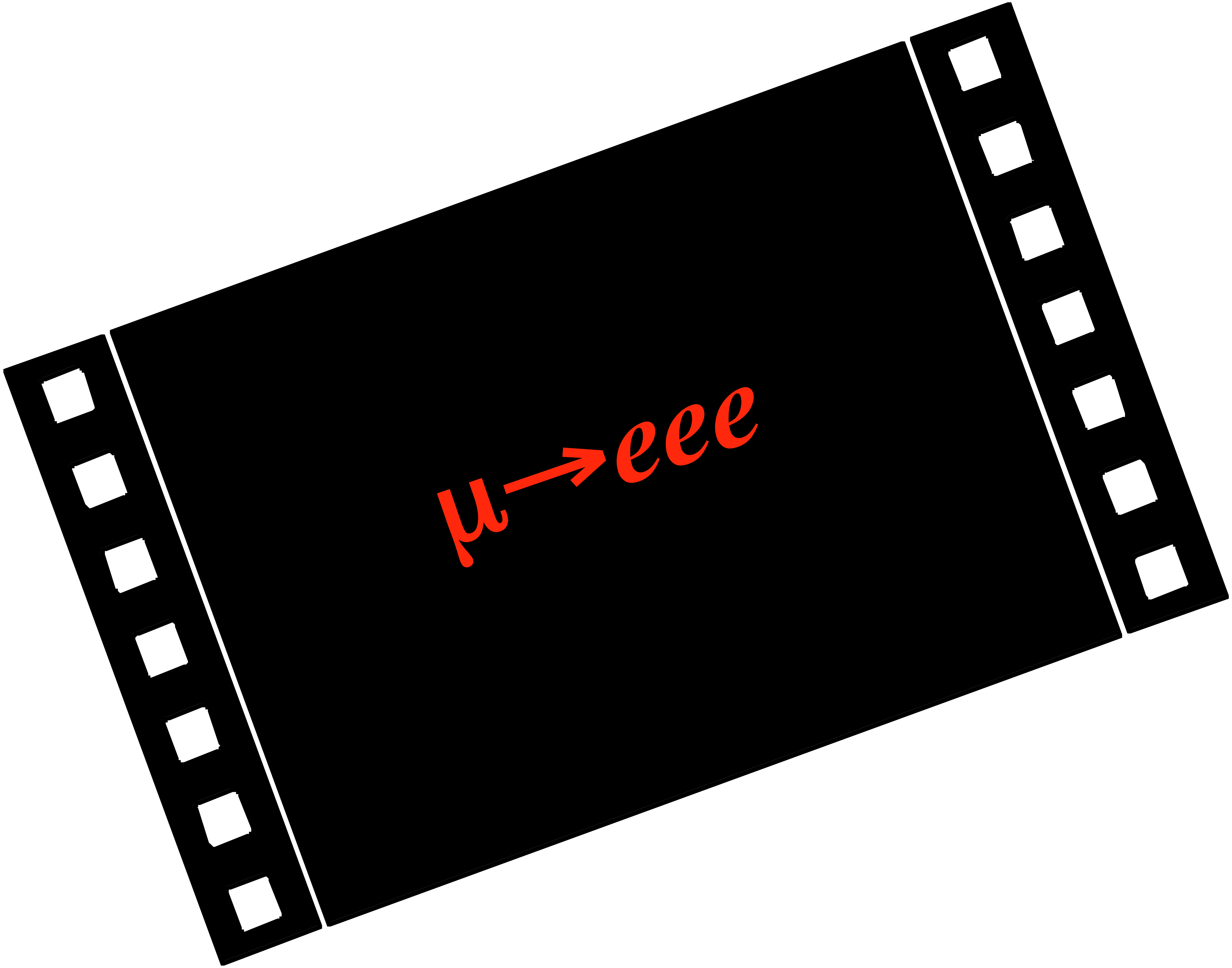
states of arts

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

N_B=0.5 events at $B(\mu \to e\gamma) \sim 10^{-13}$

With the same resolutions, $N_\mu = 10^{10}\,\mu$/s,
N_B=5000 events at $B(\mu \to e\gamma) \sim 10^{-16}$

Improvements of detector resolutions are critical.


μ→eee

Search for $\mu^+ \to e^+e^+e^-$

- Event Signature
  - simultaneous detection of three charged tracks
  - energy conservation

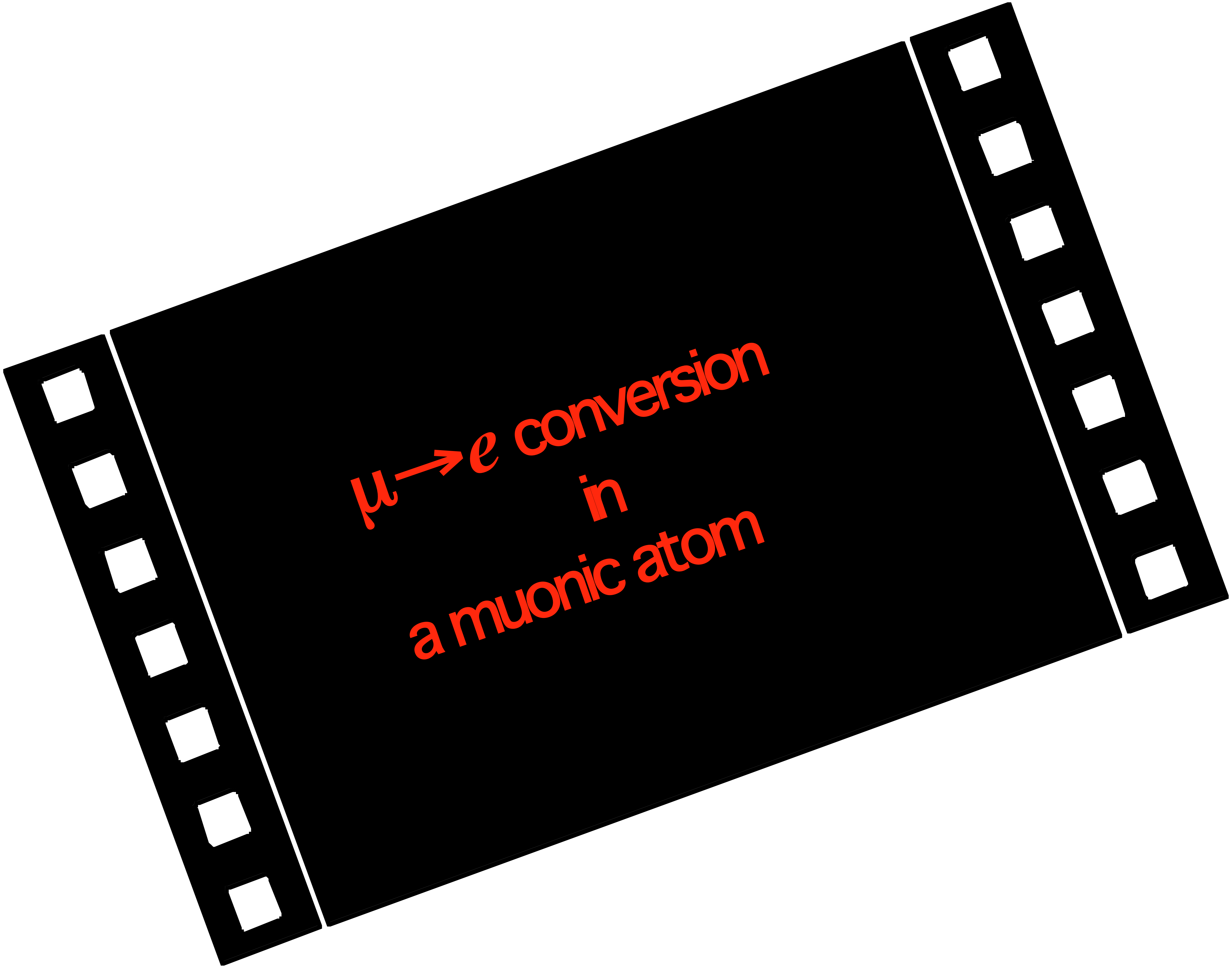
$$\sum_i E_i = m_\mu$$

  - momentum conservation

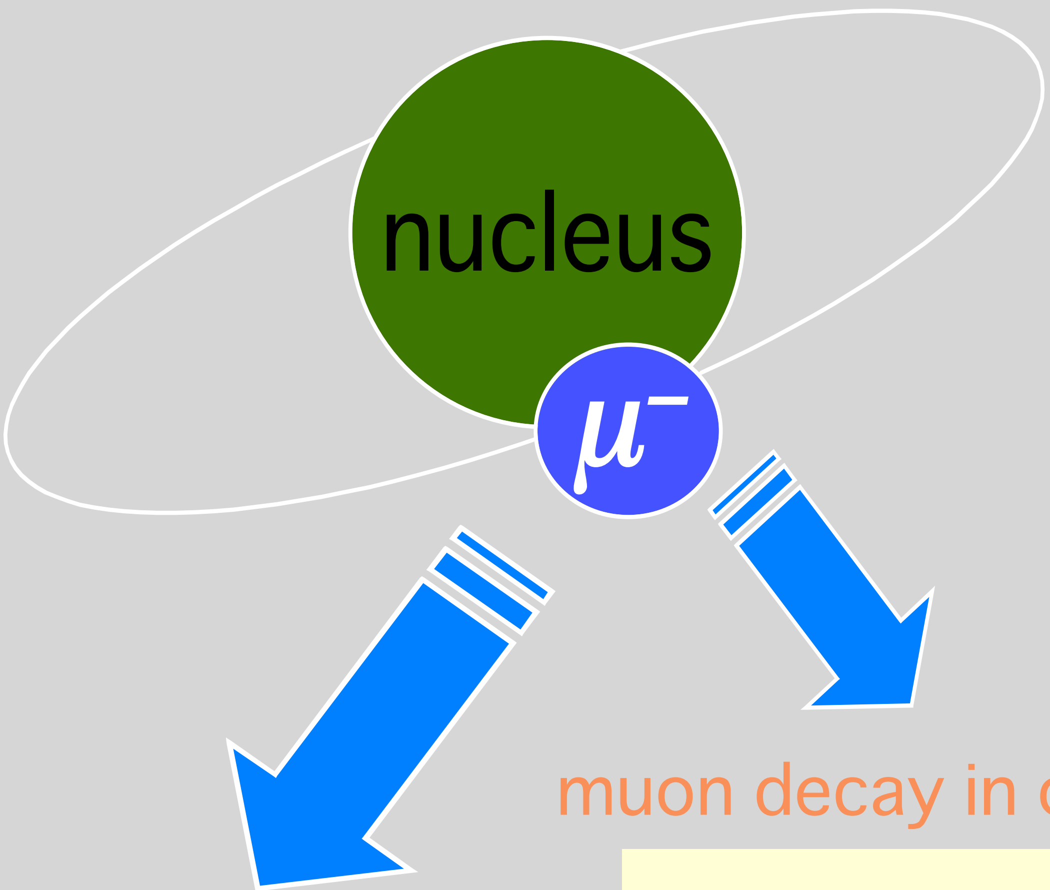
$$\sum_i \vec{p}_i = 0$$

  - vertex / timing matching
  - Backgrounds
    - allowed decay of $\mu^+ \to e^+\nu\bar{\nu}e^+e^-$
      - BR = 3.4 x 10^{-5}
    - allowed decay of $\mu^+ \to e^+e^+e^-\gamma$
      - with photon conversion
      - BR = 1.4%
    - accidental background
      - Bhabaha scattering with low inv. mass
    - curling-back events
- 1988 at PSI (SINDRUM)
  - 5x10^6 muons
  - 5 concentric multi-wire proportional chambers
  - 64 plastic scintillation counters as a trigger
  - magnetic field of 0.33 T

$$B(\mu^+ \to e^+e^+e^-) < 1.0 \times 10^{-12}$$


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

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.

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

Muon-to-Electron (**μ**-e) Conversion

μ-e Conversion
Signal and Backgrounds

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

- Signal
  - single mono-energetic electron

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

  - coherent process (the same initial and final nucleus)

$$\propto Z^5$$

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

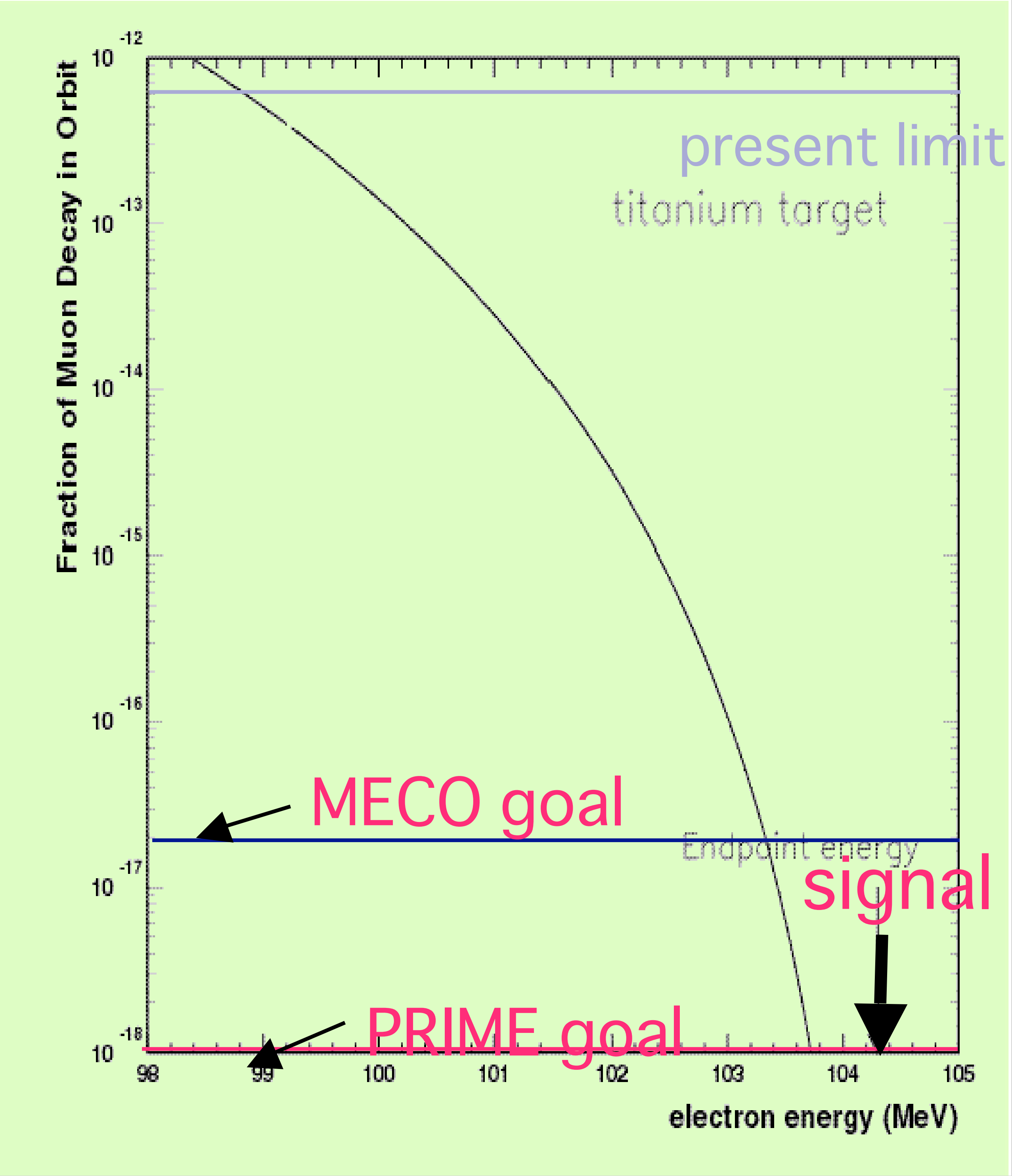
Muon Decay in Orbit in a Muonic Atom

- 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.

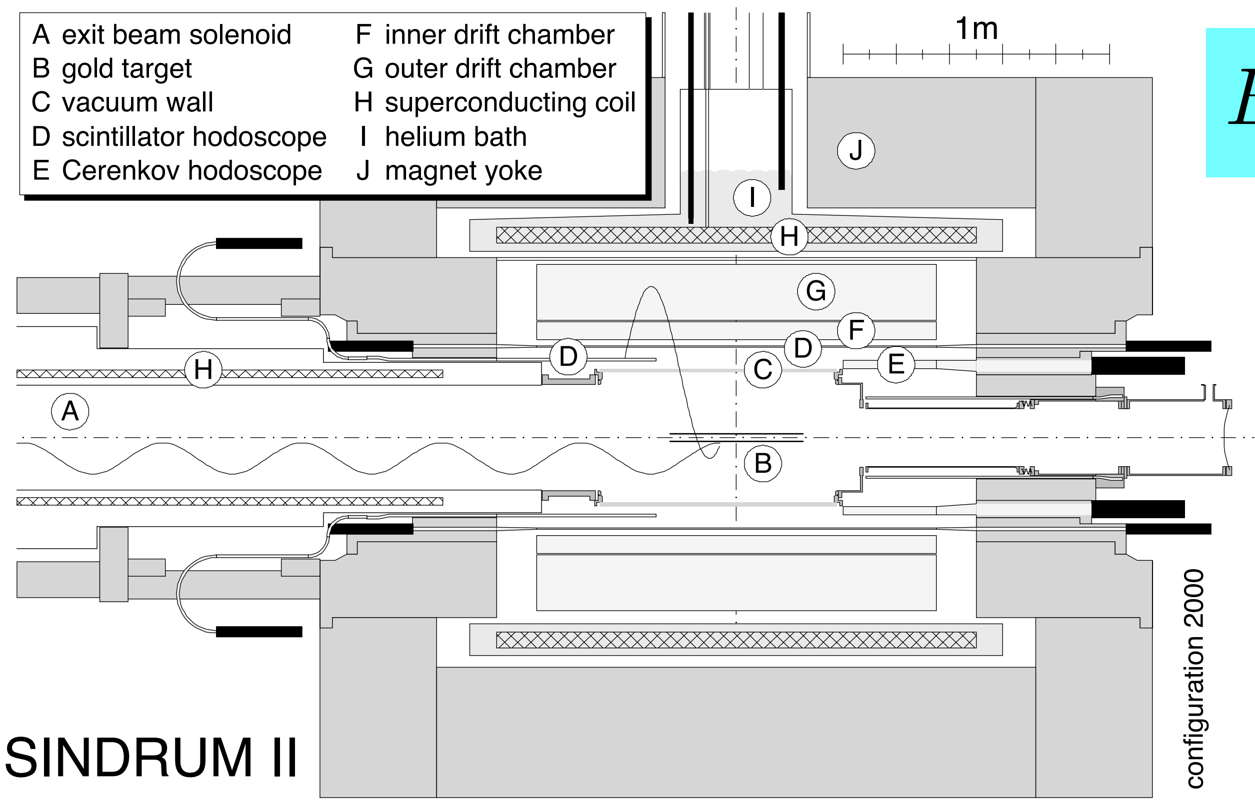
$$N(E_e)dE_e = \left(\frac{E_e}{m_\mu}\right)^2 \left(\frac{\delta_1}{m_\mu}\right)^5 [D + E\cdot\left(\frac{\delta_1}{m_\mu}\right) + F\cdot\left(\frac{\delta}{m_\mu}\right)]dE_e$$

$$\delta = E_{\mu e} - E_e$$

$$\delta_1 = (m_\mu - B_\mu) - E_{rec} - E_e$$



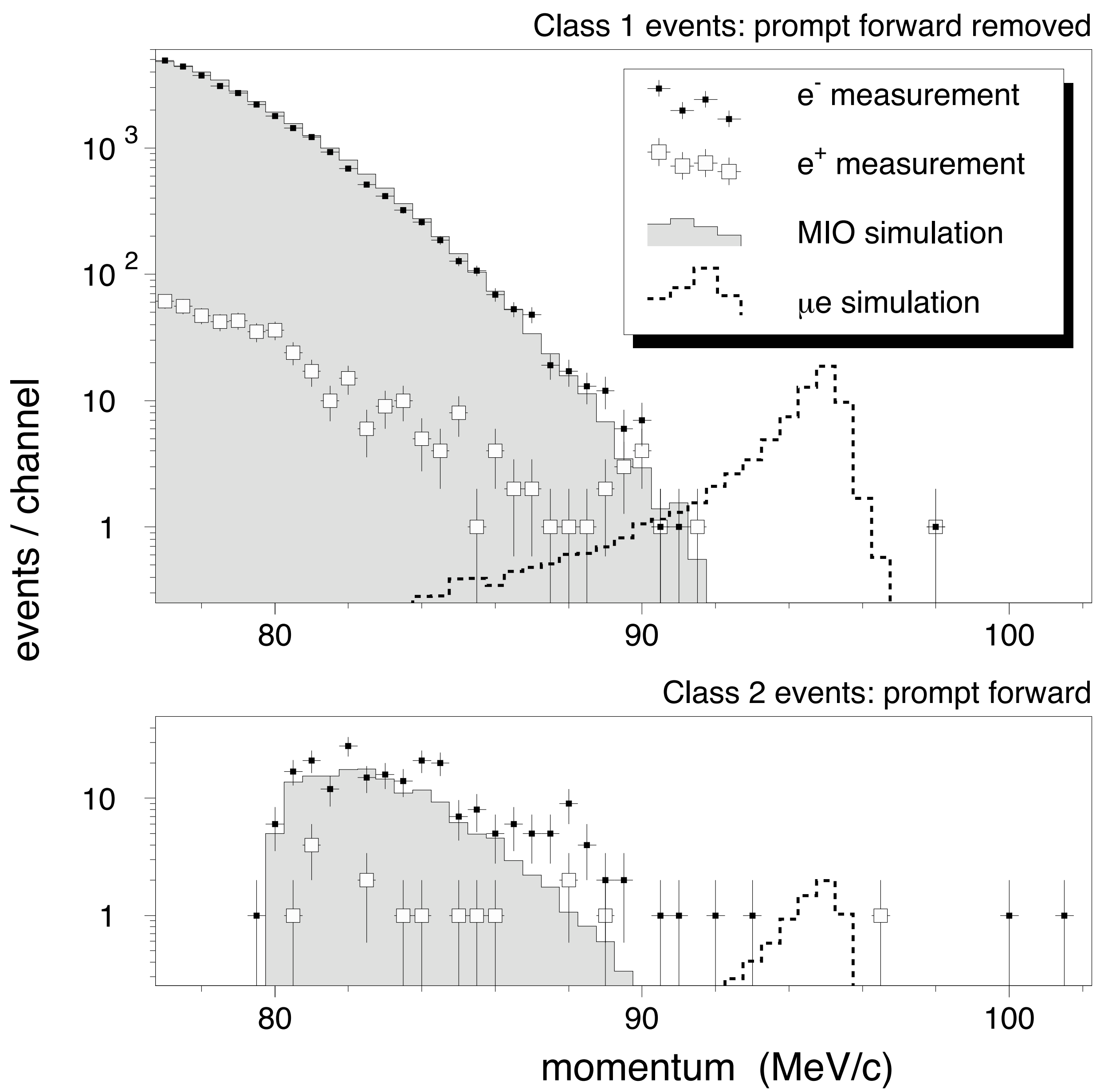
The SINDRUM-II Experiment (at PSI)



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

Published Results

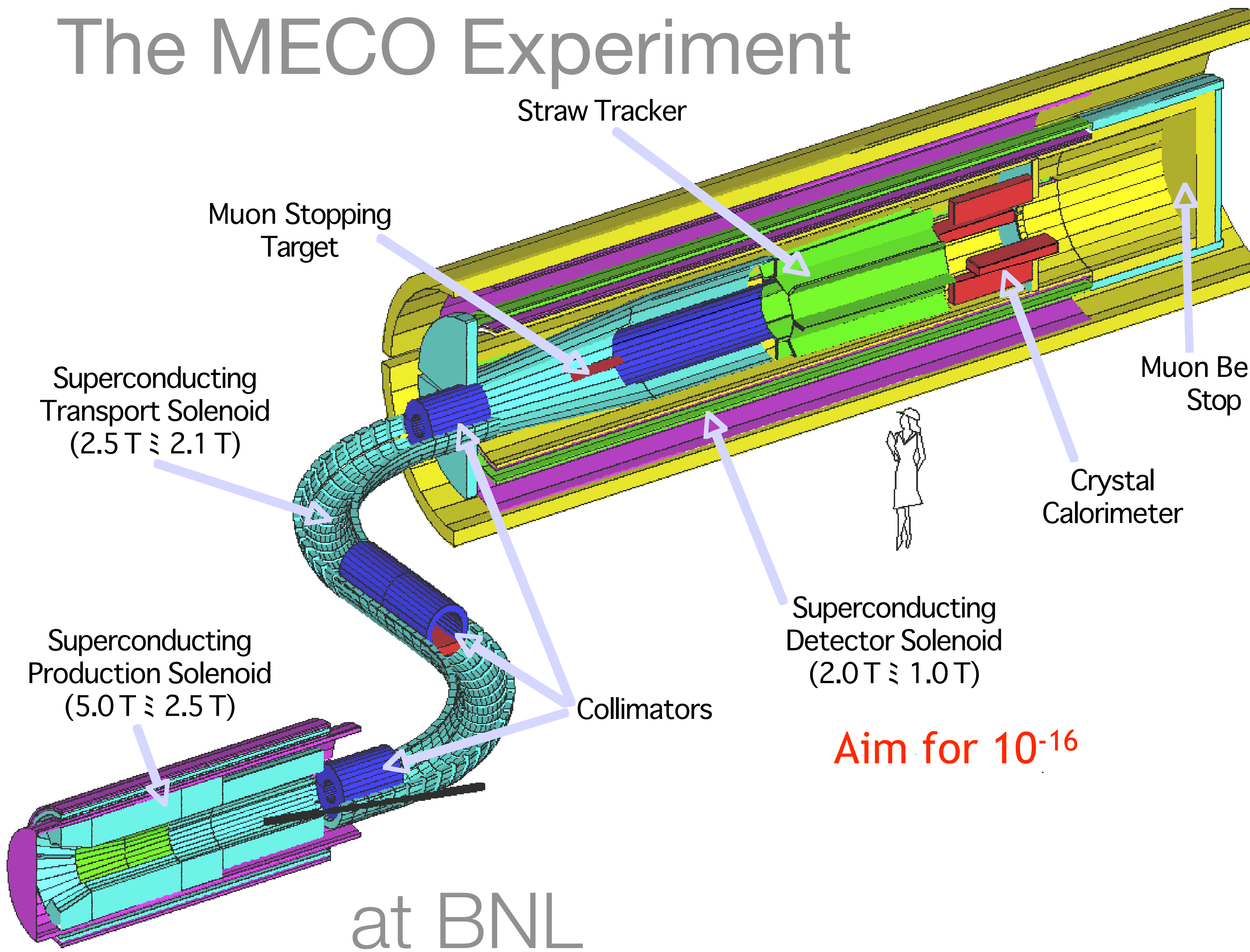
$$B(\mu^- + Ti \rightarrow e^- + Ti) < 4.3 \times 10^{-12}$$



The MELC and MECO Proposals

The MELC and MECO Proposals

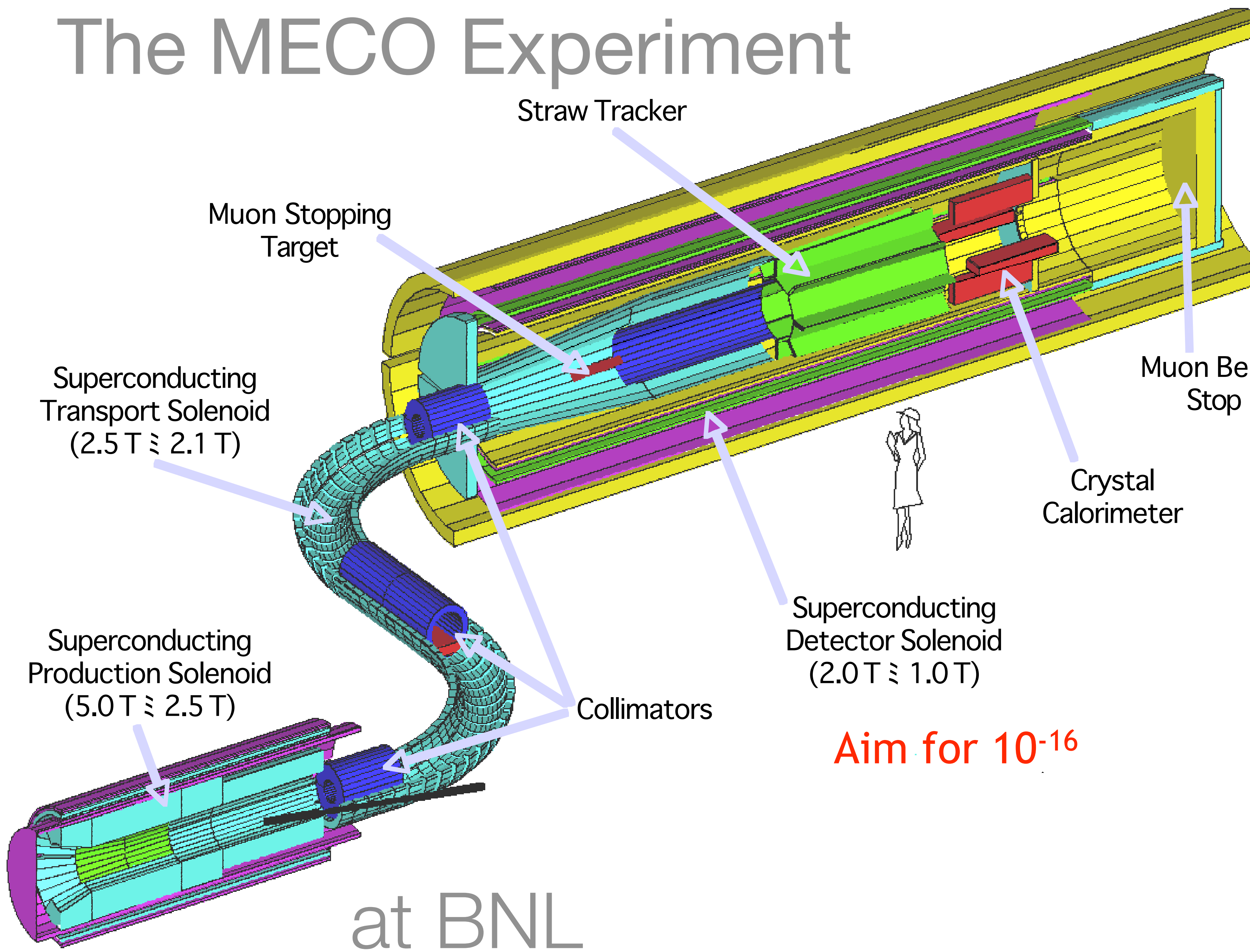
The MECO Experiment



The MELC and MECO Proposals

MELC (Russia) and then MECO (the US)

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



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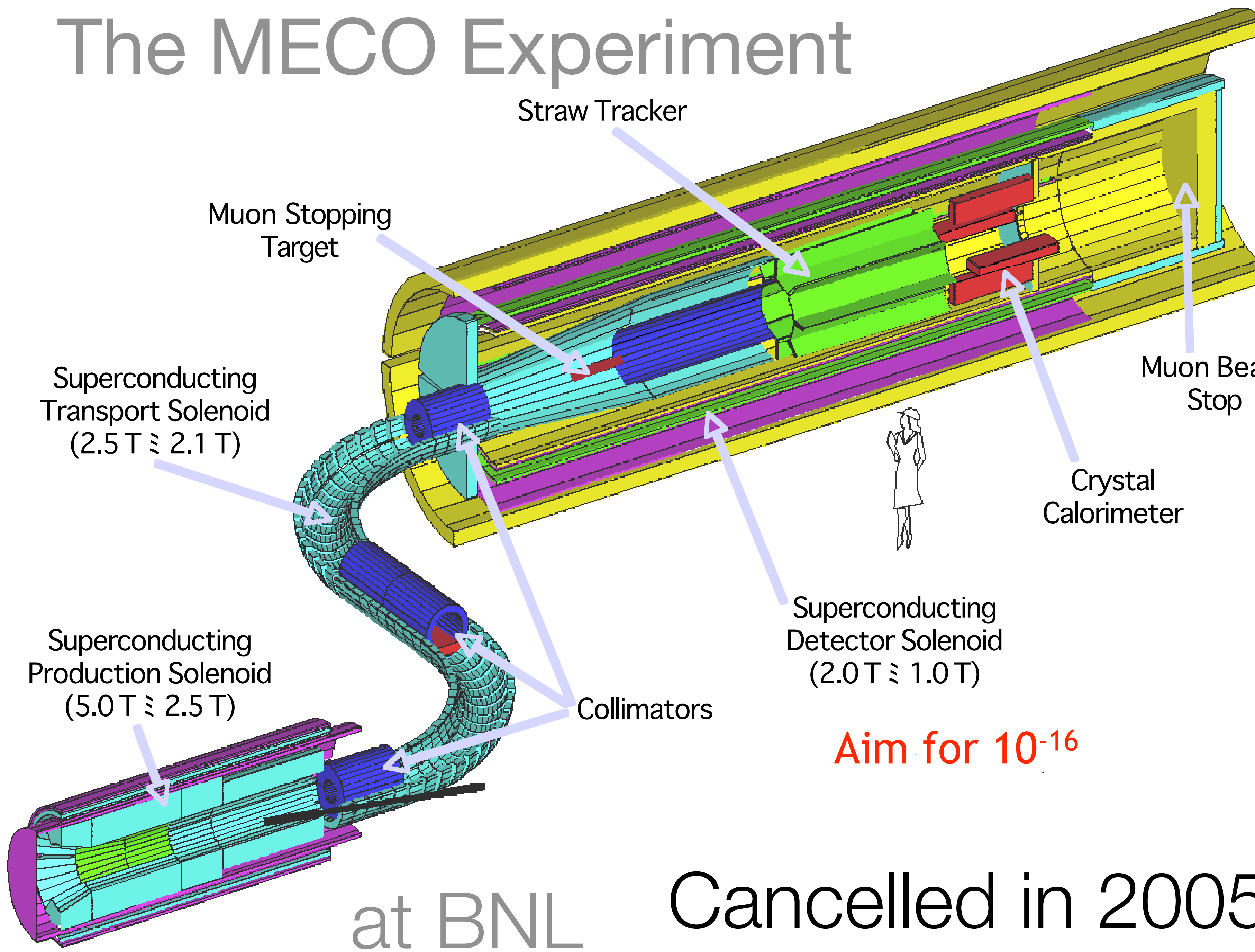

Aim for 10^{-16}

at BNL

Cancelled in 2005

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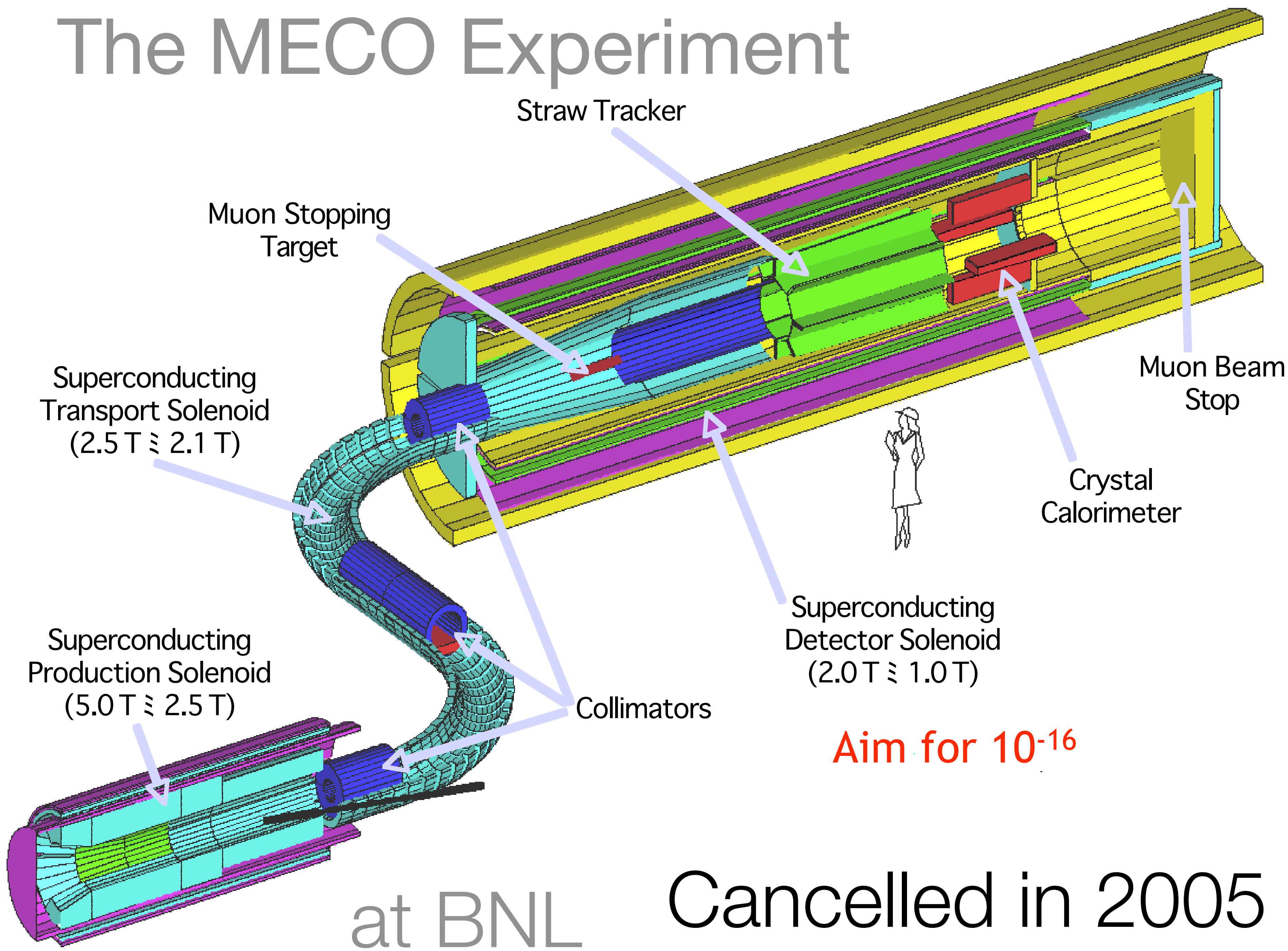
The MECO Experiment



Aim for 10^{-16}

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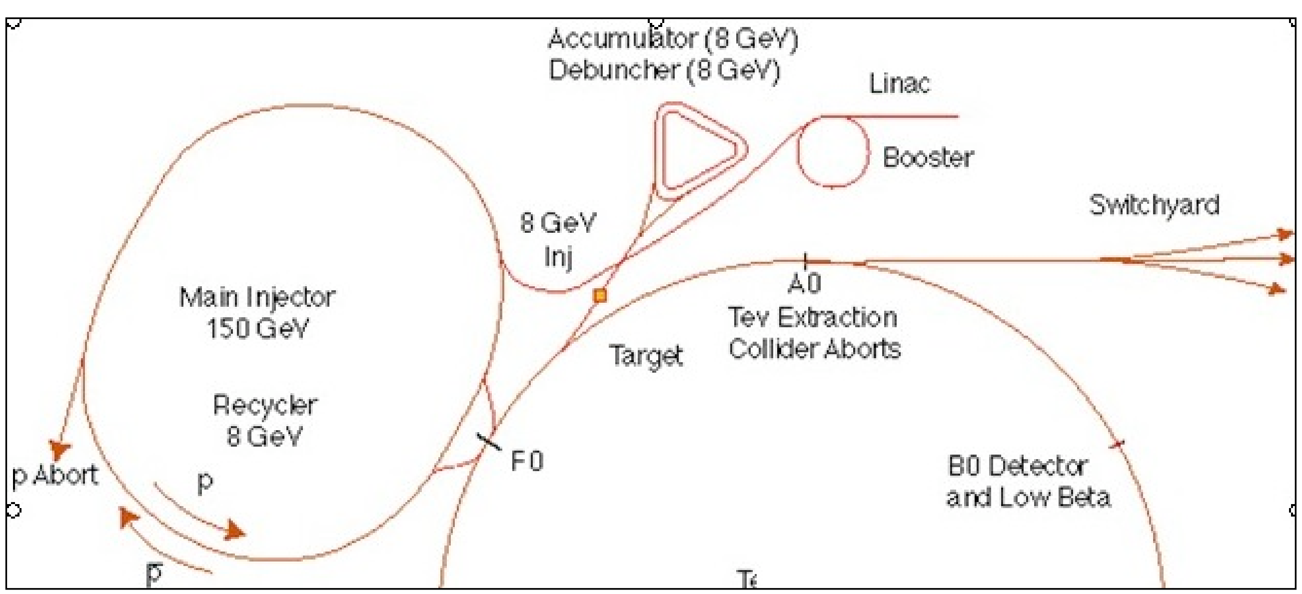
Cancelled in 2005

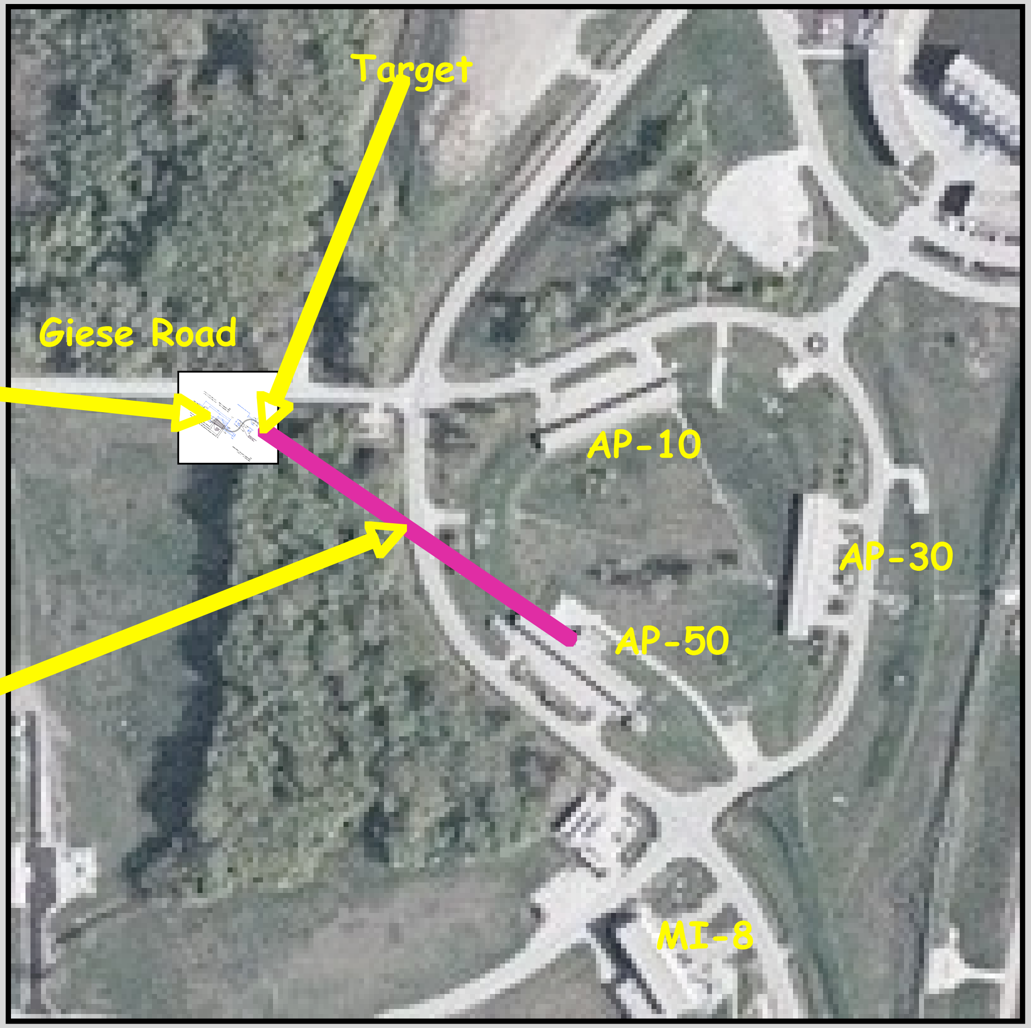
→mu2e @ Fermilab

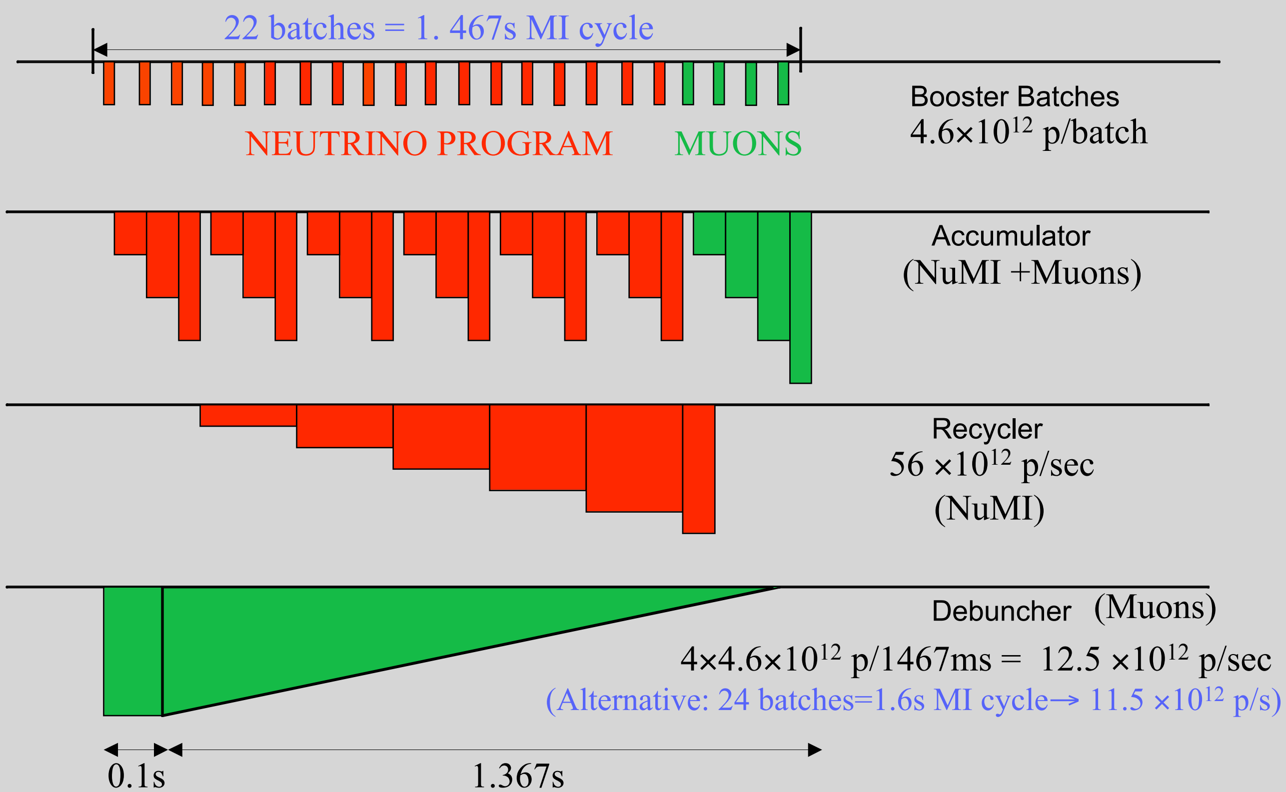
International Competition

- The mu2e Experiment at Fermilab.
  - The workshop on “mu2e” experiment was held at Fermilab on September 15th and 16th, 2006.
  - About 50 people attended.
- The mu2e Experiment
  - After the Tevatron shut-down.
  - use the antiproton accumulator ring to manipulate proton beam bunches.



Fermilab Accelerators





Comparison between $\mu \rightarrow e\gamma$ and μ-e Conversion (Experimental)

	background	challenge	beam intensity
• $\mu \rightarrow e\gamma$	accidentals	detector resolution	limited
• μ-e conversion	beam	beam background	no limitation

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- $\mu \rightarrow e\gamma$: Accidental background is given by (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.

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- 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.

Comparison between $\mu \to e\gamma$ and μ-e Conversion (Experimental)

	background	challenge	beam intensity
• $\mu \to e\gamma$	accidentals	detector resolution	limited
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- 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.

A Next Step should be μ-e conversion

Roadmap

Roadmap

If MEG finds LFV at 10^{-13}

- Experimental confirmation is needed.
- The photonic contribution of $\mu \to eee$ is out of reach since it is 6×10^{-3} smaller than $\mu \to e\gamma$. But non-photonic contribution can be searched.
- μ-e conversion at 10^{-15} or better should be performed for confirmation.

If MEG not finds LFV at 10^{-13}

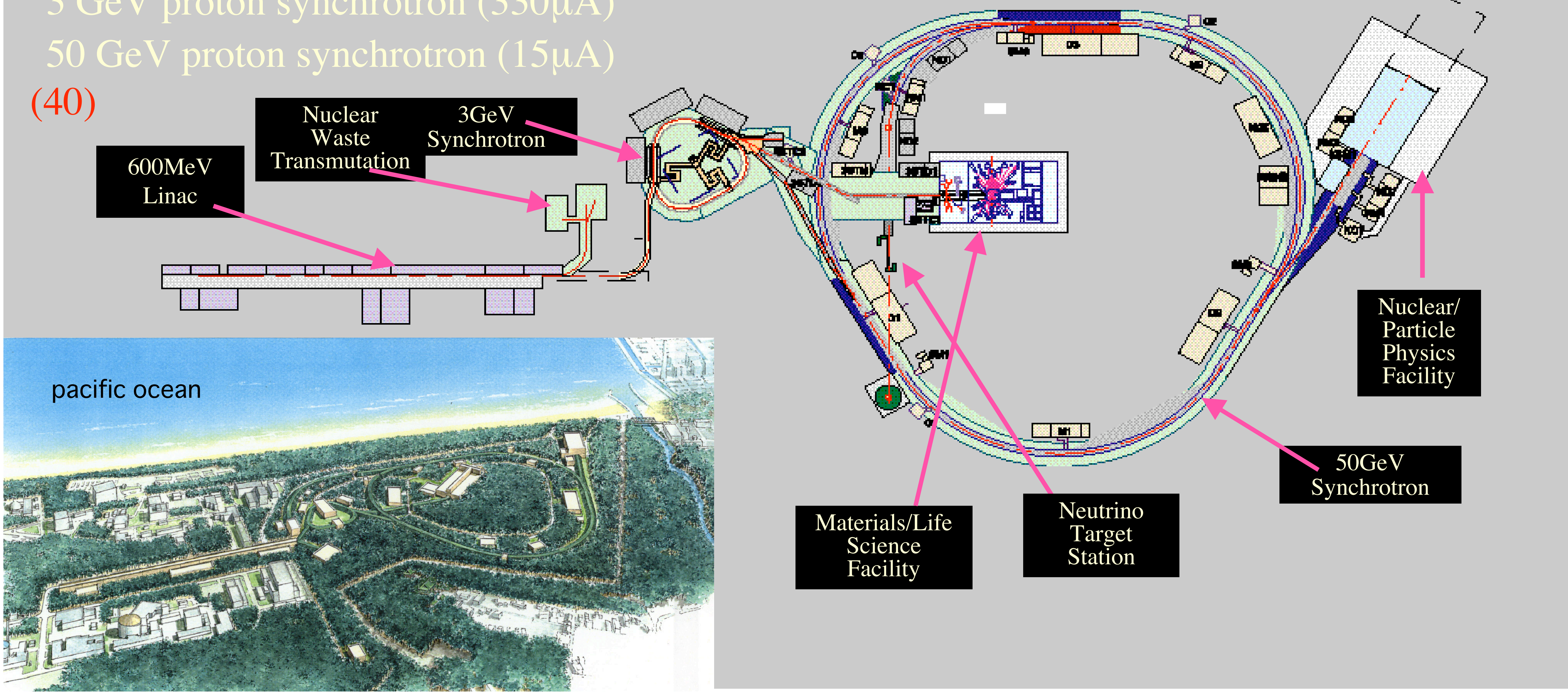
- Further experimental search is needed.
- $\mu \to e\gamma$ at 10^{-14} can be considered.
- μ-e conversion at 10^{-16} or 10^{-18} should be performed for further search.
- The non-photonic contribution could exist, and μ-e conversion or $\mu \to eee$ can be performed.

$\mu^- N \to e^- N$ is needed anyway....

@J-PARC

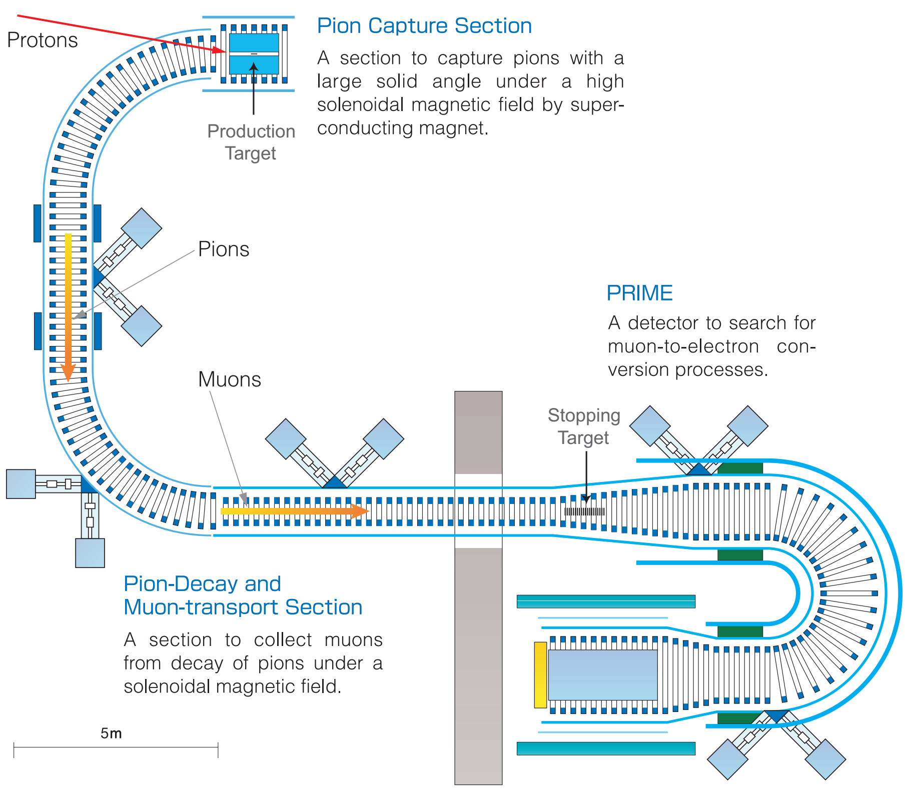
J-PARC
(Japan Proton Accelerator Research Complex)

400 (200) MeV proton linac
3 GeV proton synchrotron (330μA)
50 GeV proton synchrotron (15μA)
(40)



PRISM and Phase-1 (P1) at J-PARC

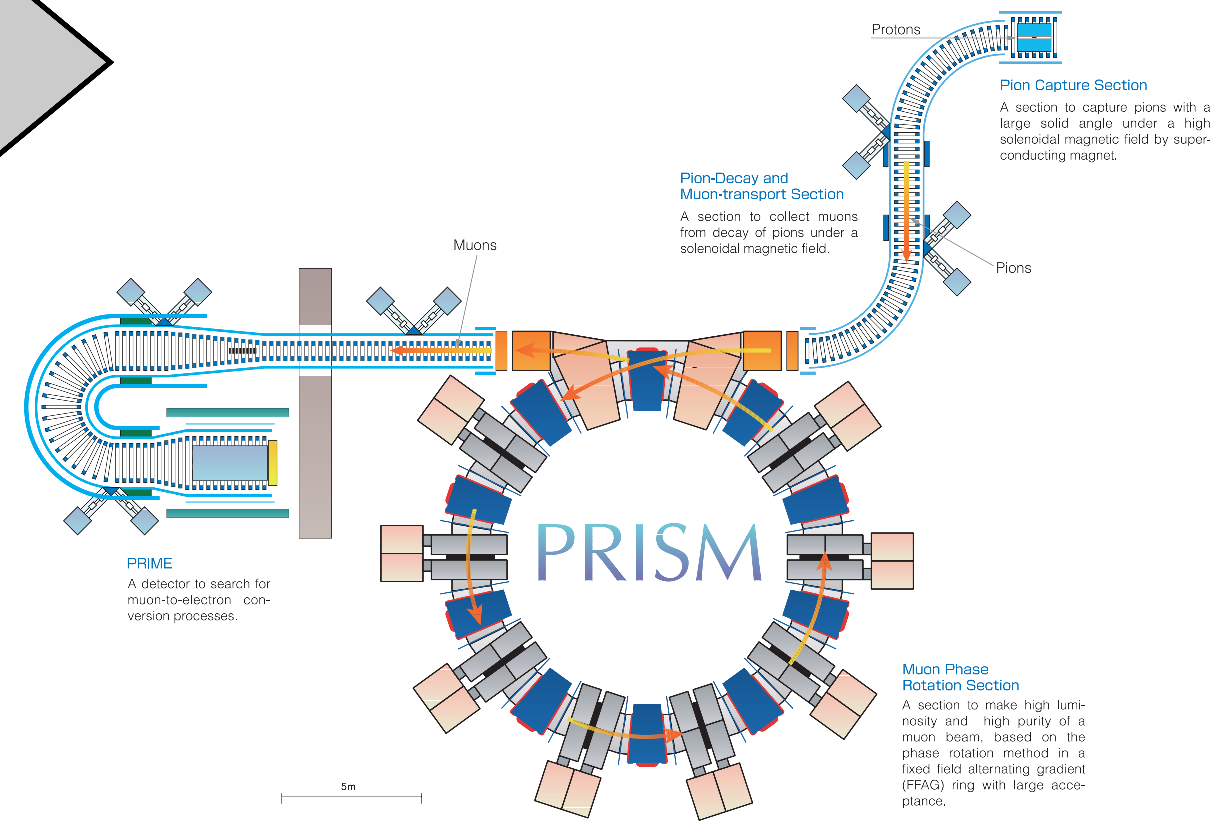
Phase 1 (P1)



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

- 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

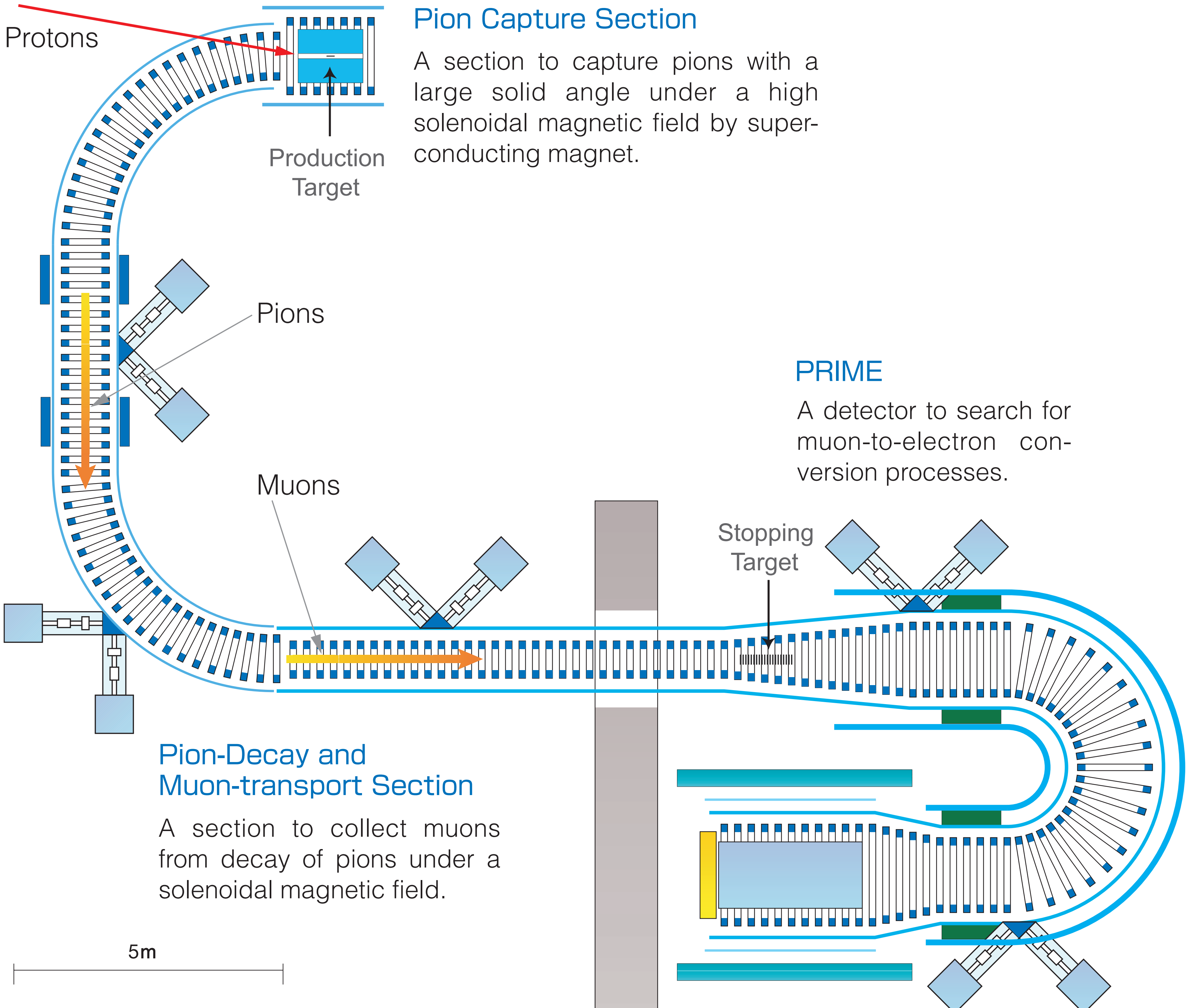
PRISM



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

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

Phase 1 (P1)



Pion Capture Section

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

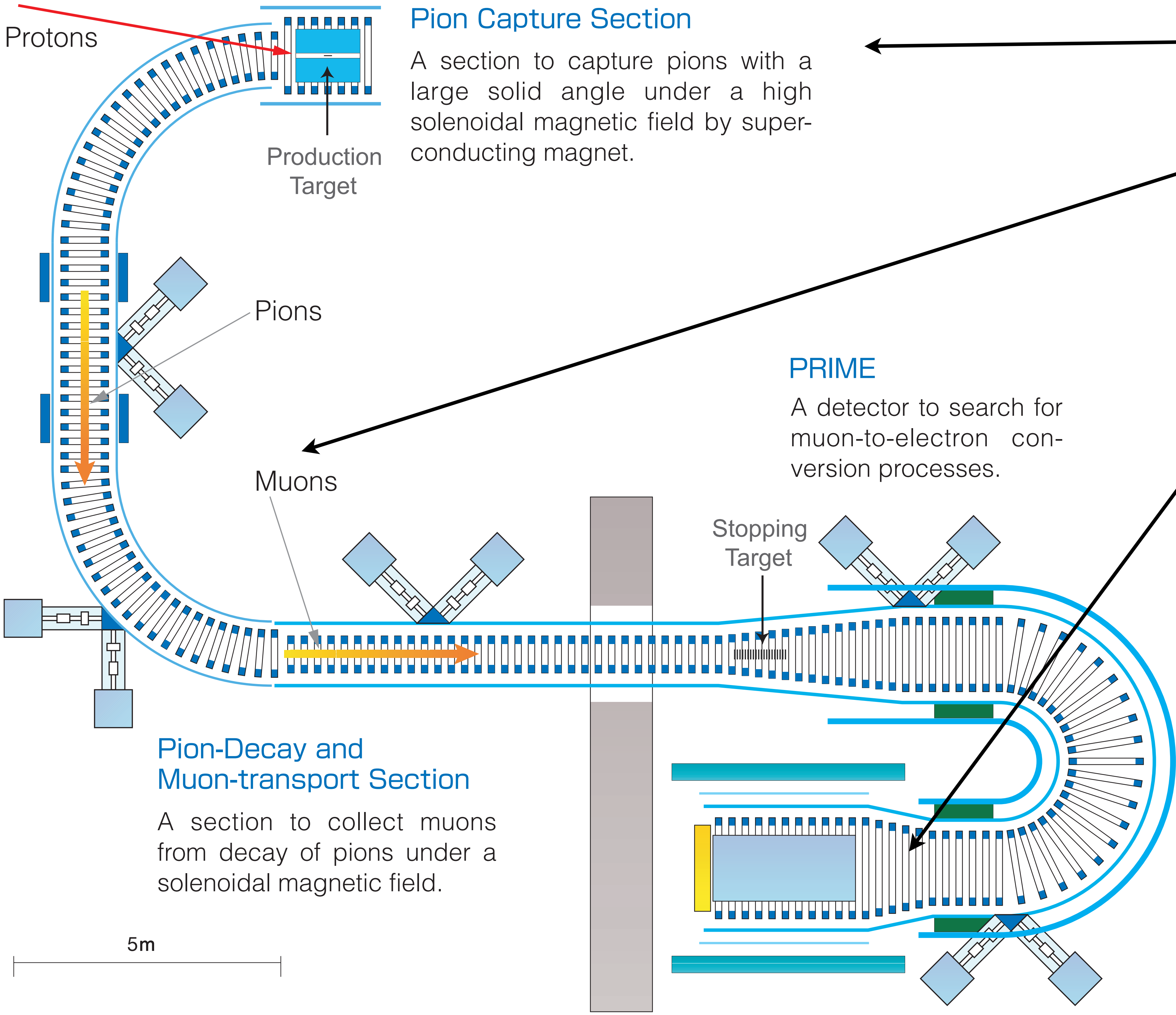
PRIME

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

Pion-Decay and Muon-transport Section

A section to collect muons from decay of pions under a solenoidal magnetic field.

Phase 1 (P1)

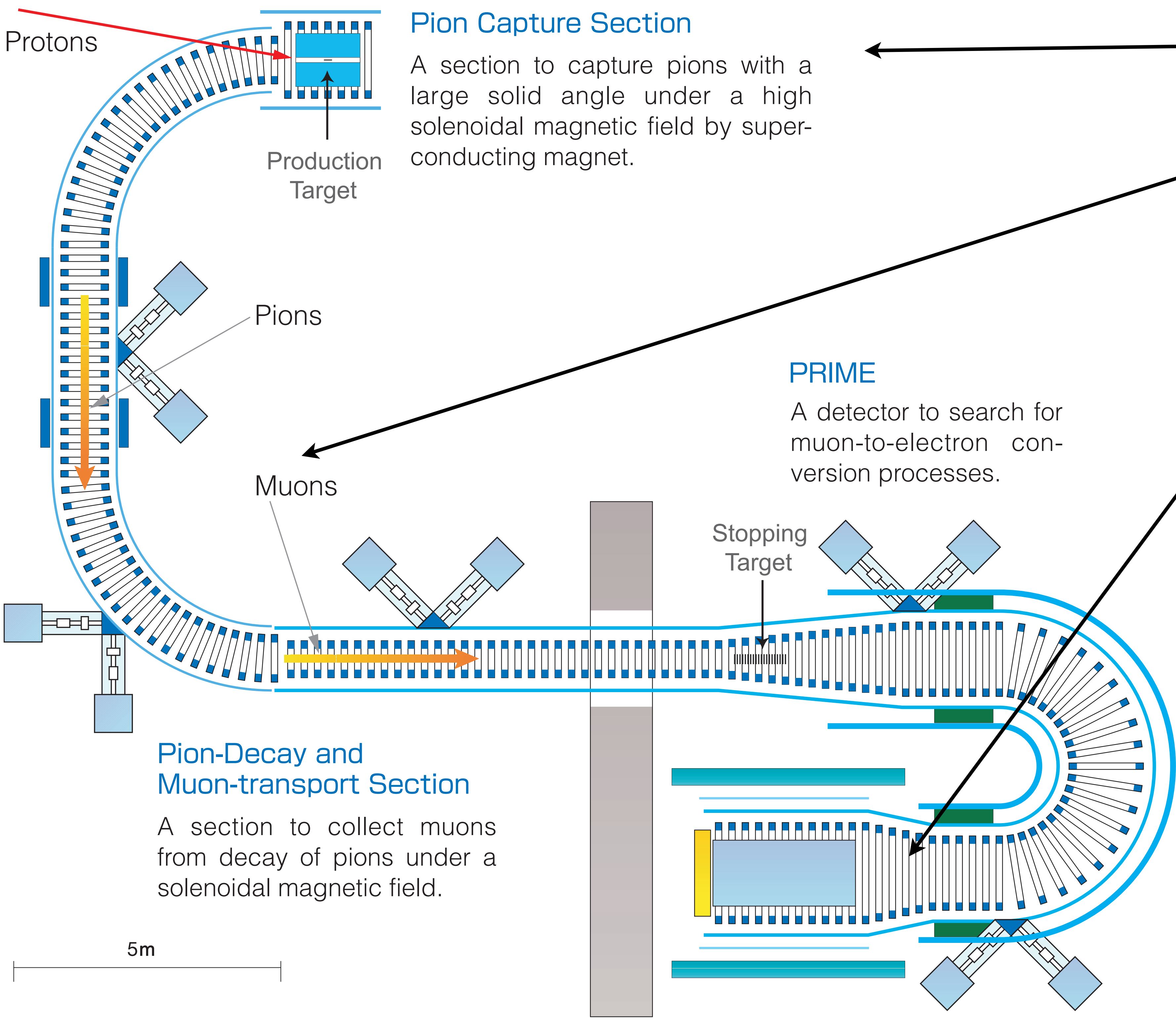


Proton Beam

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

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

Phase 1 (P1)



Proton Beam

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

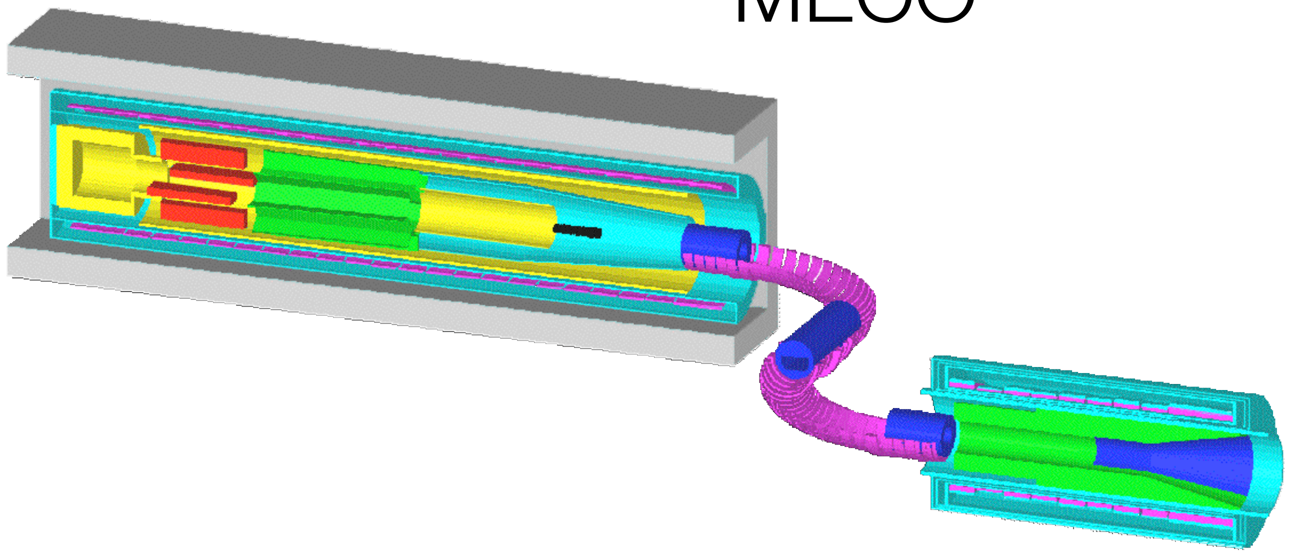
The Detector
- Muon Stopping Target
- Electron Transport
- Electron Detection

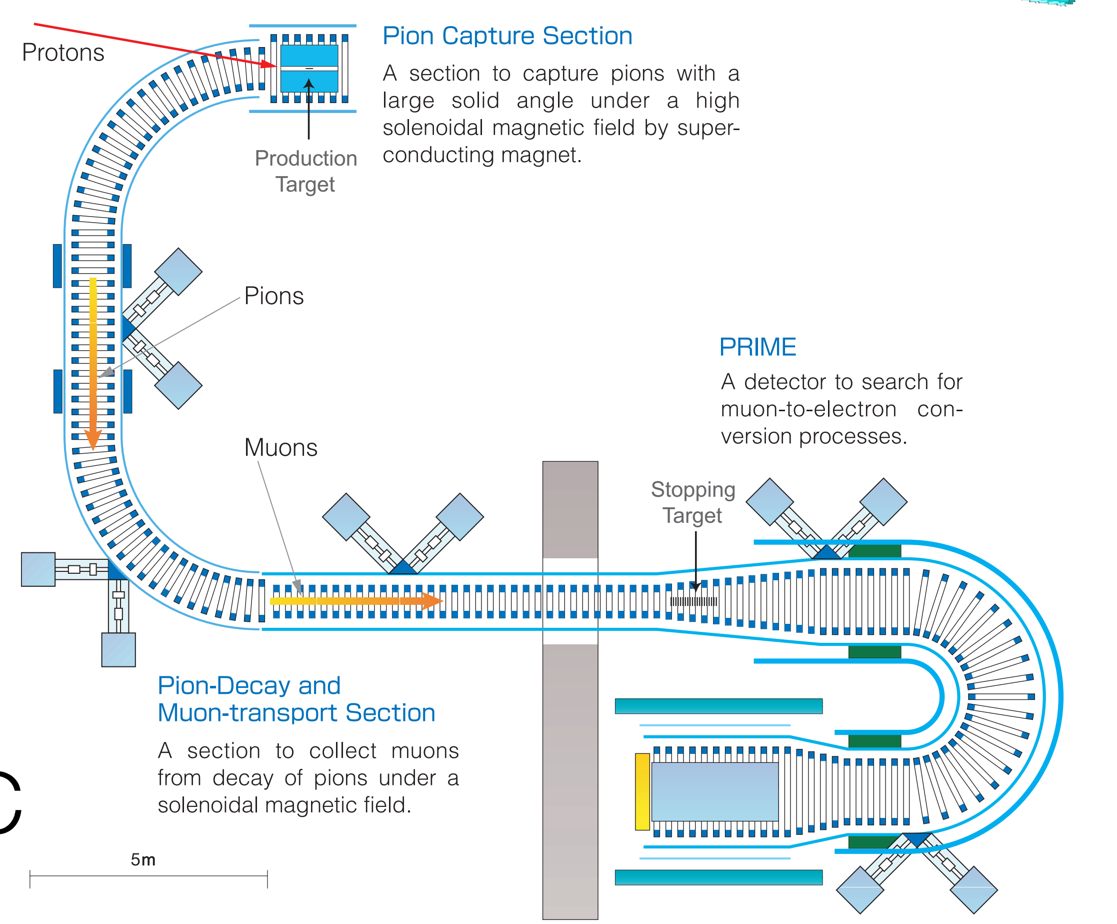
LOI was submitted to J-PARC PAC in December. 2006.
The full proposal will be submitted this summer.

Comparison with the MECO Experiment

- Proton Target
  - tungsten (MECO)
  - graphite (J-PARC)
- Muon Transport
  - Magnetic field distributions are different.
  - Efficiencies of the muon transports are almost the same.
- Spectrometer
  - For 10^{11} stopping muons/sec
  - Straight Solenoid (MECO)
    - ~500 kHz/wire
  - Curved Solenoid (J-PARC)
    - ~ 300 DIO tracks/sec

MECO





P1
@J-PARC

Charged Particle Trajectory in Curved Solenoids

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

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

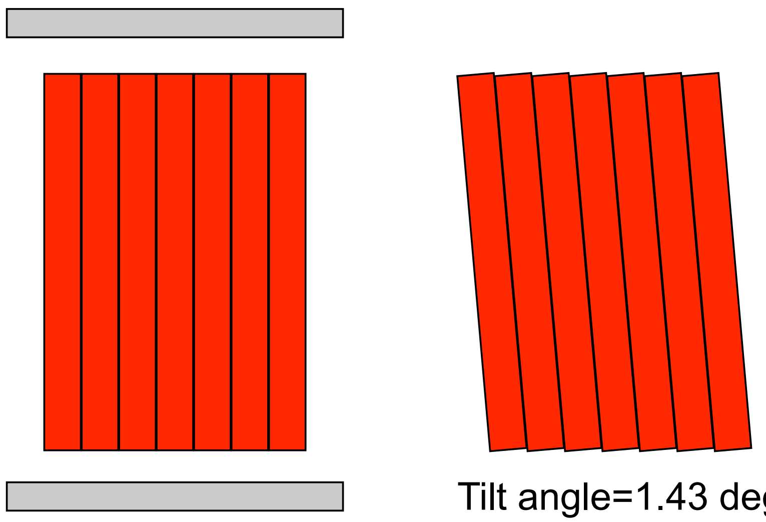
D : drift distance
B : Solenoid field
θ_{bend} *: Bending angle of the solenoid channel*
p : Momentum of the particle
q : Charge of the particle
θ *: atan(*P_T/P_L*)*

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

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

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

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



Tilt angle=1.43 deg.

Signal Sensitivity of P1@J-PARC (in LOI)

- 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 which is $6\text{x}10^{17}$ muons.
  - f_{cap} is a fraction of muon capture, which is 0.6 for aluminum.
  - A_e is the detector acceptance, which is 0.07.

total protons muon transport efficiency muon stopping efficiency	$8\text{x}10^{20}$ 0.0024 0.29
# of stopped muons	$6\text{x}10^{17}$

$$B(\mu^- + Al \rightarrow e^- + Al) = \frac{1}{6 \times 10^{17} \times 0.6 \times 0.07} = 4 \times 10^{-17}$$

$$B(\mu^- + Al \rightarrow e^- + Al) < 10^{-16} \quad \text{(90\% C.L.)}$$

Background Rejection Summary of P1@J-PARC

	Backgrounds	Events	Comments
(1)	Muon decay in orbit	0.05	230 keV resolution
	Radiative muon capture	<0.001	
	Muon capture with neutron emission	<0.001	
	Muon capture with charged particle emission	<0.001	
(2)	Radiative pion capture*	0.12	prompt
	Radiative pion capture	0.002	late arriving pions
	Muon decay in flight*	<0.02	
	Pion decay in flight*	<0.001	
	Beam electrons*	0.08	
	Neutron induced*	0.024	for high energy neutrons
	Antiproton induced	0.007	for 8 GeV protons
(3)	Cosmic-ray induced	0.04	10^{-4} veto efficiency
	Pattern recognition errors	<0.001	
	Total	0.34	

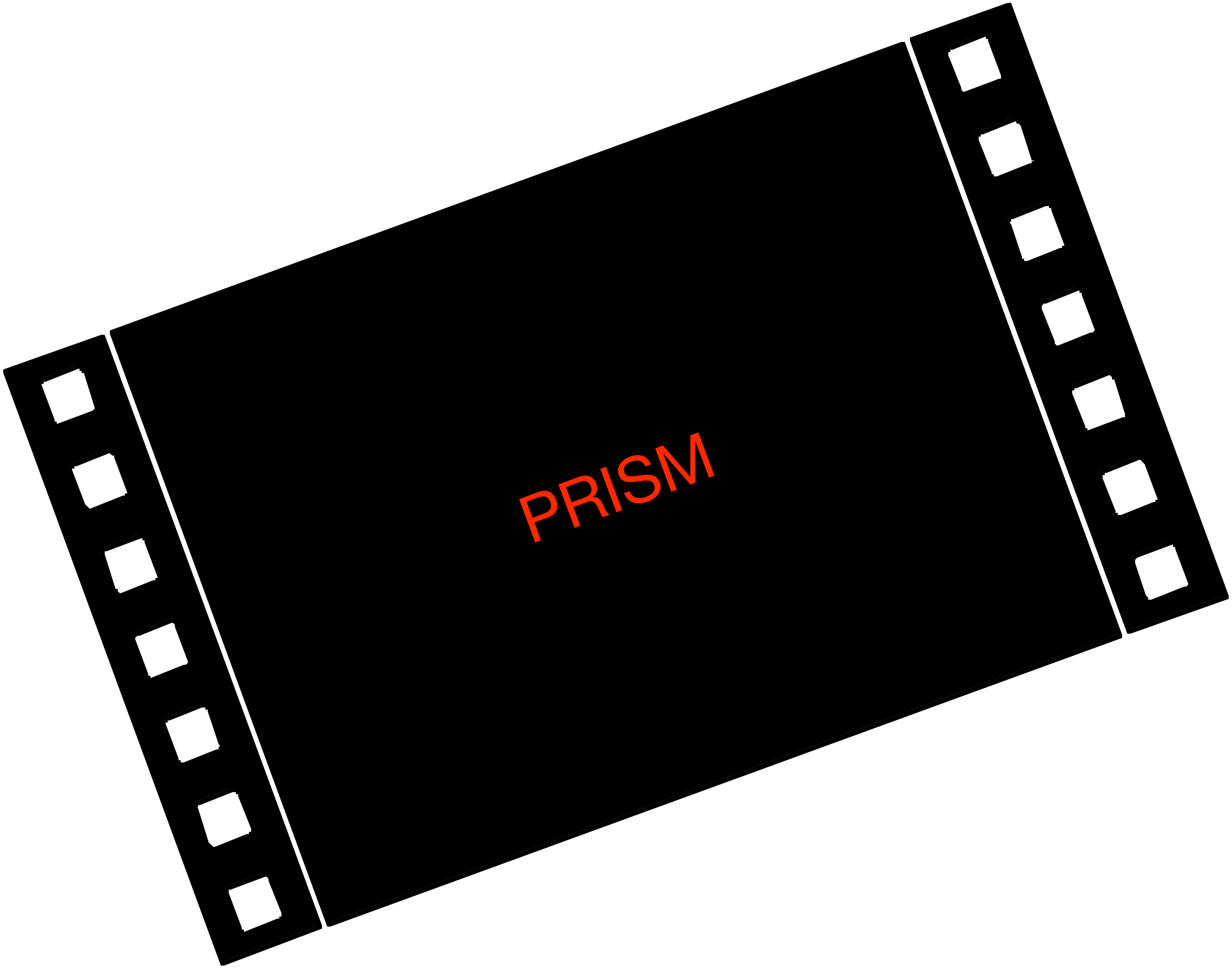
Timeline

Funding starting

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

The earliest scenario (and in reality be delayed.....).

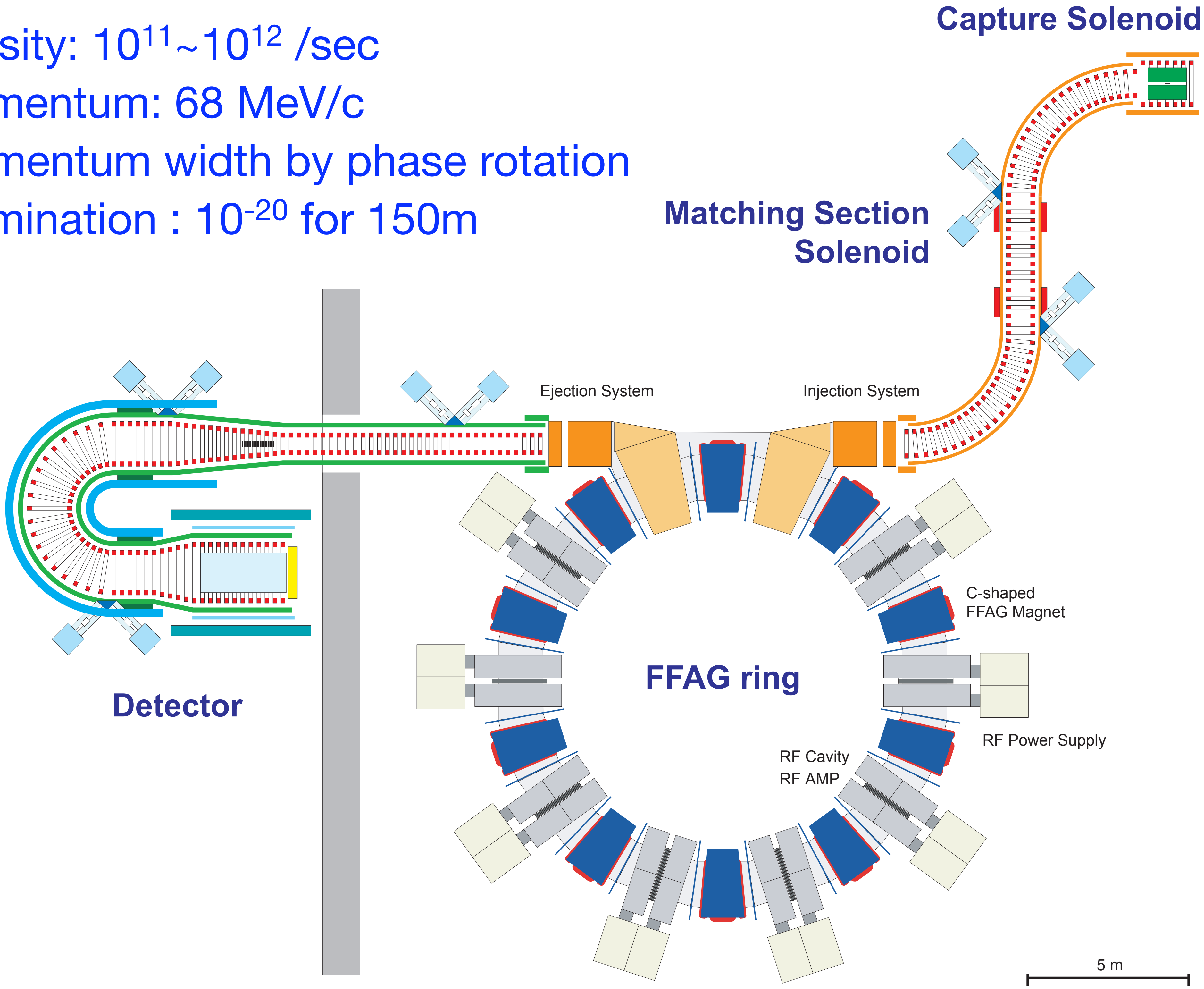
2007	2008	2009	2010	2011	2012
	J-PARC starts	T2K starts			


PRISM

PRISM Muon Beam

PRISM=Phase Rotated Intense Slow Muon source

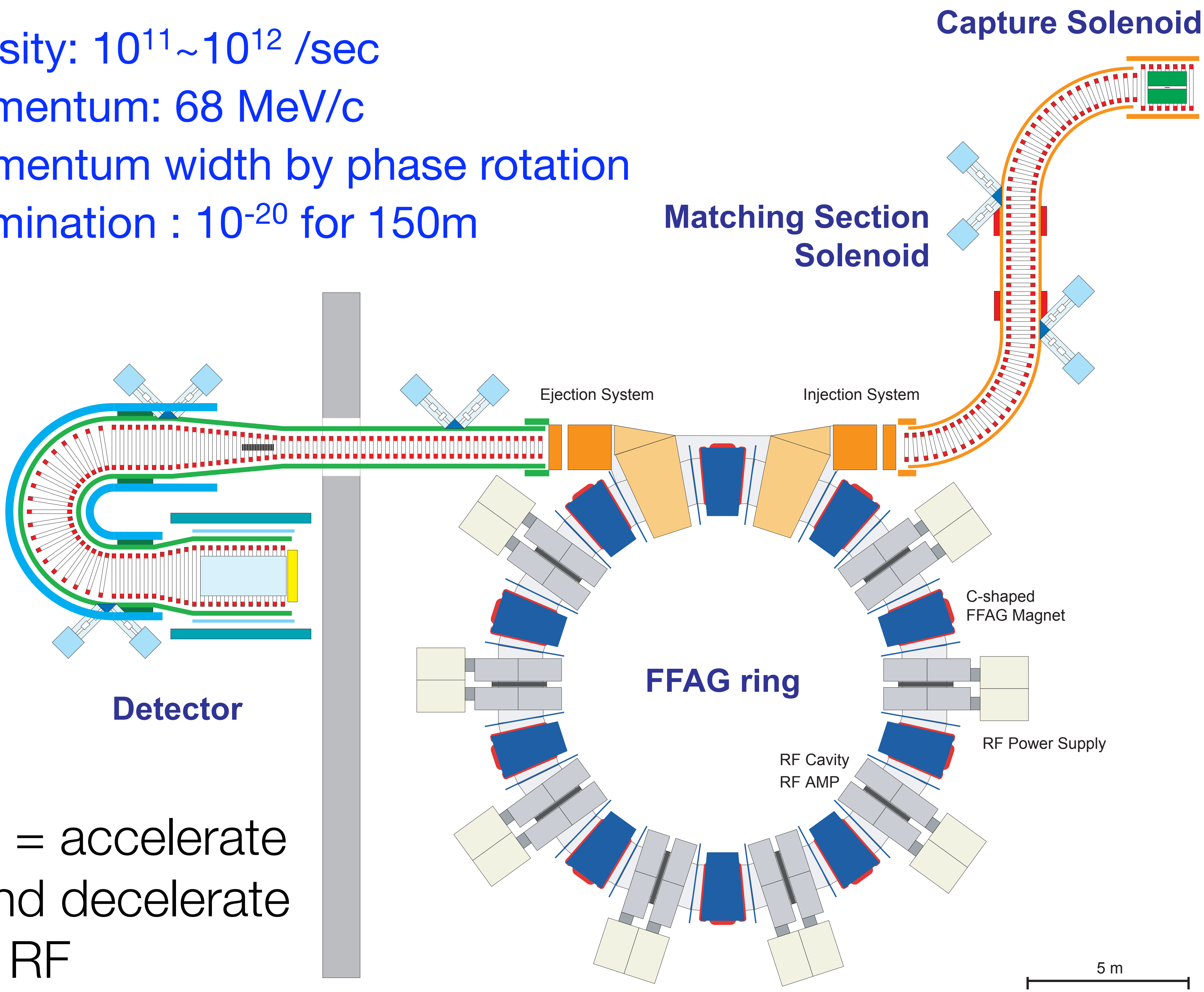
- muon intensity: 10^{11}~10^{12} /sec
- central momentum: 68 MeV/c
- narrow momentum width by phase rotation
- pion contamination : 10^{-20} for 150m



PRISM Muon Beam

PRISM=Phase Rotated Intense Slow Muon source

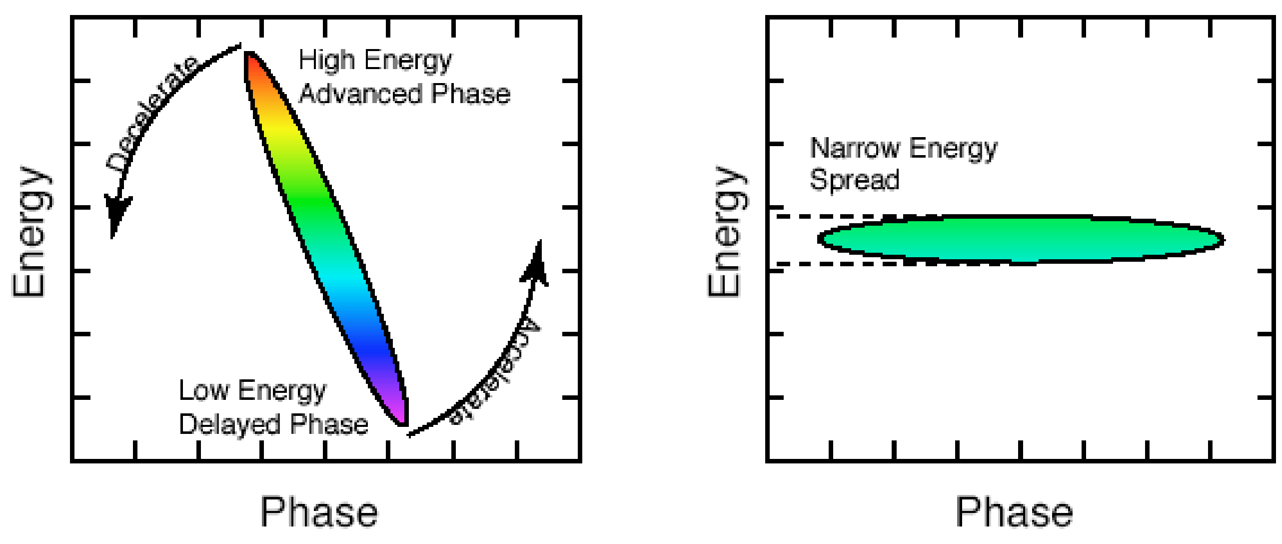
- muon intensity: $10^{11}\sim10^{12}$ /sec
- central momentum: 68 MeV/c
- narrow momentum width by phase rotation
- pion contamination : 10^{-20} for 150m



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) ?



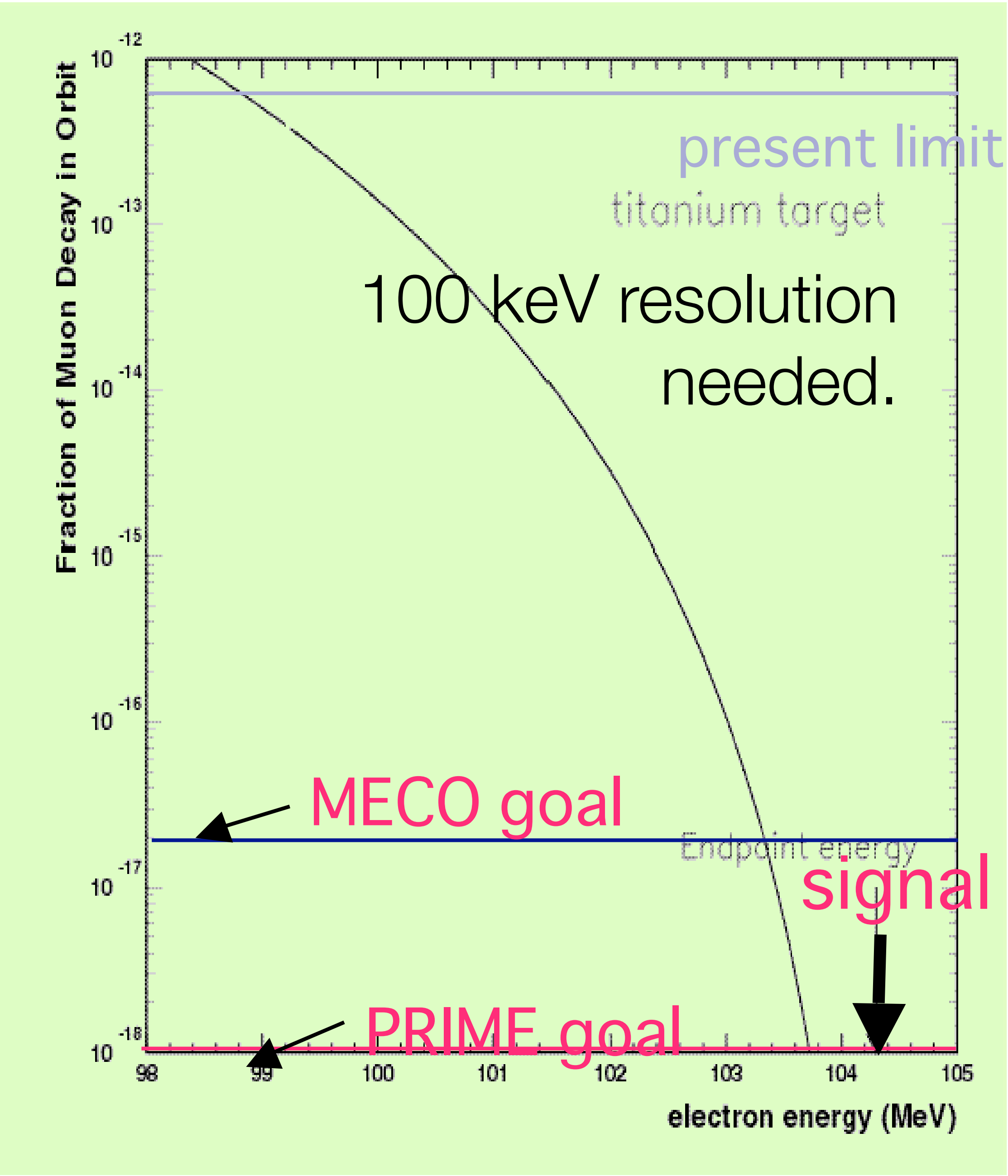
PRISM/PRIME Sensitivity for μ-e conversion

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

preliminary

	PRIME
proton beam power	0.6 MW
muon intensity	2×10^{11}/sec
acceptance	0.22
time window	100%
running period	5 year
Single Event Sensitivity	6×10^{-19}

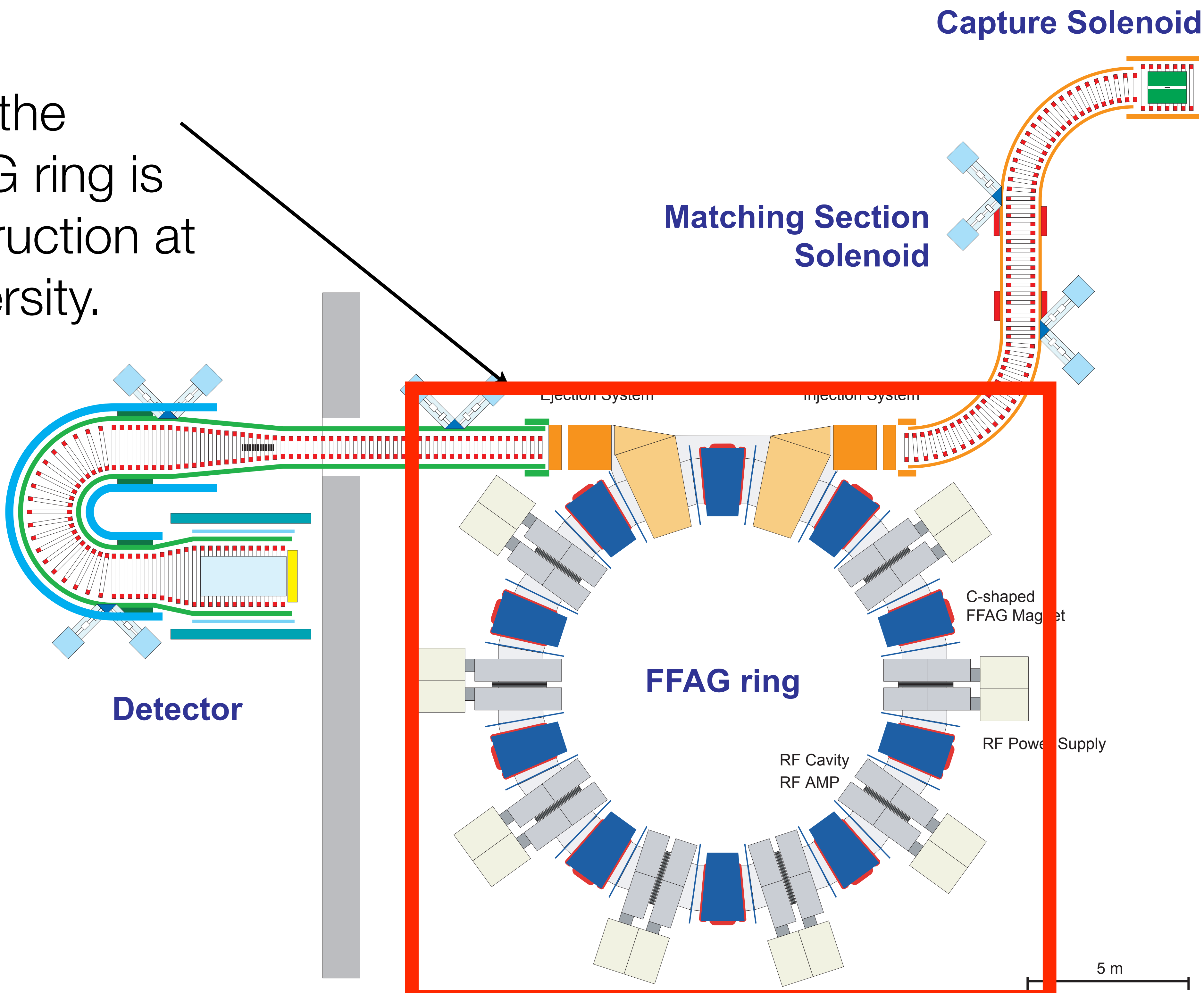
Work in Progress



from the PRISM/PRIME LOI (2006)

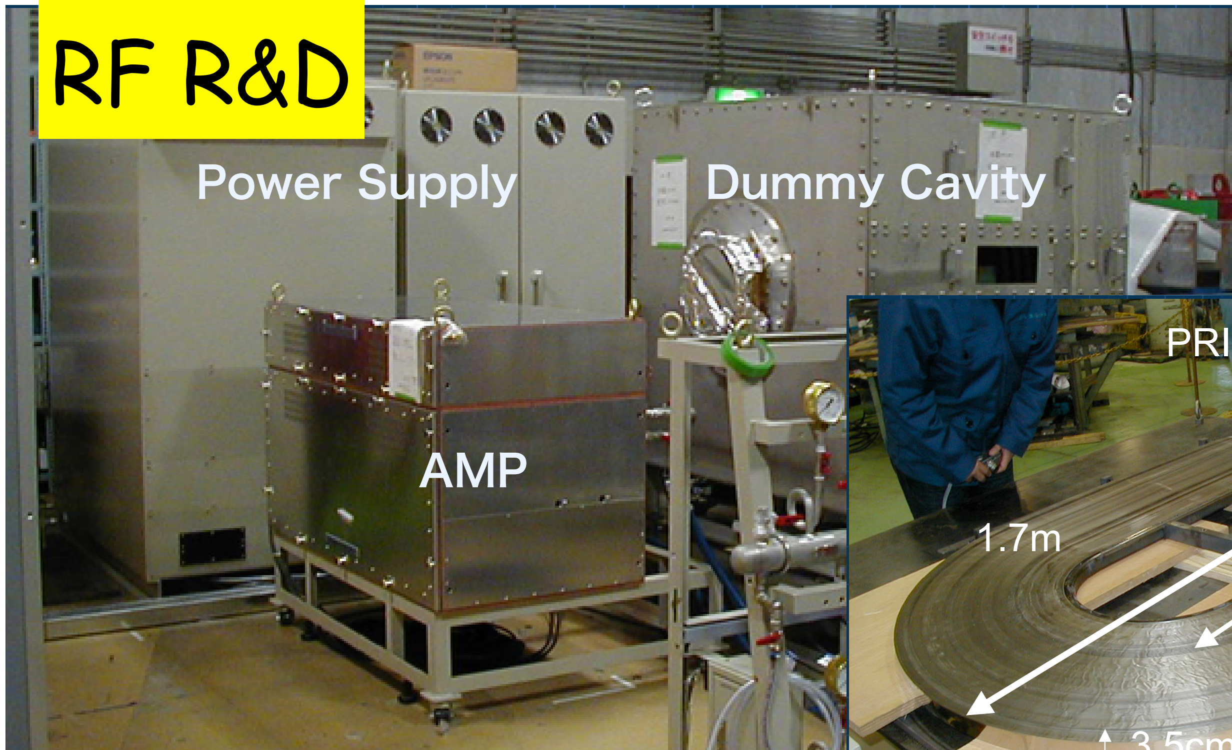
PRISM FFAG Ring R&D

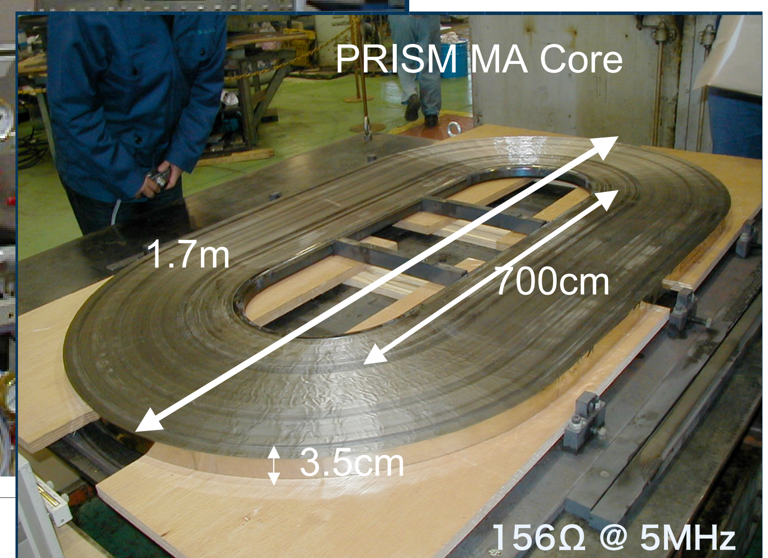
A portion of the PRISM-FFAG ring is under construction at Osaka University.

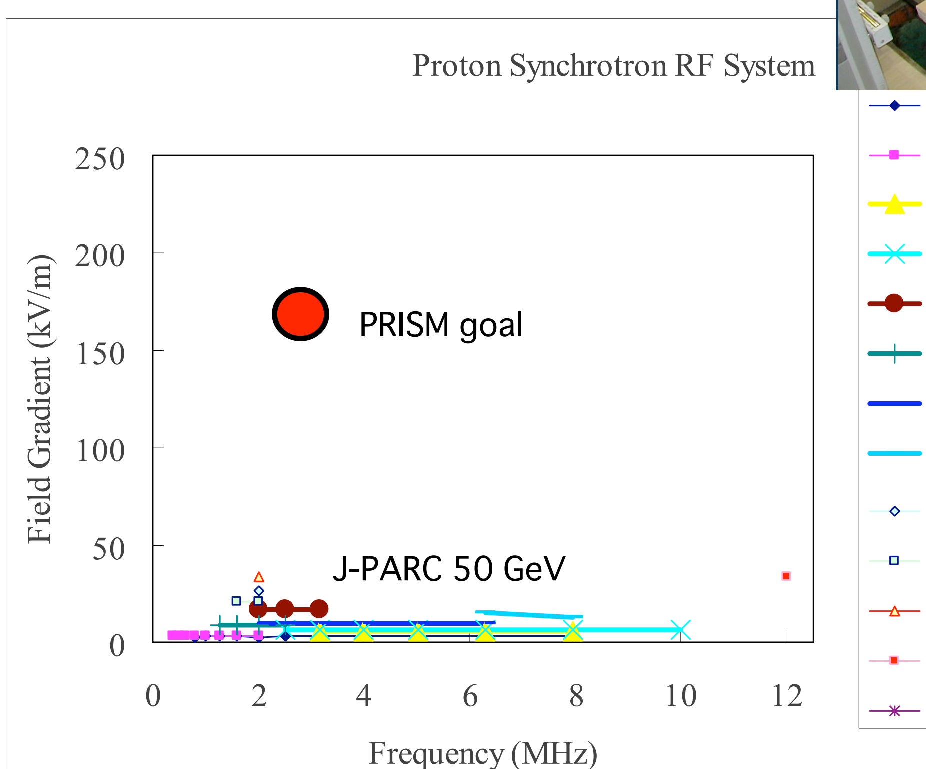


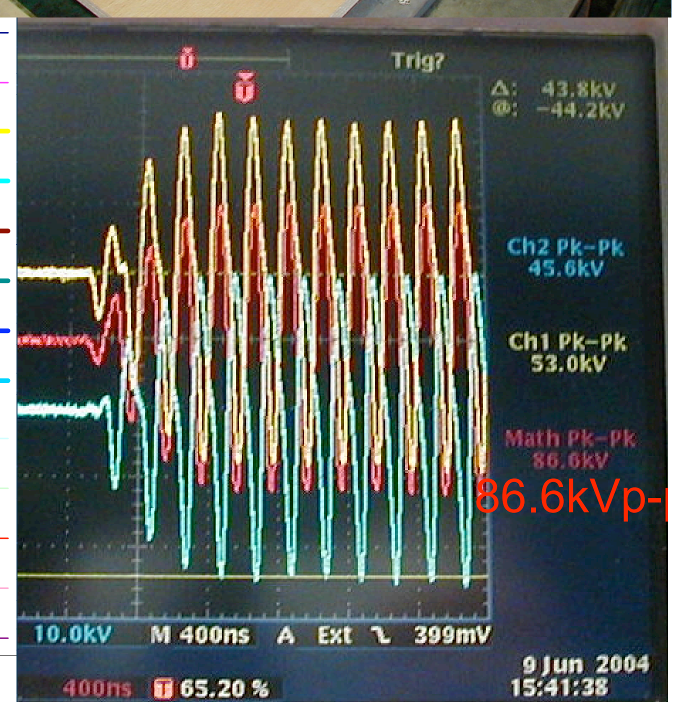
PRISM FFAG R&D is Going...

PRISM FFAG R&D is Going...



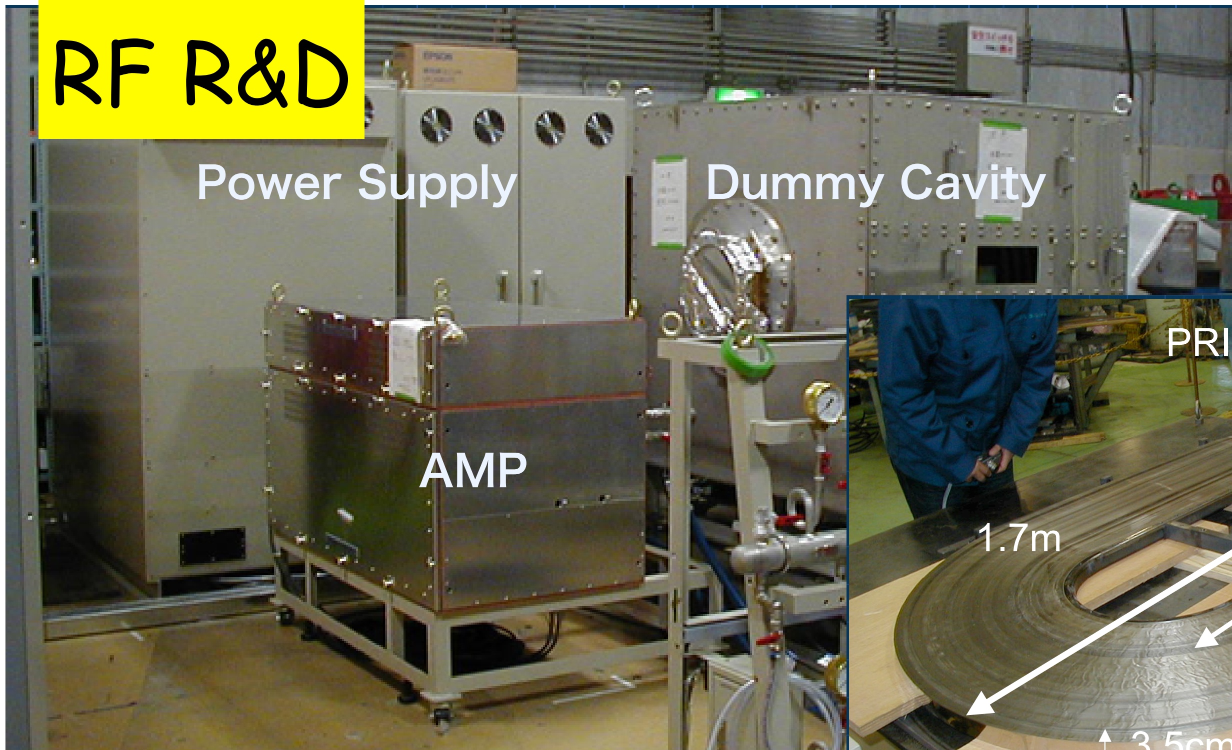


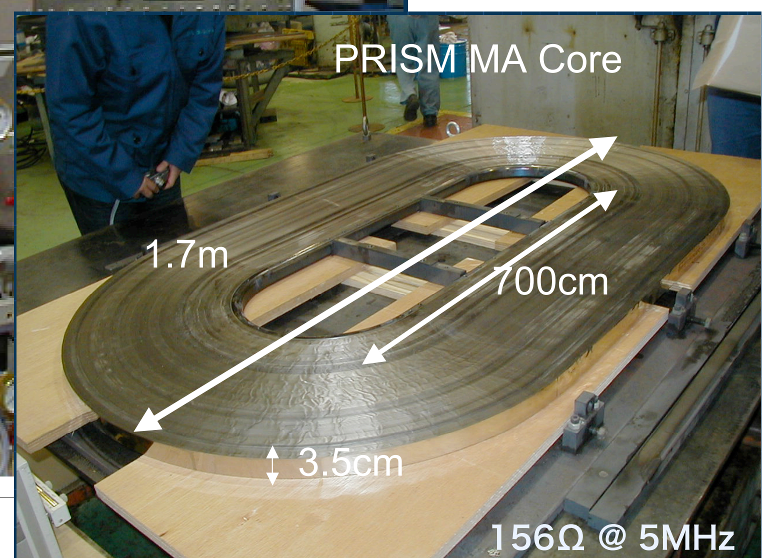


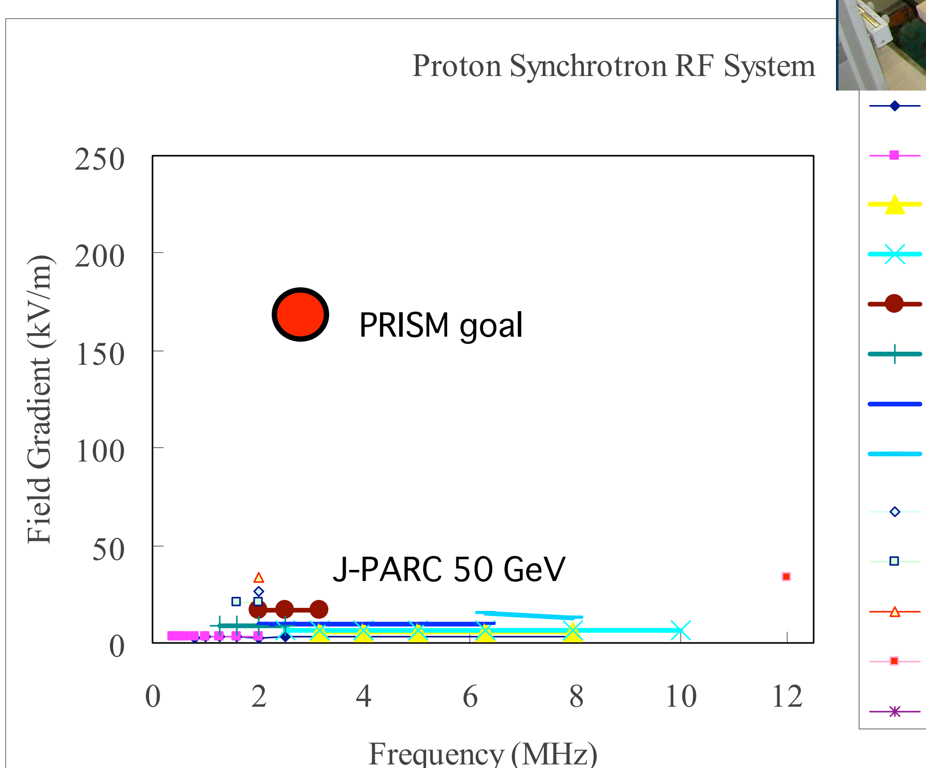


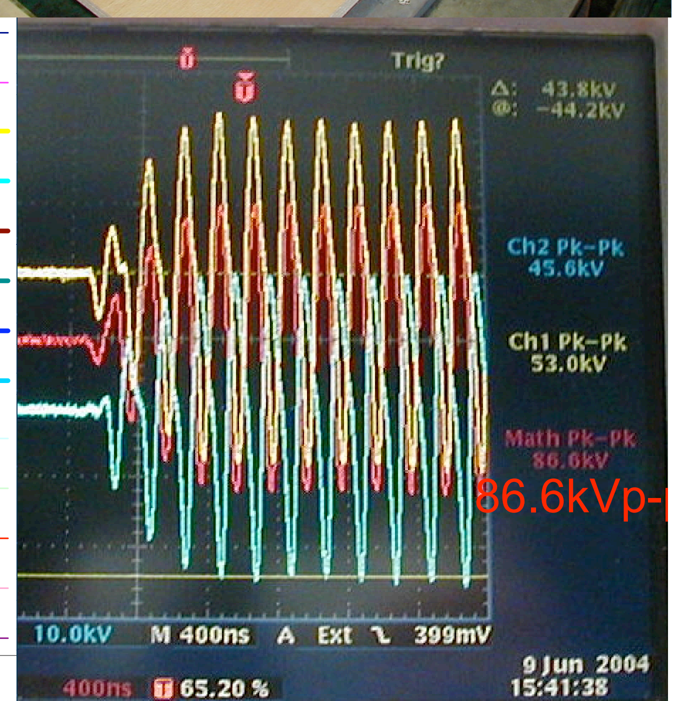
PRISM FFAG R&D is Going...

RF R&D

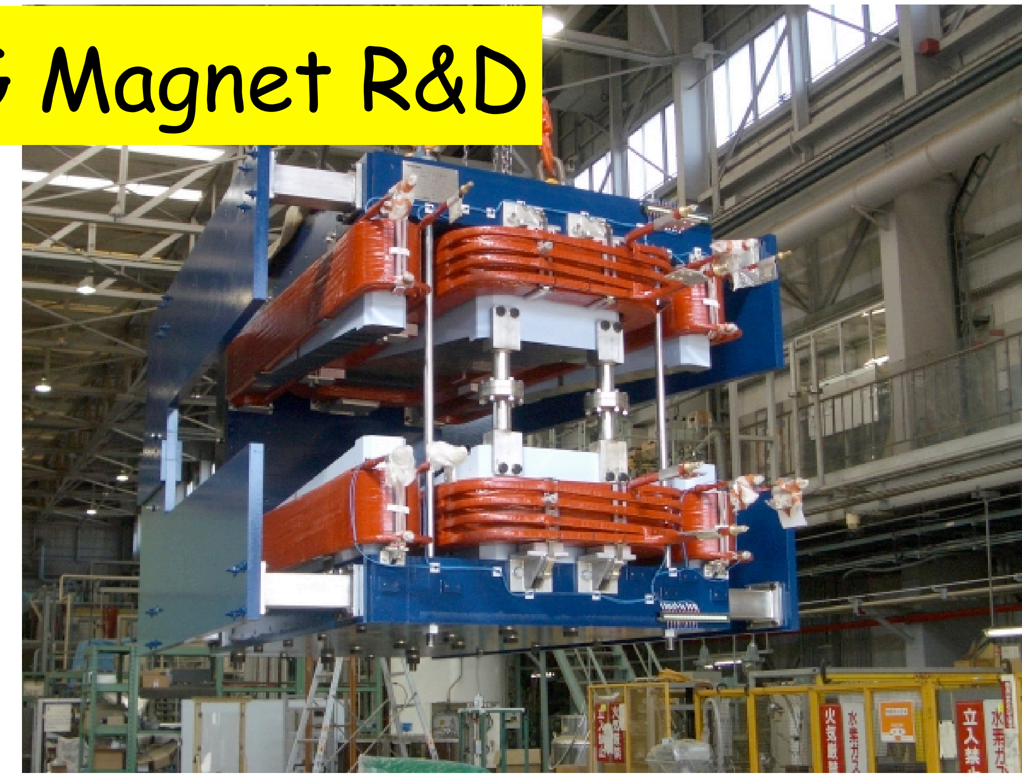


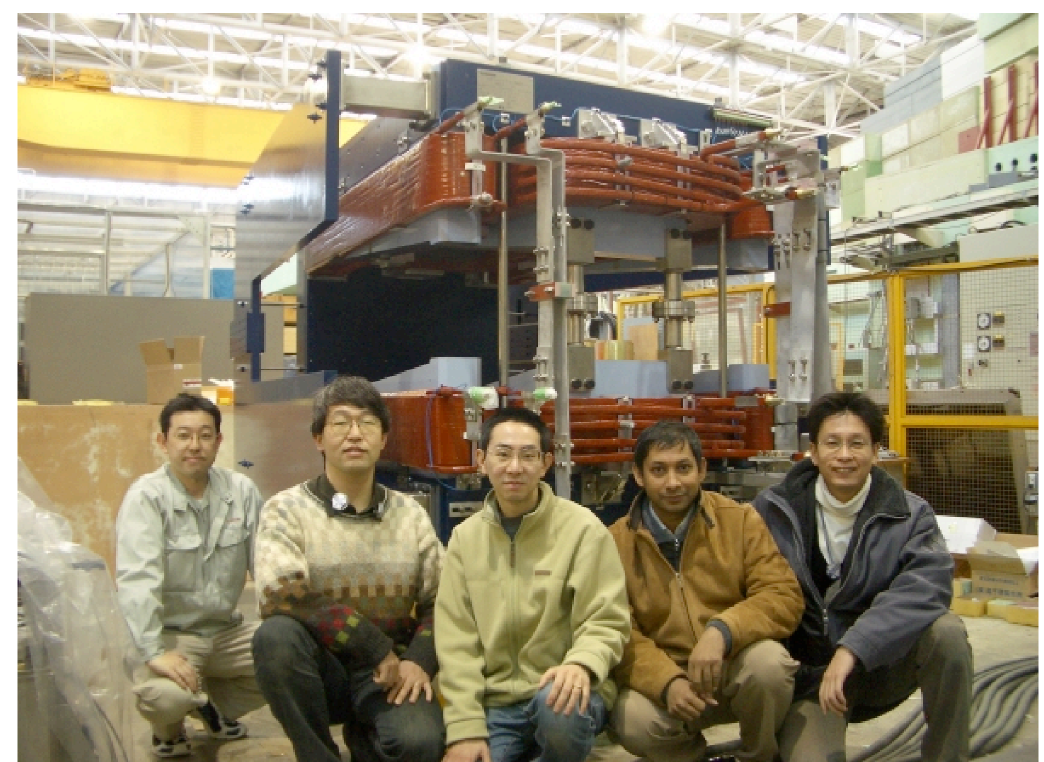




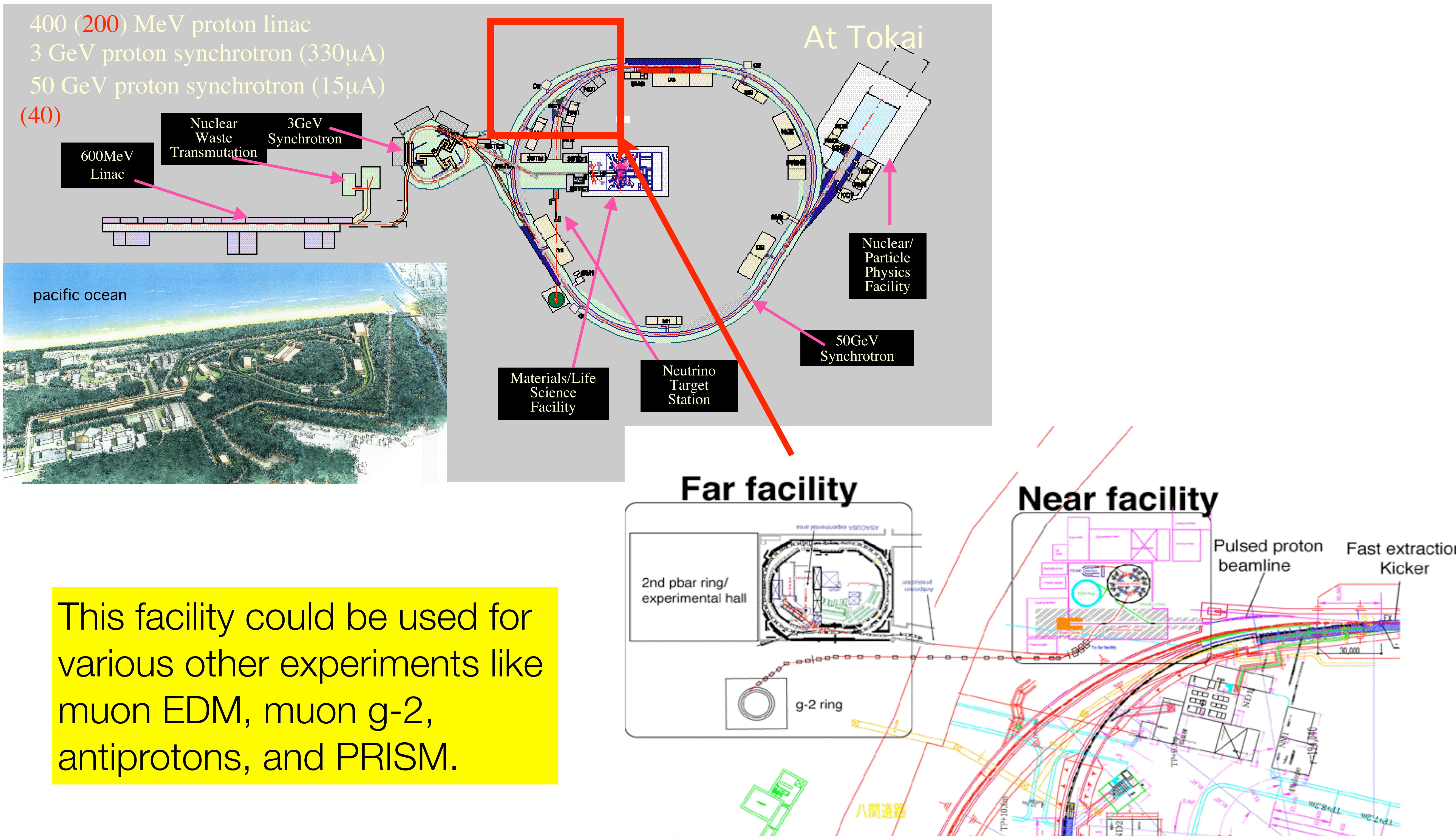


FFAG Magnet R&D





The Second Pulsed Proton Exp. Hall



This facility could be used for various other experiments like muon EDM, muon g-2, antiprotons, and PRISM.

@ PSI

Future LFV Searches at PSI as It Is.

- Features of PSI muon beams
  - ~ 10^8 muons/sec
  - continuous time structure

$$B(\mu^+ \to e^+\gamma) < 10^{-14}$$

- After the MEG experiment ($< 10^{-13}$) completes, it should be considered.
- To reduce accidental backgrounds, the improvement of the detector resolutions is mandatory to take 10^8 muons/sec. A total of the resolution improvement factor should be a factor of 10.
- Pileup effects also considered.
- Other tricks to reduce backgrounds ?

$$B(\mu^+ \to e^+e^+e^-) < 10^{-14}$$?

- After the MEG experiment ($< 10^{-13}$) completes, the photonic contribution is limited down to 6×10^{-17}. Only non-photonic physics can be searched.
- To reduce accidental backgrounds, improvement of the detector resolutions is mandatory.
- Several kinematical constraints would help reducing backgrounds, but increasing acceptance would be an issue.

Future Muon Physics at PSI with a Would-be Pulsed Intense Beam

- If a pulsed intense muon beam is available, there are many variety of muon particle physics that can be done, such as

$$\mathrm{EDM}\ d_\mu < 10^{-24}\mathrm{e}\cdot\mathrm{cm}$$

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

- High Intensity
  - 10^{11} - 10^{12} muons with 1 MW beam power
  - solenoid pion capture
    - such as the proposed J-PARC experiment, MECO, neutrino factory, etc.
- Pulsing a Beam
  - muon beam kickers
    - in μLAN
  - chopping ion sources
    - in the old SIN μ-e conversion experiment.
  - a proton storage ring
    - example : ASTOR

IEEE Transactions on Nuclear Science, Vol. NS-30, No. 4, August 1983

ASTOR, CONCEPT OF A COMBINED ACCELERATION AND STORAGE RING FOR THE PRODUCTION OF INTENSE PULSED OR CONTINUOUS BEAMS OF NEUTRINOS, PIONS, MUONS, KAONS AND NEUTRONS

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Summary

A new concept for a high intensity accelerator for 2 GeV protons using the continuous 590 MeV beam from the present ring cyclotron has been worked out at SIN. To suppress the cosmic background in neutrino experiments a pulsed beam with high peak current and low duty cycle is required. Using the so called phase expansion effect[1,2] one can combine the acceleration and storage effect in a single isochronous cyclotron ASTOR. With the help of several RF cavities, positioned at different radii it is possible to operate ASTOR either in a pulsed mode at 1500 Hz or in a continuous mode. The anticipated beam powers are .8 MW and 4 MW respectively. The ASTOR concept is also applicable in a possible kaon factory design, acting as an interface between the SIN ring cyclotron and a 50 Hz synchrotron for 15 to 20 GeV protons.

Introduction

In the ASTOR concept a proton beam is first accelerated and then stored before being ex-

Equation (2) shows that the energy gain at injection should be as low as possible in order to obtain a high stacking efficiency. With precessional injection one can clear the injection septum even with a relatively low energy gain. The ideal would be H^- -injection with stripping, a method which has been investigated for the TRIUMF kaon factory project[3].

A schematic layout of ASTOR is shown in fig.1. With the use of several RF cavities, positioned at different radii as shown in fig.2, it is possible to operate ASTOR in the following two modes :

1. Continuous mode:
   Acceleration of a continuous (CW) 590 MeV proton beam to its final energy (like a conventional cyclotron).

2. Pulsed mode:
   Acceleration plus storage of the proton beam at the final energy and extraction as a single short pulse with a fast kicker.

ASTOR at SIN (1983)

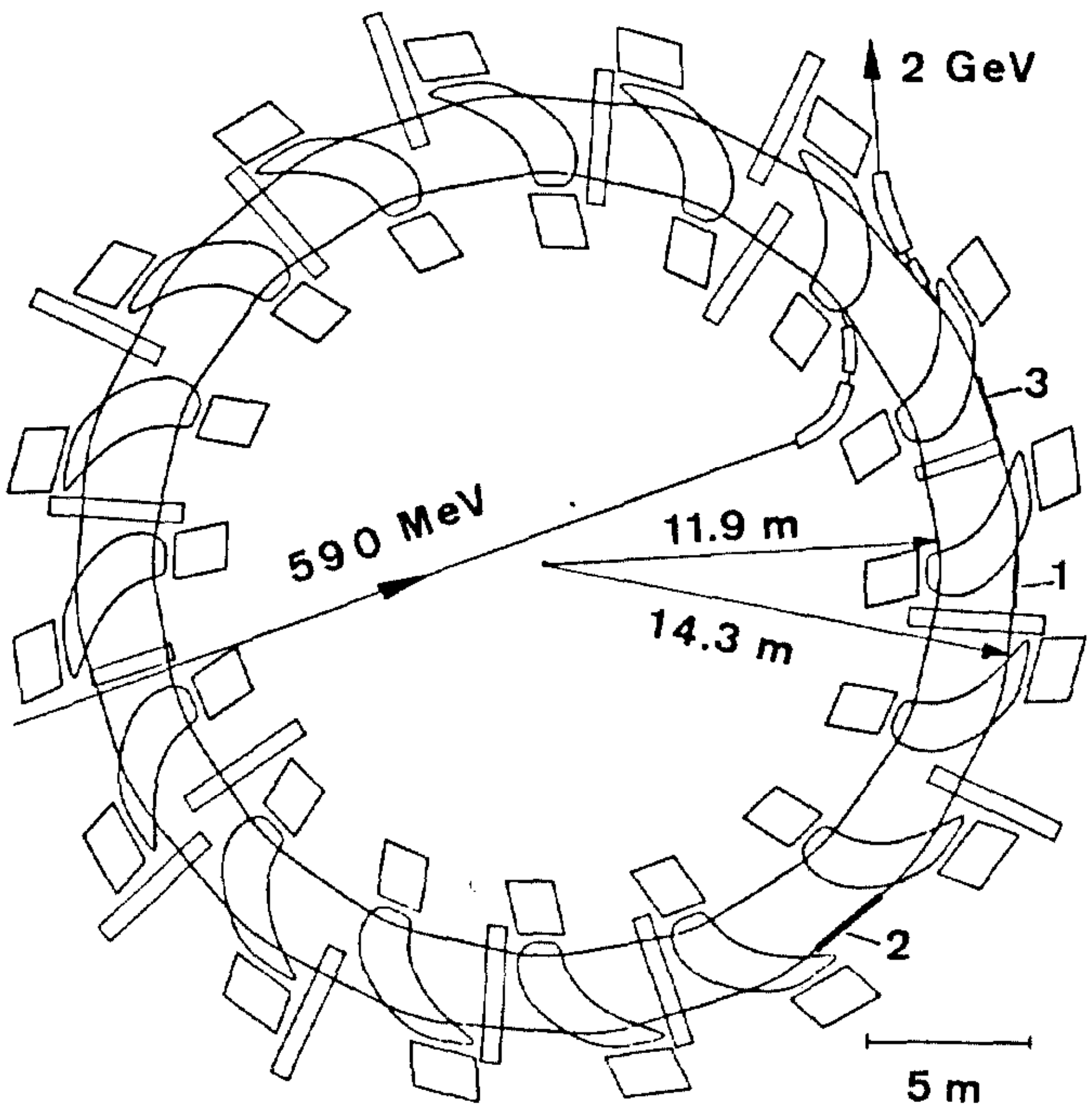

Figure 1: Layout of ASTOR , a .59 - 2 GeV isochronous cyclotron. The ring consists of 16 sector magnets, 14 RF cavities of 50 Mhz and 2 flat top cavities of 100 Mhz. In the continuous mode the beam is extracted with an electrostatic septum (1), while in the pulsed mode the beam is deflected vertically by a fast kicker (2) into a magnetic channel (3).

Table 1 : Reference design for ASTOR .

Energy interval	.59 - 2 GeV
Radius interval	11.90 - 14.35 m
Number of sector magnets	16
Total magnet weight	6000 t
Max. magnetic field	2 T
Max. spiral angle	60°
Horizontal focusing frequency	1.7 - 3.9
Vertical focusing frequency	.7 - .8
Harmonic of acceleration	16
Cavities 50 MHz ,600 kV	6+6+2
Cavities 100 MHz ,600 kV (flat top)	2
Continuous beam mode :	
Average current <I>	2 mA
Orbit separation at extraction	>2.5 mm
Pulsed beam mode :	
Average current <I>	.4 mA
Number of stacked turns	500
Protons per pulse	1.5*10**12
Pulse length of extracted beam	260 ns
Peak current	1 A
Repetition frequency	1500 Hz
Field strength of kicker	.02 T*m
Duty cycle	5*10**-4
Phase width of injected beam	10°
Momentum spread of extracted beam	±.7 %

Summary

- Physics motivation of charged lepton flavor violation (LFV) with muons is very strong and robust.
- It is sensitive to new physics beyond the Standard Model, in particular SUSY-GUTs or SUSY-Seesaw models, models of extra-dimensions etc.
- $\mu \to e\gamma$, $\mu \to eee$ and μ-e conversion are the major LFV processes of muons.
- The MEG experiment at PSI is an only experiment currently under preparation and will start in 2007 with a sensitivity of 10^{-13}.
- At J-PARC with pulsed proton beams, a search for μ-e conversion is seriously considered with staging approach.
  - Phase-1@J-PARC, which is planned to start early by using slowly-extracted pulsed proton beam, aims a sensitivity of 10-16.
  - As phase-2, PRISM with a muon storage ring will be considered with fast extraction beam.
- If a pulsed intense muon beam from a cyclotron would be available, more variety of muon physics can be considered.