Experimental Review of Charged Lepton Flavor Violation

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Florence, Italy

Outline

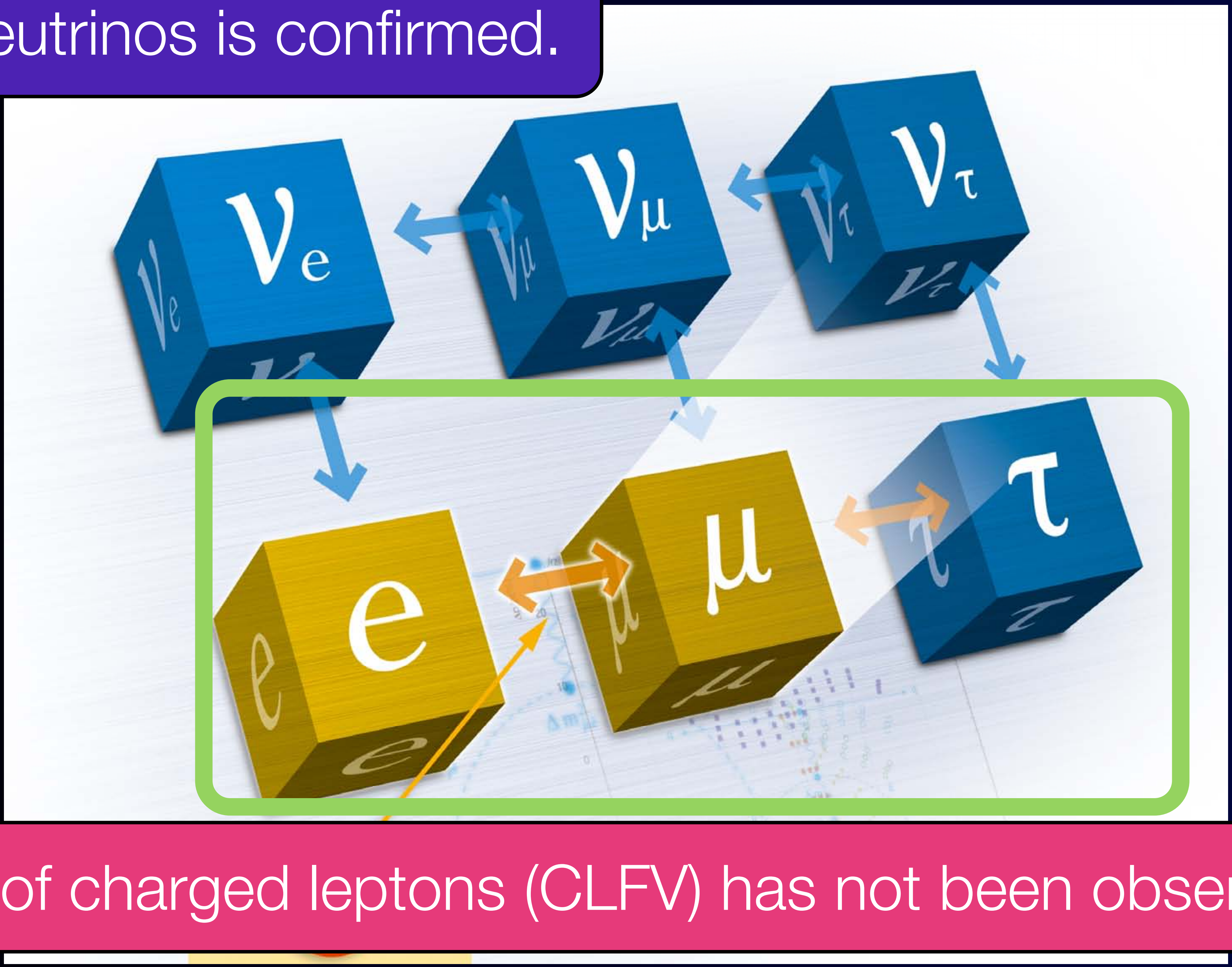
- Why Charged Lepton Flavor Violation (CLFV)?
- CLFV Processes with Muons
  - $\mu \to e\gamma$
    - MEG
  - $\mu \to eee$
    - Mu3e
  - μ-e conversion
    - Mu2e
    - COMET
    - DeeMe
    - COMET Phase-I
- MuSIC@Osaka U. facility
- CLFV Processes with Taus
- Summary

Why Charged Lepton Flavor Violation (CLFV)?

What is Charged Lepton Flavor Violation (CLFV) ?

What is Charged Lepton Flavor Violation (CLFV) ?

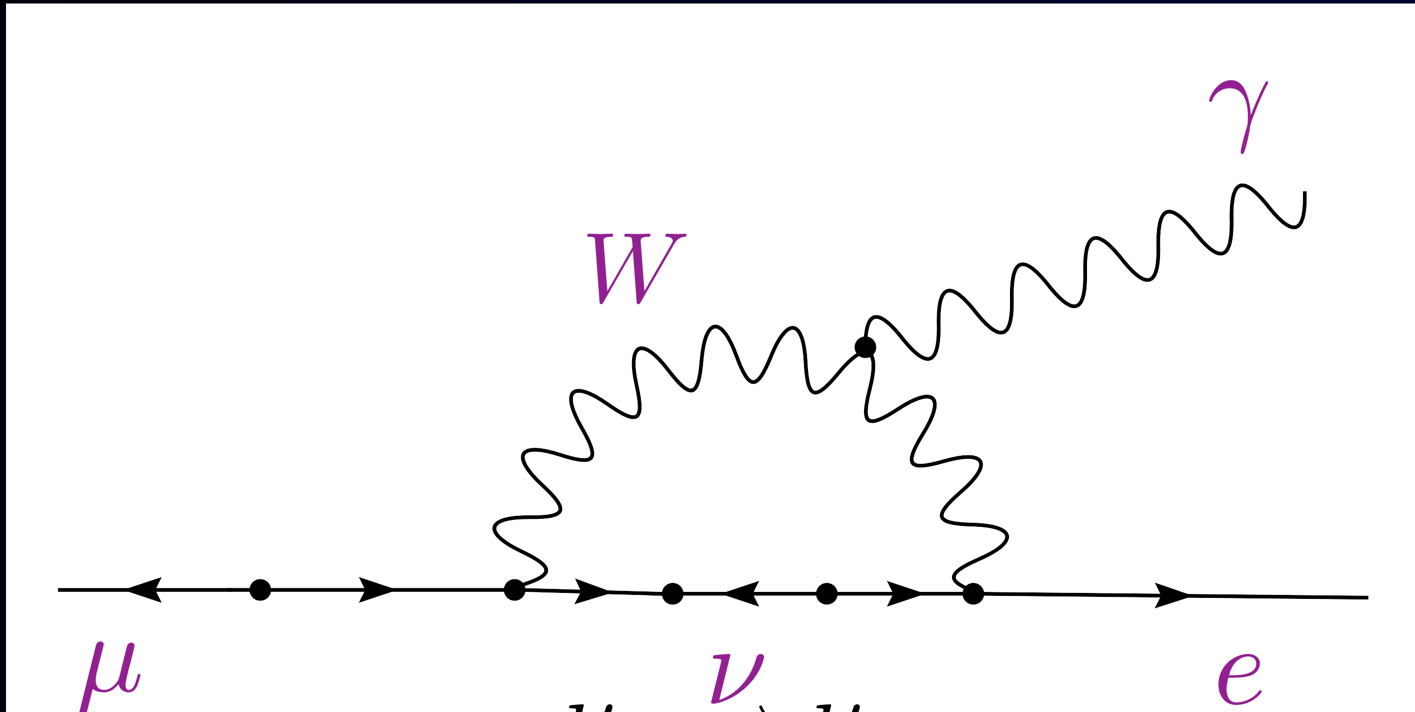
LFV of neutrinos is confirmed.



LFV of charged leptons (CLFV) has not been observed.

CLFV in the SM with Massive Neutrinos

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



$\nu_\mu \xrightarrow{\nu} \nu_e$

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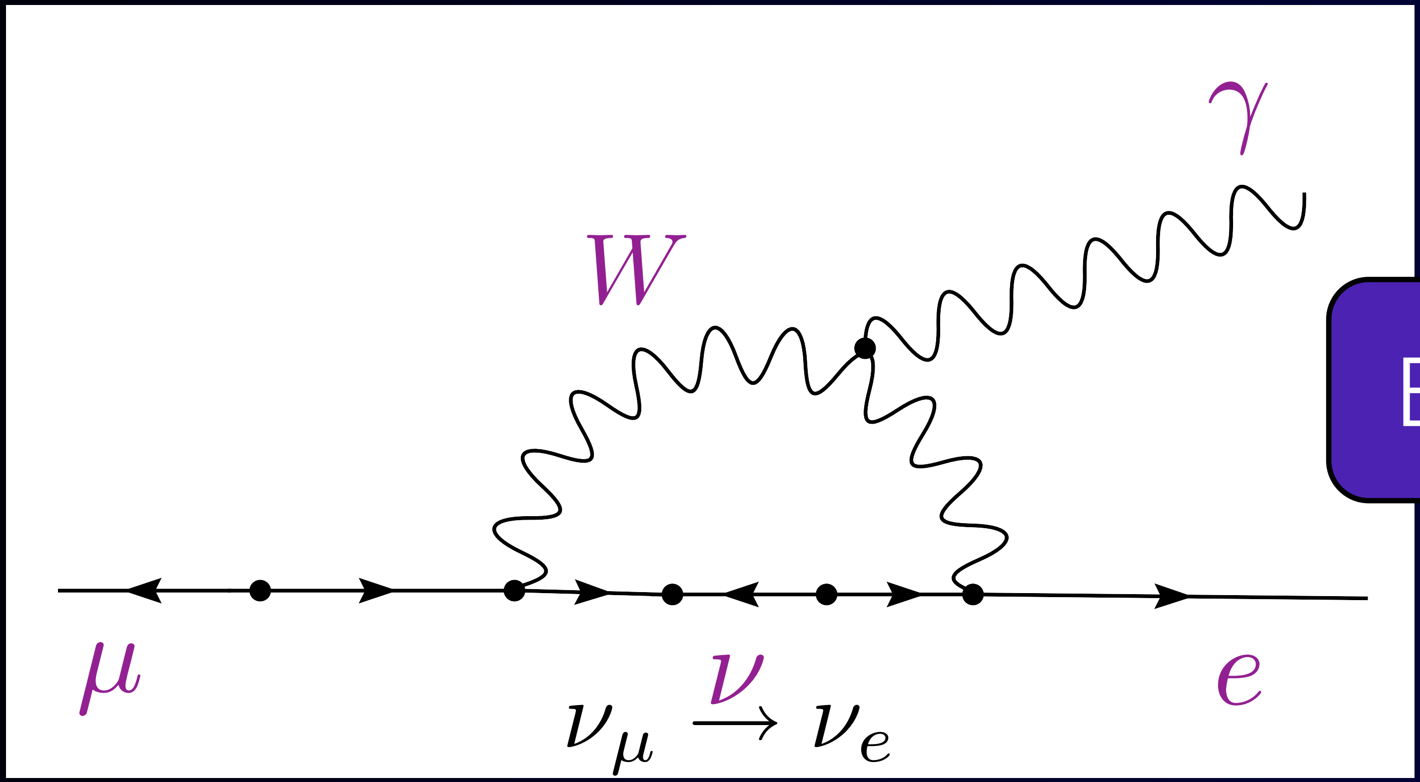

BR~O(10^{-54})

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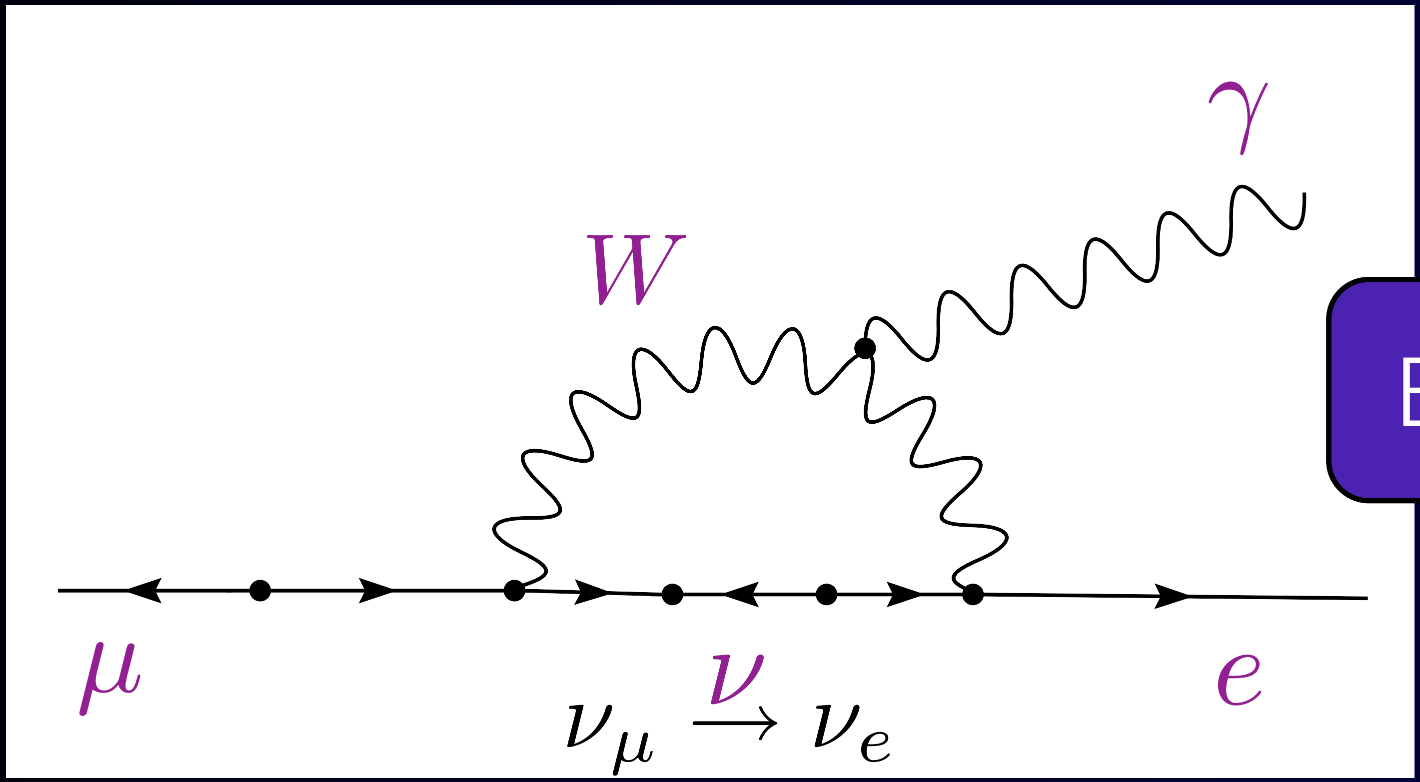

BR~O(10^{-54})

Observation of CLFV would indicate a clear signal of physics beyond the SM with massive neutrinos.

Sensitivity to High Energy Scale Physics
Exercise (1) : Tree Level

A. de Gouvea's effective interaction

$$L_{\rm CLFV} = \frac{1}{1+\kappa}\frac{m_\mu}{\Lambda^2}\bar{\mu}_{\rm R}\sigma^{\mu\nu}e_{\rm L}F_{\mu\nu} + \frac{\kappa}{1+\kappa}\frac{1}{\Lambda^2}(\bar{\mu}_{\rm L}\gamma^{\mu}e_{\rm L})(\bar{q}_{\rm L}\gamma_{\mu}q_{\rm L})$$

Λ: energy scale of new physics

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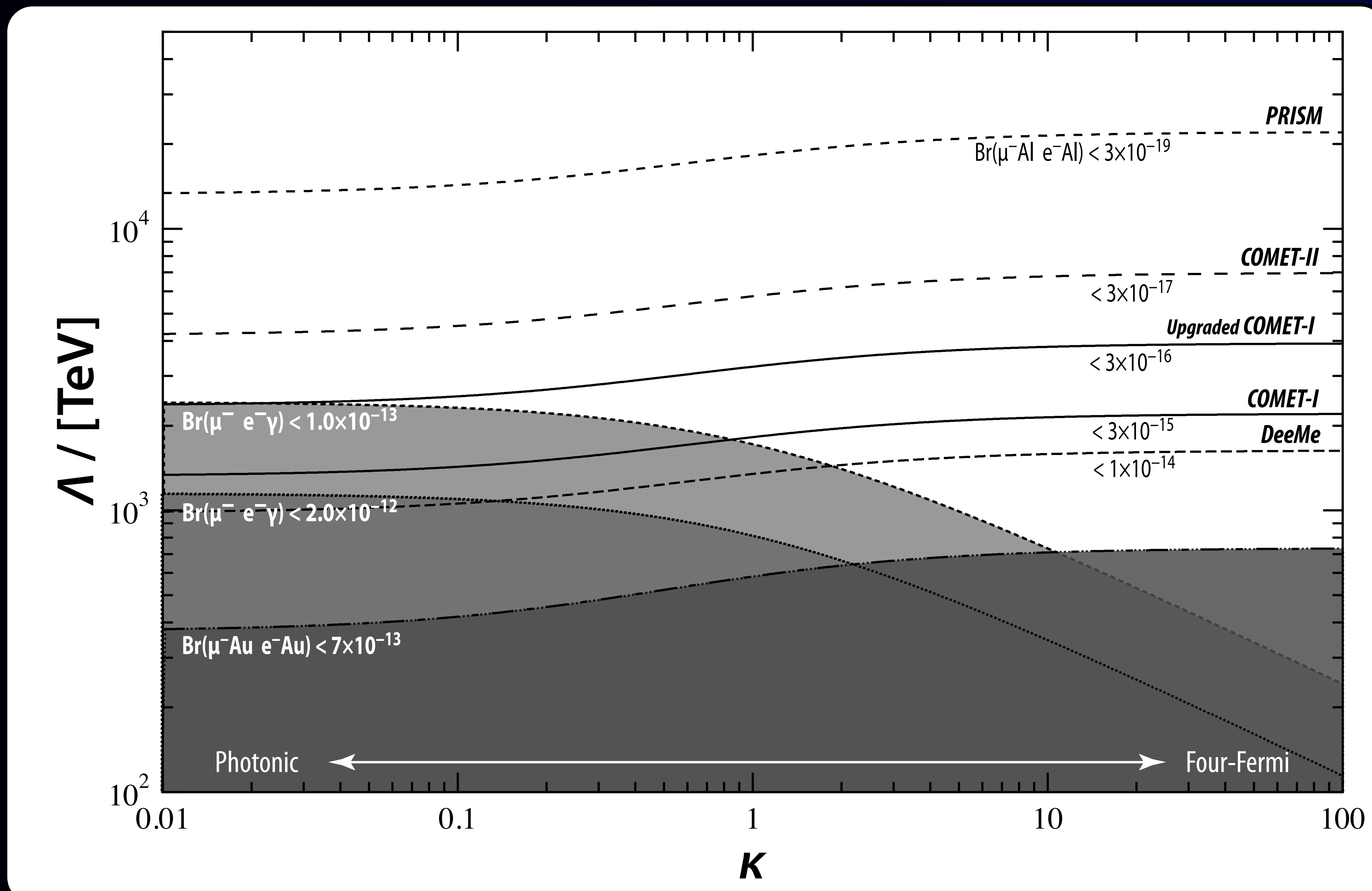

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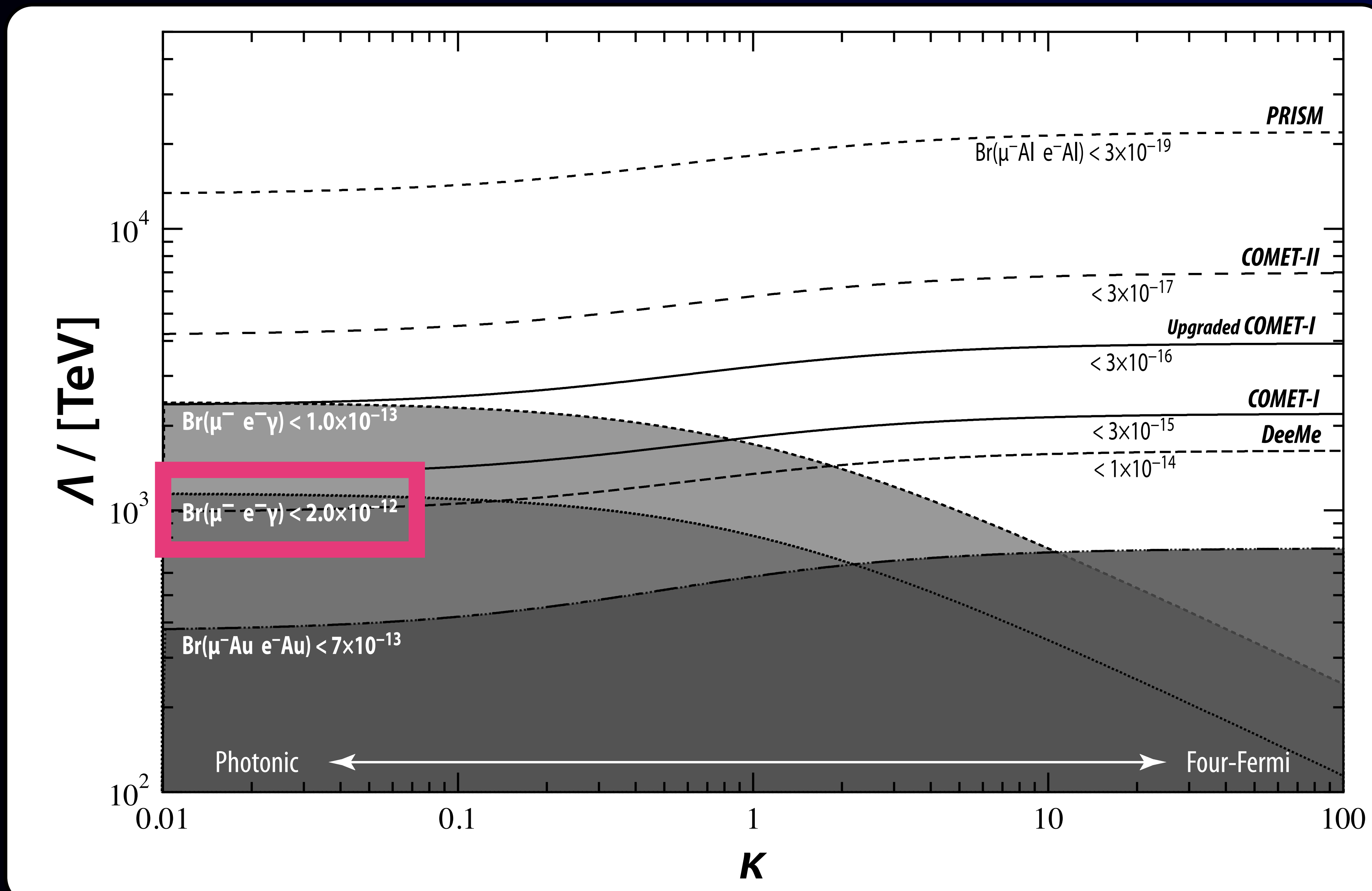
Λ: energy scale of new physics

O(10^3)TeV



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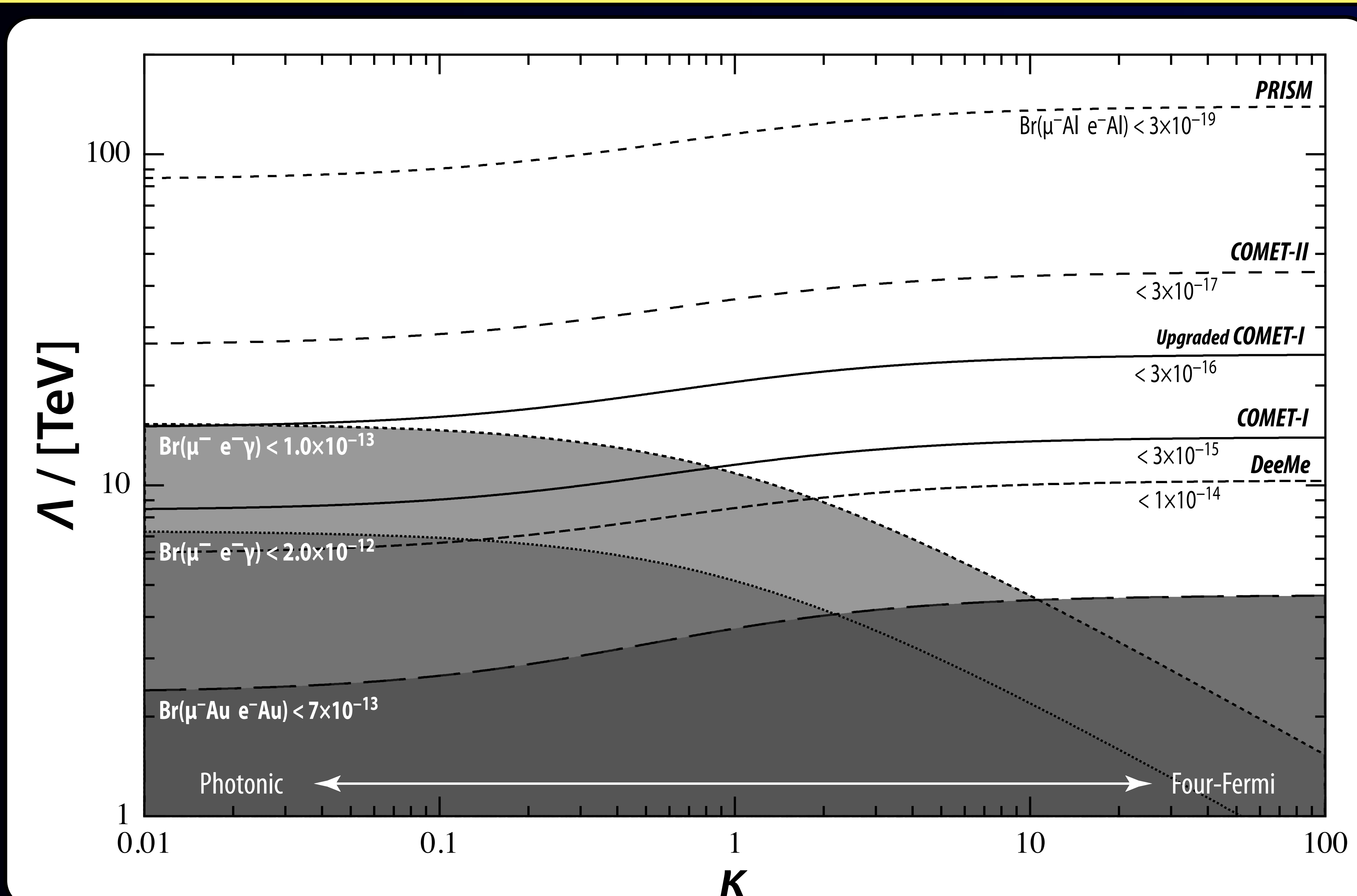

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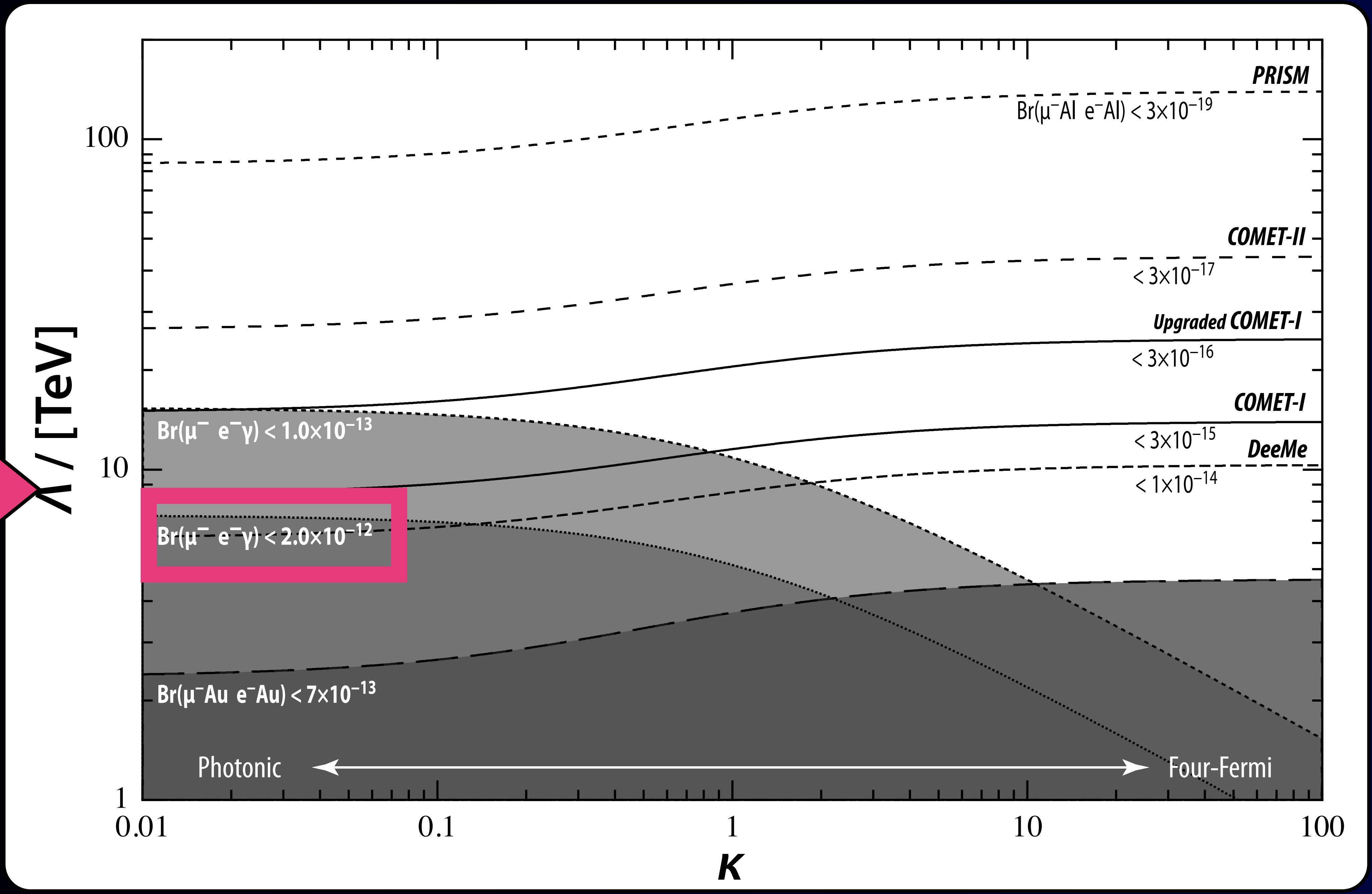
O(1)TeV



Flavor mixing couplings gives additional reduction on the Λ reach.

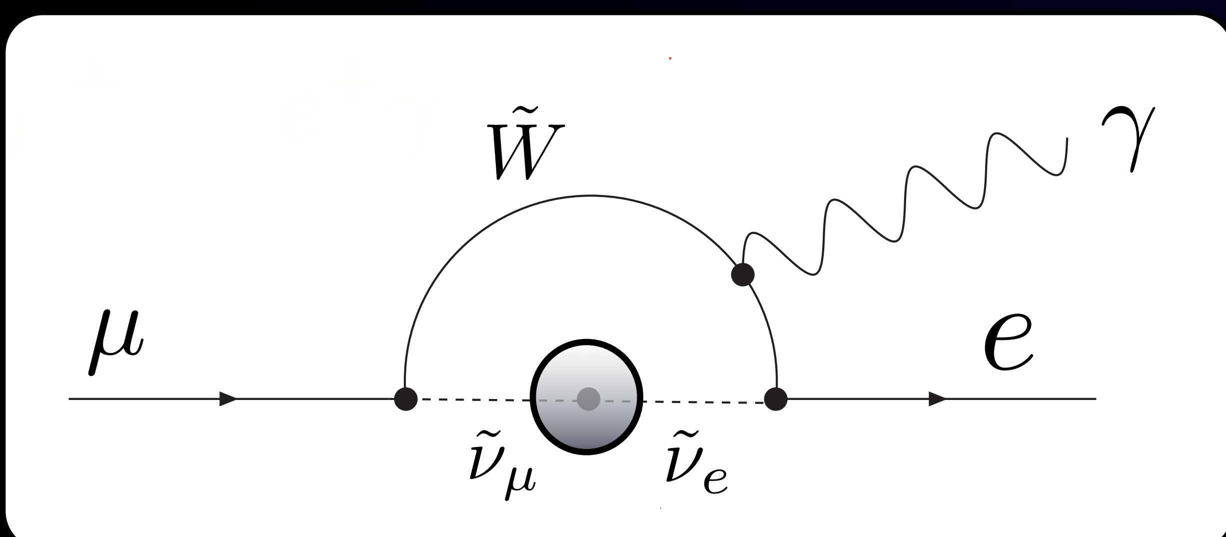
Sensitivity to High Energy Scale Physics
Exercise (2) : Loop Level (SUSY models)

Sensitivity to High Energy Scale Physics Exercise (2) : Loop Level (SUSY models)

- For loop diagrams,

$$\mathrm{BR}(\mu \to e\gamma) = 1 \times 10^{-11} \times \left(\frac{2\mathrm{TeV}}{\Lambda}\right)^4 \left(\frac{\theta_{\mu e}}{10^{-2}}\right)^2 \qquad y = \frac{g^2}{16\pi^2}\theta_{\mu e}$$

> sensitive to TeV energy scale with reasonable mixing



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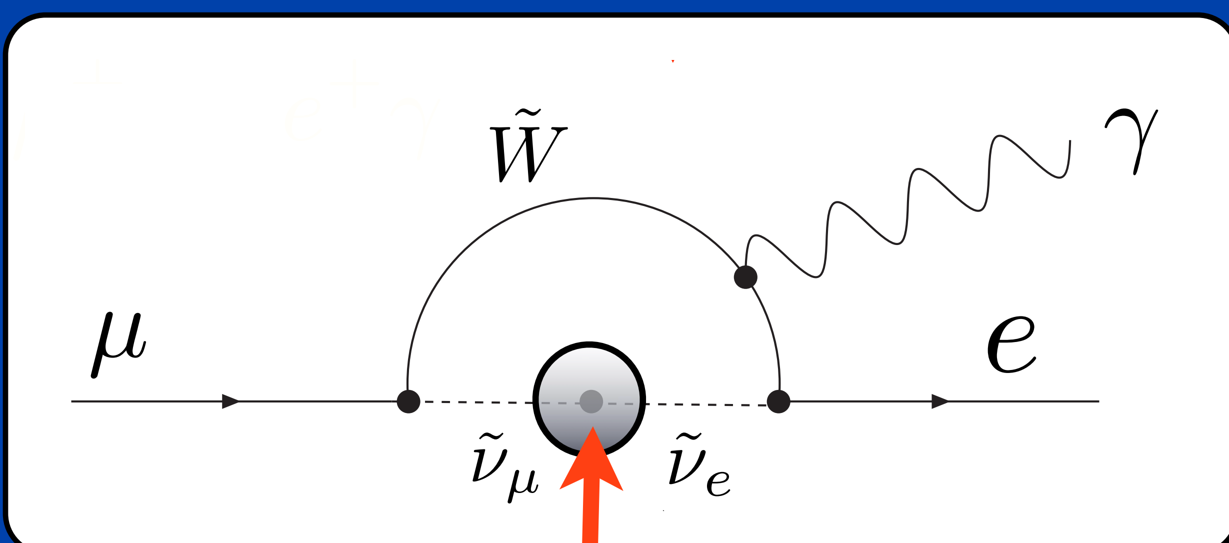


example diagram for SUSY (~TeV)

Physics at about 10^{16} GeV

slepton mixing (from RGE)

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

SUSY-GUT model

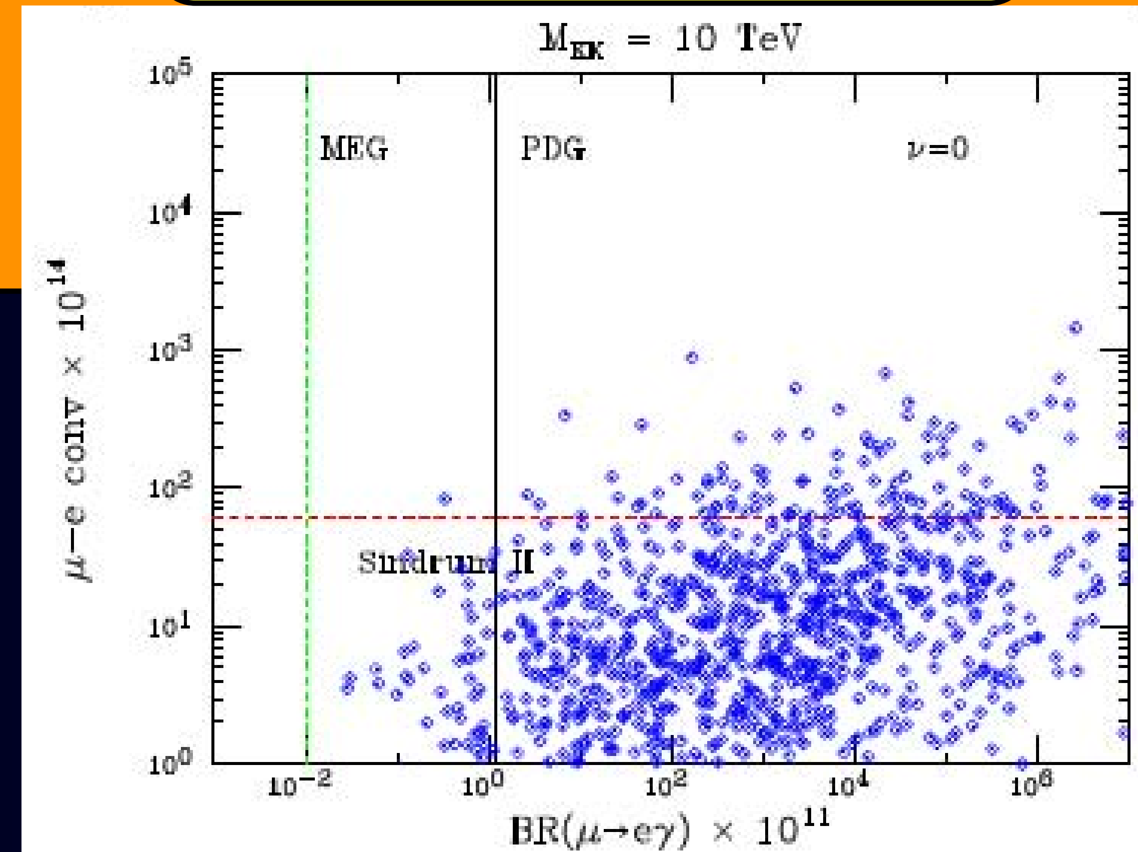
$$(m^2_{\tilde{L}})_{21} \sim \frac{3m_0^2 + A_0^2}{8\pi^2} h_\tau^2 U_{31} U_{32} \frac{M_{GUT}}{M_{R_s}}$$

SUSY neutrino seesaw model

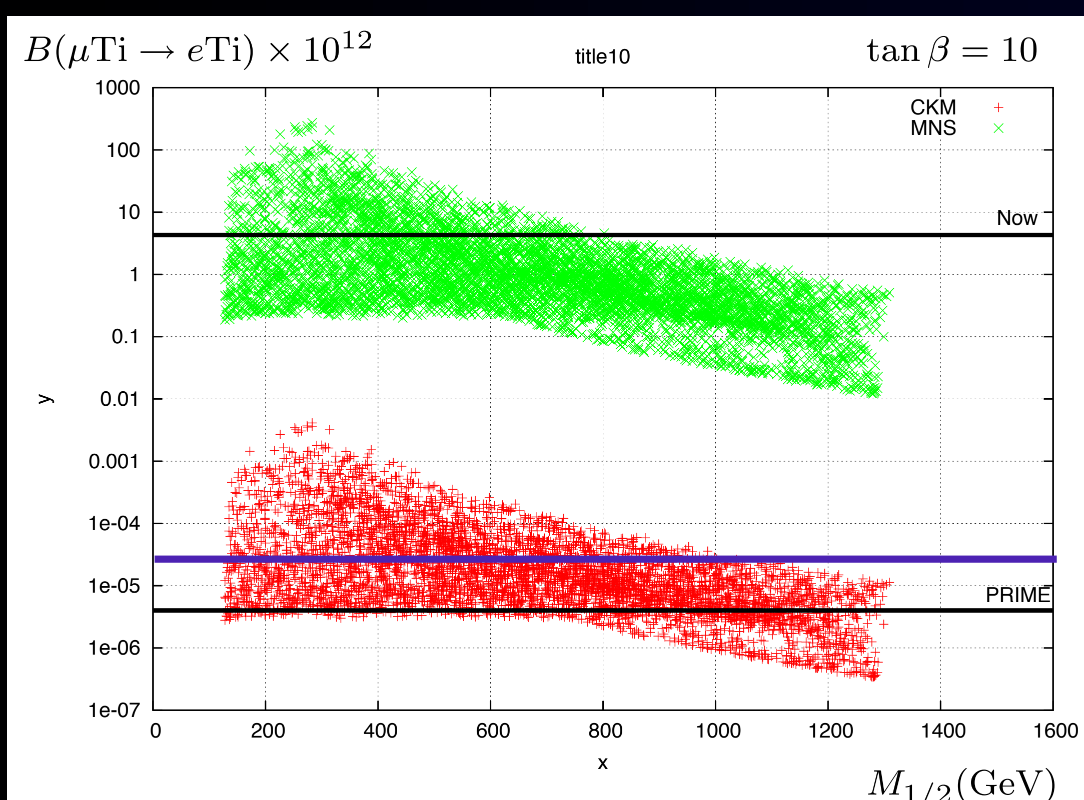
CLFV Predictions

Various BSM models predict sizable CLFV.

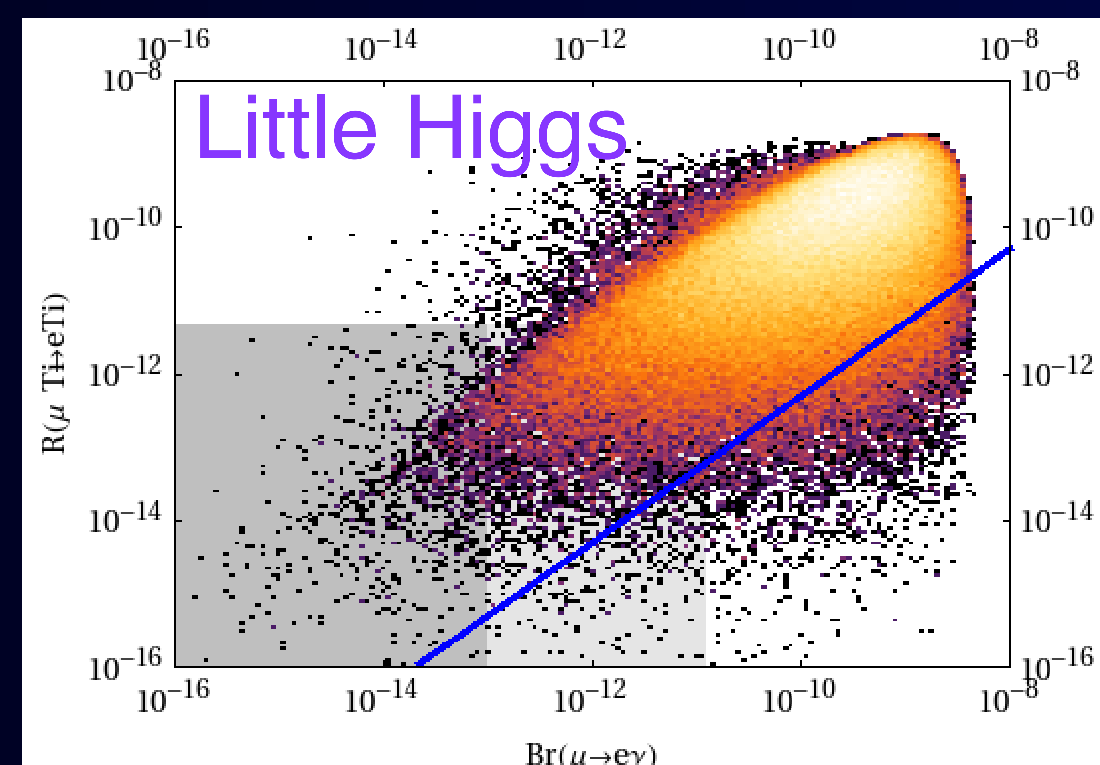
extra dimension model



SUSY model



little Higgs model



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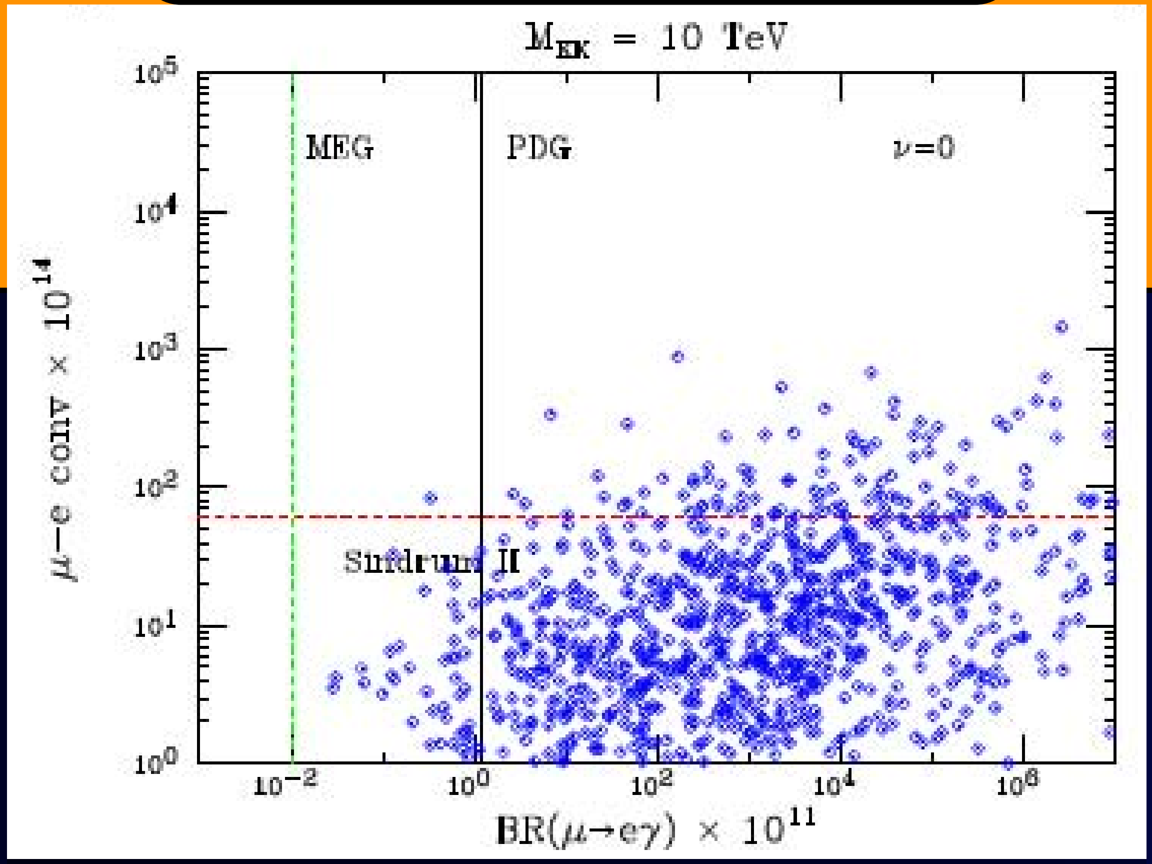

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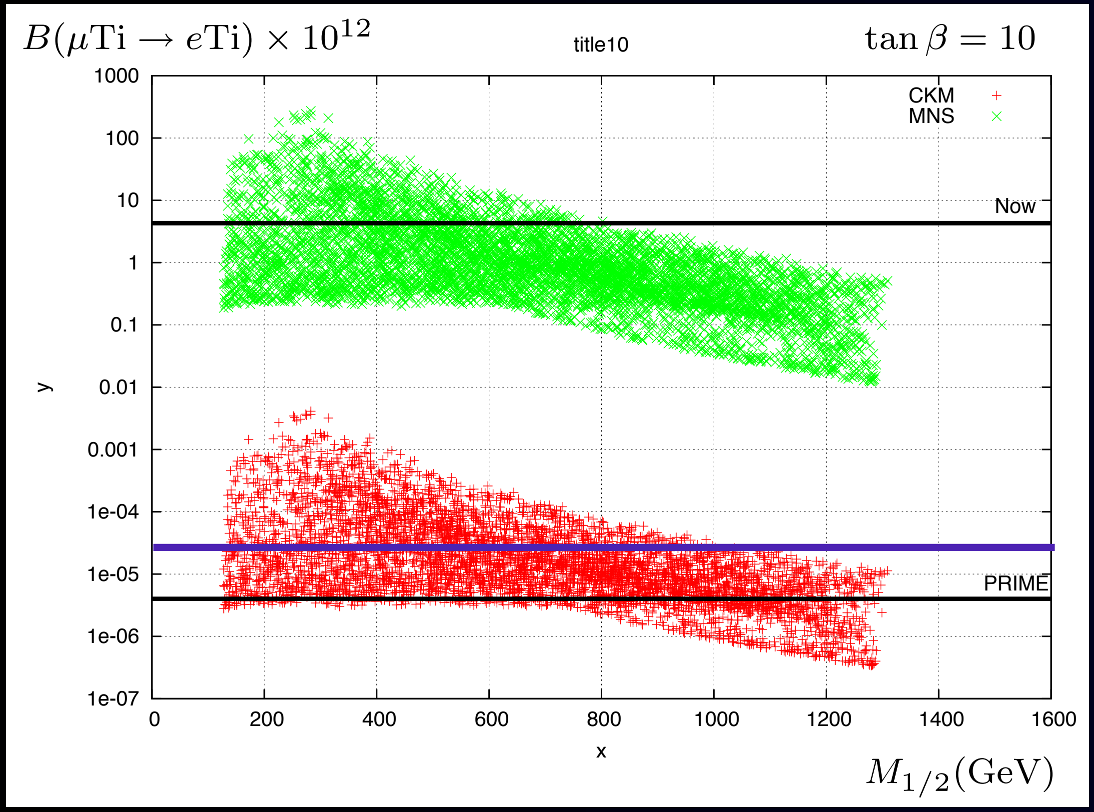
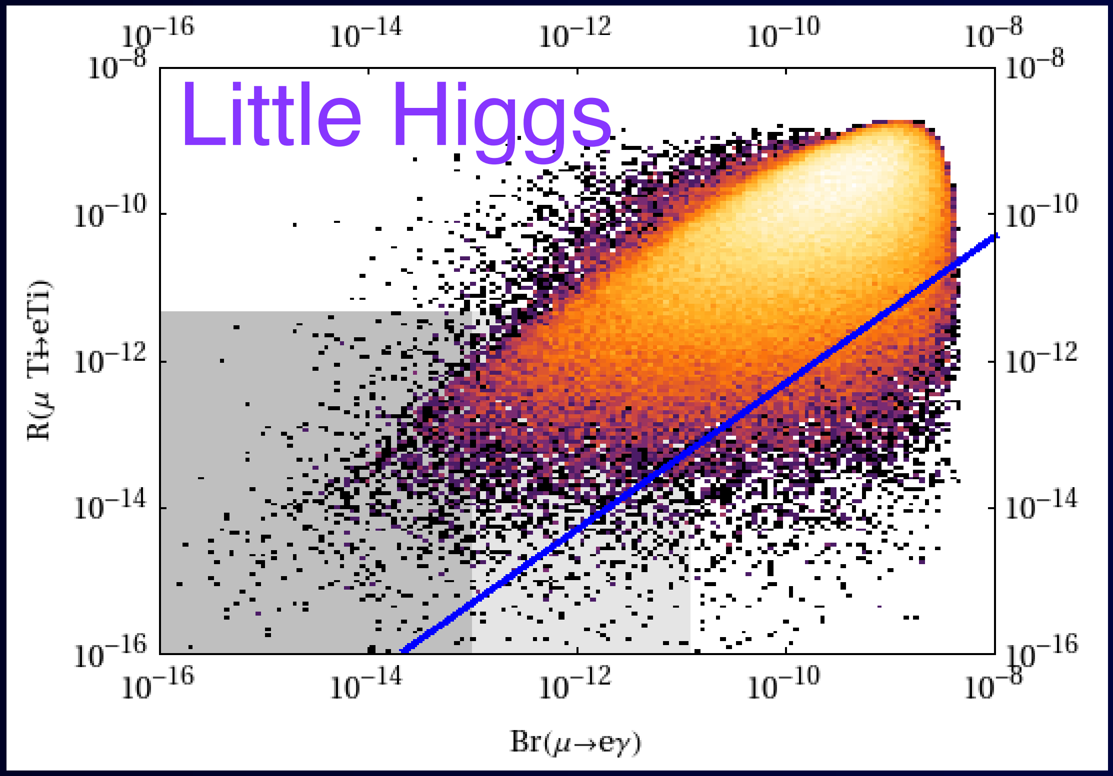


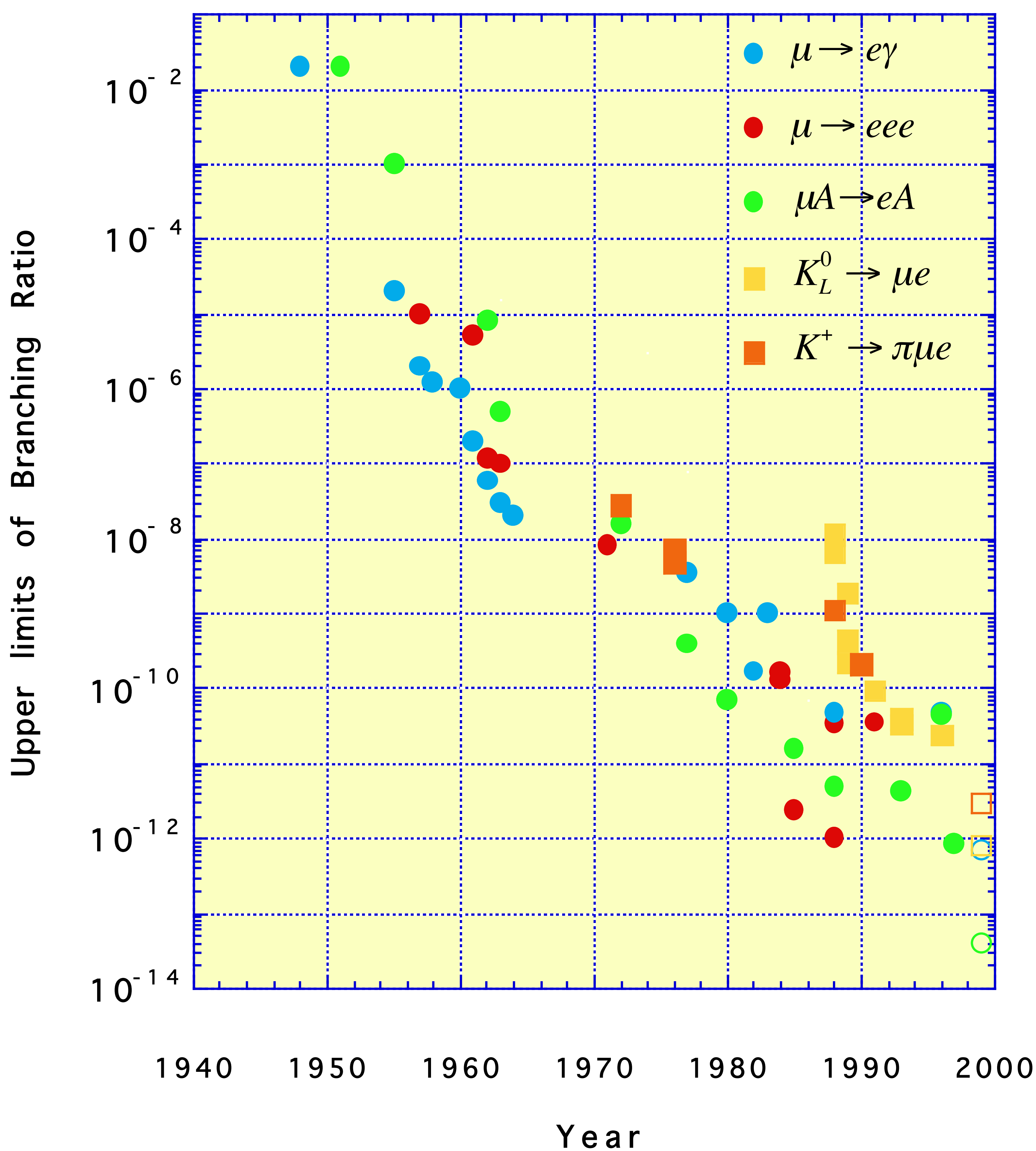
10^4

little Higgs model



muon CLFV Experiments

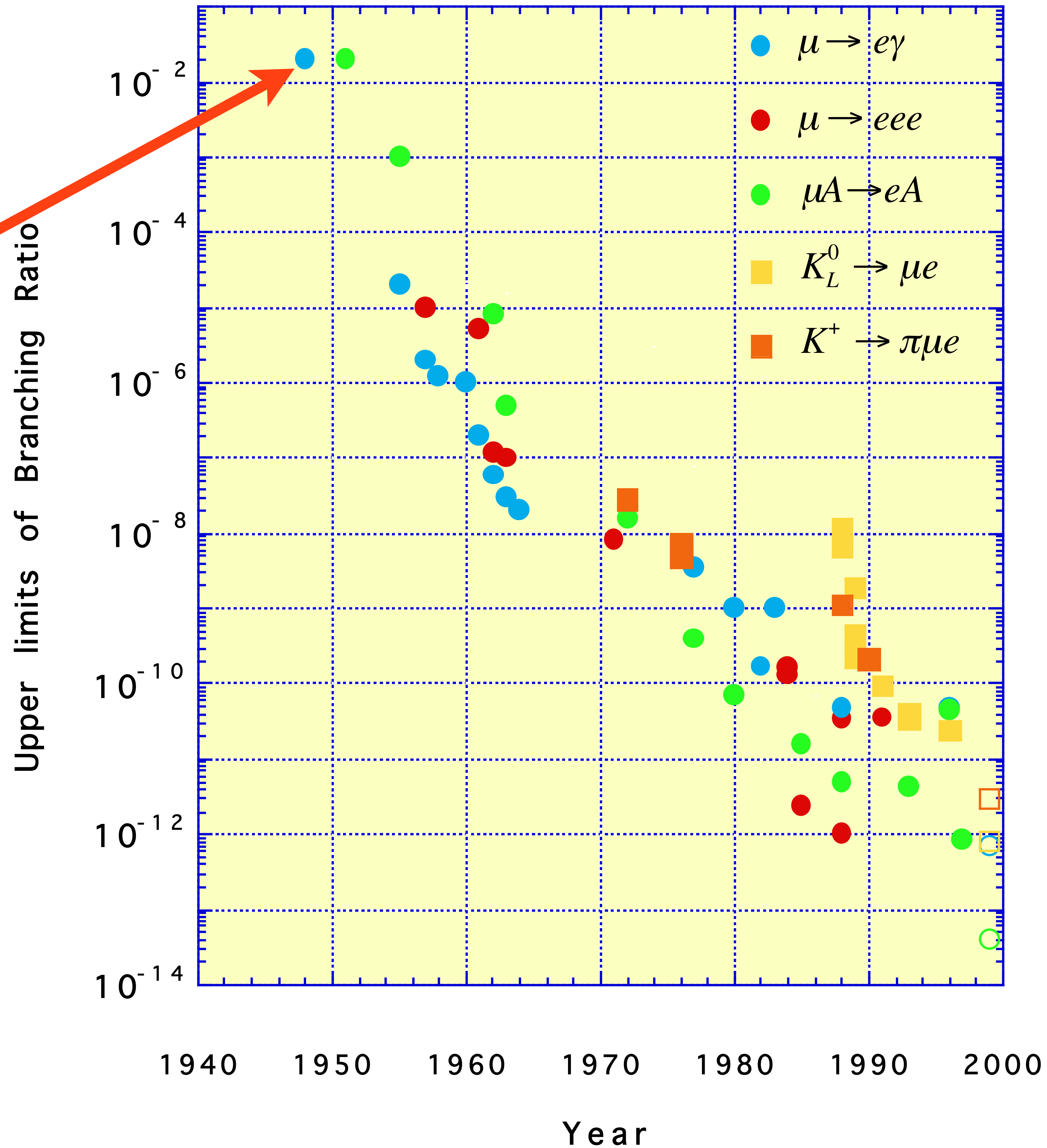
CLFV History



CLFV History

First cLFV search

Pontecorvo in 1947



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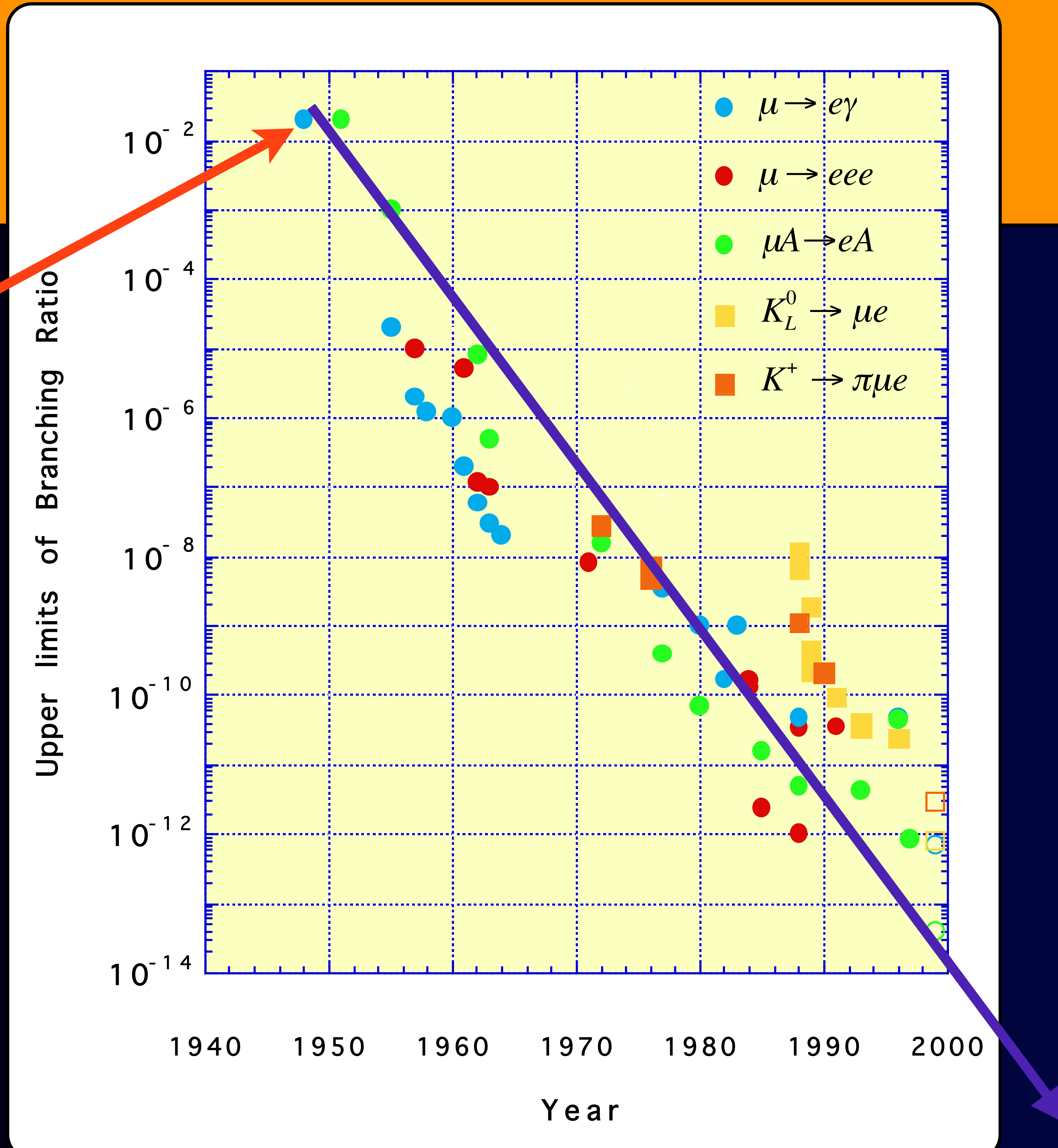
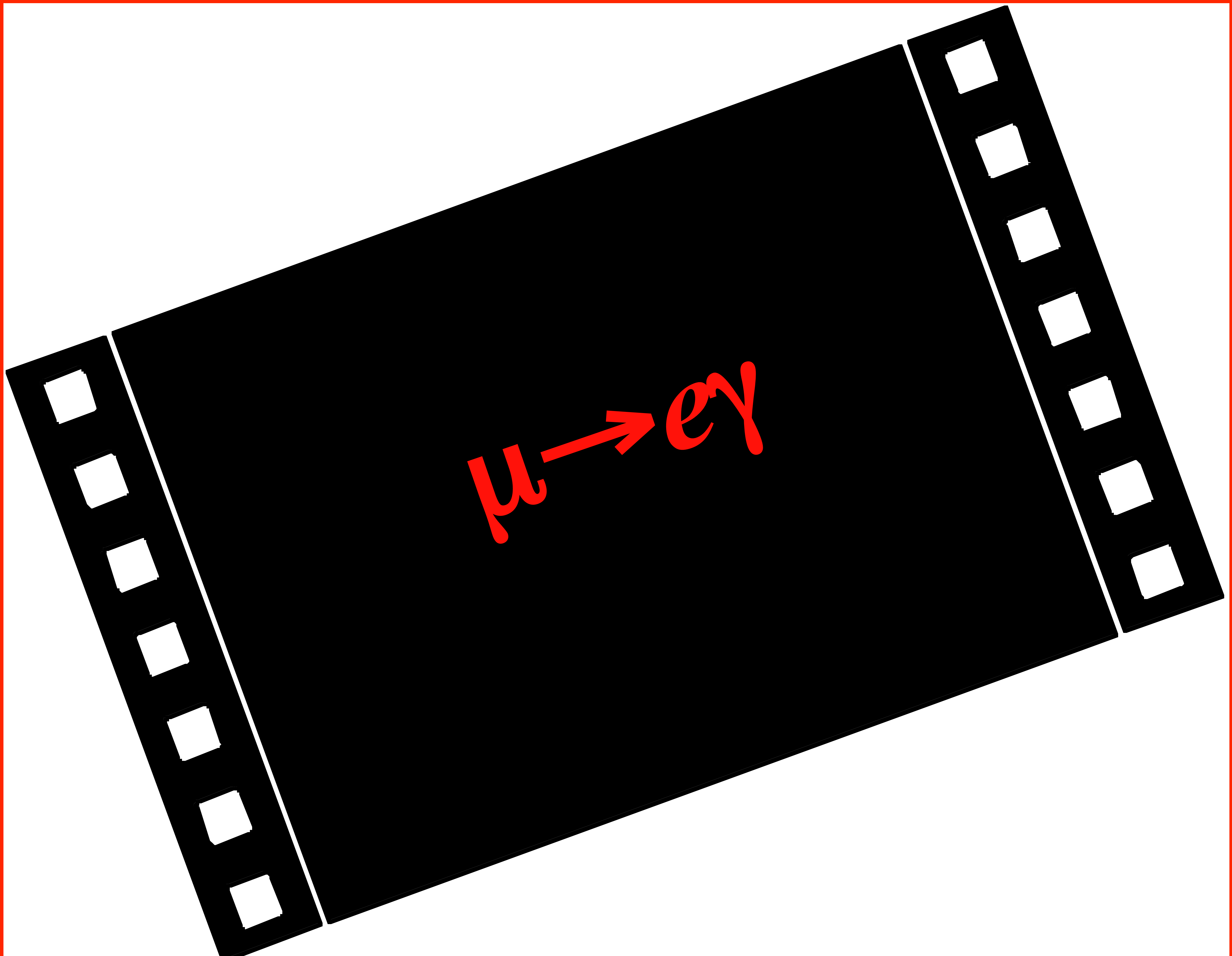


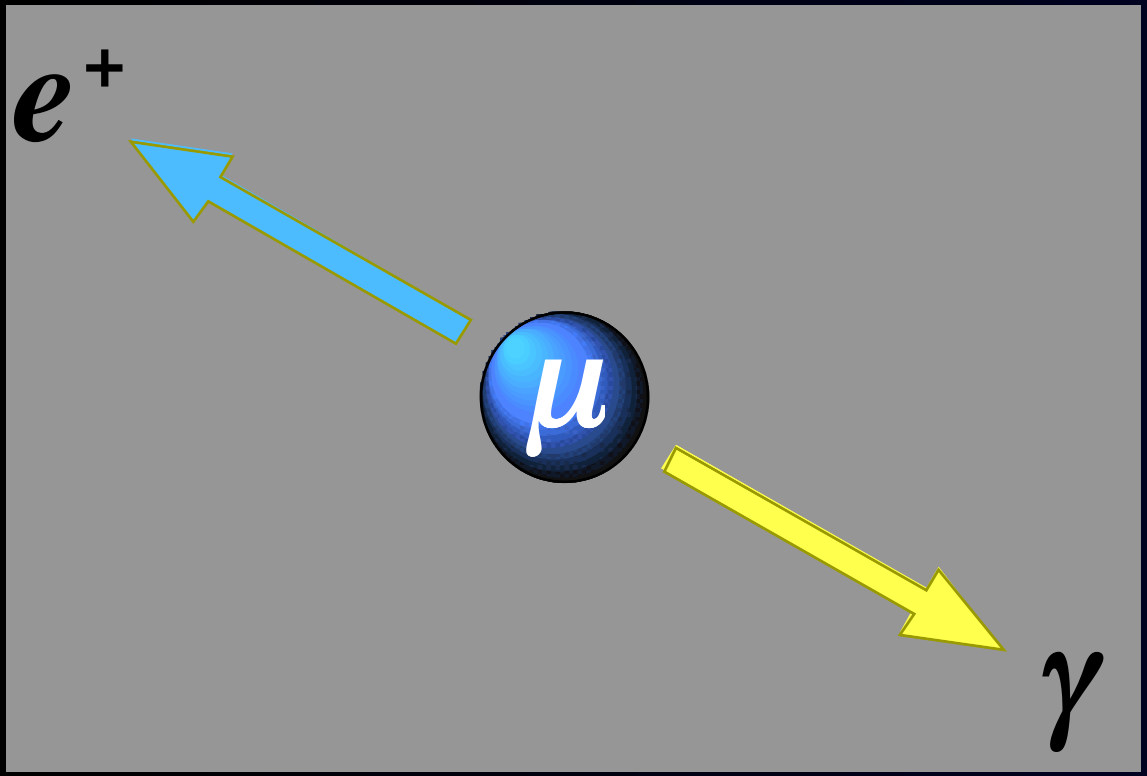
Present Limits and Expectations in Future

process	present limit	future	
$\mu \to e\gamma$	$<2.4 \times 10^{-12}$	$<10^{-14}$	MEG at PSI
$\mu \to eee$	$<1.0 \times 10^{-12}$	$<10^{-16}$	Mu3e at PSI
$\mu N \to eN$ (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 KEKB/B
$\tau \to eee$	$<3.6 \times 10^{-8}$	$<10^{-9} - 10^{-10}$	super KEKB/B
$\tau \to \mu\gamma$	$<4.5 \times 10^{-8}$	$<10^{-9} - 10^{-10}$	super KEKB/B
$\tau \to \mu\mu\mu$	$<3.2 \times 10^{-8}$	$<10^{-9} - 10^{-10}$	super KEKB/B


μ→eγ

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

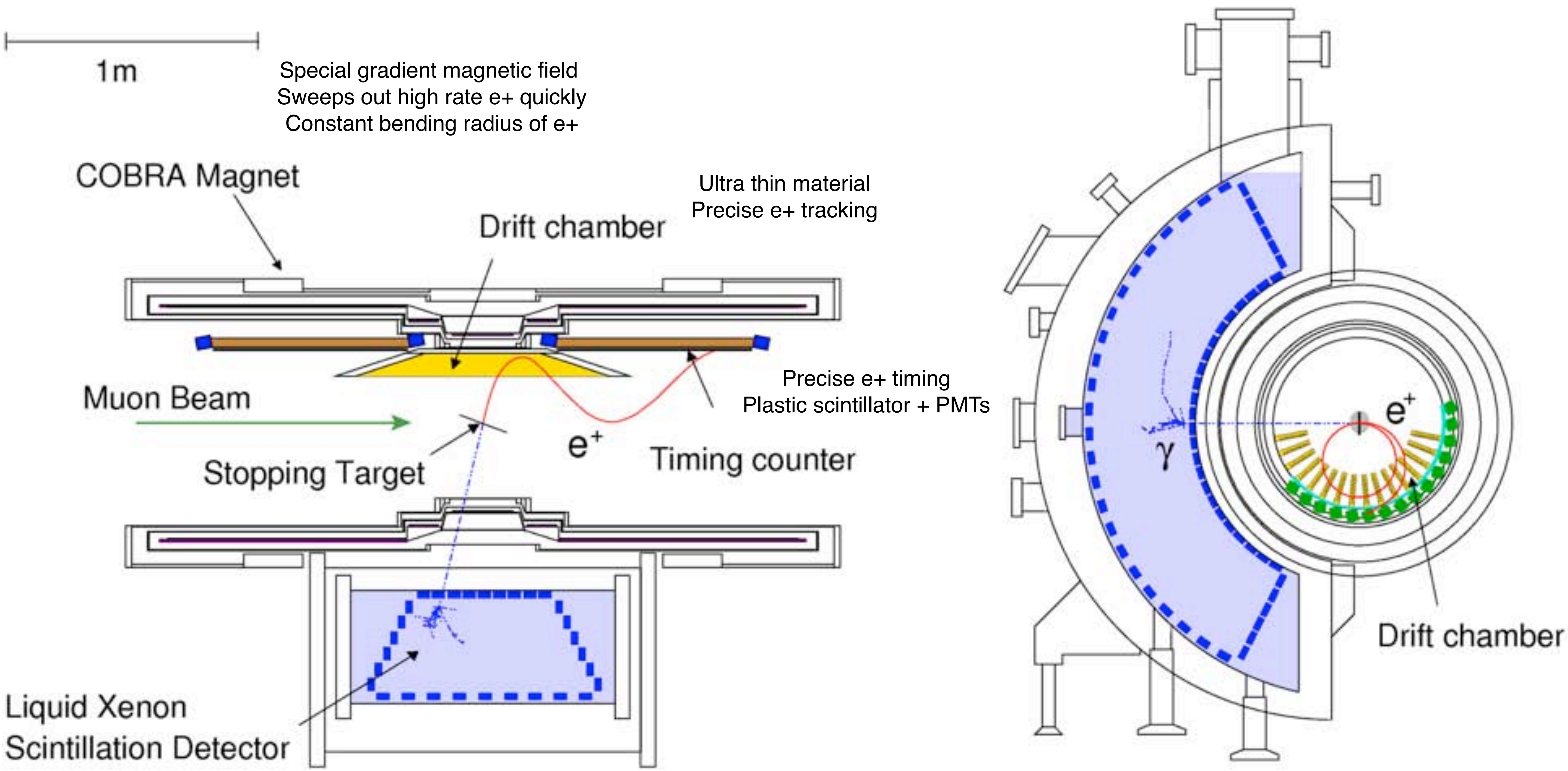
- Event Signature
  - $E_e = m_\mu/2$, $E_\gamma = m_\mu/2$ (=52.8 MeV)
  - angle $\theta_{\mu e}$=180 degrees (back-to-back)
  - time coincidence



- 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.

MEG Experiment

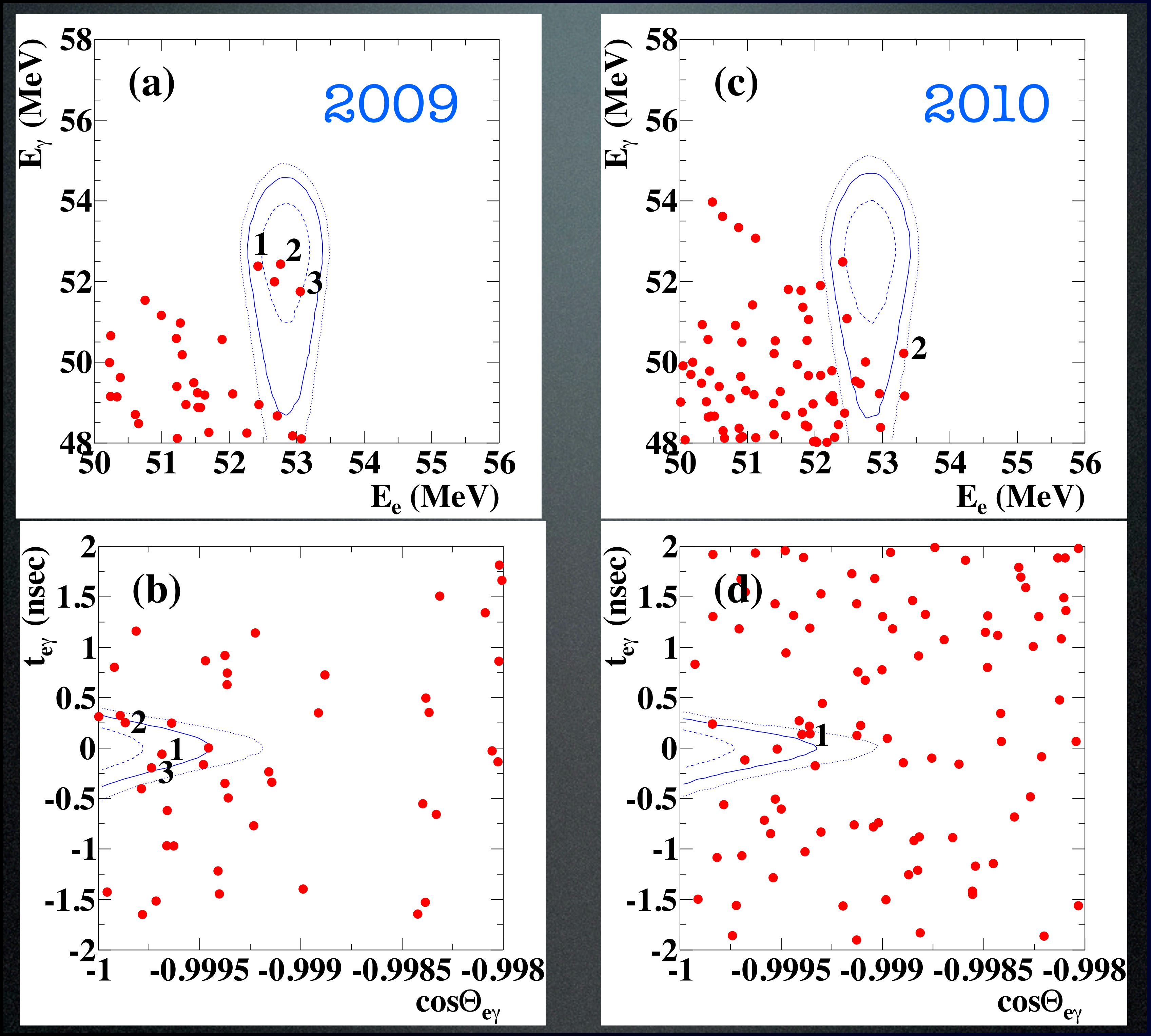
$3x10^7 \mu/s$@PSI, Switzerland



2.7 ton of liquid xenon
Homogeneous detector
Good time, position, energy resolution

Waveform digitizer for all detectors

MEG 2009 and 2010 Data Results



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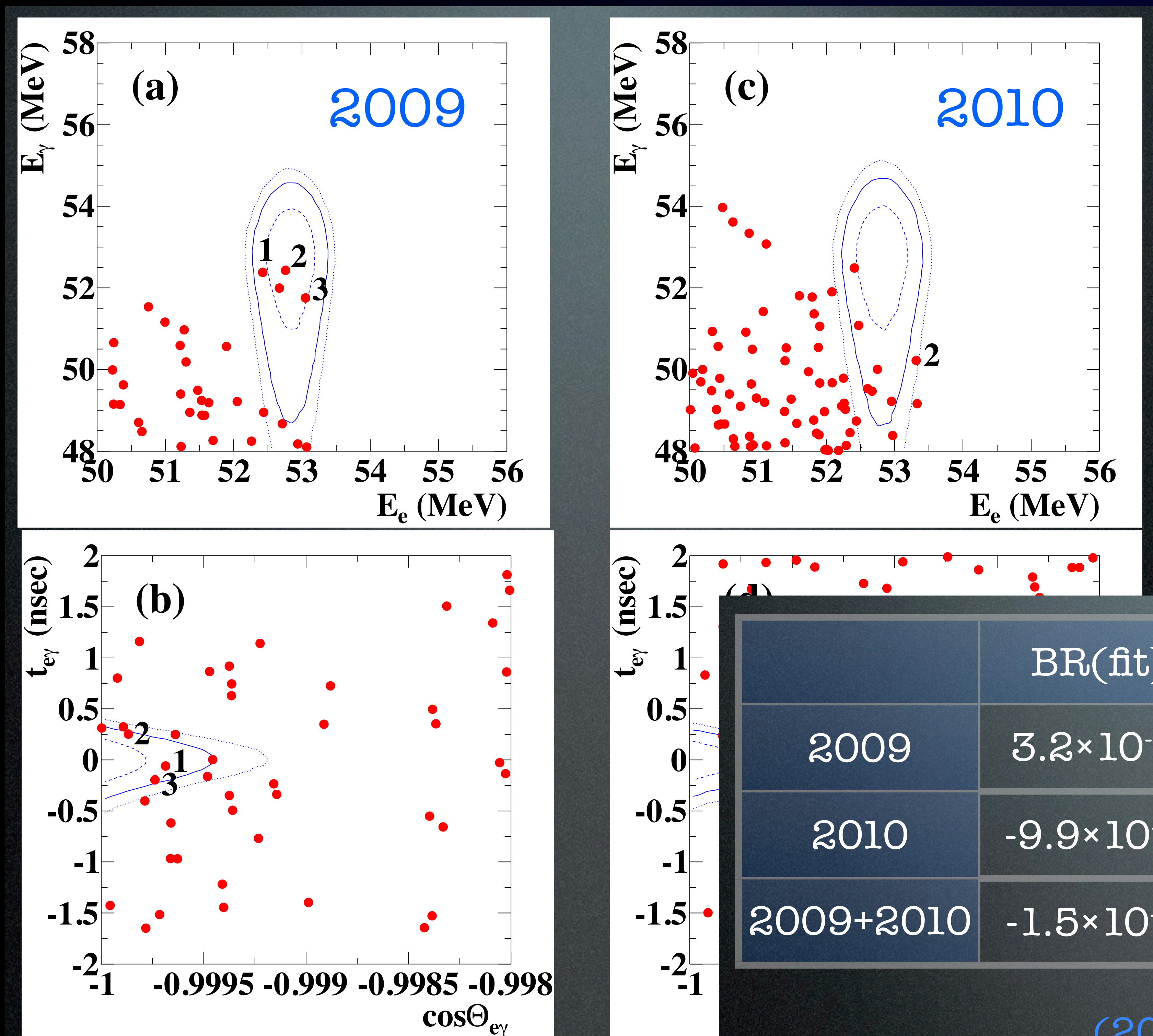

	BR(fit)	LL 90%	UL 90%
2009	3.2×10^{-12}	1.7×10^{-13}	9.6×10^{-12}
2010	-9.9×10^{-13}	--	1.7×10^{-12}
2009+2010	-1.5×10^{-13}	--	2.4×10^{-12}

combined result

(2009+2010expected UL = 1.6×10^{-12})

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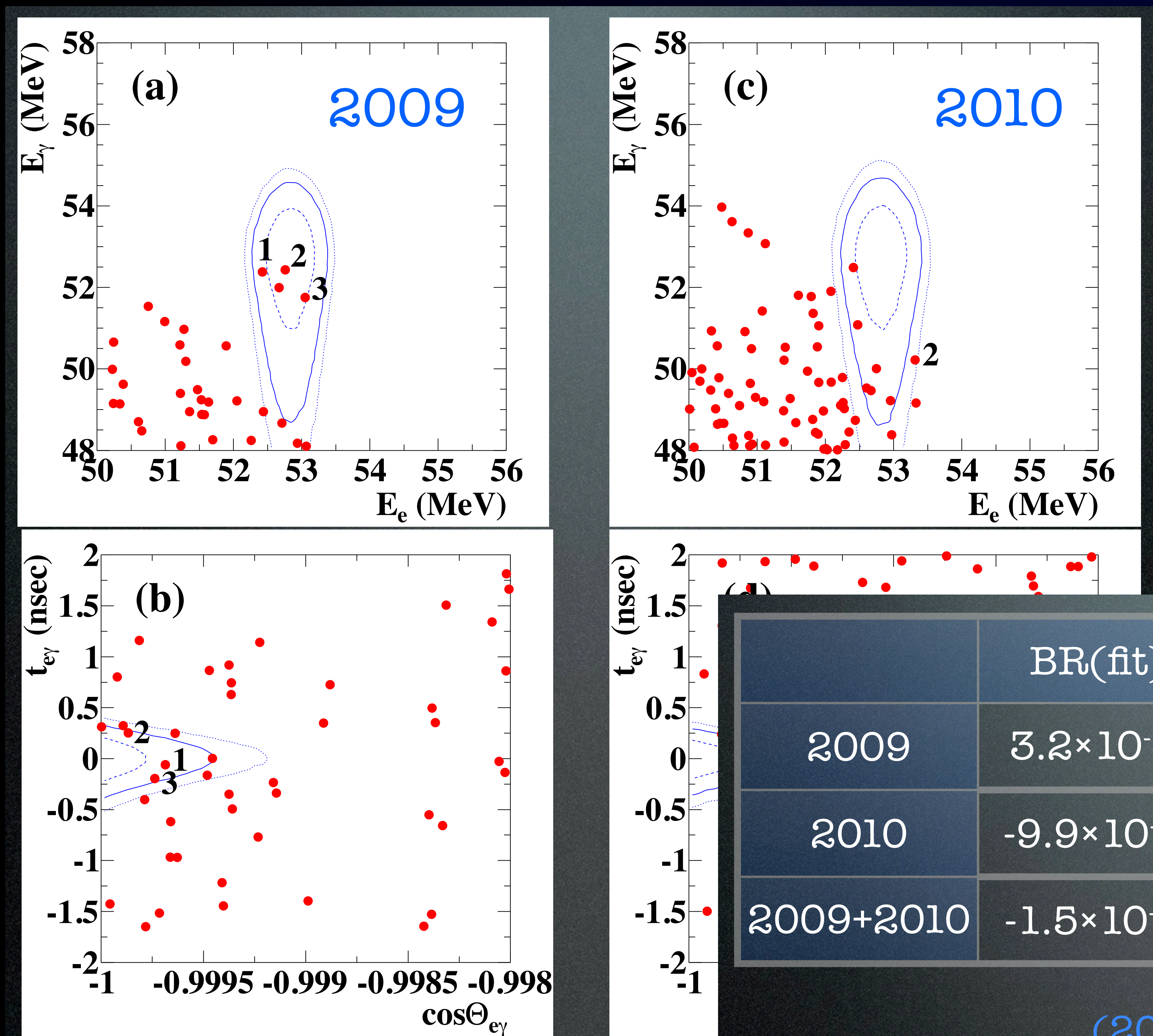

With 2011 and 2012 data, MEG aims at $0(10^{-13})$.

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MEG II for O(10^{-14})

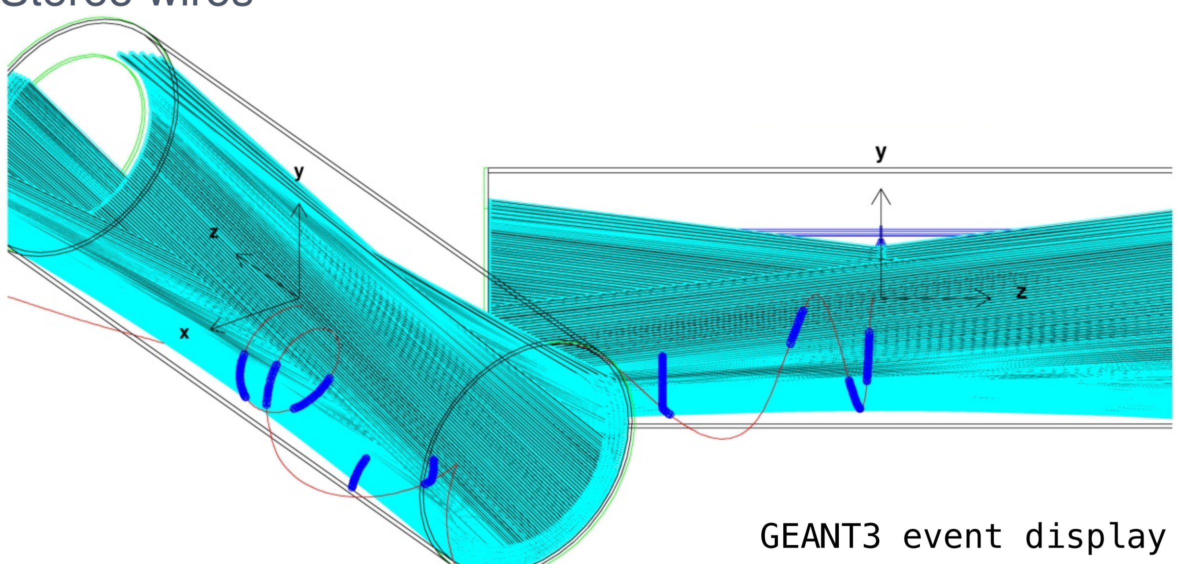
from Sawada's talk at Neutrino2012

Several studies are ongoing for the upgrade of MEG to improve the sensitivity by one order of magnitude, $\mathcal{O}(10^{-14})$.

Proposal in the next year.

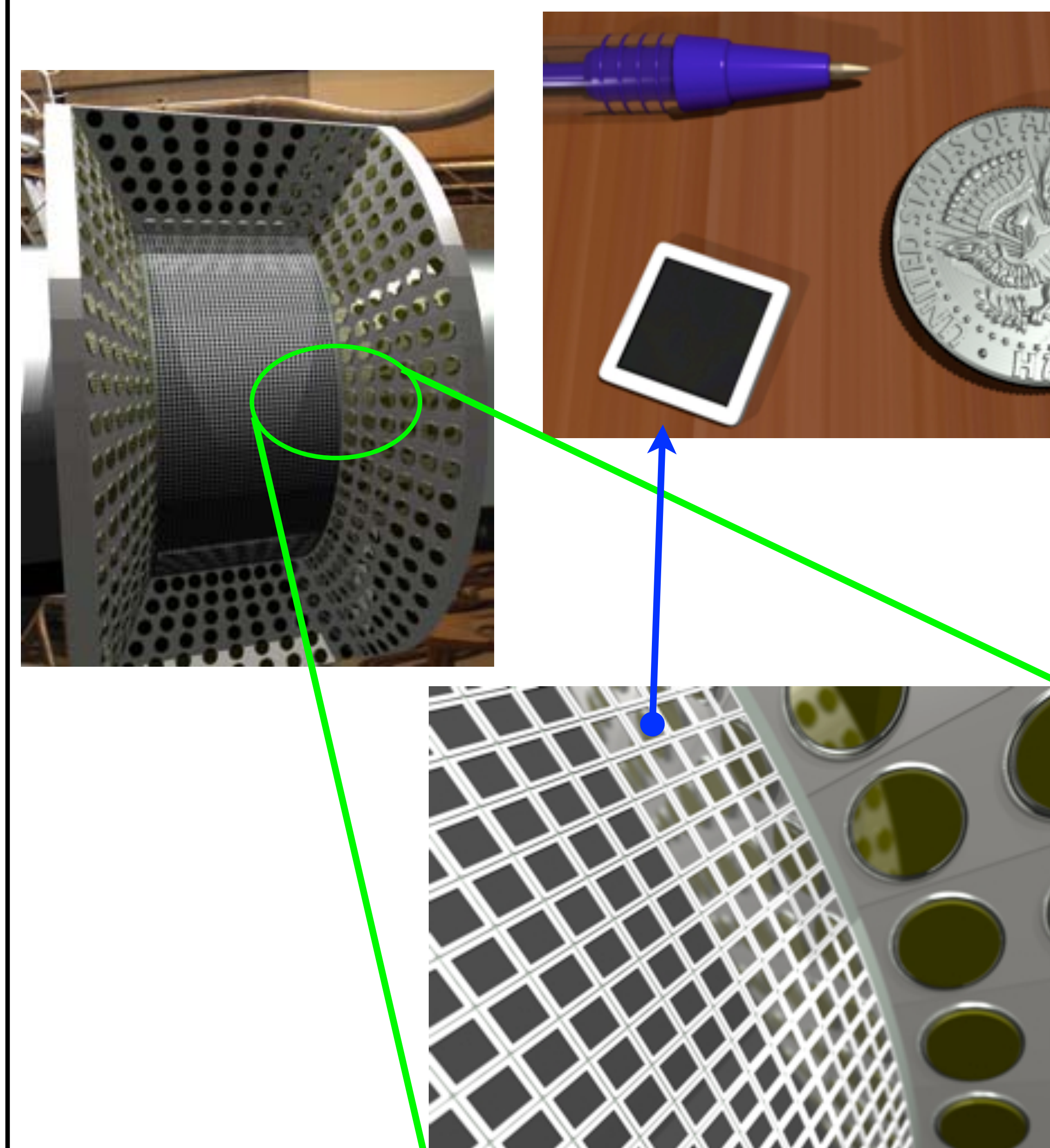
- 3 times higher beam intensity
- LXe γ detector upgrade with MPPC
- Unique volume gas chamber
- Active target / SVT / Thin e^+ timing counter...

Cylindrical drift chamber
Stereo wires

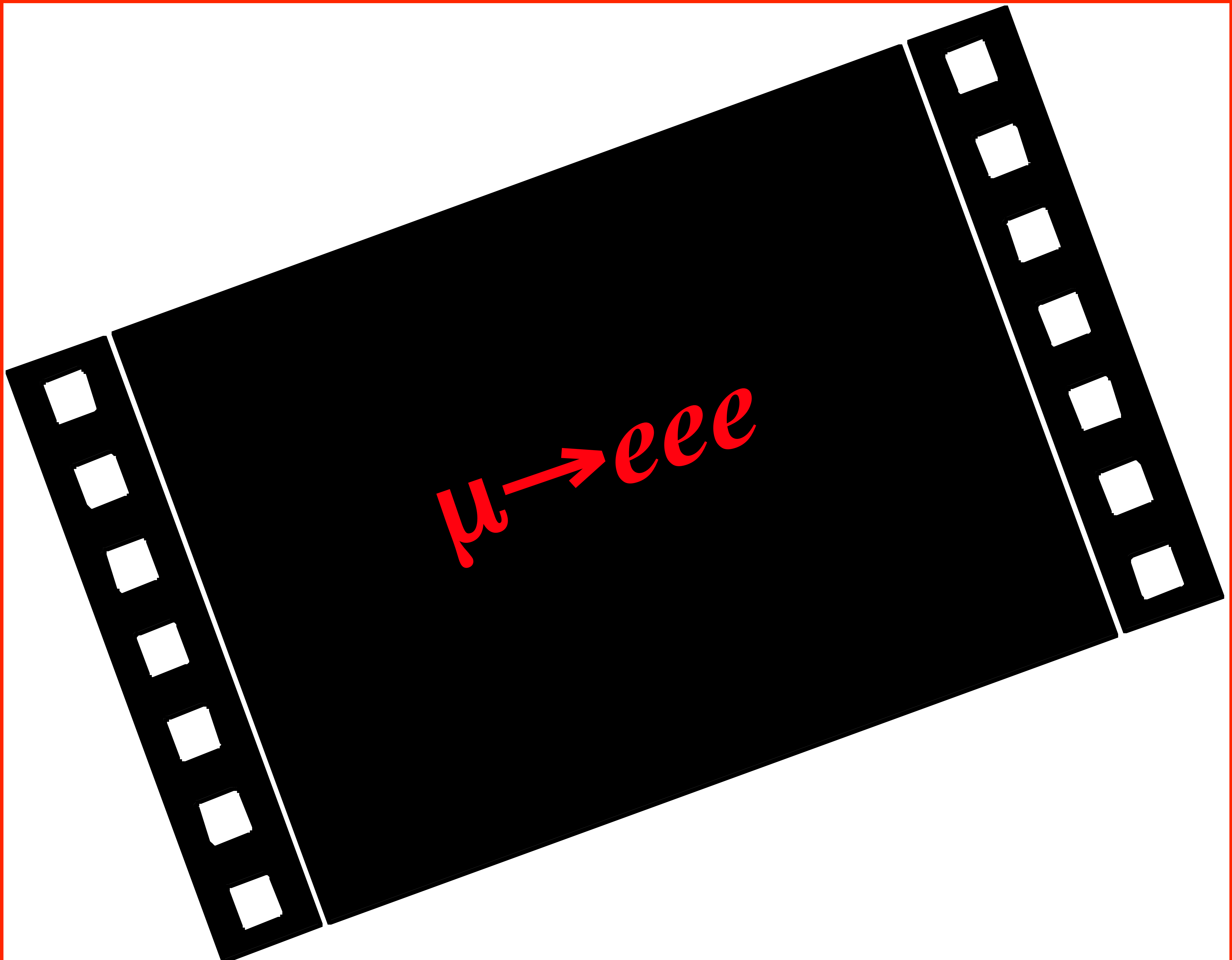


GEANT3 event display

~4000 MPPCs (15 x 15 mm) on the γ ray entrance face
Development of new large MPPC for LXe

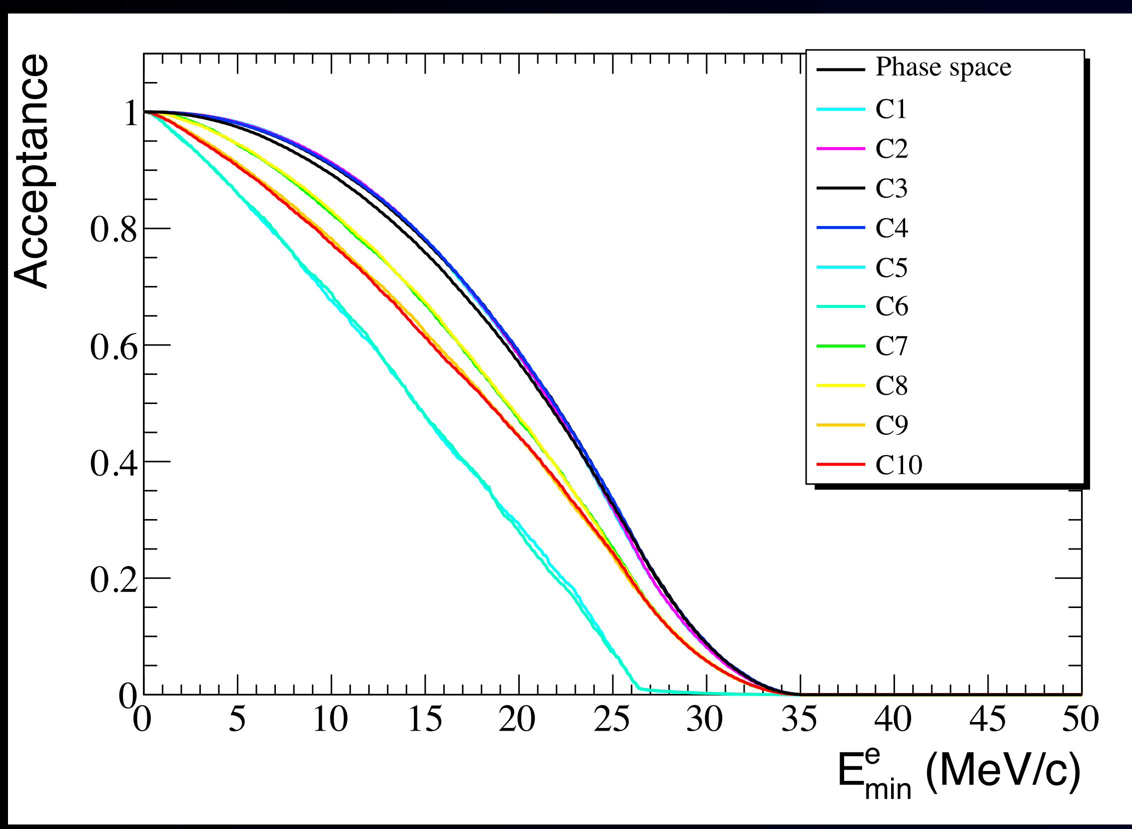


Computer graphics


μ→eee

What is $\mu \to eee$?

- Event Signature
  - $\Sigma E_e = m_\mu$
  - $\Sigma P_e = 0$ (vector sum)
  - common vertex
  - time coincidence



acceptance of lowest $e^{\pm}$ vs. its minimum p

- Backgrounds
  - physics backgrounds
    - $\mu \to e\nu\nu ee$ decay ($B=3.4\times10^{-5}$) when two neutrinos carry very small energies.
  - accidental backgrounds
    - positrons in $\mu \to e\nu\nu$
    - electrons in $\mu \to eee\nu\nu$ or $\mu \to e\nu\nu\gamma$ ($B=1.2\times10^{-2}$) with photon conversion or charge mis-id or Bhabha scattering.

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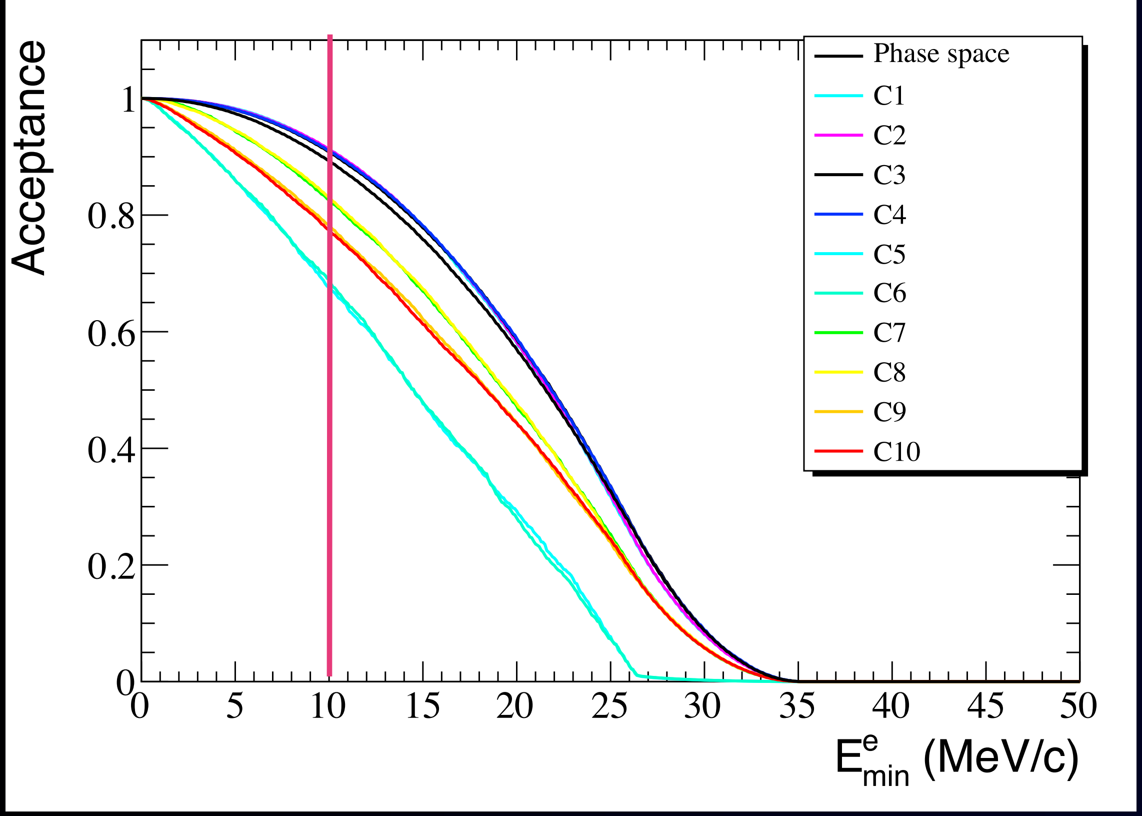

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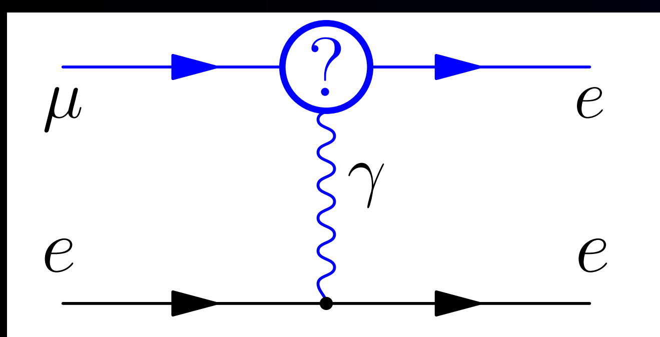
Physics Sensitivity: μ→eγ vs. μ→eee

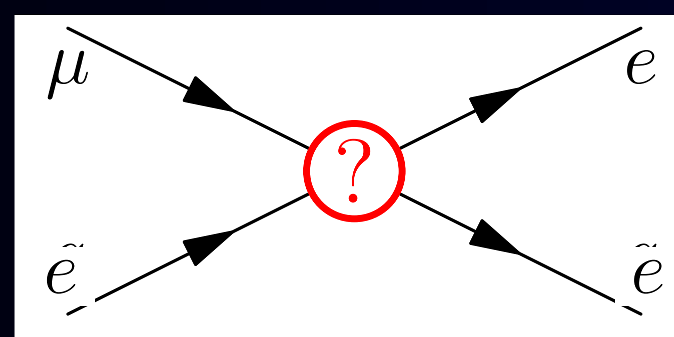
constructive

$$L_{\rm CLFV} = \frac{1}{1+\kappa}\frac{m_\mu}{\Lambda^2}\bar{\mu}_{\rm R}\sigma^{\mu\nu}e_{\rm L}F_{\mu\nu} + \frac{\kappa}{1+\kappa}\frac{1}{\Lambda^2}(\bar{\mu}_{\rm L}\gamma^\mu e_{\rm L})(\bar{e}_{\rm L}\gamma_\mu e_{\rm L})$$

Photonic (dipole) interaction

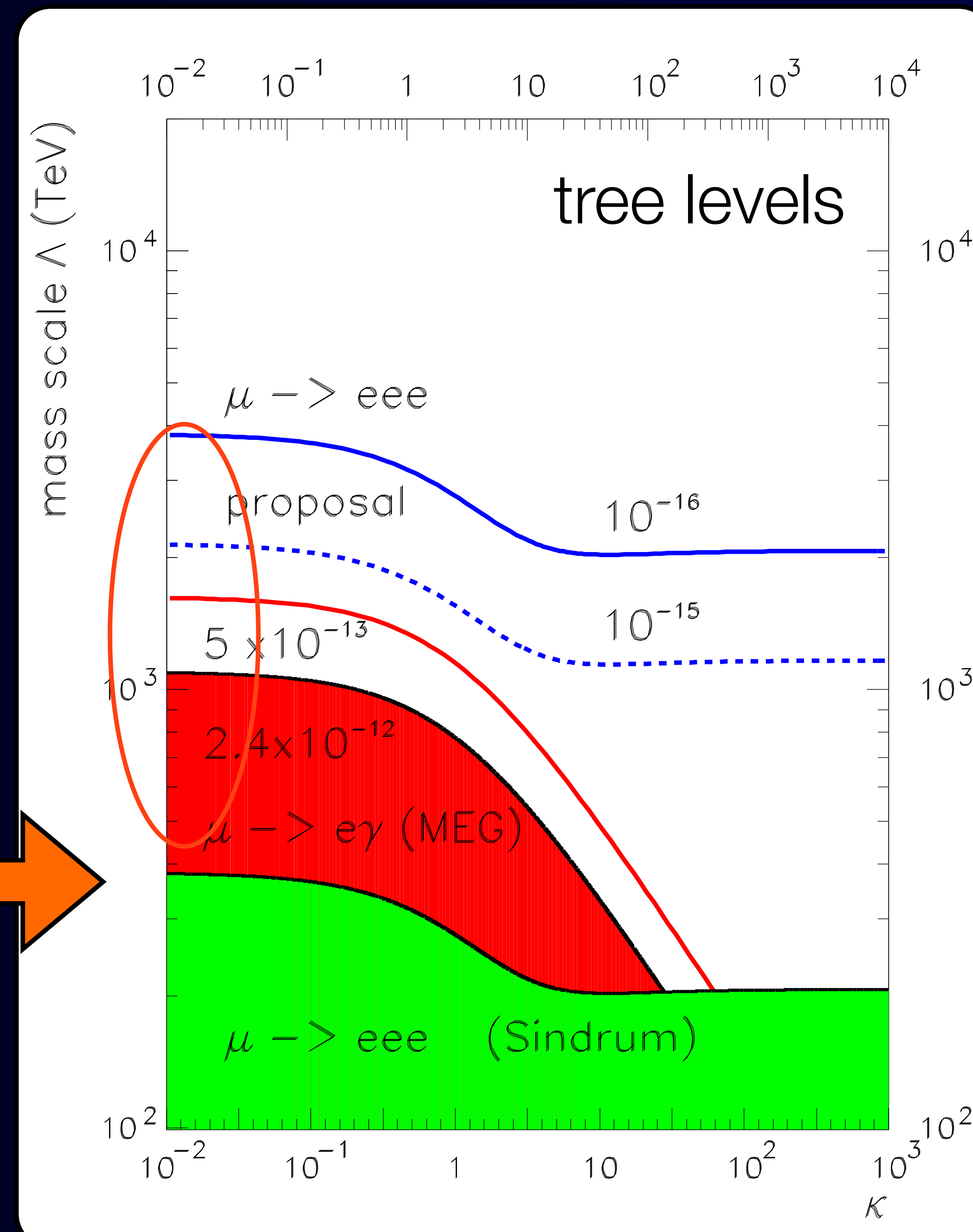


Contact interaction



if photonic contribution dominates,

$$\frac{\mathrm{B}(\mu \to eee)}{\mathrm{B}(\mu \to e\gamma)} \approx 0.006$$

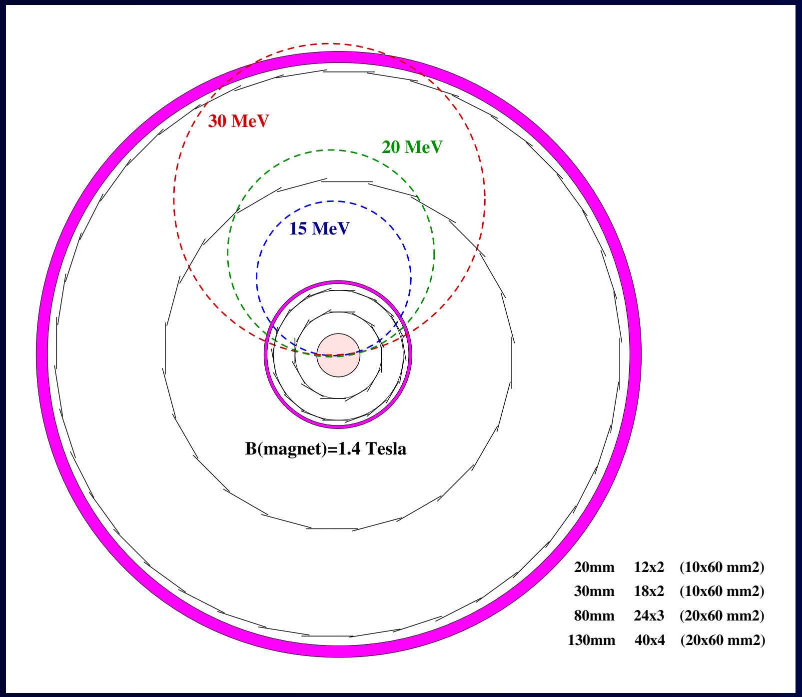


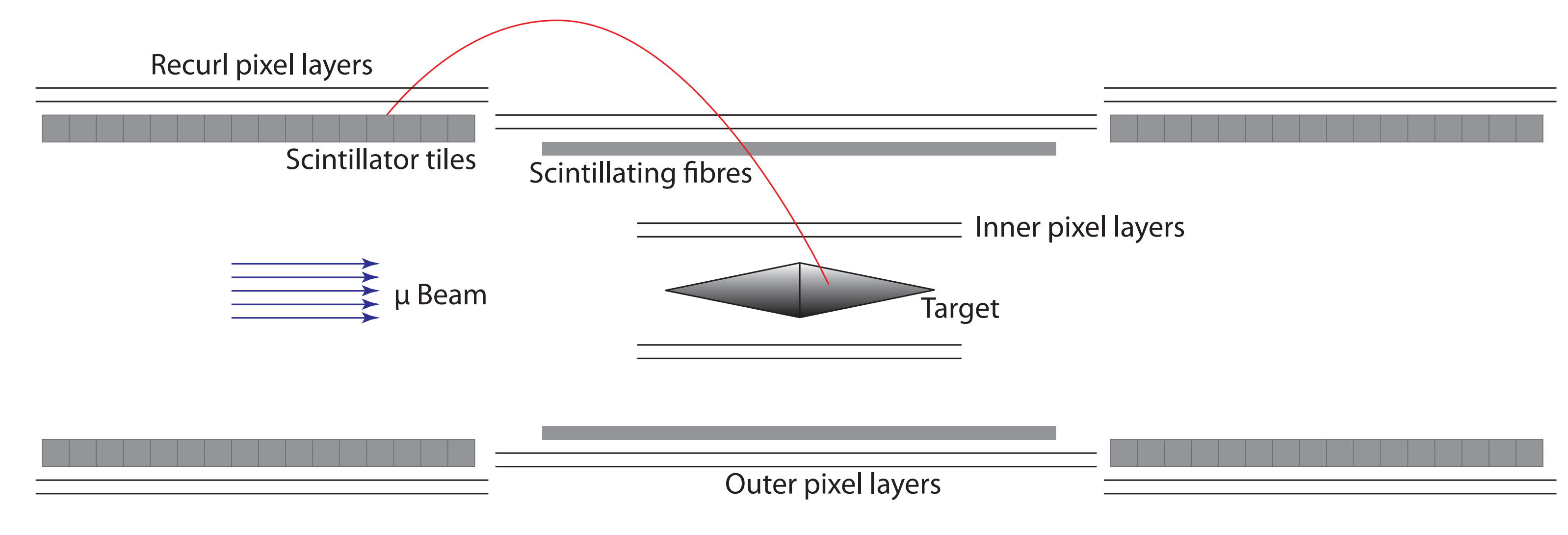
Mu3e at PSI (LOI)

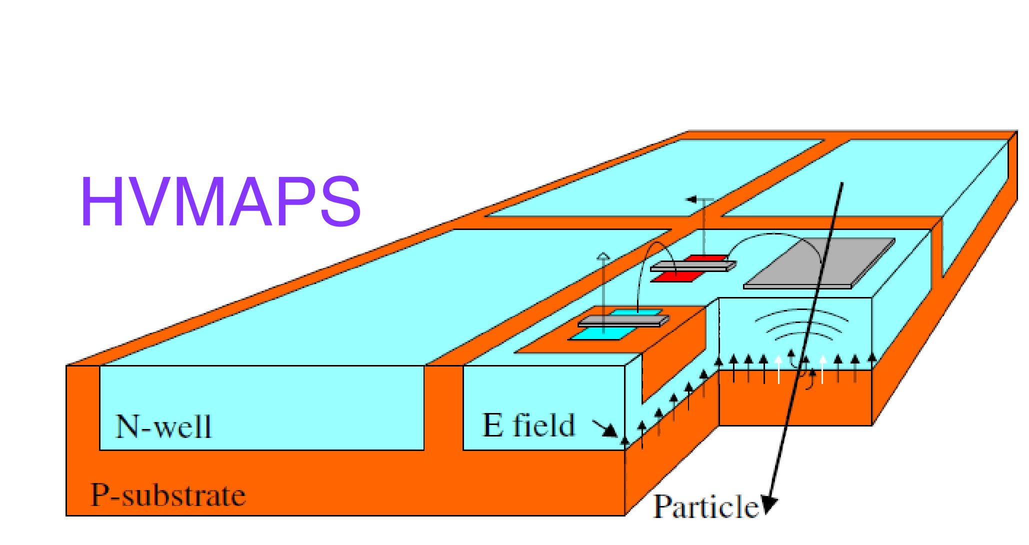
New

- thin silicon pixel detectors (<50μm thick) with high position resolution
  - high voltage monolithic active pixel (HVMAPS)
  - three (two) cylinders with double layers
- SciFi hodoscopes with high timing resolution.

- Stage-I (2014-2017)
  - $B \sim 10^{-15}$ with 2×10^{8} μ/s at πE5
- Stage-2 (2018-)
  - $B < 10^{-16}$ with 2×10^{9} μ/s at new muon source



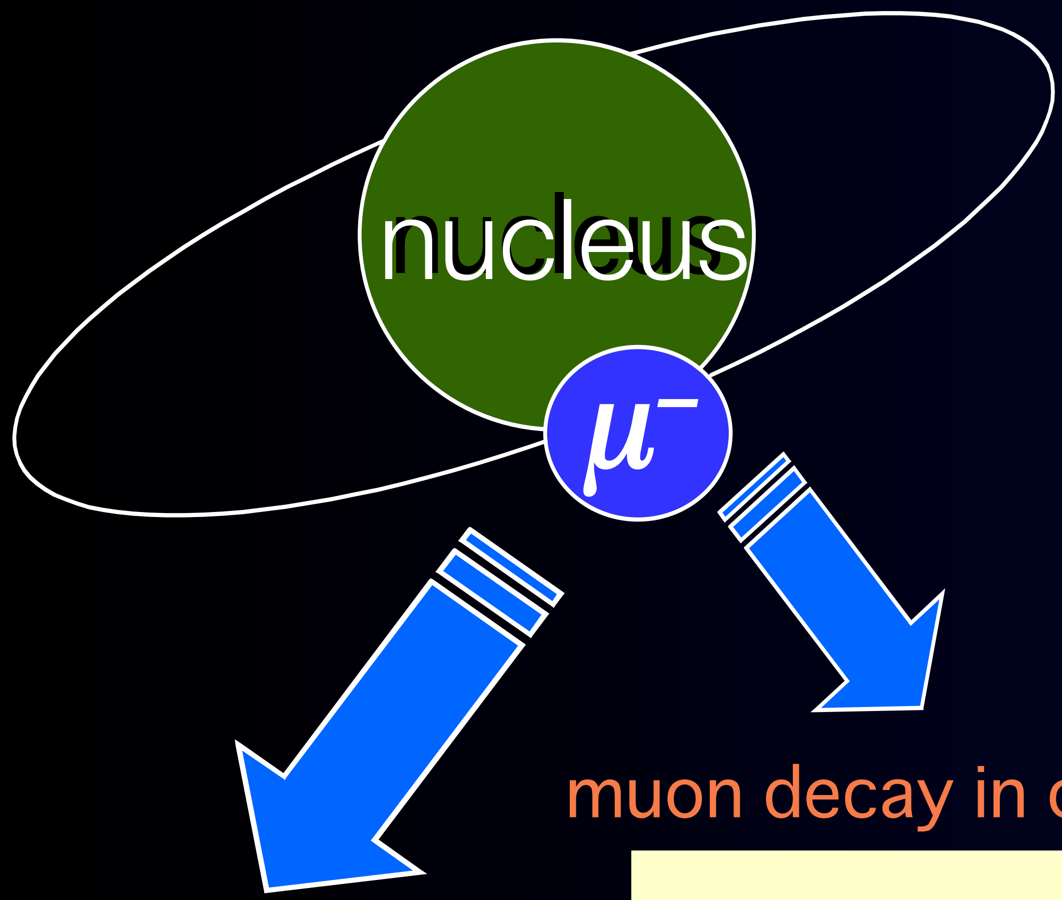




$\mu \rightarrow e$ conversion in a muonic atom

What is 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

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

Event Signature :

a single mono-energetic electron of 100 MeV

Backgrounds:

(1) physics backgrounds
  ex. muon decay in orbit (DIO)
(2) beam-related backgrounds
  ex. radiative pion capture, muon decay in flight,
(3) cosmic rays, false tracking

Physics Sensitivity: μ→eγ vs. μ-e conversion

constructive

$$L_{\rm CLFV} = \frac{1}{1+\kappa}\frac{m_\mu}{\Lambda^2}\bar{\mu}_{\rm R}\sigma^{\mu\nu}e_{\rm L}F_{\mu\nu} + \frac{\kappa}{1+\kappa}\frac{1}{\Lambda^2}(\bar{\mu}_{\rm L}\gamma^\mu e_{\rm L})(\bar{q}_{\rm L}\gamma_\mu q_{\rm L})$$

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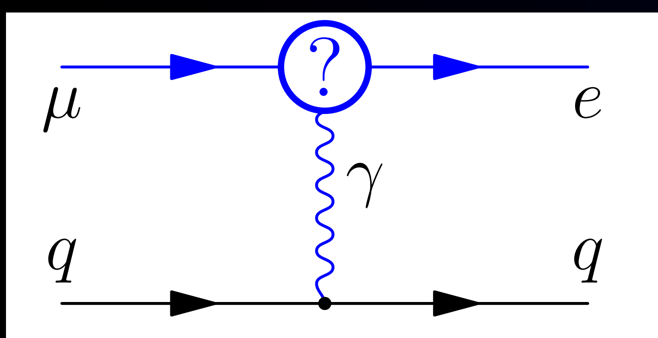
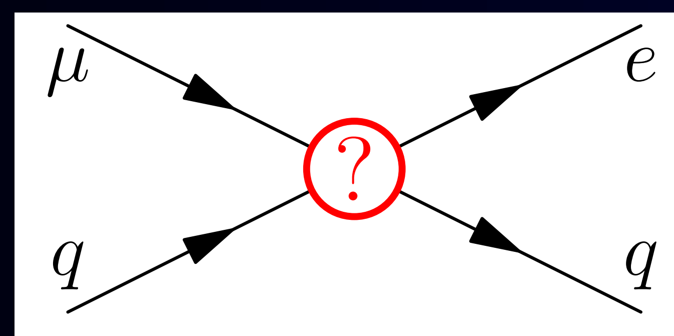


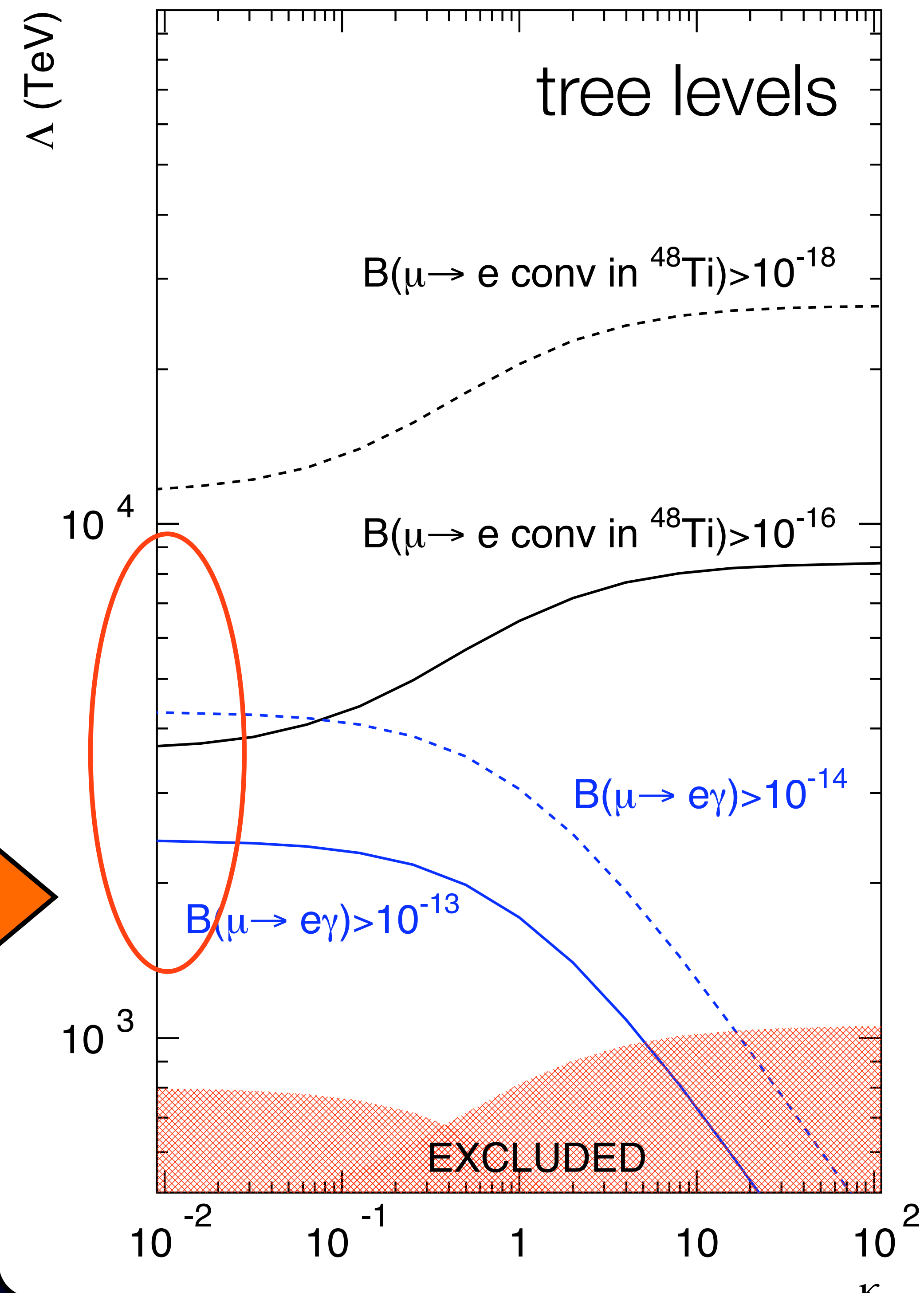
Contact interaction



if photonic contribution dominates,

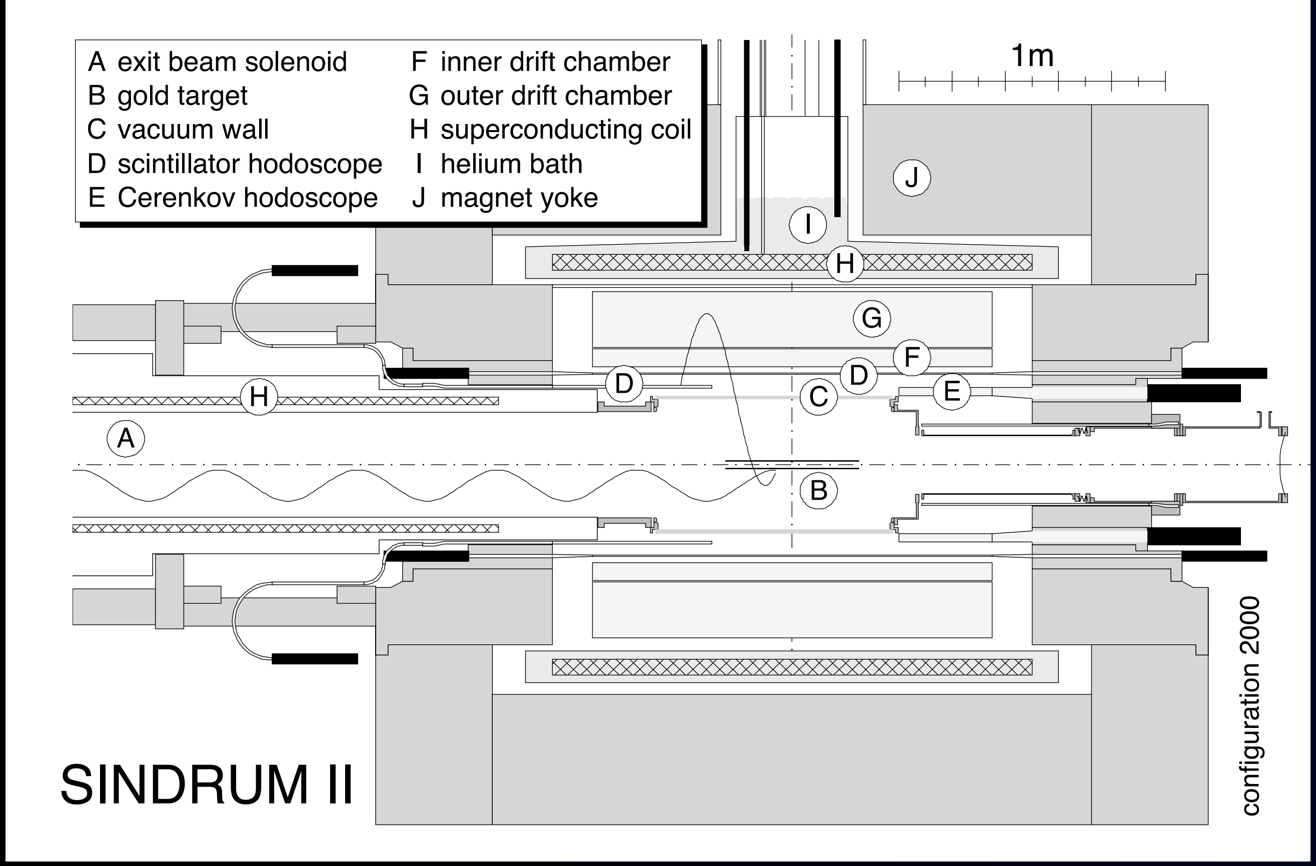
$$\frac{B(\mu N \to eN)}{B(\mu \to e\gamma)} = \frac{G_F^2 m_\mu^4}{96\pi^3\alpha} \times 3 \times 10^{12} B(A,Z) \sim \frac{B(A,Z)}{428}$$

- for aluminum, about 1/390~0.003
- for titanium, about 1/230



Previous Measurements

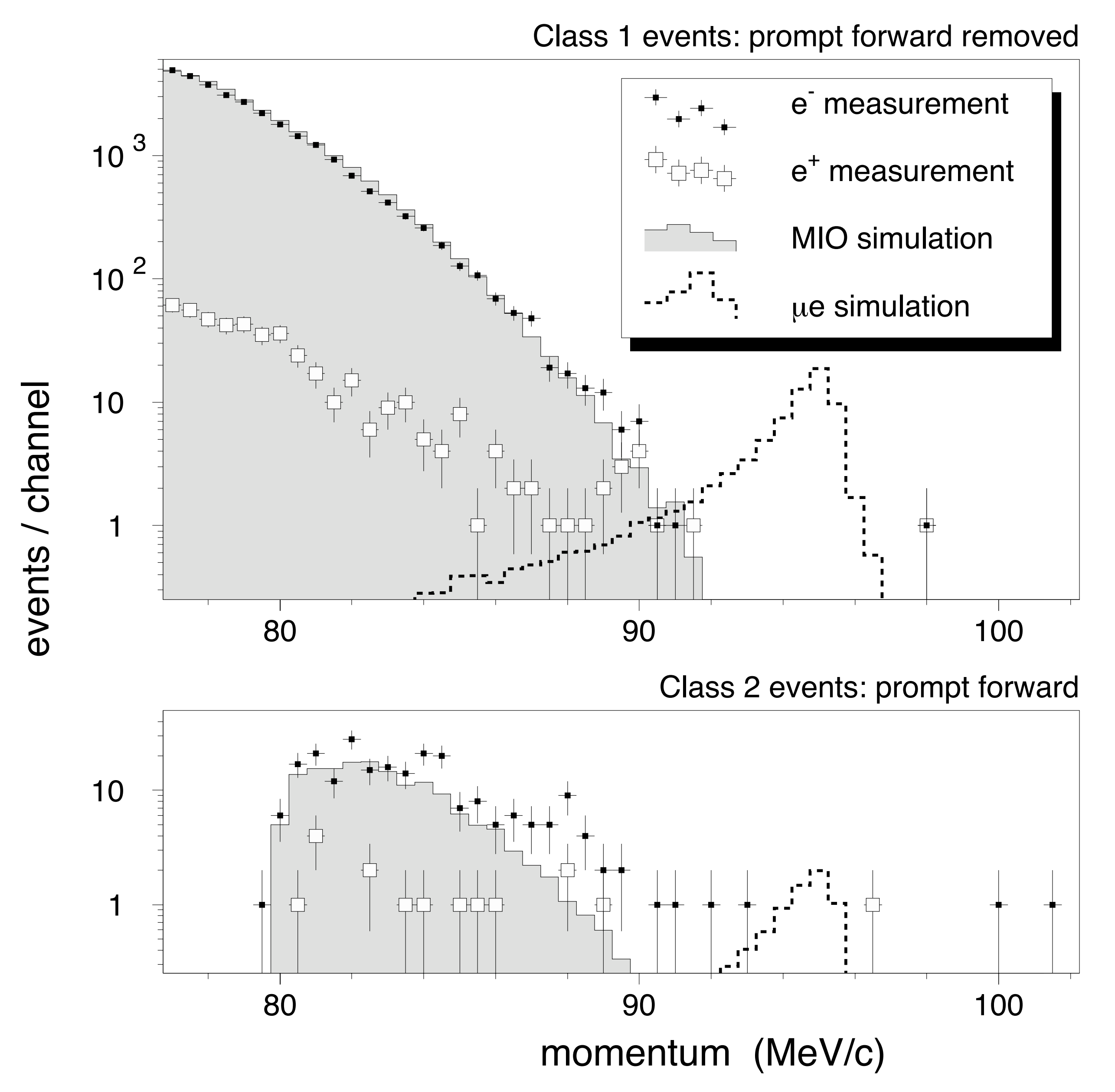
SINDRUM-II (PSI)



PSI muon beam intensity ~ $10^{7\text{-}8}$/sec beam from the PSI cyclotron. To eliminate beam related background from a beam, a beam veto counter was placed. But, it could not work at a high rate.

Published Results (2004)

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



Improvements for Signal Sensitivity

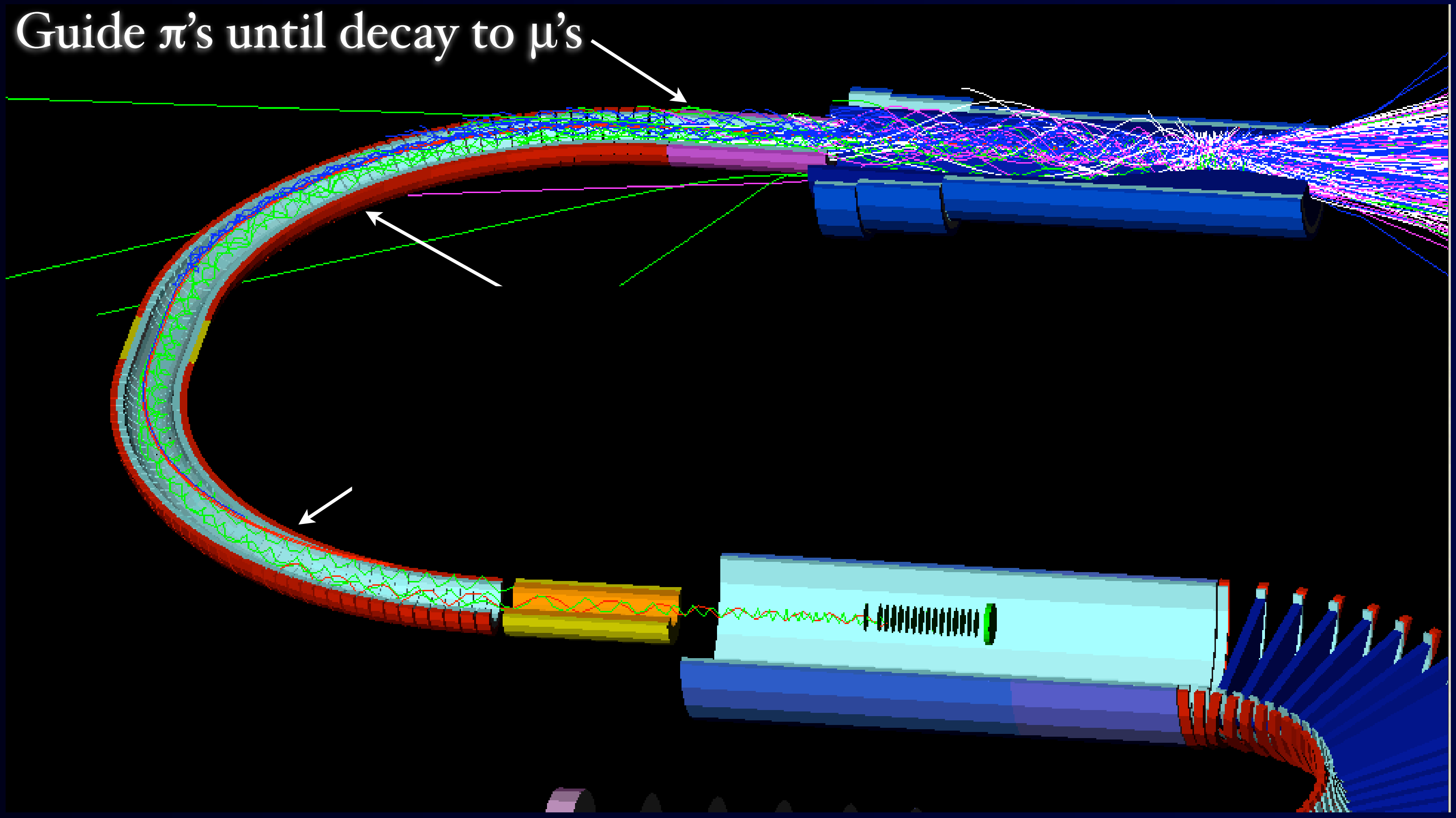
To achieve a single sensitivity of 10^{-17}, we need

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

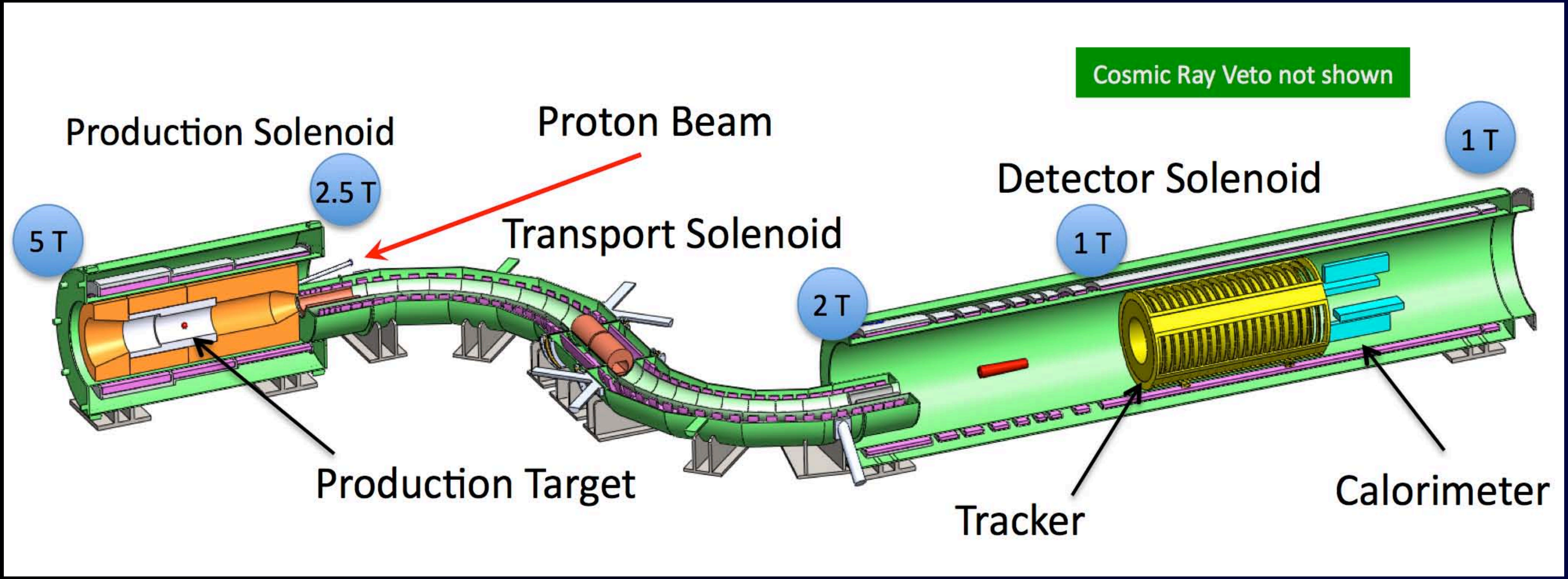
proton extinction = #protons between pulses/#protons in a pulse $< 10^{-9}$

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

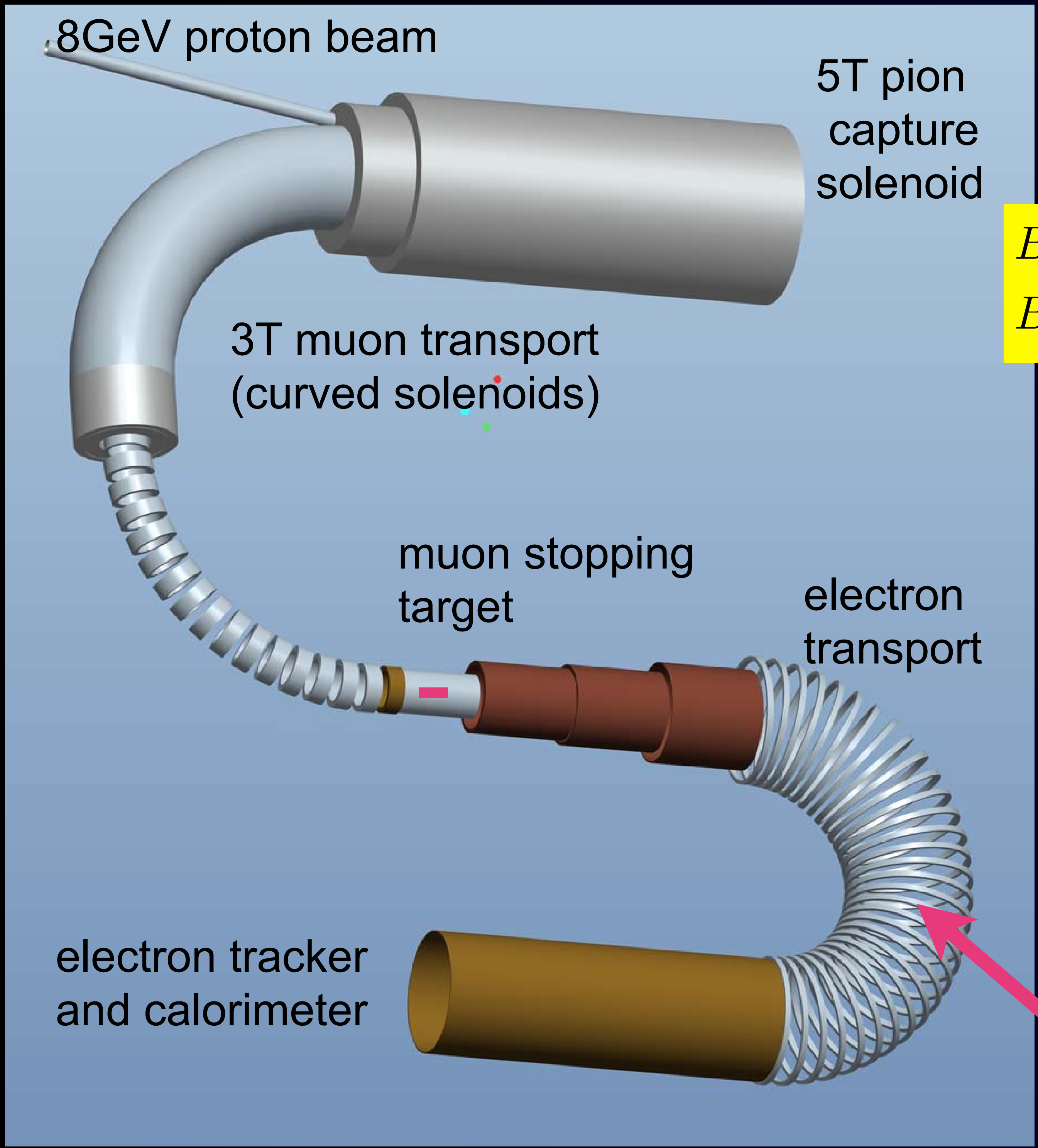
μ-e conversion : Mu2e at Fermilab



$$B(\mu^- + Al \to e^- + Al) = 5 \times 10^{-17} \quad \text{(S.E.)}$$
$$B(\mu^- + Al \to e^- + Al) < 10^{-16} \quad (90\%\text{C.L.})$$

- Reincarnation of MECO at BNL.
- Antiproton buncher ring is used to produce a pulsed proton beam.
- Approved in 2009, and CD0 in 2009, and CD1 review, next week
- Data taking starts in about 2019.

μ-e conversion : COMET (E21) at J-PARC



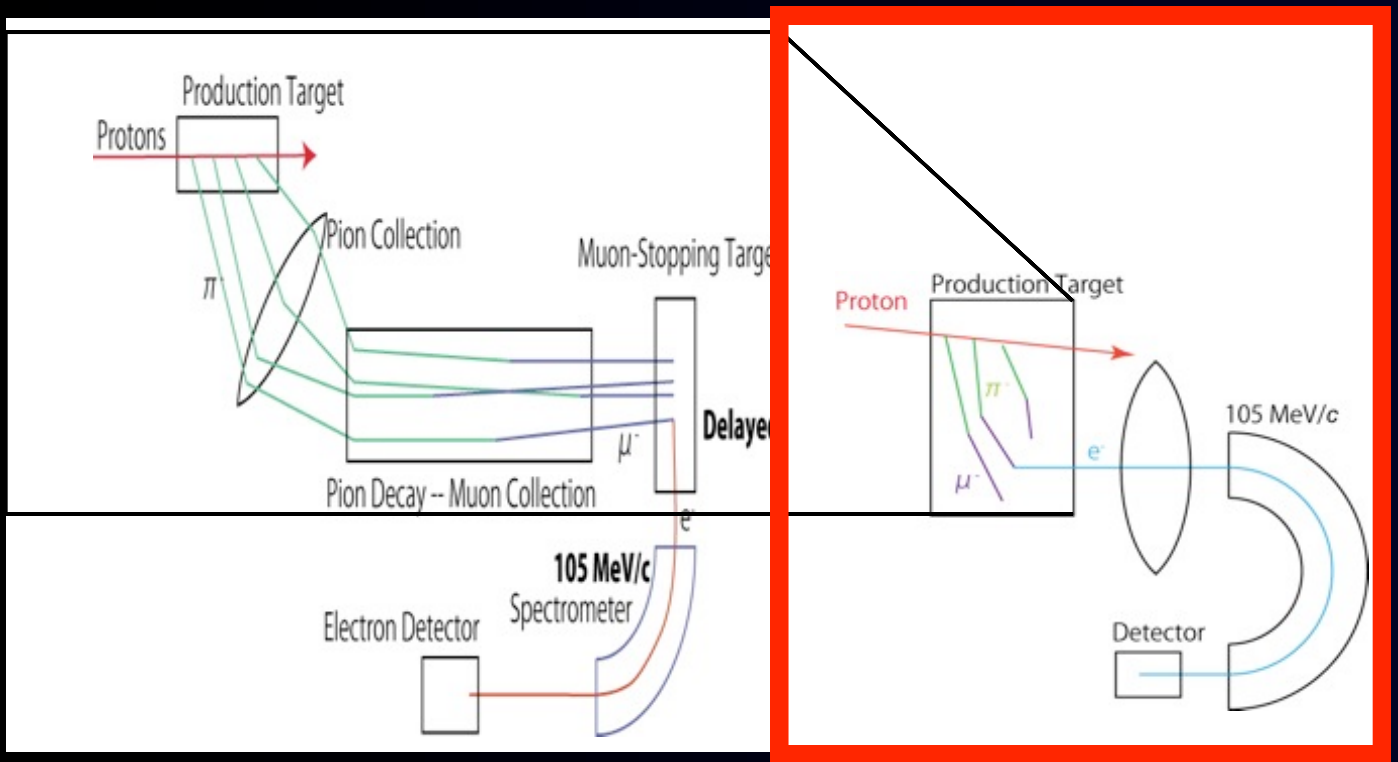
Experimental Goal of COMET

$$B(\mu^- + Al \rightarrow e^- + Al) = 2.6 \times 10^{-17}$$
$$B(\mu^- + Al \rightarrow e^- + Al) < 6 \times 10^{-17} \quad (90\% C.L.)$$

- 10^{11} muon stops/sec for 56 kW proton beam power.
- C-shape muon beam line and C-shape electron transport followed by electron detection system.
- Stage-1 approved in 2009.

Electron transport with curved solenoid would make momentum and charge selection.

μ-e conversion : DeeMe at J-PARC/MLF



ordinary μ-e conversion

DeeMe

proton target = pion production target+ muon transport + muon stopping target

Experimental Goal of DeeMe

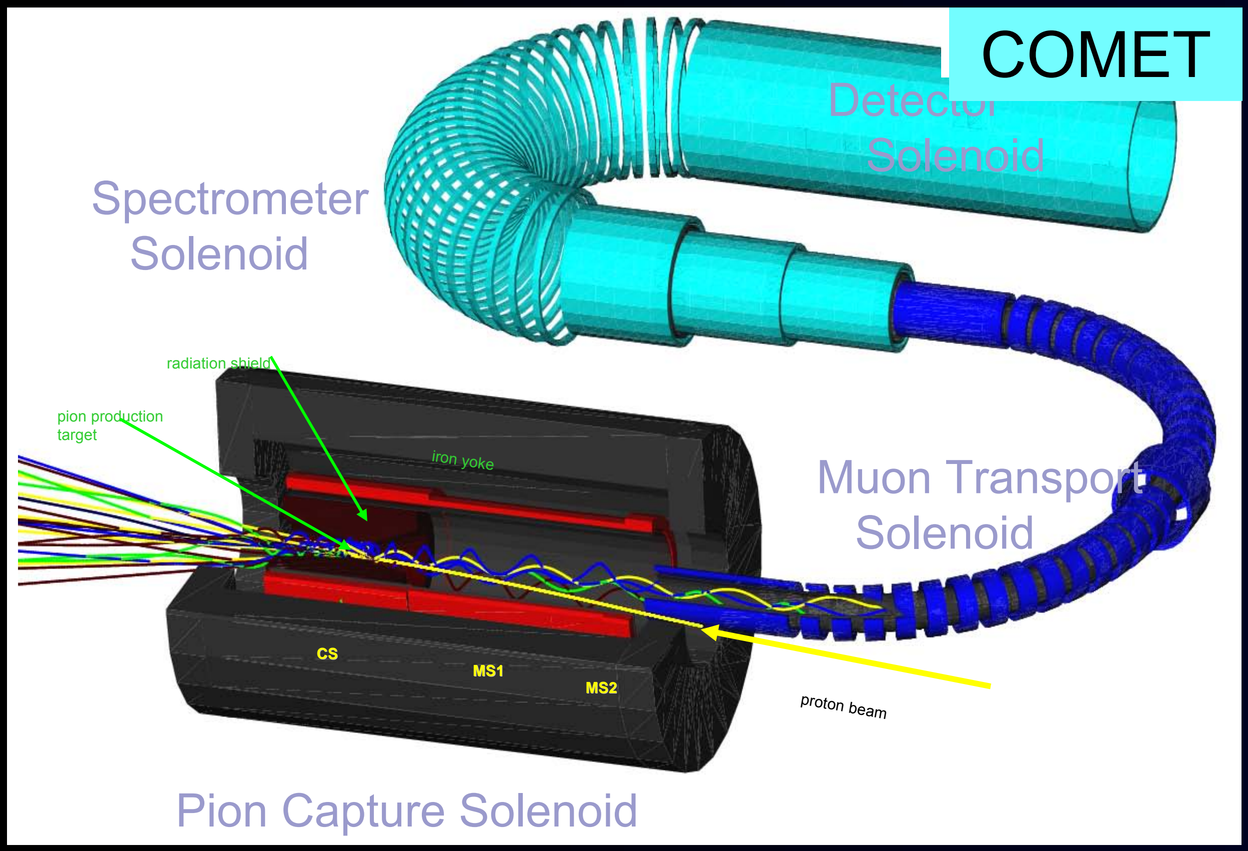
$$B(\mu^- + Si \to e^- + Si) = 1.4 \times 10^{-14} \quad \text{(S.E.)}$$
$$B(\mu^- + Si \to e^- + Si) < 3.5 \times 10^{-14} \quad \text{(90\%C.L.)}$$

- use SiC target for proton target
- use 3 GeV RCS at MUSE facility in J-PARC/MLF.
- 15×10^9 muon stopped for 2×10^7 s running.
- not stage-1 approved at J-PARC PAC of IPNS, KEK

- Advantage
  - quick and not-expensive
    - by Grant-in-aid
- Disadvantage
  - zero length muon beamline
    - high proton extinction 10^{-17} required because of pions
  - thick muon stopping target
    - poor e^- momentum resolution

R&D Milestones

R&D Milestones for μ-e conversion



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

single event sensitivity: 2.6×10^{-17}

1 **Reduction of Backgrounds**

Beam pulsing

measurement is done between beam pulses to reduce beam related backgrounds. And proton beam extinction of $<10^{-9}$ is required.

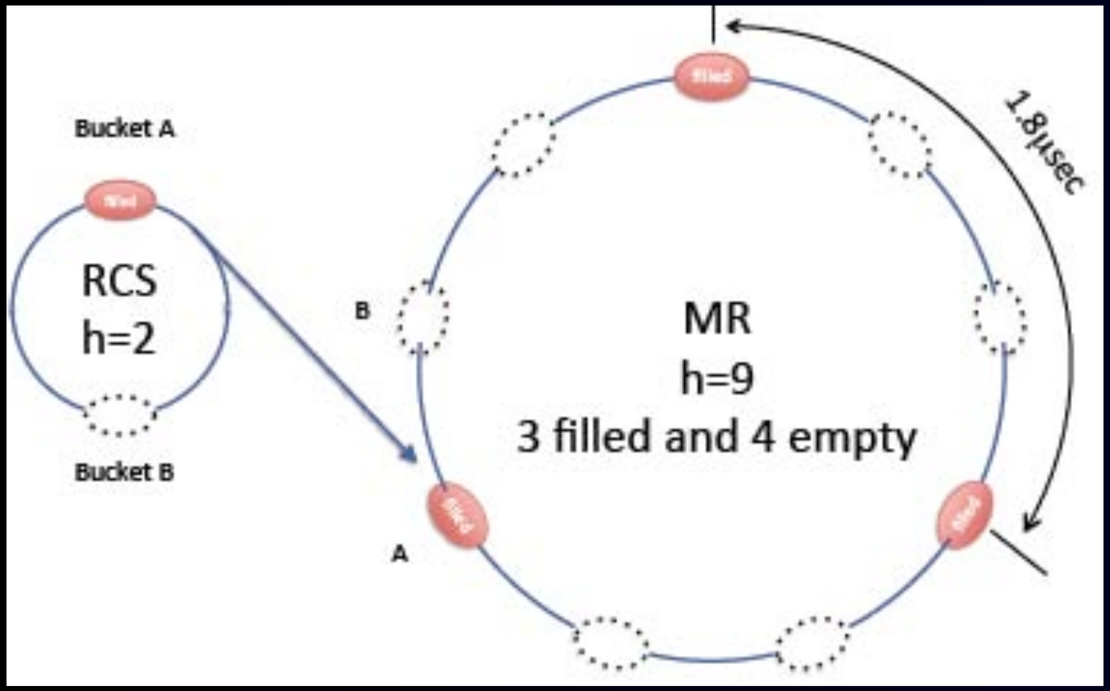
2 **Increase of Muon Intensity**

Pion capture system $\times 10^3$

high field superconducting solenoid magnets surrounding a pion production target

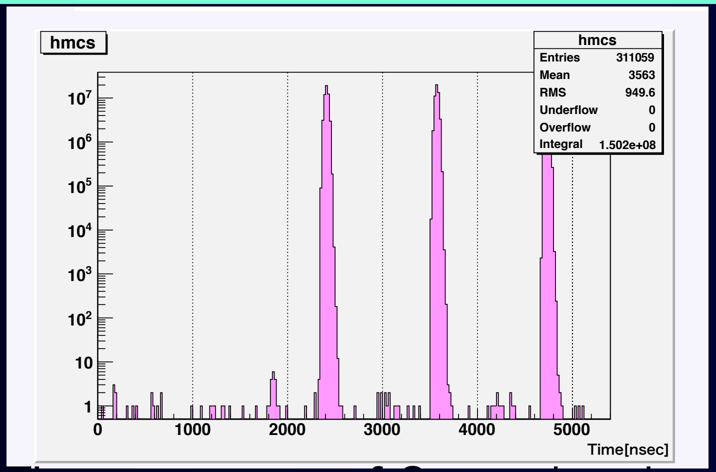
1 Proton Beam Extinction Studies (COMET)

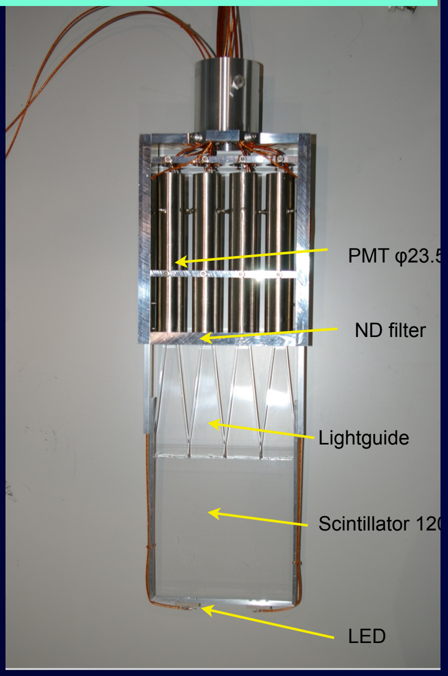
1 Proton Beam Extinction Studies (COMET)



Measured at abort beamline (2010)

Measured at secondary beamline (2010)

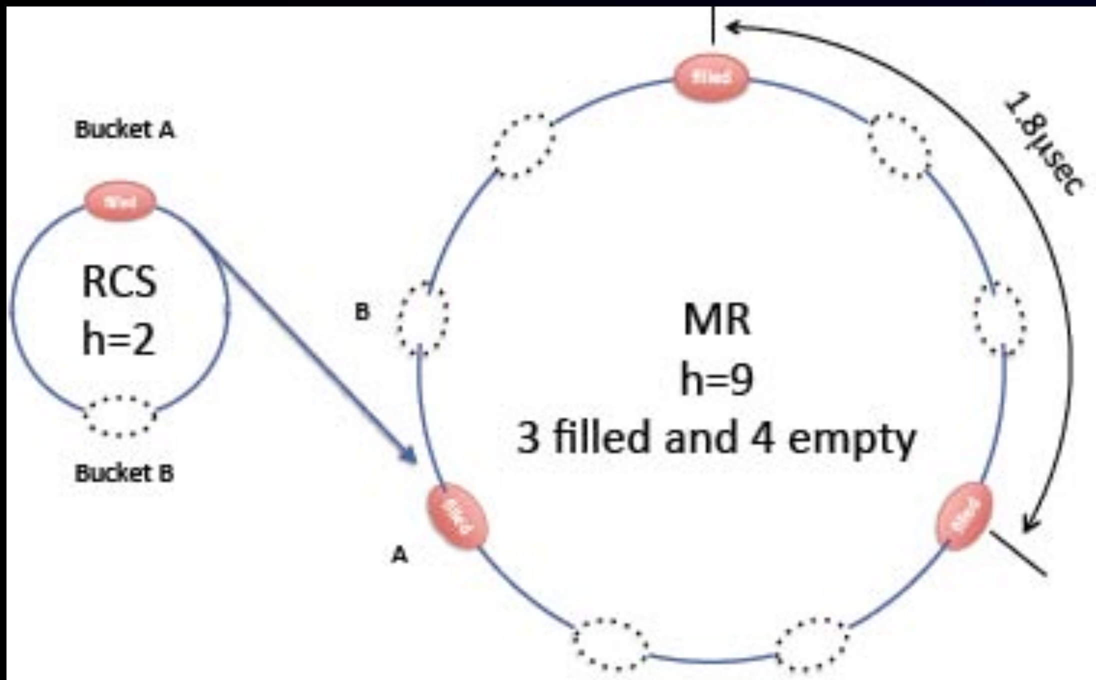




J-PARC MR proton extinction

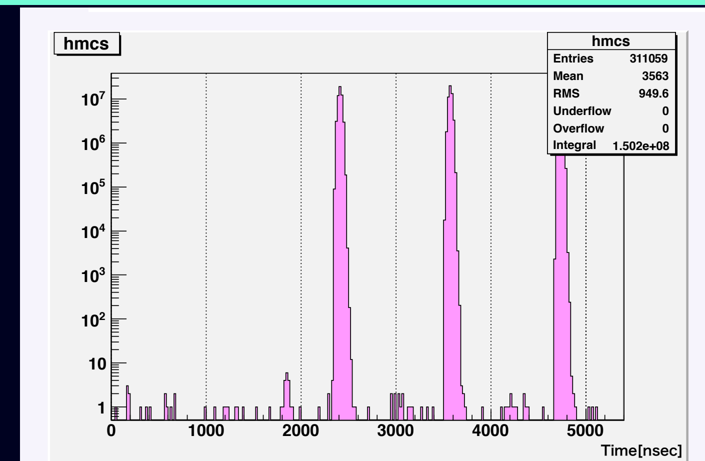
~ O(10^{-7})

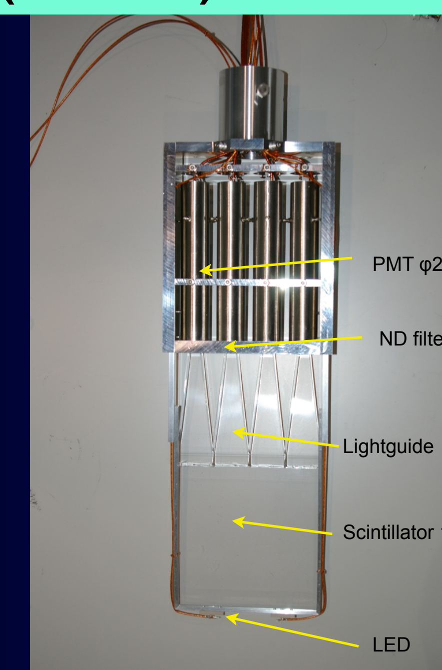
1 Proton Beam Extinction Studies (COMET)



Measured at abort beamline (2010)

Measured at secondary beamline (2010)





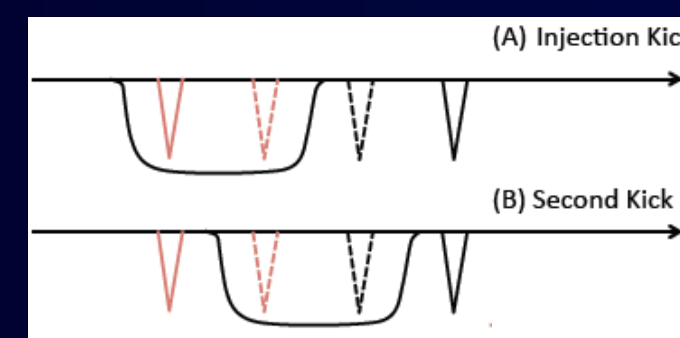
J-PARC MR proton extinction

~ O(10^{-7})

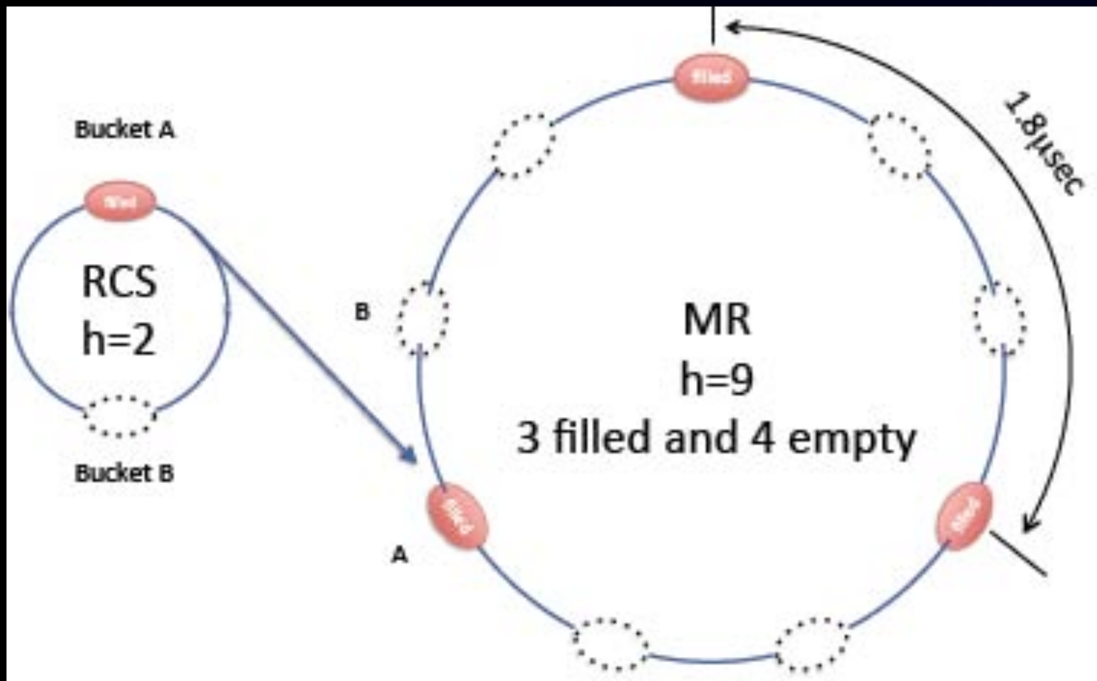
Double Injection Kicking

Tested at the abort (2010)

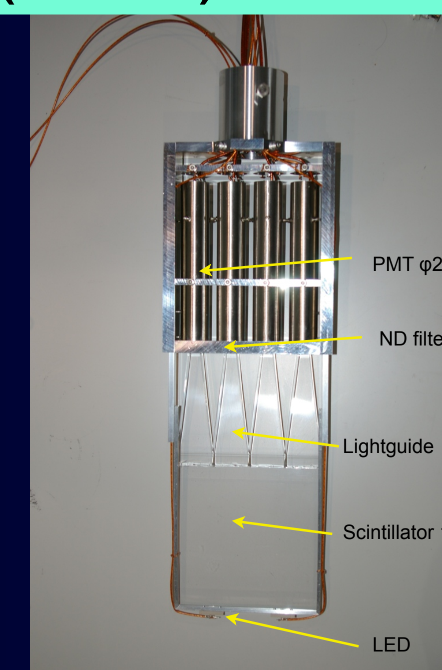
x additional O(10^{-6})



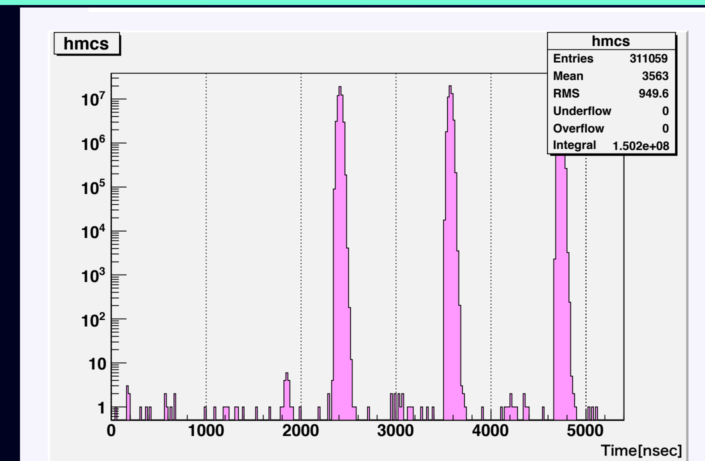
1 Proton Beam Extinction Studies (COMET)



Measured at abort beamline (2010)



Measured at secondary beamline (2010)



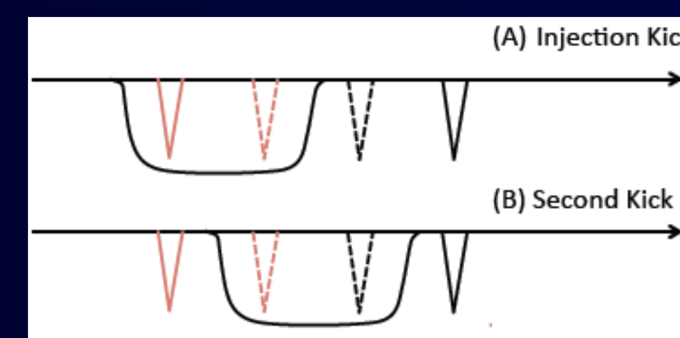
J-PARC MR proton extinction

~ O(10^{-7})

Double Injection Kicking

Tested at the abort (2010)

x additional O(10^{-6})

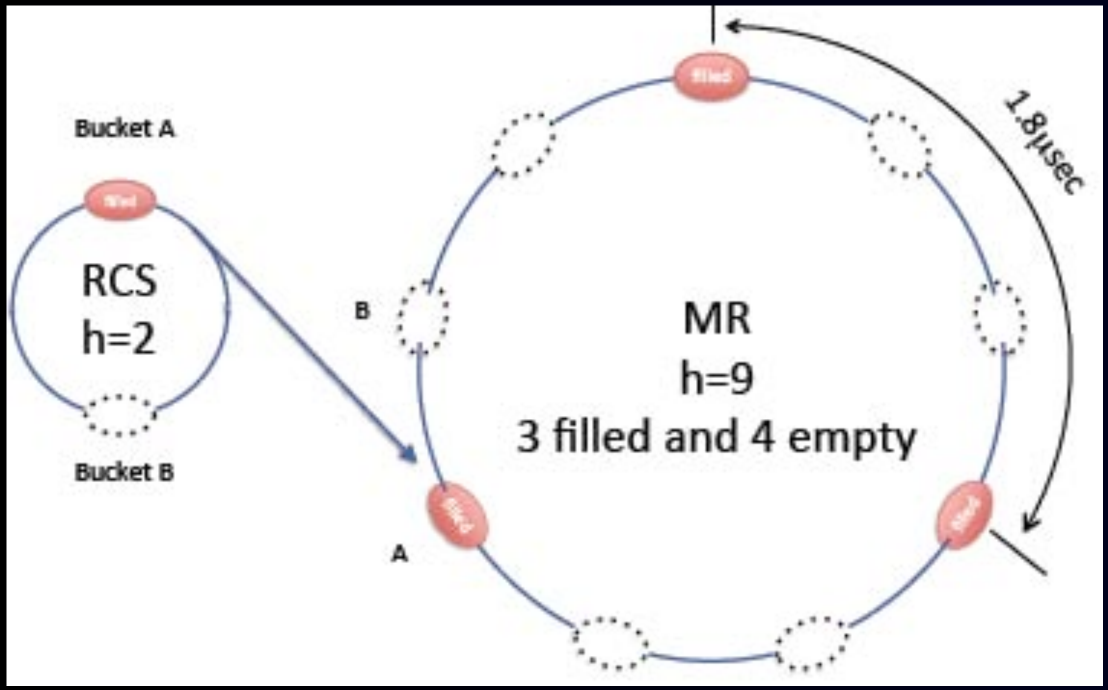


External Extinction Device

AC dipole magnet R&D

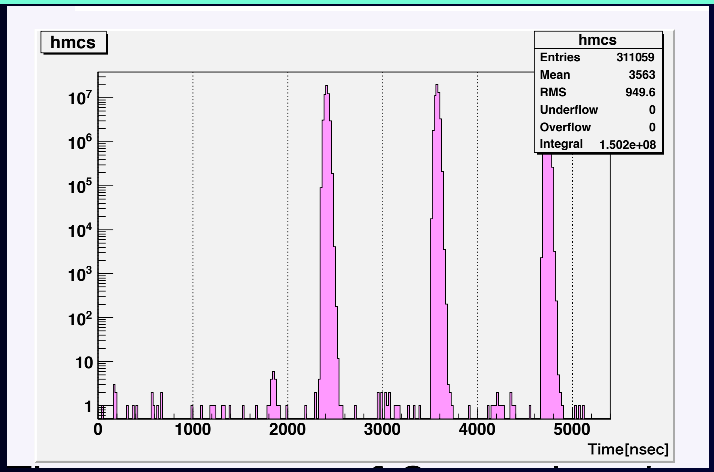
x additional O(10^{-3})

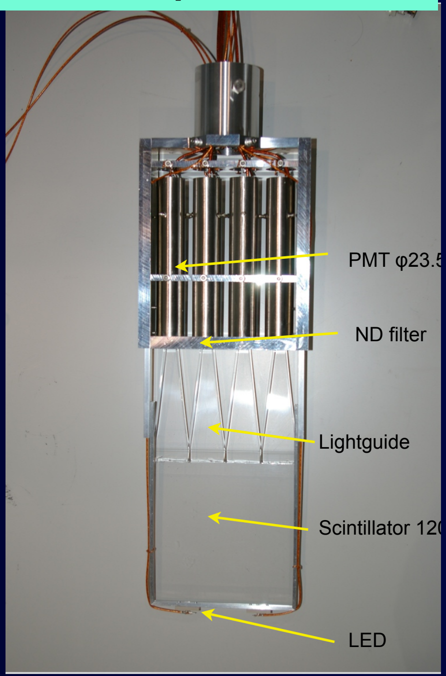
1 Proton Beam Extinction Studies (COMET)



Measured at abort beamline (2010)

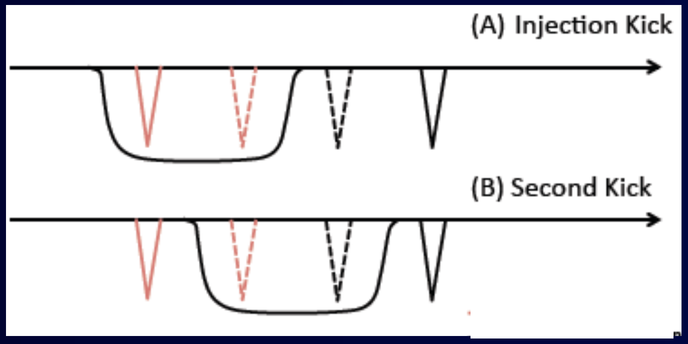
Measured at secondary beamline (2010)





J-PARC MR proton extinction

~ $O(10^{-7})$



Double Injection Kicking

Tested at the abort (2010)

x additional $O(10^{-6})$

External Extinction Device

AC dipole magnet R&D

x additional $O(10^{-3})$

Confident to achieve proton extinction of <$O(10^{-9})$.

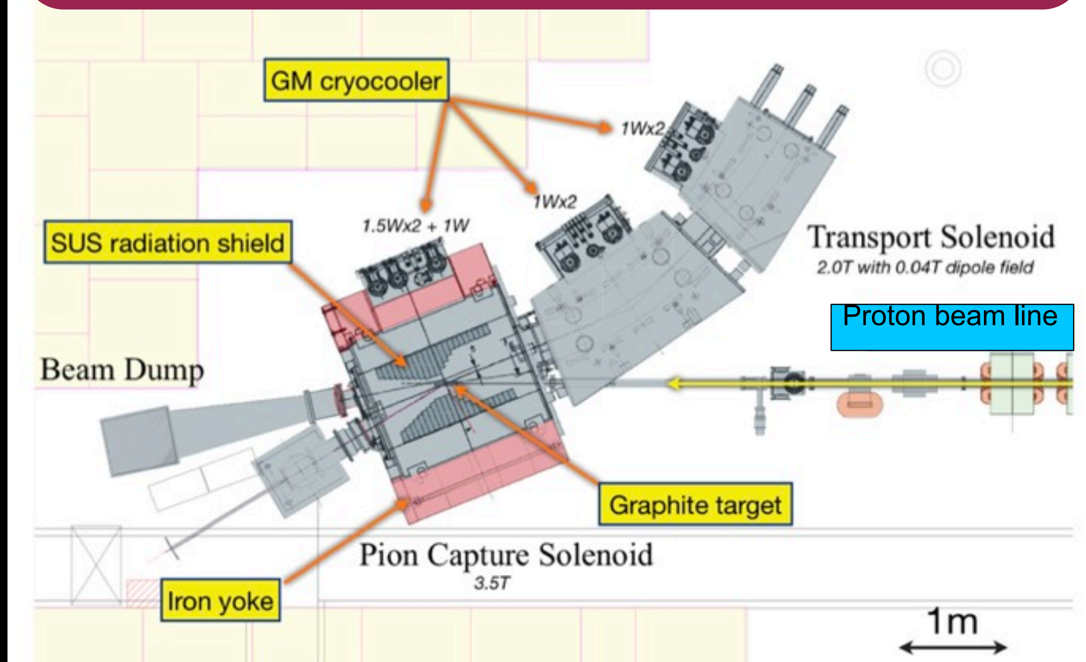
2 Pion Capture System@MuSIC

Pion Capture System@MuSIC

Demonstration of Pion Capture System

RCNP cyclotron
400 MeV, 1μA

MuSIC@Osaka-U



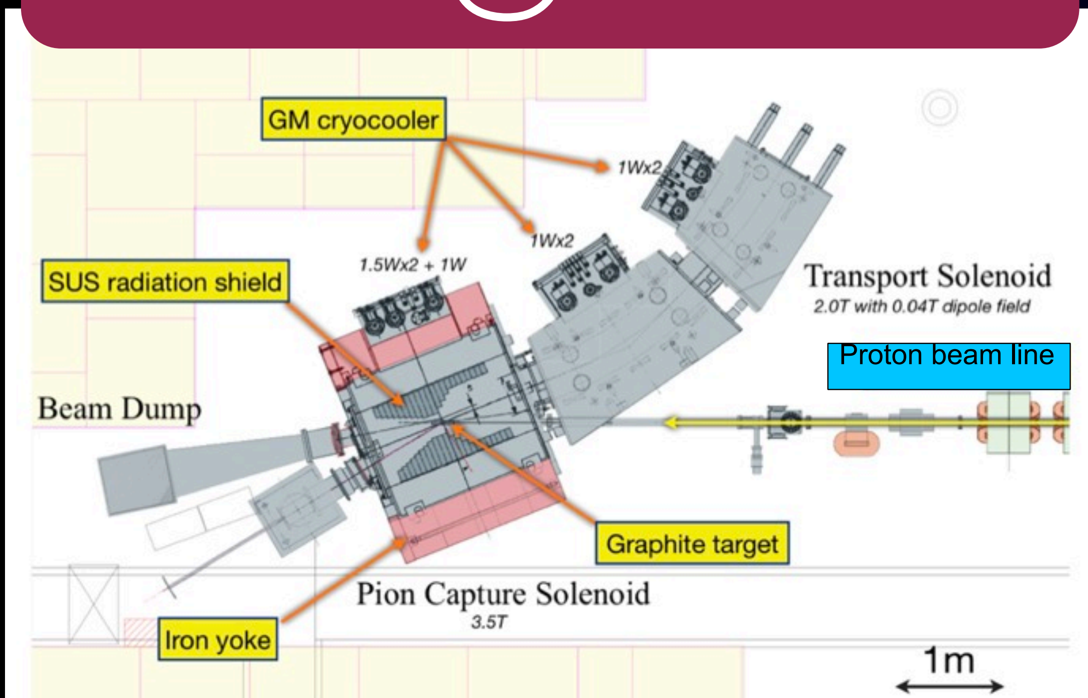
2

Pion Capture System@MuSIC

Demonstration of Pion Capture System

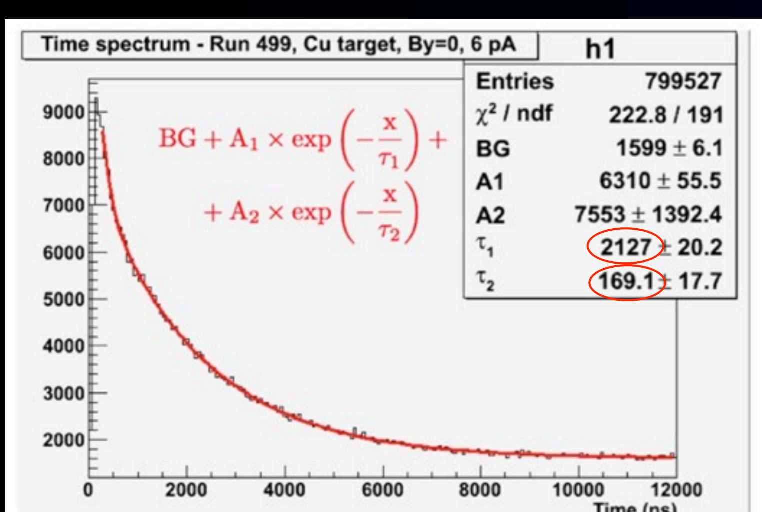
RCNP cyclotron
400 MeV, 1μA

MuSIC@Osaka-U

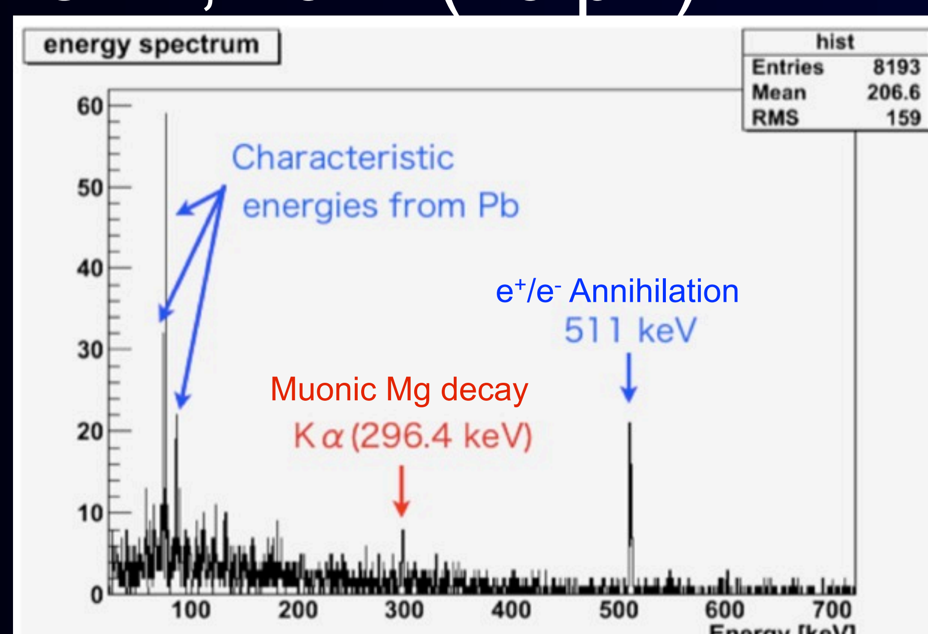


preliminary

Measurements on June 21, 2011 (26 pA)



	Free muon*	Cu**	Plastic scint.**
τ (ns)	2197.03 ± 0.04	163.5 ± 1	2026.3 ± 1.5



MuSIC muon yields

μ^+ : 3x10^8/s for 400W

μ^- : 1x10^8/s for 400W

cf. 10^8/s for 1MW @PSI
Req. of x10^3 achieved...

COMET Phase-I

COMET Phase-I (staged scenario) - from J-PARC PAC report, March 2012

New

Reflecting the PAC's high evaluation of the physics associated with the COMET experiment and the positive results in the report recently published by a sub-committee of Japanese Association on High Energy Physics (JAHEP) on the future high energy physics projects, the COMET experiment is a high priority component for the J-PARC program. Considering that this high-priority experiment needs a large investment in infrastructure and hence a long time to realize, it is important to start the construction of the COMET beam line in the next 5 years.

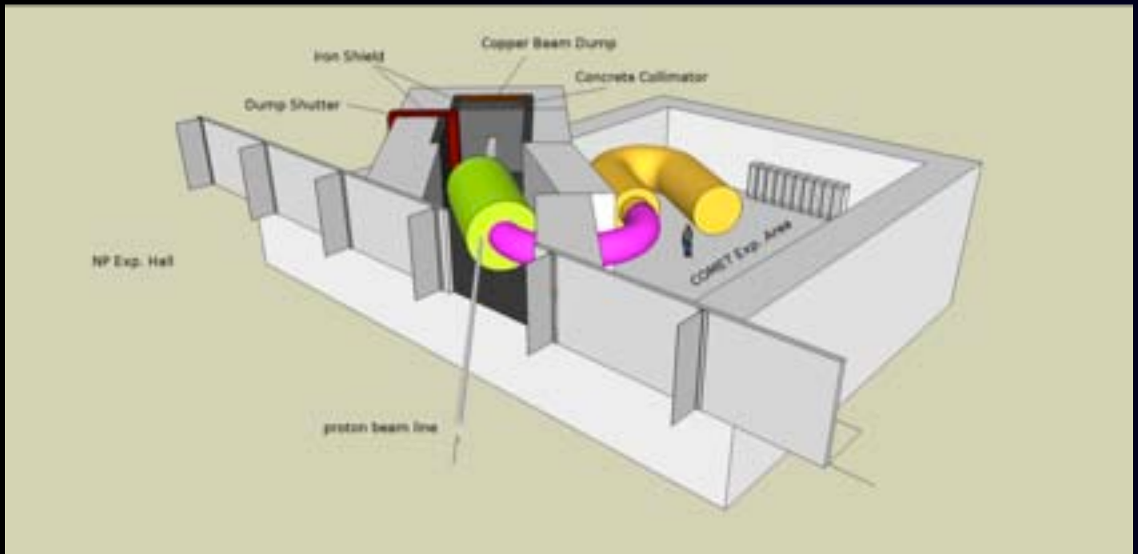
The IPNS proposes, as the first priority item in the next five-year plan, that the upstream part of the high-p beam line be constructed and co-used by the COMET experiment and that the first half of the muon capture solenoid be constructed simultaneously.

A consequence of this plan is that the K1.1BR beam line will not be usable after the installation of the production target of COMET. This conflict, as was pointed out by the PAC in the last meeting, will have a serious impact on the TREK experiments (E06 and P36). The PAC is requested to consider and comment on this in its evaluation during the meeting.

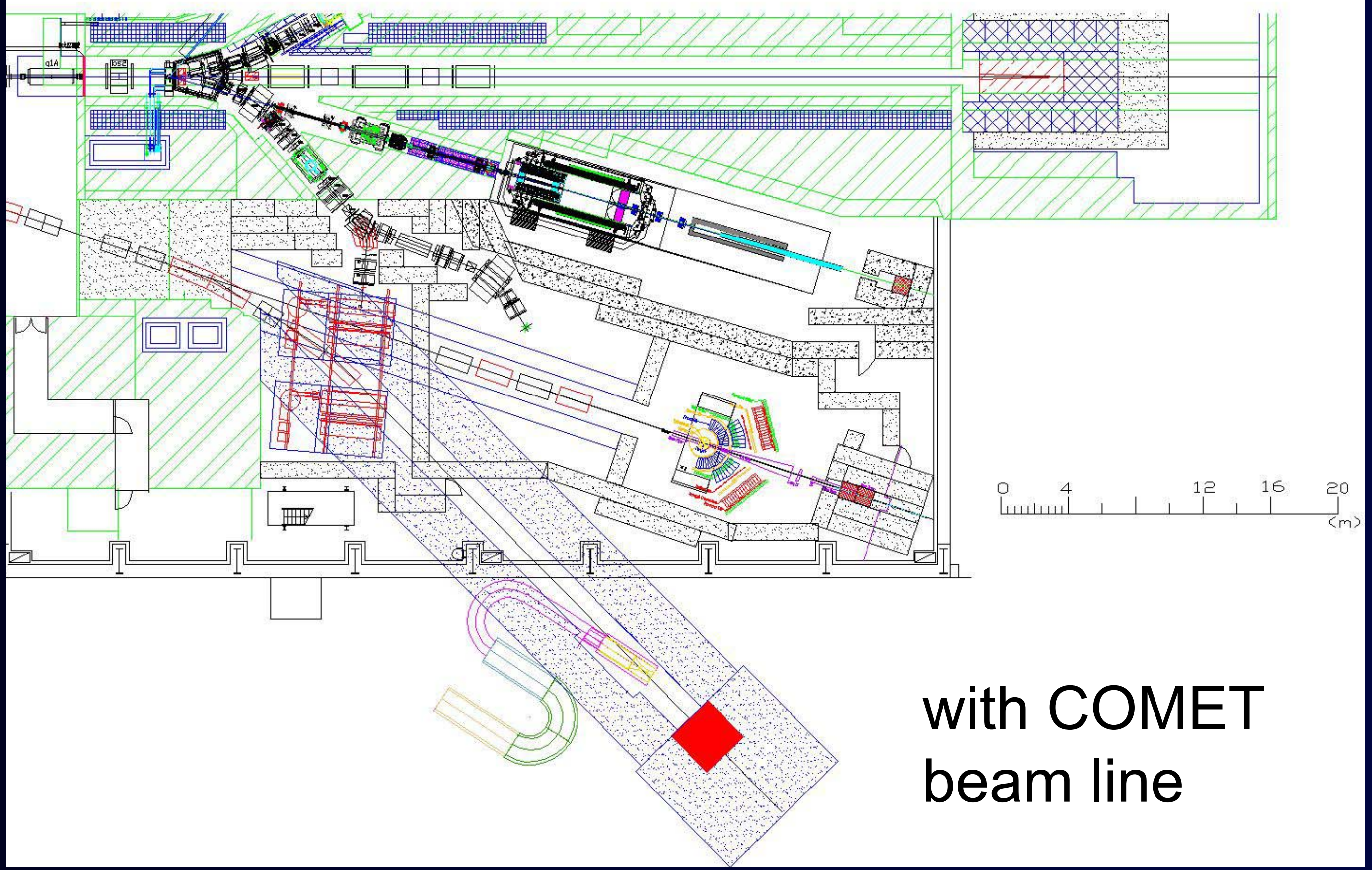
COMET Phase-I (staged scenario)

New

- IPNS/KEK determined
  - COMET Phase-I as one of the J-PARC mid-term projects from JFY2013.
  - The other is the high-P proton beam line, which is the upstream line of the COMET.

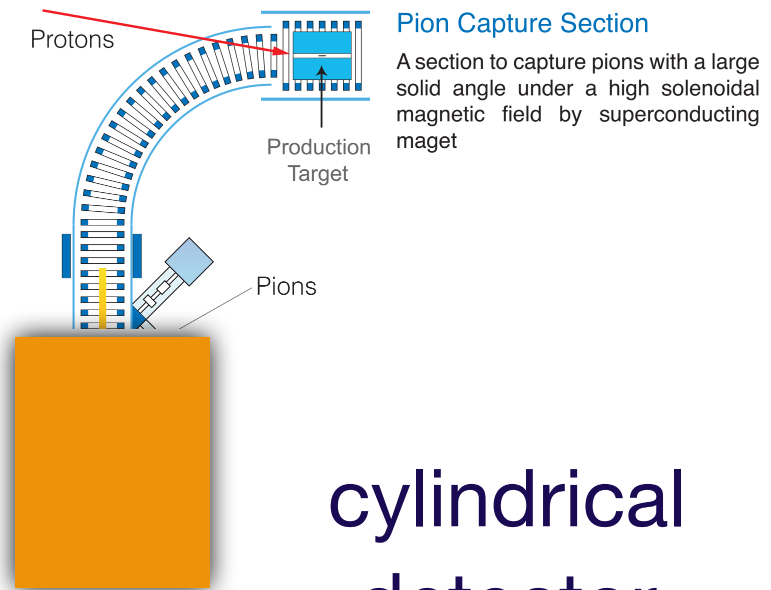


Beam line plan at southern area



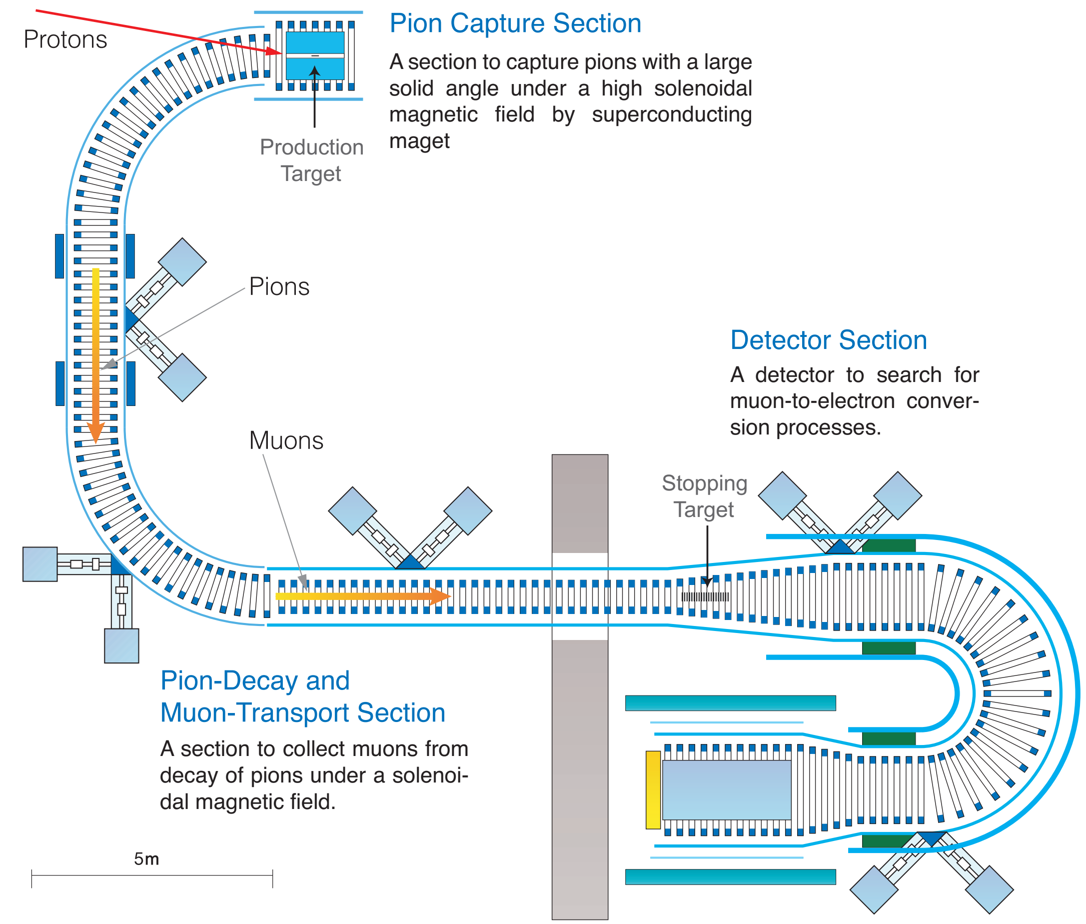
COMET Staged Scenario
Phase-I (2016~) and Phase-II (2020~)

Phase1



cylindrical detector

Phase2



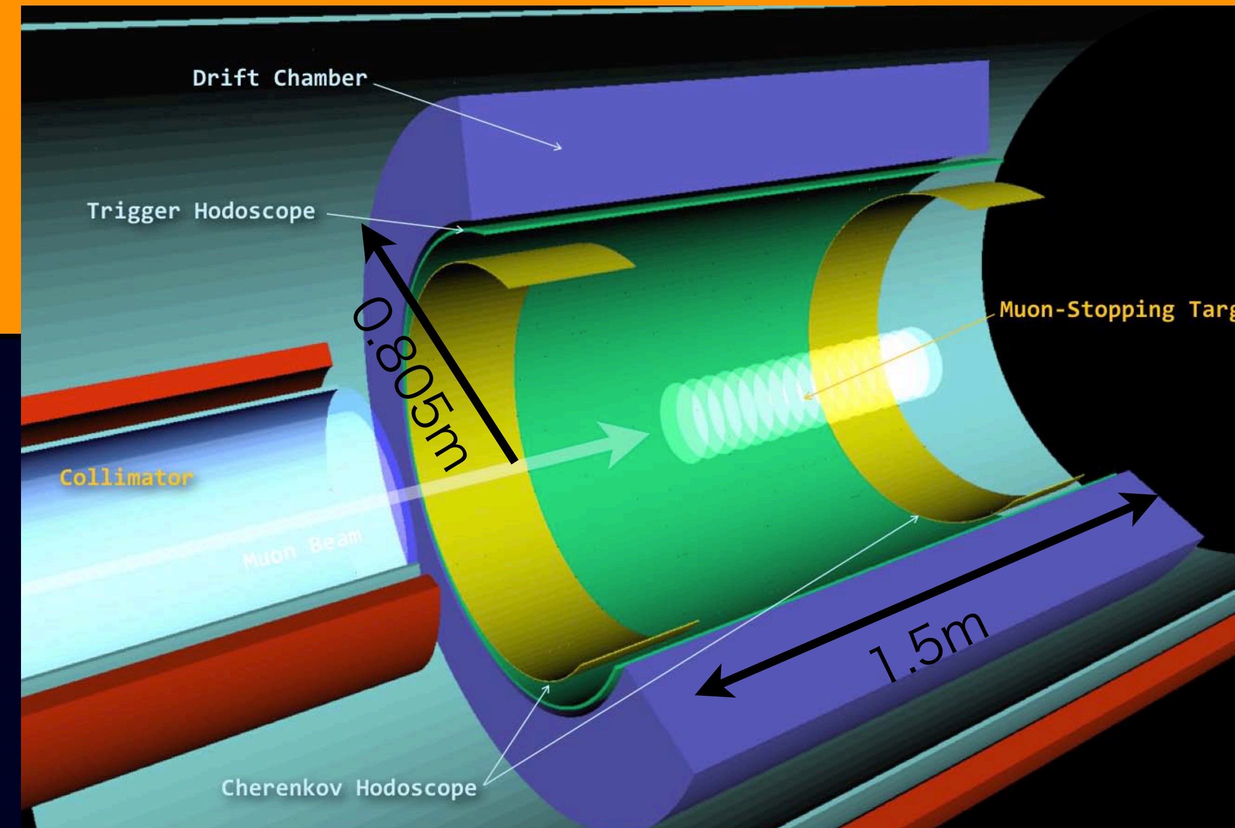
- $B(\mu+Al \rightarrow e+Al)<7\times10^{-15}$ @ 90%CL
- Beam and background study

- $B(\mu+Al \rightarrow e+Al)<6\times10^{-16}$ @ 90%CL

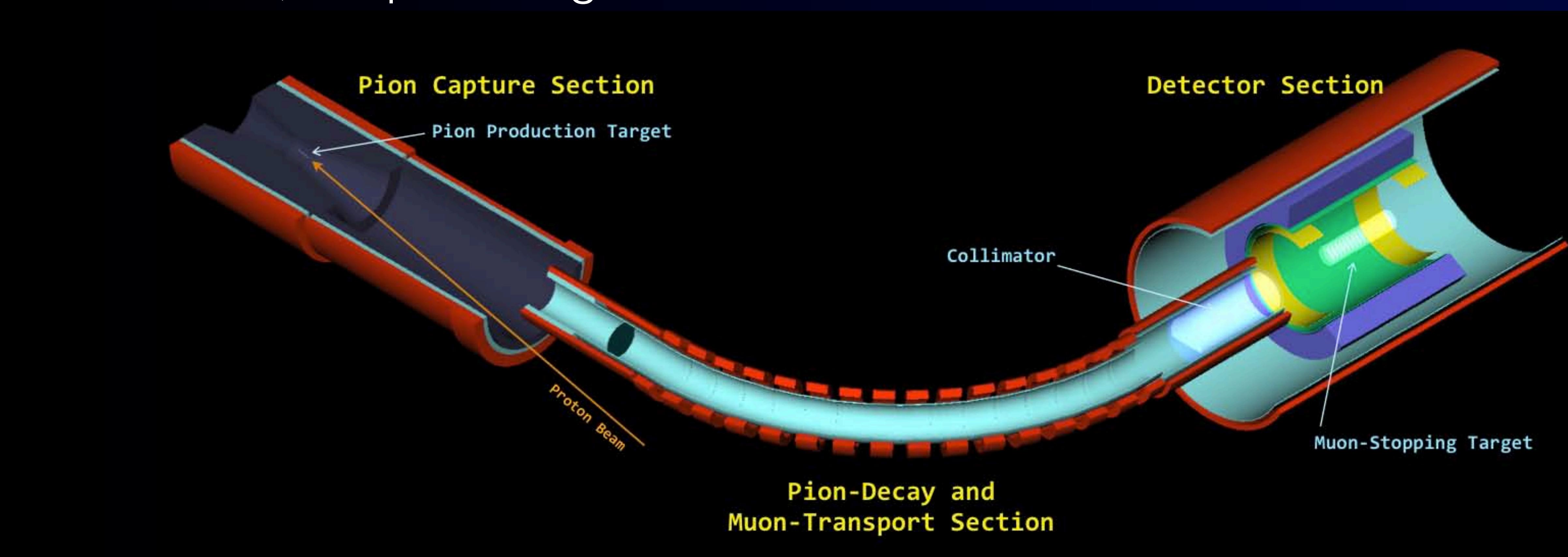
COMET Phase-I

New

- COMET Phase-I (LOI) aims ....
  - BG studies for Phase-II
  - intermediate sensitivity
    - SE sensitivity~3×10^{-15} for 10^6 s (12 days) with 3 kW proton beam power (with 5×10^9 stopped μ/s).
  - if no BG, keep running for 10^7 s.

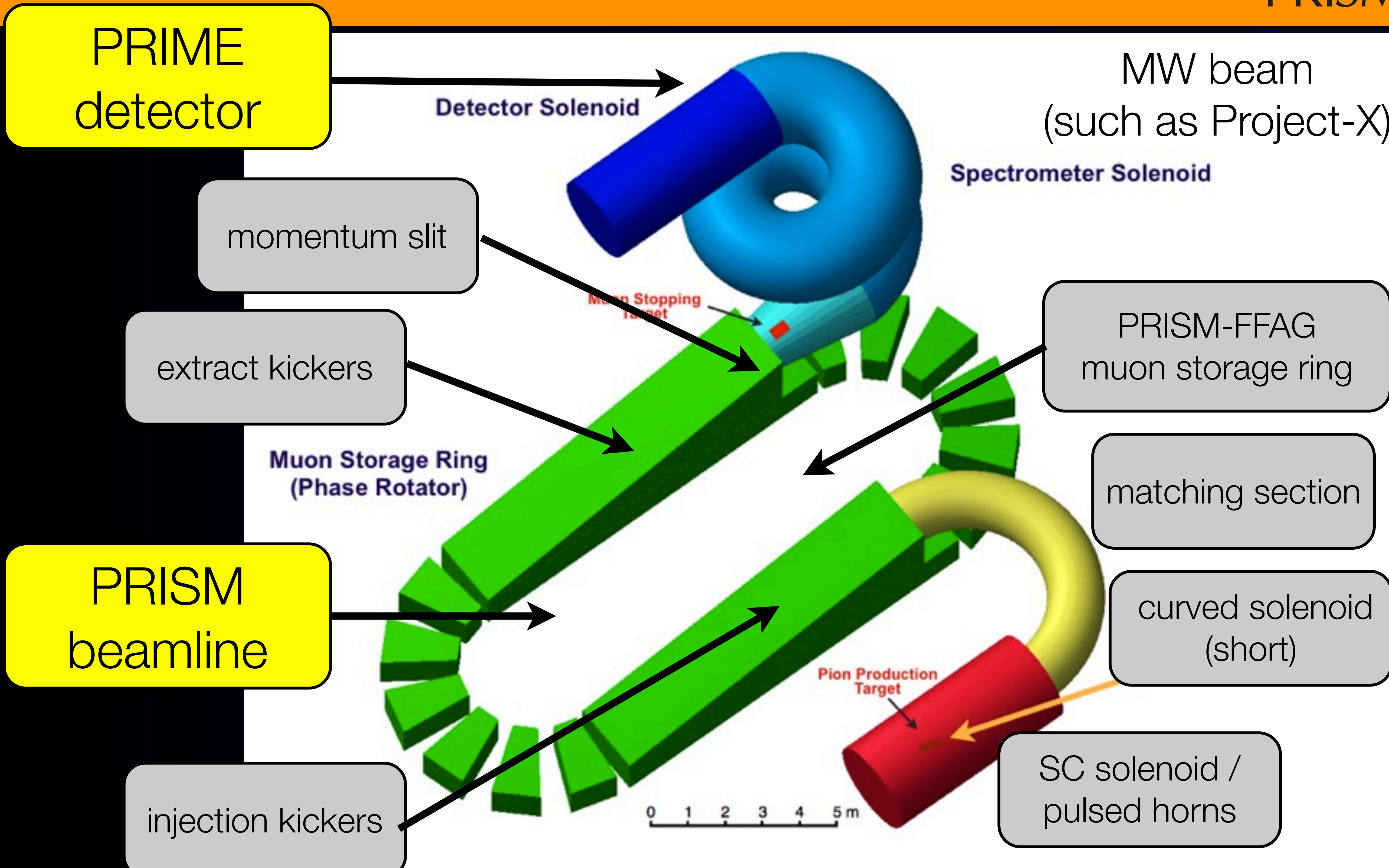


cylindrical drift chamber



Future Future Prospects of μ-e conversion of 3x10^{-19}

μ-e conversion at S.E. sensitivity of 3×10^{-19}
PRISM/PRIME (with muon storage ring)



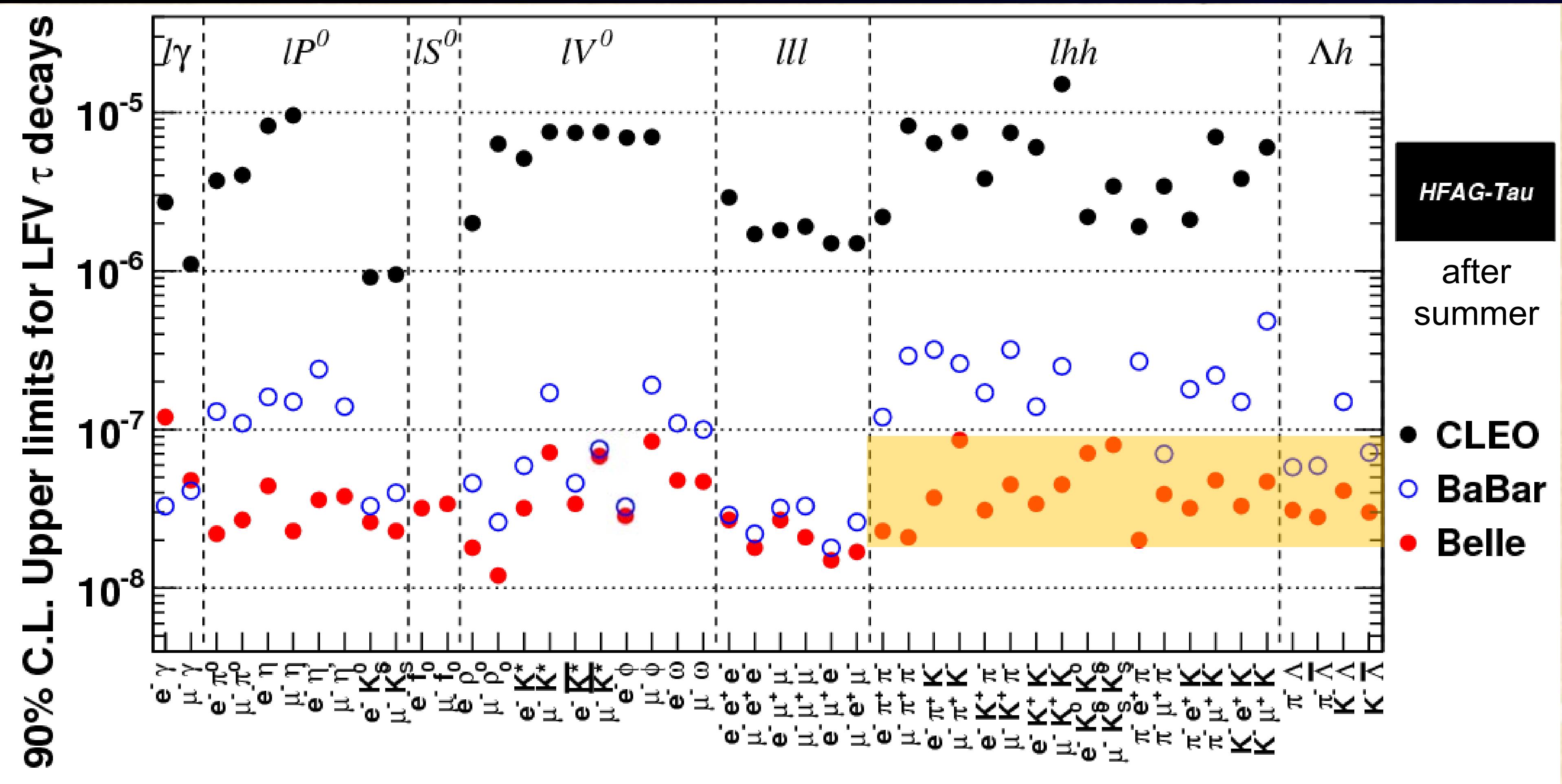
R&D on the PRISM-FFAG Muon Storage Ring at Osaka University

demonstration of phase rotation has been done.

τ CLFV Decay Experiments

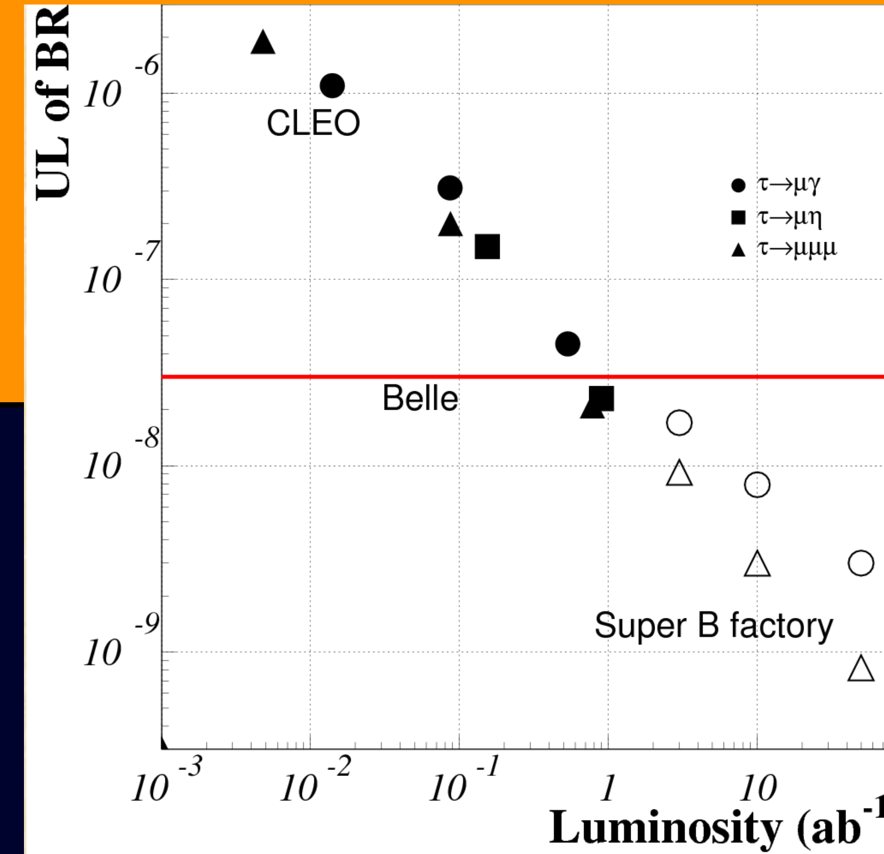
CLFV with Taus at e^+e^- colliders

- B factories produce many taus of more than 10^8 in total (σ~0.9nb).
- $\tau \to l\gamma$ is background-limited, and improved by $1/\sqrt{N}$.

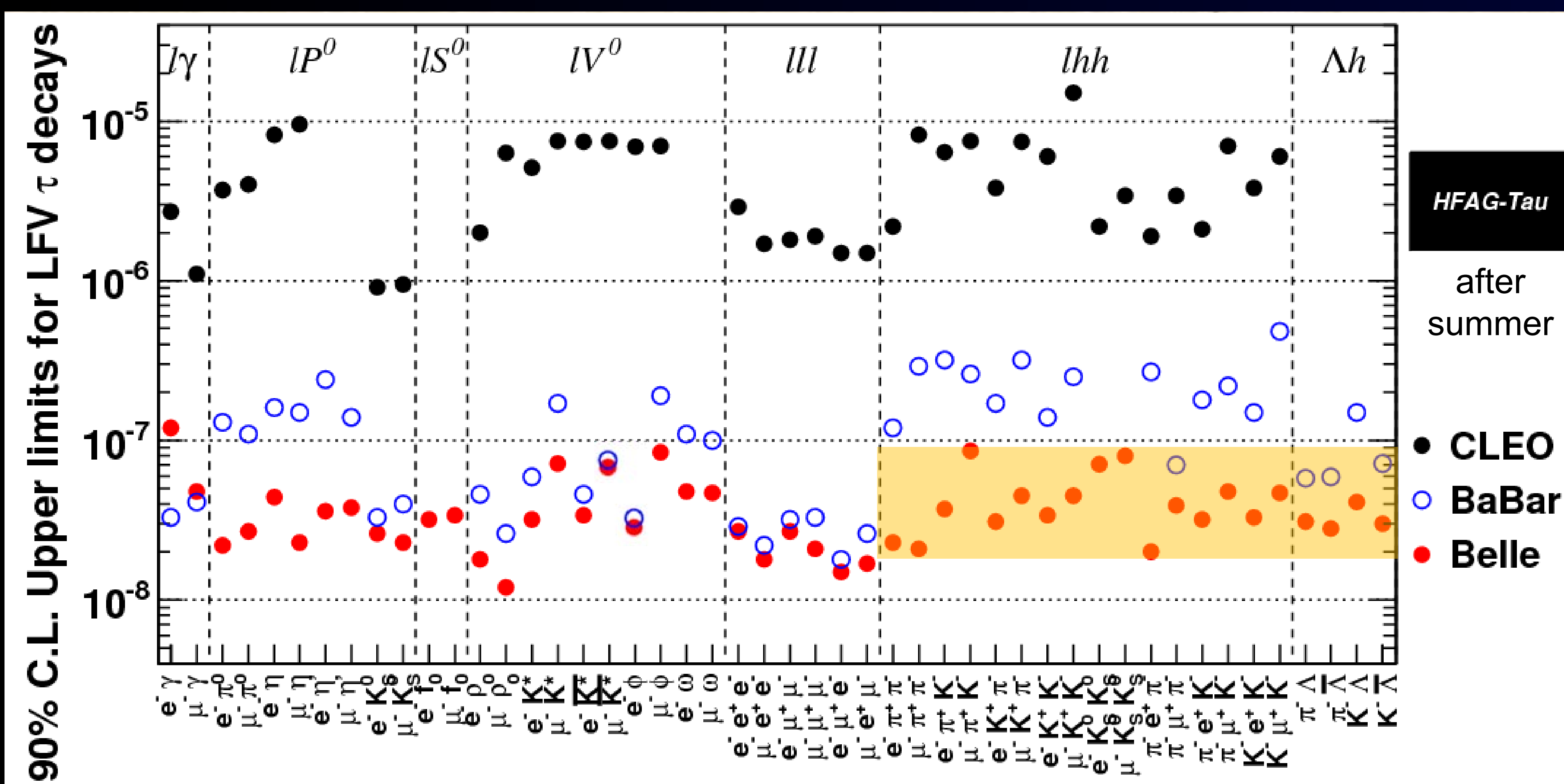


Reach upper limits around 10^{-8} ~100x more sensitive than CLEO

CLFV with Taus at e^+e^- colliders



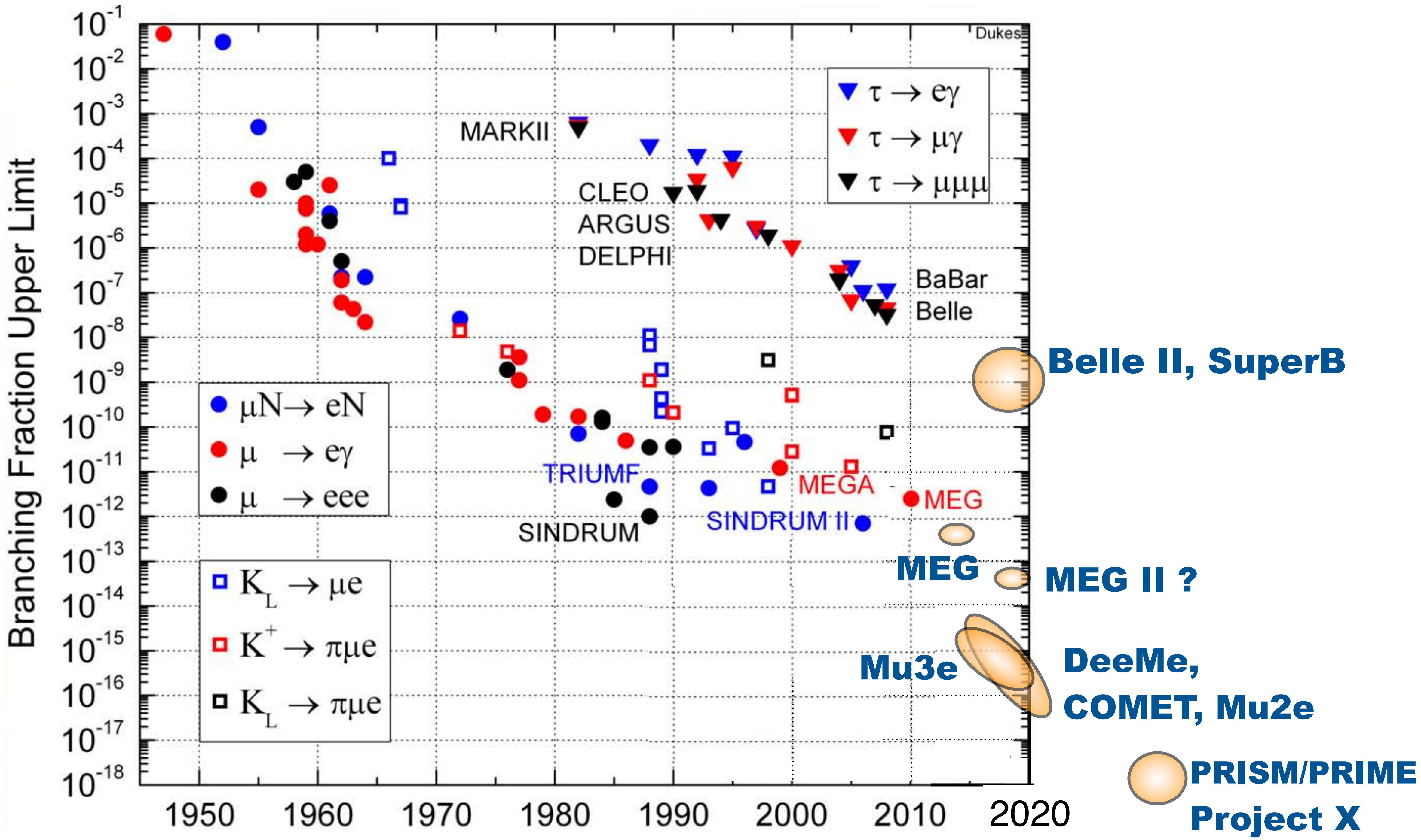
- B factories produce many taus of more than 10^8 in total (σ~0.9nb).
- τ→lγ is background-limited, and improved by $1/\sqrt{N}$.



Reach upper limits around 10^{-8} ~100x more sensitive than CLEO

Super B factories will produce a factor of O(10) times taus.
B(τ→μγ)~O(10^{-9})
B(τ→μμμ) ~O(10^{-10})
at 50 (ab^{-1}).

CLFV Future Prospects



Based on slide presented by Craig Dukes at Tau 2010

Summary

Summary

- CLFV would give the best opportunity to search for BSM. (So far, no BSM signals at the LHC.)
- The field of CLFV gets important and exciting.
- Future experimental prospects on CLFV are promising.
- MEG : ~10^{-13} (~2013), ~10^{-14} (>2014)
- COMET Phase-I : <$10^{-(14-15)}$ (2016/17),
- DeeMe : ~<2×10^{-14} (~2014).
- Mu2e and COMET Phase-II : <10^{-16} (~2020),
- Mu3e@PSI : <10^{-16} (>2016),
- PRISM/PRIME for <10^{-18} is underway.
- MuSIC@Osaka ~10^{8} μ/s with 400 W.
- Tau CLFV by Super B factories : ~$10^{-(9-10)}$ (2015/16~)