Charged Lepton Flavor Violation - Introduction -

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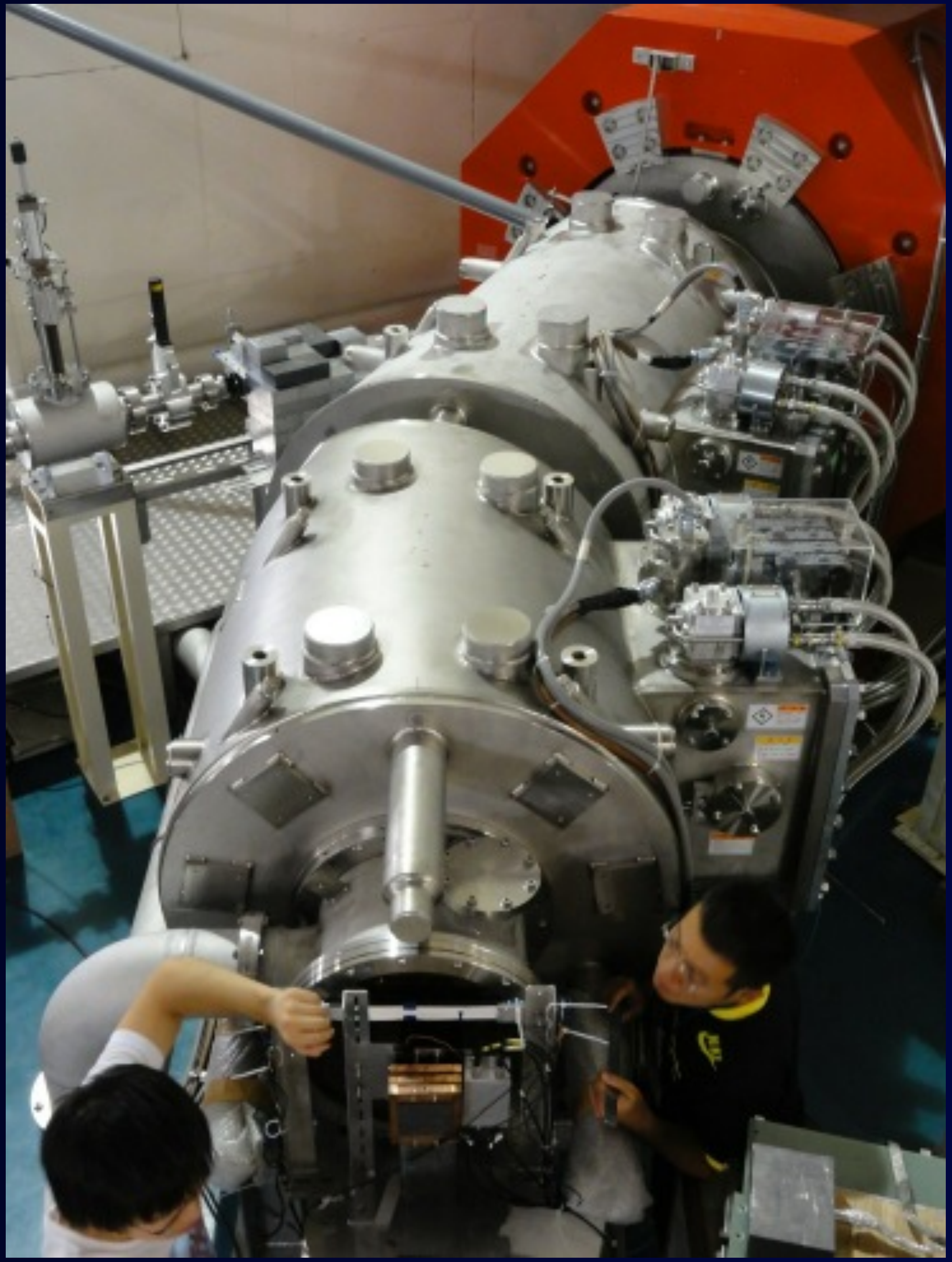
Xth Rencontres du Vietnam
Flavor Physics

July 31st, 2014

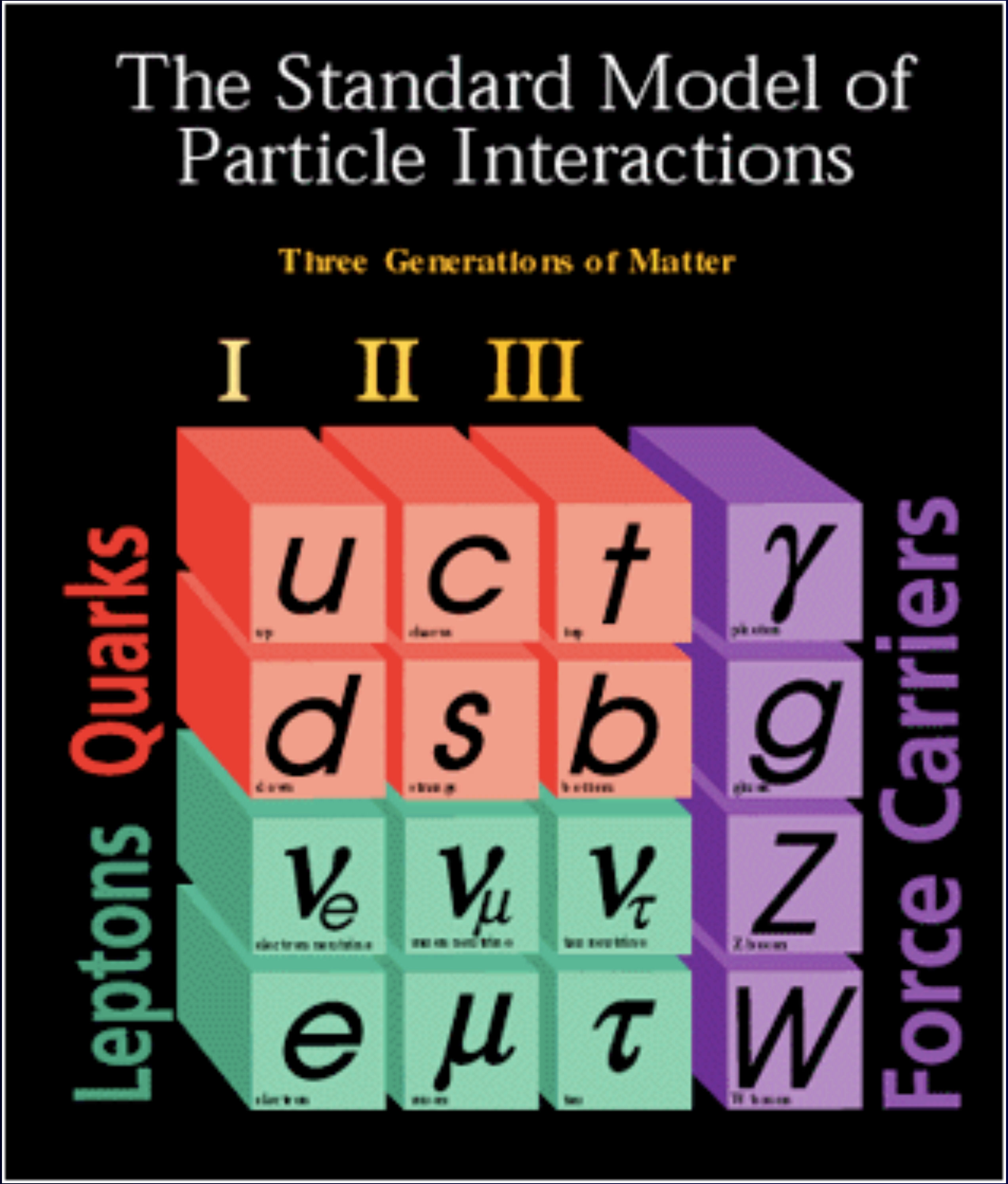
Outline

- Why Charged Lepton Flavor Violation (CLFV) ?
- New Physics in CLFV
- CLFV Experiments
- CLFV in Tau Decays
- CLFV in Muon Decays
  - $\mu \to e\gamma$
  - $\mu N \to eN$
- Highly Intense Muon Sources
  - MuSIC at Osaka University
- Summary



Why CLFV ?

The Higgs boson has been found, but no new particles are found yet...



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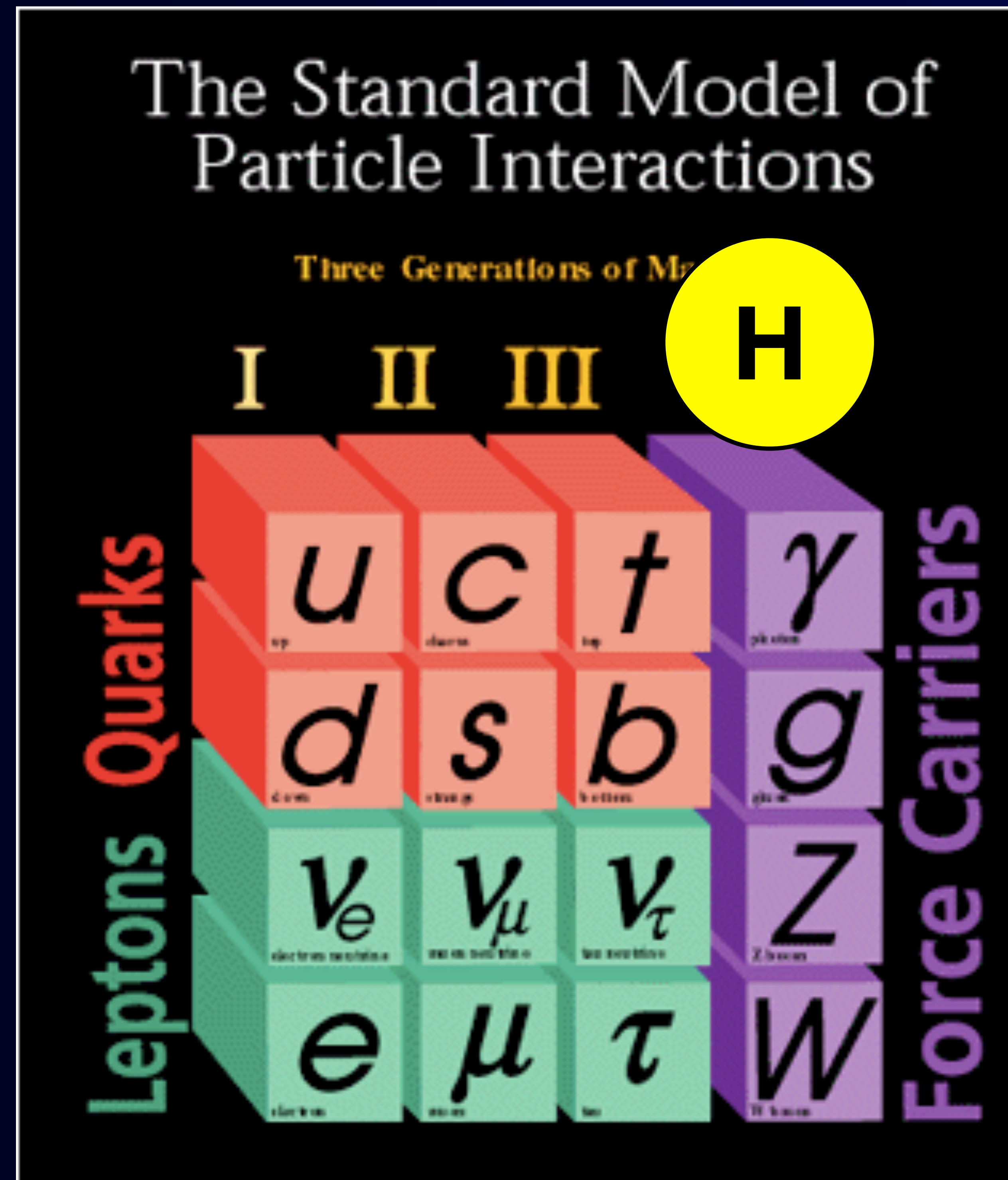

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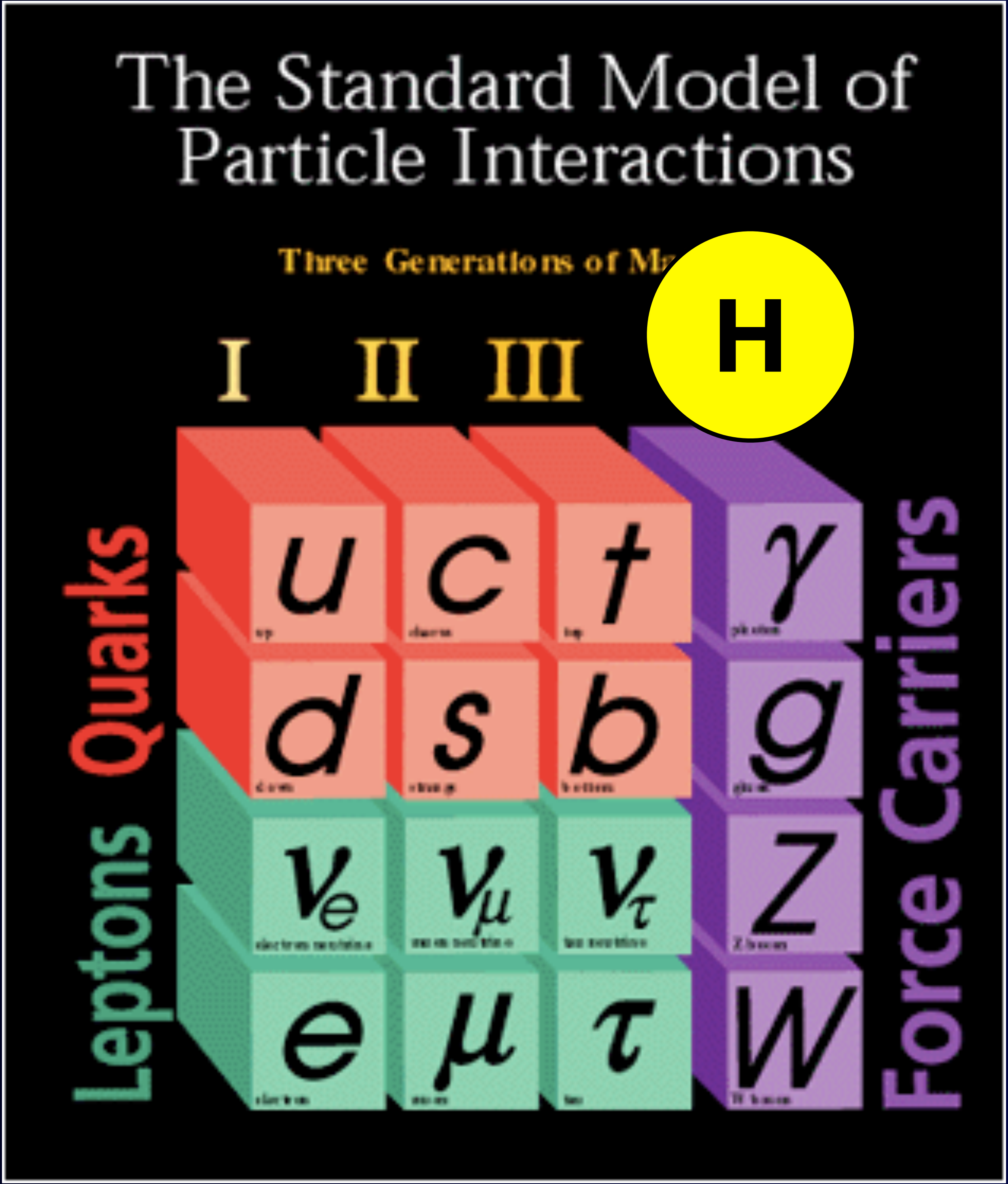

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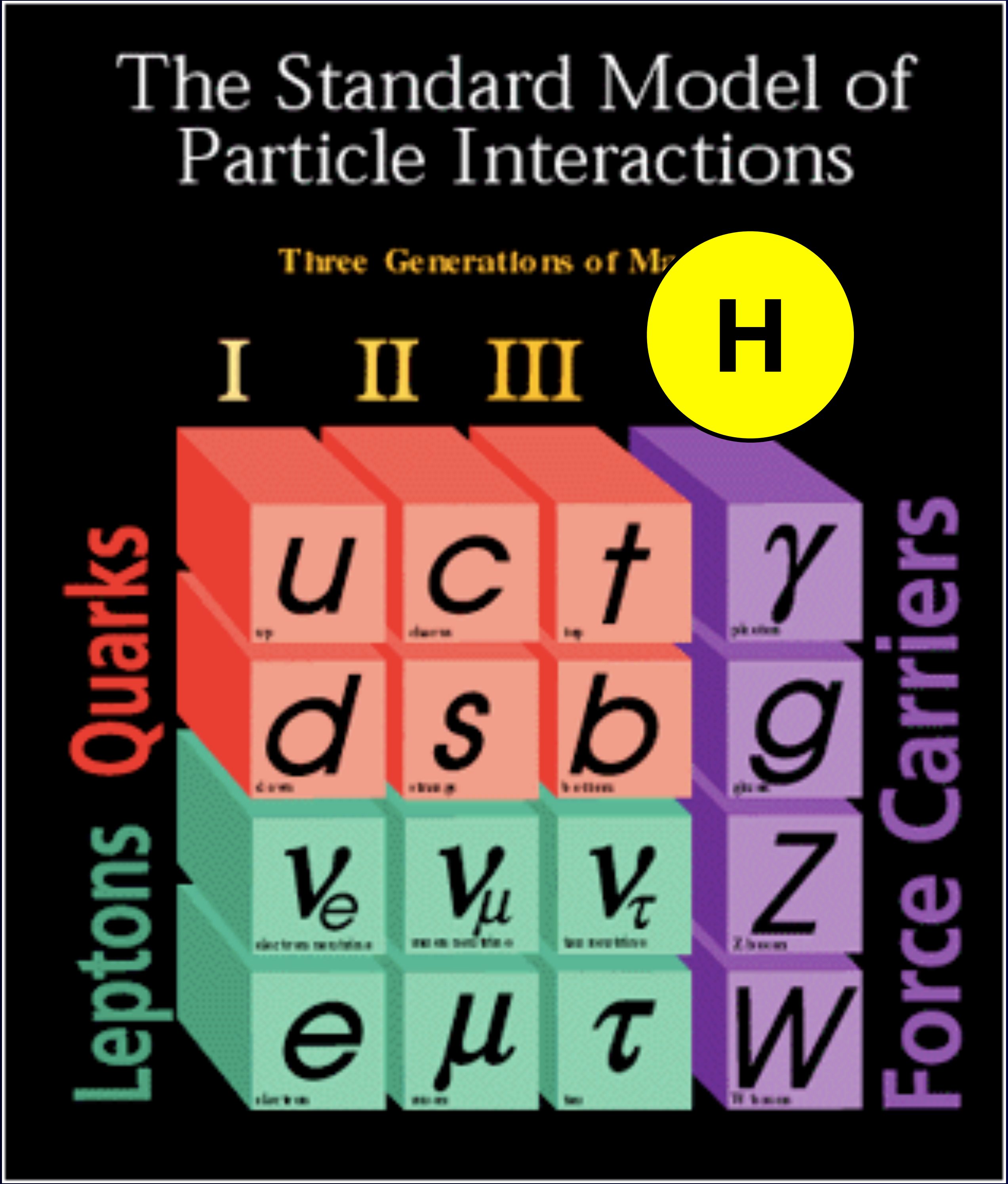
The Standard Model is considered to be incomplete.
New Physics is needed.



New Physics Search in Charged Lepton Flavor

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with new physics contributions

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{C_{\text{NP}}}{\Lambda^2} O_{ij}^{(6)} \ ,$$

Dimension 6 Operation for New Physics
Λ is the energy scale of new physics

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Charged Lepton Flavor

For instance, $\mu \to e\gamma$ ($B < 5.7 \times 10^{-13}$),

$$\frac{C_{\text{NP}}}{\Lambda^2} O_{ij}^{(6)} \to \frac{C_{\mu e}}{\Lambda^2} \overline{e}_L \sigma^{\rho\nu} \mu_R \Phi F_{\rho\nu}$$

$$\Lambda > 2 \times 10^5 \ \text{TeV} \times (C_{\mu e})^{\frac{1}{2}} \ .$$

$\Lambda > O(10^5)$ TeV

Guideline for Rare Decay Searches

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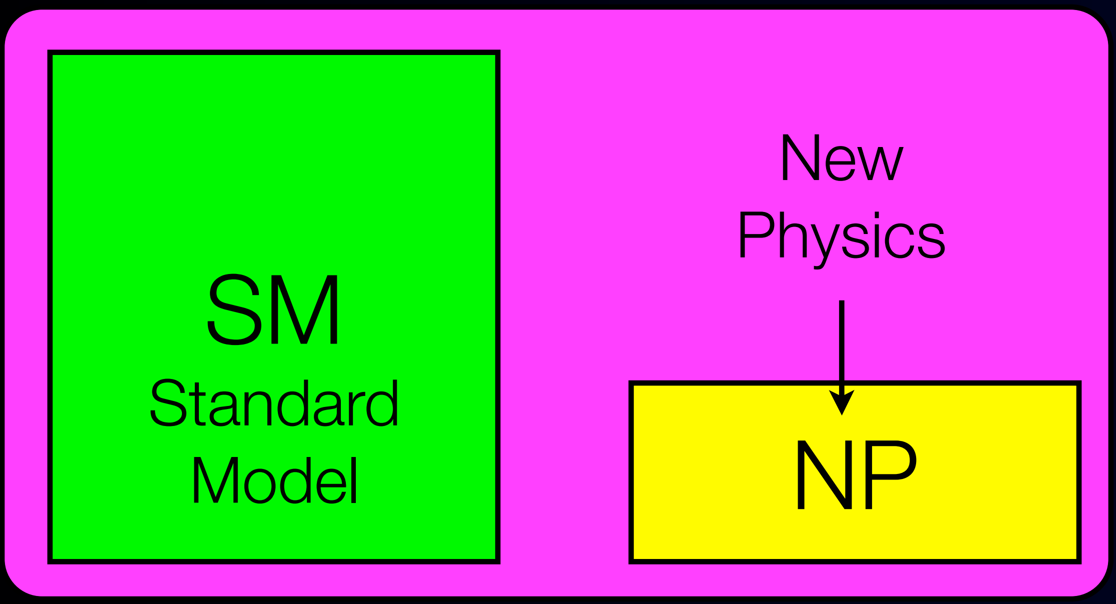

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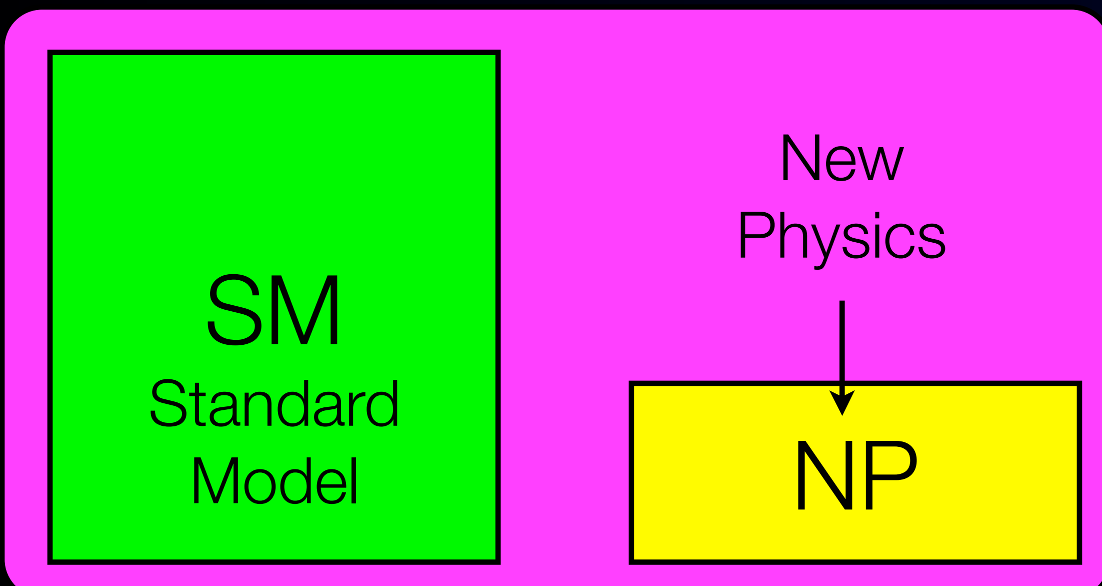

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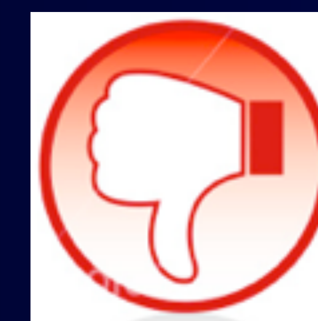

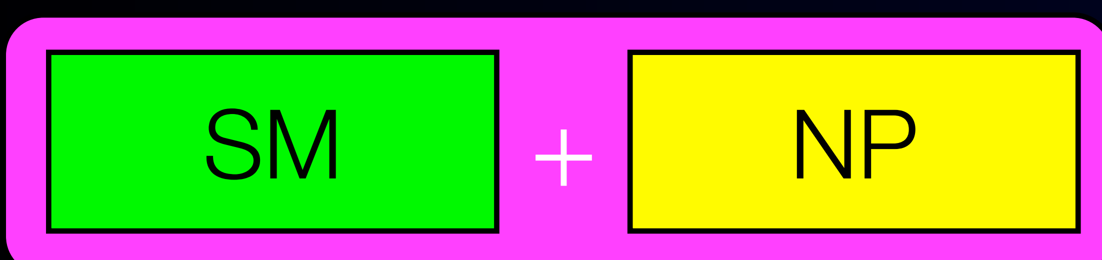

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$$B \sim \frac{1}{\sqrt{N}}$$

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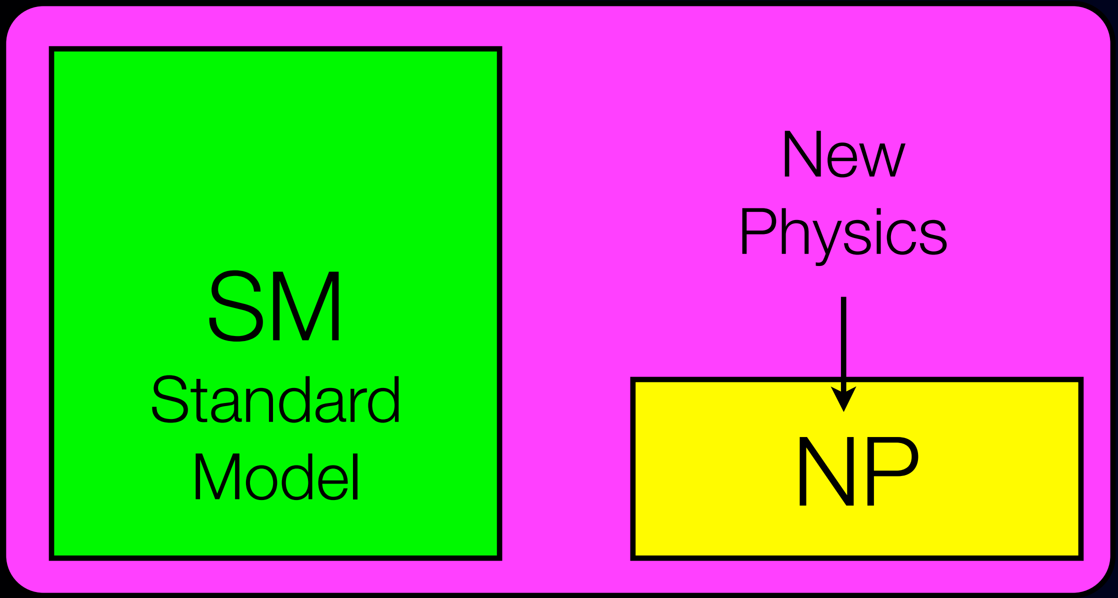

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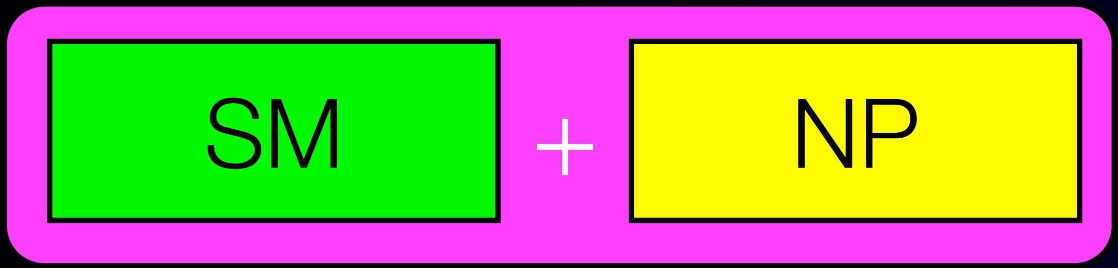

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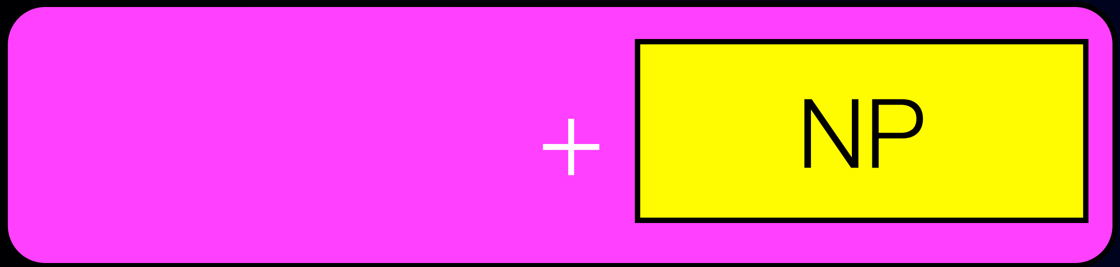

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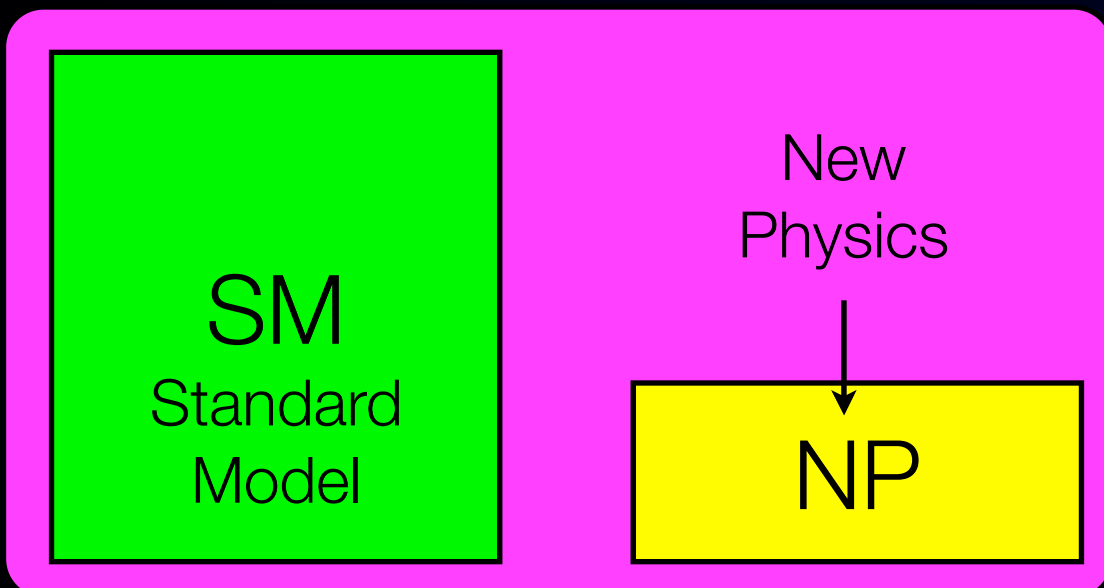

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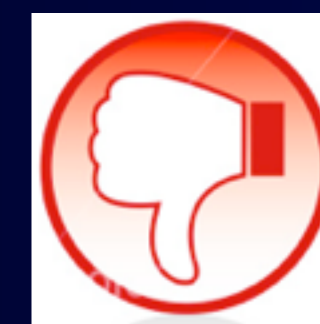

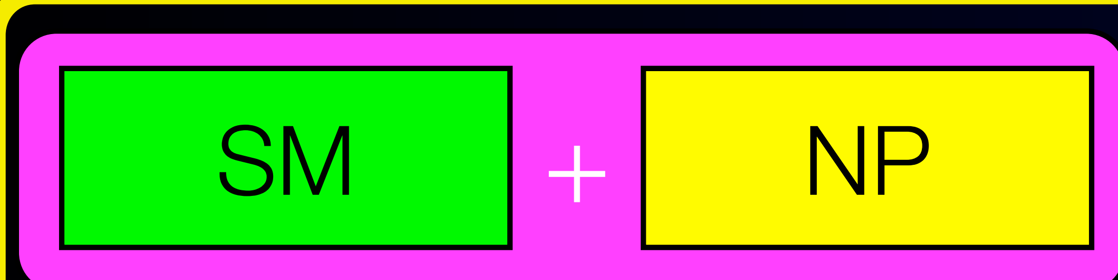

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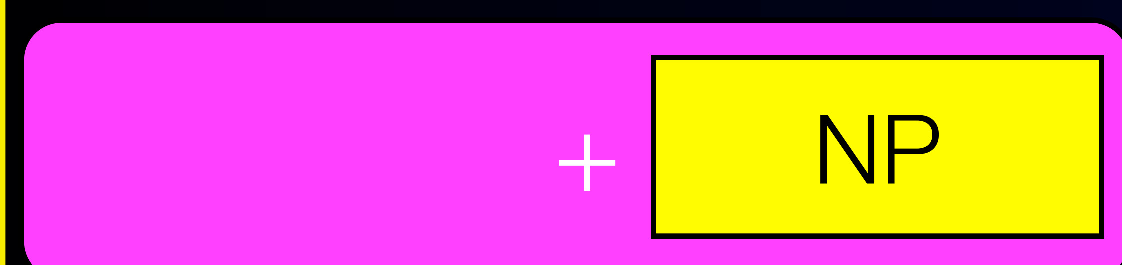

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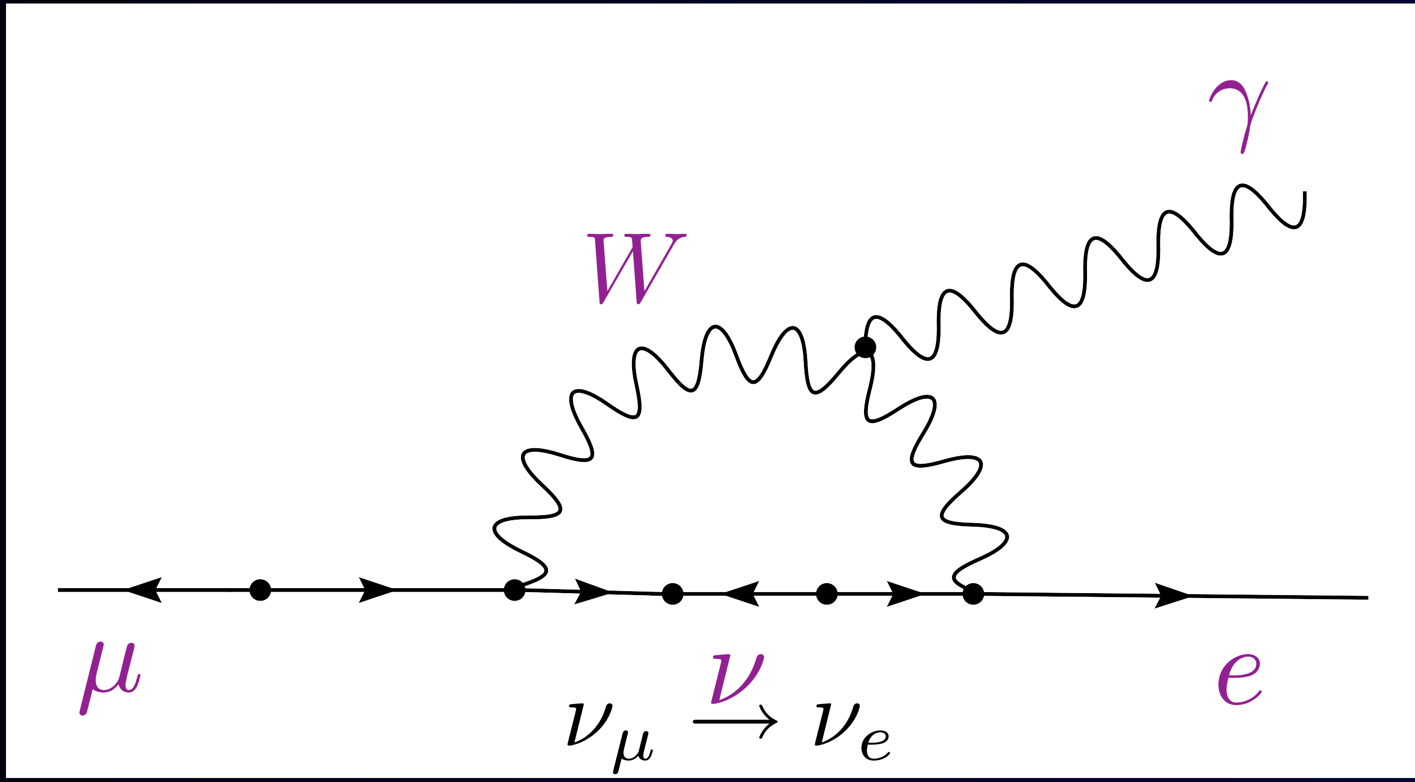
$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_l (V_{MNS})^*_{\mu l}(V_{MNS})_{el}\frac{m^2_{\nu_l}}{M^2_W}\right|^2$$



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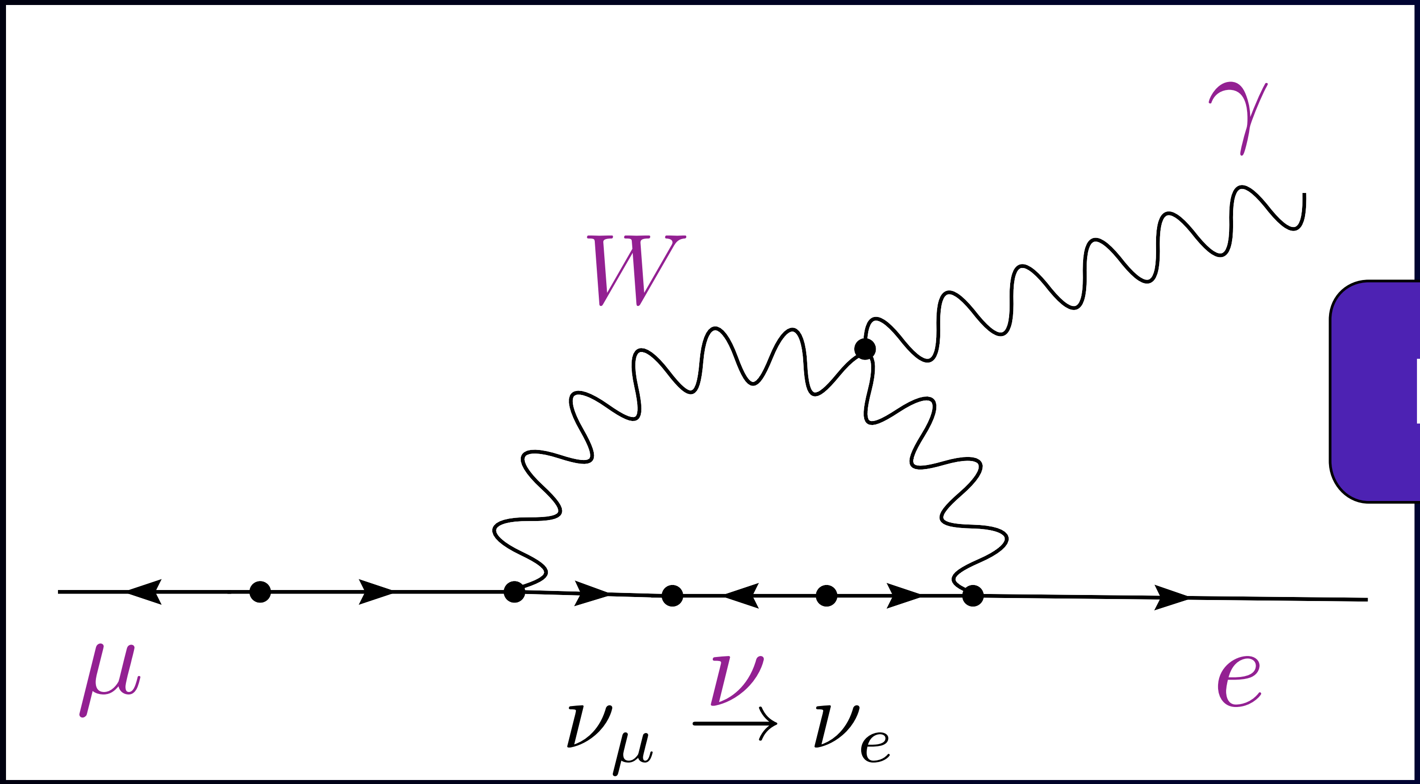

BR~O(10^{-54})

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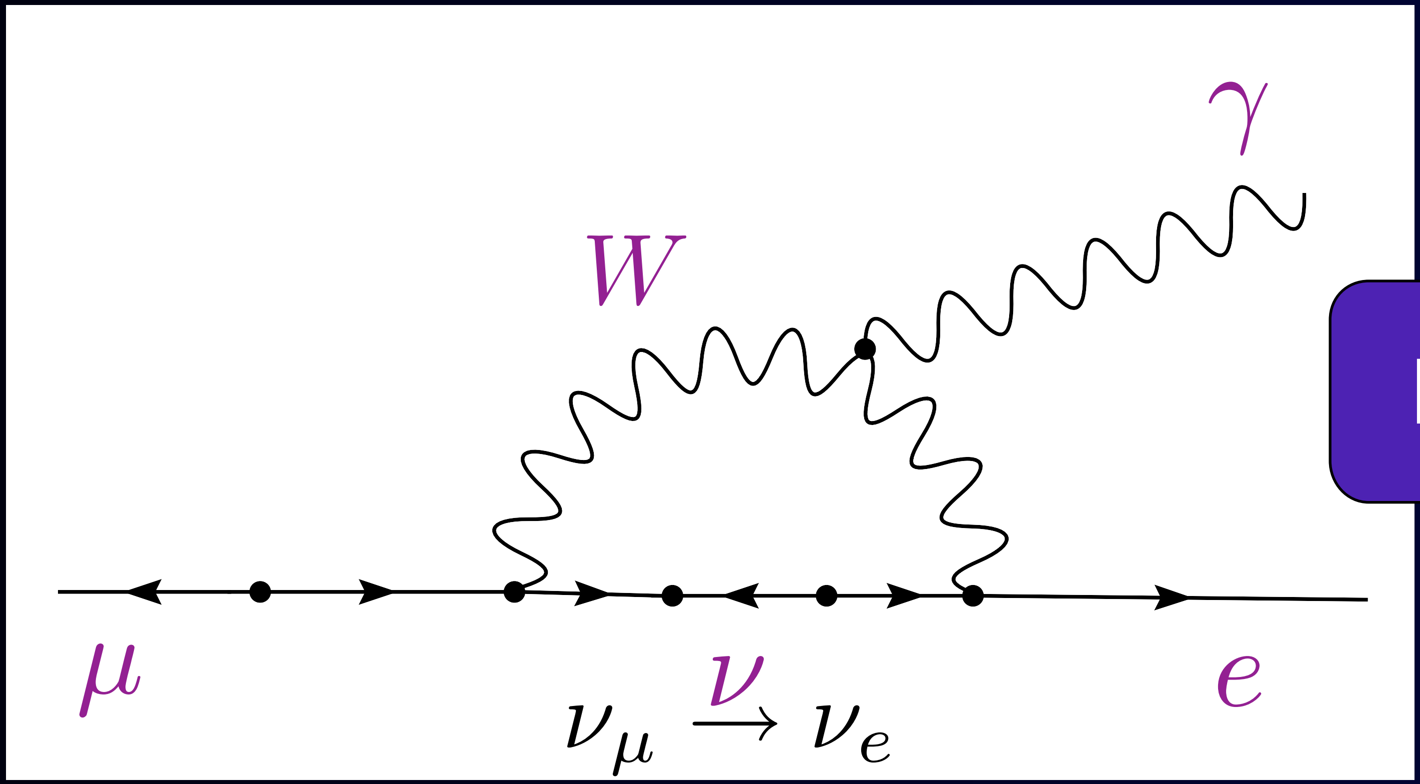

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Observation of CLFV would indicate a clear signal of physics beyond the SM with massive neutrinos.

Quark FCNC vs. Lepton FCNC (CLFV)

FCNC: The Standard Model contributions are either highly suppressed or forbidden.

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Quark (suppressed)

amplitude

$$|A_{\rm SM} + \varepsilon_{\rm NP}|^2 \sim |A_{\rm SM}|^2 + \underline{2Re(A_{\rm SM}\varepsilon_{\rm NP})} + |\varepsilon_{\rm N}|^2$$

Lepton (forbidden)

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CLFV Drawback : Rate ~ $1/\Lambda^4$, high sensitivity is required.

New Physics in CLFV

Various Models Predict CLFV

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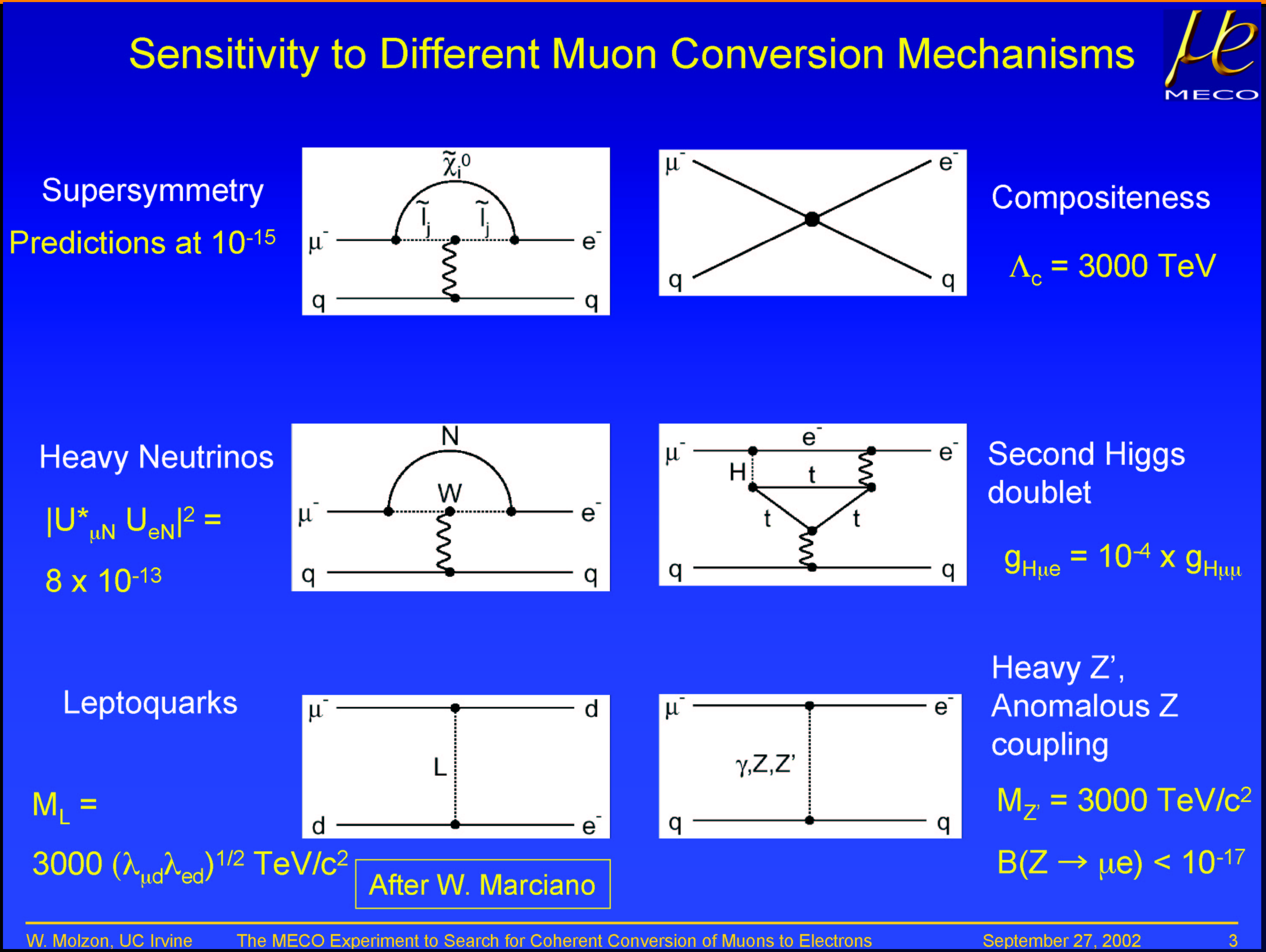

Example of Sensitivity to NP in High Energy Scale : SUSY models

- 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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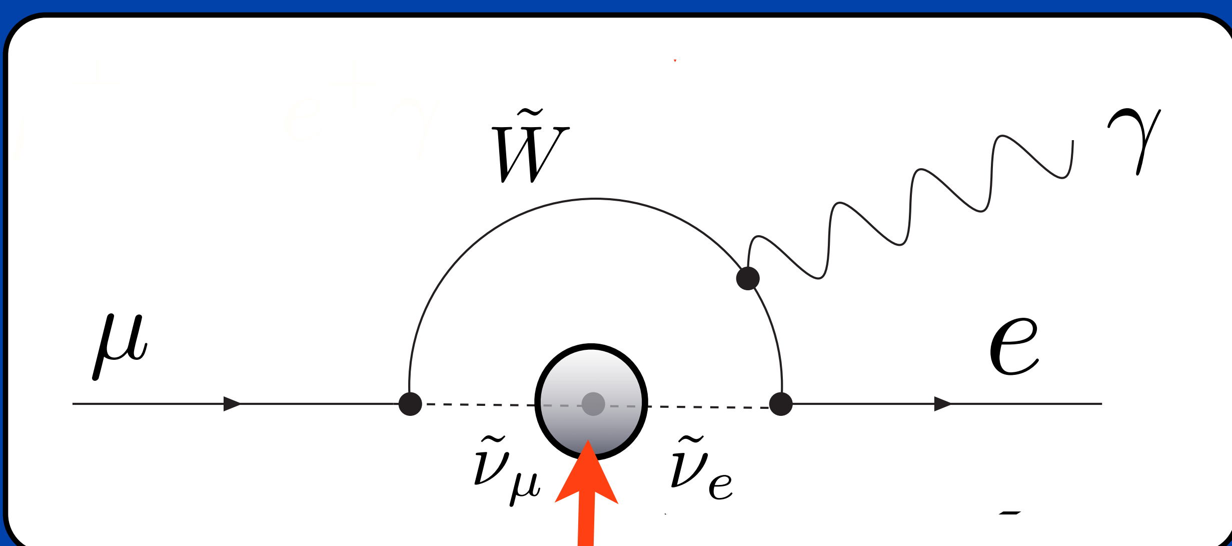

example diagram for SUSY (~TeV)

slepton mixing (from RGE)

Physics at about 10^{16} GeV

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

SUSY-GUT model

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

SUSY neutrino seesaw model

CLFV Predictions

Various BSM models predict sizable muon CLFV, as well as tau CLFV.

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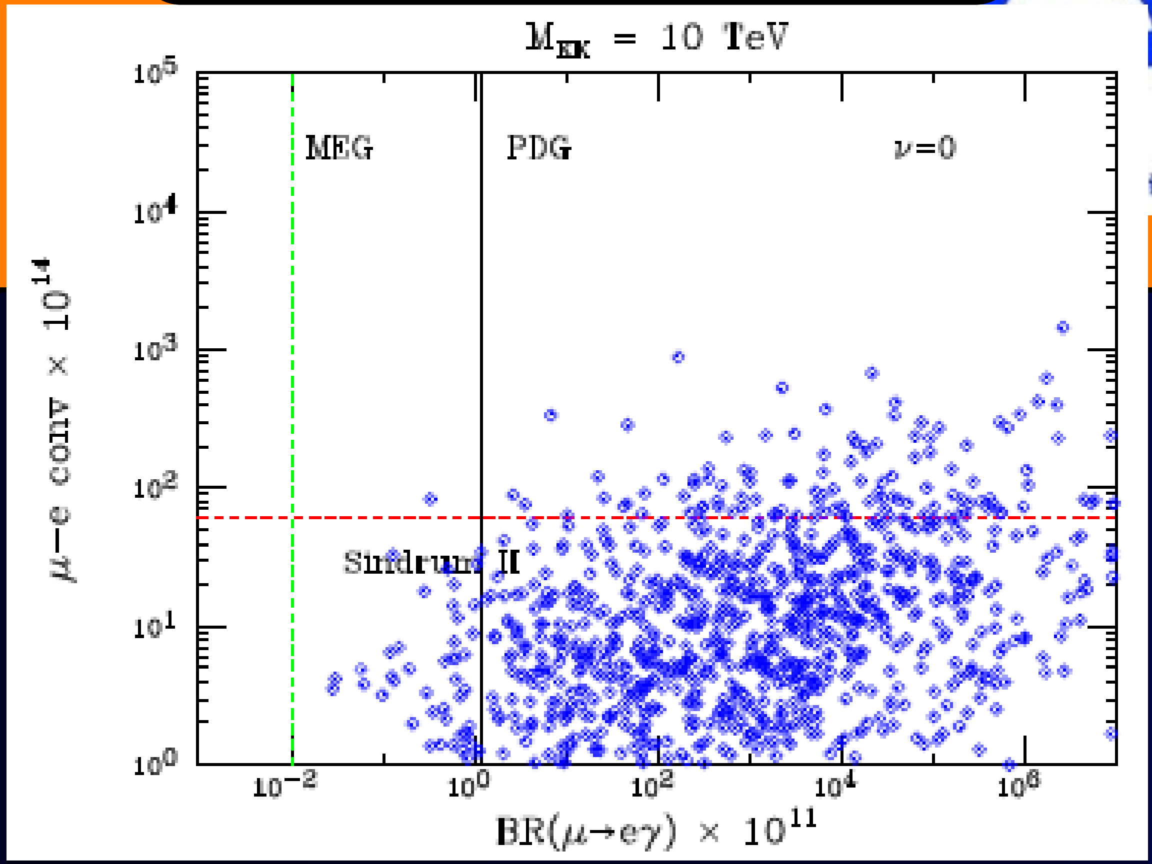
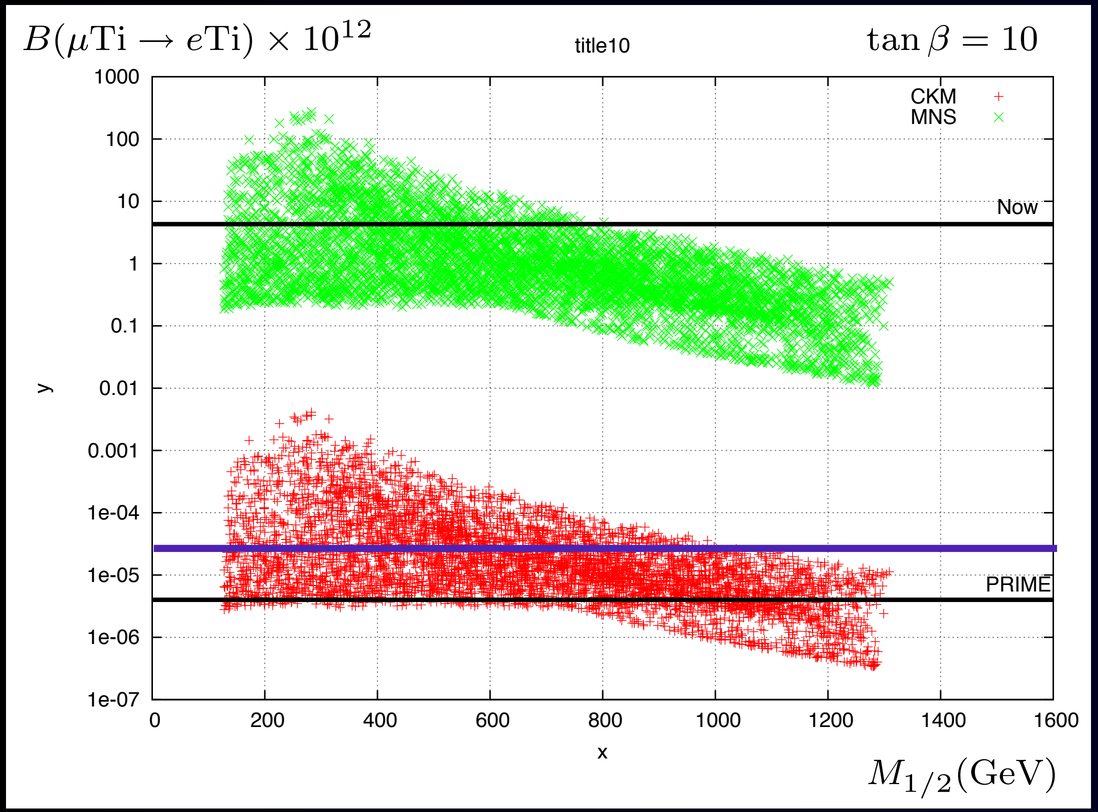
extra dimension model

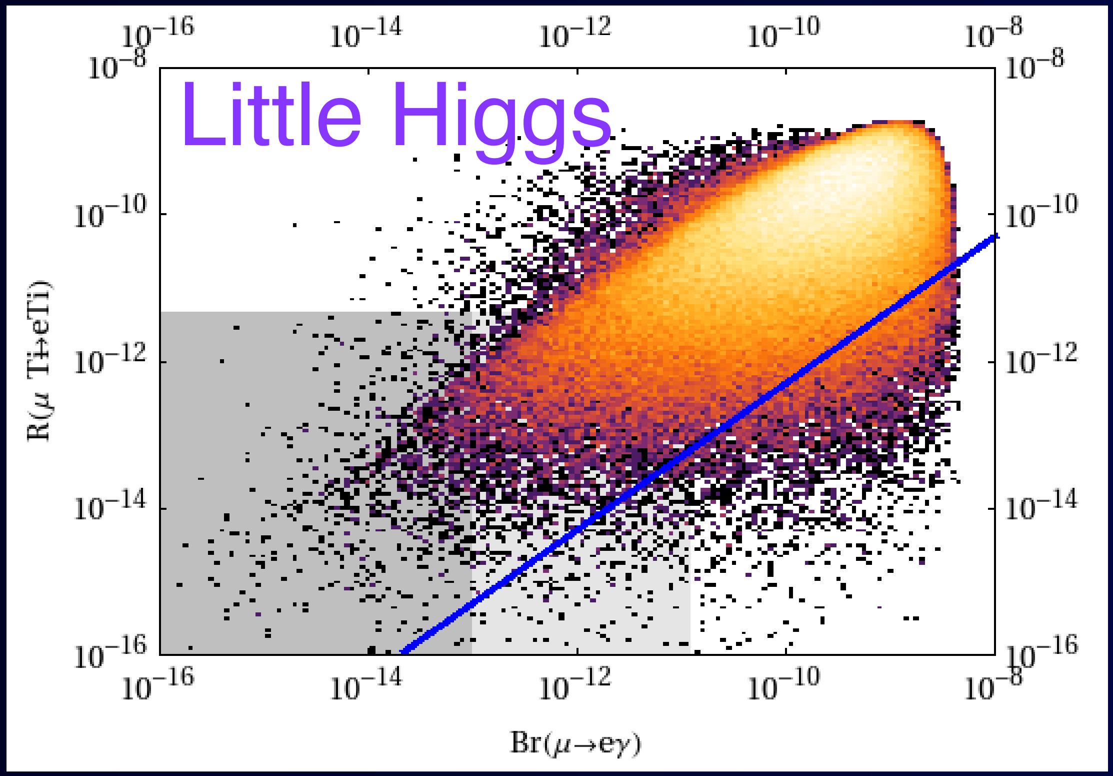


SUSY model



10^4

little Higgs model



"DNA of New Physics" (a la Prof. Dr. A.J. Buras)

W. Altmannshofer, A.J. Buras, S. Gori, P. Paradisi and D.M. Straub

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

These are a subset of a subset listed by Buras and Girrbach MFV, CMFV, $2HDM_{\overline{MFV}}$, LHT, SM4, SUSY flavor. SO(10) – GUT, $SSU(5)_{HN}$, FBMSSM, RHMFV, L-R, RS_0, gauge flavor, ……….

The pattern of measurement:
★★★ large effects
★★ visible but small effects
★ unobservable effects
is characteristic,
often uniquely so,
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GLOSSARY	
AC [10]	RH currents & U(1) flavor symmetry
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d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
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in More Details.

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see Frank Deppisch' talk

ex. CLFV and neutrino mass generation
and more

CLFV Experiments

Quarks, Neutrinos, and Charged Leptons

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Quarks

Quark mixing observed

Quarks, Neutrinos, and Charged Leptons

Osaka University

Quarks

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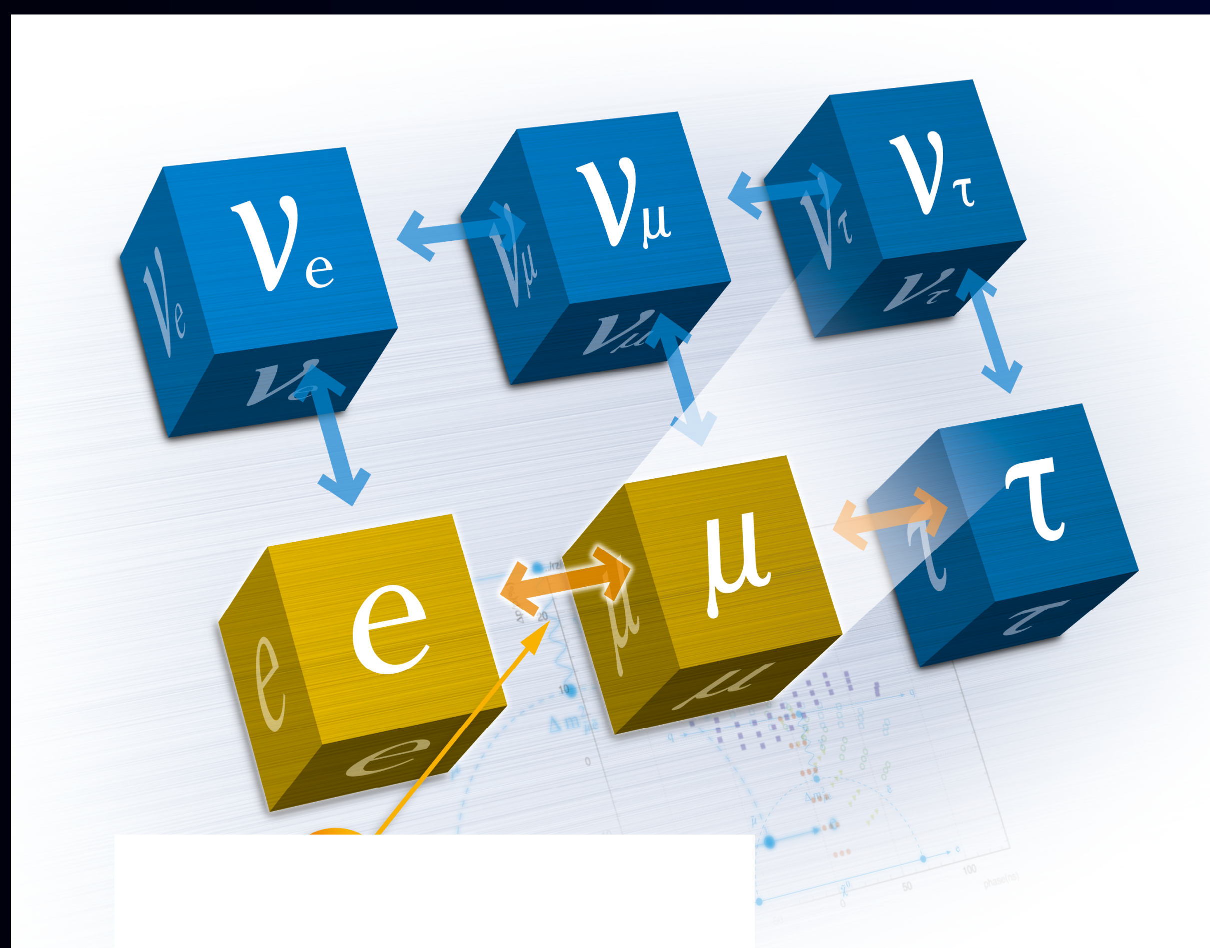

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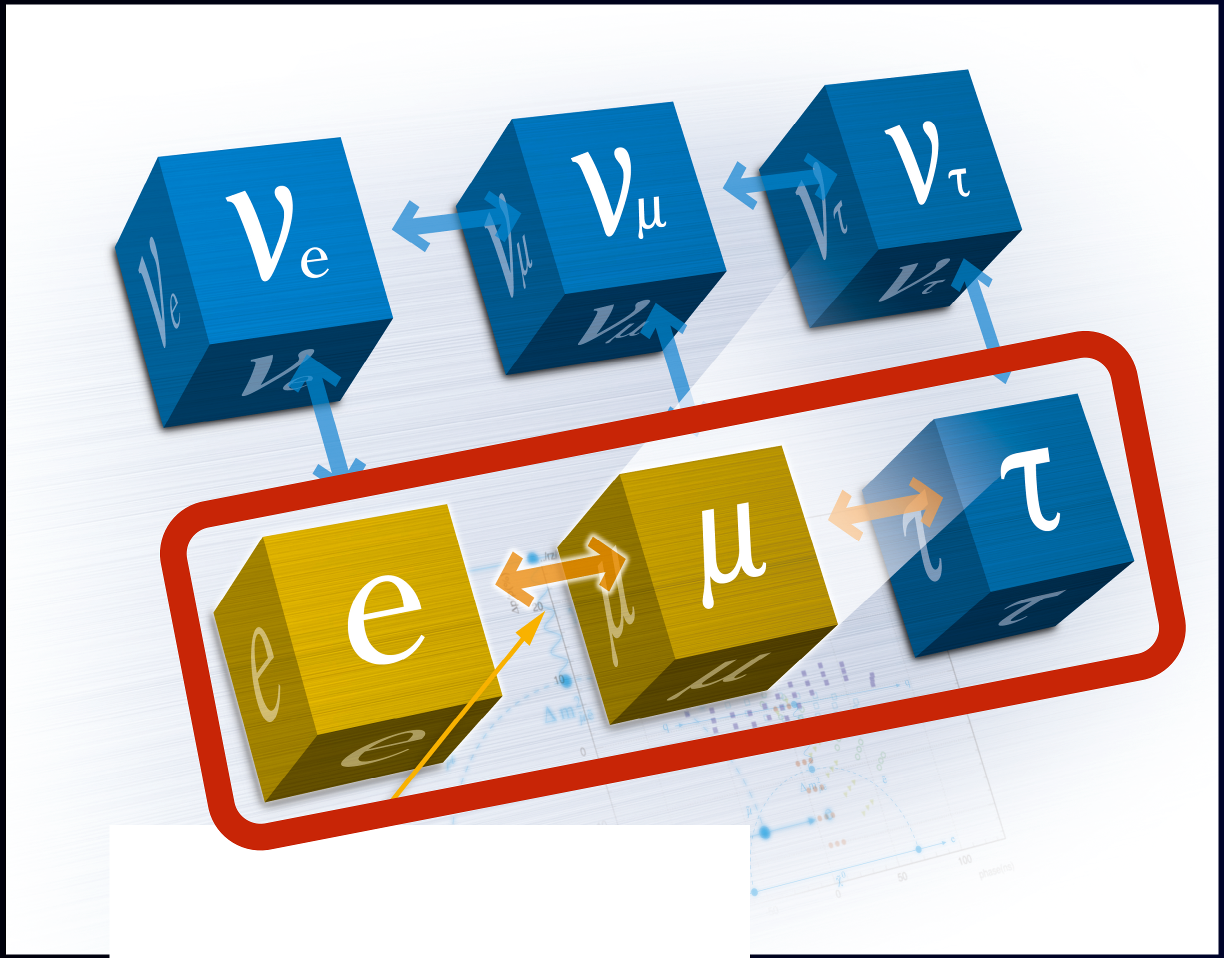
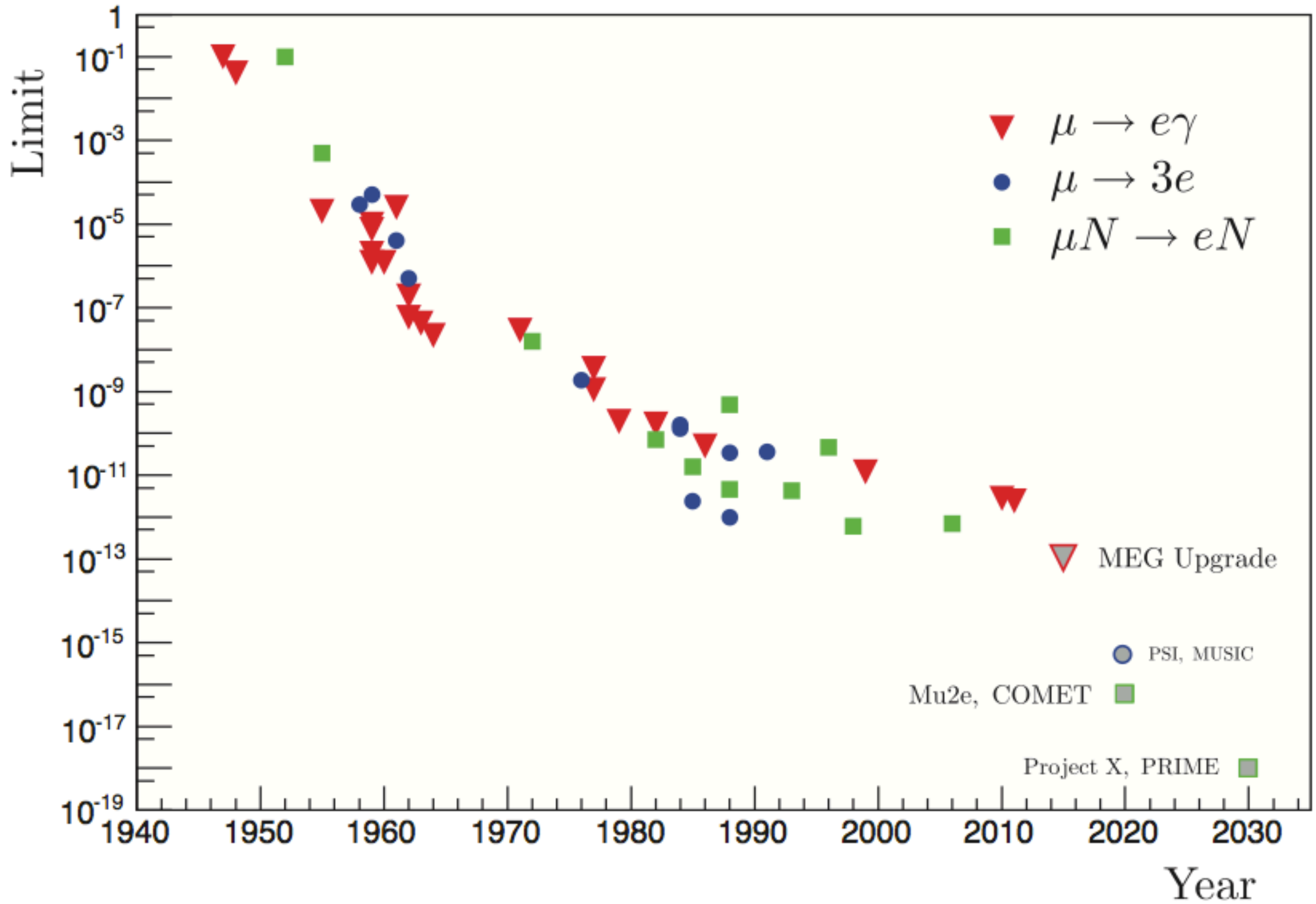


Neutrino mixing observed

Charged lepton mixing not observed.

CLFV History



[R. Bernstein, P. Cooper, arXiv 1307.5787]

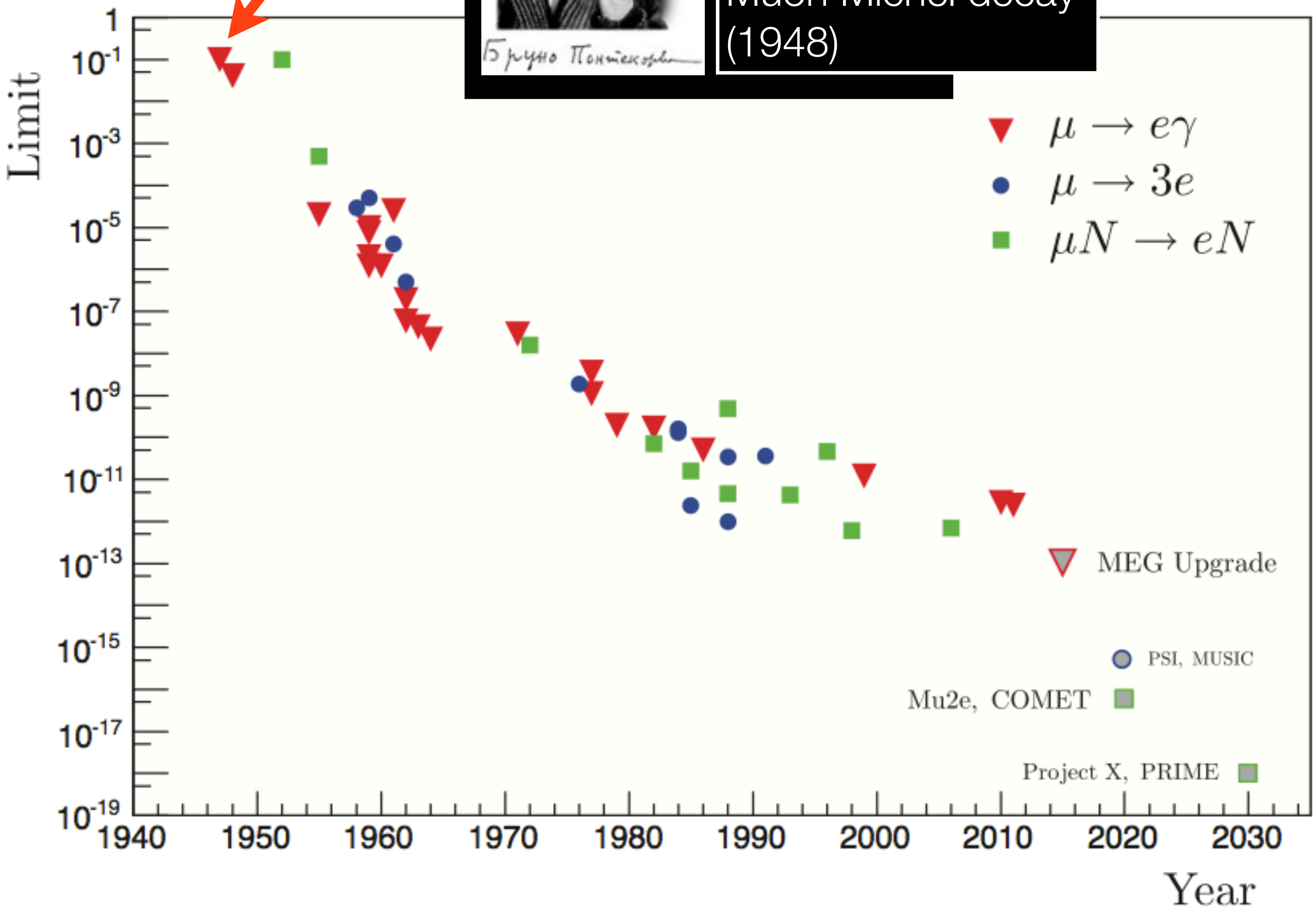
CLFV History

Osaka University

First CLFV search

Pontecorvo in 1947

Muon Michel decay (1948)



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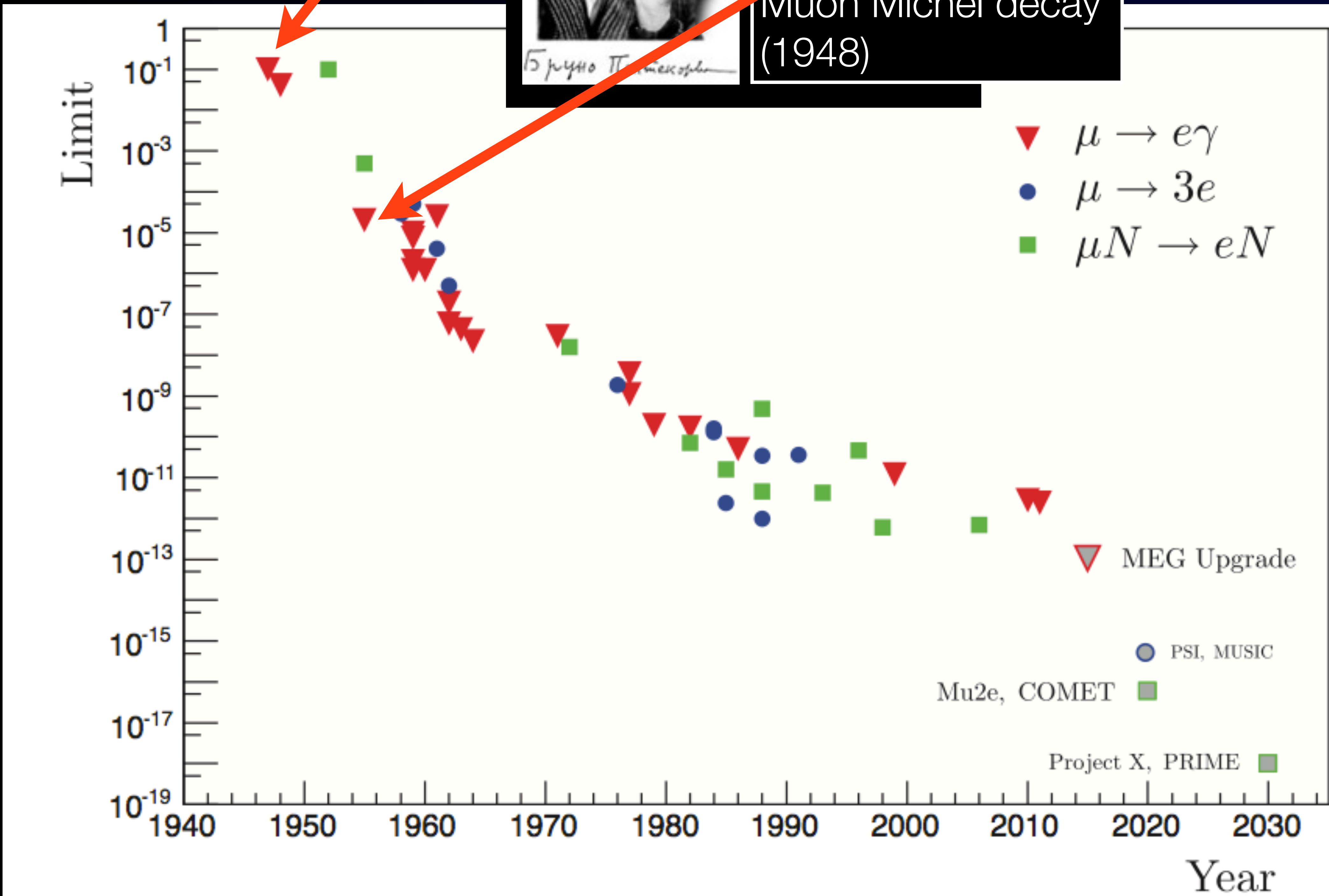

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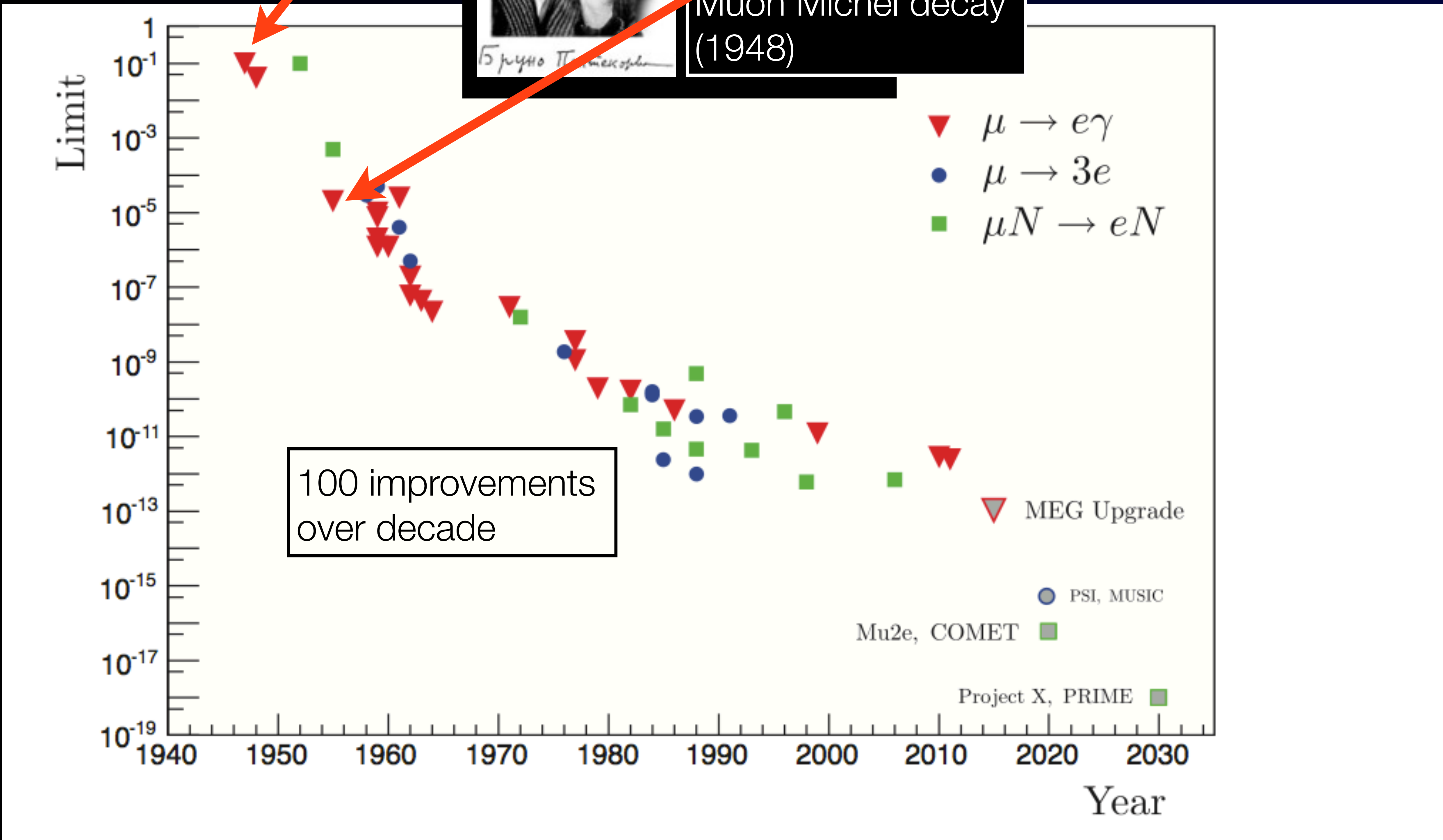

100 improvements over decade

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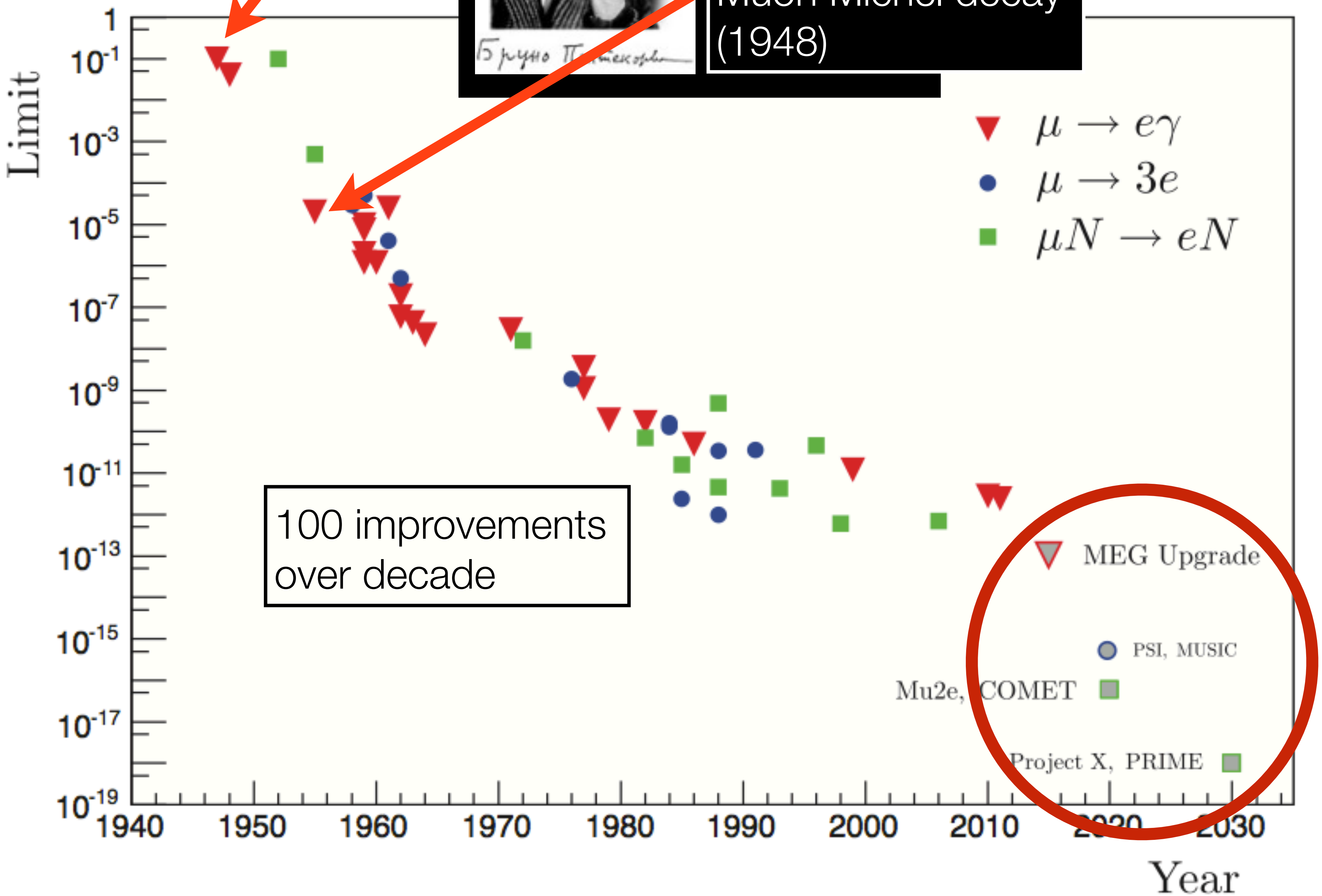

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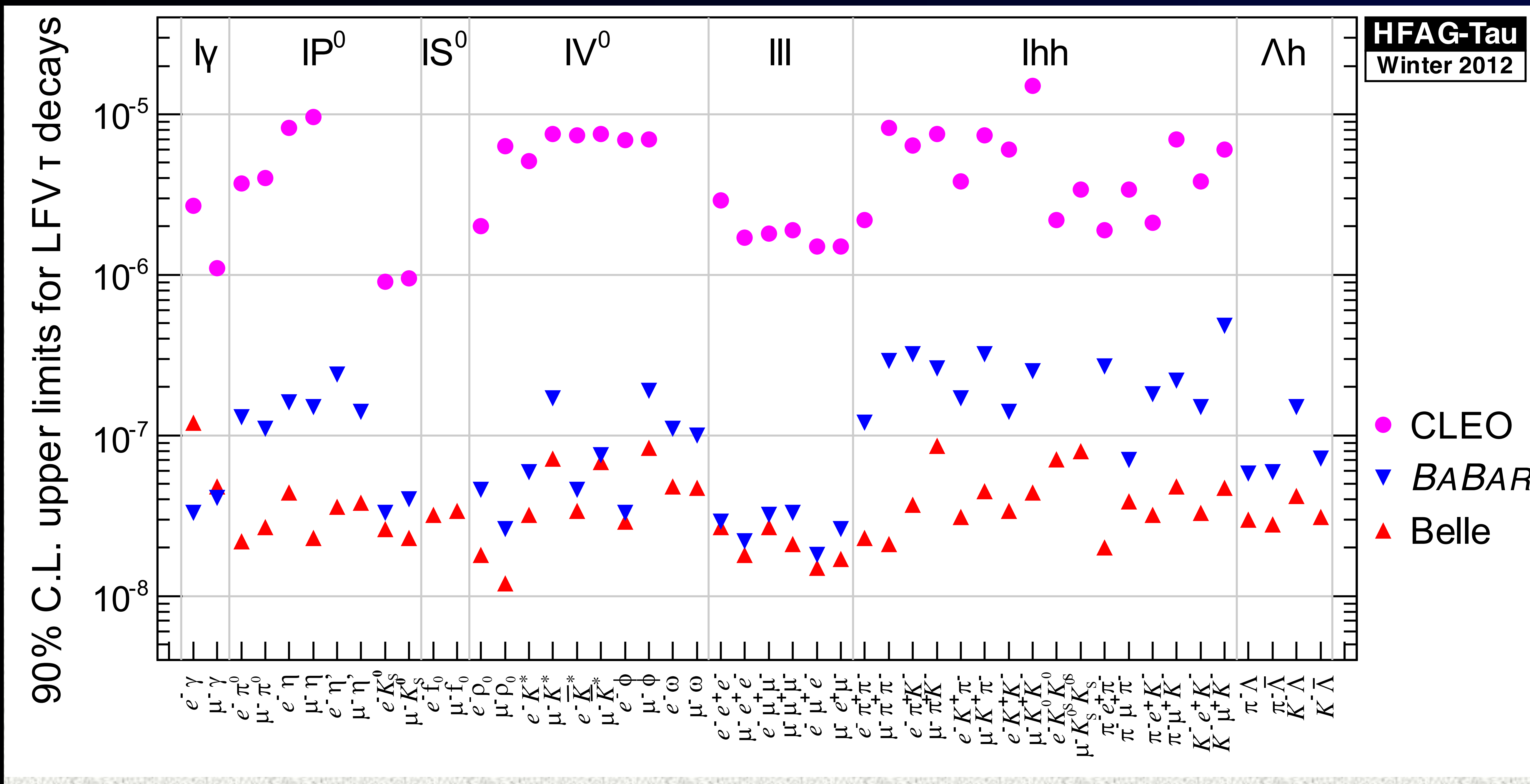
Present Limits and Future Expectations

process	present limit	future	
$\mu \rightarrow e\gamma$	<5.7 x 10	<10	MEG
$\mu \rightarrow eee$	<1.0 x 10	<10	Mu3e
$\mu N \rightarrow eN$ *(in Al)*	none	<10	Mu2e / COMET
$\mu N \rightarrow eN$ *(in Ti)*	<4.3 x 10	<10	Mu2e / COMET
$\tau \rightarrow e\gamma$	<3.3 x 10	<10	super KEKB
$\tau \rightarrow eee$	<3.4 x 10	<10	super KEKB
$\tau \rightarrow \mu\gamma$	<4.4 x 10	<10	super KEKB
$\tau \rightarrow \mu\mu\mu$	<2.1 x 10	<10	super KEKB/LHCb

CLFV in Tau Decays

CLFV in Tau Decays

CLFV in Tau Decays



B(τ→μμμ) < 6.3 x 10^{-8} (from LHCb)

Future Prospects on CLFV in Tau Decays

Future Prospects on CLFV in Tau Decays

Super KEKB
(50 ab^{-1})

LHCb upgrade

Future Prospects on CLFV in Tau Decays

Super KEKB
(50 ab^{-1})

LHCb upgrade

- $\tau \to l\nu$ at level $(0.2\text{-}1)\times10^{-9}$ by Belle-II
- $\tau \to \mu\mu\mu$ at the level of $(0.1\text{-}8)\times10^{-9}$ by LHCb with 50 fb^{-1}.

CLFV
in Muon Decays

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

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

List of cLFV Processes with Muons

Osaka University

ΔL=1

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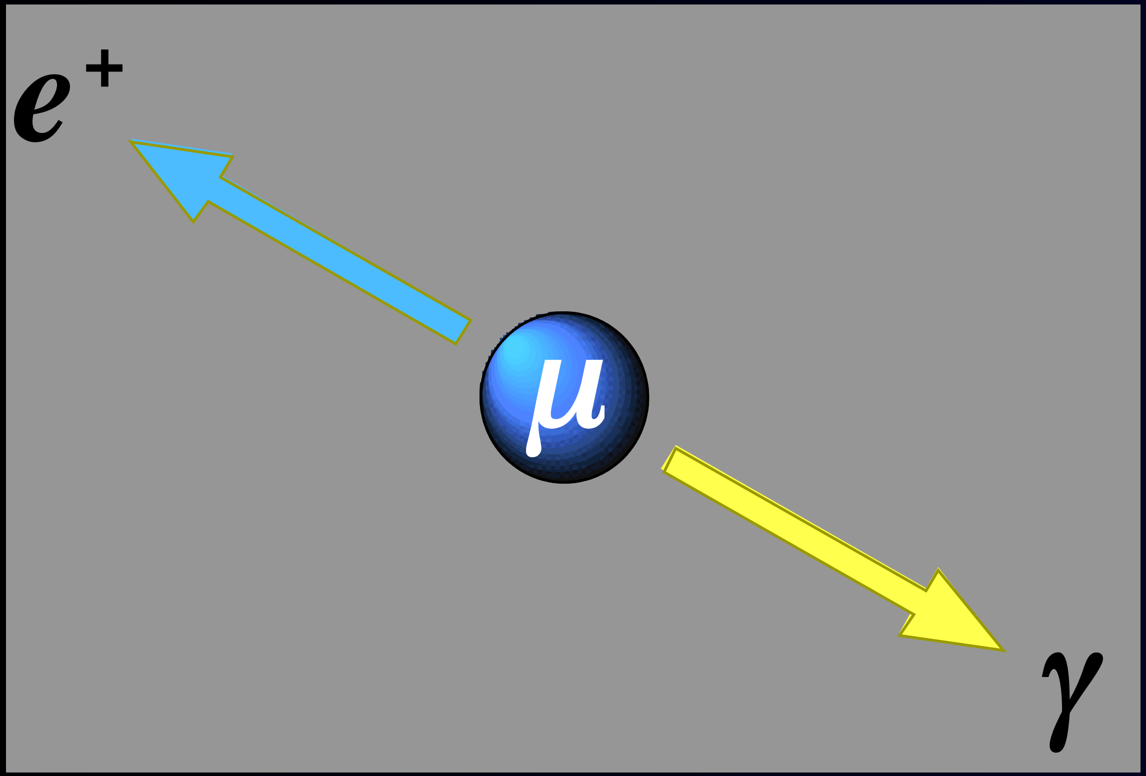
- $\nu_\mu + N(A,Z) \to \mu^+\mu^+\mu^- + N(A,Z-1)$

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

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

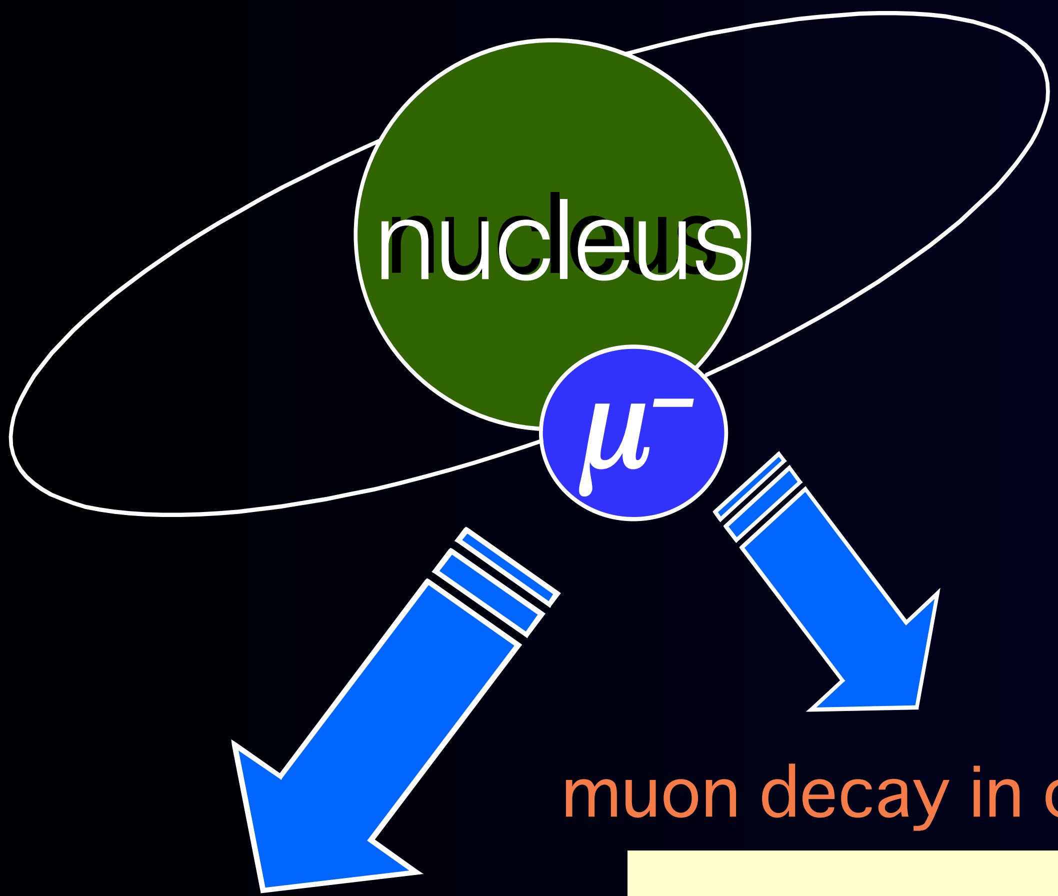


- Backgrounds
  - prompt physics backgrounds
    - radiative muon decay $\mu \rightarrow e\nu\nu\gamma$ when two neutrinos carry very small energies.
  - accidental backgrounds
    - positron in $\mu \rightarrow e\nu\nu$
    - photon in $\mu \rightarrow e\nu\nu\gamma$ or photon from e^+e^- annihilation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

What is Muon to Electron Conversion?

What is Muon to Electron Conversion?

1s state in a muonic atom



muon decay in orbit

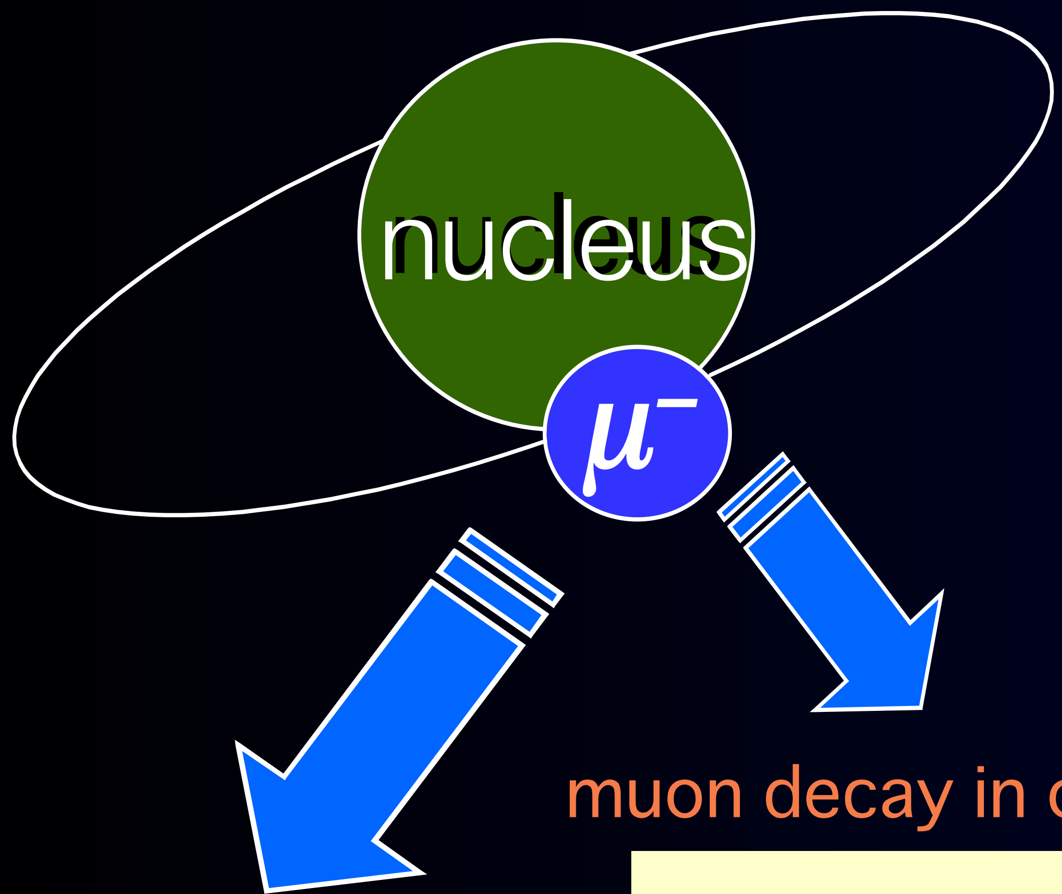
$$\mu^- \to e^- \nu \bar{\nu}$$

nuclear muon capture

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

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: $\mu \rightarrow e\gamma$ vs. μ-e conversion

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

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

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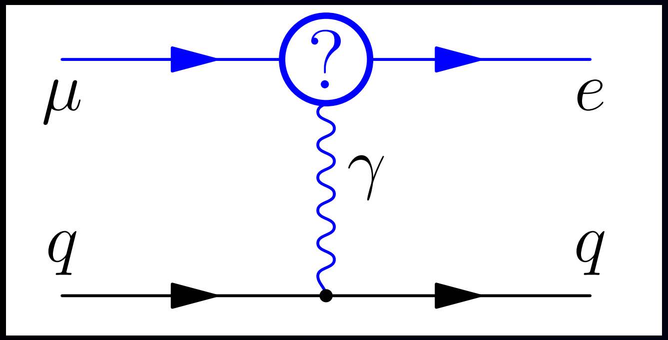
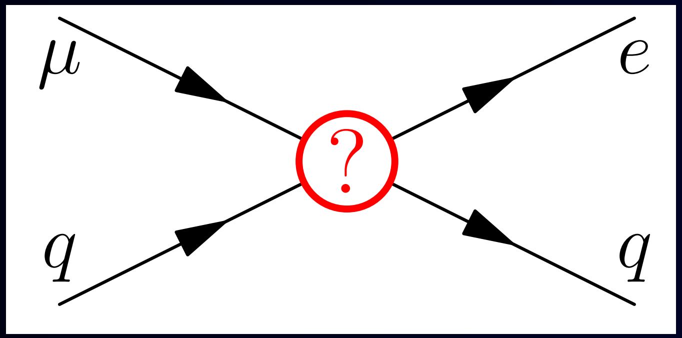
Photonic (dipole) interaction



Contact interaction



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

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

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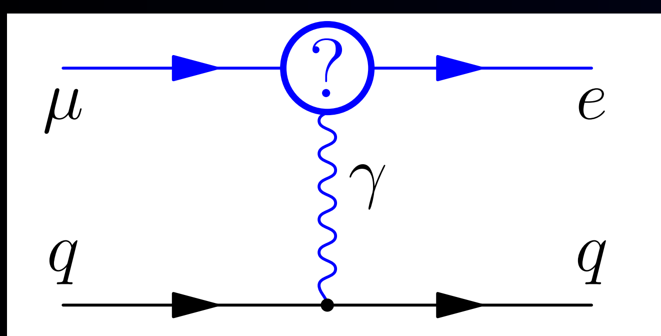

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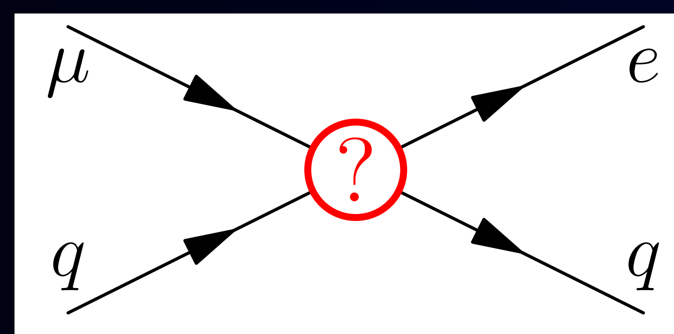

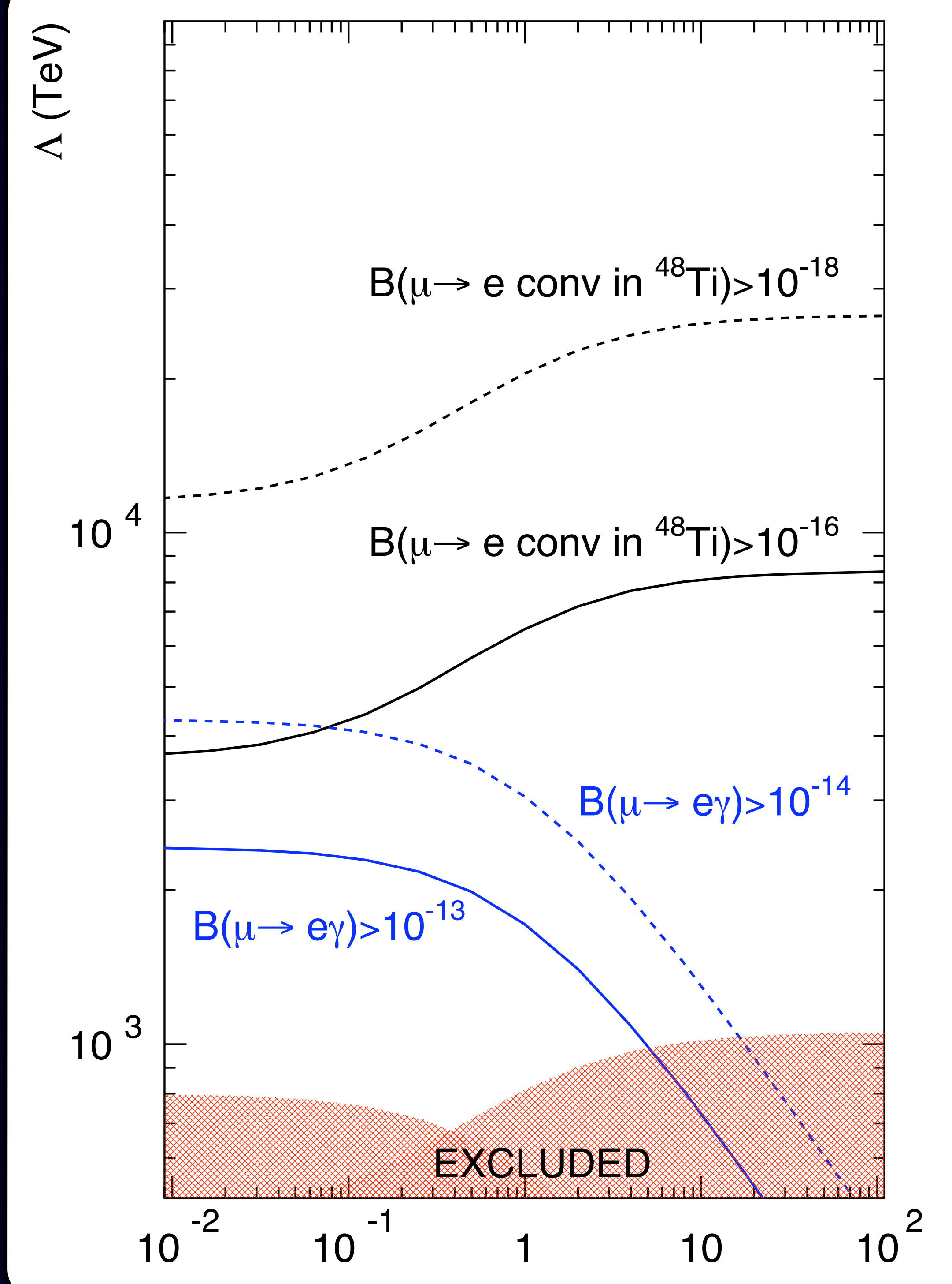

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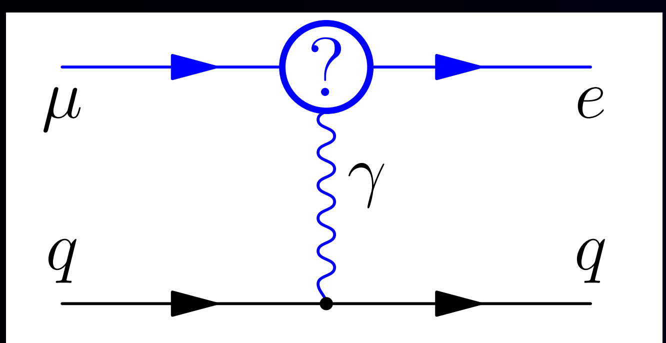

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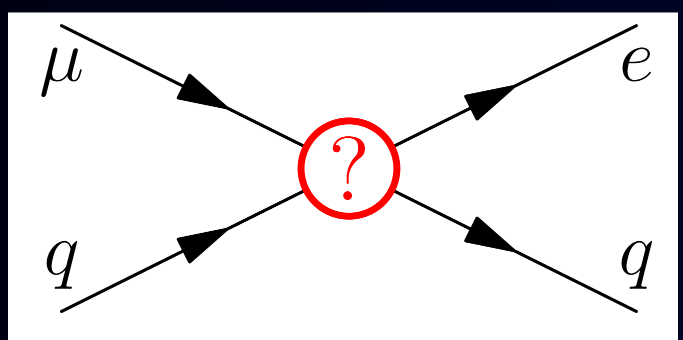
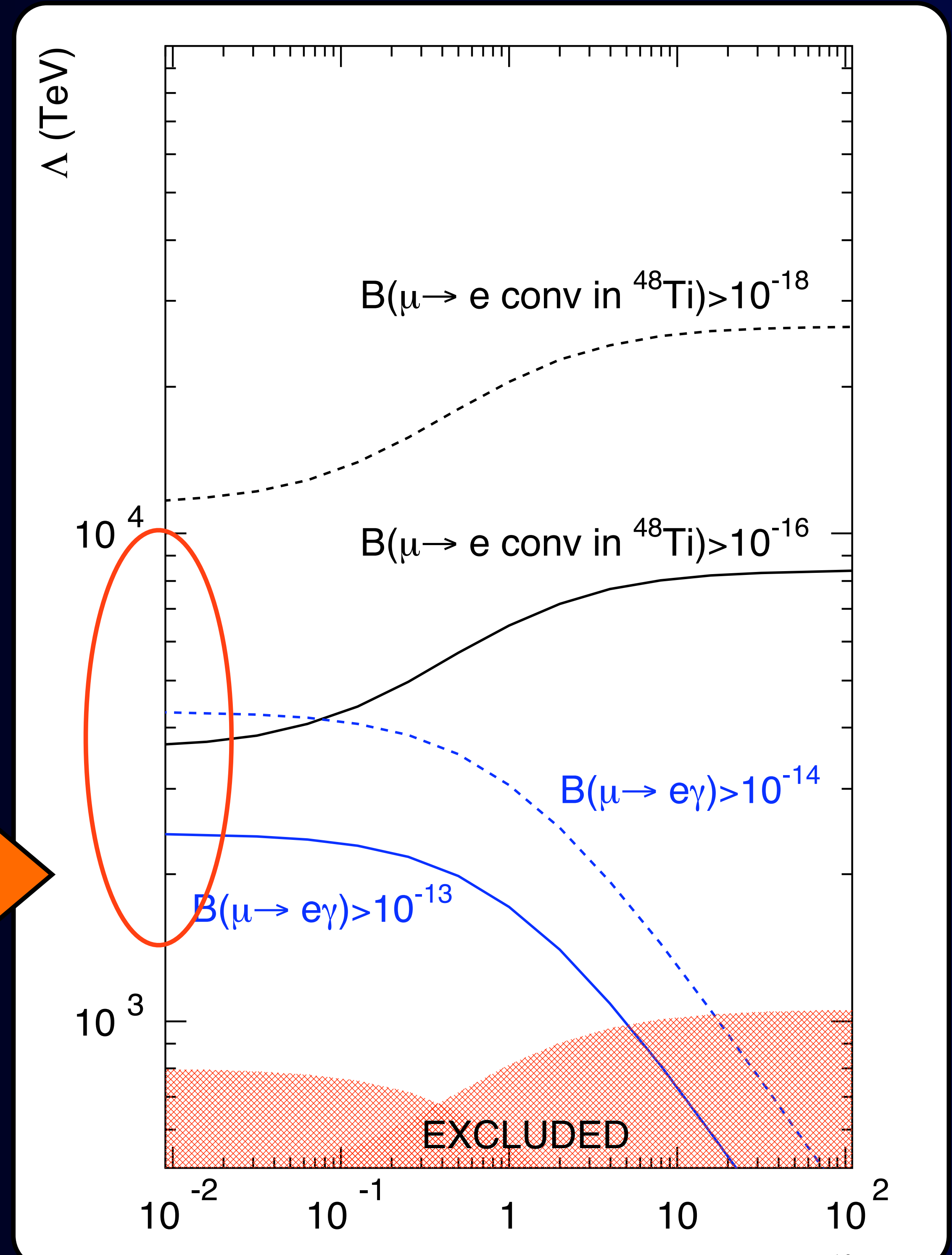


if photonic contribution dominates,

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

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



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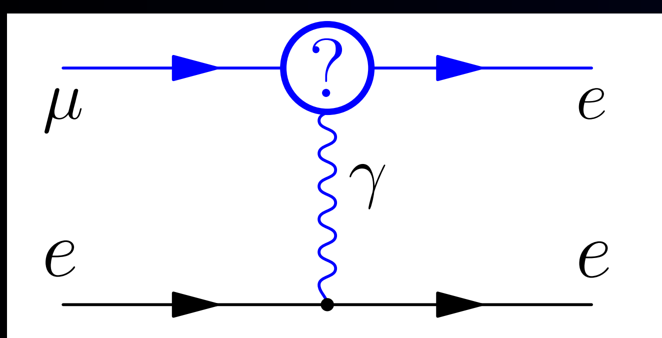

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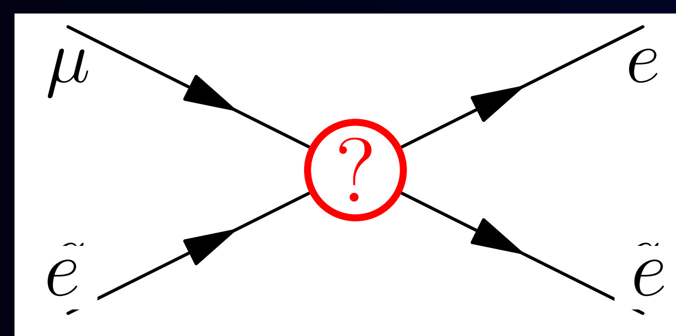

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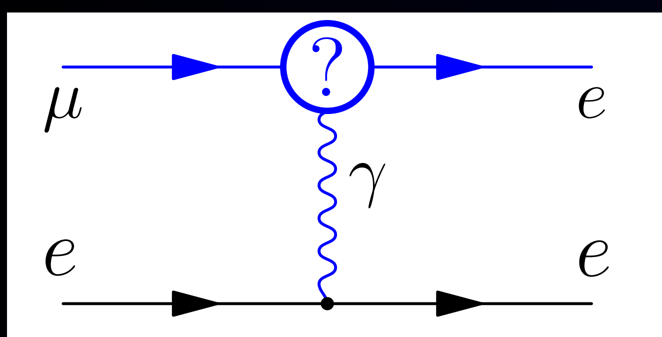

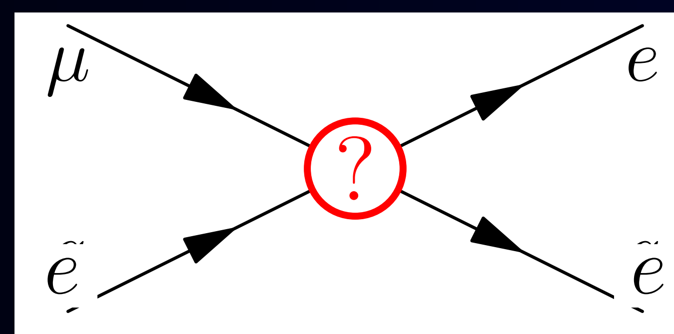

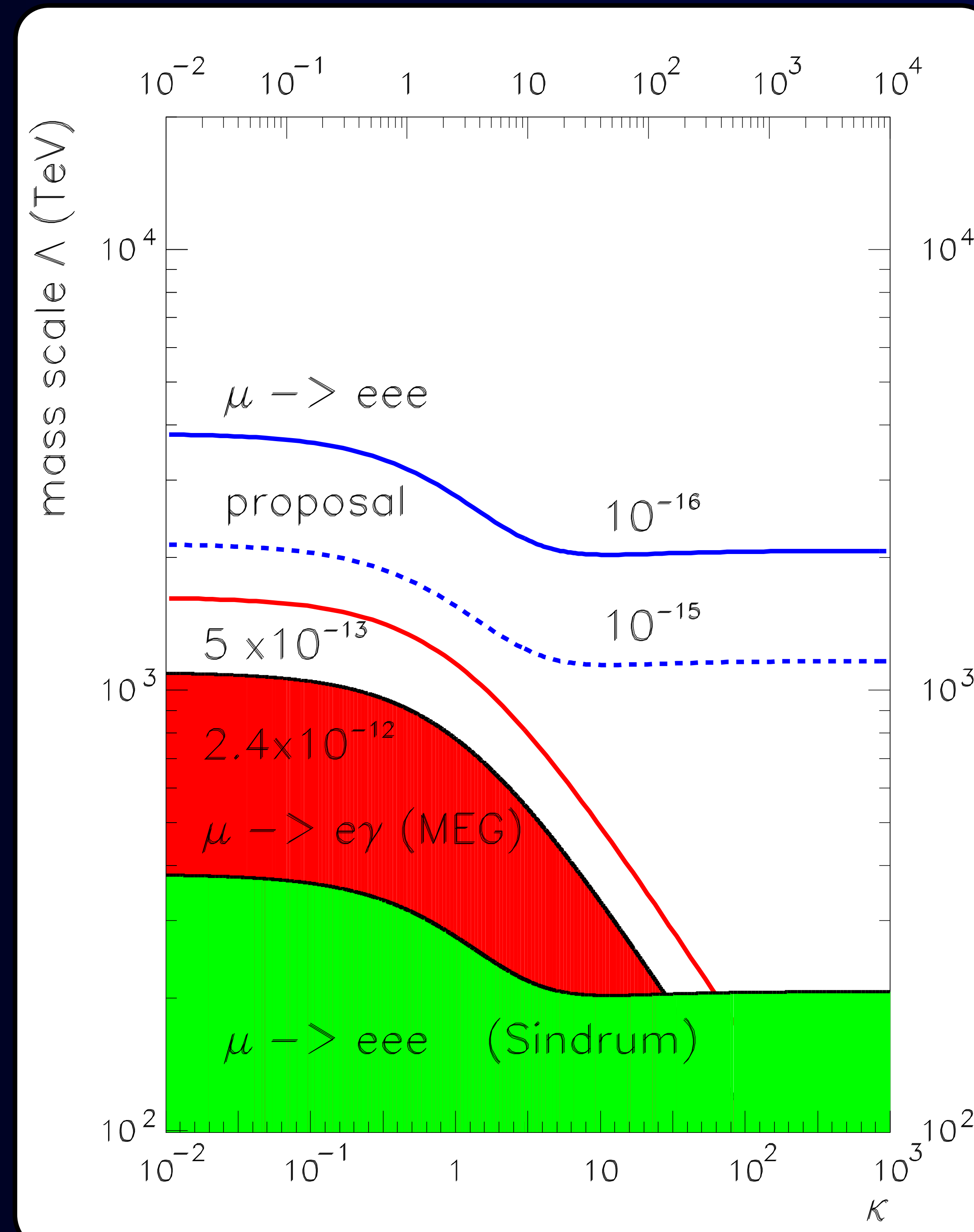

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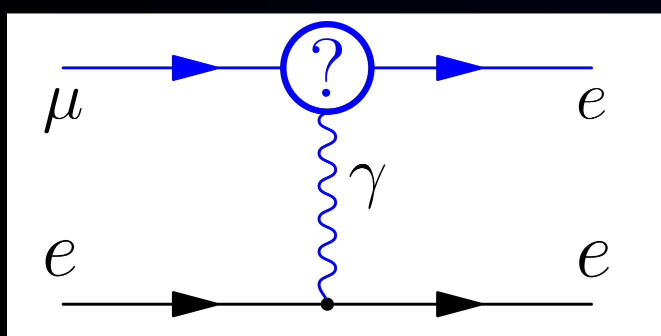

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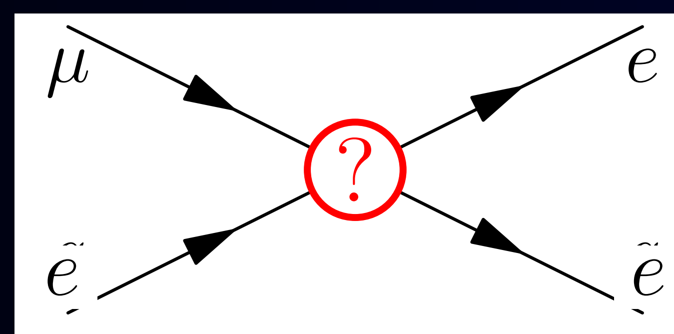
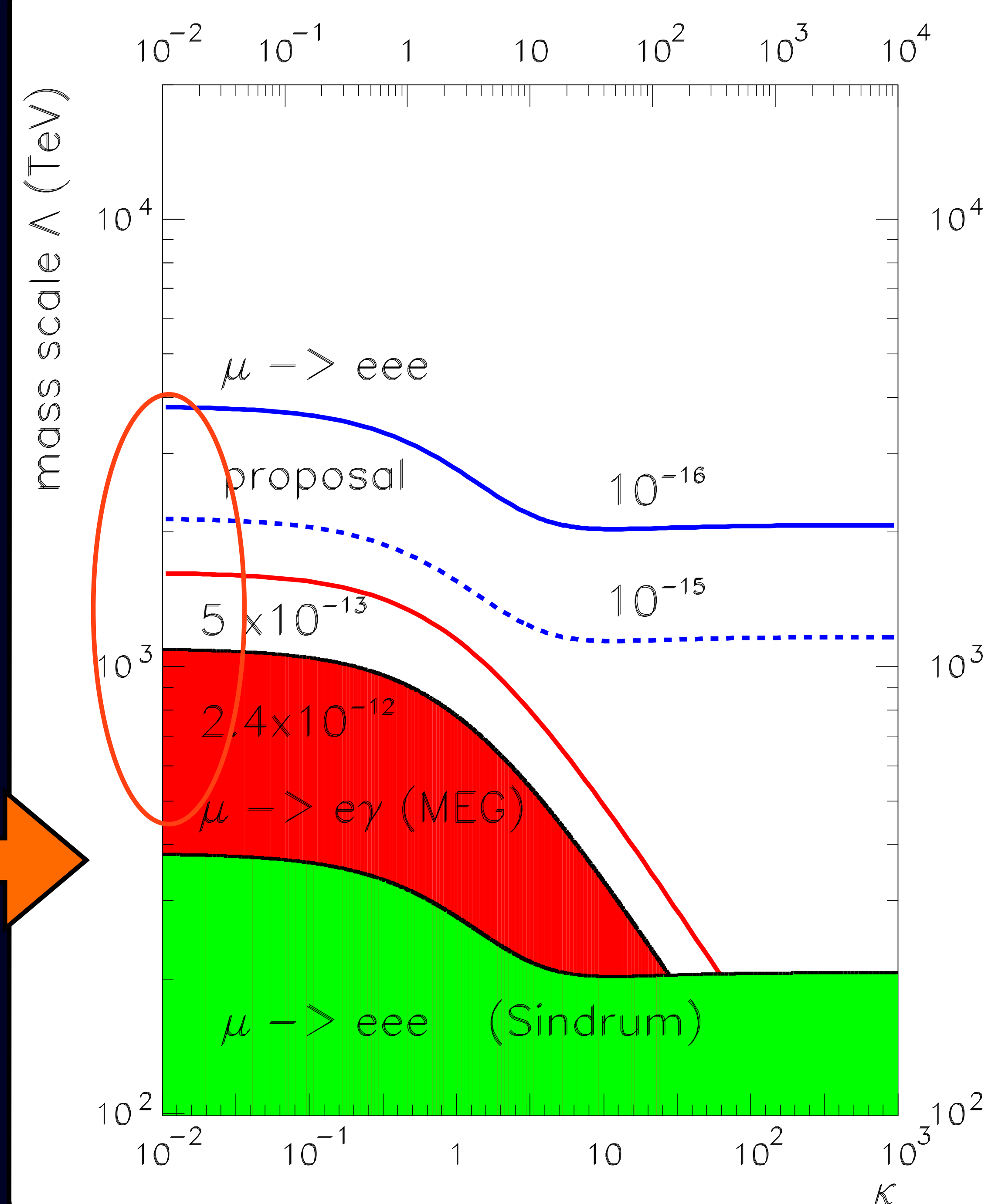


if photonic contribution dominates,

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



Experimental Comparison between μ→eγ/μ→eee and μ-e Conversion

Experimental Comparison between μ→eγ/μ→eee and μ-e Conversion

Process	Major backgrounds	Beam	Issues
$\mu^+ \to e^+\gamma$	accidental	DC beam	detector resolution
$\mu^+ \to e^+e^+e^-$	accidental	DC beam	detector resolution
$\mu^- N \to e^- N$	beam-related	pulsed beam	beam qualities

Experimental Comparison between μ→eγ/μ→eee and μ-e Conversion

Osaka University

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μ→eγ and μ→eee:
Accidental background is given by $(\text{rate})^2$. The detector resolutions have to be improved.

Experimental Comparison between μ→eγ/μ→eee and μ-e Conversion

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μ→eγ and μ→eee:
Accidental background is given by $(\text{rate})^2$. The detector resolutions have to be improved.

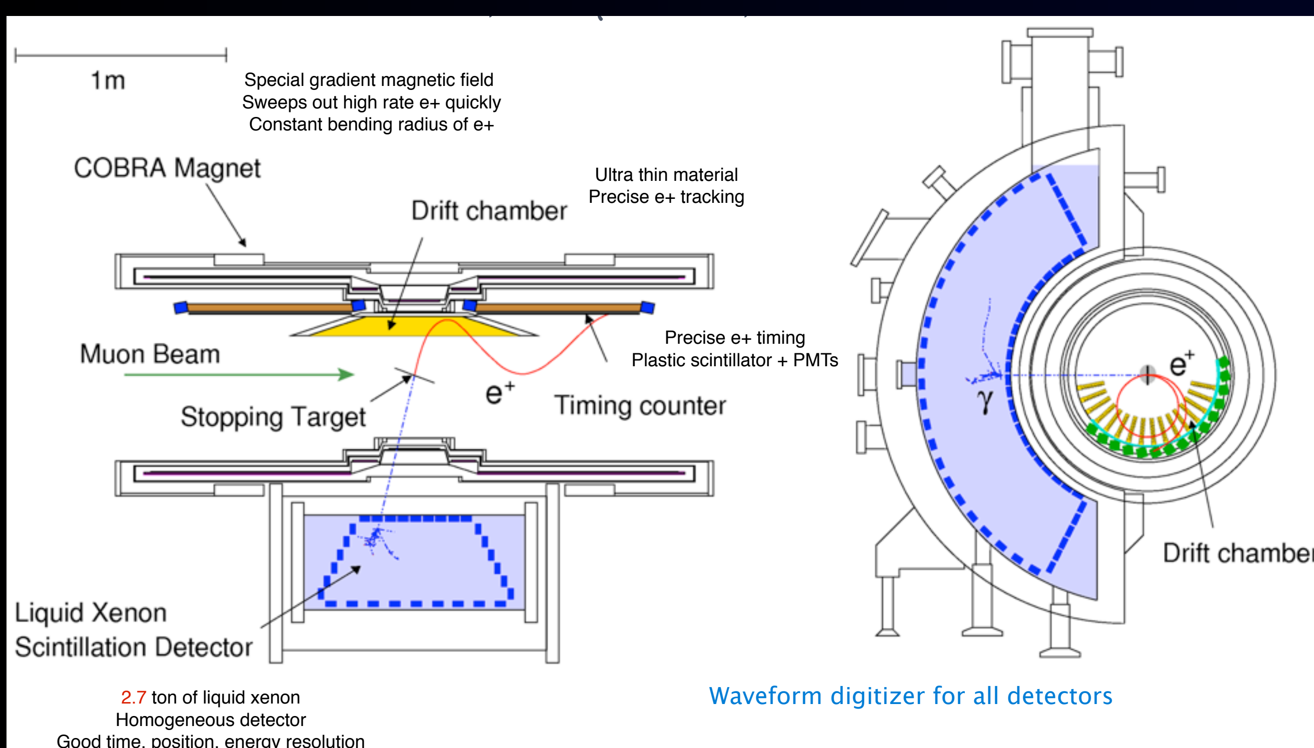
μ-e conversion:
A higher beam intensity can be taken because of no coincidence. Beam backgrounds can be under control.

CLFV Experiments in Muon Decays

CLFV Experiments in Muon Decays

$\mu \to e\gamma$ MEG @PSI

- Detector upgrade would include e^+ tracking and liq.Xe detector.
- The upgrade MEG will start in 2015 or 2016, aiming $O(10^{-14})$



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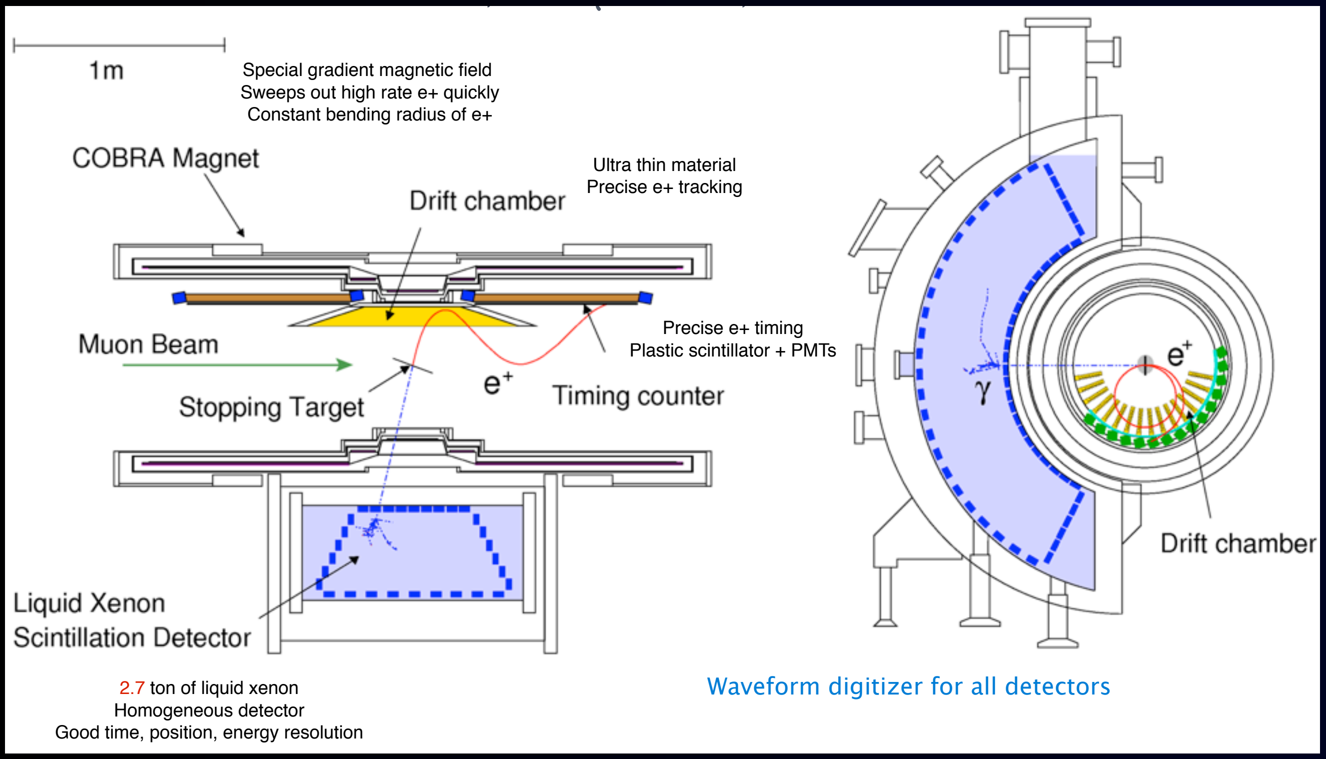
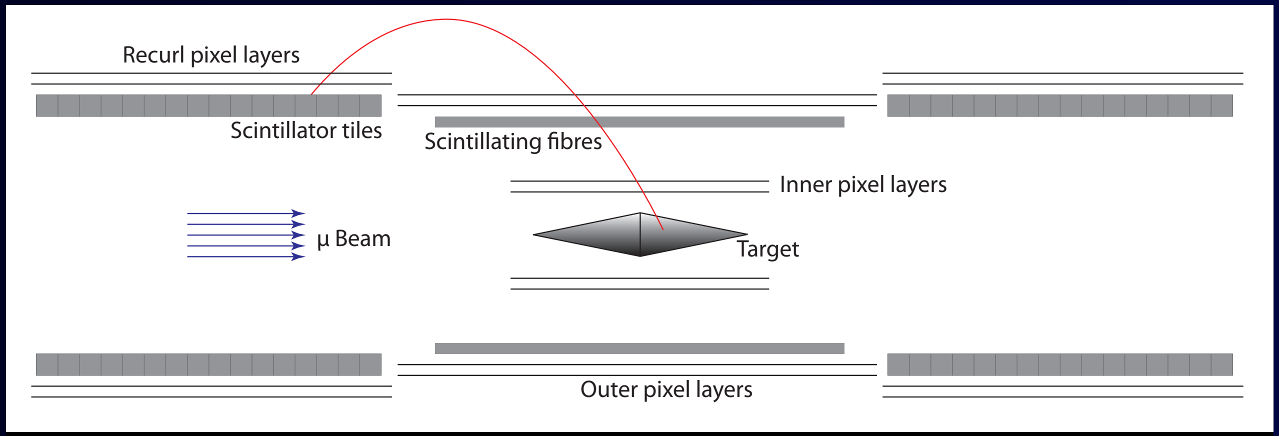
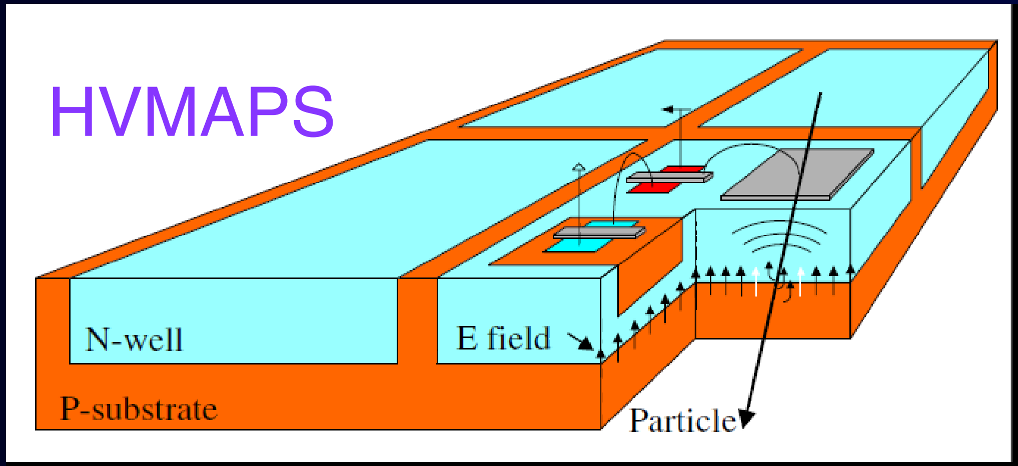
μ→eee   Mu3e   @PSI

- search for μ→eee.
- approved at PSI last week
- staged approach, 10^{-14} in 2015, and 10^{-16} in 2017.







CLFV Experiments in Muon Decays

Osaka University

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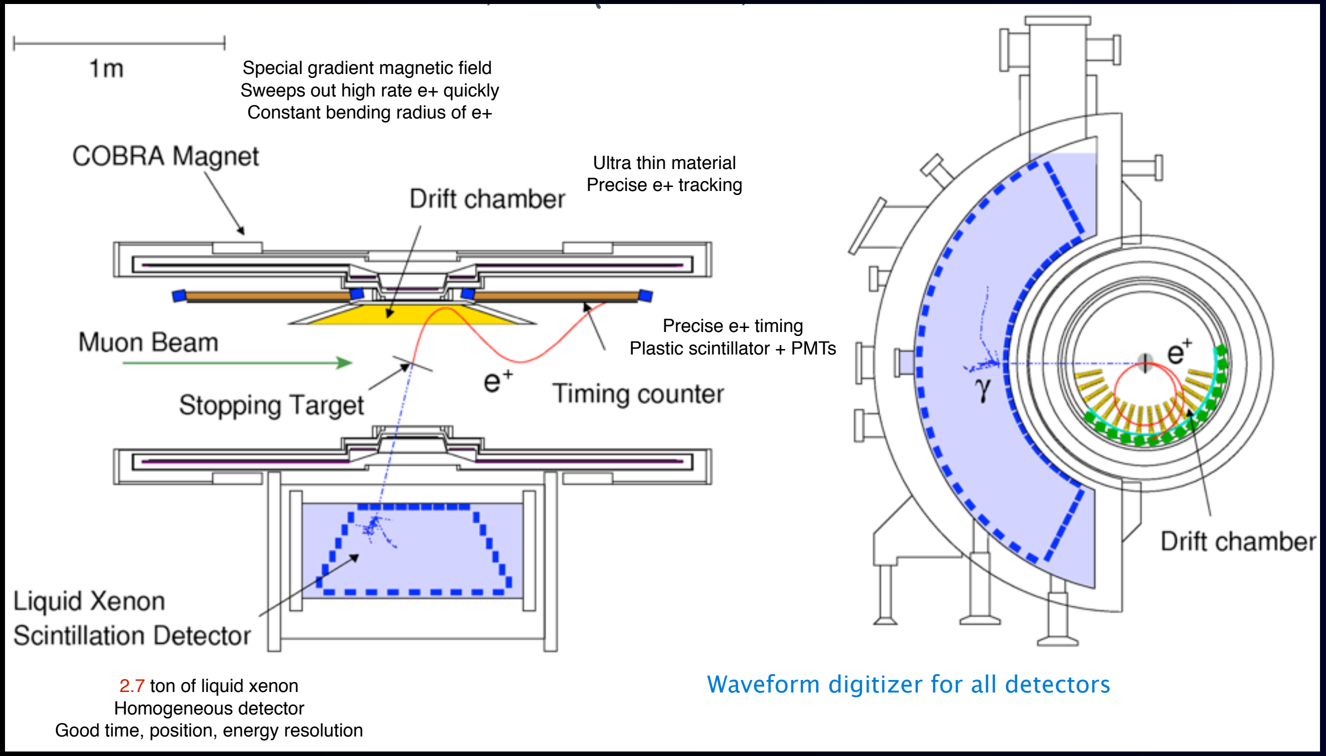

see Dmitry Grigoriev's talk

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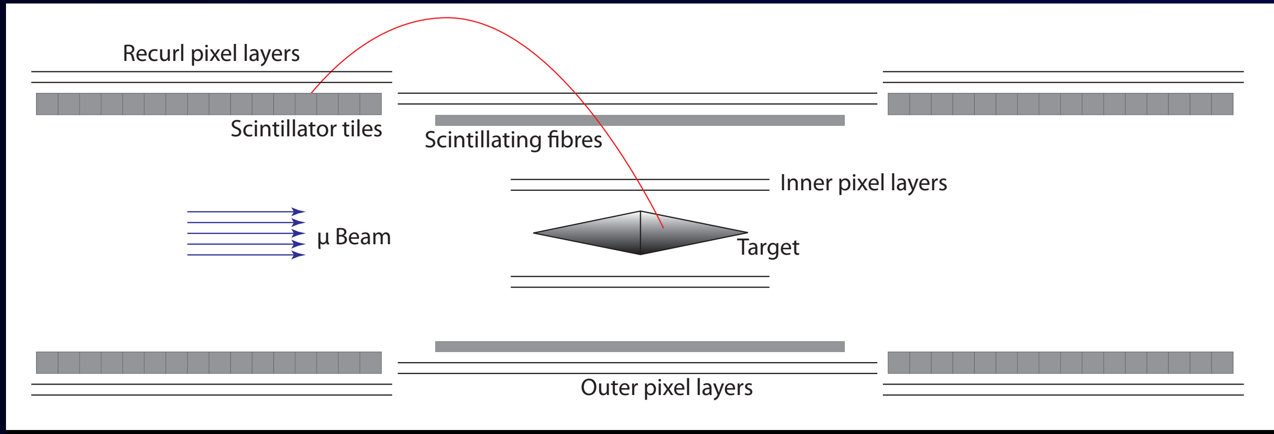
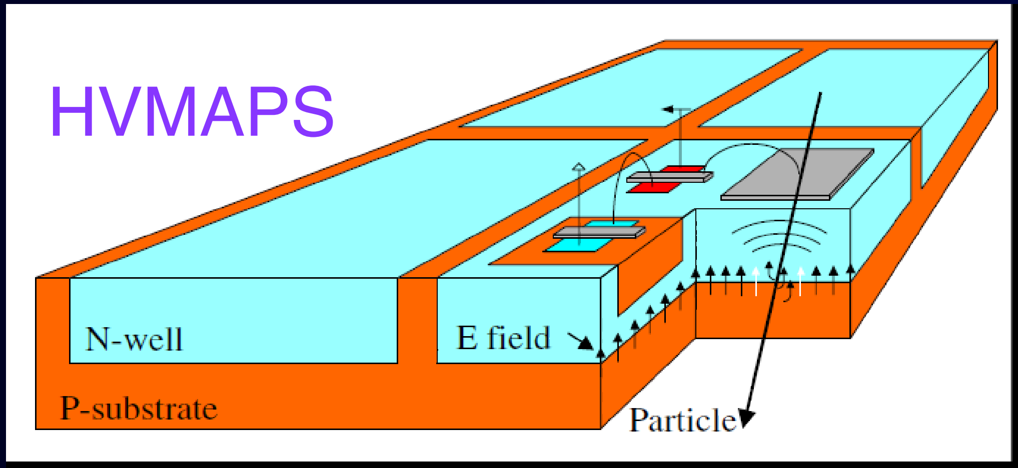




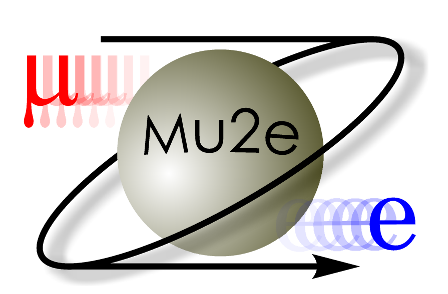
CLFV Experiments in Muon Decays

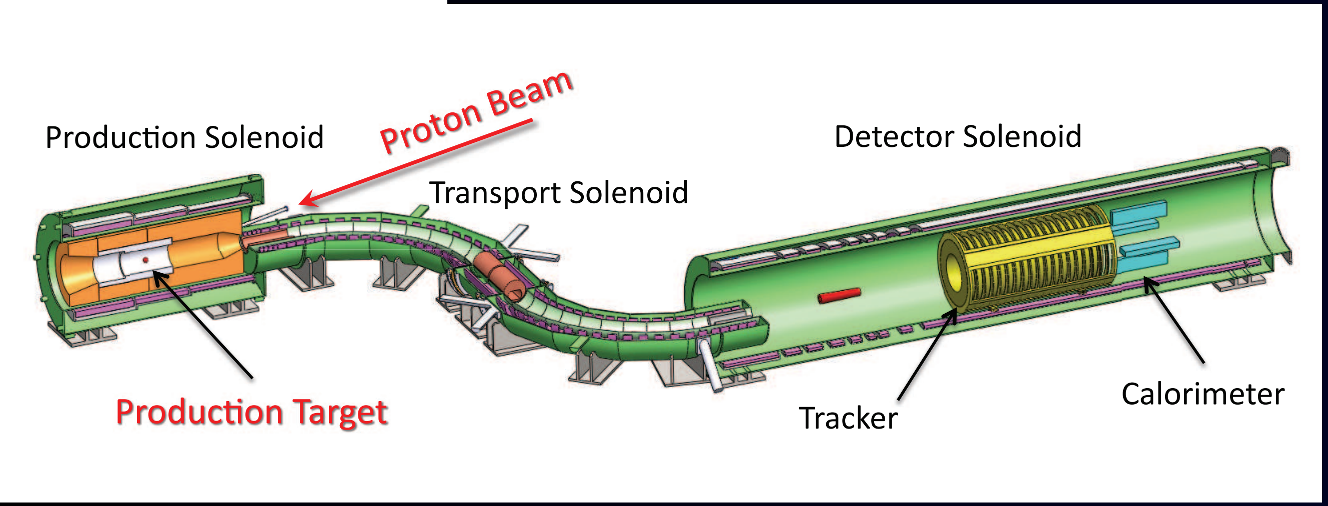
CLFV Experiments in Muon Decays

Osaka University

μN→eN Mu2e @FNAL

- SES < 3×10^{-17}
- DOE CD2 review in 2014
- start in 2019





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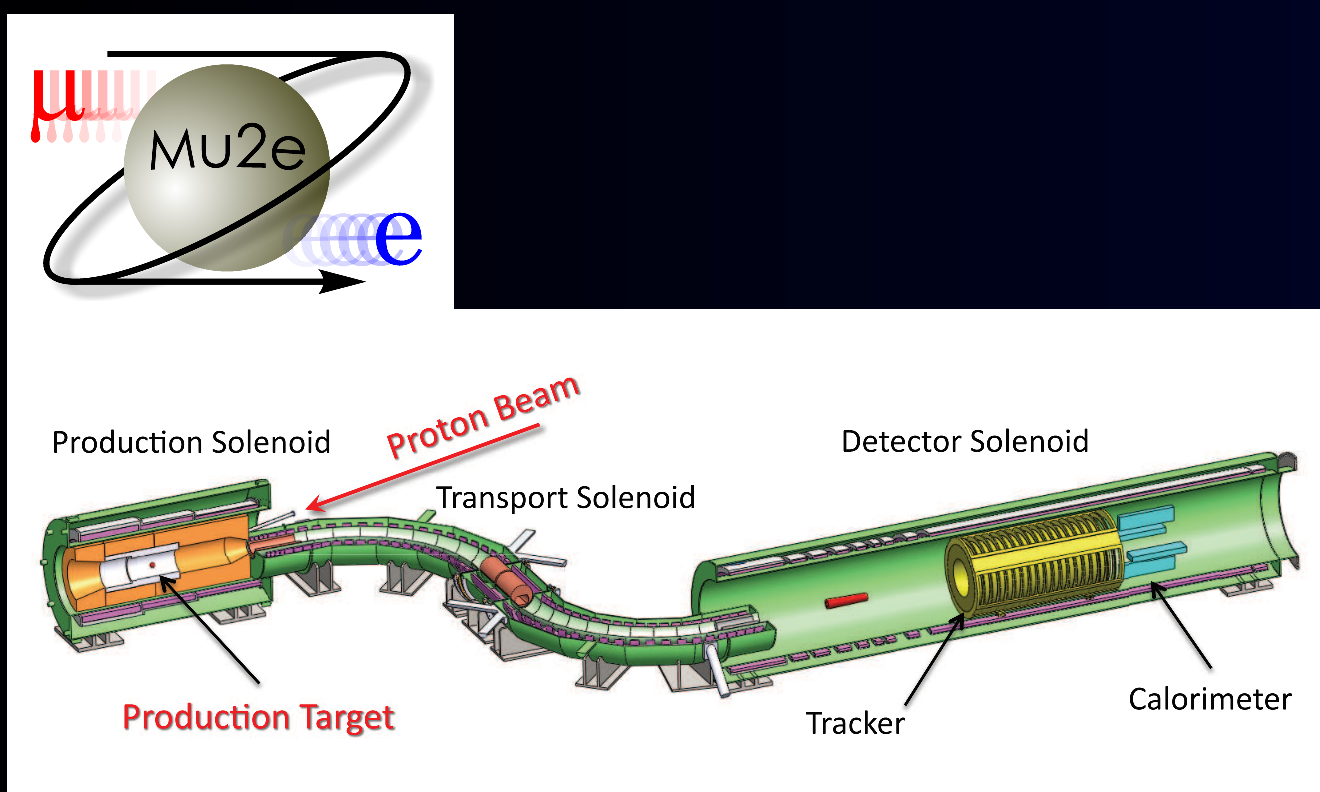
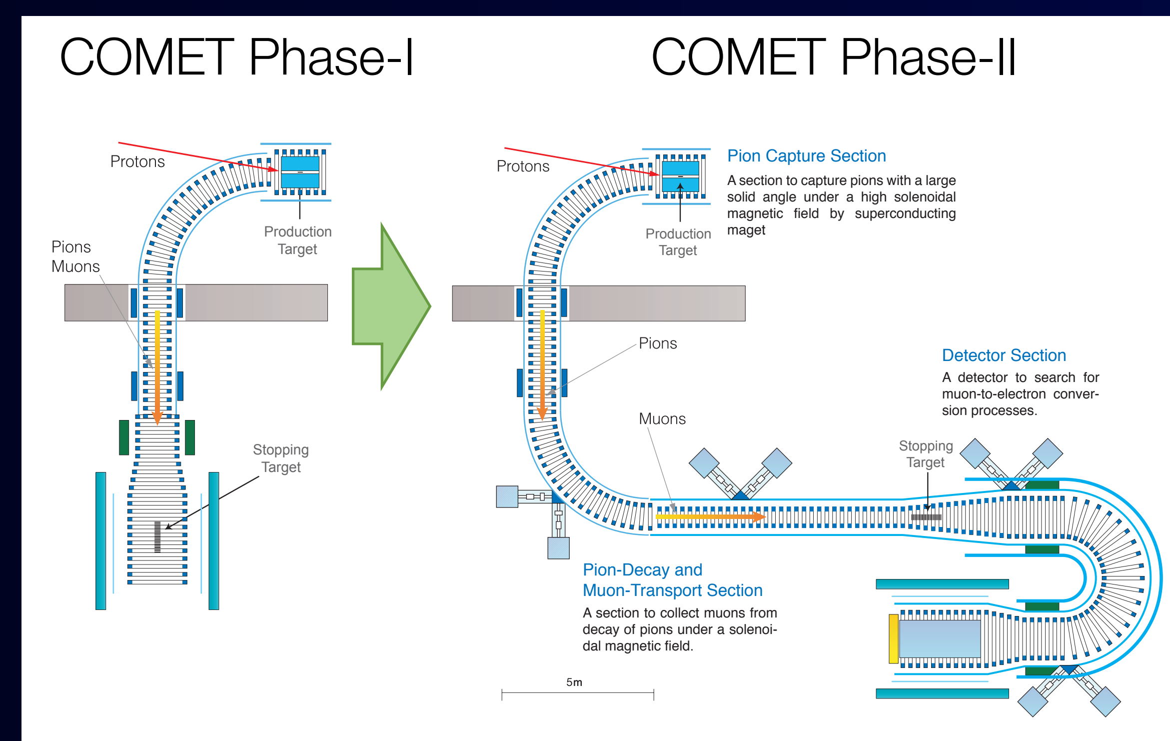


μN→eN **COMET** @J-PARC

- staged approach
- COMET Phase-I < 3×10^{-15}, 2016
- COMET Phase-II < 3×10^{-17}, 2019



CLFV Experiments in Muon Decays

Osaka University

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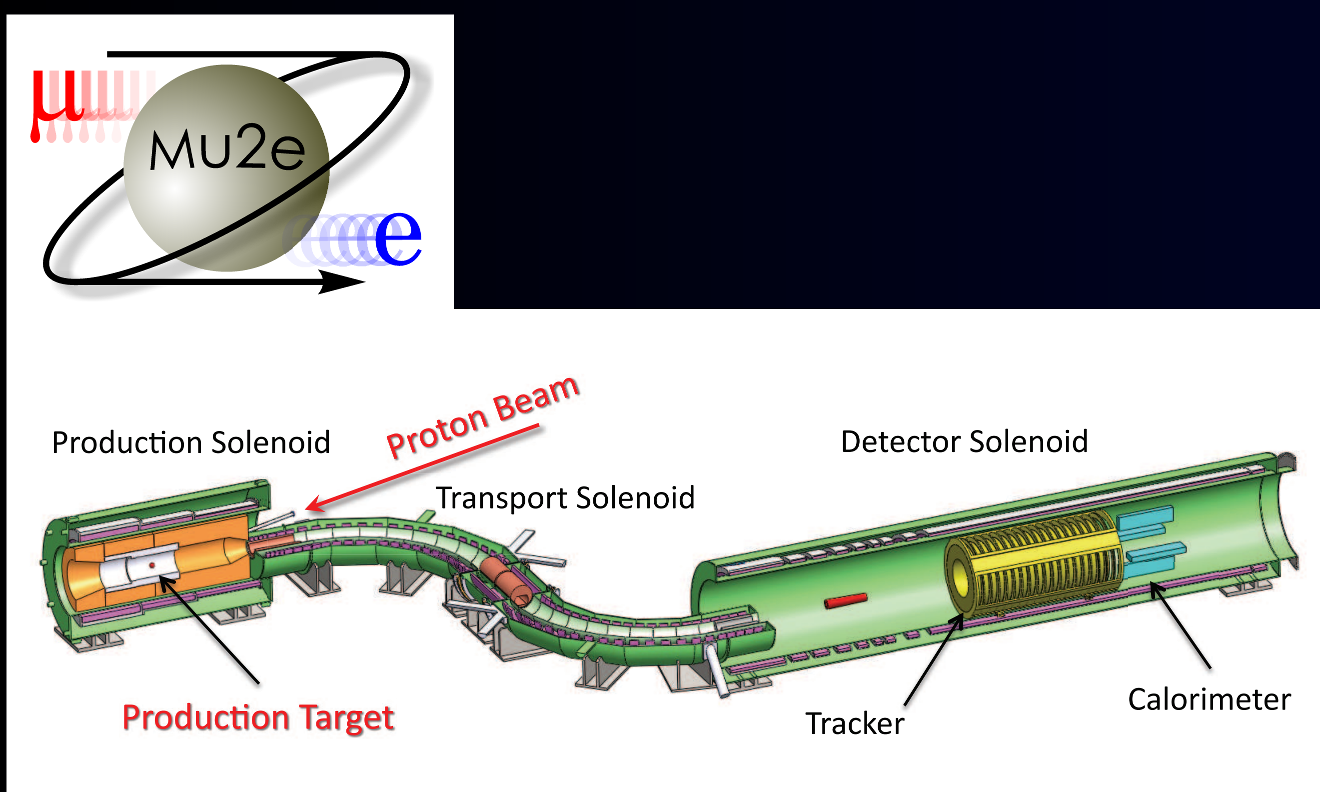

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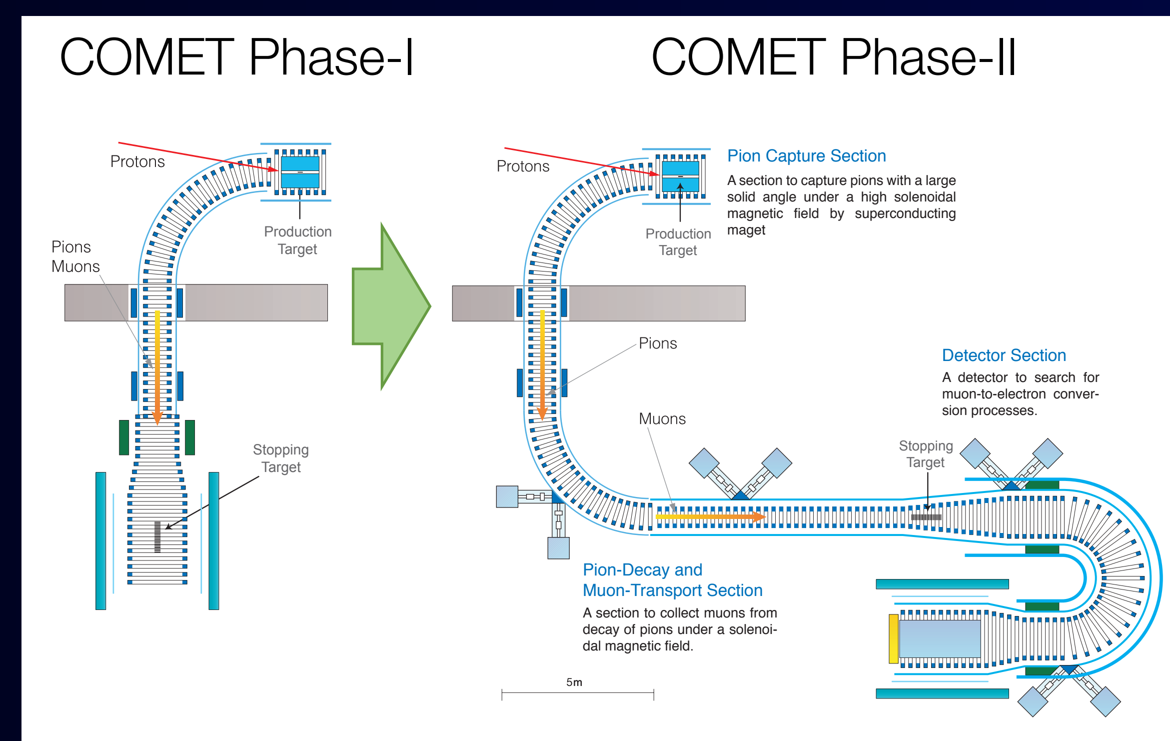

see Giovanni Tassielli's talk

CLFV Experiments in Muon Decays

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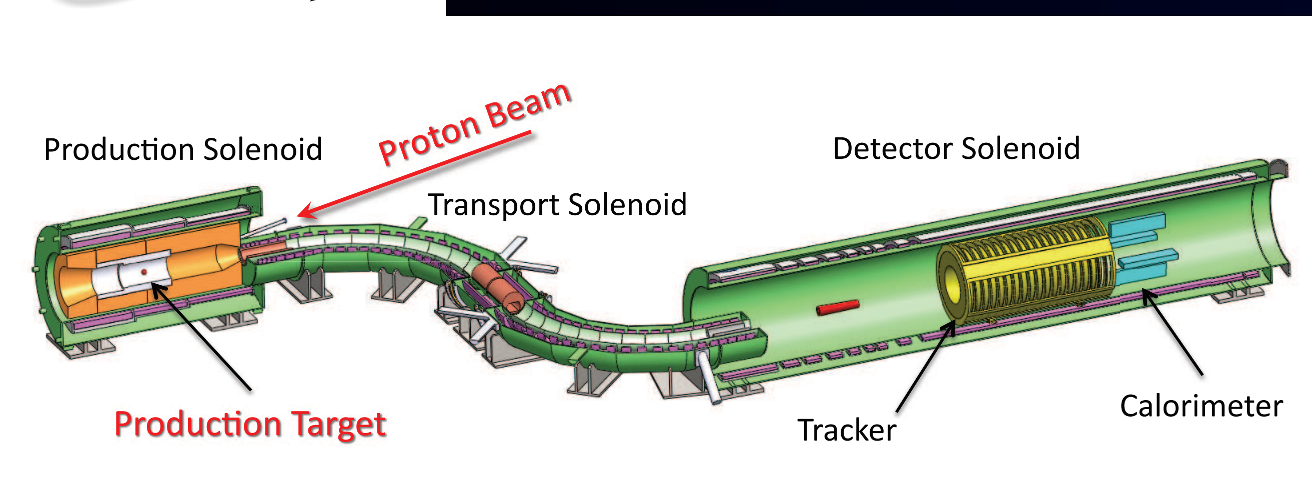

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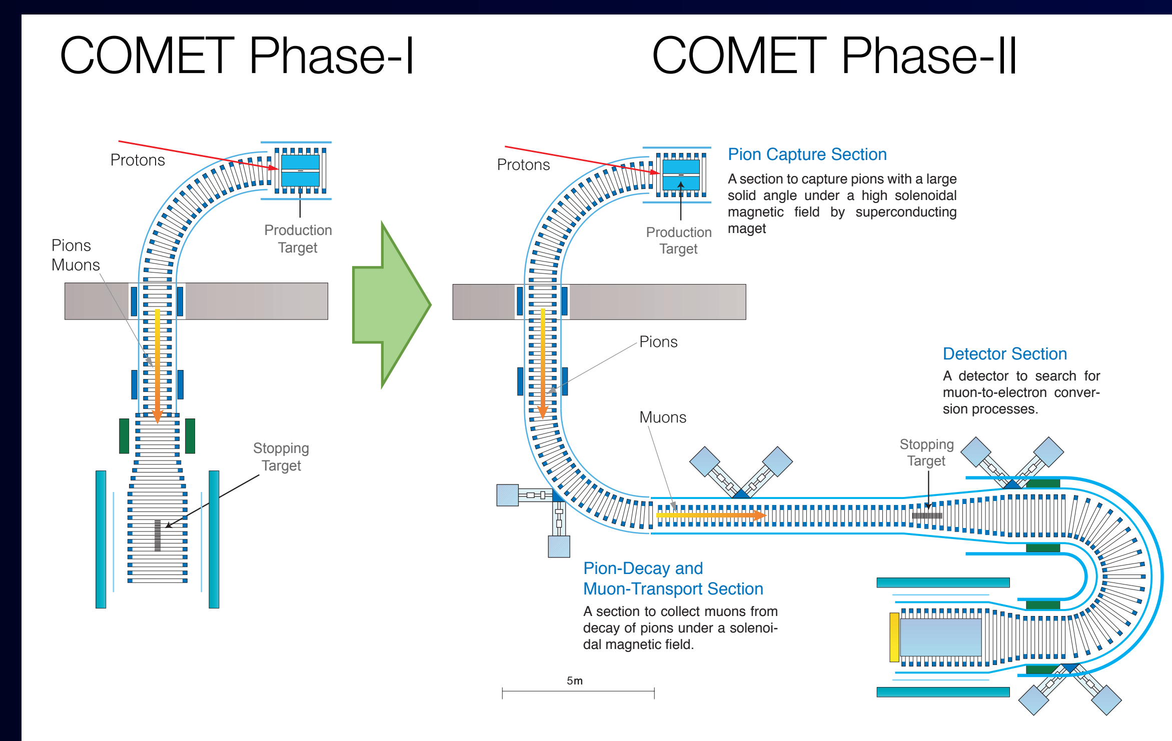
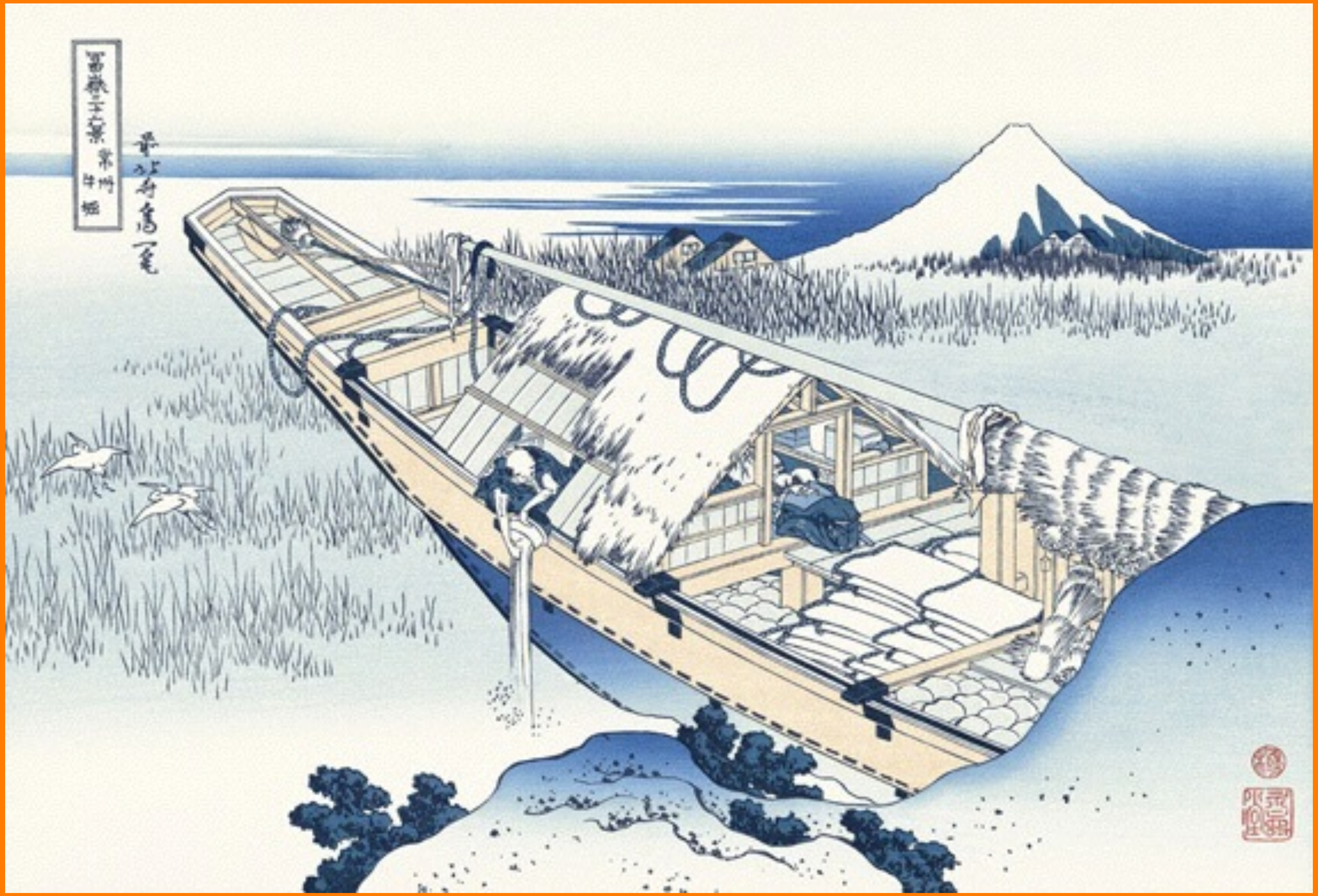


see Tran Hoai Nam's talk

Breakthrough
in Muon Sources



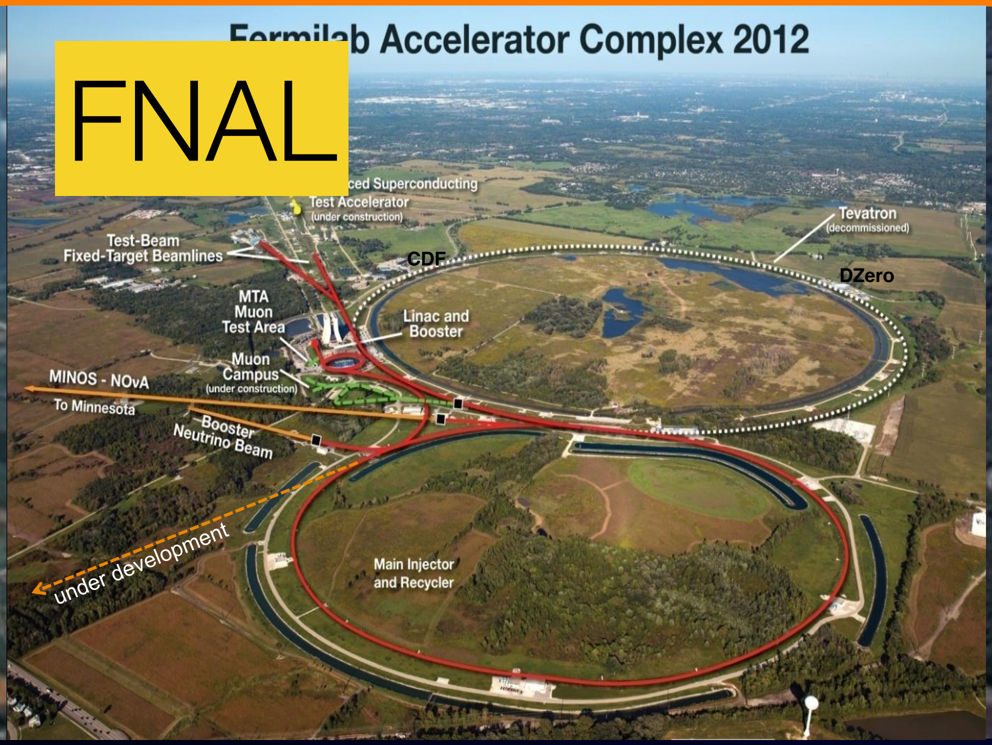
High Energy Scale Reach in CLFV

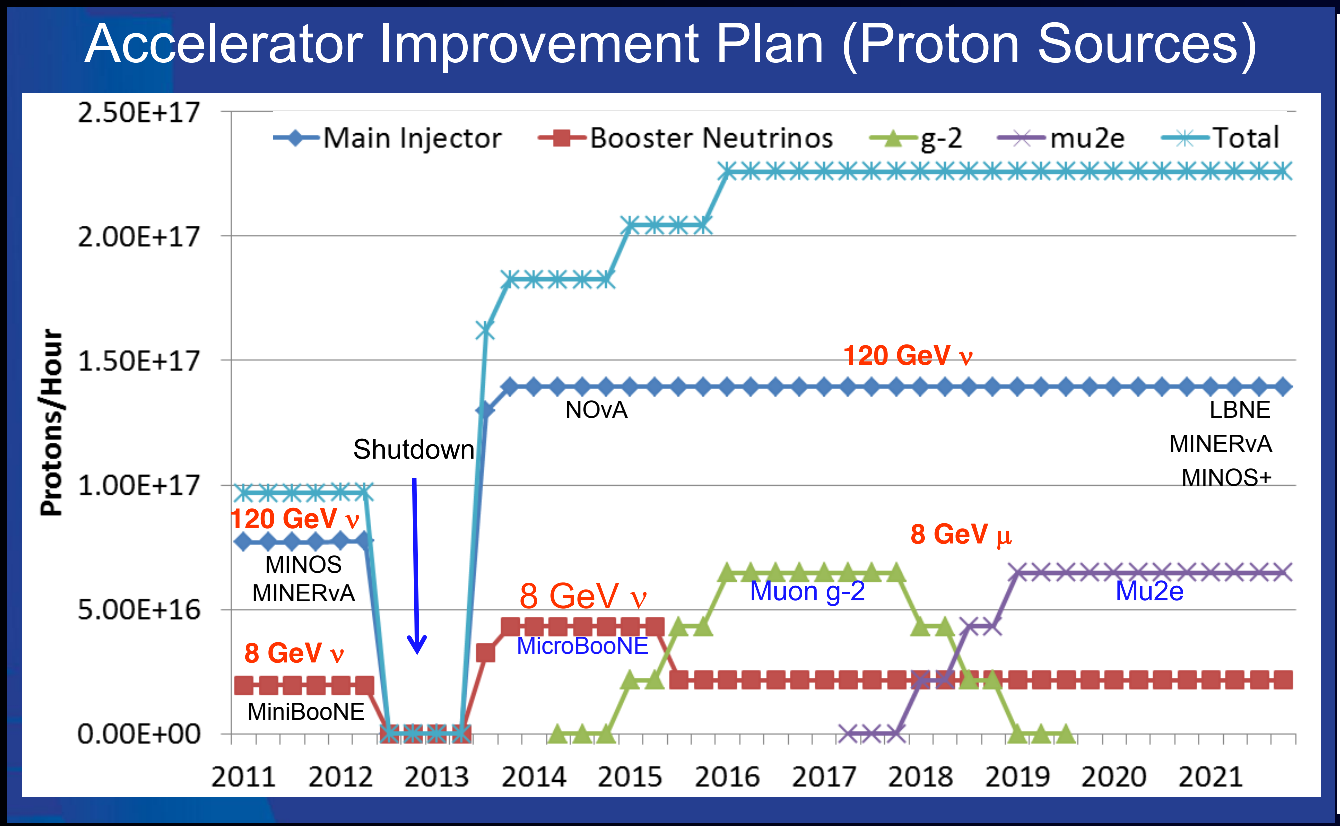
High Energy Scale Reach in CLFV

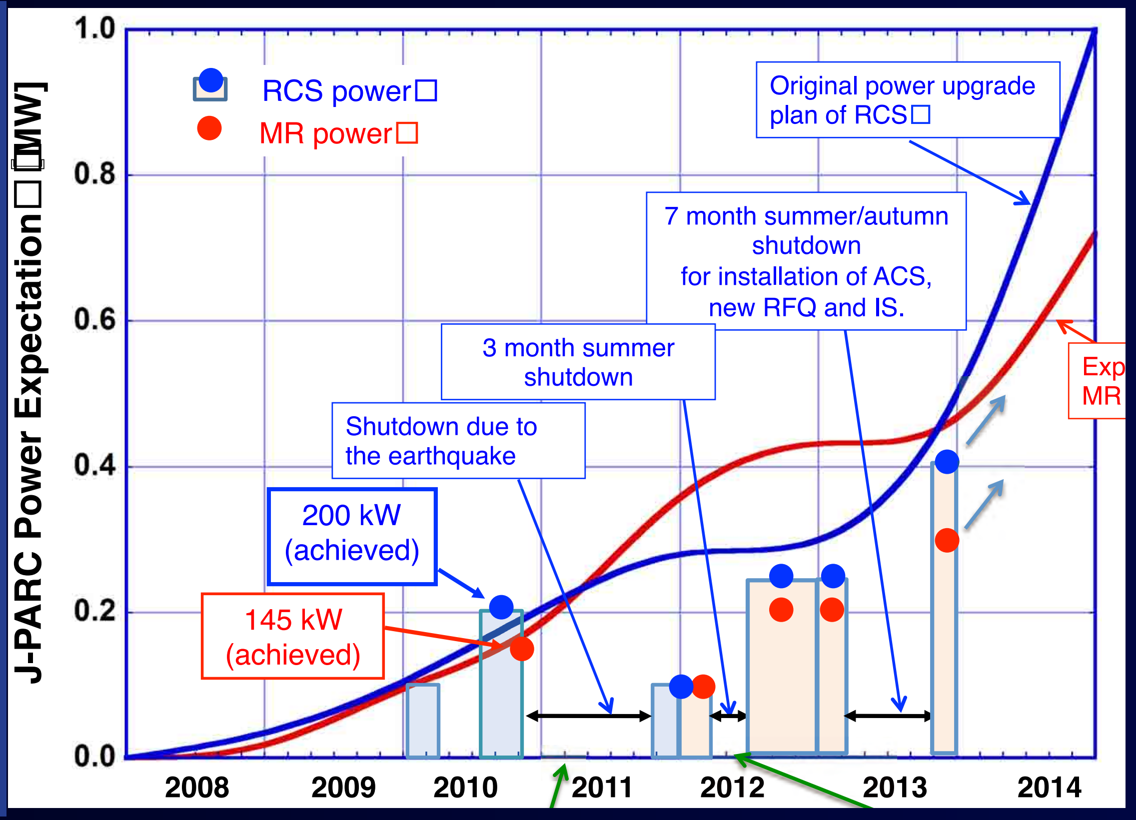
$$R \sim \frac{1}{\Lambda^4}$$

Can we improve the Λ reach by an order of magnitude ?
We must have at least 10^4 times the number of parent particles in rare decays.

Proton Accelerators (X10)







MuSIC Facility at Osaka University
- Frontend of Mu2e / COMET -

Osaka University

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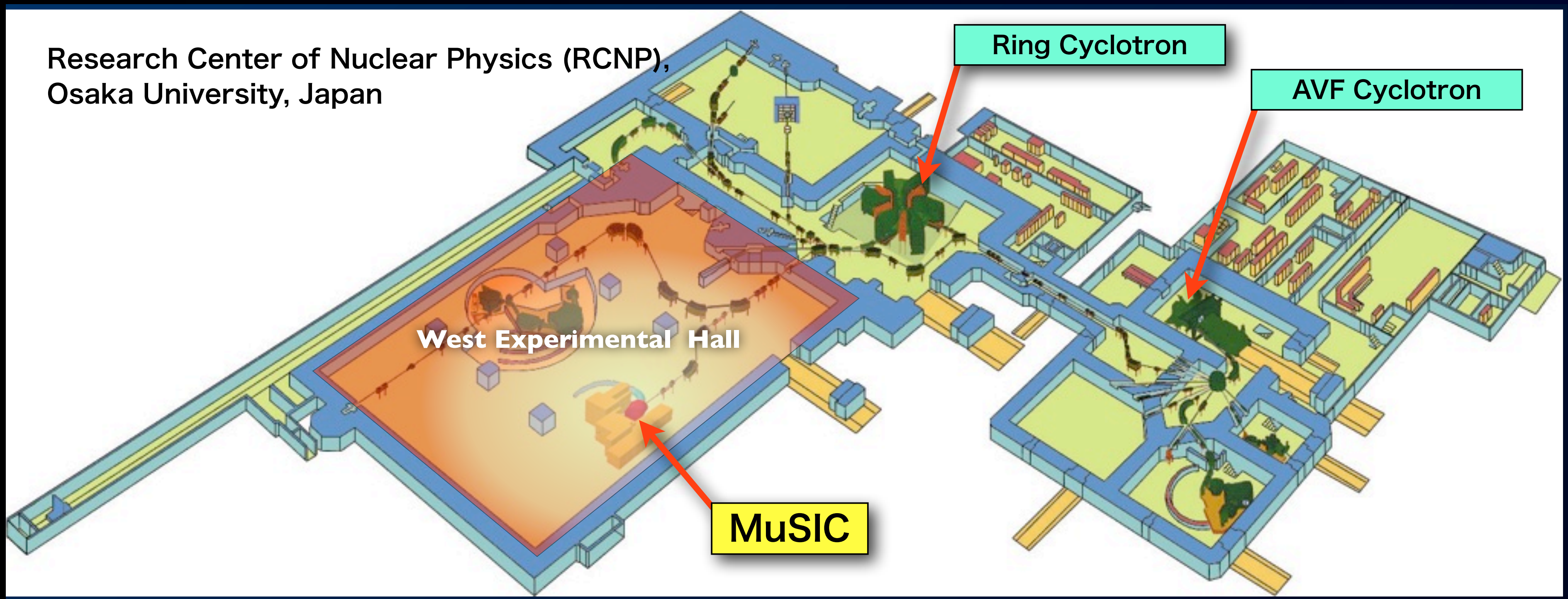
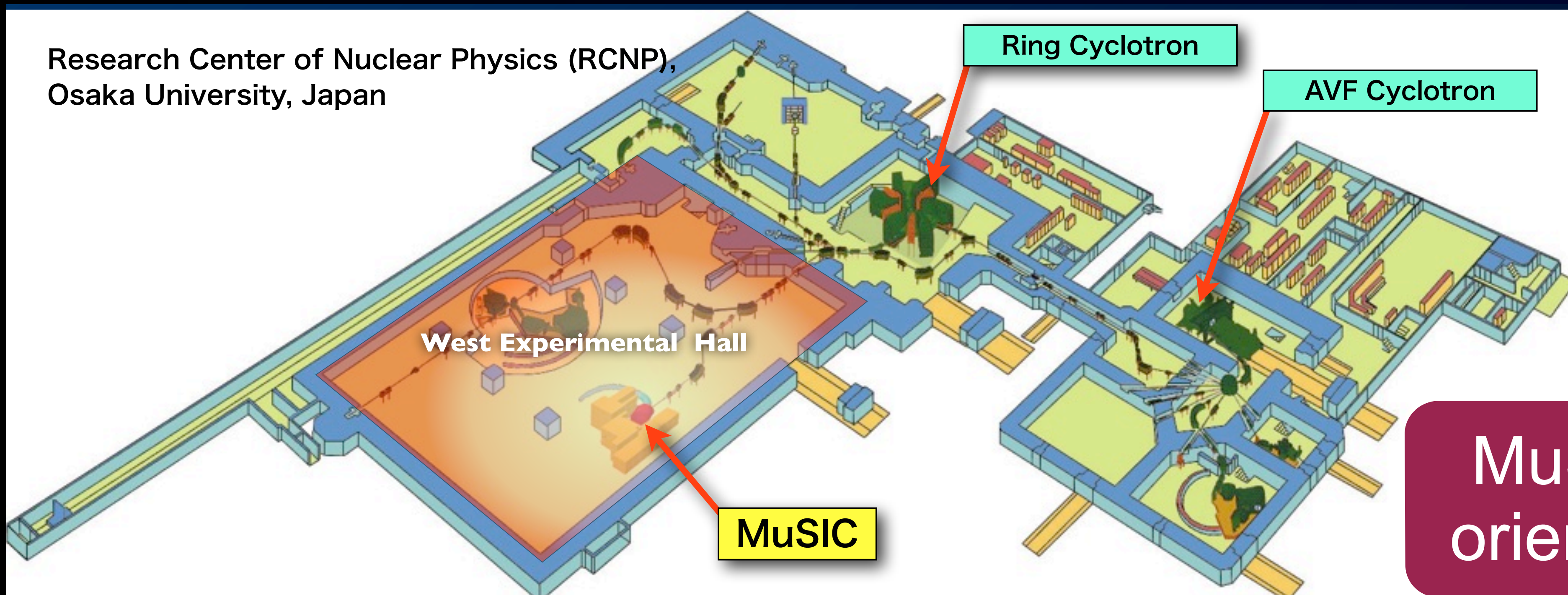


RCNP cyclotron
400 MeV, 1μA

- RCNP has two cyclotrons. A proton beam with 392MeV, 1 μA is provided from the Ring Cyclotron (up to 5 μA in near future).
- The MuSIC is in the largest experimental hall, the west experimental hall.

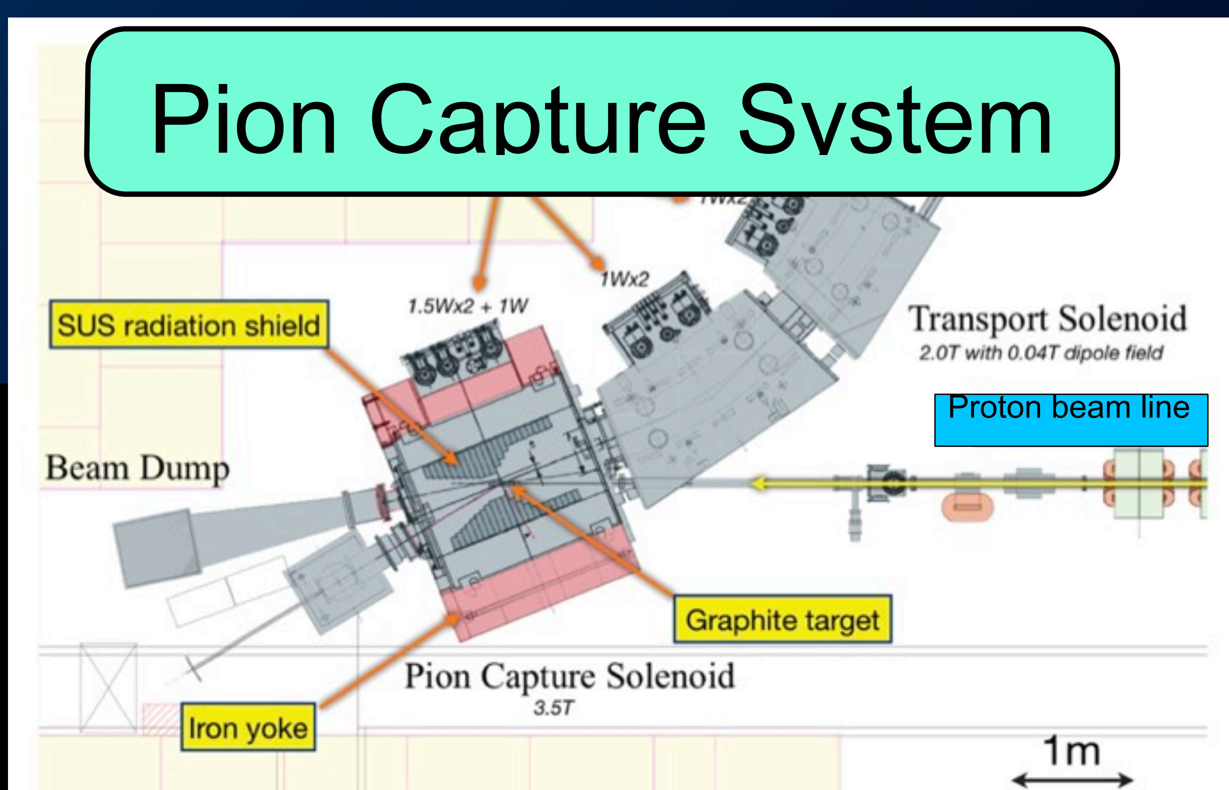
MuSIC Facility at Osaka University
- Frontend of Mu2e / COMET -



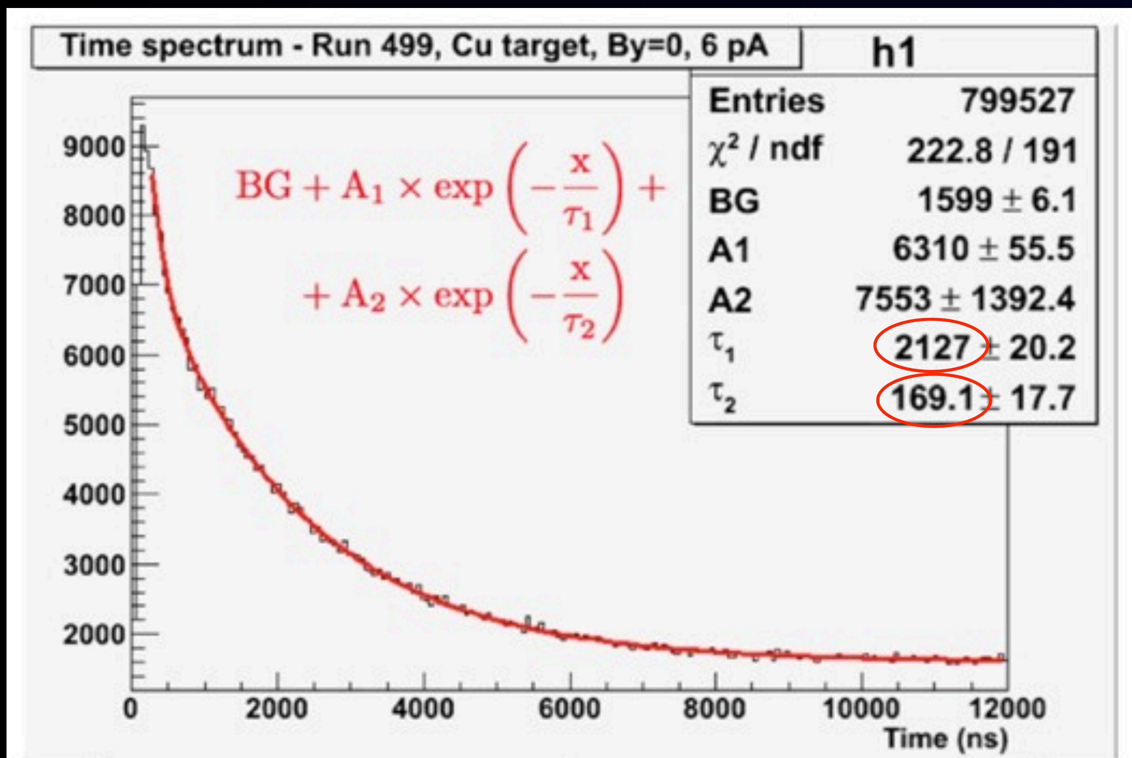
RCNP cyclotron
400 MeV, 1μA

MuSIC = Muon Science oriented Intense Channel

Pion Capture System

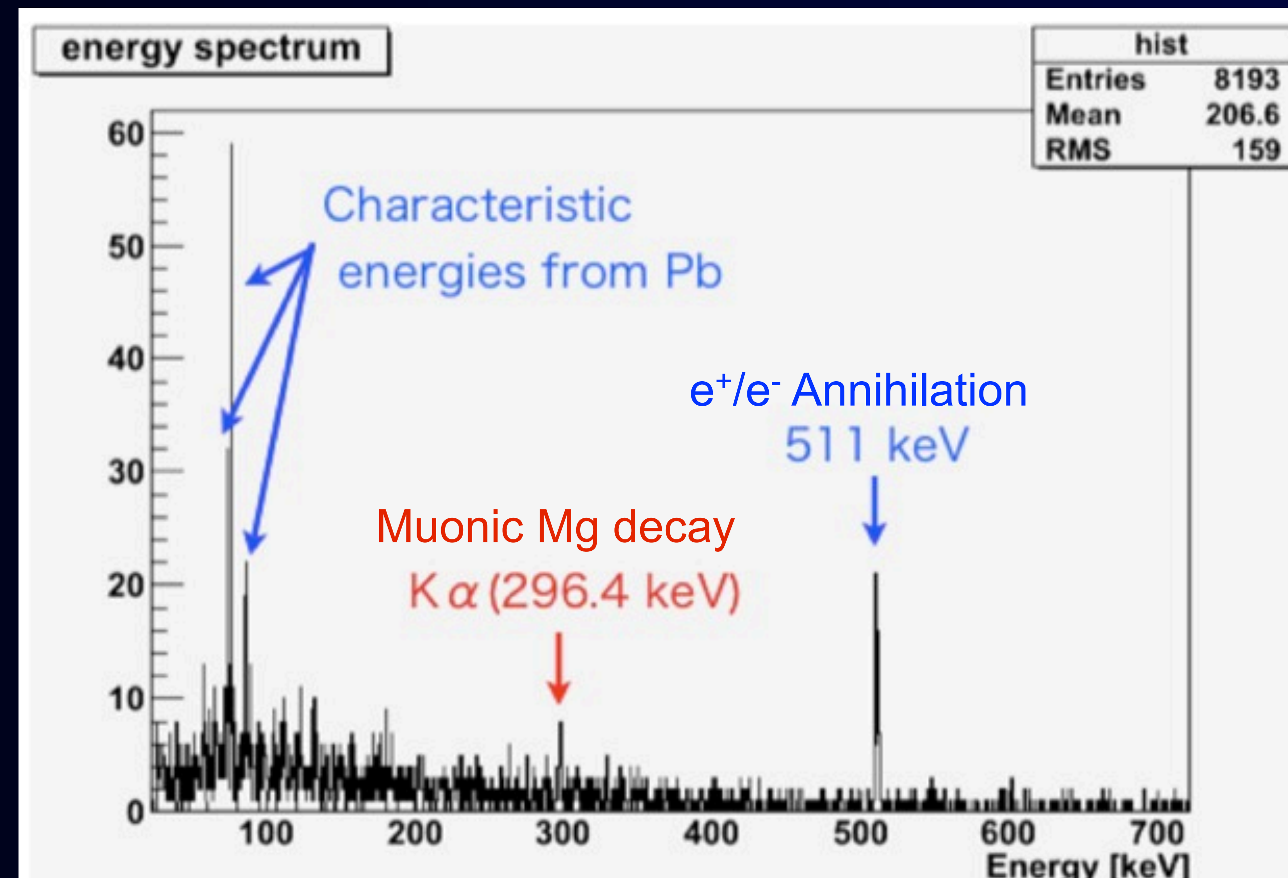


MuSIC Facility at Osaka University
Muon Production Efficiency (x1000)



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

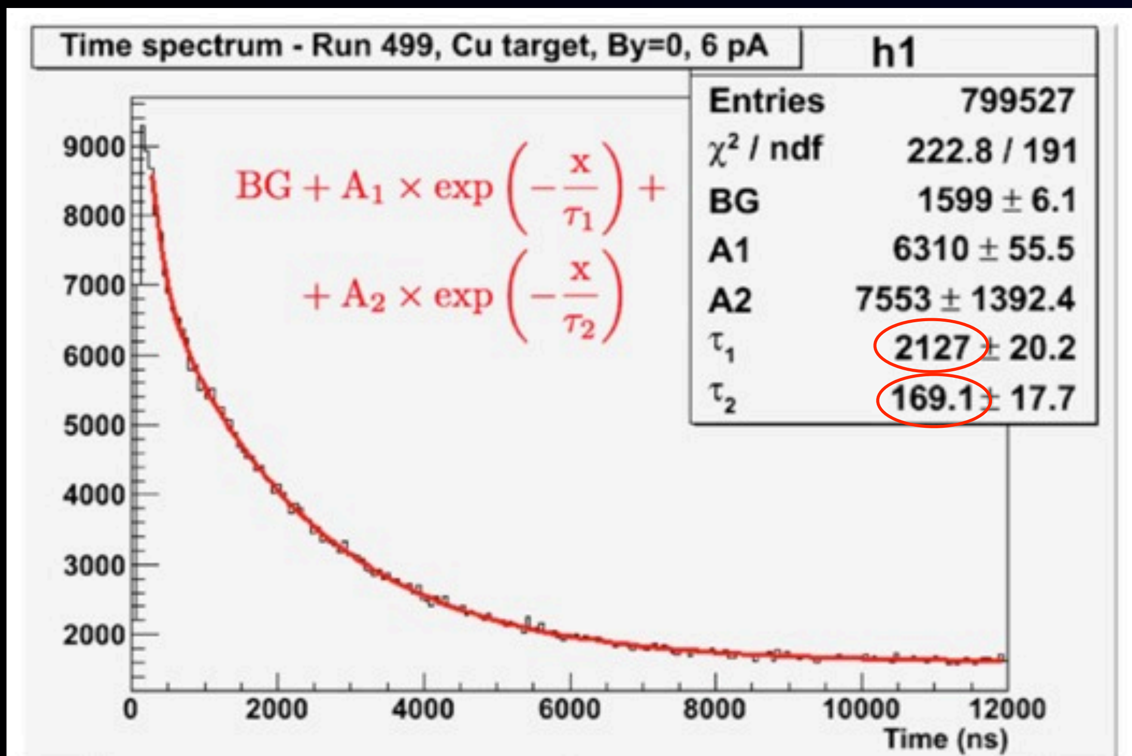
positive muons



negative muons

MuSIC Facility at Osaka University
Muon Production Efficiency (x1000)

Osaka University



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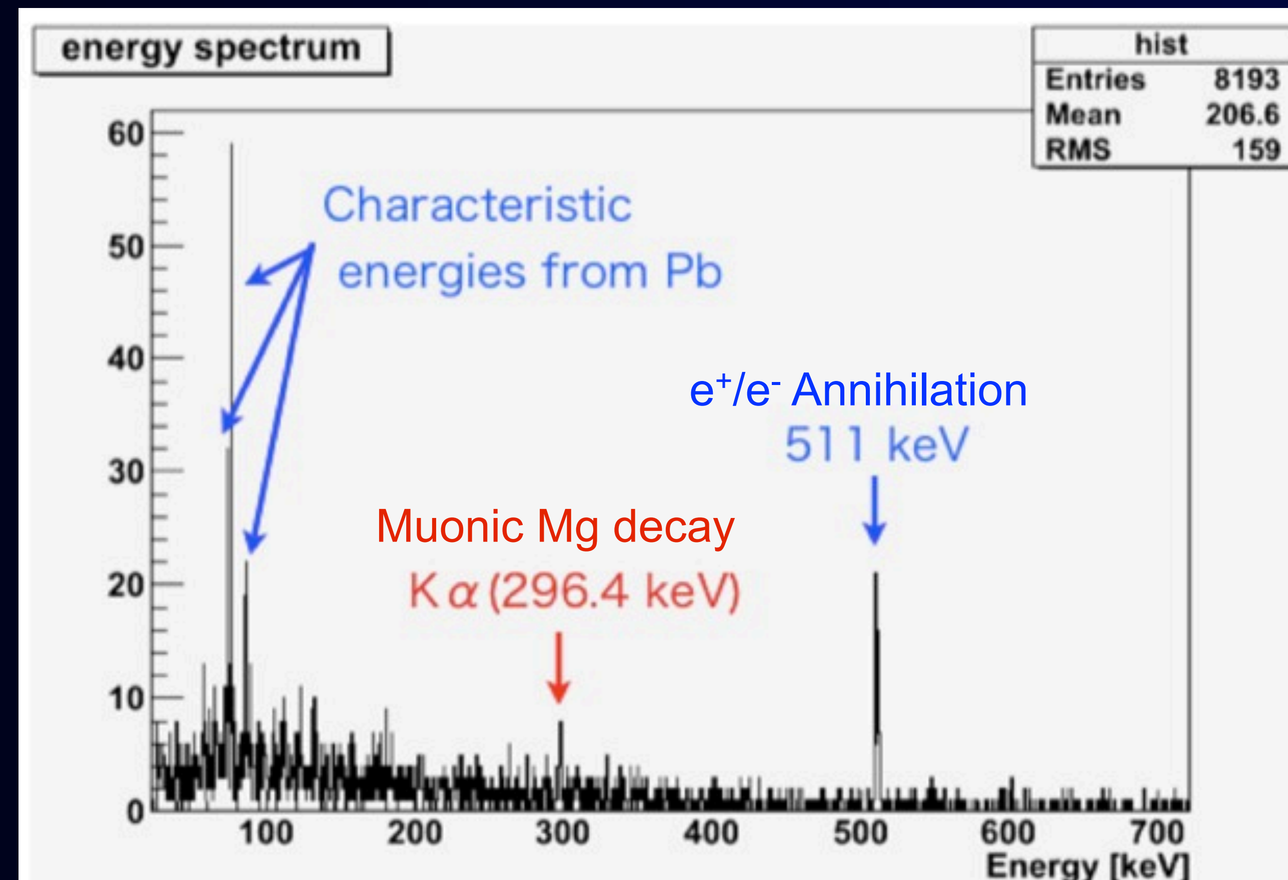

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MuSIC muon yields

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μ^- : 1×10^8/s for 400W

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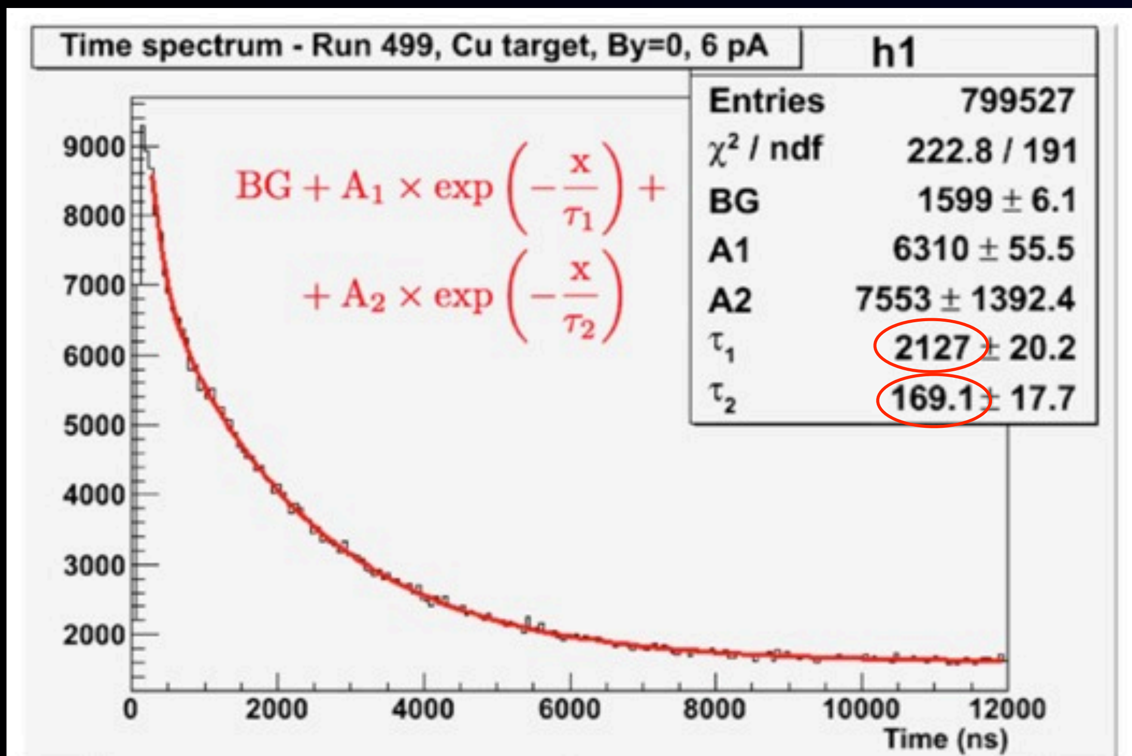

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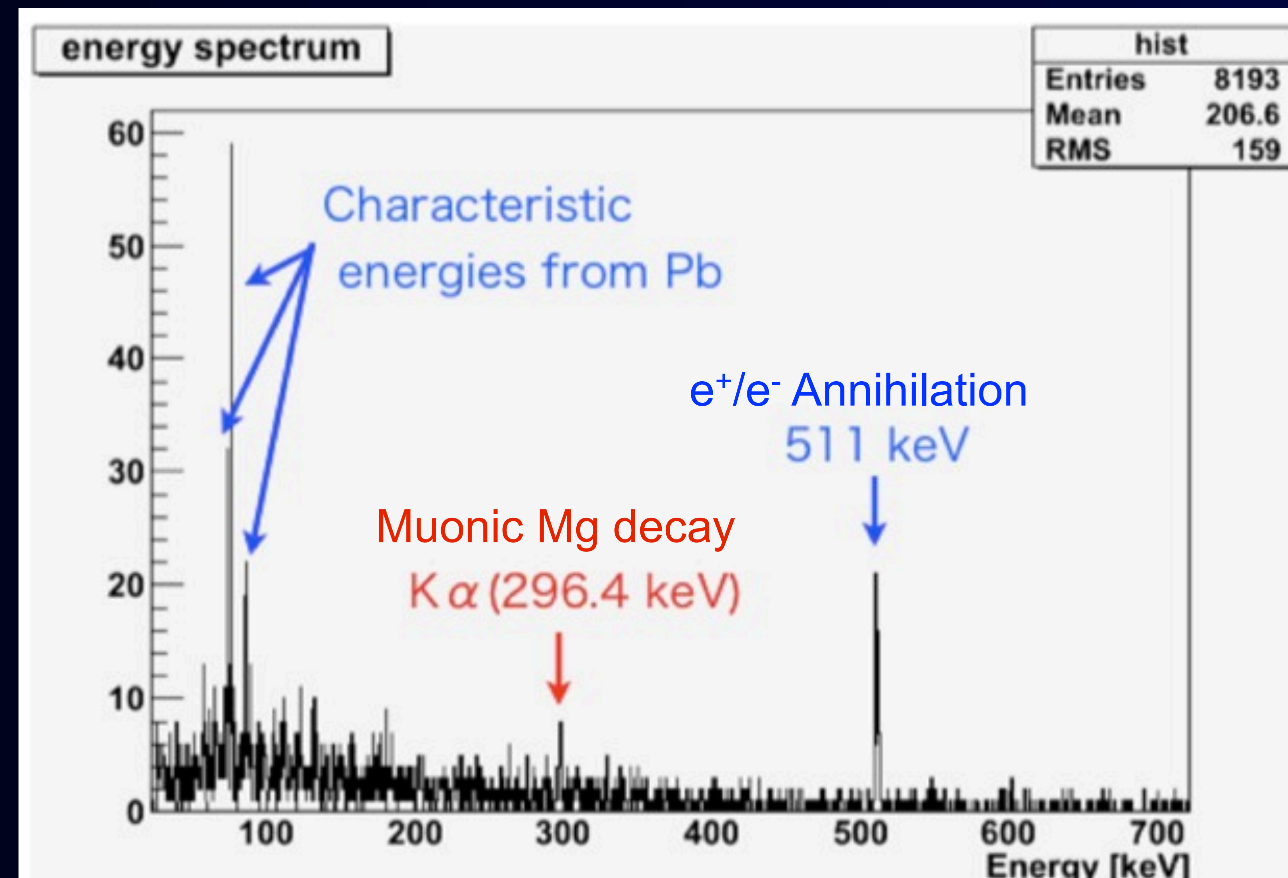

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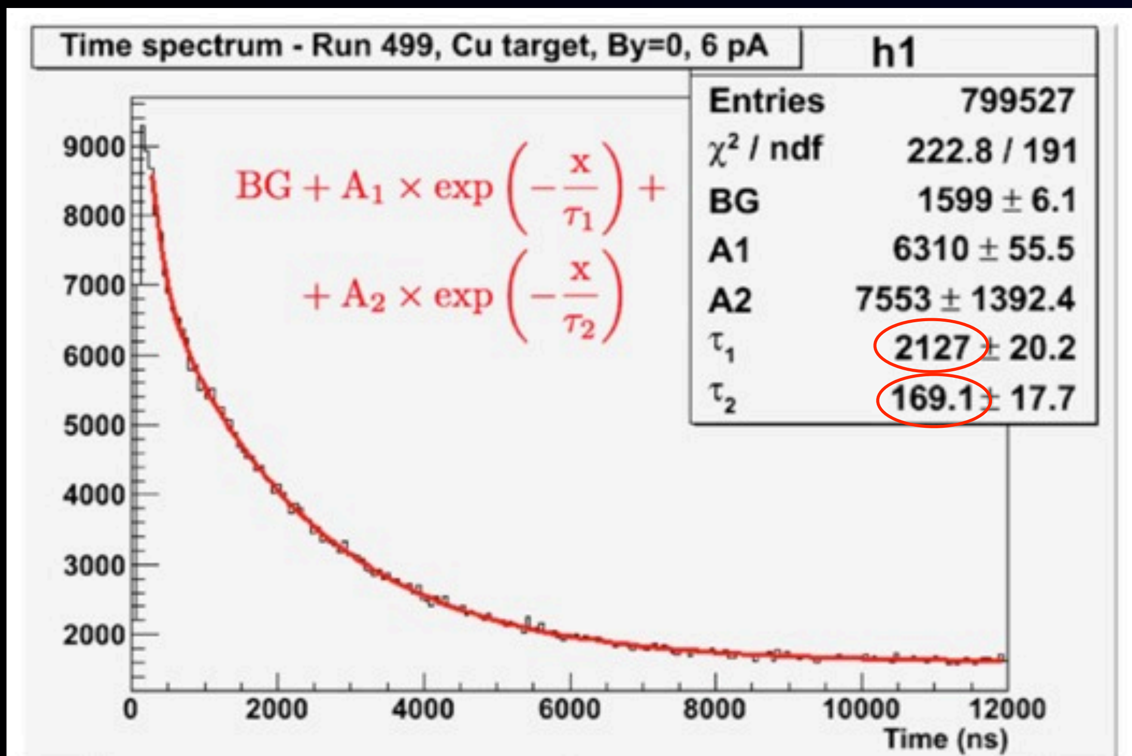

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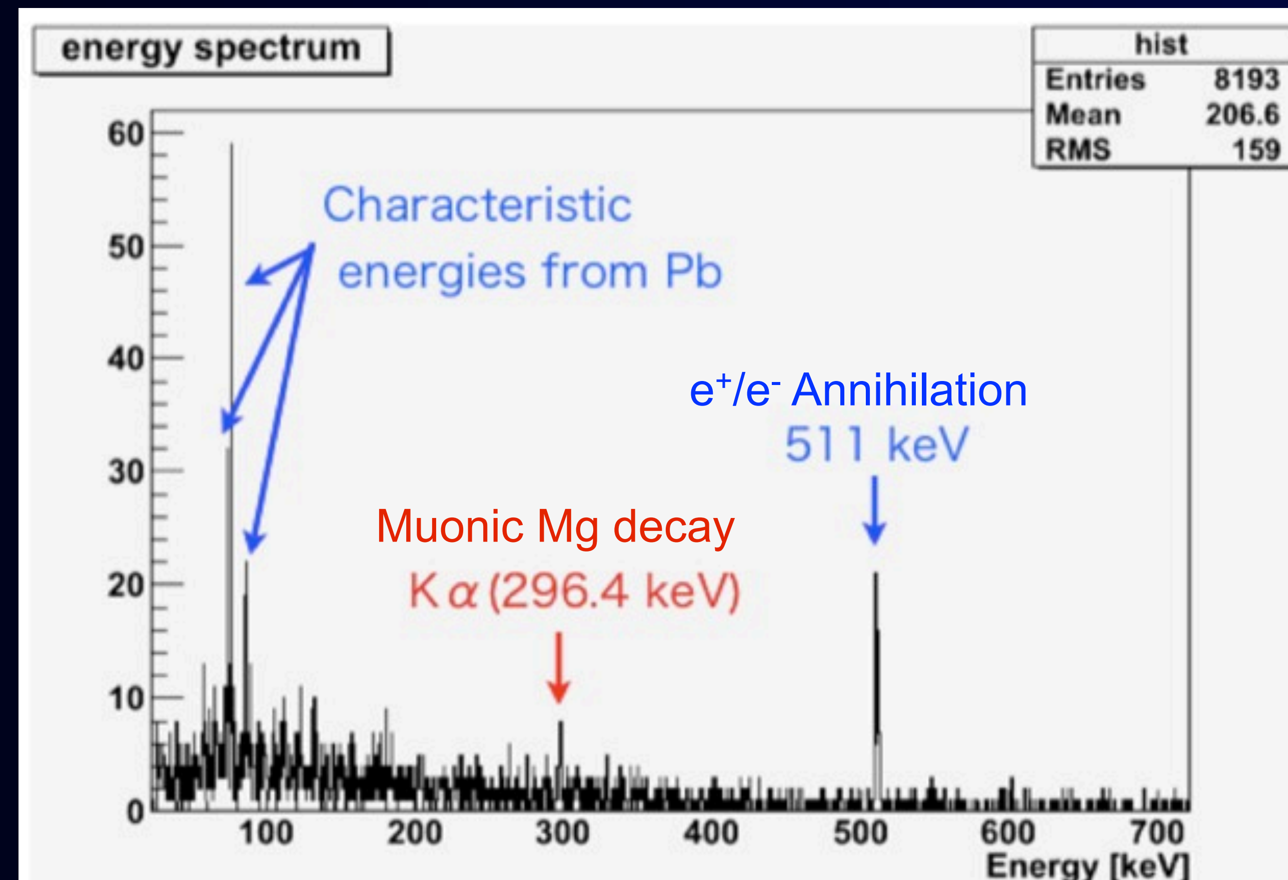

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Demonstration of Pion Capture System

High Energy Scale Reach in CLFV

Osaka University

$$R \sim \frac{1}{\Lambda^4}$$

Can we improve the Λ reach by an order of magnitude ?
We must have at least 10^4 times the number of parent particles in rare decays.

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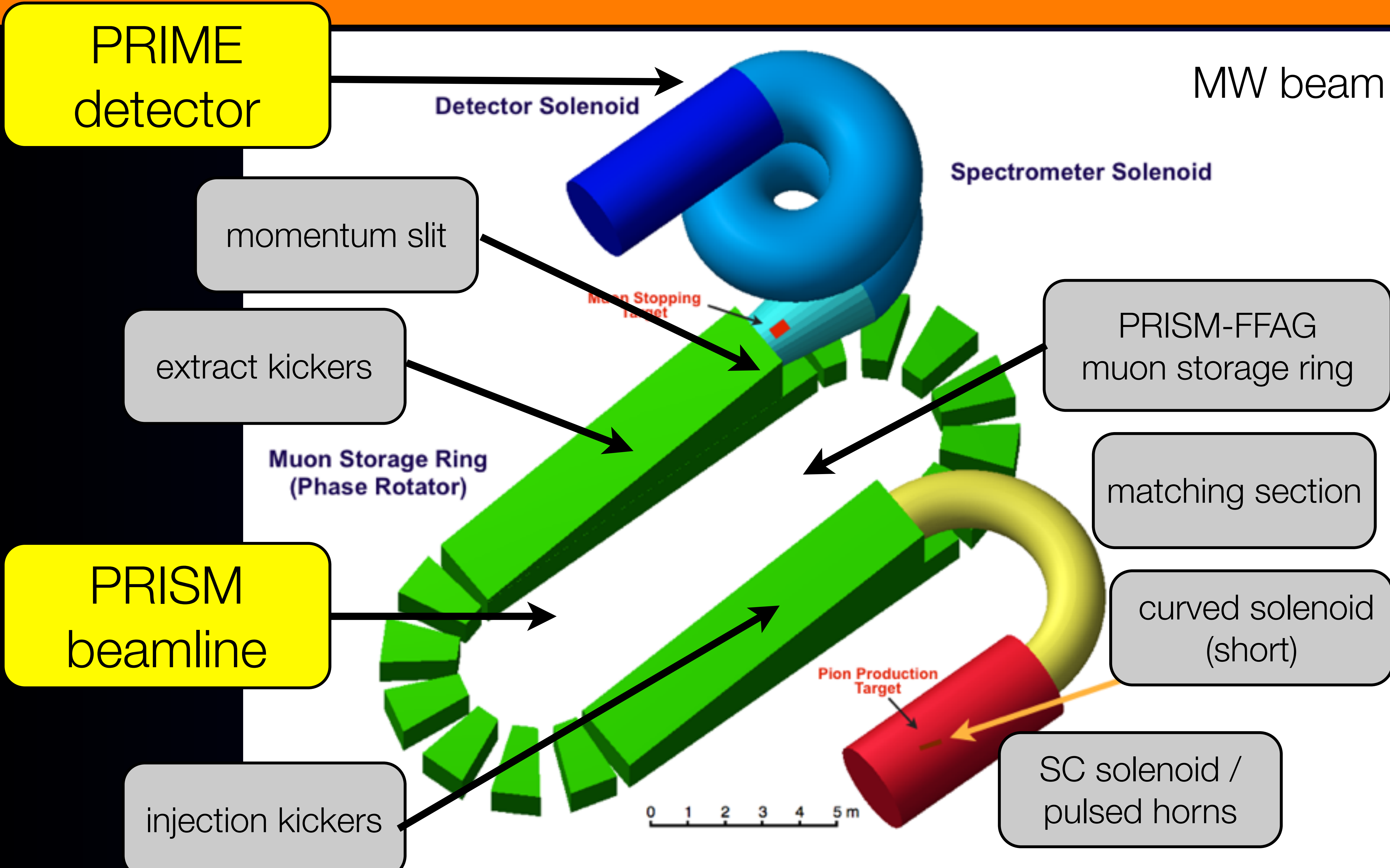
Yes, now it is possible for muons with the novel pion capture system.

PRISM/PRIME : Future Search for μ-e Conversion at $3x10^{-19}$



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Backup

Production and Collection of Pions and Muons

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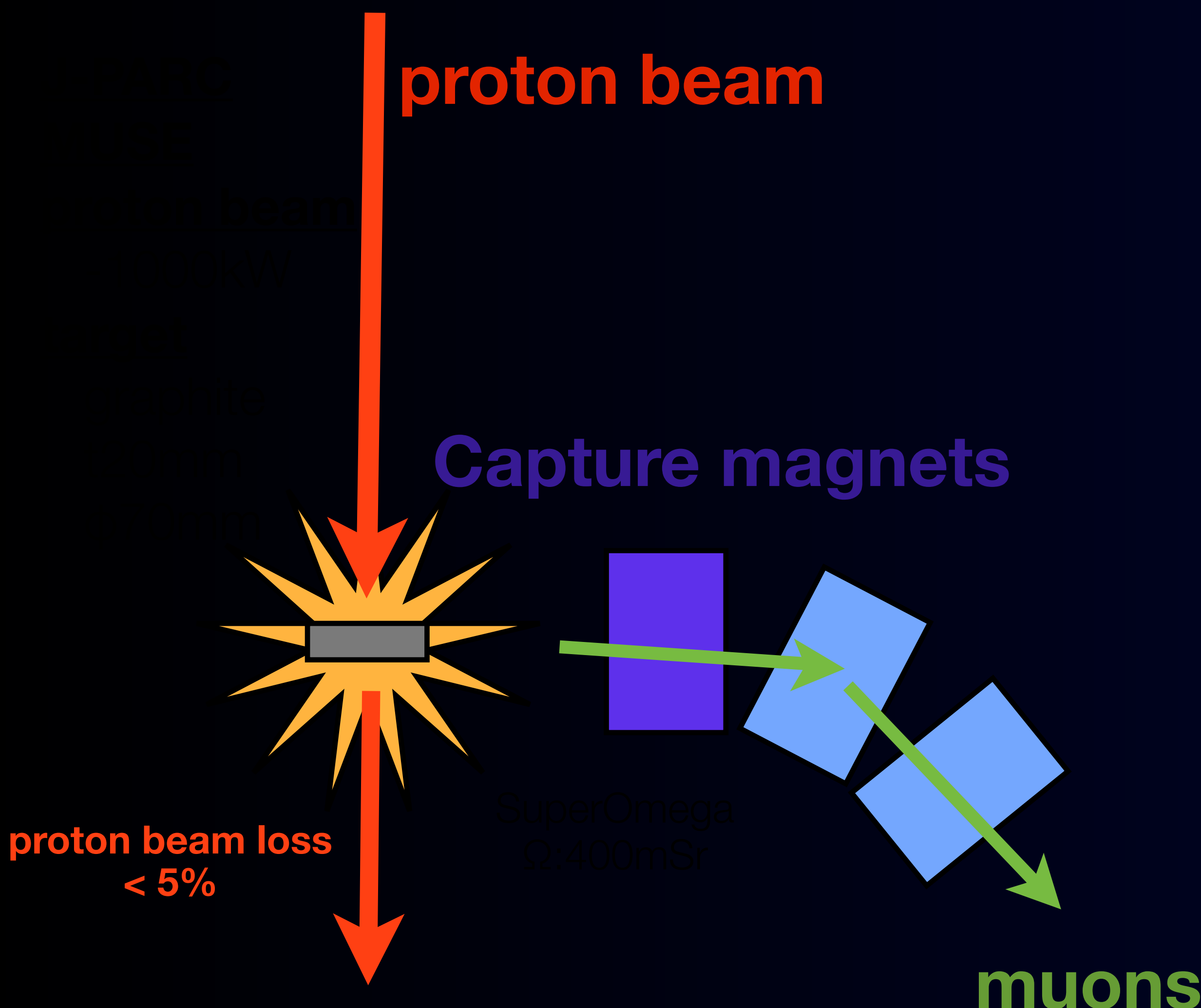
Conventional muon beam line



Production and Collection of Pions and Muons

Osaka University

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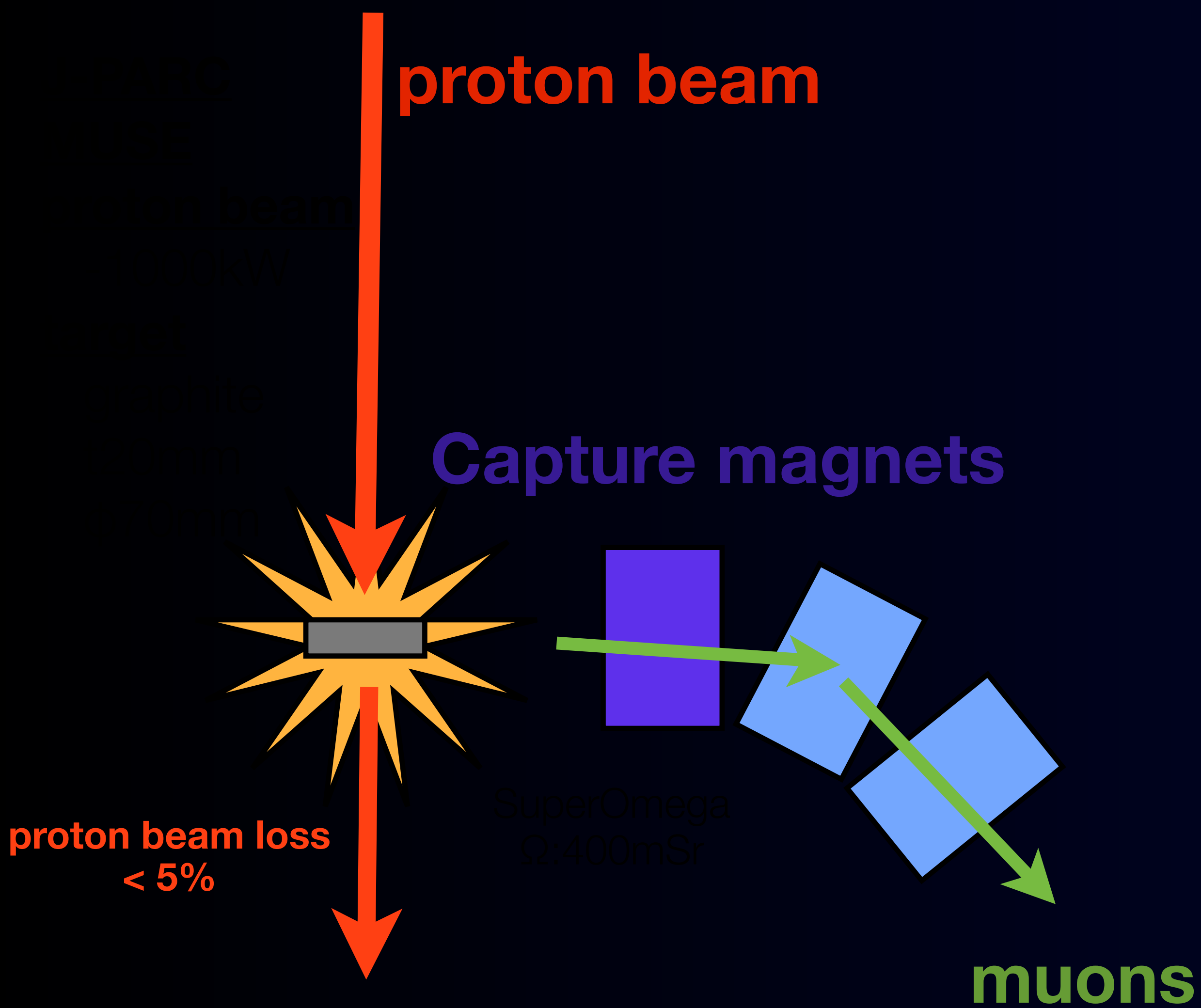
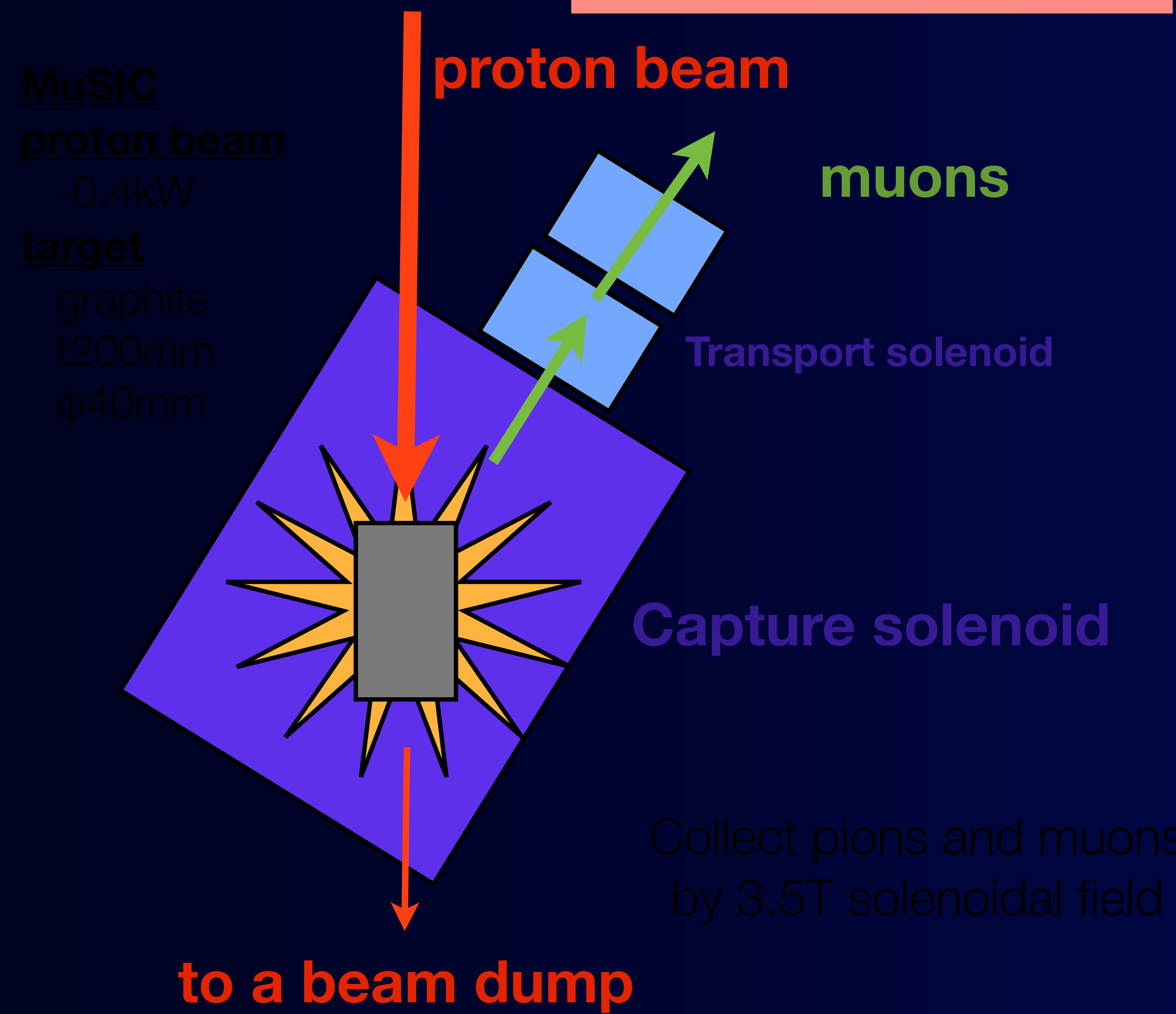


Much efficient

MuSIC,COMET,PRISM,
Neutrino factory,
Muon collider



Large solid angle & thick target