Overview of Charged Lepton Flavor Violation

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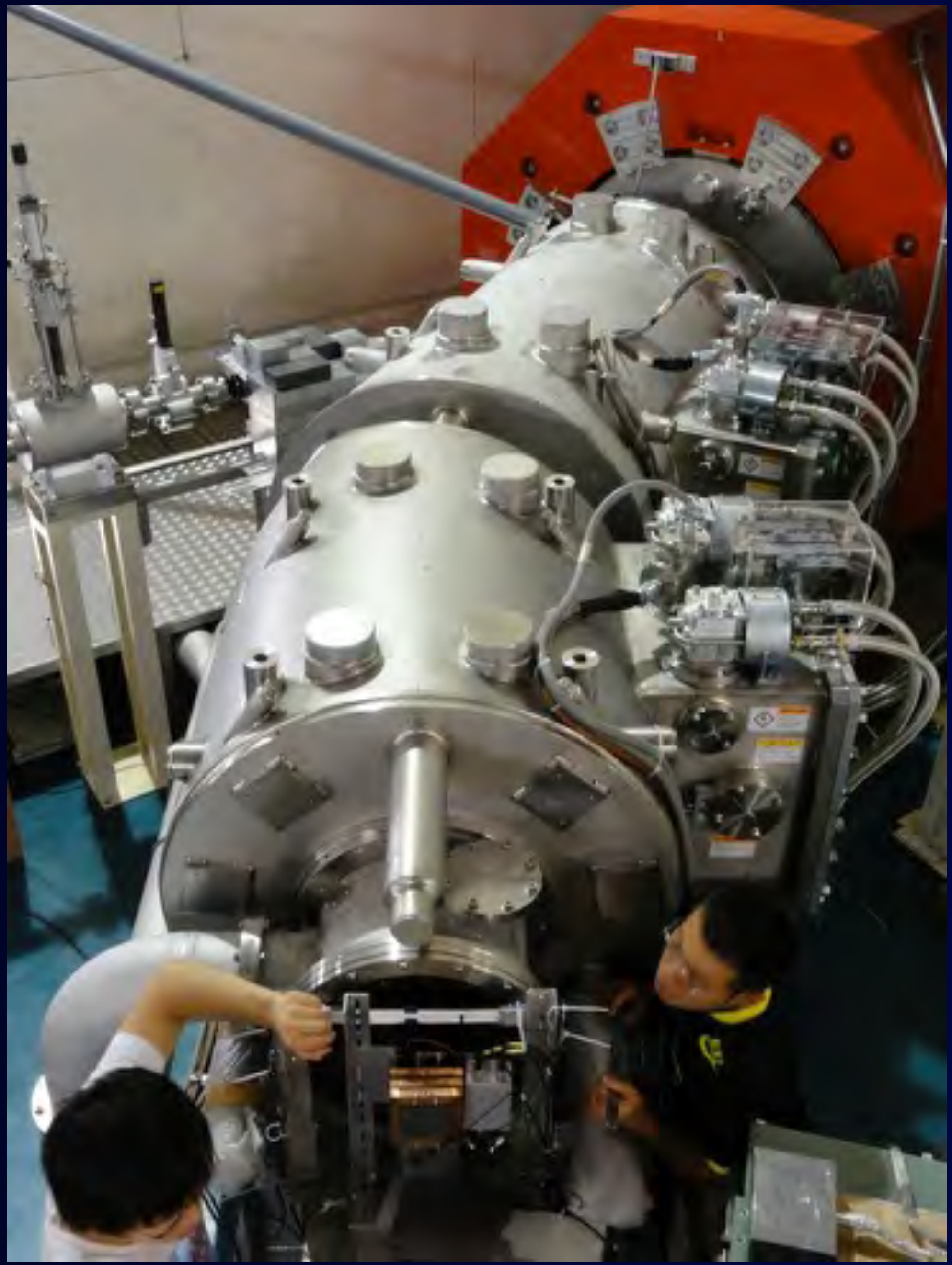
LPNHE, Paris

Outline

- Why Charged Lepton Flavor Violation (CLFV) ?
- Flavour Physics in Intensity Frontier
- New Physics in CLFV
- CLFV Experiments
  - $\mu \to e\gamma$
  - $\mu \to eee$
  - $\mu N \to eN$
- COMET
- COMET Phase-I
- Breakthrough in Muon Sources
- Summary

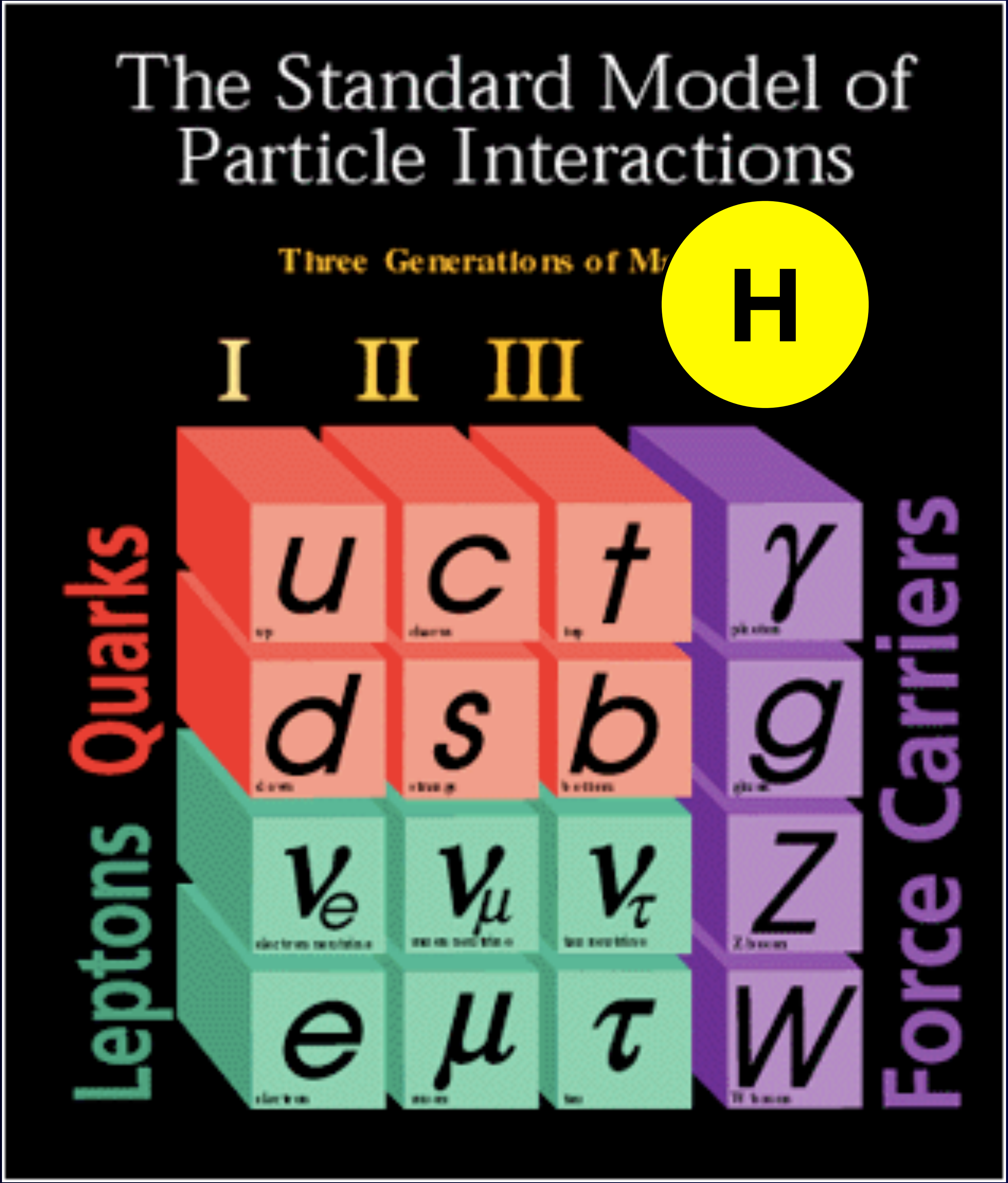


Why CLFV ?

The Standard Model with the Brout-Englert-Higgs Boson

There is a clear success of the Standard Model in reproducing all the know phenomenology.

The discovery of the Higgs boson has been made.



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Why New Physics beyond the Standard Model ?

The Standard Model is considered to be incomplete.

Experimental Evidence

- Dark Matter
- Baryogenesis
- Neutrino masses
- Origin of flavor

Theoretical Beauty

- Cosmological constant
- Hierarchy problem
- Strong CP problem
- Grand Unified Theory (GUT)

A more complete theory is need (new physics).

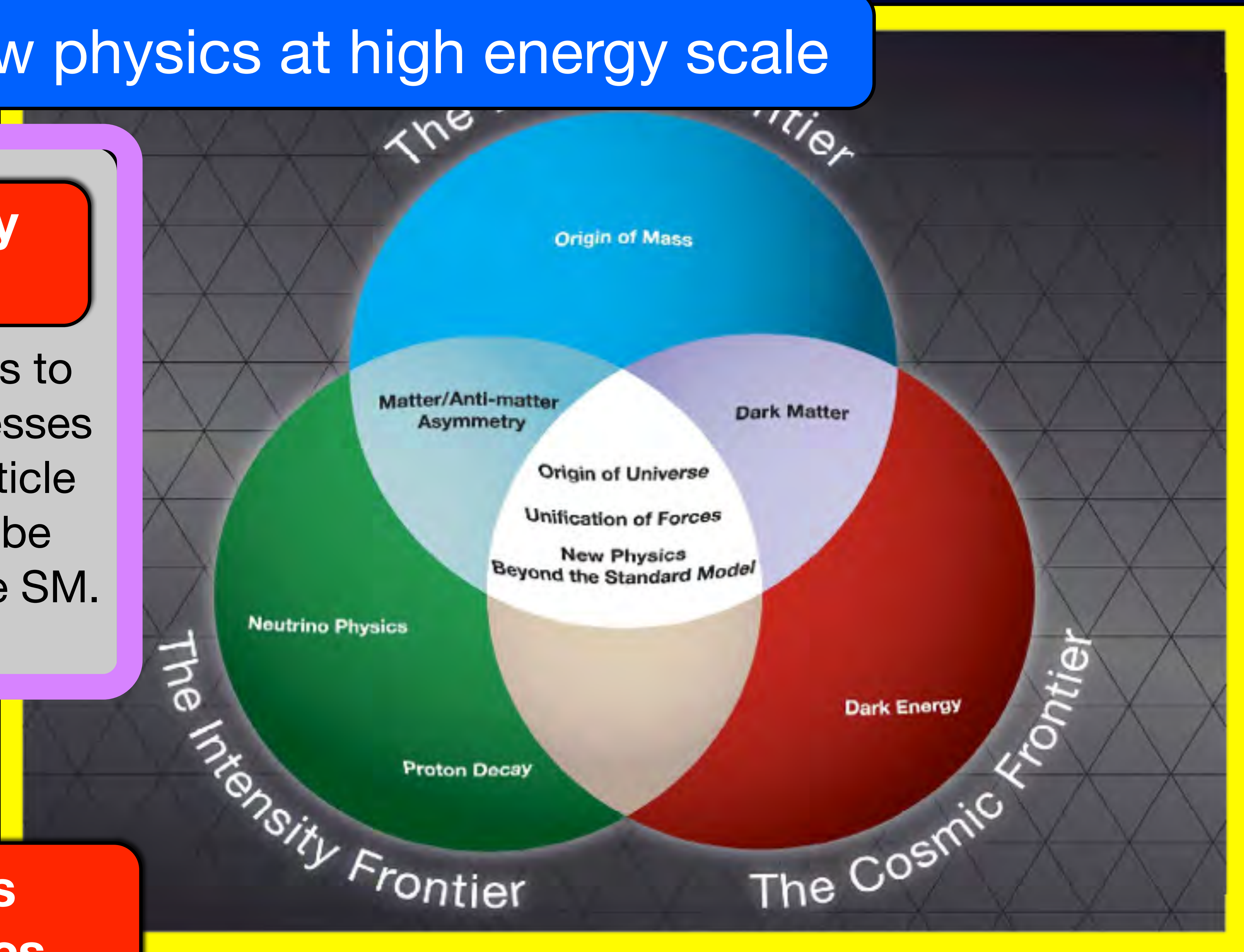
Flavour Physics in Intensity Frontier

Three Frontiers of Particle Physics to search for New Physics

To explore new physics at high energy scale

The Intensity Frontier

use intense beams to observe rare processes and study the particle properties to probe physics beyond the SM.



Rare Decays
Flavor Physics

Flavour Physics in the SM

Effective Lagrangian in the Standard Model (SM)

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm sym.break.}$$

dimension-4 operators

flavor structure

$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 + Y^{ij} \Psi_L^i \Psi_R^j \Phi + \frac{g_{ij}}{\Lambda} \Psi_L^i \Psi_L^{jT} \Phi \Phi^T ;$$

Higgs potential

Yukawa int.

fermion mass and mixing

Neutrino mass

dimension-5 Majorana neutrinos

Effective Lagrangian with New Physics

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The SM Lagrangian + new physics

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

dimension 6

Λ is the energy scale of new physics （～m_{NP}）

C_{NP} is the coupling constant.

New physics contributions are known to be small. → either
Λ is very large (new physics at high energy scale) or
C_{NP} is very small (weakly interacting).

New Physics Search in Quark Flavour

Quark Flavour

G. Isidori, Y. Nir, and G. Perez, Ann. Rev. Nucl. Part. Sci. 60 (2010) 355

[redacted]

Operator
$(\bar{s}_L \gamma^\mu d_L)^2$
$(\bar{s}_R d_L)(\bar{s}_L d_R)$
$(\bar{c}_L \gamma^\mu u_L)^2$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$
$(\bar{b}_L \gamma^\mu d_L)^2$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$
$(\bar{b}_L \gamma^\mu s_L)^2$
$(\bar{b}_R s_L)(\bar{b}_L s_R)$

New Physics Search in Quark Flavour

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dimension 6 operator

$\Lambda > O(10^3)$ TeV

Operator	Limits on Λ (TeV) ($C_{\rm NP}=1$) Re	Limits on Λ (TeV) ($C_{\rm NP}=1$) Im	Limits on $C_{\rm NP}$ ($\Lambda = 1$ TeV) Re	Limits on $C_{\rm NP}$ ($\Lambda = 1$ TeV) Im	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ε_K
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ε_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \Phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \Phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	Δm_{B_d}; $S_{\phi K_S}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	Δm_{B_d}; $S_{\phi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	Δm_{B_s}; $S_{\psi\phi}$
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	Δm_{B_s}; $S_{\psi\phi}$

New Physics Search in Charged Lepton Sector

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Charged Lepton Flavour

Charged lepton flavour violation (CLFV), $\mu \to e\gamma$ ($B<5.7\times10^{-13}$),

dimension 6 operator

$$\frac{C_{\rm NP}}{\Lambda^2} O^{(6)}_{ij} \to \frac{C_{\mu e}}{\Lambda^2} \bar{e}_L \sigma^{\rho\nu} \mu_R \Phi F_{\rho\nu}$$

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

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

The constraint in CLFV is even more severe than in the quark flavor.
The SM contribution to muon CLFV is small, of the order of $O(10^{-54})$.

Guideline for Rare Decay Searches

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SM contribution is dominant.

SM

Standard Model

New Physics

NP

SM contribution is highly suppressed.

SM + NP

Uncertainty of the SM prediction limits the sensitivity.

SM contribution has to be subtracted.

SM contribution is forbidden.

+ NP

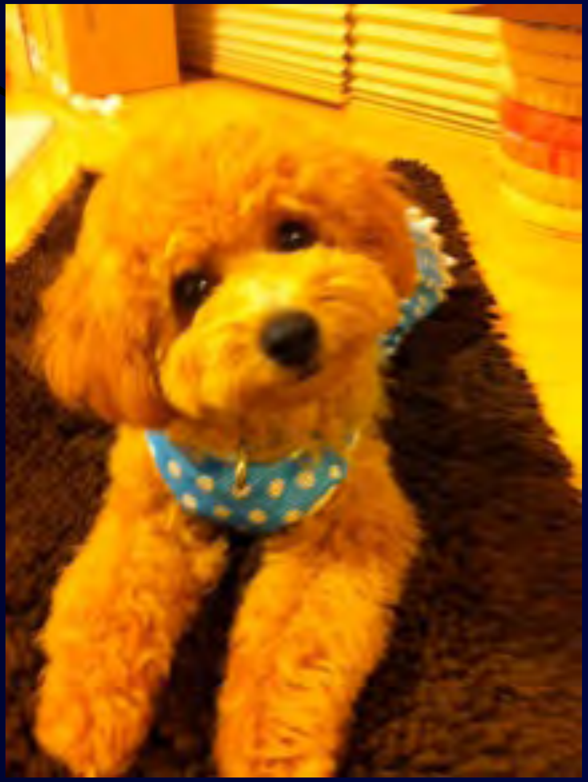
Clear signature without any subtractions

No SM contribution be subtracted.

Flavor Changing Neutral Current (FCNC) is

a process that is highly suppressed or forbidden in the SM.

my puppy, IKU, says



Flavor Changing Neutral Current (FCNC)

is process that is highly suppressed or forbidden in the SM.

FCNC in Lepton Sector

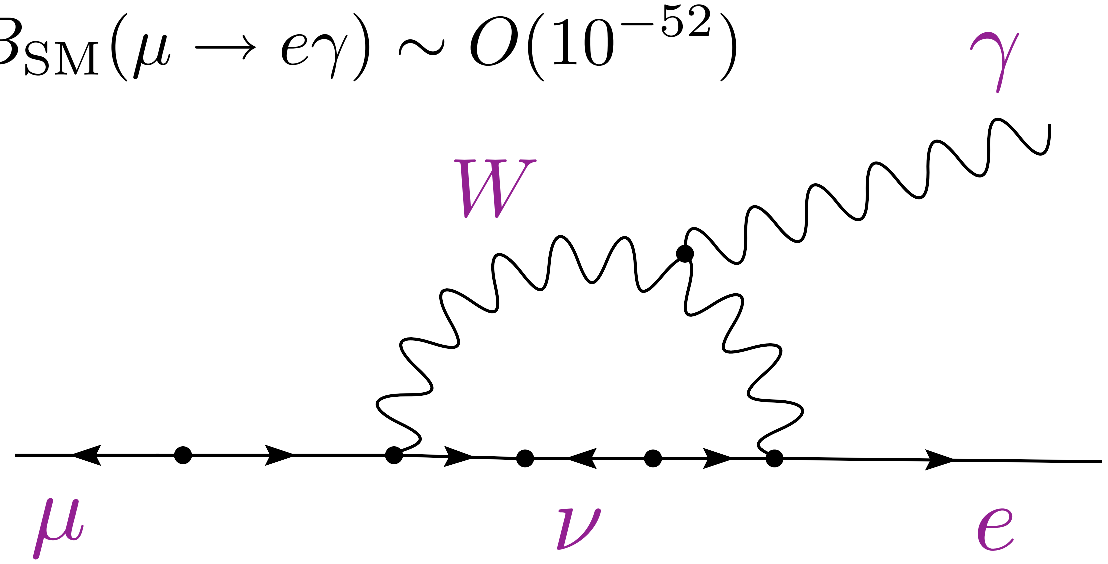
$$\mu \to e\gamma$$

$$\mu^- N \to e^- N$$

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

charged lepton flavor violation (CLFV)

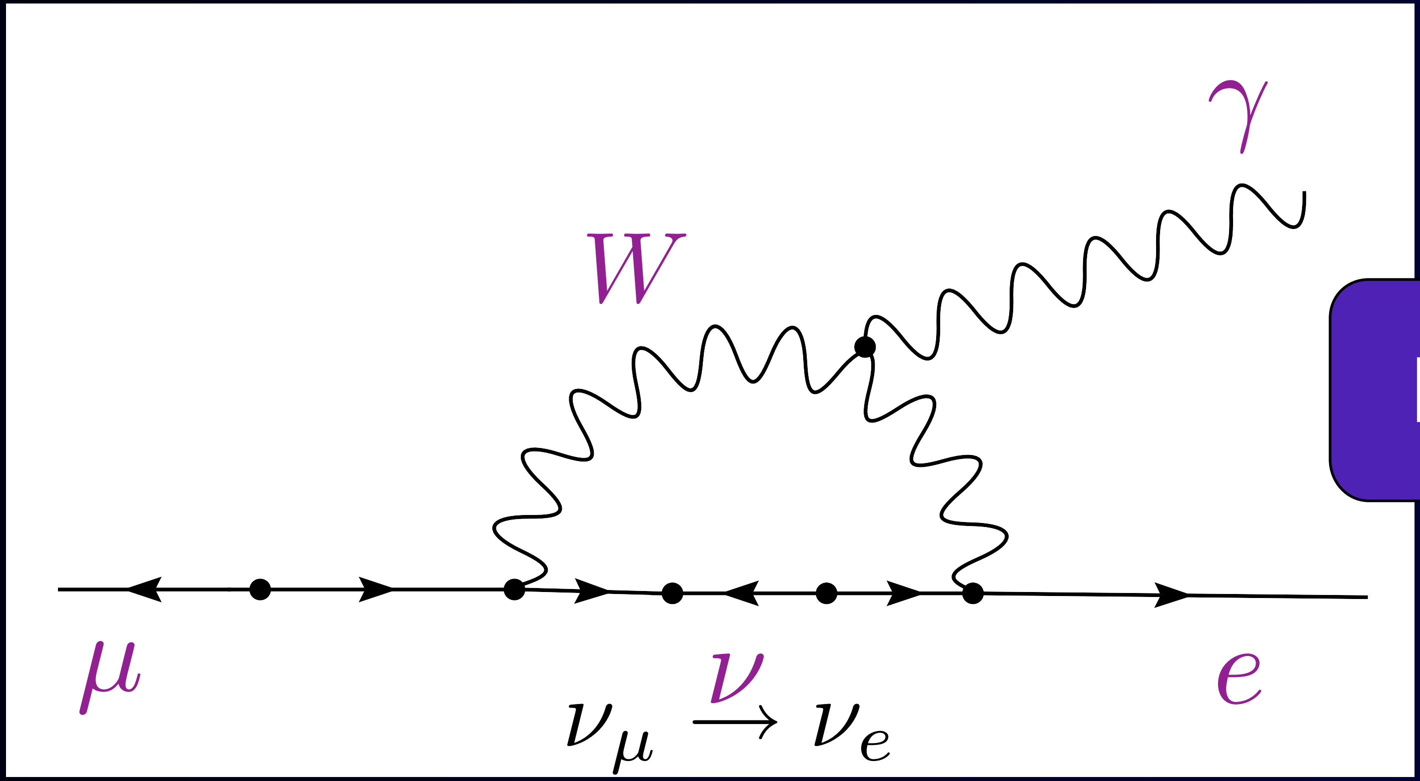
$B_{\rm SM}(\mu \to e\gamma) \sim O(10^{-52})$



The SM contributions are forbidden for cLFV.

Example : No SM Contribution in CLFV

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



BR~O(10^{-54})

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

Quark FCNC vs. Lepton FCNC (CLFV)

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

Quark (suppressed)

amplitude

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

subject to uncertainty of SM prediction

NP contribution ~ O(ε)

Lepton (forbidden)

rate

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

no limitation from uncertainty of SM prediction (can go to higher energy scale)

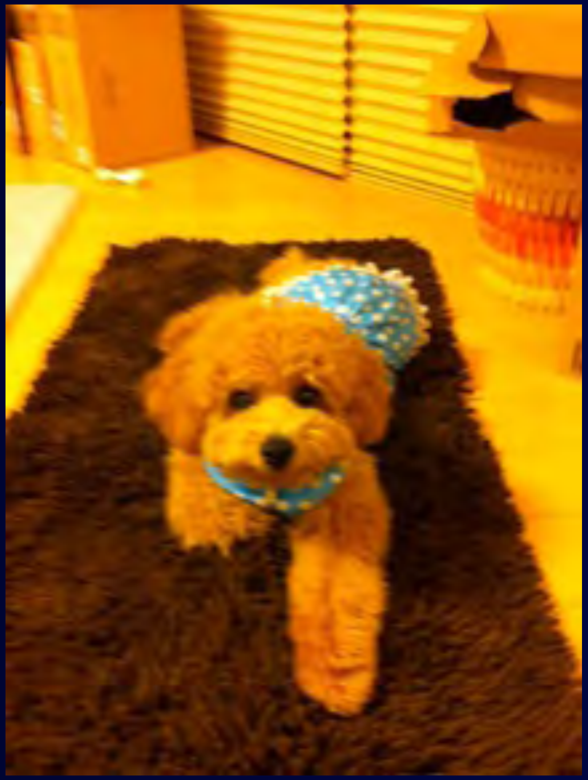
NP contribution ~ O(ε^2)

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

Why Muons ?

More is better in rare decay searches. Light particles like muons can be produced more. In particular, now we have new technology to create more muons (see later).

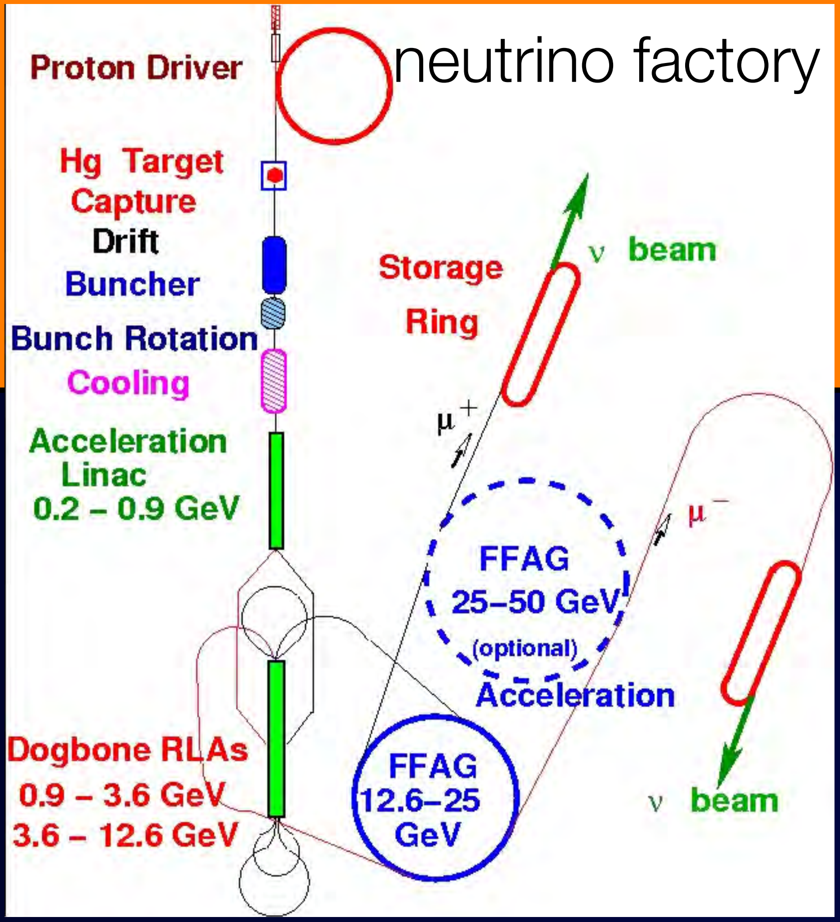
my puppy, IKU, says

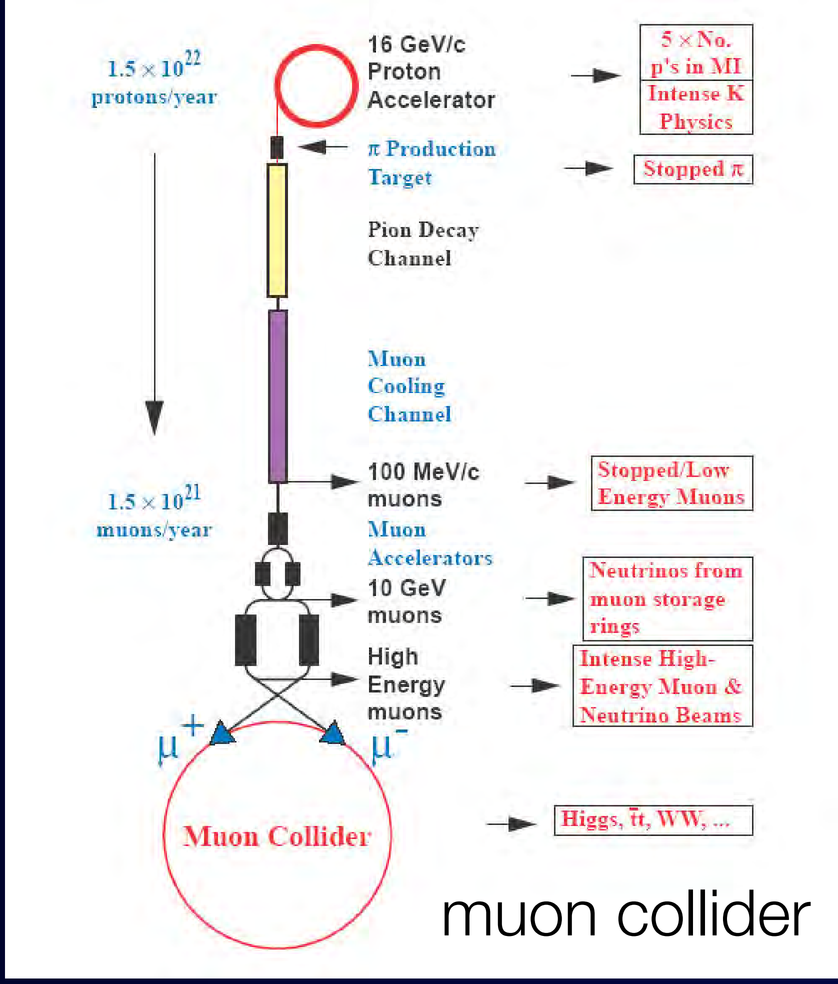


Why Muons, not Taus?

- A number of taus available at B factories are about 10 taus/sec. At super-KEKB factories, about 400 taus/sec are considered. Also some of the decay modes are already background-limited.
- A number of muons available now, which is about 10^8 muons/sec at PSI, is the largest. Next generation experiments aim 10^{11}-10^{12} muons/sec. With the technology of the front end of muon colliders and/or neutrino factories, about 10^{13}-10^{14} muons/sec are considered.

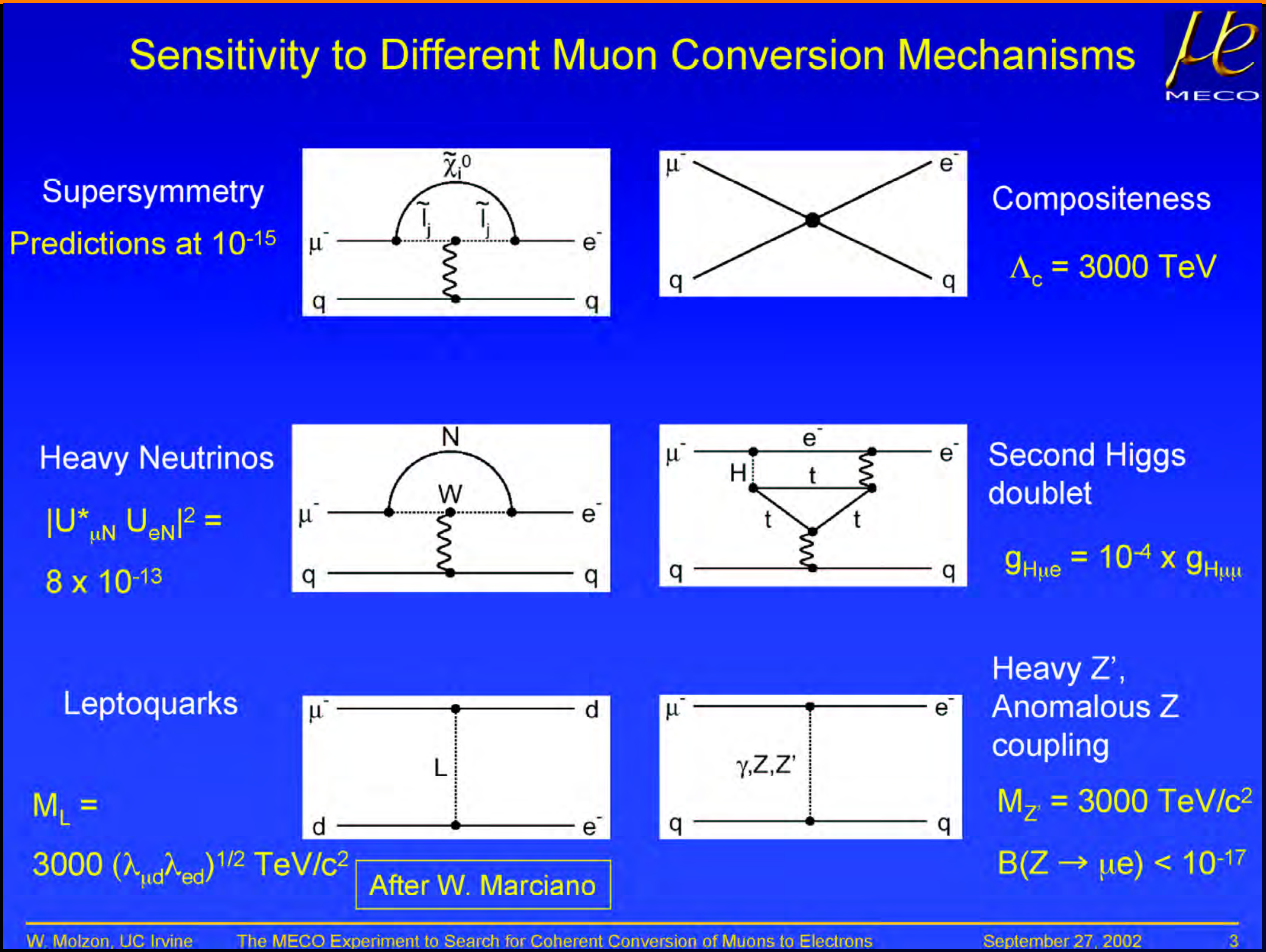
a larger window to search for new physics for muons than taus





New Physics in CLFV

Various Models Predict CLFV

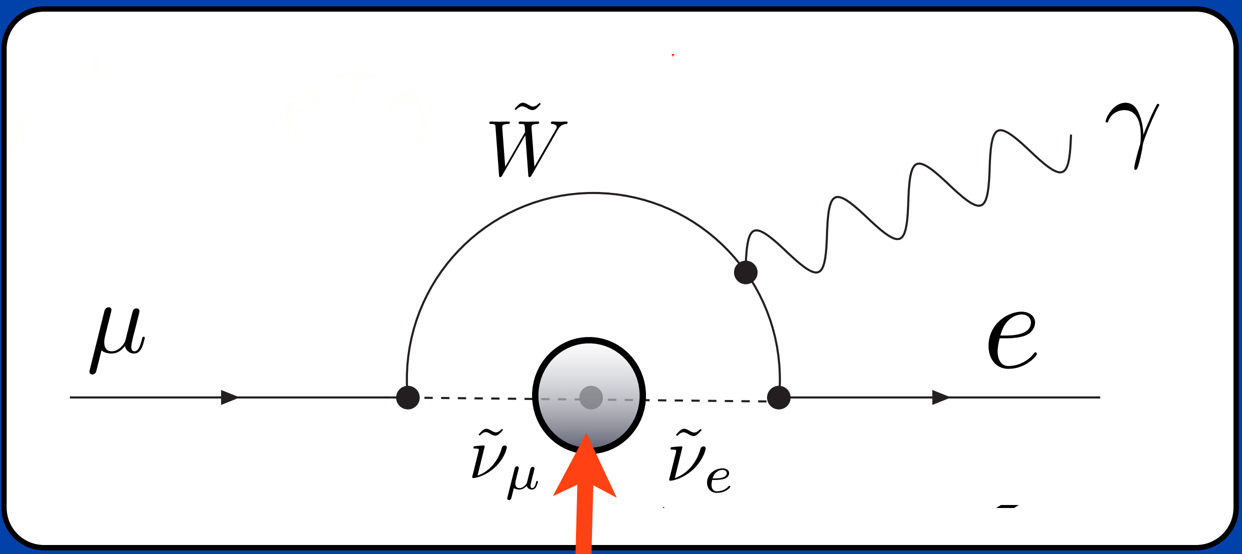


Example of Sensitivity to NP in High Energy Scale : SUSY models

- 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



example diagram for SUSY (~TeV)

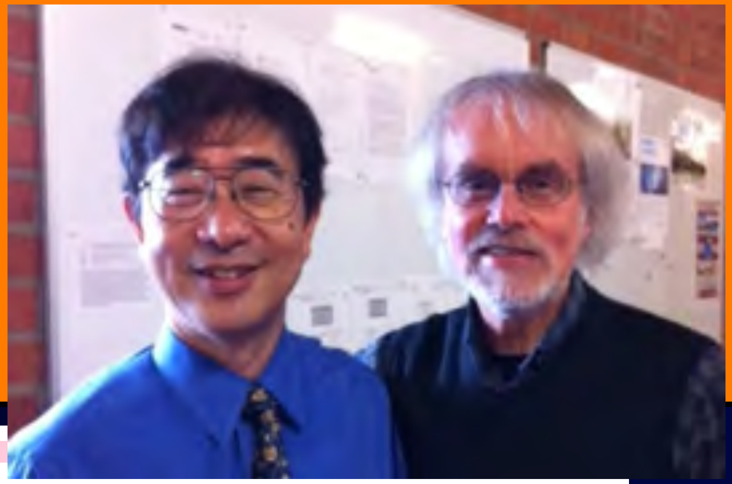
Physics at about 10^{16} GeV

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

$$(m^2_{\tilde{L}})_{21} \sim \frac{3m_0^2 + A_0^2}{8\pi^2} h_\tau^2 U_{31} U_{32} \ln \frac{M_{GUT}}{M_R}$$ SUSY neutrino seesaw 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,
of a particular model

GLOSSARY	
AC [10]	RH currents & U(1) flavor symmetry
RVV2 [11]	SU(3)-flavored MSSM
AKM [12]	RH currents & SU(3) family symmetry
δLL [13]	CKM-like currents
FBMSSM [14]	Flavor-blind MSSSM
LHT [15]	Little Higgs with T Parity
RS [16]	Warped Extra Dimensions

P5 at the US

Table 1
Summary of Scenarios

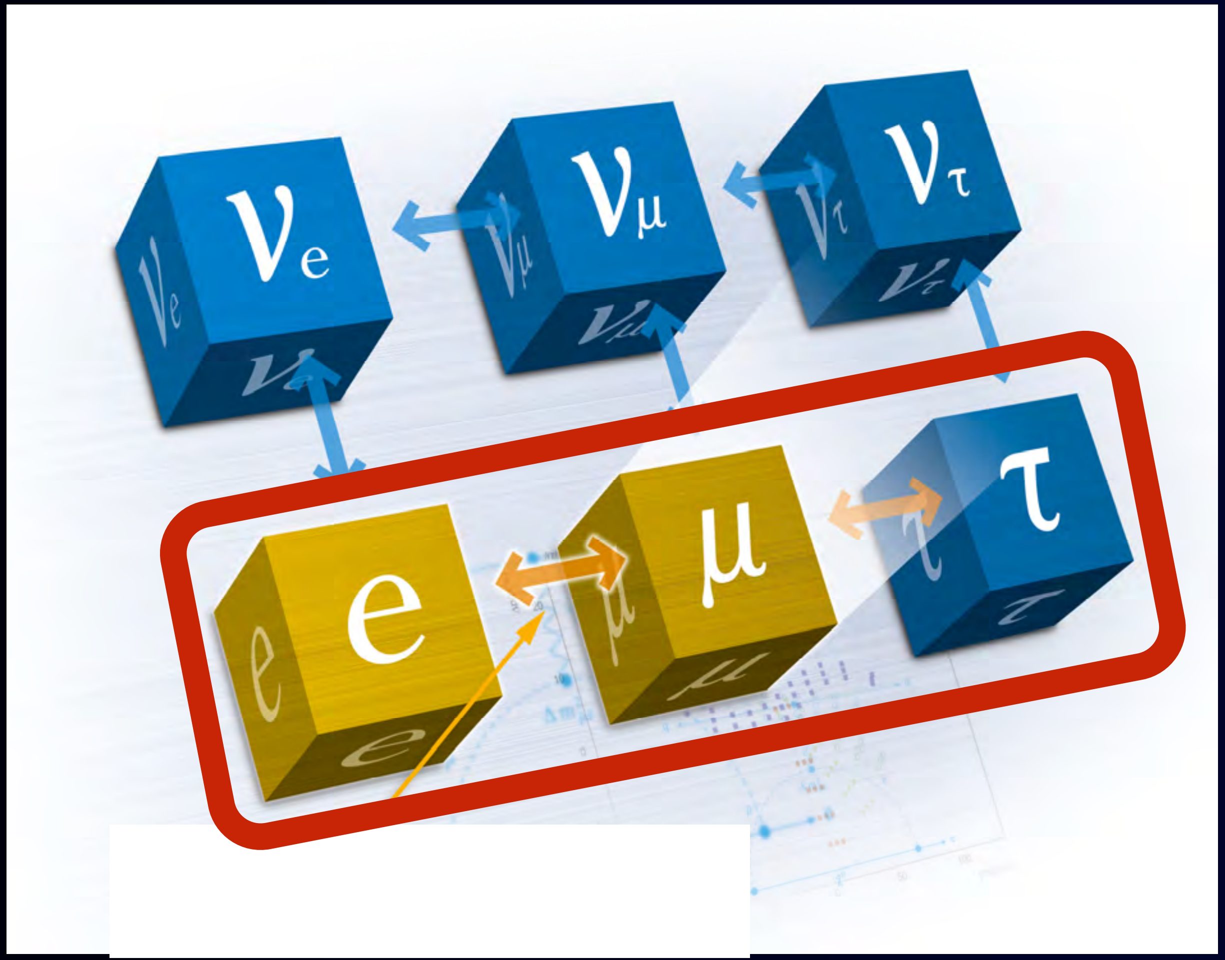
Project/Activity	Scenarios: Scenario A	Scenario B	Senario C	Science Drivers: Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown	Technique (Frontier)
Large Projects									
Muon program: Mu2e, Muon g-2	Y, Mu2e small reprofile needed	Y	Y					✓	I
HL-LHC	Y	Y	Y	✓		✓		✓	E
LBNF + PIP-II	Y, LBNF components delayed relative to Scenario B.	Y	Y, enhanced		✓			✓	I,C
ILC	R&D only	R&D, possibly small hardware contri-butions. See text.	Y	✓		✓		✓	E
NuSTORM	N	N	N		✓				I
RADAR	N	N	N		✓				I

Quarks, Neutrinos, and Charged Leptons

Quarks

quark transition observed

Leptons



neutrino transition observed

charged lepton transition not observed.

CLFV Experiments with Muons

CLFV History

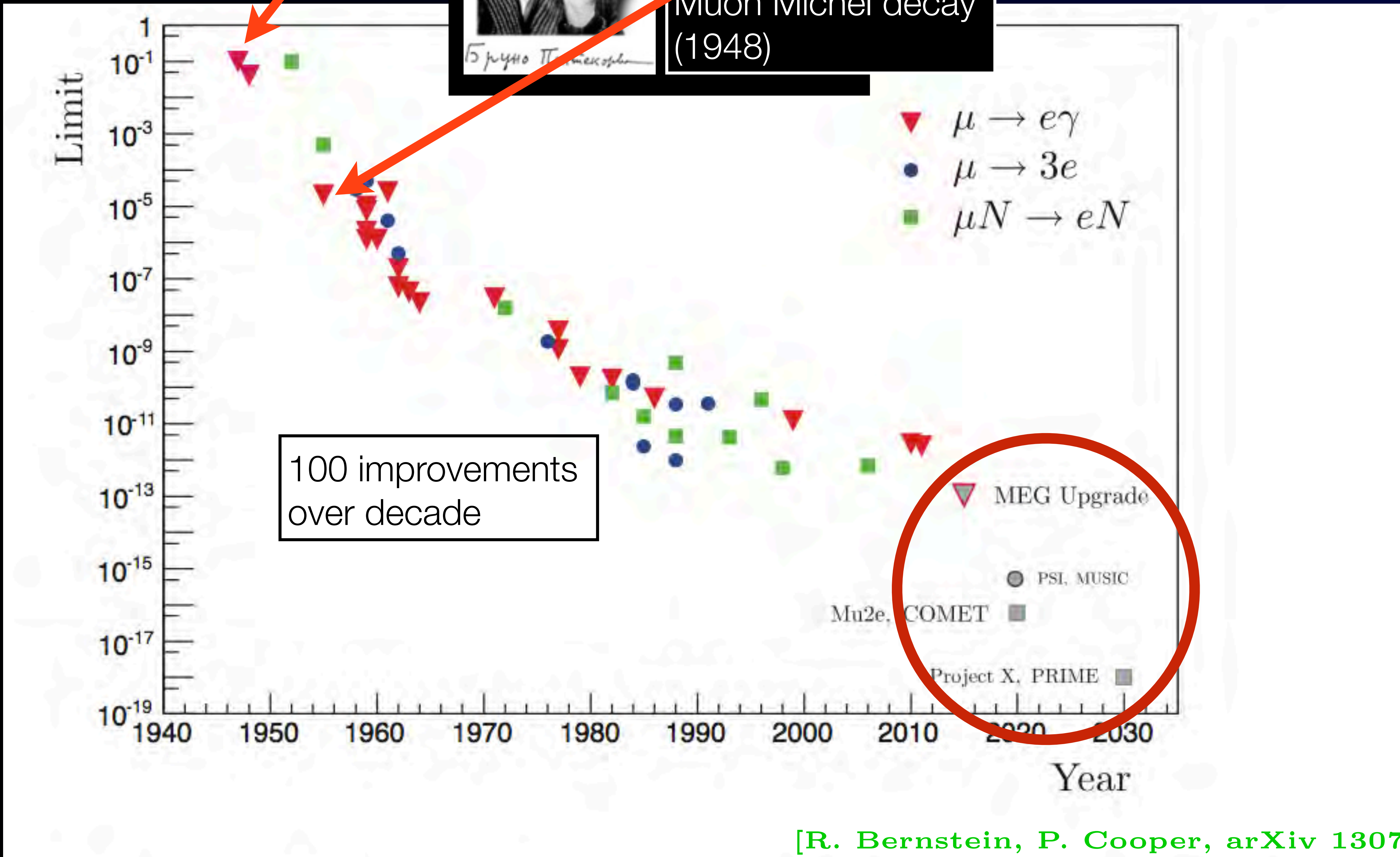
First CLFV search

Pontecorvo in 1947

Muon Michel decay (1948)

Accelerators producing muons

Feinberg's μ→eγ crisis (1955)



100 improvements over decade

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

Present Limits and Future Expectations

process	present limit	future	
$\mu \rightarrow e\gamma$	$<5.7 \times 10^{-13}$	$<10^{-14}$	MEG
$\mu \rightarrow eee$	$<1.0 \times 10^{-12}$	$<10^{-16}$	Mu3e
$\mu N \rightarrow eN$ (in Al)	none	$<10^{-16}$	Mu2e / COMET
$\mu N \rightarrow eN$ (in Ti)	$<4.3 \times 10^{-12}$	$<10^{-18}$	PRISM-PRIME
$\tau \rightarrow e\gamma$	$<3.3 \times 10^{-8}$	$<10^{-9} - 10^{-10}$	super KEKB
$\tau \rightarrow eee$	$<3.4 \times 10^{-8}$	$<10^{-9} - 10^{-10}$	super KEKB
$\tau \rightarrow \mu\gamma$	$<4.4 \times 10^{-8}$	$<10^{-9} - 10^{-10}$	super KEKB
$\tau \rightarrow \mu\mu\mu$	$<2.1 \times 10^{-8}$	$<10^{-9} - 10^{-10}$	super KEKB/LHCb

List of cLFV Processes with Muons

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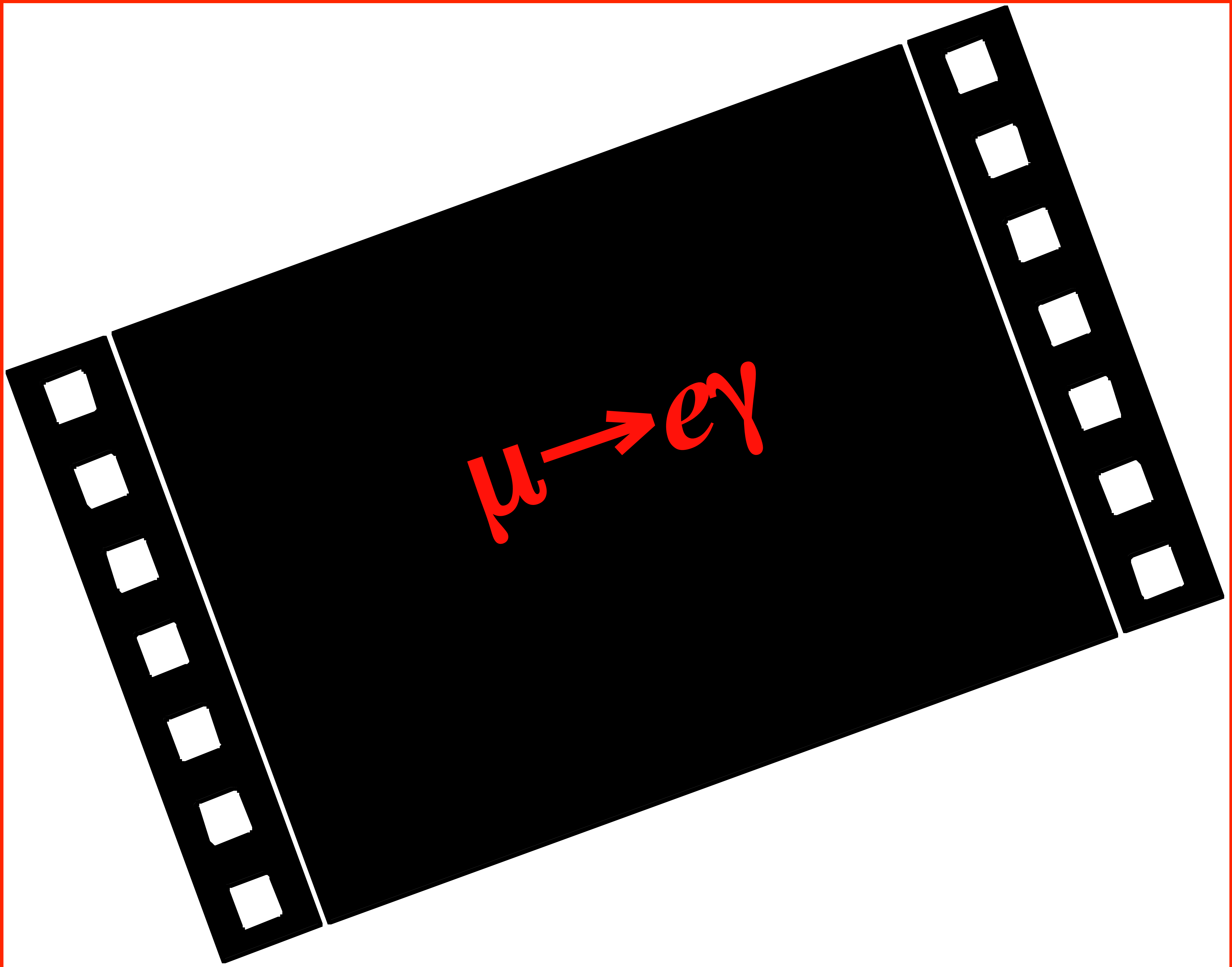
ΔL=1

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

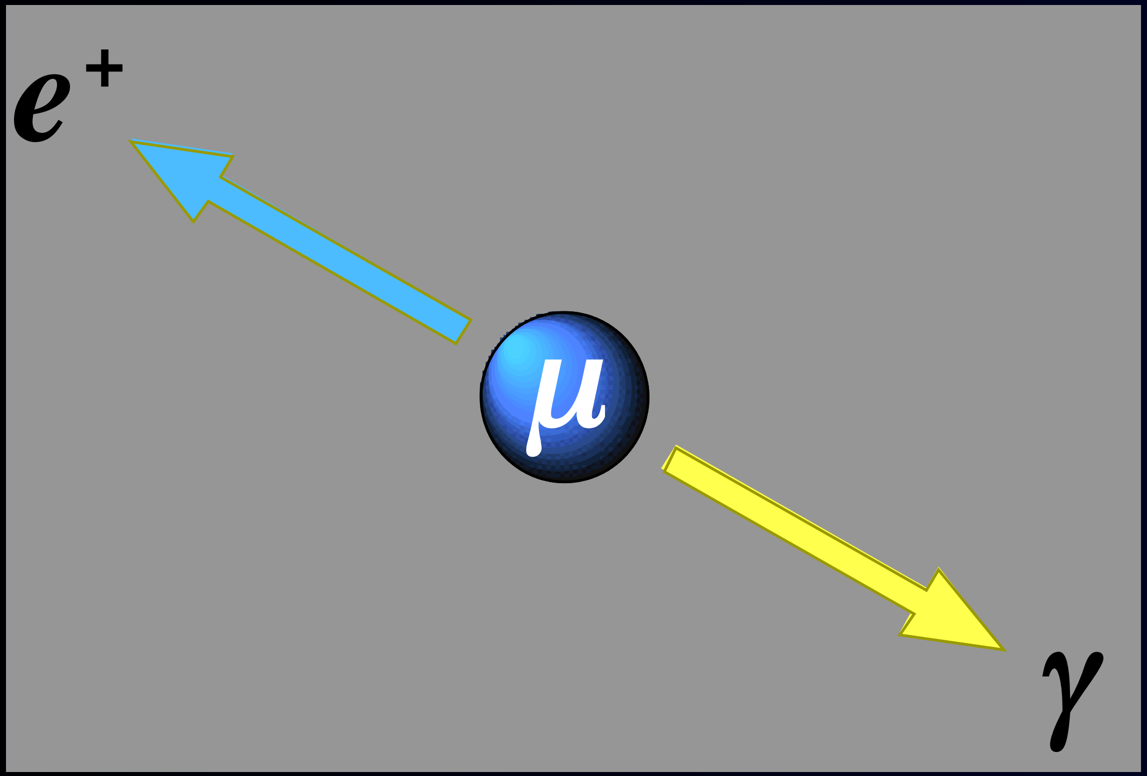
ΔL=2

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

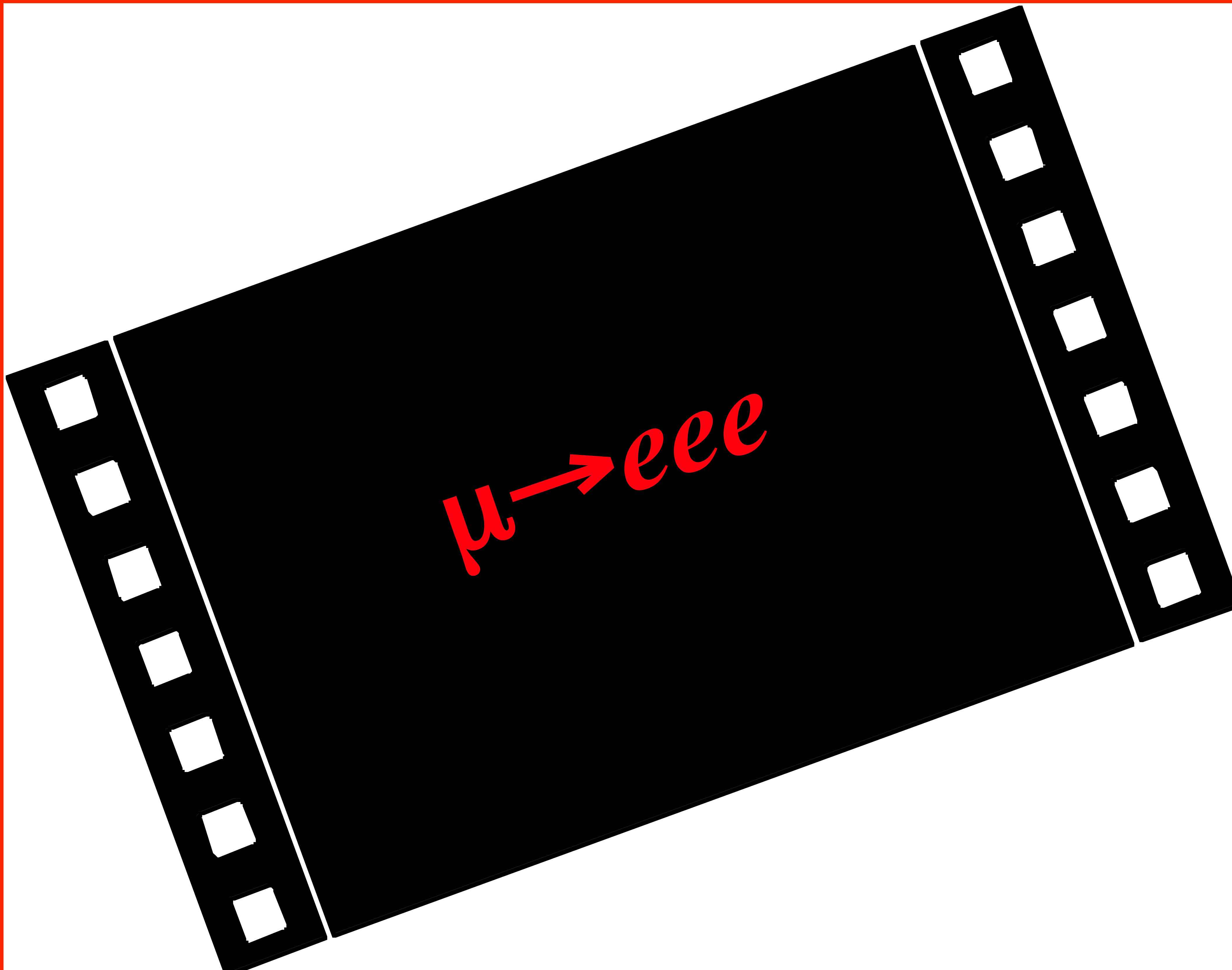

μ→eγ

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

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

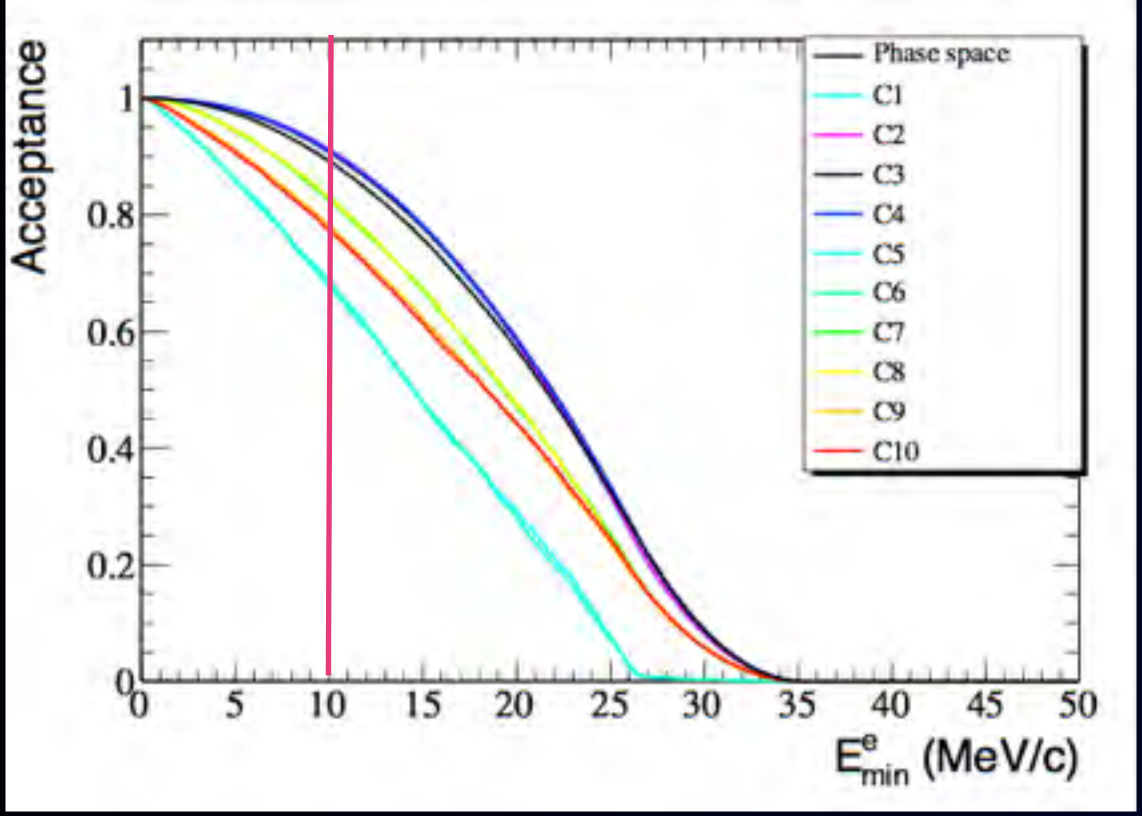


- Backgrounds
  - prompt physics backgrounds
    - radiative muon decay $\mu \to e\nu\nu\gamma$ when two neutrinos carry very small energies.
  - accidental backgrounds
    - positron in $\mu \to e\nu\nu$
    - photon in $\mu \to e\nu\nu\gamma$ or photon from e^+e^- annihilation in flight.


μ→eee

What is μ→eee ?

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



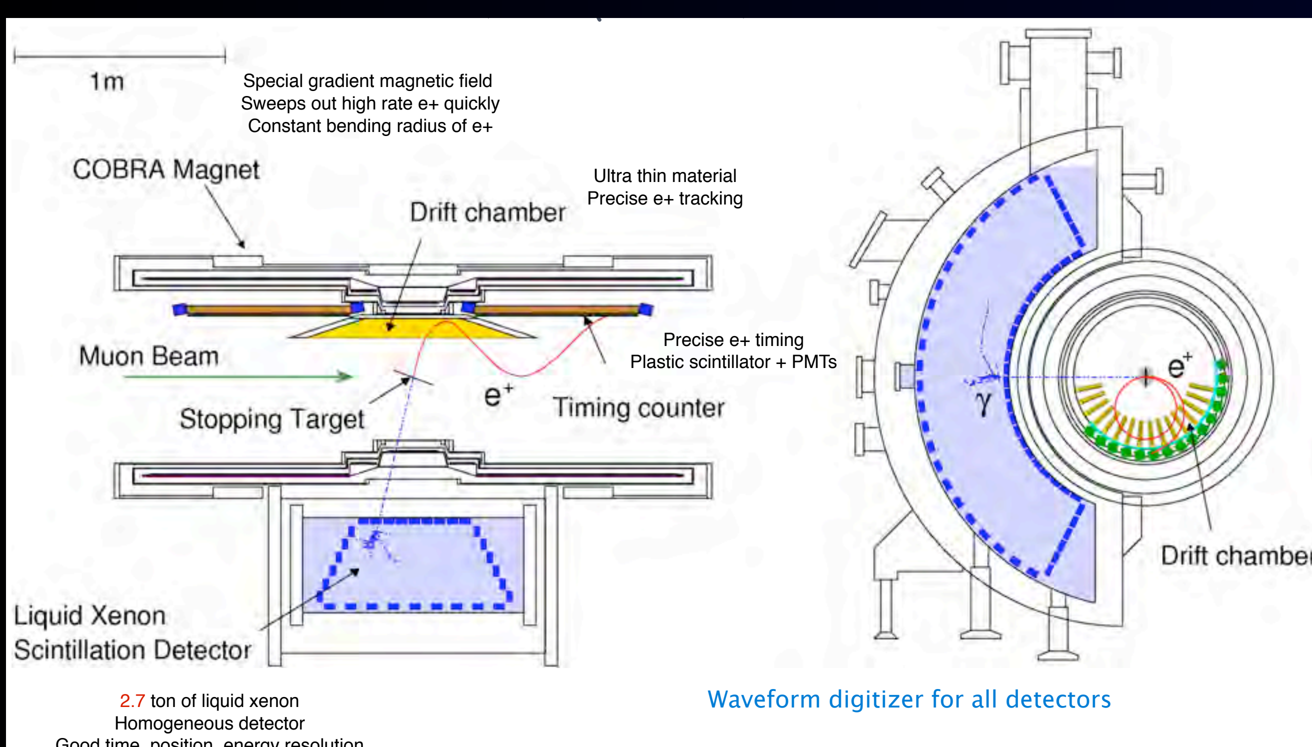
- Backgrounds
  - physics backgrounds
    - μ→eννee decay ($B=3.4\times10^{-5}$) when two neutrinos carry very small energies.
  - accidental backgrounds
    - positrons in μ→eνν
    - electrons in μ→eeeνν or μ→eννγ ($B=1.2\times10^{-2}$) with photon conversion or charge mis-id or Bhabha scattering.

acceptance of lowest $e^\pm$ vs. its minimum momentum measured.

CLFV Experiments in Muon Decays

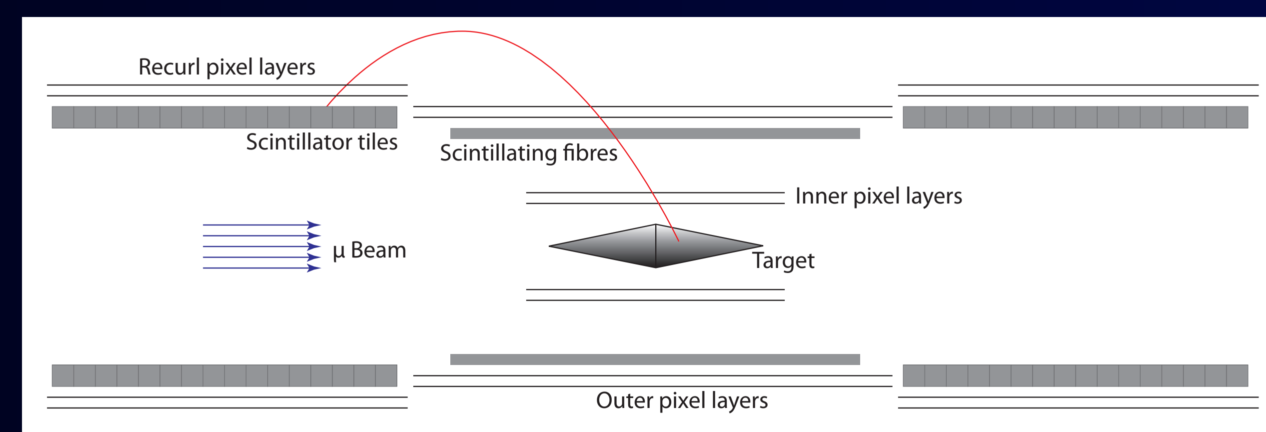
$\mu \to e\gamma$ MEG @PSI

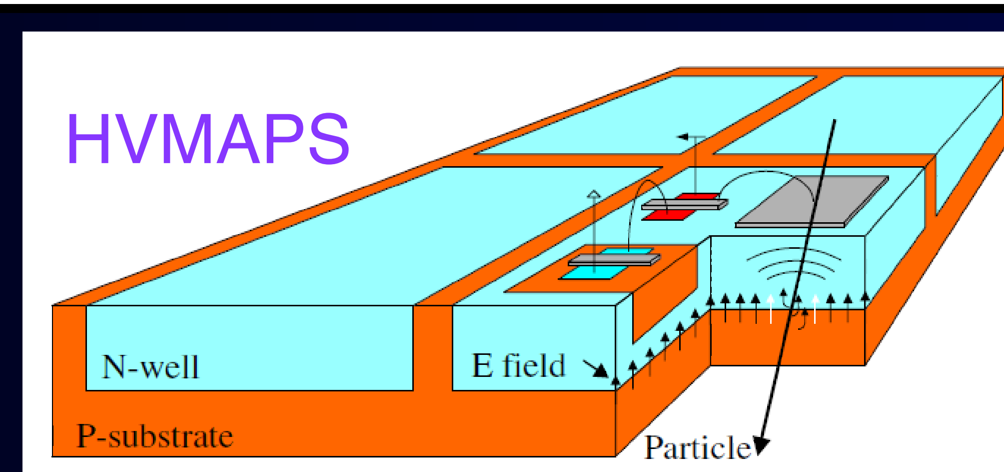
- Detector upgrade would include e^+ tracking in the COBRA spectrometer and liq.Xe detector.
- current limit < 5.7×10^{-13}
- The upgrade MEG will start in 2015 or 2016, aiming $O(10^{-14})$

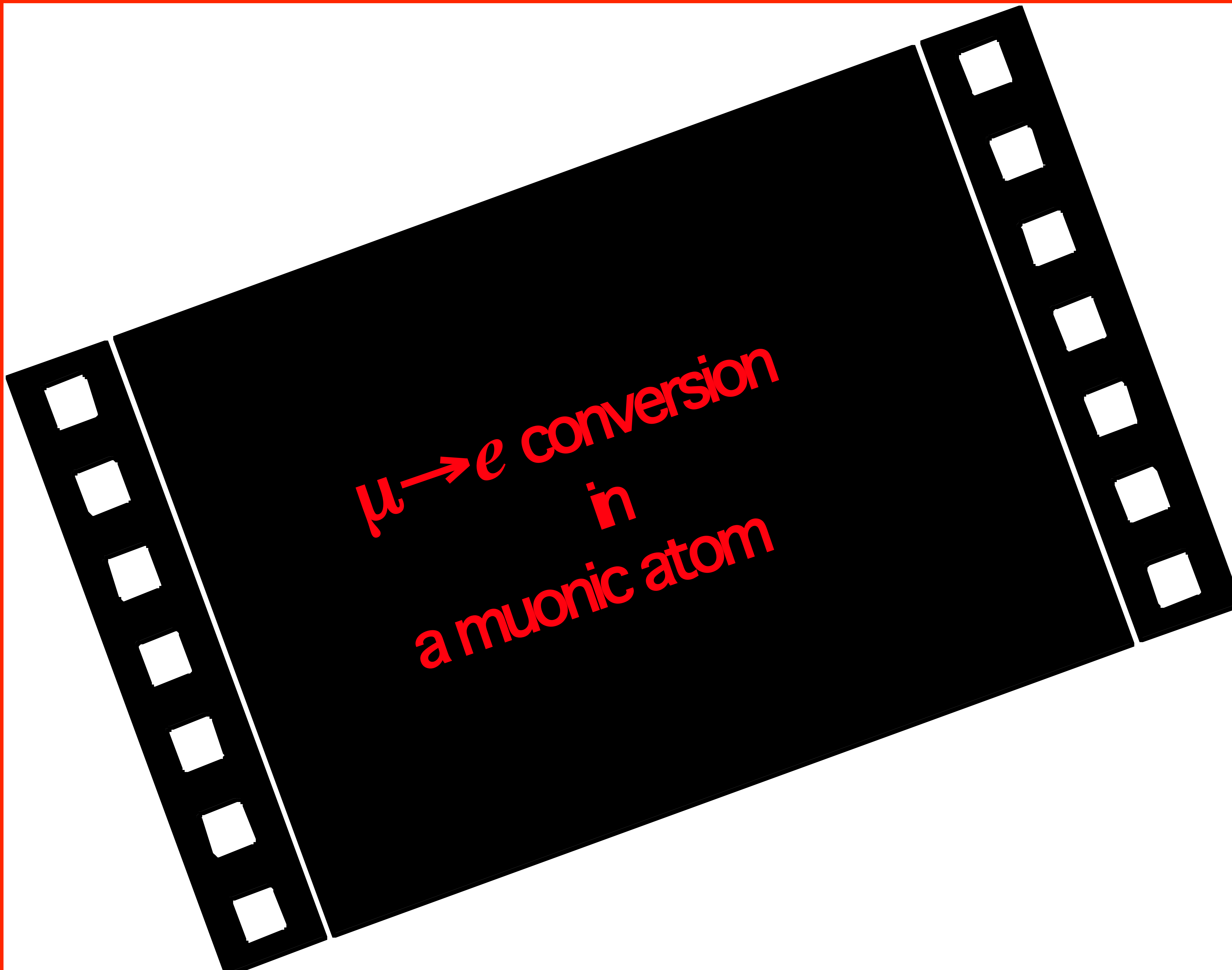


$\mu \to eee$ Mu3e @PSI

- search for $\mu \to eee$.
- approved at PSI last week
- staged approach, 10^{-14} in 2015, and 10^{-16} in 2017.

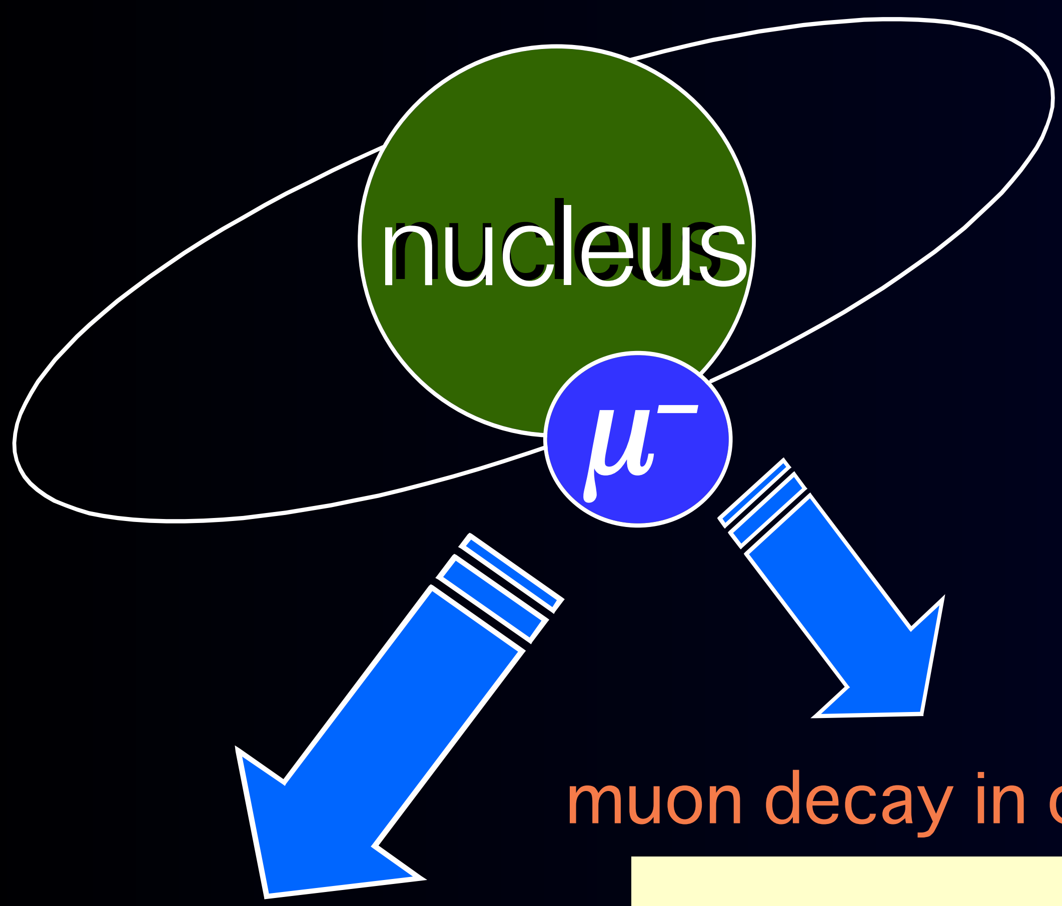





μ→e conversion
in
a muonic atom

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,

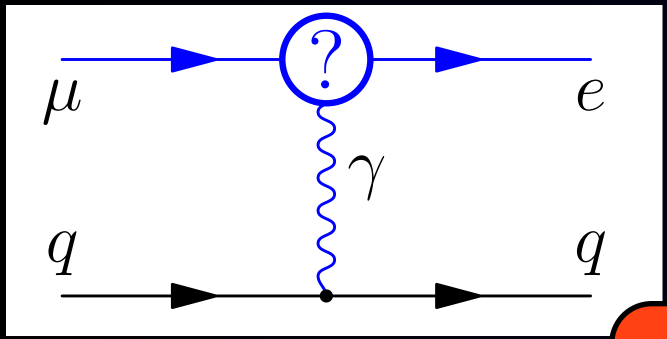
(3) cosmic rays, false tracking

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

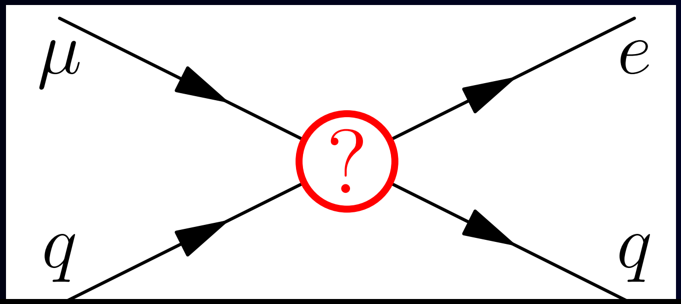
constructive

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

Photonic (dipole) interaction



Contact interaction

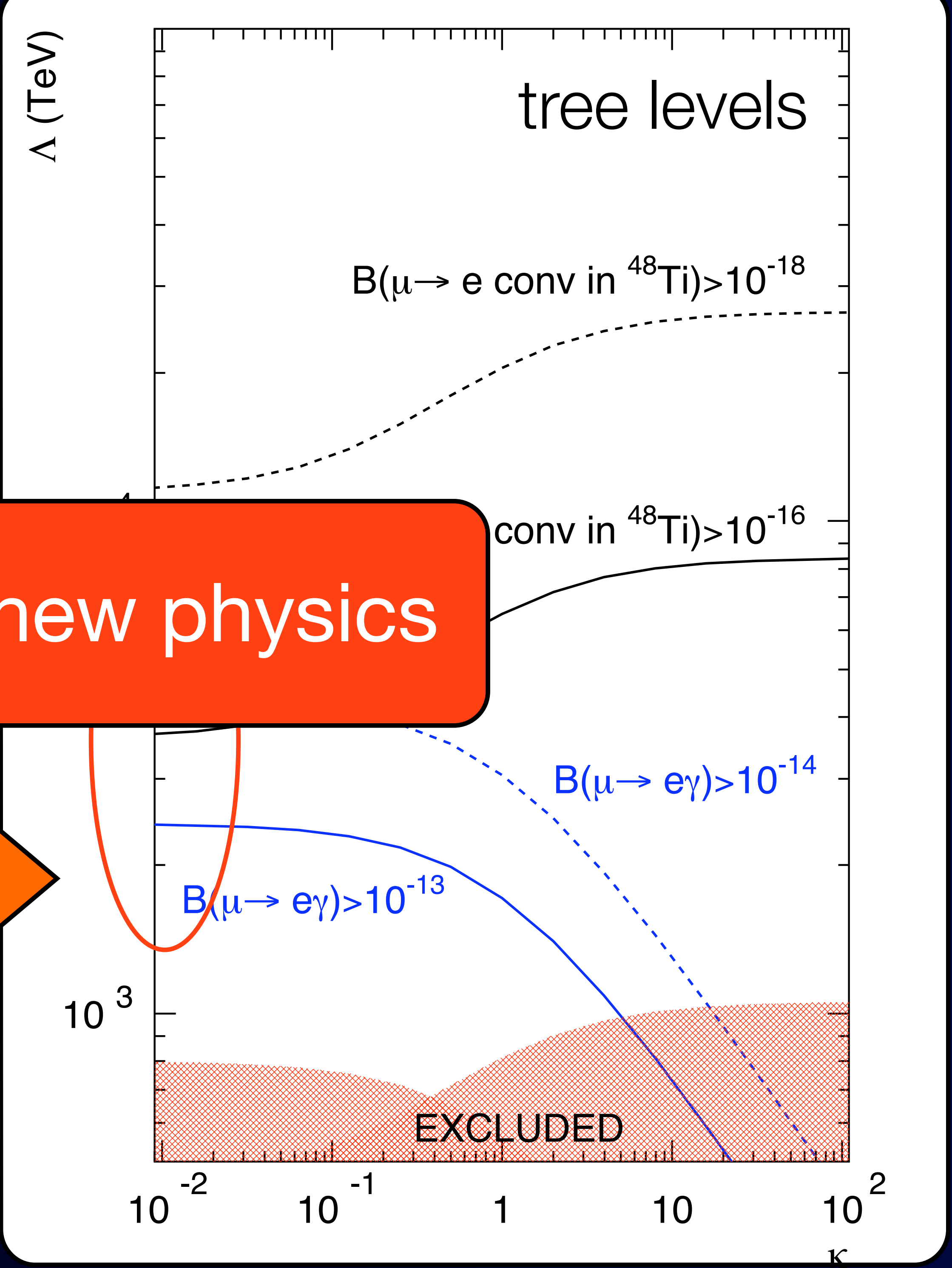


more sensitive to new physics

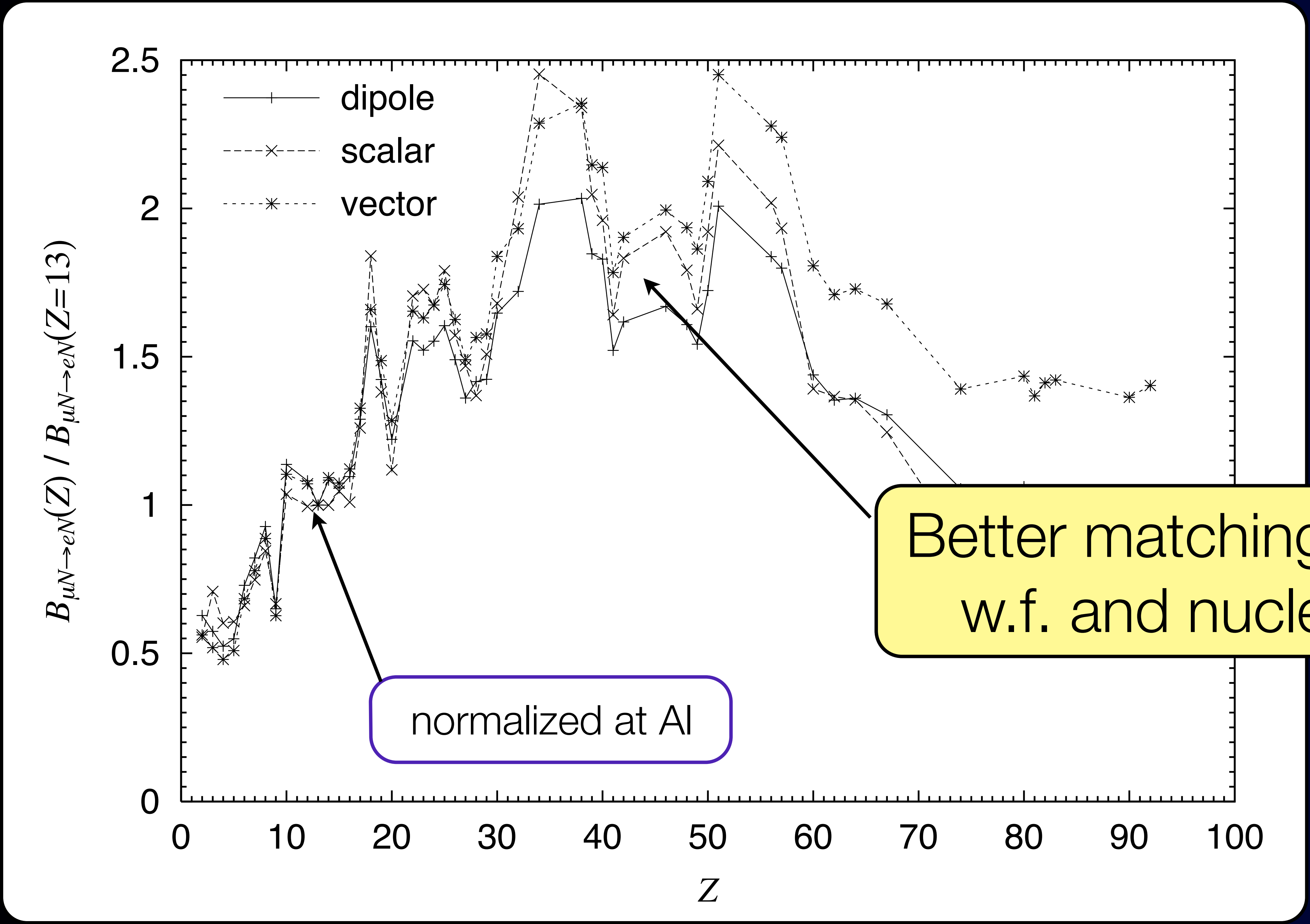
if photonic contri

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

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



μ-e Conversion : Target dependence (discriminating effective interaction)



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

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

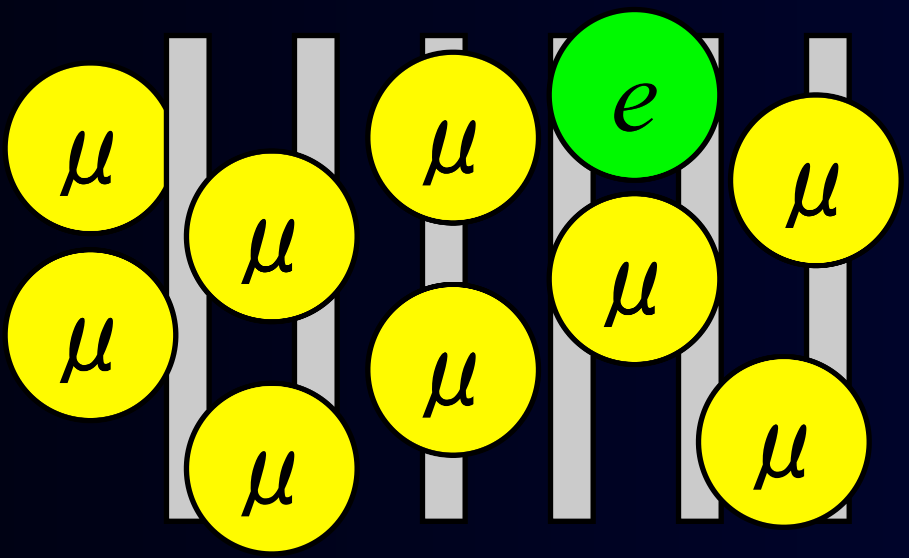
Process	Major backgrounds	Beam	Issues
$\mu^+ \to e^+\gamma$	accidental	DC beam	detector resolution
$\mu^+ \to e^+e^+e^-$	accidental	DC beam	detector resolution
$\mu^- N \to e^- N$	beam-related	pulsed beam	beam qualities

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.

μ-e conversion might be a next step.

Principle of Measurement of Measure μ-e Conversion / Meditation.....



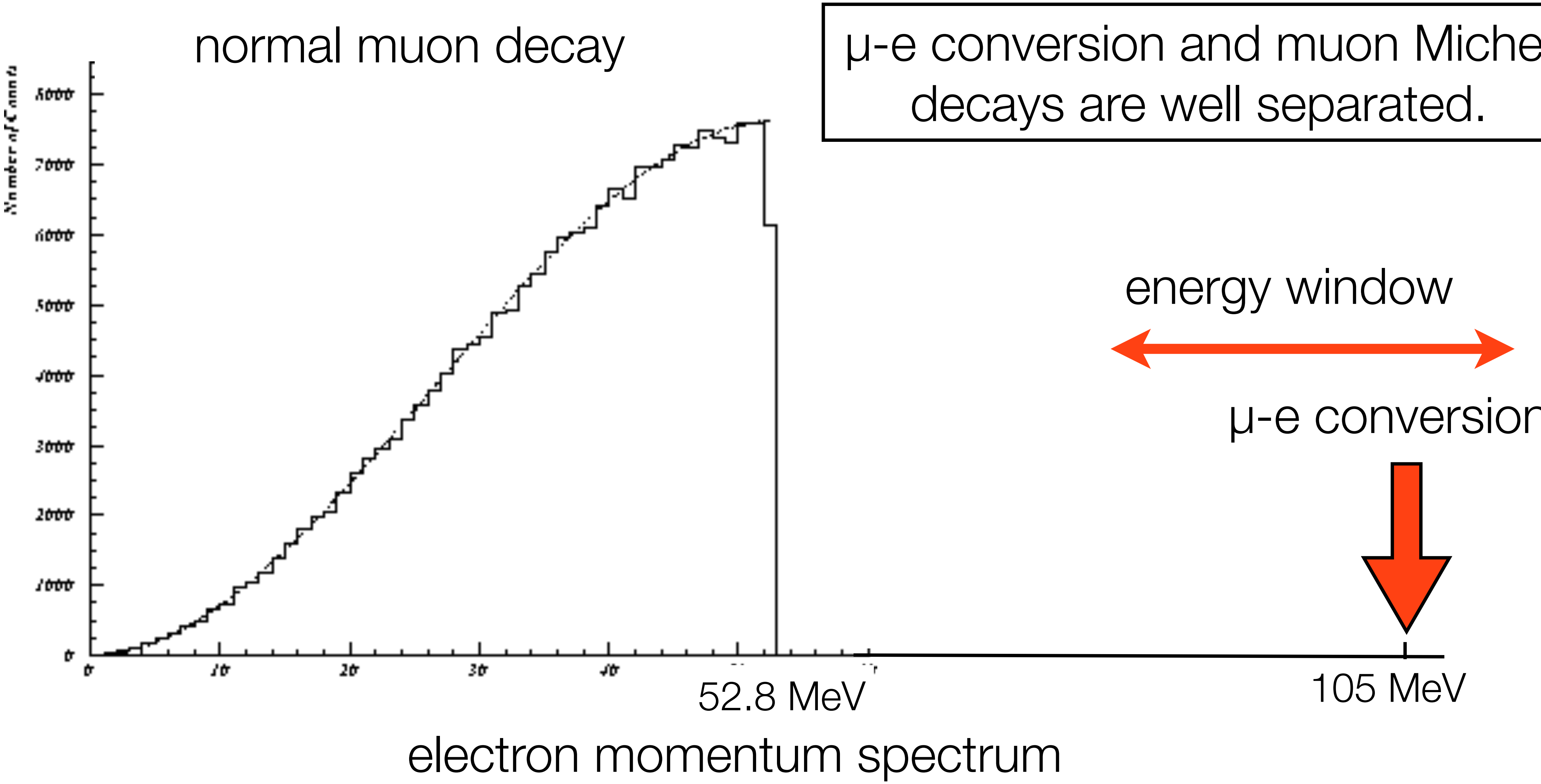
muon stopping target

Past experiments：10^{14} muons

COMET：10^{18} muons

μ-e Conversion Signal and Normal Muon Decays

μ-e conversion and muon Michel decays are well separated.

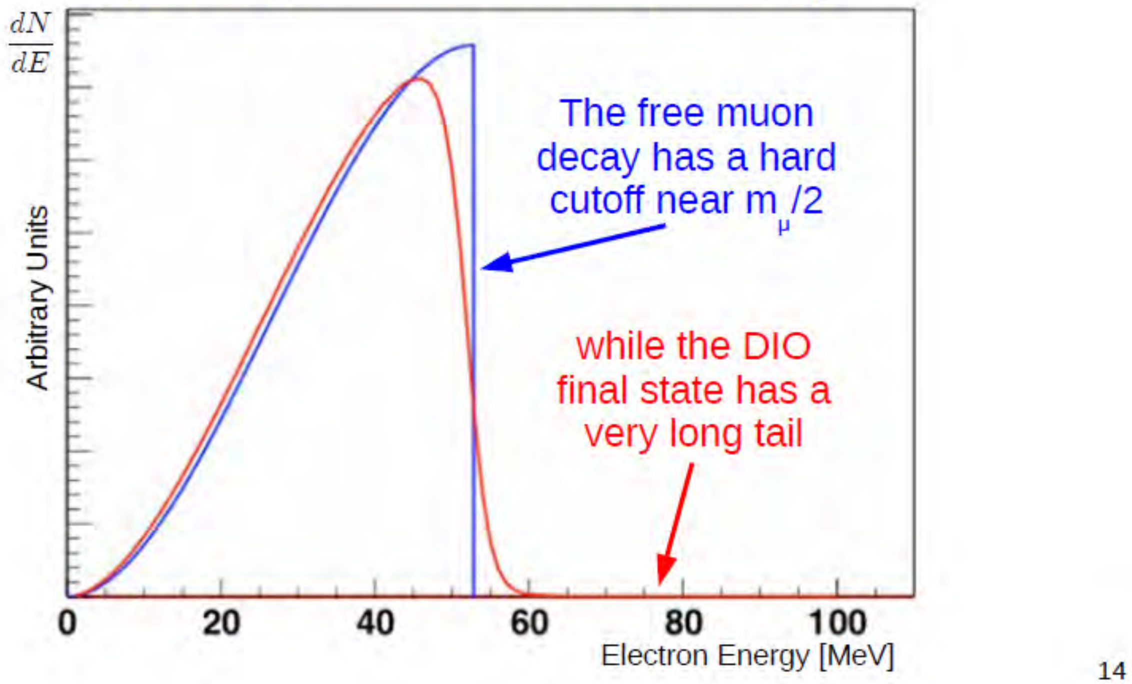


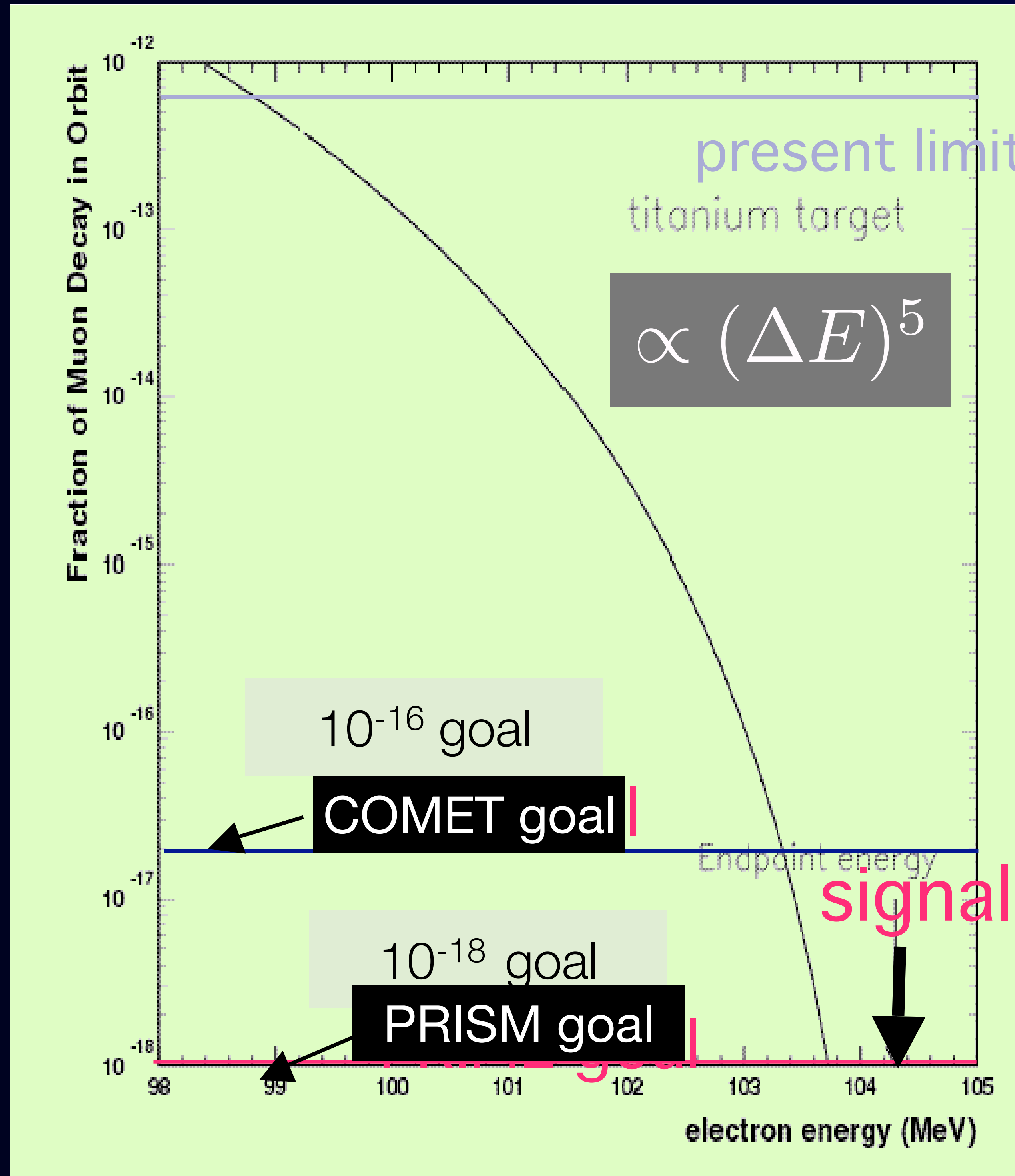
High Intensity beam can be used only for μ-e conversion

Background: Muon Decay in Orbit (DIO)

Decay-in-Orbit is the major source of delayed background in the live window

$$A(Z,N)\mu^- \rightarrow A(Z,N)e^-\bar{\nu}_e\nu_\mu$$





Good momentum resolution is needed.

Measurement Time Window for Phase-I ?

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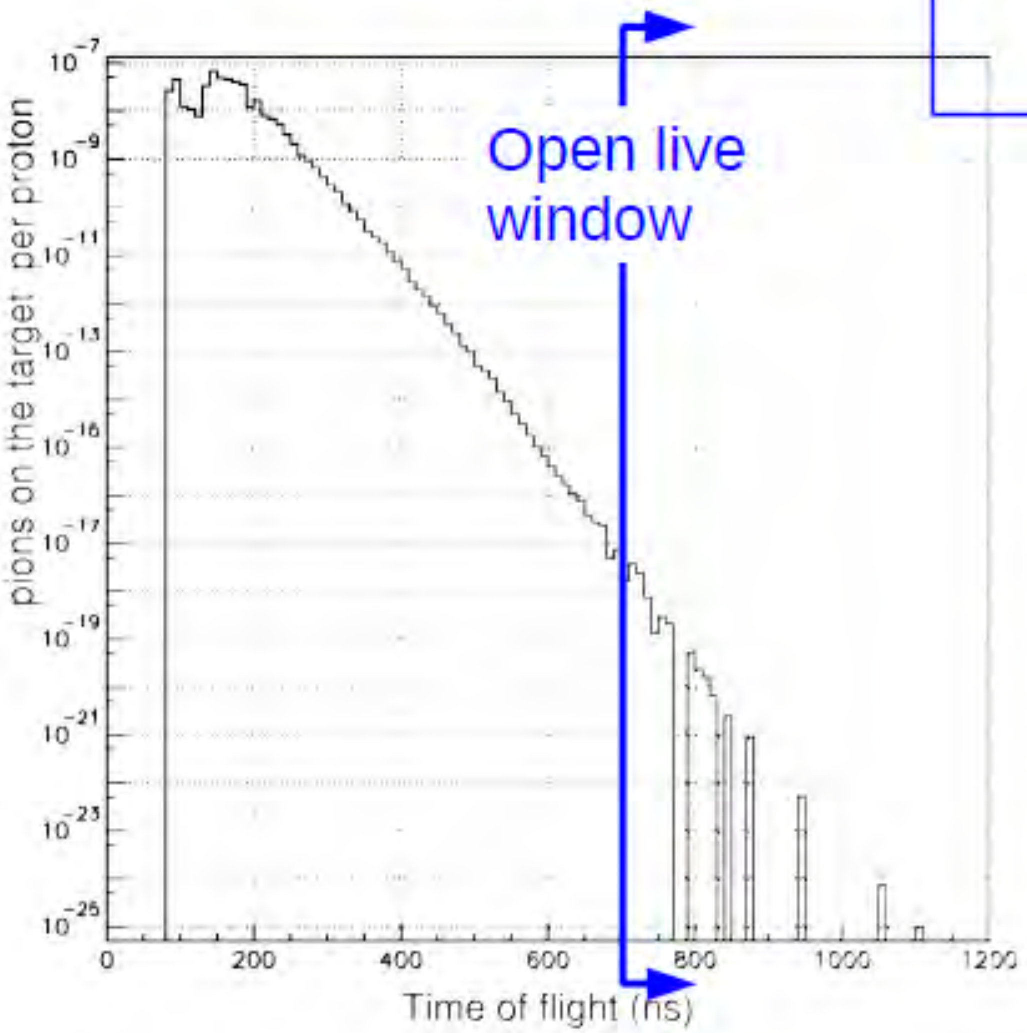
Radiative pion capture can produce electrons near the conversion energy

$$\pi^- A(Z,N) \rightarrow \gamma A(Z-1, N+1)^*$$

$\gamma \rightarrow e^+e^-$



The electron spectrum extends out to nearly m_π

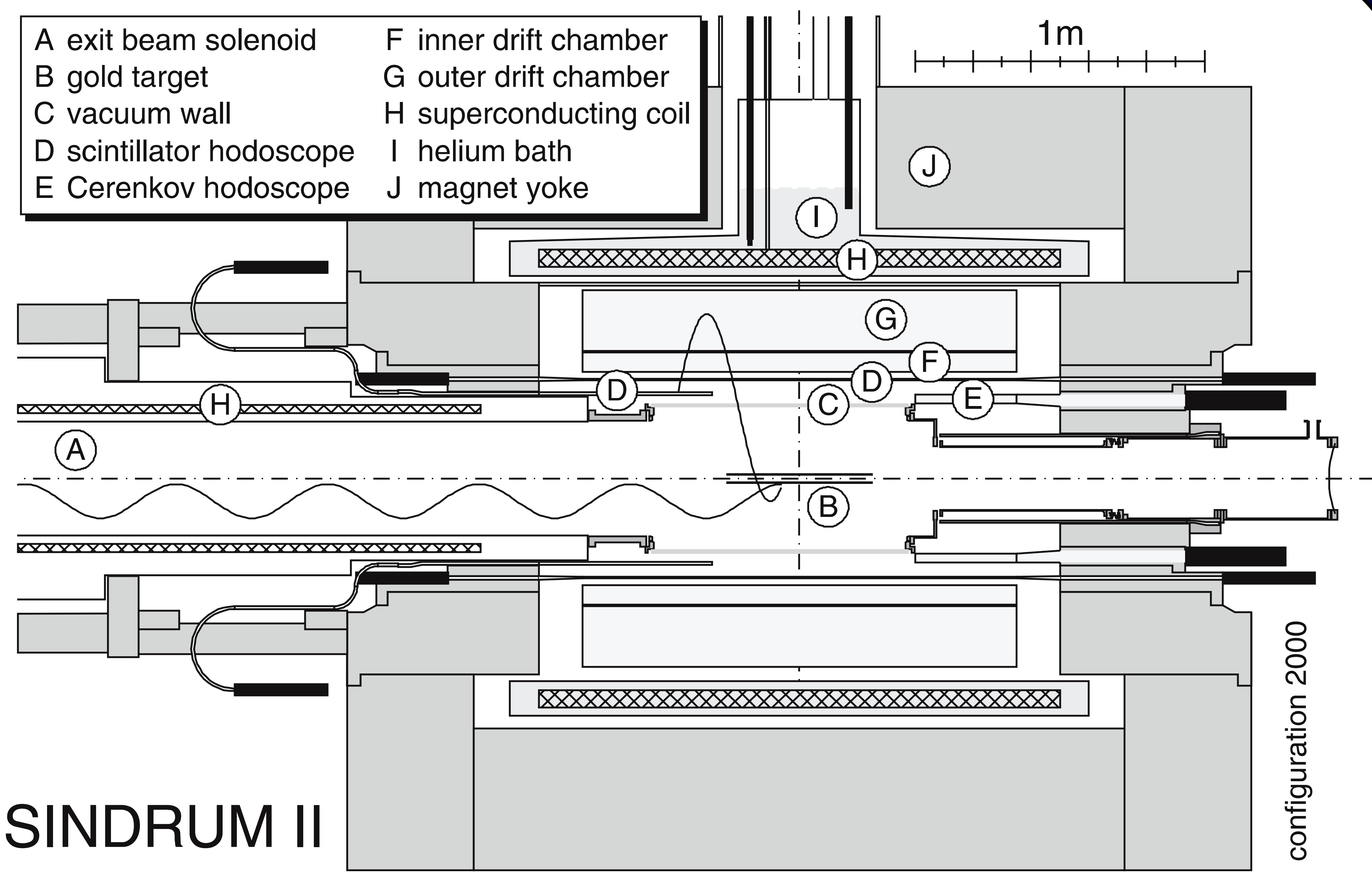
This (and other) prompt backgrounds are eliminated by keeping the DAQ dead until the background rate has fallen below some threshold.

Backgrounds for Search for μ-e conversion

intrinsic physics backgrounds	Muon decay in orbit (DIO) Radiative muon decay neutrons from muon nuclear capture Protons from muon nuclear capture Antiproton induced background
beam-related backgrounds	Radiative pion capture Beam electrons Muon decay in flights Neutron background
cosmic-ray and other backgrounds	Cosmic-ray induced background False tracking

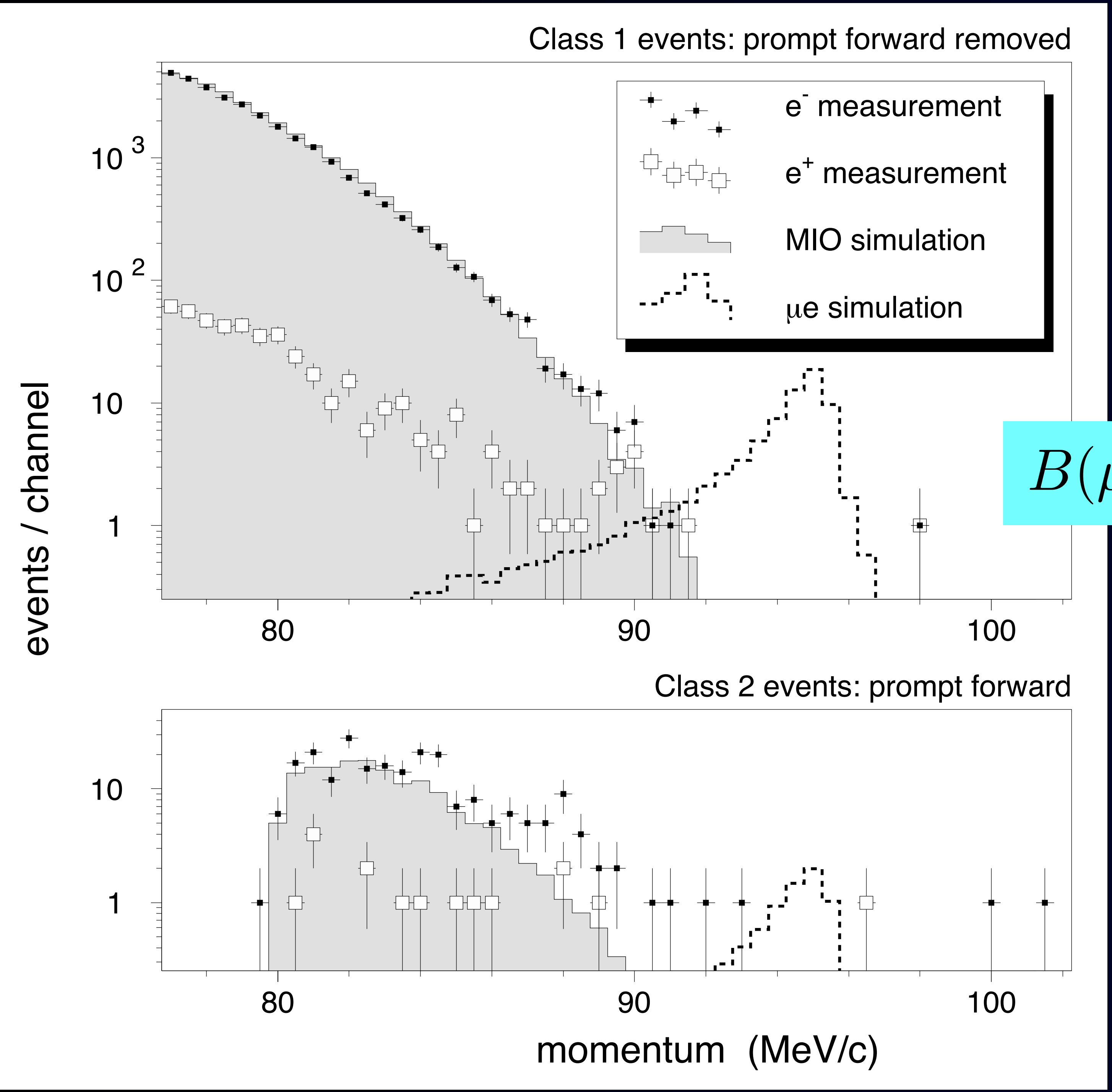
SINDRUM-II at PSI (Detector)

Osaka University



SINDRUM-II at PSI (data)

Osaka University



Published Results (2004)

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

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

Improvements for Signal Sensitivity

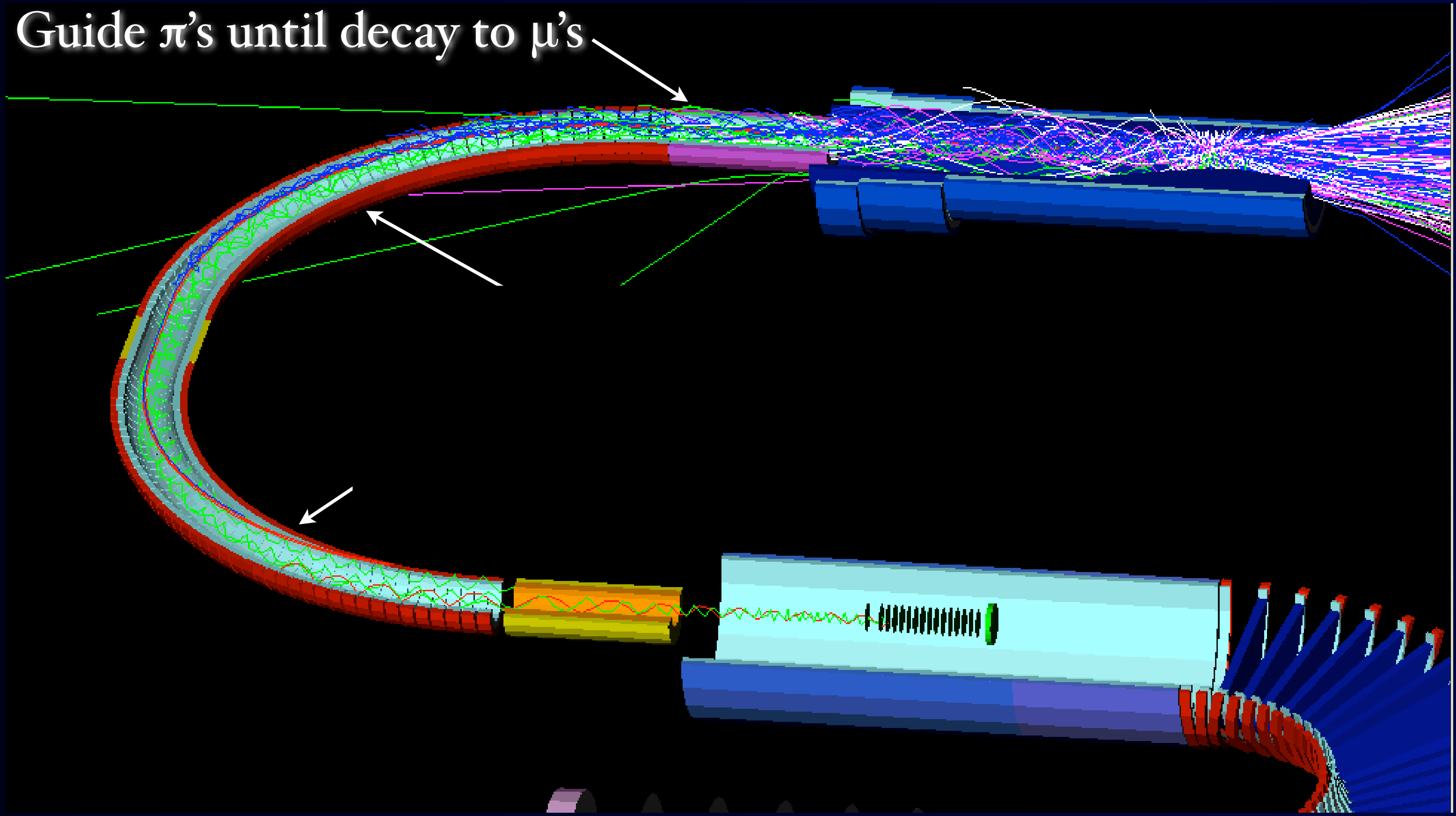
To achieve a single sensitivity of 10^{-17}, we need

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

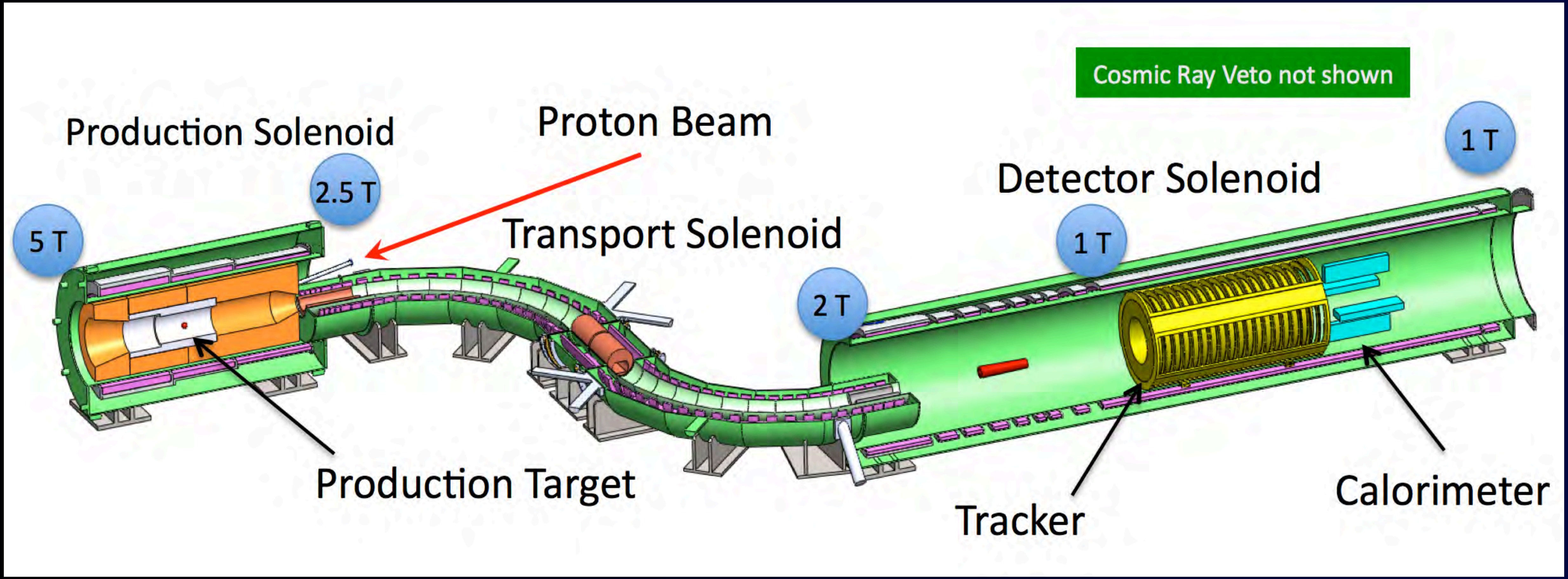
Beam-related backgrounds	→	Beam pulsing with separation of 1μsec	measured between beam pulses

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

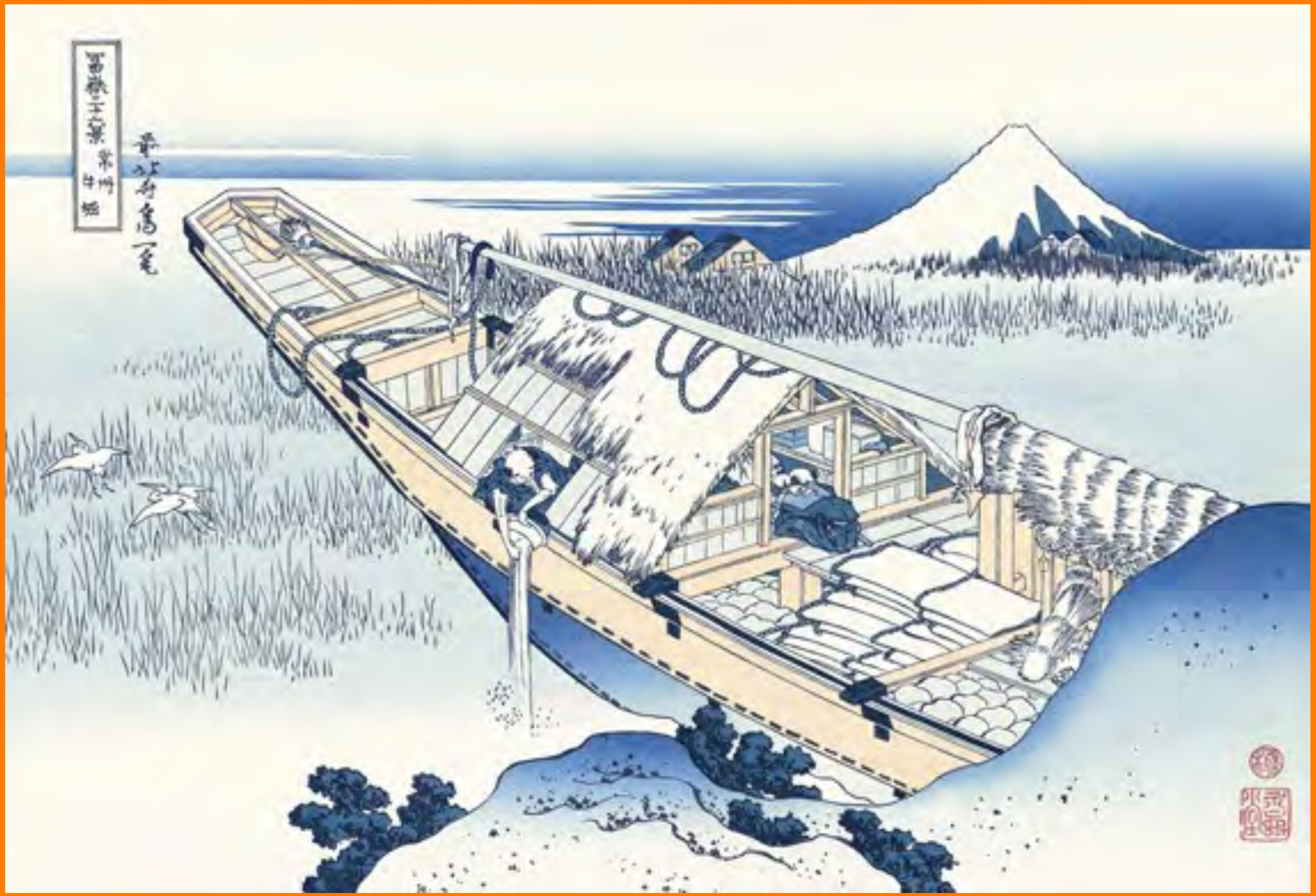
μ-e conversion : Mu2e at Fermilab



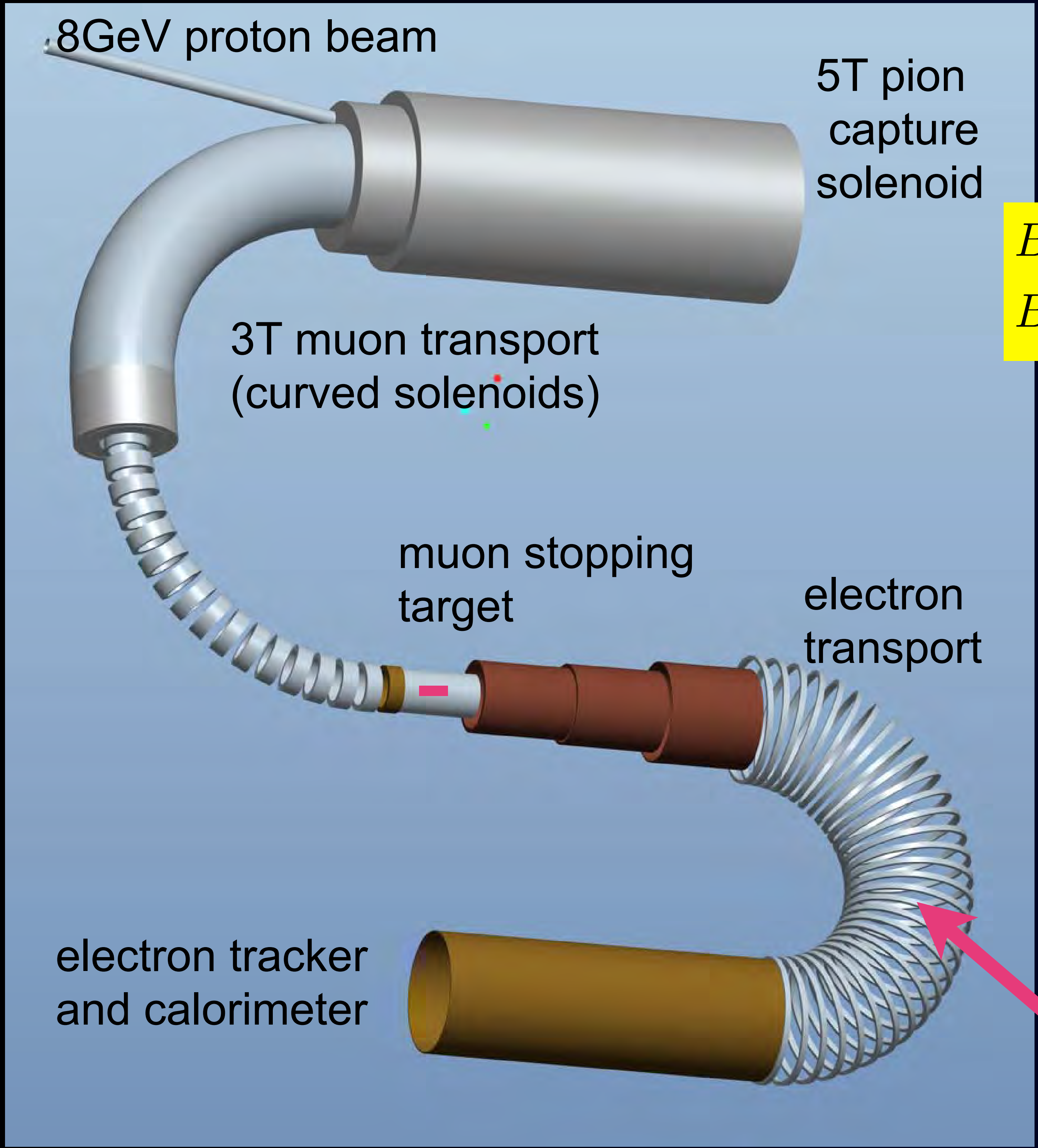
$$B(\mu^- + Al \to e^- + Al) = 5 \times 10^{-17} \quad \text{(S.E.)}$$
$$B(\mu^- + Al \to e^- + Al) < 10^{-16} \quad \text{(90\%C.L.)}$$

- 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.

COMET



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



Experimental Goal of COMET

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

- 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.

COMET Collaboration

164 collaborators
37 institutes, 12 countries

The COMET Collaboration

R. Akhmetshin[6,28], V. Anishchik[4], M. Aoki[29], R. B. Appleby[8,22], Y. Arimoto[15], Y. Bagaturia[33], Y. Ban[3], W. Bertsche[22], A. Bondar[6,28], S. Canfer[30], S. Chen[25], Y. E. Cheung[25], B. Chiladze[32], D. Clarke[30], M. Danilov[13,23], P. D. Dauncey[11], J. David[20], W. Da Silva[20], C. Densham[30], G. Devidze[32], P. Dornan[11], A. Drutskoy[13,23], V. Duginov[14], A. Edmonds[35], L. Epshteyn[6,27], P. Evtoukhovich[14], G. Fedotovich[6,28], M. Finger[7], M. Finger Jr[7], Y. Fujii[2], Y. Fukao[15], J-F. Genat[20], M. Gersabeck[22], E. Gillies[11], D. Grigoriev[6,27,28], K. Gritsay[14], R. Han[1], K. Hasegawa[15], I. H. Hasim[29], O. Hayashi[29], M. I. Hossain[16], Z. A. Ibrahim[21], Y. Igarashi[15], F. Ignatov[6,28], M. Iio[15], M. Ikeno[15], K. Ishibashi[19], S. Ishimoto[15], T. Itahashi[29], S. Ito[29], T. Iwami[29], Y. Iwashita[17], X. S. Jiang[2], P. Jonsson[11], V. Kalinnikov[14], F. Kapusta[20], H. Katayama[29], K. Kawagoe[19], V. Kazanin[6,28], B. Khazin[§6,28], A. Khvedelidze[14], M. Koike[36], G. A. Kozlov[14], B. Krikler[11], A. Kulikov[14], E. Kulish[14], Y. Kuno[29], Y. Kuriyama[18], Y. Kurochkin[5], A. Kurup[11], B. Lagrange[11,18], M. Lancaster[35], H. B. Li[2], W. G. Li[2], A. Liparteliani[32], R. P. Litchfield[35], P. Loveridge[30], G. Macharashvili[14], Y. Makida[15], Y. Mao[3], O. Markin[13], Y. Matsumoto[29], T. Mibe[15], S. Mihara[15], F. Mohamad Idris[21], K. A. Mohamed Kamal Azmi[21], A. Moiseenko[14], Y. Mori[18], N. Mosulishvili[32], E. Motuk[35], Y. Nakai[19], T. Nakamoto[15], Y. Nakazawa[29], J. Nash[11], M. Nioradze[32], H. Nishiguchi[15], T. Numao[34], J. O'Dell[30], T. Ogitsu[15], K. Oishi[19], K. Okamoto[29], C. Omori[15], T. Ota[31], H. Owen[22], C. Parkes[22], J. Pasternak[11], C. Plostinar[30], V. Ponariadov[4], A. Popov[6,28], V. Rusinov[13,23], A. Ryzhenenkov[6,28], B. Sabirov[14], N. Saito[15], H. Sakamoto[29], P. Sarin[10], K. Sasaki[15], A. Sato[29], J. Sato[31], D. Shemyakin[6,28], N. Shigyo[19], D. Shoukavy[5], M. Slunecka[7], M. Sugano[15], Y. Takubo[15], M. Tanaka[15], C. V. Tao[26], E. Tarkovsky[13,23], Y. Tevzadze[32], N. D. Thong[29], V. Thuan[12], J. Tojo[19], M. Tomasek[9], M. Tomizawa[15], N. H. Tran[29], I. Trek[32], N. M. Truong[29], Z. Tsamalaidze[14], N. Tsverava[14], S. Tygier[22], T. Uchida[15], Y. Uchida[11], K. Ueno[15], S. Umasankar[10], E. Velicheva[14], A. Volkov[14], V. Vrba[9], W. A. T. Wan Abdullah[21], M. Warren[35], M. Wing[35], T. S. Wong[29], C. Wu[2,25], G. Xia[22], H. Yamaguchi[19], A. Yamamoto[15], M. Yamanaka[24], Y. Yang[19], H. Yoshida[29], M. Yoshida[15], Y. Yoshii[15], T. Yoshioka[19], Y. Yuan[2], Y. Yudin[6,28], J. Zhang[2], Y. Zhang[2]

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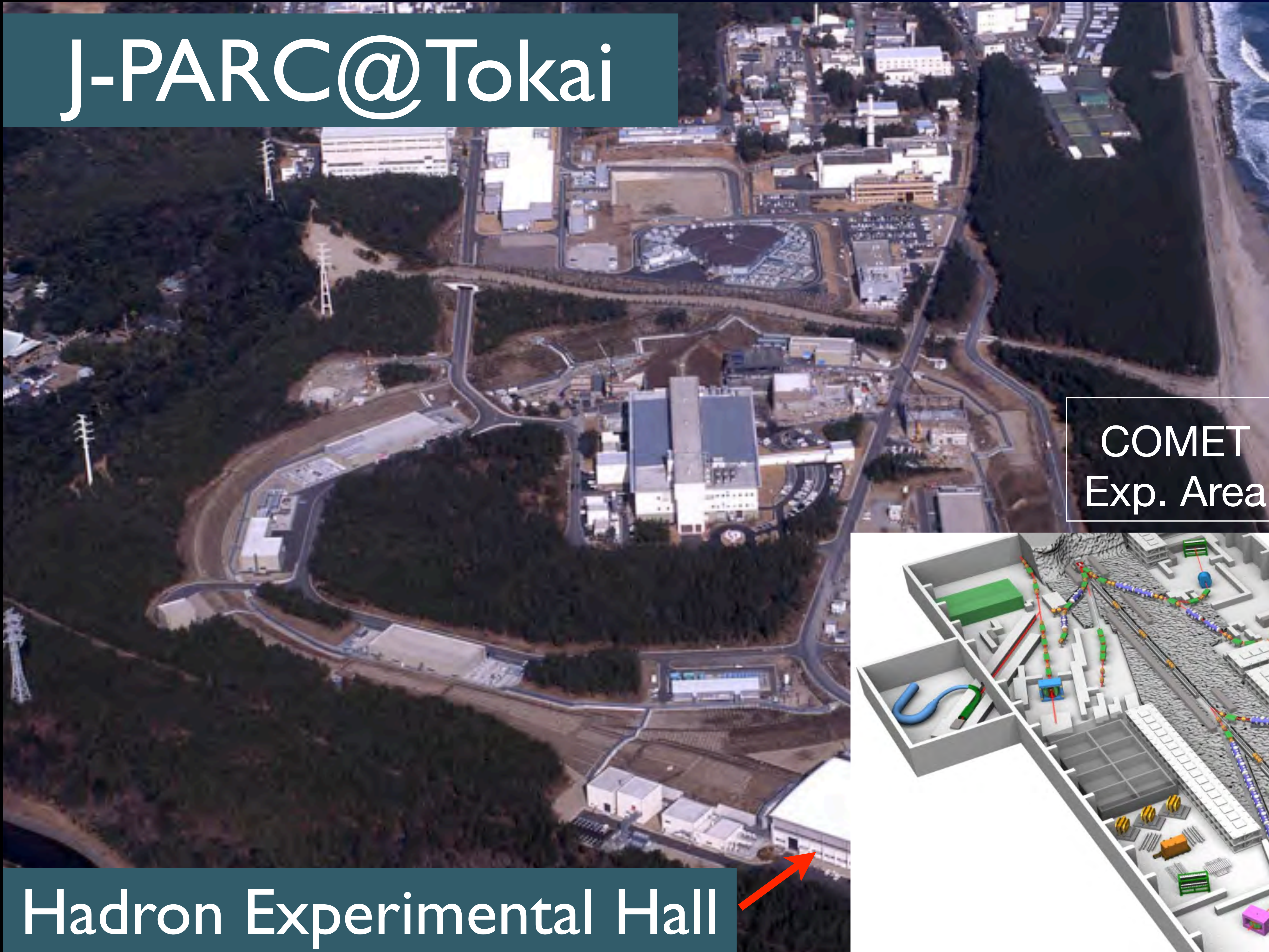
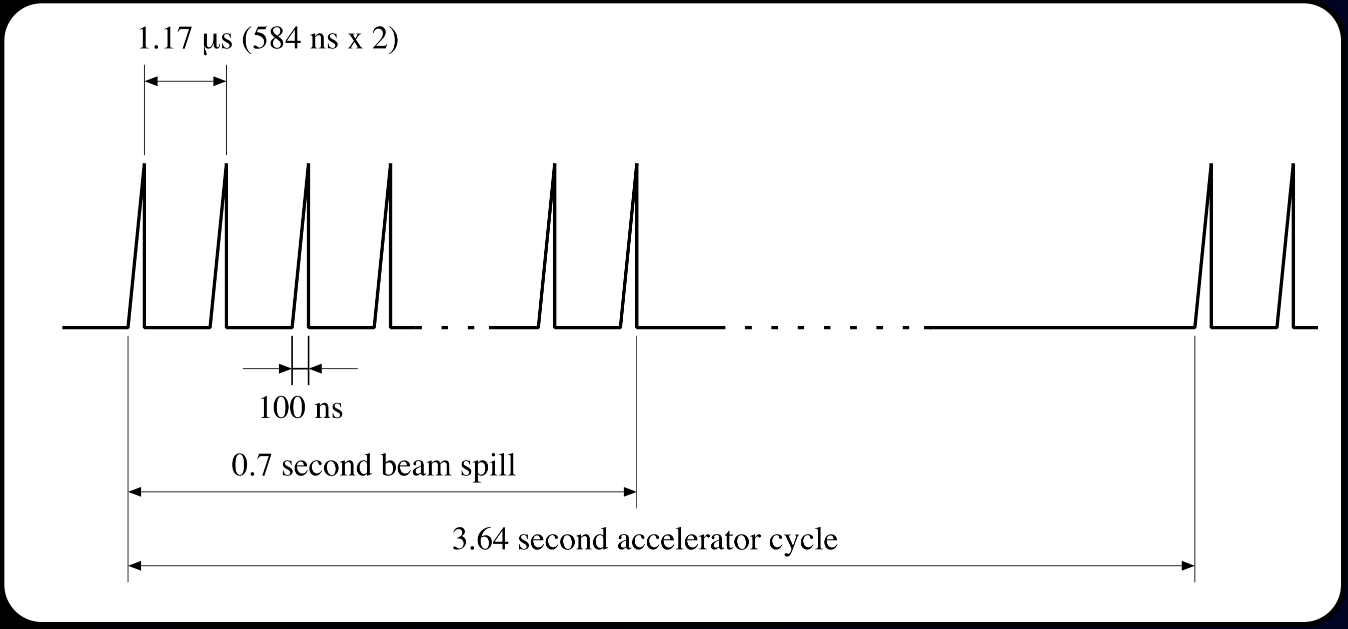
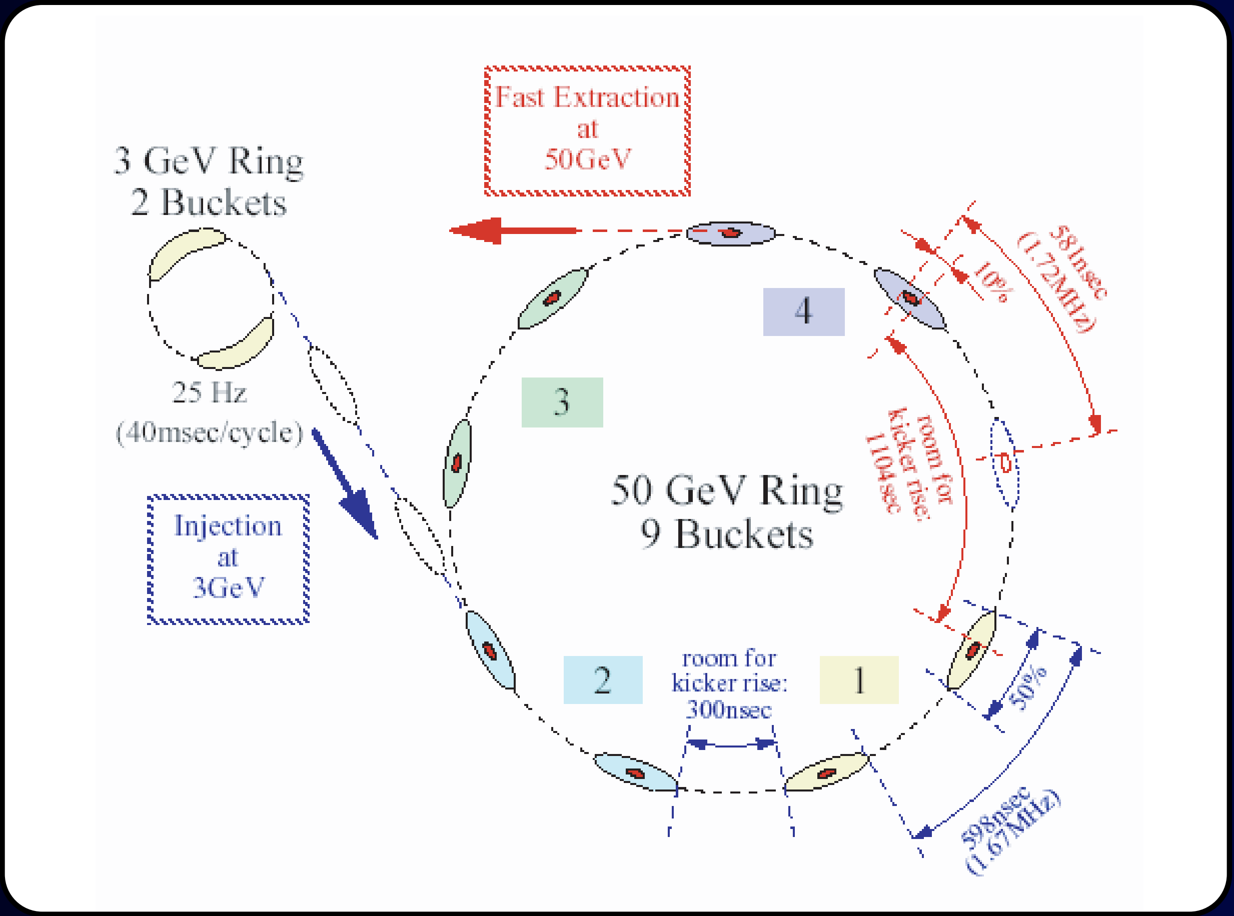
J-PARC@Tokai



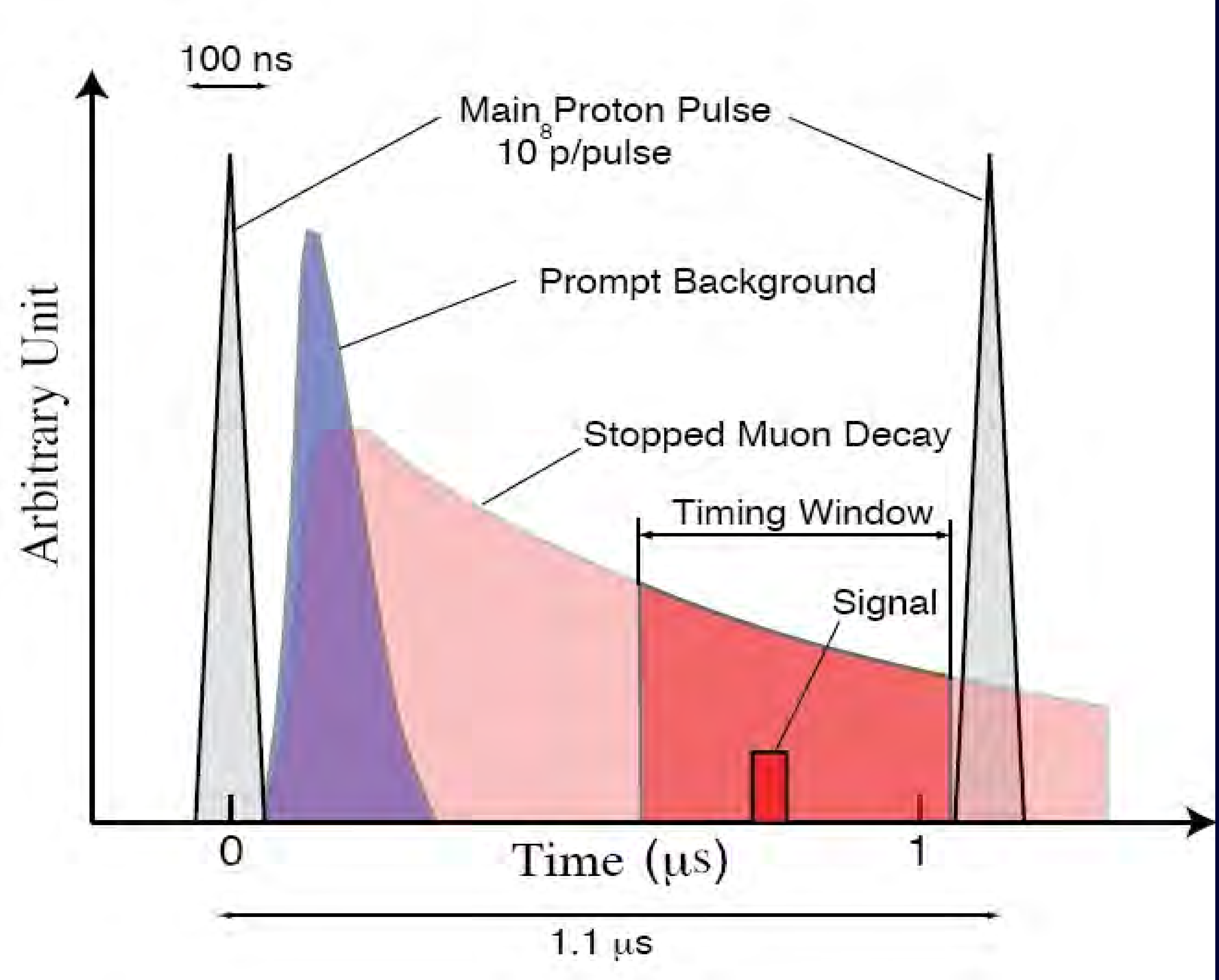
Proton Beam at J-PARC

- A pulsed proton beam is needed to reject beam-related prompt background.
- Time structure required for proton beams.
  - Pulse separation is ~ 1µsec or more (muon lifetime).
  - Narrow pulse width (<100 nsec)
- Pulsed beam from slow extraction.
  - fill every other rf buckets with protons and make slow extraction
  - spill length (flat top) ~ 0.7





Proton Beam for COMET



Charged Particle Trajectory in Curved Solenoids

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

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

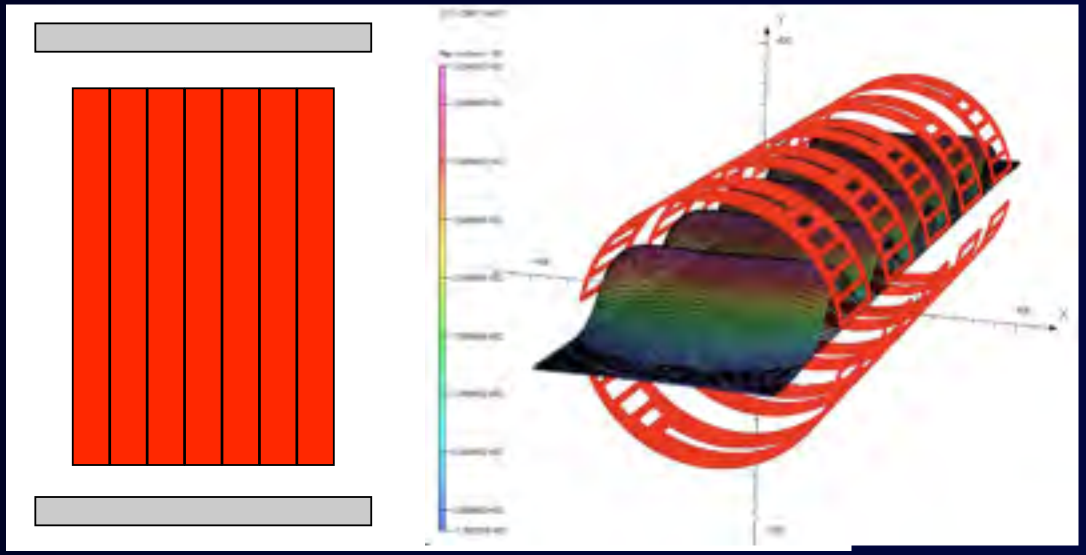
D : drift distance
B : Solenoid field
θ_{bend} *: Bending angle of the solenoid channel*
p : Momentum of the particle
q : Charge of the particle
θ *: atan(*P_T/P_L*)*

- This can be used for charge and momentum selection.

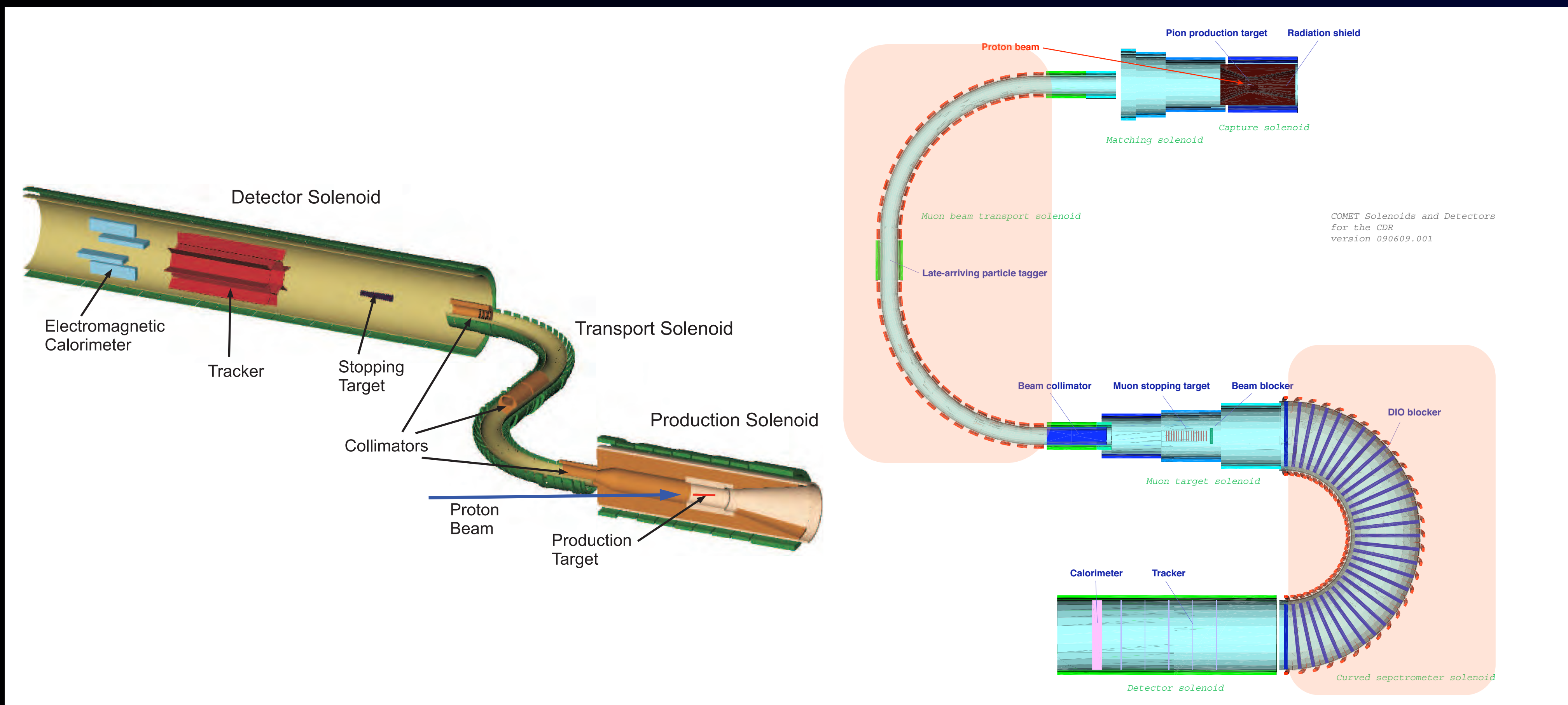
- This drift can be compensated by an auxiliary field parallel to the drift direction given by

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

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



Mu2e vs. COMET



	Mu2e	COMET
muon beam line	2x 90° bends (opposite direction)	2x 90° bend (same direction)
electron spectrometer	straight solenoid	curved solenoid

Select low momentum muons

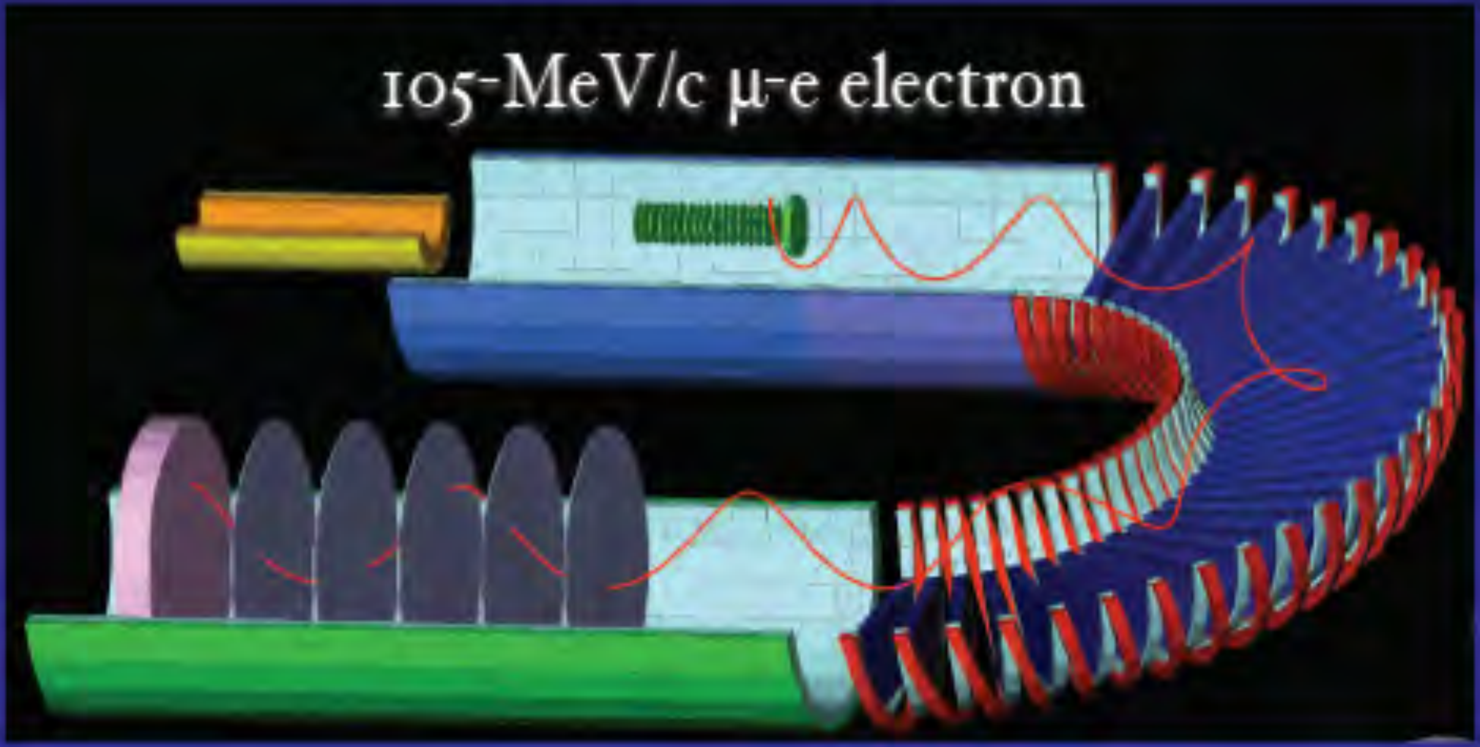
eliminate muon decay in flight

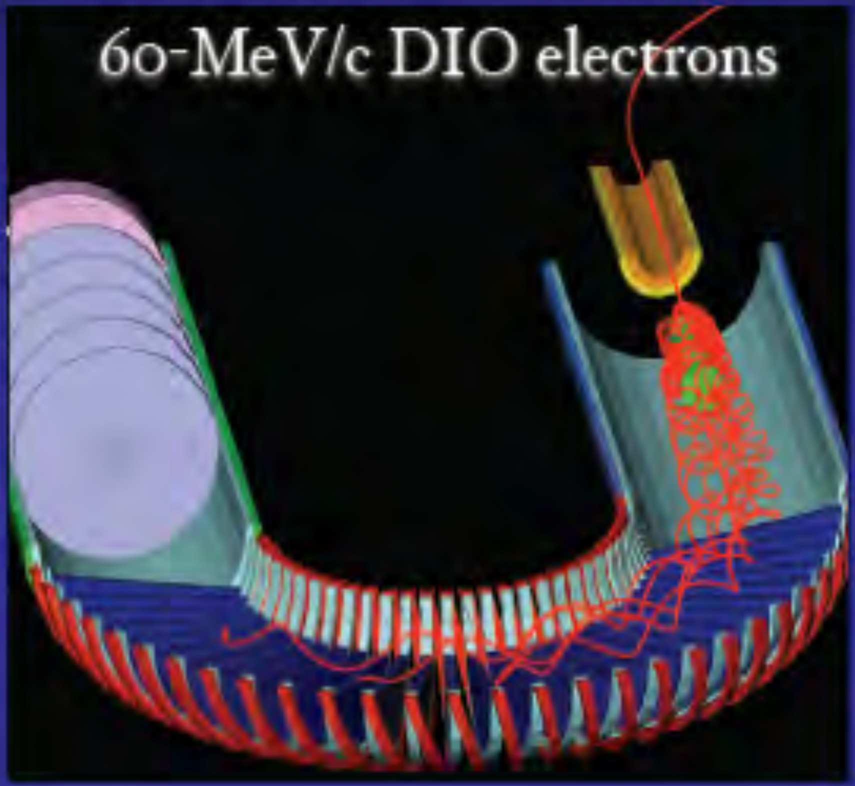
Selection of 100 MeV electrons

eliminate protons from nuclear muon capture.

eliminate low energy events to make the detector quiet.

Electron Spectrometer





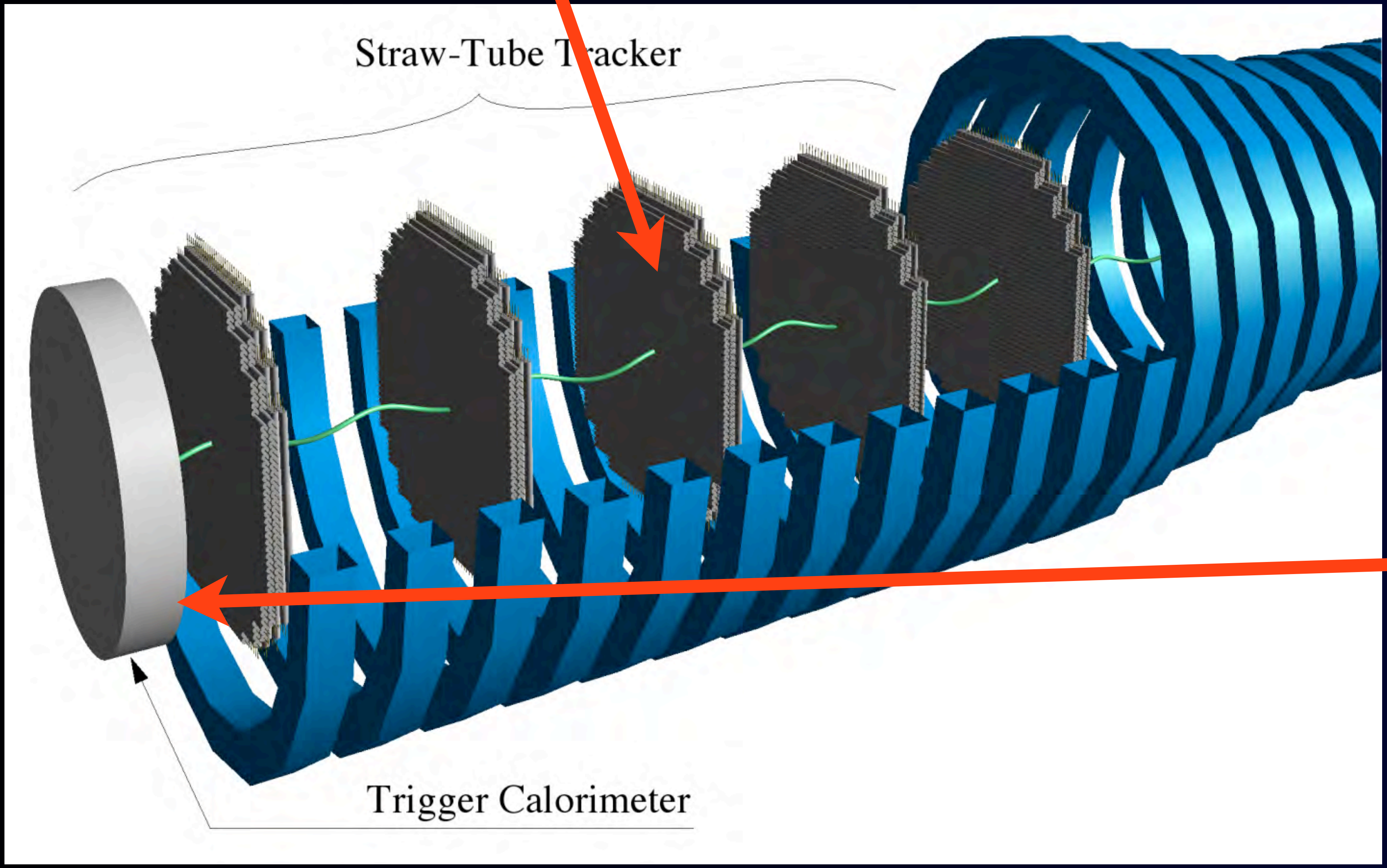
- One component that is not included in the Mu2e design.
- 1T solenoid with additional 0.17T dipole field.
- Vertical dispersion of toroidal field allows electrons with P<60MeV/c to be removed.
  - reduces rate in tracker to ~ 1kHz.

Electron Detection

Electron Tracker to measure electron momentum
- work in vacuum and under a magnetic field.
- Straw tube chambers
  - Straw tubes of 25μm thick, 5 mm diameter.
  - five plane has 2 views (x and y) with 2 layers per view.
- Planar drift chambers

Under a solenoidal magnetic field of 1 Tesla.

In vacuum to reduce multiple scattering.



Electron calorimeter to measure electron energy, make triggers and give additional hit position.
- Candidate are LYSO, GSO
- MPPC or APD readout

Signal Sensitivity (preliminary) - 2x10^7 sec

Osaka University

- Single event sensitivity

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

  - N_μ is a number of stopping muons in the muon stopping target. It is 2×10^{18} muons.
  - f_{cap} is a fraction of muon capture, which is 0.6 for aluminum.
  - A_e is the detector acceptance, which is 0.04.

total protons muon transport efficiency muon stopping efficiency	8.5×10^{20} 0.008 0.3
# of stopped muons	2.0×10^{18}

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

Background Rates

Radiative Pion Capture	0.05
Beam Electrons	$< 0.1^{\ddagger}$
Muon Decay in Flight	< 0.0002
Pion Decay in Flight	< 0.0001
Neutron Induced	0.024
Delayed-Pion Radiative Capture	0.002
Anti-proton Induced	0.007
Muon Decay in Orbit	0.15
Radiative Muon Capture	< 0.001
μ^- Capt. w/ n Emission	< 0.001
μ^- Capt. w/ Charged Part. Emission	< 0.001
Cosmic Ray Muons	0.002
Electrons from Cosmic Ray Muons	0.002
Total	0.34

‡ Monte Carlo statistics limited.

- beam-related prompt backgrounds
- beam-related delayed backgrounds
- intrinsic physics backgrounds
- cosmic-ray and other backgrounds

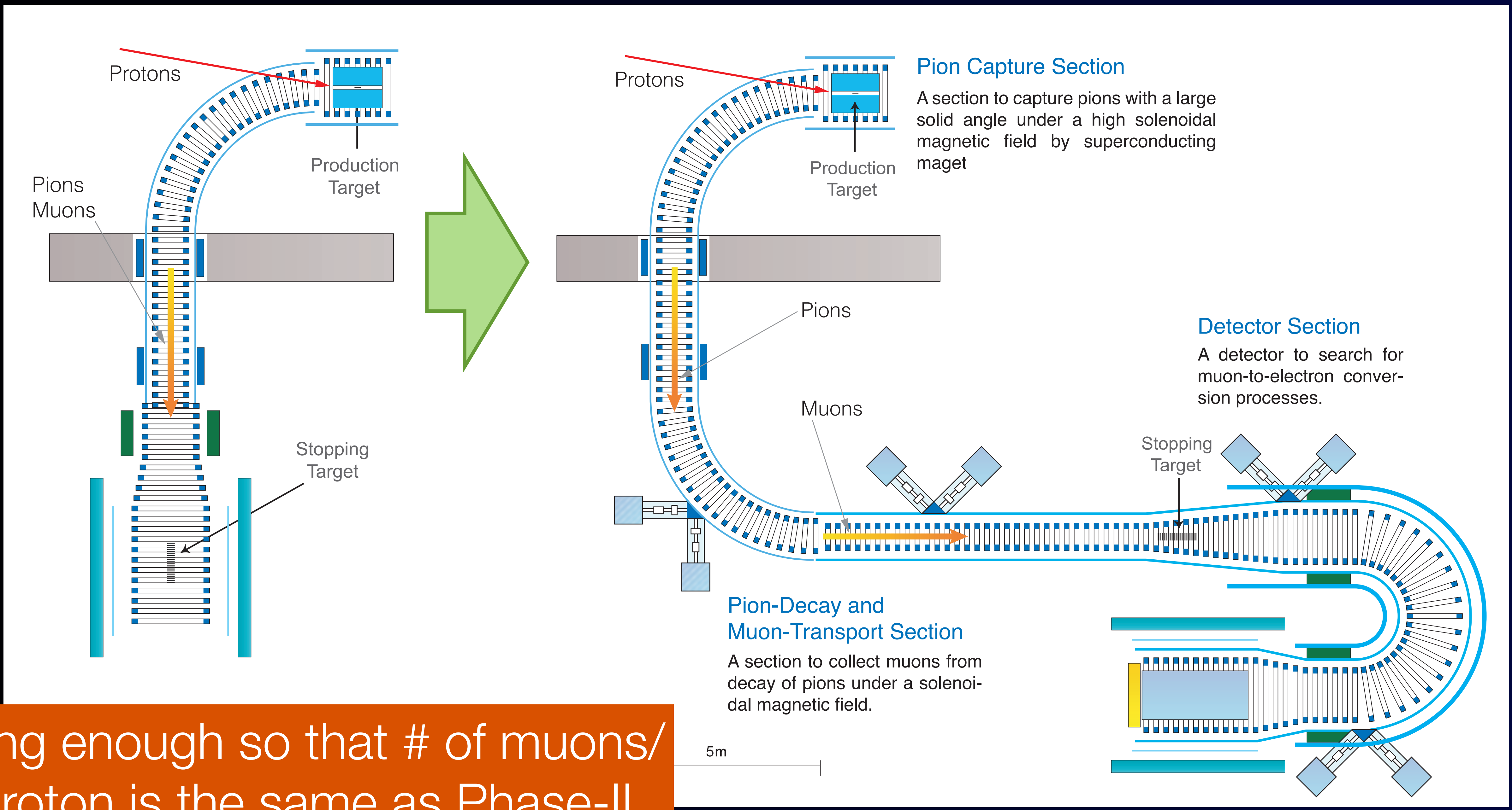
Expected background events are about 0.34.

COMET Phase-I

COMET Staged Approach (2012~)

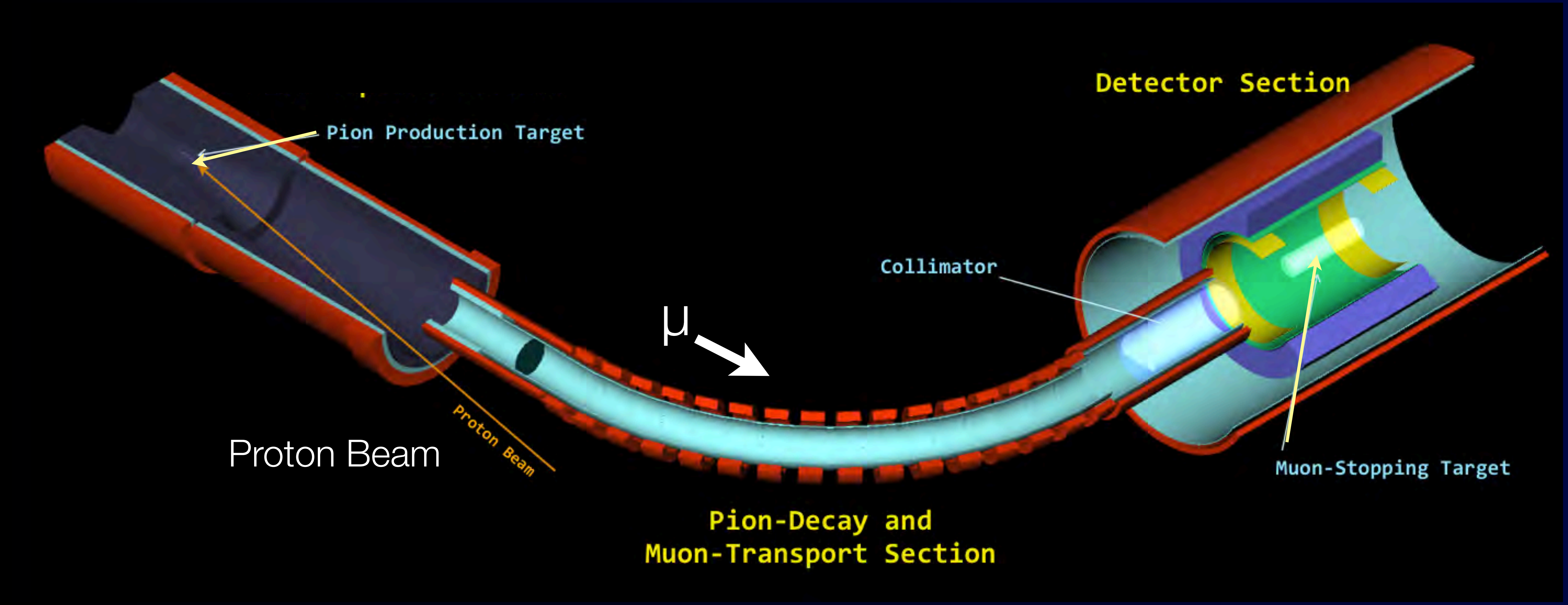
COMET Phase-I

COMET Phase-II



long enough so that # of muons/ proton is the same as Phase-II.

COMET Phase-I Experimental Layout



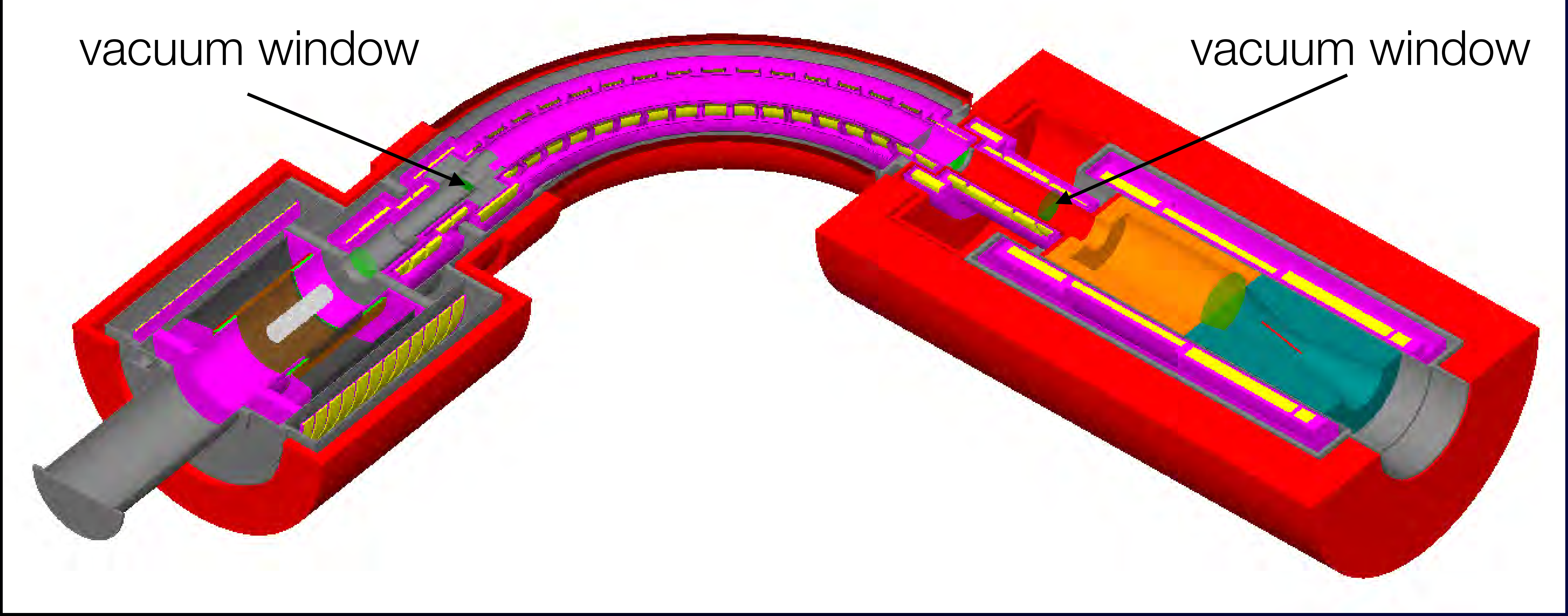
COMET muon beam-line：

$6x10^9$ muon/sec with 3kW beam produced. The world highest intensity.

COMET Phase-I detector：

About 10^{16} muons are stopped in the target. Electron from μ-e conversion will be measured

COMET Phase-I Muon Beam Line

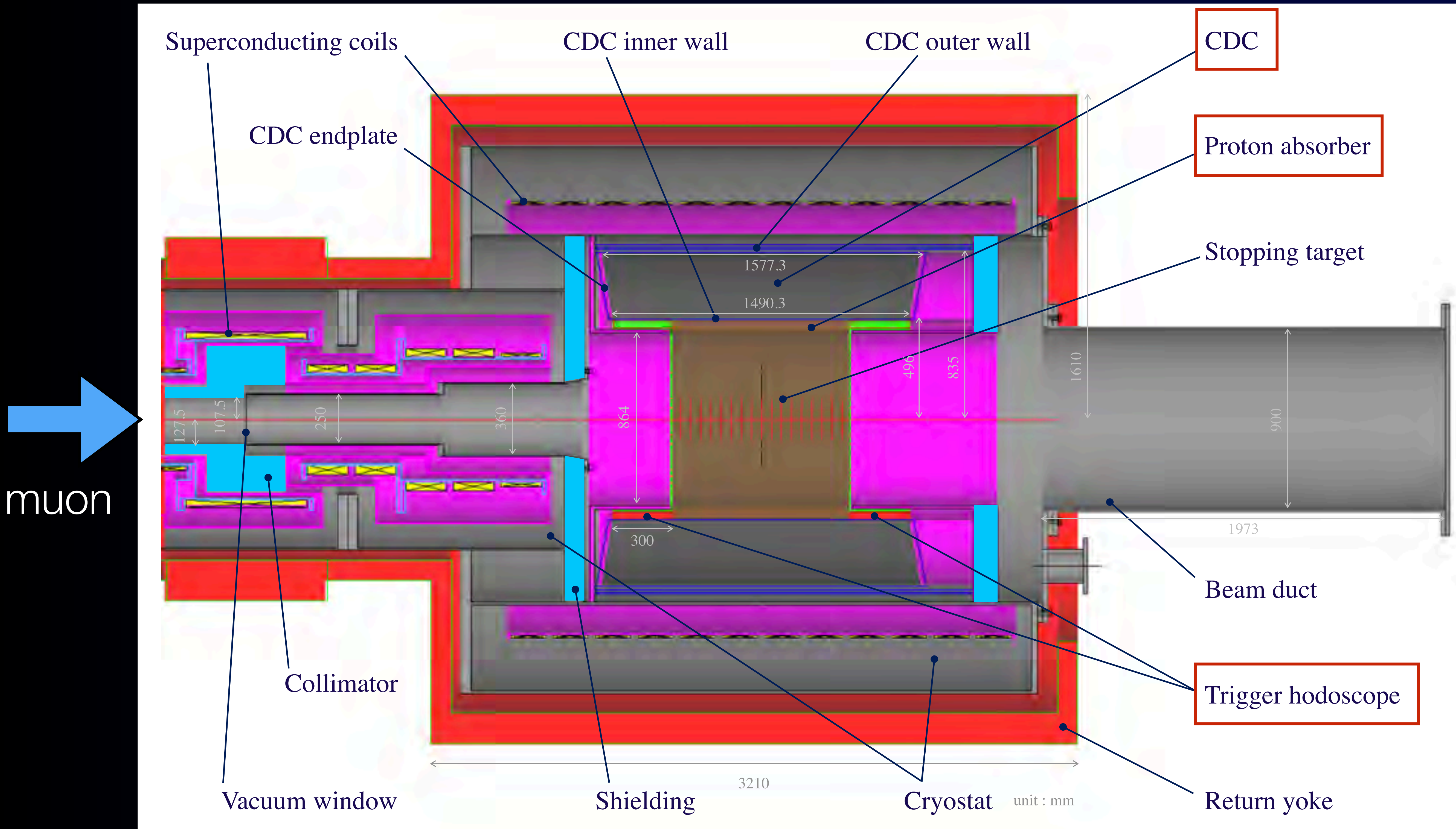


detector system

muon transport system

pion production system

CyDet (Cylindrical Detector): Layout



Signal Sensitivity with CyDet

Osaka University

Signal Acceptance

Table 28: *Breakdown of the $\mu^- N \to e^- N$ conversion signal acceptance.*

Event selection	Value	Comments
Geometrical acceptance	0.37	
Track quality cuts	0.66	
Momentum selection	0.93	103.6 MeV/c < P_e <106.0 MeV/c
Timing window	0.3	700 ns < t < 1100 ns
Trigger efficiency	0.8	
DAQ efficiency	0.8	
Track reconstruction efficiency	0.8	
Total	0.043	

Signal Sensitivity

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

- $f_{cap} = 0.6$
- $A_e = 0.043$
- $N_\mu = 1.23 \times 10^{16}$ muons

$$B(\mu^- + Al \to e^- + Al) = 3.1 \times 10^{-15}$$

$$B(\mu^- + Al \to e^- + Al) < 7 \times 10^{-15} \quad (90\% C.L.)$$

Muon intensity

about 0.00052 muons stopped/proton

With 0.4 μA, a running time of about 110 days is needed.

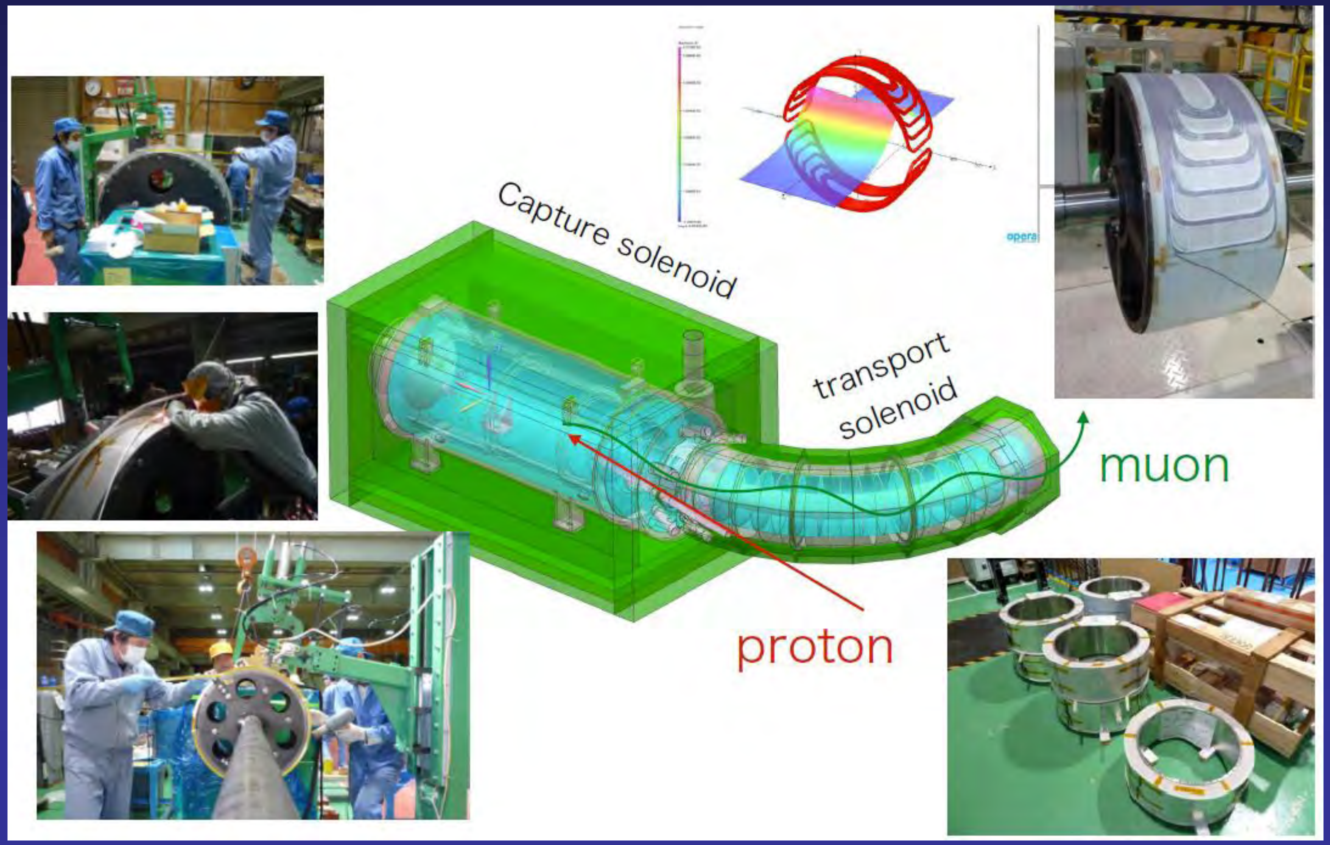
Background Estimate for μ-e conversion Search

Table 30: *Summary of the estimated background events for a single-event sensitivity of* 3.1×10^{-15} *with a proton extinction factor of* 3×10^{-11}.

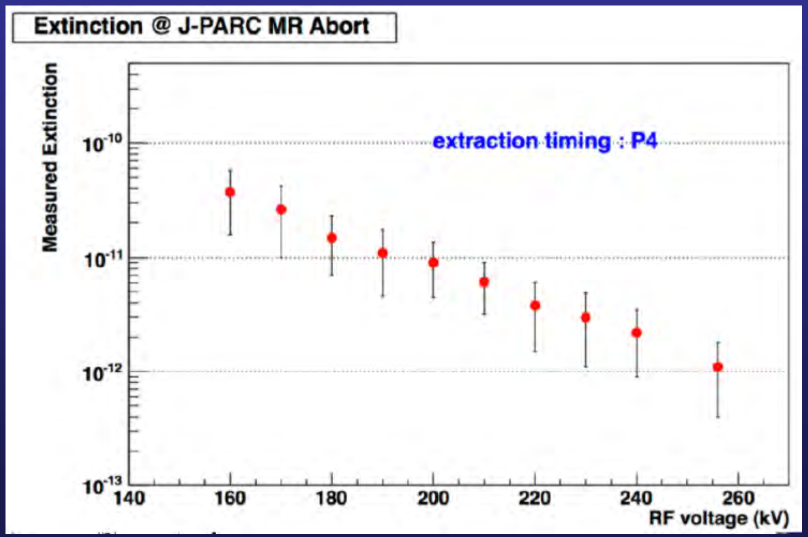
Type	Background	Estimated events
Physics	Muon decay in orbit	0.01
Physics	Radiative muon capture	5.6×10^{-4}
Physics	Neutron emission after muon capture	< 0.001
Physics	Charged particle emission after muon capture	< 0.001
Prompt Beam	Beam electrons (prompt)	8.3×10^{-4}
Prompt Beam	Muon decay in flight (prompt)	$\leq 2,0 \times 10^{-4}$
Prompt Beam	Pion decay in flight (prompt)	$\leq 2.3 \times 10^{-3}$
Prompt Beam	Other beam particles (prompt)	$\leq 2.8 \times 10^{-6}$
Prompt Beam	Radiative pion capture(prompt)	2.3×10^{-4}
Delayed Beam	Beam electrons (delayed)	~ 0
Delayed Beam	Muon decay in flight (delayed)	~ 0
Delayed Beam	Pion decay in flight (delayed)	~ 0
Delayed Beam	Radiative pion capture (delayed)	~ 0
Delayed Beam	Anti-proton induced backgrounds	0.007
Others	Electrons from cosmic ray muons	< 0.0001
Total		0.019

Construction of COMET Phase-I

Construction of COMET experimental hall and proton beam line.

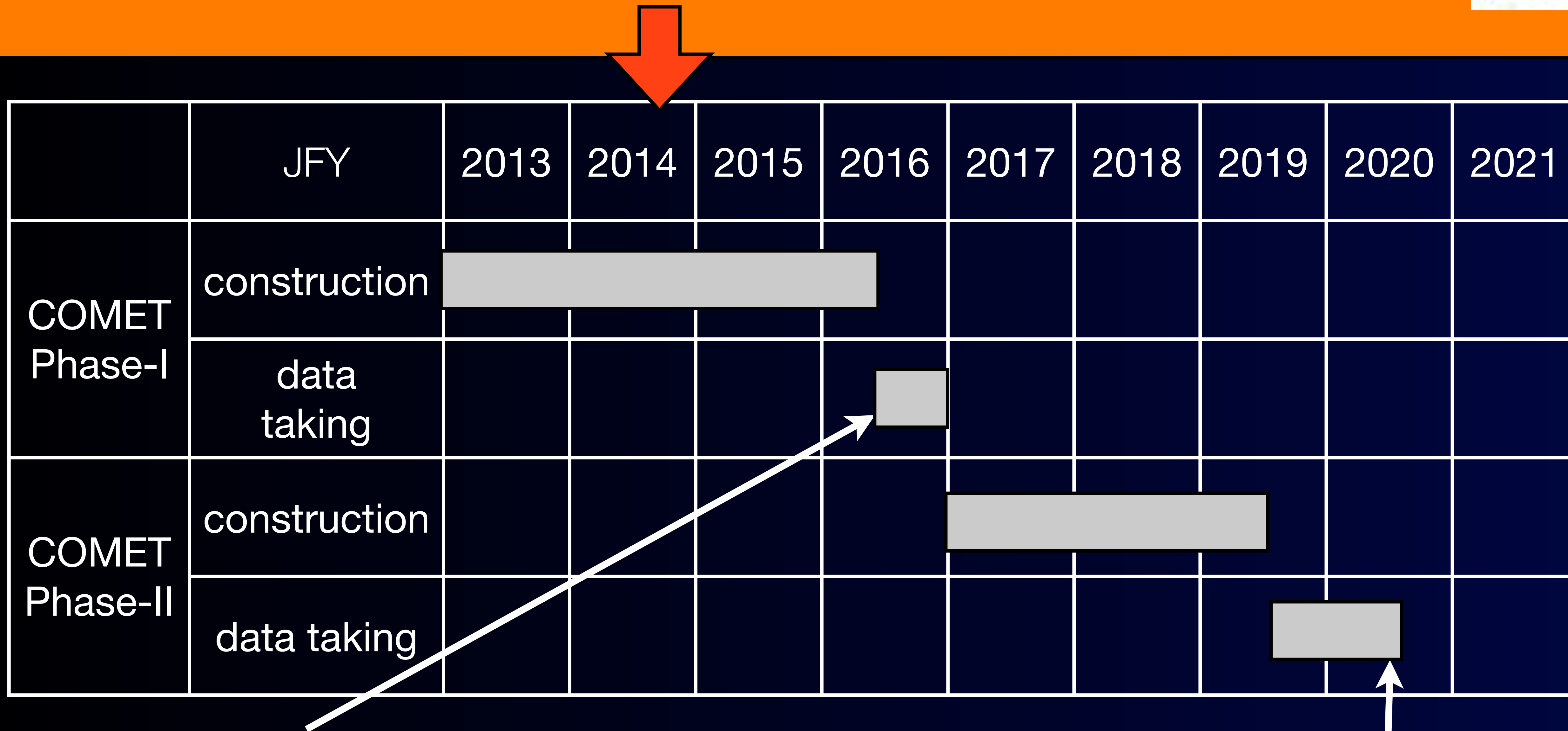


Construction of solenoids.



Beam extinction measured in May 2014. 8GeV beam without the slow extraction.

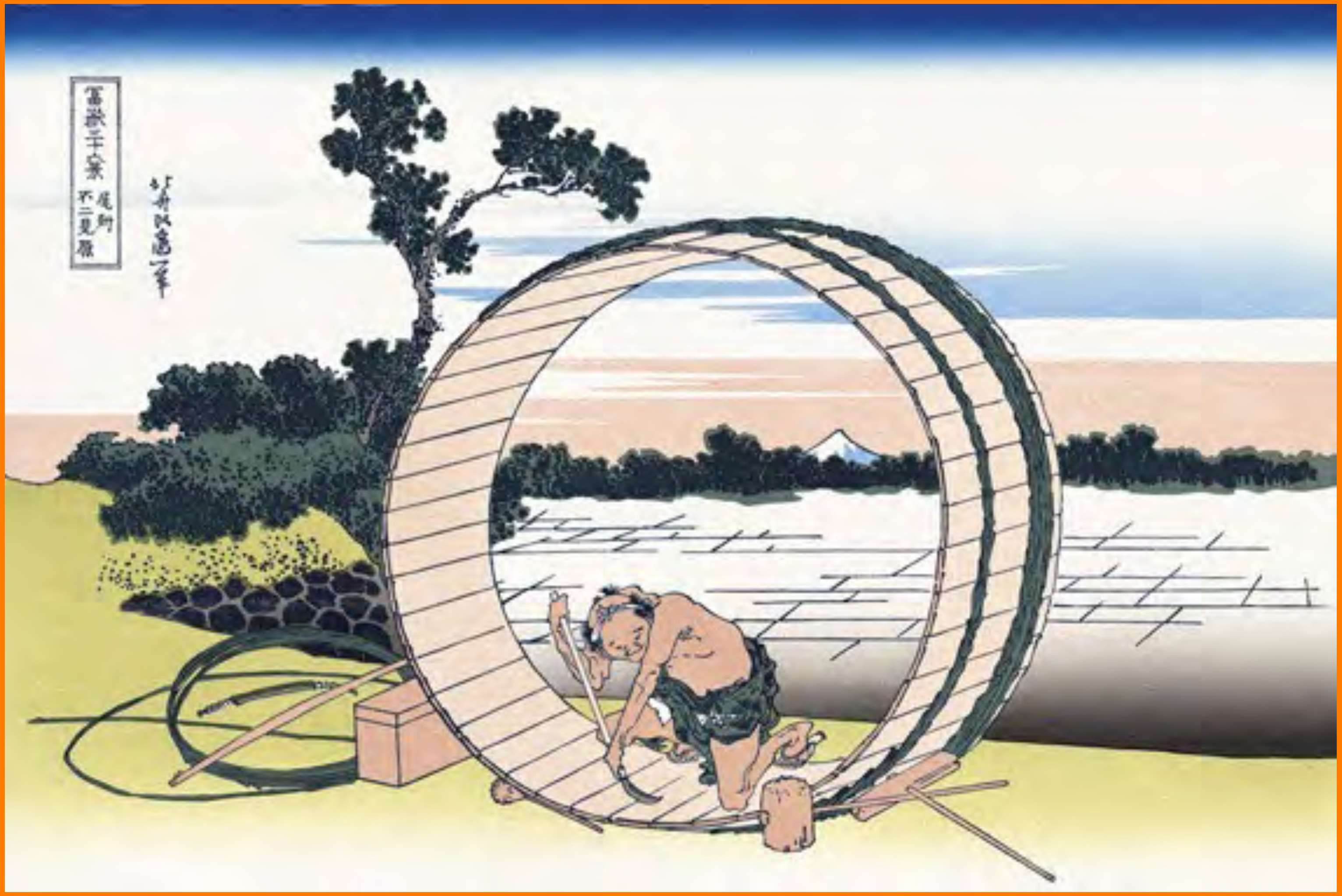
Wished Schedule of COMET



COMET Phase-I :
2016 ~
S.E.S. ~ 3×10^{-15}
(for 110 days
with 3.2 kW proton beam)

COMET Phase-II :
2019~
S.E.S. ~ 3×10^{-17}
(for 2×10^{7} sec
with 56 kW proton beam)

Breakthrough
in Muon Sources



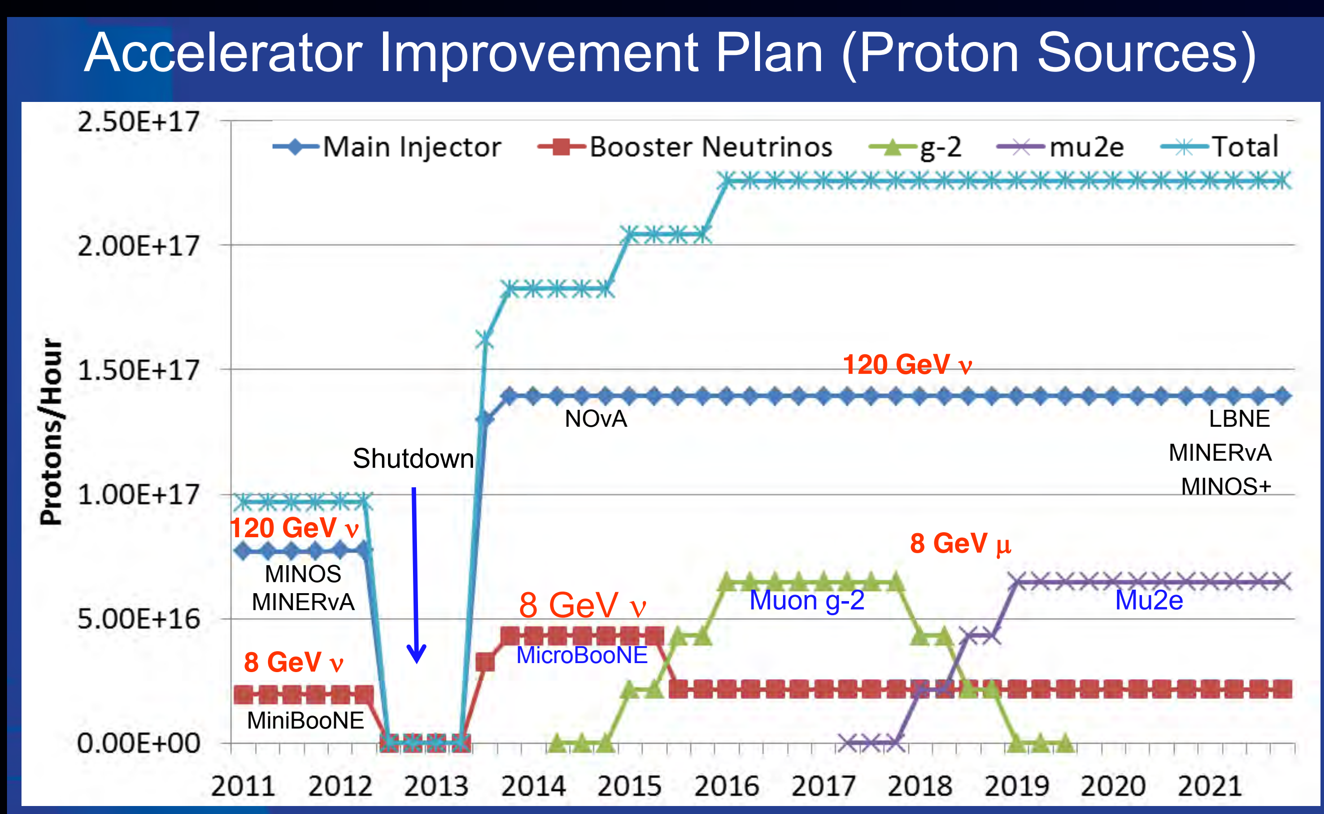
High Energy Scale Reach in CLFV

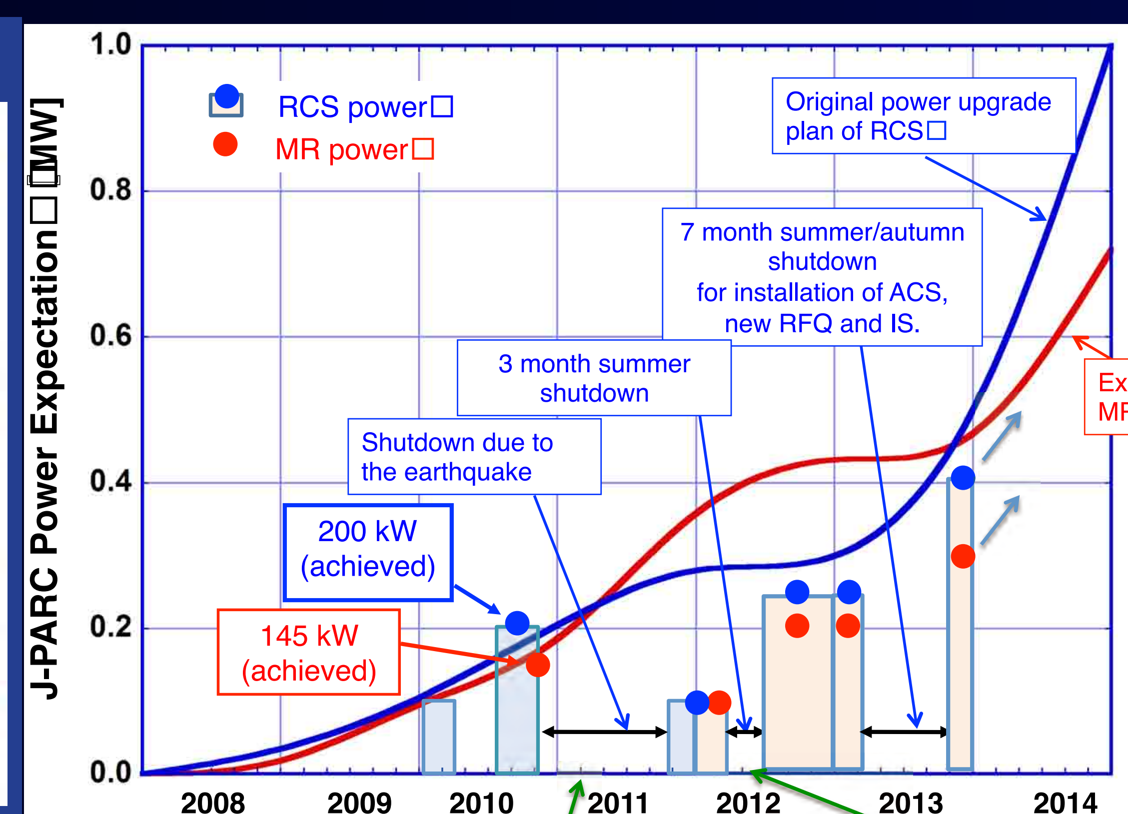
$$R \sim \frac{1}{\Lambda^4}$$

↓

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)



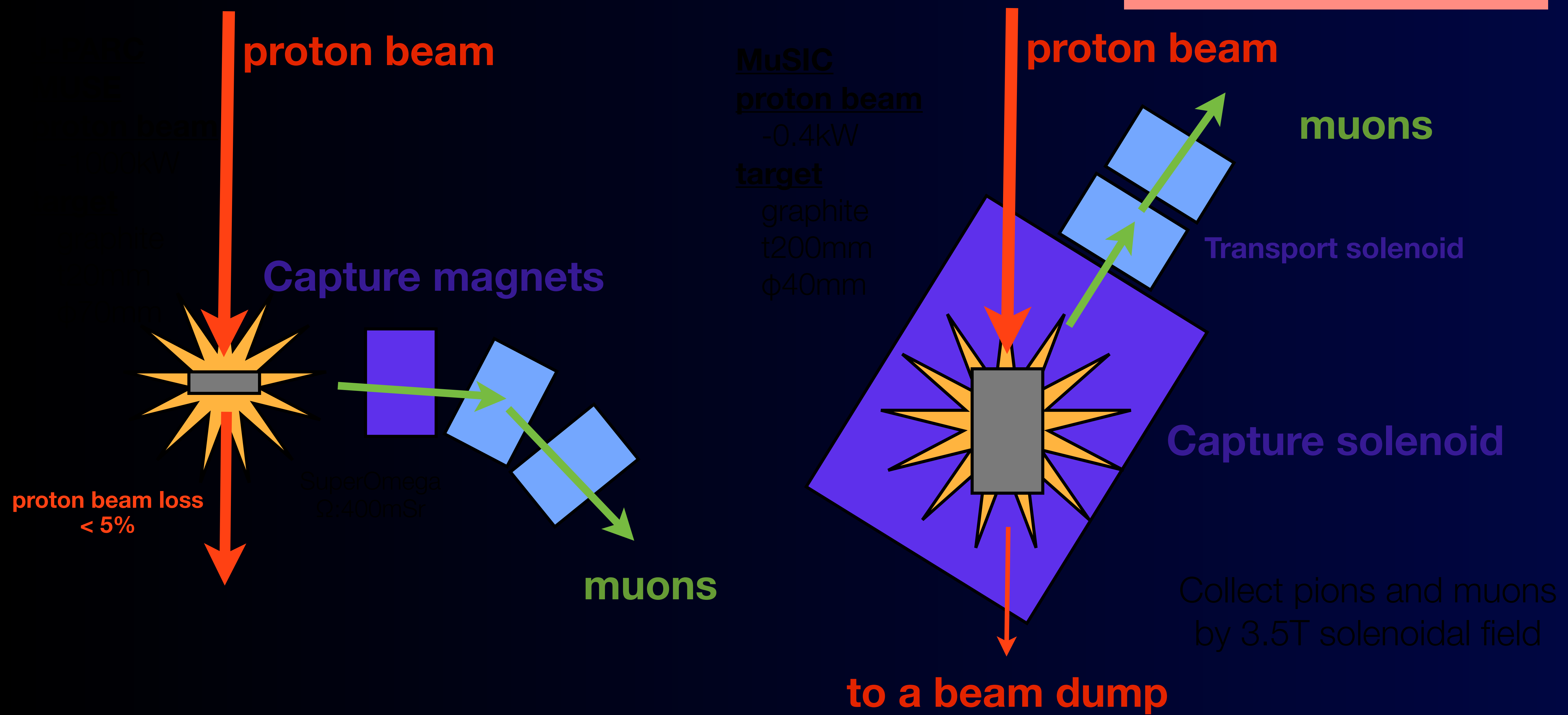


Production and Collection of Pions and Muons

Conventional muon beam line

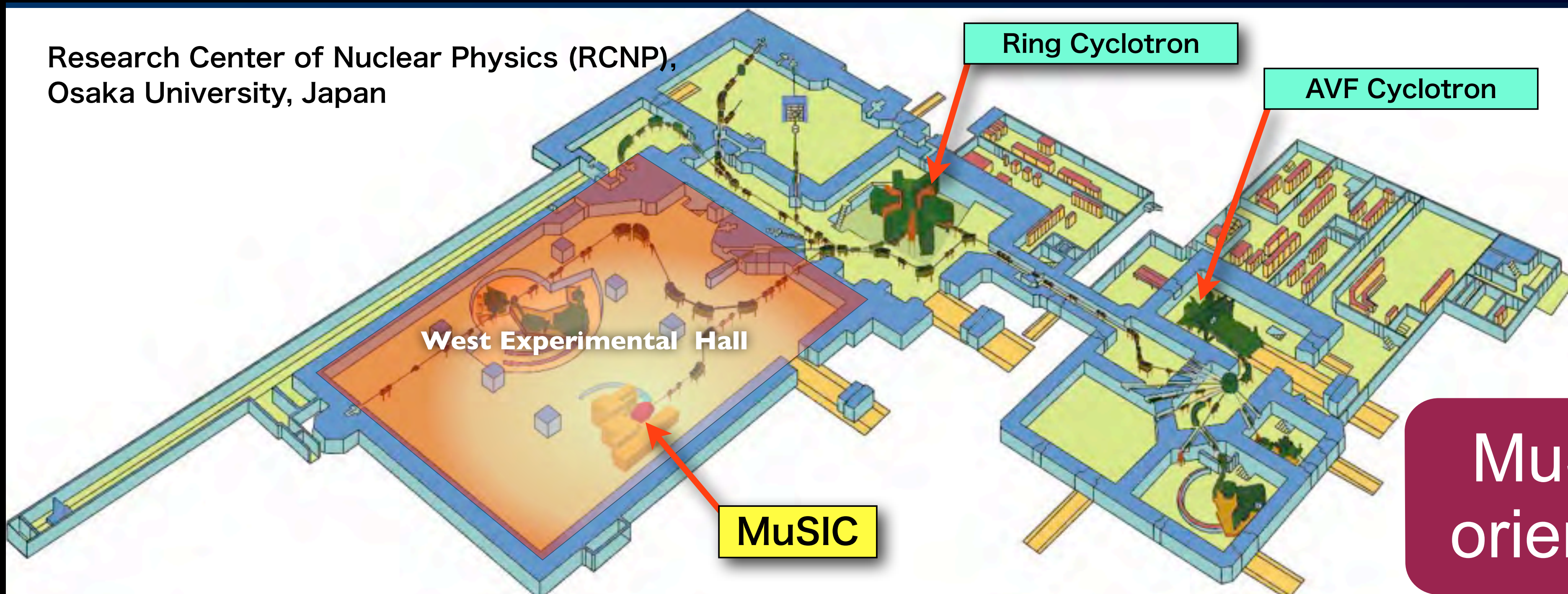
Much efficient

MuSIC,COMET,PRISM,
Neutrino factory,
Muon collider



Large solid angle & thick target

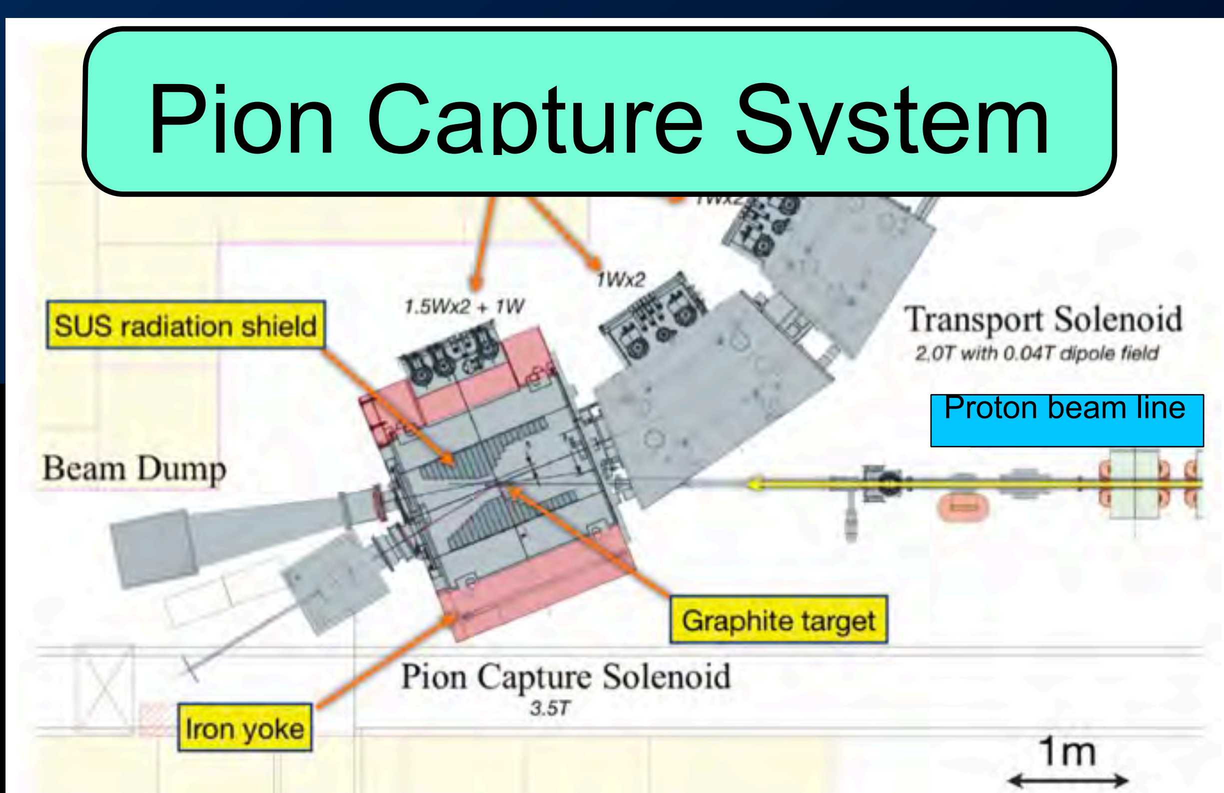
MuSIC Facility at Osaka University - Front end of COMET -



RCNP cyclotron
400 MeV, 1μA

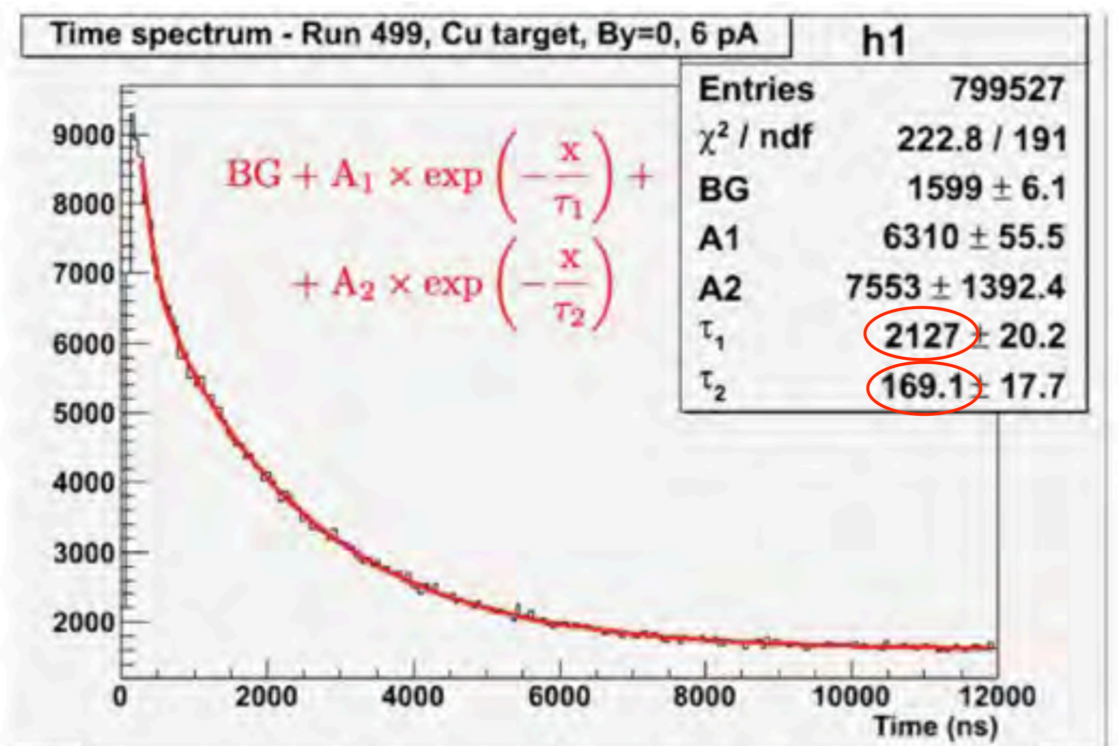
MuSIC = Muon Science oriented Intense Channel

Pion Capture System

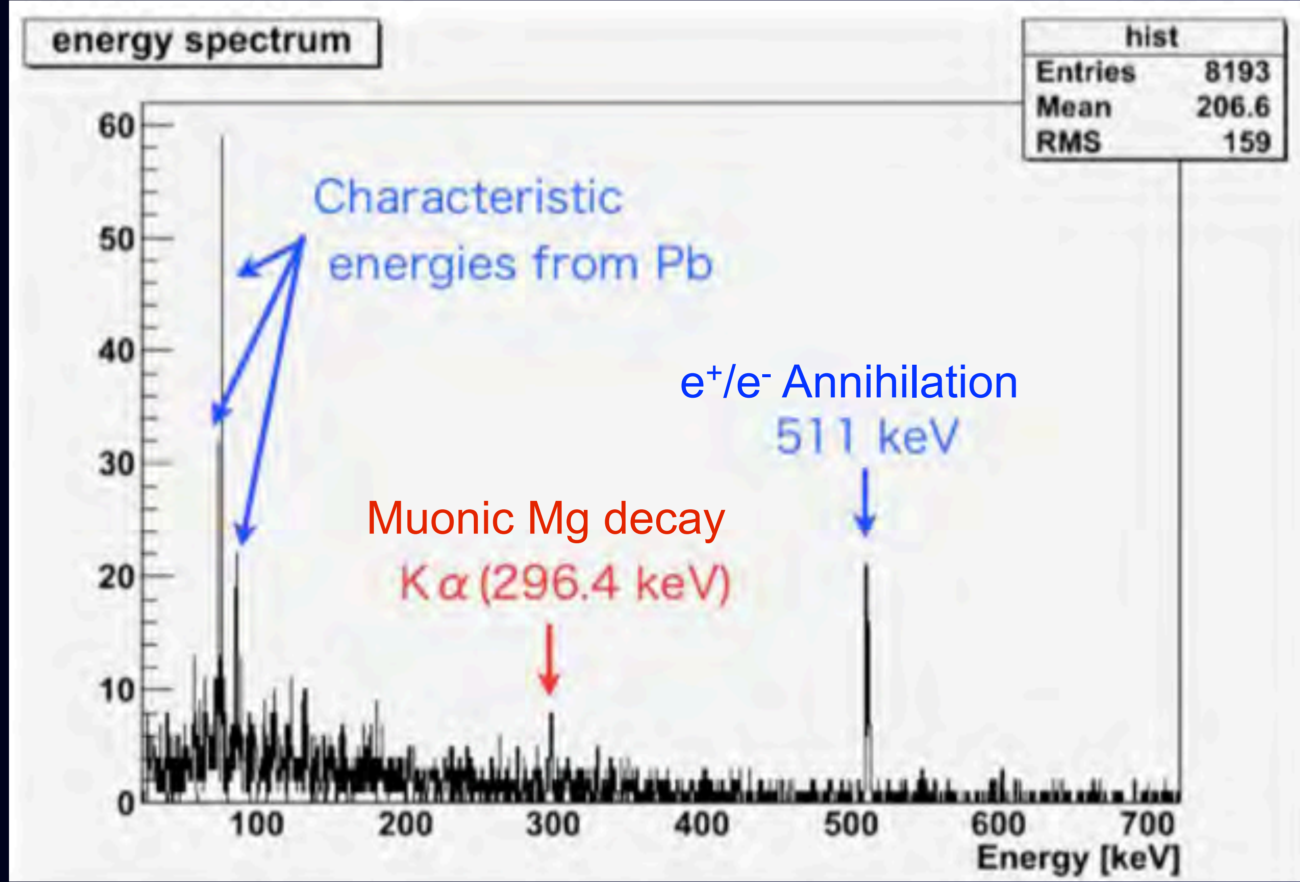


MuSIC Facility at Osaka University
Muon Production Efficiency (x1000)

Osaka University



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



positive muons

negative muons

MuSIC muon yields

μ^+ : 3x10^8/s for 400W

μ^- : 1x10^8/s for 400W

cf. 10^8/s for 1.3MW @PSI
Requirements of x10^3 achieved...

Demonstration of Pion Capture System

High Energy Scale Reach in CLFV

Osaka University

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

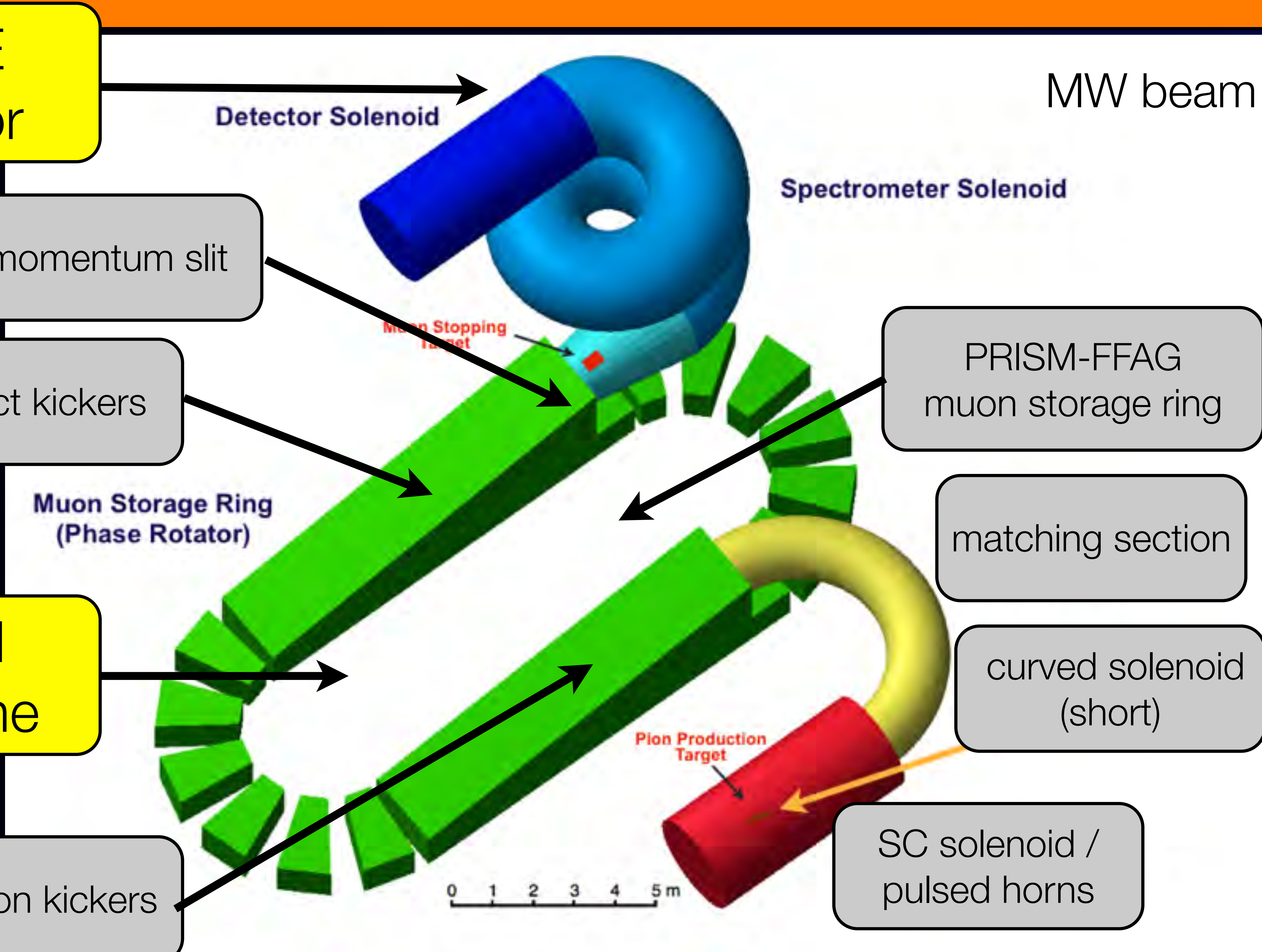
Can we improve the Λ reach by an order of magnitude ?
We must have at least 10^4 times the number of parent particles in rare decays.

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

PRISM/PRIME : Future Search for μ-e Conversion at 3×10^{-19}

PRISM

Osaka University



Summary

- Search for CLFV would provide one of the best opportunities to find new physics beyond the Standard Model.
- Future prospects on the searches for CLFV in muon decays are promising.
- High intensity muon sources provides improvements ($\times 10^4$) in μ-e conversion search
- COMET is aiming at SES~3×10^{-17}, and COMET Phase-I is doing SES~3×10^{-15}.
- COMET Phase-I is planned to start in 2016.