Physics with Low-energy, High-brightness Muon Beams - Future -

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Physics with Low-energy, High-brightness Muon Beams - Future -

Yoshitaka Kuno
Department of Physics
Osaka University, Japan

November 18, 2015
Discussions on Scientific Potential of Muon Beams
CERN

Outline

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- Physics Potentials
- Muon Static Properties
- CLFV
- Muon CLFV Experiments
- Future Prospects (μ-e conversion)
- Summary

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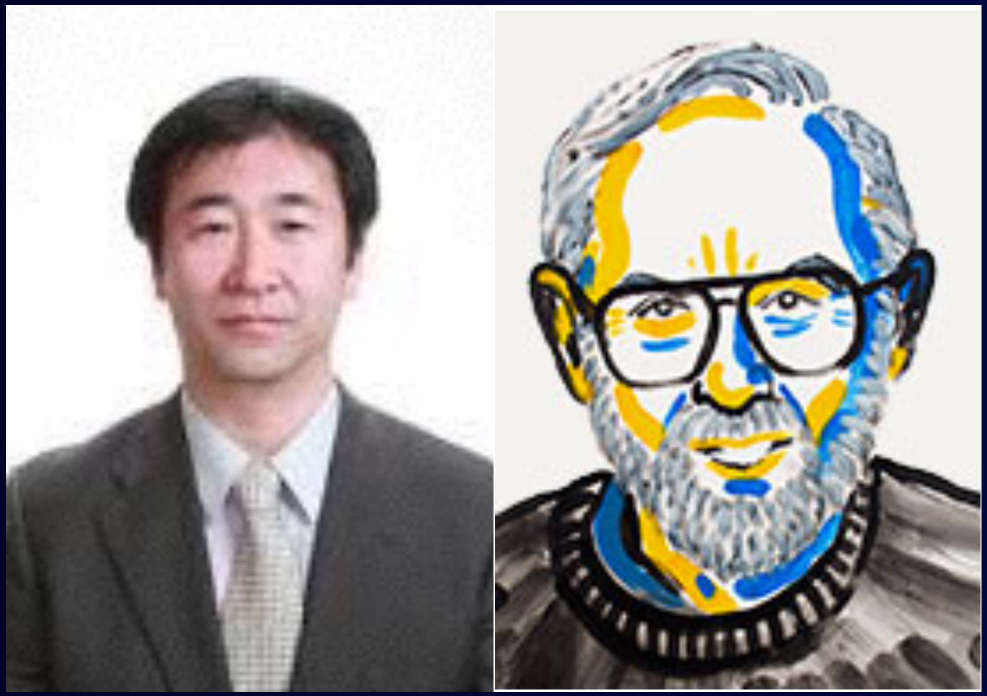

Nobel physics 2015

Physics
Potentials

New Physics Beyond the Standard Model

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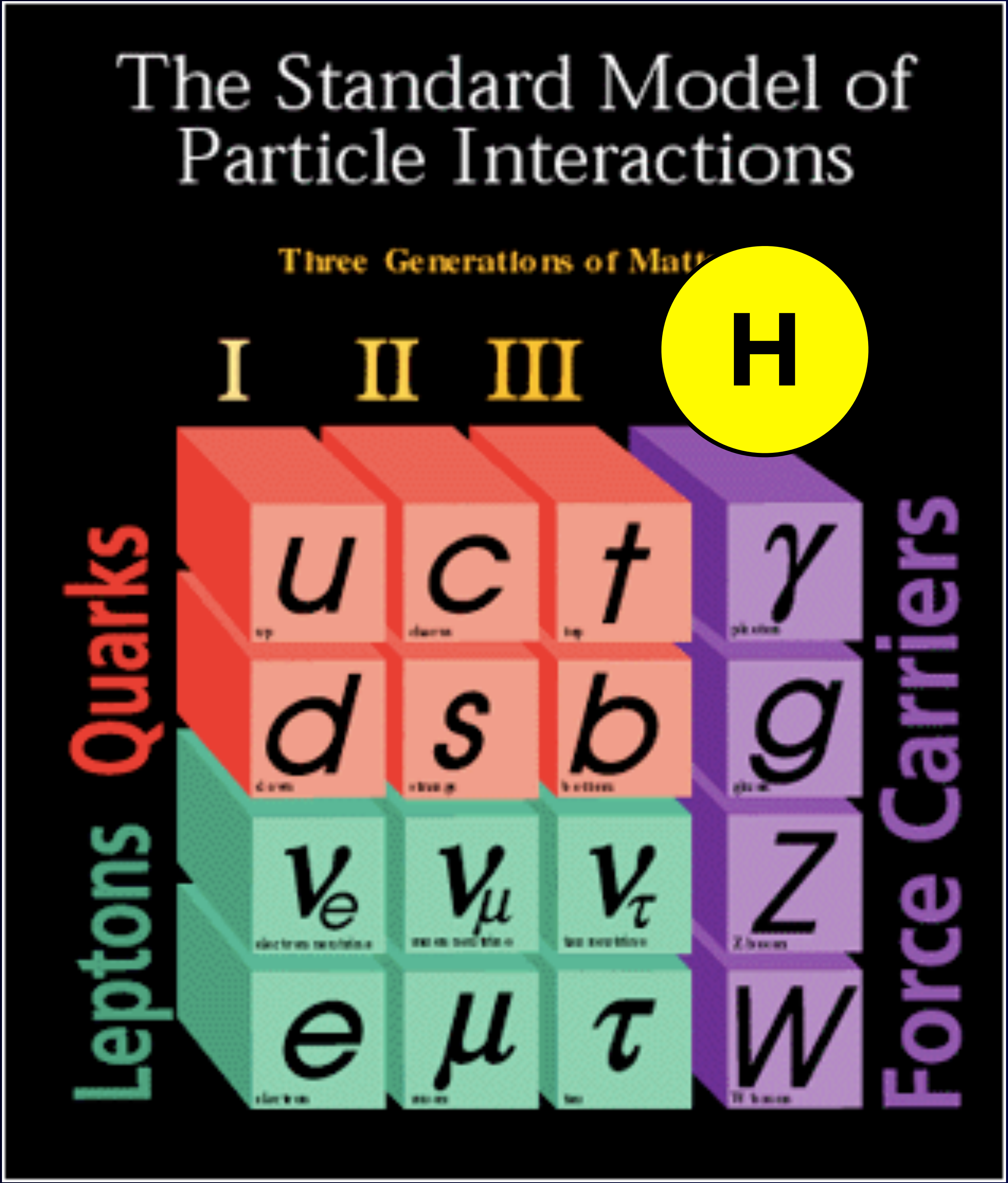
New Physics Beyond the Standard Model

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



Low Energy Muon Particle Physics

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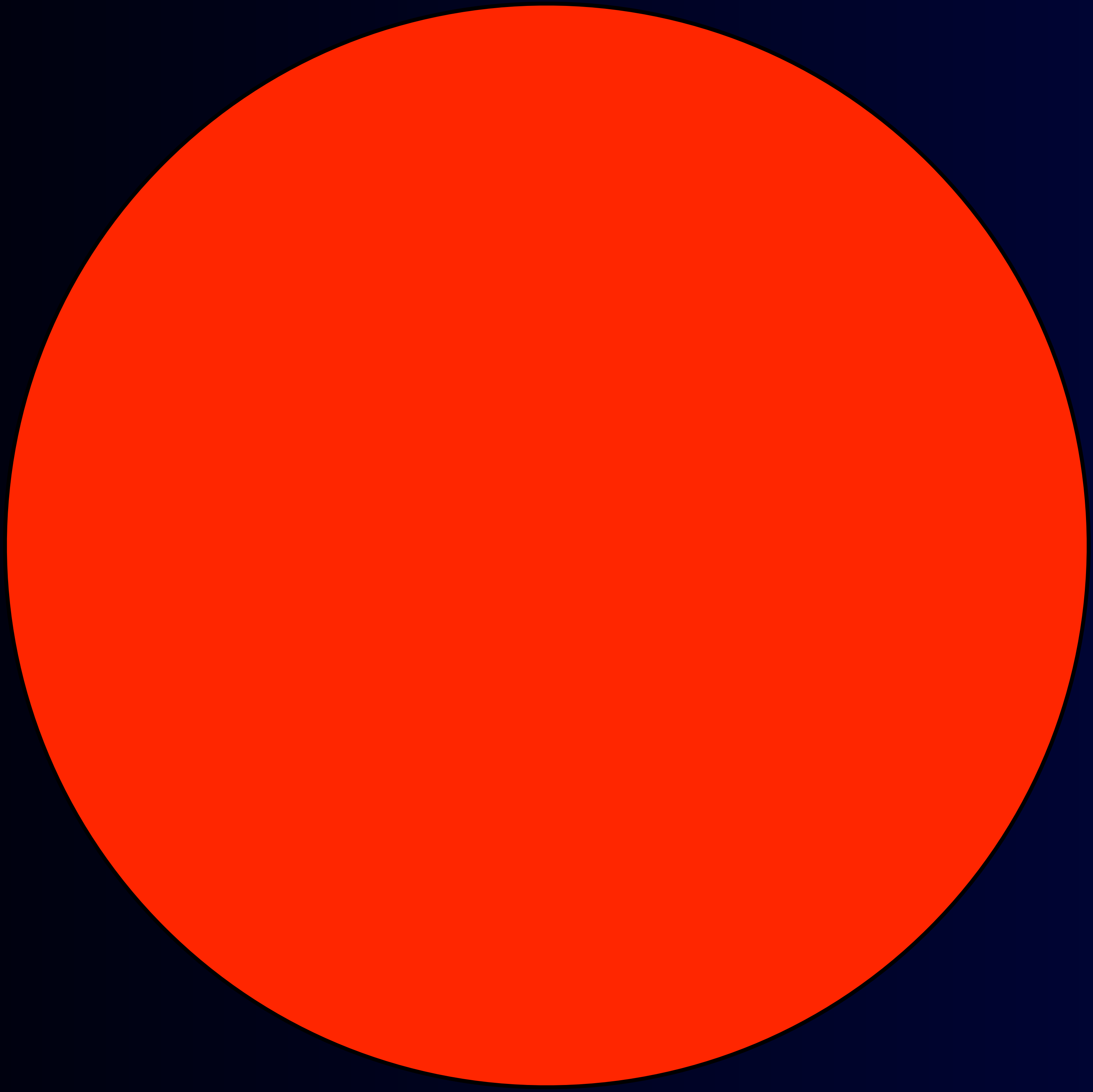

Low Energy Muon Particle Physics

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charged lepton flavor violation (CLFV)

muon decay parameters

muon EDM

muon g-2

Lamb shift of muonic atom

Low Energy Muon Particle Physics

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Muon
Static
Properties

Muon g-2:
Current Status and Expected Progress in Future

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Current Status and Expected Progress in Future

$$a_\mu = (g_\mu - 2)/2$$

Experimental value

$$a_\mu^{\rm exp} = 116592089(63) \times 10^{-11}$$

Theoretical value

$$a_\mu^{\rm SM} = 116591828(50) \times 10^{-11}$$

Deviation (more than 3σ)

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = 261(80) \times 10^{-11}$$

Experimental and theoretical uncertainties are almost the same.

Polarized muon beam needed.

Muon g-2: Current Status and Expected Progress in Future

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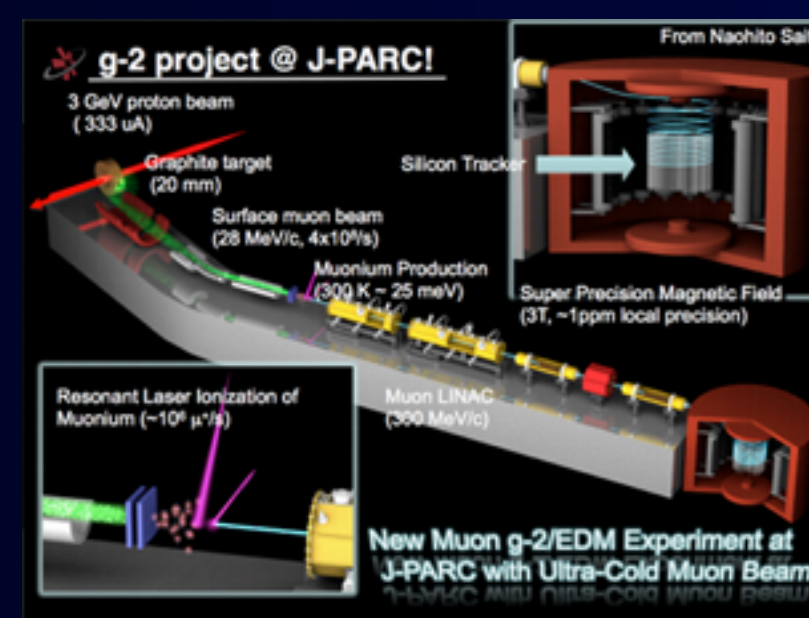
Polarized muon beam needed.

- E989@FNAL: aims at <0.14ppm (a factor of 4 improvement).

- E34@J-PARC: 0.37 then 0.14ppm



Muon EDM:
Current Status and Expected Progress in Future

Muon EDM: Current Status and Expected Progress in Future

$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

current limit (from g-2)

$$d_\mu < 2.8 \times 10^{-19} e \cdot cm$$

mass scaling of lepton EDM

$$d_\mu^{\mathrm{NP}} \propto \frac{m_\mu}{\tilde{m}^2}$$

$$d_e < 8.7 \times 10^{-29} e \cdot cm$$

Some theoretical models avoid mass scaling.

Polarized muon beam needed.

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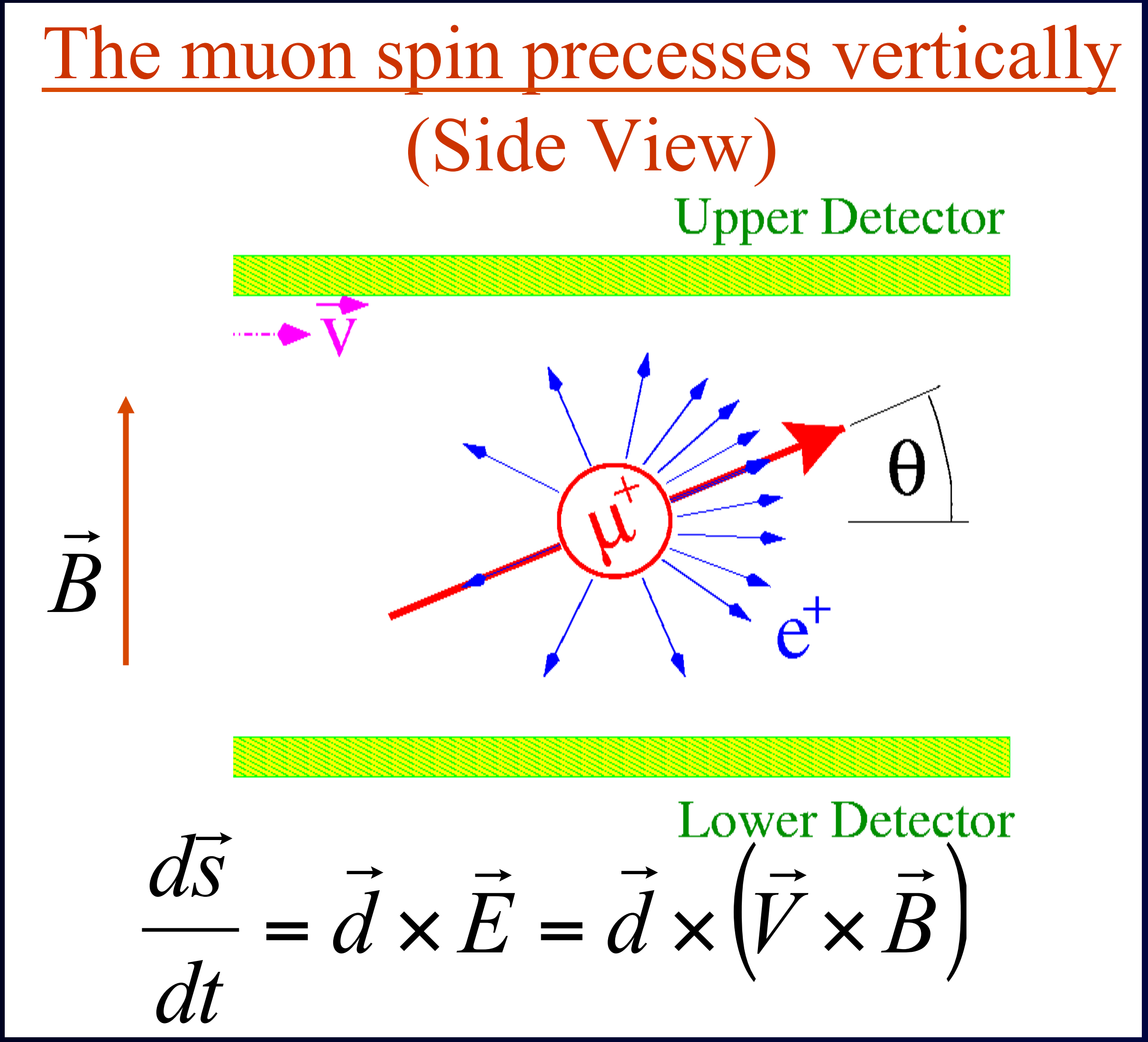
Some theoretical models avoid mass scaling.

Polarized muon beam needed.

- E34 at J-PARC: aims at EDM $d_\mu < 1.3 \times 10^{-21}$ e·cm (statistical only).
- BNL proposal on muon EDM $d_\mu < 10^{-24}$ e·cm in a storage ring.



CLFV

Flavour Transitions in Quarks, Neutrinos, and Charged Leptons

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Flavour Transitions in Quarks, Neutrinos, and Charged Leptons

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Quarks

Flavour Transitions in Quarks, Neutrinos, and Charged Leptons

Quarks

Quark transition observed

Flavour Transitions in Quarks, Neutrinos, and Charged Leptons

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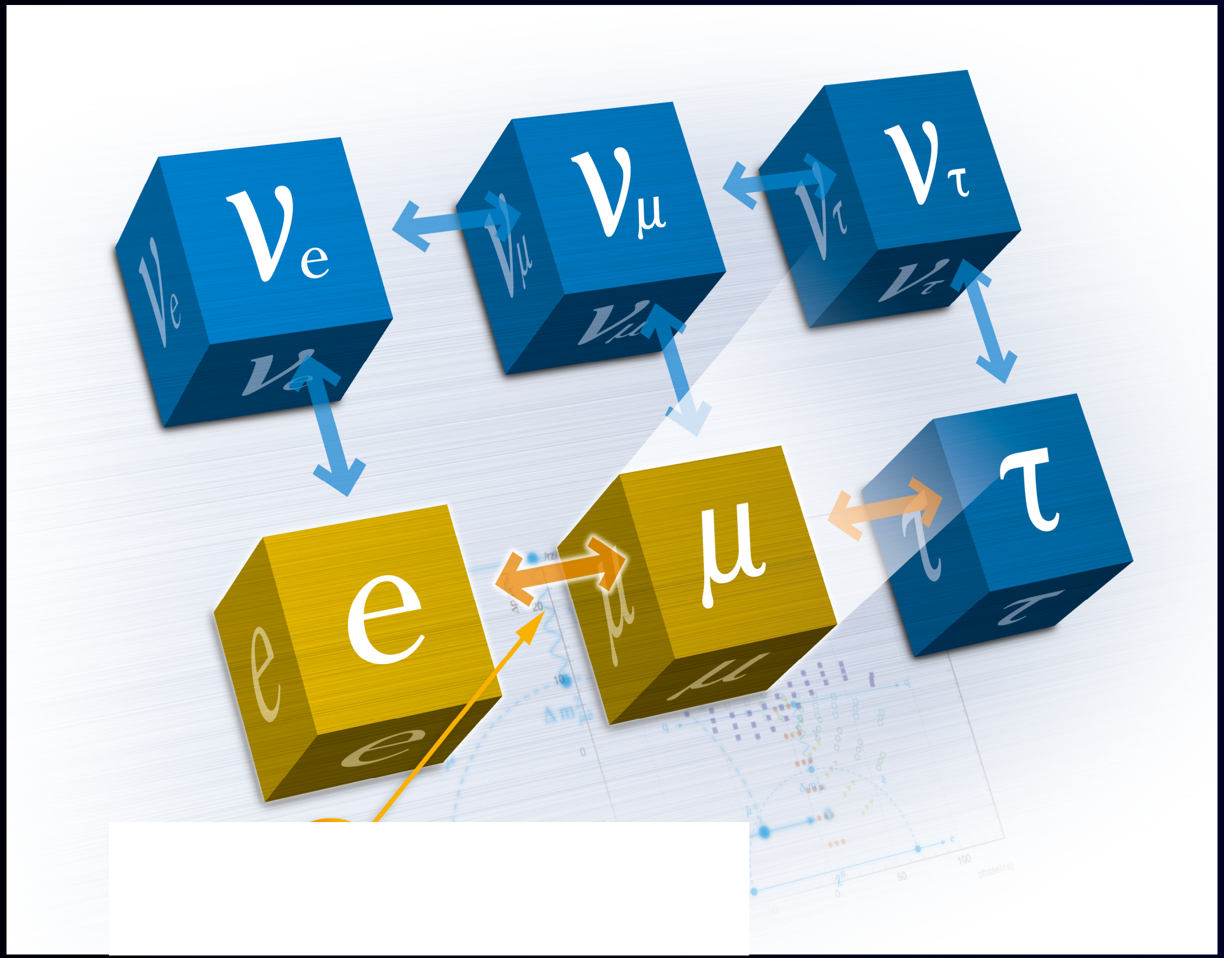

Flavour Transitions in Quarks, Neutrinos, and Charged Leptons

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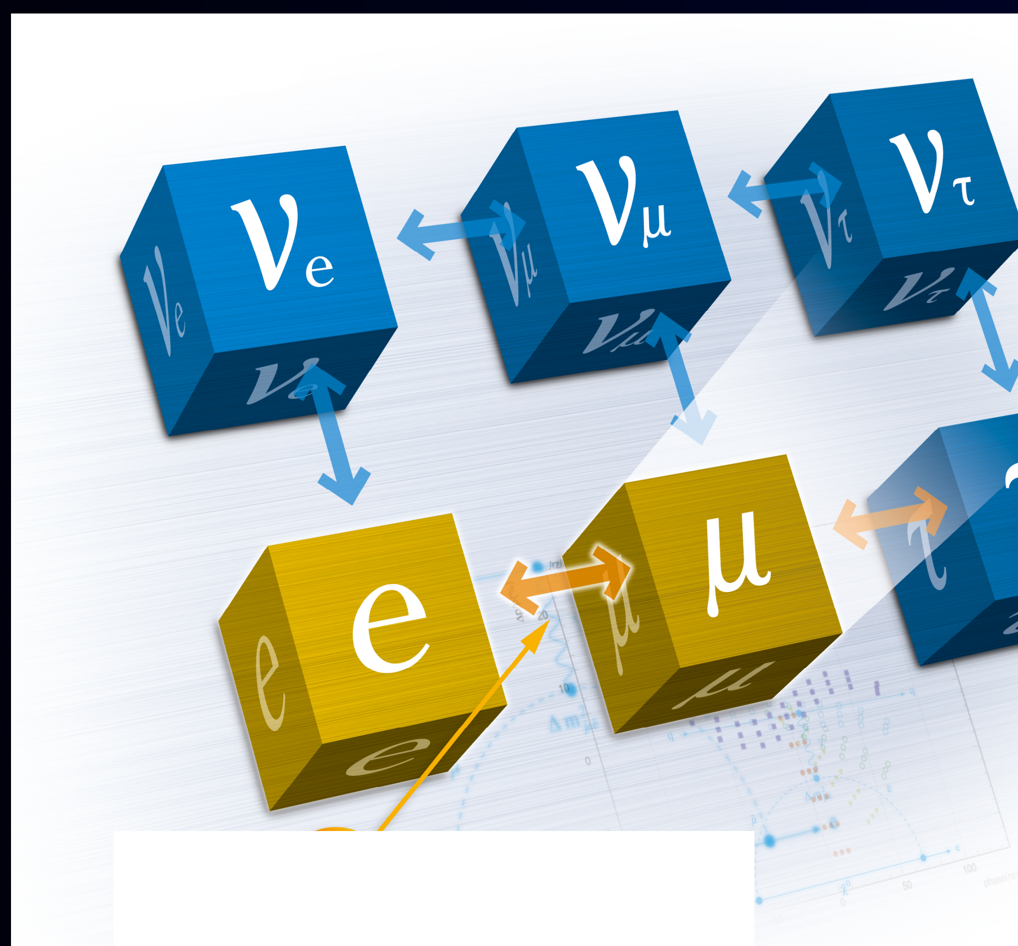
Quark transition observed

Leptons



Neutrino transition observed

Flavour Transitions in Quarks, Neutrinos, and Charged Leptons

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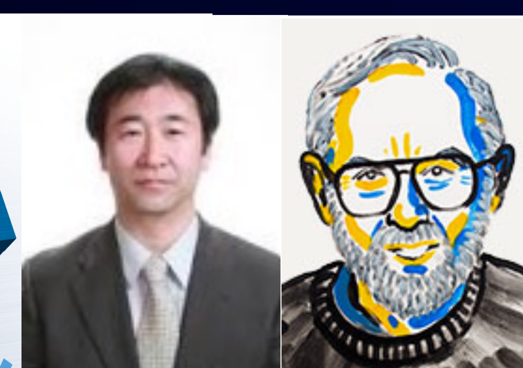


Neutrino transition observed

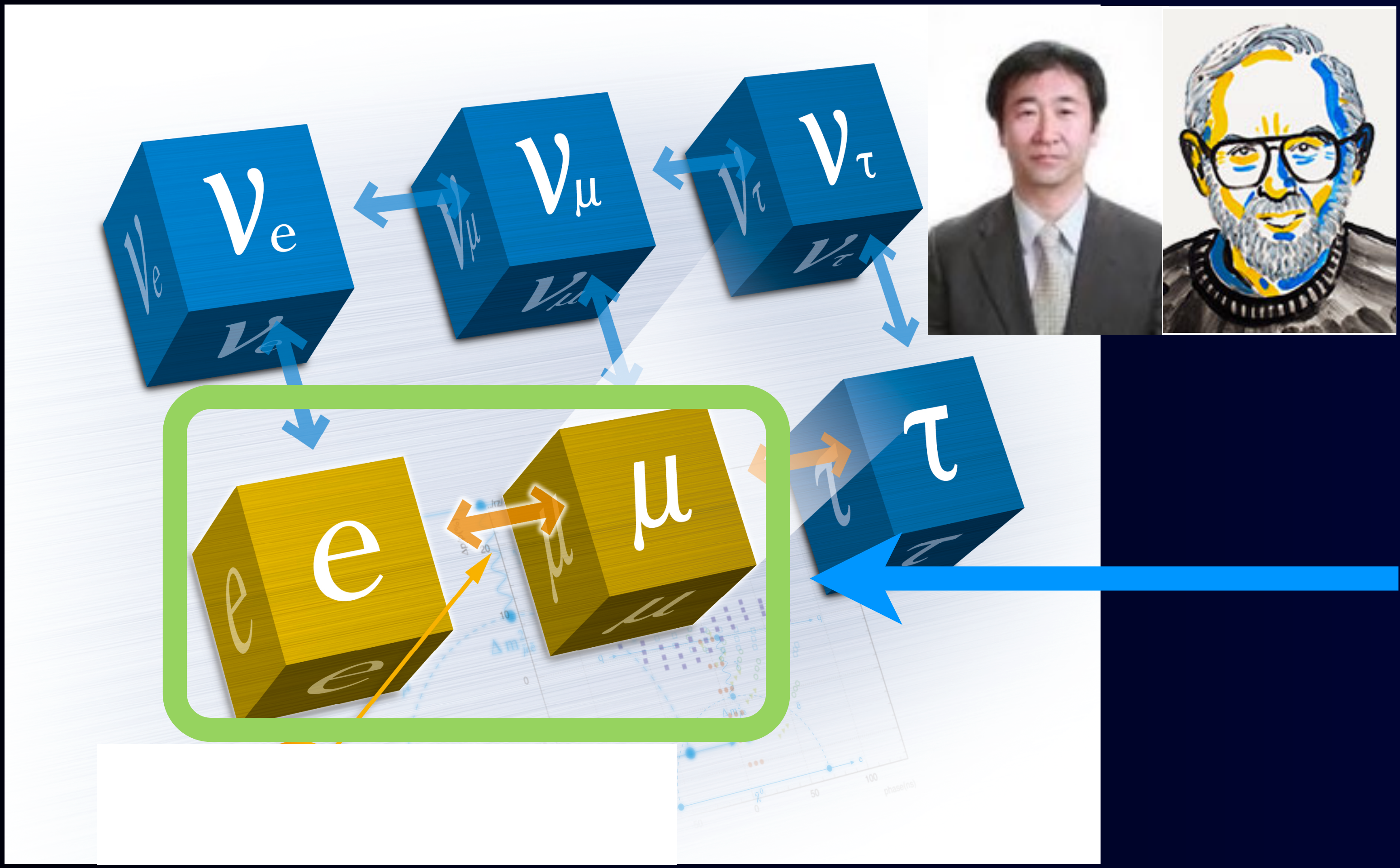
Charged lepton transition not observed.

Flavour Transitions in Quarks, Neutrinos, and Charged Leptons

Quarks

Quark transition observed

Leptons



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CLFV

Effective Lagrangian with New Physics

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

dimension 6

Λ is the energy scale of new physics （$\sim m_{NP}$)

C_{NP} is the coupling constant.

Effective Lagrangian with New Physics

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dimension 6

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

C_{NP} is the coupling constant.

New Physics could be….

very high energy scale Λ with C_{NP}~1

or

very small C_{NP} with not-high energy Λ

Effective Lagrangian with New Physics

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ex: Charged lepton flavor violation (CLFV), μ→eγ ($B<5.7\times10^{-13}$)

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

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

$\Lambda > O(10^5)$ TeV with $C_{\mu e} \sim O(1)$

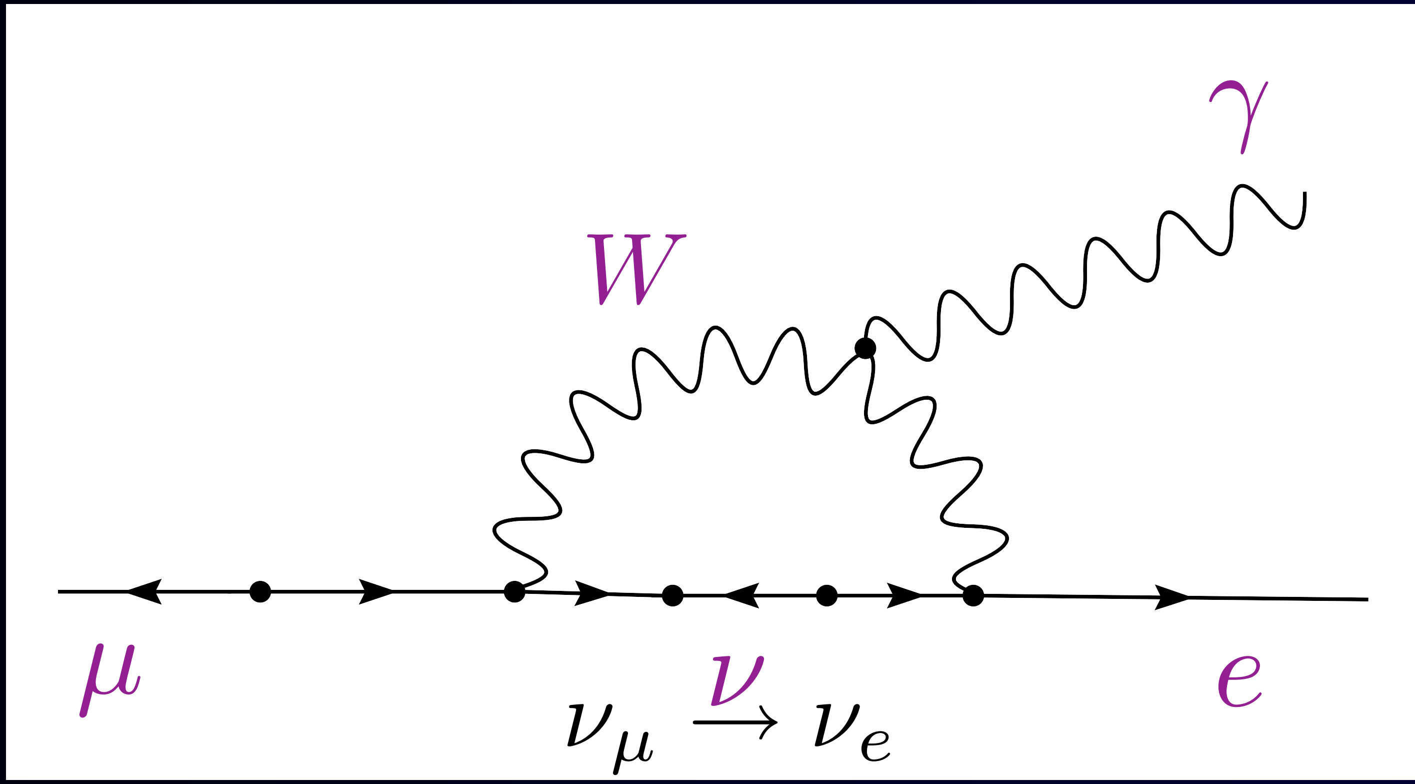
or

$C_{\mu e} \sim O(10^{-9})$ with $\Lambda < O(1)$ TeV

No SM Contribution in Charged Lepton Flavor Violation (CLFV)

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

GIM suppression



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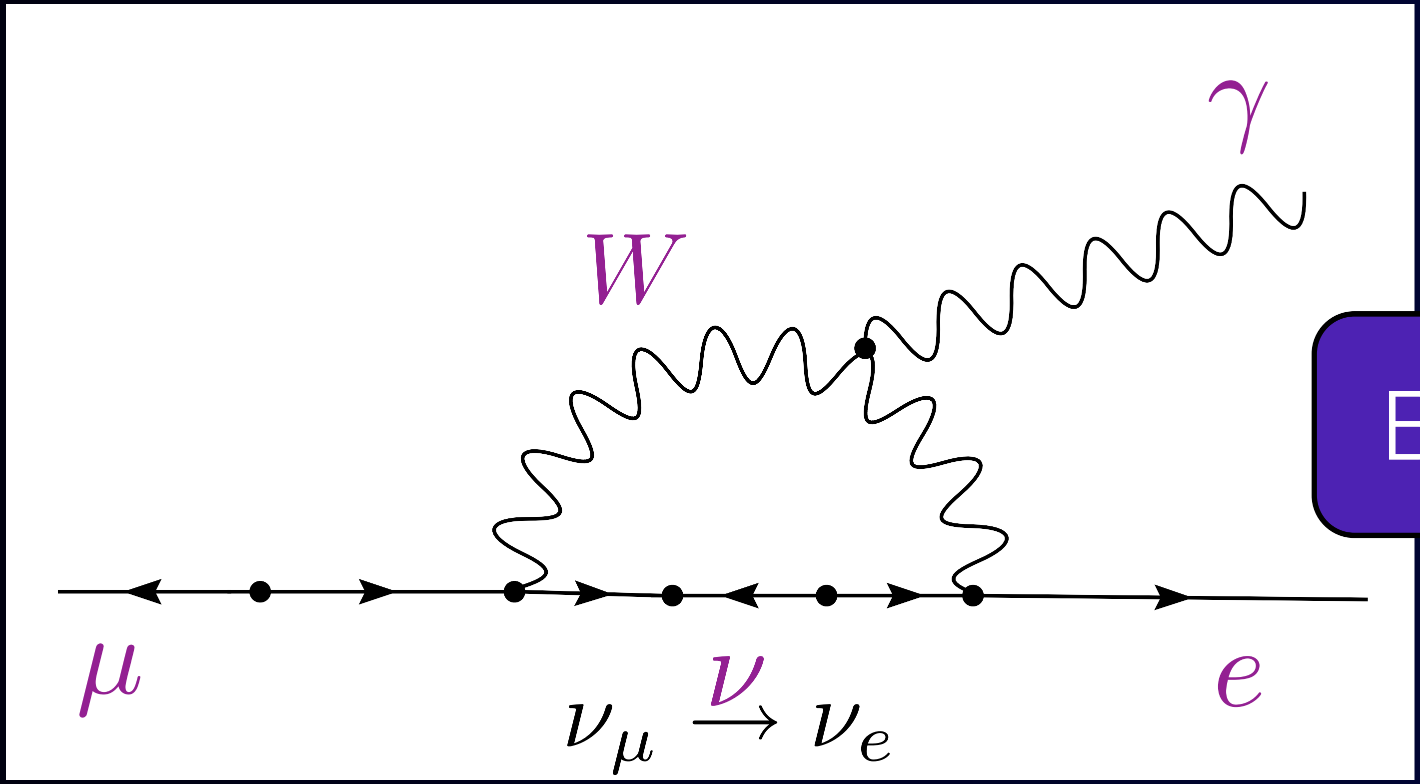

BR~O(10^{-54})

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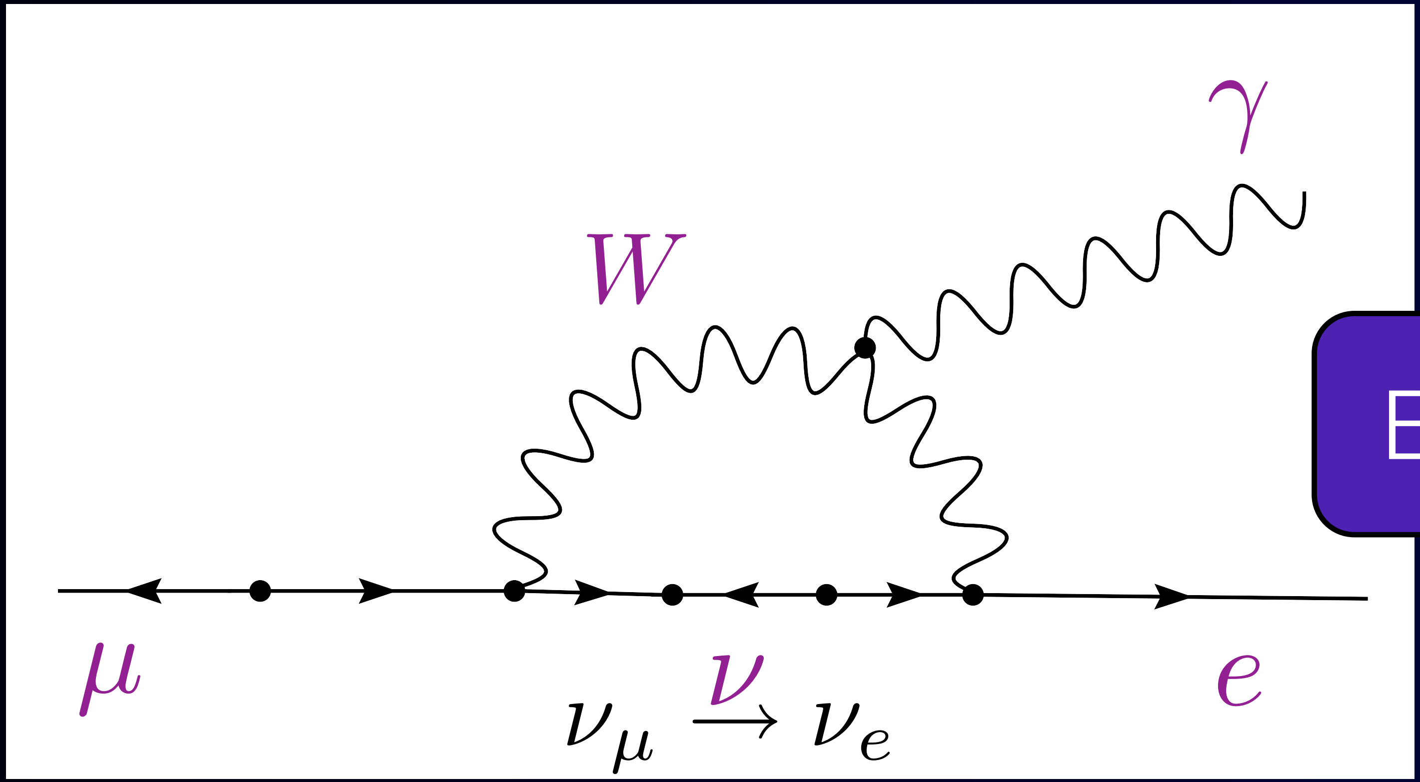

BR~O(10^{-54})

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

Quark FCNC vs. Lepton FCNC

Quark FCNC vs. Lepton FCNC

SM suppressed process

amplitude

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

subject to uncertainty of SM prediction

NP contribution ~ O(ε)

rate

SM-forbidden process

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

could go higher energy scale

NP contribution ~ O(ε^2)

Quark FCNC vs. Lepton FCNC

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SM-forbidden process

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

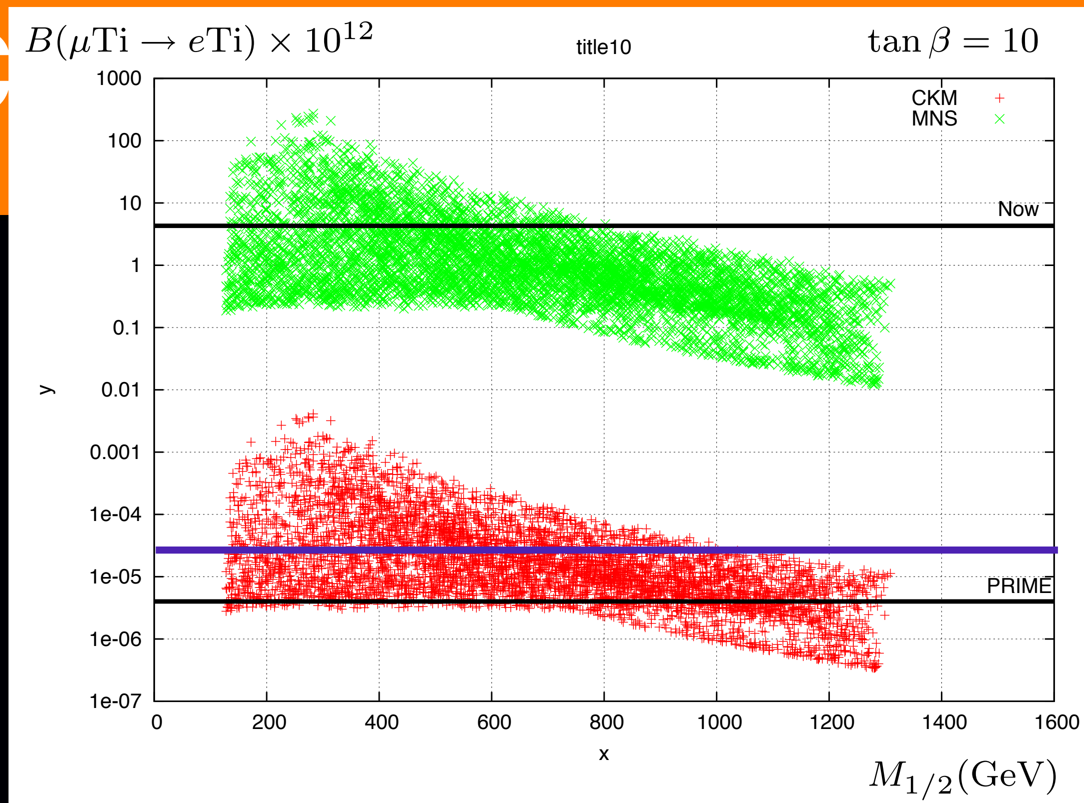
could go higher energy scale

NP contribution ~ O(ε^2)

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

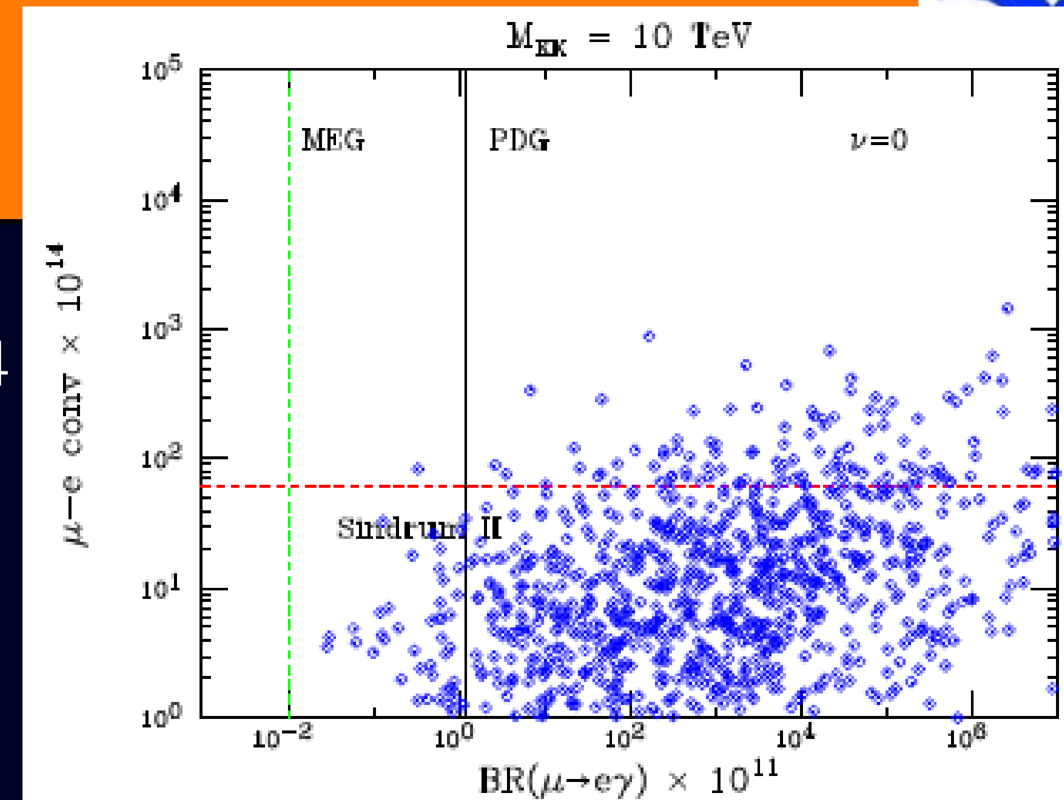
CLFV Predictions

SUSY model

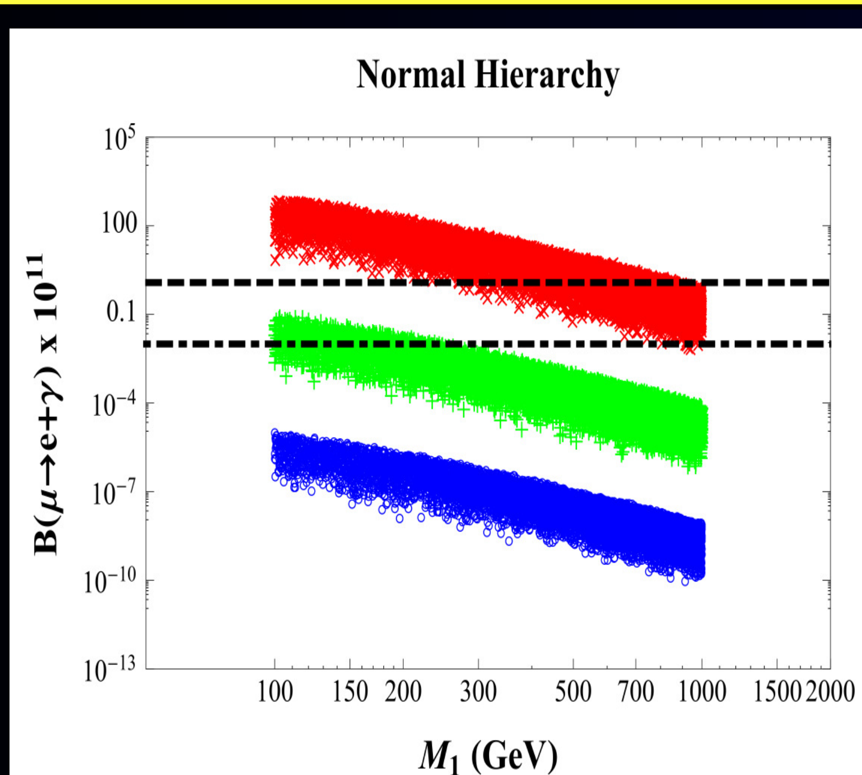


10^4

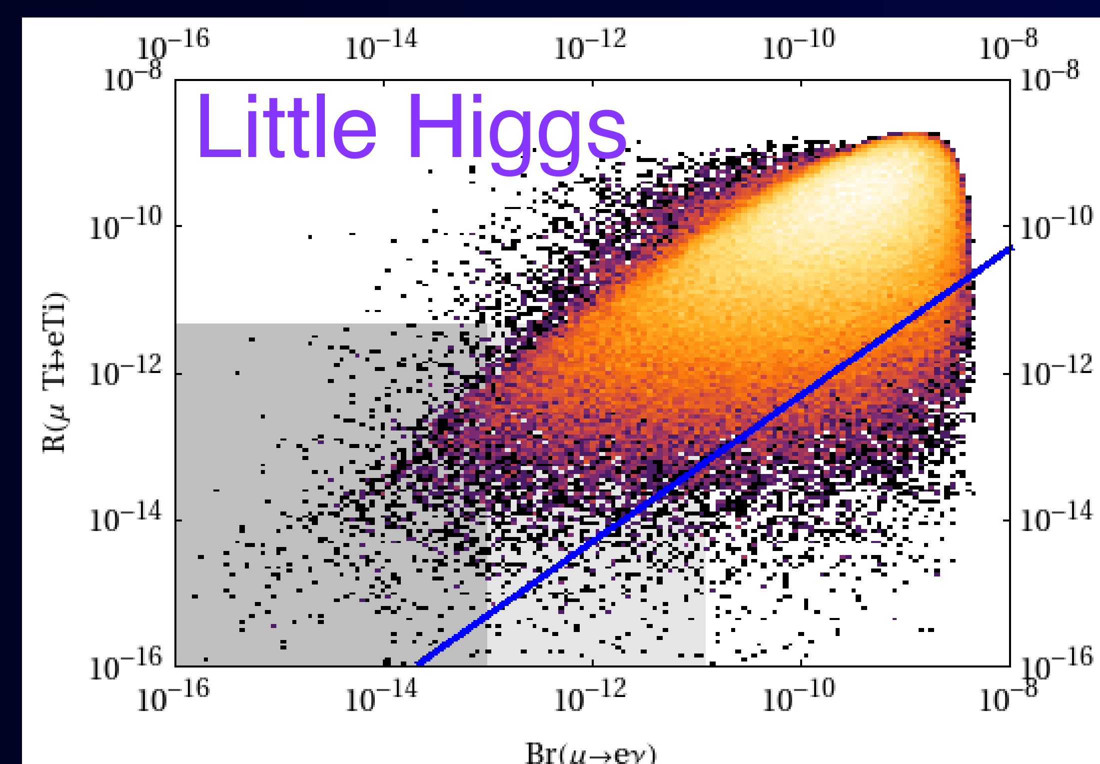
extra dimension model



low-energy seesaw model



little Higgs model



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

Osaka University

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

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

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, ……….

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$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
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$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
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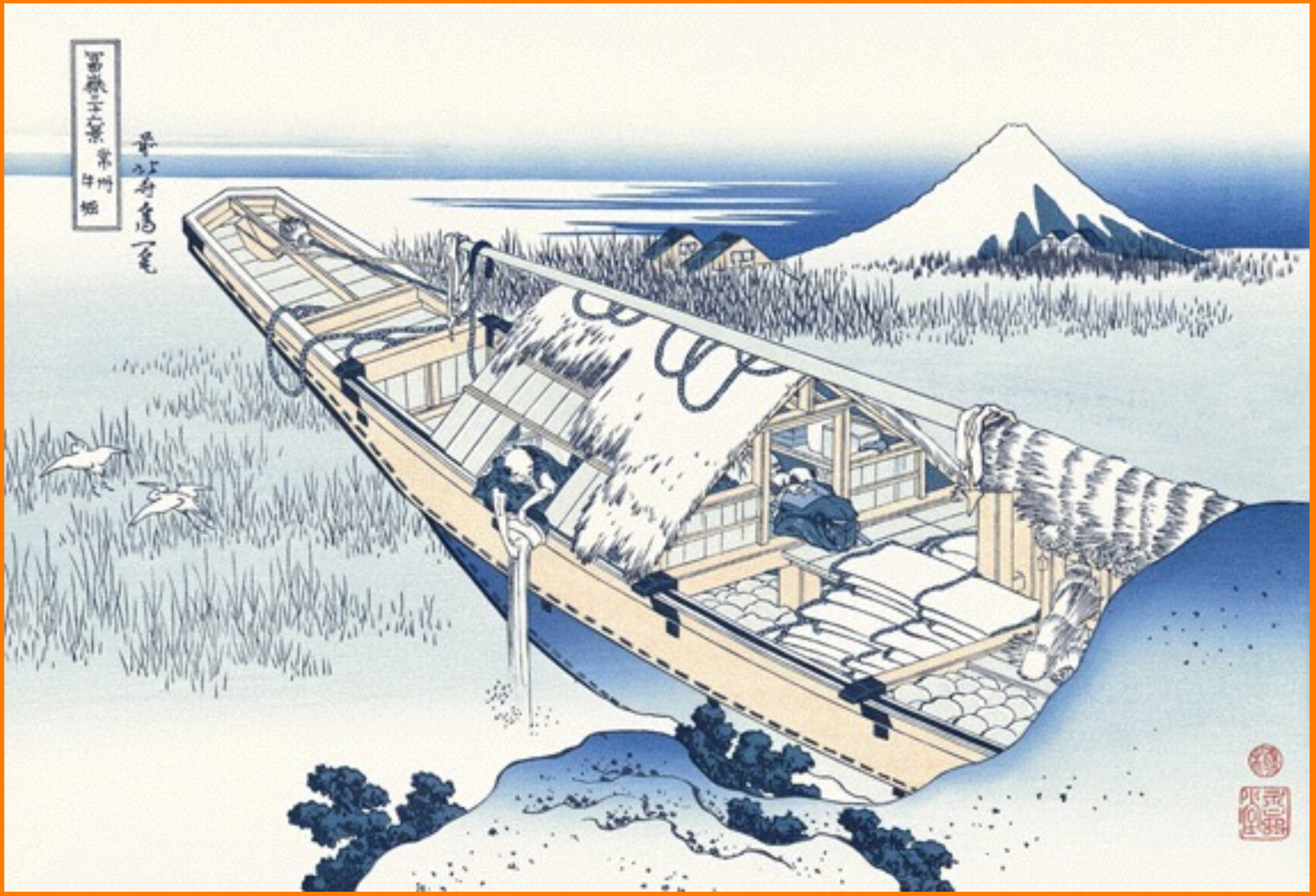
Muon CLFV Experiments



Present Limits and Expectations in Future

process	present limit	future	
$\mu \to e\gamma$	$<5.7 \times 10^{-13}$	$<10^{-14}$	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
$\tau \to e\gamma$	$<1.1 \times 10^{-7}$	$<10^{-9} - 10^{-10}$	superKEKB
$\tau \to eee$	$<3.6 \times 10^{-8}$	$<10^{-9} - 10^{-10}$	superKEKB
$\tau \to \mu\gamma$	$<4.5 \times 10^{-8}$	$<10^{-9} - 10^{-10}$	superKEKB
$\tau \to \mu\mu\mu$	$<3.2 \times 10^{-8}$	$<10^{-9} - 10^{-10}$	superKEKB/LHCb

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$\tau \rightarrow \mu\gamma$	<4.5 x 10^{-8}	<10^{-9} - 10^{-10}	superKEKB
$\tau \rightarrow \mu\mu\mu$	<3.2 x 10^{-8}	<10^{-9} - 10^{-10}	superKEKB/LHCb

What is Muon to Electron Conversion?

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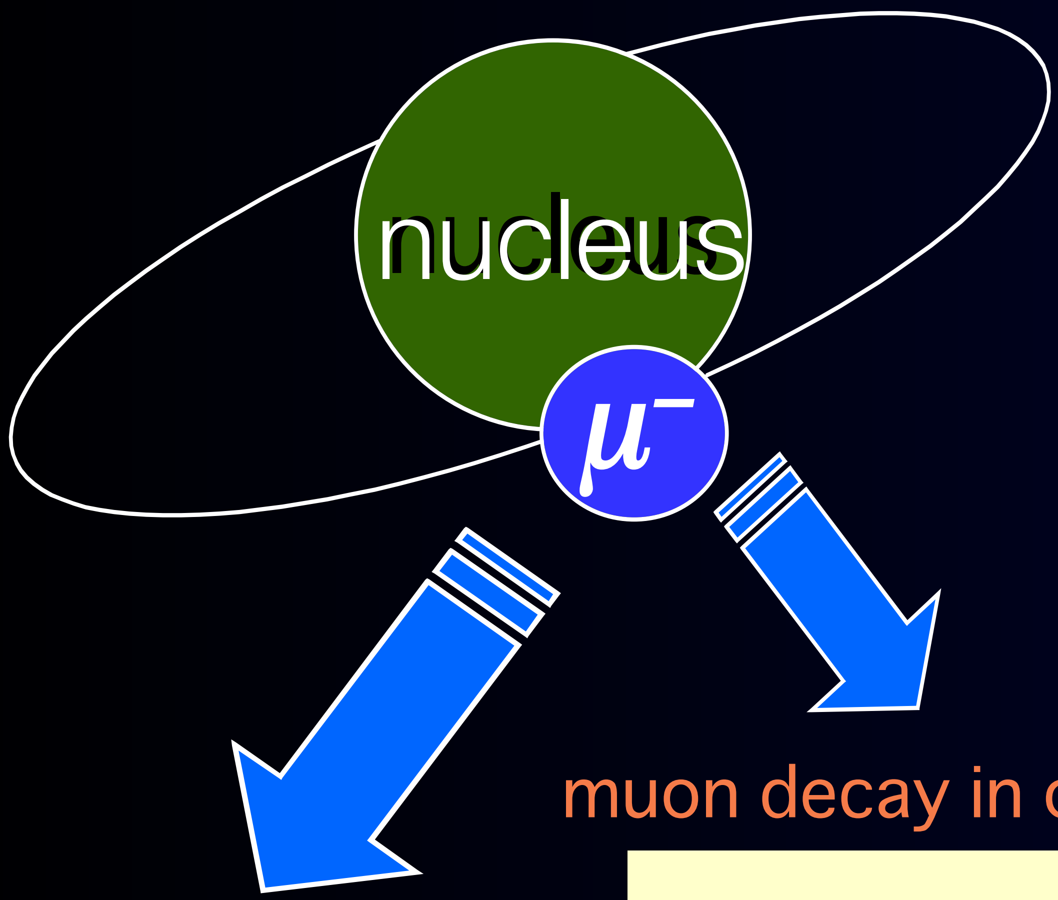
1s state in a muonic atom



muon decay in orbit

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

nuclear muon capture

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

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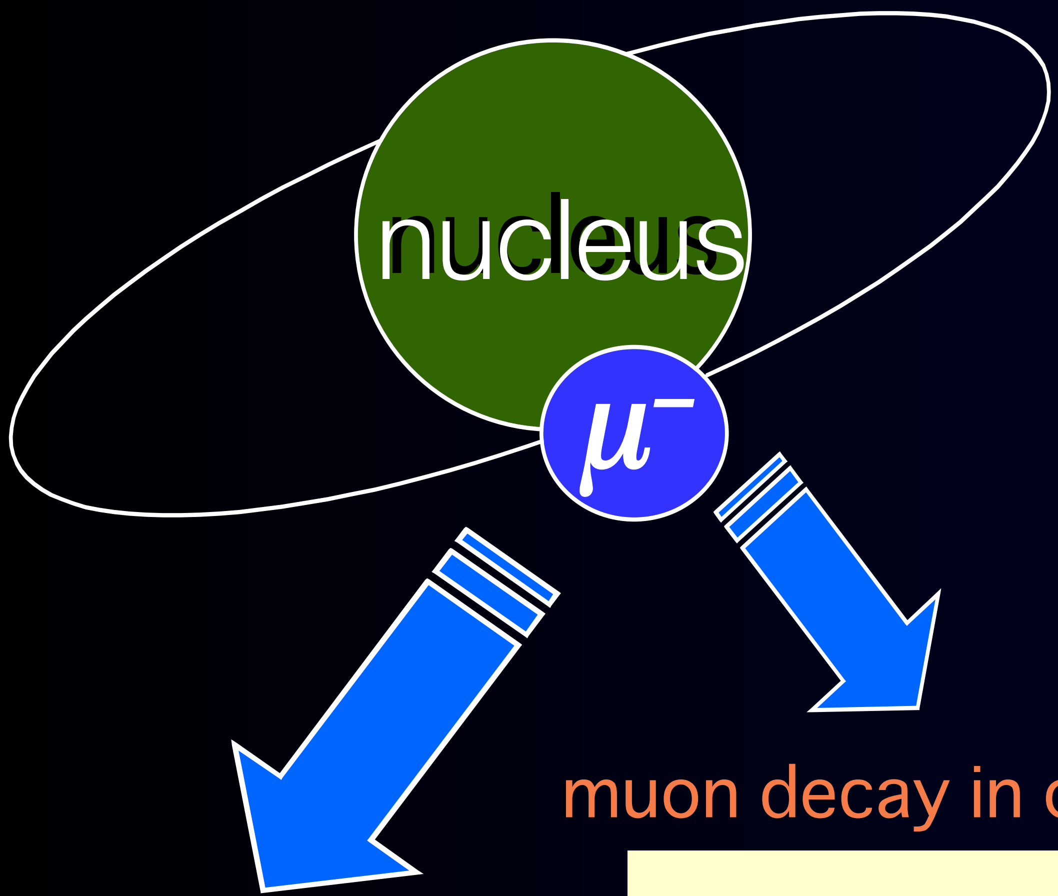
1s state in a muonic atom



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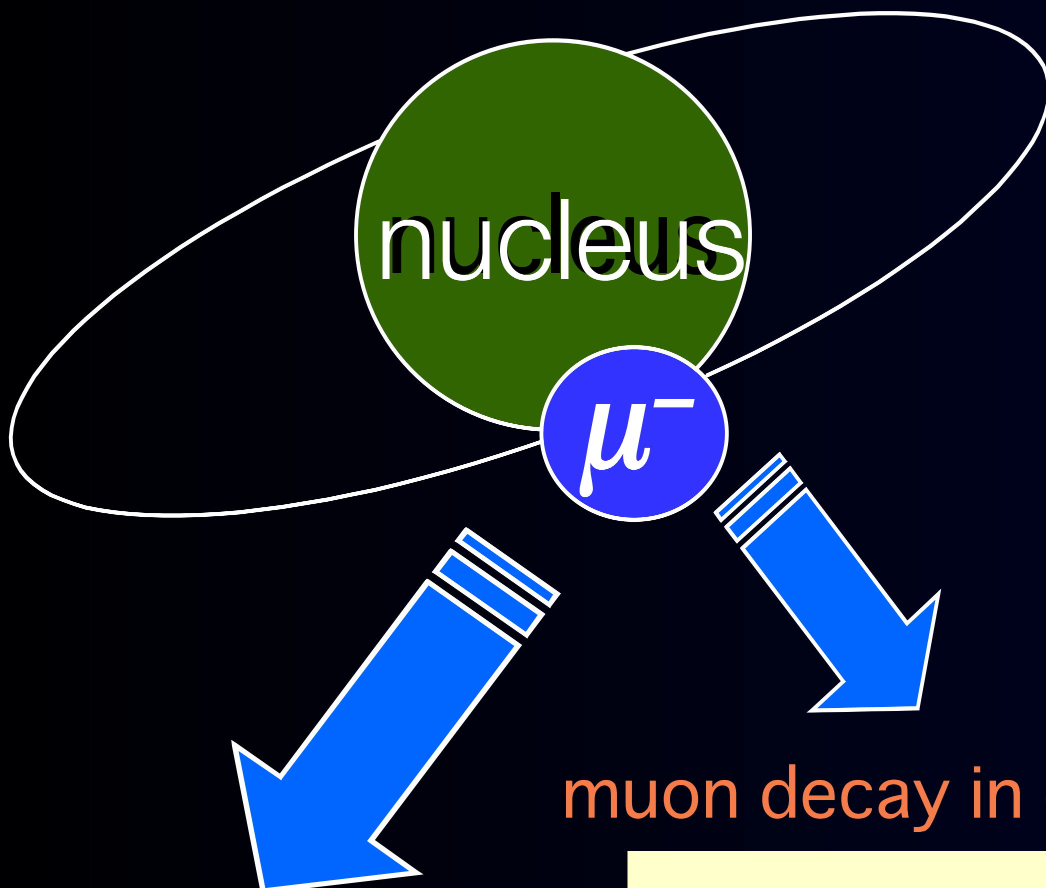
Neutrino-less muon nuclear capture

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

What is Muon to Electron Conversion?

1s state in a muonic atom



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Neutrino-less muon nuclear capture

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

Event Signature :
a single mono-energetic electron of 105 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

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$$L_{\mu \to e\gamma} = \frac{m_\mu}{\Lambda^2}\bar{\mu}_R \sigma^{\mu\nu} e_L F_{\mu\nu}$$

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μ→eγ vs. μ-e conversion

$$L_{\mu\to e\gamma} = \frac{m_\mu}{\Lambda^2}\bar{\mu}_R\sigma^{\mu\nu}e_L F_{\mu\nu}$$

$$L_{\mu N\to eN} = \frac{1}{1+\kappa}\frac{m_\mu}{\Lambda^2}\bar{\mu}_R\sigma^{\mu\nu}e_L F_{\mu\nu} + \frac{\kappa}{1+\kappa}\frac{1}{\Lambda^2}(\bar{\mu}_L\gamma^\mu e_L)(\bar{q}_L\gamma_\mu q_L)$$

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μ→eγ vs. μ-e conversion

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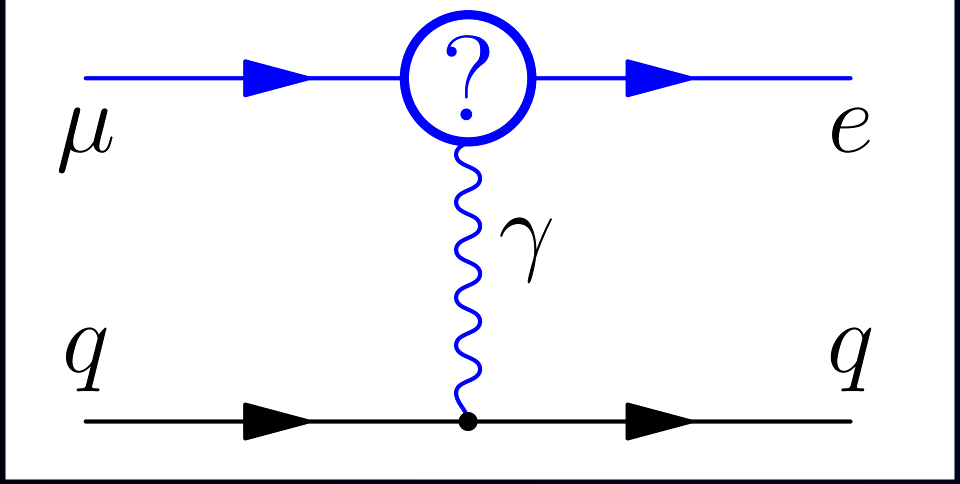
Photonic (dipole) interaction



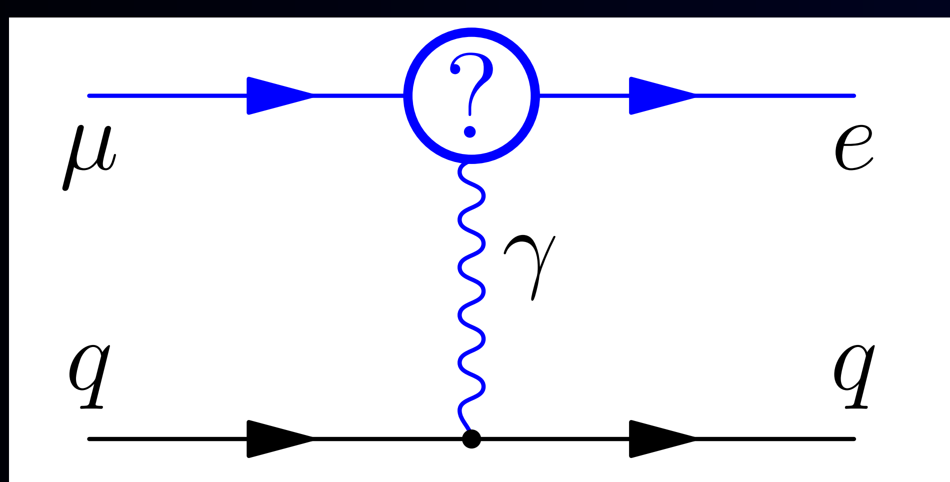
Physics Sensitivity: μ→eγ vs. μ-e conversion

$$L_{\mu\to e\gamma} = \frac{m_\mu}{\Lambda^2}\bar{\mu}_{\rm R}\sigma^{\mu\nu}e_{\rm L}F_{\mu\nu}$$

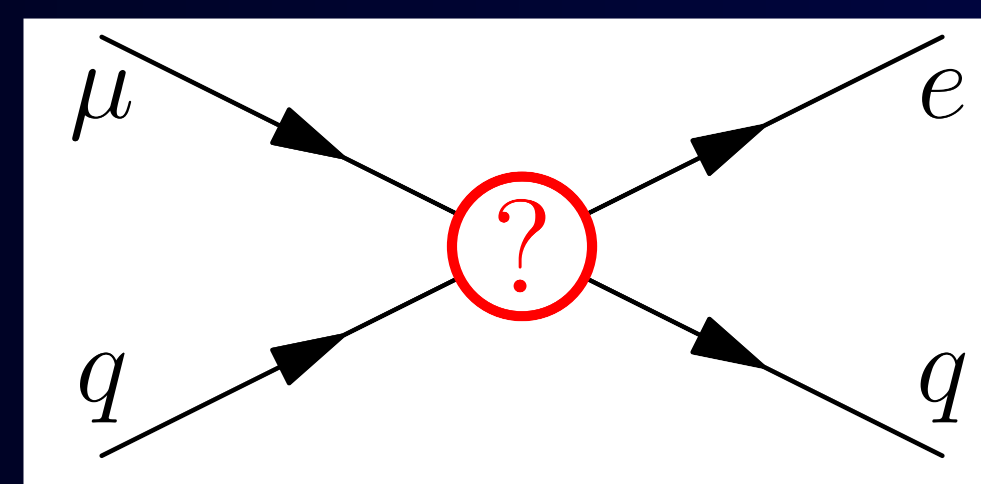
$$L_{\mu N\to eN} = \frac{1}{1+\kappa}\frac{m_\mu}{\Lambda^2}\bar{\mu}_{\rm R}\sigma^{\mu\nu}e_{\rm L}F_{\mu\nu} + \frac{\kappa}{1+\kappa}\frac{1}{\Lambda^2}(\bar{\mu}_{\rm L}\gamma^{\mu}e_{\rm L})(\bar{q}_{\rm L}\gamma_{\mu}q_{\rm L})$$

tree levels

Photonic (dipole) interaction



Contact interaction



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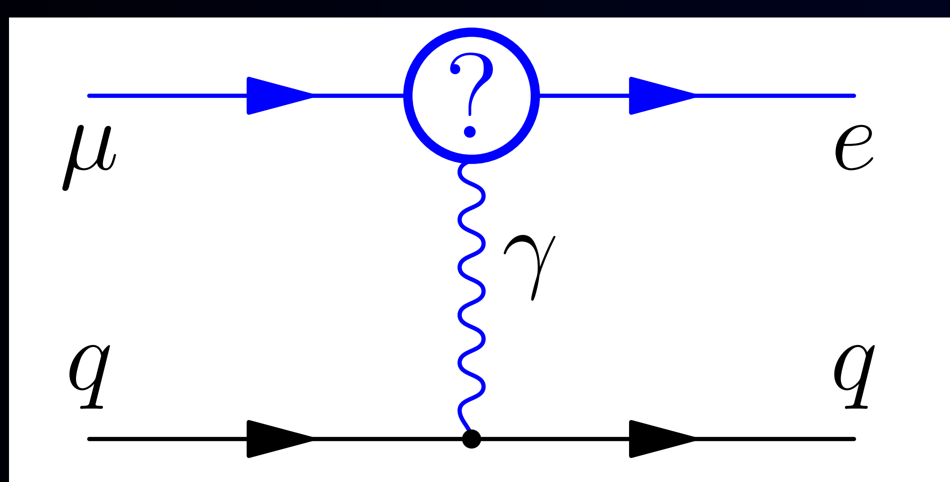

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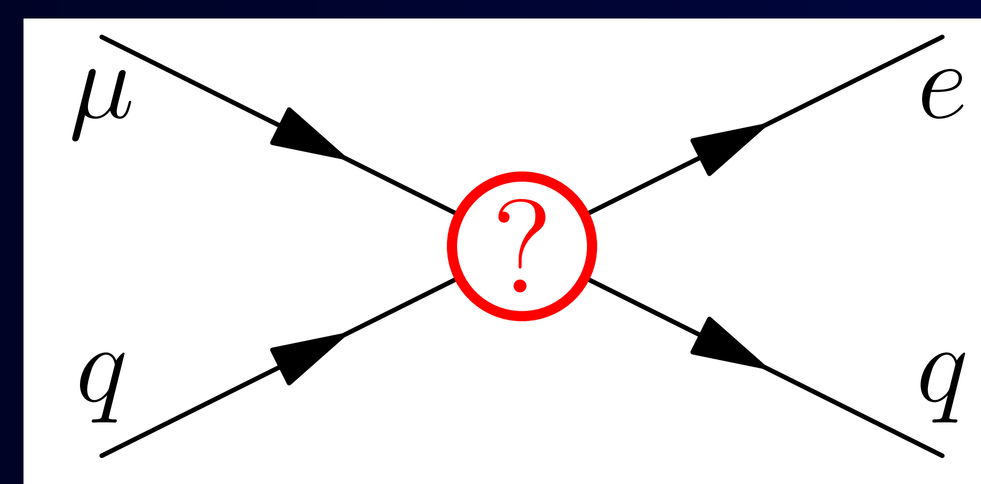


μ-e conversion sensitive to many new physics

Experimental Comparison : μ→eγ and μ-e Conversion

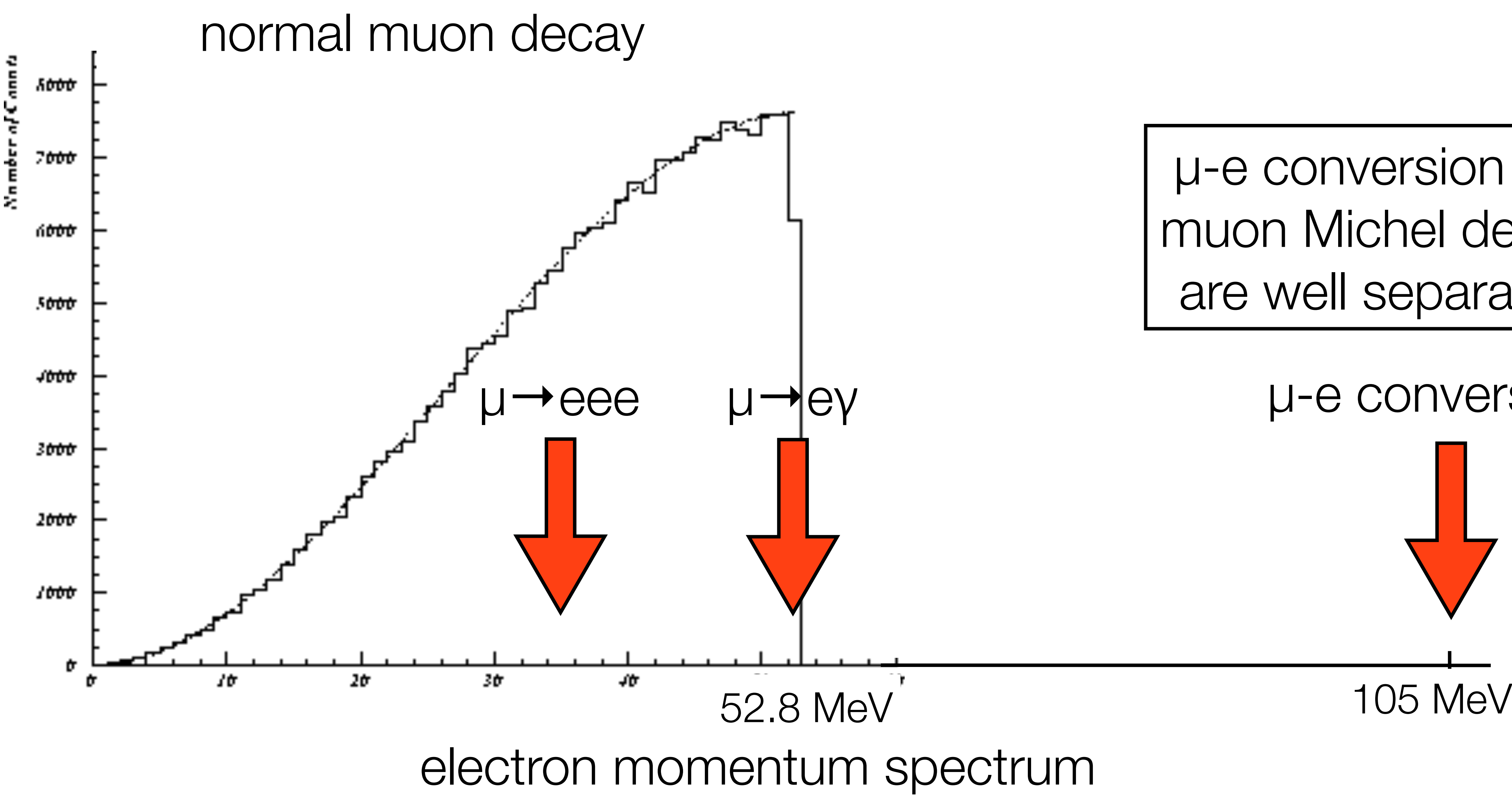
Experimental Comparison : μ→eγ and μ-e Conversion

	Beam	background	challenge	beam intensity
μ→eγ	continuous beam	accidentals	detector resolution	limited
μ→eee	continuos beam	accidentals	detector resolution	limited
μ-e conversion	pulsed beam	beam-related	beam background	no limitation

CLFV Signal and Normal Muon Decays

Osaka University

CLFV Signal and Normal Muon Decays



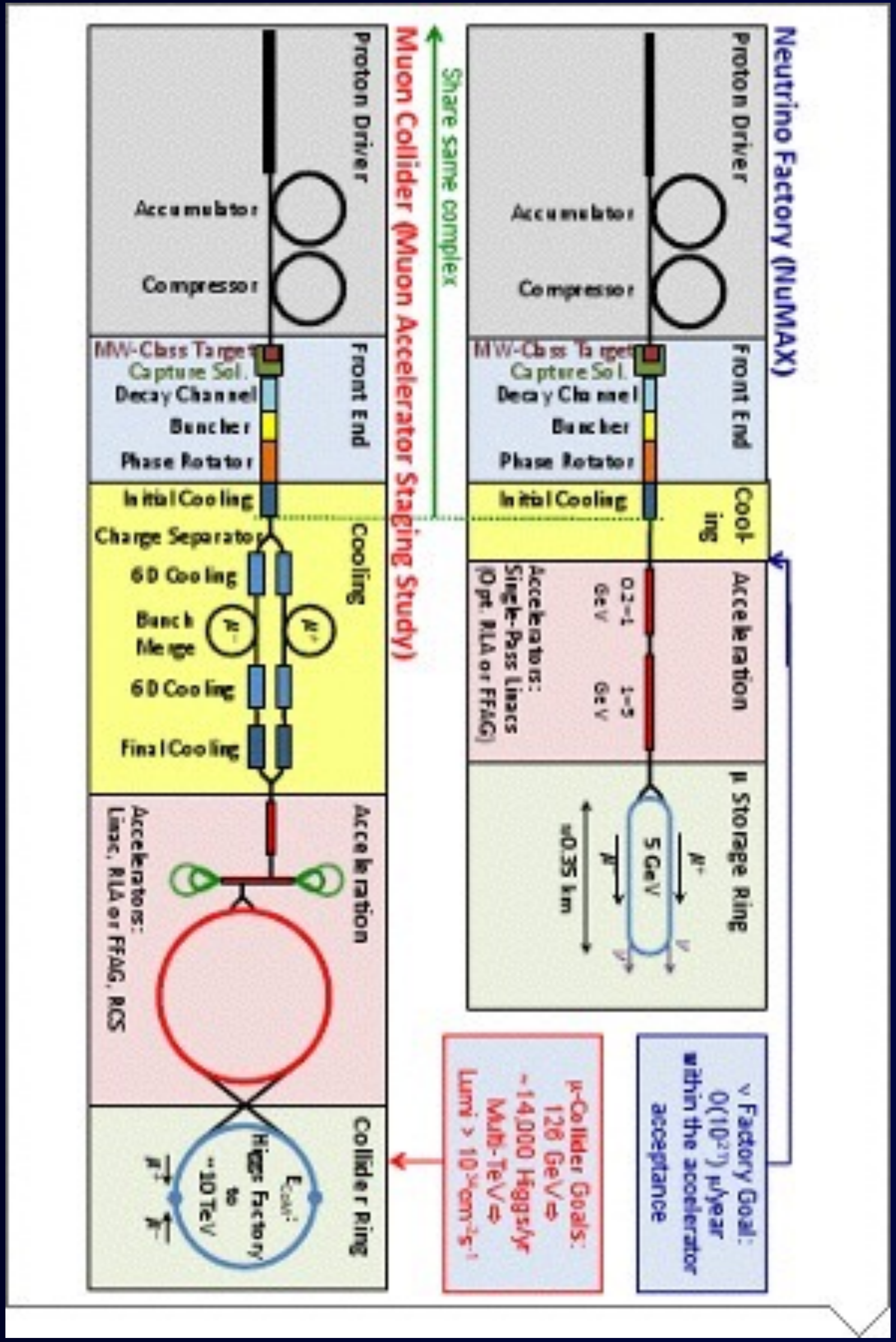
μ-e conversion and muon Michel decays are well separated.

Synergy with Muon Beam R&D

Osaka University

Synergy with Muon Beam R&D

- Pion capture in solenoid
- Phase rotation
- Muon cooling
- high power proton driver
- proton bunch length (short)
- muon beam transport
- requirements for kickers and RF (for proton driver)
- technique in machine design
- beam dynamics studies



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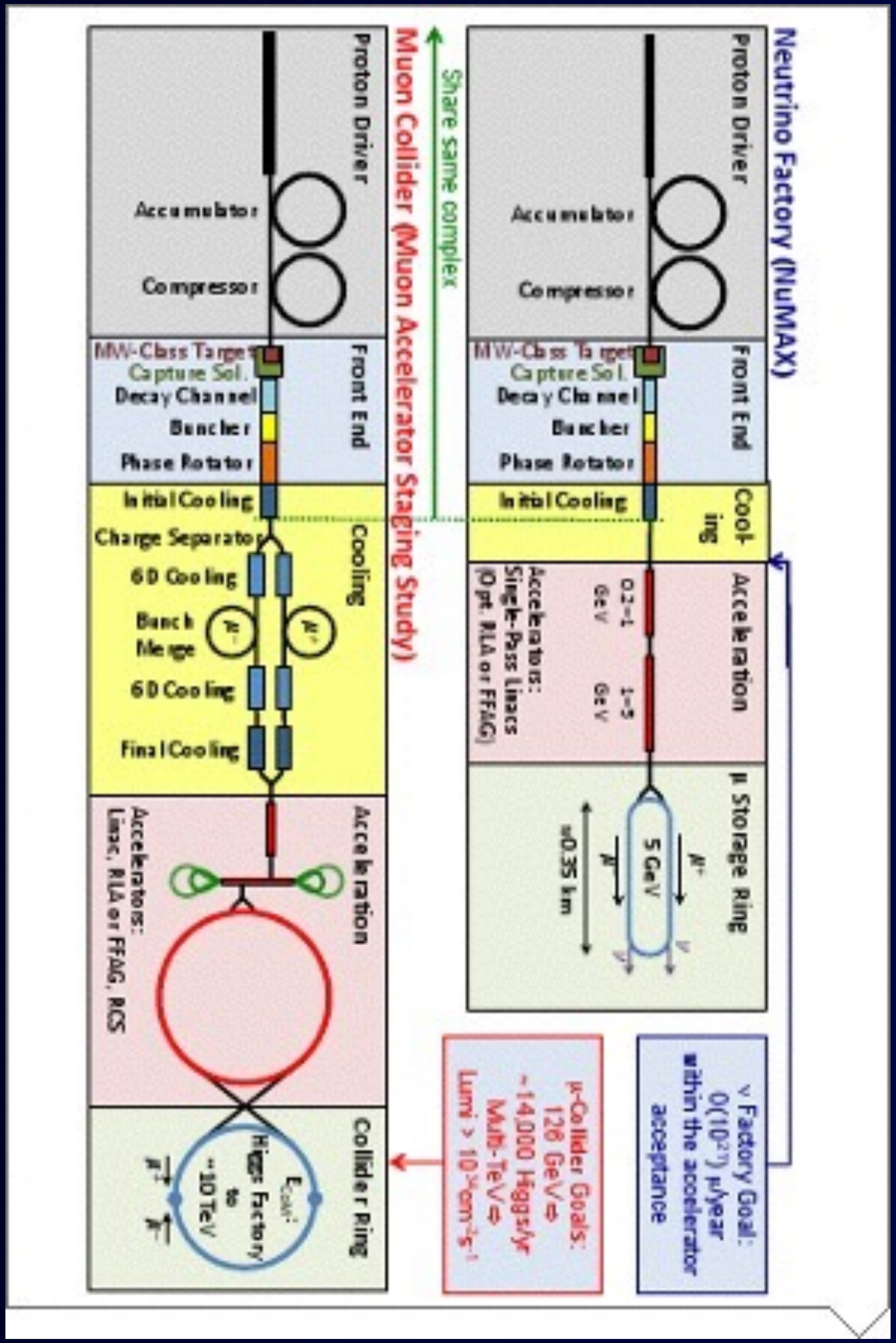


Requirements of Muon Beams for μ-e conversion

Osaka University

Requirements of Muon Beams for μ-e conversion

Osaka University

- high power proton beam
- high muon yield
- pulsed muon beam with proton extinction
- muon beam with momentum selected
- narrow energy spread of muon beam
- pure muon beam (pion$< 10^{-20}$)
- low emittance (cooled) muon beam

Future Prospects
(μ-e conversion)

… In the short-term

$$B(\mu N \to eN) \leq 10^{-16}$$

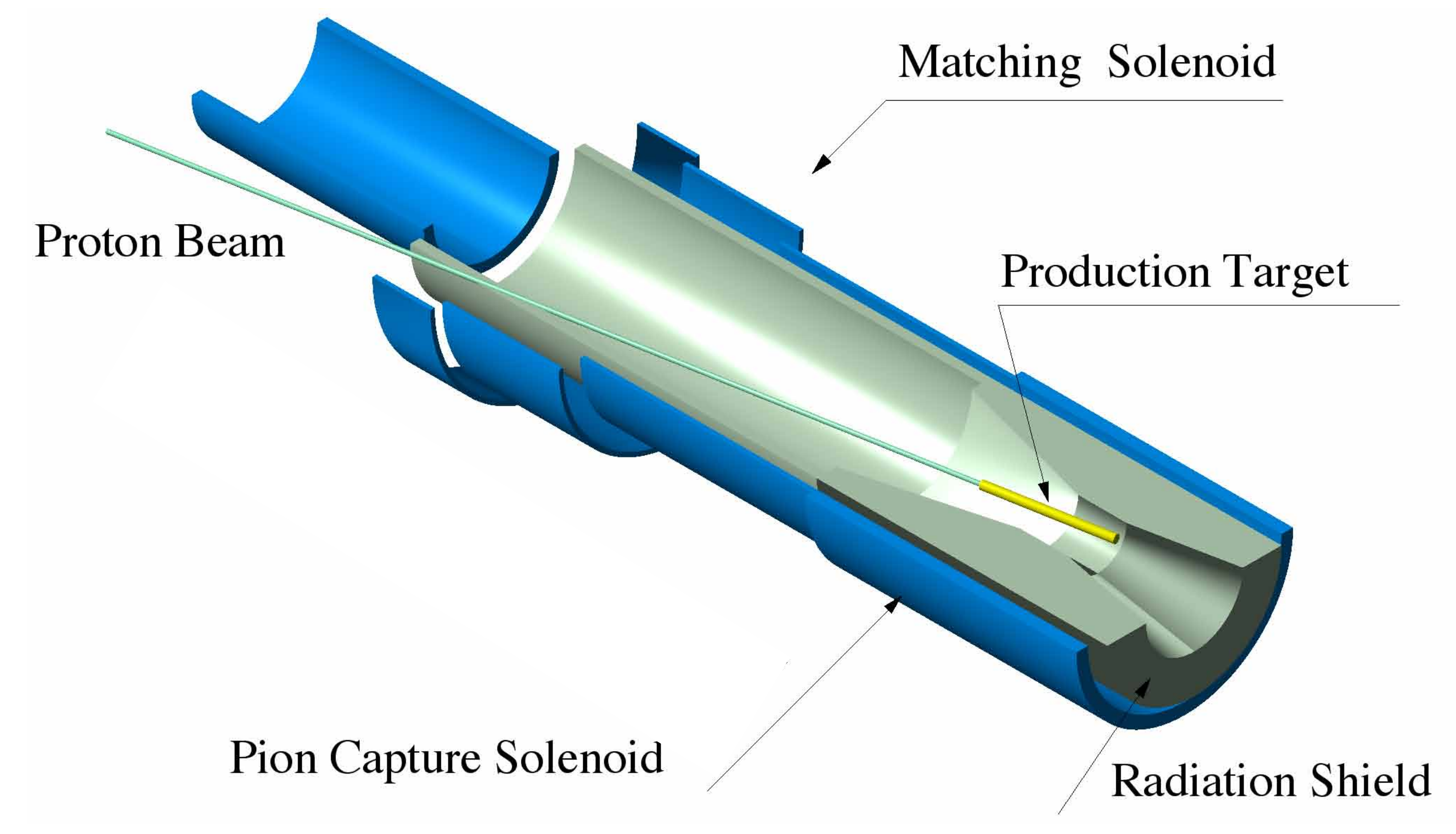
Pion Capture in Solenoids

Pion Capture in Solenoids

high muon yield

Pion Capture in Solenoids

high muon yield

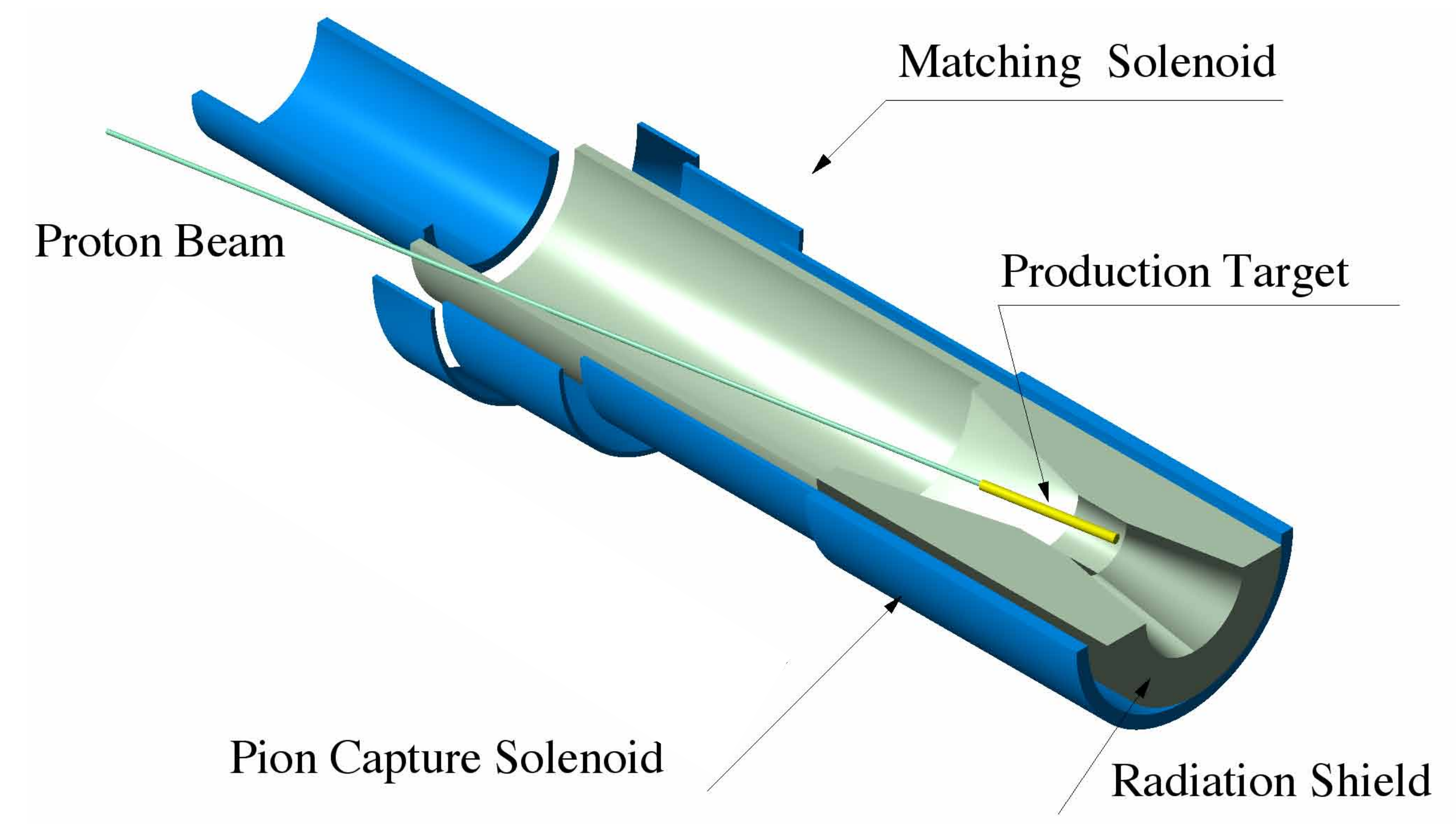


proton target in a solenoidal field (~5 T)

a long proton target (1.5~2 interaction length) of heavy material

Pion Capture in Solenoids

high muon yield



proton target in a solenoidal field (~5 T)

a long proton target (1.5~2 interaction length) of heavy material

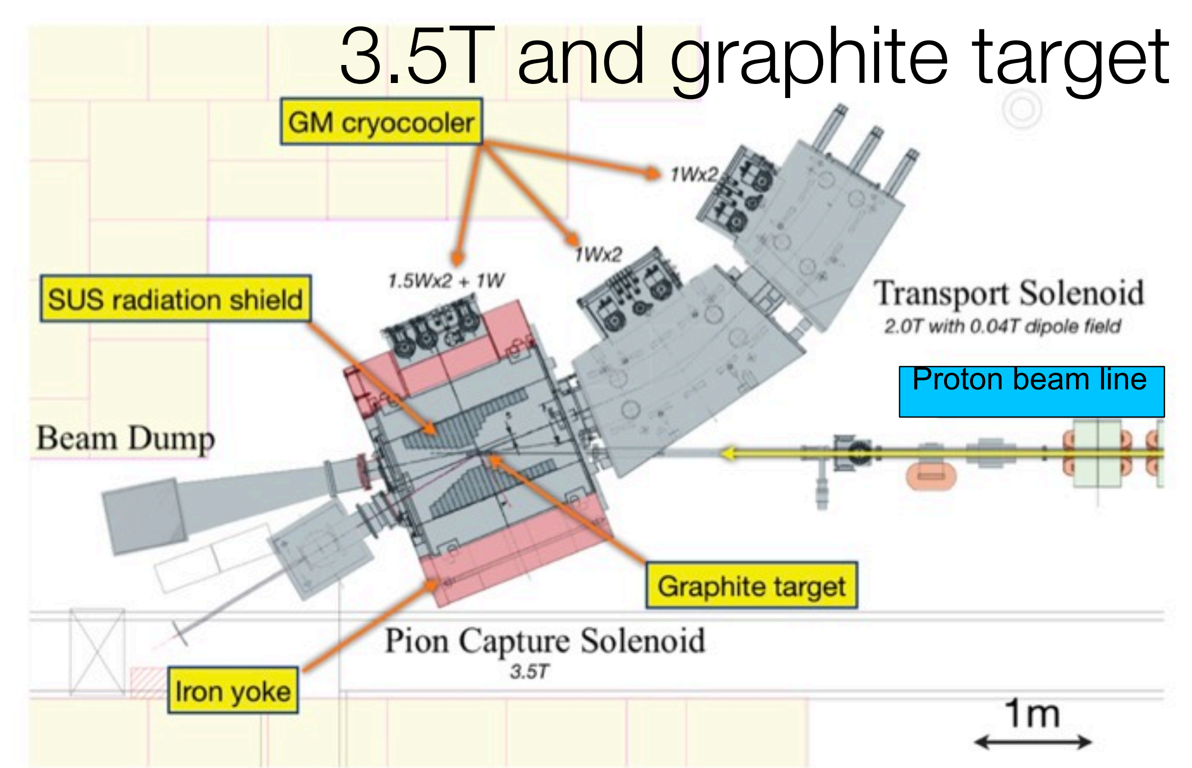
$O(10^{11})$ stopped μ^-/sec for 50 kW protons

note: dependent on solenoid field and aperture, proton target material.

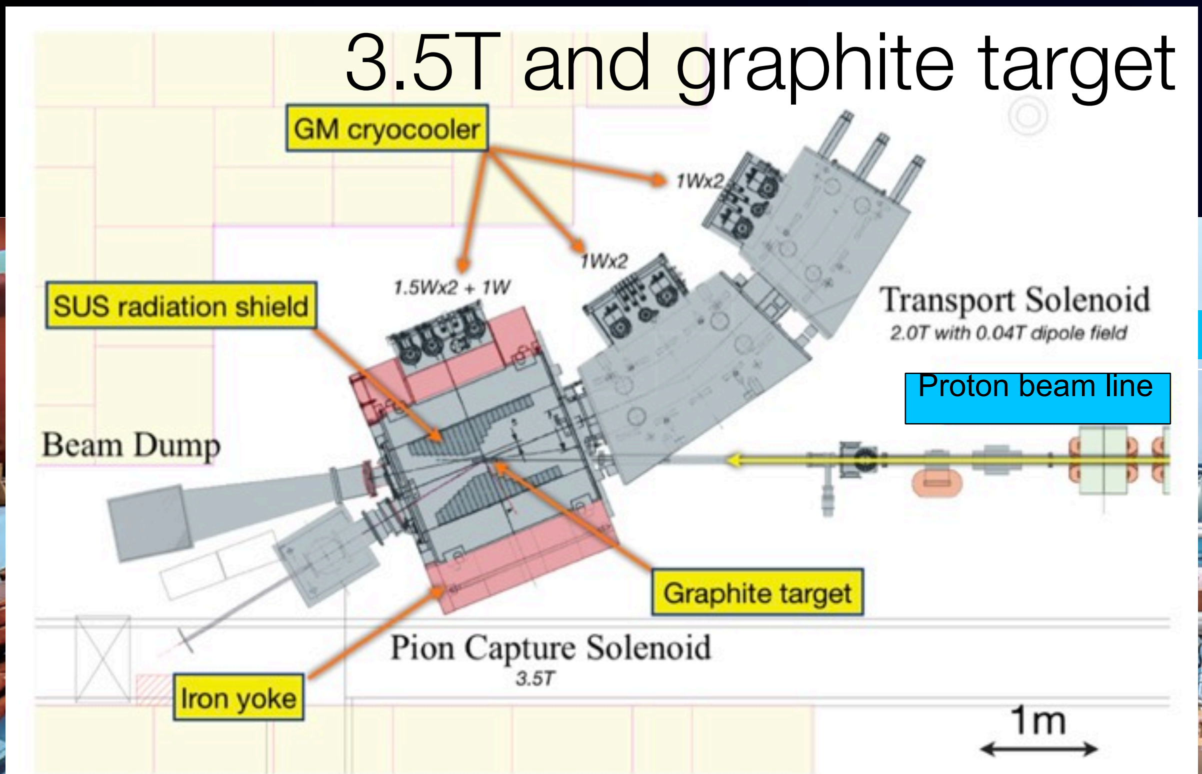
MuSIC at Osaka University
- Experimental Demonstration -

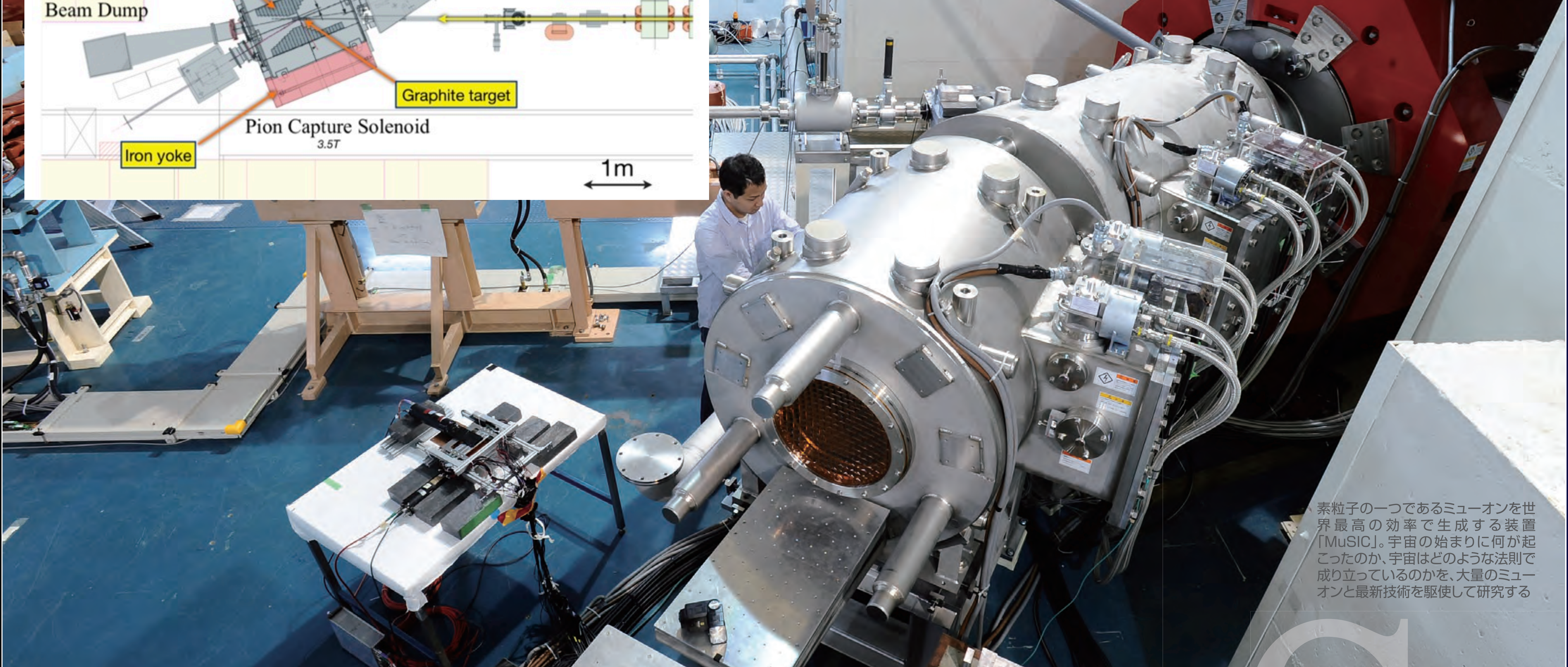
3.5T and graphite target

MuSIC at Osaka University
- Experimental Demonstration -



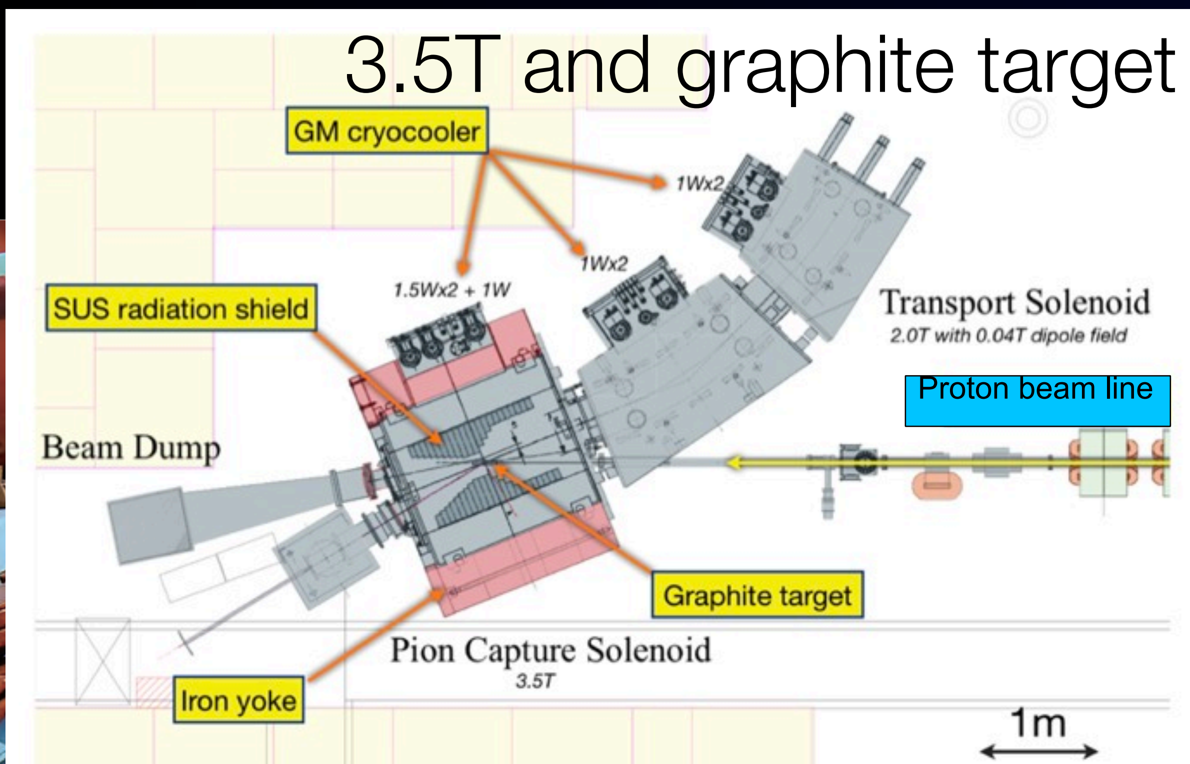
MuSIC at Osaka University
- Experimental Demonstration -

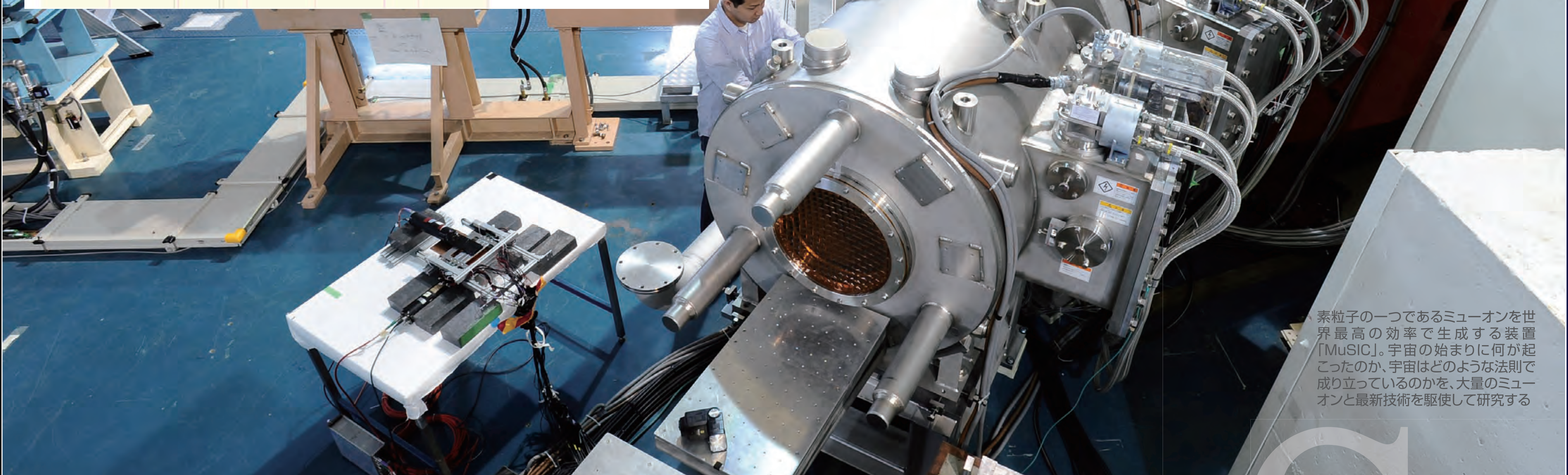




MuSIC at Osaka University
- Experimental Demonstration -

Muon Science Intense Channel (>2011)





MuSIC at Osaka University
- Experimental Demonstration -

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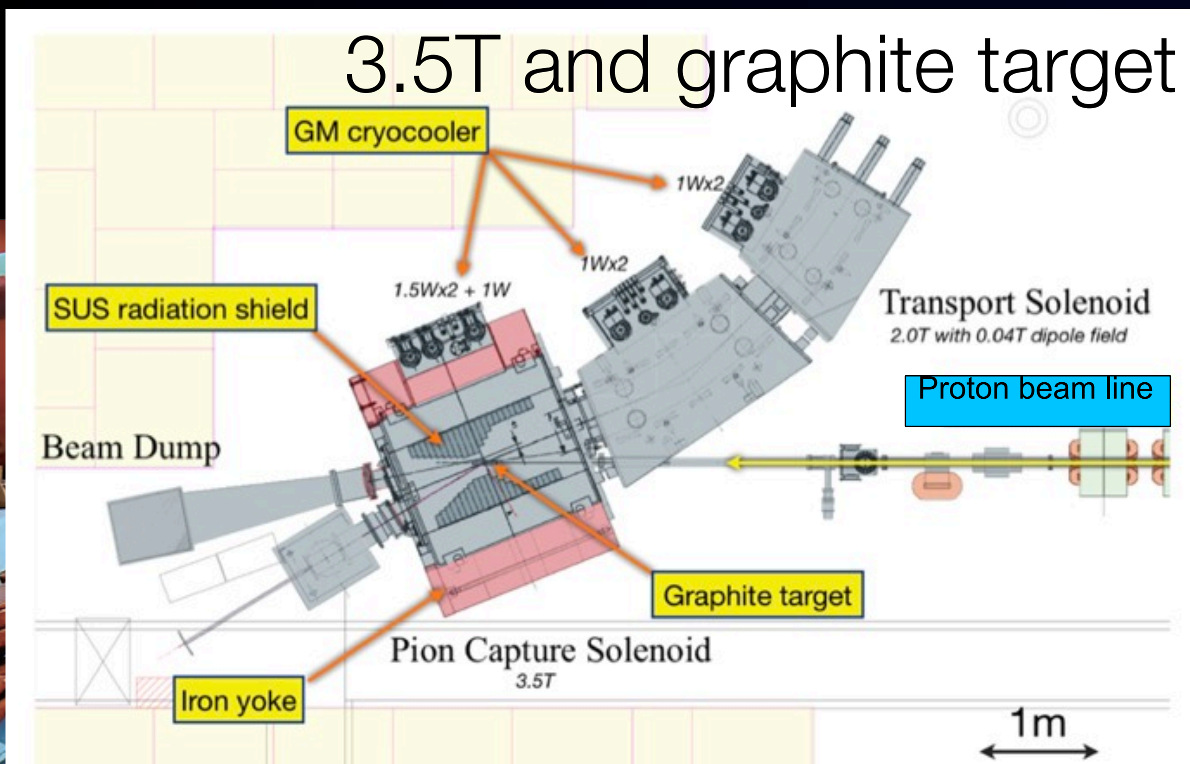
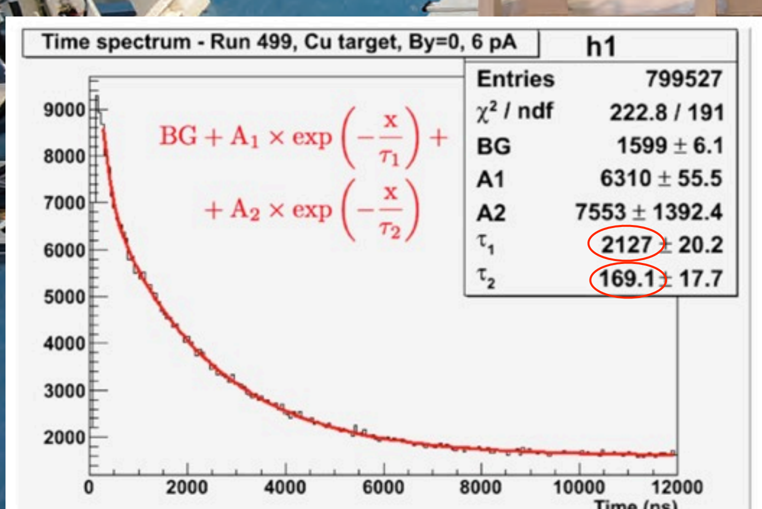
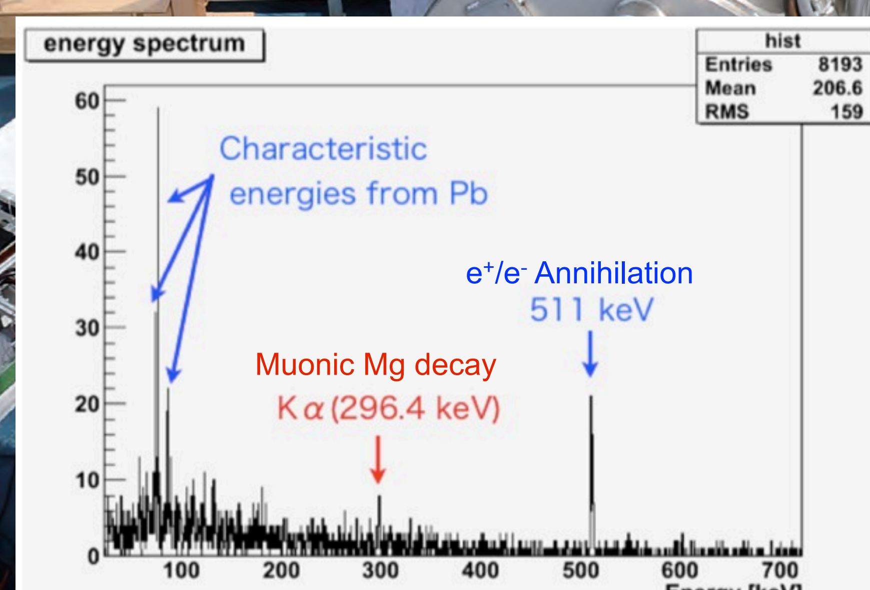




	Free muon*	Cu**	Plastic scint.**
τ (ns)	2197.03 ± 0.04	163.5 ± 1	2026.3 ± 1.5



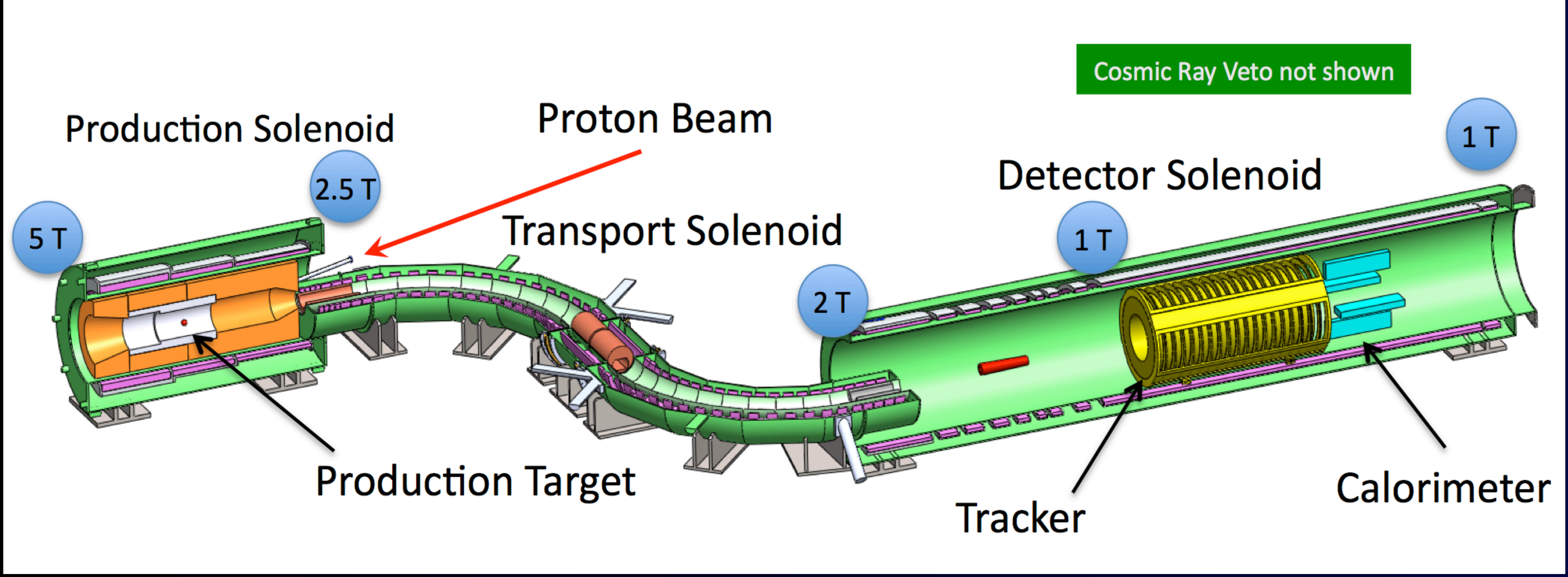
MuSIC muon yields

μ^+ : 3×10^8/s for 400W

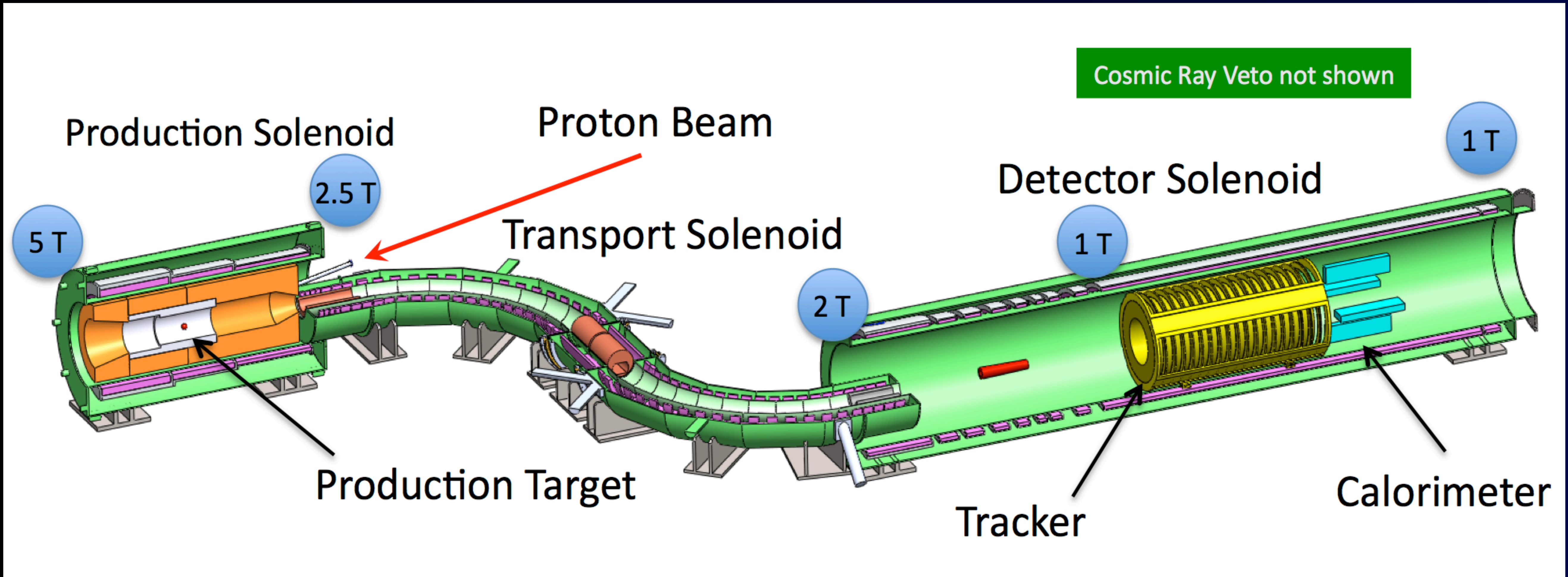
μ^- : 1×10^8/s for 400W

Mu2e at Fermilab

Mu2e at Fermilab



Mu2e at Fermilab



Single-event sensitivity : $(2.9\pm0.3)\times10^{-17}$

Total background : (0.36 ± 0.10) events

Expected limits : $< 6\times10^{-17}$ @90%C.L.

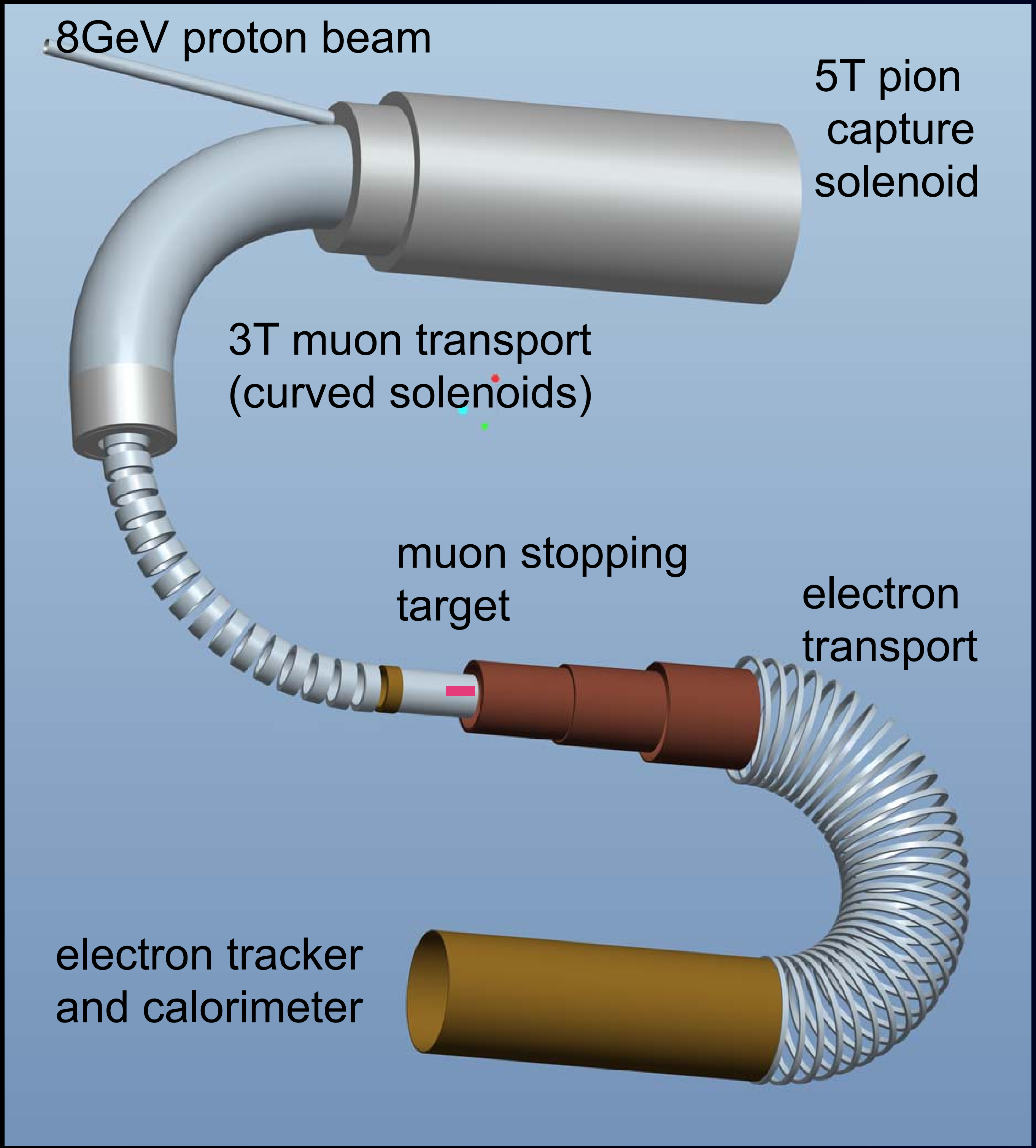
Running time: 3 years (2×10^{7}sec/year)

Mu2e: Recent Status

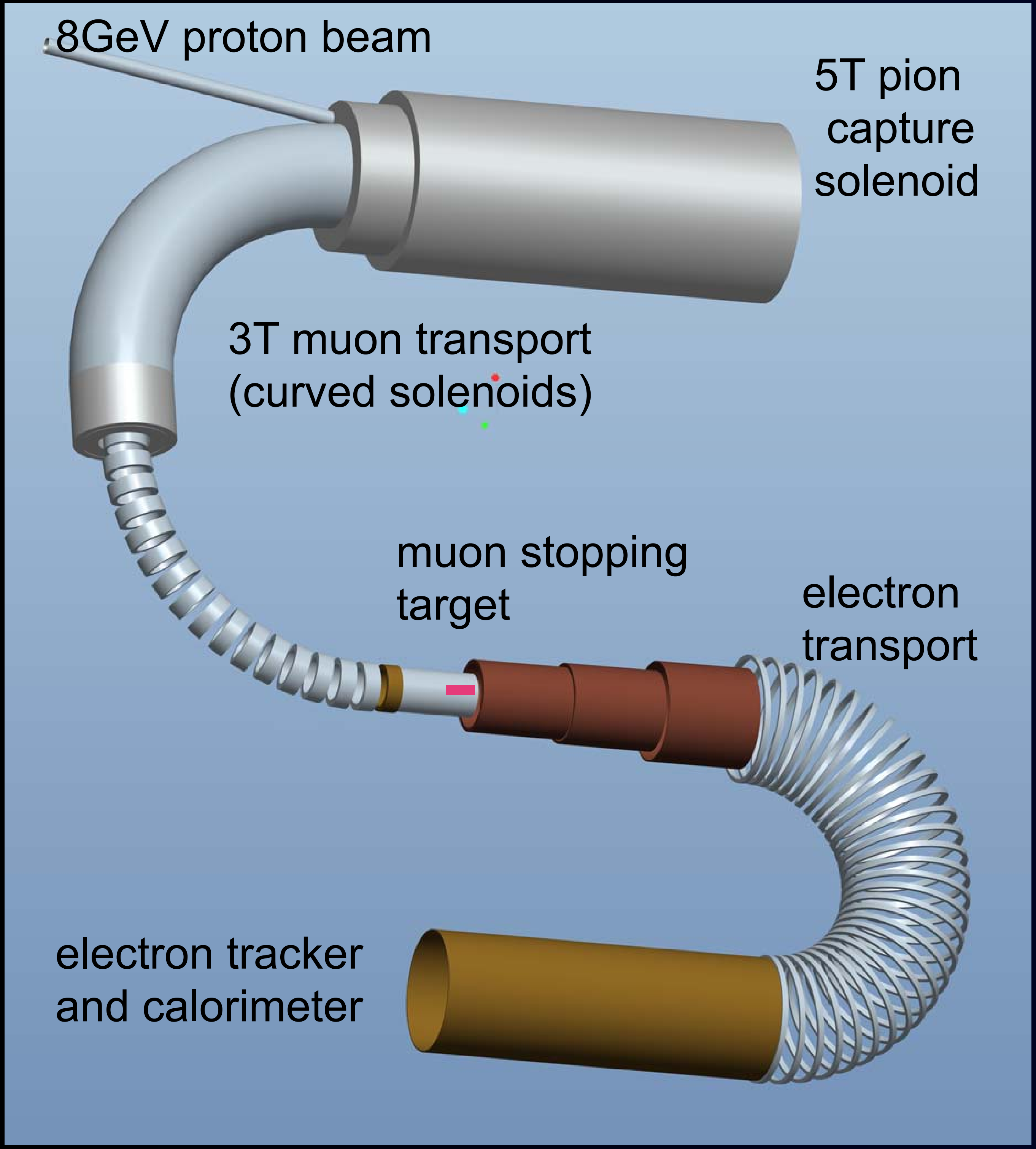
Mu2e: Recent Status

COMET at J-PARC

COMET at J-PARC



COMET at J-PARC



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

Total background : 0.32 events

Expected limits : < 6×10^{-17}@90%CL

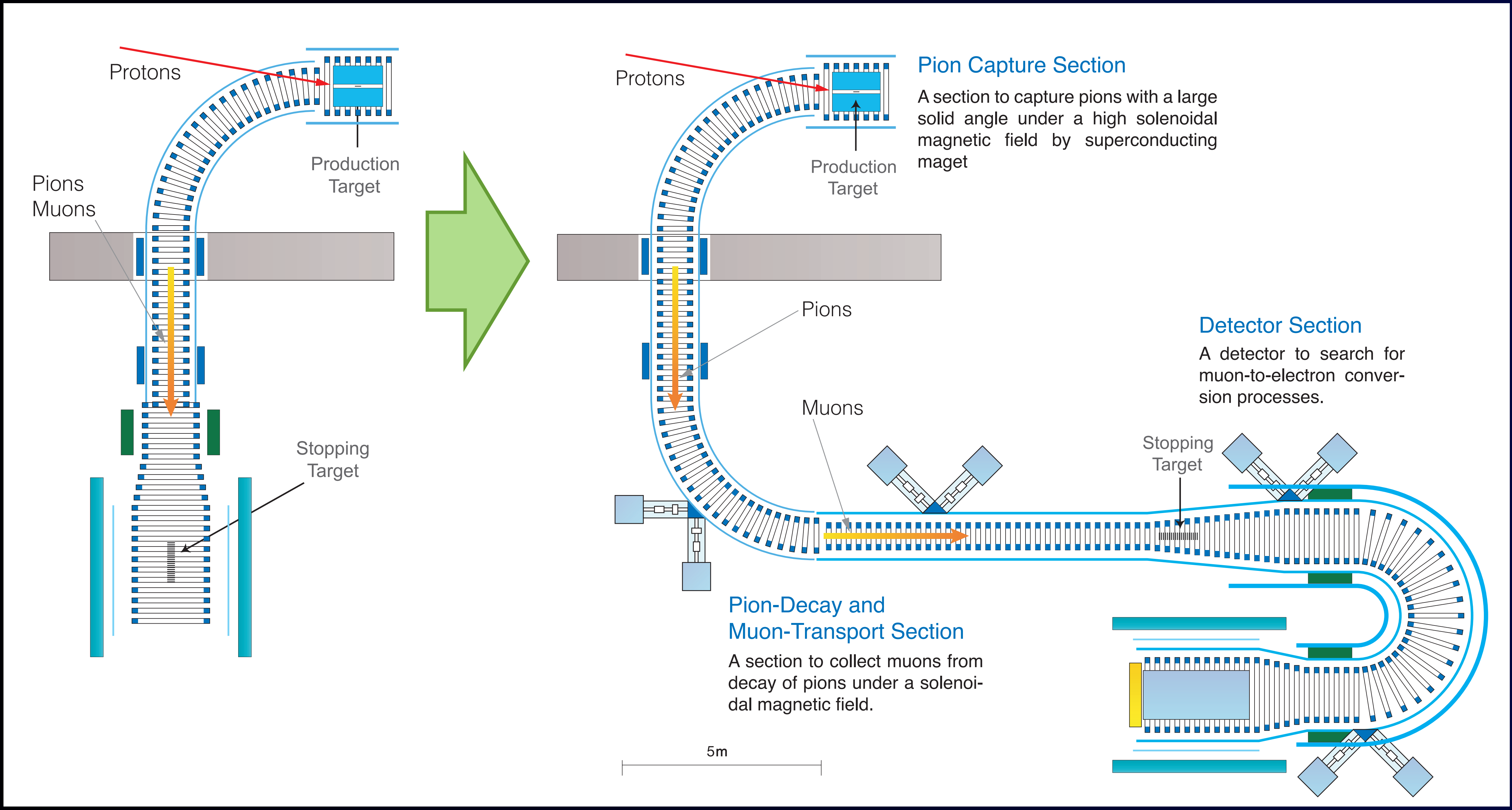
Running time: 1 years (2×10^{7}sec)

COMET Staged Approach (2012~)

COMET Staged Approach (2012~)

COMET Phase-I

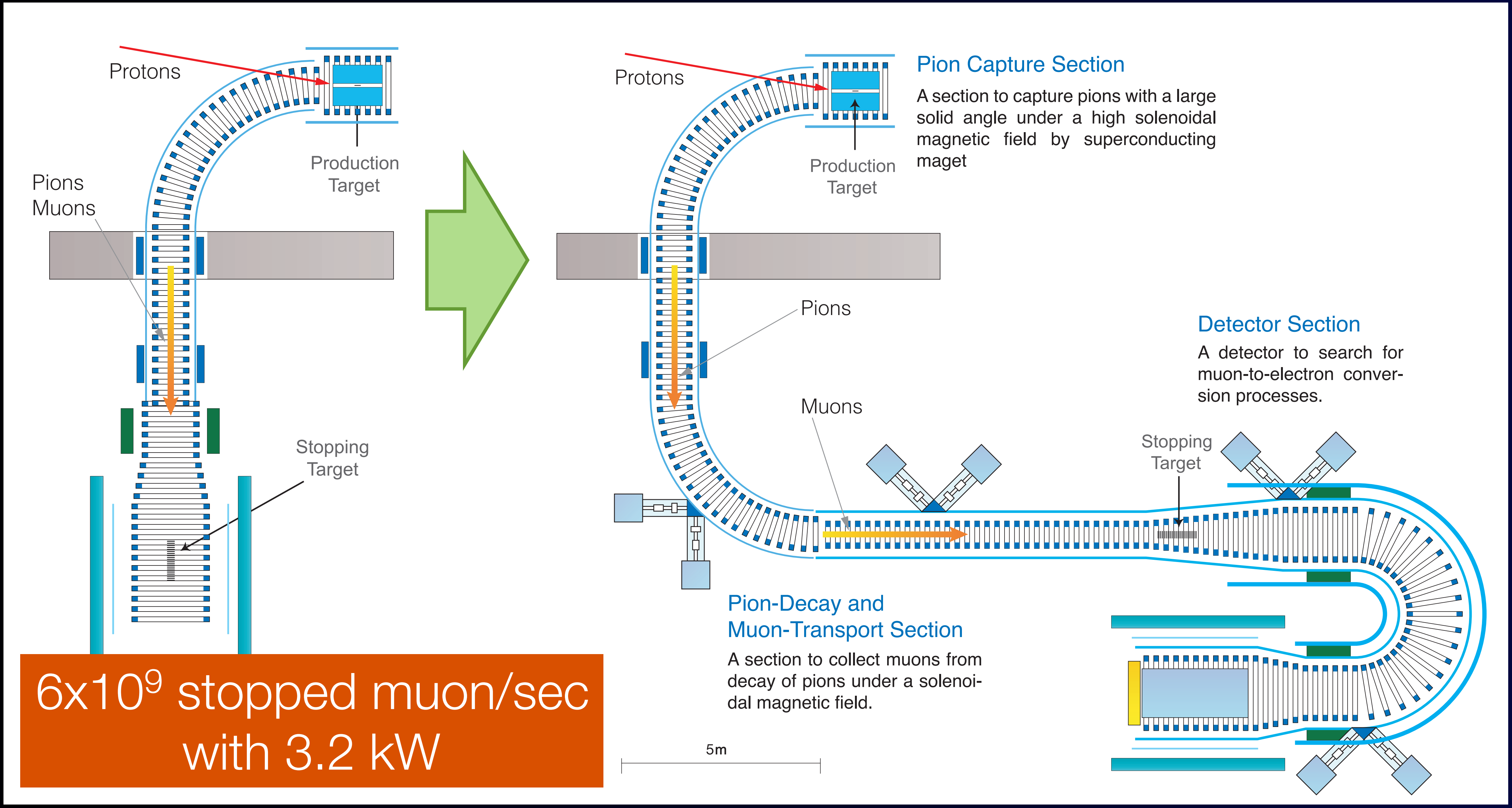
COMET Phase-II



COMET Staged Approach (2012~)

COMET Phase-I

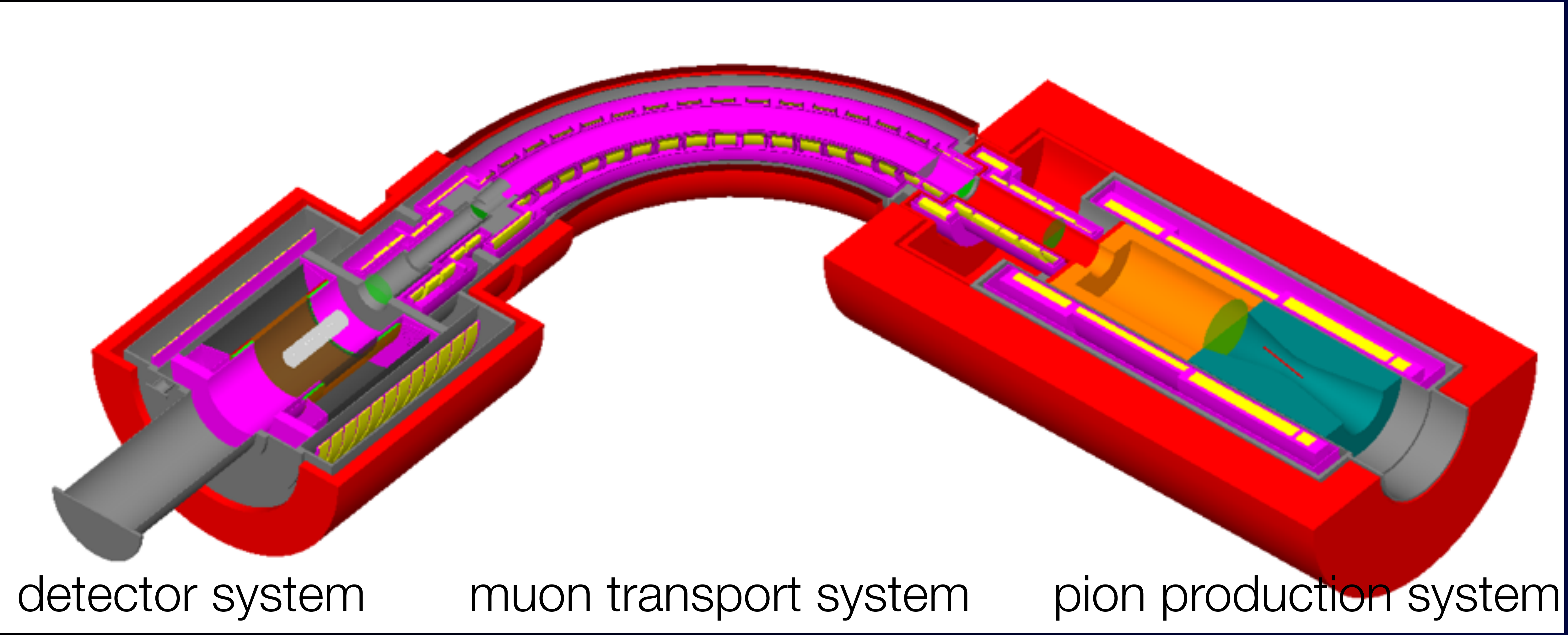
COMET Phase-II



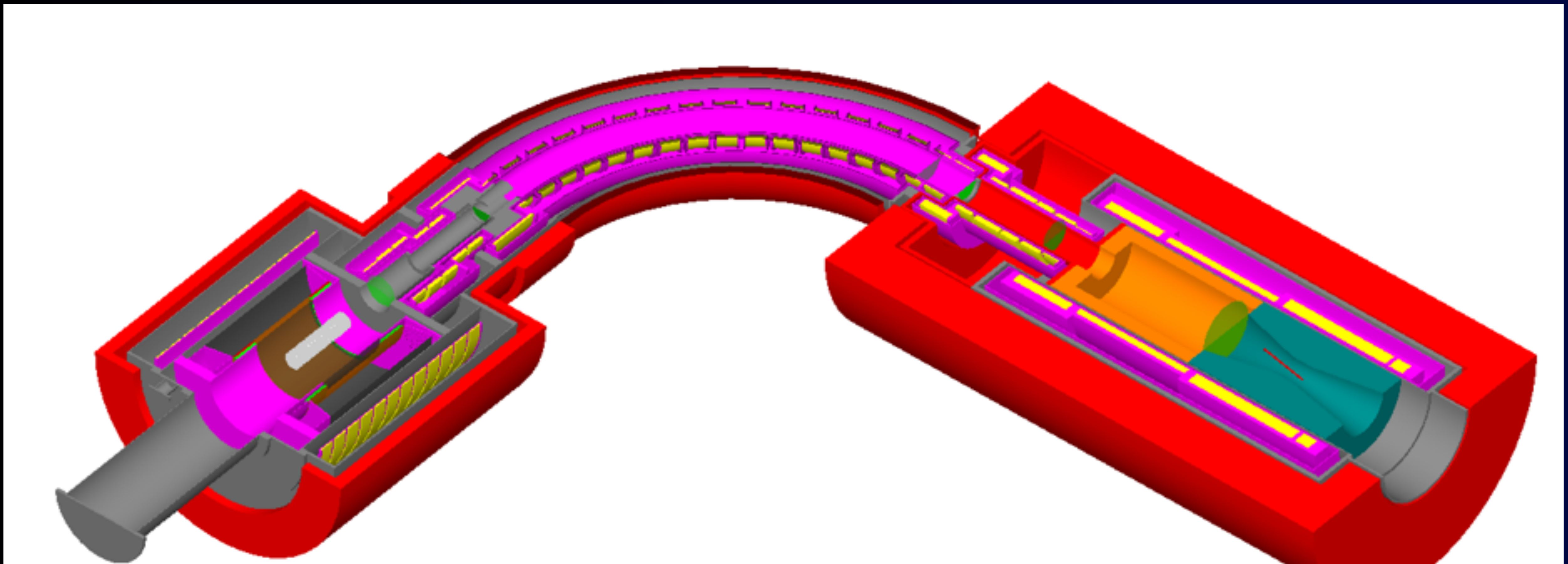
6×10^{9} stopped muon/sec with 3.2 kW

COMET Phase-I

COMET Phase-I



COMET Phase-I



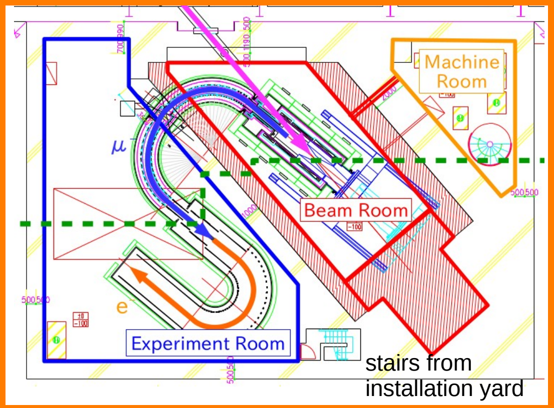
Single-event sensitivity : 3×10^{-15}

Total background : 0.2 events

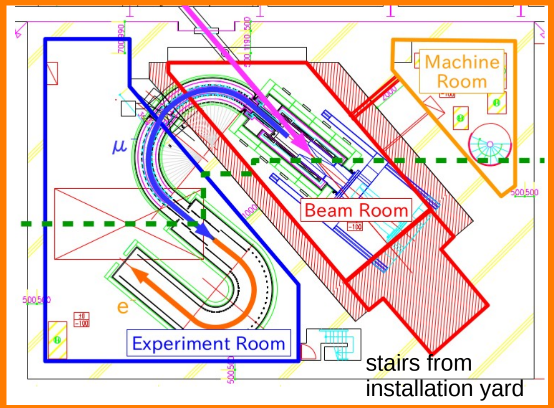
Expected limits : < 6×10^{-15} @90%CL

Running time: 1/3 years (2×10^{6}sec)

COMET Building at J-PARC



COMET Building at J-PARC



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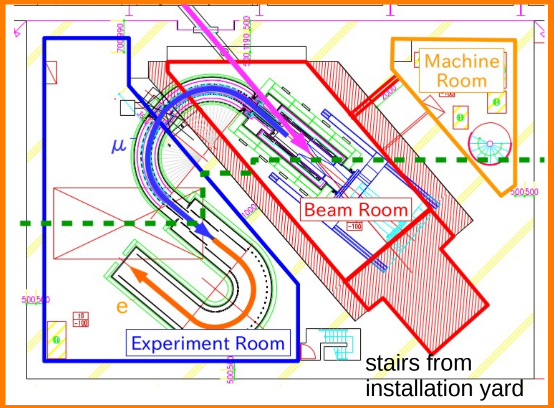
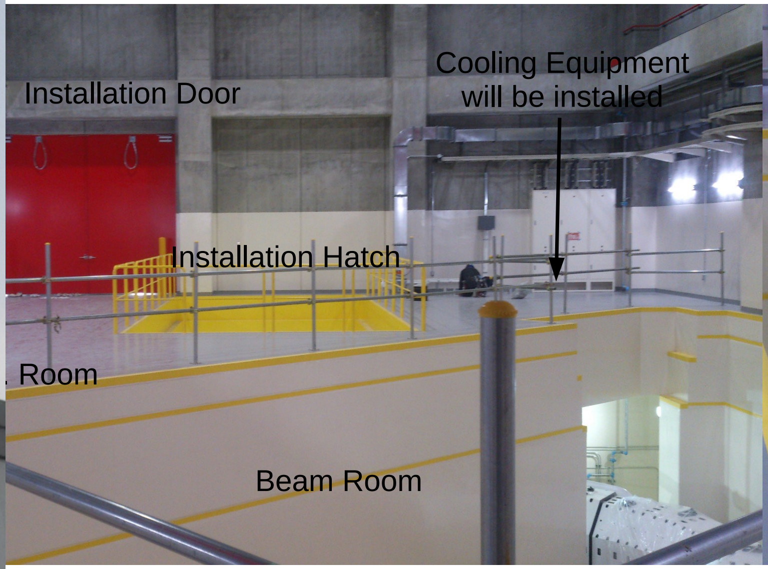
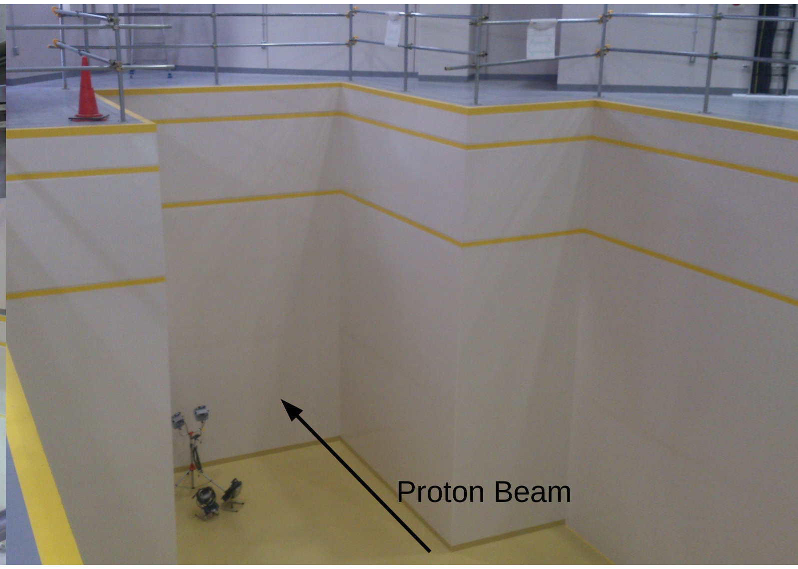


Installation Yard

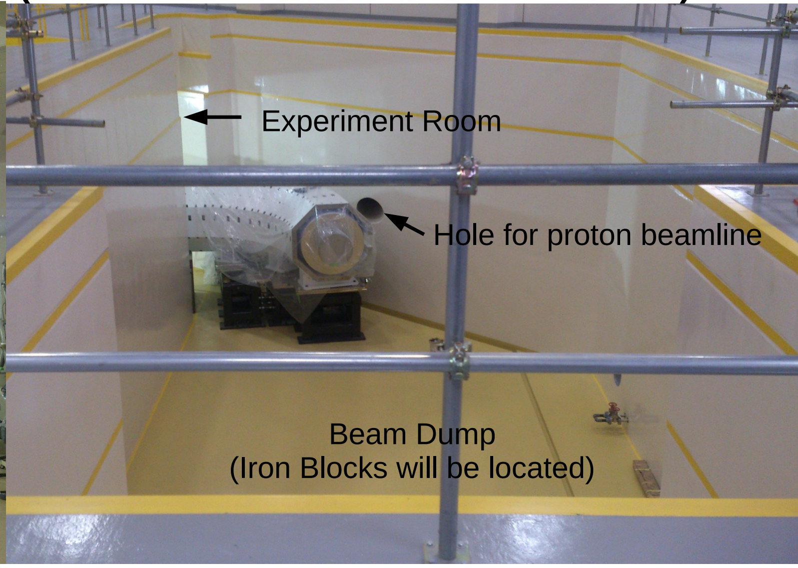


Beam Room



Experiment Room (View from Door)

Beam Room (view from Installation Yard)



Curved Solenoids for Muon Transport Completed and Delivered!

Osaka University

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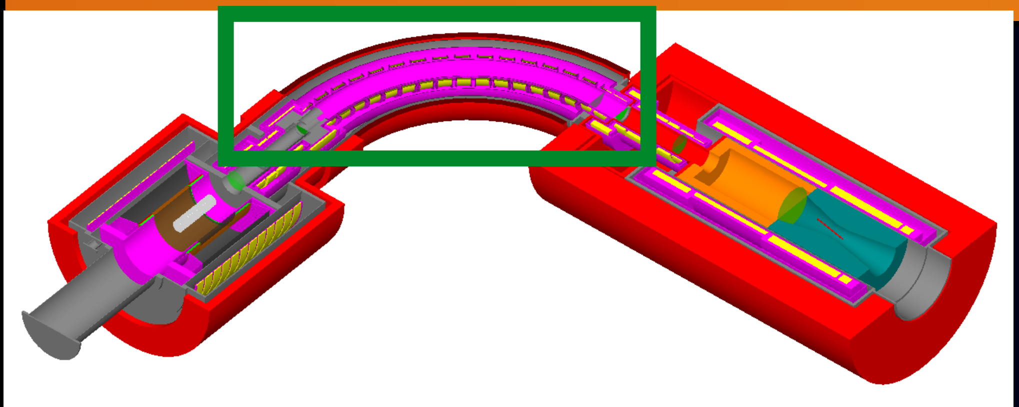

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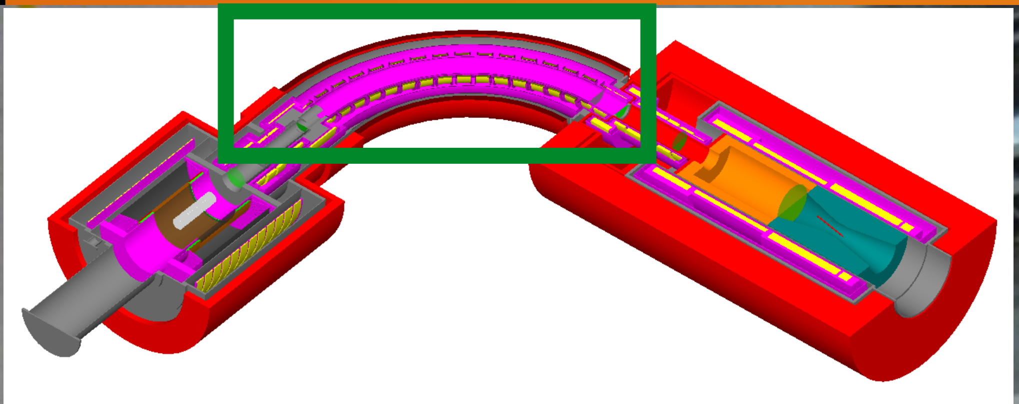
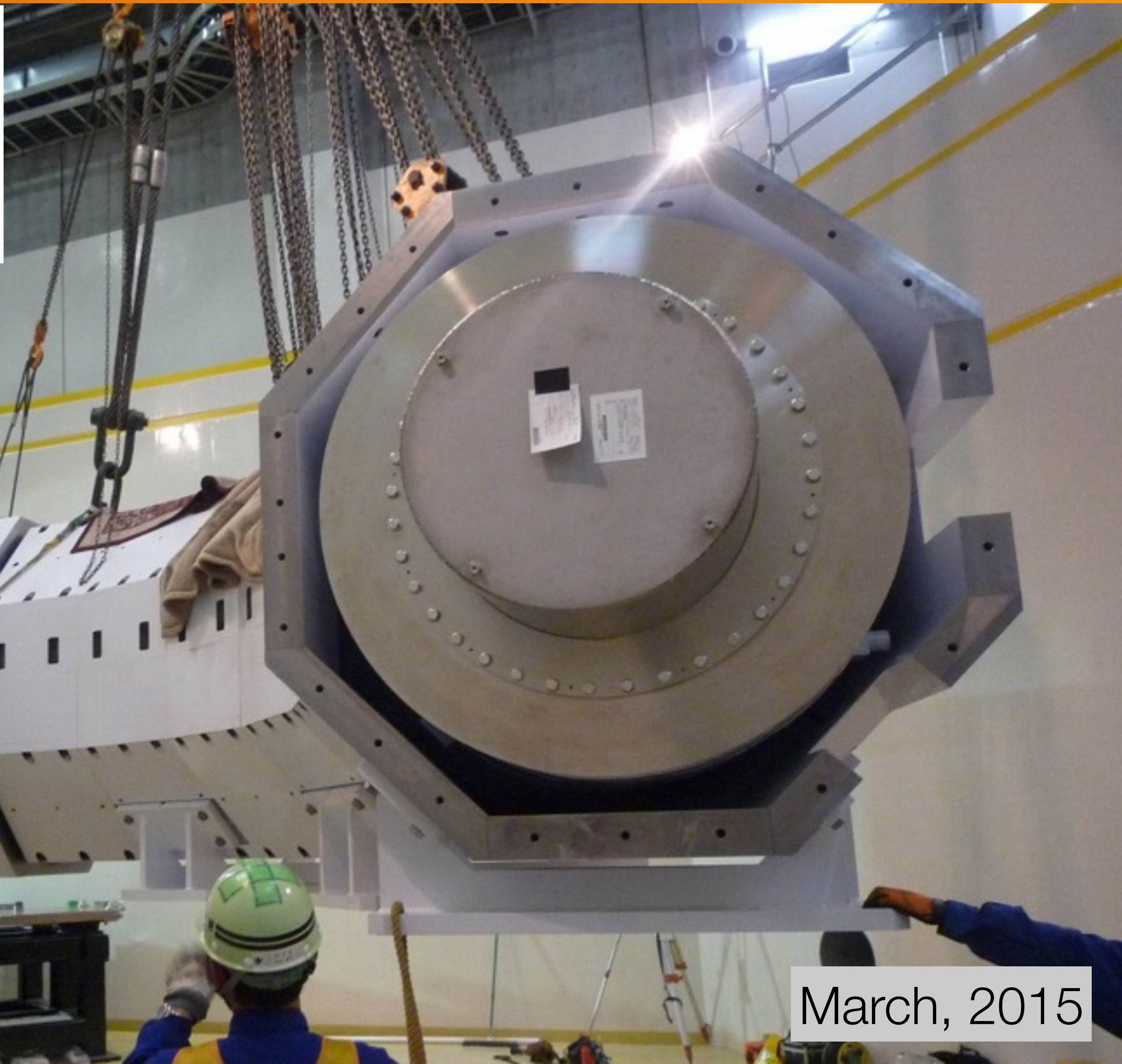




Mu2e-II at PIP-II

Mu2e-II at PIP-II

	Mu2e	Mu2e-II @ PIP-II
Proton beam energy	8 GeV	800 MeV
Beam power	8 kW	8 – 100 kW
Beam width	200 ns	(< 200 ns)
Proton on Target (POT) (*)	3.6×10^{20}	3.6×10^{21} – 4.5×10^{22}
Duty factor	0.32	0.90
Extinction	$< 10^{-10}$	$< 10^{-12}$?
Muon stops / POT	1.7×10^{-3}	1.0×10^{-4}
Muon stops / kW	7.6×10^{16}	4.7×10^{16}
Total muon stops	6.1×10^{17} (**)	4.7×10^{18} @100kW

7.7 times more muons are available. Due to low energy proton beam, less backgrounds are expected.

… In the medium term

$$B(\mu N \to eN) \leq 10^{-18}$$

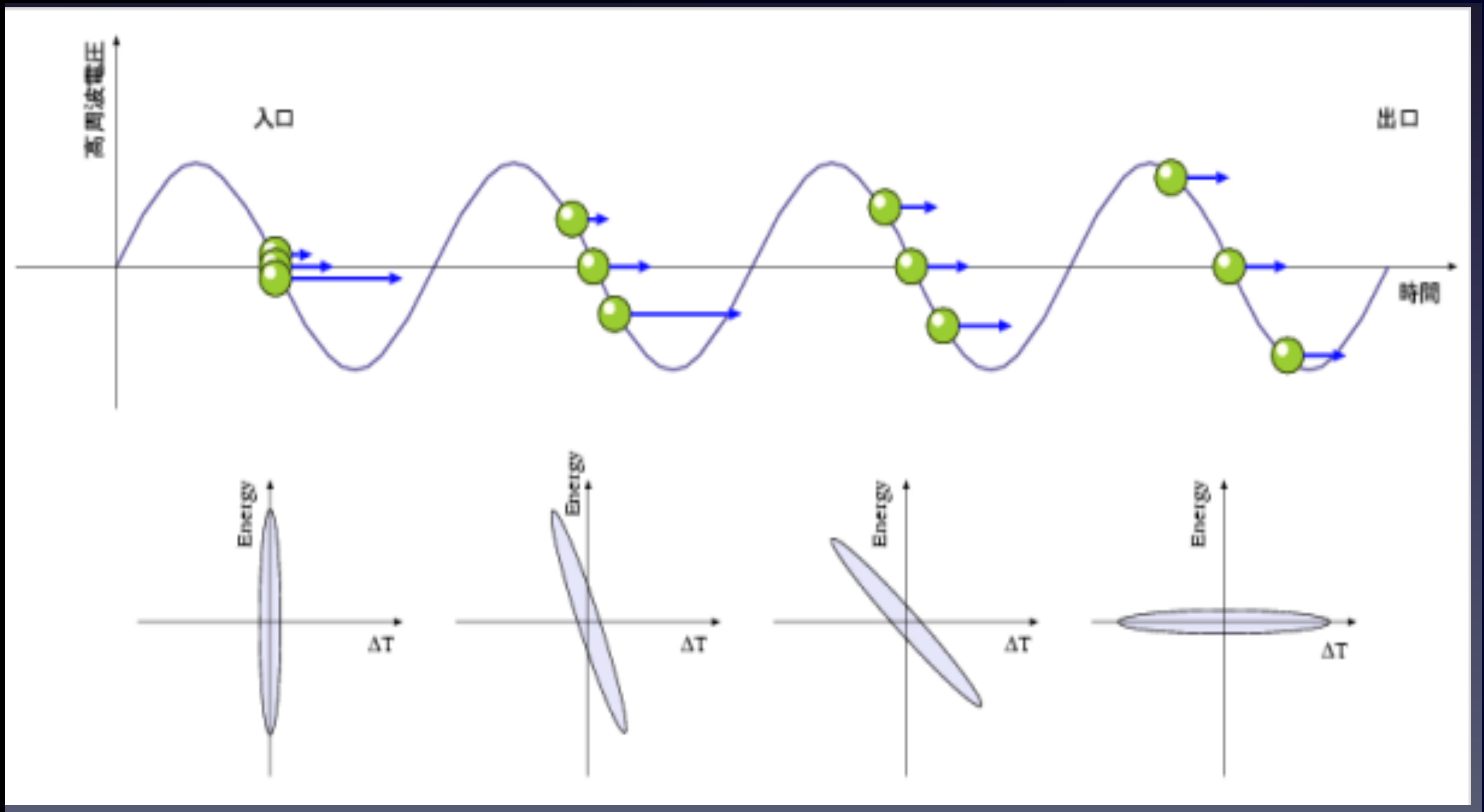
Phase Rotation

Phase Rotation

narrow energy spread of muon beam

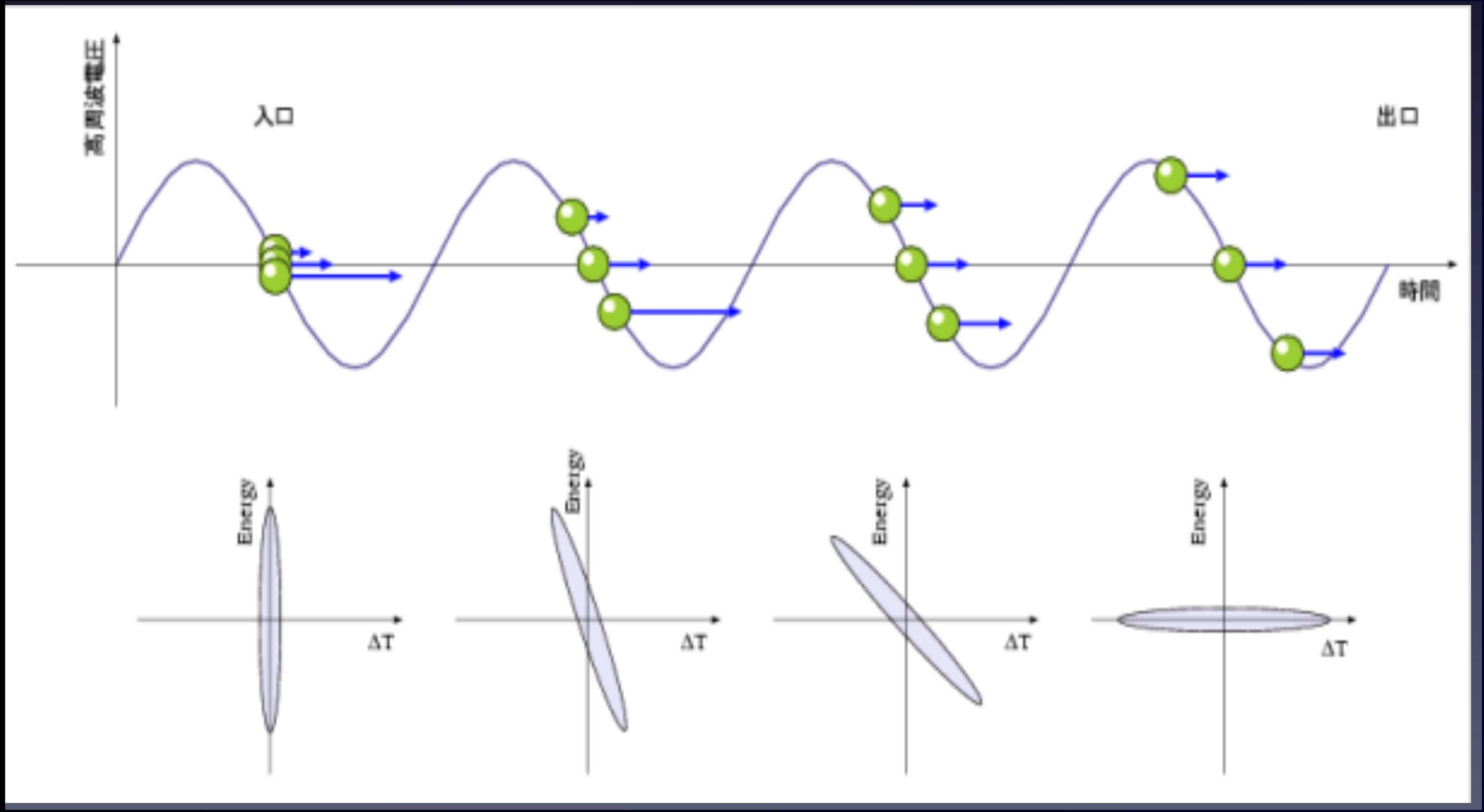
Phase Rotation

narrow energy spread of muon beam



Phase Rotation

narrow energy spread of muon beam



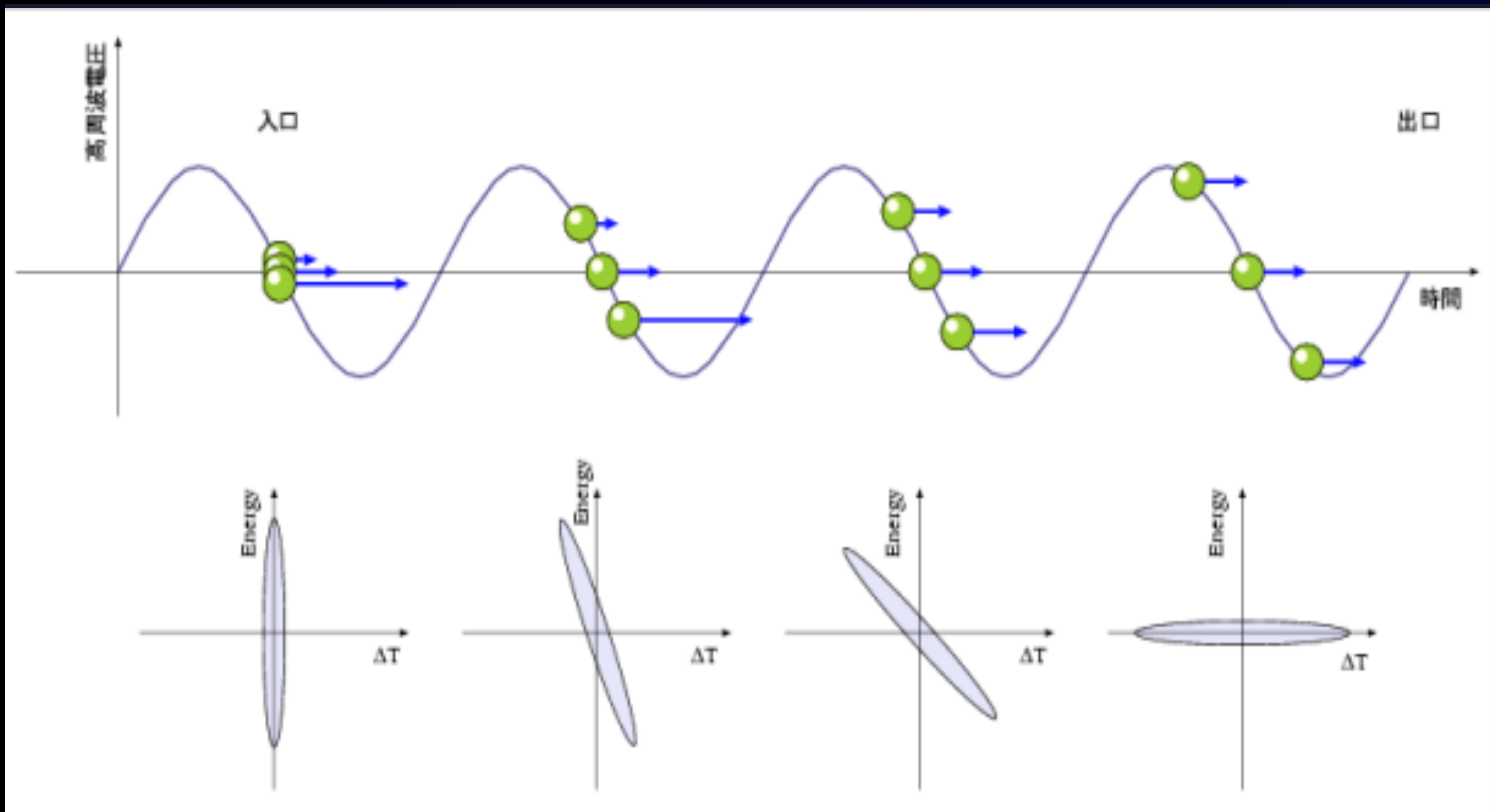
allows a thinner muon stopping target

Phase Rotation

PRISM

Osaka University

narrow energy spread of muon beam

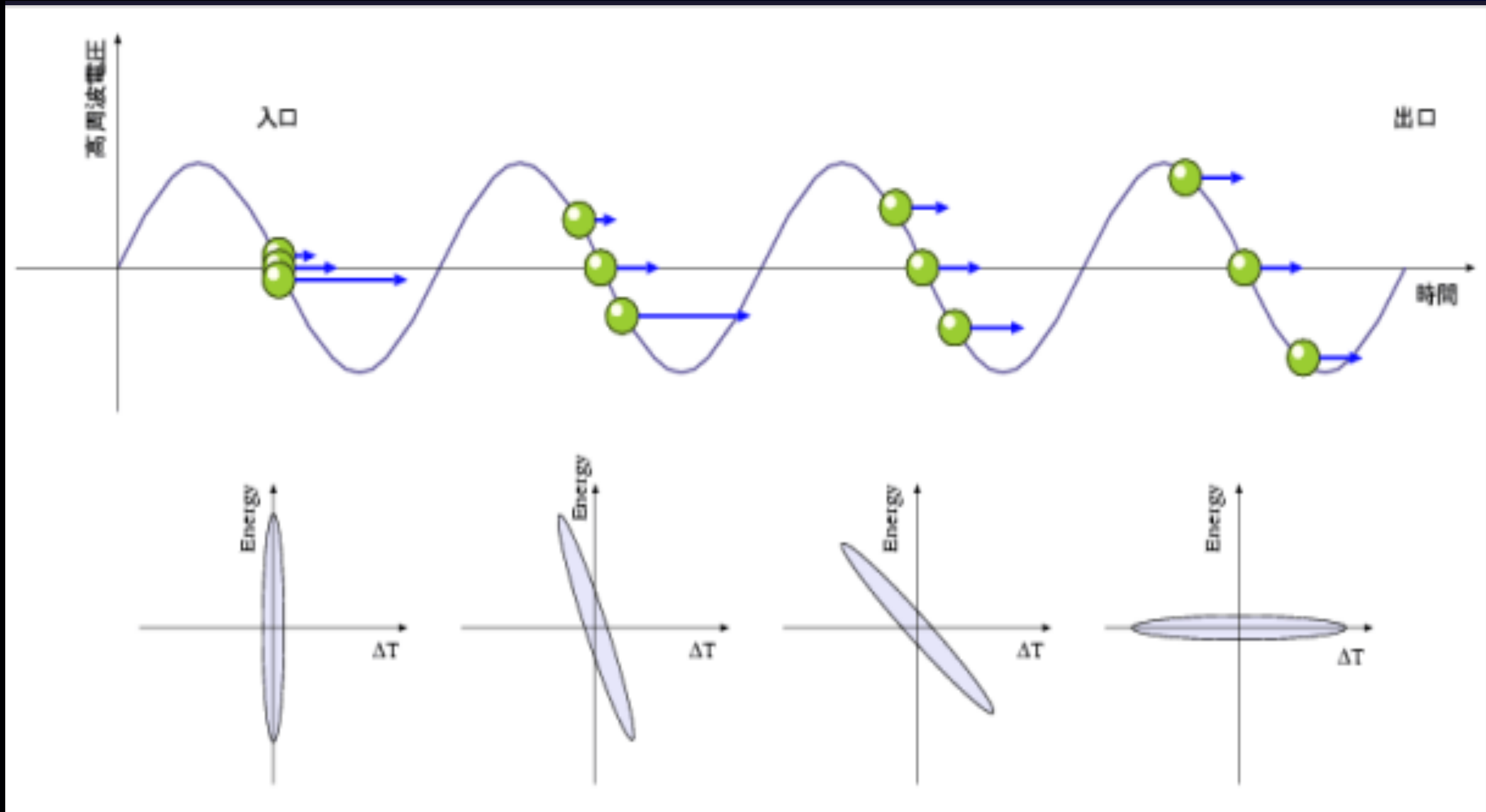


allows a thinner muon stopping target

decelerate fast muons (coming earlier) and accelerate slow muons (coming late) by RF with a narrow proton beam.

Phase Rotation

narrow energy spread of muon beam



allows a thinner muon stopping target

decelerate fast muons (coming earlier) and accelerate slow muons (coming late) by RF with a narrow proton beam.

pure muon beam (pion< 10^{-20})

PRISM (=Phase Rotated Intense Slow Muon source)

PRISM/PRIME

PRISM

Osaka University

PRIME detector

momentum slit

extract kickers

PRISM beam line

injection kickers

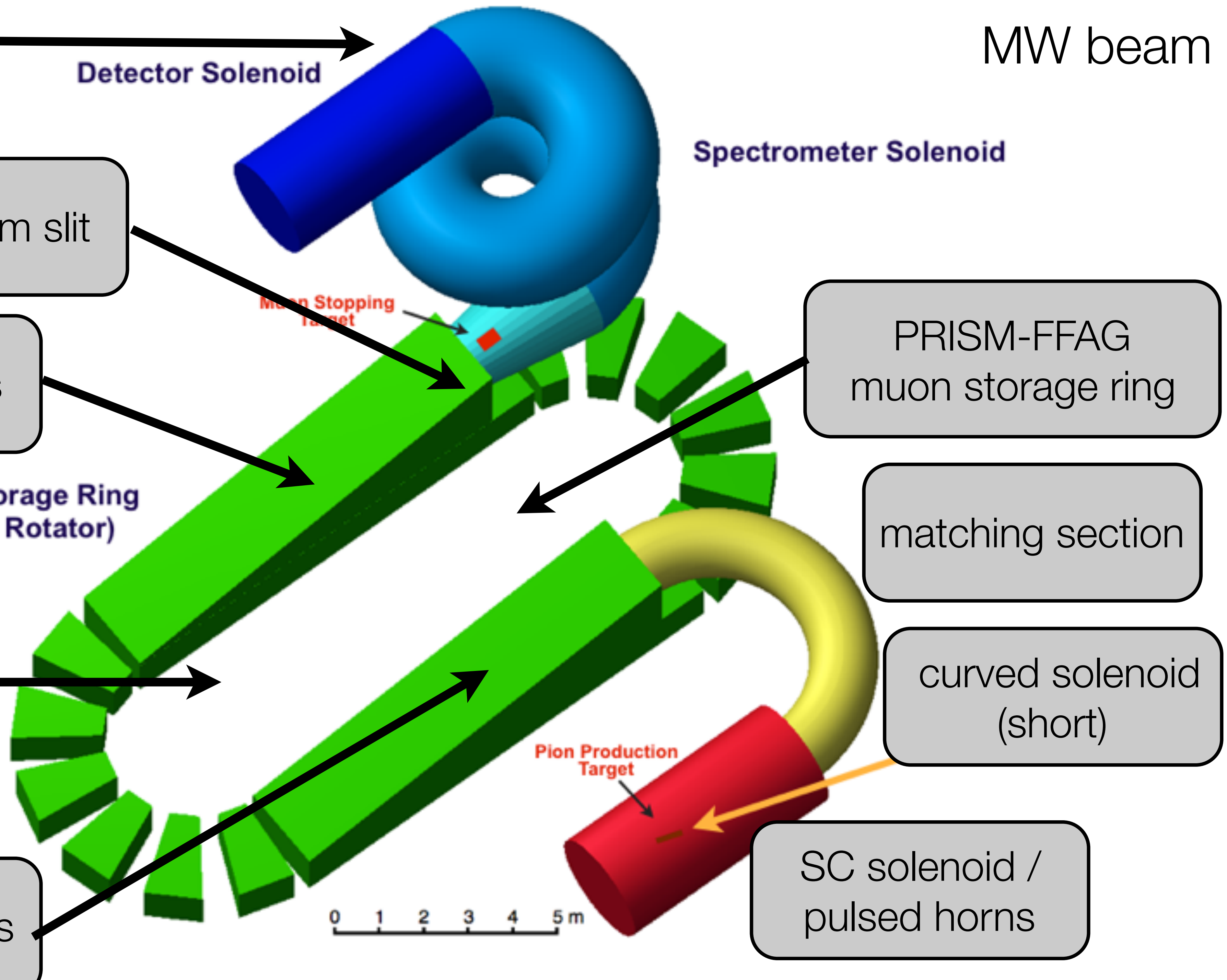
MW beam

PRISM-FFAG muon storage ring

matching section

curved solenoid (short)

SC solenoid / pulsed horns



Features of PRISM/PRIME

Features of PRISM/PRIME

Background rejection by PRISM

(1) Long muon flight length (eliminating pions in a muon beam)
(2) Narrow muon beam energy spread
(3) Muon beam energy selection
(4) Beam extinction at muons

Features of PRISM/PRIME

PRISM

Osaka University

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Rough Estimation on Experimental Sensitivity

- x(1/2) from reduced beam acceptance from solenoid to FFAG
- x3 from removing detection time window (no pion)
- x3 from pion capture improvement
- x20 from 56 kW→1MW

from MyeongJae Lee's presentation in HINT2015

Features of PRISM/PRIME

PRISM

Osaka University

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from MyeongJae Lee's presentation in HINT2015

$O(10^{13})$ stopped μ^-/sec for O(1) MW protons

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

demonstration of phase rotation has been done.

PRISM Task Force

PRISM Task Force

PRISM

Osaka University

PRISM Task Force

The aim of the PRISM-FFAG Task Force is to address the technological challenges in realising an FFAG based muon-to-electron conversion experiment, but also to strengthen the R&D for muon accelerators in the context of the Neutrino Factory and future muon physics experiments.

The following key areas of activity were identified and proposed to be covered within the Task Force:

- the physics of muon to electron conversion,
- proton source,
- pion capture,
- muon beam transport,
- injection and extraction for PRISM-FFAG ring,
- FFAG ring design including the search for a new improved version,
- FFAG hardware R&D for RF system and injection/extraction kicker and septum magnets.

J. Pasternak

UK-Japan

… In the long term

$$B(\mu N \to eN) \leq 10^{-20}$$

μ-e conversion with cooled muon beams

μ-e conversion with cooled muon beams

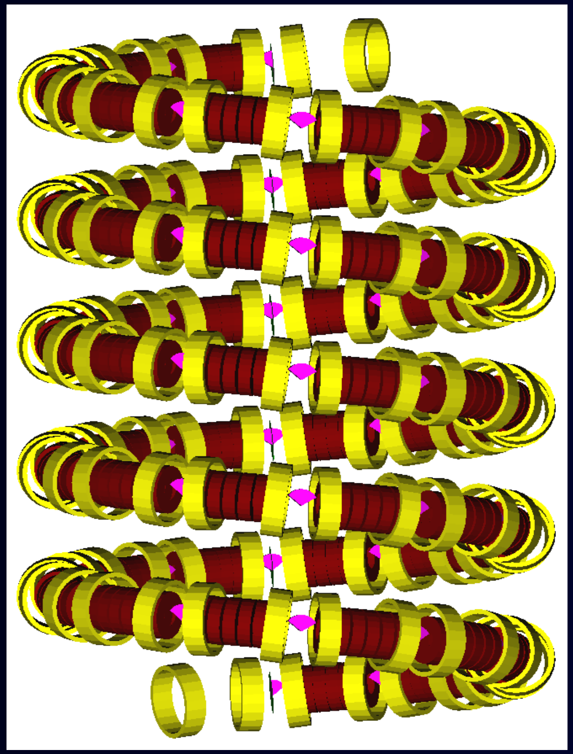
Osaka University

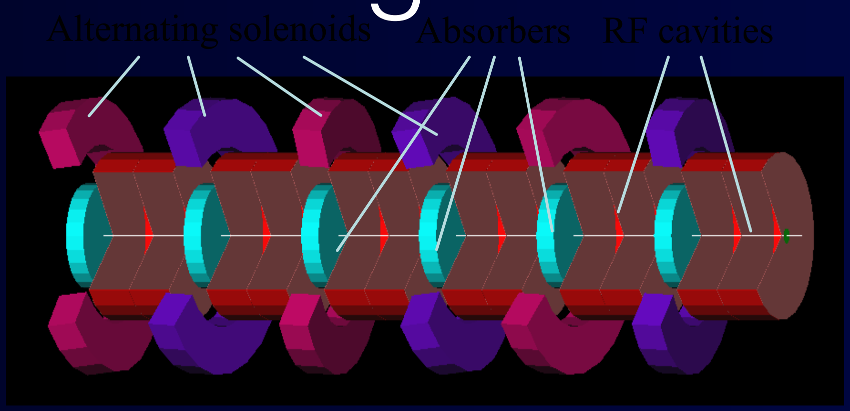
low emittance (cooled) muon beam

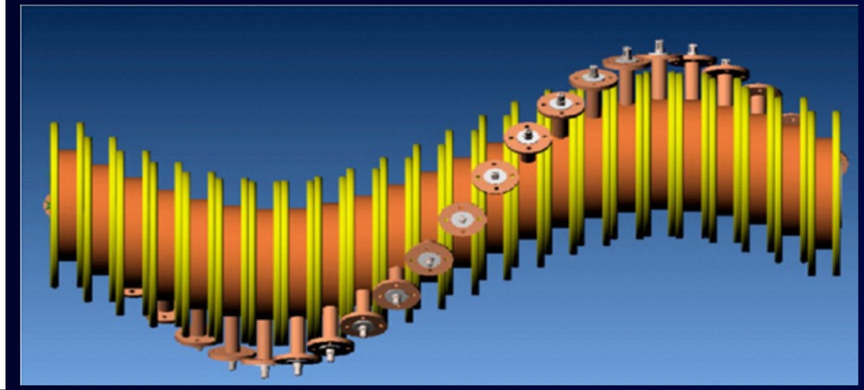
μ-e conversion with cooled muon beams

low emittance (cooled) muon beam

6D cooling







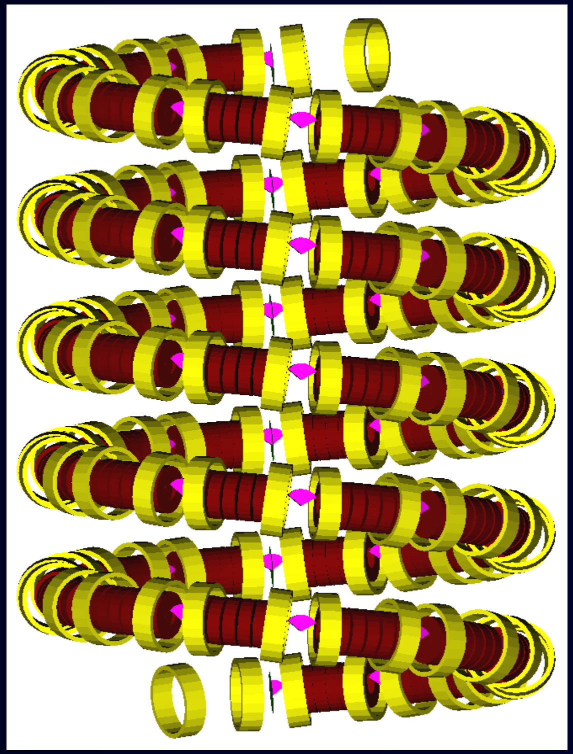
μ-e conversion with cooled muon beams

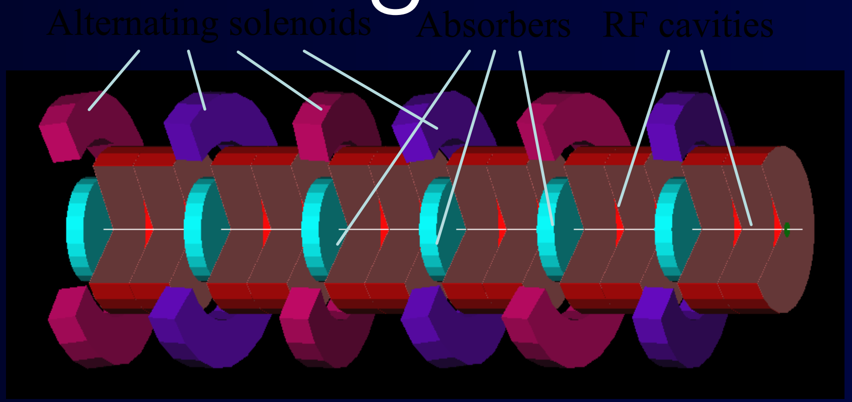
low emittance (cooled) muon beam

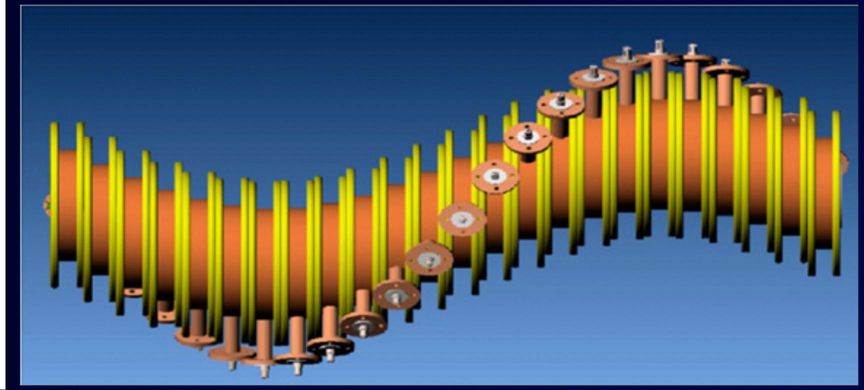
Background rejection

(1) small-size thin muon stopping target
(2) no punch-through at muon stopping target
(3) back-tracking of signal electrons

6D cooling







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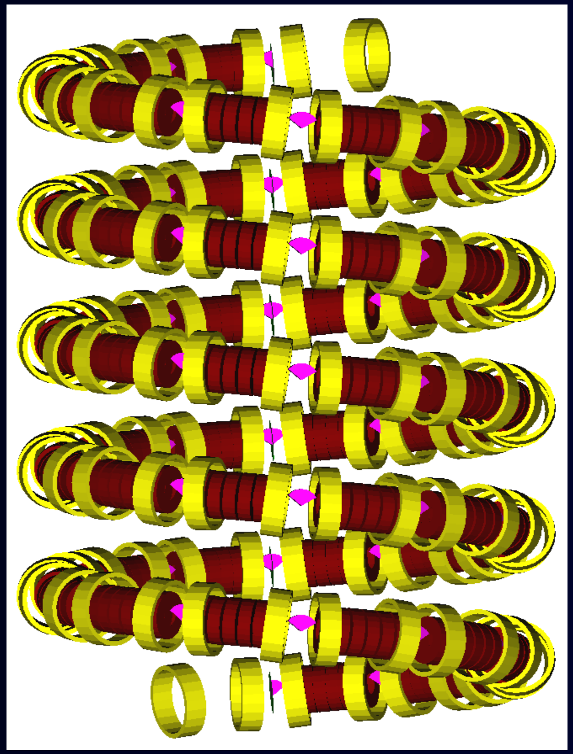
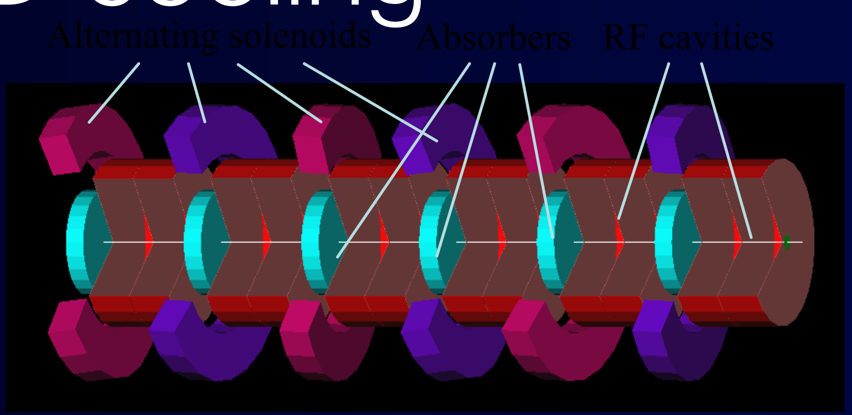
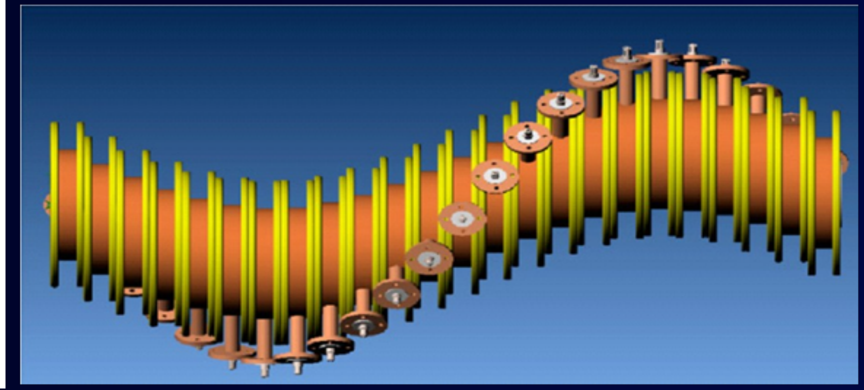
Experimental sensitivity

?

6D cooling







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