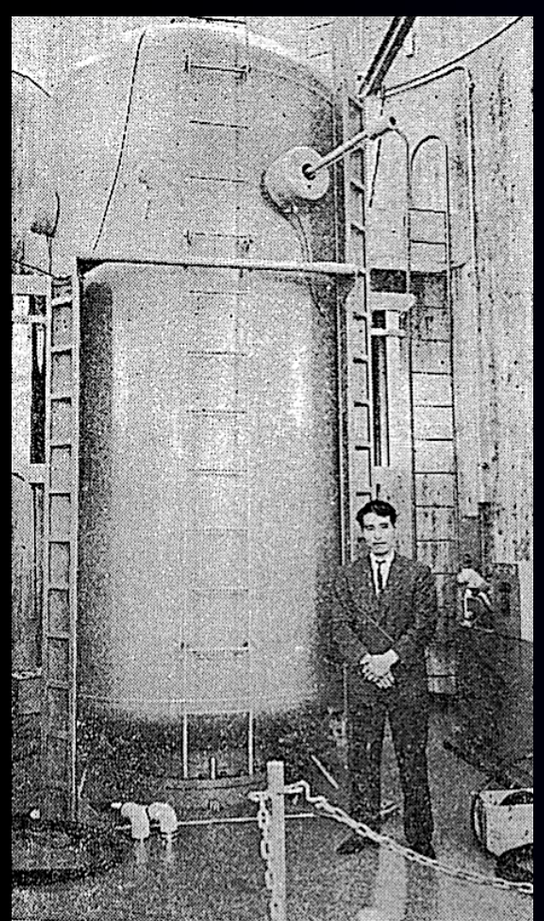
次世代への期待

フレーバー物理 (素粒子物理学)



大阪大学大学院理学研究科物理

久野良孝

杉本記念シンポジウム

平成25年4月7日

始めに

- 1981年
  - バンデで数回実験（南園先生）
  - ^{12}B偏極を保持する炭素物質
- 1978年
  - ミューオンを始める（東京大学中間子科学実験施設）
  - 最初の日本のミューオンビーム施設完成（1981年）
  - ミューオン原子核捕獲実験　$\mu^- + ^{12}C \rightarrow \nu_\mu + ^{12}B$
    - ^{12}B偏極の測定　g_p/g_A
- 2000年10月
  - 大阪大学に赴任、杉本先生と話しする機会も

1984

Osaka University

NEW PULSED-BEAM MEASUREMENT OF THE AVERAGE POLARIZATION OF ^{12}B (GROUND STATE) PRODUCED IN THE POLARI

Y. KUNO[a], J. IMAZATO[a], K.
and T. MINAMISONO[b]
[a] *Meson Science Laboratory and Departme*
Tokyo 113, Japan
[b] *Department of Physics, Osaka University*

Received 4 June 1984

The average polarization P_{av} of the re
measured by the muon spin resonance m
maintained completely under a longitudi
excited-state contributions of ^{12}B, P_{av} (gr
almost consistent with the prediction of

Volume 148B, number 4,5 PHYSICS LETTERS 29 November 1984

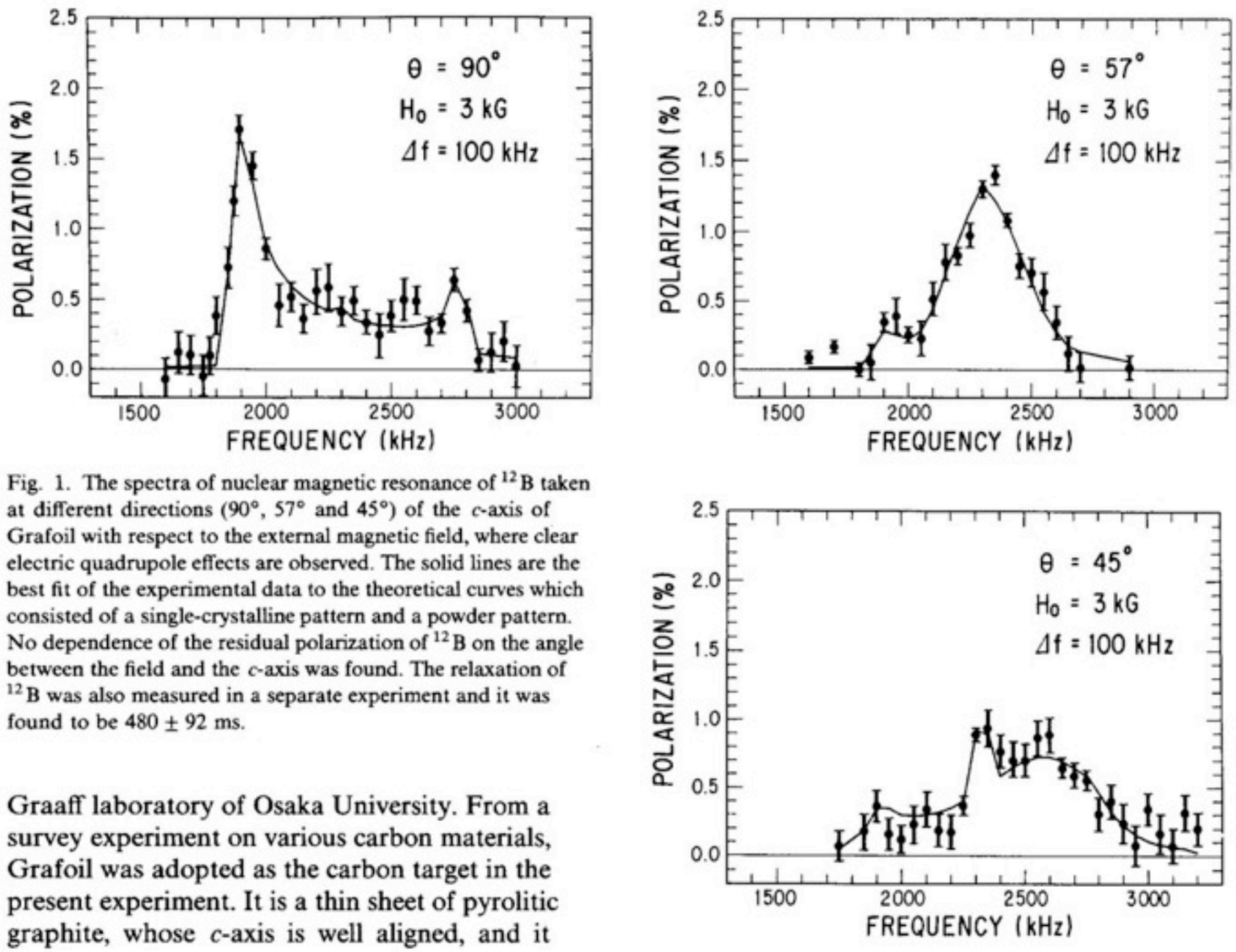
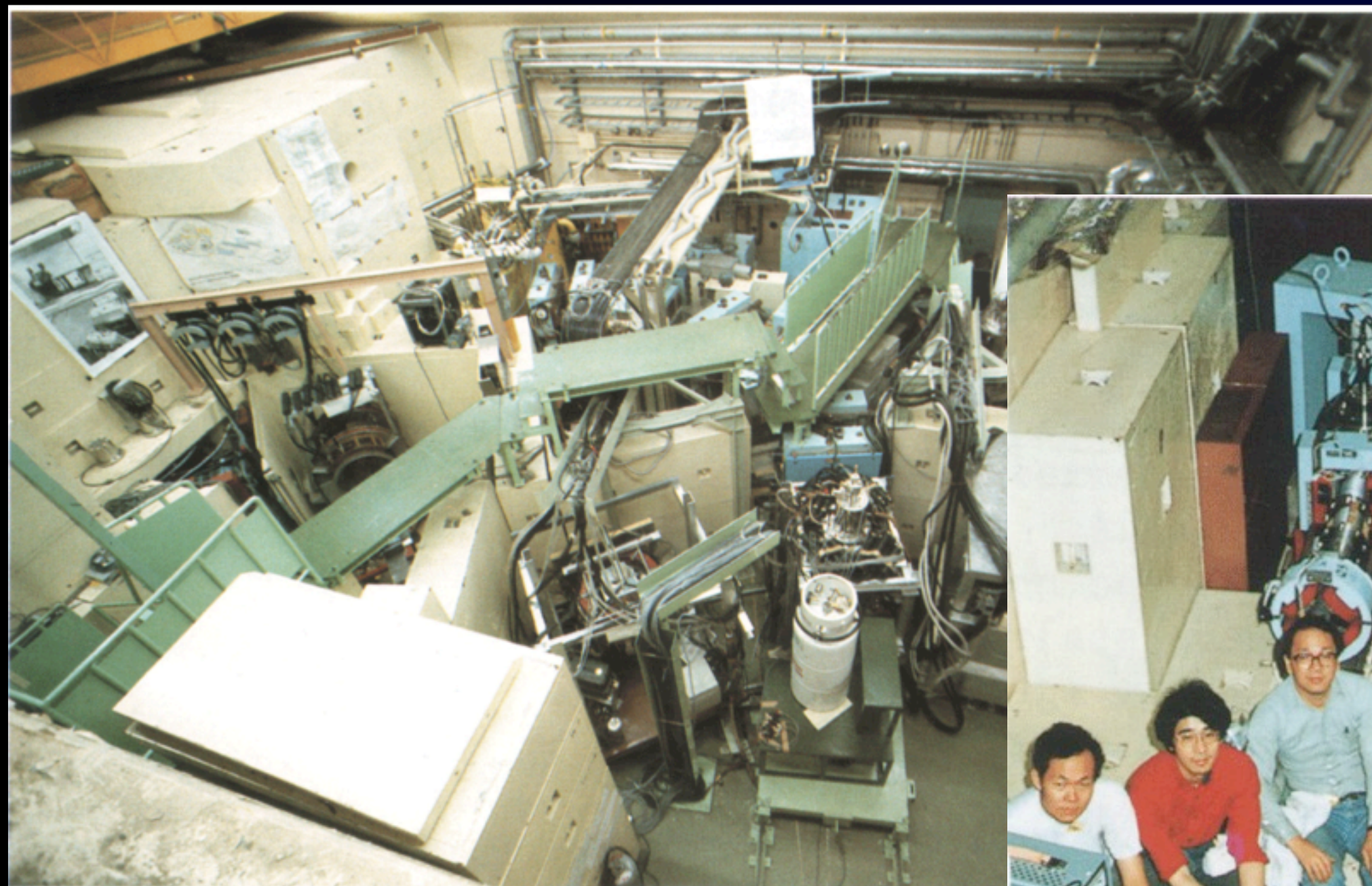
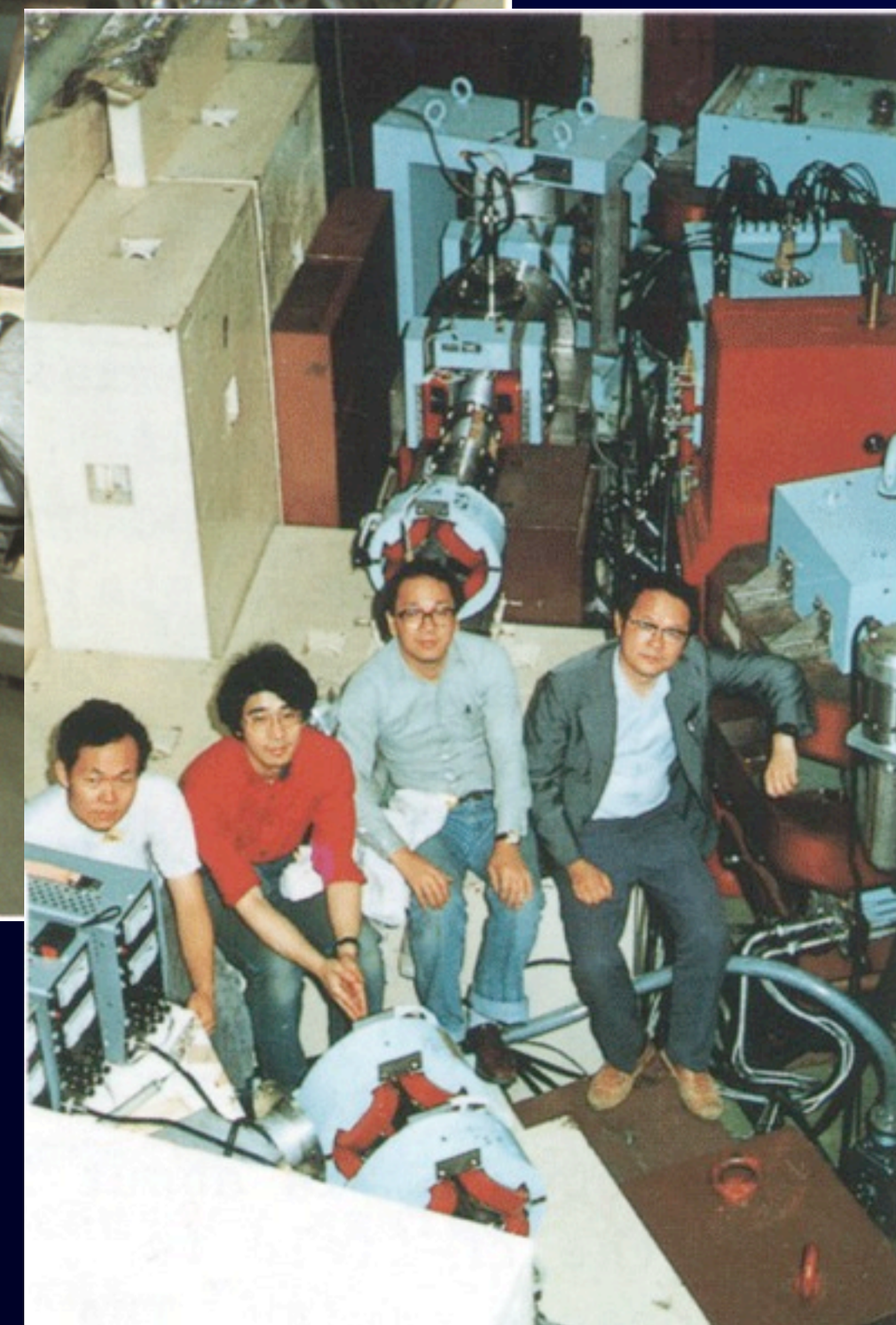


Fig. 1. The spectra of nuclear magnetic resonance of ^{12}B taken at different directions (90°, 57° and 45°) of the c-axis of Grafoil with respect to the external magnetic field, where clear electric quadrupole effects are observed. The solid lines are the best fit of the experimental data to the theoretical curves which consisted of a single-crystalline pattern and a powder pattern. No dependence of the residual polarization of ^{12}B on the angle between the field and the c-axis was found. The relaxation of ^{12}B was also measured in a separate experiment and it was found to be 480 ± 92 ms.

Graaff laboratory of Osaka University. From a survey experiment on various carbon materials, Grafoil was adopted as the carbon target in the present experiment. It is a thin sheet of pyrolitic graphite, whose c-axis is well aligned, and it

バンデでの
実験結果





BOOM (中間子科学実験施設)

私のフレーバー物理

- 1985年から
  - K中間子稀崩壊

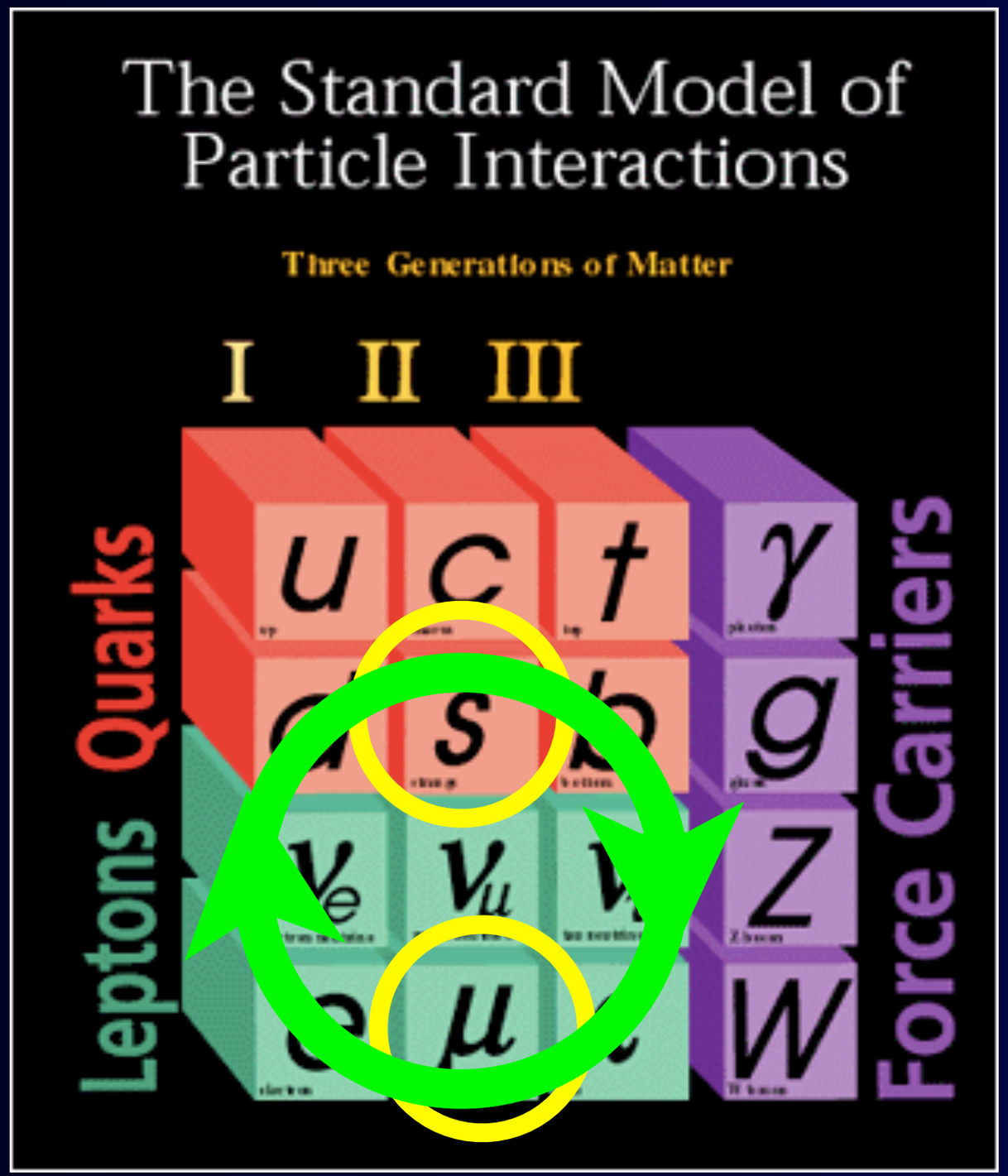
$$K^+ \to \pi^+ \nu \overline{\nu}$$

    - at BNL
  - K中間子精密実験

$$K^+ \to \pi^0 \mu^+ \overline{\nu}$$

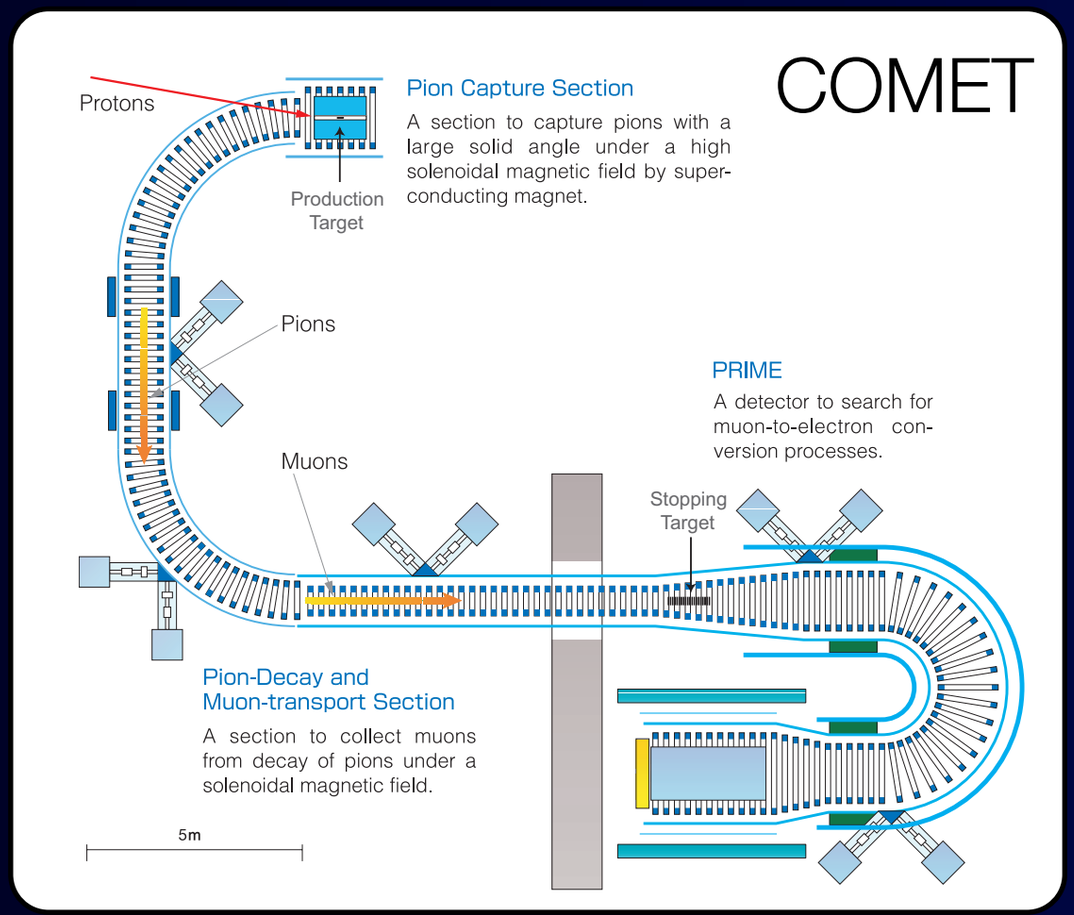
    - at KEK
- 2000年頃から
  - ミューオン稀崩壊 (素粒子実験)

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



Outline

- Muon Particle Physics
  - Search for charged lepton flavor violation (CLFV) with muons
- Physics Motivation
- COMET@J-PARC (in preparation)
- MuSIC@RCNP (2009~)
- COMET Phase-I (2013~)
- Summary



Many applogies if heard in the past.

フレーバー物理としての

ミューオン素粒子物理

woodblock prints on “Kabuki” actors
by Tsuruya Kokei (1978-2000)

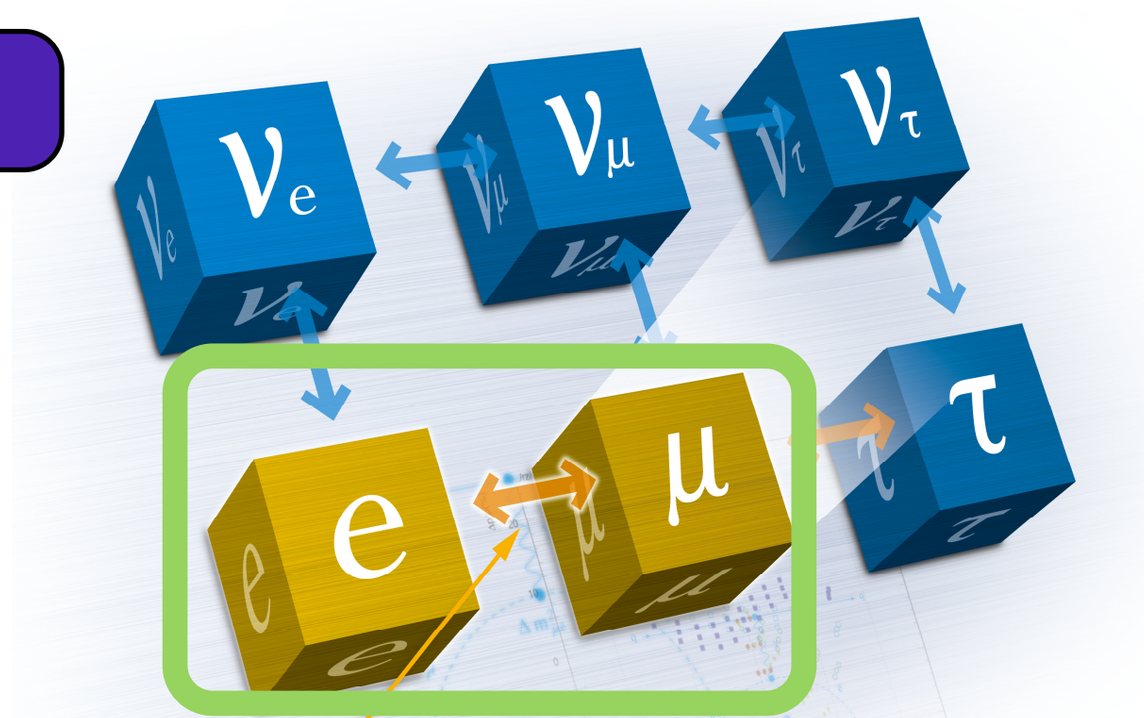
フレーバー物理（フレーバー非保存）

フレーバー非保存＝素粒子が別の素粒子に変わること

クォーク

クォークの
フレーバー非保存

レプトン



ニュートリノの
フレーバー非保存

未発見

荷電レプトンの
フレーバー非保存

荷電レプトンフレーバー非保存過程 (CLFV) の発見は最重要

素粒子物理学の課題

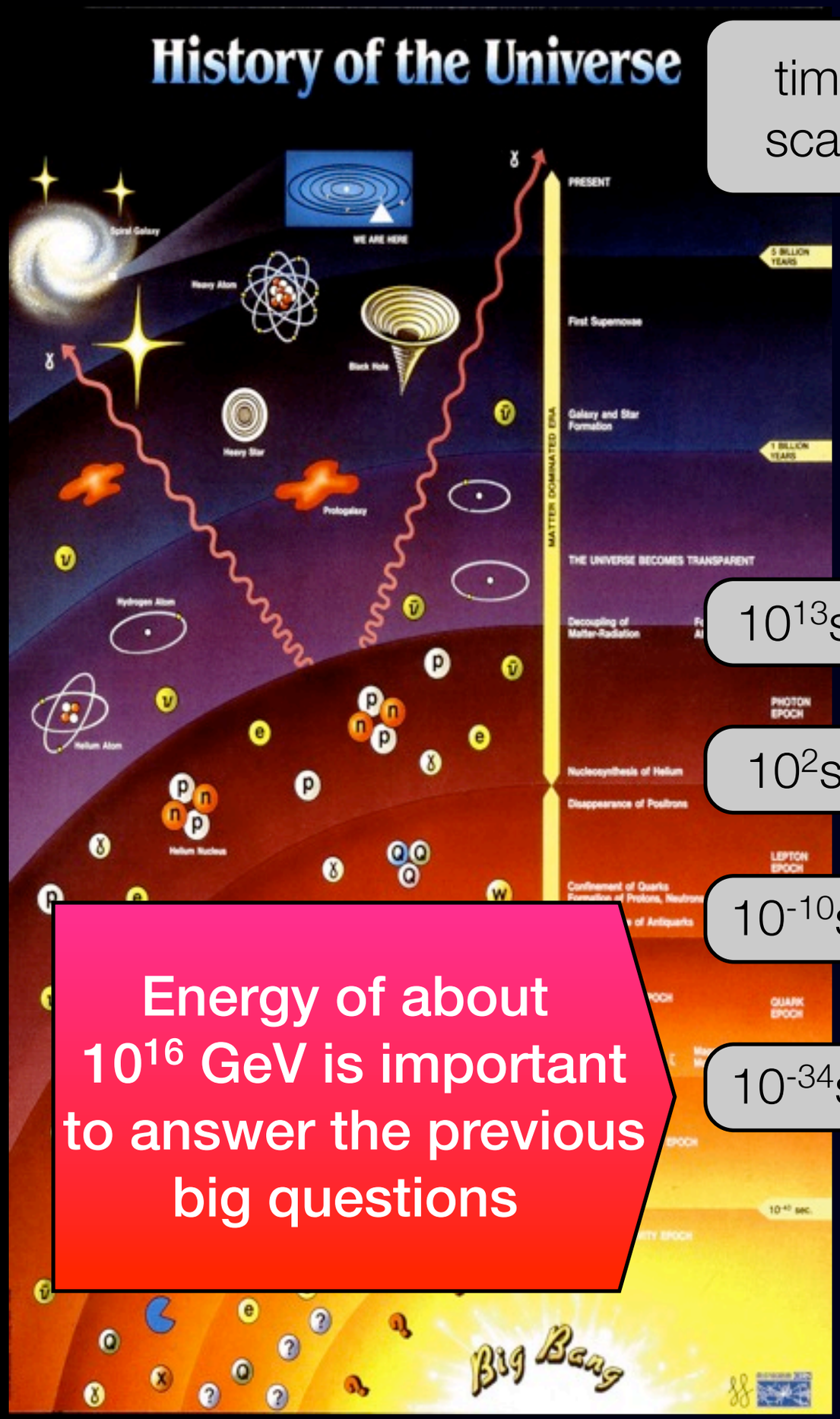
素粒子物理学の課題

素粒子標準理論はヒッグス粒子の発見でほぼ完成した。
標準理論はこれまでの実験事実をほぼすべて説明できるが、
しかし標準理論は完璧な理論でないと考えられてる。
（例：理論の中のパラメータがadhocに決められて説明できない。）

素粒子物理学の現状

- 平成24年に欧州のCERN研究所の大型ハドロンコライダー加速器 (LHC)で、素粒子標準理論で期待されるヒッグス粒子を発見。

- しかし、標準理論以外の新粒子は発見されていない。



Energy of about 10^{16} GeV is important to answer the previous big questions

time scale	energy scale
10^{13}sec	10^{-9}GeV
10^{2}sec	10^{-3}GeV
10^{-10}sec	10^{3}GeV
10^{-34}sec	10^{16}GeV
	10^{19}GeV

Electroweak Epoch
- Higgs particles
- Supersymmetry

Unification Epoch
- Grand unification of fundamental forces
- Origin of Neutrino mass (RH neutrino)
- Leptogenesis (baryogenesis)

Quantum Gravity Epoch
- Superstrings

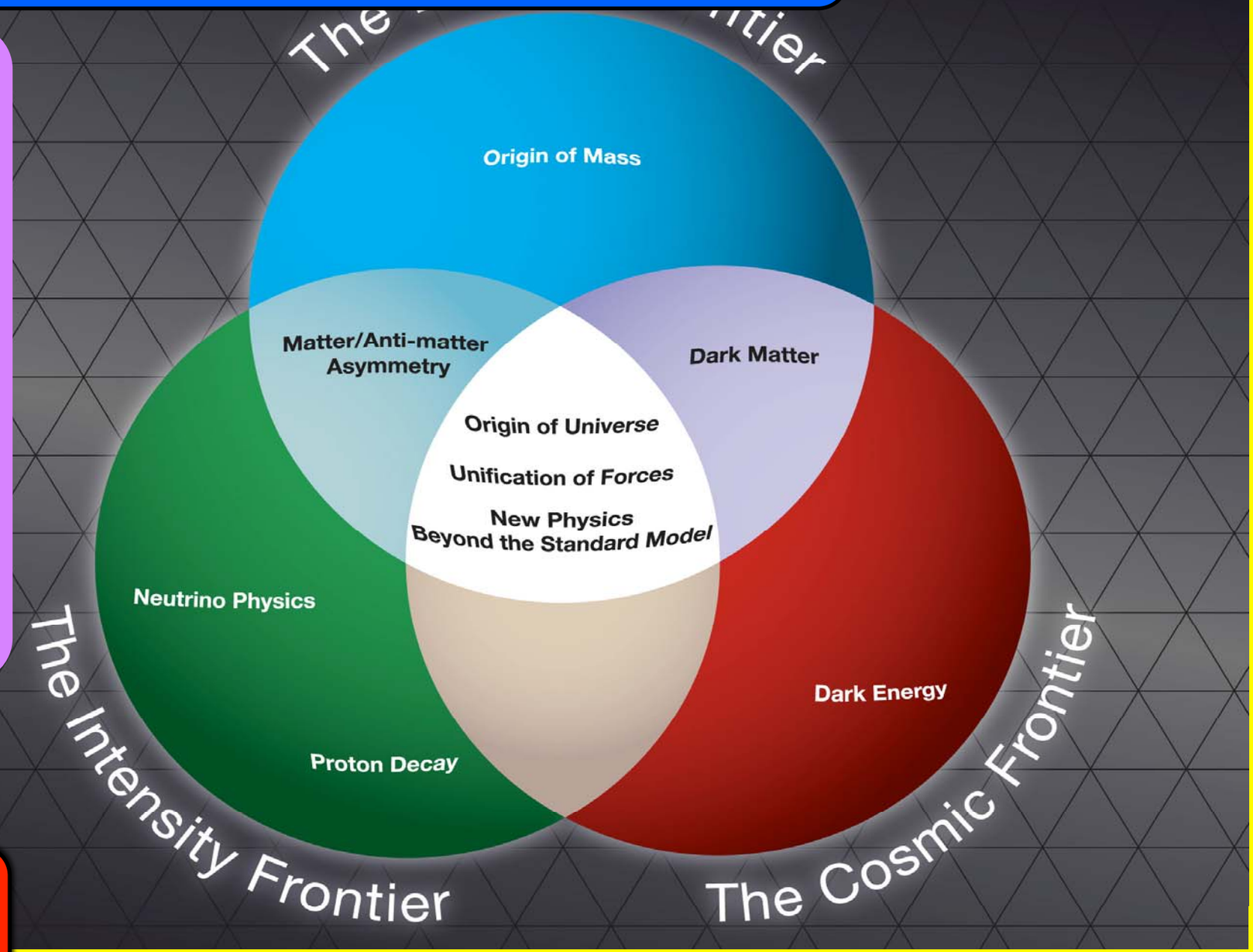
素粒子物理学の強度フロンティア

高いエネルギースケールの新物理の探索

The Intensity Frontier

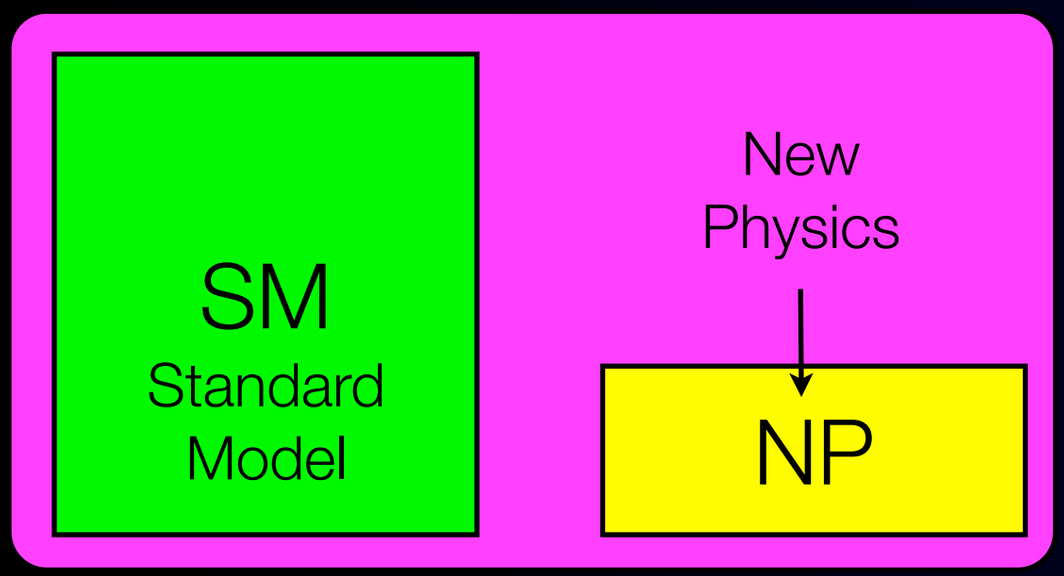
use intense beams to observe rare processes and study the particle properties to probe physics beyond the SM.

Rare Decays

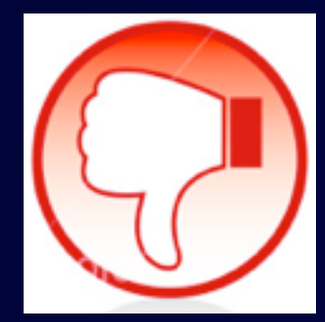


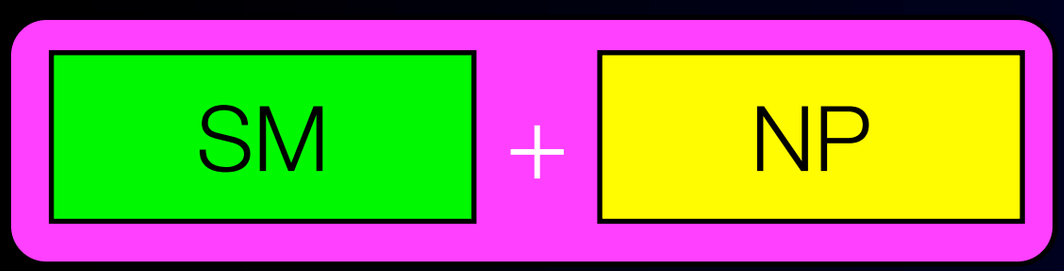
稀崩壊を選ぶガイドライン

New physics effects may be very small.



SM contribution is dominant.





SM contribution is highly suppressed.

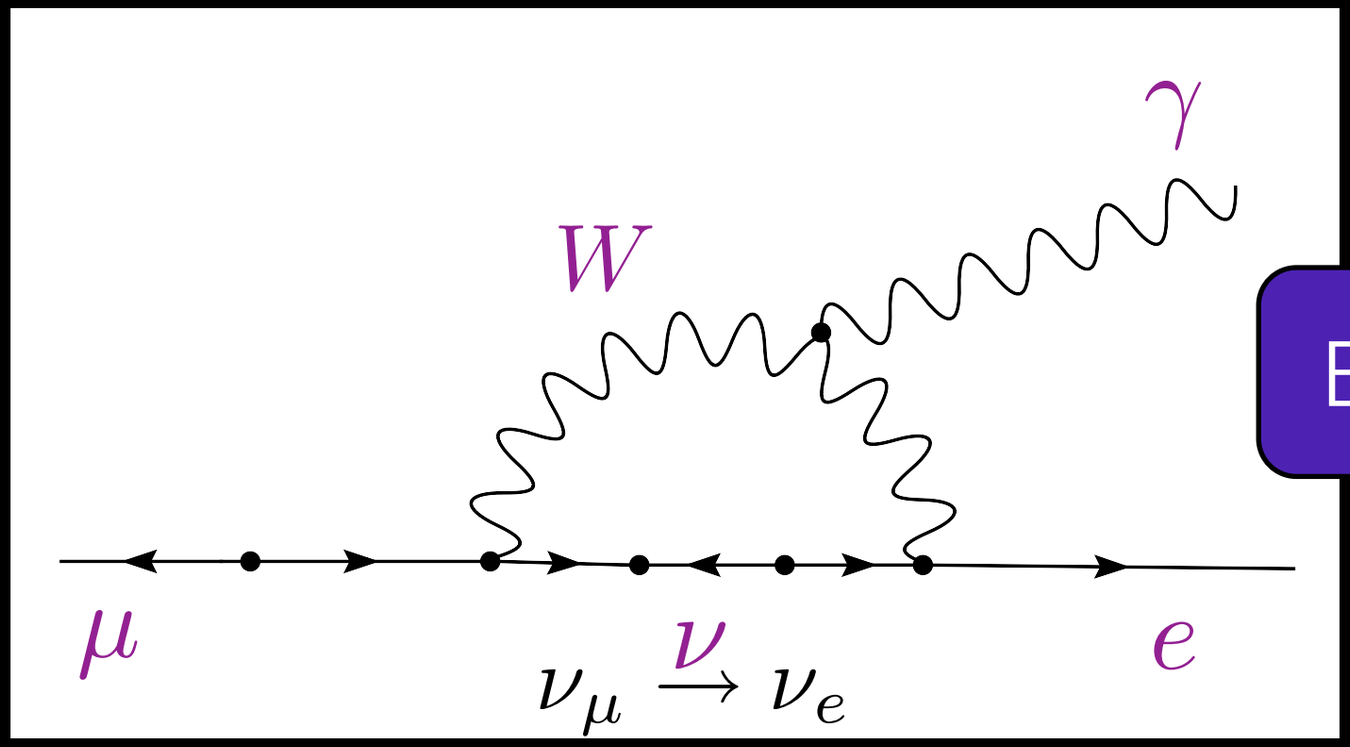
$$B \sim \frac{1}{\sqrt{N}}$$

SM contribution is forbidden.

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

CLFV過程への標準理論の寄与は小さい！

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



BR~O(10^{-54})

CLFV過程の観測は標準理論以外の新物理現象の発見

新物理エネルギースケール：荷電レプトンフレーバー非保存過程

with new physics contributions

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

Λ is the energy scale of new physics

Charged Lepton Flavour

For instance, μ→eγ (B<5.7x10^{-13}、2013),

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

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

Λ > O(10^5) TeV

The constraint in CLFV is even more severe than in the quark flavour.

稀崩壊と新物理のエネルギースケール

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

Λ: energy scale of new physics

Can we improve the Λ reach by an order of magnitude ?

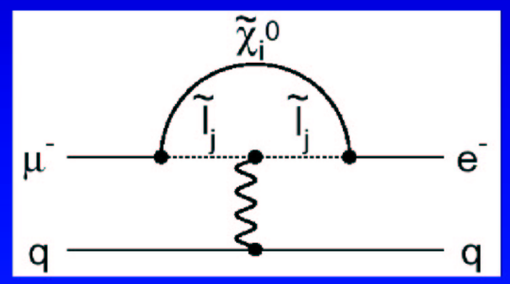
must have at least 10^4 times the number of parent particles in rare decays.

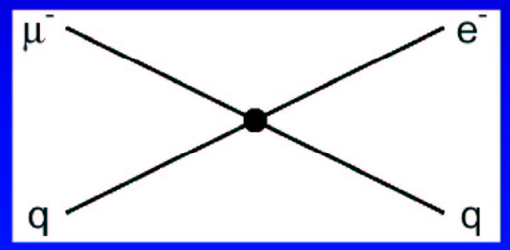
CLFVを予言する多くの新しい理論モデル

Sensitivity to Different Muon Conversion Mechanisms

Supersymmetry

Predictions at 10^{-15}





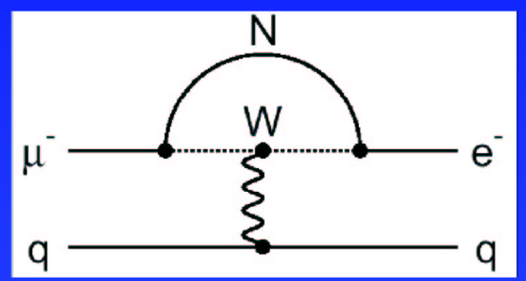
Compositeness

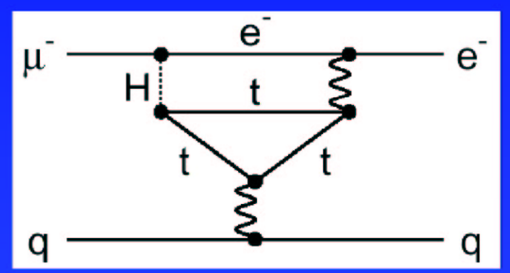
Λ_c = 3000 TeV

Heavy Neutrinos

$|U^*_{\mu N} U_{eN}|^2 =$

8×10^{-13}

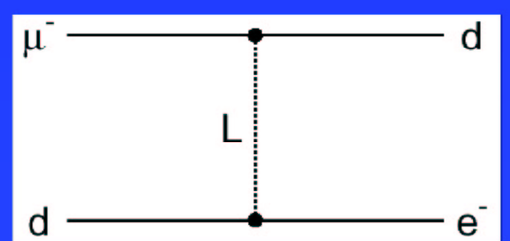


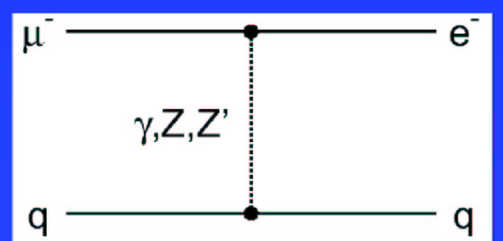


Second Higgs doublet

$g_{H\mu e} = 10^{-4} \times g_{H\mu\mu}$

Leptoquarks





Heavy Z', Anomalous Z coupling

$M_{Z'}$ = 3000 TeV/c^2

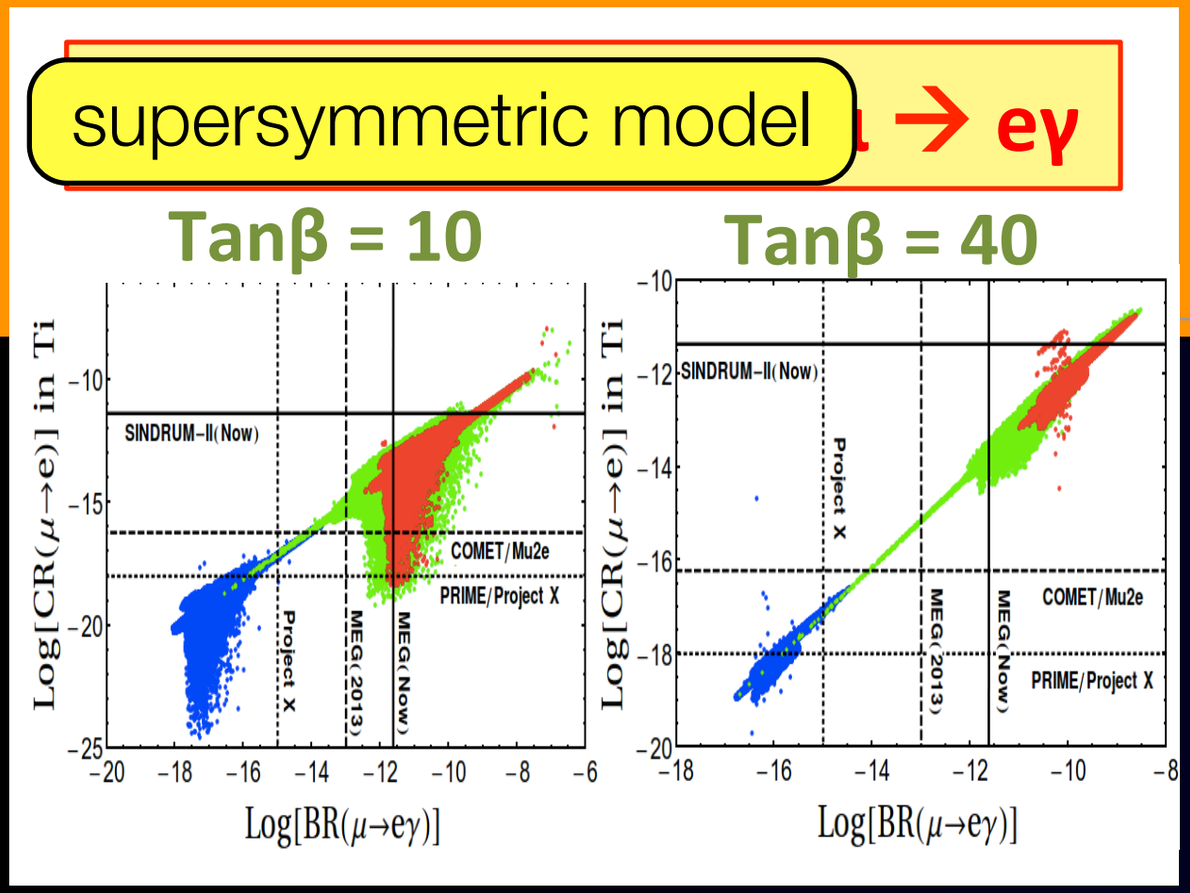
$B(Z \rightarrow \mu e) < 10^{-17}$

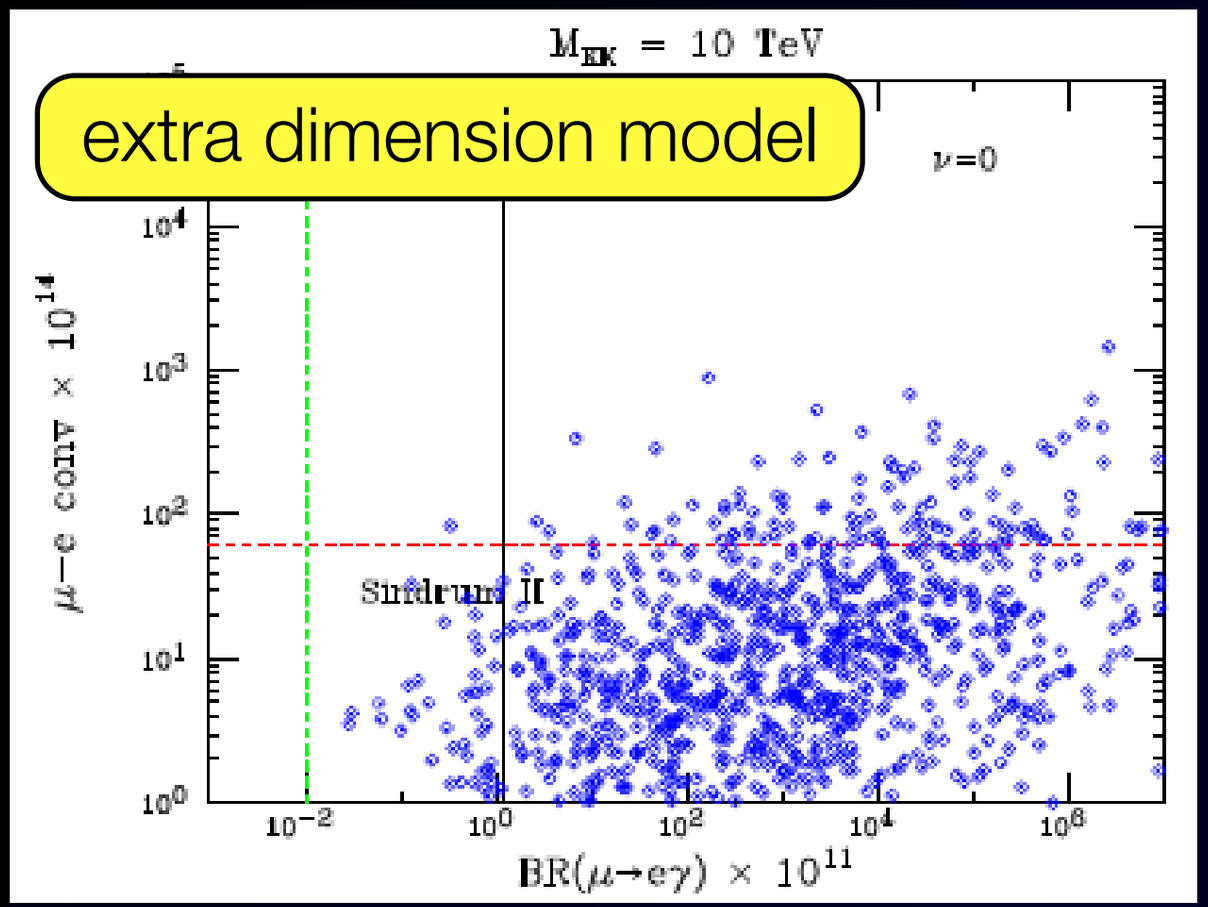
$M_L =$

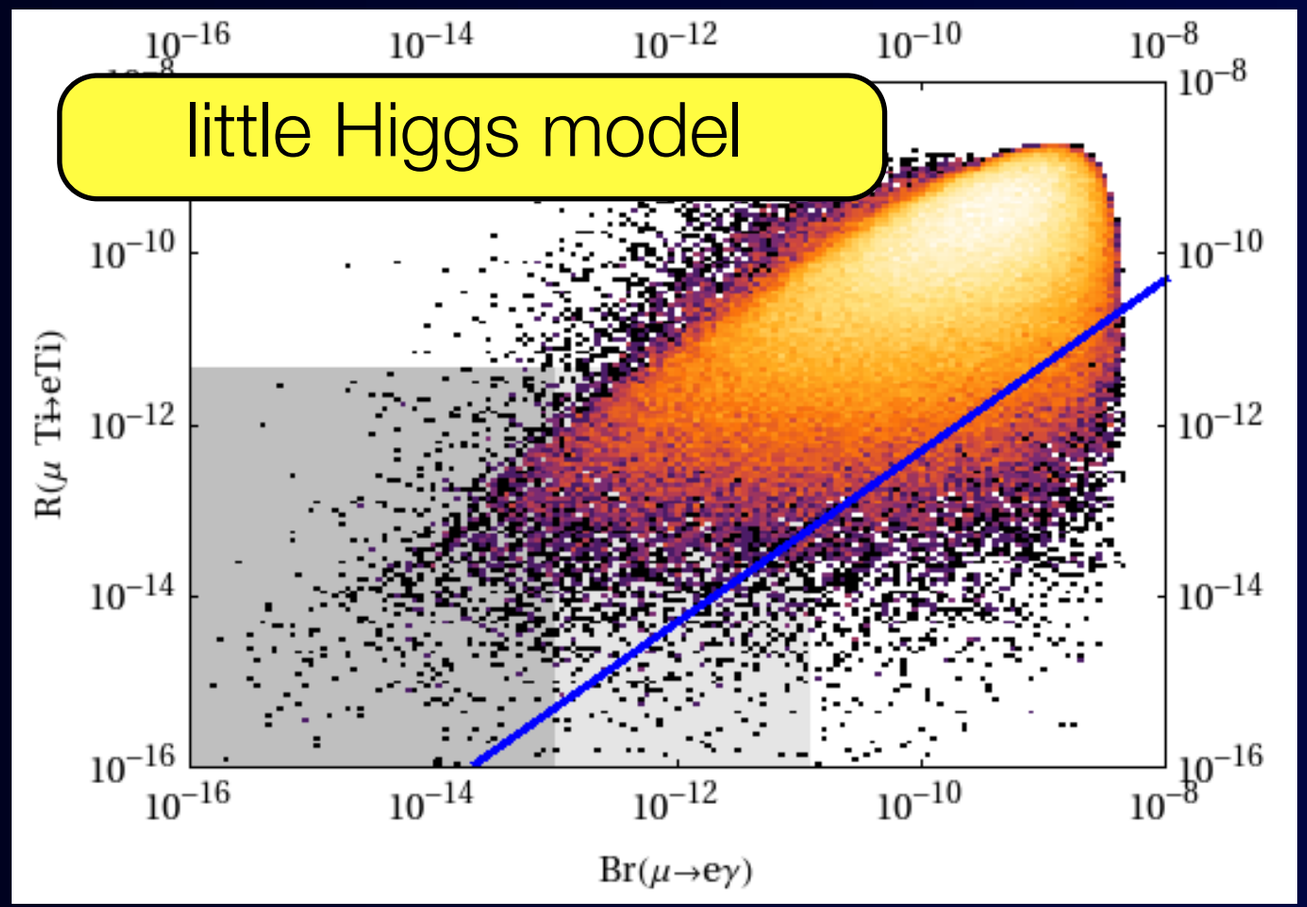
$3000\ (\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c^2

After W. Marciano

CLFV予言値



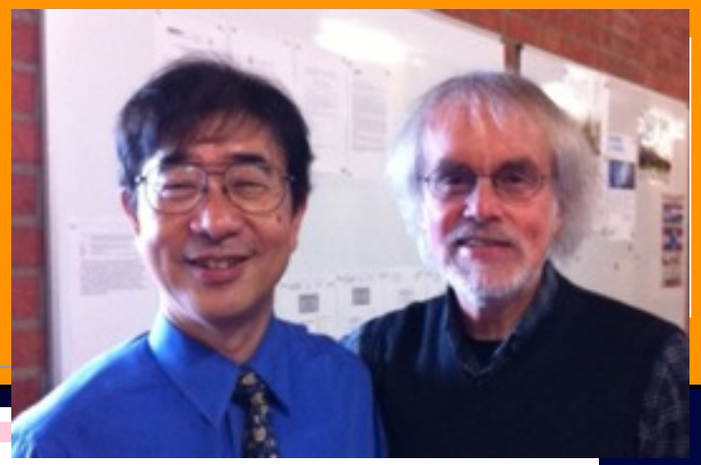




新物理理論モデルは大きな分岐比 (上限値のすぐ下) を予言

新しい物理のDNAは？

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

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

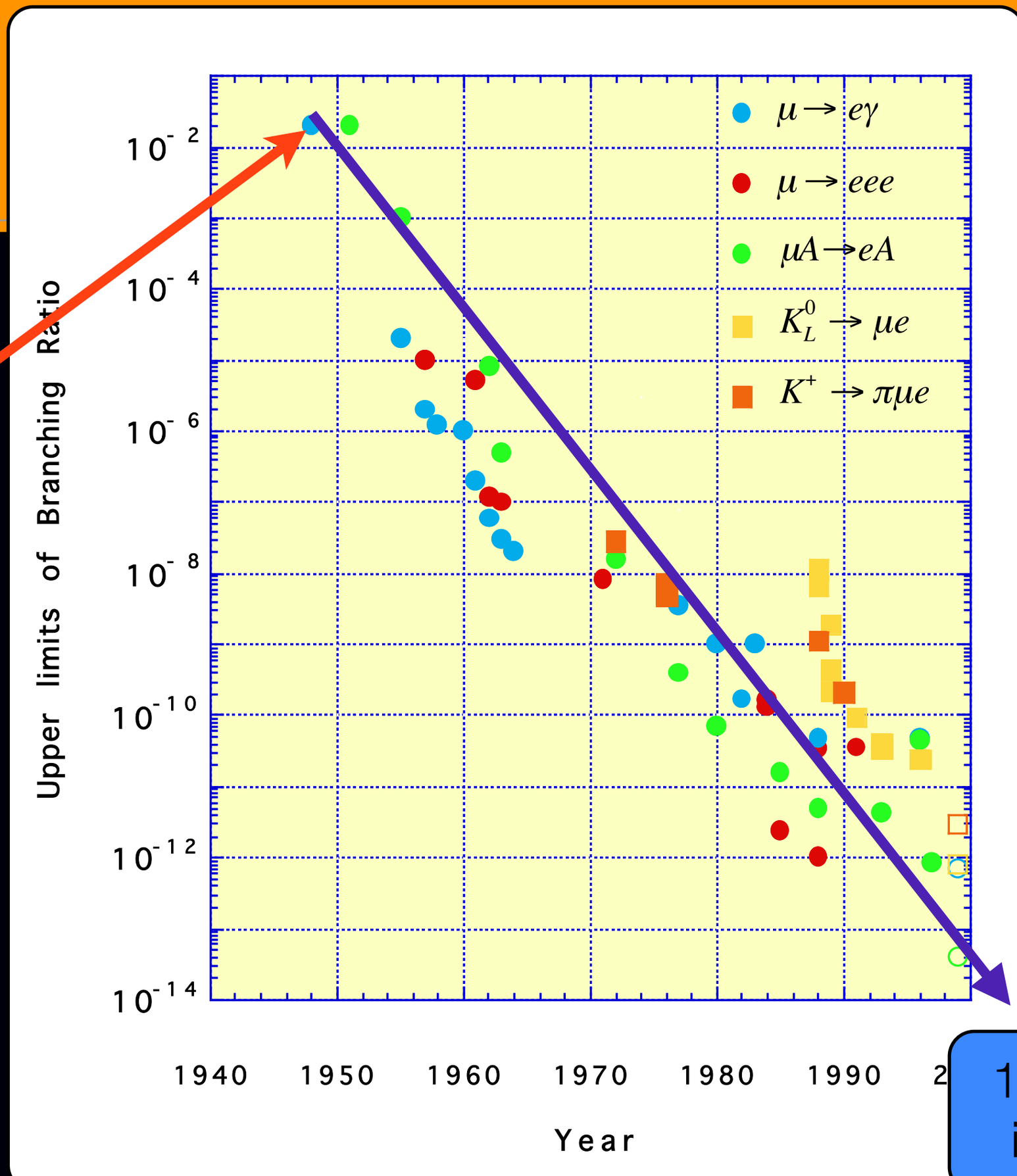
GLOSSARY	
AC [10]	RH currents & U(1) flavor symmetry
RVV2 [11]	SU(3)-flavored MSSM
AKM [12]	RH currents & SU(3) family symmetry
δLL [13]	CKM-like currents
FBMSSM [14]	Flavor-blind MSSSM
LHT [15]	Little Higgs with T Parity
RS [16]	Warped Extra Dimensions

ミューオン電子転換過程とは？

歴史

First cLFV search

Pontecorvo in 1947



10^{-16}~10^{-18} in 2020 ?

ミューオンCLFV過程と ビームとバックグラウンド

ΔL=1	current	future
$\bullet \mu^+ \to e^+\gamma$	$<10^{-13}$	$<10^{-14}$
$\bullet \mu^+ \to e^+e^+e^-$	$<10^{-12}$	$<10^{-15}$
$\bullet \mu^- + N(A,Z) \to e^- + N(A,Z)$	$<10^{-12}$	$<10^{-18}$
$\bullet \mu^- + N(A,Z) \to e^+ + N(A,Z-2)$		

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

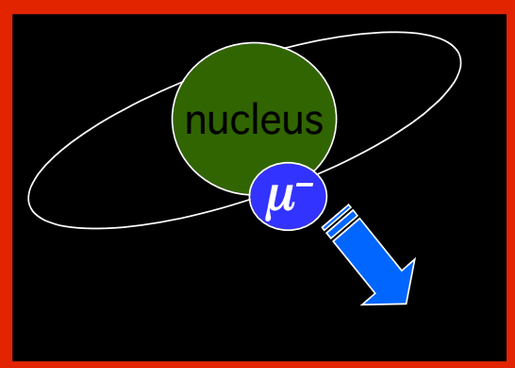
ミューオン電子転換過程は大強度ミューオンビームが使用可能

ミューオン電子転換過程とは？

ミューオン電子転換過程とは？

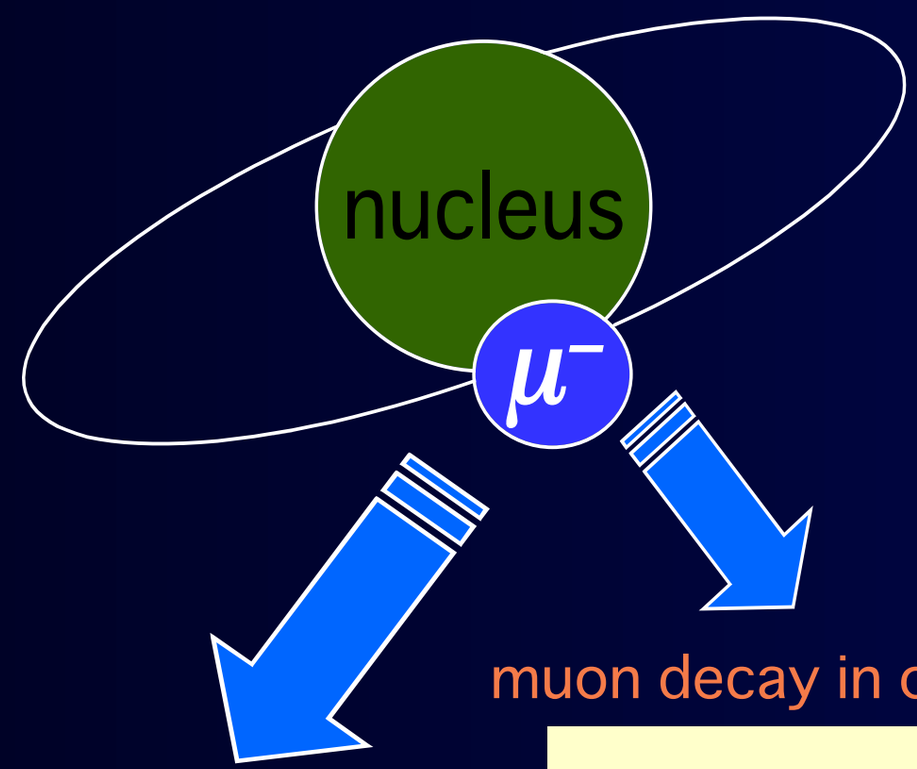
$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$

負電荷ミューオンを標的に止めてミューオン原子を作る。原子のクーロン場の元で、ミューオンが電子に変換。シグナル事象は105 MeV/cの電子が1個のみ放出。



Event Signature :
a single mono-energetic electron of 100 MeV

ミューオン原子の基底状態のミューオンの許される過程



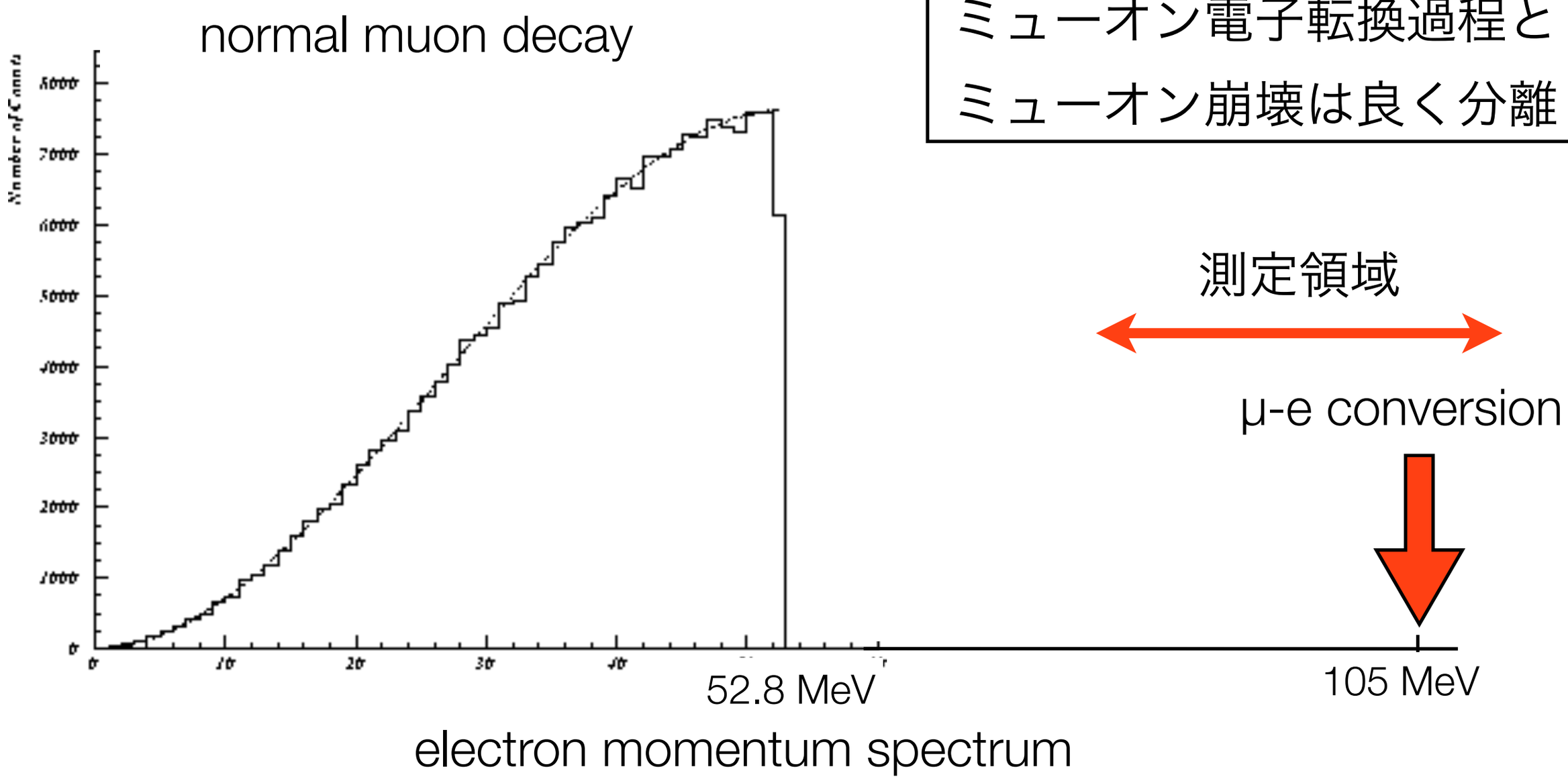
muon decay in orbit

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

nuclear muon capture

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

ミューオン電子転換過程の特徴



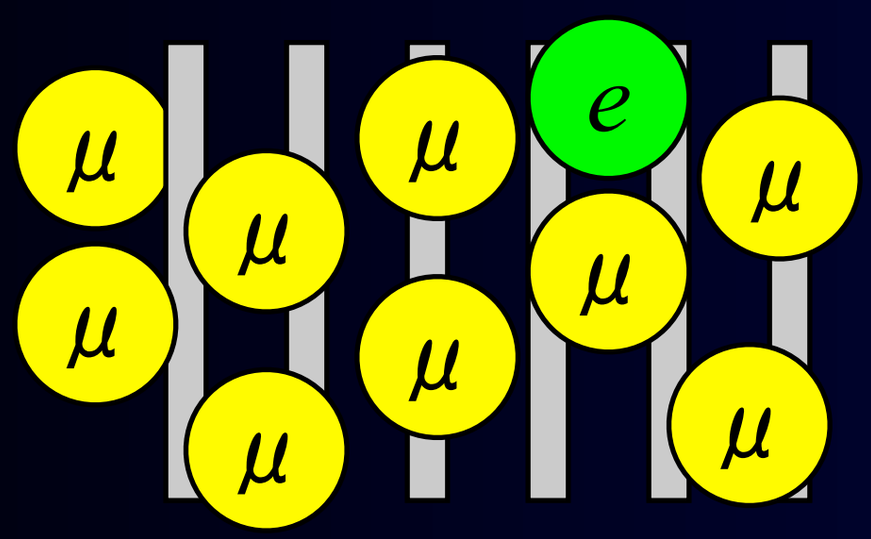
ミューオン崩壊に邪魔されずに大強度ビームを使える

ミューオン電子転換過程探索のバックグラウンド

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

ミュオン電子転換過程探索の測定原理

以前の実験：10^{14}ミューオン（100兆個）



ミューオン静止標的

新しい実験：10^{18}ミューオン（100京個）

大強度ミューオン源の必要性

If we like to achieve a search of SES < 10^{-17}
(with 10% acceptance)

10^{18} muons in totoal needed.

With the PSI muon intensity of 10^{8}/s
(1 MW), 1000 years are needed.

世界のミューオンビーム源の比較

	beam power	time structure	muon yield
PSI	1200 kW	DC	10^8/sec
TRIUMF	75 kW	DC	10^5/sec
RAL	200 kW	pulsed (50 Hz)	2×10^5/sec
J-PARC (MLF)	1000 W	pulsed (25 Hz)	2×10^7/sec

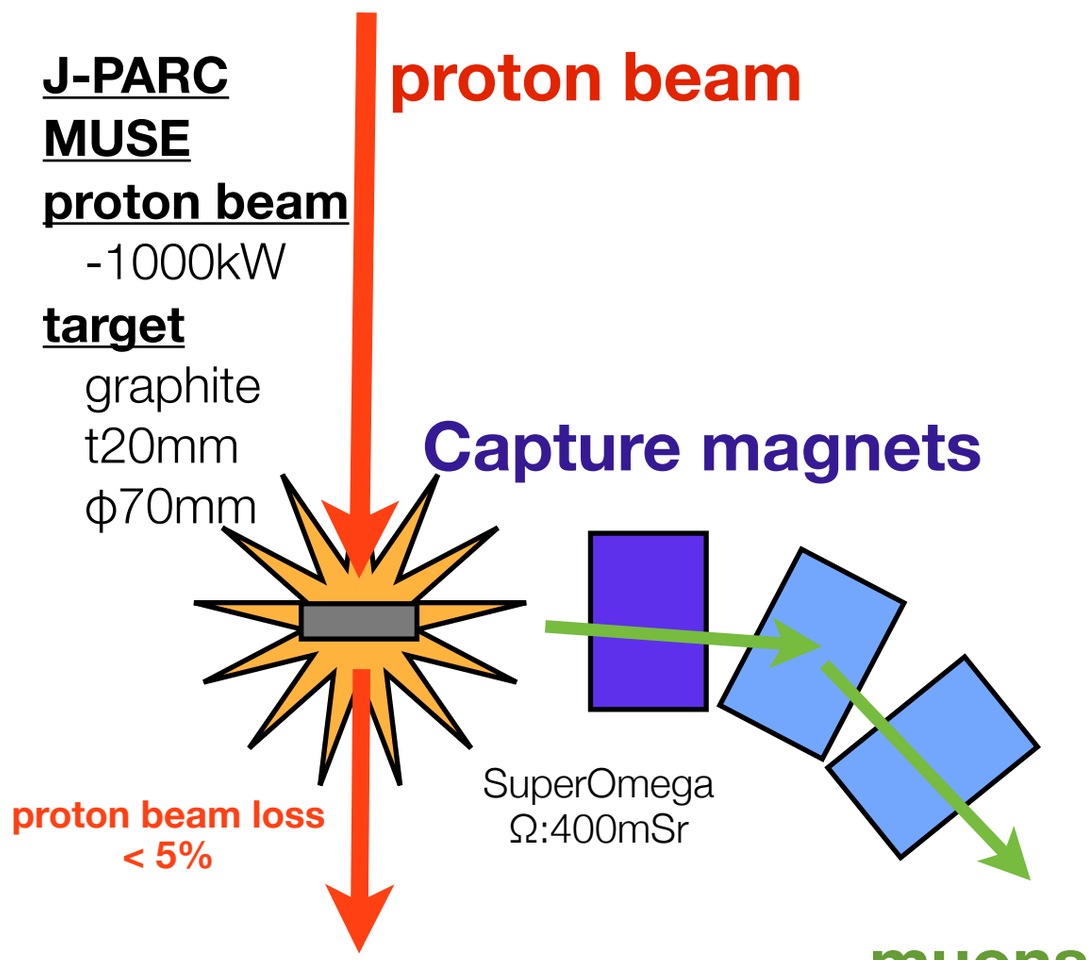
Conventional Muon Beamline

Conventional muon beamline

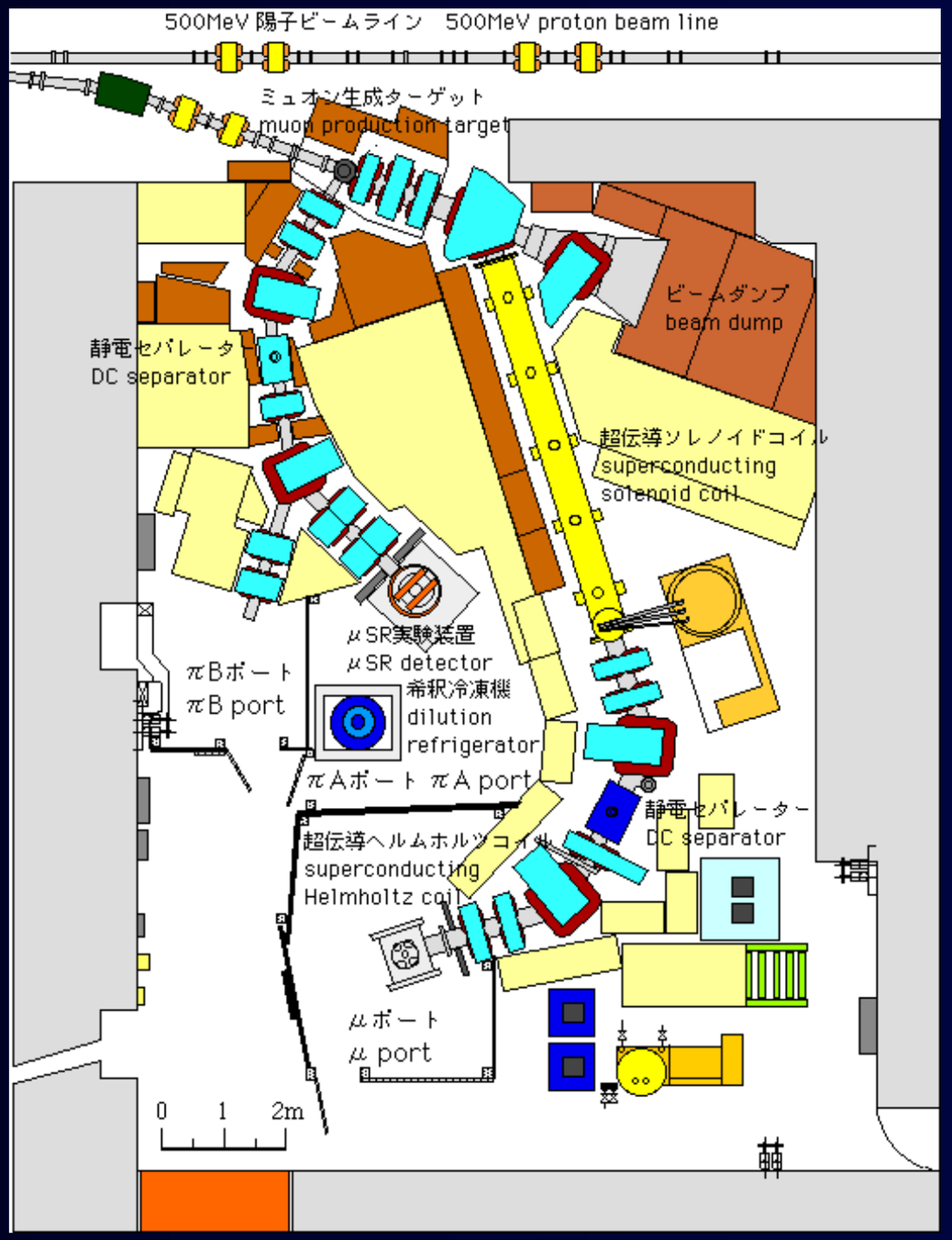
J-PARC MUSE

proton beam
-1000kW

target
graphite
t20mm
ϕ70mm

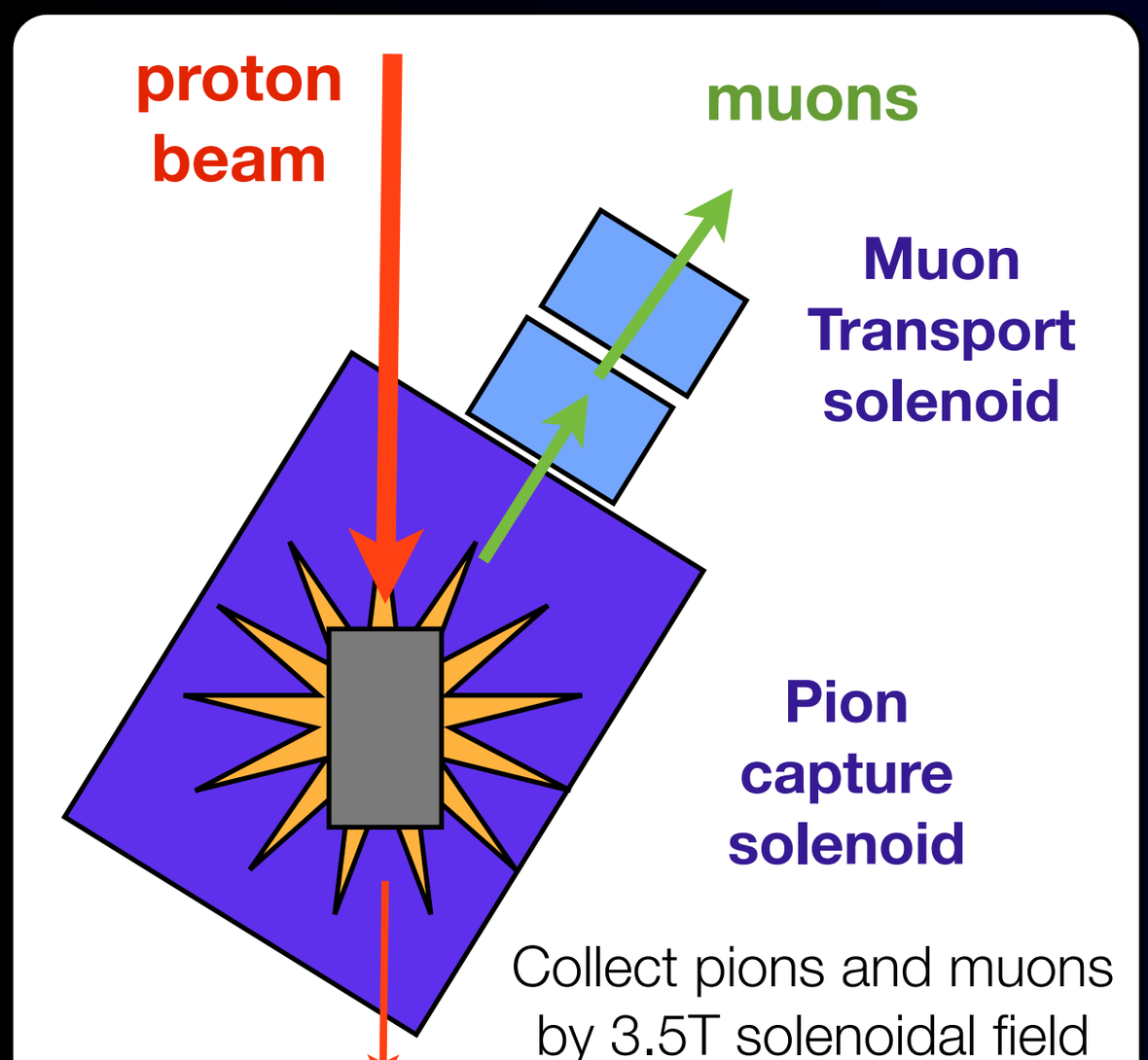


KEK 0.5GeV proton Muon facility



新しいミューオンビーム源

Novel muon beamline



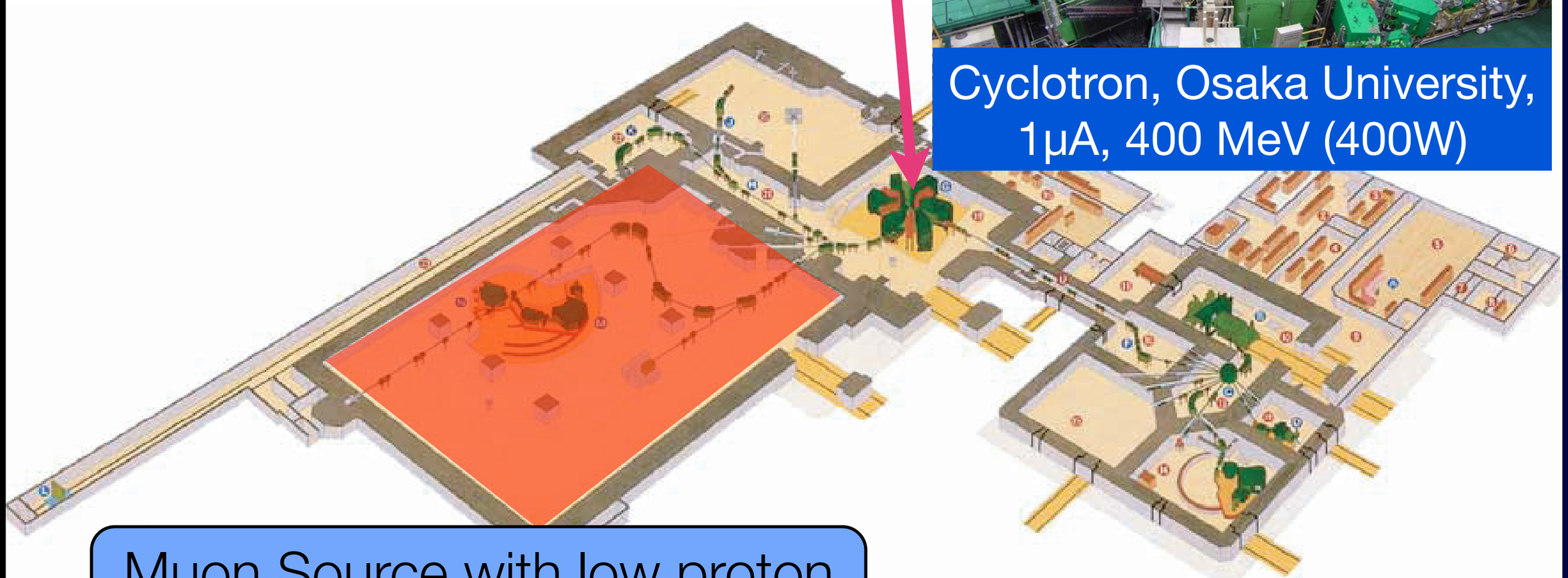
- A long pion production target of 1.5 interaction length is used.
- Pions coming out from the side of a long target are captured and transported to a muon beamline.
- Pions and muons (from pion decays) are transported through solenoid magnets.

Beam intensity improvement of about 1000 expected

核物理研究センターに
ミューオンビーム源？

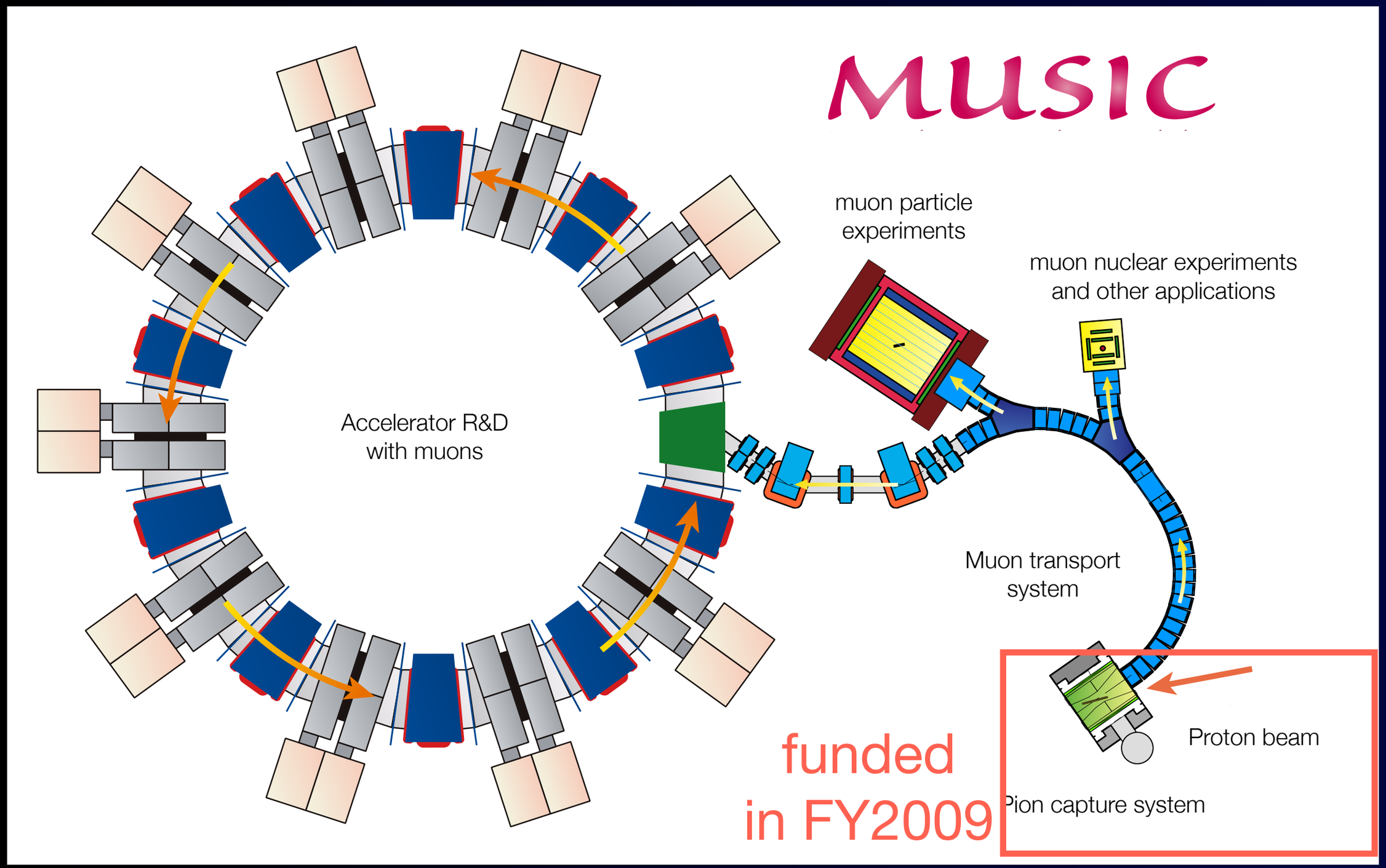
Research Center for Nuclear Physics (RCNP), Osaka University has a cyclotron of

Cyclotron, Osaka University, 1μA, 400 MeV (400W)

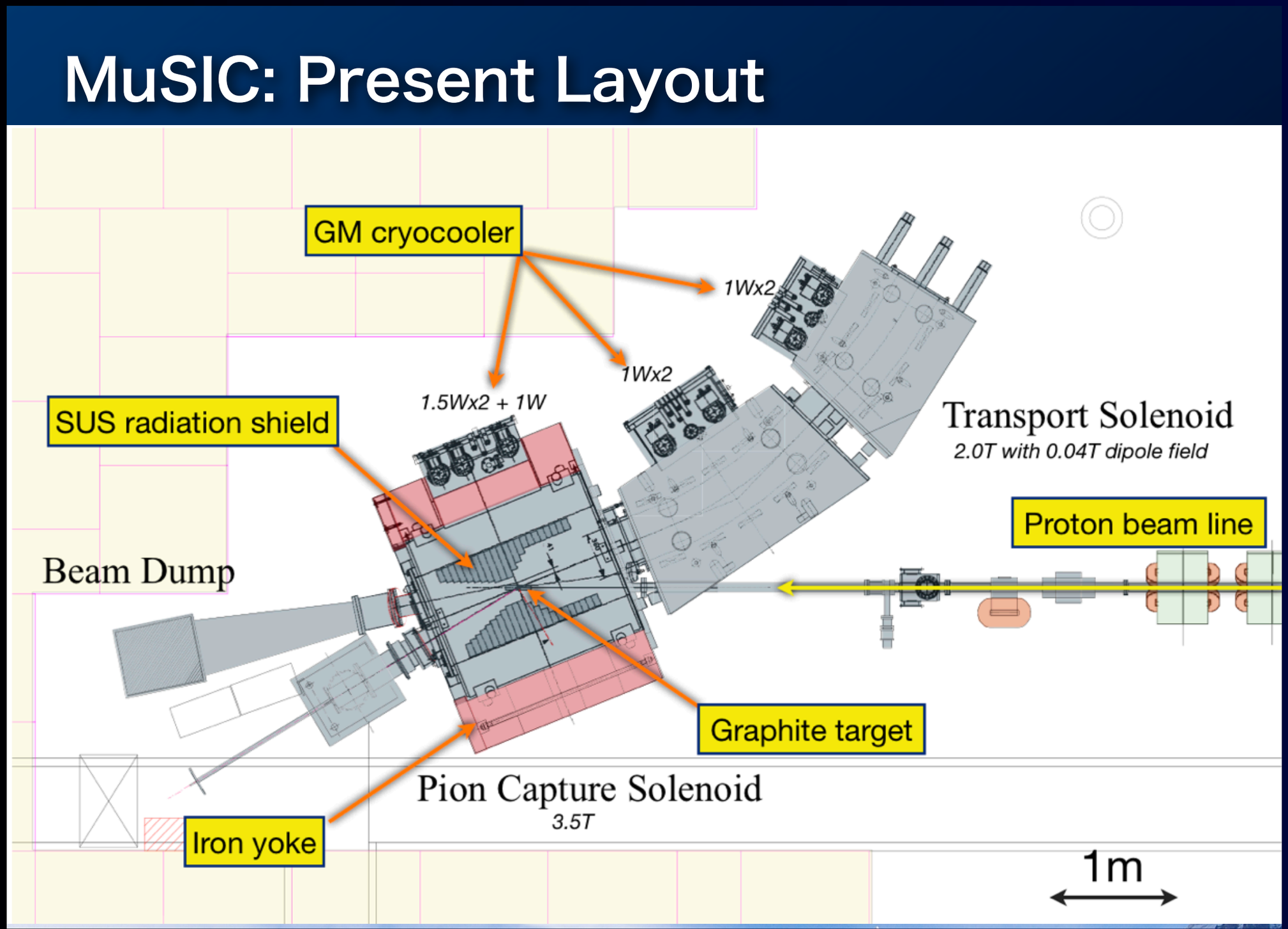


Muon Source with low proton power at Osaka U.?

MuSIC (=Muon Science Innovative Channel)



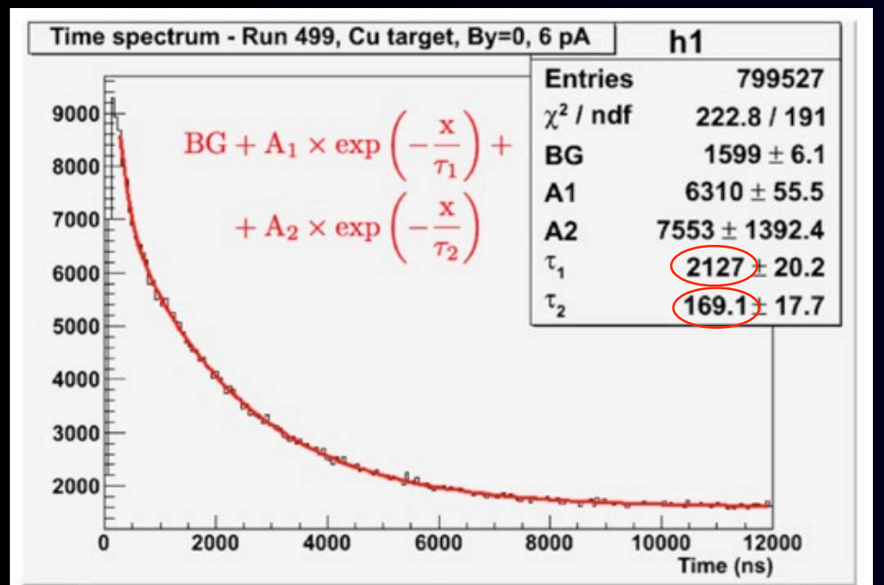
MuSIC装置（2013年）



MuSIC Layout

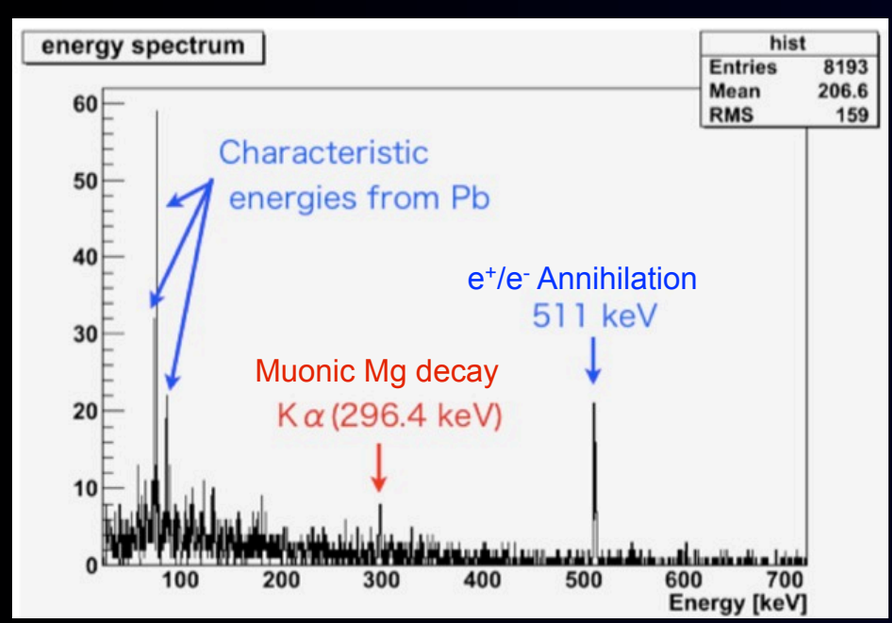
Many users, increasing, Prof. H. Ejiri, Prof. A. Shinohara et al.

MuSIC Beam Test in 2011



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

preliminary



MuSIC muon yields

μ^+ ~3×10^8/s for 400W

μ^- ~1×10^8/s for 400W

cf. 10^8/s for 1MW @PSI
Req. of $\times10^3$ achieved...

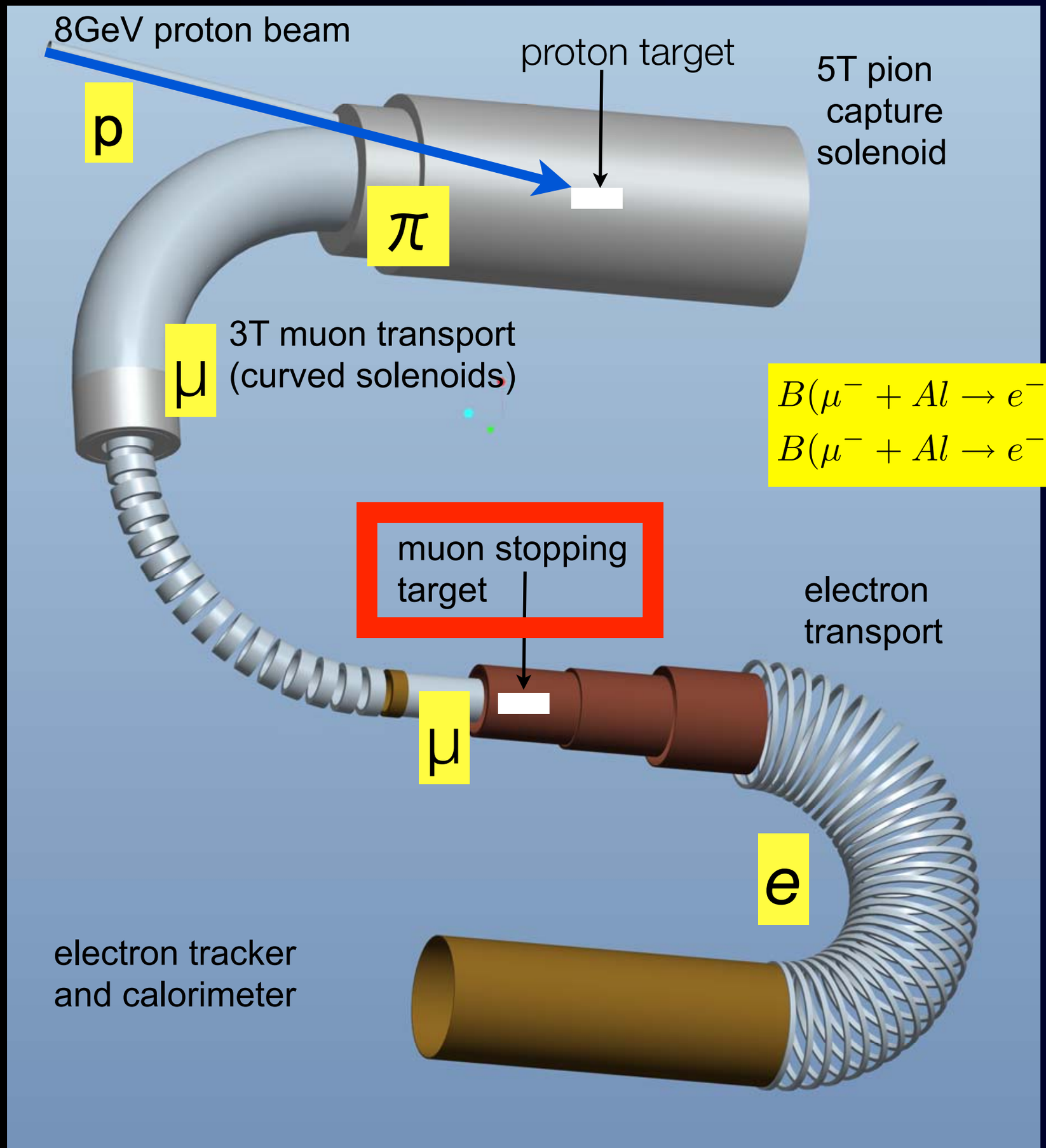
The muon beam intensity needed for COMET is guaranteed.

Measurements on June 21, 2011 (400pA)

世界のミューオンビーム源の比較

	beam power	time structure	muon yield
PSI	1200 kW	DC	10^8/sec
TRIUMF	75 kW	DC	10^5/sec
RAL	200 kW	pulsed (50 Hz)	2×10^5/sec
J-PARC (MLF)	1000 W	pulsed (25 Hz)	2×10^7/sec

COMET実験@J-PARC



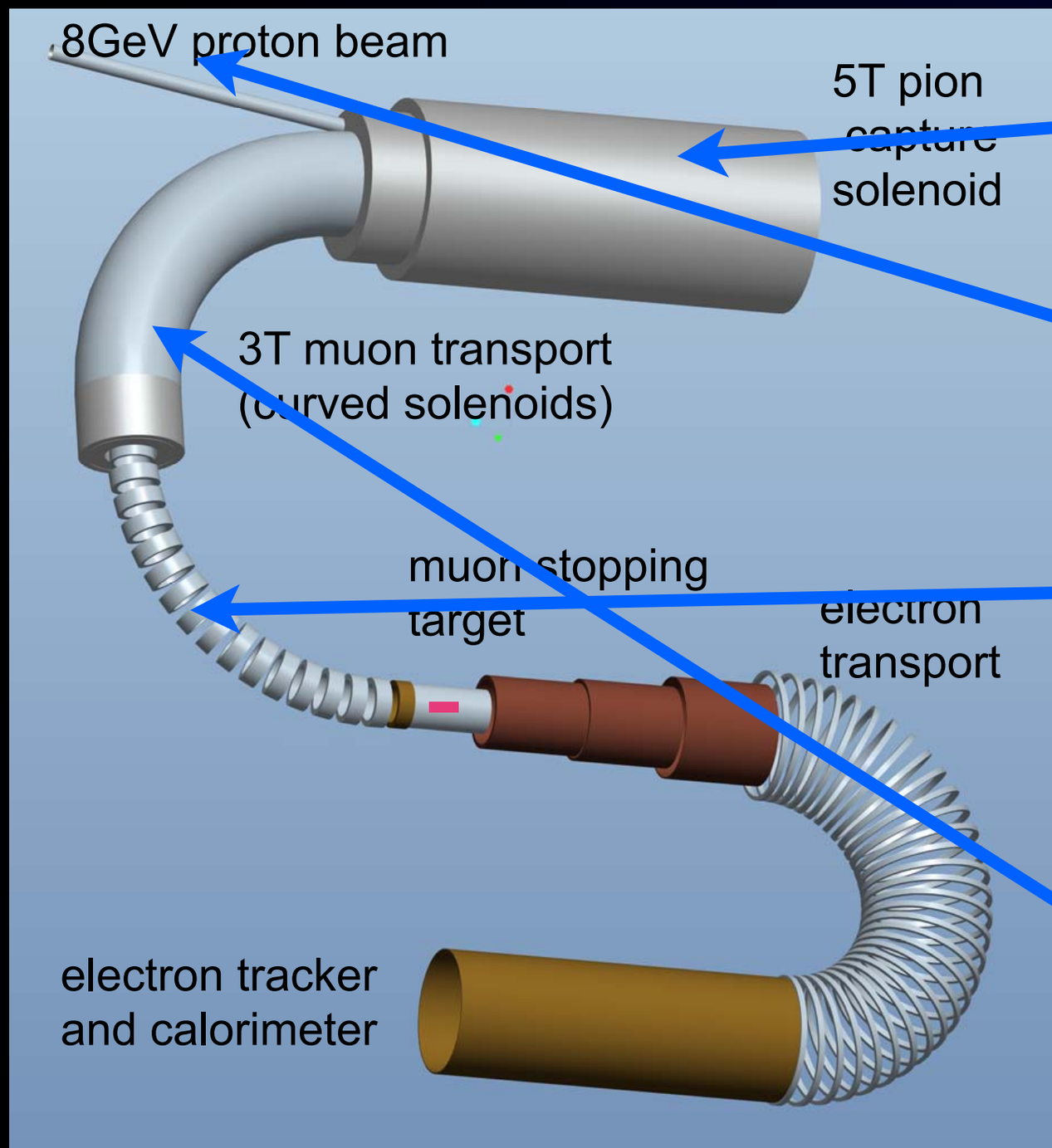
COMET

Osaka University

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

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

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



多量のミューオンを生成

パルスビームによる
バックグラウンド削減

運動量選別による
バックグラウンド削減

長いミューオンビーム
ラインによる
ビームパイオン削減

COMET Collaboration Increasing...

The COMET Collaboration

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27 institutes
12 countries
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J-PARC@東海

ハドロン実験施設

Osaka University

COMET
実験施設

Signal Sensitivity (preliminary) - 2×10^7 sec

- 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	8.5×10^{20}
muon transport efficiency	0.008
muon stopping efficiency	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

Table 11.2: Summary of Estimated Backgrounds

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.

外部の評価

研究テーマの重要性が広く認識されていること

July 15, 2012

J-PARC Program Advisory Committee

for the

Nuclear and Particle Physics Experiments at the J-PARC 50 GeV Proton Synchrotron

The COMET experiment aims to improve the experimental sensitivity to detecting muon-to-electron conversion by four orders of magnitude beyond the current measured limit. Measurements at this sensitivity level would probe the region expected by many well-studied new physics models such as SUSY-GUTs in a perspective different from the LHC. As such COMET could become one of the flagship experiments for J-PARC and Japanese physics later in the decade.

高エネルギー物理学将来計画検討小委員会

平成12年2月11日

答申

て、10^{-16}の感度を目指してR&Dが進行中のJ-PARCのCOMET実験とFermilabのmu2e実験は、μ−e転換過程発見への感度を十分持っていると考えられる。実現に向けてBeam extinctionなど達成すべき技術的課題があり、国際協力と競争の中でより強力な研究開発体制を構築することが必要である。COMETについては新しい陽子ビームラインとミューオン生成源の検討が現在進んでおり、実現すればJ-PARCでの素粒子物理研究のフラグシップ実験となり得るものである。

Erice, 25 January 2013

Proposed Update of the European Strategy for Particle Physics

h) Experiments studying quark flavour physics, investigating dipole moments, searching for charged-lepton flavour violation and performing other precision measurements at lower energies, such as those with neutrons, muons and antiprotons, may give access to higher energy scales than direct particle production or put fundamental symmetries to the test. They can be based in national laboratories, with a moderate cost and smaller collaborations. *Experiments in Europe with unique reach should be supported, as well as participation in experiments in other regions, especially Japan and the US.*

注：JapanはCOMET実験などのこと

平成 25 年 1 月 31 日

KEK ロードマップ 2013　（最終案）

大学共同利用機関法人　高エネルギー加速器研究機構

３．　5 カ年研究戦略（2014−2018）

ハドロン実験施設

ハドロン実験施設においては、ストレンジネス核物理やハドロン物理などの強い相互作用に関する研究ならびにK中間子の稀崩壊の探索に代表されるフレーバー物理の研究を推進してきた。本ロードマップ期間内の優先課題は、これらの実験の成果を継続的に挙げつつ、新1次陽子ビームラインを建設し、核物質中の中間子質量の変化をはじめとする原子核・ハドロン物理実験及び μ 粒子電子転換現象の探索実験などを着実に進めることである。

最近の良いニュース

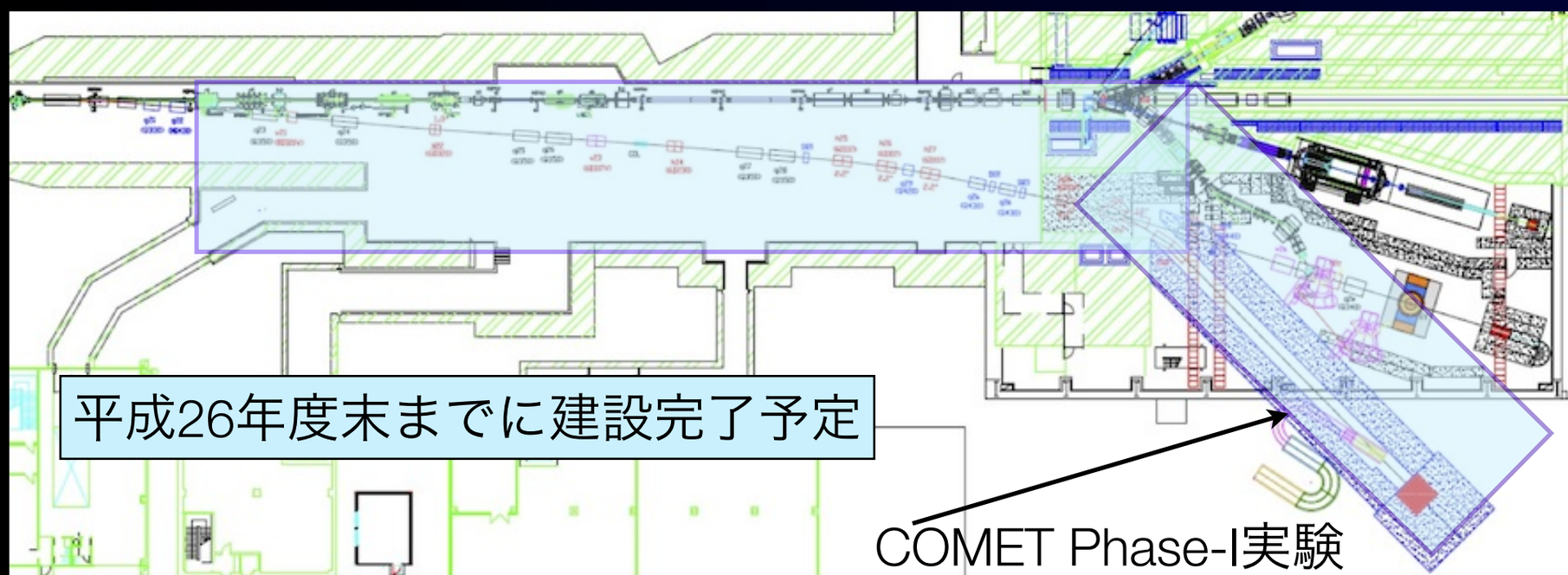
COMET Phase-I実験

最近の良いニュース

KEKで新規陽子・ミューオンビームライン建設予算が採択

J-PARCハドロンホール

平成24年度補正



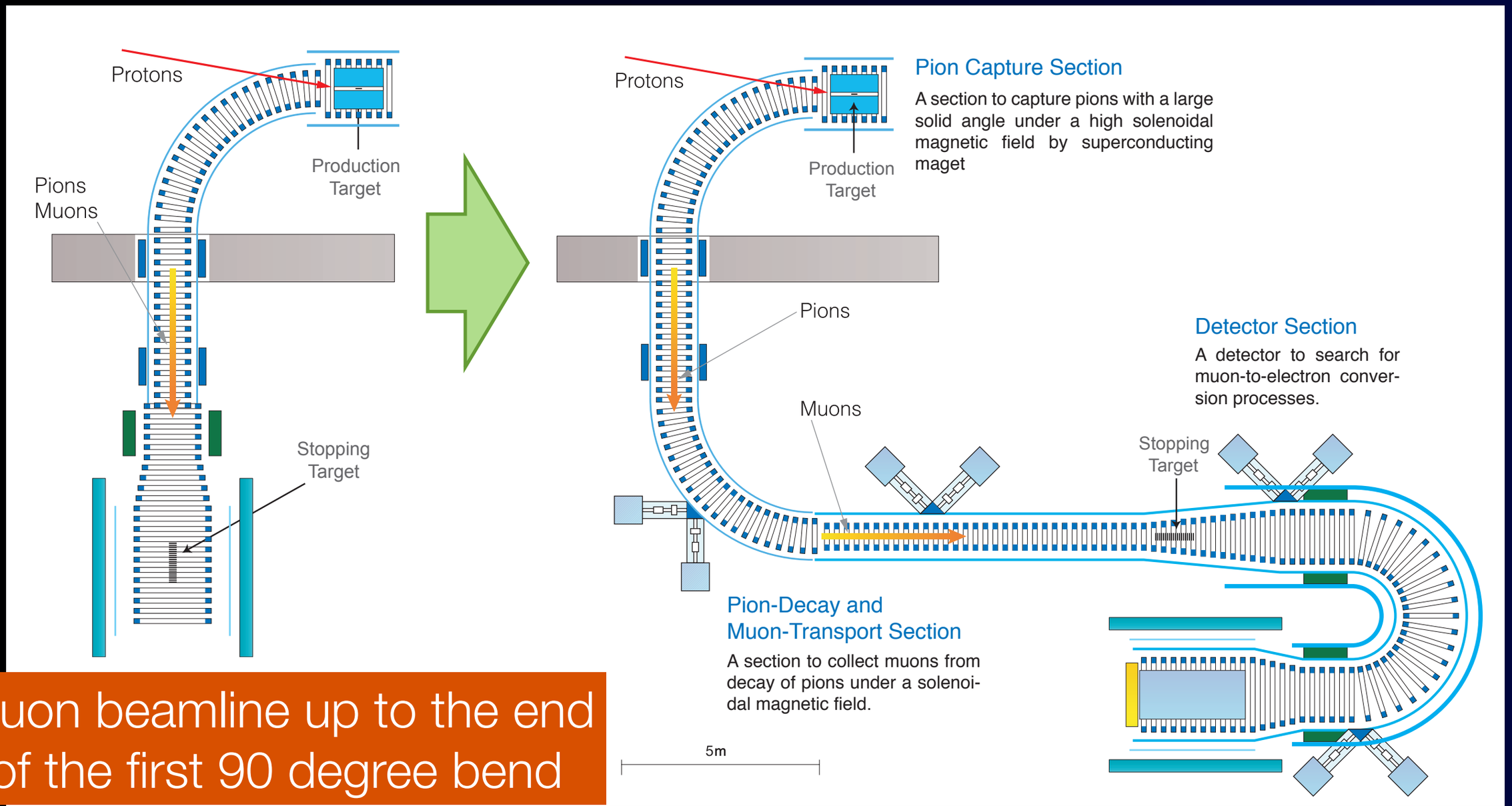
高運動量陽子の
ハドロン核物理実験

項目		担当
陽子ビームライン	共同実験設備	KEK
ミューオンビームライン		
COMET測定器	実験固有	COMET実験グループ

COMET実験の段階的アプローチ

COMET Phase-I

COMET Phase-II



muon beamline up to the end of the first 90 degree bend

COMET Phase-I実験の目的

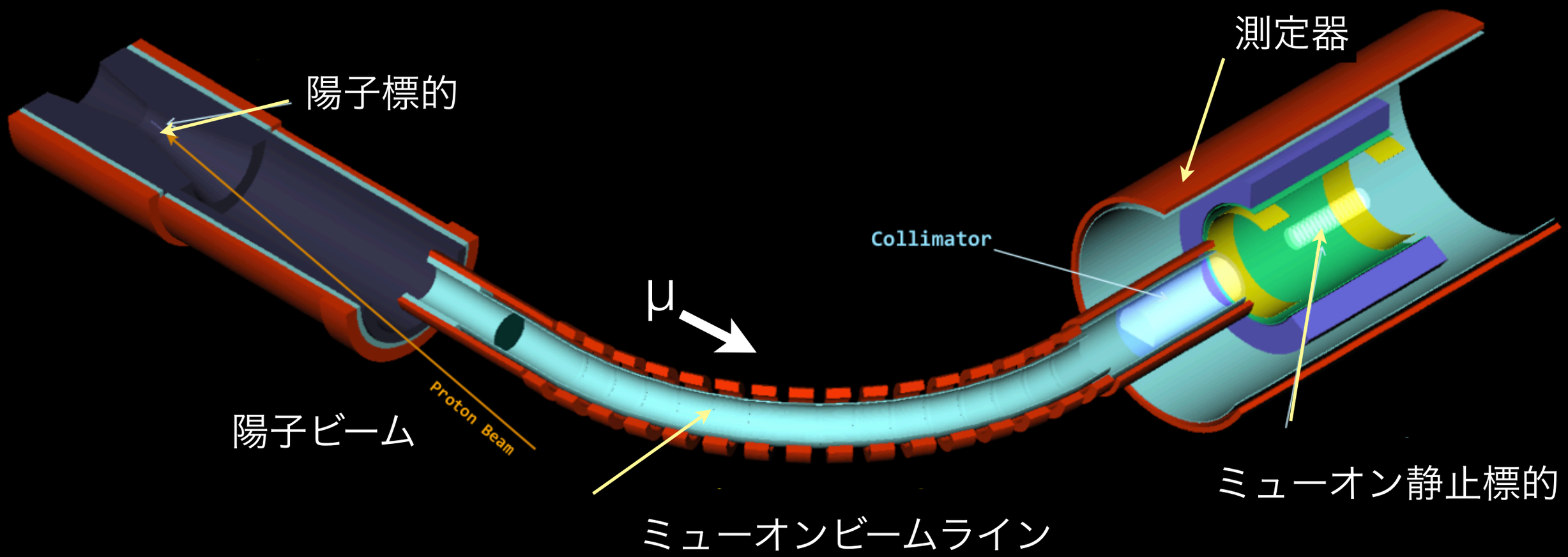
1 COMET Phase-IIのバックグランド測定

direct measurement of potential background sources for the full COMET experiment by using the actual COMET beamline constructed at Phase-I

2 ミューオン電子転換過程の探索 (100倍向上)

a search for $\mu^- - e^-$ conversion at intermediate sensitivity which would be more than 100 times better than the SINDRUM-II limit

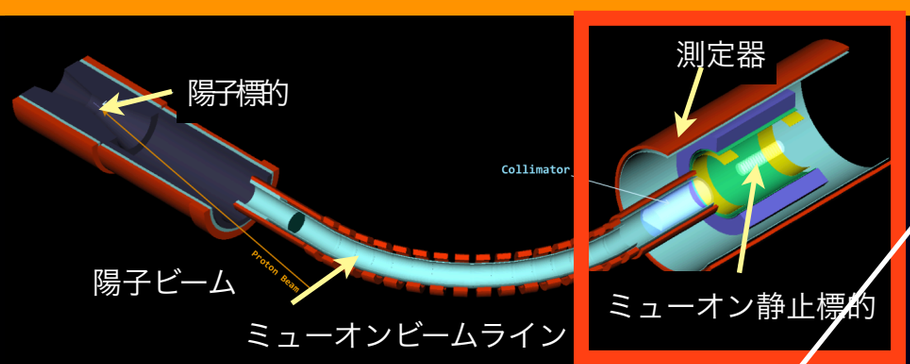
COMET Phase-I実験レイアウト

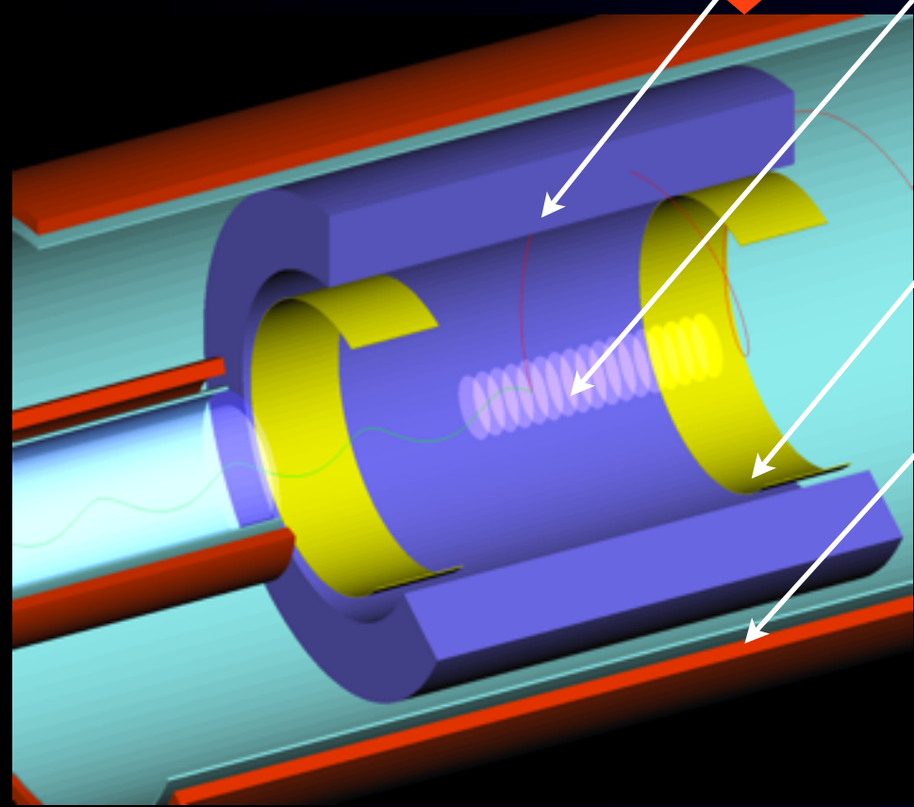


COMETミューオンビームライン：
約6x10^{9}個/秒のミューオンを３kW
陽子ビームで生成。世界最高強度。

実験方法：約10^{16}個のミューオンを静止標的に止めて、そこから放出される電子を観測する。

COMET Phase-I測定器





円筒ドリフトチェンバー (CDC)

ミューオン静止標的からの電子の運動量を測定。ミューオン電子転換過程の電子であれば105 MeV/cの運動量を持つ。

ミューオン静止標的

ミューオンを静止させるためのアルミ標的。ここからシグナル電子が発生するか調べる。

CDCトリガー装置

電子を識別してCDCのデータ取得のトリガー信号を作成。

超伝導ソレノイド磁石

運動量測定に必要な磁場を発生する。

COMET Phase-I (1.5x10^{6}秒の実験期間で)

1事象発見感度：3x10^{-15}/ミューオン捕獲

90%上限値：7x10^{-15}/ミューオン捕獲

現在の90%上限値：7x10^{-13}/ミューオン捕獲

100倍の実験感度向上

これらの装置は平成27年度まで完成、28年度に設置し、平成29年度に本実験をする。ビームラインは平成26年度末までに完成予定。

COMET Phase-Iでの実験感度

Event selection	Value	Comments
Geometrical acceptance	0.24	tracking efficiency included
Momentum selection	0.74	104.1 MeV/c < P_e <106 MeV/c
Timing selection	0.39	same as COMET
Trigger and DAQ	0.9	same as COMET
Total	0.06	

- Single event sensitivity

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

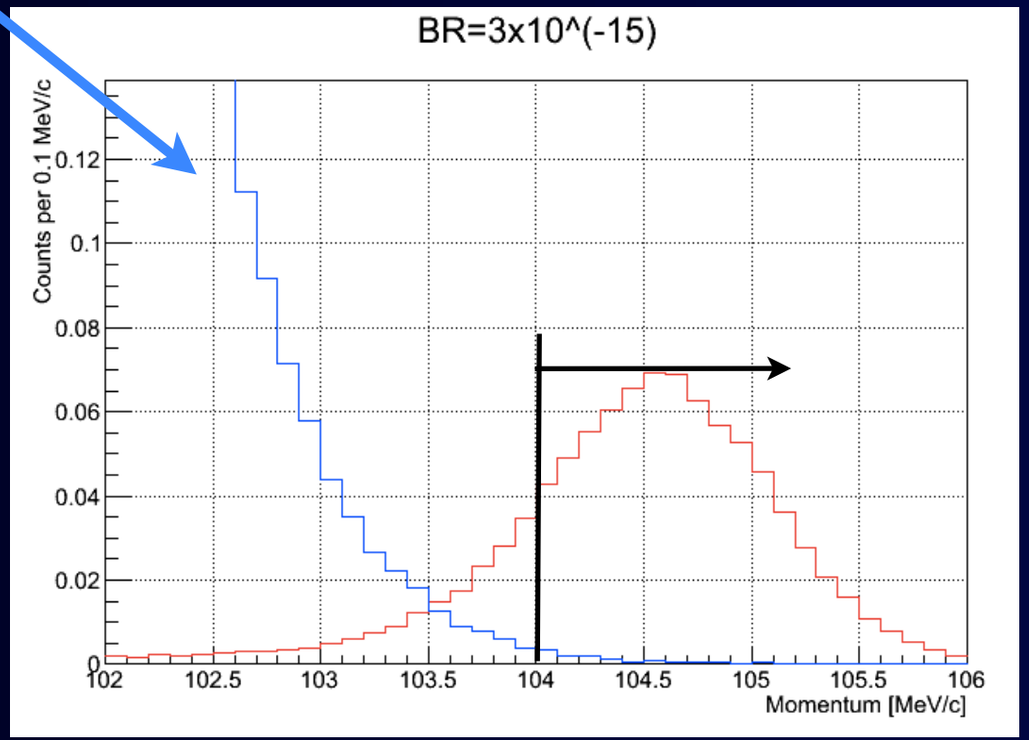
  - N_μ is a number of stopping muons in the muon stopping target. It is 8.7×10^{15} muons.
  - 5.8×10^9 stopped μ/s with 3 kW proton beam power, with 1.5×10^6 sec running.
  - f_{cap} is a fraction of muon capture, which is 0.6 for aluminum.
  - A_e is the detector acceptance, which is 0.06.

$$B(\mu^- + Al \to e^- + Al) = 3.1 \times 10^{-15}$$
$$B(\mu^- + Al \to e^- + Al) < 7 \times 10^{-15} \quad (90\% C.L.)$$

COMET Phase-Iでの背景事象の評価

Background	estimated events
Muon decay in orbit	0.01
Radiative muon capture	< 0.001
Neutron emission after muon capture	< 0.001
Charged particle emission after muon capture	< 0.001
Radiative pion capture	0.0096*
Beam electrons Muon decay in flight Pion decay in flight	< 0.00048*
Neutron induced background	~ 0*
Delayed radiative pion capture	0.002
Anti-proton induced backgrounds	0.007
Electrons from cosmic ray muons	< 0.0002
Total	0.03

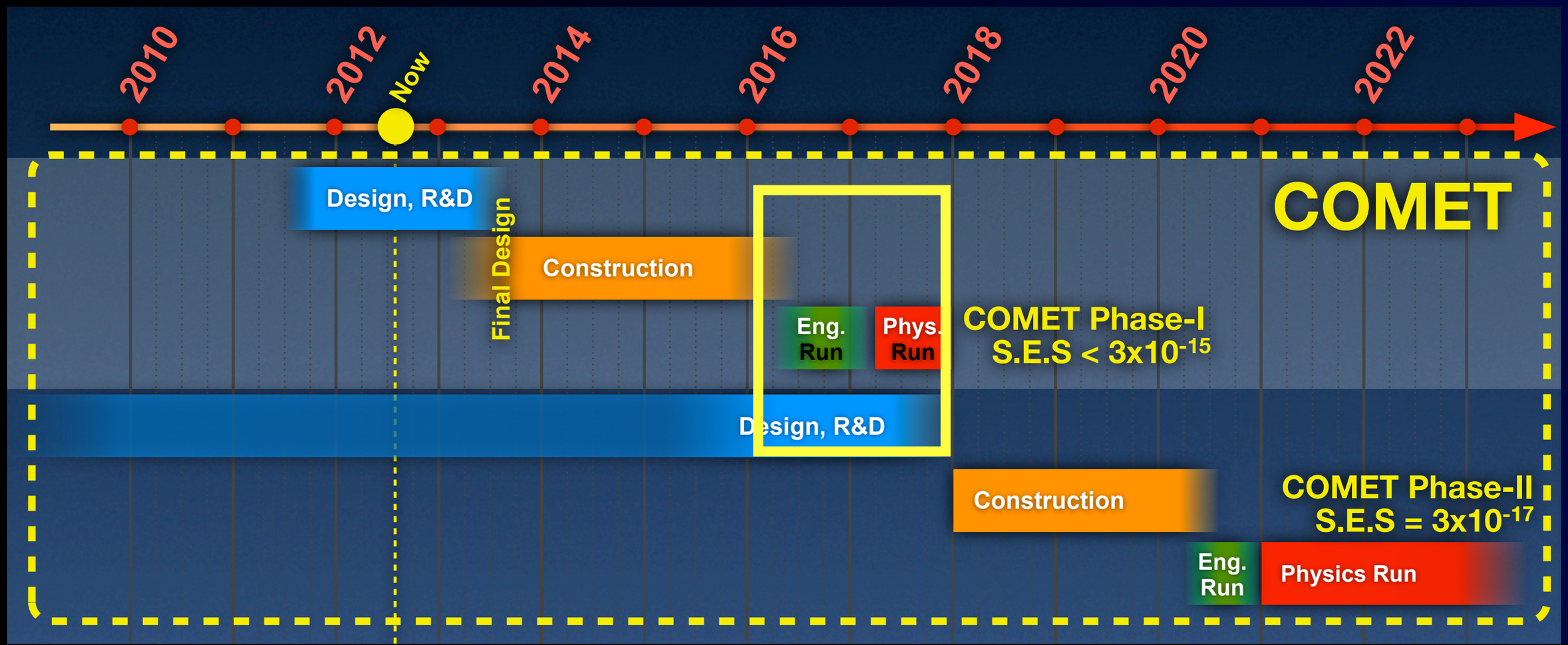
DIO



with proton extinction factor of 3×10^{-11}

Expected BG events are about 0.03 at S.E.S. of 3×10^{-15}.

COMET Phase-IとPhase-IIのスケジュール



まとめ

- ミューオンを使った荷電レプトンフレーバー非保存過程探索は、素粒子物理学で新物理を発見するのに重要。特に、ミューオン電子転換過程は最も期待できる。
- J-PARCにて、ミューオン電子転換過程を$<10^{-16}$の実験感度で探索するCOMET実験を提案。
- 第1段階COMET Phase-Iを予算化された。2016年頃の実験スタートを目標。
- ご期待ください。