Recent Progress on a Search for Muon to Electron Conversion at J-PARC at J-PARC

Yoshitaka Kuno
Department of Physics
Osaka University

December 13th, 2012
LPNHE, Paris, France

Outline

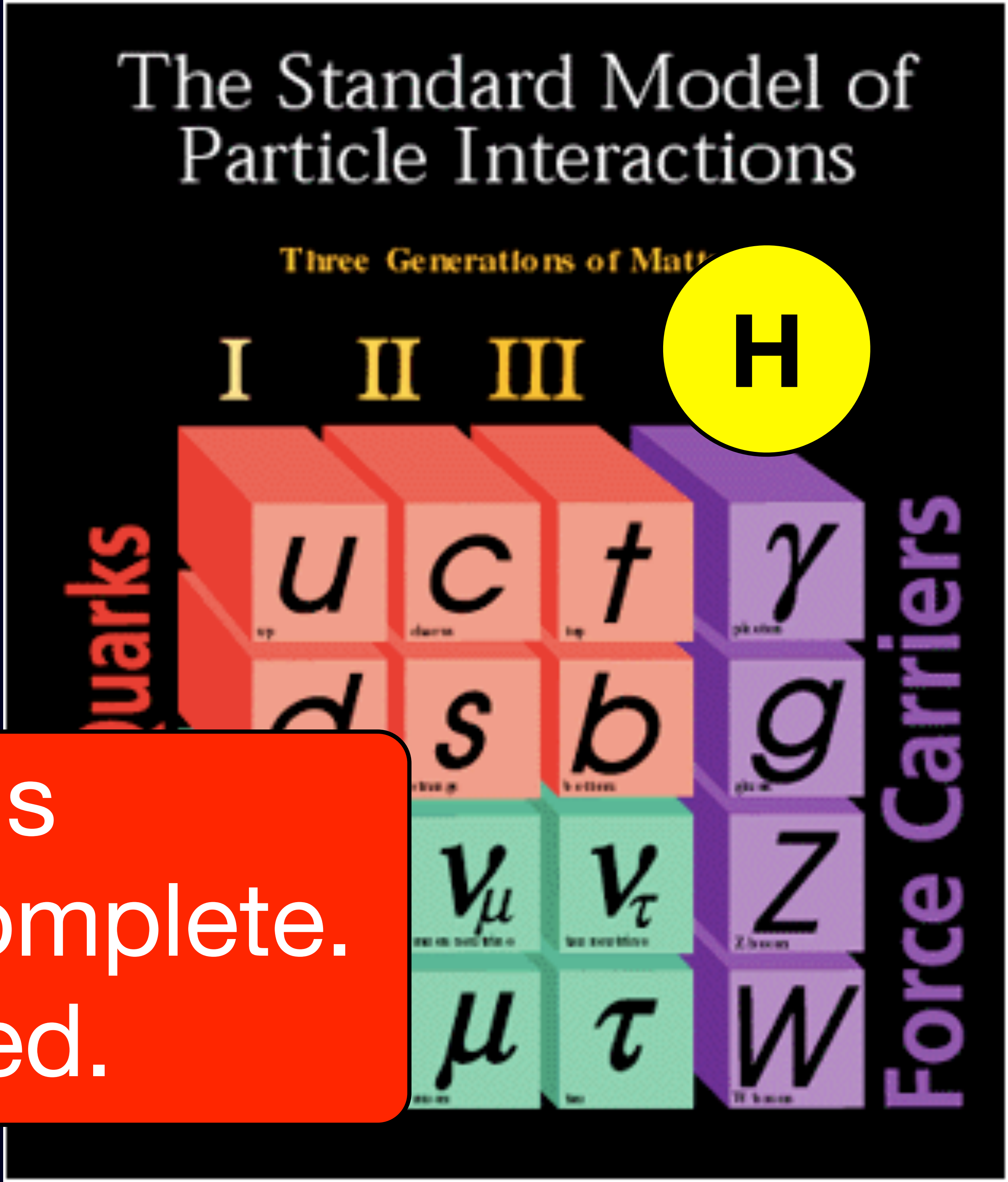
- Why Charged Lepton Flavor Violation (CLFV)?
- COMET@J-PARC
- MuSIC@Osaka University
- COMET Phase-I@J-PARC
- Summary

Why Charged Lepton Flavor Violation (CLFV)?

Now, the Standard Model has the Higgs boson

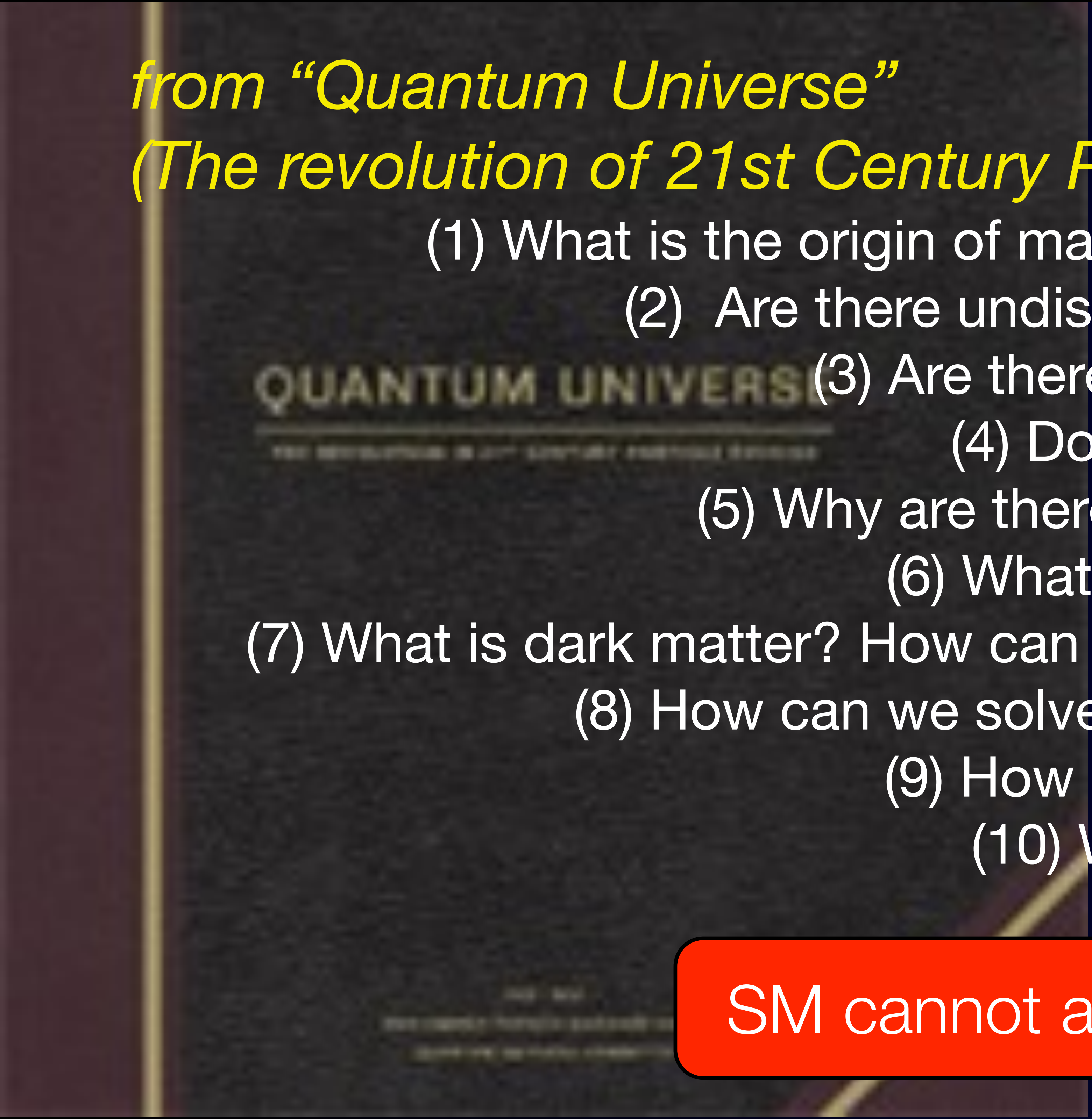
Congratulation for the discovery of the Higgs.

The Standard Model can explain most of the experimental results. However, there are many undetermined parameters and issues.



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

Why Are We Doing Elementary Particle Physics ?

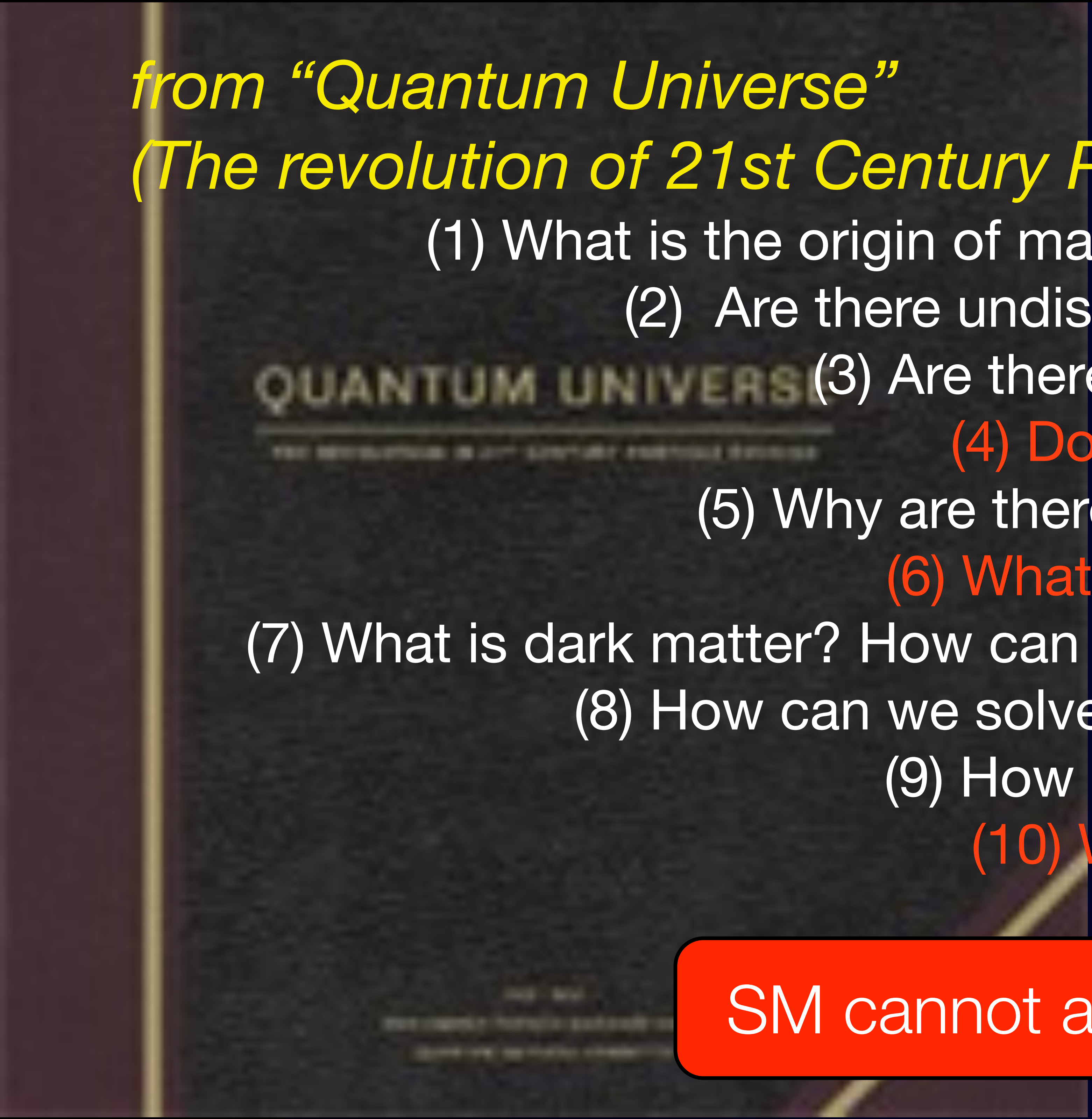


from "Quantum Universe"
(The revolution of 21st Century Particle Physics)

(1) What is the origin of mass for fundamental particles?
(2) Are there undiscovered principles of nature?
(3) Are there extra dimensions of space?
(4) Do all the forces becomes one?
(5) Why are there so many kinds of particles?
(6) What happened to the antimatter?
(7) What is dark matter? How can we make it in the laboratory?
(8) How can we solve the mystery of dark energy?
(9) How did the universe come to be?
(10) What are neutrinos telling us?

SM cannot answer those questions.

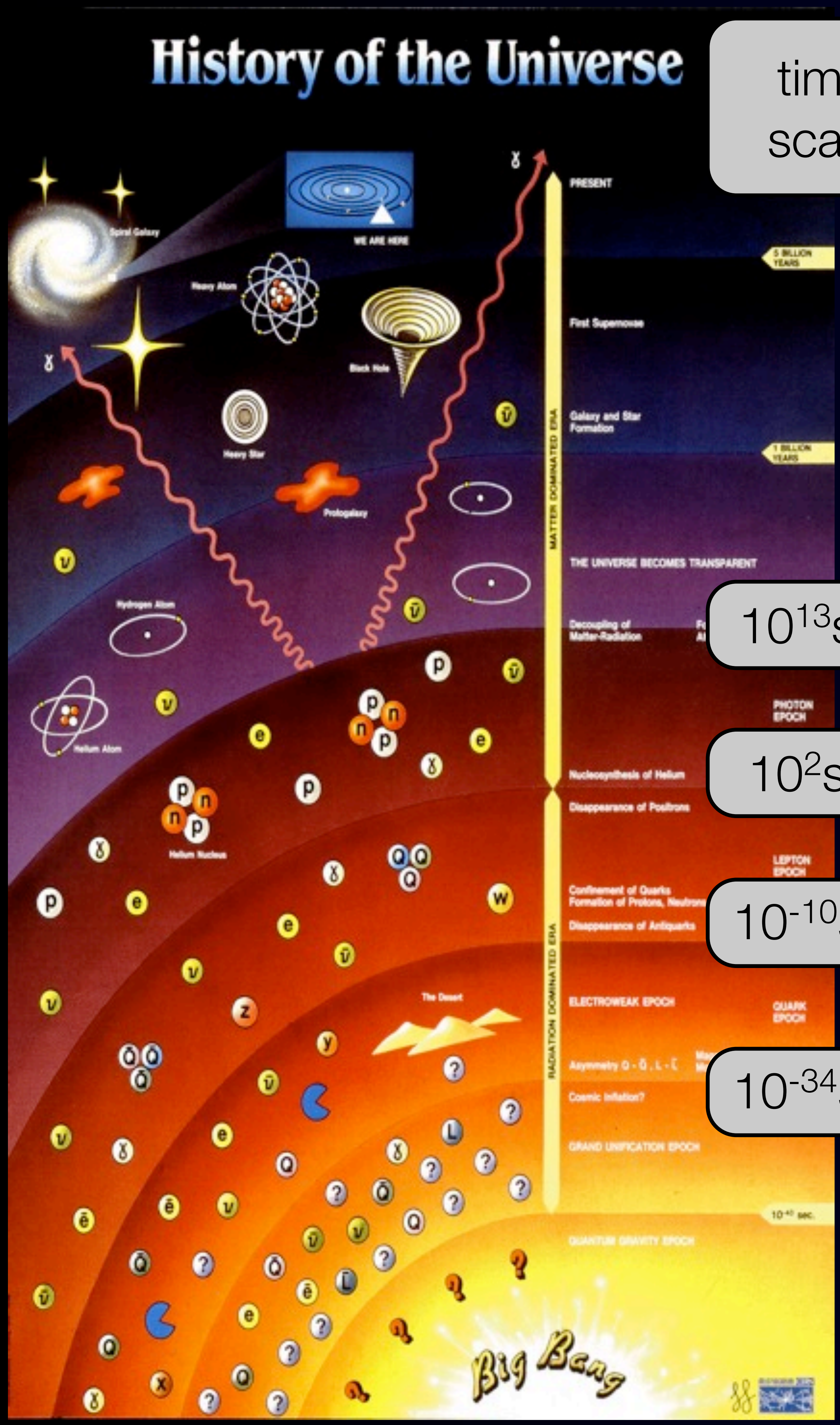
Why Are We Doing Elementary Particle Physics ?

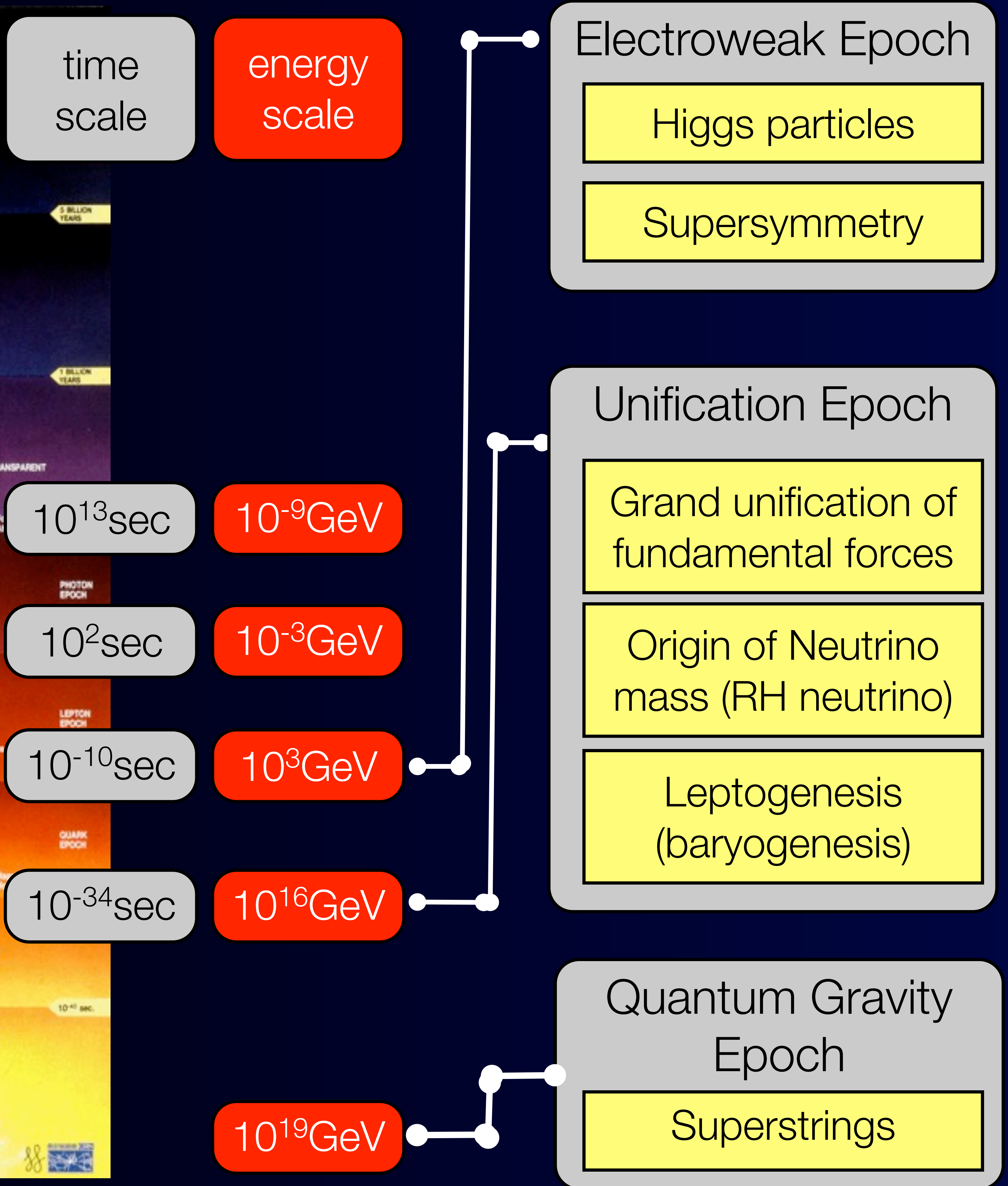


from "Quantum Universe"
(The revolution of 21st Century Particle Physics)

(1) What is the origin of mass for fundamental particles?
(2) Are there undiscovered principles of nature?
(3) Are there extra dimensions of space?
(4) Do all the forces becomes one?
(5) Why are there so many kinds of particles?
(6) What happened to the antimatter?
(7) What is dark matter? How can we make it in the laboratory?
(8) How can we solve the mystery of dark energy?
(9) How did the universe come to be?
(10) What are neutrinos telling us?

SM cannot answer those 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

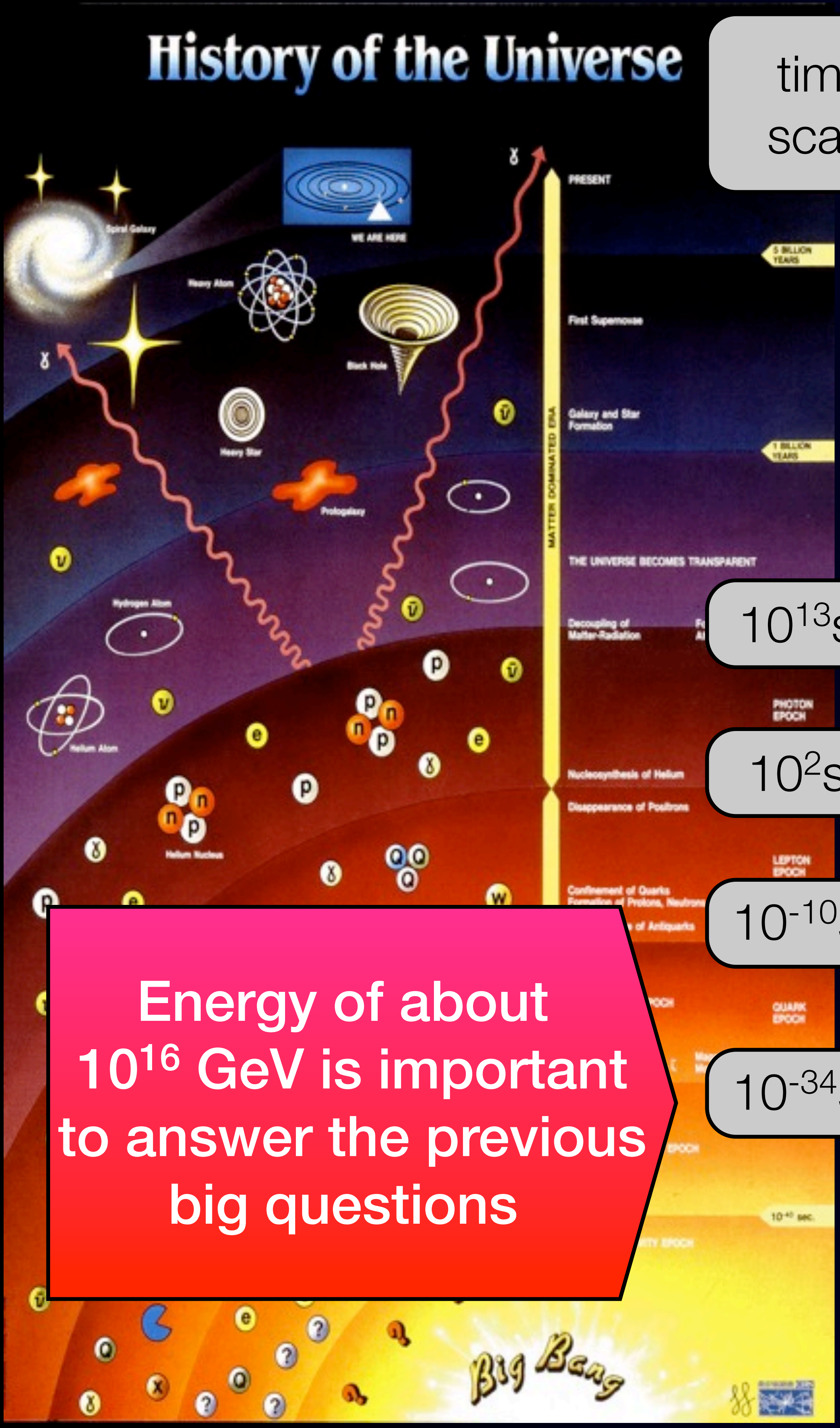
- Higgs particles
- Supersymmetry

Unification Epoch

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

Quantum Gravity Epoch

- Superstrings



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

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

Electroweak Epoch

- Higgs particles
- Supersymmetry

Unification Epoch

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

Quantum Gravity Epoch

- Superstrings

The Intensity Frontier is.....

- Energy scale reached by the intensity frontier would be much higher than that of accelerators of O(1 TeV) through quantum radiative corrections (renormalization group equation = RGE).

Quantum Corrections

- Effects are small.
  - Rare process searches
  - High precision measurements
- High intensity machine is needed.
- Indirect searches

$$\Delta E \sim \frac{\hbar}{2\Delta t}$$

Uncertainty principle

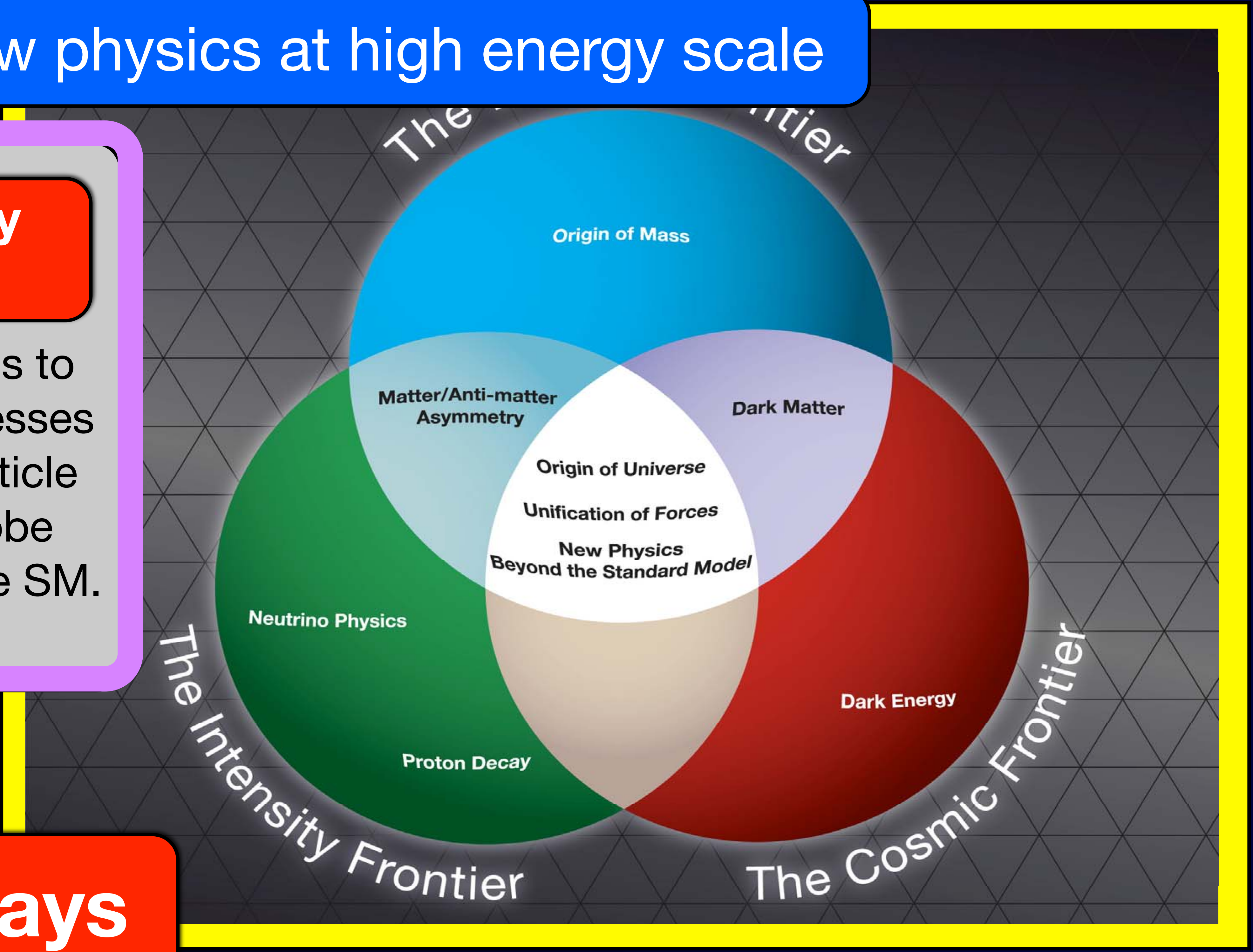
Three Frontiers of Particle Physics

To explore new physics at high energy scale

The Intensity Frontier

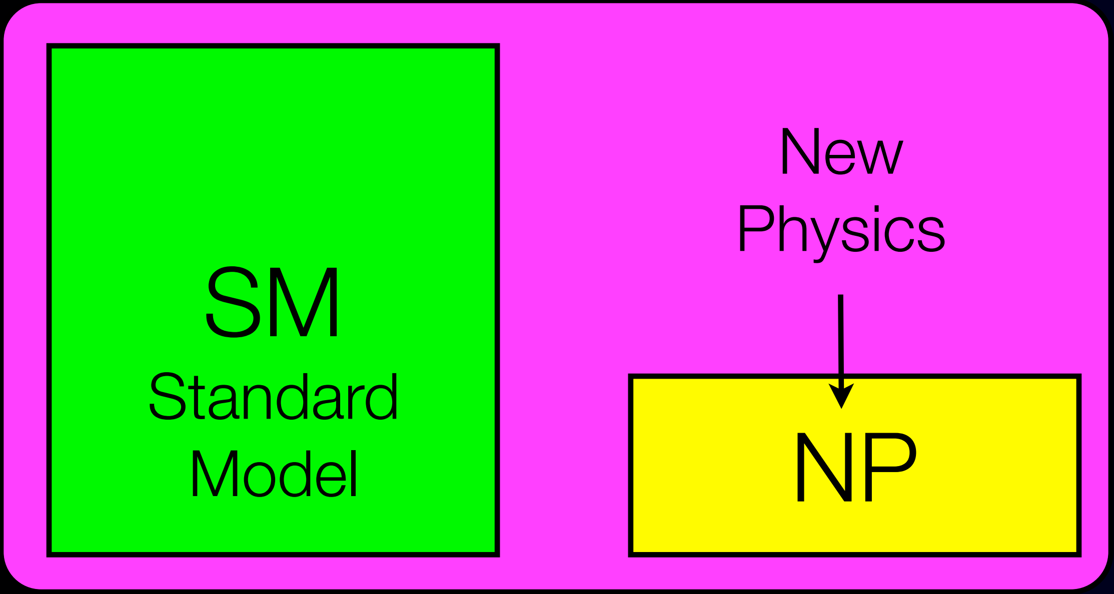
use intense beams to observe rare processes and study the particle properties to probe physics beyond the SM.

Rare Decays



Guideline for Rare Decay Searches

New physics effects may be very small.

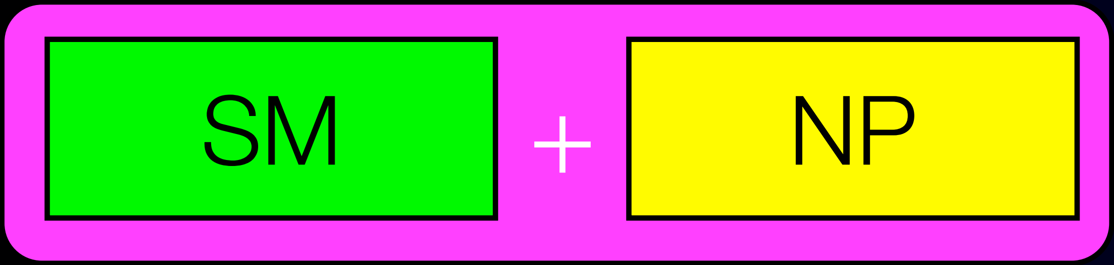

SM
Standard
Model

New
Physics

NP

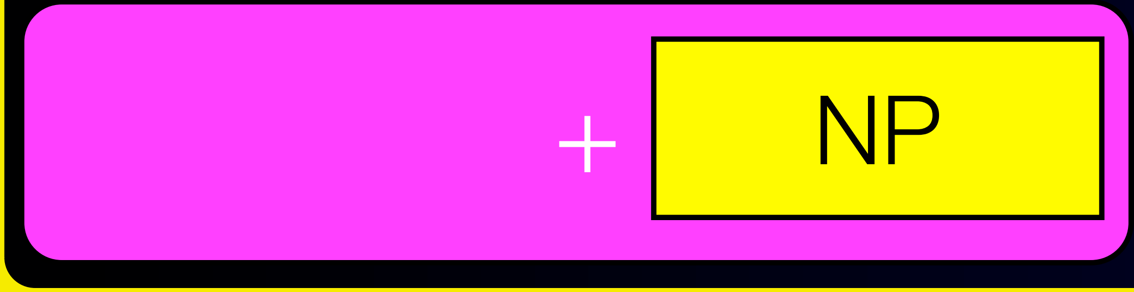
SM contribution is dominant.

👎


SM + NP

SM contribution is highly suppressed.

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


+ NP

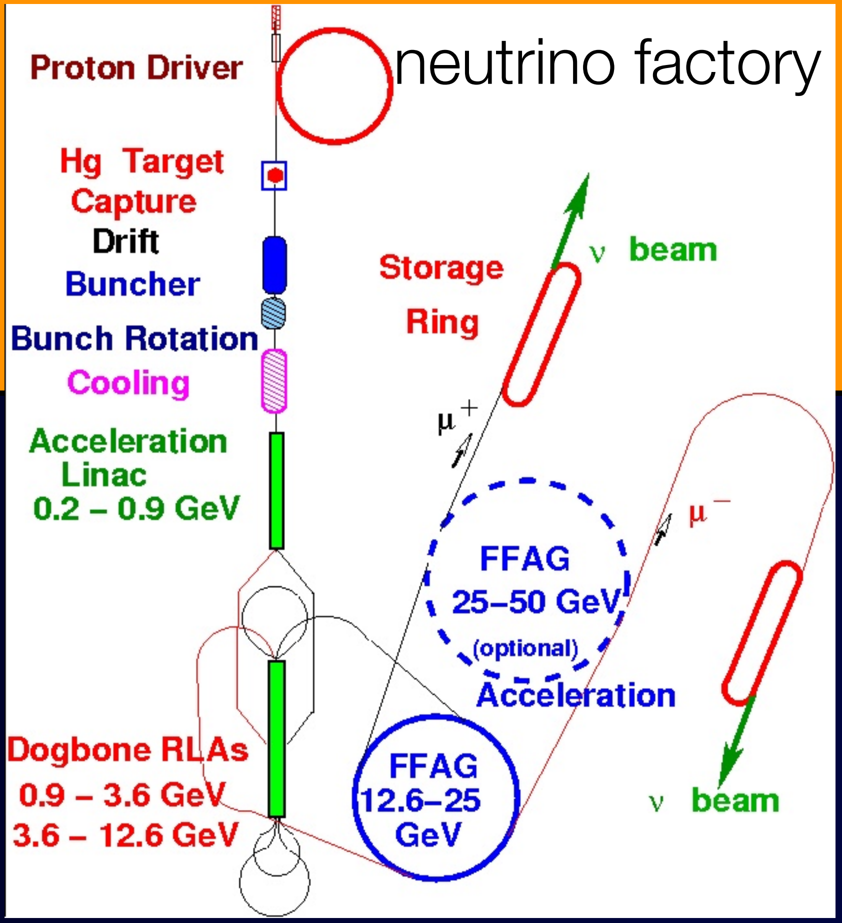
SM contribution is forbidden.

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

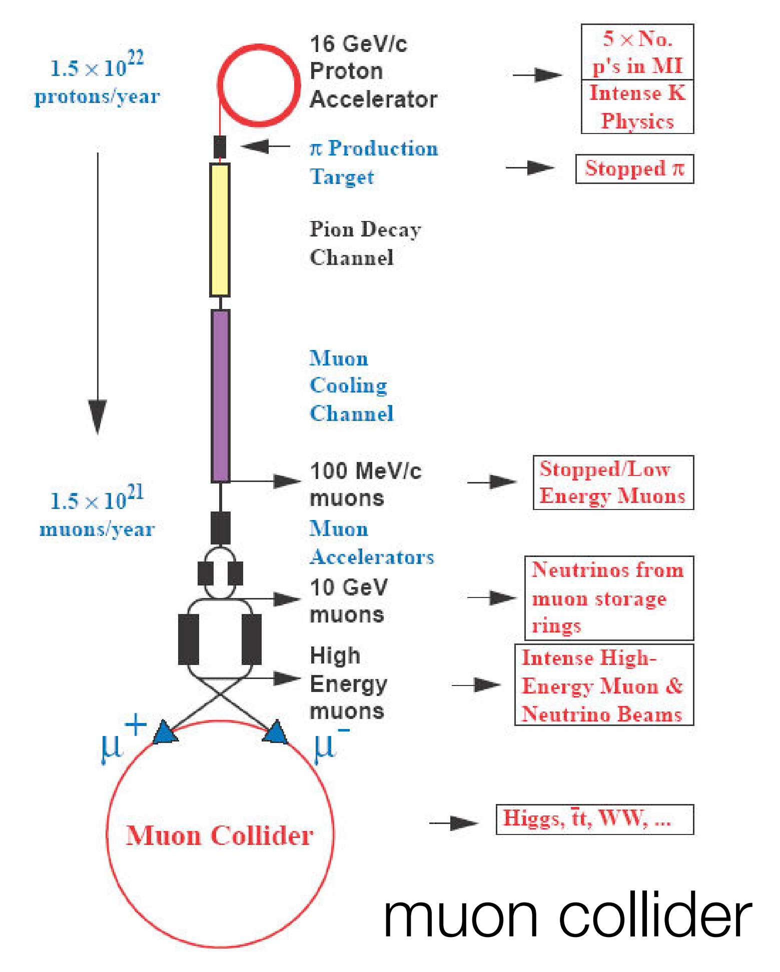
Which Processes at Low Energy ?

- Processes which are forbidden or highly suppressed in the Standard Model would be the best ones to search for new physics beyond the Standard Model.
- Flavor Changing Neutral Current Process (FCNC)
- FCNC in the quark sector
  - $b \to s\gamma$, $K \to \pi\nu\nu$, etc.
  - Allowed in the Standard Model.
  - Need to study deviations from the SM predictions.
    - Uncertainty of more than a few % (from QCD) exists.
- FCNC in the lepton sector
  - $\mu \to e\gamma$, $\mu + N \to e + N$, etc. (lepton flavor violation =LFV)
  - Not allowed in the Standard Model ($\sim 10^{-50}$ with neutrino mixing)
  - Need to study deviations from none
    - clear signature and high sensitivity

Why Muons, not Taus?



- A number of taus available at B factories are about 1-10 taus/sec. At super-B factories, about 100 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

What is Charged Lepton Flavor Violation (CLFV) ?

LFV of neutrinos is confirmed.

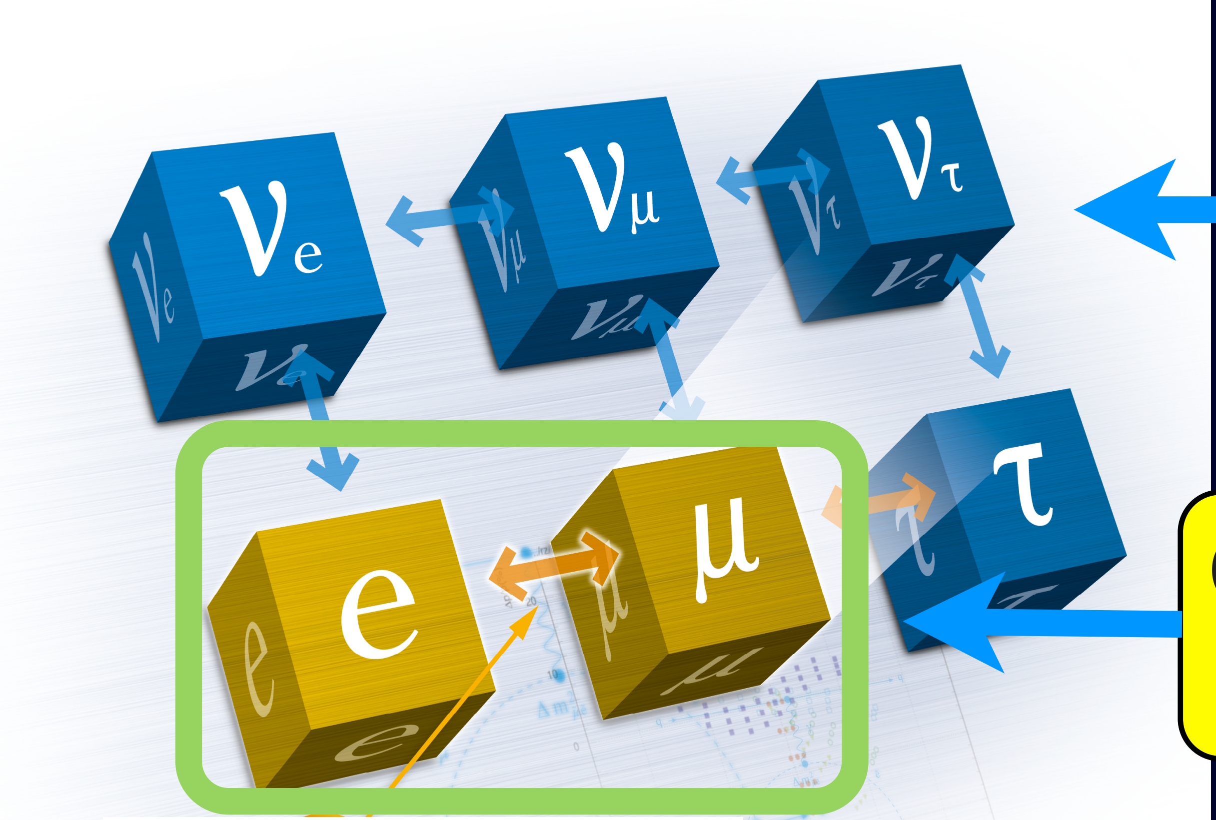
LFV of charged leptons (CLFV) has not been observed.

Quarks, Neutrinos, and then Charged Leptons

Quarks

Quark mixing observed

Leptons



Neutrino mixing observed

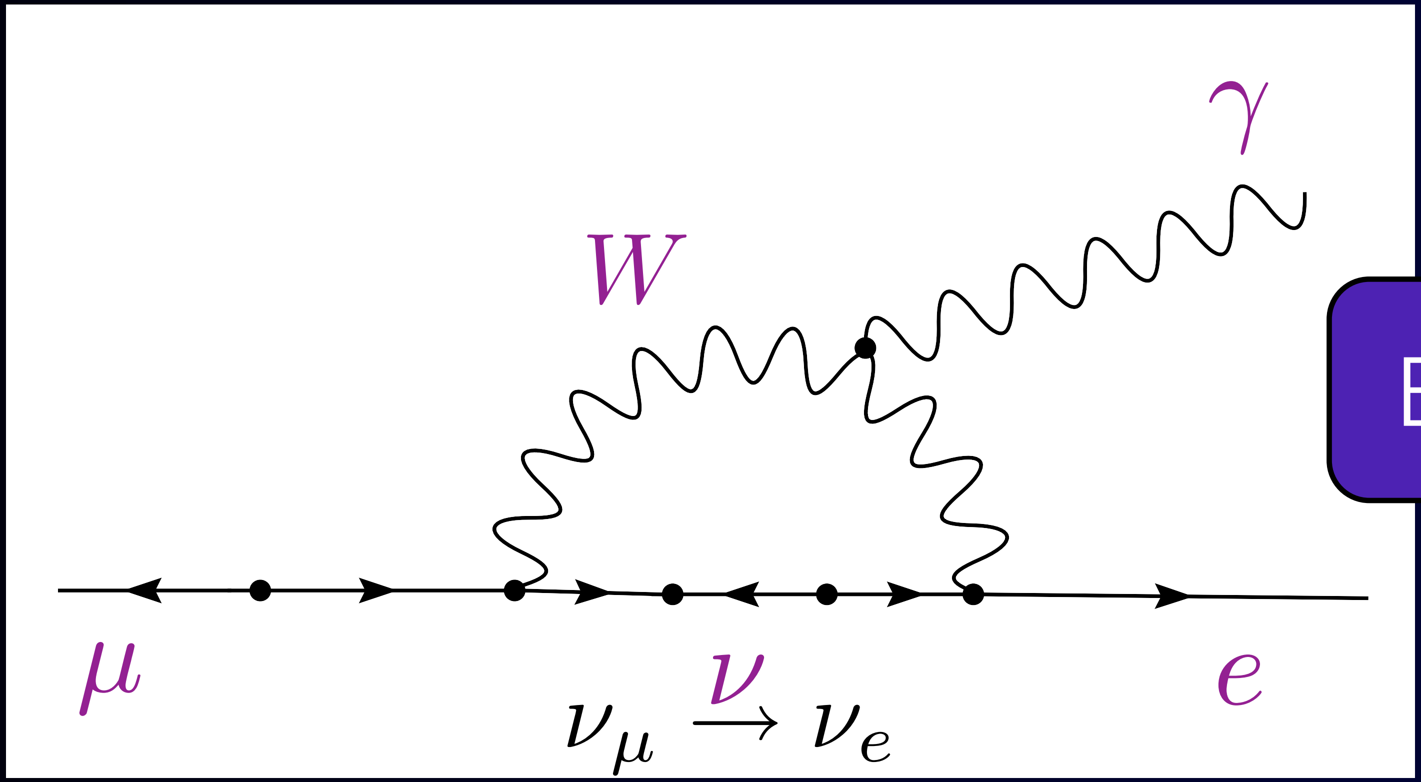
Charged lepton mixing not observed.

Charged Lepton Flavor Violation (CLFV)

Nobel Prize-wining class research

Example : No SM Contribution in Charged Lepton Flavor Violation (CLFV)

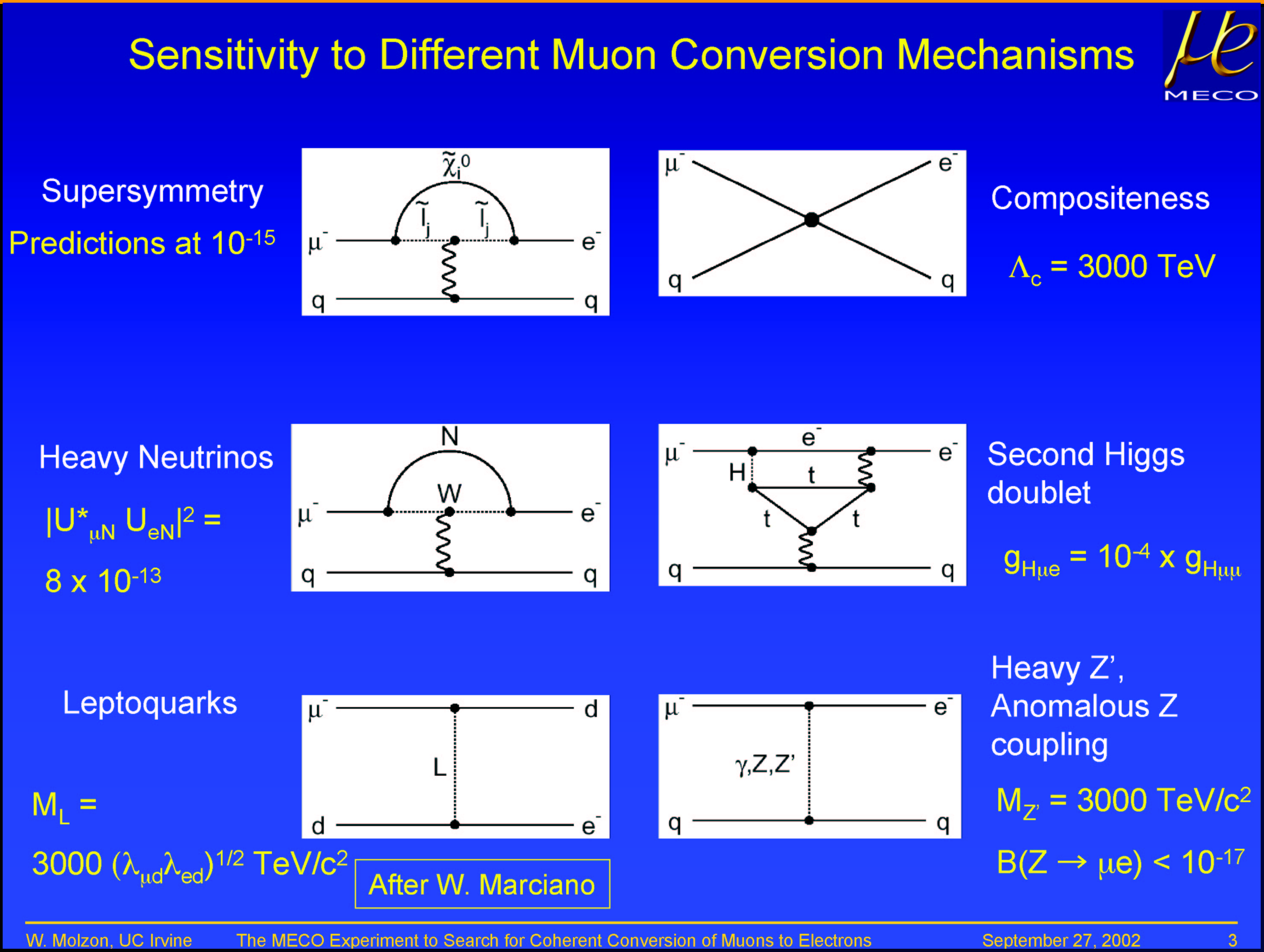
$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_l (V_{MNS})^*_{\mu l}(V_{MNS})_{el}\frac{m^2_{\nu_l}}{M^2_W}\right|^2$$



BR~O(10^{-54})

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

Various Models Predict Charged Lepton Mixing.



Sensitivity to Different Muon Conversion Mechanisms

Supersymmetry

Predictions at 10^{-15}

Compositeness

$\Lambda_c = 3000$ 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

$M_L =$

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

Heavy Z', Anomalous Z coupling

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

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

After W. Marciano

Sensitivity to High Energy-scale Physics Exercise (1) :

Take an example of rare decay of μ→eγ ($Br<10^{-11}$)

$$\mathcal{L}_{\rm LFV} = y\frac{em_\mu}{\Lambda^2}\bar{\mu}_R\sigma^{\mu\nu}e_L F_{\mu\nu} + \text{h.c.} + \cdots$$

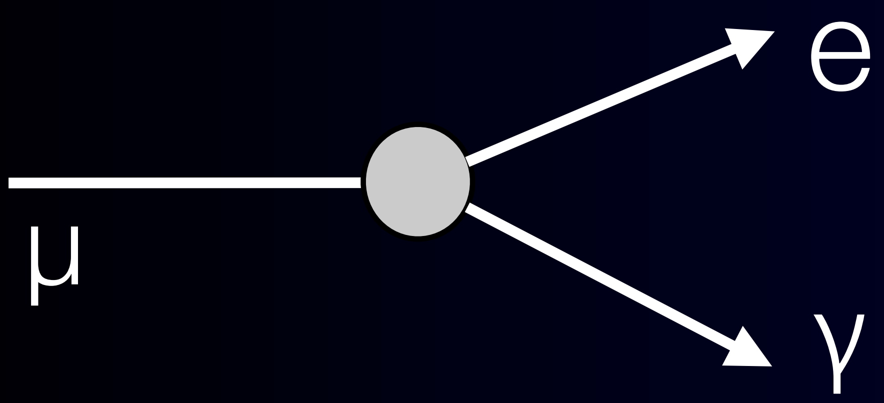
$$\text{BR}(\mu\to e\gamma) = y^2\frac{3(4\pi)^3\alpha}{G_F^2\Lambda^4}$$

Λ :new physics scale

- For tree diagrams,

$$\text{BR}(\mu\to e\gamma) = 1\times 10^{-11}\times\left(\frac{400\text{TeV}}{\Lambda}\right)^4\left(\frac{y}{1}\right)^2$$

> sensitive to energy scale higher than 400 TeV



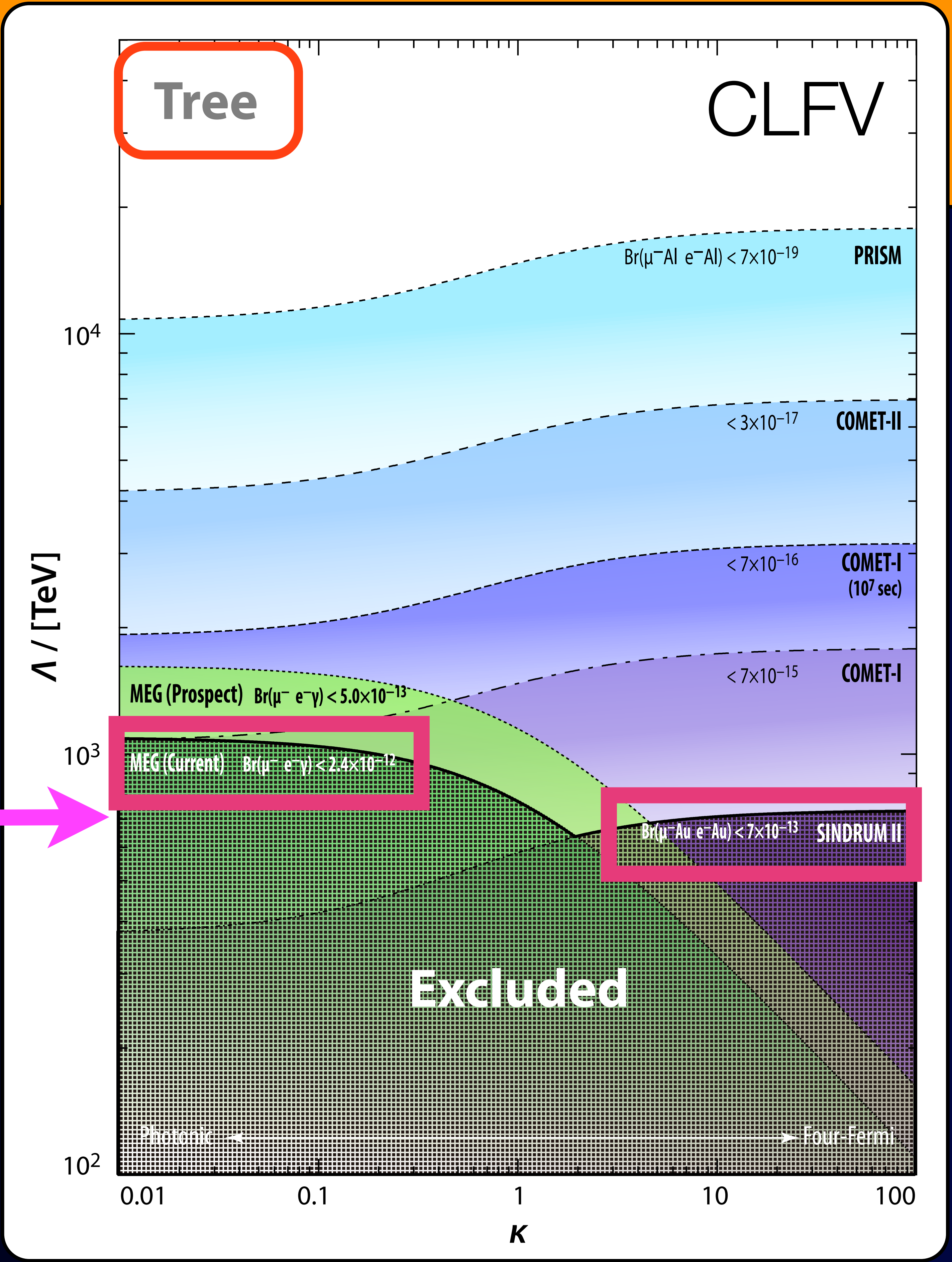
Example: Sensitivity to Energy Scale of NP

A. de Gouvea's effective interaction for μ-e conversion

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

Λ: energy scale of new physics

$O(10^3)$TeV



$$B(\mu \to e\gamma) < 2.4 \times 10^{-12}$$

$$B(\mu N \to eN) < 7 \times 10^{-13}$$

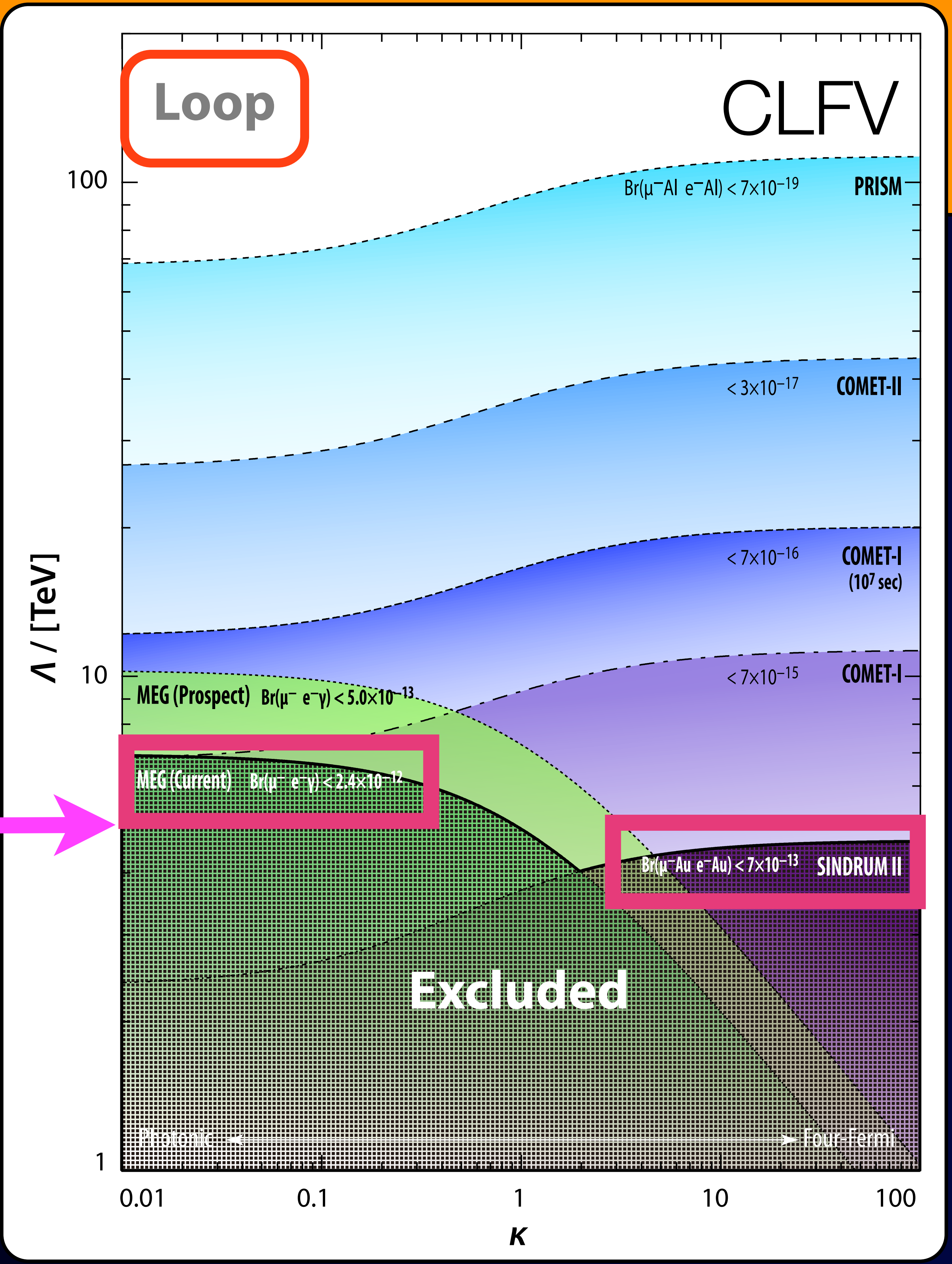
Example: Sensitivity to Energy Scale of NP

A. de Gouvea's effective interaction
for μ-e conversion

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

Λ: energy scale of new physics

O(1)TeV



With loop suppression

Flavor mixing couplings gives additional reduction on the Λ reach.

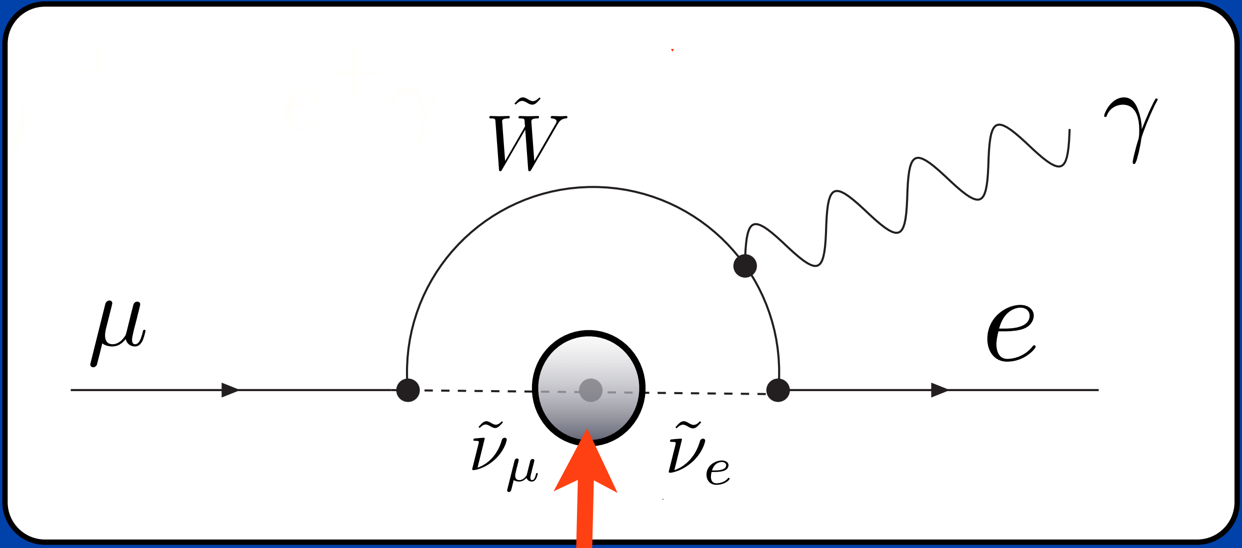
Example: Sensitivity to Energy Scale of NP
Loop contribution in SUSY models

- For loop diagrams,

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

$$y = \frac{g^2}{16\pi^2}\theta_{\mu e}$$

> 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

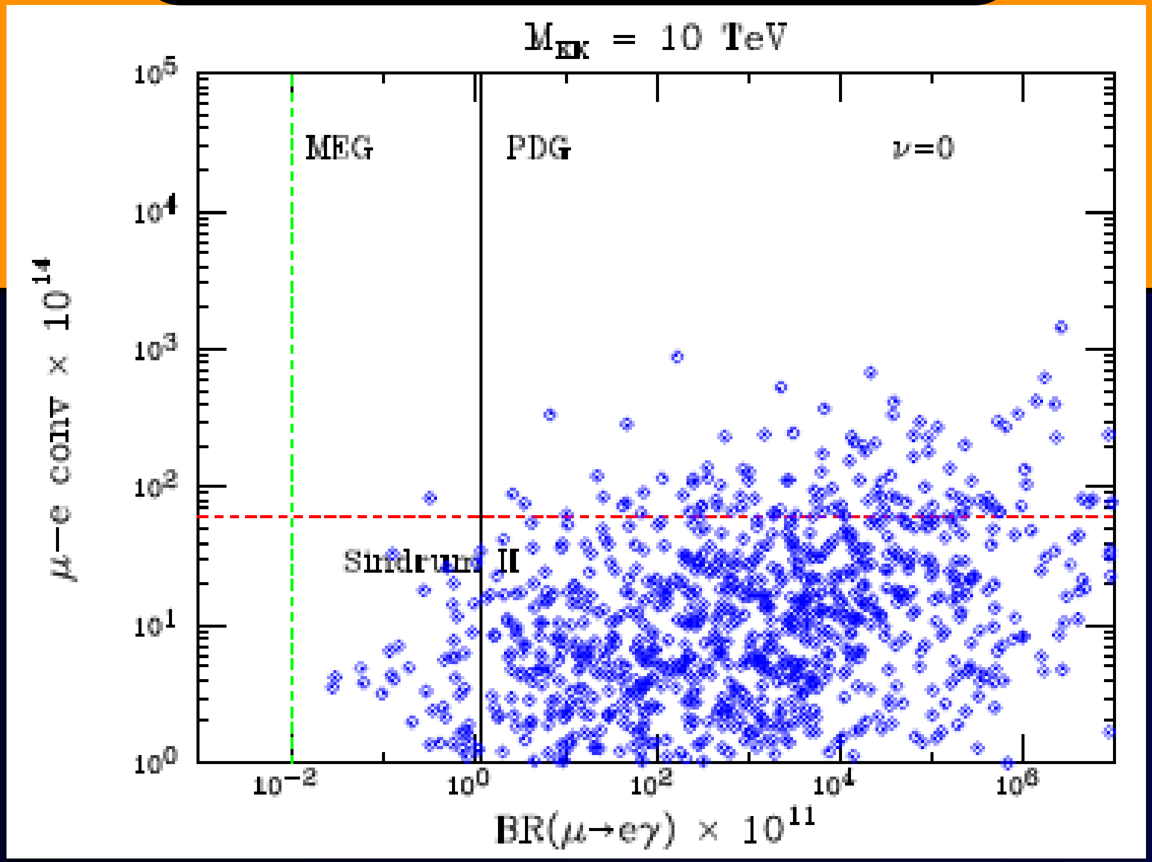
$$(m^2_{L})_{21} \sim \frac{3m_0^2 + A_0^2}{8\pi^2} h_\tau^2 U_{31} U_{32} \ln \frac{M_{GUT}}{M_R}$$

SUSY neutrino seesaw model

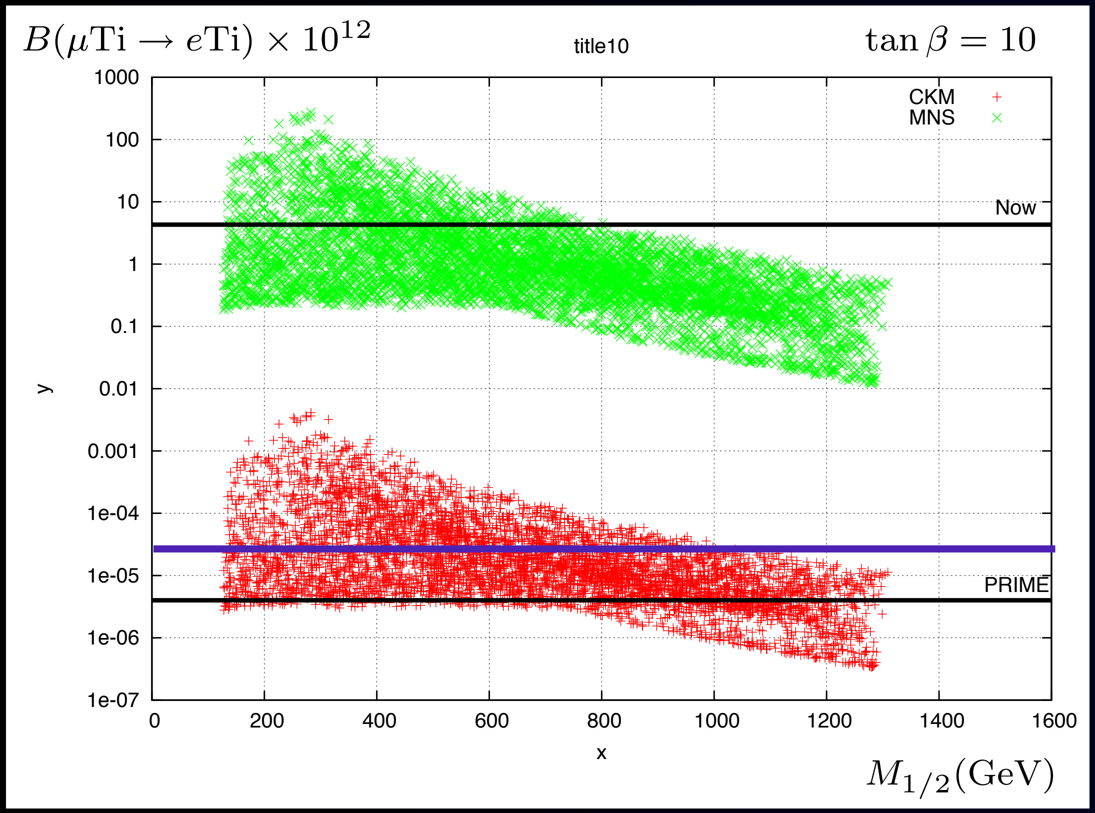
CLFV Predictions

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

extra dimension model

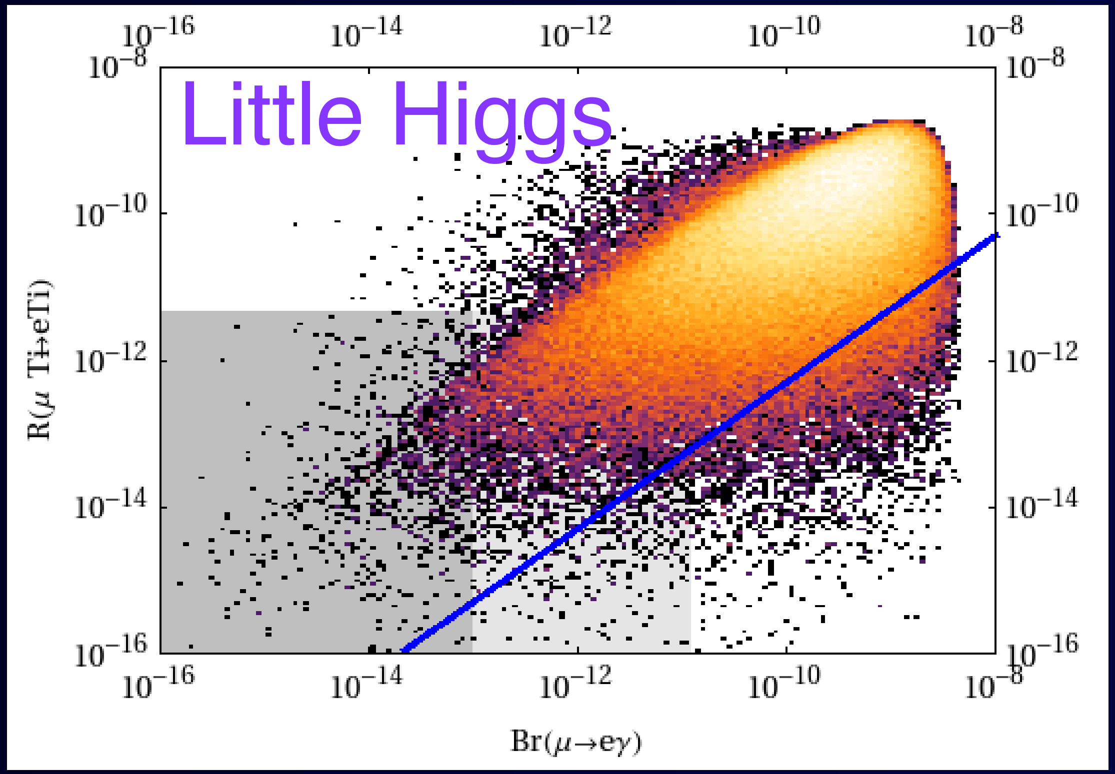


SUSY model



10^4

little Higgs model



CLFV and Neutrino

How to Validate Neutrino Seesaw Mechanism?
SUSY-Seesaw ?

1 Majorana Nature of Neutrinos

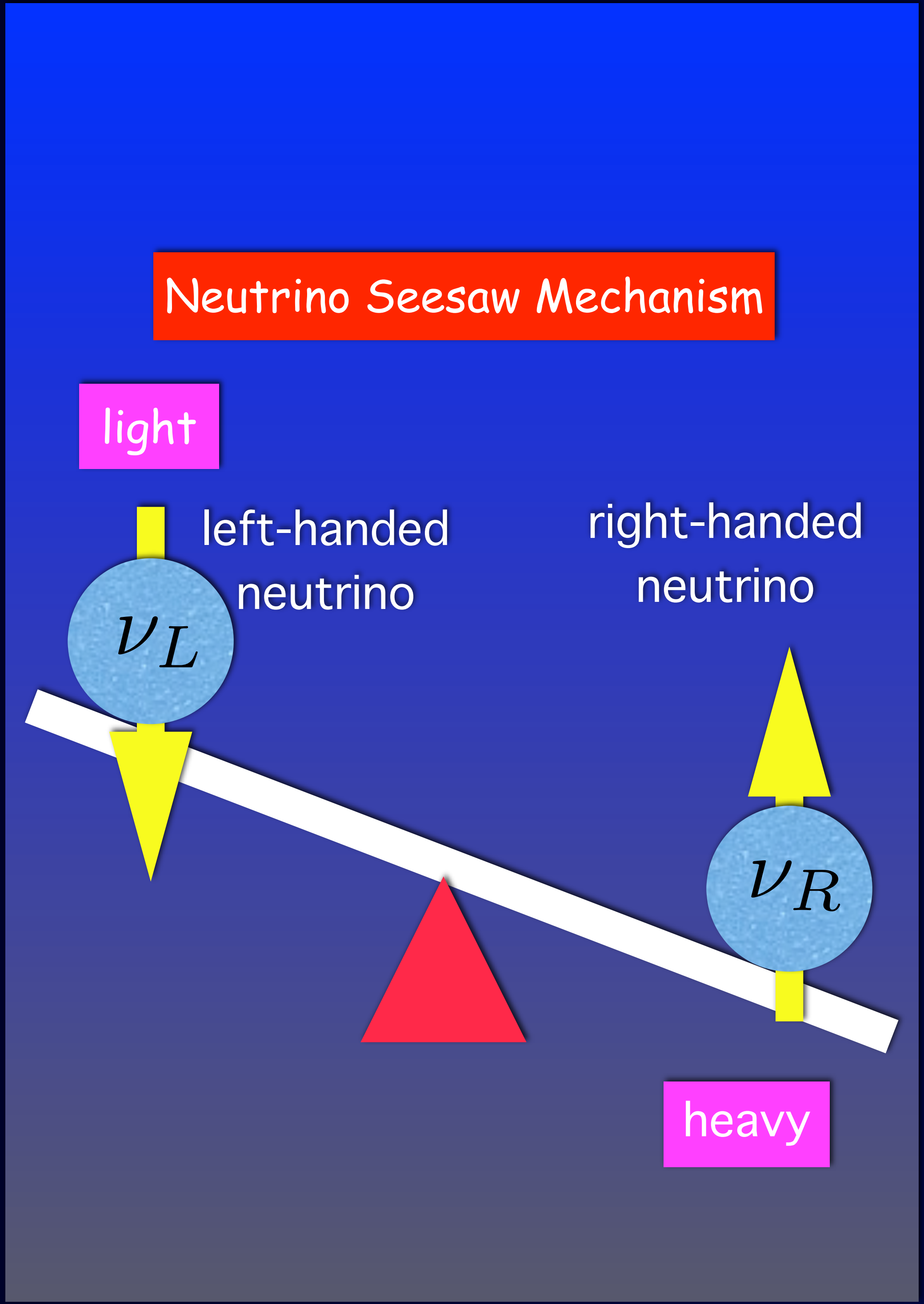
Neutrinoless Double Beta Decays

Neutrinoless double beta decays address whether neutrinos are Majorana-type or not?

2 Heavy Partner of Neutrinos

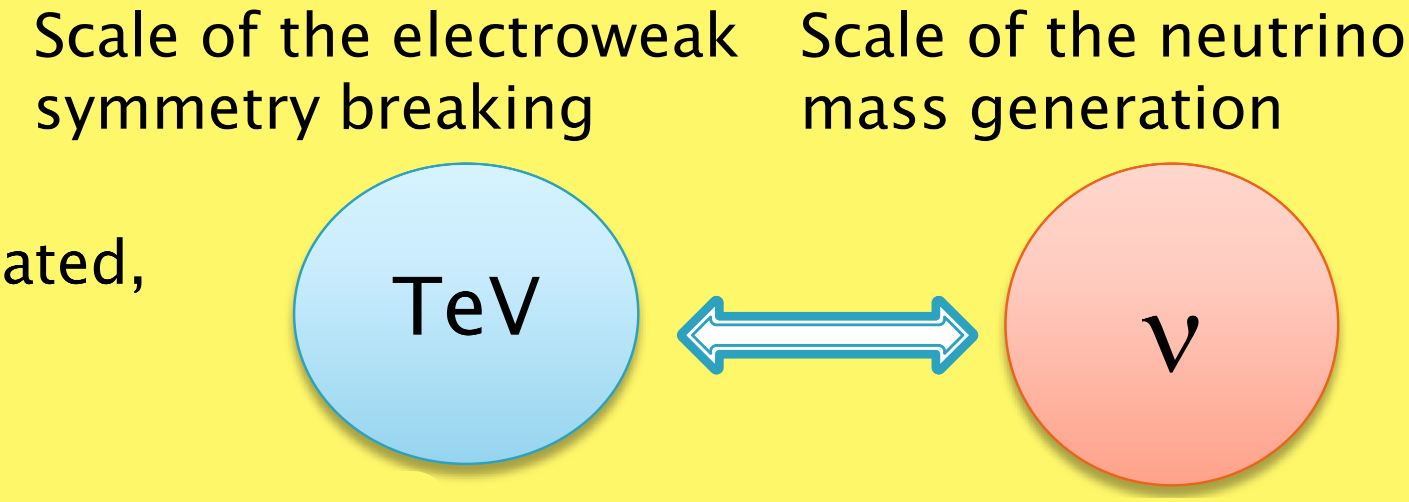
CLFV

Search for CLFV is sensitive to the energy scale of heavy right-handed neutrinos in the neutrino seesaw models.



from Y. Okada san's slide (2010)

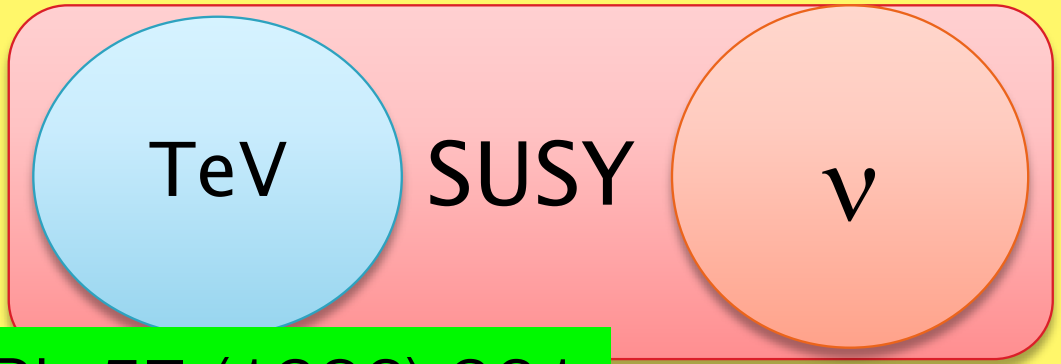
CLFV and Neutrino Mass Generation



If two scales are well separated,
LFVs are suppressed.

$\boxed{\text{CLFV}\sim O(10^{-54})}$

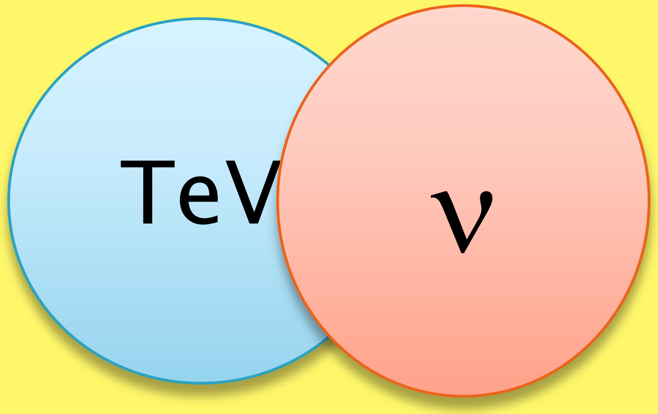
1



In supersymmetric models,
large LFV signals are expected
even if two scales are separated.

F. Borzumati and A. Masiero, PRL 57 (1986) 961

2



If two scales are close,
large LFVs are expected.

- Neutrino mass from loop
- Triplet Higgs for neutrino mass
- Left-right symmetric model

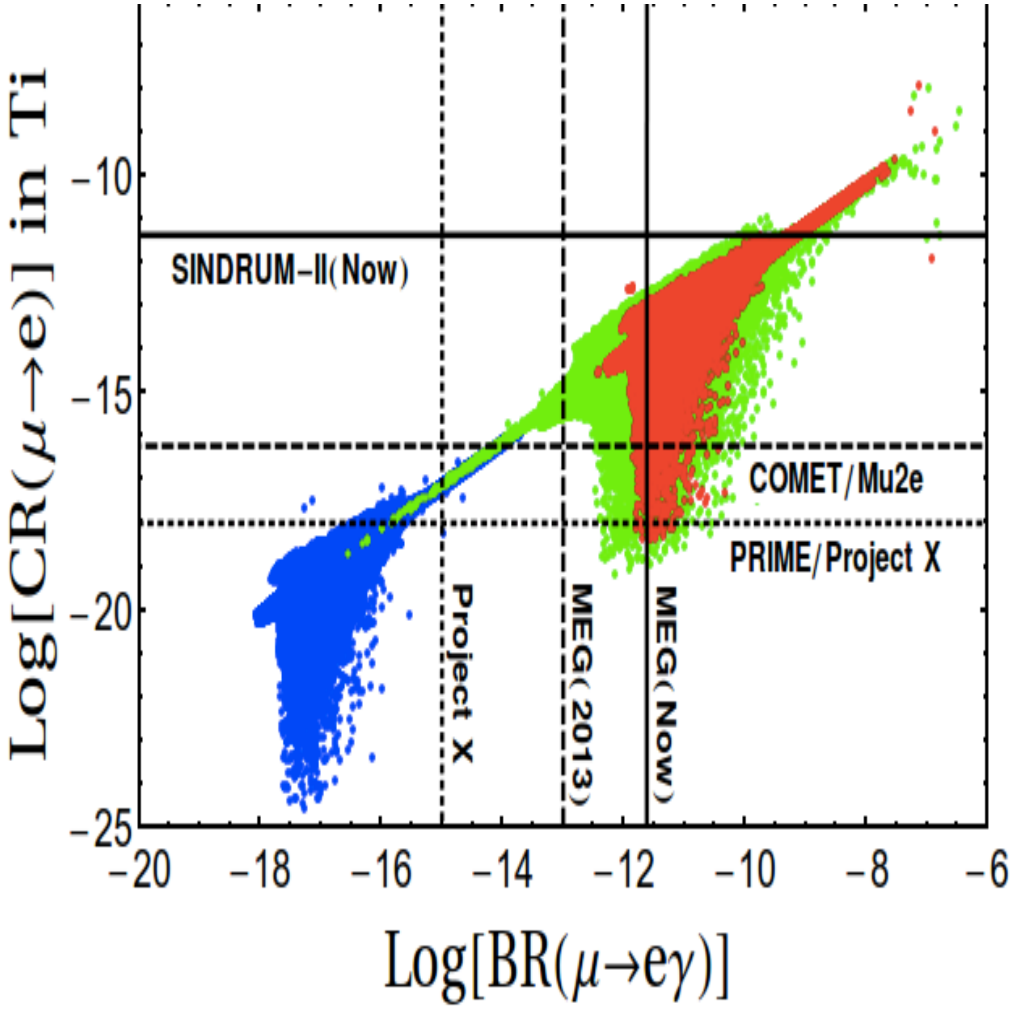
arXiv:1207.7227v1 [hep-ph] 31 Jul 2012

1

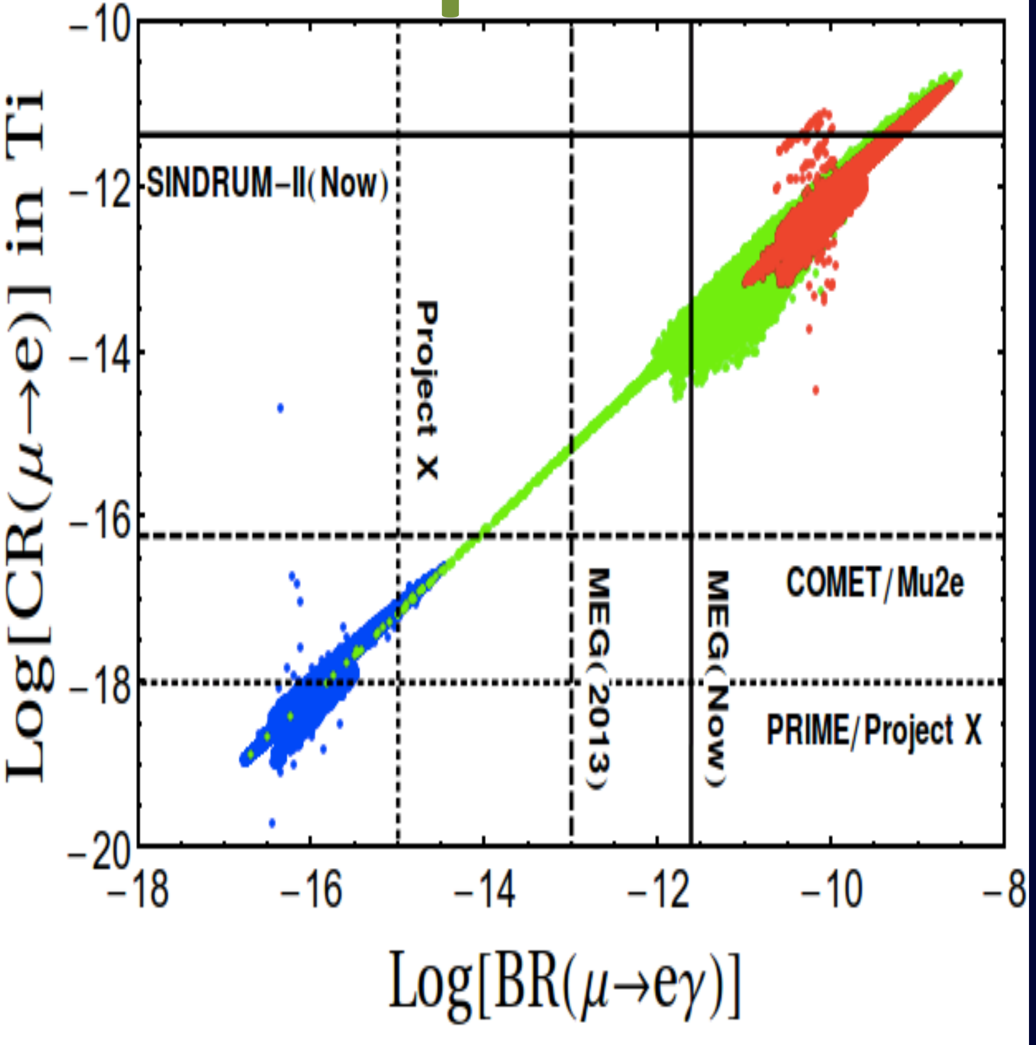
SUSY Predictions (a la A. Masiero)

μ – e conversion vs μ → eγ

Tanβ = 10

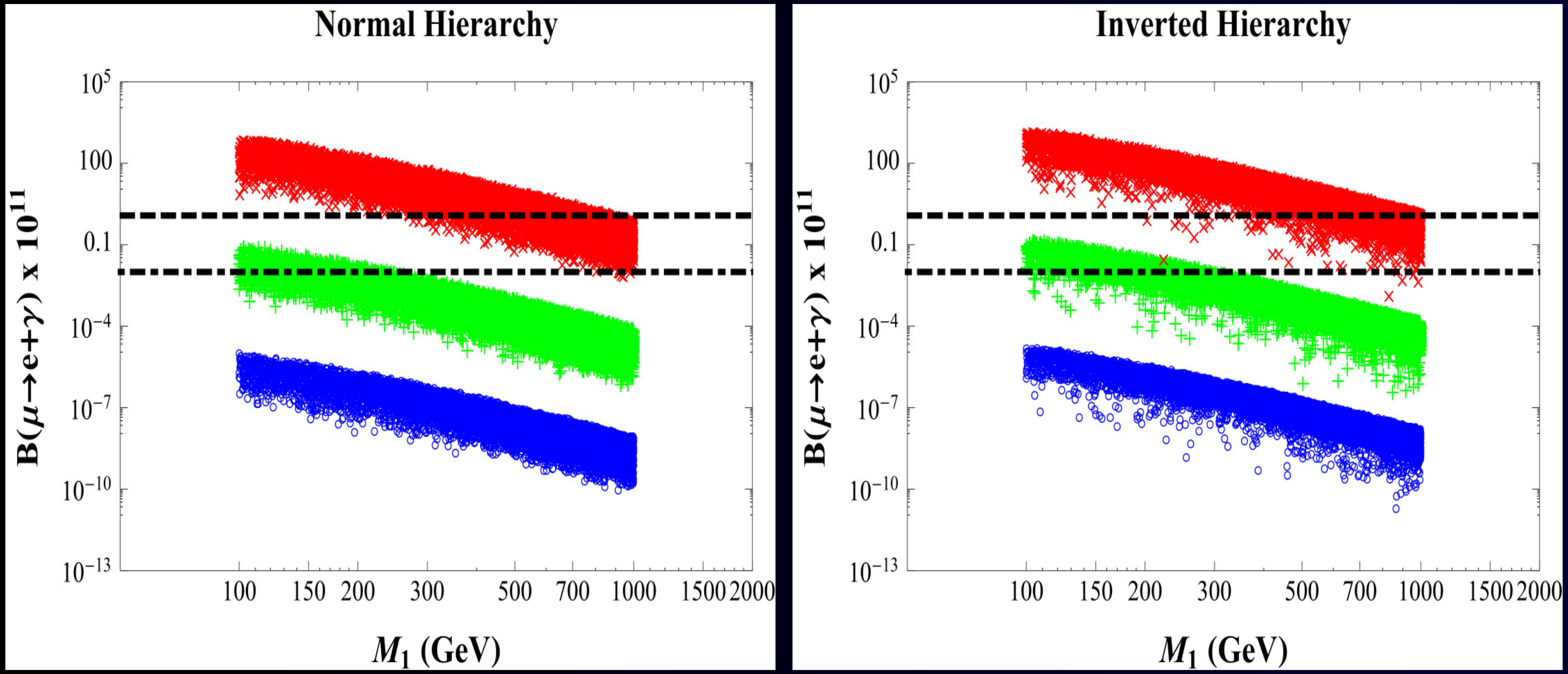


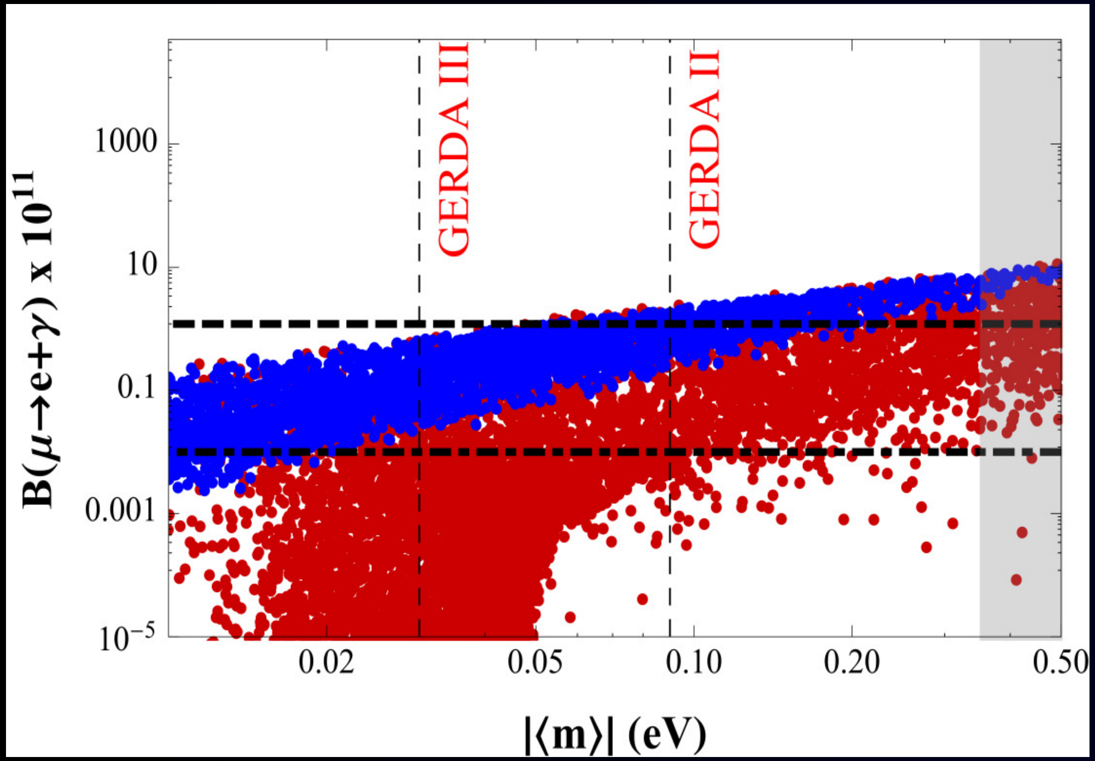
Tanβ = 40



A. Ibara, E. Molinaro, S.T. Petcov, Phys. Rev. D84 (2011) 013005

2 CLFV with TeV Seesaw (Type-I)

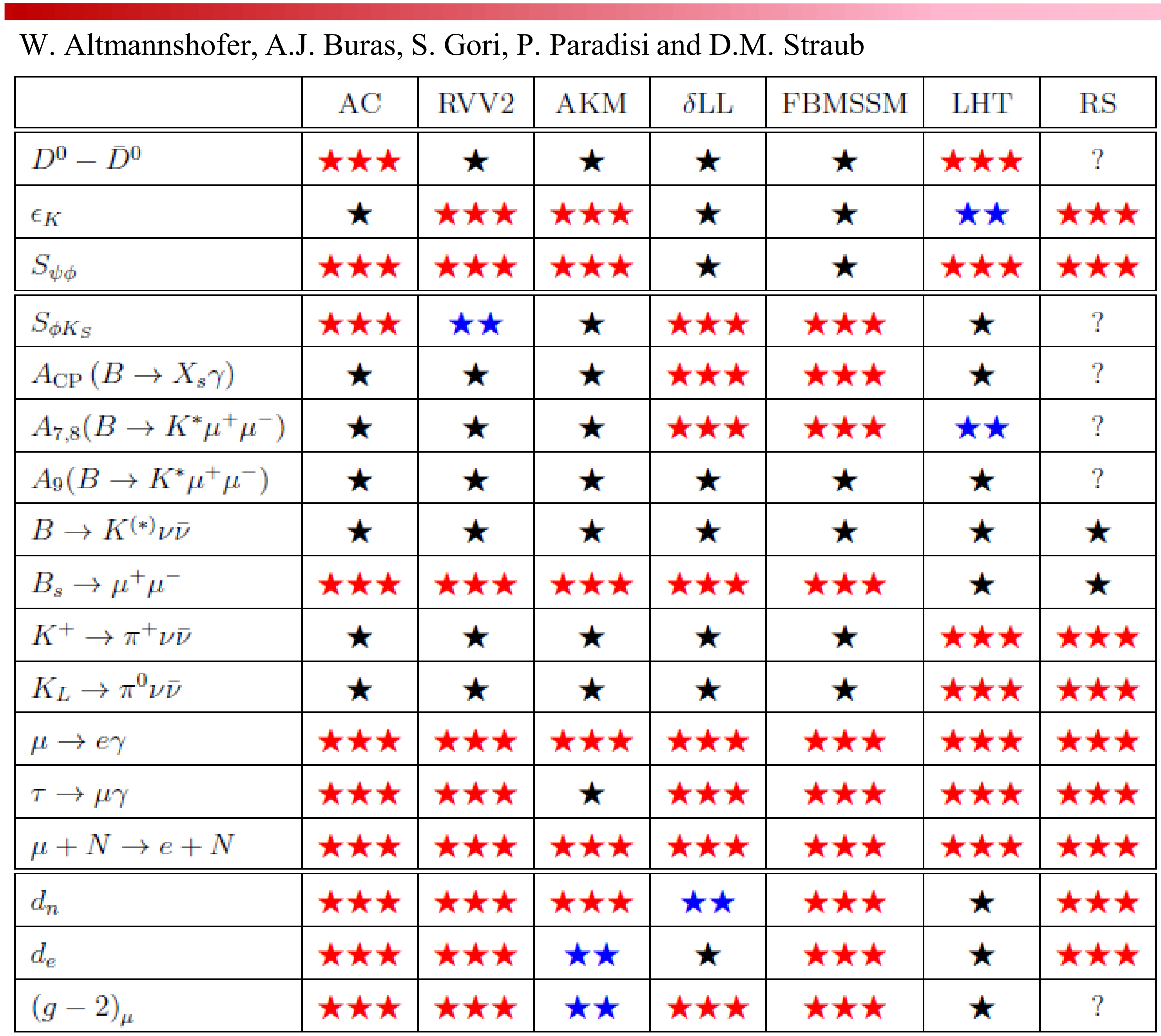




TeV seesaw type-I models predict sizable branching ratio of CLFV with right-handed neutrino mass of O(TeV).

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

from D. Hitlin’s talk [368]



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

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

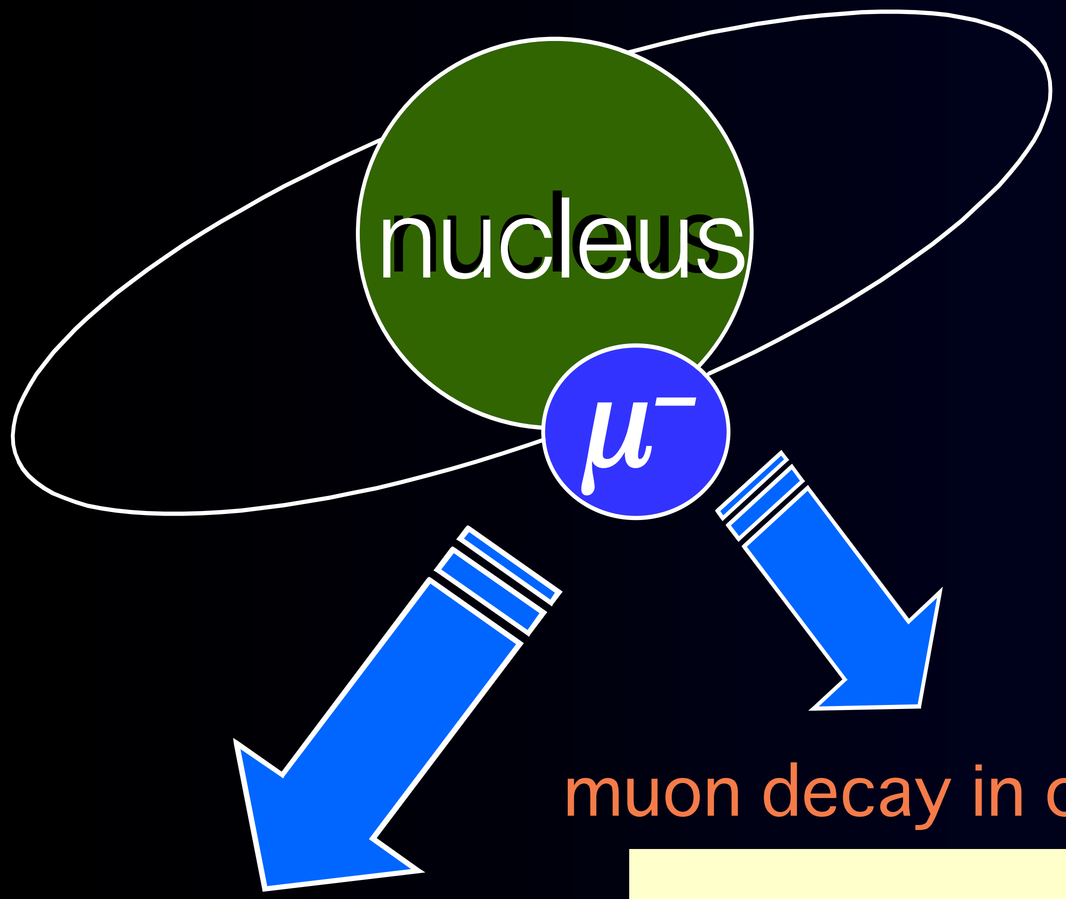
The pattern of measurement:
★★★ large effects
★★ visible but small effects
★ unobservable effects
is characteristic,
often uniquely so,
of a particular model

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

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:

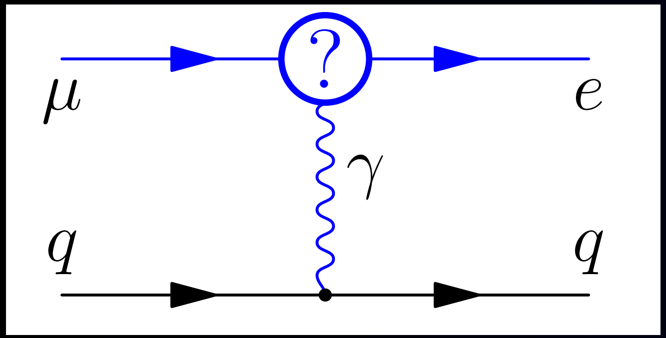
(1) physics backgrounds
  ex. muon decay in orbit (DIO)
(2) beam-related backgrounds
  ex. radiative pion capture, muon decay in flight,
(3) cosmic rays, false tracking

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

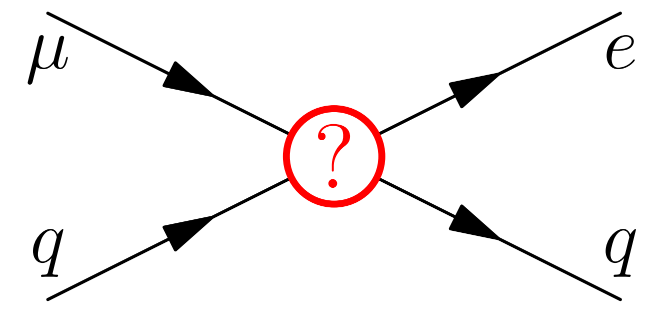
constructive

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

Photonic (dipole) interaction



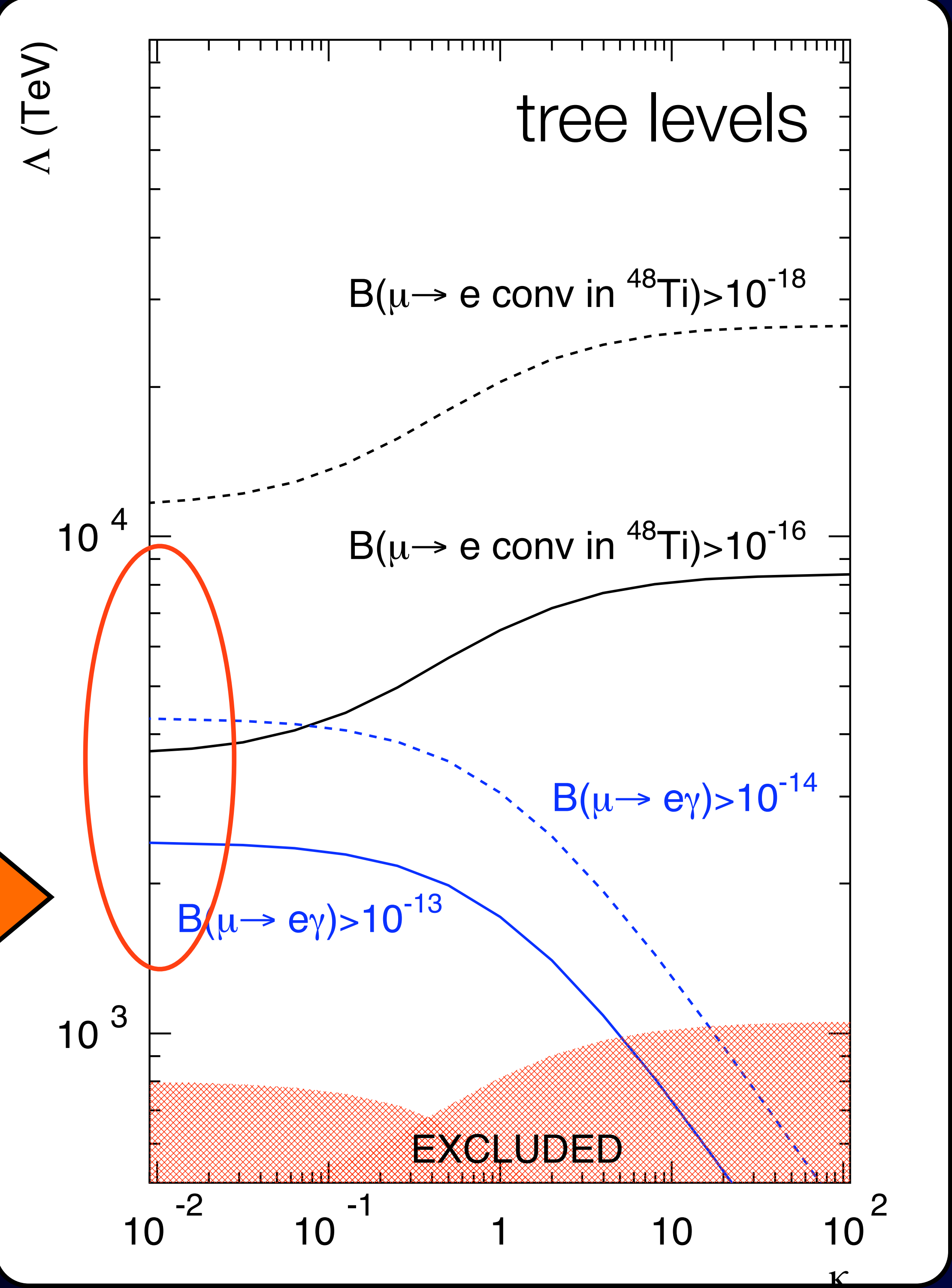
Contact interaction



if photonic contribution dominates,

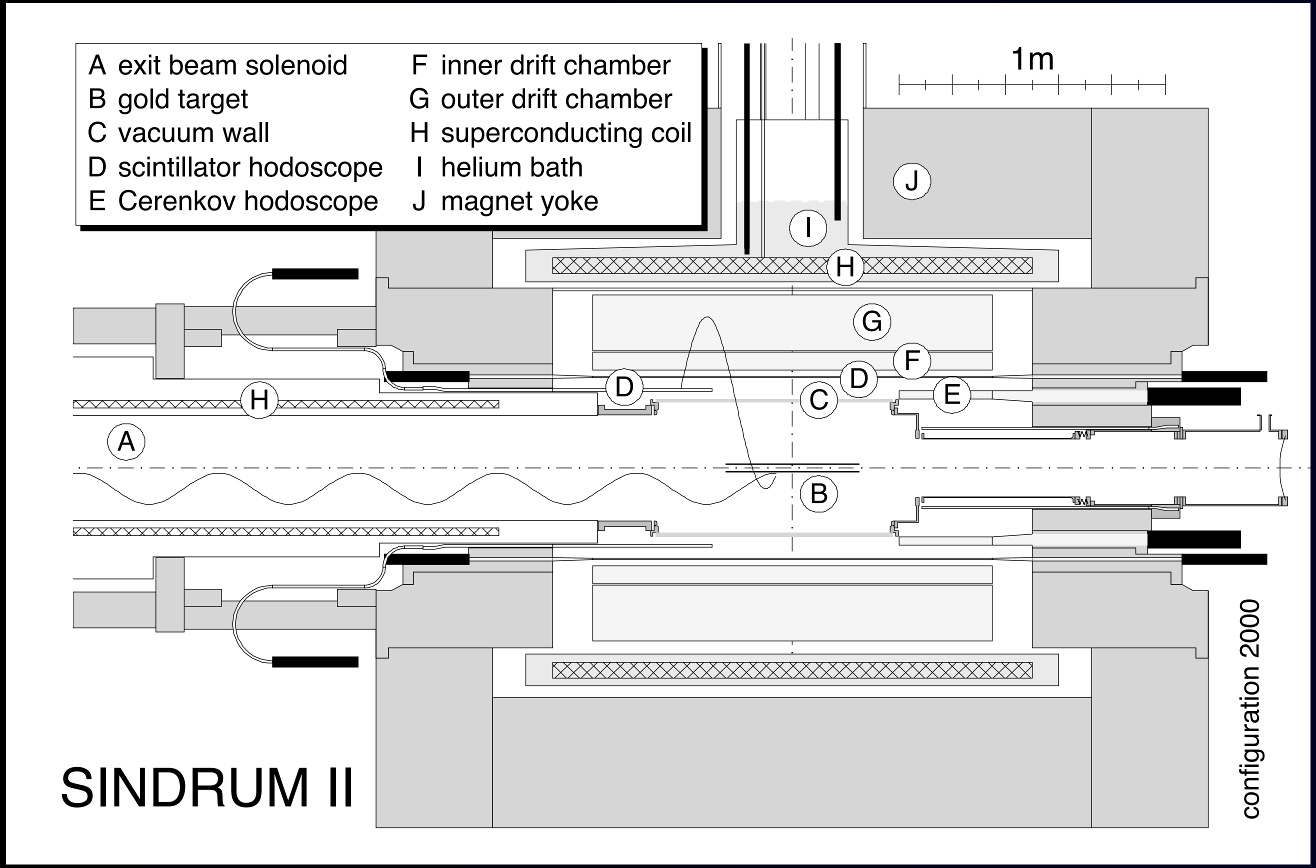
$$\frac{B(\mu N\to eN)}{B(\mu\to e\gamma)} = \frac{G_F^2 m_\mu^4}{96\pi^3\alpha}\times 3\times 10^{12}B(A,Z) \sim \frac{B(A,Z)}{428}$$

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



Previous Measurements

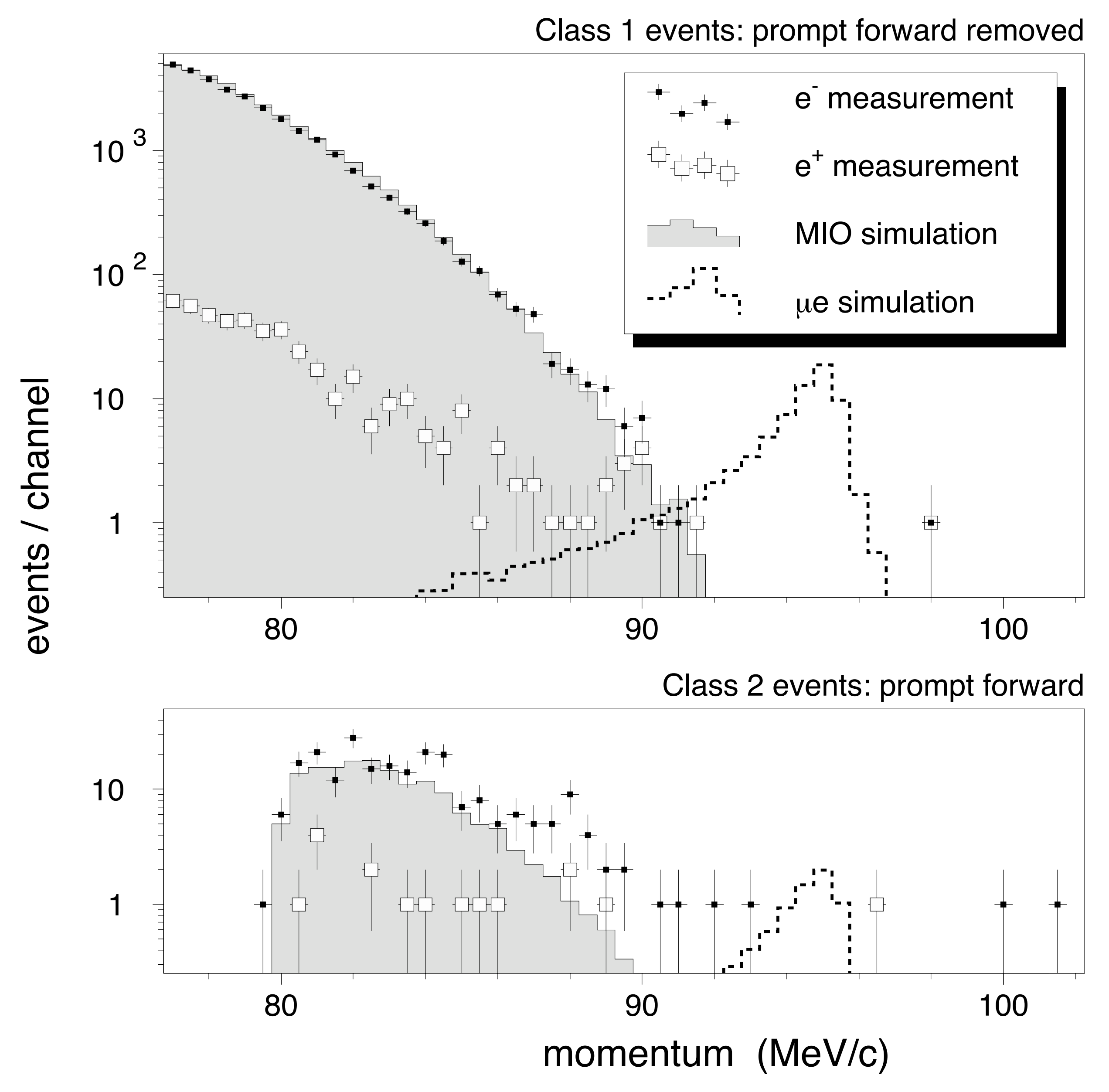
SINDRUM-II (PSI)



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

Published Results (2004)

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



Improvements for Signal Sensitivity

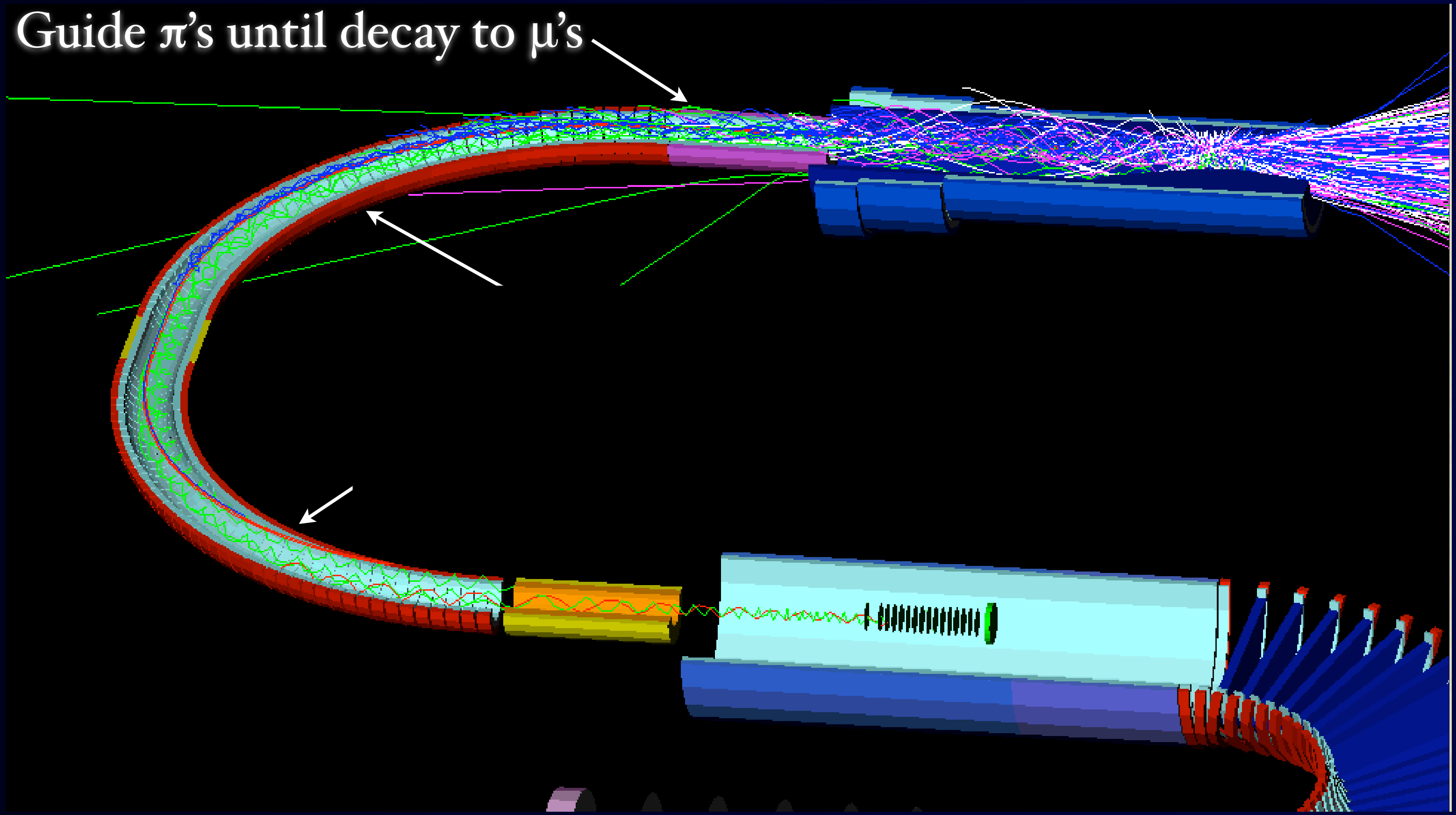
To achieve a single sensitivity of 10^{-17}, we need

10^{11} muons/sec (with 10^{7} sec running)

whereas the current highest intensity is 10^{8}/sec at PSI.

Pion Capture and Muon Transport by Superconducting Solenoid System

(10^{11} muons for 50 kW beam power)



Improvements for Background Rejection

Beam-related backgrounds

Beam pulsing with separation of 1μsec

measured between beam pulses

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

Muon DIO background

low-mass trackers in vacuum & thin target

improve electron energy resolution

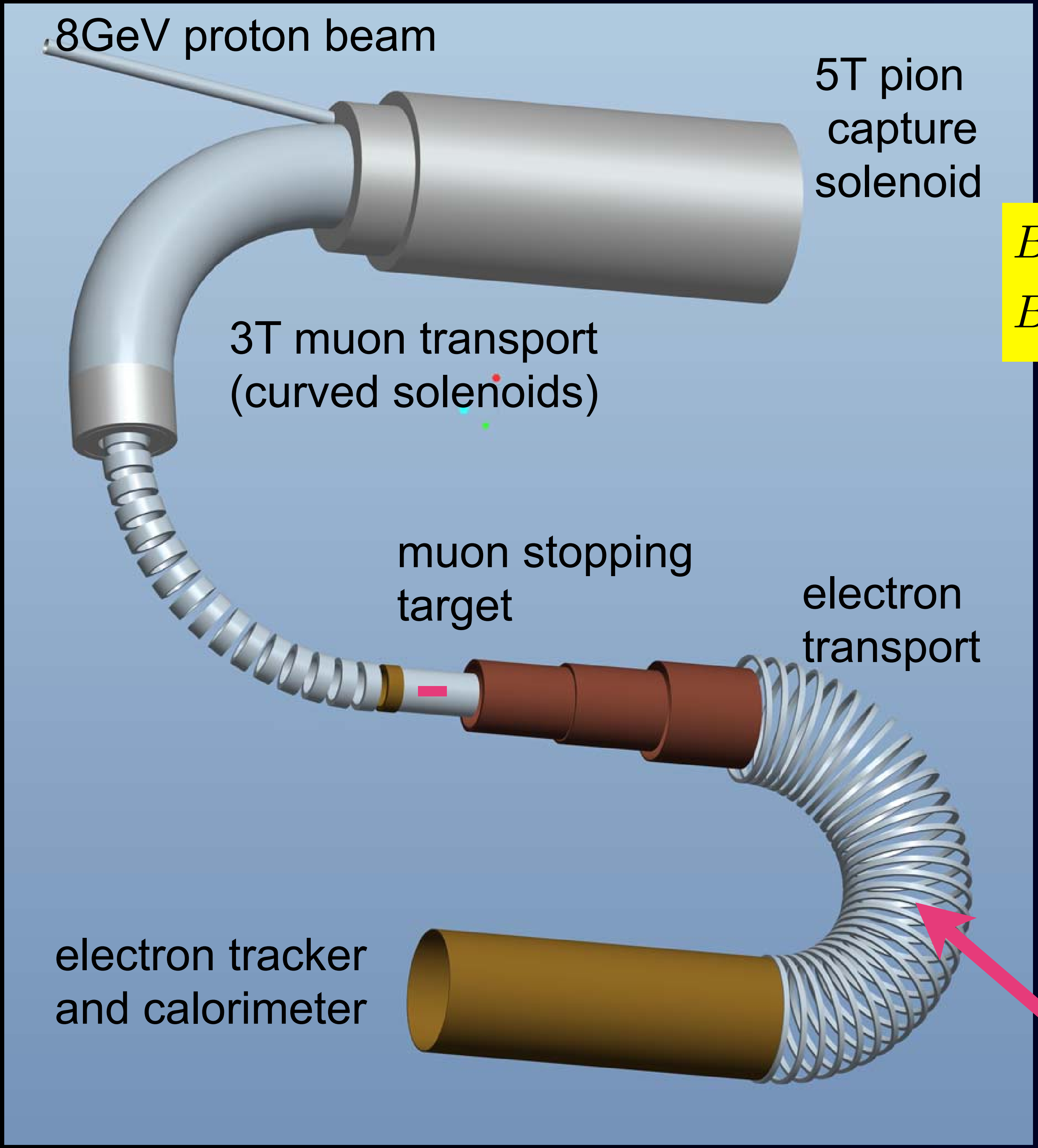
Muon DIF background

curved solenoids for momentum selection

eliminate energetic muons (>75 MeV/c)

base on the MELC proposal at Moscow Meson Factory

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



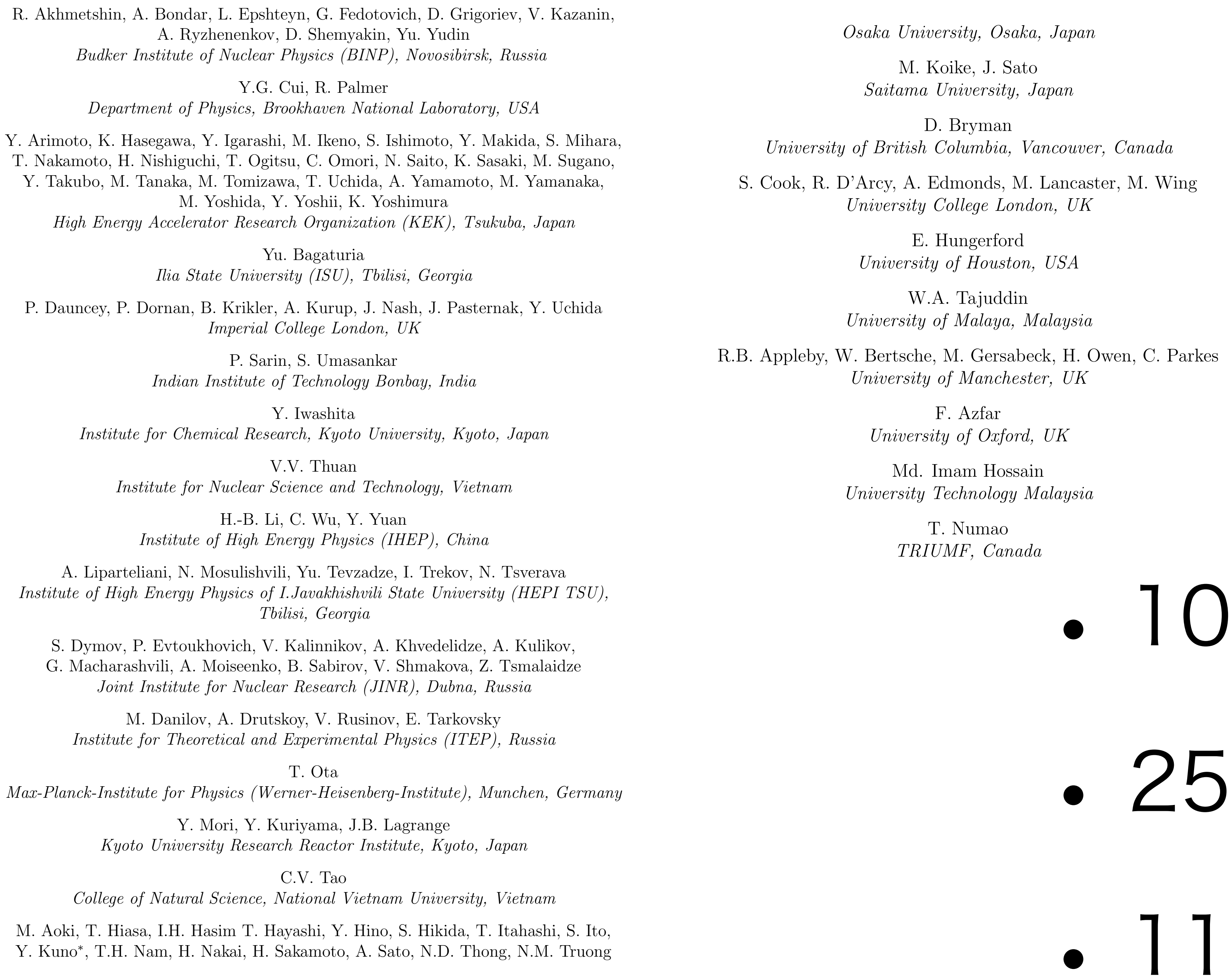
Experimental Goal of COMET

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

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

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

COMET Collaboration



R. Akhmetshin, A. Bondar, L. Epshteyn, G. Fedotovich, D. Grigoriev, V. Kazanin,
A. Ryzhenenkov, D. Shemyakin, Yu. Yudin
Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia

Y.G. Cui, R. Palmer
Department of Physics, Brookhaven National Laboratory, USA

Y. Arimoto, K. Hasegawa, Y. Igarashi, M. Ikeno, S. Ishimoto, Y. Makida, S. Mihara,
T. Nakamoto, H. Nishiguchi, T. Ogitsu, C. Omori, N. Saito, K. Sasaki, M. Sugano,
Y. Takubo, M. Tanaka, M. Tomizawa, T. Uchida, A. Yamamoto, M. Yamanaka,
M. Yoshida, Y. Yoshii, K. Yoshimura
High Energy Accelerator Research Organization (KEK), Tsukuba, Japan

Yu. Bagaturia
Ilia State University (ISU), Tbilisi, Georgia

P. Dauncey, P. Dornan, B. Krikler, A. Kurup, J. Nash, J. Pasternak, Y. Uchida
Imperial College London, UK

P. Sarin, S. Umasankar
Indian Institute of Technology Bonbay, India

Y. Iwashita
Institute for Chemical Research, Kyoto University, Kyoto, Japan

V.V. Thuan
Institute for Nuclear Science and Technology, Vietnam

H.-B. Li, C. Wu, Y. Yuan
Institute of High Energy Physics (IHEP), China

A. Liparteliani, N. Mosulishvili, Yu. Tevzadze, I. Trekov, N. Tsverava
*Institute of High Energy Physics of I.Javakhishvili State University (HEPI TSU),
Tbilisi, Georgia*

S. Dymov, P. Evtoukhovich, V. Kalinnikov, A. Khvedelidze, A. Kulikov,
G. Macharashvili, A. Moiseenko, B. Sabirov, V. Shmakova, Z. Tsmalaidze
Joint Institute for Nuclear Research (JINR), Dubna, Russia

M. Danilov, A. Drutskoy, V. Rusinov, E. Tarkovsky
Institute for Theoretical and Experimental Physics (ITEP), Russia

T. Ota
Max-Planck-Institute for Physics (Werner-Heisenberg-Institute), Munchen, Germany

Y. Mori, Y. Kuriyama, J.B. Lagrange
Kyoto University Research Reactor Institute, Kyoto, Japan

C.V. Tao
College of Natural Science, National Vietnam University, Vietnam

M. Aoki, T. Hiasa, I.H. Hasim T. Hayashi, Y. Hino, S. Hikida, T. Itahashi, S. Ito,
Y. Kuno*, T.H. Nam, H. Nakai, H. Sakamoto, A. Sato, N.D. Thong, N.M. Truong

Osaka University, Osaka, Japan

M. Koike, J. Sato
Saitama University, Japan

D. Bryman
University of British Columbia, Vancouver, Canada

S. Cook, R. D'Arcy, A. Edmonds, M. Lancaster, M. Wing
University College London, UK

E. Hungerford
University of Houston, USA

W.A. Tajuddin
University of Malaya, Malaysia

R.B. Appleby, W. Bertsche, M. Gersabeck, H. Owen, C. Parkes
University of Manchester, UK

F. Azfar
University of Oxford, UK

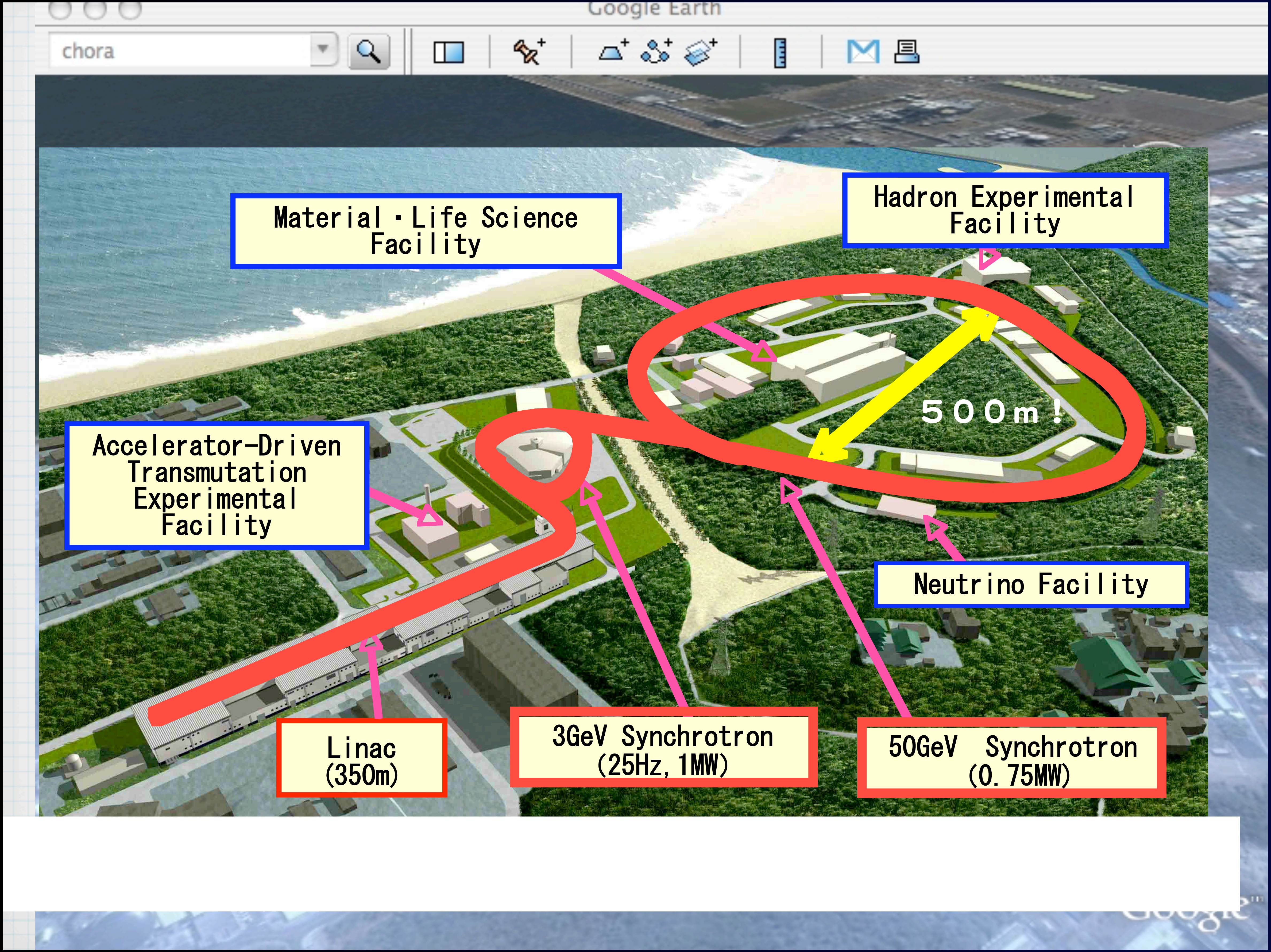
Md. Imam Hossain
University Technology Malaysia

T. Numao
TRIUMF, Canada

- 107 collaborators
- 25 institutes
- 11 countries

Proton Beam

J-PARC at Tokai, Japan



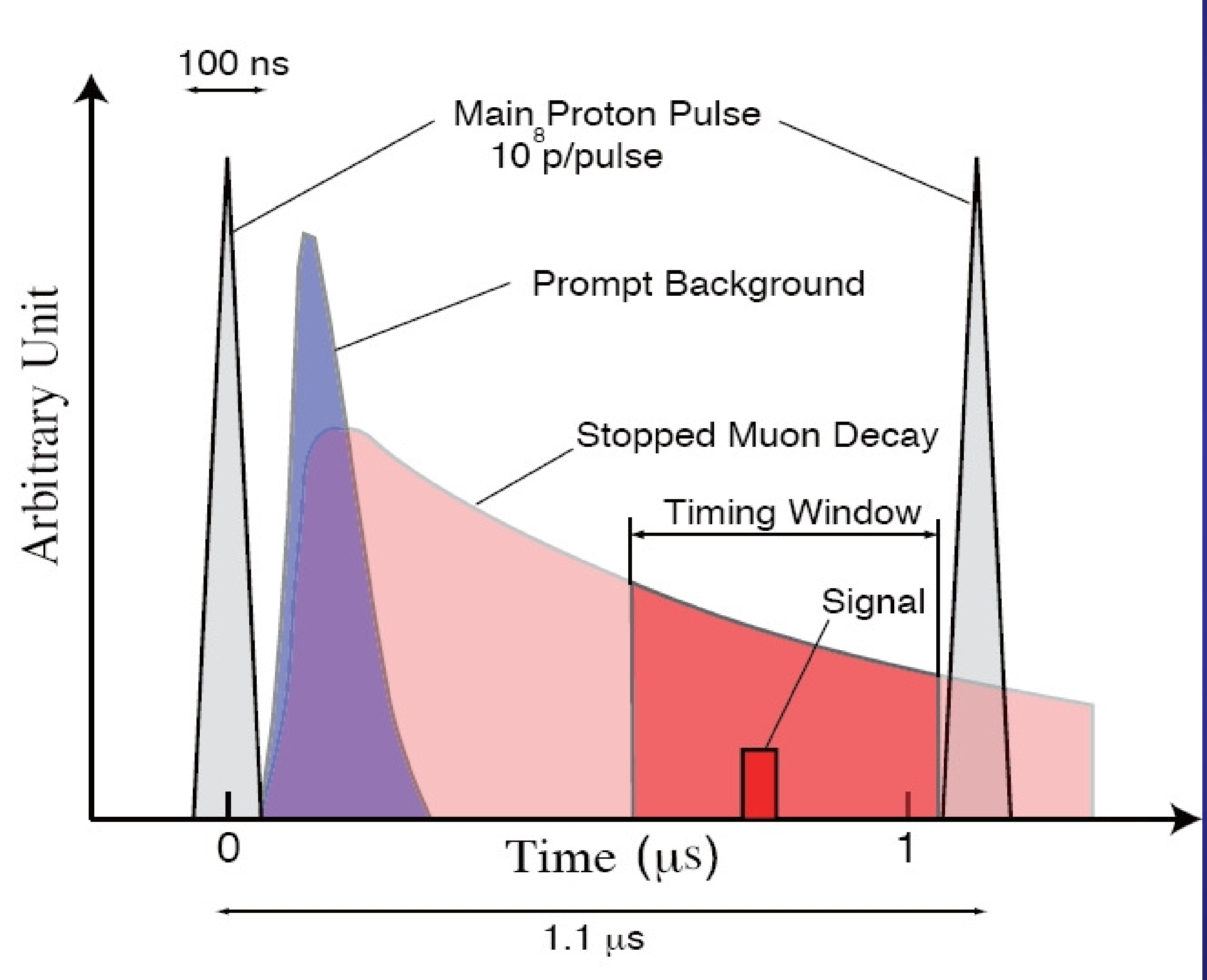
Proton Beam for COMET

- Muonic lifetime is dependent on target Z. For Al lifetime is 880ns.

Bunch Structure

Bunch Separation	1.3 µs
Bunch Length	100ns
Protons per Bunch	1.2×10^8
Bunches per Spill	5.3×10^5
Spill time	0.7s
Extinction	10^{-9}

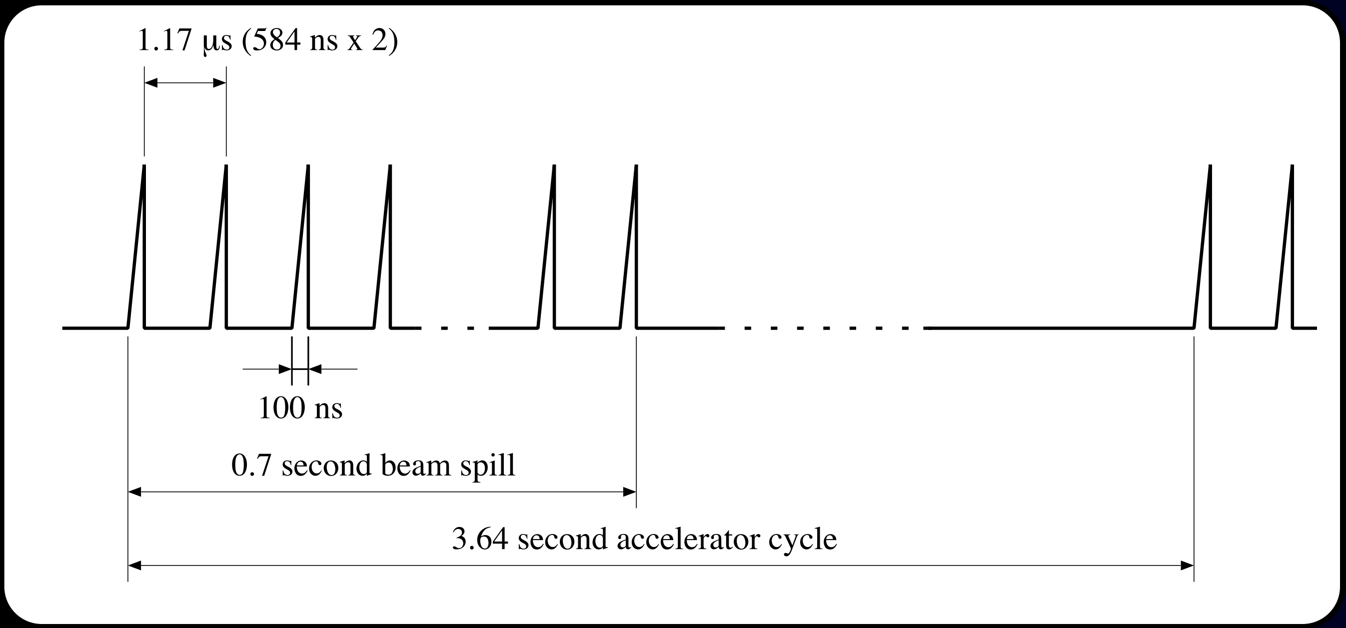
- Background rate needs to be low in order to achieve sensitivity of $<10^{-16}$.
- Extinction is very important.
  - Without sufficient extinction, all processes in prompt background category could become a problem.

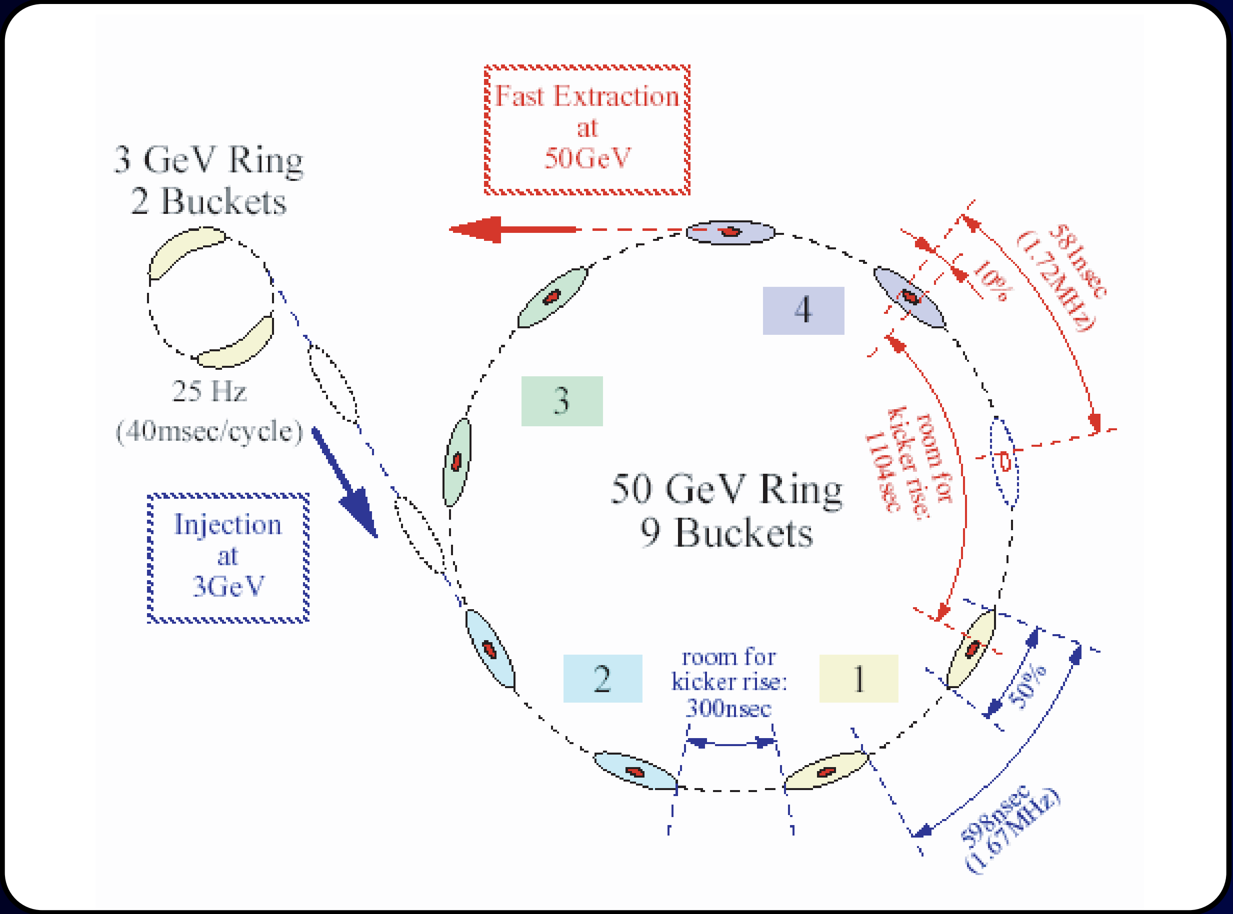


Proton Beam at J-PARC

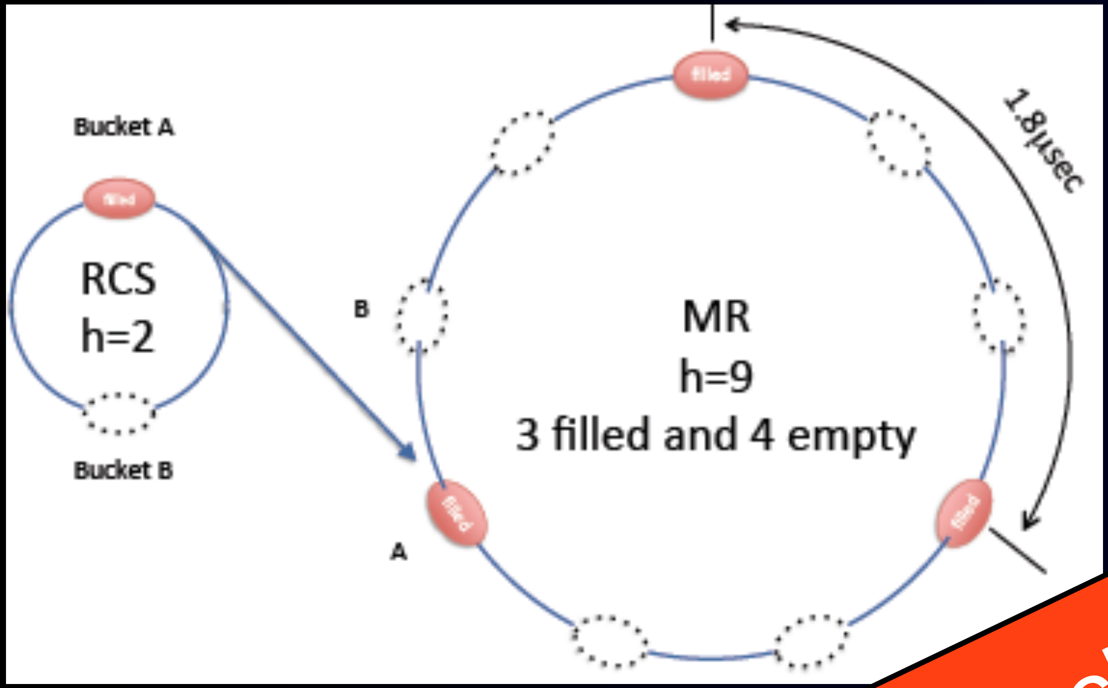
- A pulsed proton beam is needed to reject beam-related prompt background.
- Time structure required for proton beams.
  - Pulse separation is ~ 1μsec or more (muon lifetime).
  - Narrow pulse width (<100 nsec)

- Pulsed beam from slow extraction.
  - fill every other rf buckets with protons and make slow extraction
  - spill length (flat top) ~ 0.7



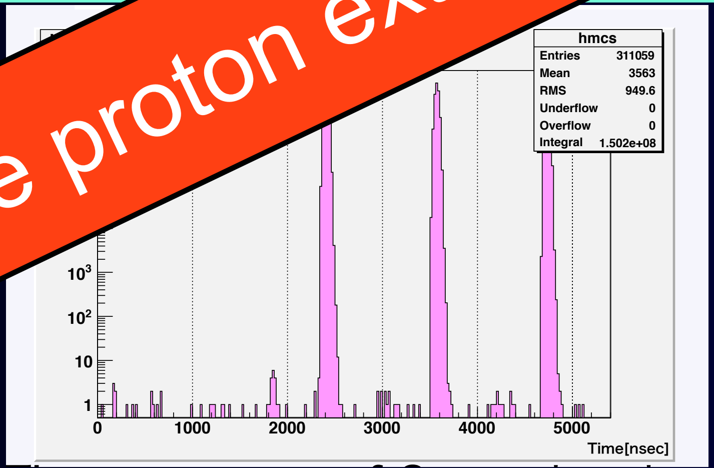


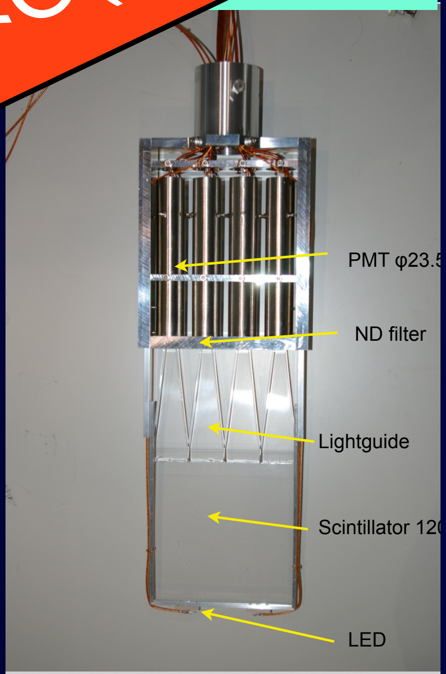
Proton Extinction Measruements at J-PARC



Measured at
beamli

Measured at se
beamline (





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

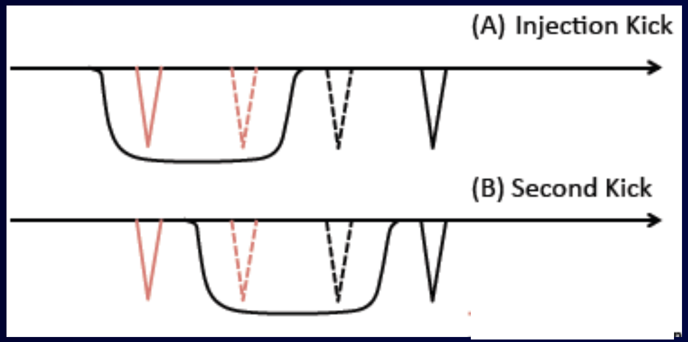
J-PARC MR pr
extinct

$O(10^{-7})$

jection
Kicking

Tested at the abort (2010)

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



External Extinction Device

AC dipole magnet R&D

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

Muon Beam

Charged Particle Trajectory in Curved Solenoids

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

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

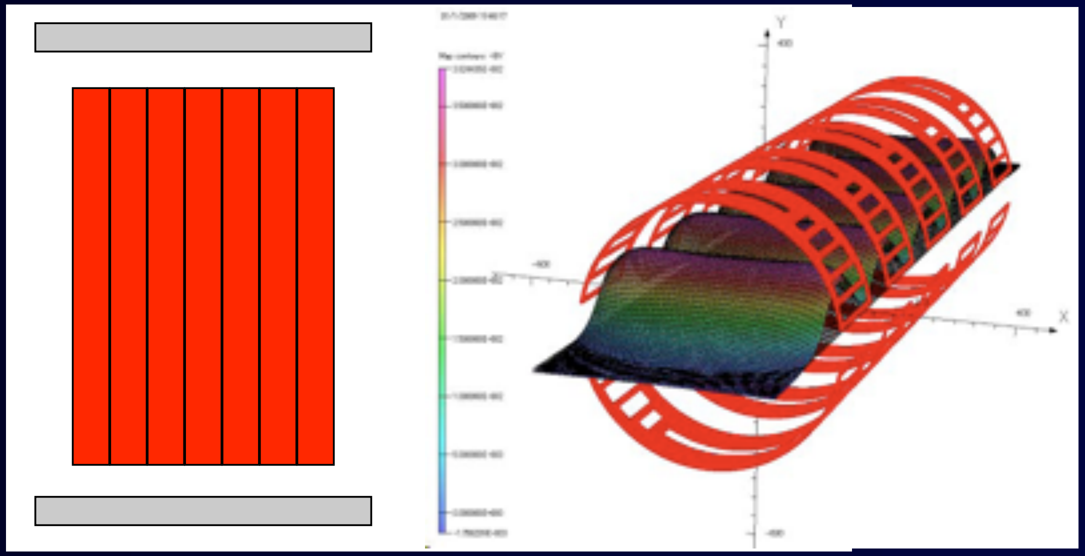
D : *drift distance*
B : *Solenoid field*
θ_{bend} : *Bending angle of the solenoid channel*
p : *Momentum of the particle*
q : *Charge of the particle*
θ : *atan*(P_T/P_L)

- This can be used for charge and momentum selection.

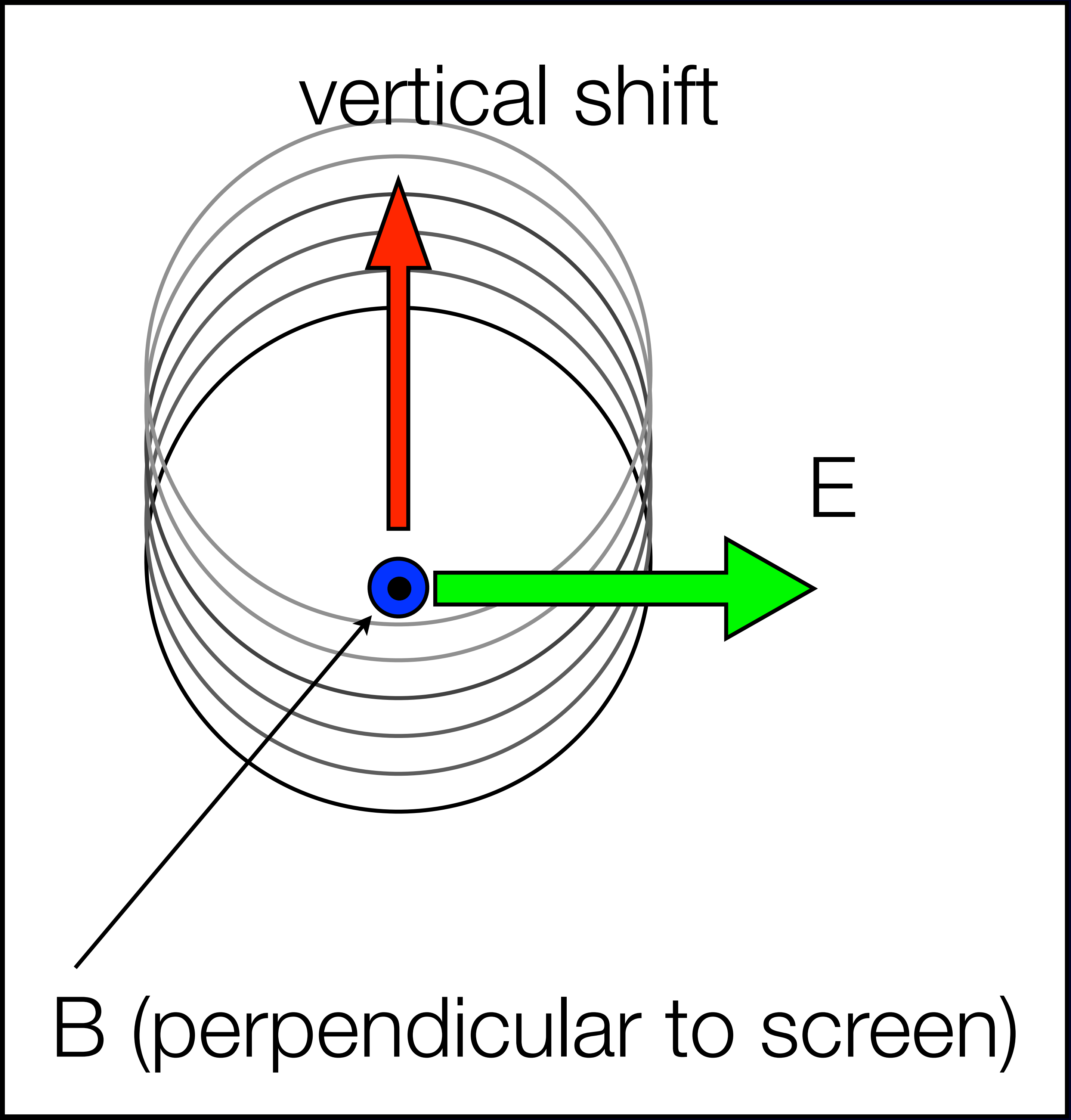
- This drift can be compensated by an auxiliary field parallel to the drift direction given by

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

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



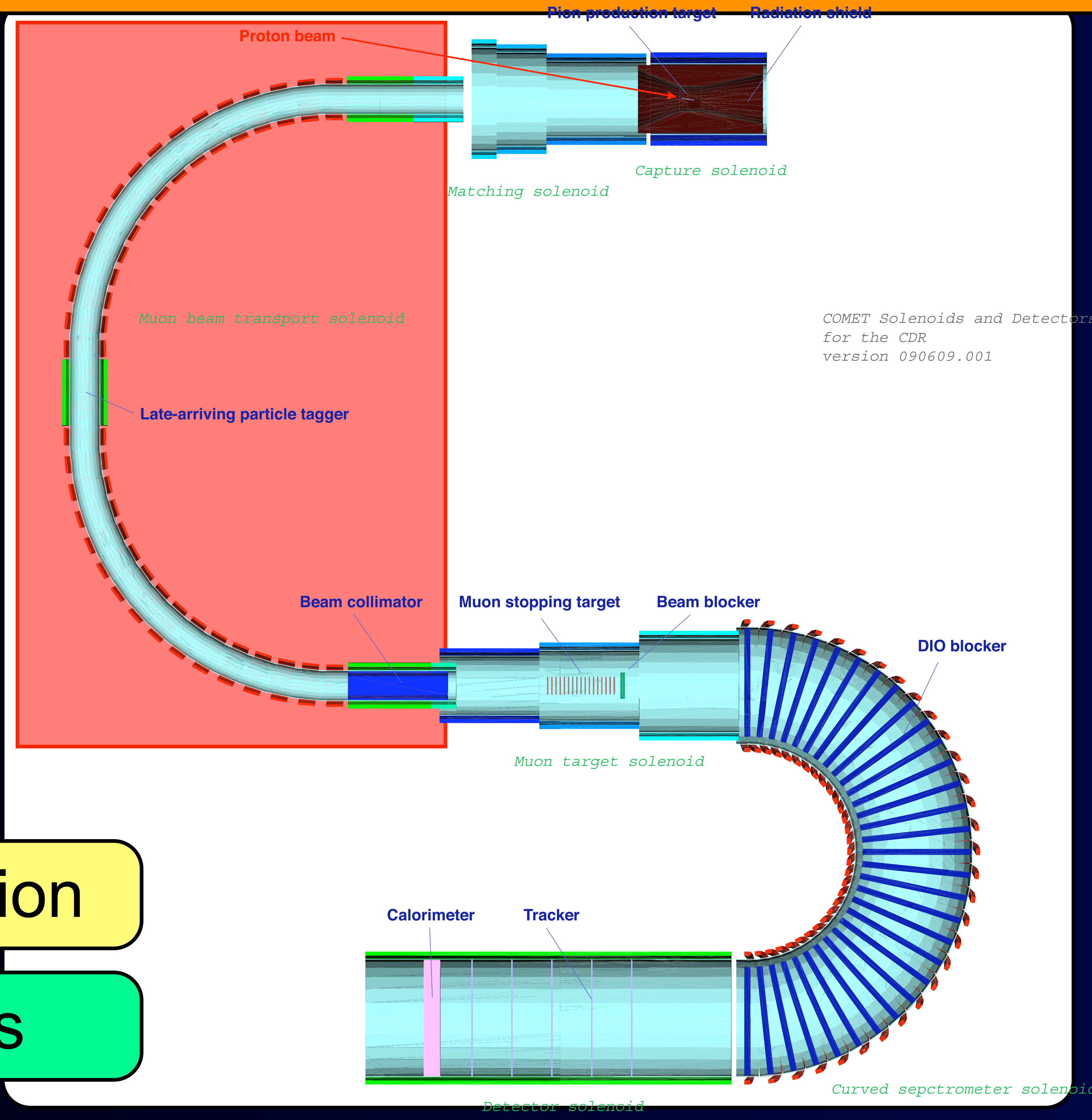
EM Physics for Particle Trajectories in Toroidal Magnetic Field



- For helical trajectory in a curved mag. field, a centrifugal force gives E in the radial direction.
- To compensate a vertical shift, an electric field in the opposite direction shall be applied, or a vertical mag. field that produces the desired electric field by v x B, can be applied.

Muon Transport System for COMET

- The muon transport system consists of curved solenoids.
  - bore radius : 175 mm
  - magnetic field : 2 T
  - bending angle : 180 degrees
  - radius of curvature : 3 m
- Dispersion is proportional to a bending angle.
- muon collimator after 180 degree bending.
- Elimination of muon momentum > 70 MeV/c

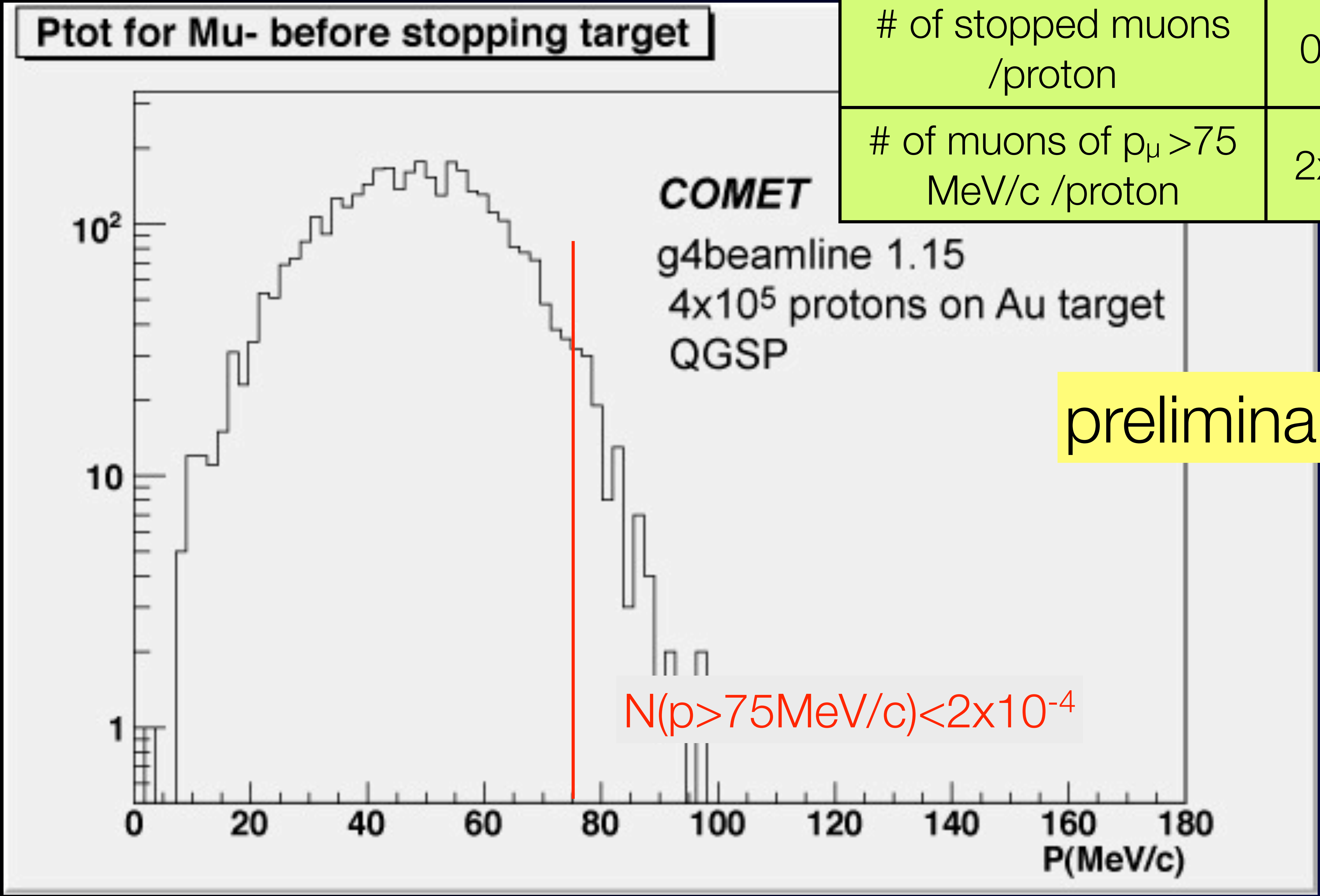


good momentum selection

no high-energy muons

Muon Momentum Spectrum at the End of the Transport Beam Line

# of muons /proton	0.009
# of stopped muons /proton	0.003
# of muons of $p_\mu > 75$ MeV/c /proton	2×10^{-4}



N(p>75MeV/c)<2×10^{-4}

preliminary

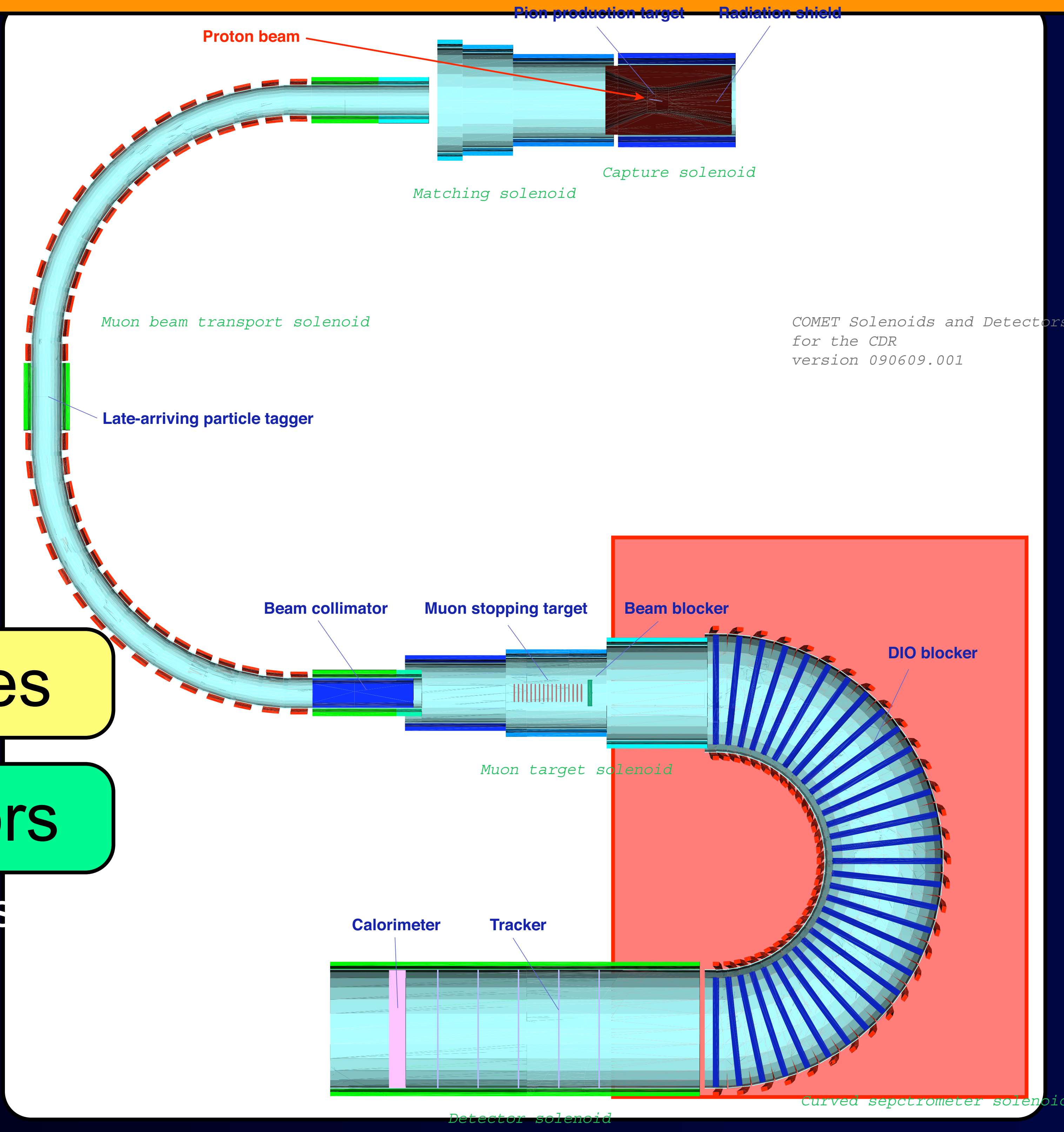
Electron Transport System for COMET

- The electron transport
  - bore : 700 mm
  - magnetic field : 1T
  - bending angle : 180 degrees
- Electron momentum ~ 104 MeV/c
- Elimination of negatively-charged particles less than 80 MeV/c
- Elimination of positively-charged particles (like protons from muon capture)

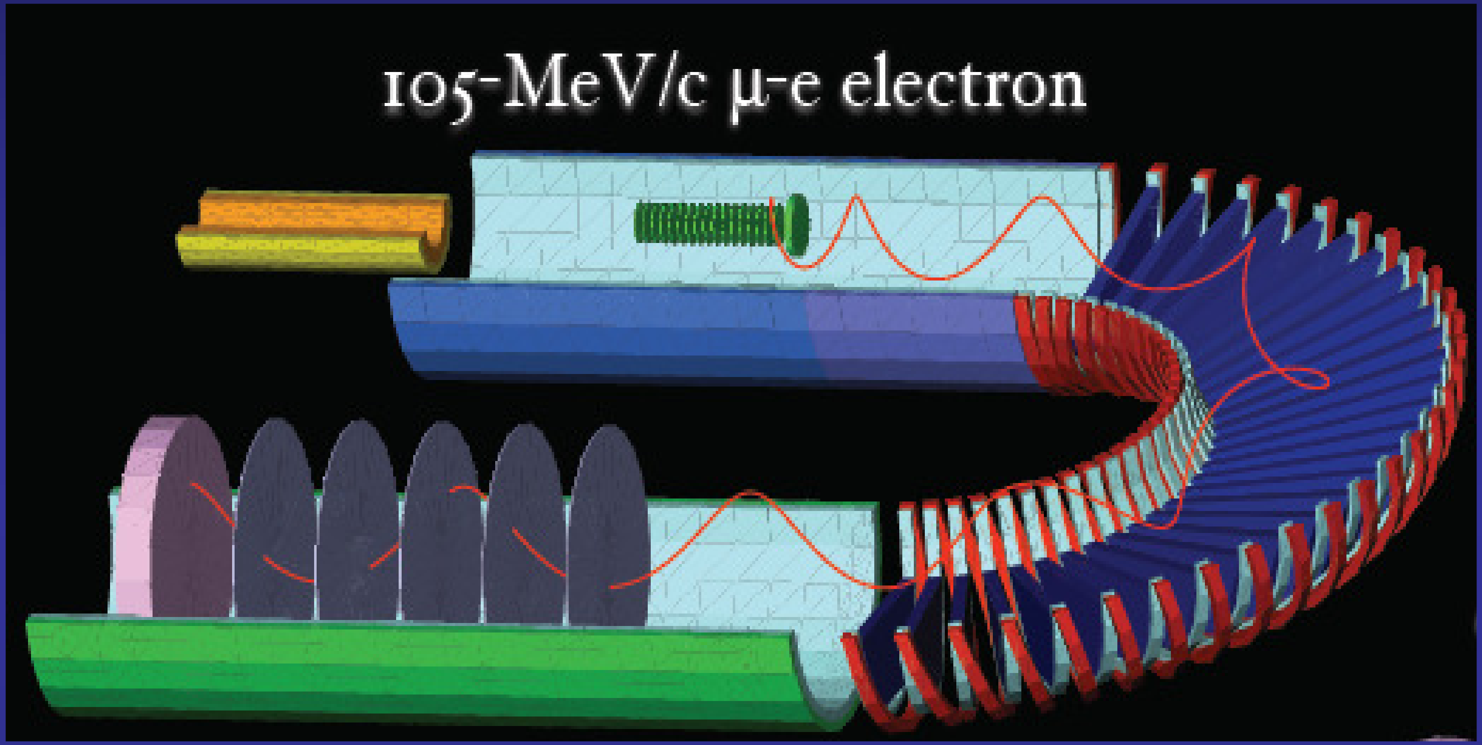
reduction of detector rates

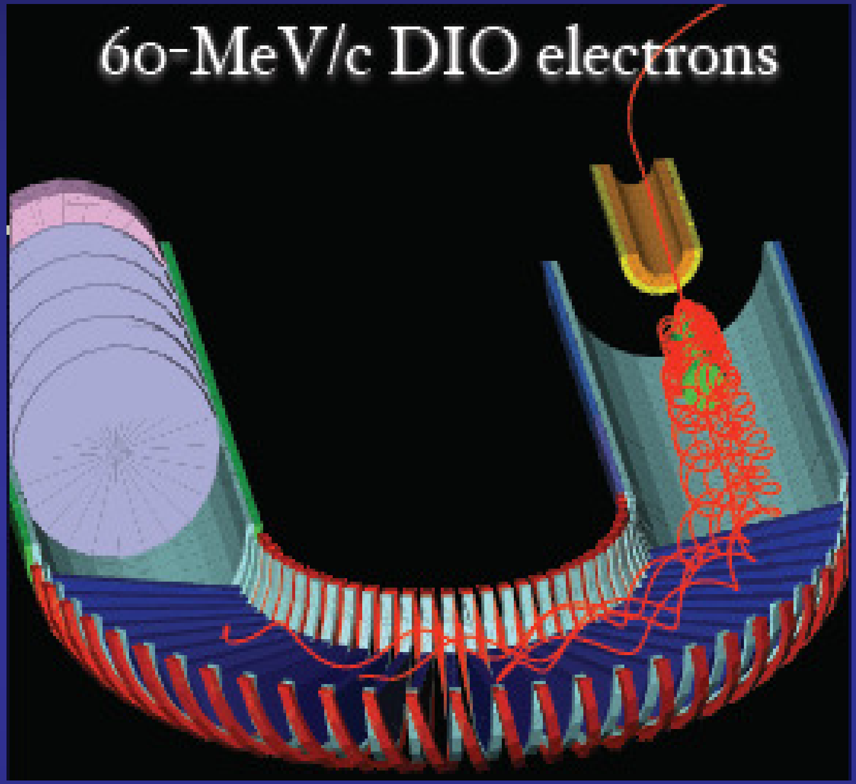
no protons in the detectors

- a straight solenoid where detectors are placed follows the curved spectrometer.



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.

Detector

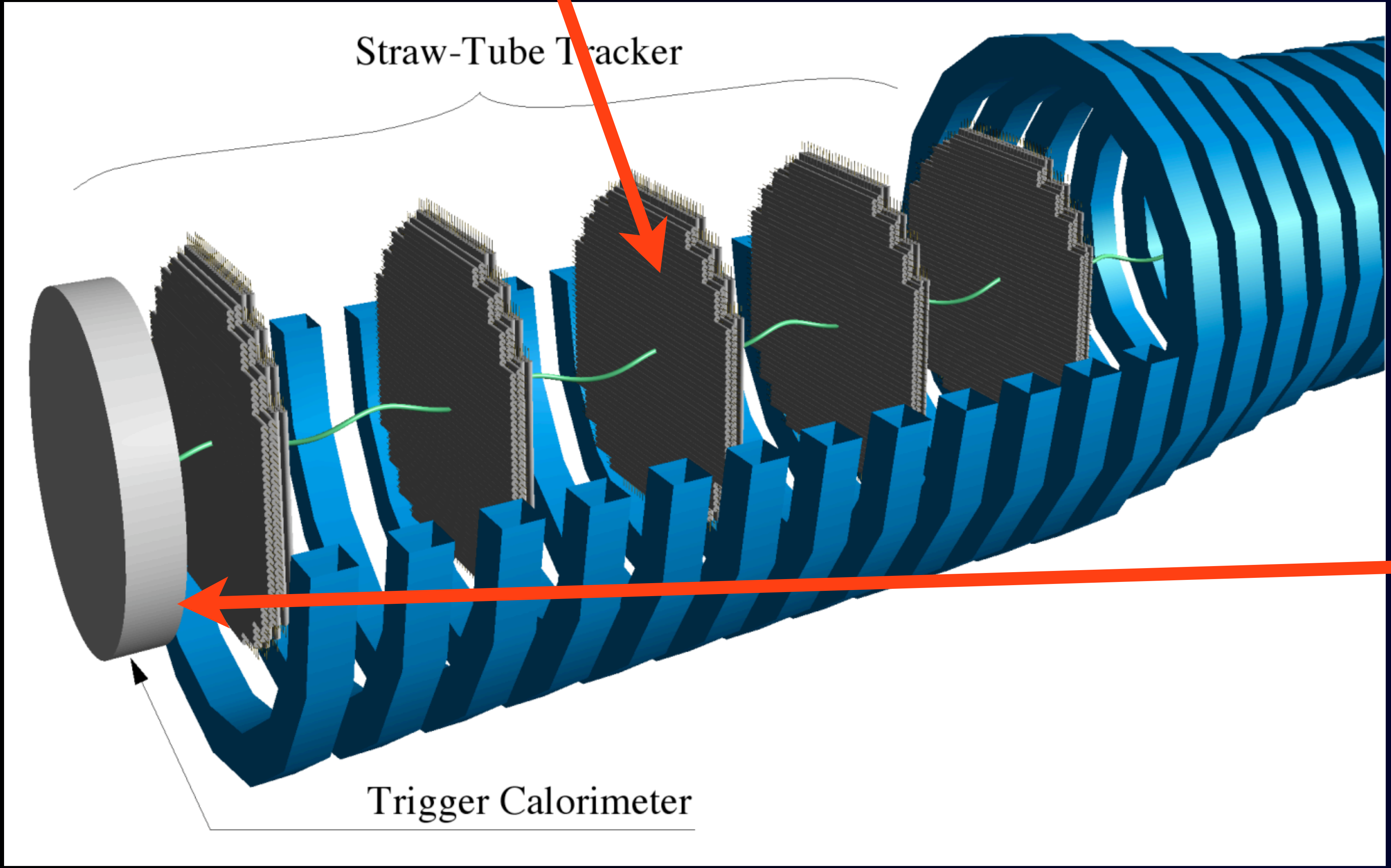
Electron Detection

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.

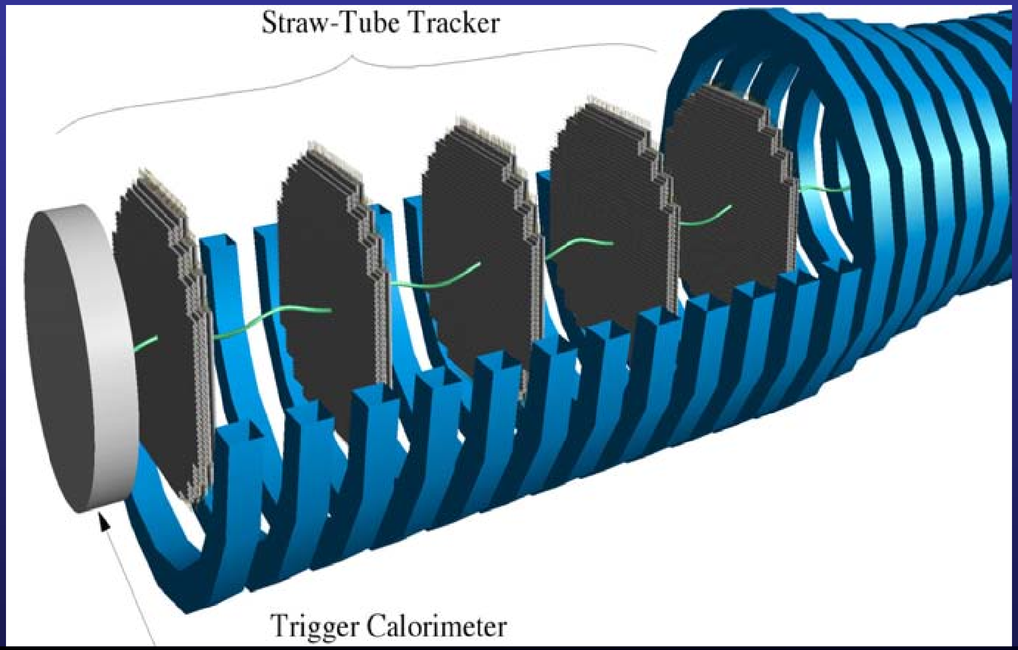


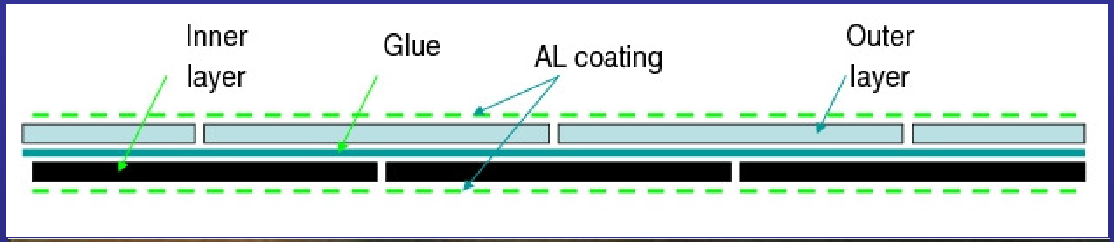
Electron calorimeter to measure electron energy, make triggers and give additional hit position.

- Candidate are LYSO, GSO
- MPPC or APD readout

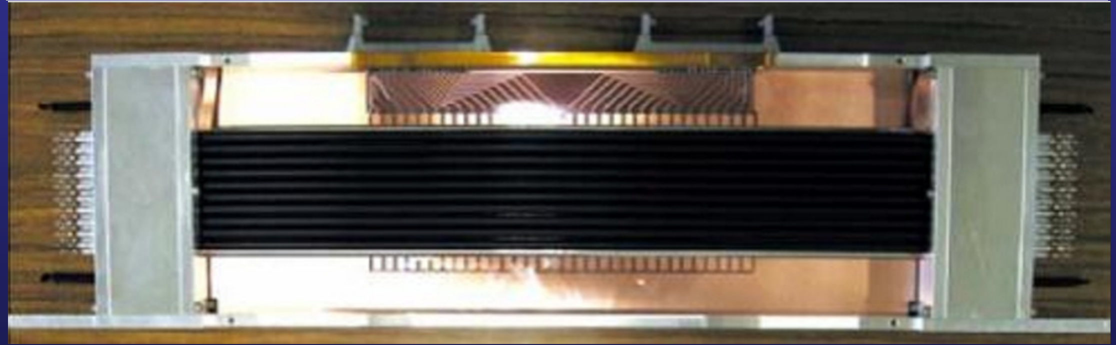
COMET Electron Tracker

- Requirements
  - operate in a 1T solenoid field.
  - operate in vacuum (to reduce multiple scattering of electrons).
  - 800kHz charged particle rate and 8MHz gamma rates
  - 0.4% momentum and 700µm spatial resolution.
- Current design utilises straw tube chambers
  - Straw tubes 5mm in diameter. Wall composed of two layers of 12µm thick metalized Kapton glued together.
- 5 planes 48cm apart with 2 views (x and y) per plane and 2 layers per view (rotated by 45° to each other).





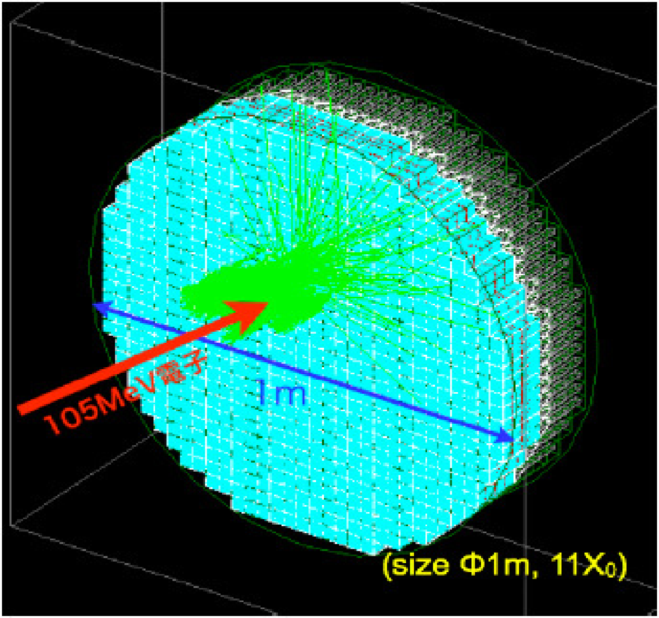
Straw wall cross-section.

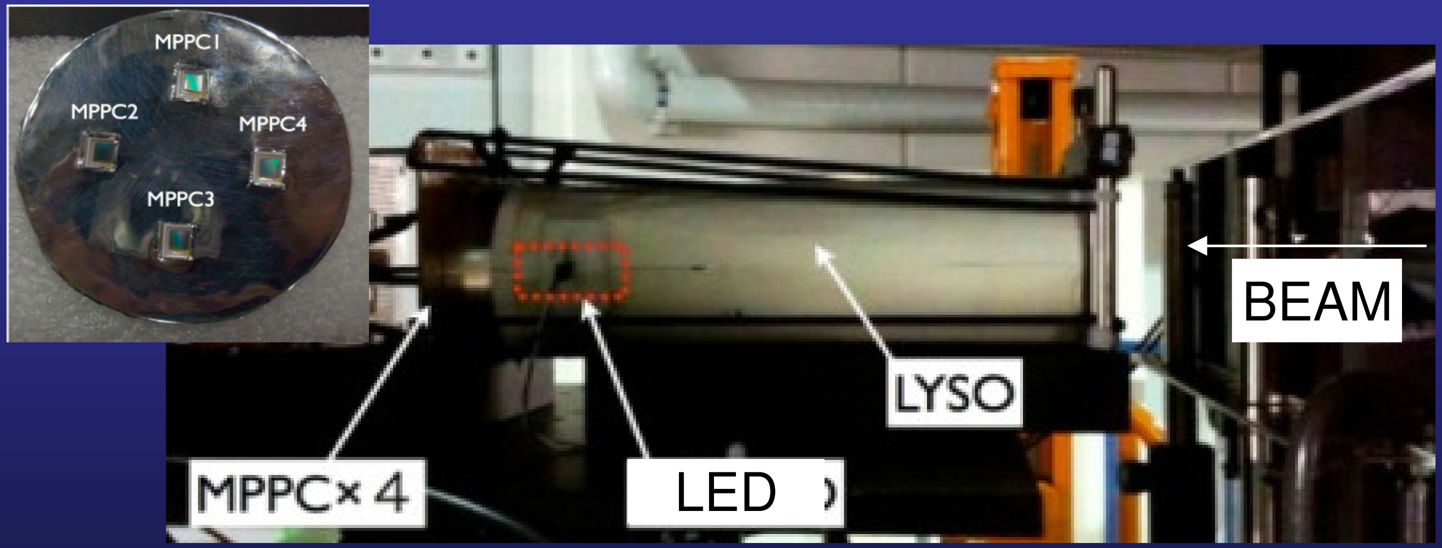


350mm long seamless straw tube prototype.

COMET Electron Calorimeter

- Measure energy, PID and give additional position information. Can be used to make a trigger decision.
- 5% energy and 1cm spatial resolution at 100MeV
  - High segmentation (3x3x15 cm^3 crystals)
- Candidate inorganic scintillator materials are Cerium-doped Lutetium Yttrium Orthoscilicate (LYSO) or Cerium-doped Gd_2SiO_5 (GSO).
- Favoured read out technology is multi–pixel photon counters (MPPC).
  - high gains, fast response times and can operate in magnetic fields.
- R&D by Osaka group. Further beam tests planned for November.

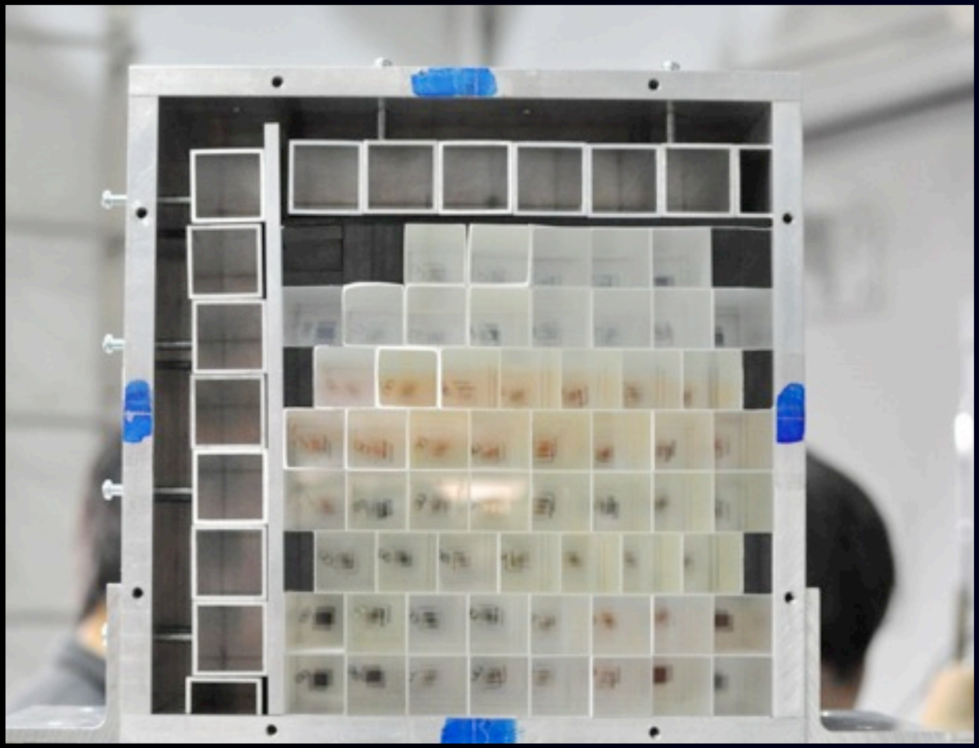




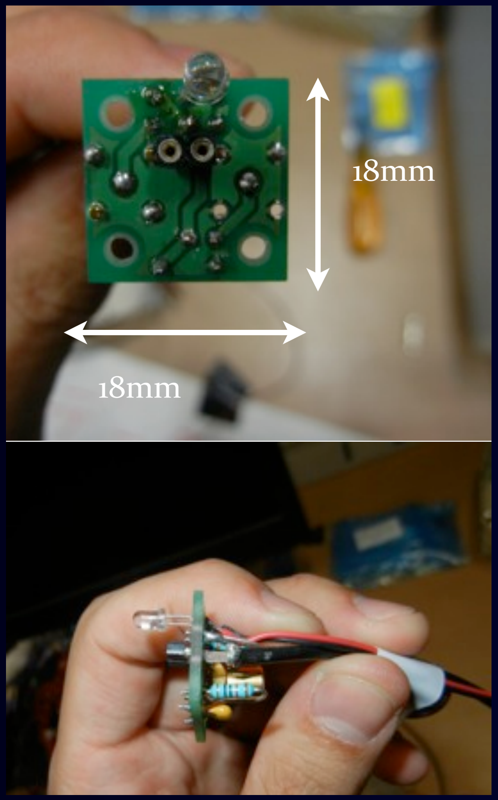
100 MeV electron beam tests at Tohoku University

R&D on Electron Calorimeter

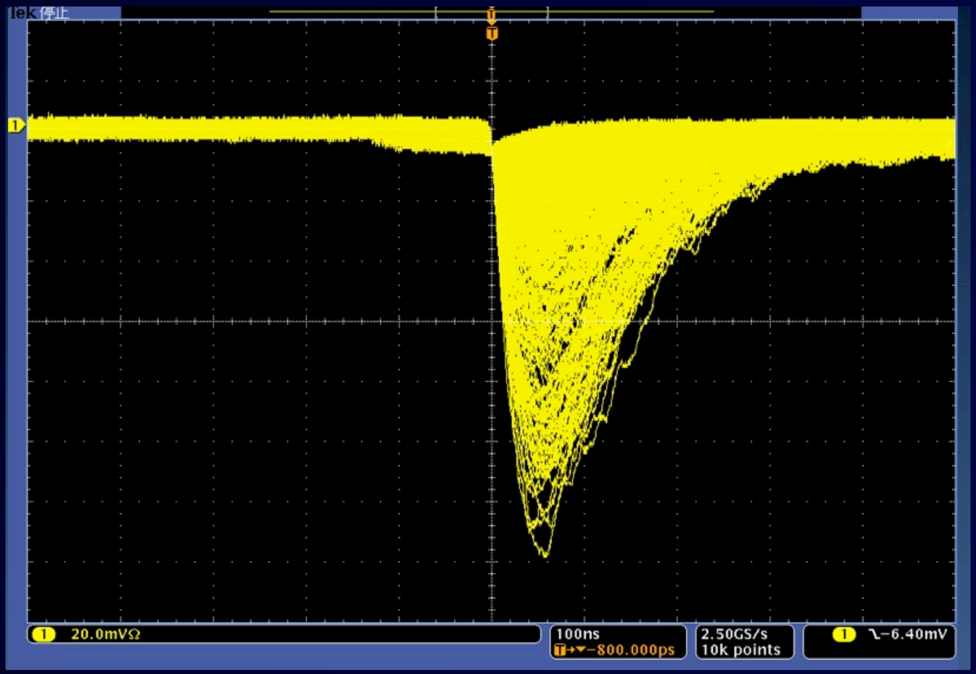
- Candidates of scintillating crystals are GSO(Ce), LYSO, $LaBr_3$ and others.
- Candidates of Calorimeter readout of MPPC and APD.
- The beam test of GSO with either MPPC and APD was done with electron beam at Tohoku Univ. in 2009 and 2010.
- Data analysis goes underway.



GSO(Ce) Crystals



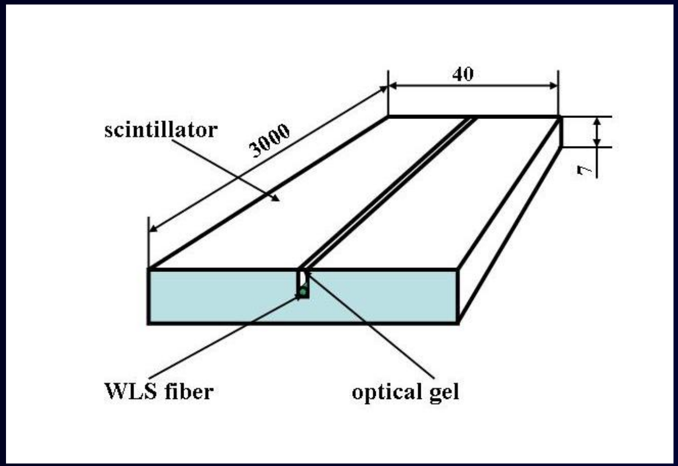
MPPC and readout

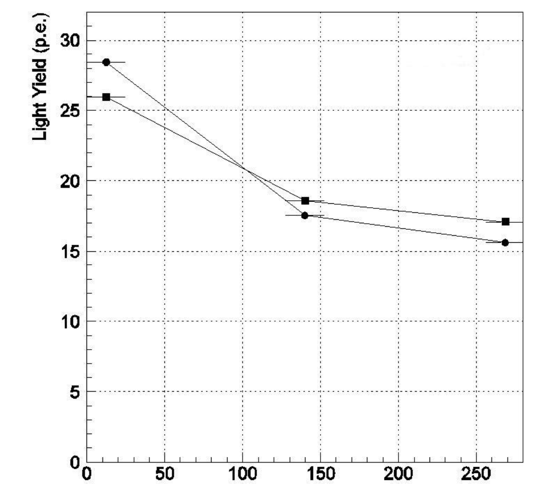


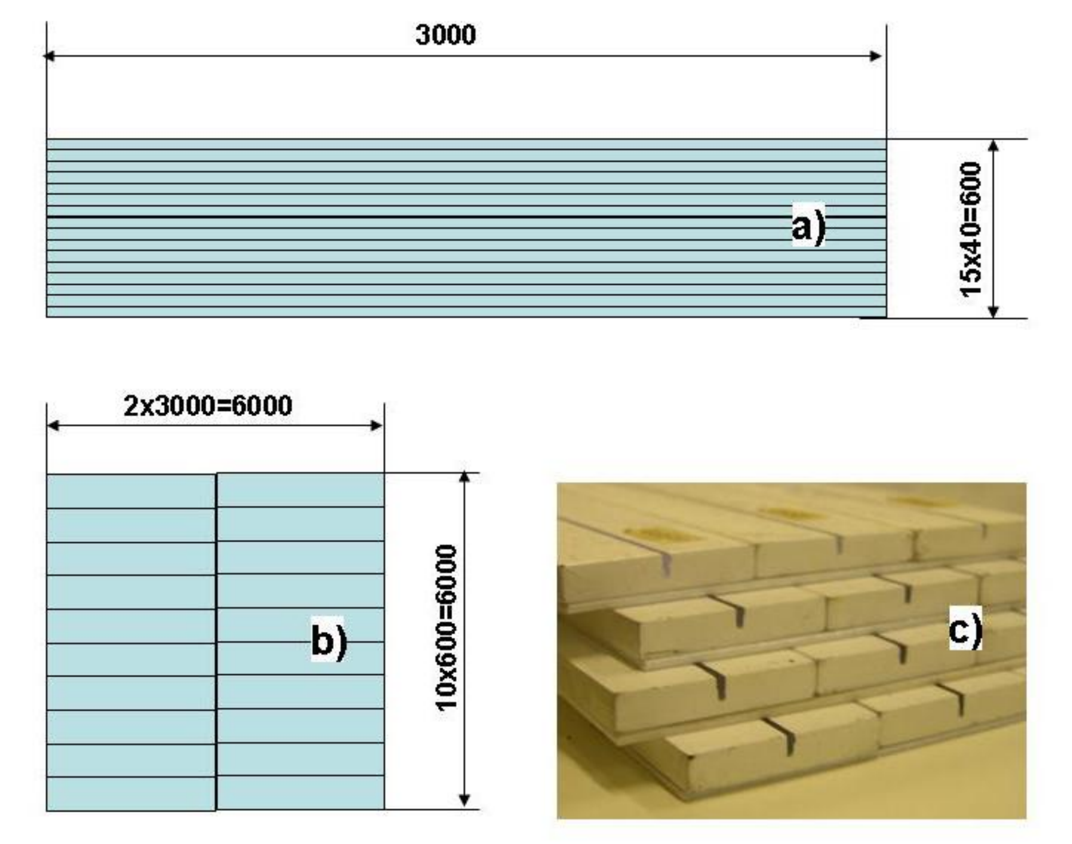
signal from MPPC for GSO(Ce)

R&D on Cosmic Ray Veto

- The active cosmic ray veto system has been designed and tested by the BINP (Novosibirsk) and ITEP (Moscow) group.
- Plastic scintillators with fiber readout by SiPM or APD.
- The light yield at a far end is even 15 pe. The counter efficiency for MIP is 99.7% with 55 pixel threshold.







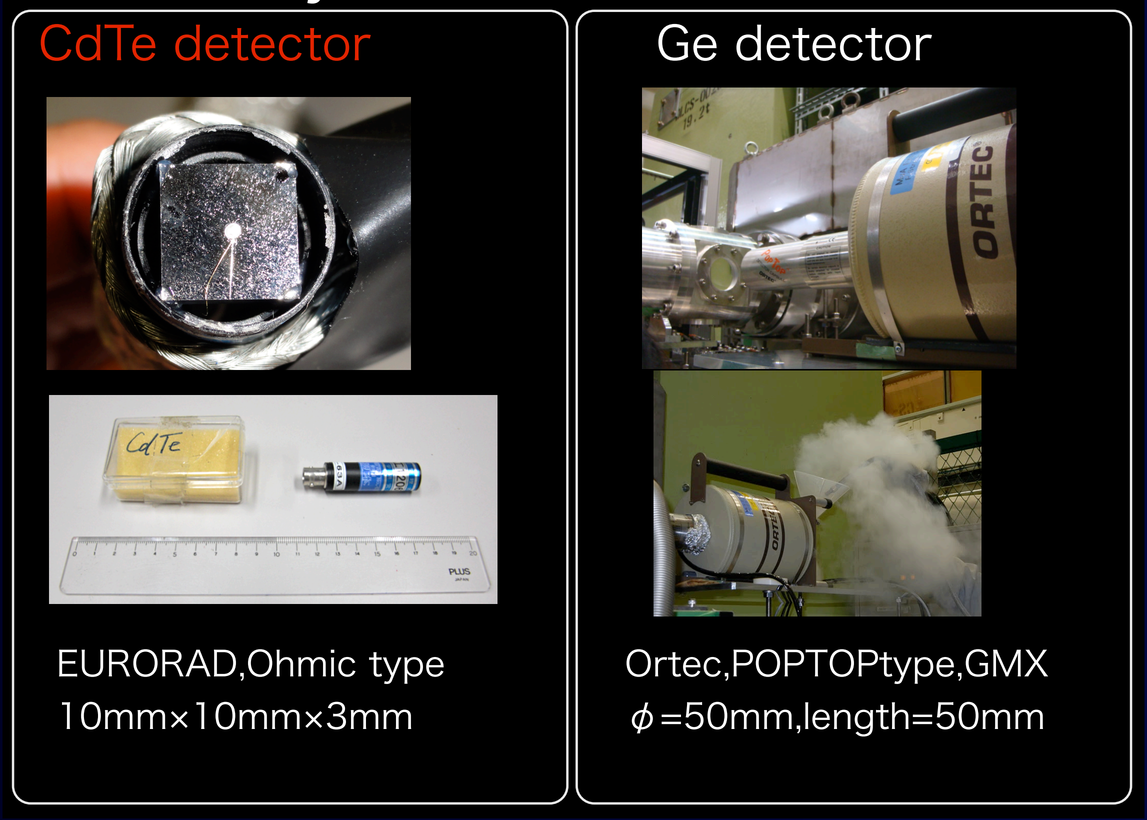
Plastic scintillators with fiber readout (basic module).

R&D on Stopping Muon Monitor System

- To monitor a number of stopping muons, muonic X-rays from the muon stopping target (made of aluminum) is to be measured.

Al	**347keV** (0.811)	413keV (0.058)	436keV (0.019)	**66keV** (0.422)	89keV (0.072)	100keV (0.031)

- Two different detectors, Ge and CdTe were tested at the J-PARC MLF muon facilities in fall, 2010.
- Detector efficiencies and transition rates are studied.
- R&D on Multi-pixel detectors is being done.
- Location of the muonic X-ray detectors at COMET is being studied.

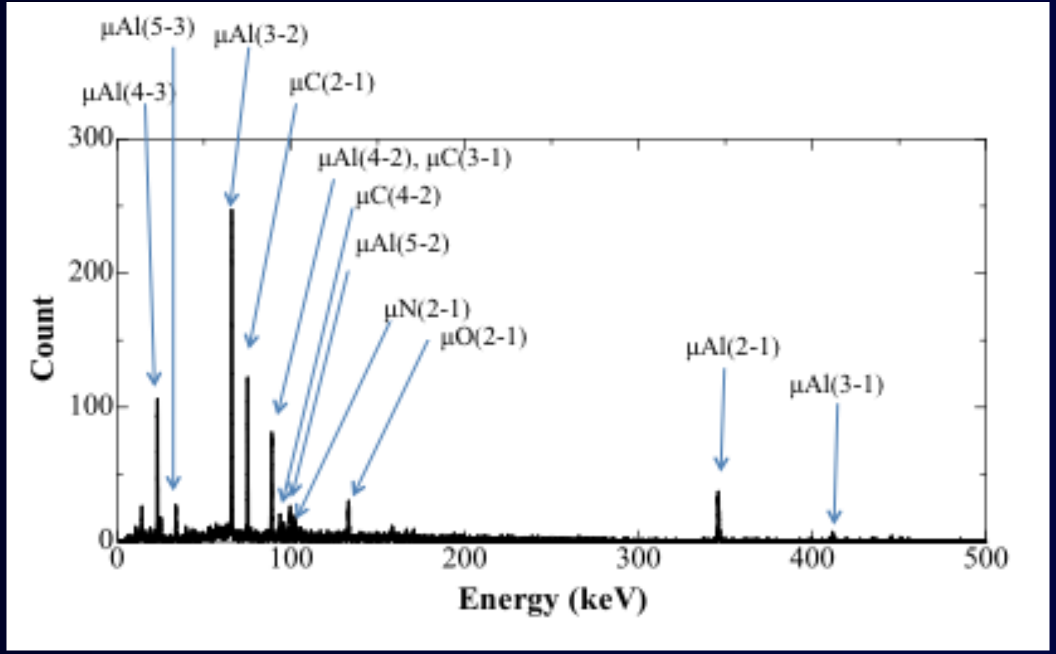


CdTe detector

EURORAD,Ohmic type
10mm×10mm×3mm

Ge detector

Ortec,POPTOPtype,GMX
ϕ=50mm,length=50mm



Measured muonic X-rays from aluminum

Sensitivity and Backgrounds

Signal Sensitivity (preliminary) - 2x10^7 sec

- Single event sensitivity

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

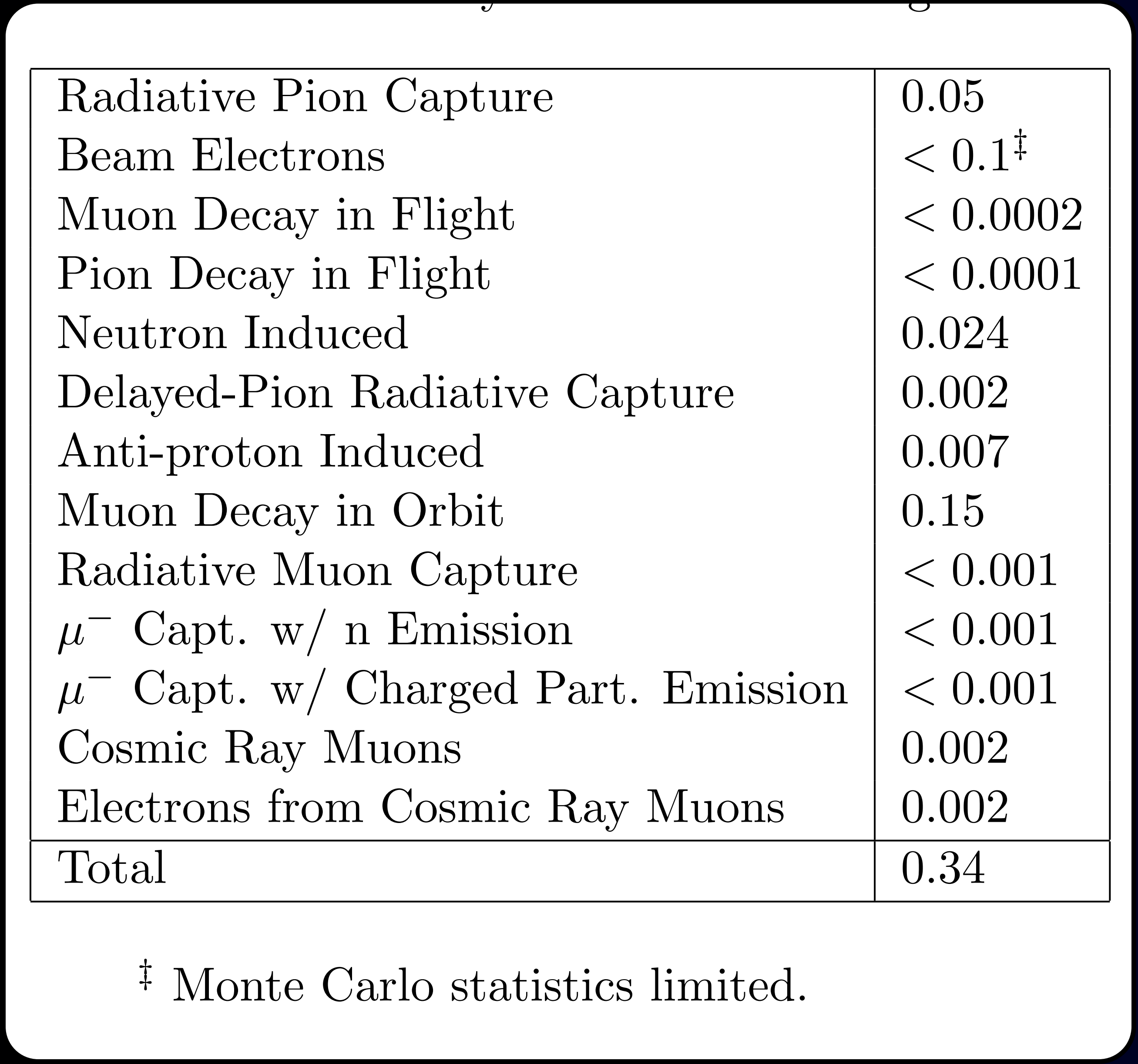
  - N_μ is a number of stopping muons in the muon stopping target. It is 2x10^{18} muons.
  - f_{cap} is a fraction of muon capture, which is 0.6 for aluminum.
  - A_e is the detector acceptance, which is 0.04.

total protons muon transport efficiency muon stopping efficiency	8.5x10^{20} 0.008 0.3
# of stopped muons	2.0x10^{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.

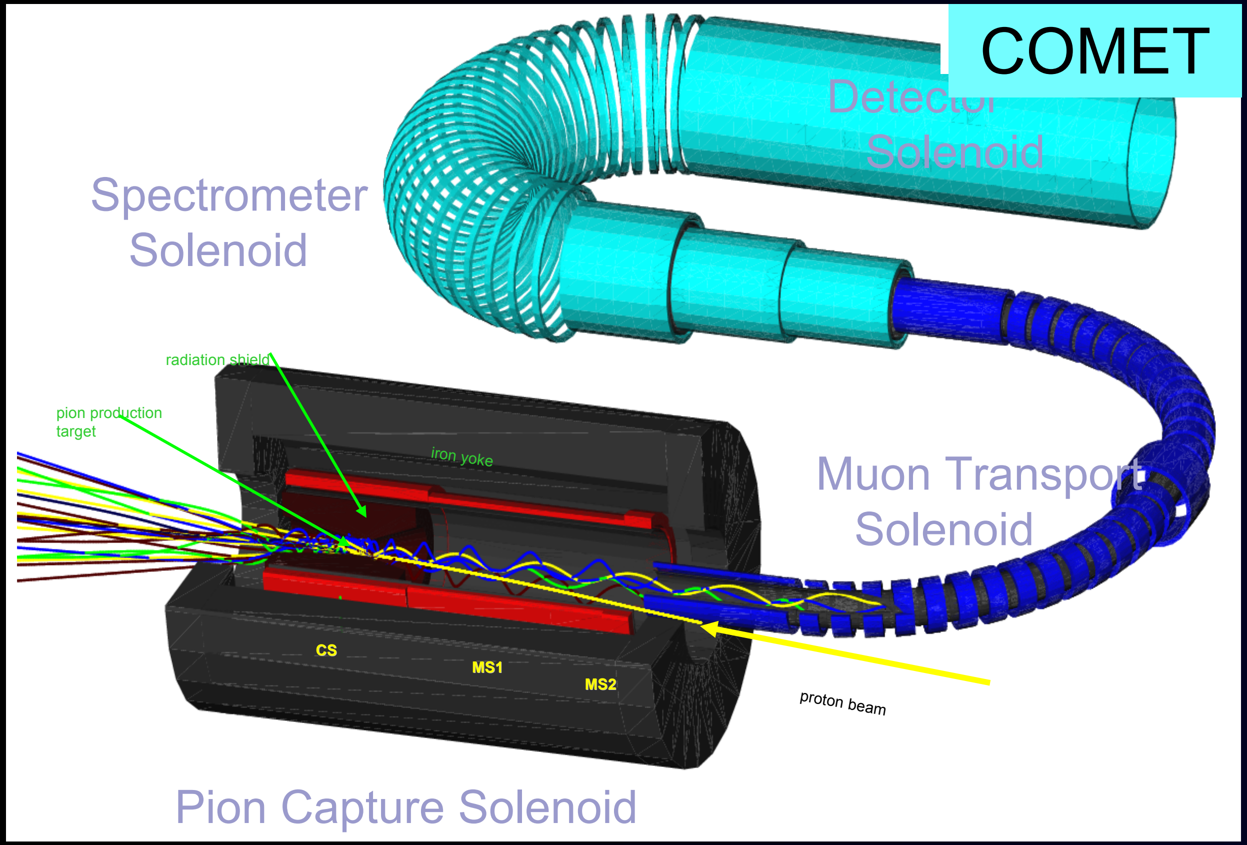
BG with asterisk needs
beam extinction.

Background Rejection Summary (preliminary)

	Backgrounds	Events	Comments
(1)	Muon decay in orbit	0.05	230 keV resolution
	Radiative muon capture	<0.001	
	Muon capture with neutron emission	<0.001	
	Muon capture with charged particle emission	<0.001	
(2)	Radiative pion capture*	0.12	prompt
	Radiative pion capture	0.002	late arriving pions
	Muon decay in flight*	<0.02	
	Pion decay in flight*	<0.001	
	Beam electrons*	0.08	
	Neutron induced*	0.024	for high energy neutrons
	Antiproton induced	0.007	for 8 GeV protons
(3)	Cosmic-ray induced	0.10	10^{-4} veto & 2x10^{7}sec run
	Pattern recognition errors	<0.001	
	Total	0.4	

R&D Milestones

R&D Milestones for μ-e conversion



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

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

1 Reduction of Backgrounds

Beam pulsing

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

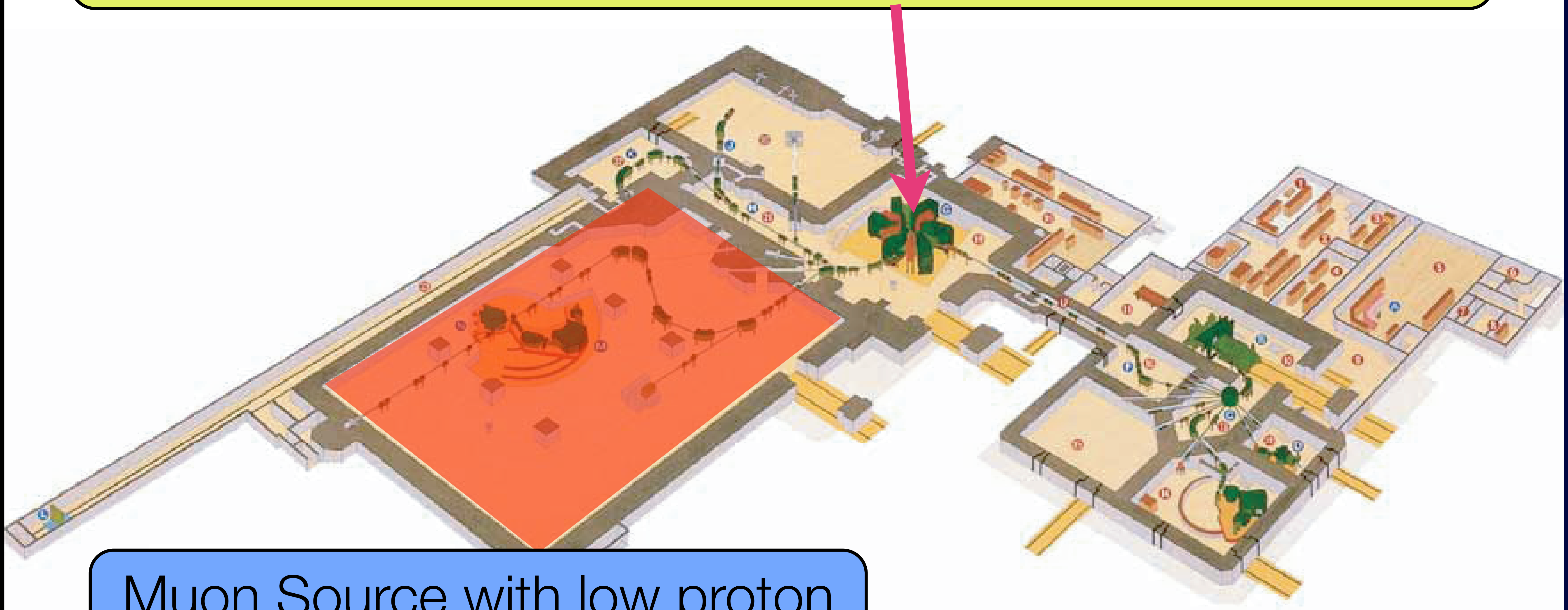
2 Increase of Muon Intensity

Pion capture system $\times 10^3$

high field superconducting solenoid magnets surrounding a pion production target

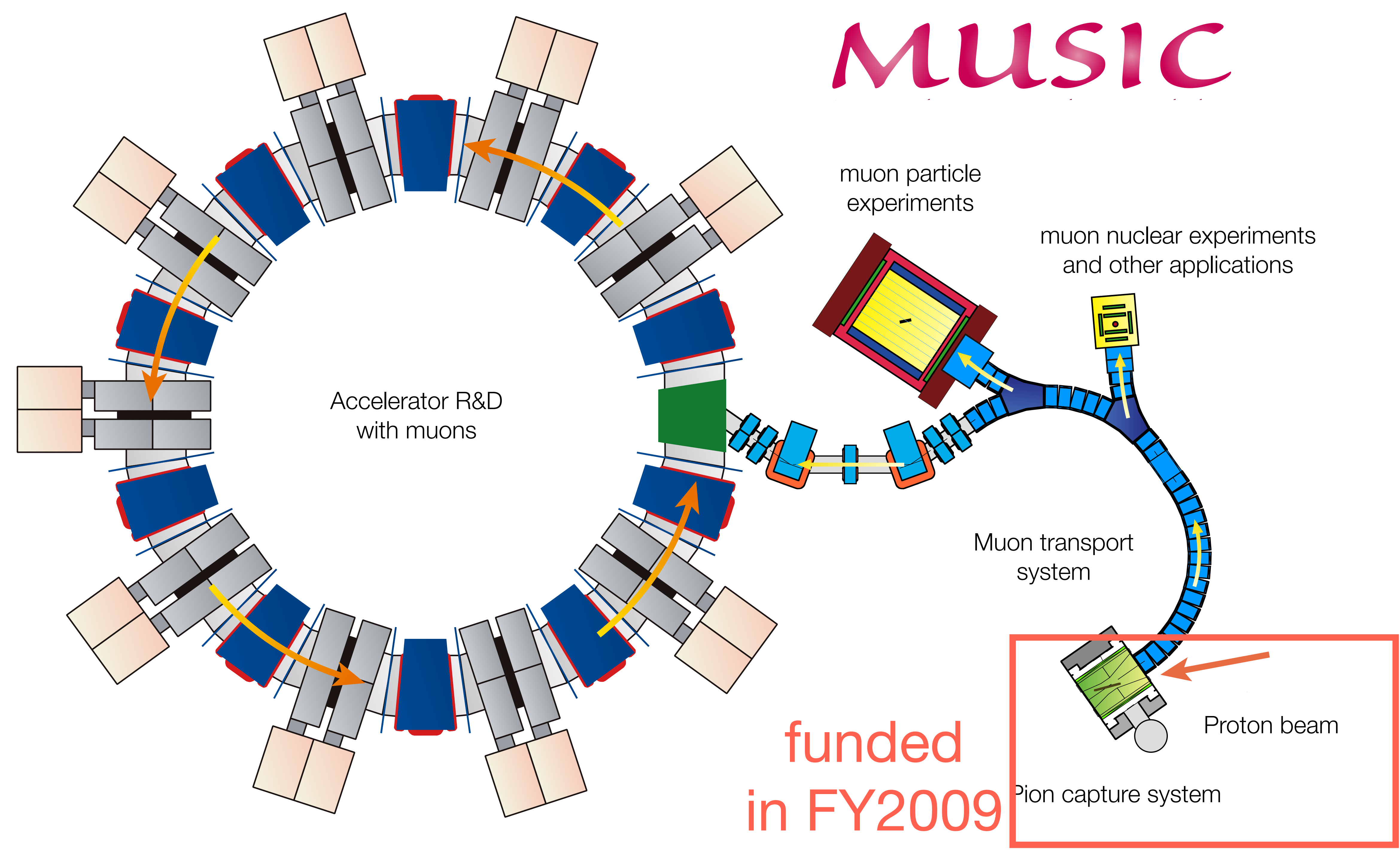
Research Center for Nuclear Physics (RCNP), Osaka University

Research Center for Nuclear Physics (RCNP), Osaka University has a cyclotron of 400 MeV with 1 microA. The energy is above pion threshold.



Muon Source with low proton power at Osaka U.?

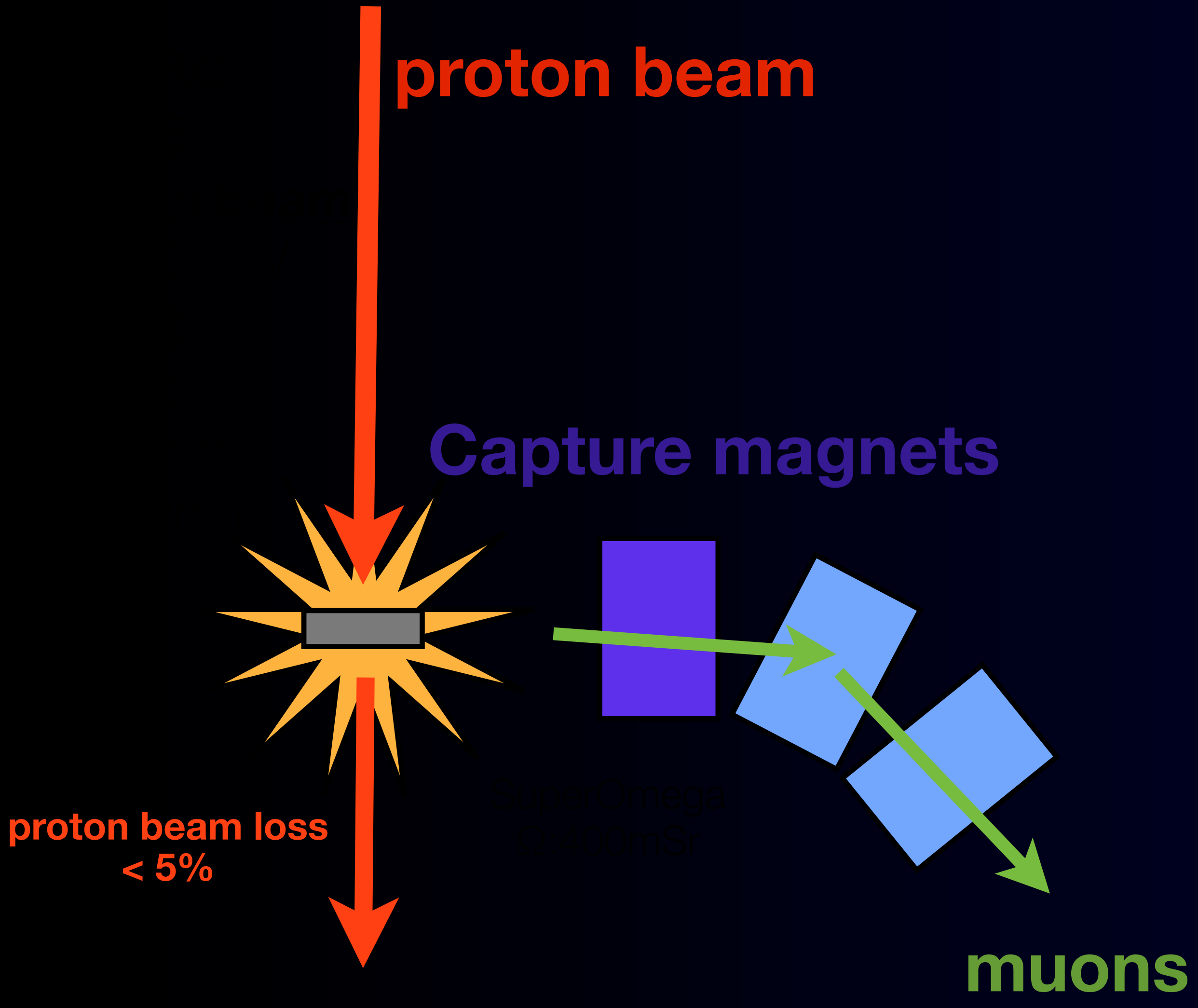
MuSIC (=Muon Science Innovative Channel)



funded in FY2009

Production and Collection of Pions and Muons

Conventional muon beam line



proton beam

Capture magnets

SuperOmega
Ω:400mSr

proton beam loss
< 5%

muons

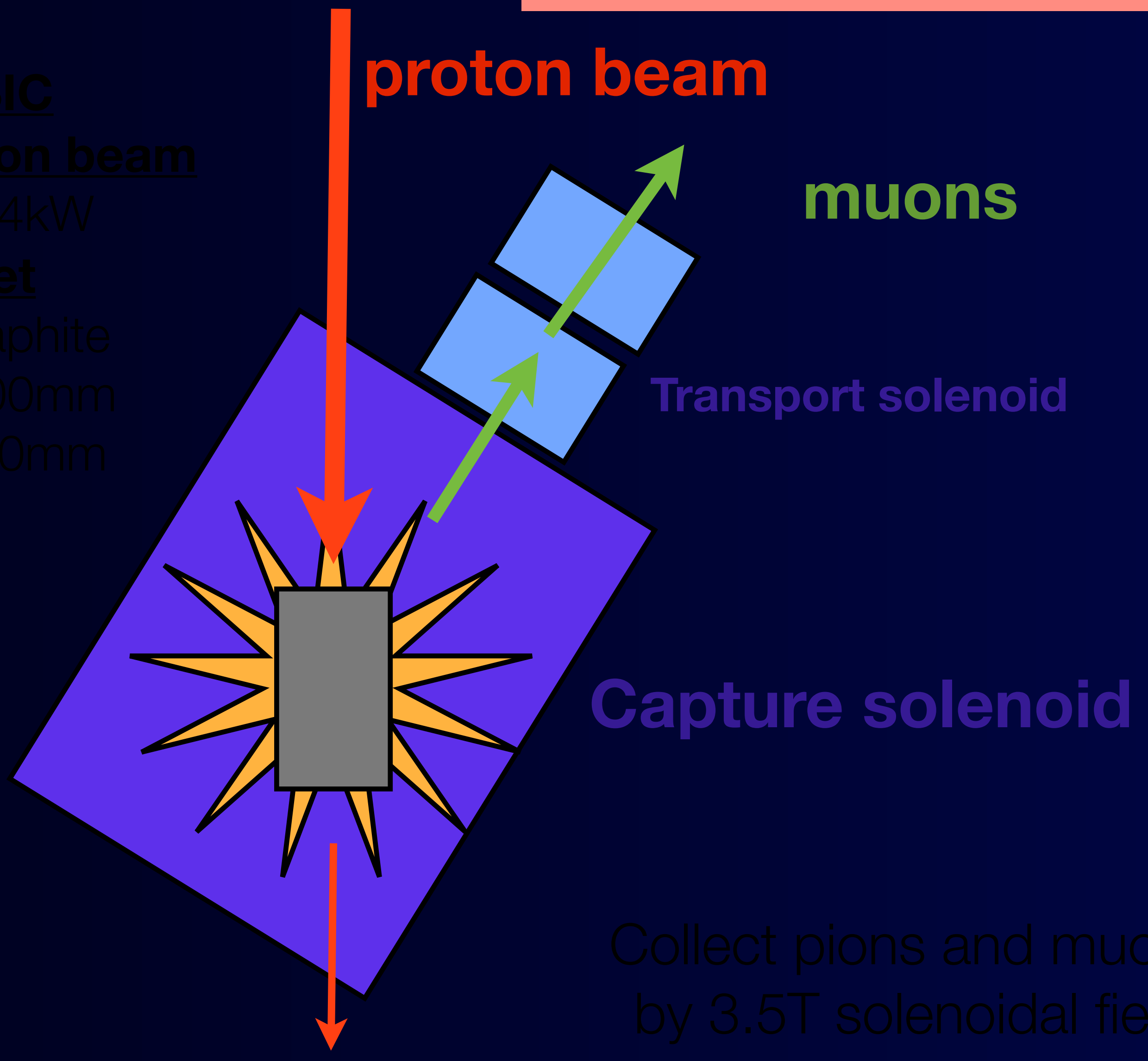
Much efficient

MuSIC,COMET,PRISM,
Neutrino factory,
Muon collider

MuSIC

proton beam
-0.4kW

target
graphite
t200mm
φ40mm



proton beam

muons

Transport solenoid

Capture solenoid

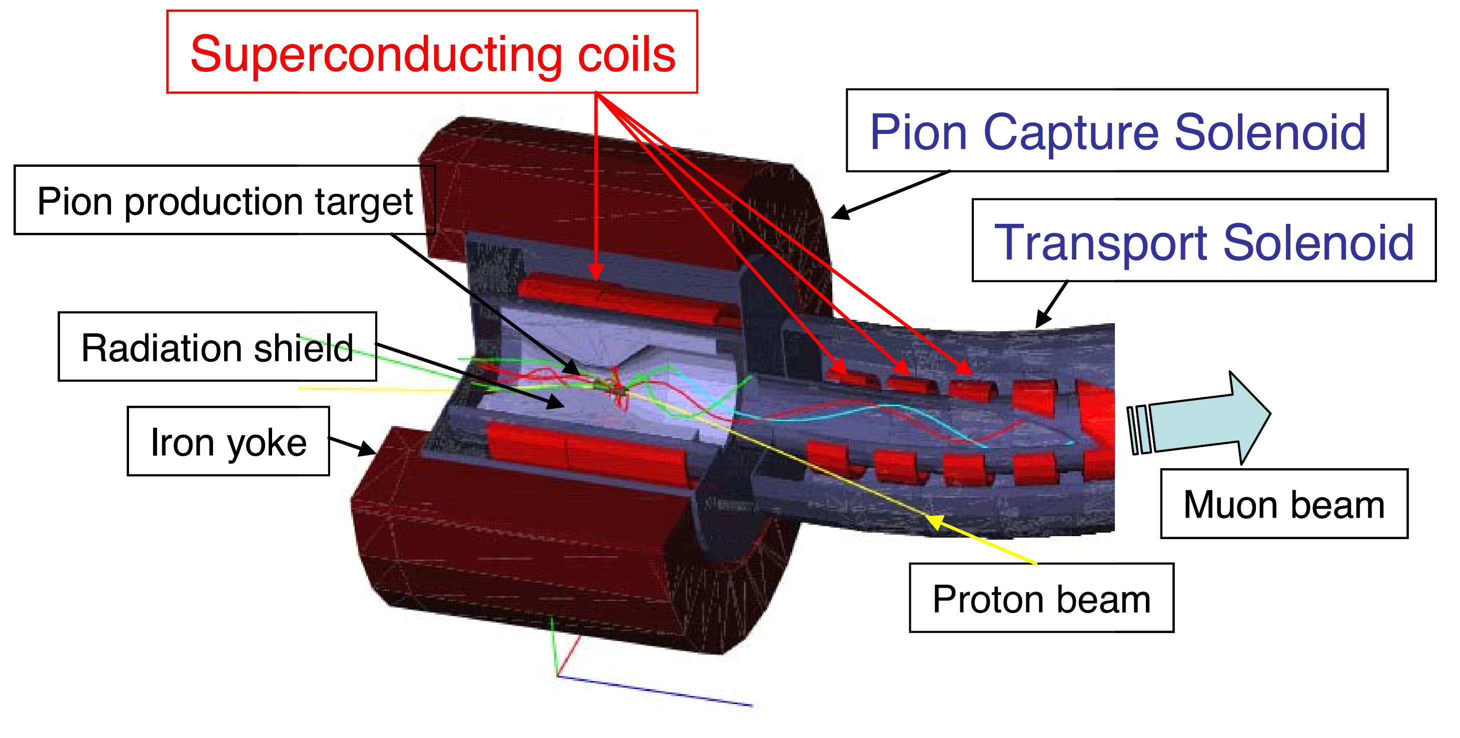
Collect pions and muons
by 3.5T solenoidal field

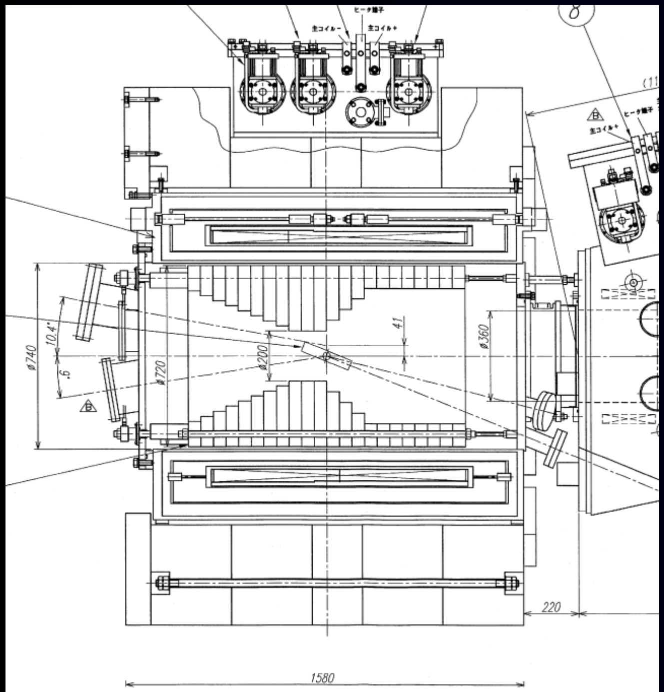
to a beam dump

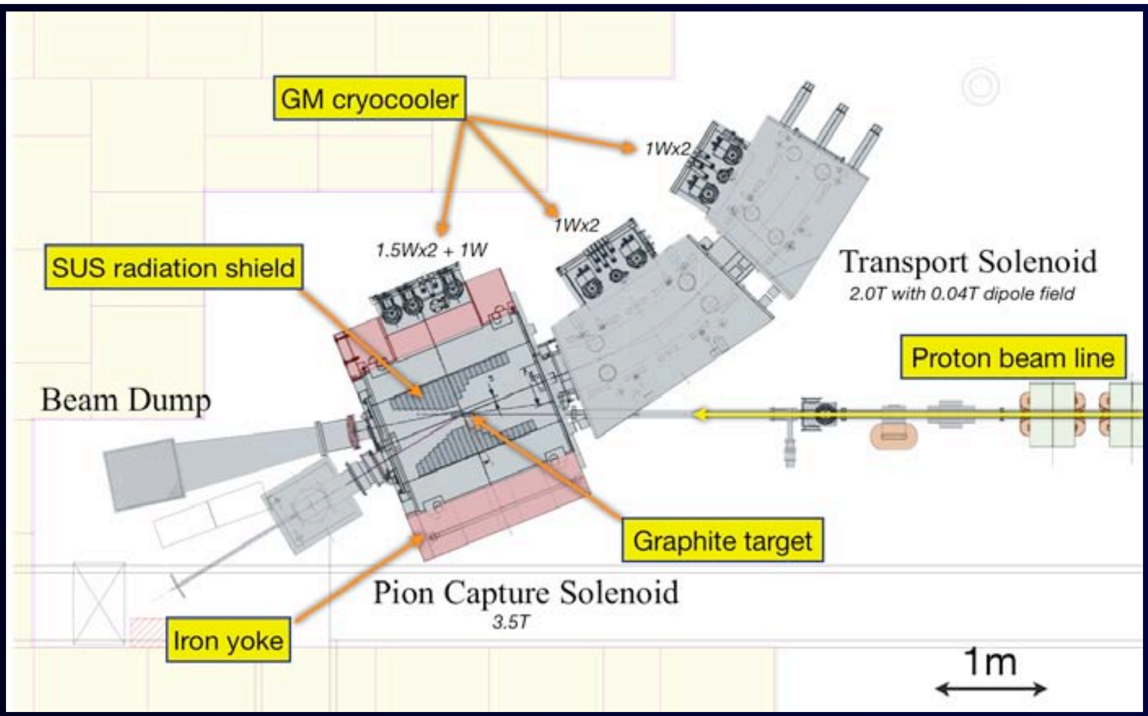
Large solid angle & thick target

Pion Capture System at MuSIC@Osaka-U

- Pion Capture SC Solenoid :
  - 3.5 T at central
  - diameter 740mm
  - SUS radiation shield
- Transport SC solenoids
  - 2 T magnetic field
  - 8 thin solenoids
- Graphite target for pion production

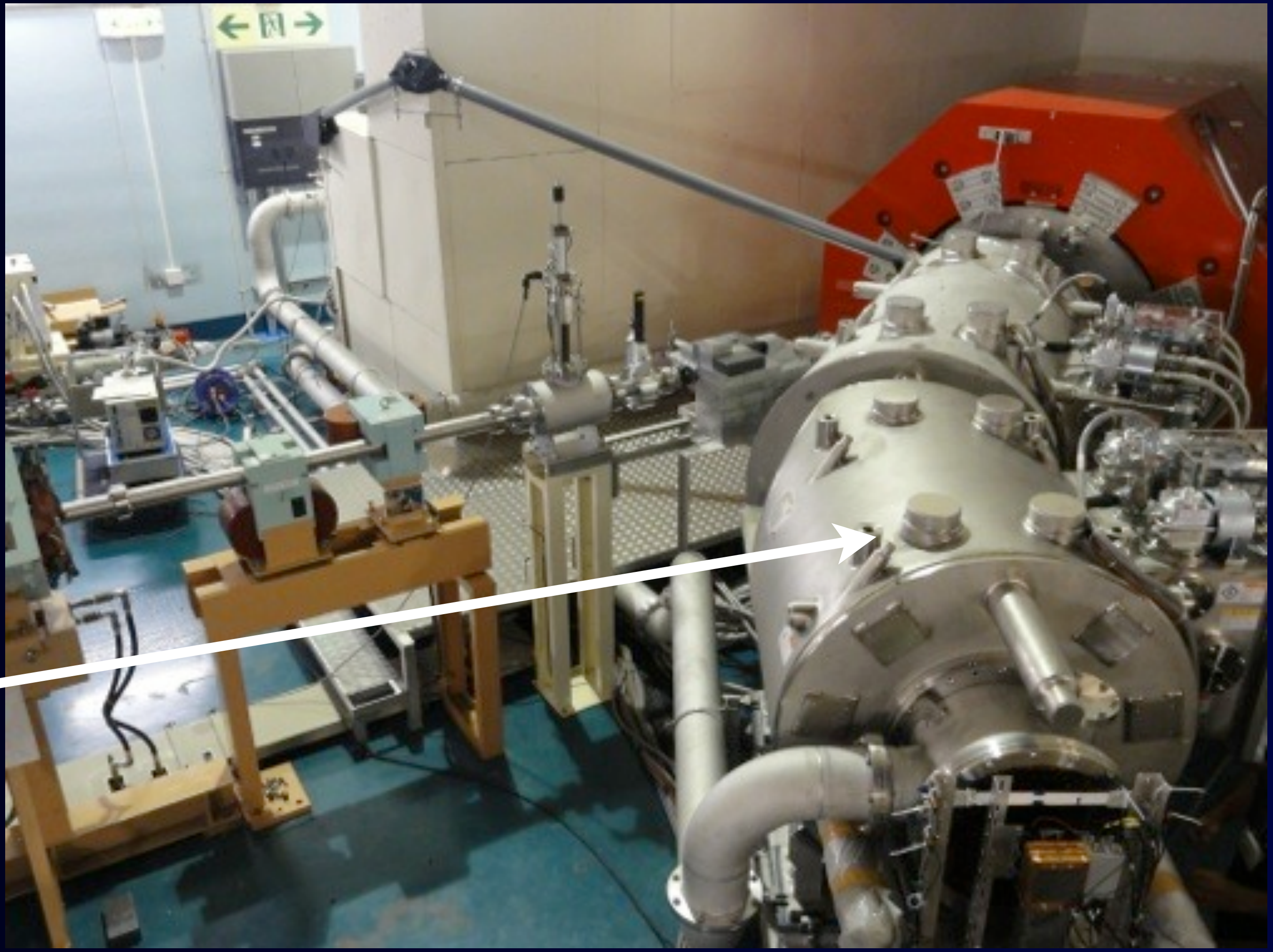






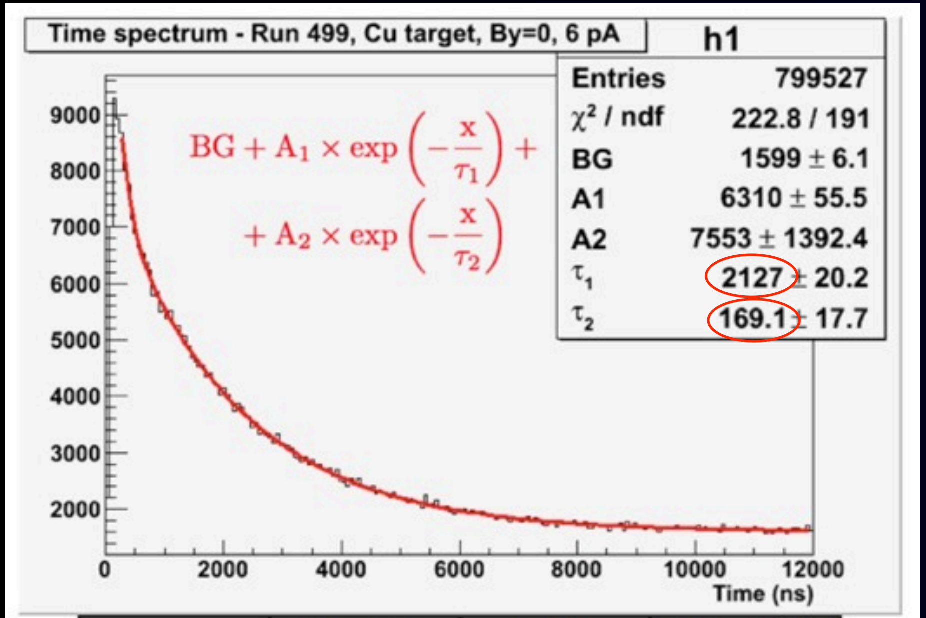
proton beam line

pion capture
superconducting
solenoid



muon transport
superconducting
solenoid

MuSIC Beam Test in 2011



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

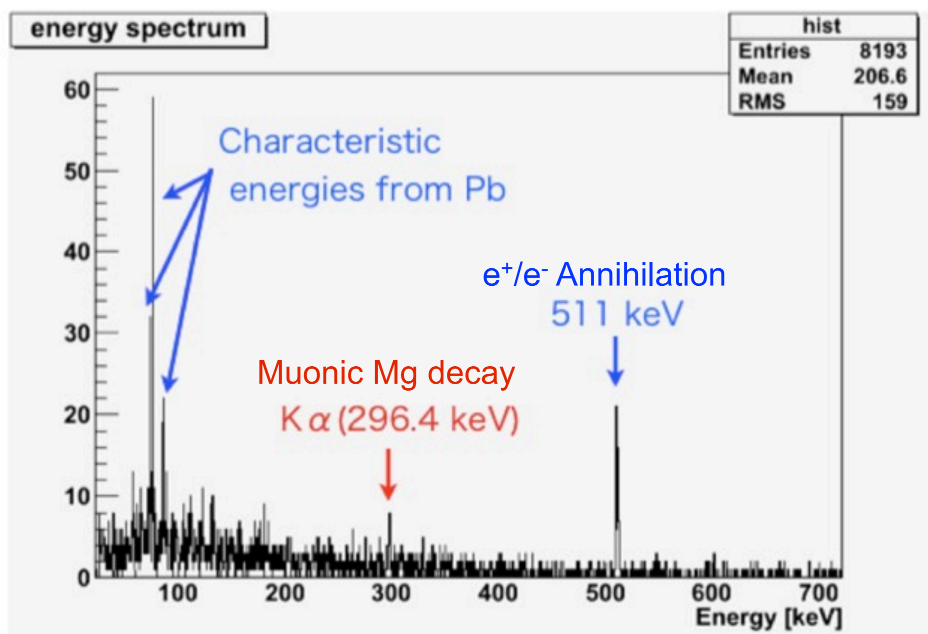
preliminary

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 x10^3 achieved...

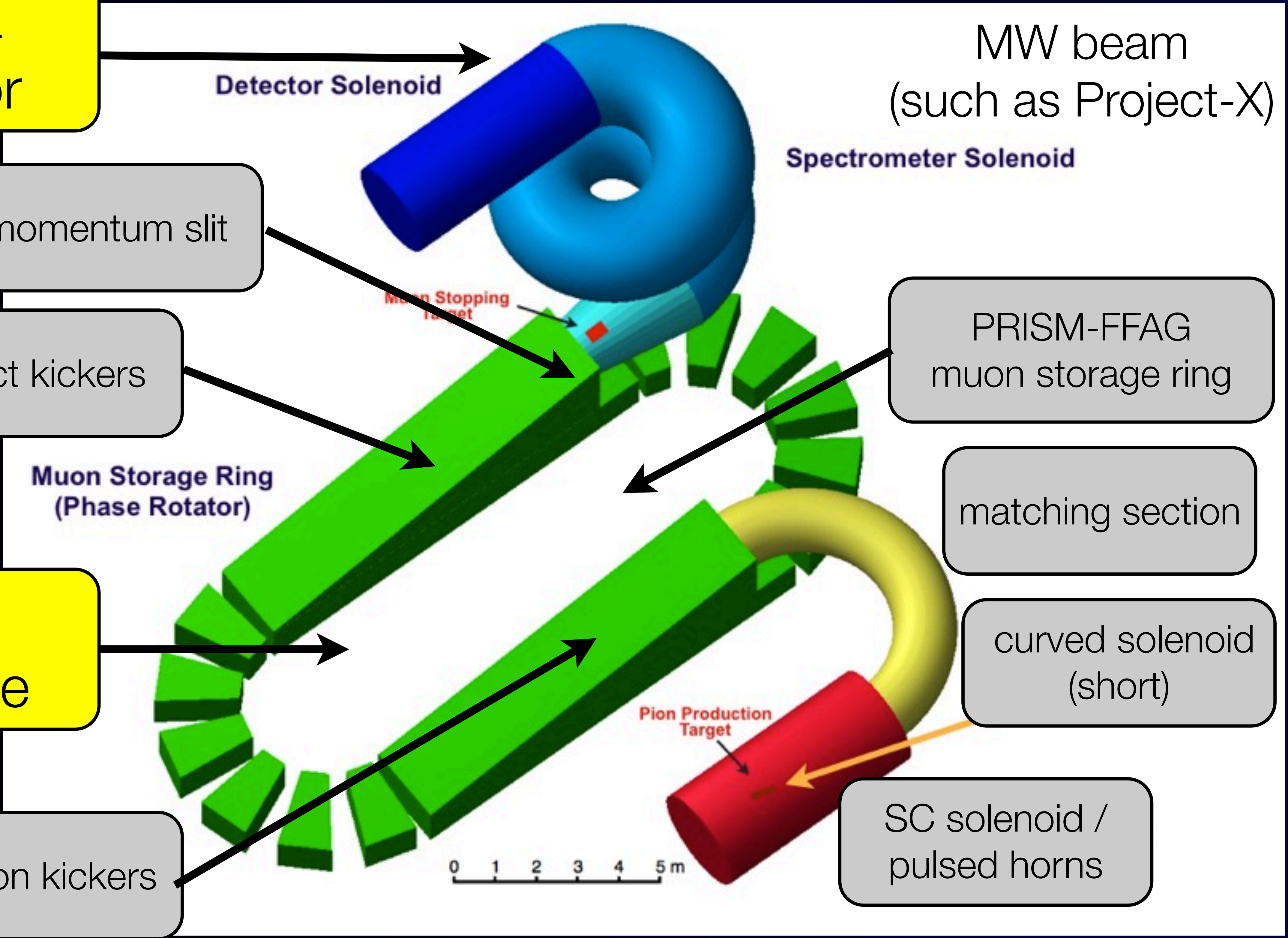


Great opportunities to carry out muon particle physics from NOW!

Measurements on June 21, 2011 (6 pA)

Future Future Prospects of μ-e conversion of 3×10^{-19}

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



MW beam
(such as Project-X)

PRIME detector

momentum slit

extract kickers

PRISM-FFAG muon storage ring

matching section

PRISM beamline

curved solenoid (short)

SC solenoid / pulsed horns

injection kickers

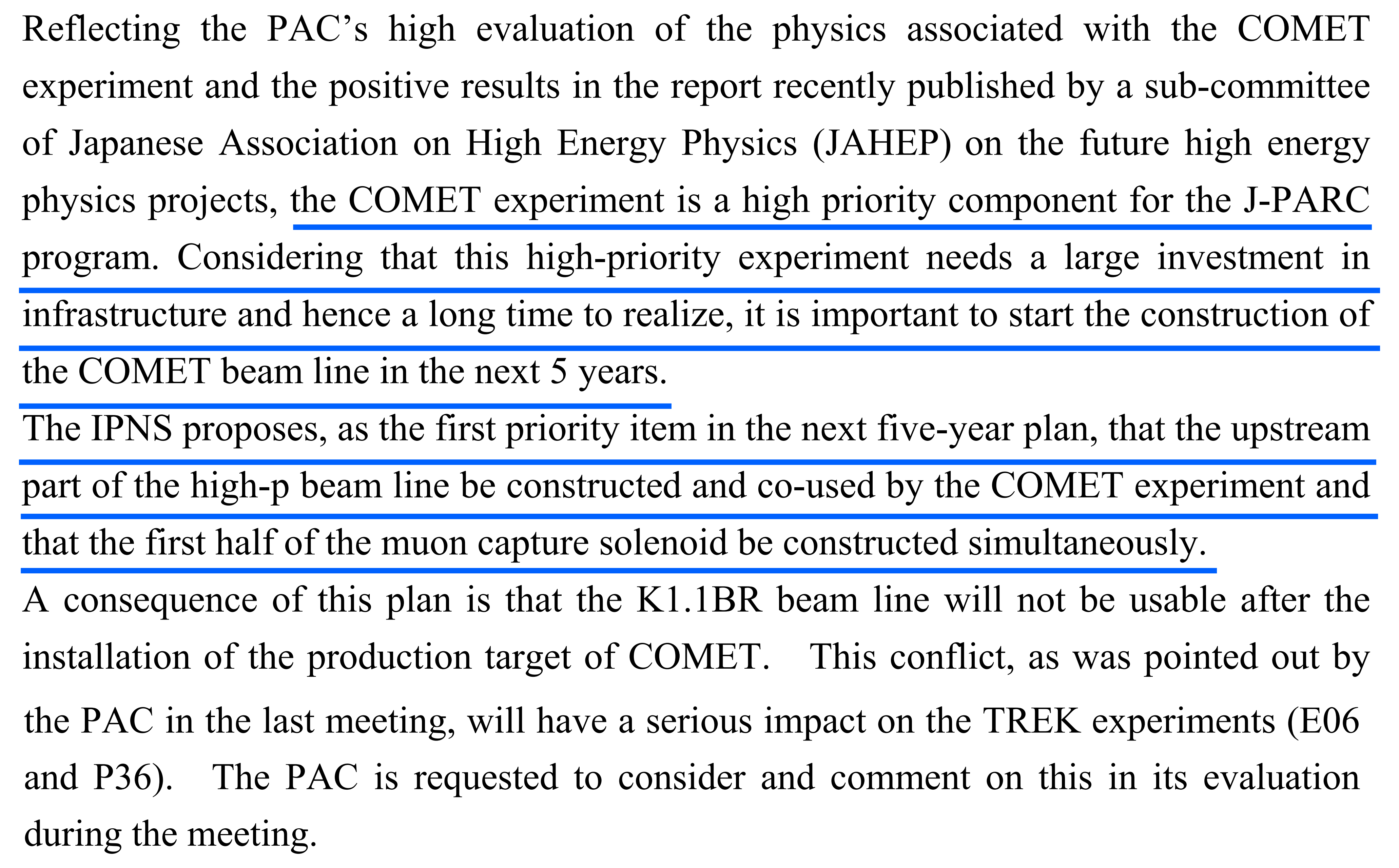
R&D on the PRISM-FFAG Muon Storage Ring at Osaka University

PRISM-FFAG (6 sectors) in RCNP, Osaka

demonstration of phase rotation has been done.

COMET Phase-I

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



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

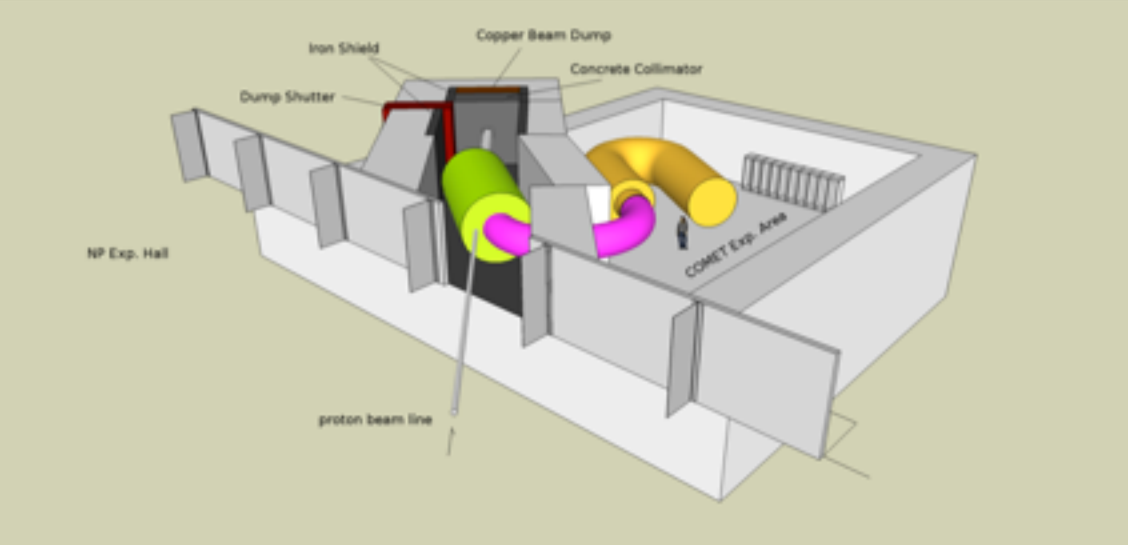
The IPNS proposes, as the first priority item in the next five-year plan, that the upstream part of the high-p beam line be constructed and co-used by the COMET experiment and that the first half of the muon capture solenoid be constructed simultaneously.

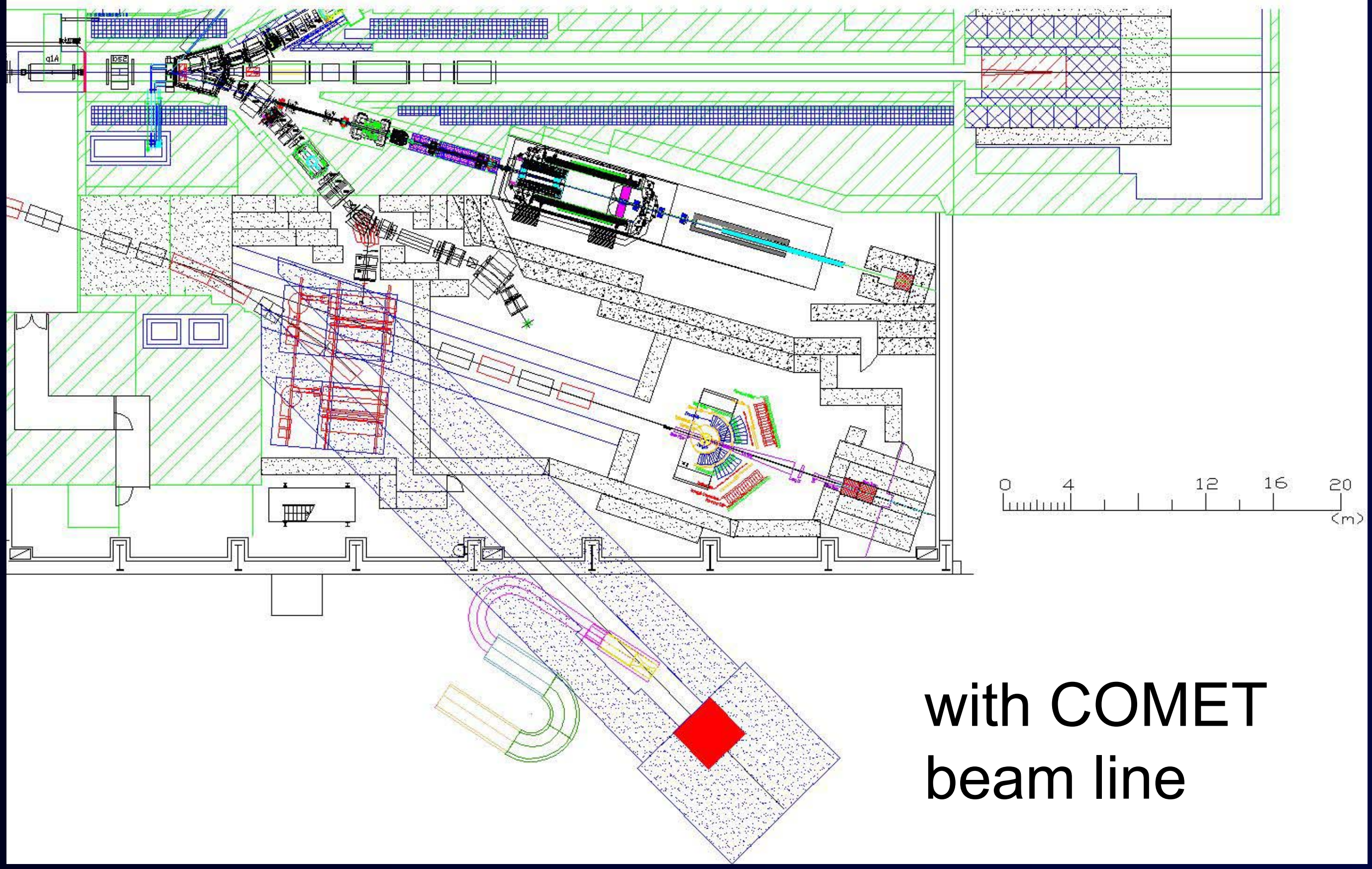
A consequence of this plan is that the K1.1BR beam line will not be usable after the installation of the production target of COMET. This conflict, as was pointed out by the PAC in the last meeting, will have a serious impact on the TREK experiments (E06 and P36). The PAC is requested to consider and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

COMET Phase-I (staged scenario)

New

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



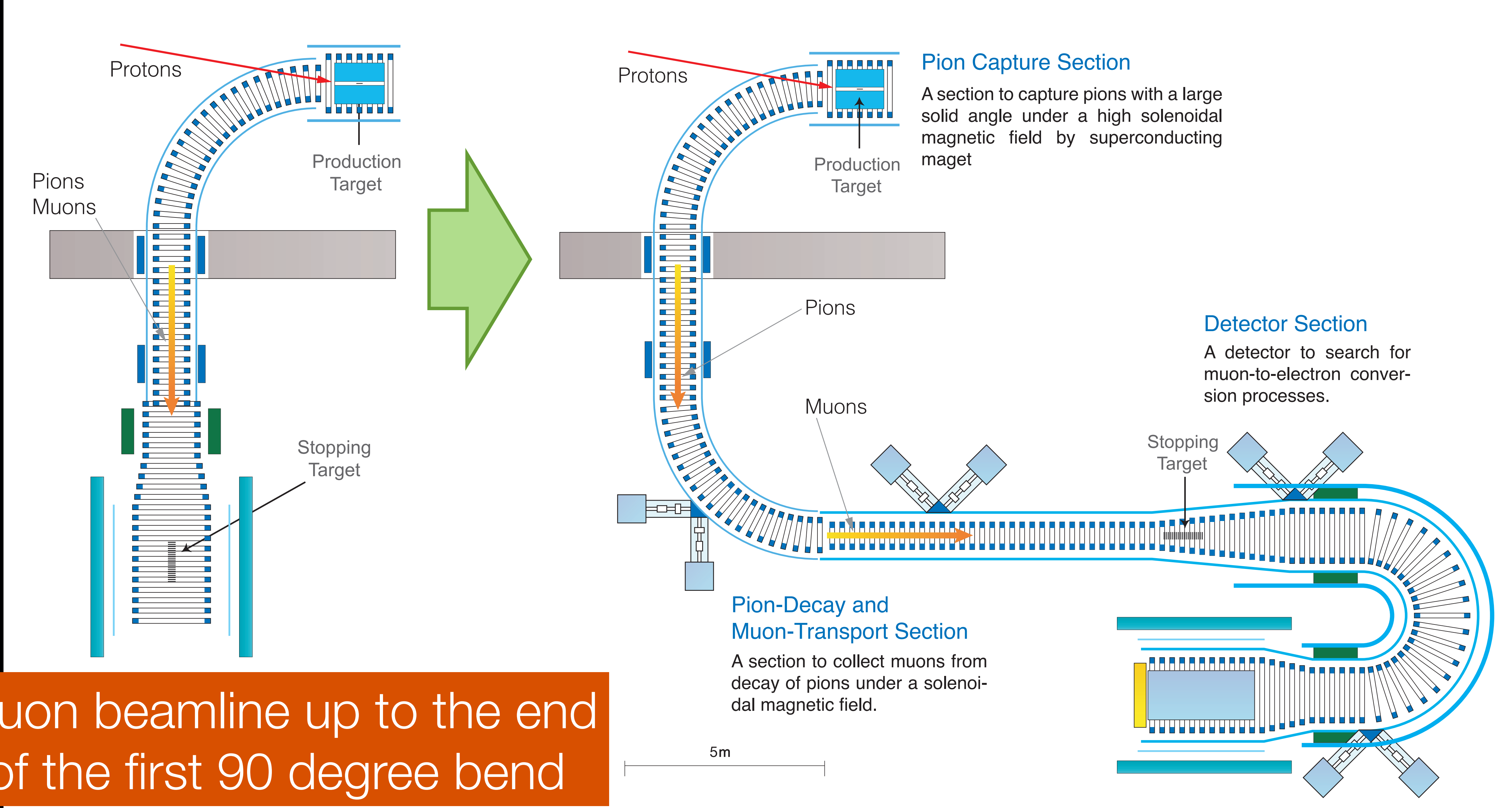

Beam line plan at southern area

with COMET beam line

COMET Staged Approach

COMET Phase-I

COMET Phase-II



Pion Capture Section

A section to capture pions with a large solid angle under a high solenoidal magnetic field by superconducting maget

Detector Section

A detector to search for muon-to-electron conversion processes.

Pion-Decay and Muon-Transport Section

A section to collect muons from decay of pions under a solenoidal magnetic field.

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

Goals of COMET Phase-I

1 **Background Study for COMET Phase-II**

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

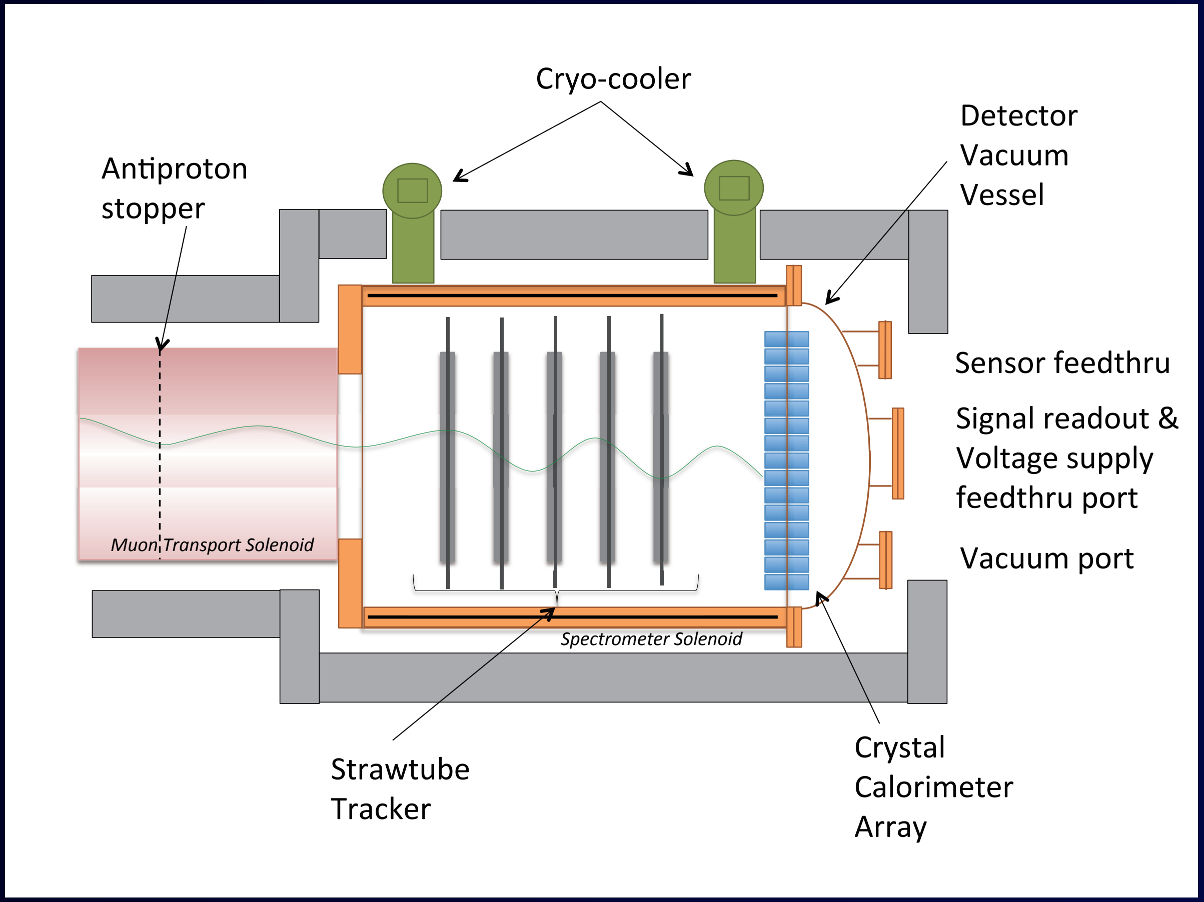
2 **Search for μ-e conversion**

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

Background Studies

- measure almost all background sources
  - muons, pions, electrons, neutrons, antiprotons, photons
- same detector technology used in COMET Phase-II
  - SC spectrometer solenoid
  - straw tube transverse tracker
  - crystal calorimeter
- particle ID with dE/dX and E/P

schematic layout

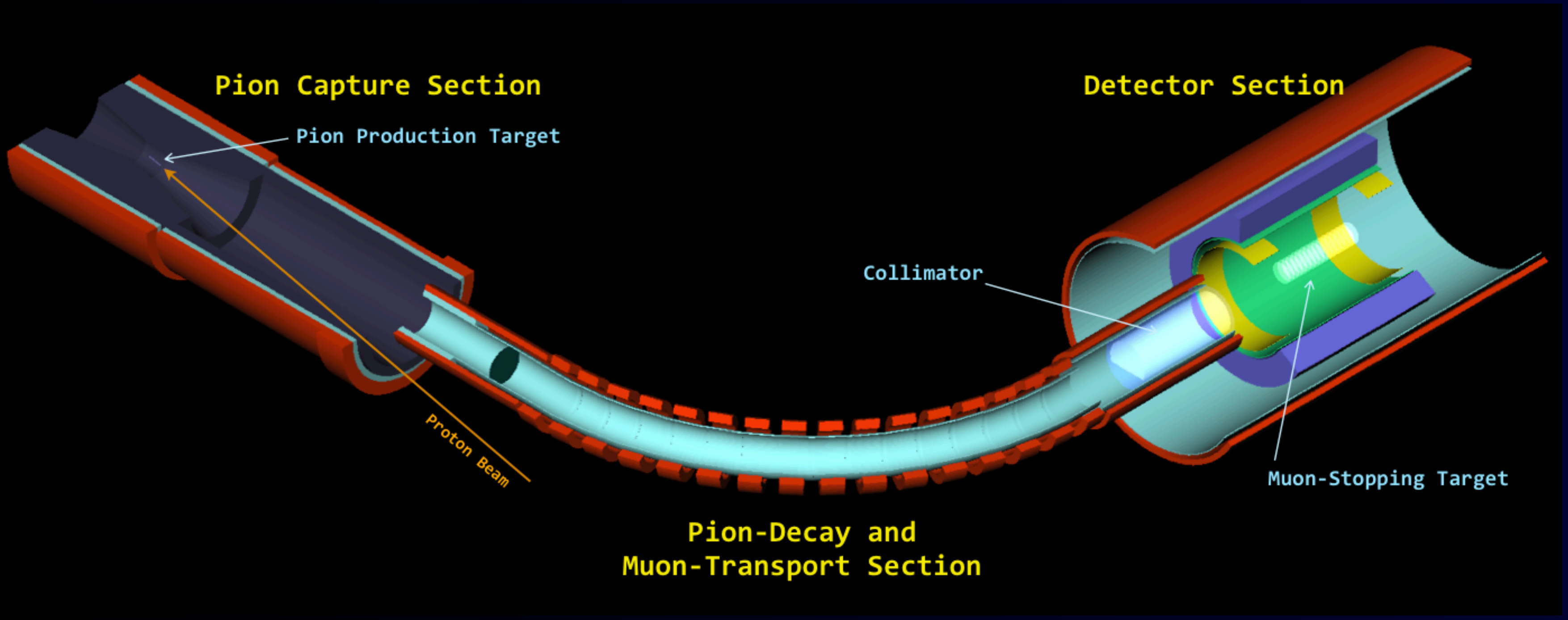


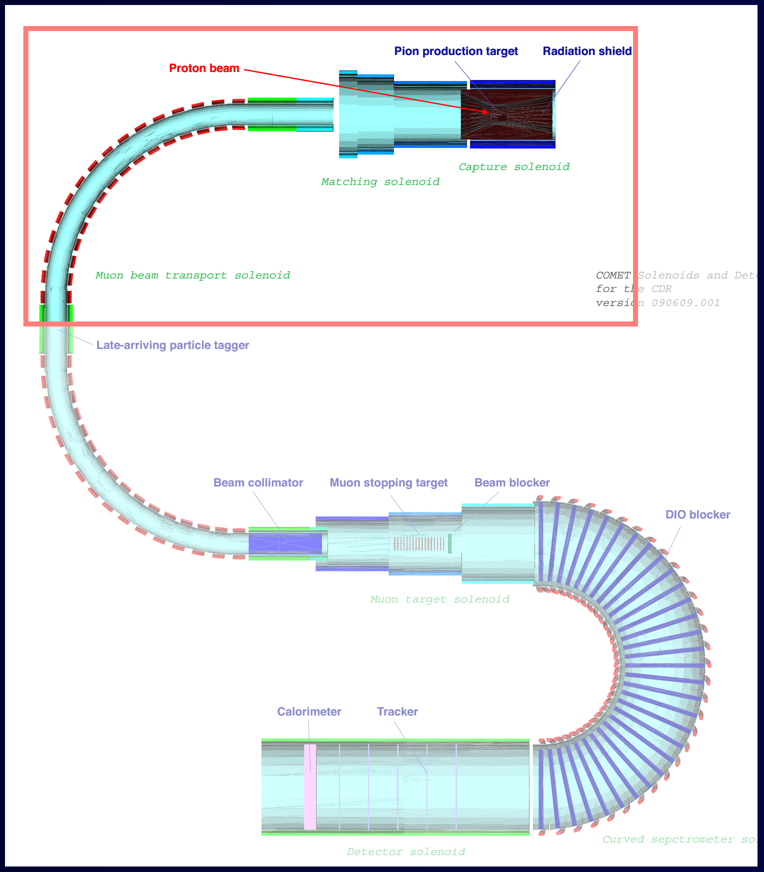
aim to know the known BG &
aim to know the unknown BG

COMET Phase-I (staged scenario)

New

- Phase-I would cover ....
  - proton beam line
  - muon beam line up to the end of the first 90° bend
  - no detector
- Funding starts in JFY2013
- Experiment may start in JFY2016/17?

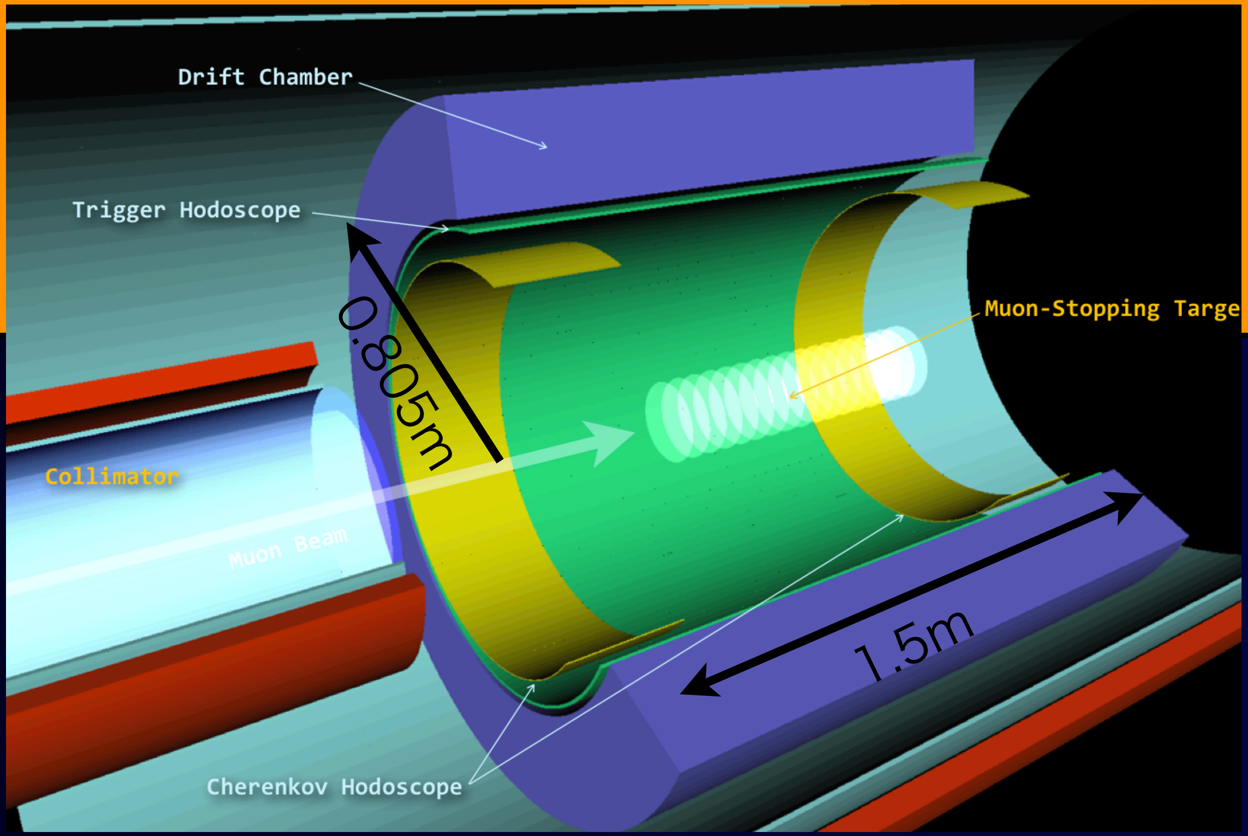


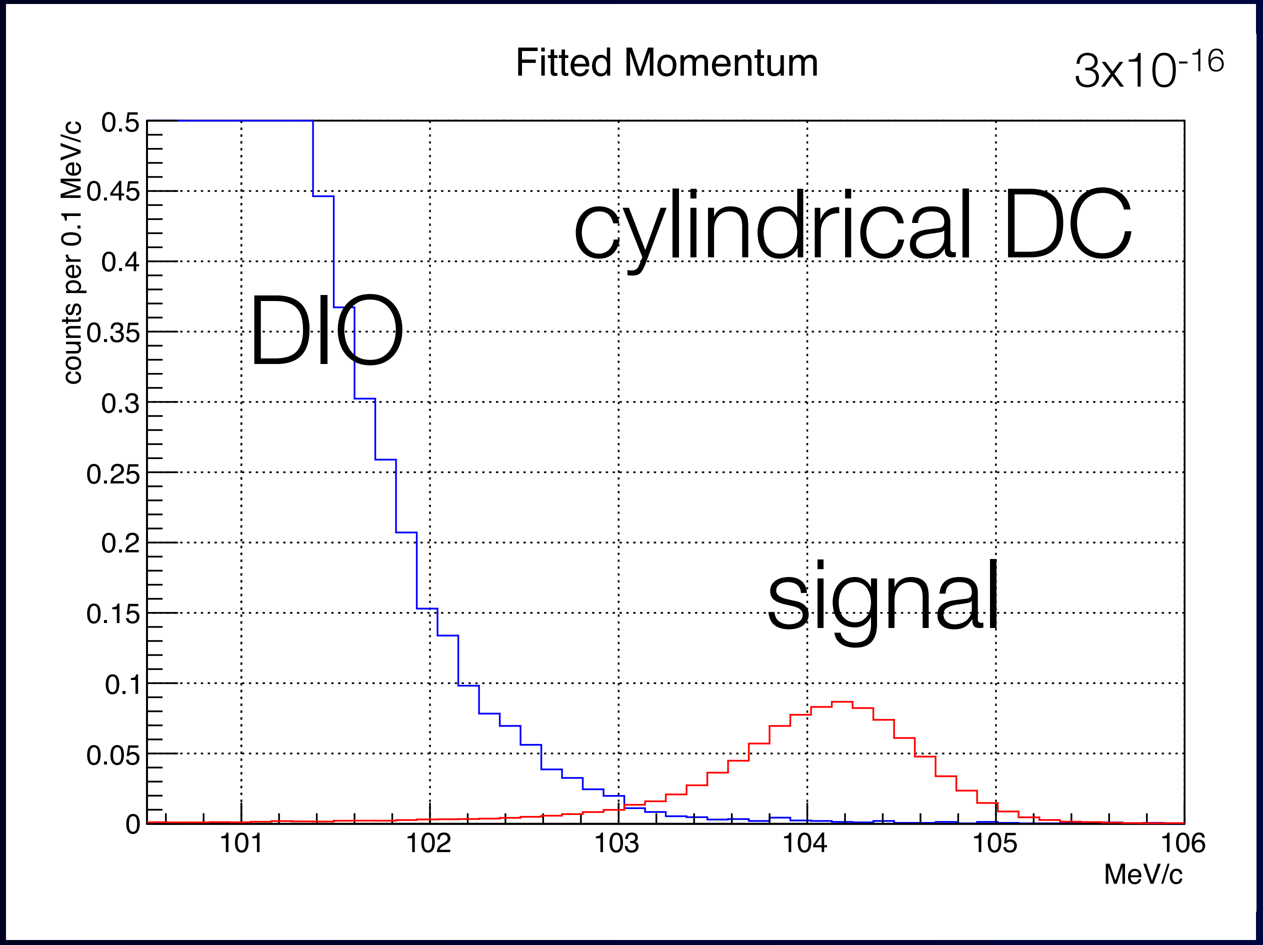


COMET Phase-I

New

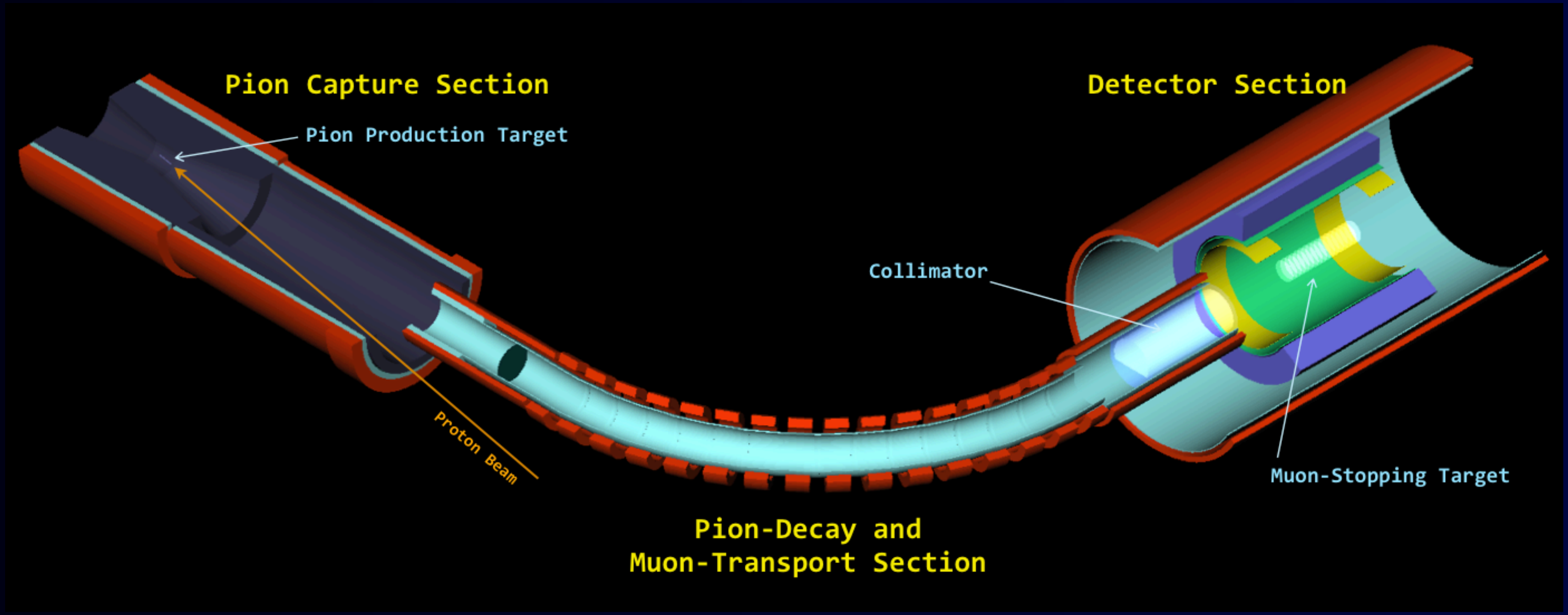
- COMET Phase-I (LOI) aims ....
  - BG studies for Phase-II
    - mini Full COMET detector
    - extinction measurement
  - intermediate sensitivity
    - cylindrical drift chamber (copy of BESS-II CDC)
    - SE sensitivity~3×10^{-15} for 10^6 s (12 days) with 3 kW proton beam power (with 5×10^9 stopped μ/s).
  - if no BG, keep running for 10^7 s.
- Detector cost should be covered by the collaboration.
- The proposal submitted soon.



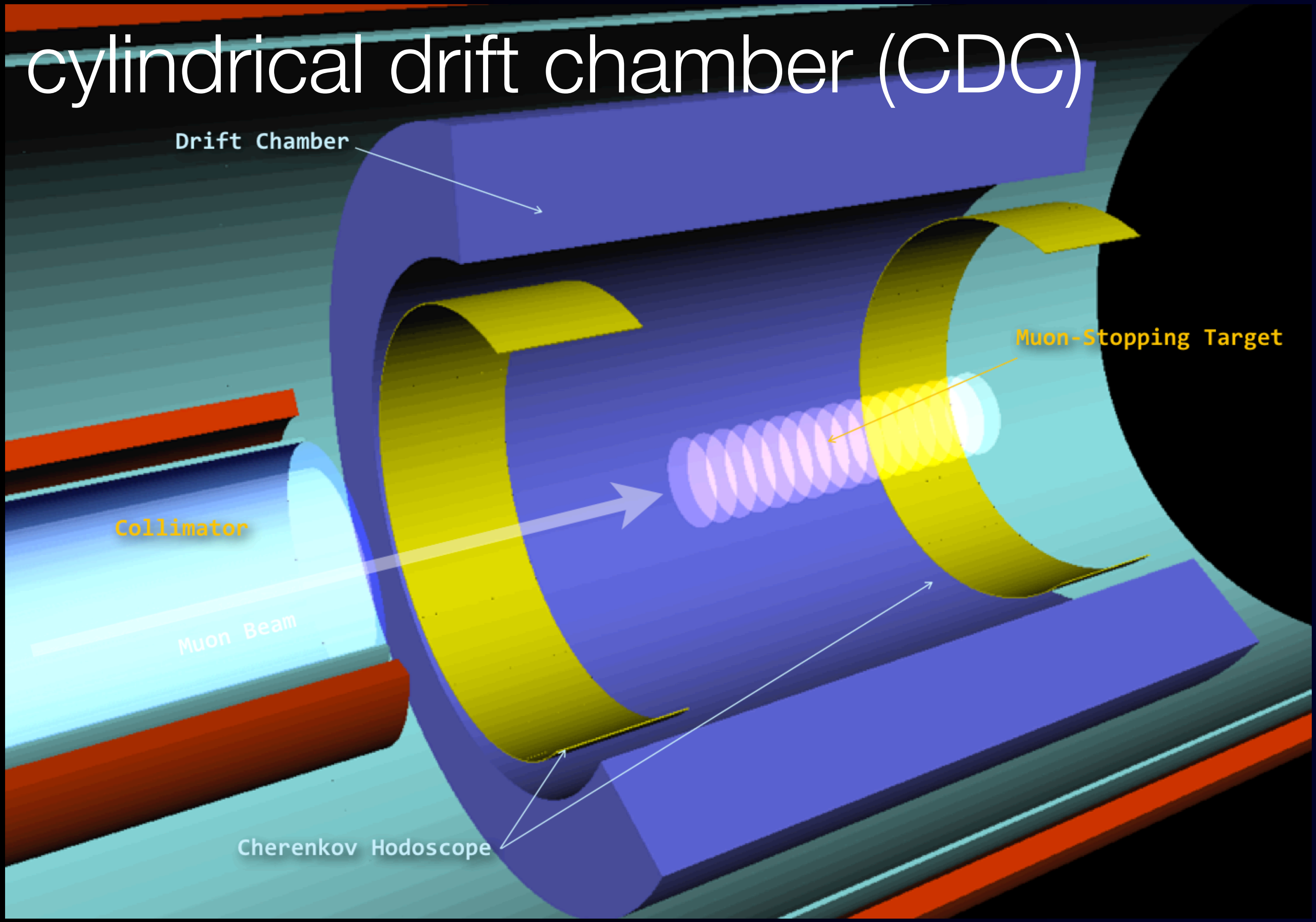


COMET Phase-I Muon Beam

- Muons
  - muons/proton almost same
- Pions
  - shorter beamline
  - Phase-I 6.9x10^{-5}/proton
  - Phase-II 3.5x10^{-7}/proton
- Neutrons
  - x10^{3} neutrons (only 90 degree bend)



Search for μ-e conversion at Intermediate Sensitivity (CDC case)

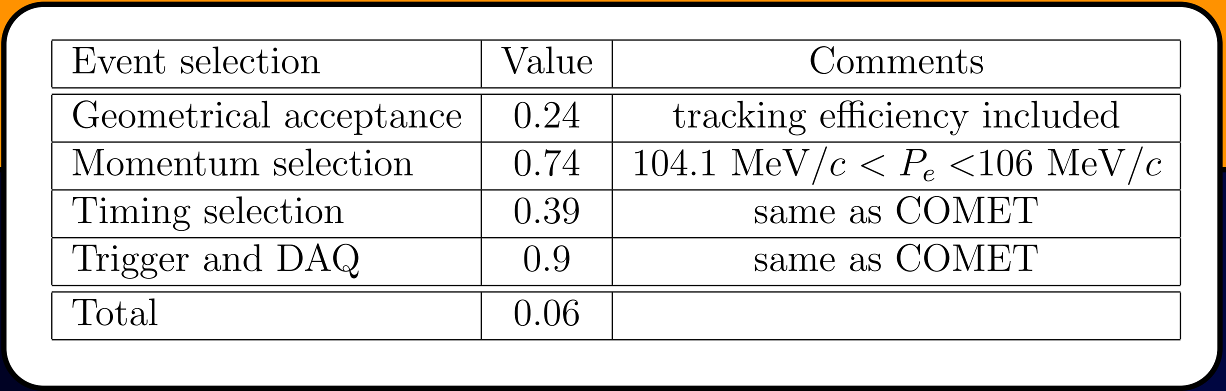

cylindrical drift chamber (CDC)

Design Philosophy

by keeping an open end in a solenoid geometry, beam particles continue downstream and escape the detector.

- CDC design is based on Belle II CDC (small cell part)
- Design difference (from LOI)
  - He:C$_2$H$_6$ (=50:50) gas
  - trigger counters at the both ends (smaller acceptance)
  - no proton absorber
- CDC hit rates
  - 40 kHz/wire at the innermost layer by proton emission from muon capture (0.15 per capture)
- CDC trigger rate
  - 270 Hz from DIO

Signal Event Sensitivity (SES) for COMET Phase-I



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

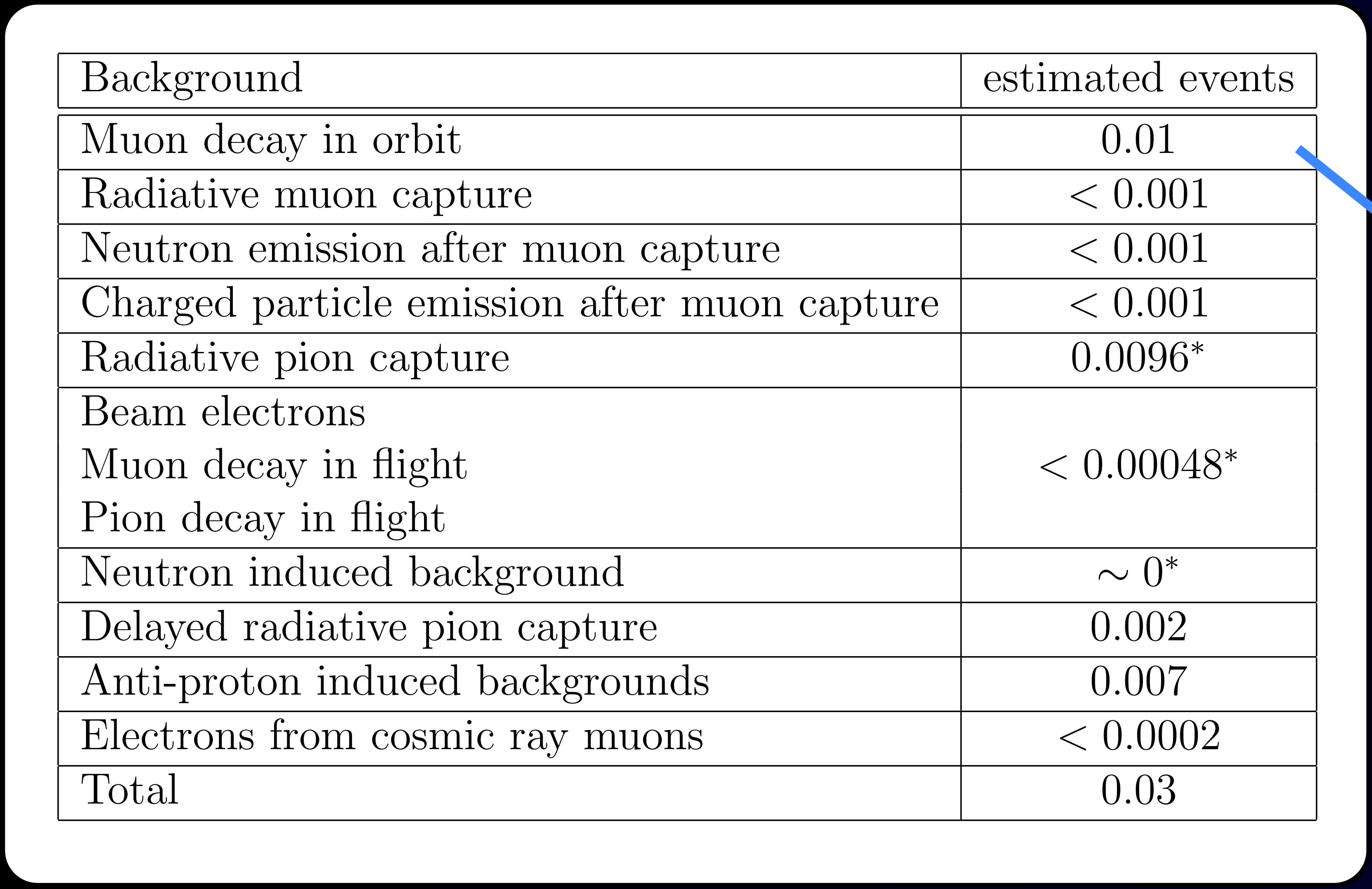
$$B(\mu^- + Al \rightarrow e^- + Al) \sim \frac{1}{N_\mu \cdot f_{cap} \cdot A_e},$$

  - 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.

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

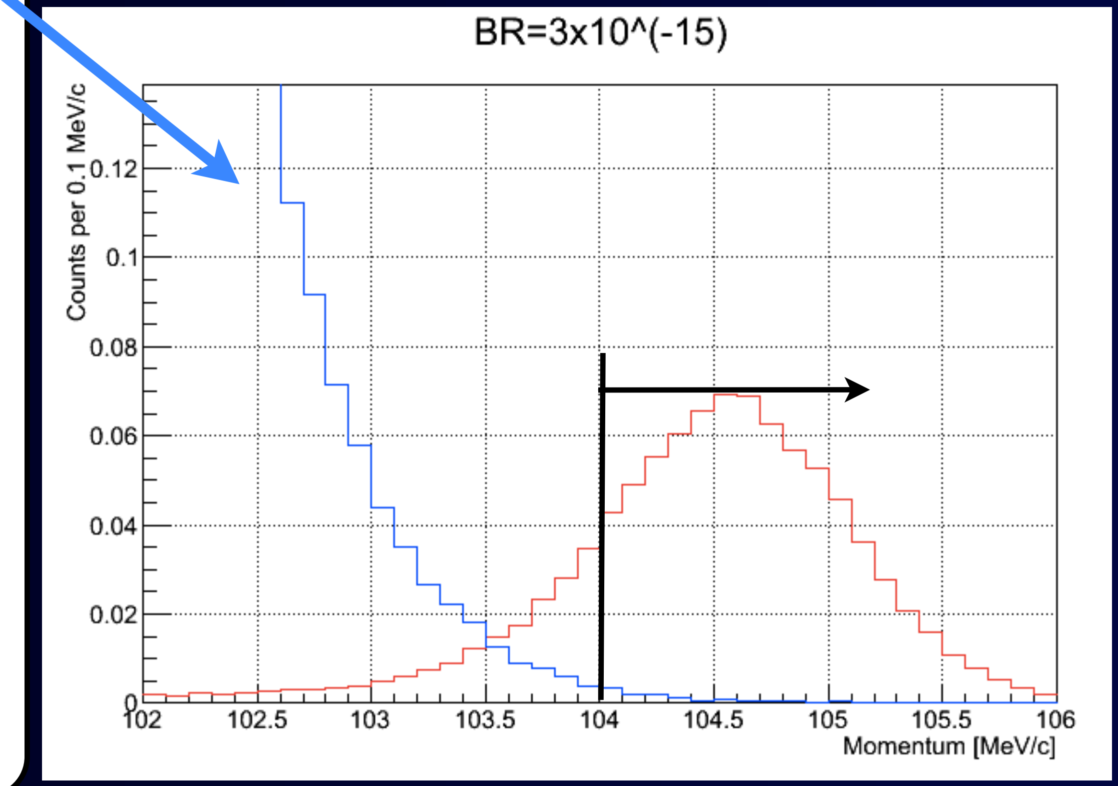
$$B(\mu^- + Al \rightarrow e^- + Al) < 7 \times 10^{-15} \quad (90\% C.L.)$$

Background Estimation for COMET Phase-I



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

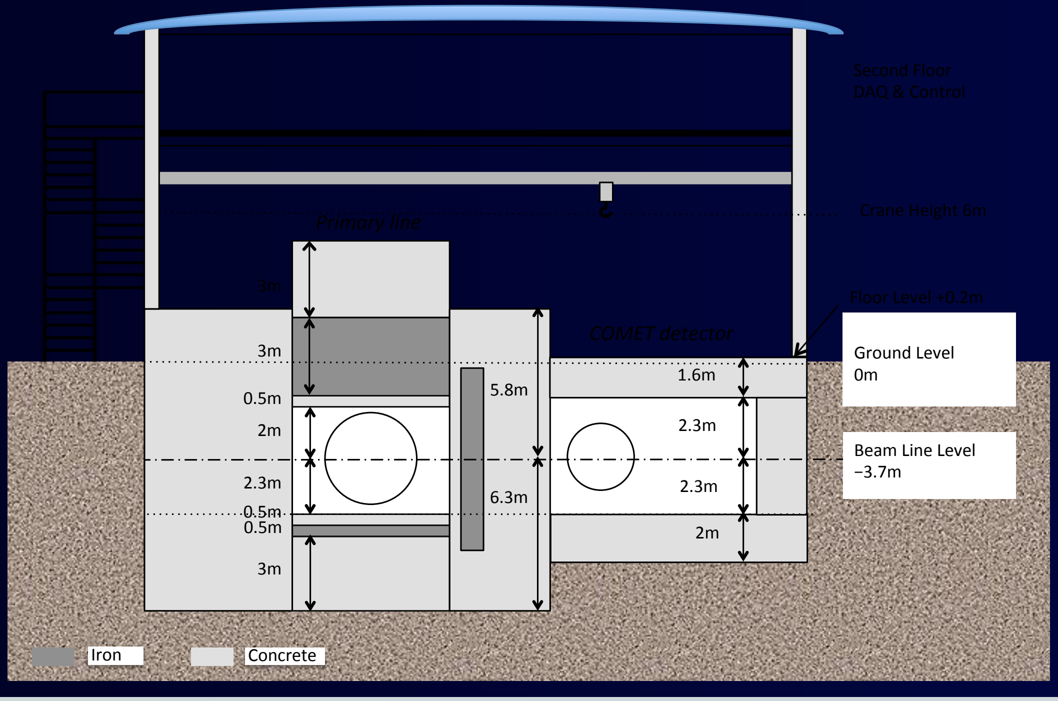


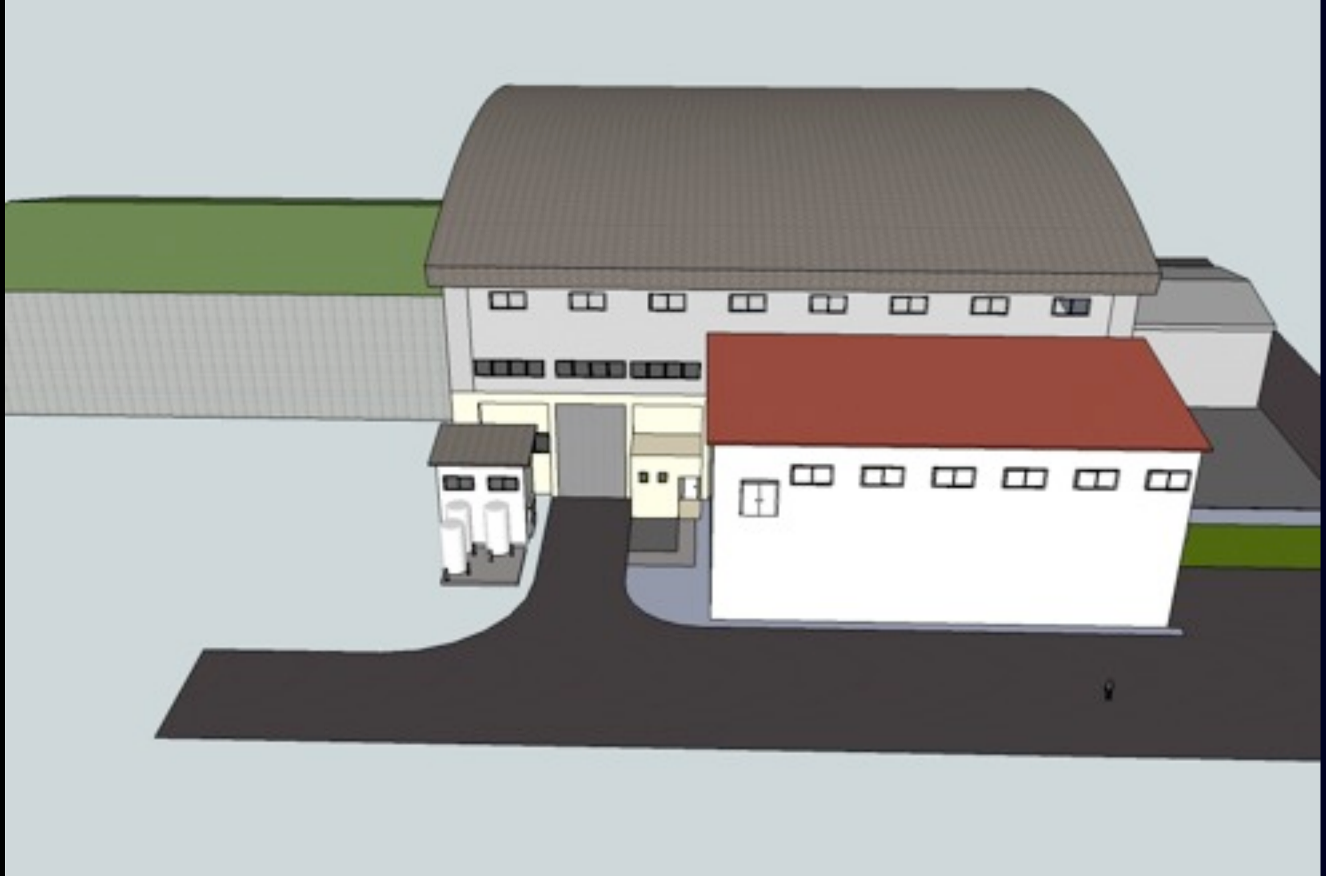
with proton extinction factor of $3x10^{-11}$

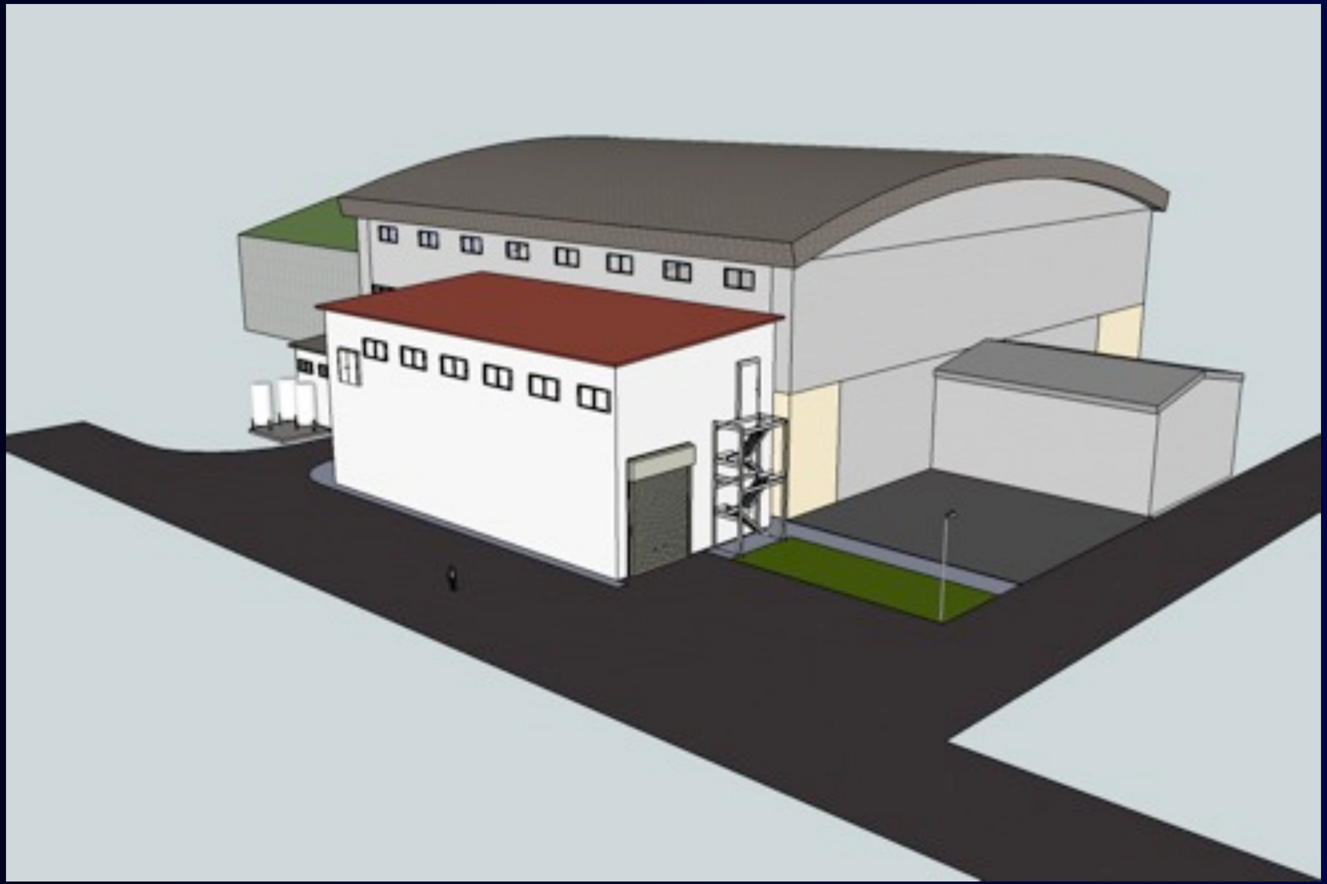
Expected BG events are about 0.03 at S.E.S. of $3x10^{-15}$.

Status of Facility Construction

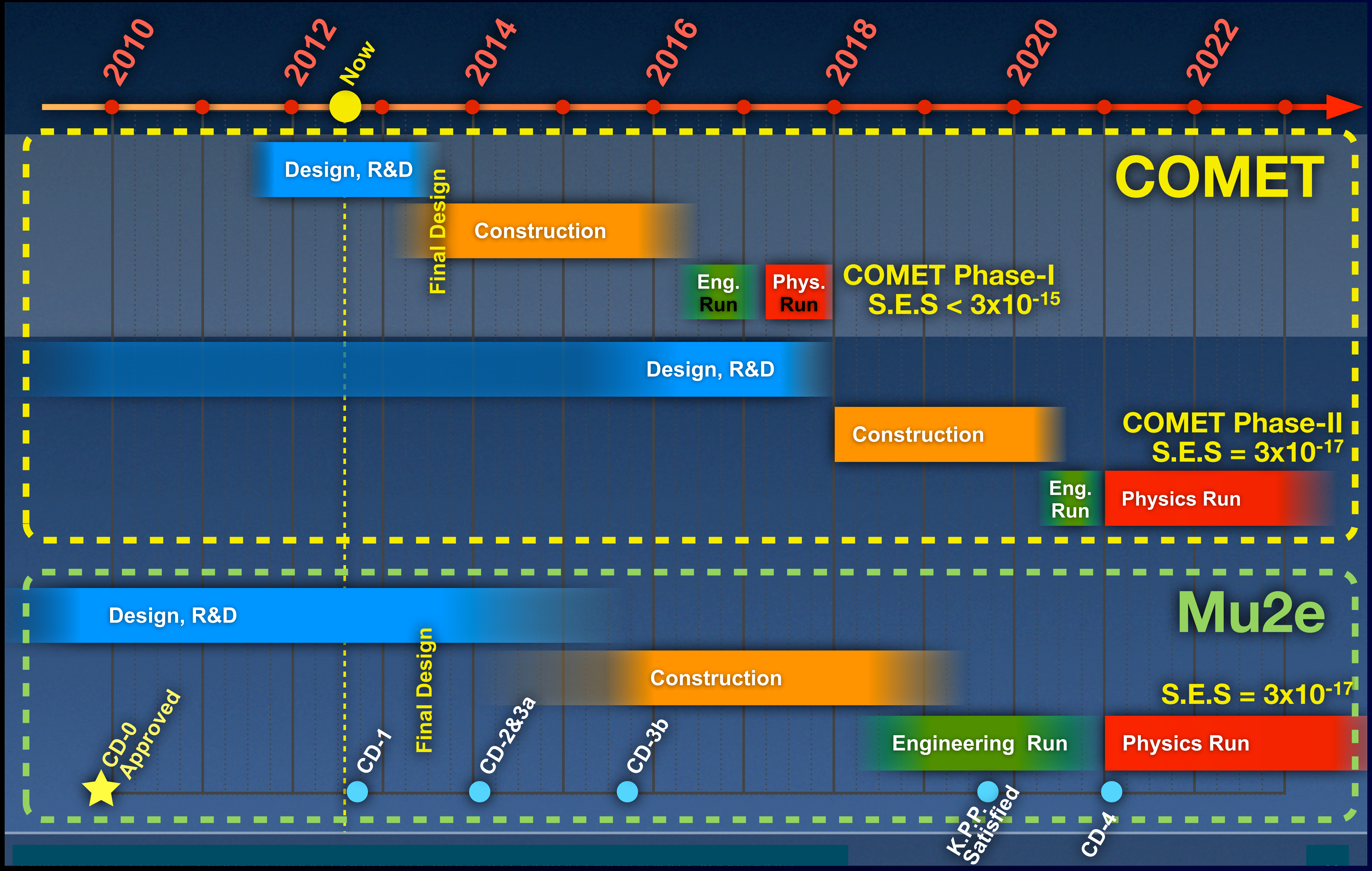
- Design work in progress with help of Hadron Hall Facility Group, consulting a design farm
- Primary beam area
- Experimental area
- Ground floor for service/power supply/refrigerator
- Compressor will be installed in a separate building







Schedule of COMET and Mu2e



Comparison of COMET Phase-I / Phase-II and Mu2e

90% C.L. upper limit is 7×10^{-13} (SINDRUM)

	S.E. sensitivity	BG events at aimed sensitivity	running time (sec)	Year	Comments
COMET Phase-I	3×10^{-15}	0.03	1.5×10^{6}	~2016	Proposal (2012)
COMET Phase-II	3×10^{-17}	0.34	2×10^{7}	~2019	CDR (2009)
Mu2e	3×10^{-17}	0.4	3x (2×10^{7})	~2019	J. Miller's talk at SSP2012

Summary

- CLFV would give the best opportunity to search for BSM. (So far, no BSM signals at the LHC.)
- The field of CLFV gets important and exciting.
- COMET at J-PARC is aiming at S.E. sensitivity of 3×10^{-17}.
- The COMET Phase-I is aiming at S.E. sensitivity of 3×10^{-15} and hopefully the construction will start in 2013.
- R&D on PRISM/PRIME for S.E.3×10^{-19} is going.
- and ... MuSIC@Osaka ~10^8 μ/s with 400 W.

IKU (go ahead)