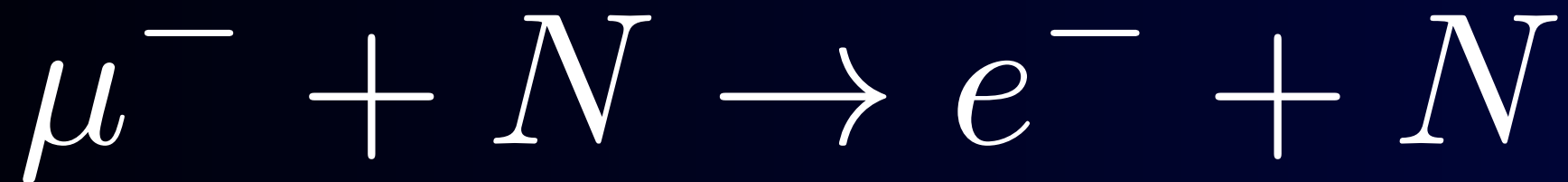


Muon to Electron Conversion with COMET at J-PARC

Yoshitaka Kuno
Department of Physics,
Osaka University, Japan

October 23rd 2019
International Workshop on Baryon and Lepton Number
Violation (BLV2019)
Madrid, Spain

muon to electron conversion in a muonic atom



(charged lepton flavour violation)

outline

- Physics Motivation of Charged Lepton Flavour Violation
- Muon to electron conversion
- COMET at J-PARC
- COMET Phase-I (under preparation)
- Summary

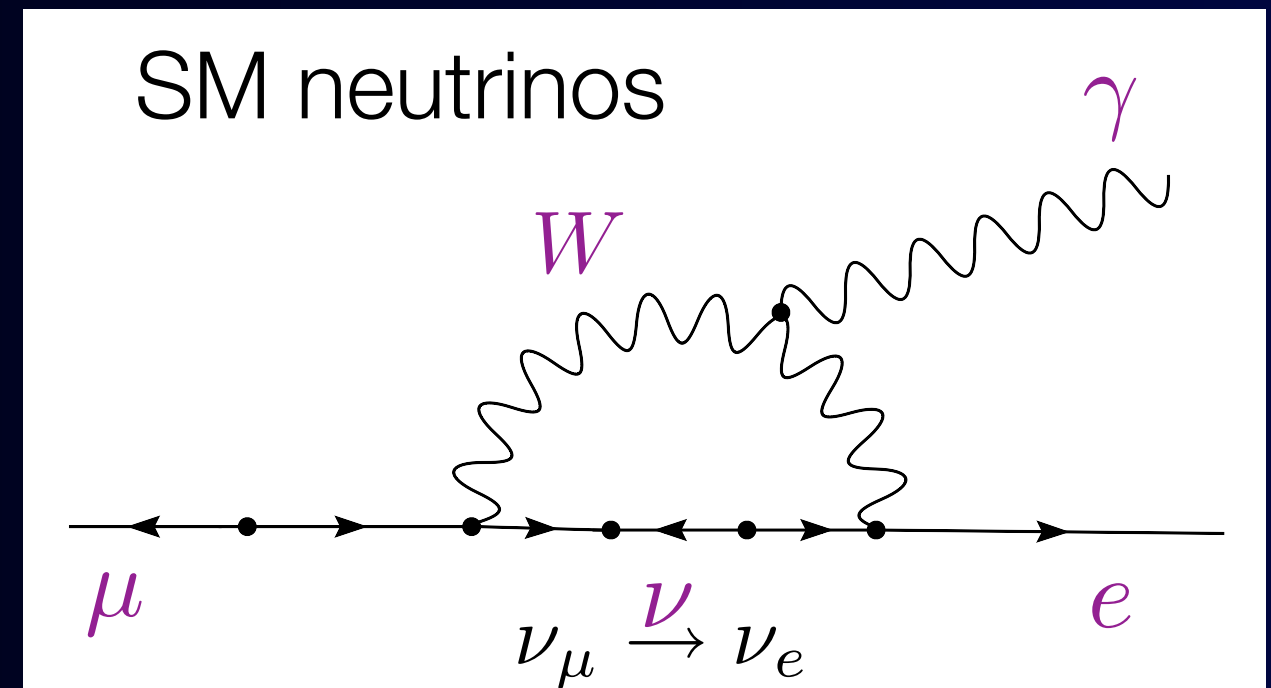
Charged Lepton Flavour Violation for BSM Search



CLFV in the SM



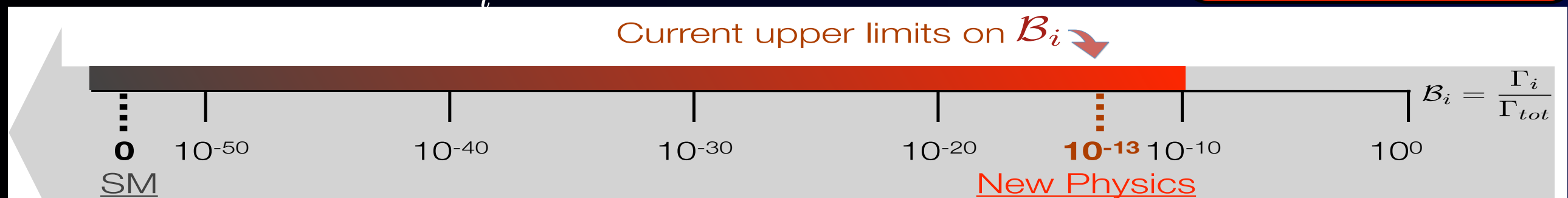
Neutral lepton flavour violation has been observed. Lepton mixing in the SM has been established.



S.T. Petcov, Sov.J. Nucl. Phys. 25 (1977) 340

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

BR $\sim O(10^{-54})$



1 CLFV has a large window for BSM w/o SM backgrounds.

CLFV in BSM



Effective Field Theory (EFT) Approach

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d>4} \frac{C^{(d)}}{\Lambda^{d-4}}$$

Λ is the energy scale of new physics
 $C^{(d)}$ is the coupling constant.

from $BR(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$

$$\frac{C^6}{\Lambda^2} \mathcal{O}^6 \rightarrow \frac{C^6}{\Lambda^2} \bar{e}_L \sigma^{\rho\nu} \mu_R \Phi F_{\rho\nu}$$



$$\Lambda \sim \mathcal{O}(10^4) \text{ TeV}$$

c.f. $\Delta m_K, \epsilon'$

	$ C_a [\Lambda = 1 \text{ TeV}]$	$\Lambda \text{ (TeV)} [C_a = 1]$	CLFV Process
$C_{e\gamma}^{\mu e}$	2.1×10^{-10}	6.8×10^4	$\mu \rightarrow e\gamma$
$C_{le}^{\mu\mu\mu e, e\mu\mu\mu}$	1.8×10^{-4}	75	$\mu \rightarrow e\gamma$ [1-loop]
$C_{le}^{\mu\tau\tau e, e\tau\tau\mu}$	1.0×10^{-5}	312	$\mu \rightarrow e\gamma$ [1-loop]
$C_{e\gamma}^{\mu e}$	4.0×10^{-9}	1.6×10^4	$\mu \rightarrow eee$
$C_{ll,ee}^{\mu eee}$	2.3×10^{-5}	207	$\mu \rightarrow eee$
$C_{le}^{\mu eee, ee\mu e}$	3.3×10^{-5}	174	$\mu \rightarrow eee$
$C_{e\gamma}^{\mu e}$	5.2×10^{-9}	1.4×10^4	$\mu^- \text{Au} \rightarrow e^- \text{Au}$
$C_{lq,ld,ed}^{e\mu}$	1.8×10^{-6}	745	$\mu^- \text{Au} \rightarrow e^- \text{Au}$
$C_{eq}^{e\mu}$	9.2×10^{-7}	1.0×10^3	$\mu^- \text{Au} \rightarrow e^- \text{Au}$
$C_{lu,eu}^{e\mu}$	2.0×10^{-6}	707	$\mu^- \text{Au} \rightarrow e^- \text{Au}$

F. Feruglio, P. Paradisi and A. Pattori, Eur. Phys. J. C 75 (2015) no.12, 579

G. M. Pruna and A. Signer, JHEP 1410 (2014) 014

CLFV in BSM - Future Searches



Future planned CLFV experiments (with muons) expecting improvements by an additional factor of $>10,000$ or more (will be described later) would probe

$$\Lambda \sim \mathcal{O}(10^5) \text{ TeV}$$

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

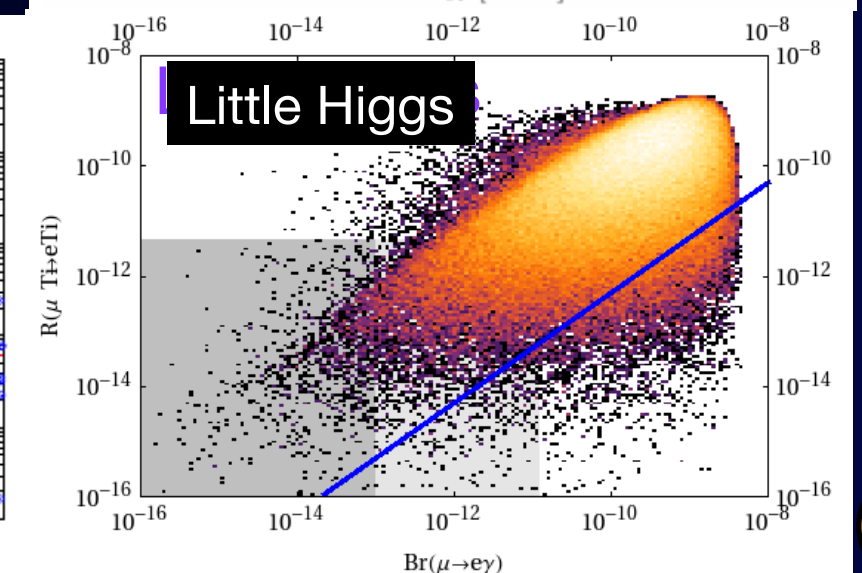
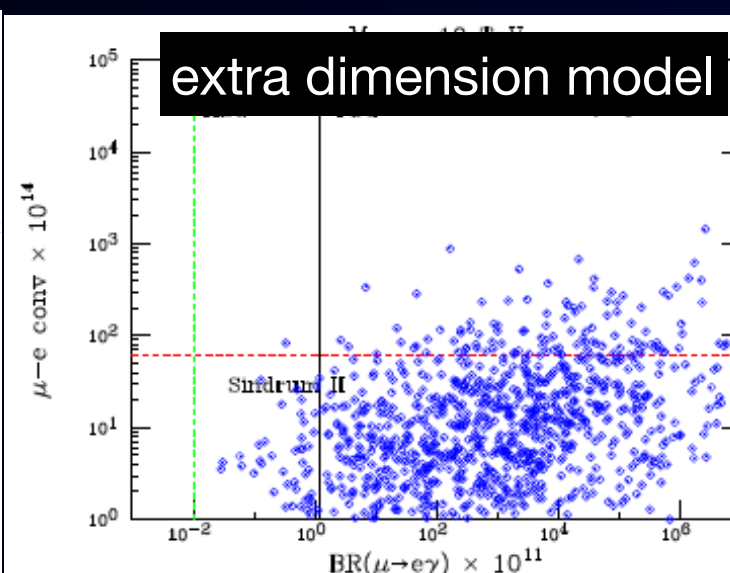
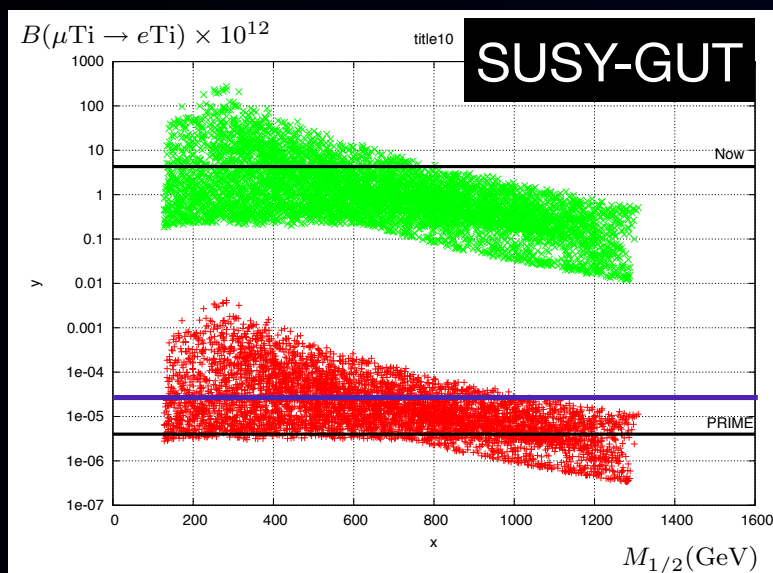
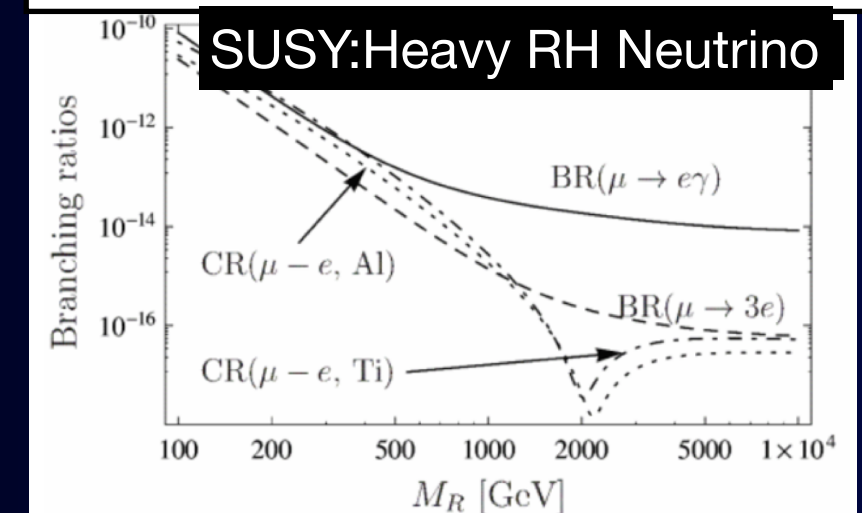
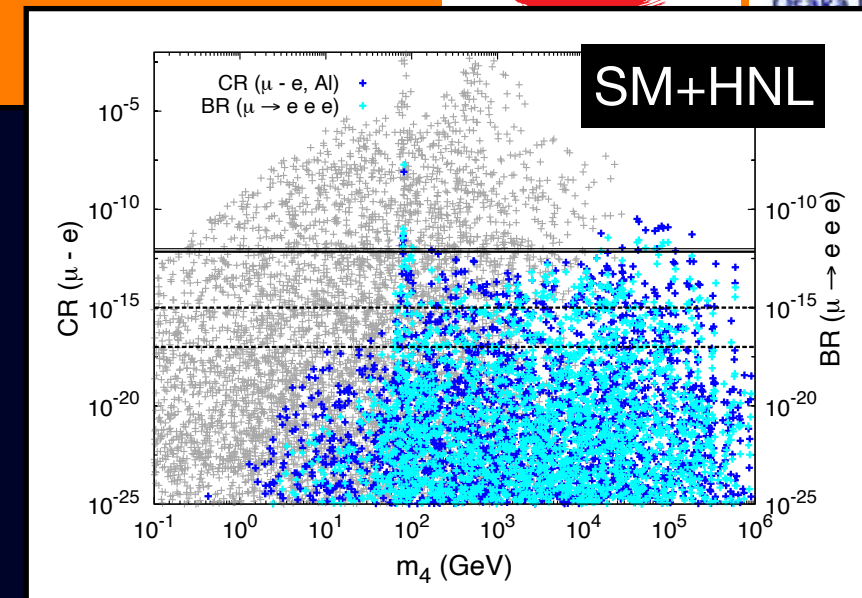
2 CLFV would explore scales way beyond the energies that our present and future colliders can directly reach.

It is crucial in establishing where is the next fundamental scale above the electroweak symmetry breaking.

Model dependent CLFV



- SM + NHL (neutral heavy lepton)
- large extra dimensions
- extended Higgs sector
- additional vector boson (Z')
- leptoquark
- SUSY-GUT and SUSY seesaw
- R-parity violating SUSY
- low-energy seesaw
- etc. etc.



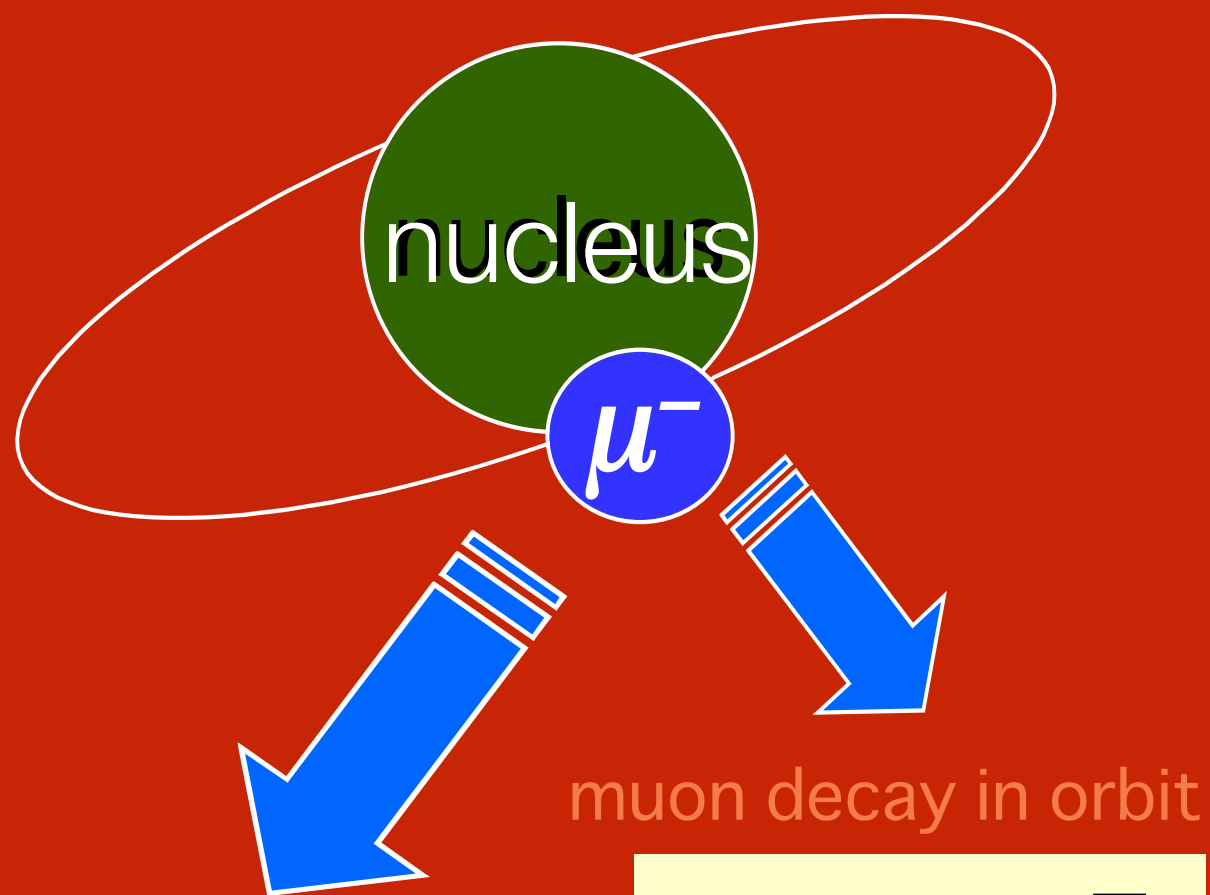
$\mu \rightarrow e$ conversion
in
a muonic atom

$$\text{CR}(\mu^- \text{N} \rightarrow e^- \text{N}) \equiv \frac{\Gamma(\mu^- \text{N} \rightarrow e^- \text{N})}{\Gamma(\mu^- \text{N} \rightarrow \text{all})}$$



$\mu \rightarrow e$ Conversion in a muonic atom

1s state in a muonic atom



muon decay in orbit

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

nuclear muon capture

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

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

coherent process

$$\propto Z^5$$

(for the case that the final nucleus is the ground state.)

Event Signature :

a single mono-energetic electron of 105 MeV

	Z	CR limit
sulphur	16	$< 7 \times 10^{-11}$
titanium	22	$< 4.3 \times 10^{-12}$
copper	39	$< 1.6 \times 10^{-8}$
gold	79	$< 7 \times 10^{-13}$
lead	82	$< 4.6 \times 10^{-11}$

Backgrounds for μ -e conversion



intrinsic physics
backgrounds

Muon decay in orbit (DIO)
Radiative muon capture (RMC)
neutrons from muon nuclear capture
Protons from muon nuclear capture

beam-related
backgrounds

Radiative pion capture (RPC)
Beam electrons
Muon decay in flights
Neutron background
Antiproton induced background

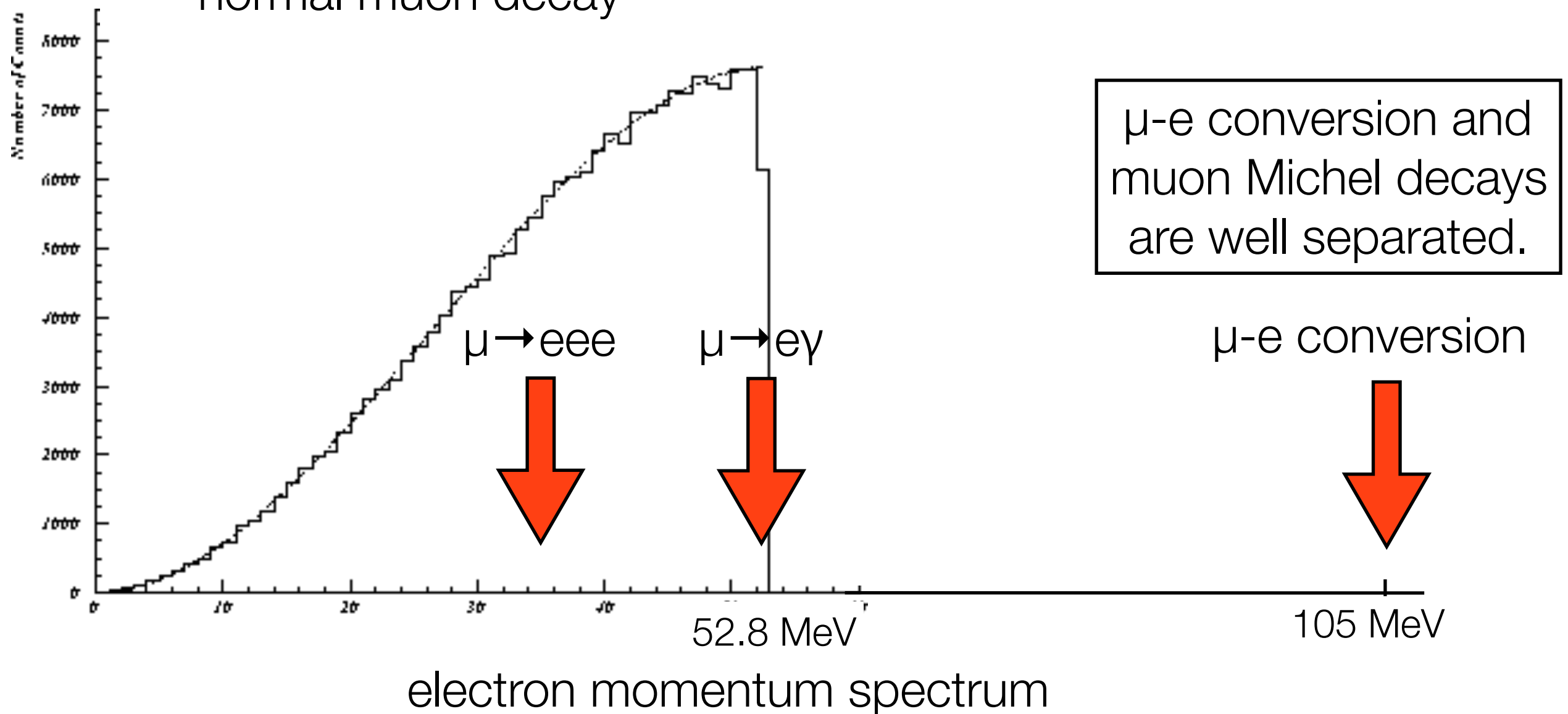
cosmic-ray and other
backgrounds

Cosmic-ray induced background
False tracking

Experimental Comparison : $\mu \rightarrow e\gamma$ and μ -e Conversion



normal muon decay



In order to make a new-generation experiment ...

$$B(\mu N \rightarrow e N) \leq 10^{-16}$$

1

Improvements for Signal Sensitivity

- Muon Production



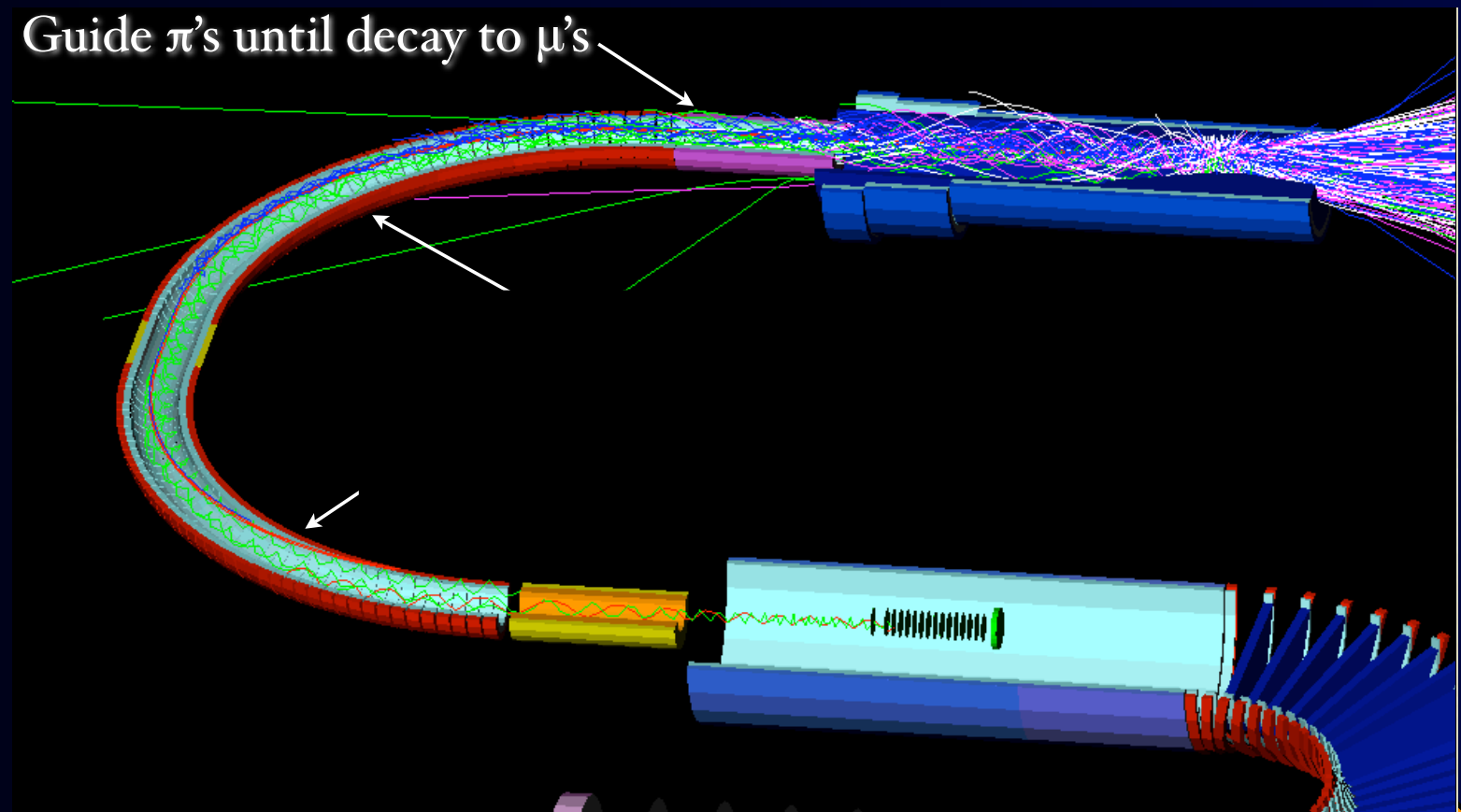
To achieve a single sensitivity of $<10^{-16}$, we need

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

2×10^{11} muons for
56 kW beam power

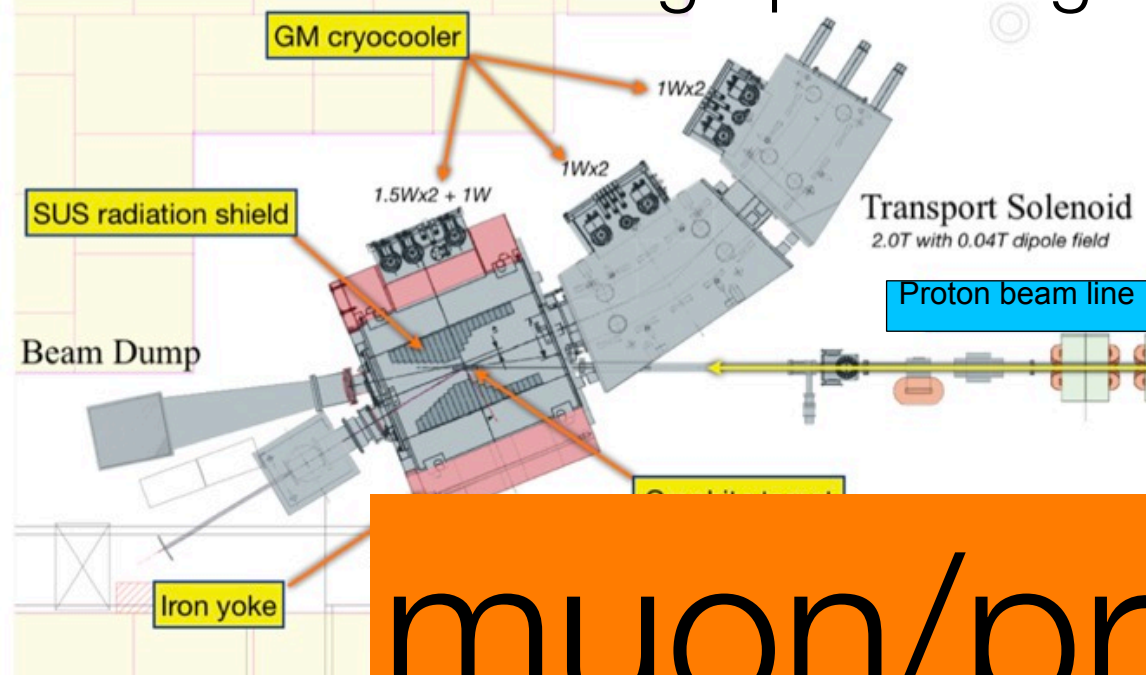


MuSIC at RCNP, Osaka University

- Highly Intense Muon Source -

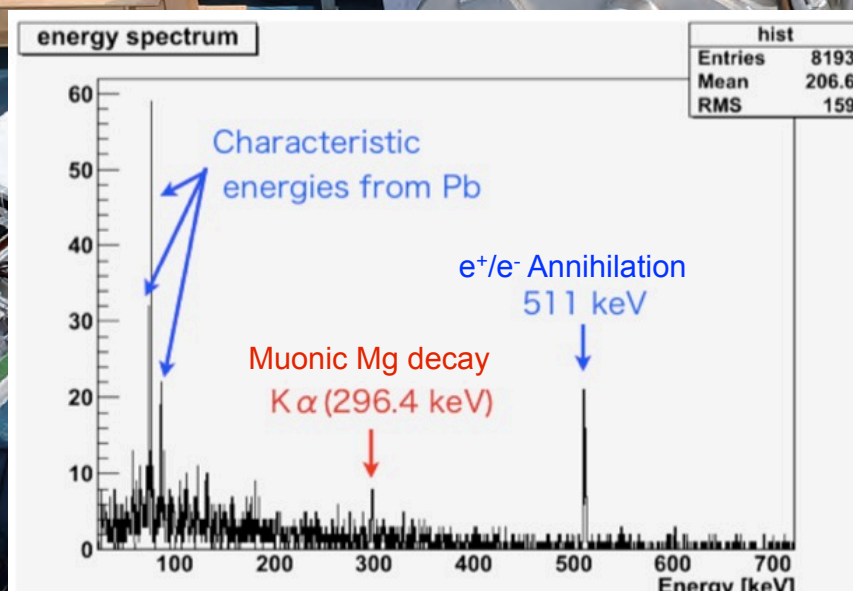
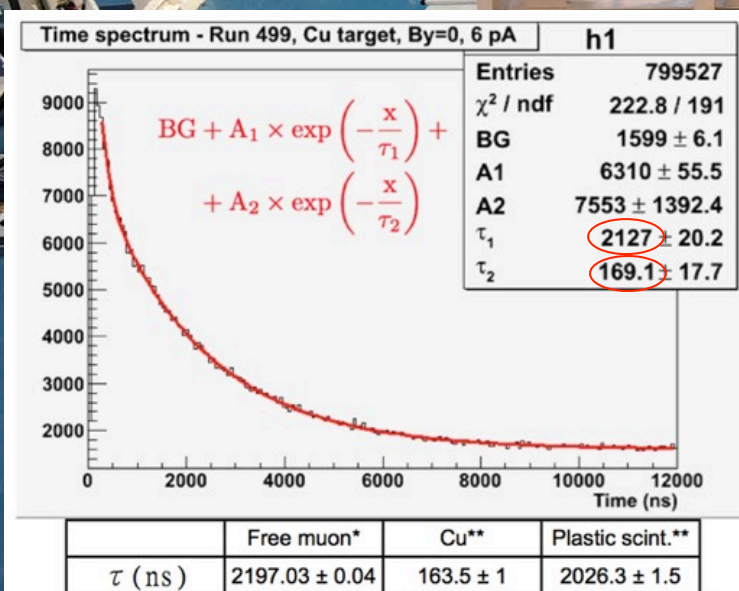


3.5T and graphite target



Muon Science Intense Channel (>2011)

muon/proton ~ x1000



MuSIC muon yields

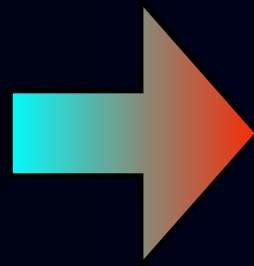
μ^+ : $3 \times 10^8/\text{s}$ for 400W

μ^- : $1 \times 10^8/\text{s}$ for 400W

2 Improvements for Background Rejection



Beam-related
backgrounds

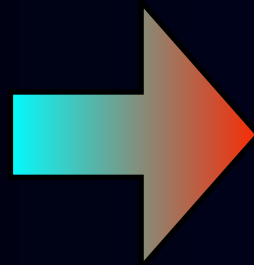


Beam pulsing with
separation of 1 μsec

measured
between beam
pulses

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

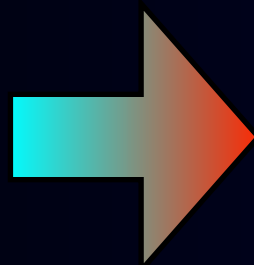
Muon DIO
background



low-mass trackers in
vacuum & thin target

improve
electron energy
resolution

Muon DIF
background



curved solenoids for
momentum selection

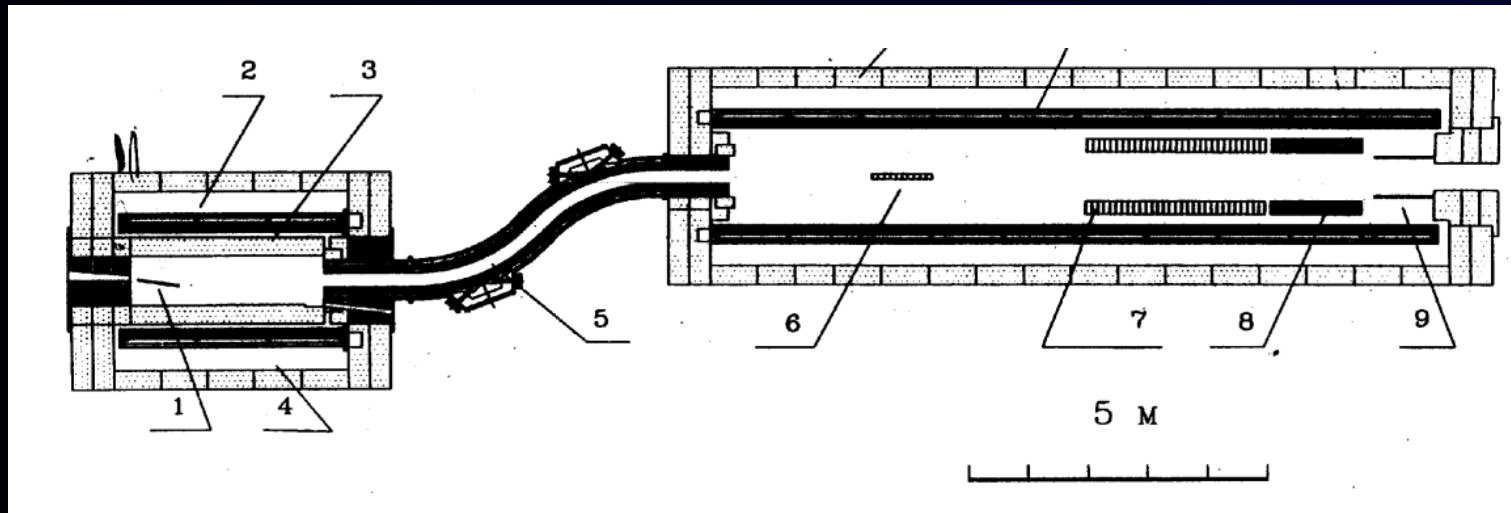
eliminate
energetic muons
(>75 MeV/c)

based on the MELC proposal at Moscow Meson Factory

From MELC to MECO



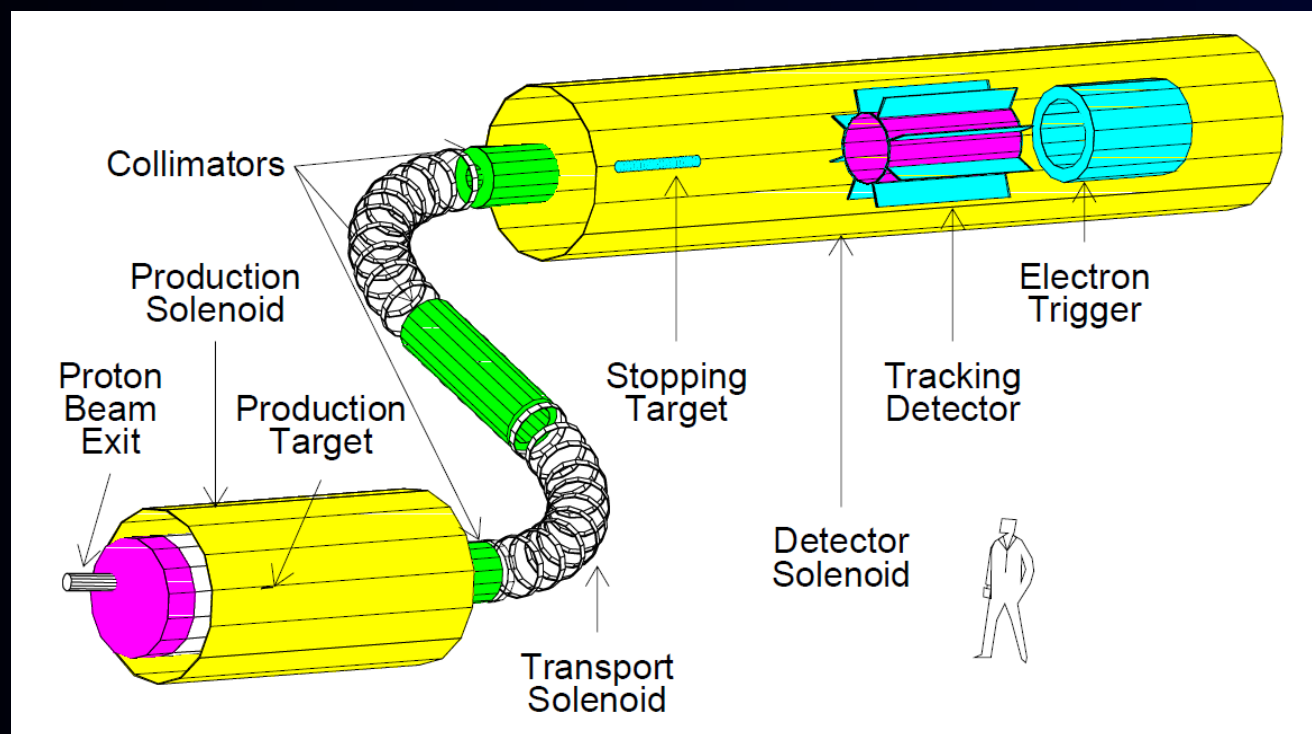
MELC



Proposal (1992)
at Moscow
Meson Factory

R. M. Dzhilkibaev and V. M. Lobashev, Sov. J. Nucl. Phys. 49, 384 (1989)

MECO



BNL E940 (1997)
one of the RSVP (rare
symmetry violating
processes with KOPIO)

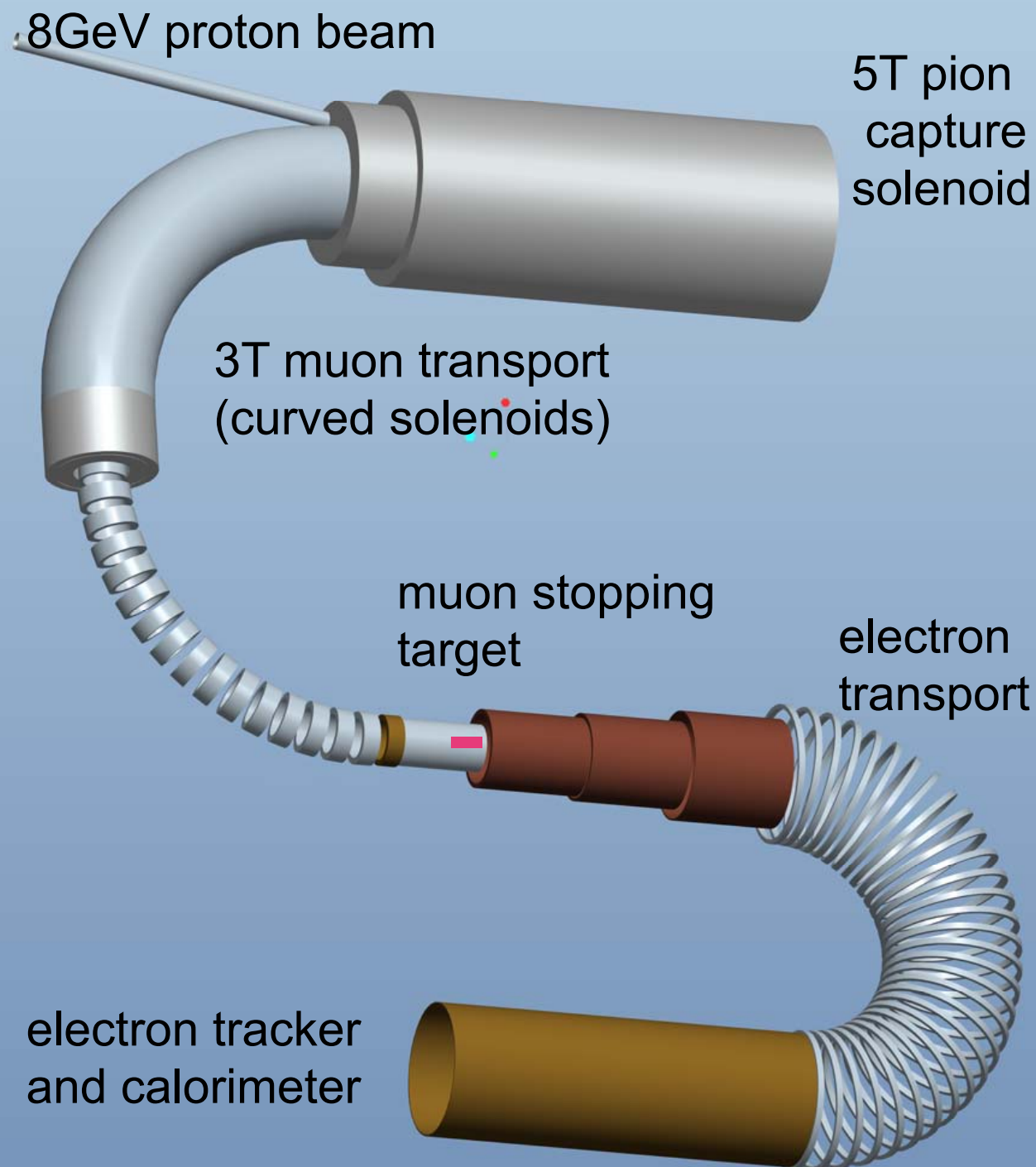
terminated in 2005

COMET@J-PARC



COMET = COherent Muon to Electron Transition

COMET at J-PARC: E21

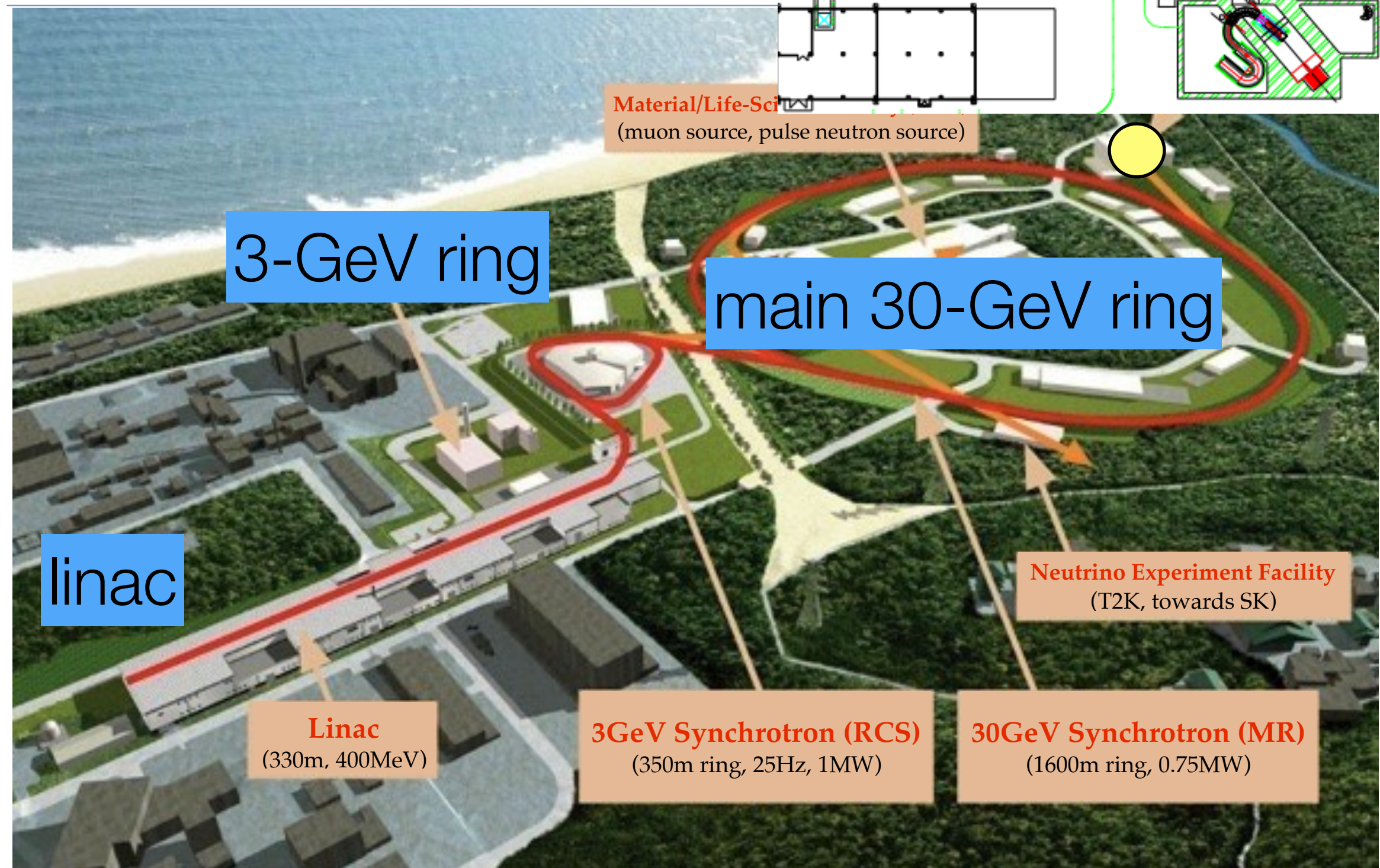
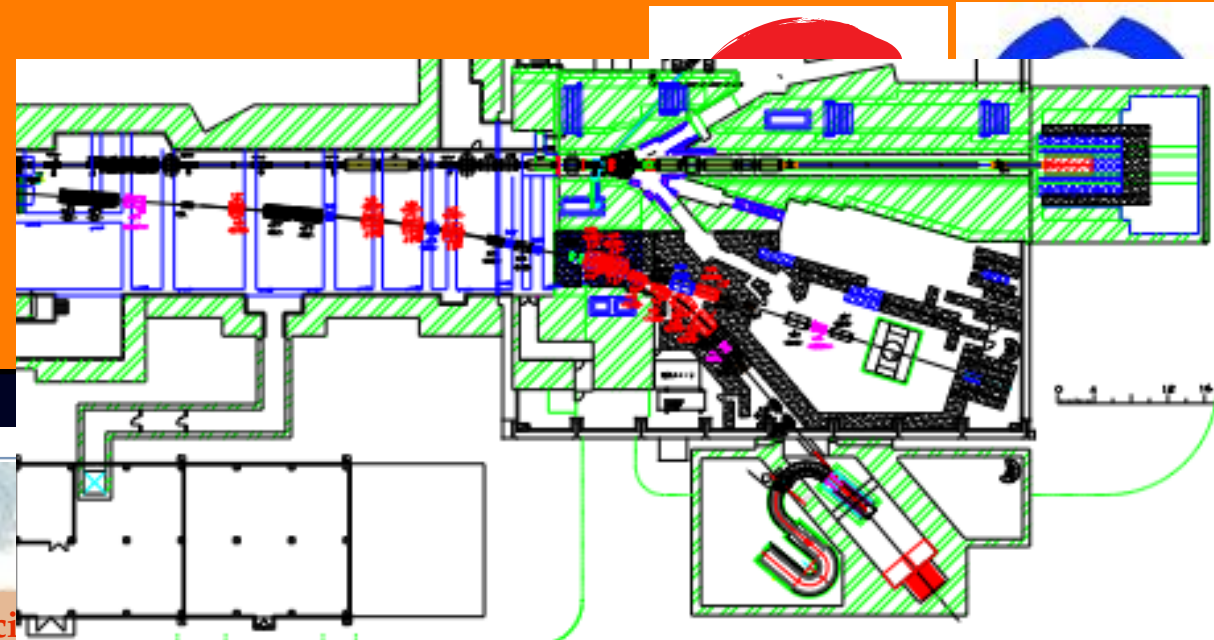


Single event sensitivity : 2.6×10^{-17}
Total background : 0.32 events
Expected limits : $< 6 \times 10^{-17} @ 90\% \text{CL}$
Running time: 1 years ($2 \times 10^7 \text{sec}$)

proton beam power = 56 kW



Proton Accelerator J-PARC



COMET Collaboration



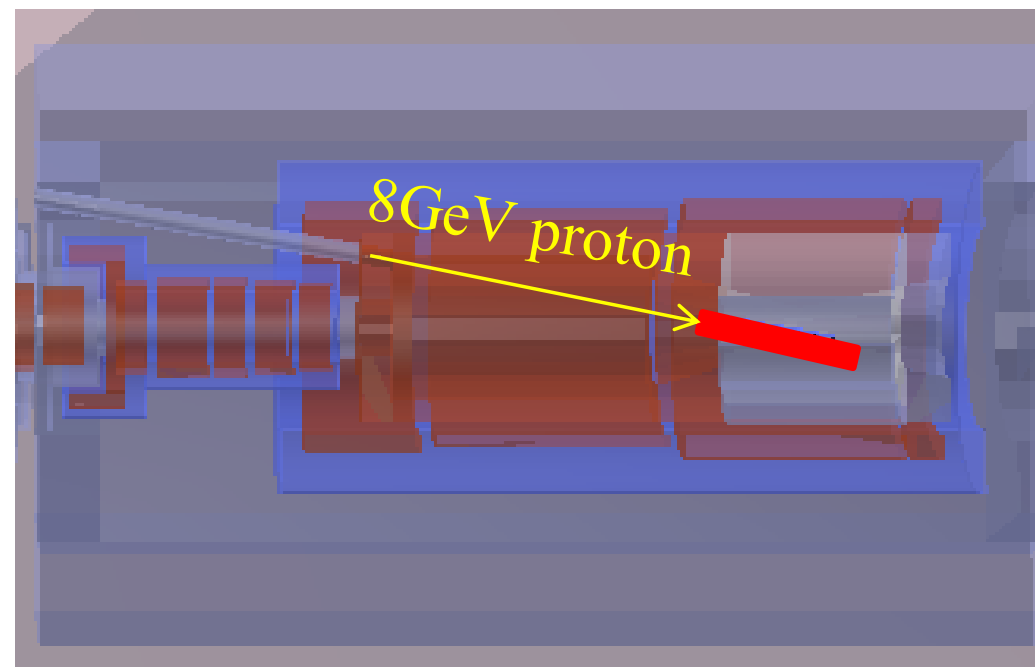
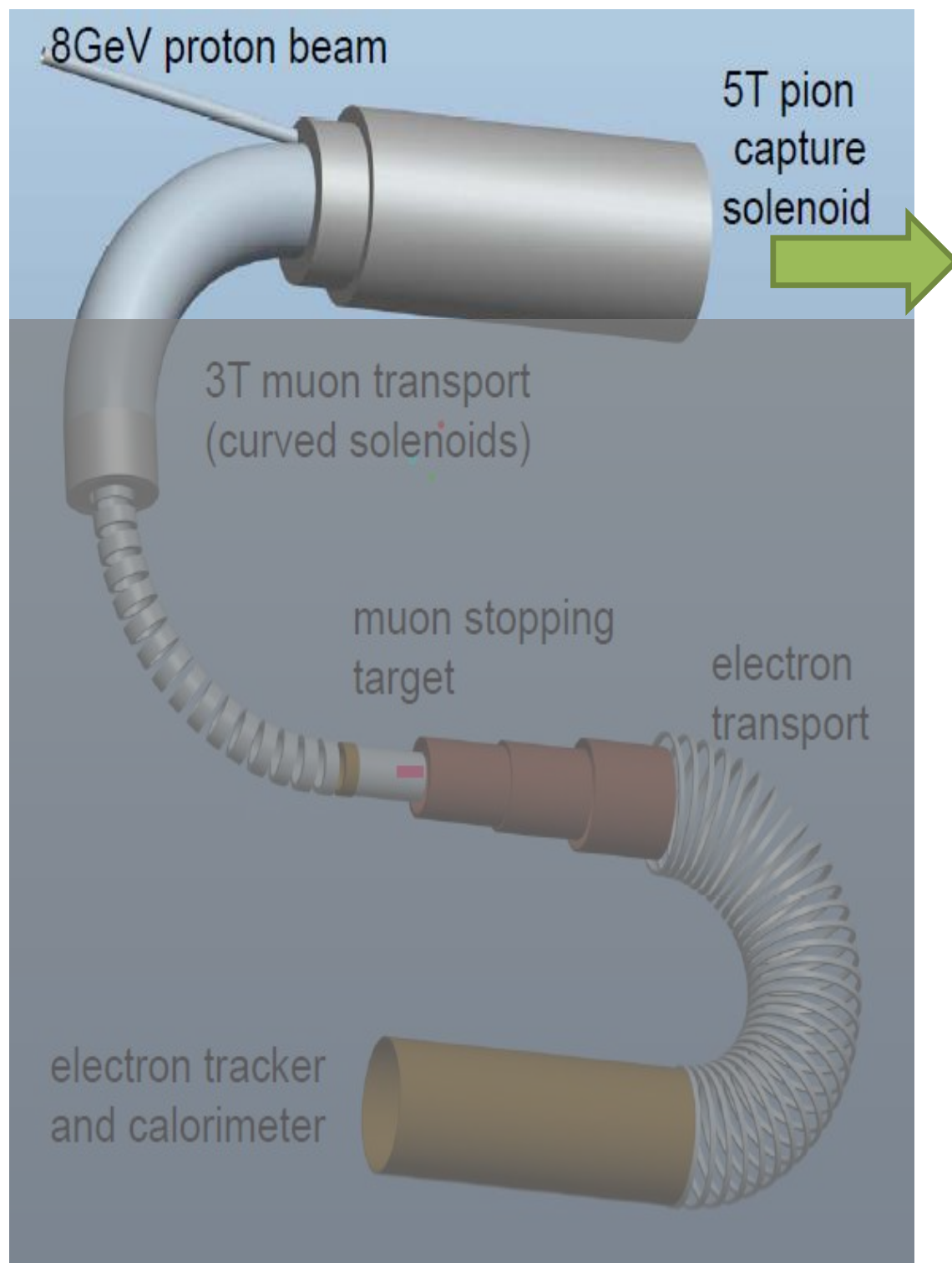
PI: Y. Kuno

The COMET Collaboration

R. Abramishvili¹¹, G. Adamov¹¹, R. Akhmetshin^{6,31}, V. Anishchik⁴, M. Aoki³², Y. Arimoto¹⁸, I. Bagaturia¹¹, Y. Ban³, A. Bondar^{6,31}, Y. Calas⁷, S. Canfer³³, Y. Cardenas⁷, S. Chen²⁸, Y. E. Cheung²⁸, B. Chiladze³⁵, D. Clarke³³, M. Danilov^{15,26}, P. D. Dauncey¹⁴, J. David²³, W. Da Silva²³, C. Densham³³, G. Devidze³⁵, P. Dornan¹⁴, A. Drutskoy^{15,26}, V. Duginov¹⁶, L. Epshteyn^{6,30}, P. Evtoukhovich¹⁶, G. Fedotov^{6,31}, M. Finger⁸, M. Finger Jr⁸, Y. Fujii¹⁸, Y. Fukao¹⁸, J-F. Genat²³, E. Gillies¹⁴, D. Grigoriev^{6,30,31}, K. Gritsay¹⁶, E. Hamada¹⁸, R. Han¹, K. Hasegawa¹⁸, I. H. Hasim³², O. Hayashi³², Z. A. Ibrahim²⁴, Y. Igarashi¹⁸, F. Ignatov^{6,31}, M. Iio¹⁸, M. Ikeno¹⁸, K. Ishibashi²², S. Ishimoto¹⁸, T. Itahashi³², S. Ito³², T. Iwami³², X. S. Jiang², P. Jonsson¹⁴, V. Kalinnikov¹⁶, F. Kapusta²³, H. Katayama³², K. Kawagoe²², N. Kazak⁵, V. Kazanin^{6,31}, B. Khazin^{6,31}, A. Khvedelidze^{16,11}, T. K. Ki¹⁸, M. Koike³⁹, G. A. Kozlov¹⁶, B. Krikler¹⁴, A. Kulikov¹⁶, E. Kulish¹⁶, M. Lancaster¹⁴, D. Lomidze¹⁵, O. Markin¹⁵, hamed Kam¹⁵, T. Nakamoto³⁶, T. Numao³⁶, J. O'Dell³³, T. Ogitsu¹⁸, K. Oishi²², K. Okamoto³², C. Omori¹⁸, T. Ota³⁴, J. Pasternak¹⁴, C. Plostinar³³, V. Ponariadov⁴⁵, A. Popov^{6,31}, V. Rusinov^{15,26}, A. Ryzhenenkov^{6,31}, B. Sabirov¹⁶, N. Saito¹⁸, H. Sakamoto³², P. Sarin¹³, K. Sasaki¹⁸, A. Sato³², J. Sato³⁴, Y. K. Semertzidis^{12,17}, D. Shemyakin^{6,31}, N. Shigyo²², D. Shoukavy⁵, M. Slunicka⁸, A. Straessner³⁷, D. Stöckinger³⁷, M. Sugano¹⁸, Y. Takubo¹⁸, M. Tanaka¹⁸, S. Tanaka²², C. V. Tao²⁹, E. Tarkovsky^{15,26}, Y. Tevzadze³⁵, T. Thanh²⁹, N. D. Thong³², J. Tojo²², M. Tomasek¹⁰, M. Tomizawa¹⁸, N. H. Tran³², H. Trang²⁹, I. Trekov³⁵, N. M. Truong³², Z. Tsamalaidze^{16,11}, N. Tsverava^{16,35}, T. Uchida¹⁸, Y. Uchida¹⁴, K. Ueno¹⁸, E. Velicheva¹⁶, A. Volkov¹⁶, V. Vrba¹⁰, W. A. T. Wan Abdullah²⁴, M. Warren³⁸, M. Wing³⁸, T. S. Wong³², C. Wu^{2,28}, H. Yamaguchi²², A. Yamamoto¹⁸, Y. Yang²², W. Yao², Y. Yao², H. Yoshida³², M. Yoshida¹⁸, Y. Yoshii¹⁸, T. Yoshioka²², Y. Yuan², Y. Yudin^{6,31}, J. Zhang², Y. Zhang², K. Zuber³⁷

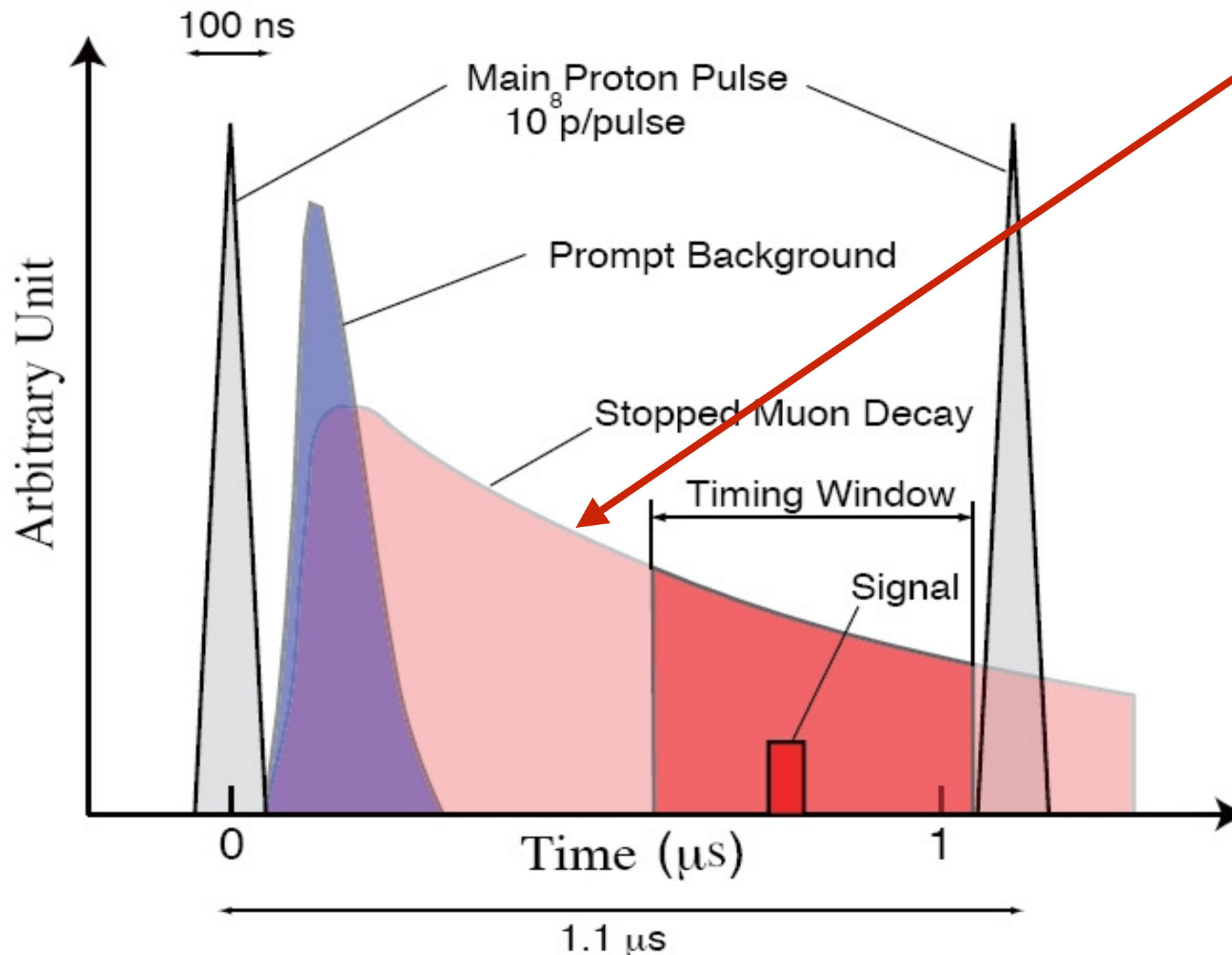
about 200 collaborators
41 institutes, 17 countries

Pion Capture Section



- 8 GeV 56 kW proton beam
- Thick target with **1~2 hadron interaction length**
- Powerful capture magnet: **5 T**
 - Large inner bore to fit in the shielding
 - **Adiabatic decreasing** field: focusing and mirroring
- Expected muon yield: **10^{11} muon/sec!** (10^8 @ PSI)

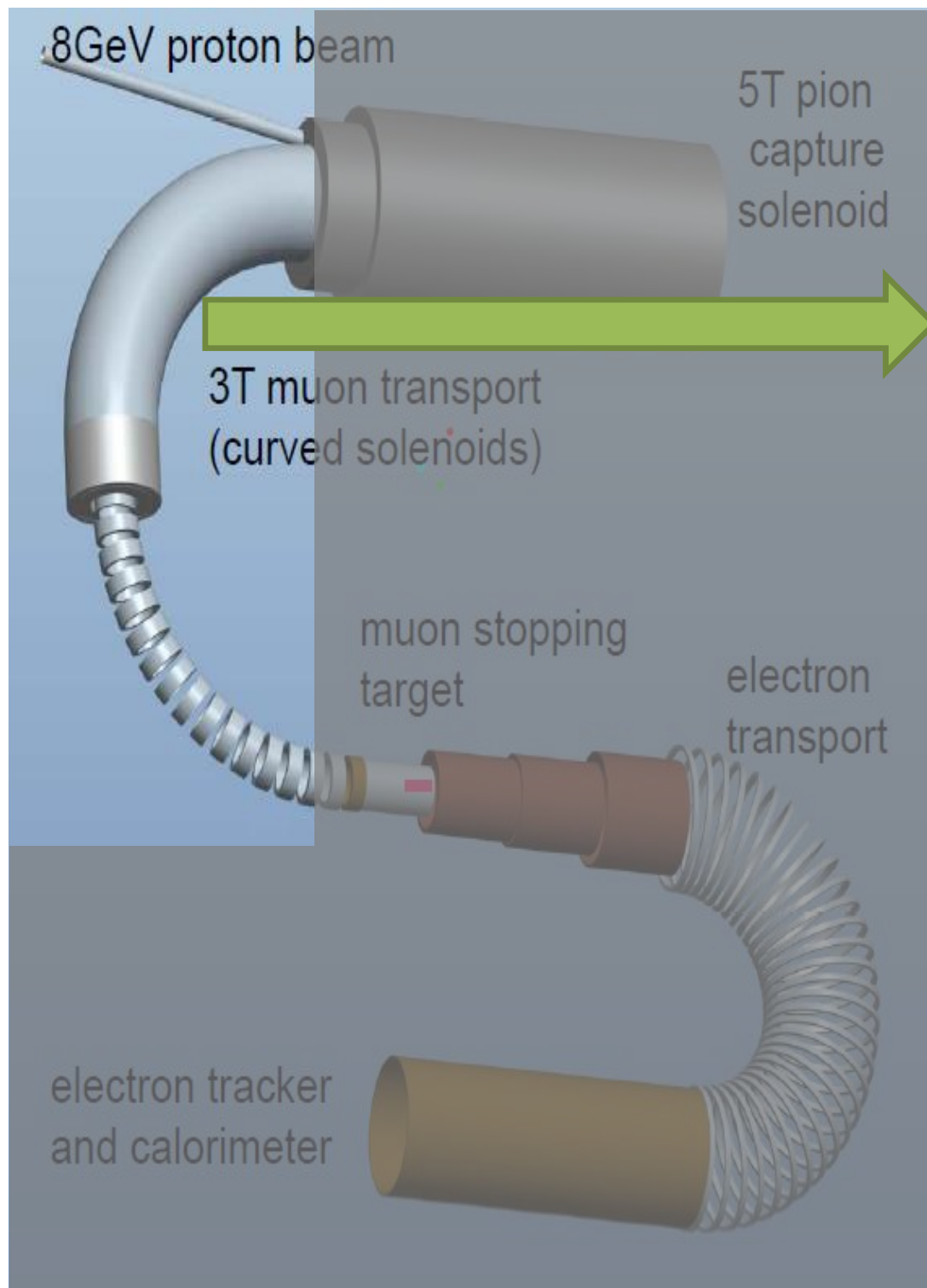
Pulsed 8-GeV Proton Beam for COMET



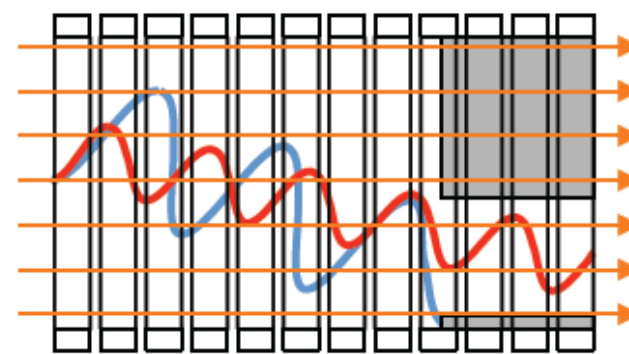
A lifetime of a muonic atom in aluminium ~ 864 ns

proton extinction factor (between pulses) $\sim 10^{-10}$

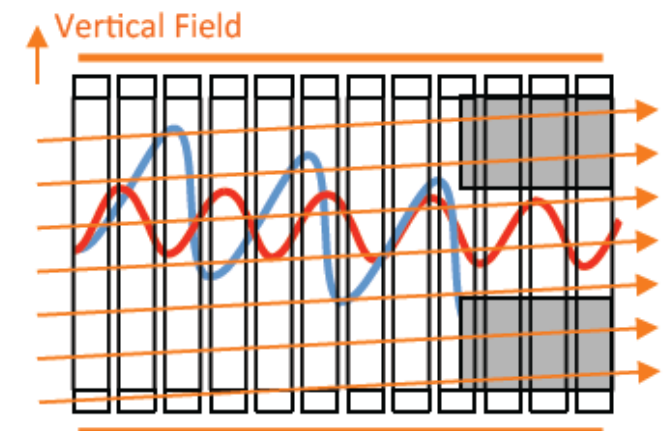
Muon Transport Section



Drift vertically, proportional to momentum.



Vertical field as “correction”

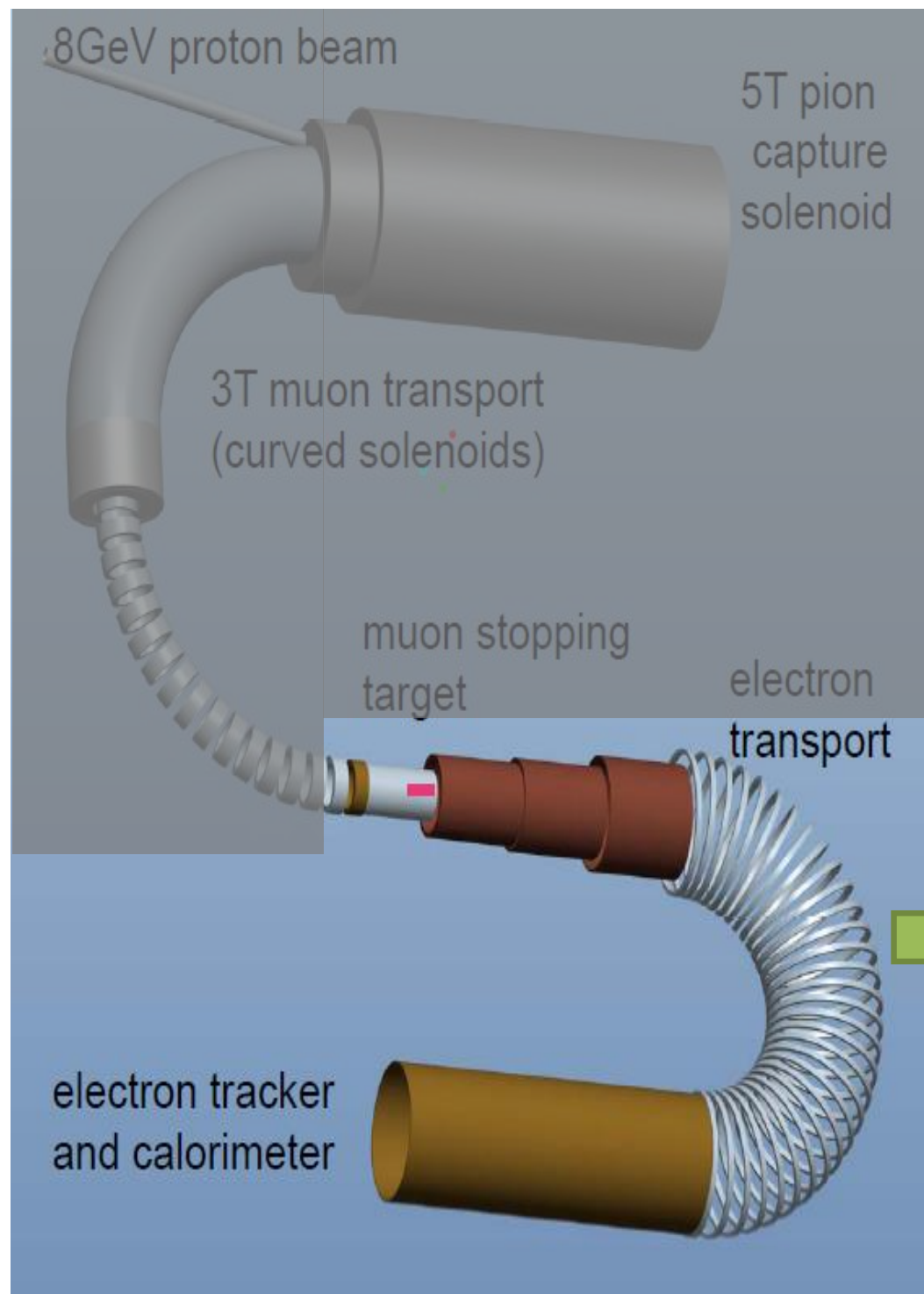


— High momentum track
— Low momentum track

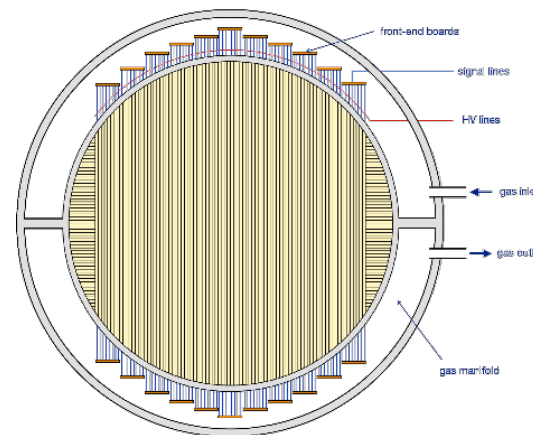
■ Beam collimator

- Use **C shape** curved solenoid
 - Beam gradually disperses
 - Charge & momentum
 - **Dipole field** to pull back muon beam
 - Can be used to tune the beam
 - Collimator placed in the end
 - Utilize the dispersion in **180** degrees

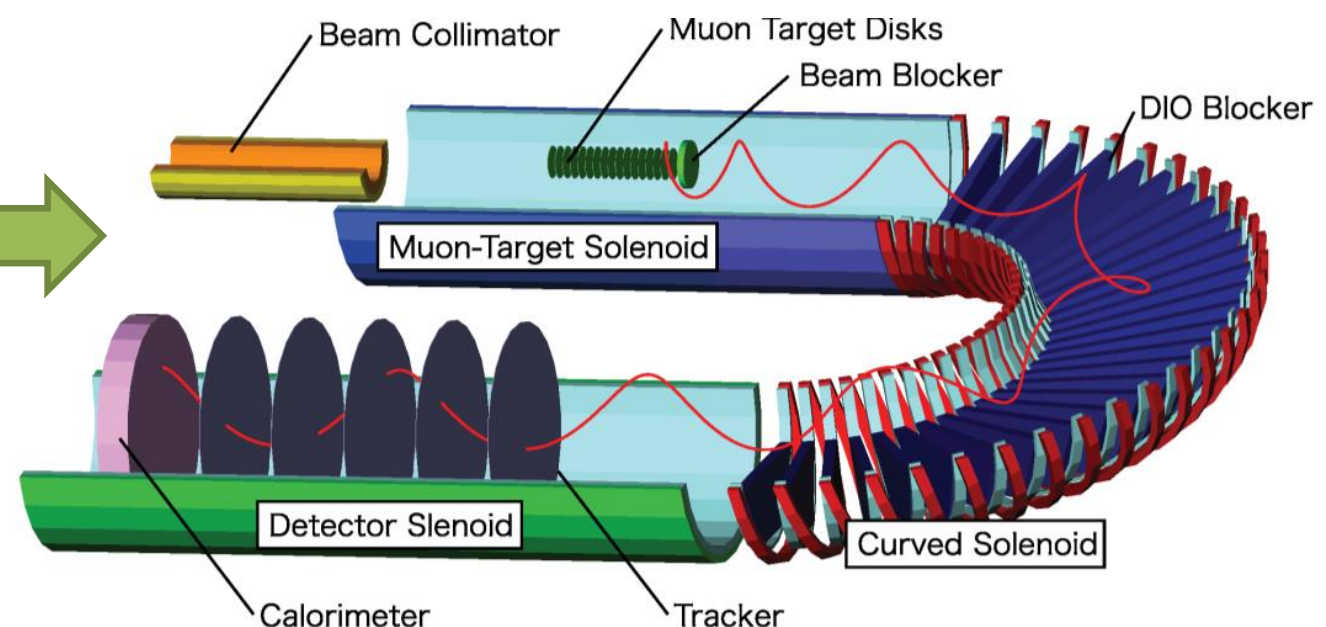
Muon Stopping Target and Detector Section



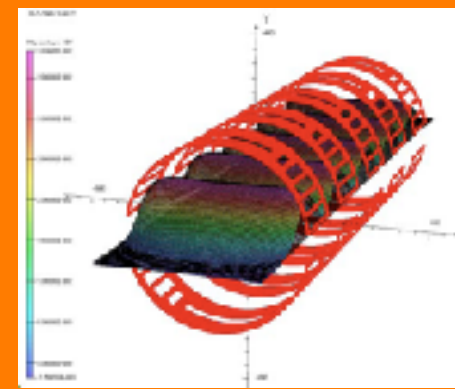
- Use **straw tracker** to measure the momentum
 - Really light: put in vacuum, 12 micro meter thin straw



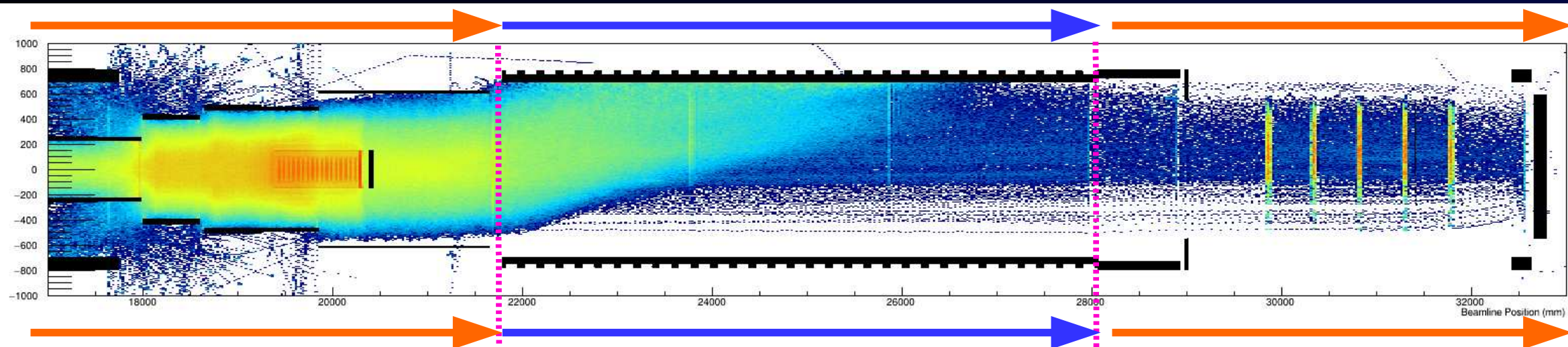
- **Electromagnetic calorimeter**
 - Providing trigger, TOF and PID



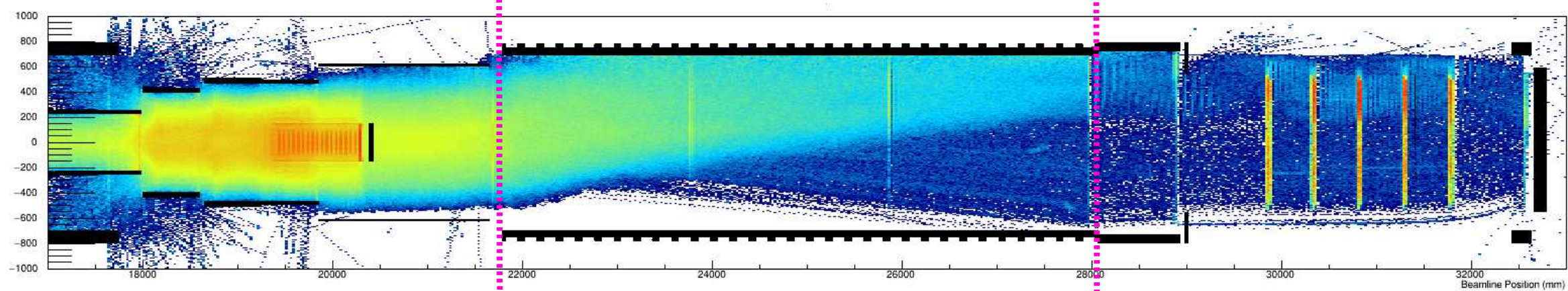
Curved Solenoid + Dipole Magnetic Field



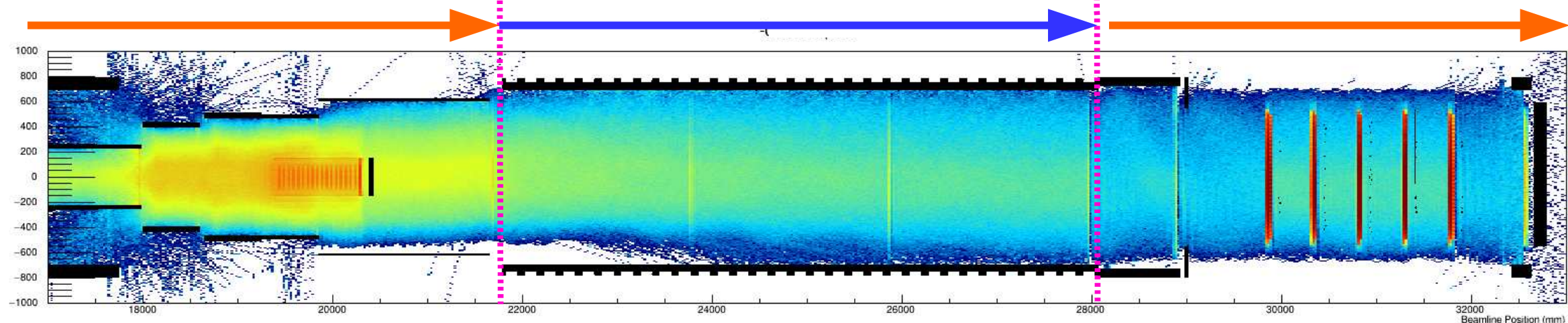
no
dipole



-0.08T
dipole



-0.22T
dipole



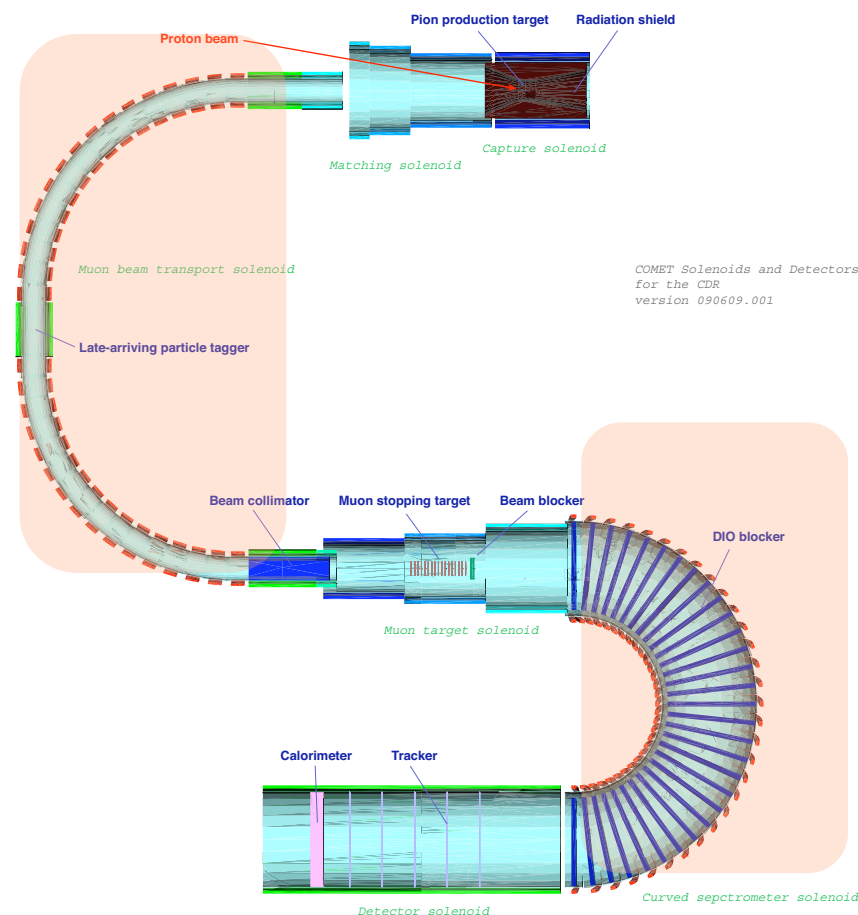
Stopping Target

Electron Spectrometer

Detector

COMET Features

- difference from the original MECO



COMET Solenoids and Detectors
for the CDR
version 090609.001

Selection of low momentum muons

- eliminate 105 MeV electrons from muon decays in flight

momentum selection capability
is proportional to bending angle

Selection of 105 MeV signal electrons

- eliminate neutrons and gamma-rays from muon target
- eliminate protons from muon target
- eliminate low energy electrons from muon decays from muon target

muon
beam line

2x 90° bend
(same direction)

electron
spectrometer

180° bend
curved solenoids

Staged Approach

COMET Phase-I



Phase-I

proton beam power = 3.2 kW

Single event sensitivity : 2×10^{-15}
a factor of 100 improvement
Running time: 0.4 years (1.2×10^7 s)

proton
beam

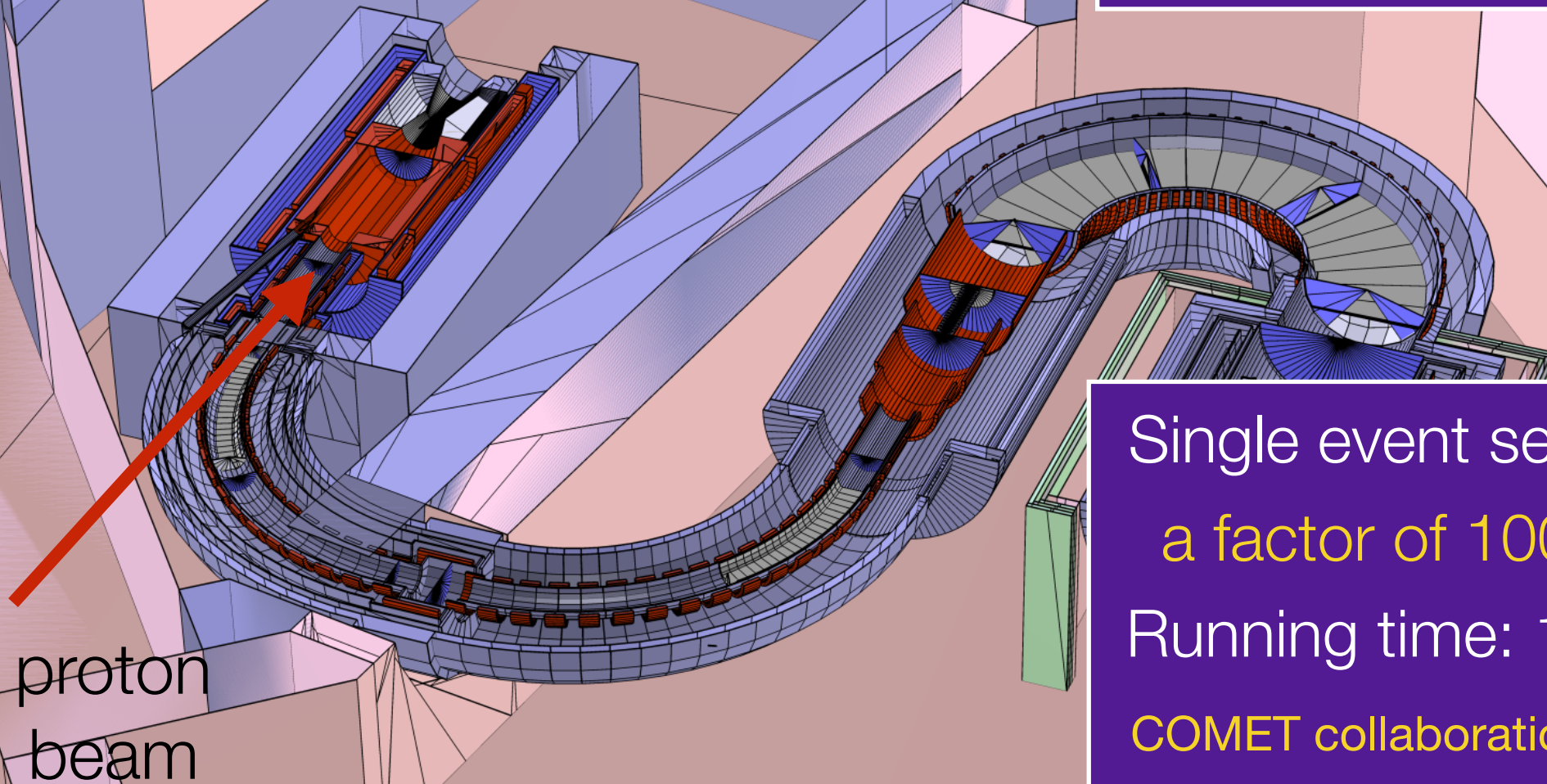
COMET Phase-II



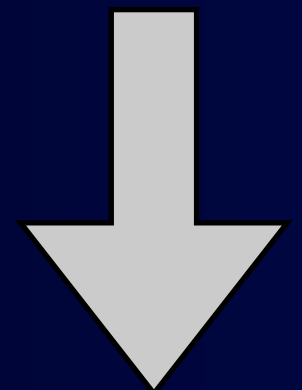
Phase-II

proton beam power = 56 kW

Single event sensitivity : 2.6×10^{-17}
a factor of 10,000 improvement
Running time: 1 years (2×10^7 sec)



Single event sensitivity : $O(10^{-18})$
a factor of 100,000 improvement
Running time: 1 years (2×10^7 sec)
COMET collaboration, arXiv:1812.07824, 2018



COMET Phase-I Status



Two Detectors, CyDet and StrECAL , for COMET Phase-I



an apparatus to
search for μ -e
conversion at
Phase-I

an apparatus to
measure a muon
beam at Phase-I
and a prototype for
Phase-II

Cylindrical Drift Chamber

Muon Stopping Target

Trigger Hodoscope

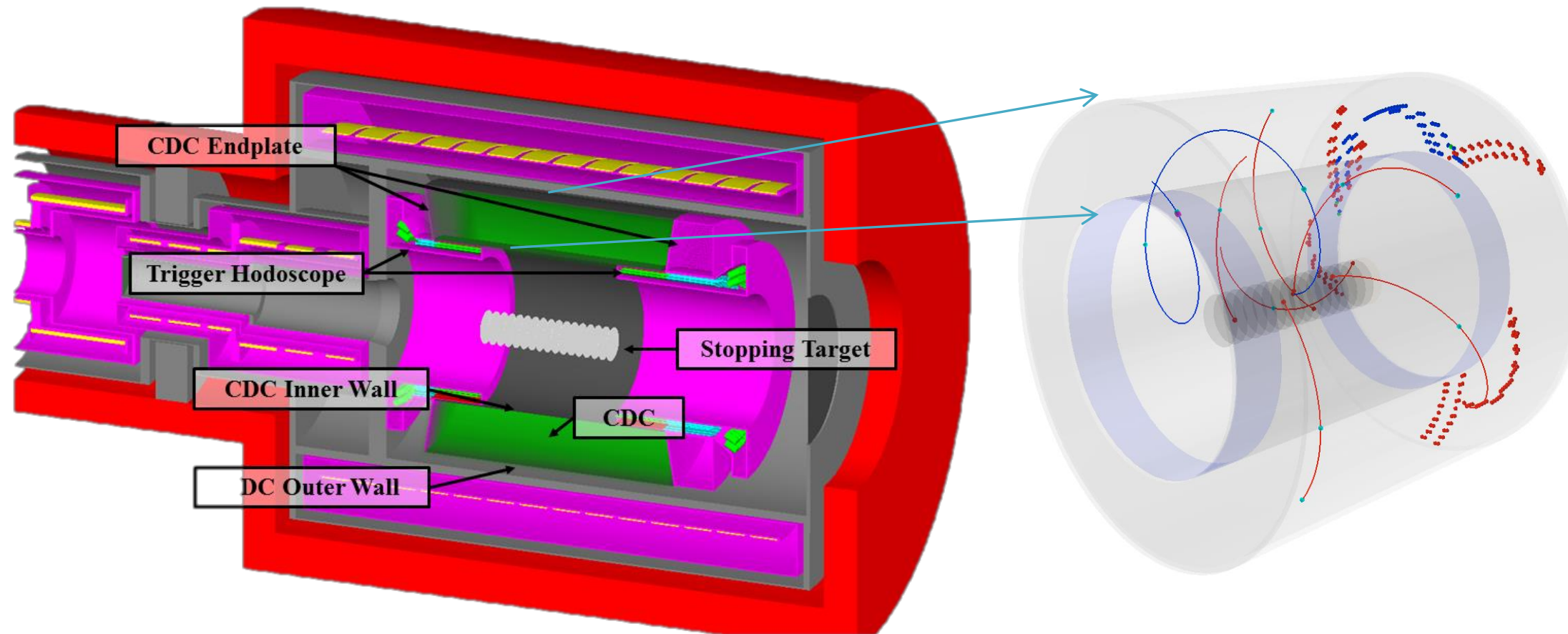
CyDet

Straw Tube Tracker

ECAL

StrECAL

CyDet (Cylindrical Detector System)

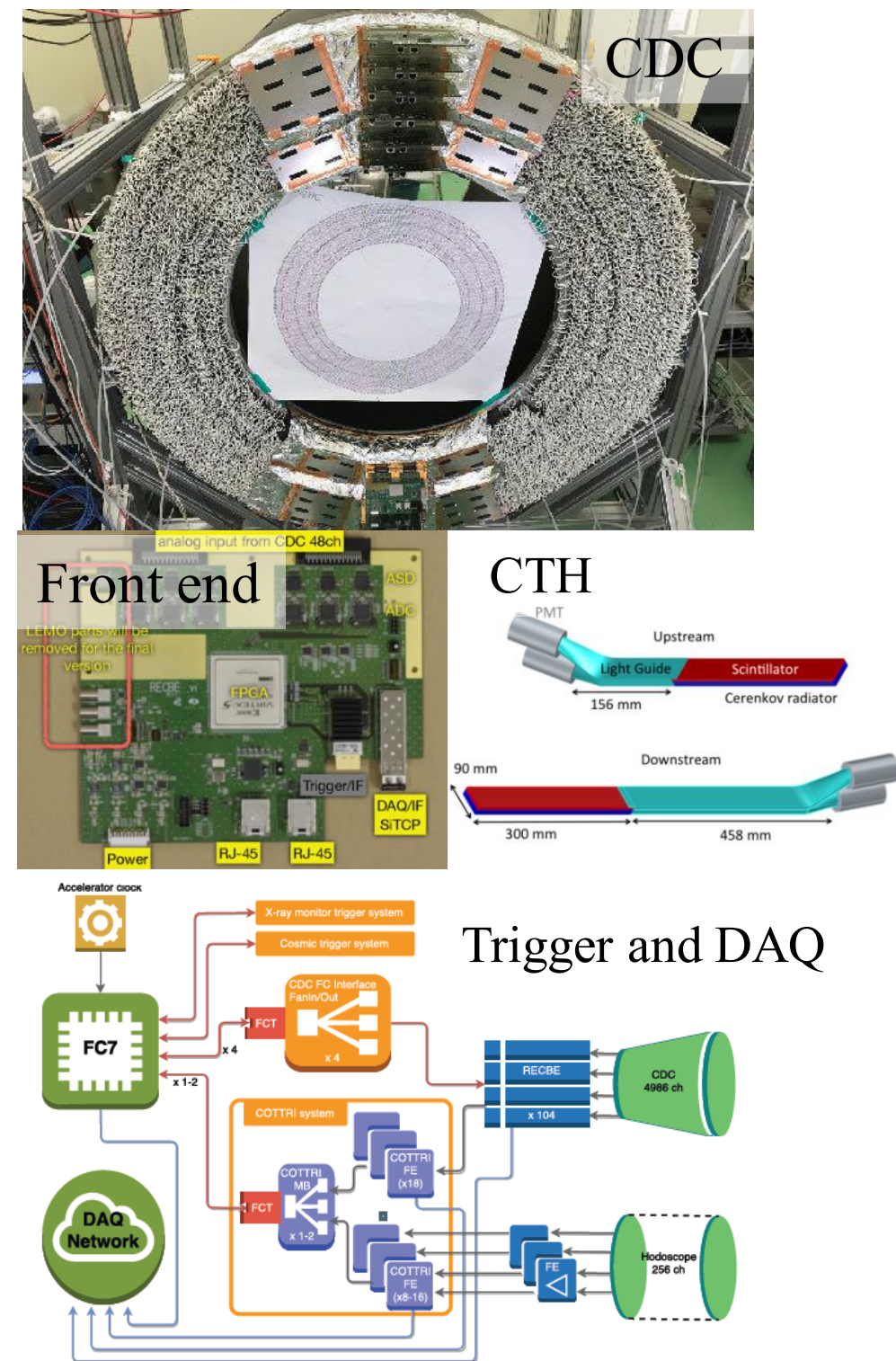


- Specially designed for Phase-I. Consists of:
 - Cylindrical trigger hodoscope (CTH):
 - Two layers: plastic scintillator for t_0 and Cerenkov counter for PID.
 - Cylindrical drift chamber (CDC):
 - All stereo layers: z information for tracks with few layers' hits.
 - Helium based gas: minimize multiple scattering.
 - Large inner bore: to avoid beam flash and DIO electrons.

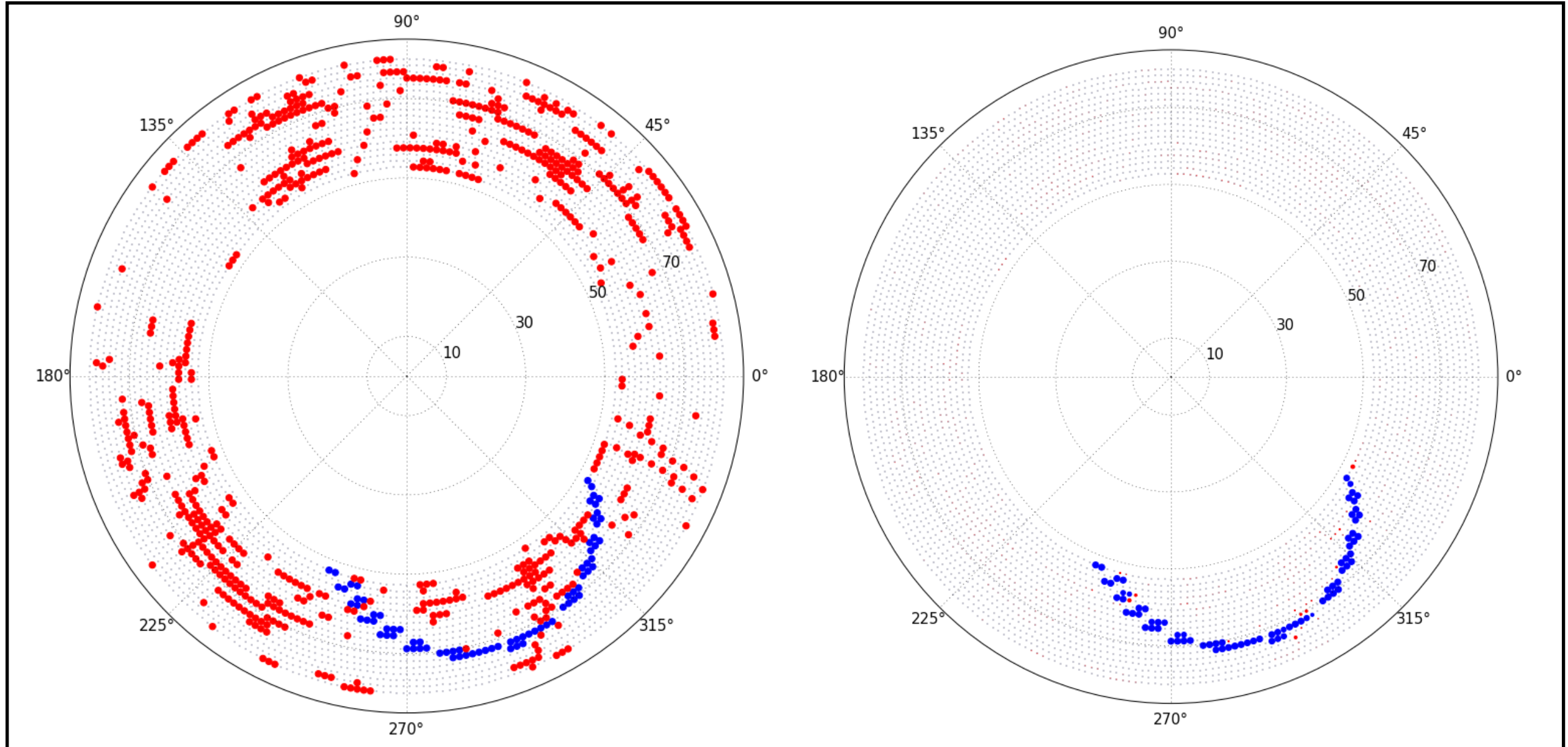
CyDet (Cylindrical Detector System)



- Cylindrical Drift chamber (CDC)
 - Prototype tests finished in 2015. 150 μm spatial resolution and 99% hit efficiency were achieved.
 - Construction of the chamber was finished in 2016.
 - Cosmic ray test is under data taking phase.
- Front end electronics
 - Based on RECBE boards from BELLE-II
 - Finished the production and mass tests of 108 boards.
 - Radiation tests are published / to be published.
- Trigger system
 - Cylindrical trigger hodoscope (CTH) under mechanical design.
 - Trigger logic and trigger board design finished. Communication tests with FCT-FC7 trigger system is on going.



Track Finding in COMET Phase-I Machine Learning

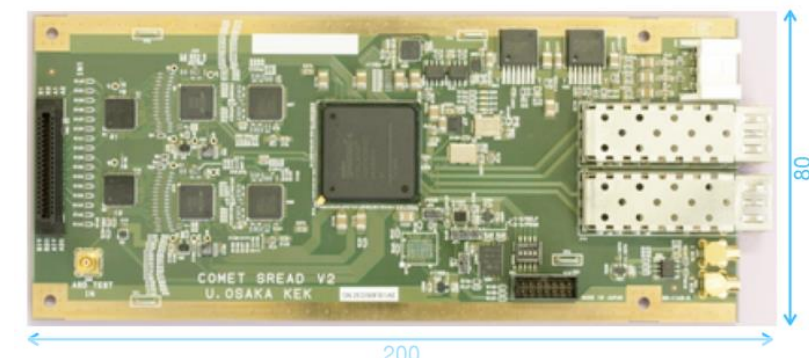
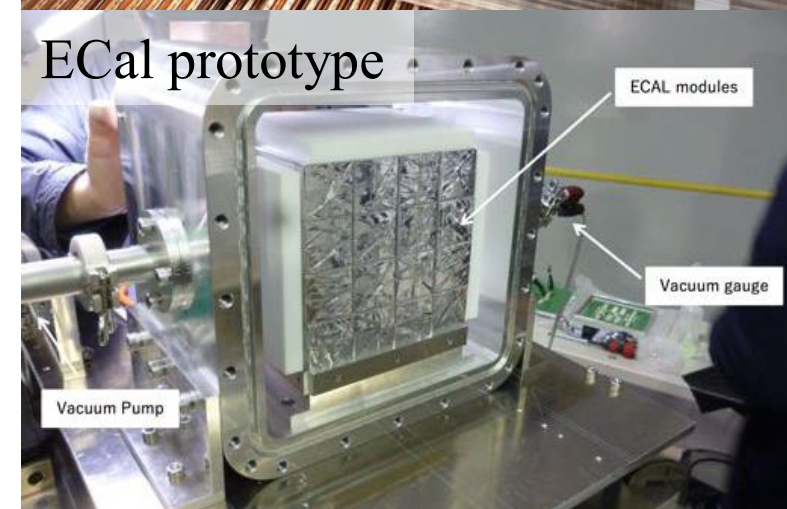


based on Boosted Decision Tree Method and Hough transformation

StrECAL (Straw Chamber+ECAL)

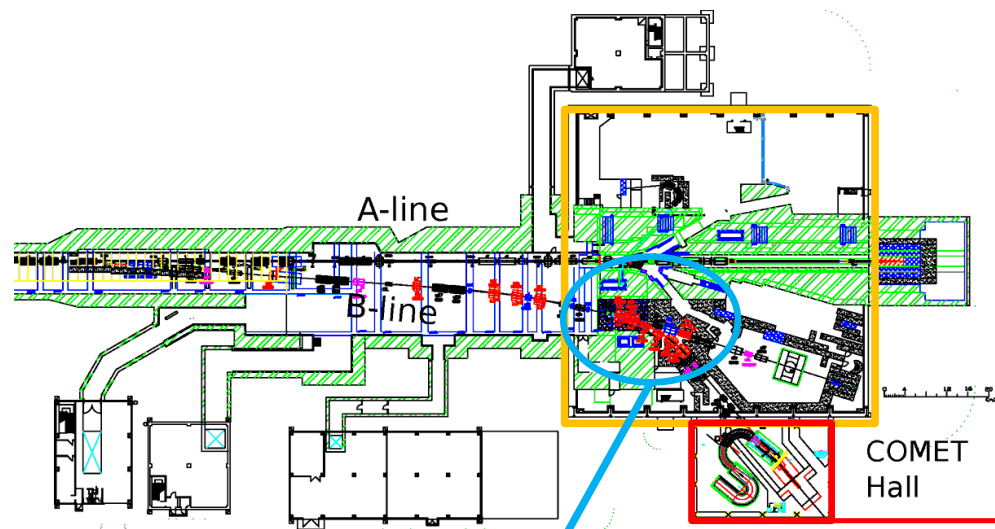


- Straw tube detector
 - Finished vacuum test with 20 μ m straw tubes.
 - Mass production for Phase-I finished.
 - Tested with 100 MeV electron beam. 150 μ m spatial resolution achieved.
- Electromagnetic calorimeter
 - Tested GSO and LYSO. Preliminary resolutions are 5.7% and 4.6% for each. LYSO chosen as final option.
- Front end electronics
 - Finished designing (ROESTI/EROS) based on DRS4 with GHz sampling rate.
 - Radiation tests results published.



Front end electronics: ROESTI/EROS

COMET Facility



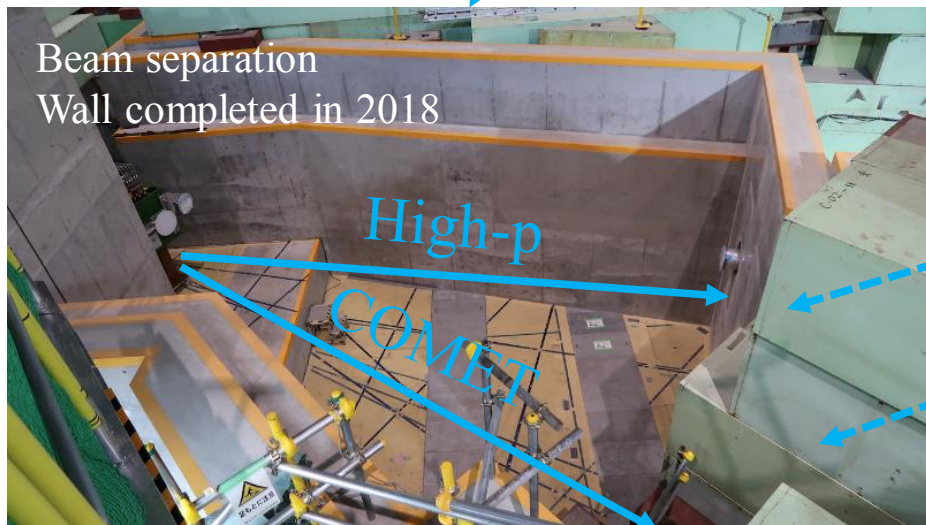
COMET Experimental Hall
Constructed in 2015



Installation Yard in 2015



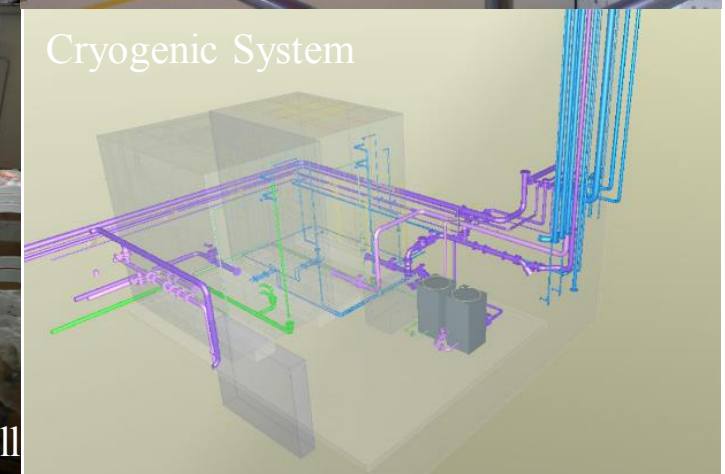
Beam separation
Wall completed in 2018



Experiment Room in 2019



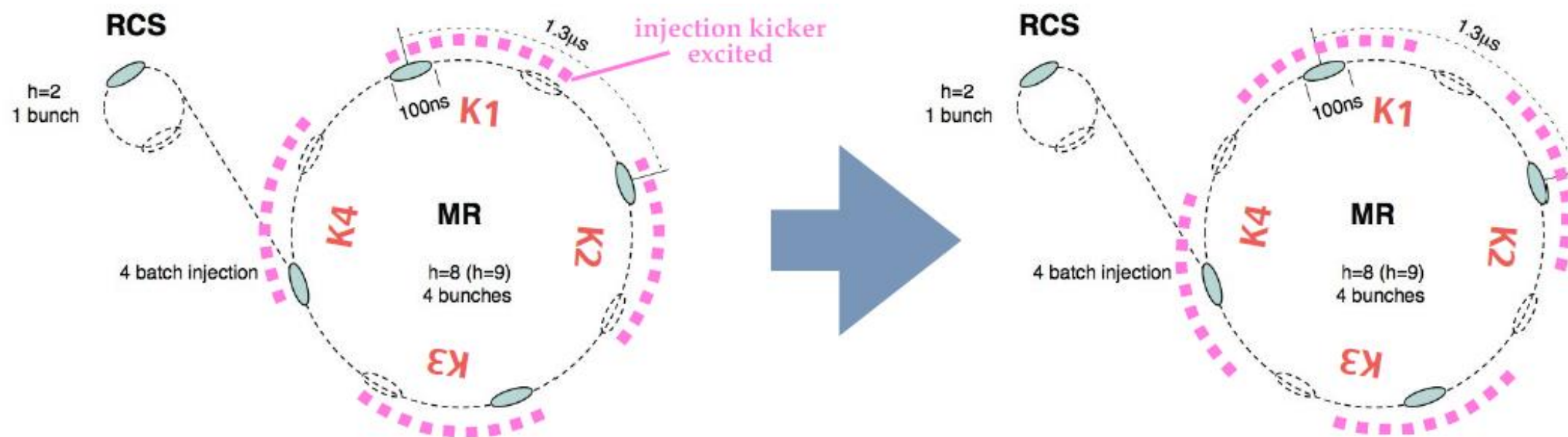
Cryogenic System



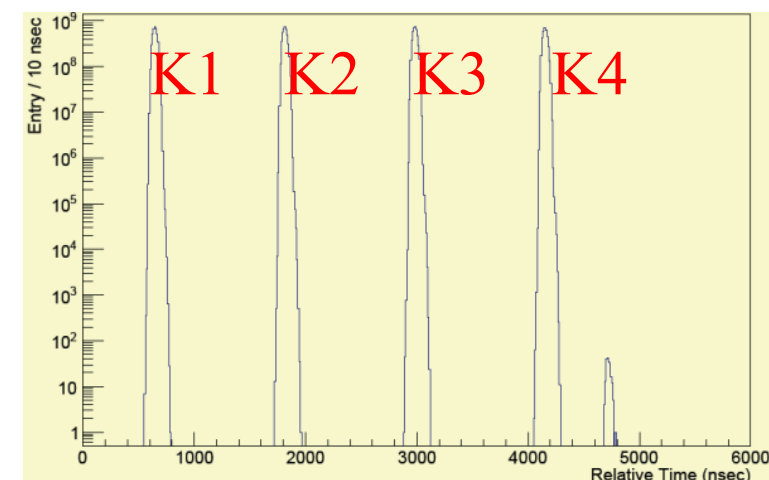
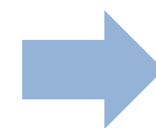
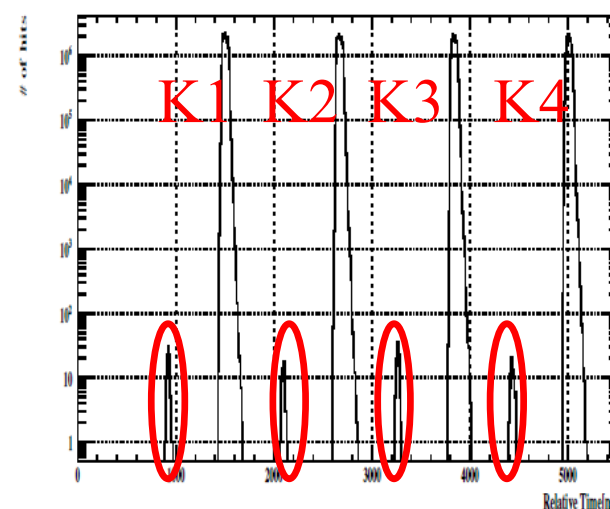
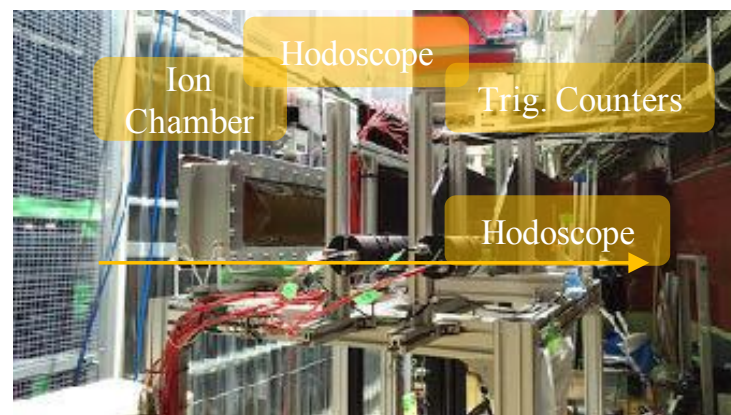
- Experimental Hall building completed
- Cryogenic system under construction
- Proton beamline will be ready this year
 - Shield wall & power station completed. 2 more magnets to be located soon.

Proton Extinction Measurement

- To make the proton extinction factor $< 10^{-10}$
 - Shift the kicker phase by half period to avoid residual protons in the empty bucket.

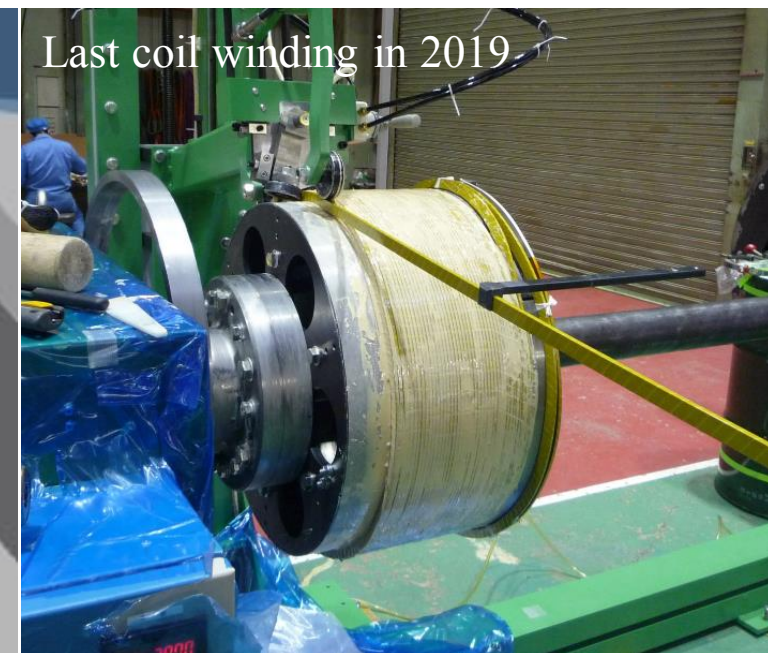
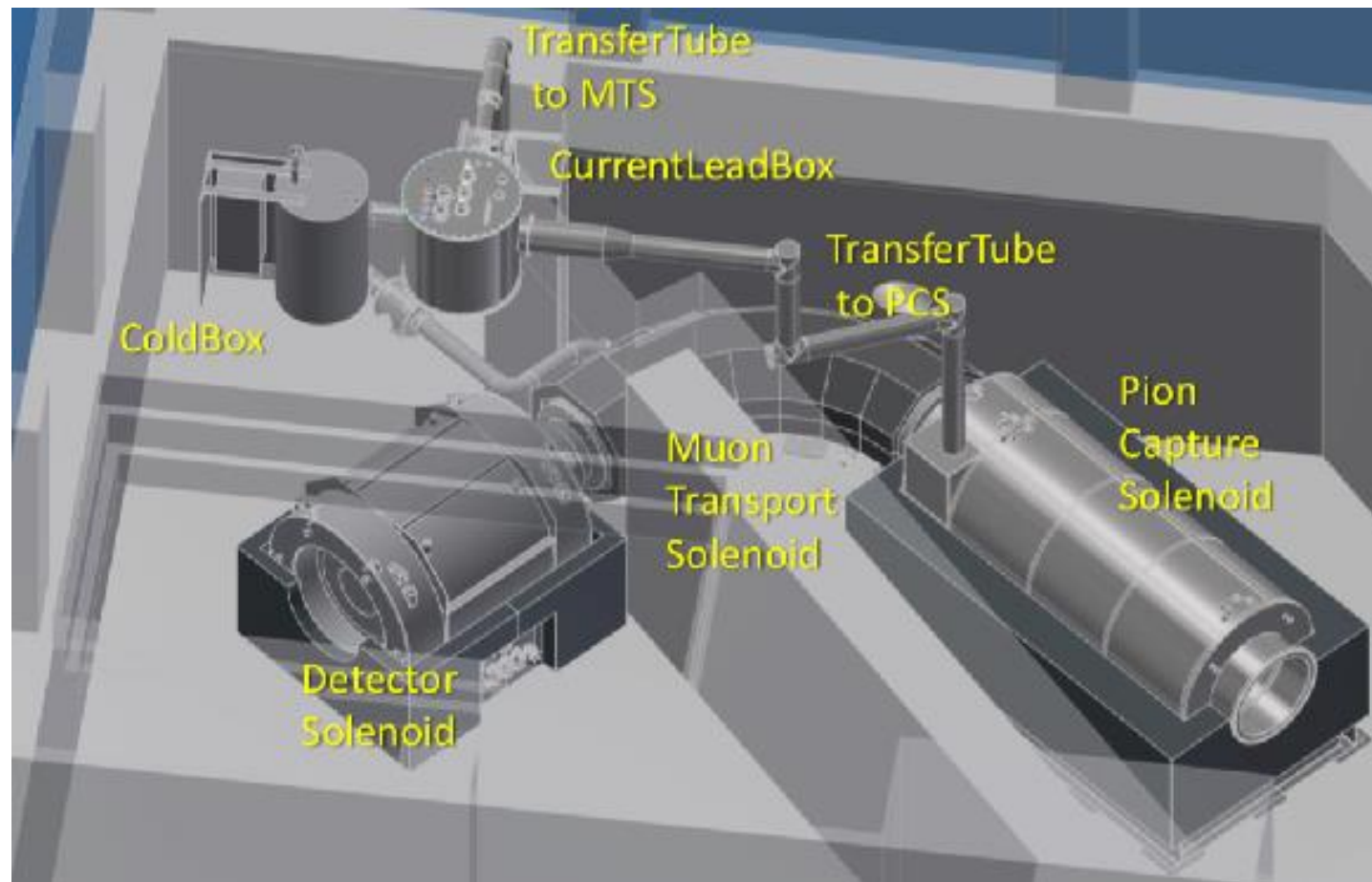


- Tested **SX** in early 2018, proton extinction factor $< 6 \times 10^{-11}$



**The rear end small peak is solved this year!*

Construction of Superconducting Solenoids

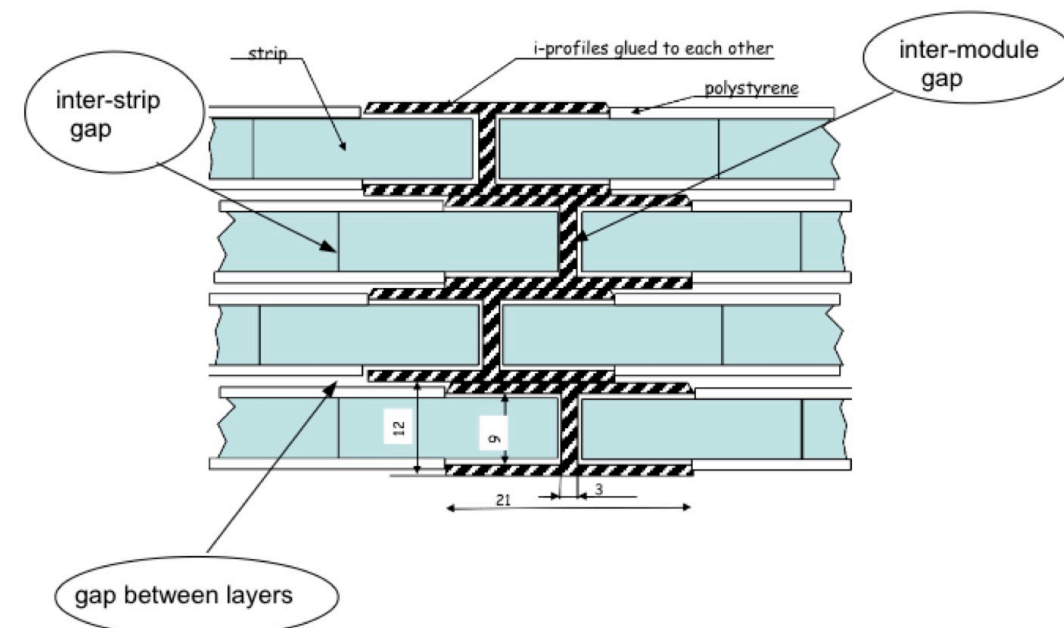
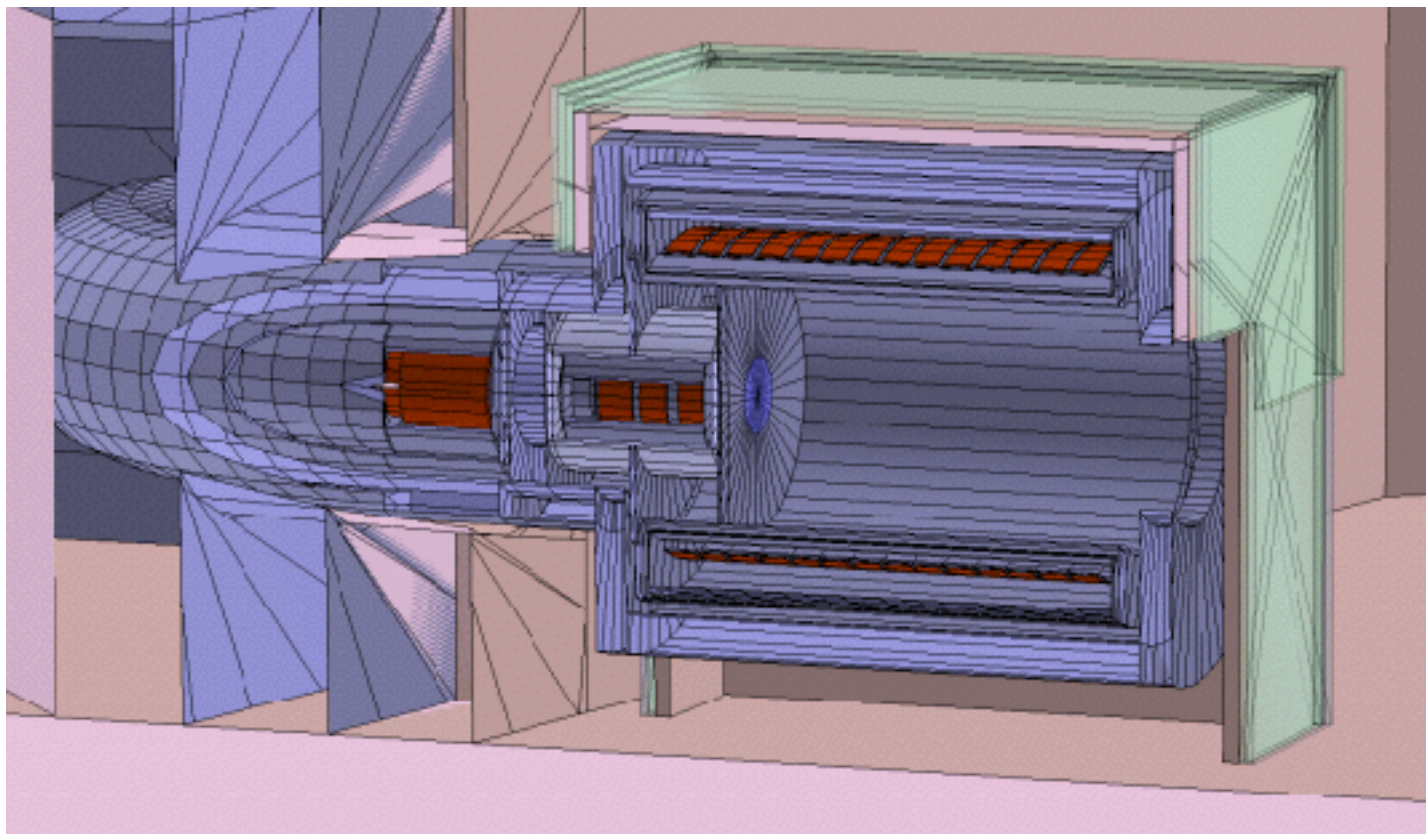
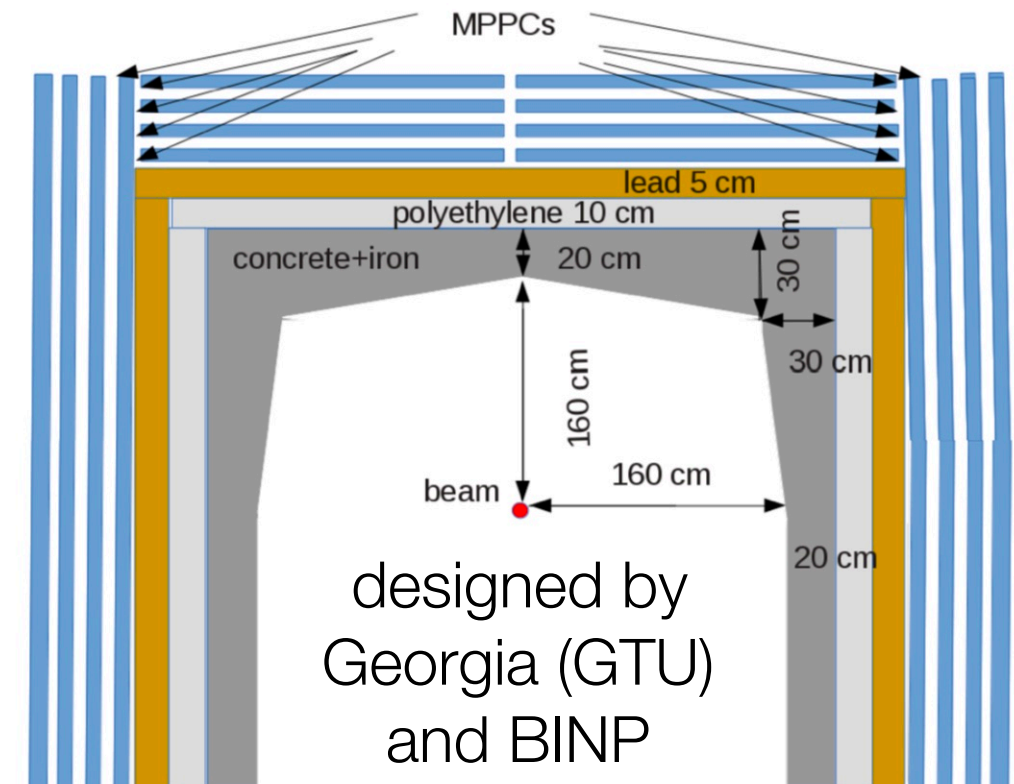


- Capture solenoid
 - Last coil under winding.
- Transport solenoid
 - Installed and ready for cryogenic test.
- Bridge & detector solenoid
 - DS coil and cryostat ready. BS coil delivered.
- Cryogenic system:
 - Refrigerator test completed.
 - Helium transfer tube in production.

Active Cosmic Ray Veto System



- Scintillator slabs with Sci-fibers embedded
 - SiPM readout, need radiation tolerance
 - 5 walls, each wall composed of panels
 - readout ASIC from LHCb from LPC
- Resistive Plate Chamber (RPC)
 - used in high neutron yield area.
 - LPC design, radiation tolerance



COMET Phase-I

Physics Sensitivity (a la TDR)



Event selection	Value
Online event selection efficiency	0.9
DAQ efficiency	0.9
Track finding efficiency	0.99
Geometrical acceptance + Track quality cuts	0.18
Momentum window (ϵ_{mom})	0.93 $103.6 < p_e < 106.0 \text{ MeV/c}$
Timing window (ϵ_{time})	0.3 $700 < t_e < 1170 \text{ ns}$
Total	0.041

$$B(\mu^- + \text{Al} \rightarrow e^- + \text{Al}) = \frac{1}{N_\mu \cdot f_{\text{cap}} \cdot f_{\text{gnd}} \cdot A_{\mu-e}},$$

Number of muons stopped inside targets

Fraction of μ -e conversion to the ground state = 0.9

Fraction of muons to be captured by Al target = 0.61

• 3×10^{-15} S.E.S. achievable in ~ 150 days of DAQ time corresponds to $N_\mu = 1.5 \times 10^{16}$

COMET Phase-I

Backgrounds (a la TDR)



Type	Background	Estimated events
Physics	Muon decay in orbit	0.01
	Radiative muon capture	0.0019
	Neutron emission after muon capture	< 0.001
	Charged particle emission after muon capture	< 0.001
Prompt Beam	* Beam electrons	
	* Muon decay in flight	
	* Pion decay in flight	
	* Other beam particles	
	All (*) Combined	≤ 0.0038
	Radiative pion capture	0.0028
	Neutrons	$\sim 10^{-9}$
Delayed Beam	Beam electrons	~ 0
	Muon decay in flight	~ 0
	Pion decay in flight	~ 0
	Radiative pion capture	~ 0
	Anti-proton induced backgrounds	0.0012
Others	Cosmic rays [†]	< 0.01
Total		0.032

[†] This estimate is currently limited by computing resources.

Other Physics Programs at COMET



μ^- to e^+ conversion in muonic atom

$$\mu^- + N(A, Z) \rightarrow e^+ + N(A, Z - 2) \quad \text{ground or excited final states.}$$

Lepton number violation (LNV) and
Lepton flavour violation (LFV)

signal signature

$$E_{\mu e^+} = m_\mu - B_\mu - E_{rec} - (M(A, Z - 2) - M(A, Z))$$

backgrounds

- radiative muon nuclear capture (RMC)
 $\mu^- + N(A, Z) \rightarrow N(A, Z - 1) + \nu + \gamma$

$$E_{RMC} = m_\mu - B_\mu - E_{rec} - (M(A, Z - 1) - M(A, Z))$$

- **Current limits :**

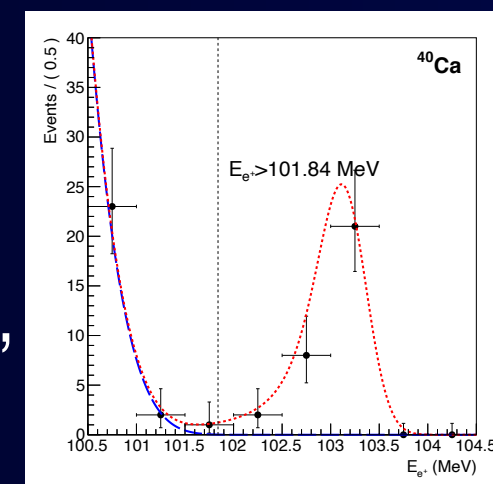
$$\mu^- + \text{Ti} \rightarrow e^+ + \text{Ca}(\text{gs}) \leq 1.7 \times 10^{-12}$$

$$\mu^- + \text{Ti} \rightarrow e^+ + \text{Ca}(\text{ex}) \leq 3.6 \times 10^{-11}$$

J. Kaulard et al. (SINDRUM-II)
Phys. Lett. B422 (1998) 334.

- **Future prospects:**

- Mu2e or
COMET can
improve with
proper targets,



T. Geib, A. Merie, K. Zuber, Phys. Lett. B764 (2017) 157-162

B. Yeo, YK, M. Lee and K. Zuber, Phys. Rev. D96 (2017) 075027

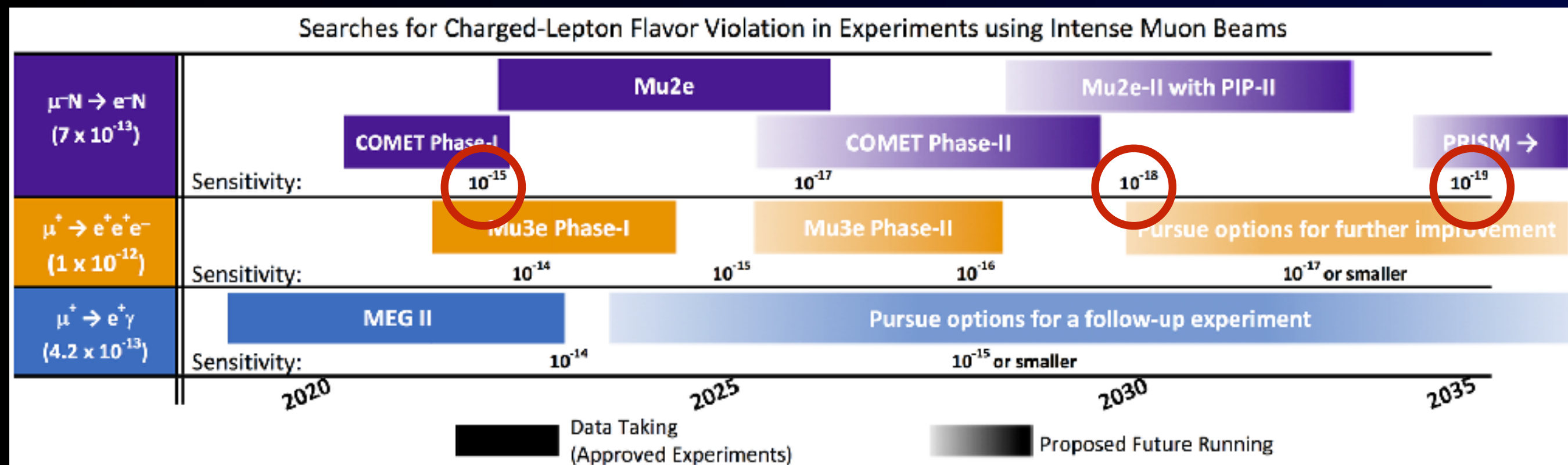
Future Schedule of Muon CLFV



Schedule of “golden” $\mu \rightarrow e$ Transition processes in 2025 and beyond



Timeline in a white paper submitted to EPPSU 2020



BR 10^{-15} 10^{-18} 10^{-19}

Summary



- μ -e conversion in a muonic atom has a unique discovery potential for BSM.
- Current limits probe new physics at 10^4 TeV. Next generation experiments improve their sensitivities, probing 10^5 TeV.
- COMET Phase-I at J-PARC is aiming at a 100 times improvement over the current limit (i.e. S.E. sensitivity of 3×10^{-15}), whilst Phase-II aims at a factor of 10,000.
- The Phase-II sensitivity is considered to improve by another 10 times within the beam power and time originally assumed.
- COMET will start soon.

my dog, IKU

