The COMET Experiment

1. Introduction
2. COMET Overview
3. Current Status of Phase-I
4. Prospects for Phase-II
5. Summary

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Charged Lepton Flavor Violation

The establishment of the **Standard Model** and the observation of the **Neutrino Oscillation** worked-out very much in the particle physics.

However, There are still mysteries like

- dark matter ?? / dark energy?
- why does our universe consist of dominant “matter” ? (not anti-matter)
- absolute neutrino mass ? why so small ?

Processes of the CLFV

- highly prohibited in the SM with Neutrino Oscillation (= no/less SM background)
- are very rare events/decays
- not found yet !
- if found, immediately indicates something beyond the SM

That’s why “CLFV” is interesting!

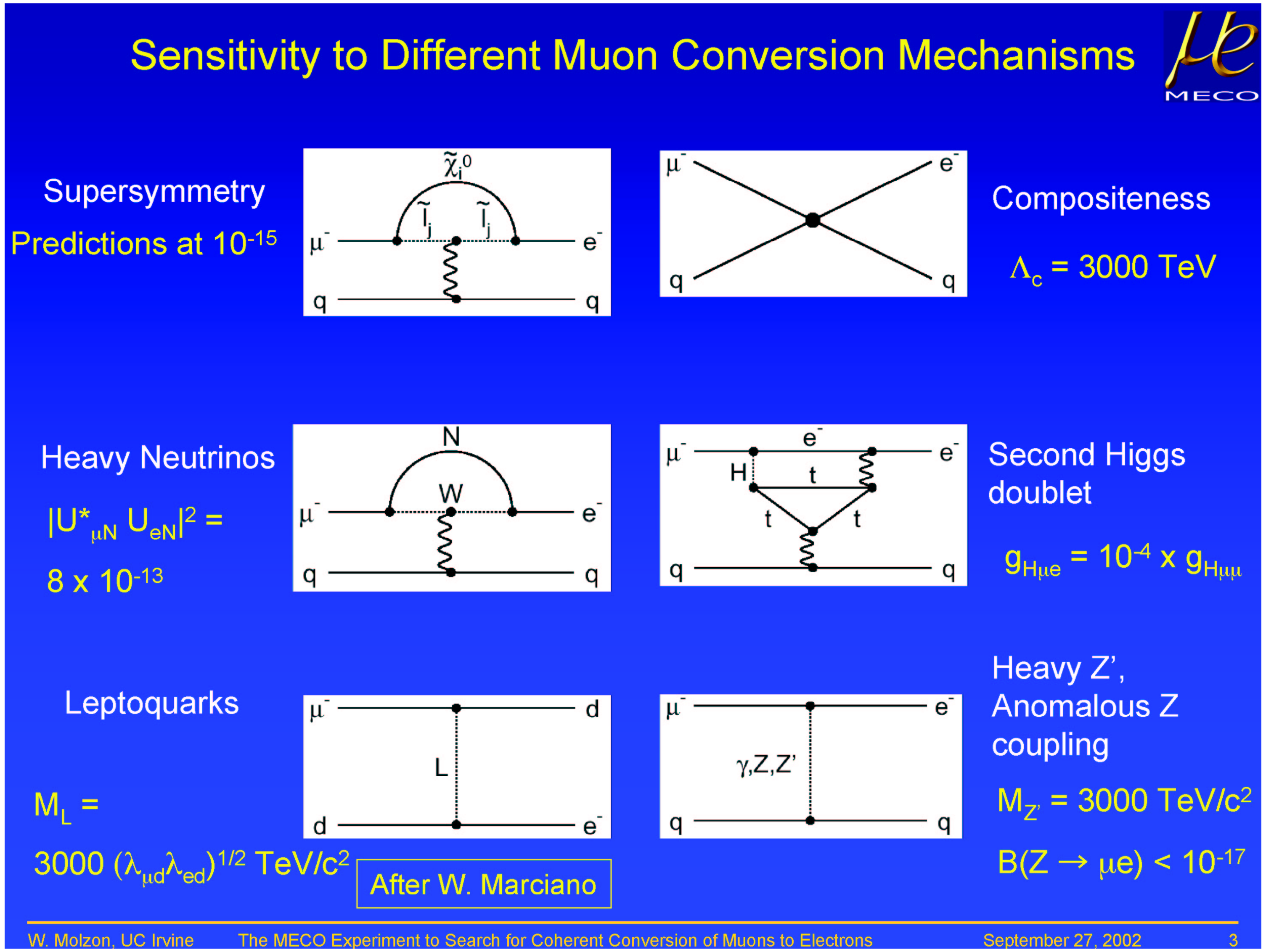
beyond the SM with CLFV

e.g. Branching ratio of “$\mu \rightarrow e\gamma$ ”calculated in the SM with Neutrino Oscillation is

$$\mathrm{Br}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^{*}_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W}\right|^2 < 10^{-54}$$

← impossible to detect in the current technology

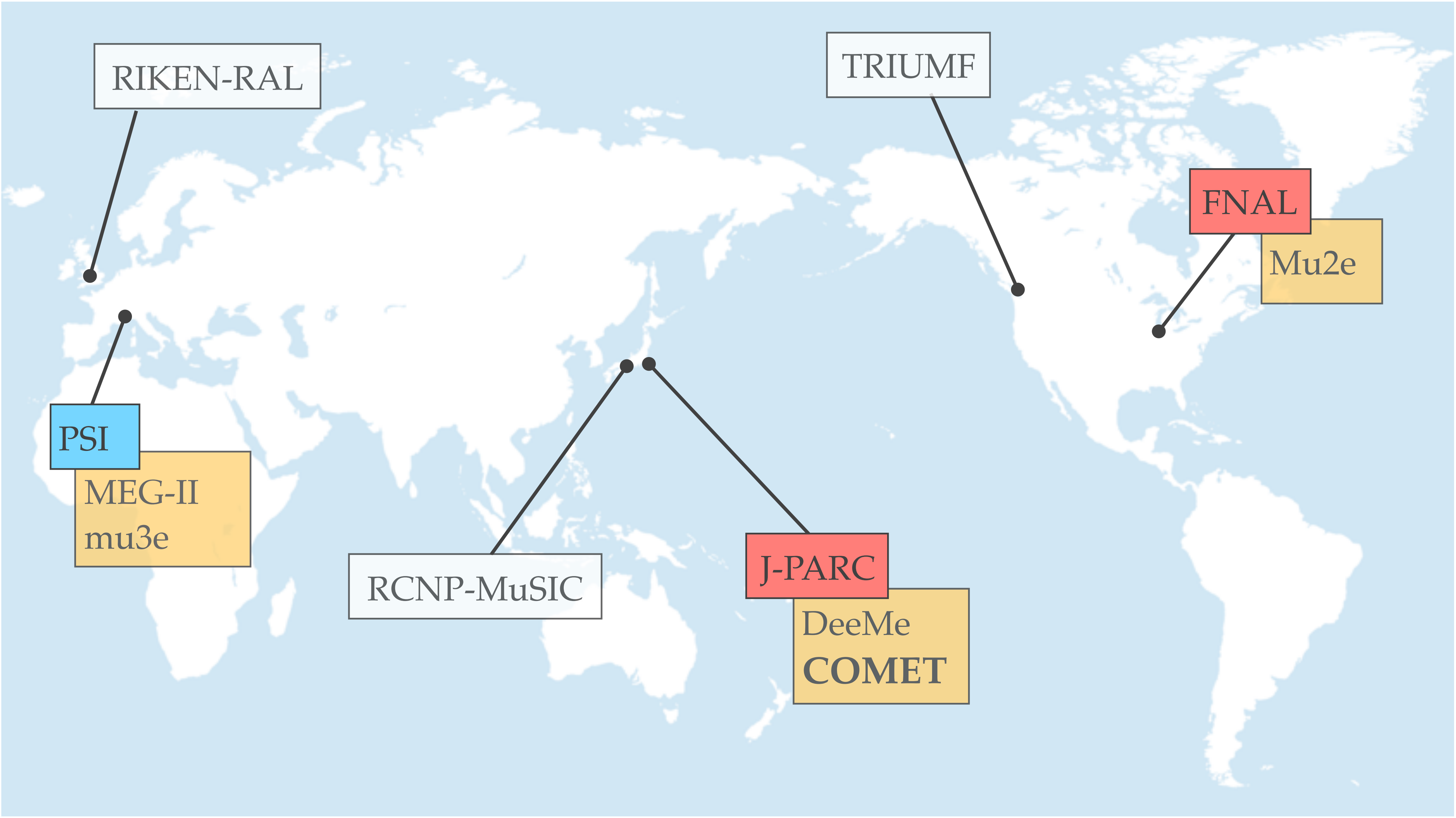
No background from the SM, so this is advantage for New Physics search



Many models such as SUSY, little Higgs, Heavy Neutrino (See-Saw), Extra Dimension etc. beyond the SM predict the CLFV processes in ~TeV scale, corresponding to the branching ratio of $10^{-14\text{-}17}$ in the muon decay.

CLFV search is a strong probe for various New Physics!

CLFV Search with Muon



DC Muon Beam	suitable for "coincidence" experiments
Pulsed Muon Beam	suitable for **"μ-e conversion"** experiments

COMET Experiment

Search for "μ-e conversion" in Japan at J-PARC hadron hall

Experimental Goal :

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

This goal is **10,000 times improvement** from the current limit given by the SIDRUM-II experiment (2006).

Current World Limit :

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

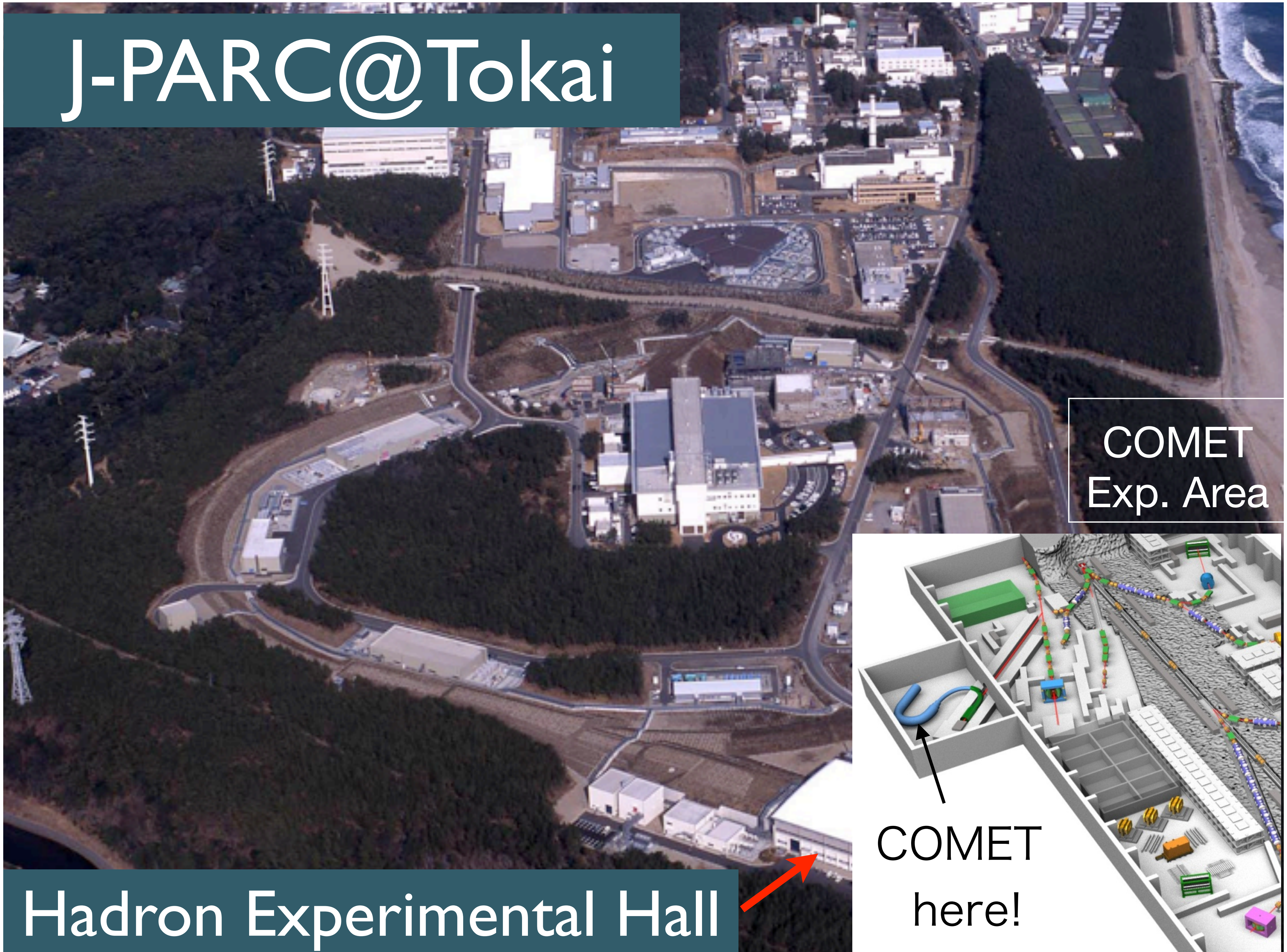
Important Keys for COMET

1. Increase of Muon Intensity with an Innovative Pion Capture System

   MuSIC in RCBP-Osaka University demonstrated more than x 10^3 improvement of pion capture efficiency with larger target and surrounding superconducting solenoid to capture pions.

2. Reduction of Background by Pulsed-Beam and Long-Transport Line

COMET at J-PARC E21



The COMET Collaboration

175+ collaborators,
33 institutes
from 15 countries

R. Abramishvili[11], G. Adamov[11], R. Akhmetshin[6,31], V. Anishchik[4], M. Aoki[32], Y. Arimoto[18], I. Bagaturia[11], Y. Ban[3], A. Bondar[6,31], Y. Calas[7], S. Canfer[33], Y. Cardenas[7], S. Chen[28], Y. E. Cheung[28], B. Chiladze[35], D. Clarke[33], M. Danilov[15,26], P. D. Dauncey[14], W. Da Silva[23], C. Densham[33], G. Devidze[35], P. Dornan[14], A. Drutskoy[15,26], V. Duginov[16], L. Epshteyn[6,30,31], P. Evtoukhovich[16], G. Fedotovich[6,31], M. Finger[8], M. Finger Jr[8], Y. Fujii[18], Y. Fukao[18], E. Gillies[14], D. Grigoriev[6,30,31], K. Gritsay[16], E. Hamada[18], R. Han[1], K. Hasegawa[18], I. H. Hasim[32], O. Hayashi[32], Z. A. Ibrahim[24], Y. Igarashi[18], F. Ignatov[6,31], M. Iio[18], M. Ikeno[18], K. Ishibashi[22], S. Ishimoto[18], T. Itahashi[32], S. Ito[32], T. Iwami[32], X. S. Jiang[2], P. Jonsson[14], T. Kachelhoffer[7], V. Kalinnikov[16], F. Kapusta[23], H. Katayama[32], K. Kawagoe[22], N. Kazak[5], V. Kazanin[6,31], B. Khazin[6,31], A. Khvedelidze[16,11], T. K. Ki[18], M. Koike[39], G. A. Kozlov[16], B. Krikler[14], A. Kulikov[16], E. Kulish[16], Y. Kuno[32], Y. Kuriyama[21], Y. Kurochkin[5], A. Kurup[14], B. Lagrange[14,21], M. Lancaster[38], M. J. Lee[12], H. B. Li[2], W. G. Li[2], R. P. Litchfield[14,38], T. Loan[29], D. Lomidze[11], I. Lomidze[11], P. Loveridge[33], G. Macharashvili[35], Y. Makida[18], Y. Mao[3], O. Markin[15], Y. Matsumoto[32], A. Melnik[5], T. Mibe[18], S. Mihara[18], F. Mohamad Idris[24], K. A. Mohamed Kamal Azmi[24], A. Moiseenko[16], Y. Mori[21], M. Moritsu[32], E. Motuk[38], Y. Nakai[22], T. Nakamoto[18], Y. Nakazawa[32], J. Nash[14], J. -Y. Nief[7], M. Nioradze[35], H. Nishiguchi[18], T. Numao[36], J. O'Dell[33], T. Ogitsu[18], K. Oishi[22], K. Okamoto[32], C. Omori[18], T. Ota[34], J. Pasternak[14], C. Plostinar[33], V. Ponariadov[45], A. Popov[6,31], V. Rusinov[15,26], B. Sabirov[16], N. Saito[18], H. Sakamoto[32], P. Sarin[13], K. Sasaki[18], A. Sato[32], J. Sato[34], Y. K. Semertzidis[12,17], N. Shigyo[22], D. Shoukavy[5], M. Slunecka[8], A. Straessner[37], D. Stöckinger[37], M. Sugano[18], Y. Takubo[18], M. Tanaka[18], S. Tanaka[22], C. V. Tao[29], E. Tarkovsky[15,26], Y. Tevzadze[35], T. Thanh[29], N. D. Thong[32], J. Tojo[22], M. Tomasek[10], M. Tomizawa[18], N. H. Tran[32], H. Trang[29], I. Trekov[35], N. M. Truong[32], Z. Tsamalaidze[16,11], N. Tsverava[16,35], T. Uchida[18], Y. Uchida[14], K. Ueno[18], E. Velicheva[16], A. Volkov[16], V. Vrba[10], W. A. T. Wan Abdullah[24], M. Warren[38], M. Wing[38], M. L. Wong[32], T. S. Wong[32], C. Wu[2,28], H. Yamaguchi[22], A. Yamamoto[18], T. Yamane[32], Y. Yang[22], W. Yao[2], B. K. Yeo[12], H. Yoshida[32], M. Yoshida[18], Y. Yoshii[18], T. Yoshioka[22], Y. Yuan[2], Yu. Yudin[6,31], J. Zhang[2], Y. Zhang[2], K. Zuber[37]

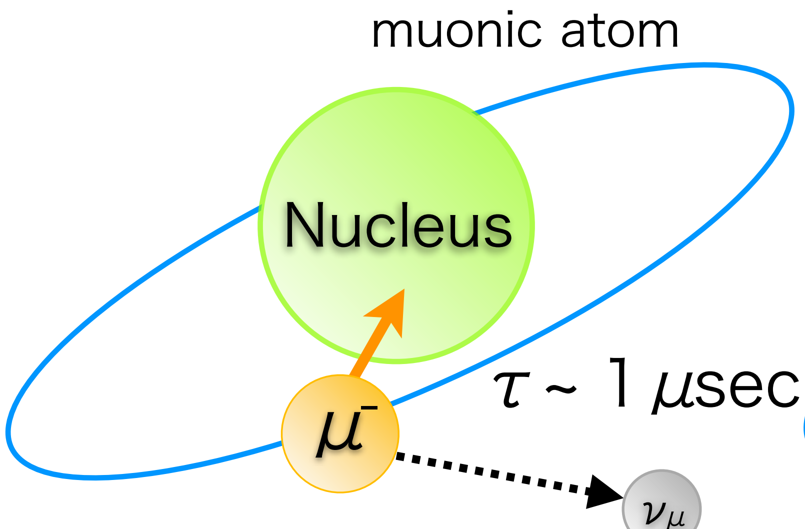
+ more

μ - e conversion search

1. Generate **"muonic atom"** by muon stopping at the target
2. Measure emitted electron momentum from muonic atom
   A. **spectrum of decay in orbit** is continuous with sharp edge at 52.8 MeV
   B. **μ-e conversion signal** is a mono-energetic ~ 105 MeV peak
   (neutrinoless muon decay → emitted electron has all energy of the decay)
3. Spectroscopic search for μ-e conversion signal

Backgrounds — in the SM

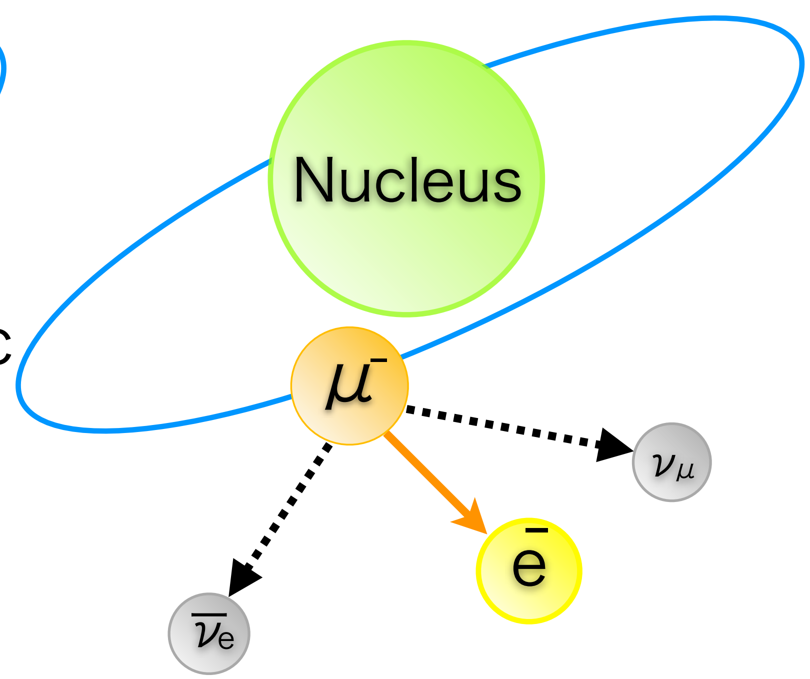
Muon Capture



* electron not emitted

$$\mu + N \rightarrow \nu_\mu + N$$

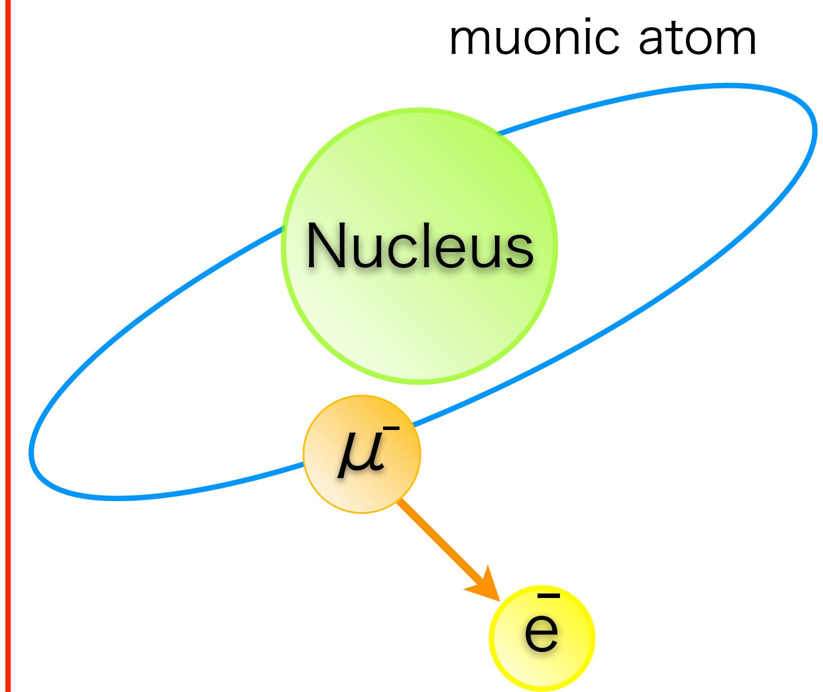
Decay In Orbit (DIO)



$$\mu \rightarrow e\ \bar{\nu}_e\ \nu_\mu$$

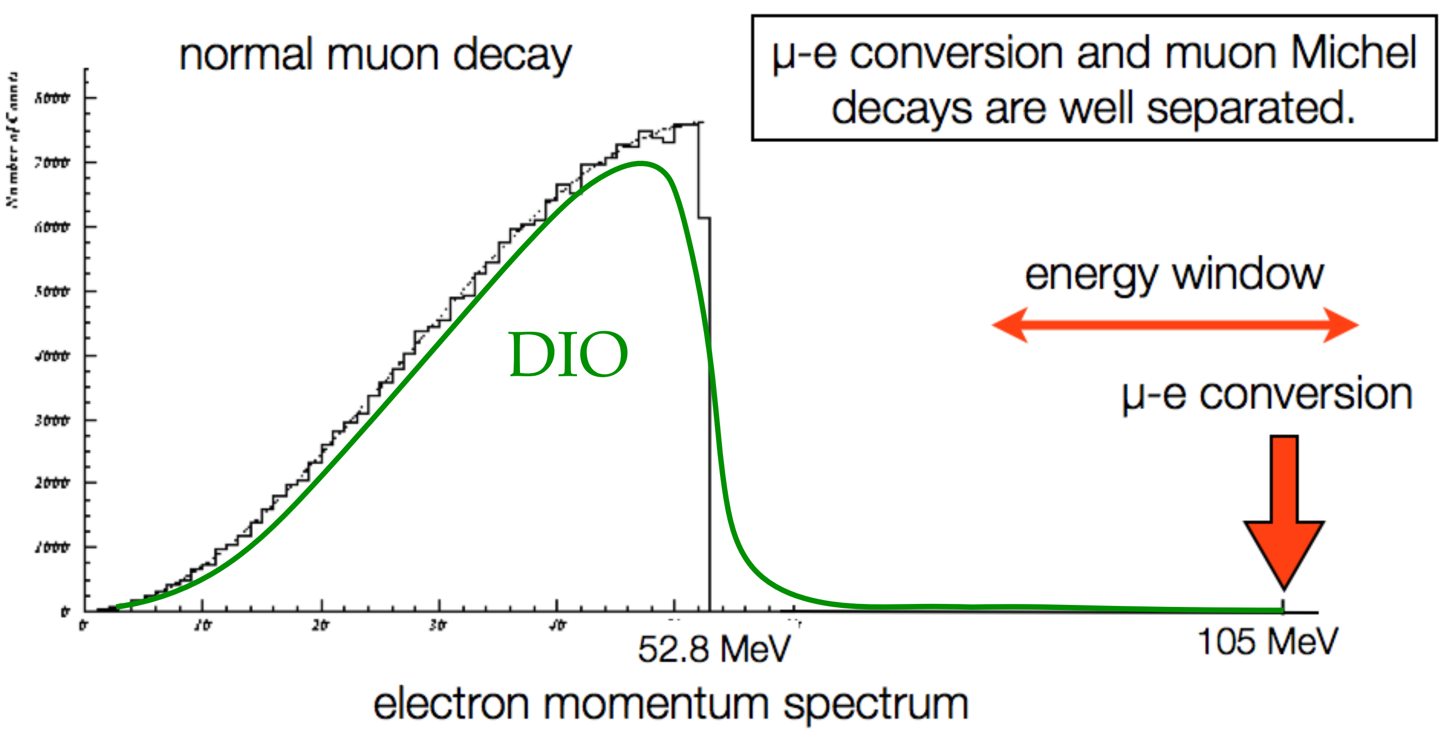
Signal — beyond the SM

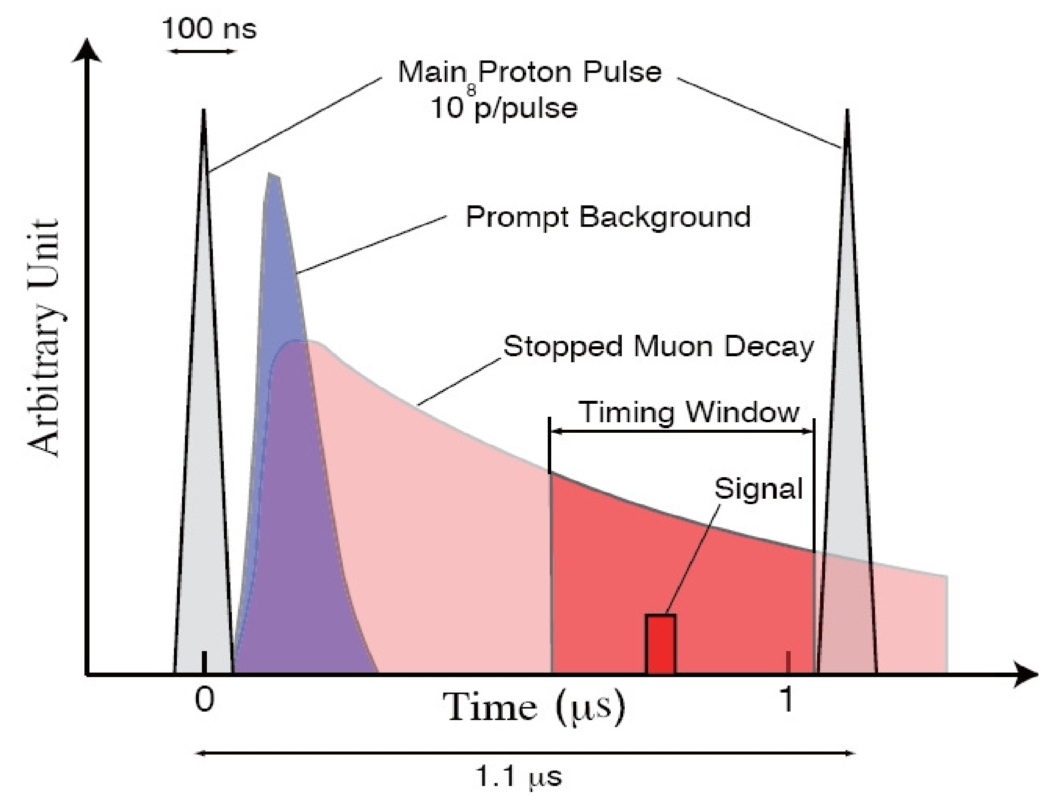
μ - e conversion



$$\mu N \rightarrow e N$$

Strategy of COMET





Intrinsic Background

DIO spectrum has longer tail up to ~105 MeV

→ require **high momentum resolution** to separate the tail and signal

Beam-related Background

Radiative pion capture, muon decay in flight and so on

→ require **pulsed beam** and **excellent proton extinction < 10^{-9}**

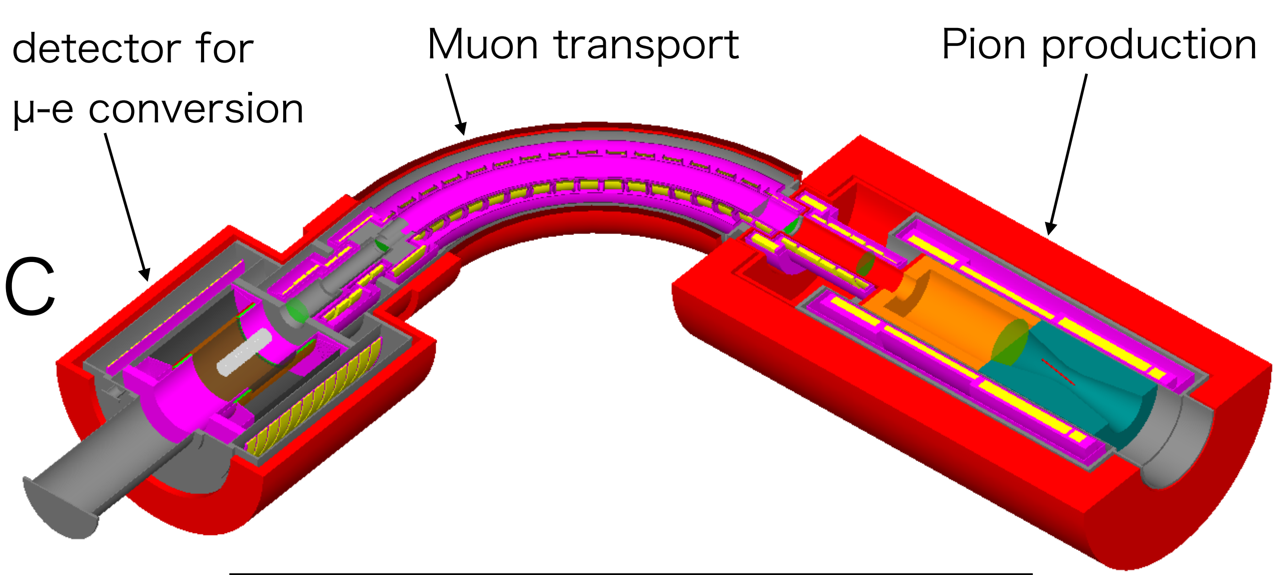
To achieve our target sensitivity, we take staging approach.

COMET Phase-I

COMET Phase-I Goal :

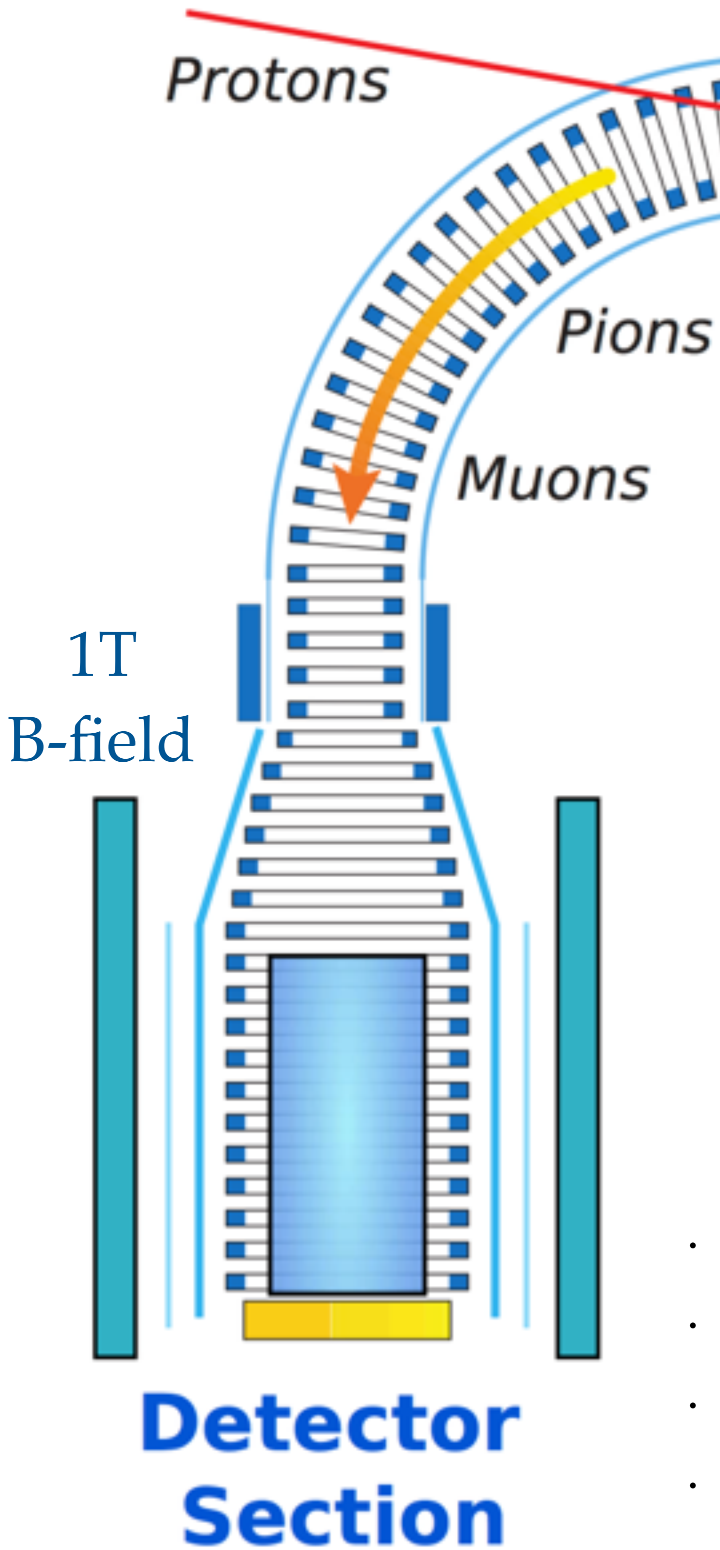
$$B(\mu^- + Al \rightarrow e^- + Al) = 3.0 \times 10^{-15} \ \text{(S.E.S)}$$
$$B(\mu^- + Al \rightarrow e^- + Al) < 7 \times 10^{-15} \ (90\% C.L.)$$

- With shorter muon transport solenoid (90° bending)
- Not-full power operation of proton beam (3.2 kW)
- **Quick and Low-Cost Construction** to get result earlier
  - under construction since ~2013, budget funded (not fully).
  - expecting to start in 2018/2019
- Containing R&D for Phase-II
  - Background Measurement
  - Detector Development
- Aiming Stage-2 Approval in J-PARC soon (in summer 2016)
- Technical Design Report (2016) is available online. http://comet.kek.jp/

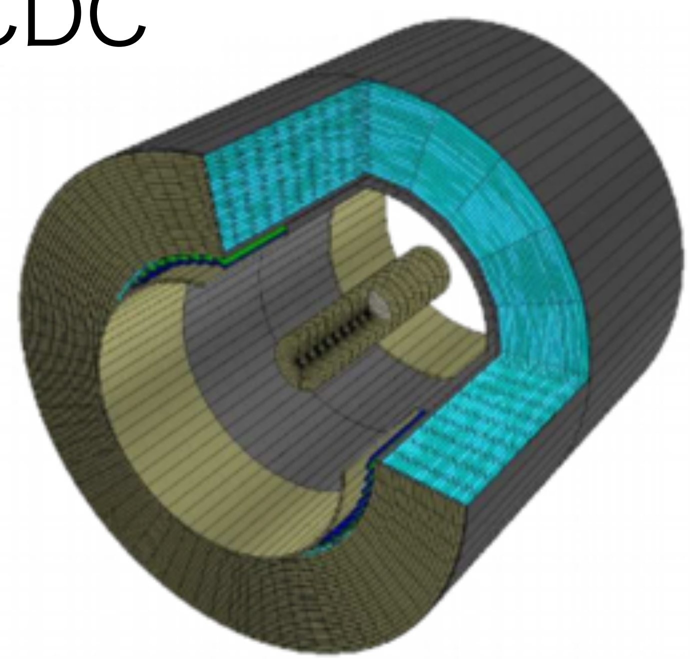


COMET Phase-I Layout

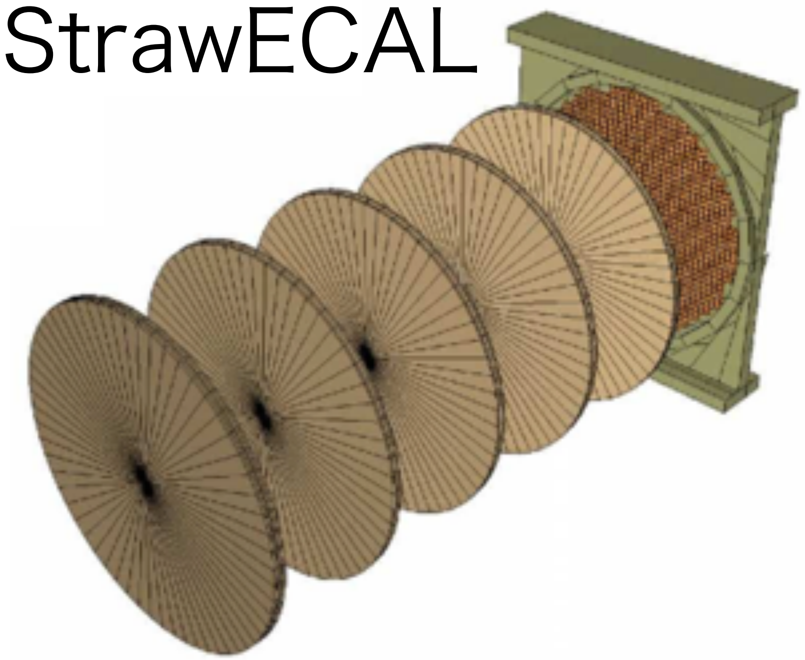
COMET Phase-I Detectors



CDC



StrawECAL



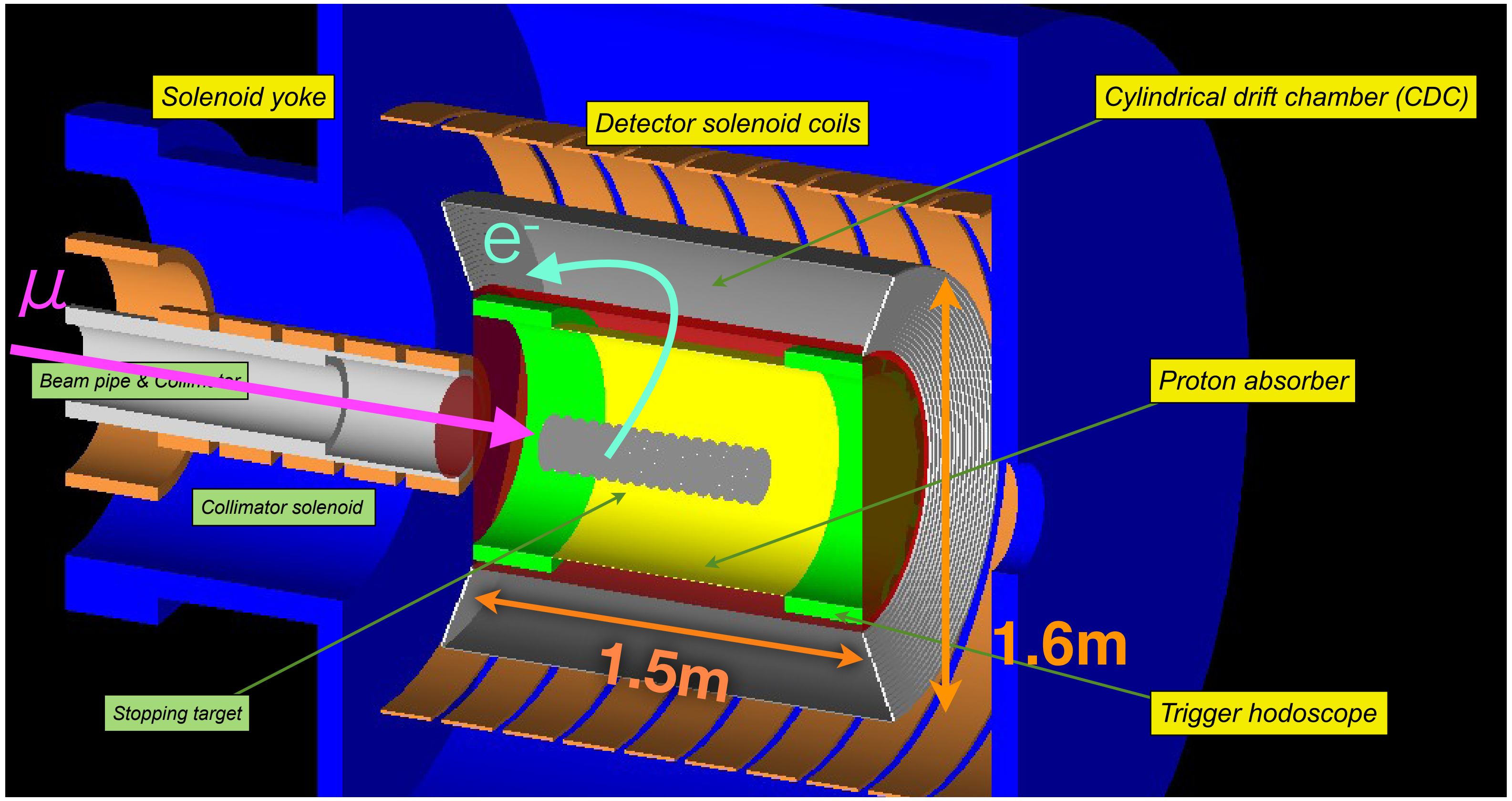
- Cylindrical Drift Chamber
- for physics search in Phase-I
- muon stopping target at center
- ~20,000 wires with He base gas

- Straw Tracker
  + Energy Calorimeter
- for background measurement
- also as R&D for Phase-II

Cylindrical Drift Chamber

COMET CDC

- Surrounding target
- 19 layers structure
  - ~5,000 sense wires
  - ~15,000 field wires
- All stereo layers
- He base gas
  (He : iC_4H_{10} = 10 : 90)

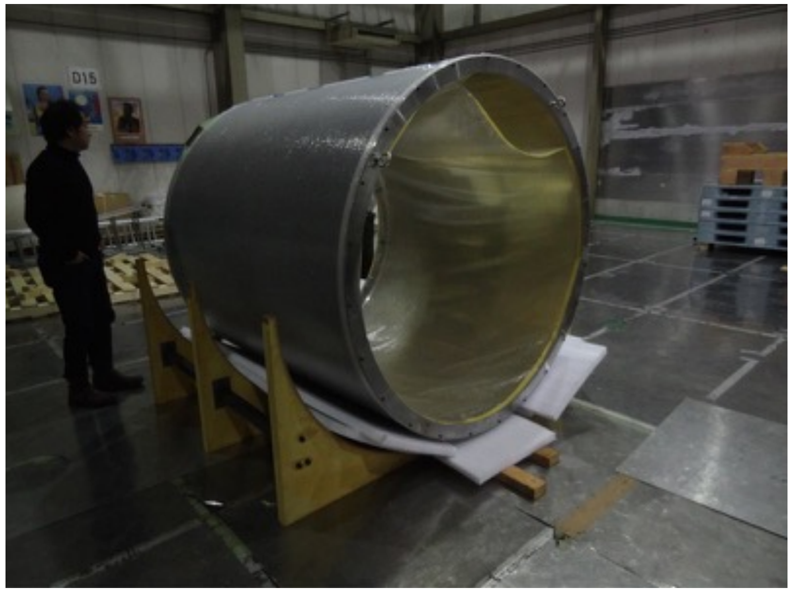


- Study of prototype chamber is done (still ongoing)
  - basic performance study was done
  - spatial resolution < 200 μm
  - ongoing final test with 1T magnetic field in KEK
- Design was fixed based on Belle-II CDC with modification for COMET
- Construction started in 2014, now still underway

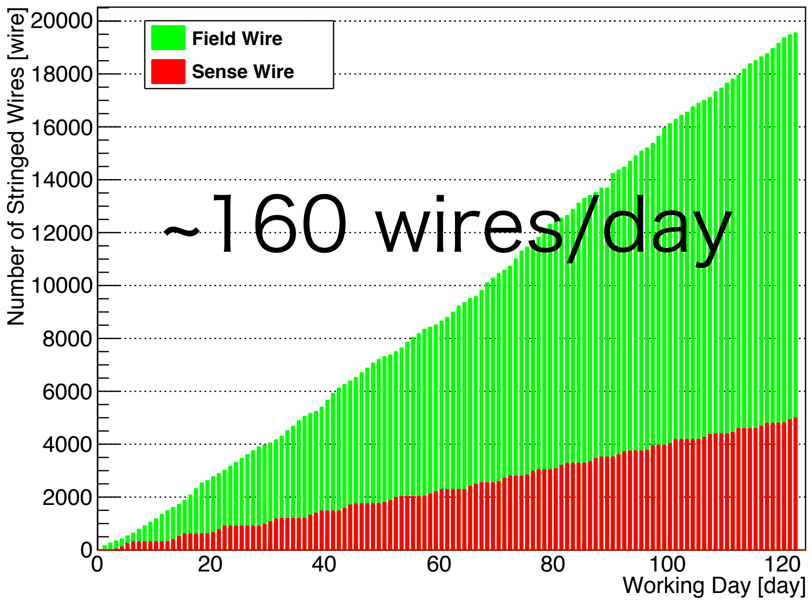
* Many thanks for Belle-II CDC group to help us!

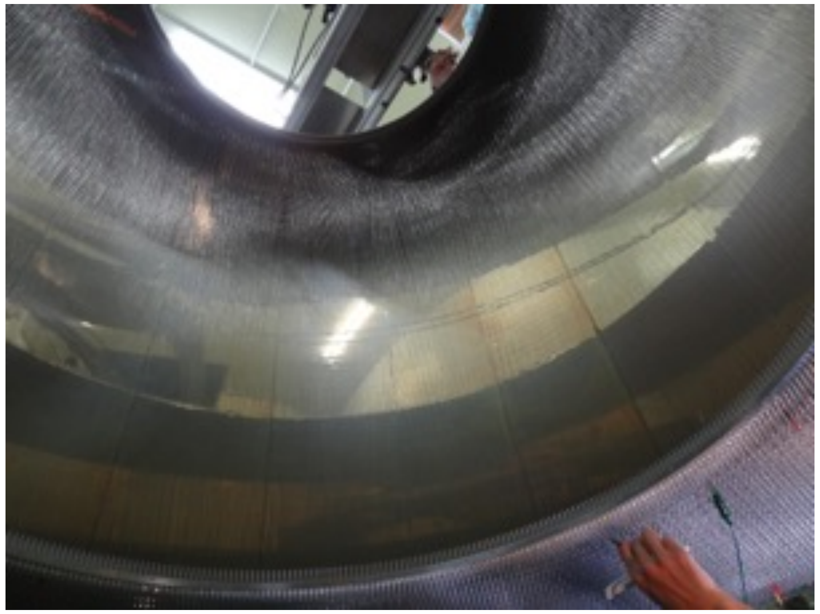
CDC Construction

Wiring in KEK



CFRP outer/inner wall



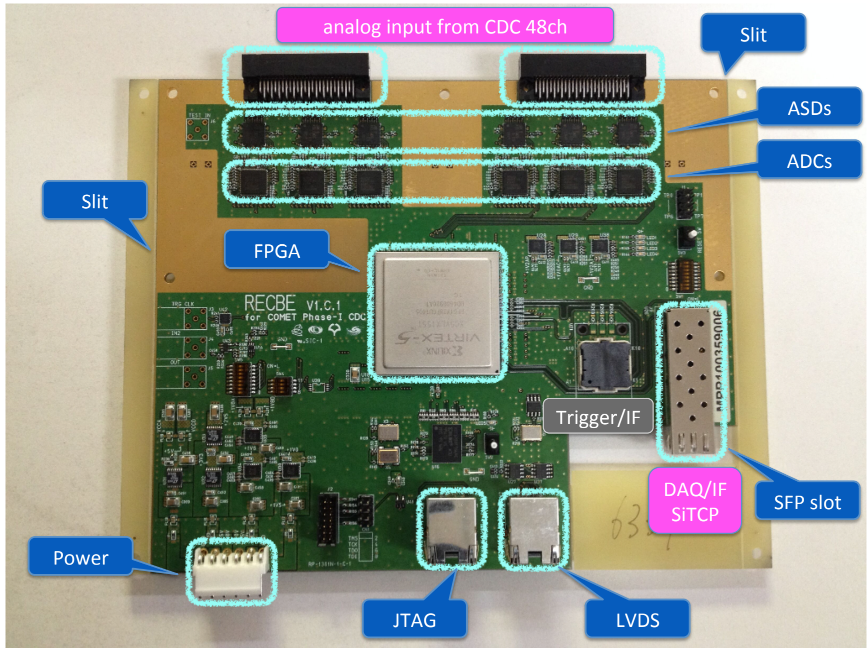


Wiring Completed!

The inner wall will be installed soon,

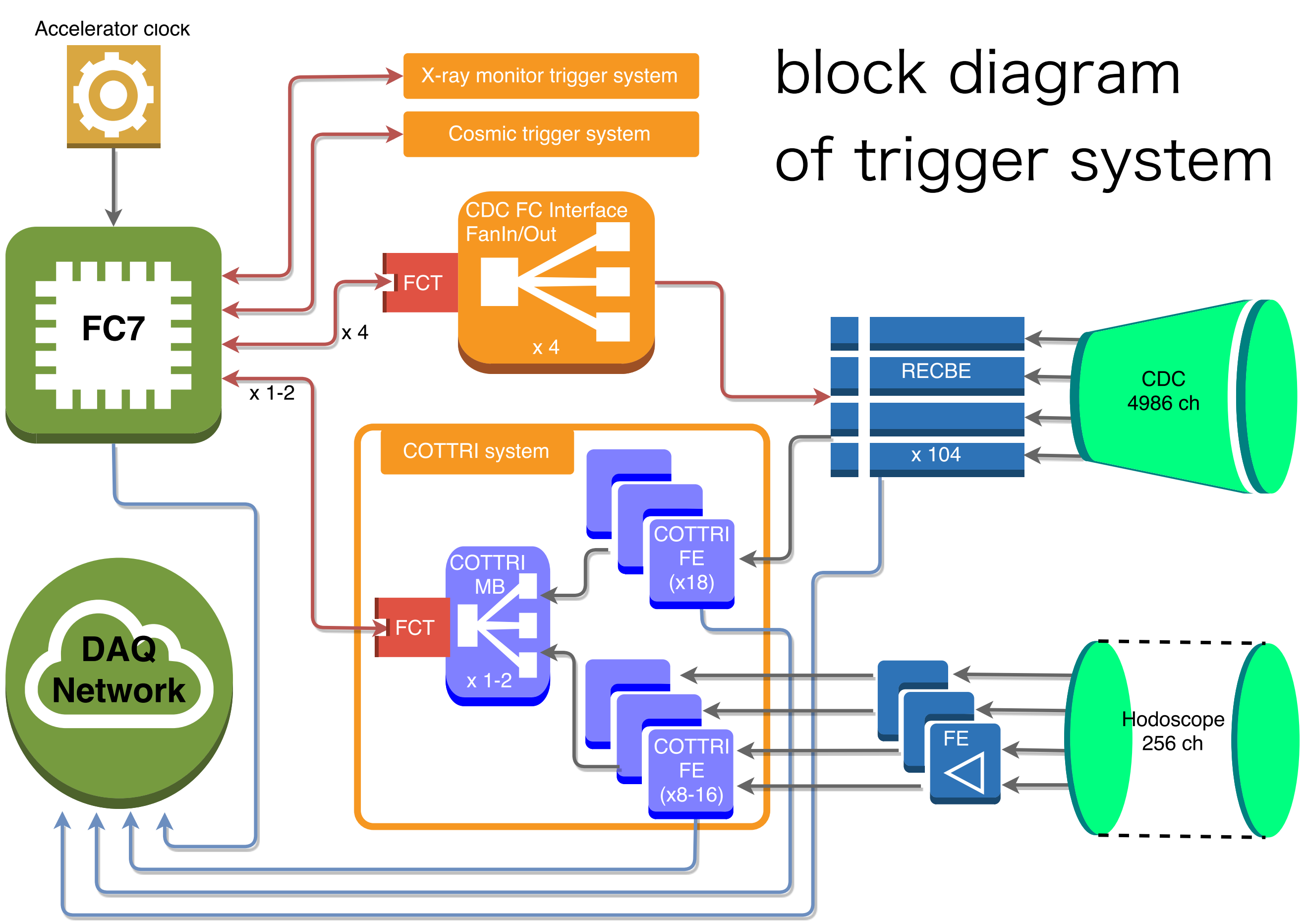
and the CDC commissioning will start in summer 2016.

Read-out Electronics and DAQ

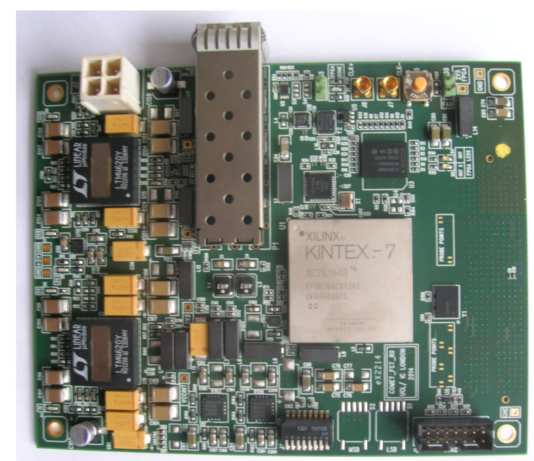


RECBE (semi-copy of Belle-II CDC read-out)

- 48ch read-out per board
- 960MHz TDC and 10bit ADC
- 1Gbps SiTCP communication
- 128 RECBEs mass production done!
- performance test ongoing

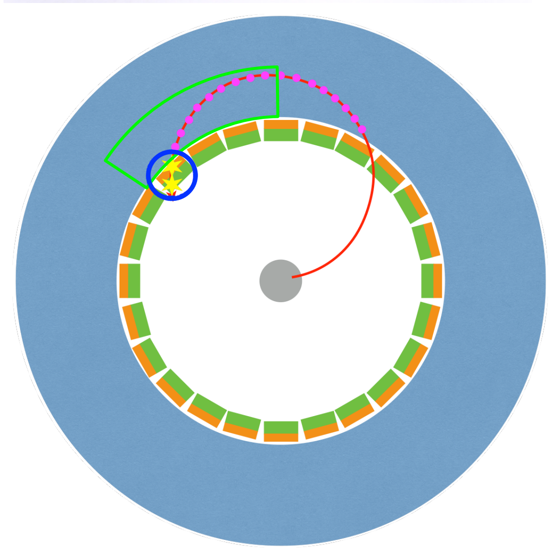


block diagram of trigger system



FCT board

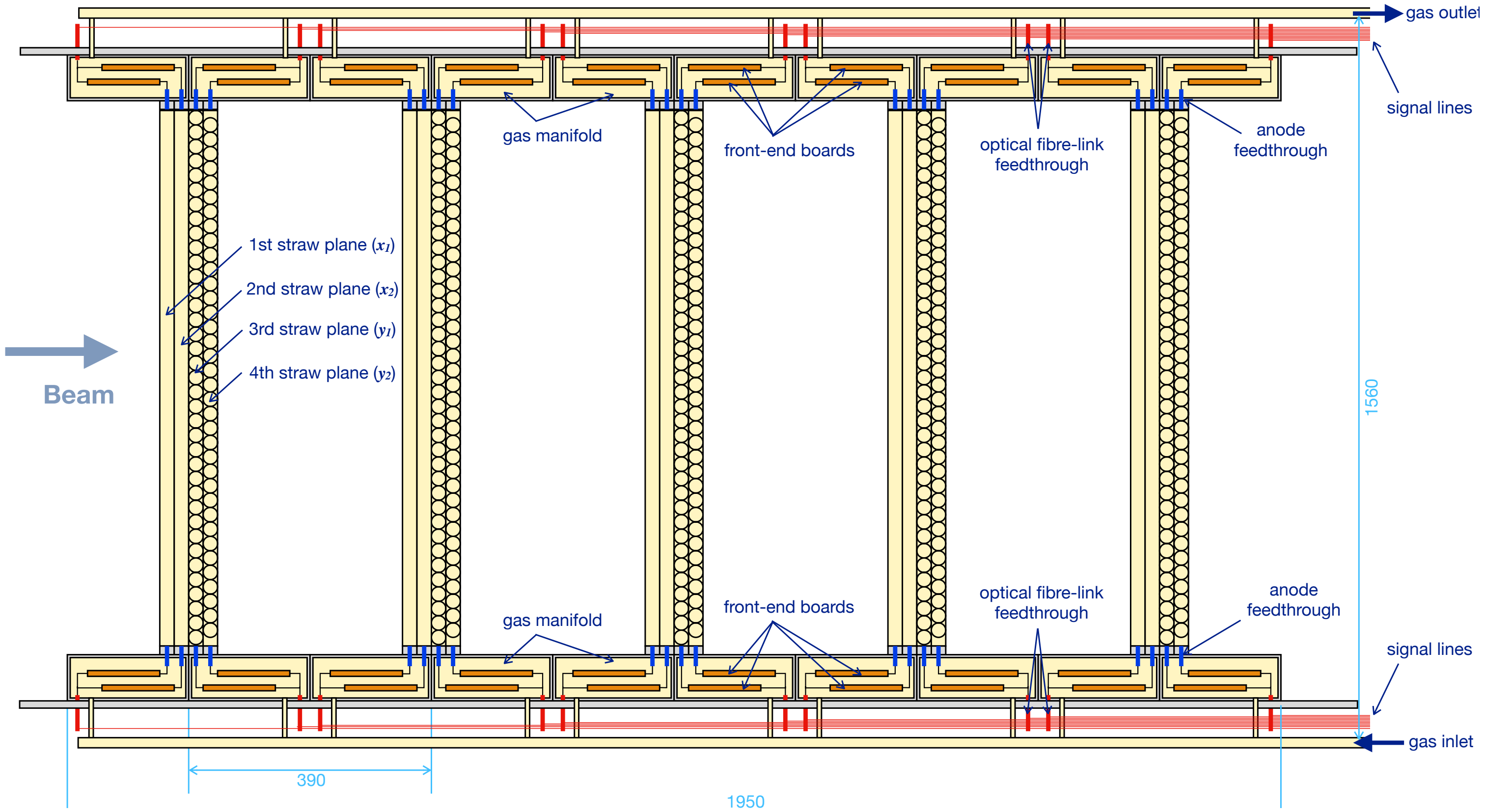
- intermediate board between trigger and various read-out
- prototyping done



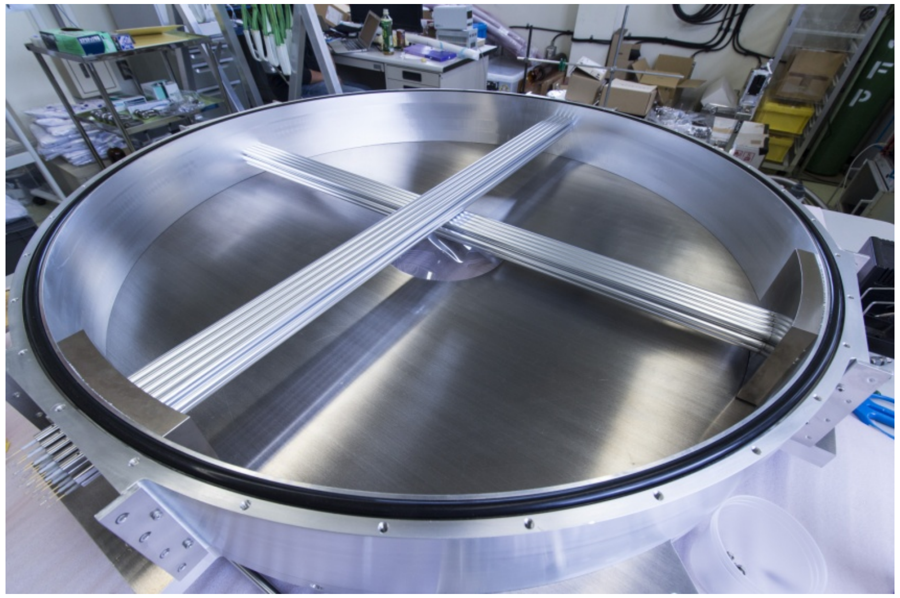
Tracking Trigger

- triggering with track finding to reduce trigger rate
- under development

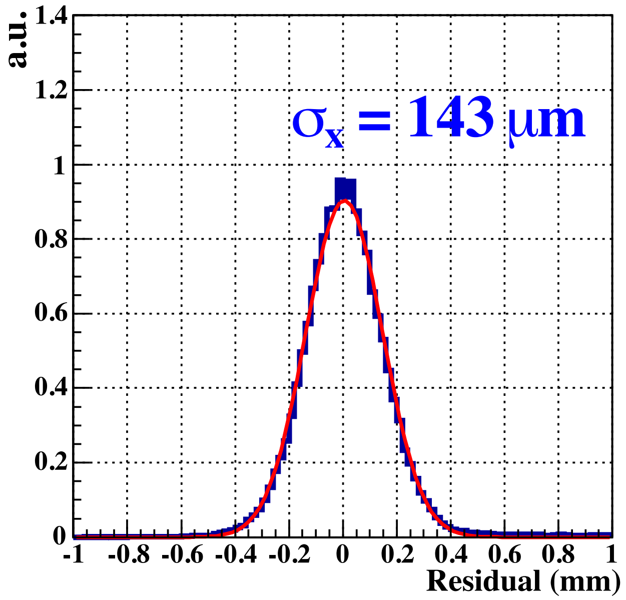
Straw Tracker



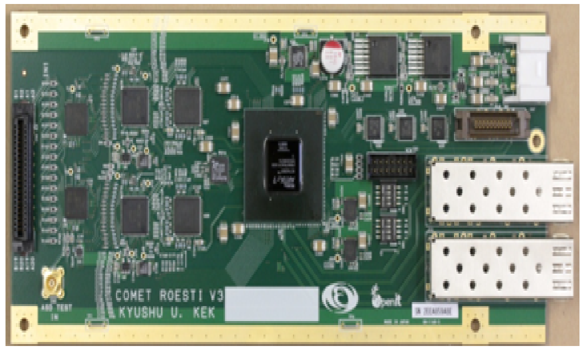
- Tracker with Straw-tube
  - 9.75mm diameter
  - PET 20μm thickness
  - 2-Dimensional config.
  - a station has 2x2 layers
  - 5 stations for Phase-I
- Operation in vacuum to improve momentum res.
- R&D ongoing



Prototype Straw Station

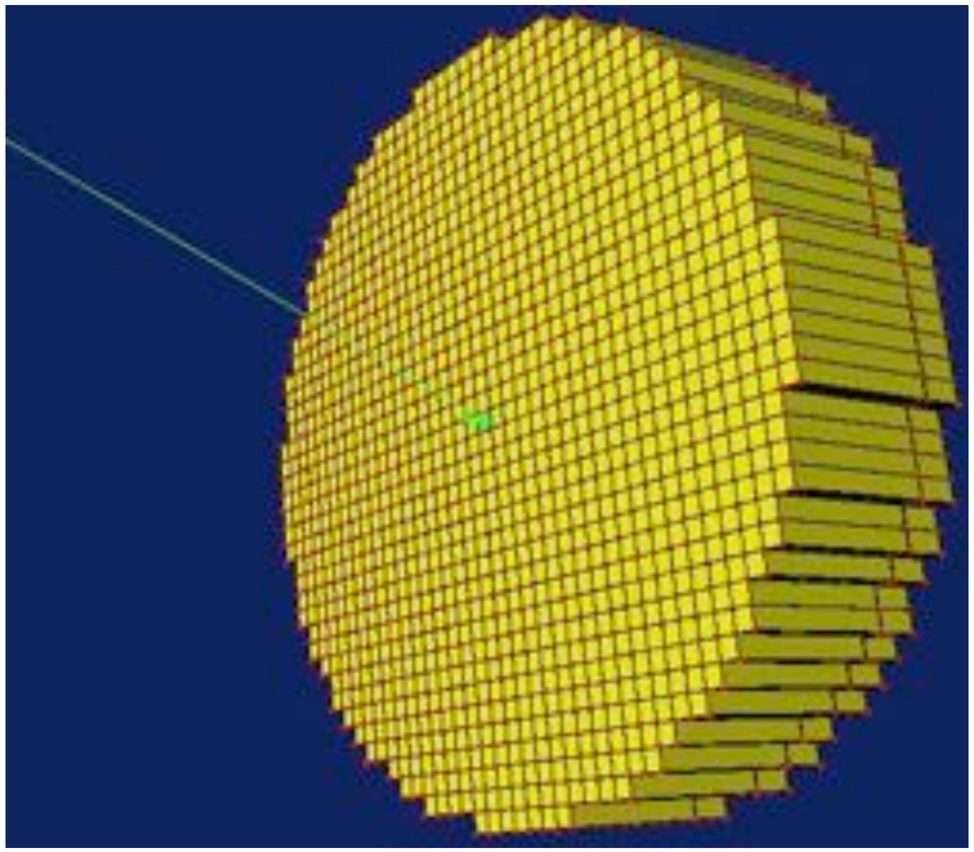


Spatial Resolution

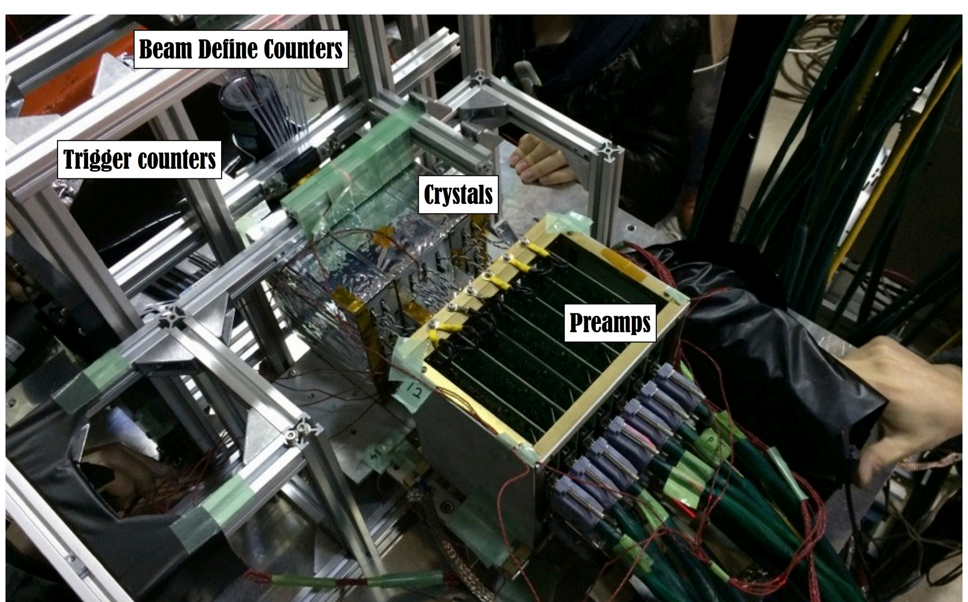


ROESTI : read-out electronics (developed for COMET, DRS4)

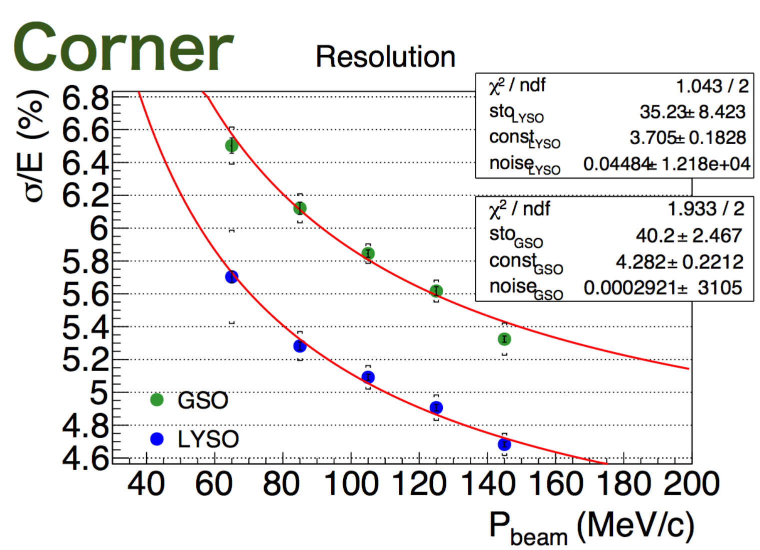
Energy Calorimeter (ECAL)

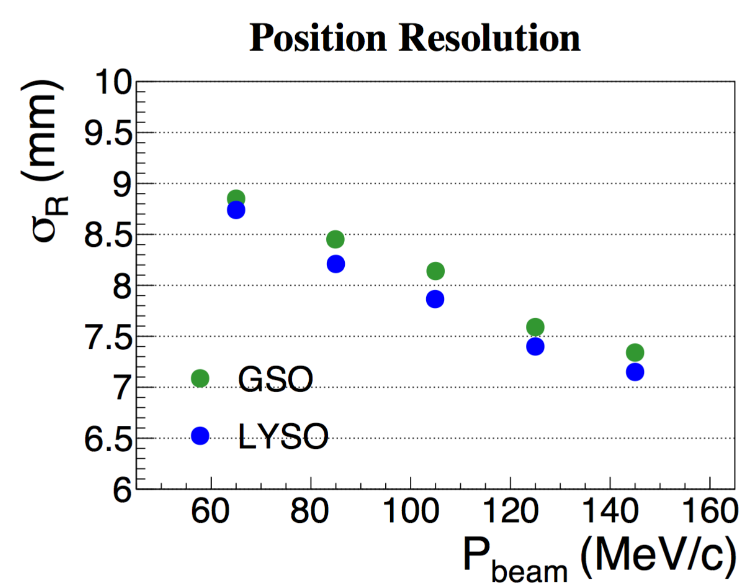


- Energy Measurement for PID
  - combination of crystals units
  - 2 crystal candidates GSO and LYSO
- After several R&D, we decided to use **LYSO** by considering cost and their performance
- R&D continues for the prototyping



set up of beam test



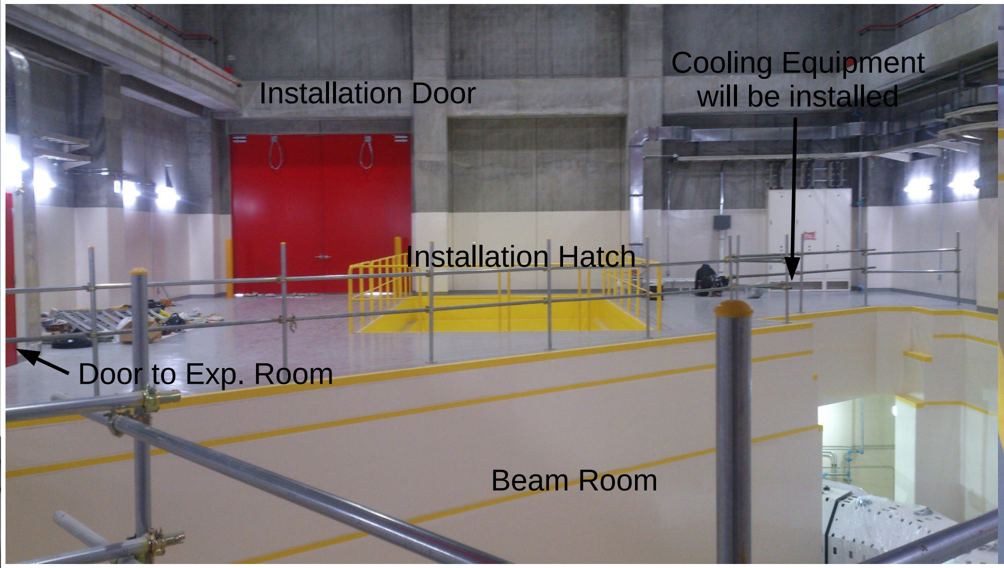


performance test results

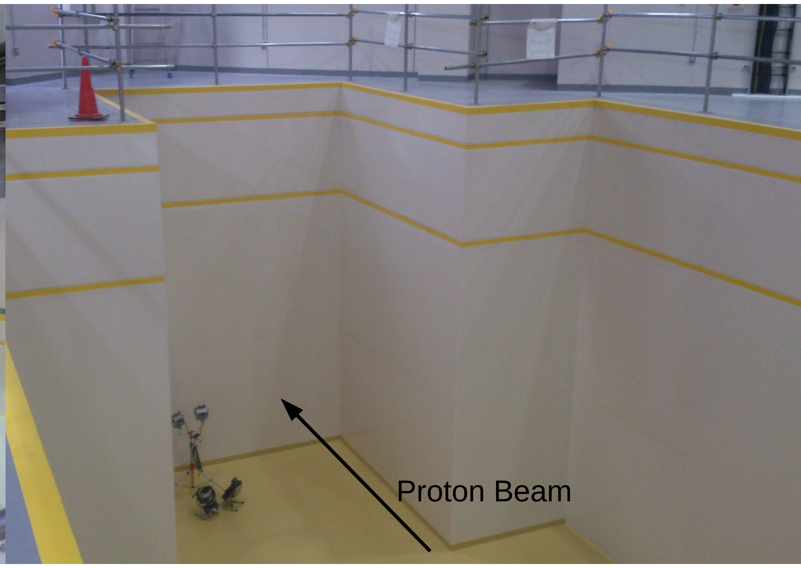
Construction of COMET Hall

COMET Hall next to Hadron Hall

Installation Yard

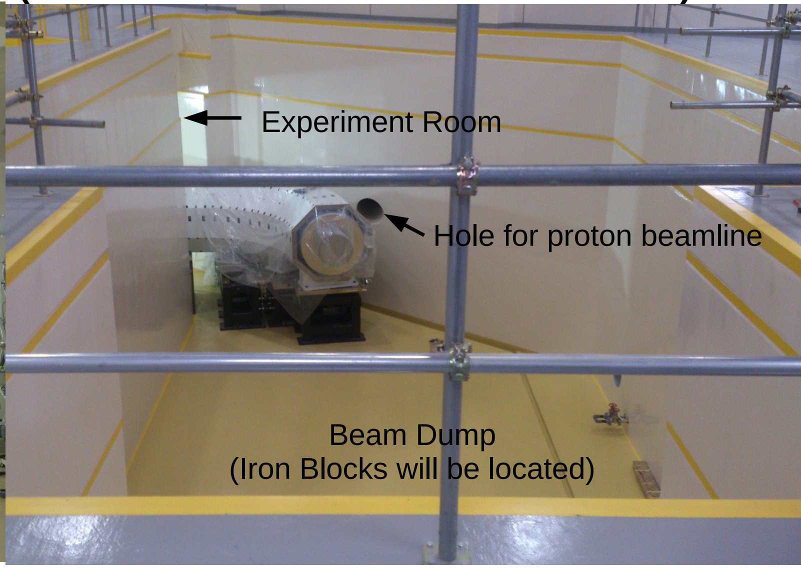


Beam Room



Experiment Room
(View from Door)

Beam Room
(view from Installation Yard)

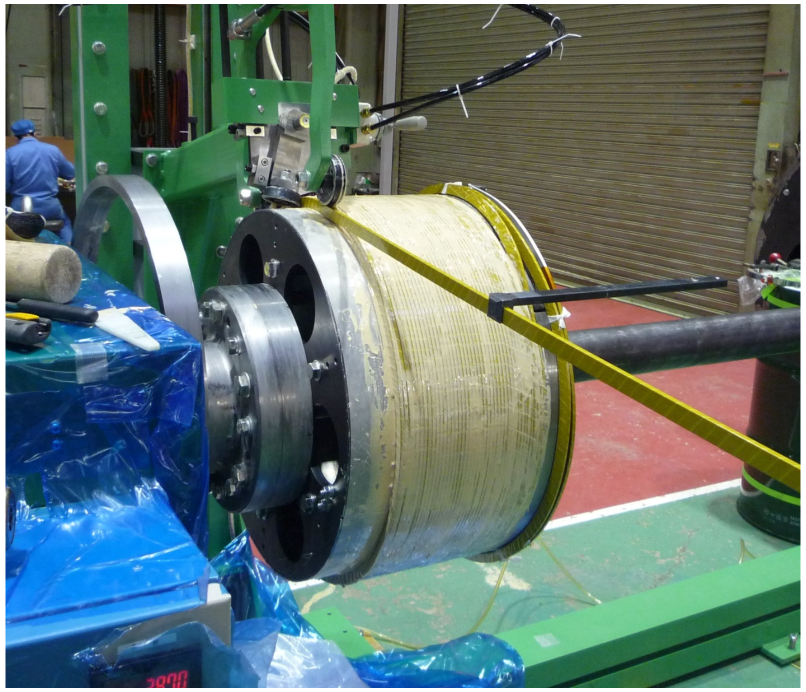


Construction of Solenoid

Pion capture solenoid system

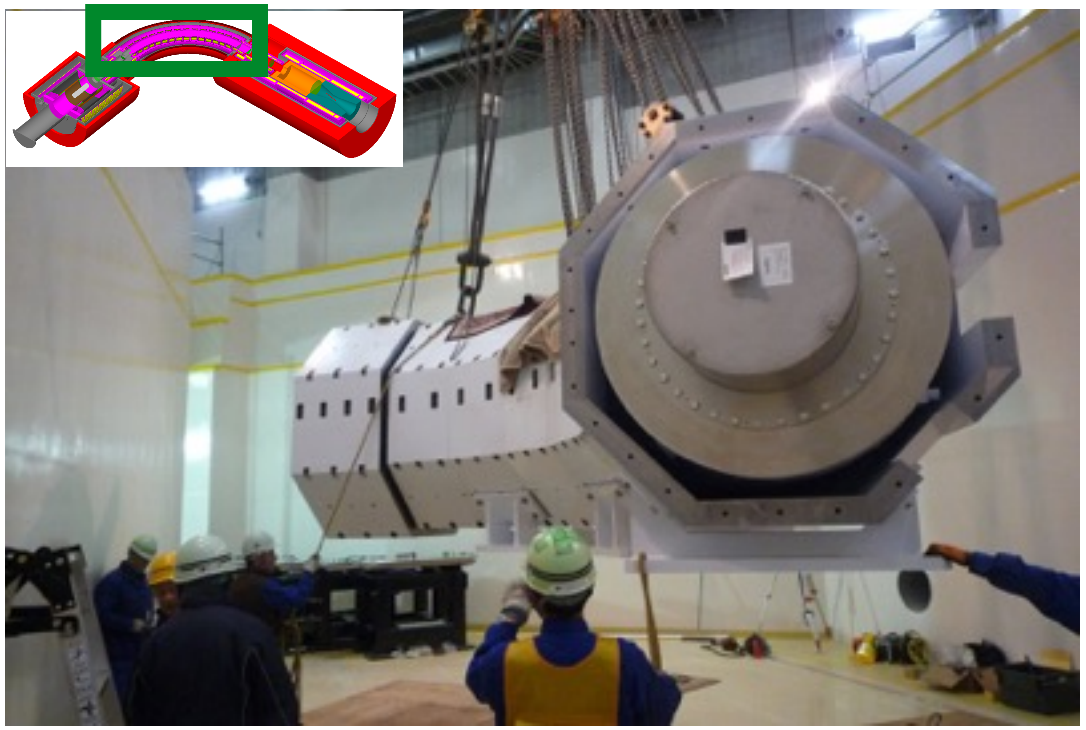
- The delivery of aluminum stabilized superconductors is being made (10 km in 2013, 12 km in 2014, and 8 km in 2015).
- TS1a coil winding is made by a new winding machine.
- CS and MS coils will be made in 2016

TS1a coil winding



Muon transport solenoid system

- The muon transport system (TS2-TS3) has been constructed and delivered by Toshiba Co. in 2015

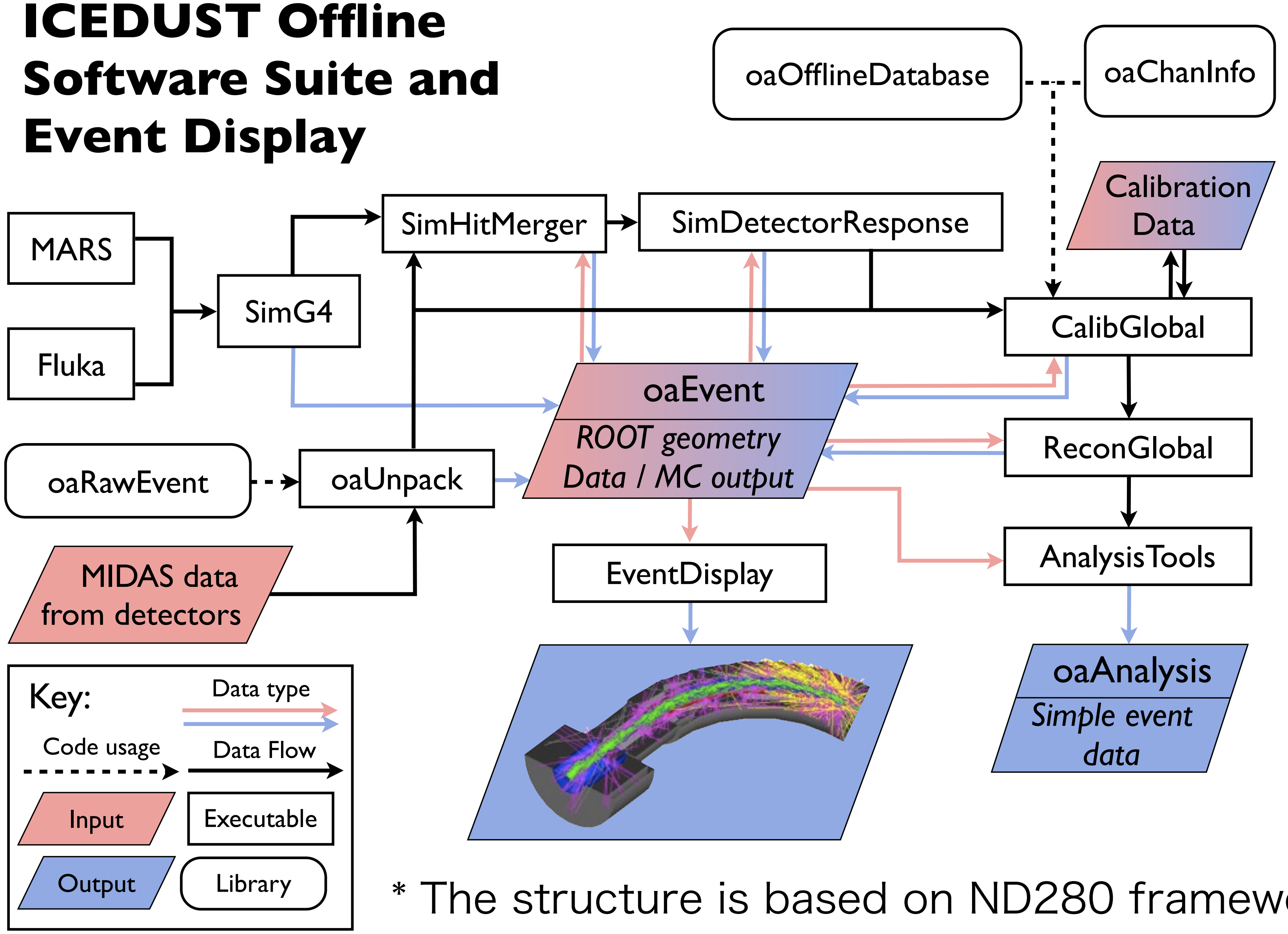


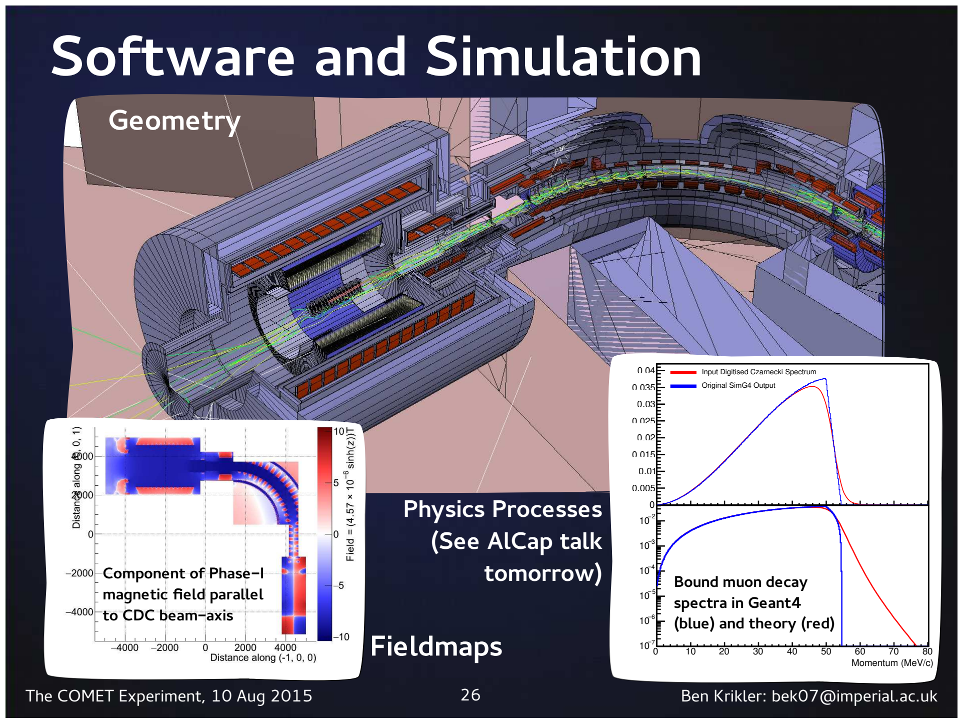
Detector solenoid system

- under construction, will be completed (maybe) in 2016

Software Framework "ICEDUST"

ICEDUST Offline Software Suite and Event Display





an example for Phase-I

* The structure is based on ND280 framework.

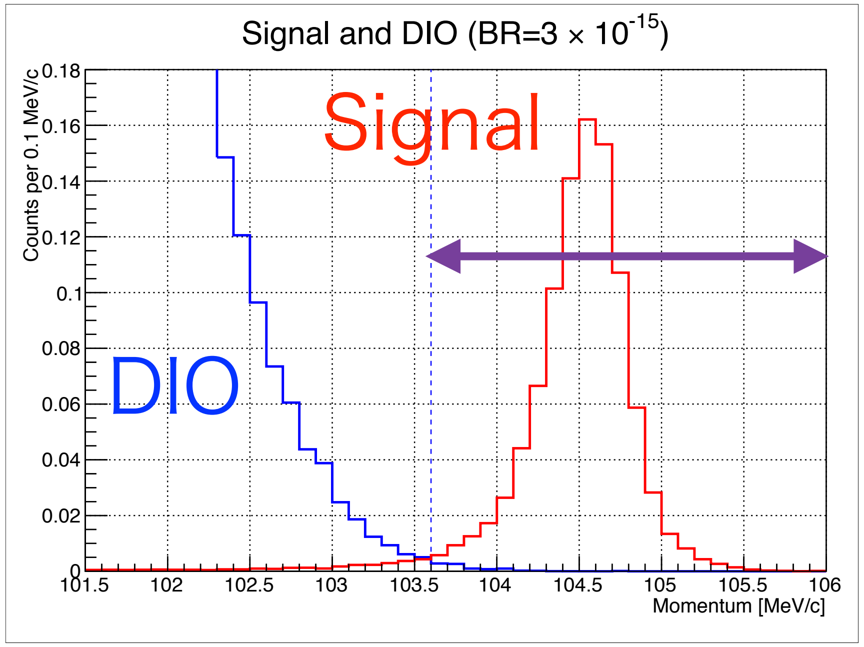
The framework "ICEDUST" has almost been ready in 2015.
Still need to be implemented more, such as detector response.
The simulation and analysis is/will be studied with ICEDUST now.
Mass MC events generation is ongoing for more higher statistics study.

Sensitivity Estimation in COMET Phase-I

Signal Acceptance

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

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



Signal Sensitivity

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

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

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

Muon intensity

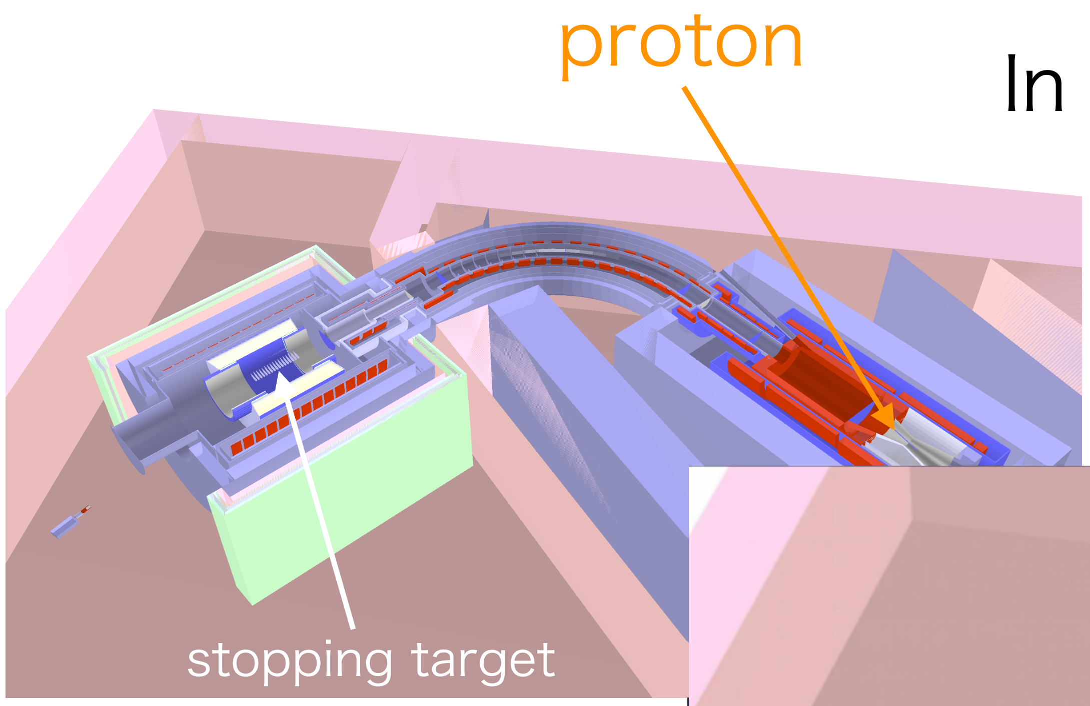
about 0.00052 muons stopped/proton

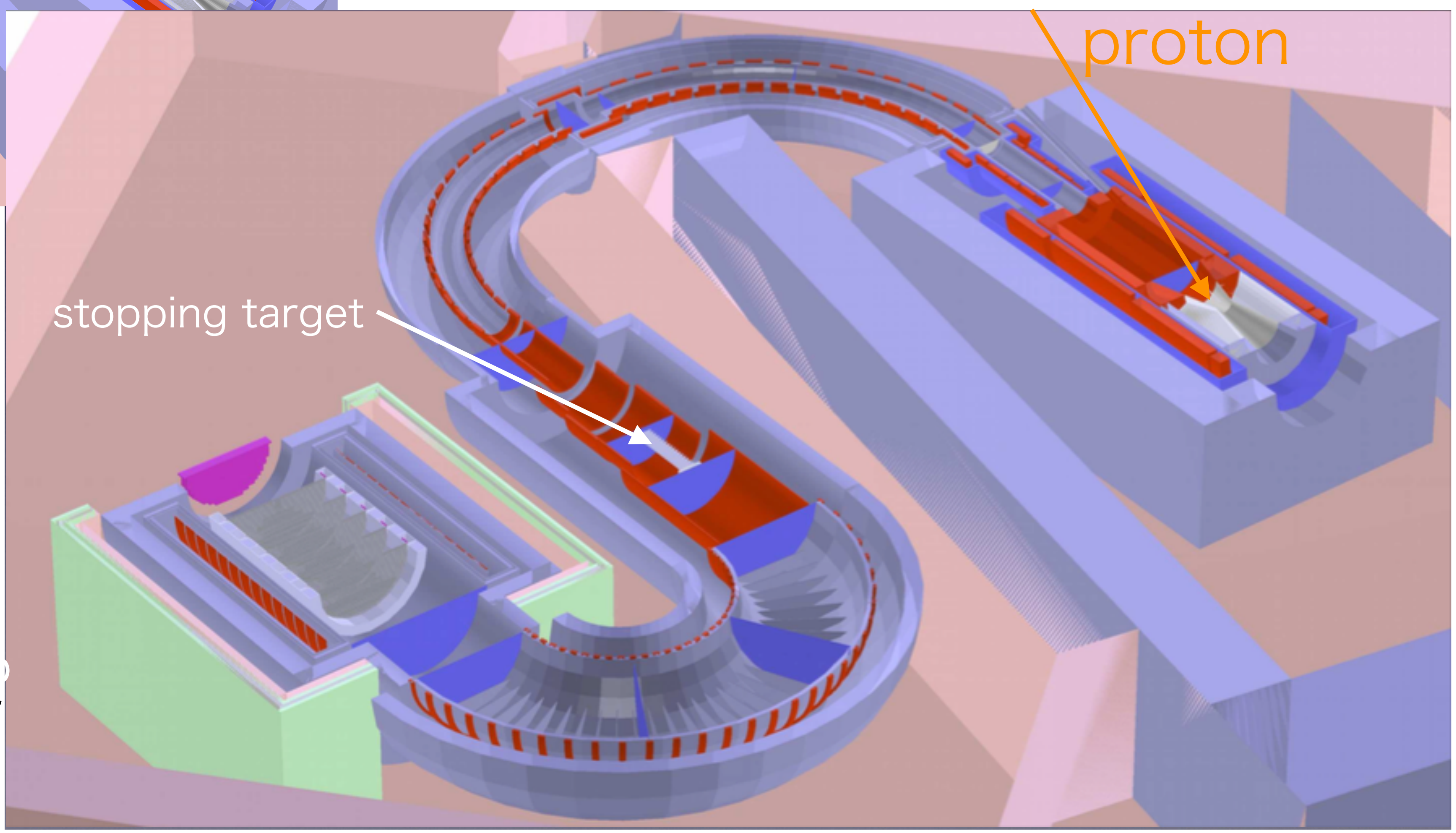
With 0.4 μA, a running time of about 110 days is needed.

toward COMET Phase-II

In Phase-I setup

- 3.2 kW proton beam operation
- 90 degree muon transport solenoid
- CDC in a spectrometer solenoid



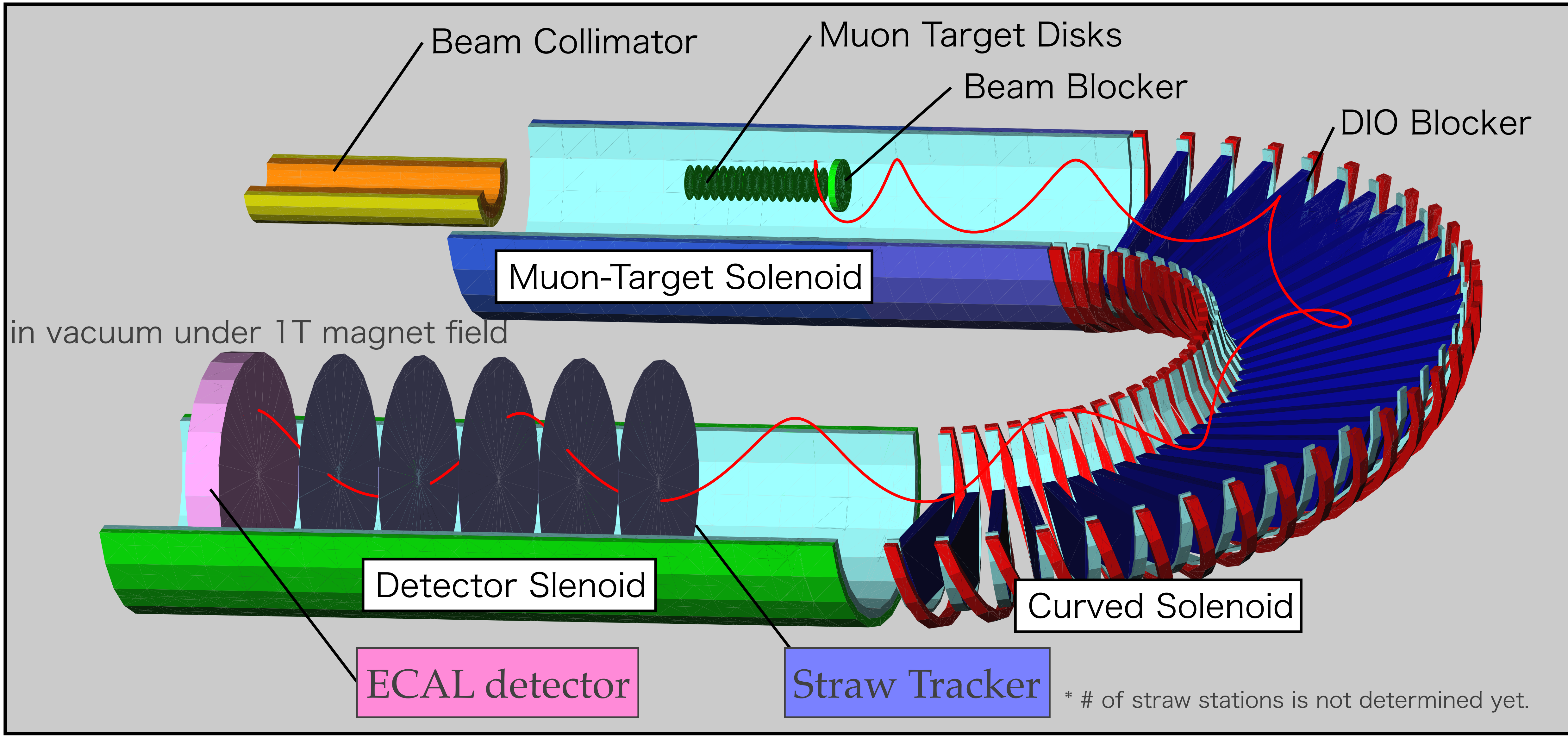


S-Shape Design in Phase-II

In **Phase-II** setup

- 56 kW proton beam
- 180 degree transport solenoid for muon
- 180 degree spectrometer solenoid for electron
- StrawECAL detector

Phase-II Detector



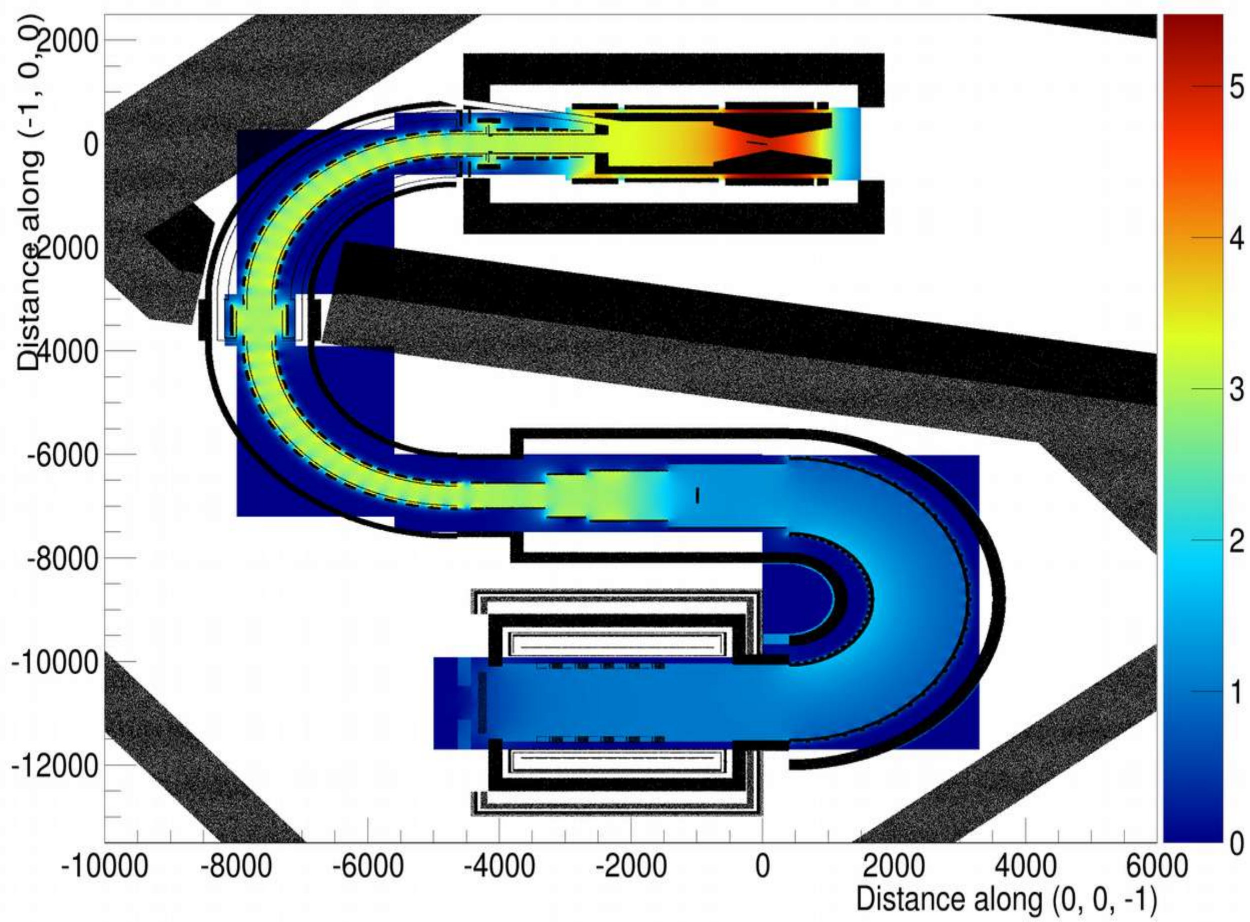
- 180° curved solenoid for higher momentum resolution in the muon/electron transport
- Less dense detectors (Straw Tracker and ECAL in vacuum)

Phase-II Goal :
(in a year operation)

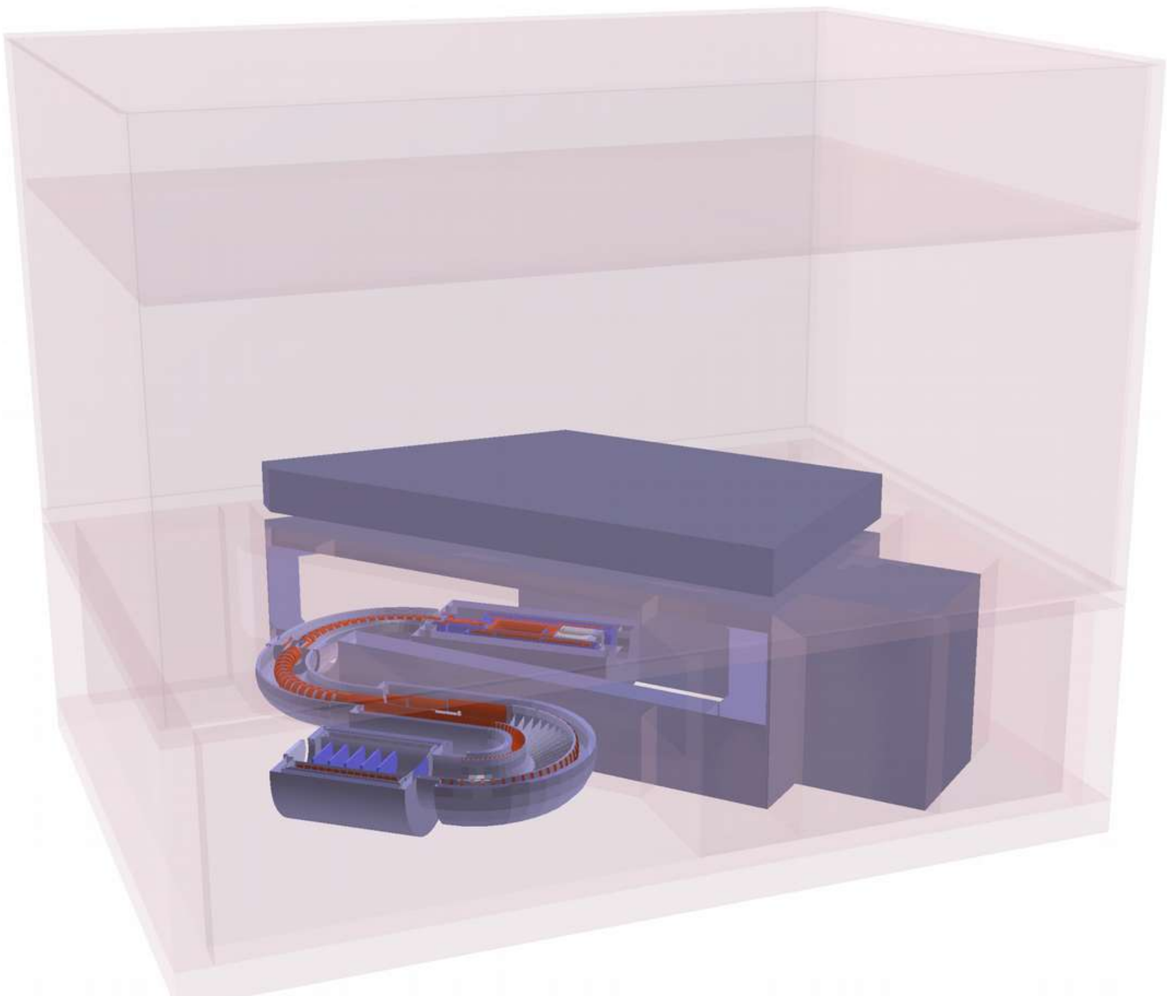
$$B(\mu^- + Al \rightarrow e^- + Al) = 2.6 \times 10^{-17} \text{ (S.E.S)}$$
$$B(\mu^- + Al \rightarrow e^- + Al) < 6 \times 10^{-17} \quad (90\% C.L.)$$

Status of COMET Phase-II

- Development of Phase-I StrawECAL is essentially R&D for Phase-II
- ICEDUST framework enables feasible study for Phase-II



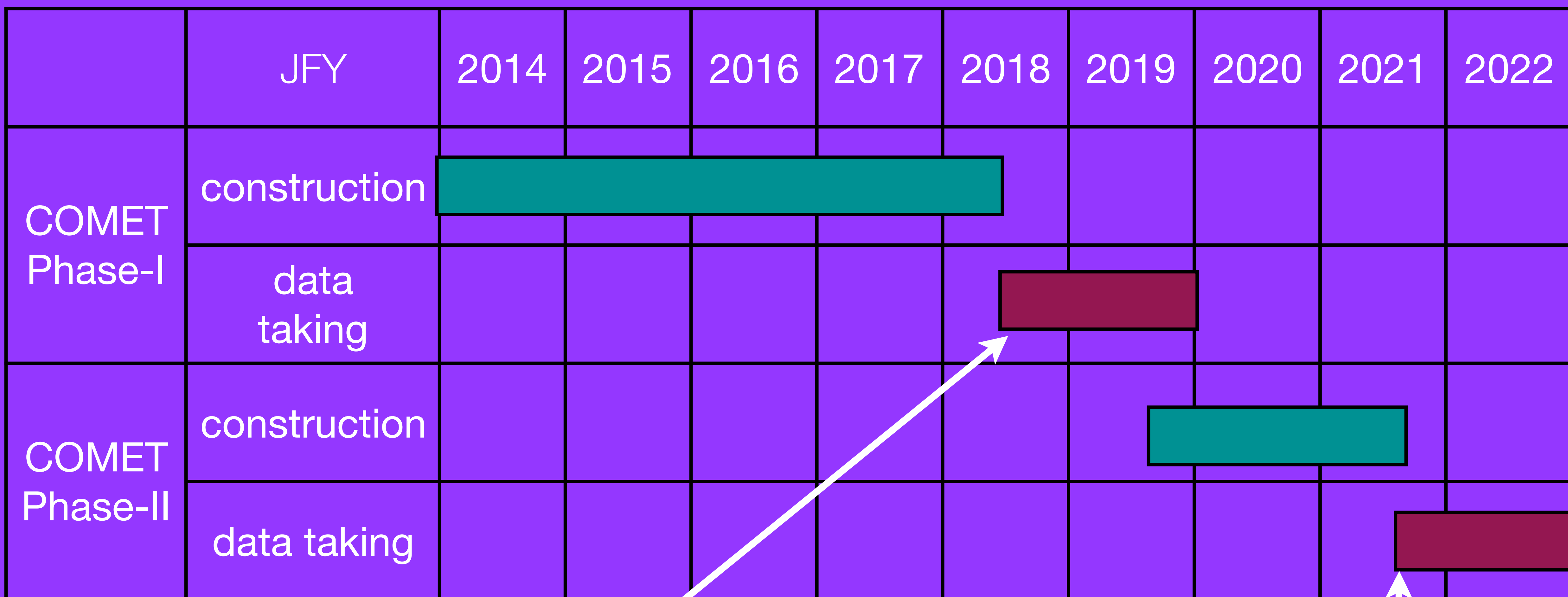
field map design for Phase-II



simulation setup for Phase-II

- Working for further foundation in Phase-II, and negotiating with J-PARC facility for operation schedule for Phase-II

COMET Timeline



COMET Phase-I :
2018 ~
S.E.S. ~ 3×10^{-15}
(for 110 days
with 3.2 kW proton beam)

COMET Phase-II :
2021 ~
S.E.S. ~ 3×10^{-17}
(for 2×10^{7} sec
with 56 kW proton beam)

Summary

- COMET is an experiment search for "μ-e conversion" at J-PARC
  - aiming improvement the sensitivity x 10,000 better than the past
  - staging approach called Phase-I (under construction) / Phase-II
- **COMET Phase-I** is now under construction
  - aiming improvement the sensitivity x 100 better than the past

Phase-I Goal :
(in 110 days operation)

$$B(\mu^- + Al \rightarrow e^- + Al) = 3.0 \times 10^{-15} \ \mathrm{(S.E.S)}$$
$$B(\mu^- + Al \rightarrow e^- + Al) < 7 \times 10^{-15} \quad (90\% C.L.)$$

  - CDC detector for physics search will be constructed soon
  - the other system is also under construction
  - expecting to **start in 2018/2019**, stay tuned! http://comet.kek.jp/
- R&D for **COMET Phase-II** is underway.
  - expecting to start in 2021/2022, aiming further higher sensitivity

Backup

Biography of "μ-e conversion" search

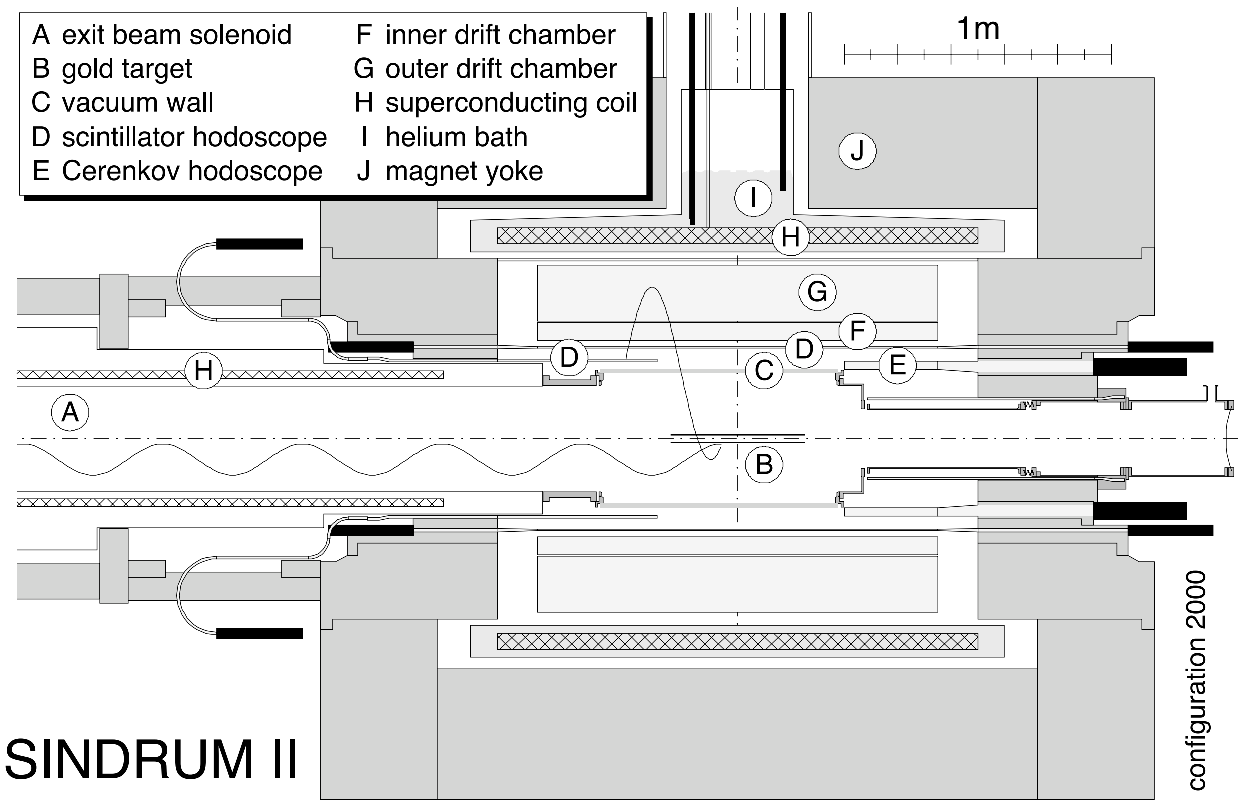
Phy. Rep., 432, 2 (2013)

Table 4
History of $\mu N \to eN$ conversion experiments. Lagarrigue and Peyrou (1952) saw $\approx 1\sigma$ signals for Sn and Sb; we have averaged their results and set an approximate limit. We thank E. Craig Dukes for help in the preparation of this Table.

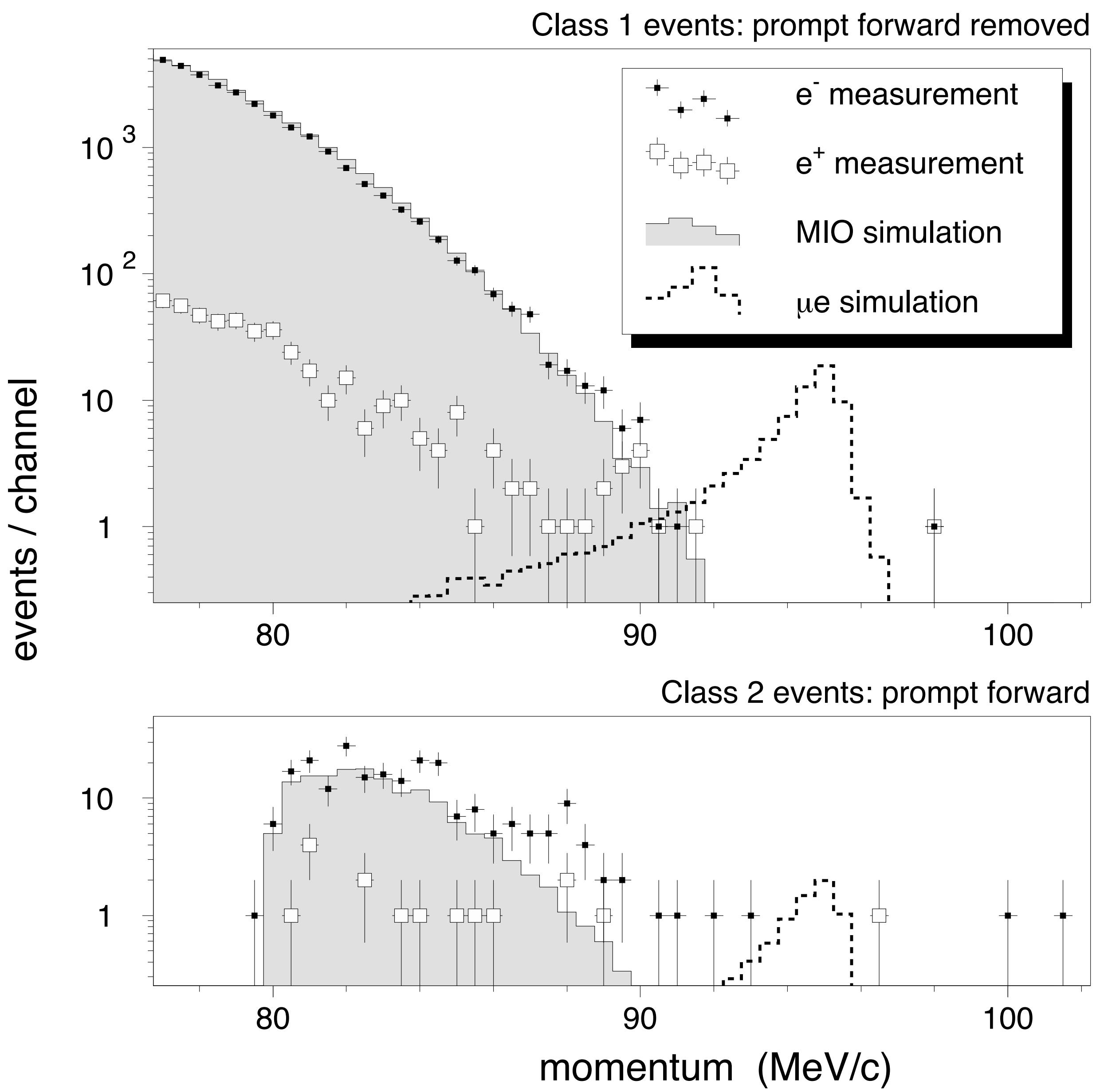
Year	90% Limit	Lab/Collaboration	Reference	Material
1952	1.0×10^{-1}	Cosmic Ray	Lagarrigue and Peyrou (1952)	Sn, Sb
1955	5.0×10^{-4}	Nevis	Steinberger and Wolfe (1955)	Cu
1961	4.0×10^{-6}	LBL	Sard et al. (1961)	Cu
1961	5.9×10^{-6}	CERN	Conversi et al. (1961)	Cu
1962	2.2×10^{-7}	CERN	Conforto et al. (1962)	Cu
1964	2.2×10^{-7}	Liverpool	Bartley et al. (1964)	Cu
1972	2.6×10^{-8}	SREL	Bryman et al. (1972).	Cu
1977	4.0×10^{-10}	SIN	Badertscher et al. (1977)	S
1982	7.0×10^{-11}	SIN	Badertscher et al. (1982)	S
1988	4.6×10^{-12}	TRIUMF	Ahmad et al. (1988)	Ti
1993	4.3×10^{-12}	SINDRUM II	Dohmen et al. (1993)	Ti
1995	6.5×10^{-13}	SINDRUM II	Eggli (1995)	Ti
1996	4.6×10^{-11}	SINDRUM II	Honecker et al. (1996)	Pb
2006	7.0×10^{-13}	SINDRUM II	Bertl et al. (2006)	Au

The current limit is given by SINDRUM-II experiment, but the experiment started in 1980s, so some experiments are planed to update the limit very soon. In Japan, DeeMe and COMET experiments are planed and under construction.

SINDRUM-II at PSI



Published Results (2006)

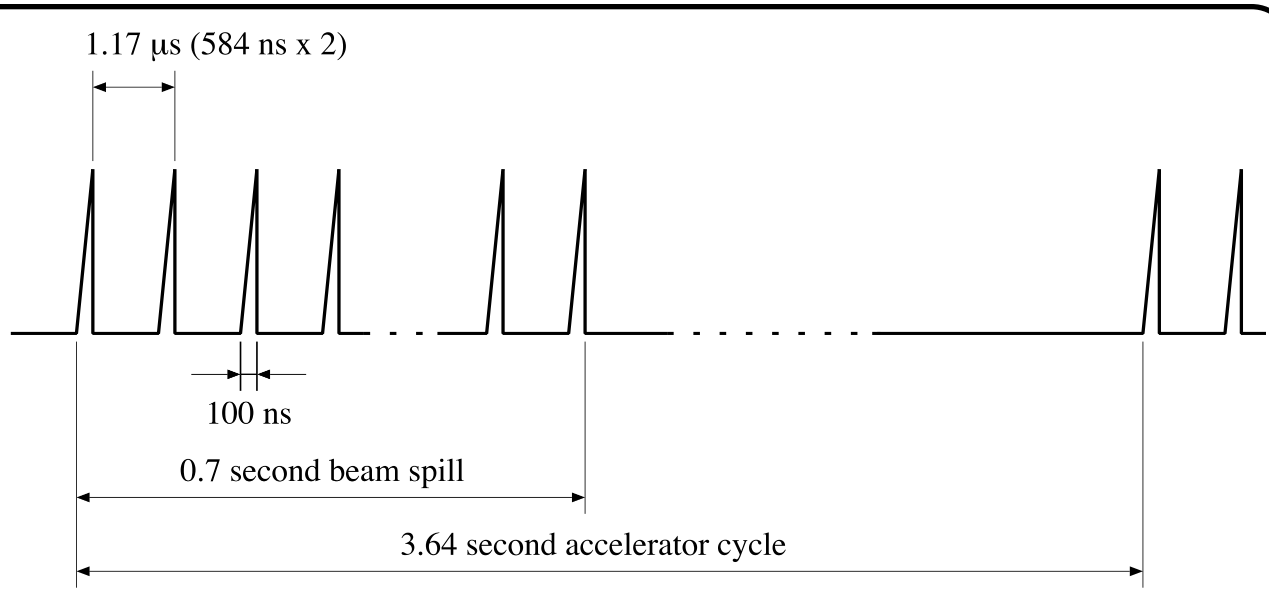


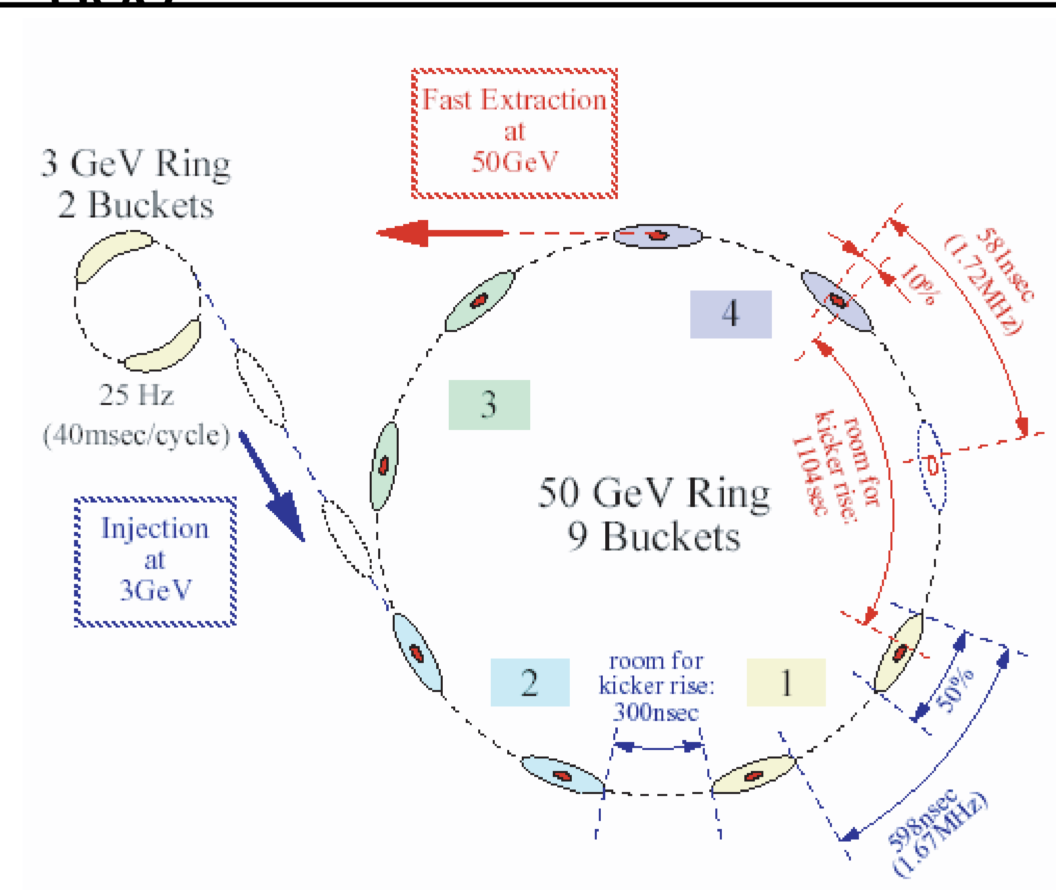
PSI muon beam intensity ~ $10^{7\text{-}8}$/sec beam from the PSI cyclotron. To eliminate beam related background from a beam, a beam veto counter was placed. But, it could not work at a high rate.

Current World Best Limit : $B(\mu^- + Au \rightarrow e^- + Au) < 7 \times 10^{-13}$

Proton Beam at J-PARC

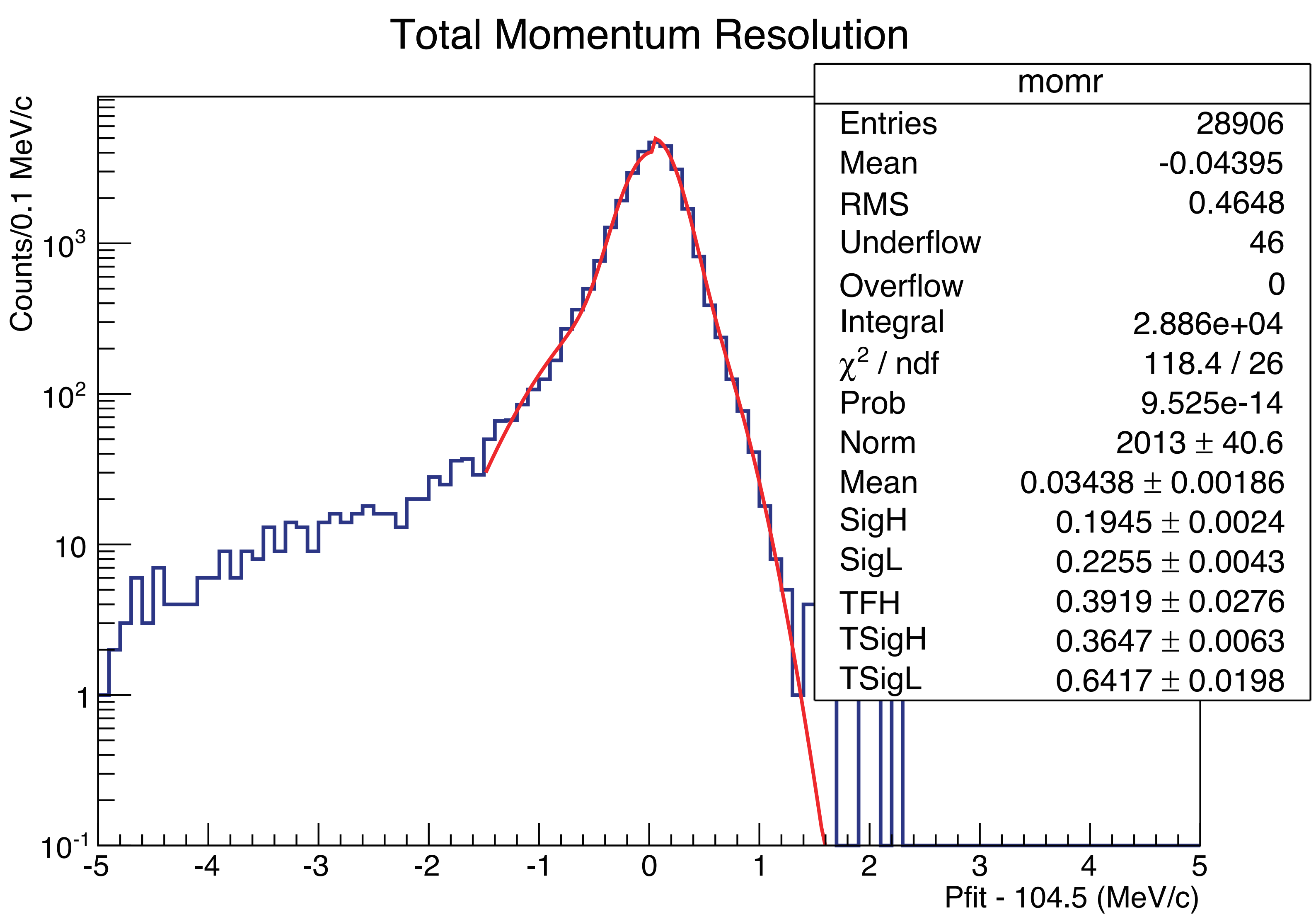
- A pulsed proton beam is needed to reject beam-related prompt background.
- Time structure required for proton beams.
  - Pulse separation is ~ 1μsec or more (muon lifetime).
  - Narrow pulse width (<100 nsec)
- Pulsed beam from slow extraction.
  - fill every other rf buckets with protons and make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





(simulation result)

CDC Momentum Resolution



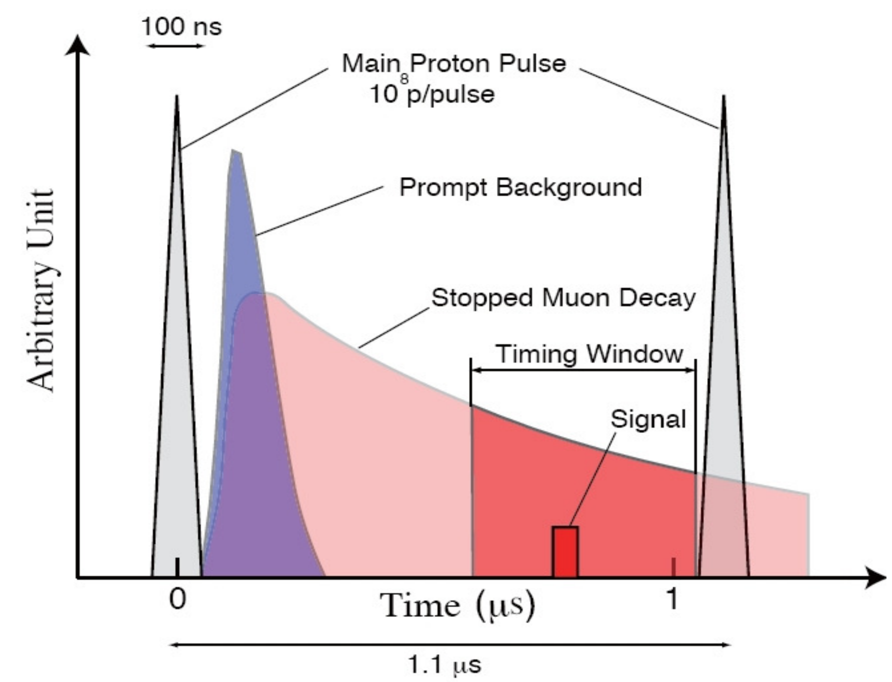
about 200 keV/c achieved.

σ of the core Gaussian at the high momentum side `SigH`	195 keV/c
σ of the core Gaussian at the high momentum side `SigL`	226 keV/c
Fraction in the tail distribution `TFH`	39%
σ of the tail Gaussian at the high momentum side `TSigH`	365 keV/c
σ of the tail Gaussian at the low momentum side `TSigL`	642 keV/c

Backgrounds List

Intrinsic physics backgrounds		
1	Muon decay in orbit (DIO)	Bound muons decay in a muonic atom
2	Radiative muon capture (external)	$\mu^- + A \to \nu_\mu + A' + \gamma$, followed by $\gamma \to e^- + e^+$
3	Radiative muon capture (internal)	$\mu^- + A \to \nu_\mu + e^+ + e^- + A'$,
4	Neutron emission after after muon capture	$\mu^- + A \to \nu_\mu + A' + n$, and neutrons produce e^-
5	Charged particle emission after muon capture	$\mu^- + A \to \nu_\mu + A' + p$ (or d or α), followed by charged particles produce e^-
Beam related prompt/delayed backgrounds		
6	Radiative pion capture (external)	$\pi^- + A \to \gamma + A'$, $\gamma \to e^- + e^+$
7	Radiative pion capture (internal)	$\pi^- + A \to e^+ + e^- + A'$
8	Beam electrons	e^- scattering off a muon stopping target
9	Muon decay in flight	μ^- decays in flight to produce e^-
10	Pion decay in flight	π^- decays in flight to produce e^-
11	Neutron induced backgrounds	neutrons hit material to produce e^-
12	$\overline{p}$ induced backgrounds	$\overline{p}$ hits material to produce e^-
Other backgrounds		
14	Cosmic-ray induced backgrounds	
15	False tracking	

Table 8: *A list of potential backgrounds for a search for $\mu^- N \to e^- N$ conversion.*



Background Estimation

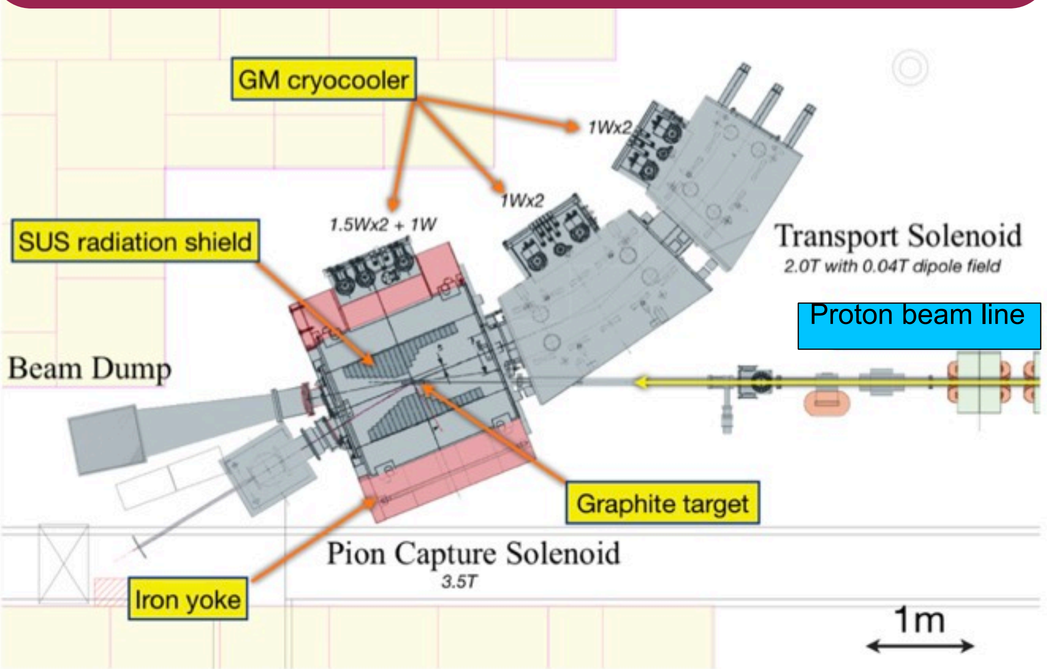
Table 19.8: *Summary of the estimated background events for a single-event sensitivity of* 3×10^{-15} *in COMET Phase-I with a proton extinction factor of* 3×10^{-11}.

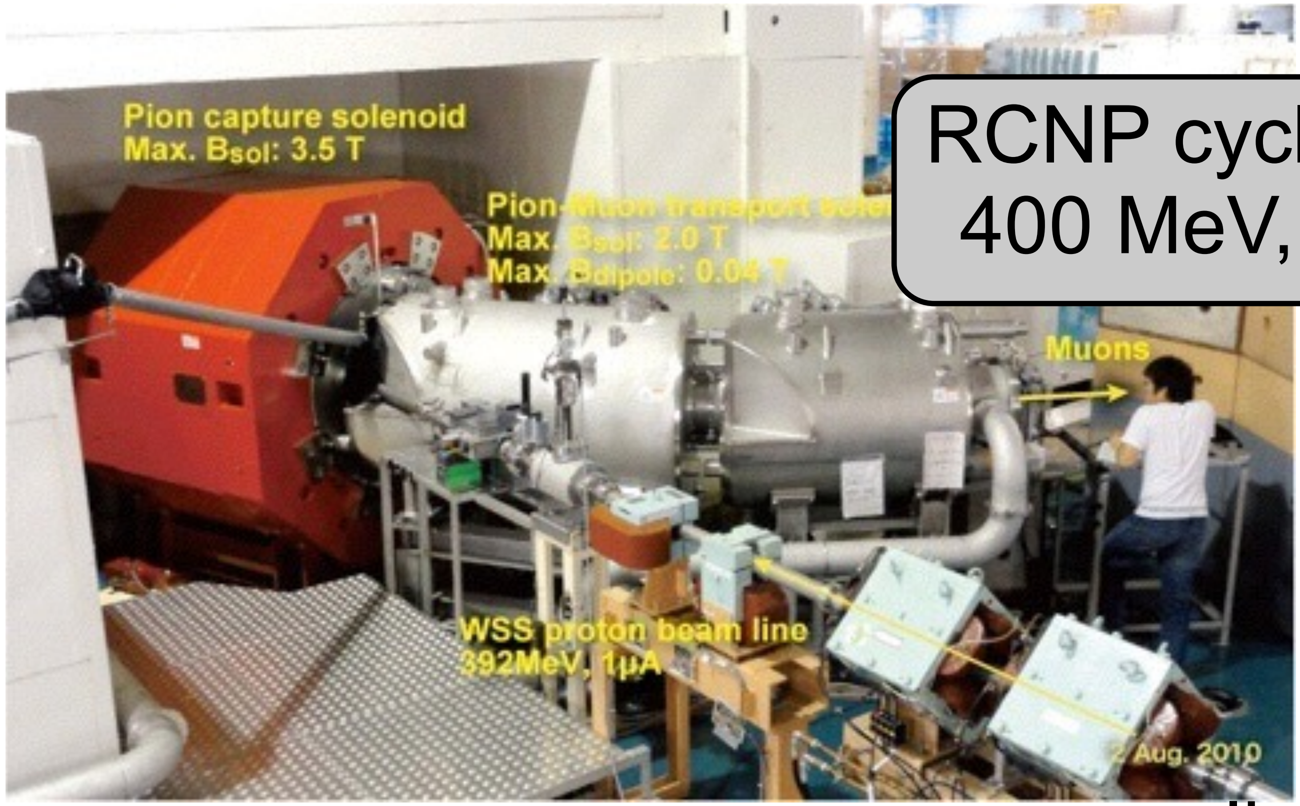
Type	Background	Estimated events
Physics	Muon decay in orbit	0.01
	Radiative muon capture	0.0019
	Neutron emission after muon capture	< 0.001
	Charged particle emission after muon capture	< 0.001
Prompt Beam	* Beam electrons	
	* Muon decay in flight	
	* Pion decay in flight	
	* Other beam particles	
	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.

RCNP-MuSIC

MuSIC@Osaka-U

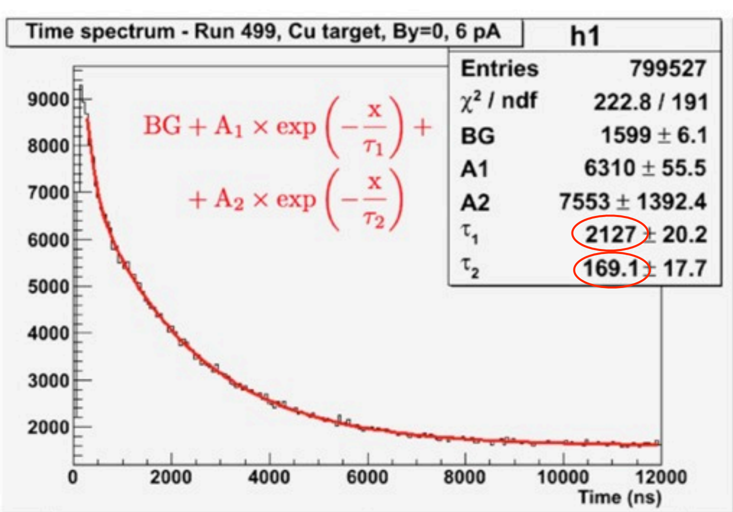




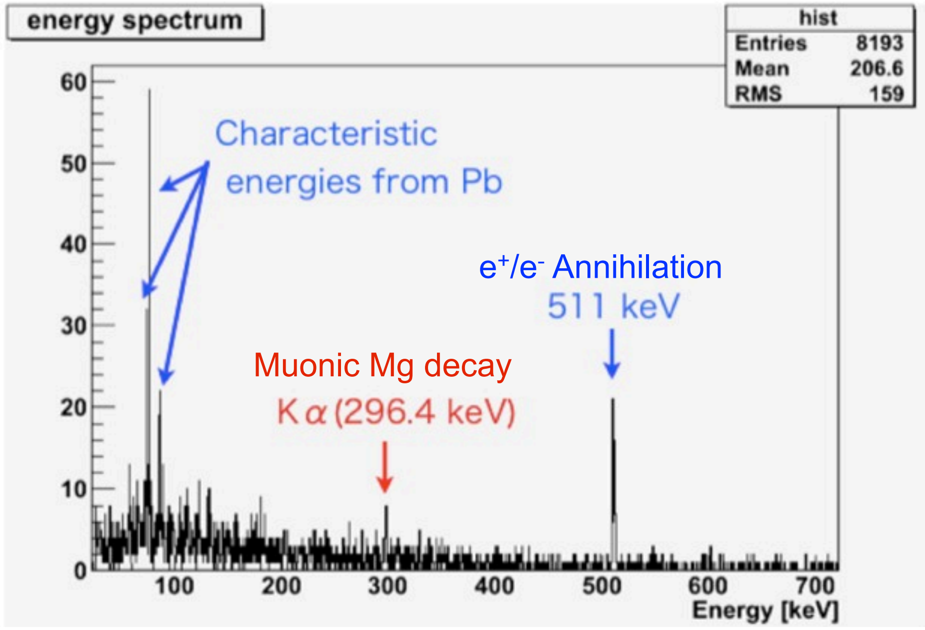
RCNP cyclotron
400 MeV, 1μA

preliminary

Measurements on June 21, 2011 (26 pA)



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



MuSIC muon yields

μ^+ : 3×10^8/s for 400W

μ^- : 1×10^8/s for 400W

cf. 10^8/s for 1MW @PSI

Req. of x10^3 achieved...

Present Limit and Future Prospects

process	present limit	future	
$\mu \to e\gamma$	$<5.7 \times 10^{-13}$	$<10^{-14}$	MEG at PSI
$\mu \to eee$	$<1.0 \times 10^{-12}$	$<10^{-16}$	Mu3e at PSI
$\mu N \to eN$ (in Al)	none	$<10^{-16}$	Mu2e / COMET
$\mu N \to eN$ (in Ti)	$<4.3 \times 10^{-12}$	$<10^{-18}$	PRISM
$\tau \to e\gamma$	$<1.1 \times 10^{-7}$	$<10^{-9} - 10^{-10}$	superKEKB
$\tau \to eee$	$<3.6 \times 10^{-8}$	$<10^{-9} - 10^{-10}$	superKEKB
$\tau \to \mu\gamma$	$<4.5 \times 10^{-8}$	$<10^{-9} - 10^{-10}$	superKEKB
$\tau \to \mu\mu\mu$	$<3.2 \times 10^{-8}$	$<10^{-9} - 10^{-10}$	superKEKB/LHCb

PRISM/PRIME Experiment

MW beam

aiming S.E.S ~ 3×10^{-19}