Search for Muon to Electron Conversion at J-PARC: **COMET Phase-I Experiment**

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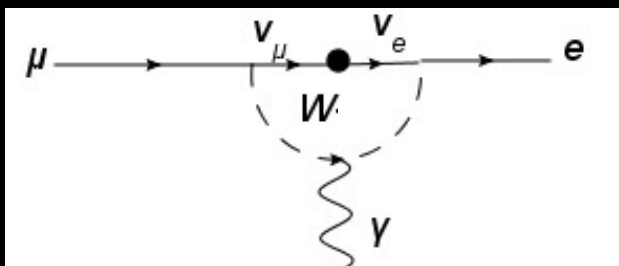
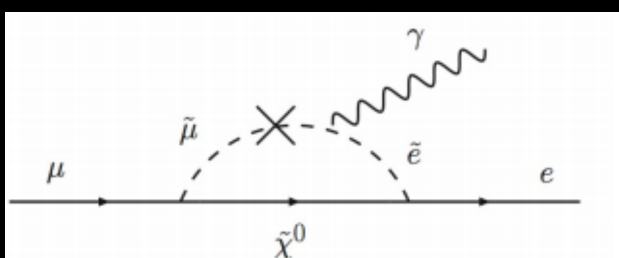
Sep 25, 2017, NUFACT 2017

Muon LFV

Note : $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$

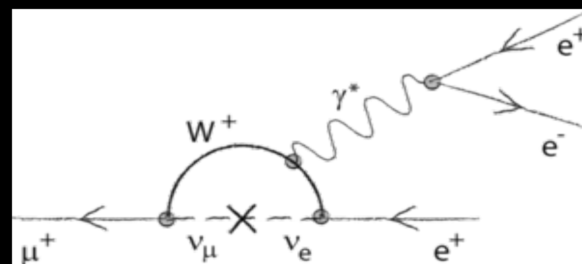
$\mu^+ \rightarrow e^+ \gamma$

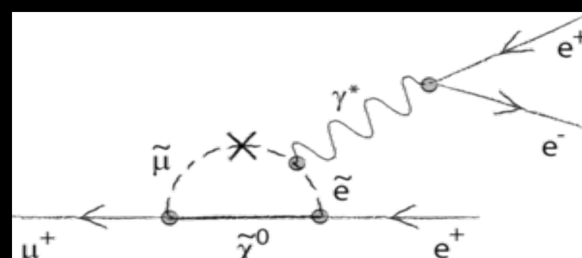




- MEG (PSI)
- MEG upgrade (planned)

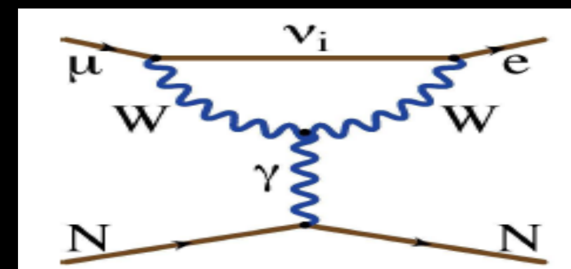
$\mu^+ \rightarrow e^+ e^- e^+$

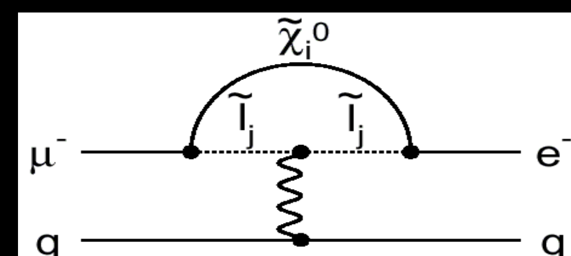




- Mu3e (PSI, planned)

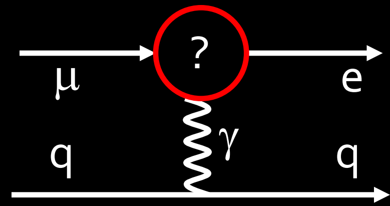
$\mu^- N \rightarrow e^- N$

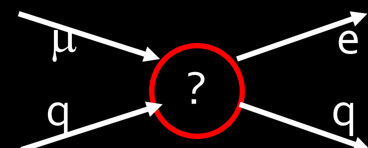




- Mu2e (FNAL)
- DeeMe (J-PARC)
- **COMET** (J-PARC)

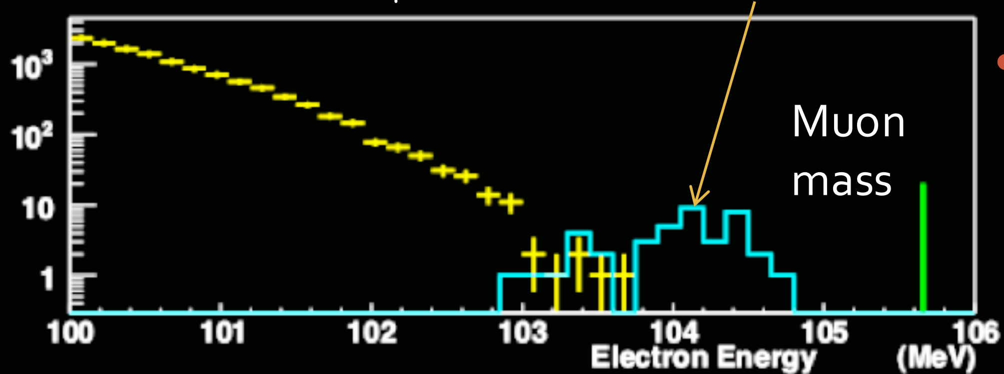
Muon Conversion: $\mu^- N \rightarrow e^- N$





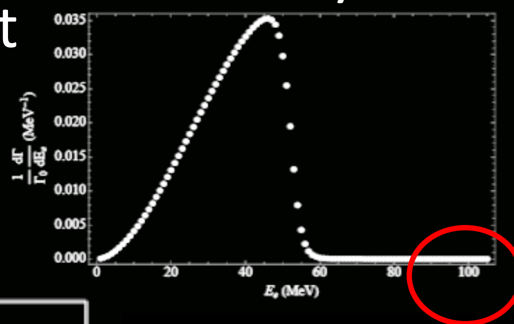
Signal

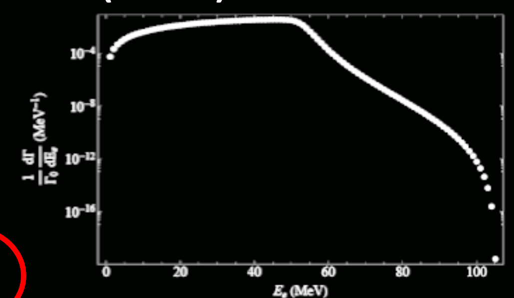
- Muon stops at Al (or Ti) target, captured in 1s orbit
- Decay with mono-energetic electron
  - $E = m_\mu - E_{rec} - E_B \sim 105\text{MeV}$



Background

- Decay-In-Orbit (DIO)

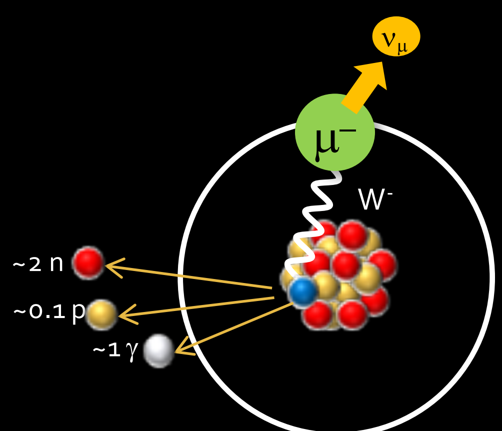


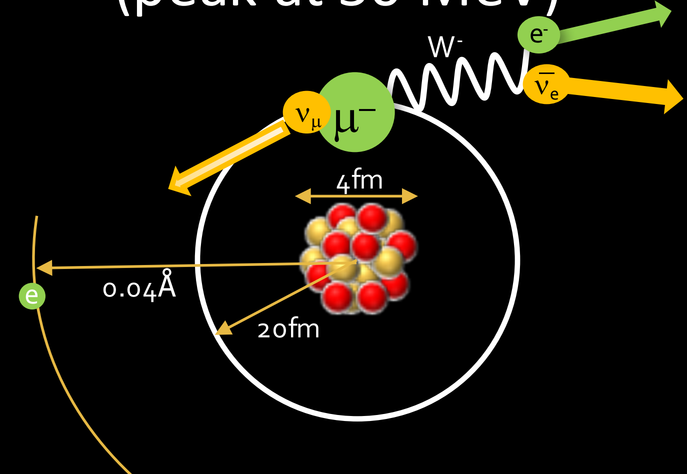


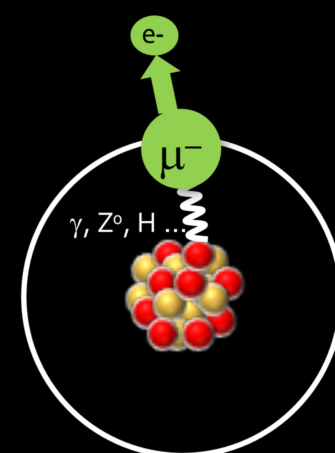
- Prompt background (to beam arrival)
  - Muon/pion decay in flight
  - Radiative pion capture: $\pi N \rightarrow \gamma X$; $\gamma \rightarrow e+e-$
  - Cosmic, Anti-proton…

Stopped μ- in matter

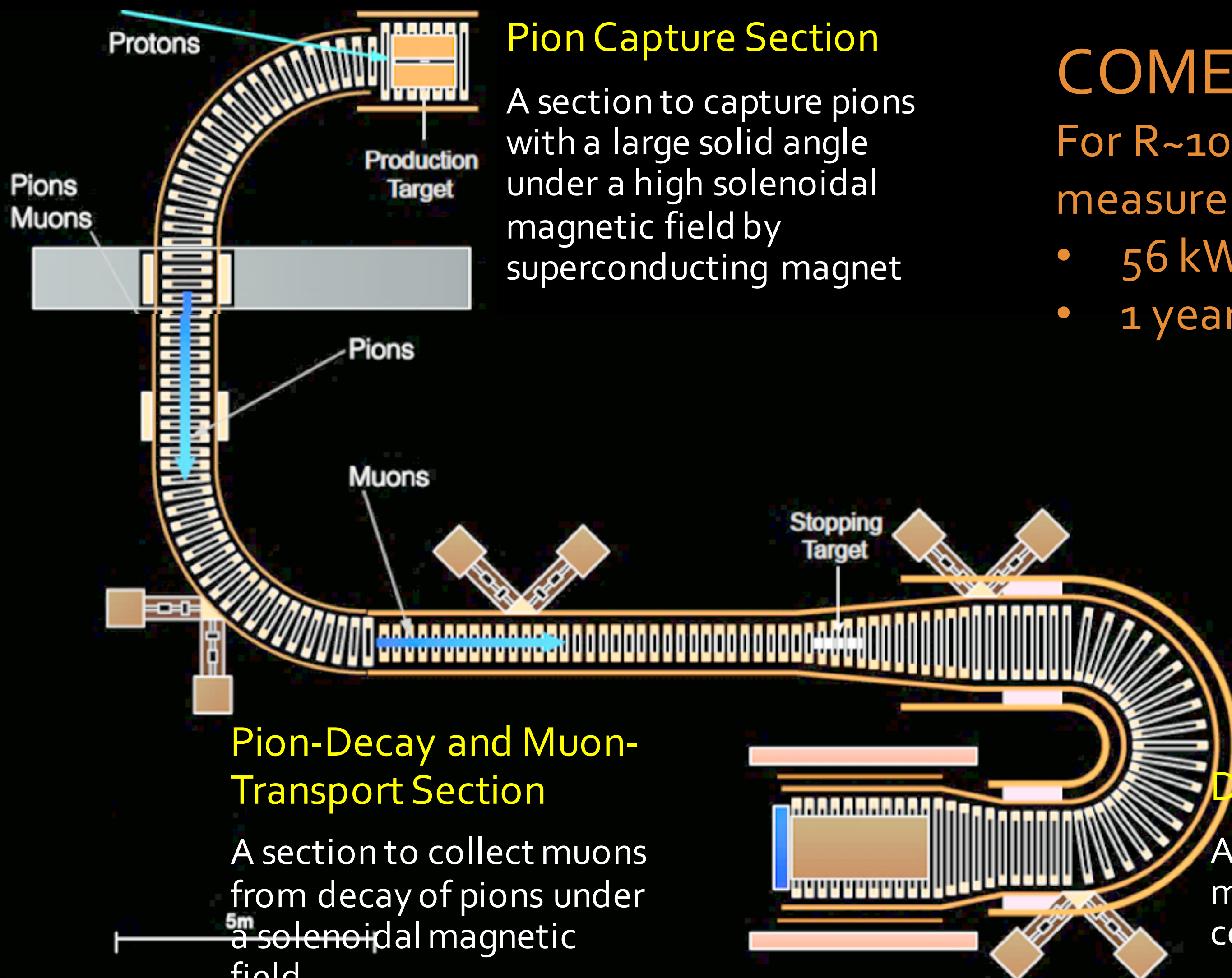
- Muon capture : 61% (Al)
  - $\mu^- + p \rightarrow \nu_\mu + n$
  - Muon decay coherently with nucleus
  - Source of background hits
- Decay in orbit (DIO) : 39% (Al)
  - $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$
  - (Dynamically) free decay of muon inside atom
  - E(e,max,Al) ~< m_μ ~ 104MeV (peak at 50 MeV)
- **Muon conversion**
  - $\mu^- + N \rightarrow e^- + N$
  - Muon conversion coherently with nucleus







COMET Experiment



Pion Capture Section

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

COMET Phase-II

For R~10^{-17} muon conversion measurement

- 56 kW proton beam
- 1 year DAQ

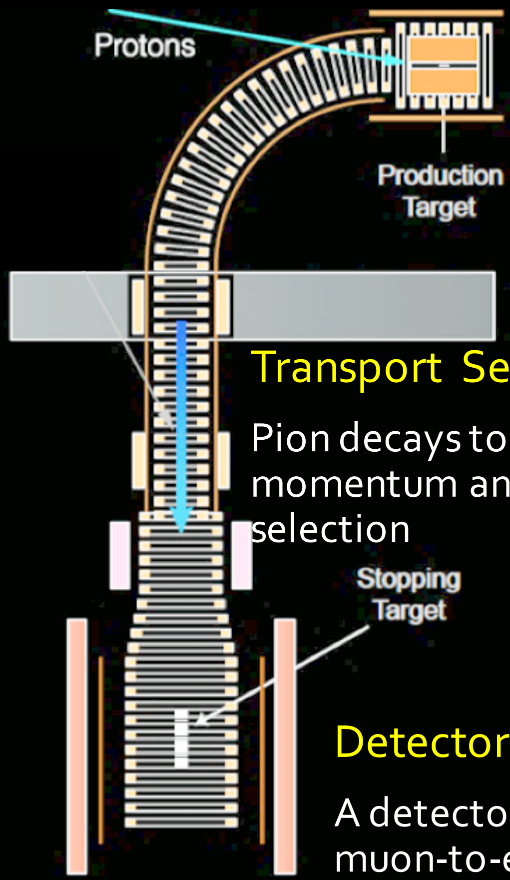
Pion-Decay and Muon-Transport Section

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

Detector Section

A detector to search for muon-to-electron conversion process

COMET Experiment



Pion Capture Section

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

Transport Section

Pion decays to muon, with momentum and charge selection

Detector Section

A detector to search for muon-to-electron conversion process

COMET Phase-II

For $R \sim 10^{-17}$ muon conversion measurement

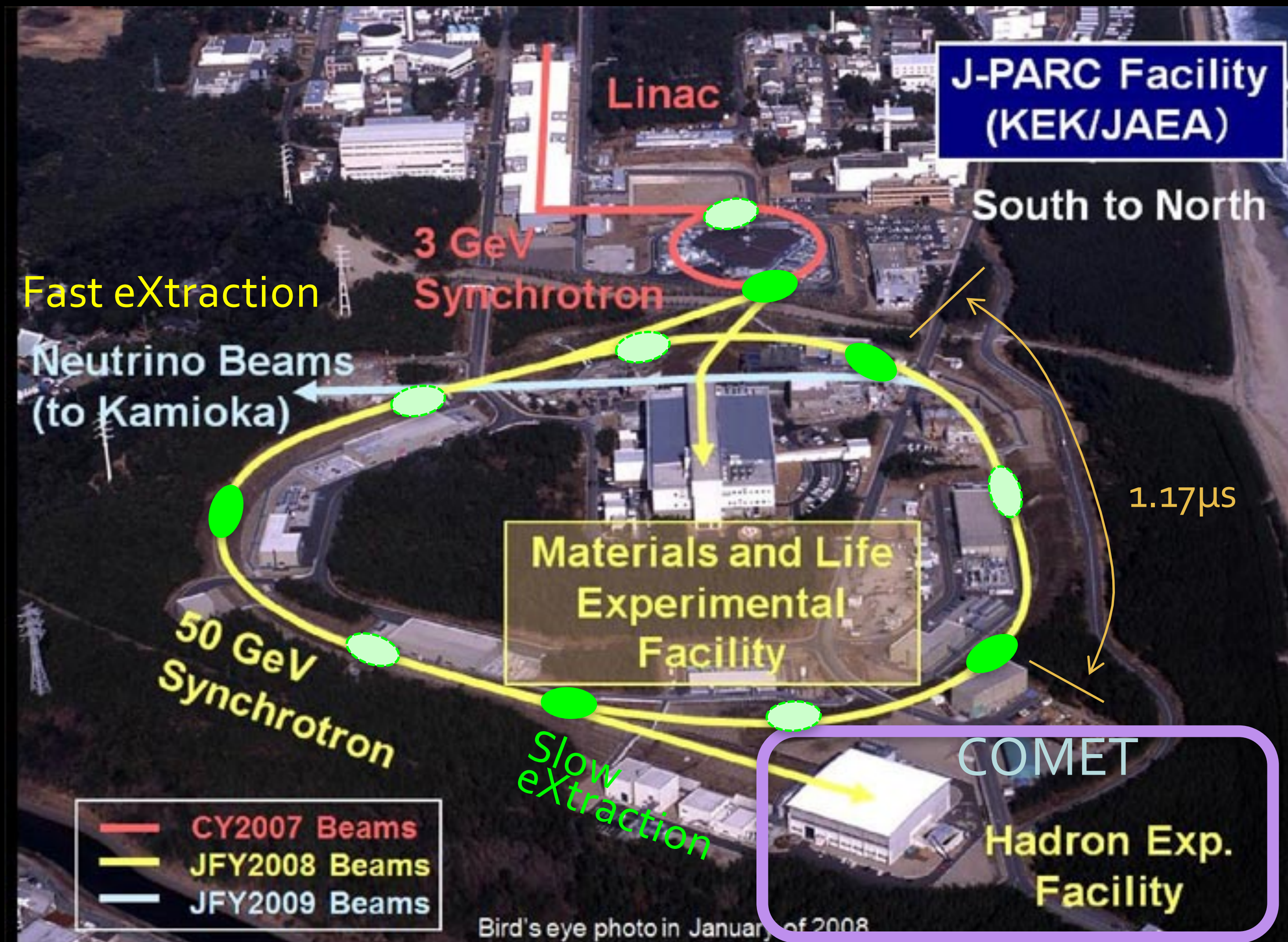
- 56 kW proton beam
- 1 year DAQ

COMET-Phase-I

For BG measurement, $R \sim 10^{-15}$ muon conversion

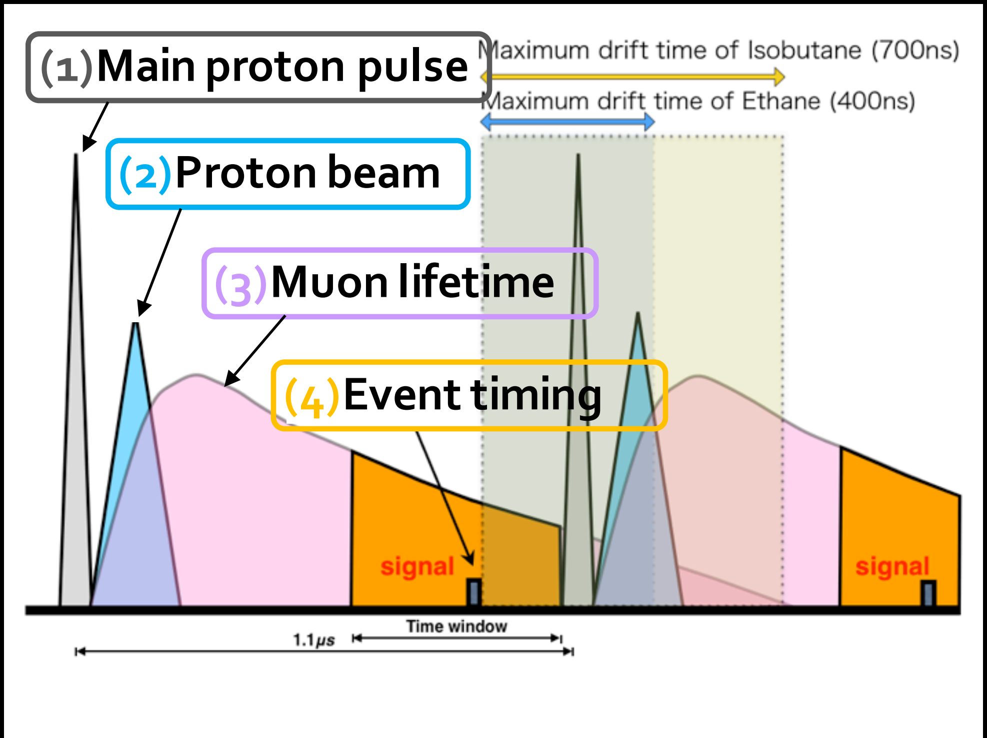
- 3.2kW proton beam
- Half year DAQ

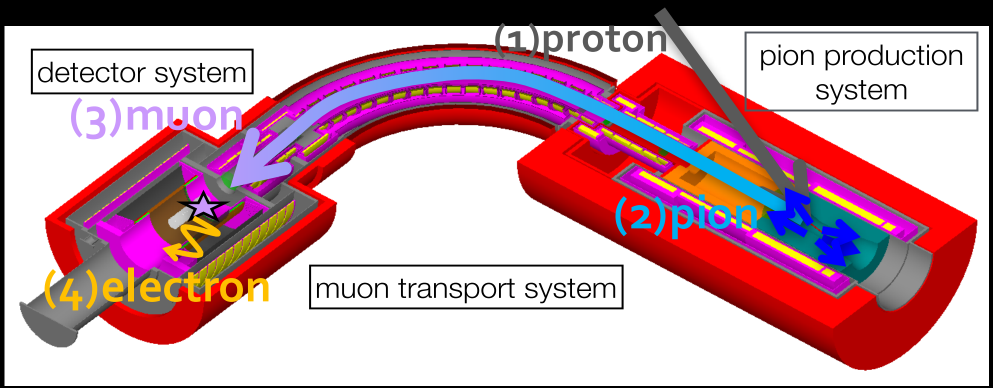
Facility / Beams



8GeV, 3.2kW pulsed proton beam in Phase-I, 4/9 (or 3/9) buckets filled in MR

Experimental Principle

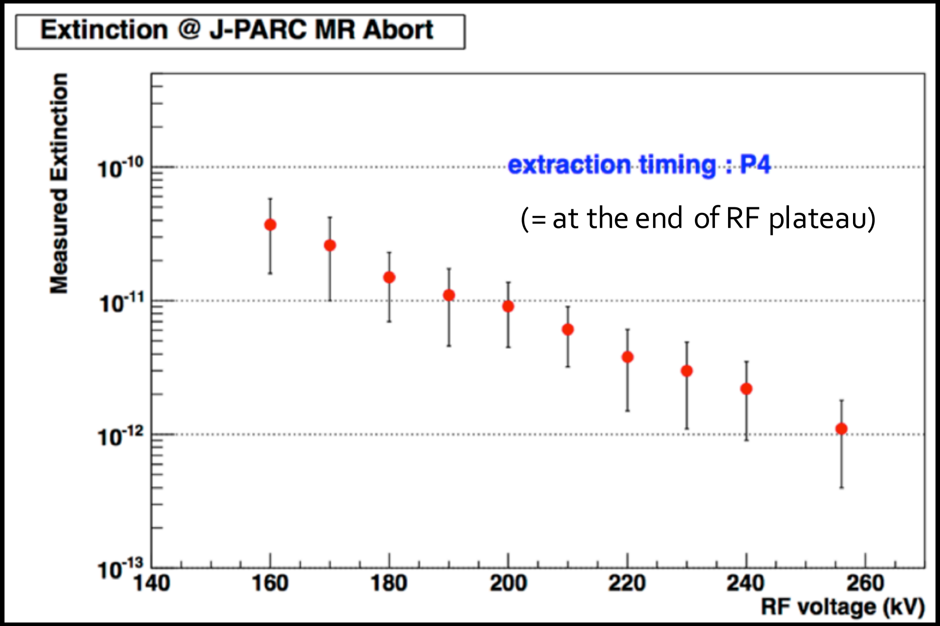




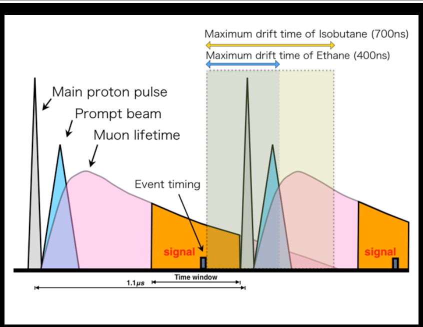
1. Protons arrive at production target
2. Pions and muons arrive at stopping target
3. Captured muon decay with finite lifetime
4. Some time after muon beam arrival, electron is measured

- Any other beam particles in this time window are backgrounds
  - Bunch beam with high extinction factor

Pulsed Proton Beam

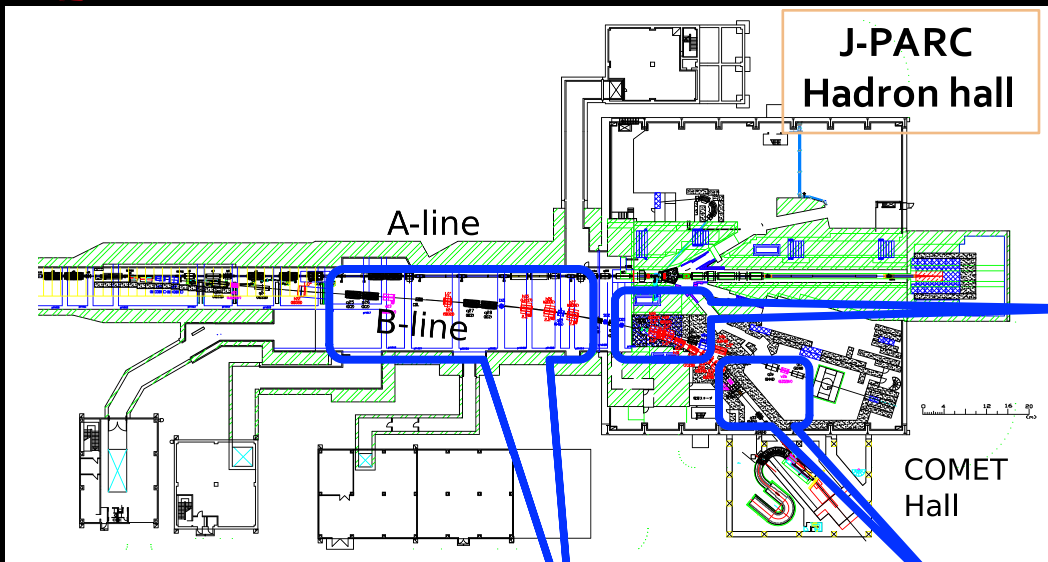


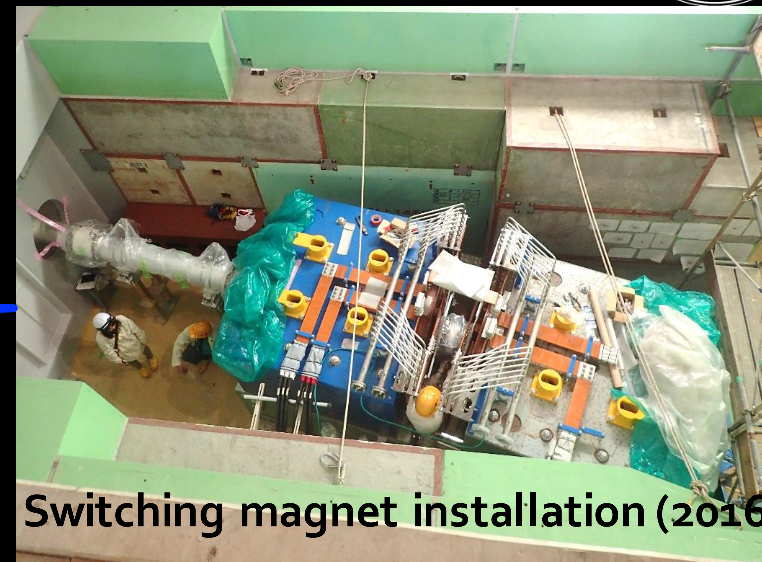
Beam Power	3.2 kW
Energy	8 GeV
Average current	0.4 μA
Beam Emittance	10π mm・mrad
Proton/bunch	$<10^{10}$
Extinction	10^{-9}
Bunch separation	1~2 μs
Bunch length	100ns



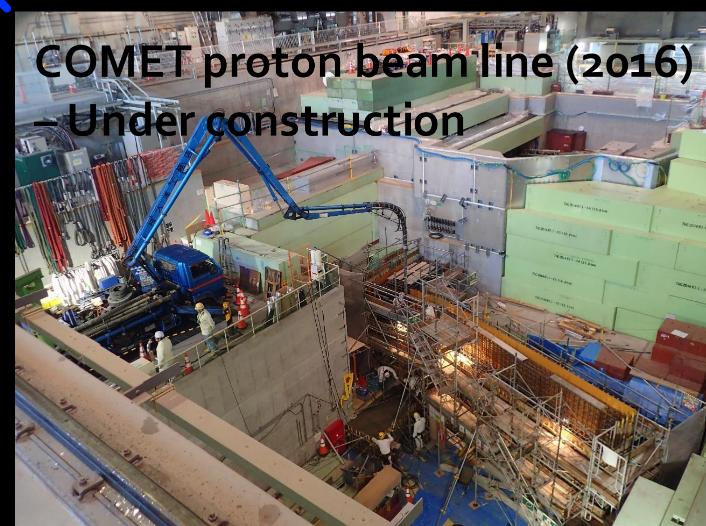
- Pulsed proton beam
  - Beam background with proton pulse is major BG hit source
  - High extinction between beam enables localizing signal event in time
- $\sim 10^{-11}$ extinction factor measured by increasing MR RF voltage (May 2014), both at 8GeV and 30GeV, in Fast Extraction (@ Abort line)
- More test with Slow Extraction early next year

Accelerator Facility



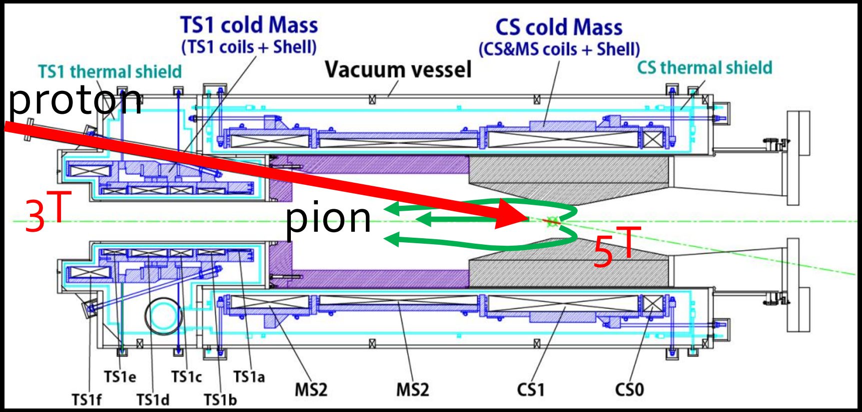

Switching magnet installation (2016)

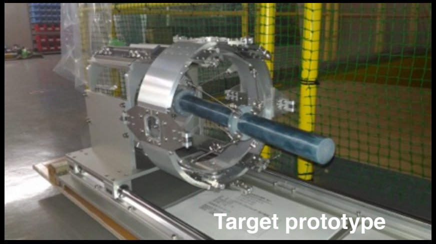

Switching yard (2014)
– Almost ready

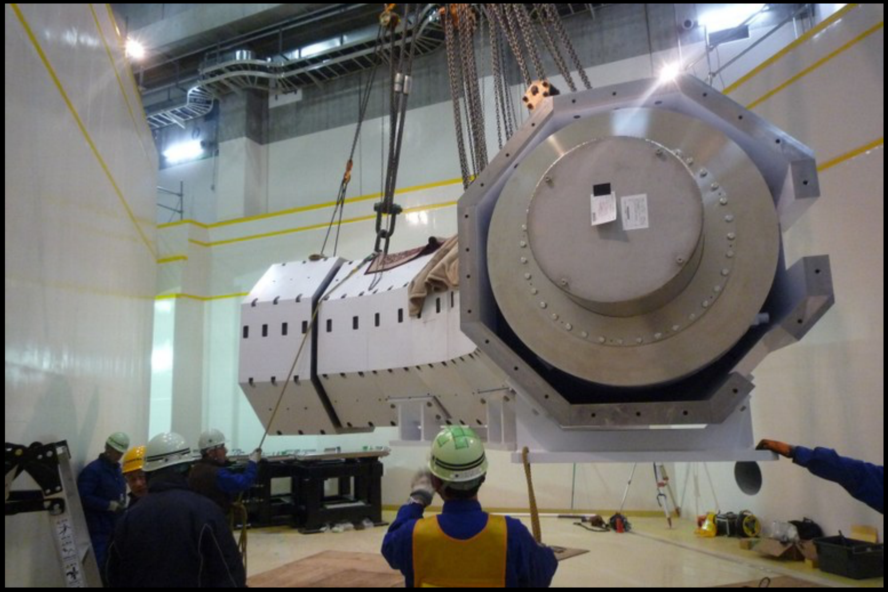

COMET proton beam line (2016)
– Under construction

Solenoids

- Pion Capture Solenoid
  - Downstream parts ready, Upstream parts this and next year
  - All SC wires prepared
- Transport Solenoid
  - Ready, test and installation, alignment

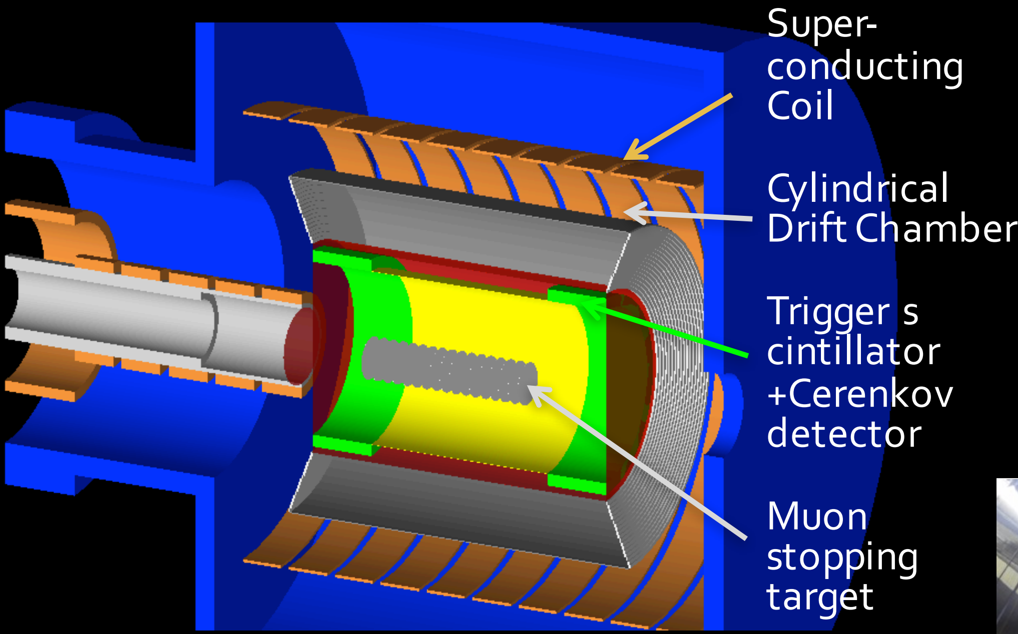


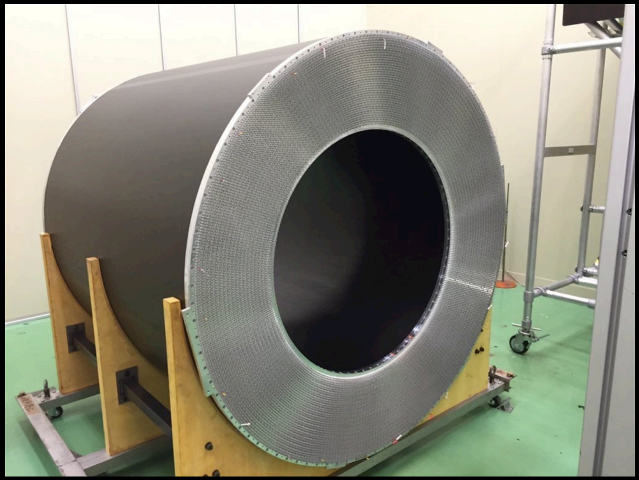


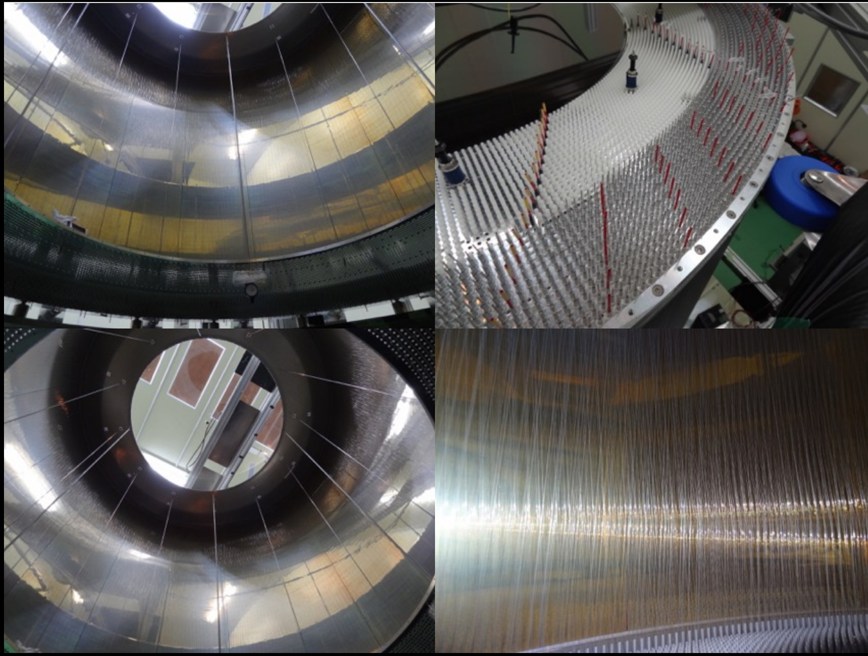


Cylindrical Detector system

(Detector for muon conversion search)



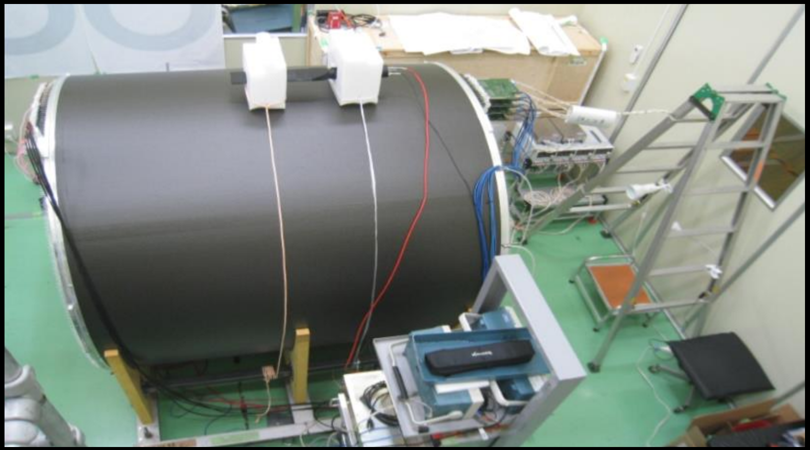


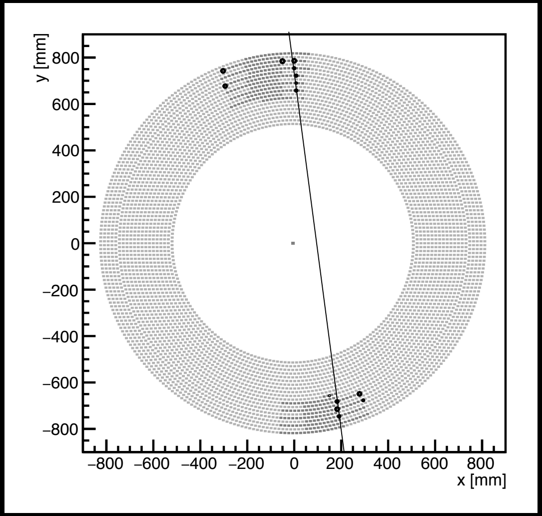


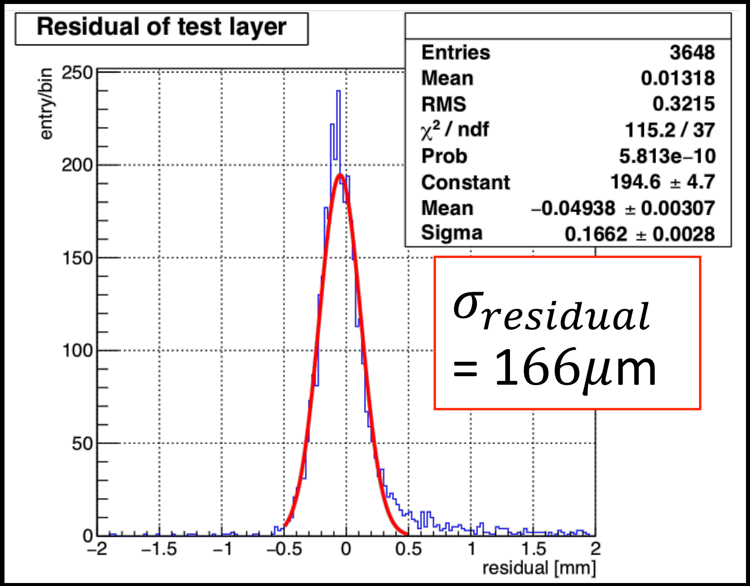
- All stereo-wire drift chamber, 18 layers, ~5000 sense wires
- Hodoscope for timing and trigger
- Construction completed June 2016, Cosmic ray test from August 2016

CDC CR test @ KEK

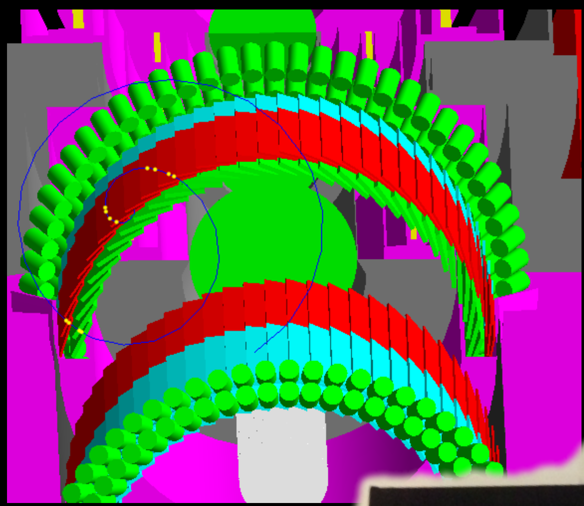
- Spatial resolution better than 200μm requirement measured from cosmic run

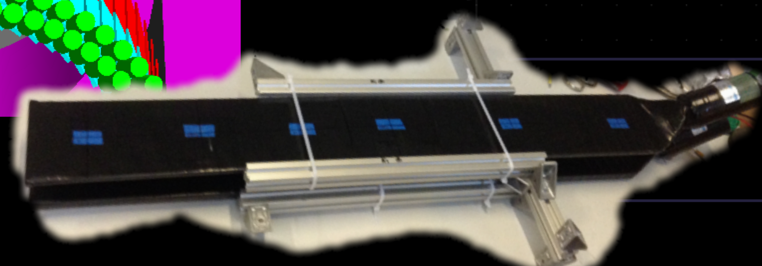


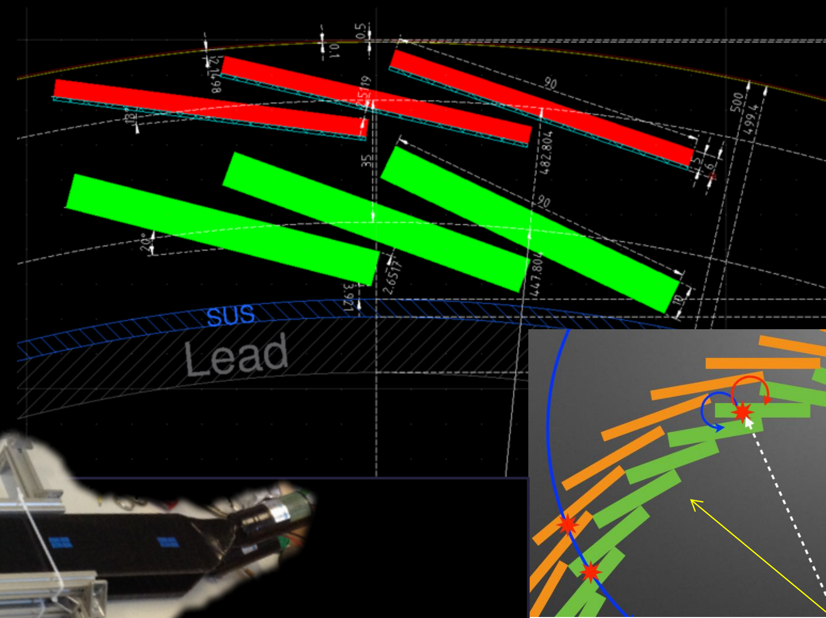




CTH: Trigger Hodoscope







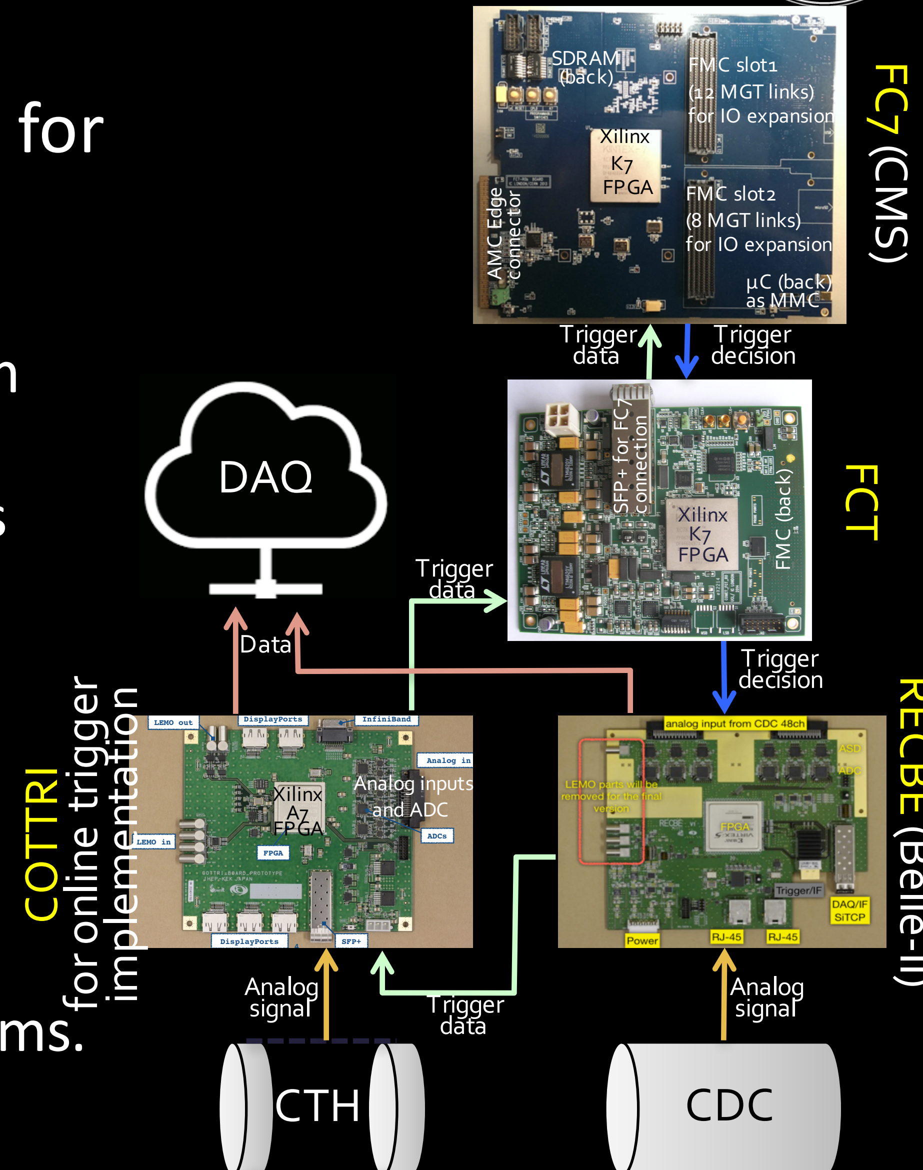
- Twisted, overlapped two scintillators + two Cerenkov detectors
- Primary hit rate too high for trigger

	Upstream Scintillator	Upstream Cherenkov	Downstream Scintillator	Downstream Cherenkov
Average rate @200 ~ 1170 ns (MHz)	3.5	1.5 - 2	4	3

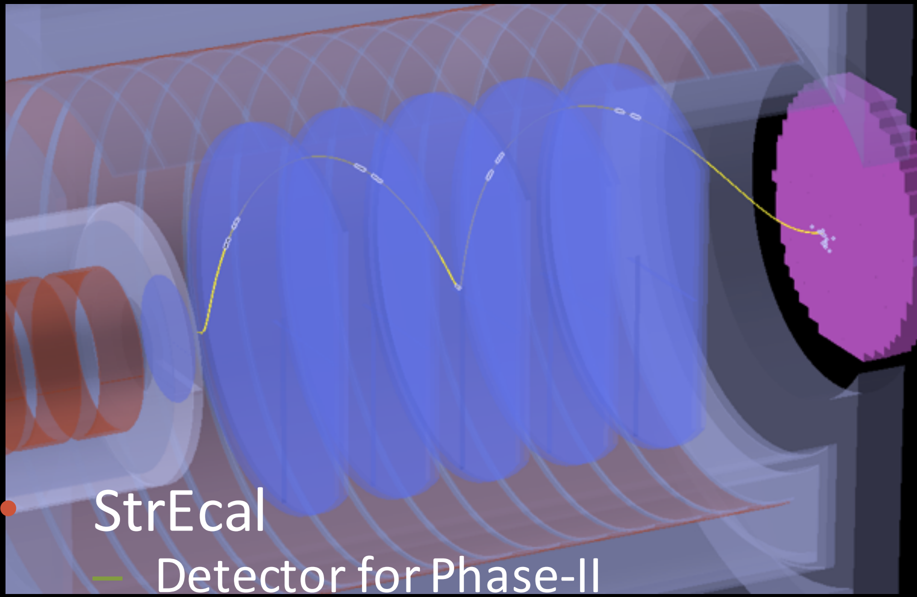
- Adding lead shielding, require 4-fold coincidence for trigger : primary trigger rate 20 – 30 kHz

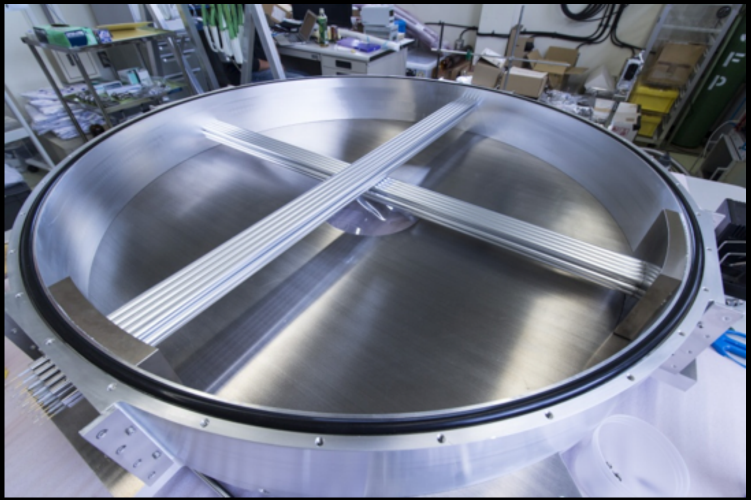
Trigger / DAQ

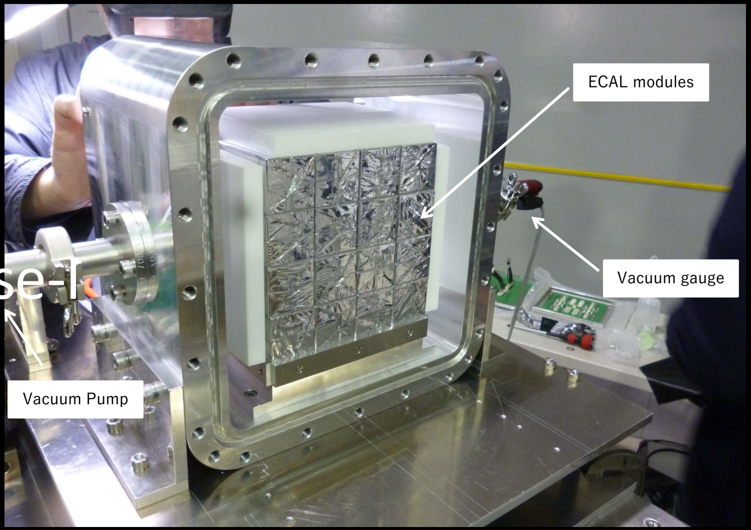
- High trigger rate (20-30 kHz) for DAQ
  - Mostly background hits
  - Beam electron, secondary from capture neutron/gamma
  - Online trigger suppress BG hits
- A configurable and flexible Trigger system
  - Central system based on commercial CERN product and a custom interface board
  - Ensuring commonality in interfacing with different systems.



Straw - Electron Calorimeter Detector (Detector for background measurement)

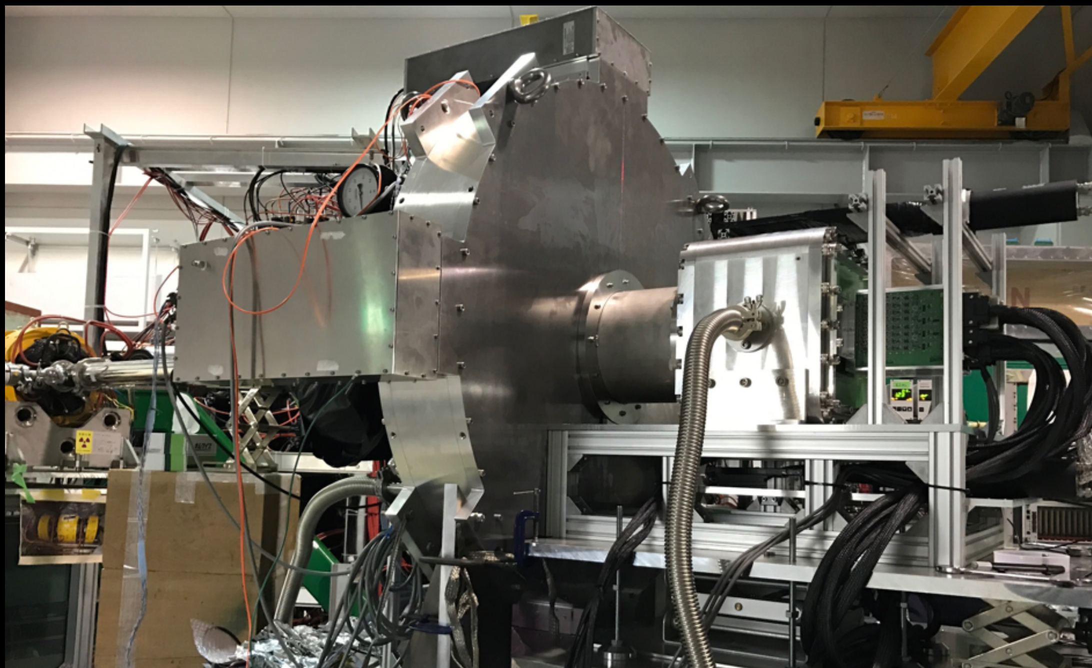




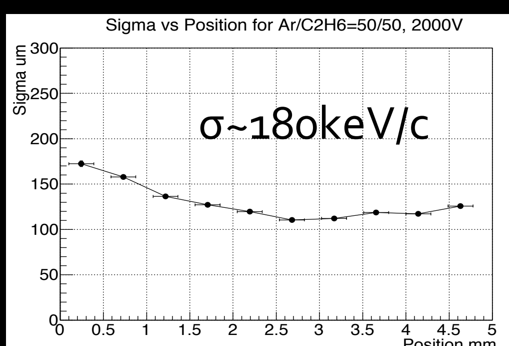


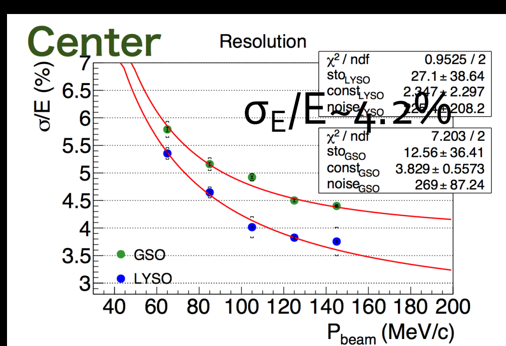
- StrEcal
  - Detector for Phase-II
  - 5 station of straw detectors+ ~2000 LYSO calorimeter
- Beam measurement program at Phase-I
  - Particle composition, beam profile
  - 1/1000 reduced beam
    - no radiation tolerance, pile-up issue.
  - CyDet rolls out and StrEcal installed

Integrated Beam Test for StrEcal



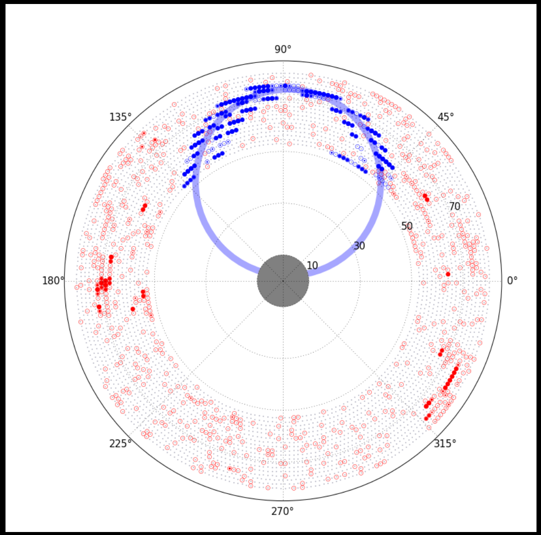
- Integrated test with beam at Tohoku univ.
- Mar 2016 and Mar 2017
- Including
  - One Straw chamber prototype
  - 8x8 LYSO calorimeter
  - MIDAS DAQ
  - DRS4 based RO
  - Trigger based on FC7+GBT
- All successful operation and test, data under analysis
  - Preliminary data matches with prototype tests

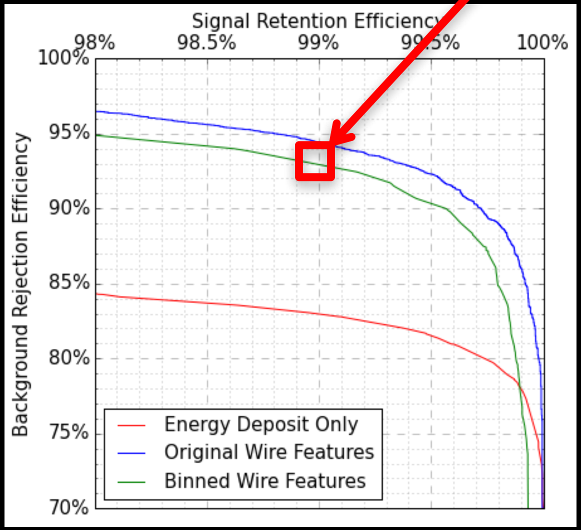


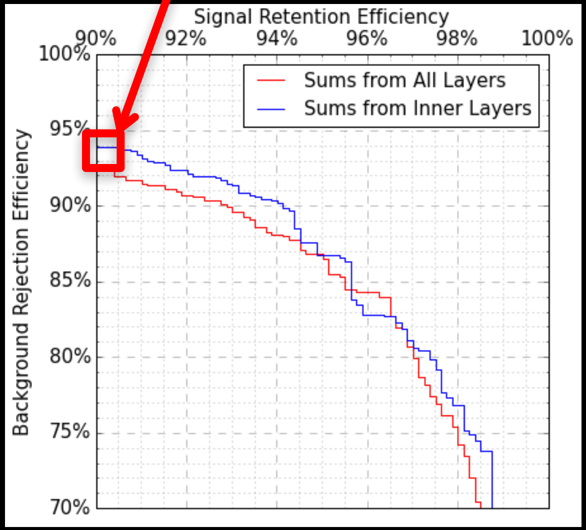


CDC BG Rejection, Reconstruction

- Signal / BG hit discrimination using BDT
  - Signal efficiency = 0.99, when BG rejection = 0.95
  - 1/20 BG hit reduction : trigger rate = 1 ~ 2 kHz
- Signal / BG event discrimination
  - Signal efficiency = 0.90, when BG rejection = 0.95
  - Hardware implementation on trigger system under development
- Offline track reconstruction with Kalman filter

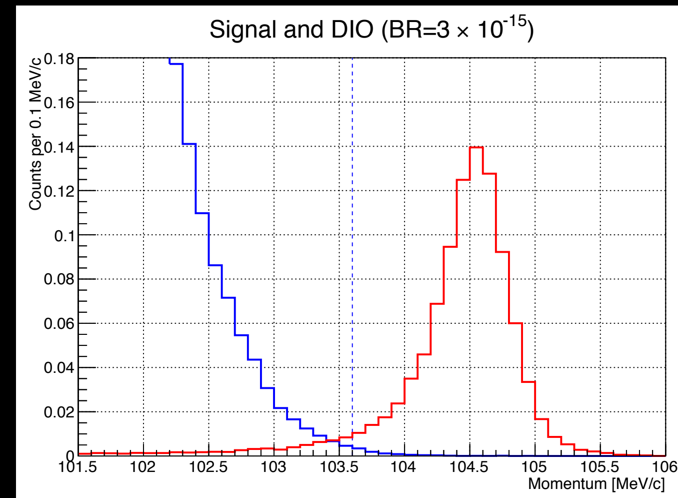






Physics sensitivity

- Net acceptance = 4.1%
  - Online efficiency ~0.99
  - Geometric acceptance + track quality ~0.18
  - 103.6 MeV < p < 106MeV : 0.93
  - 700ns < t < 1170 ns : 0.3
- Background = 0.032
  - RPC ~ 0.003
  - DIO ~ 0.01
  - Cosmic <0.01
- SES(Phase-I) ~ 3.1×10^{-15}
  - SES(Phase-II) ~ 2.5×10^{-17}

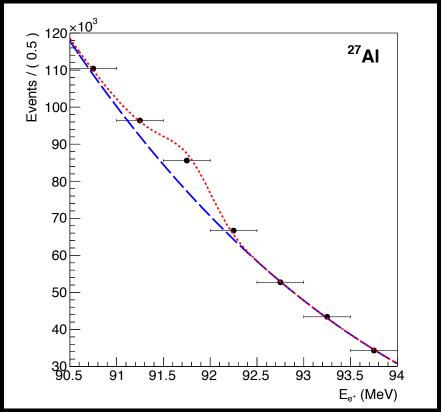


Type	Background	Estimated events
Physics	Muon decay in orbit	0.01
	Radiative muon capture	0.0019
	Neutron emission after muon capture	< 0.001
	Charged particle emission after muon capture	< 0.001
Prompt Beam	* Beam electrons	
	* Muon decay in flight	
	* Pion decay in flight	
	* Other beam particles	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

LNV physics: μ^--e^+ Conversion

$$\mu^- + N(A,Z) \rightarrow e^+ + N(A,Z-2)$$



Nμ-stop = 10^{18}, BR($\mu^- e^+$)=1.7×10^{-12}

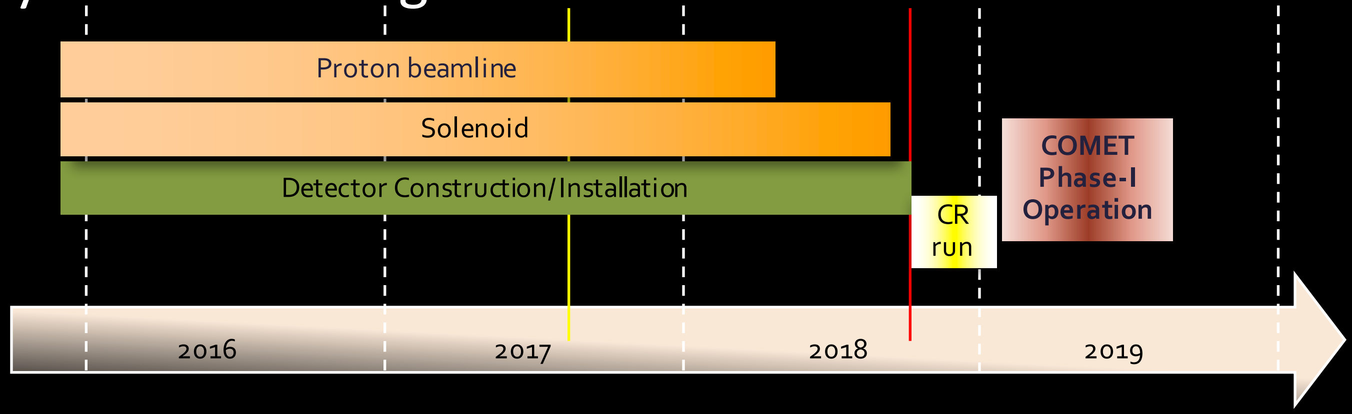
Atom	$E_{\mu^- e^+}$ (MeV)	$E_{\mu^- e^-}$ (MeV)	E^{end}_{RMC} (MeV)	N.A. (%)	f_{cap} (%)	τ_{μ^-} (ns)	A_T
^{27}Al	92.30	104.97	101.34	100	61.0	864	0.191
^{32}S	101.80	104.76	102.03	95.0	75.0	555	0.142
^{40}Ca	103.55	104.39	102.06	96.9	85.1	333	0.078
^{48}Ti	98.89	104.18	99.17	73.7	85.3	329	0.076
^{50}Cr	104.06	103.92	101.86	4.4	89.4	234	0.038
^{54}Fe	103.30	103.65	101.93	5.9	90.9	206	0.027
^{58}Ni	104.25	103.36	101.95	68.1	93.1	152	0.009
^{64}Zn	103.10	103.04	101.43	48.3	93.0	159	0.011
^{70}Ge	100.67	102.70	100.02	20.8	92.7	167	0.013

Candidate for muon stopping target

- Similar process with $0\nu\beta\beta$ in eμ sector
  - Provides clues in LNV and Majorana ν
  - Another physics case with COMET Phase-I detector
- Experimentally simple but hard to achieve good sensitivity
  - By flipping charge
  - RMC background dominates
- Replacing Al target to other nuclei may allow O(10^4) sensitivity improvement (arXiv:1705.07464)

Schedules

- Highly recognized by KEK IPNS, stage-2 of COMET Phase-I approved (i.e. project full funded, beam will be delivered)
- Phase-I physics data taking in 2019
  - Depending on budget allocation
  - Cosmic run at 2018, 4 weeks of engineering run
  - 5 month data taking
- Phase-II R&D in parallel with Phase-I R&D and data taking
- Phase-II physics data taking in 2021~2022
  - 1 year data taking



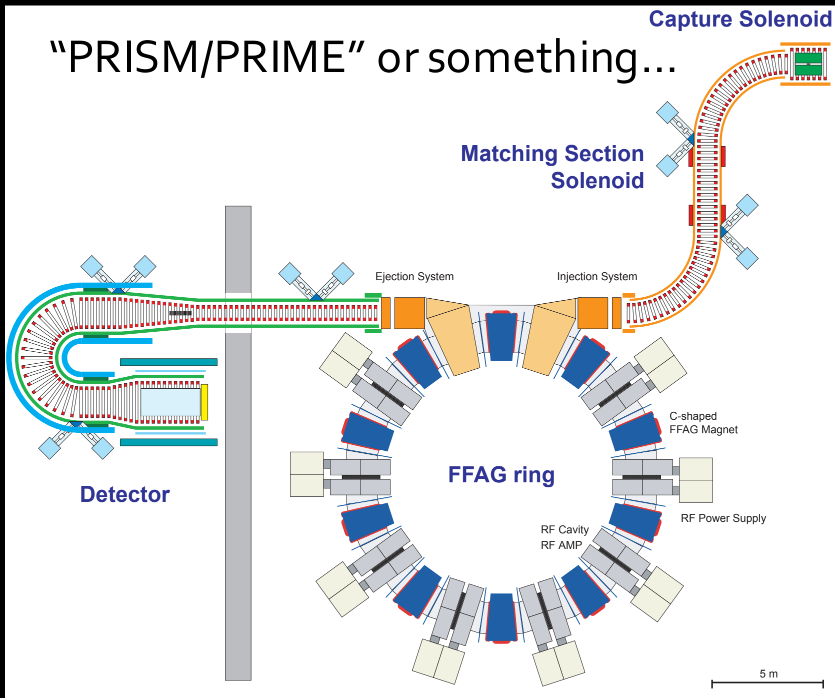
Summary…

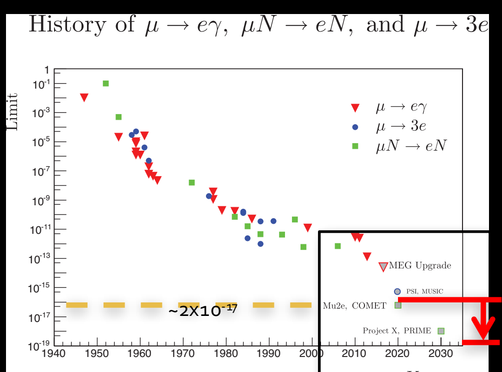
- SES : 3.1×10^{-15}
  - SES (Phase-II @~2022): 2.5×10^{-17}
- Start data taking at 2019
- Half year data taking for
  - Muon conversion measurement
  - Beam measurement
- … and the Future?


COMET Collaboration meeting@KEK 26-30 Jan 2015

176 collaborators,
33 institutes, 15 countries

… and the Future up to $O(10^{-19})$





x10~100 improvement?!

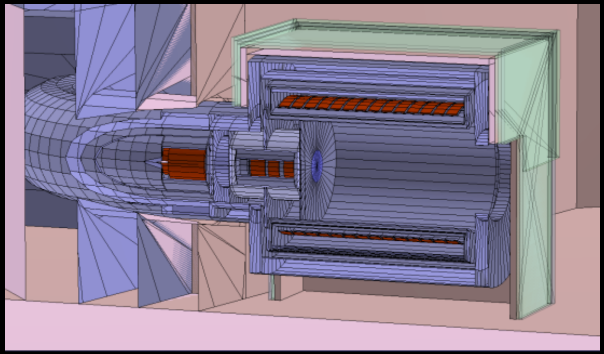
- x(1/2) from reduced beam acceptance from solenoid to FFAG
- x3 from removing detection time window (no pion)
- x3 from pion capture improvement
- x20 from 56 kW→1MW

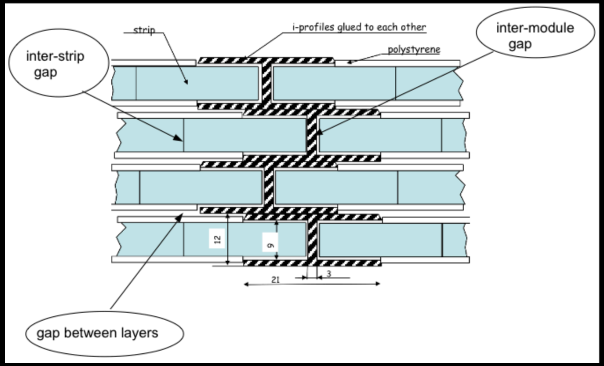
- Multi GW beam
- PRISM (Phase Rotated Intense Slow Muon source)

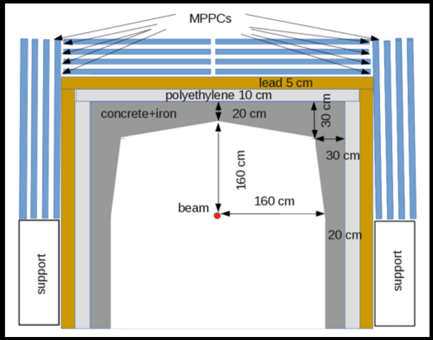
Backups

Cosmic ray / Neutron

- To suppress Cosmic Ray muon to factor of 10^{-4}
  - Decay in flight, interaction with detector material
  - Note: CDC can full-reconstruct CR
- Neutron issue
  - SiPM weak to neutron irradiation, generates noise at Strip sensor
  - Internal Neutron Shield reduces neutron from stopping target
  - Similar neutron flux expected from proton target, shielding around beamline under study

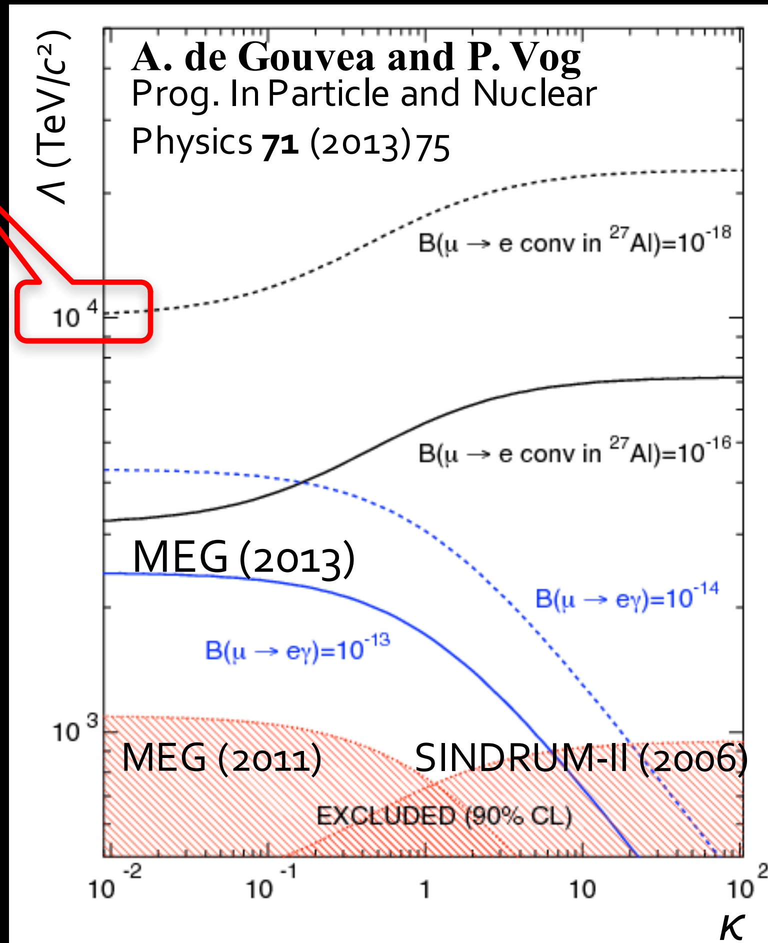


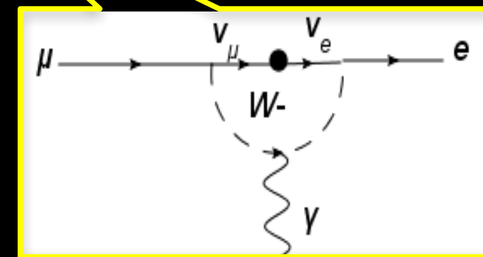




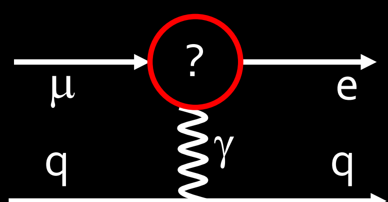
μN→eN vs μ→eγ

Probing O(10^4) TeV mass scale,
➔ Much higher energy scale than LHC

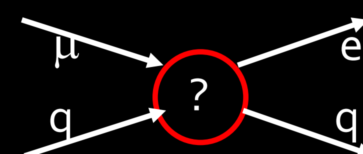




Dipole Interaction



Contact interaction



$$L_{CLFV} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\sum_{q=u,d}\bar{q}_L\gamma_\mu q_L\right)$$