COMET Muon to Electron Conversion Experiment at J-PARC

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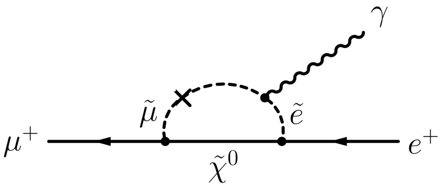
The 24th International Workshop on Neutrinos From Accelerators

COMET (COherent Muon to Electron Transition)

Muon LFV

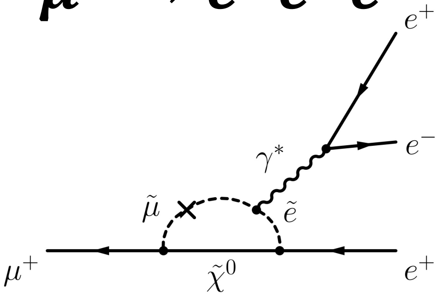
$\mu^+ \to e^+\gamma$



- MEG
- MEG II (PSI)

<4.2x10^-13 @90% CL
MEG, 2016

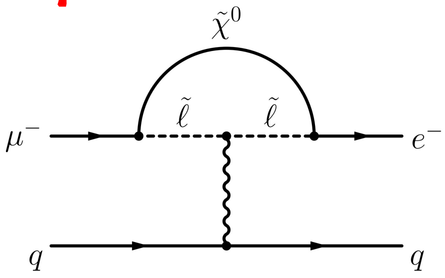
$\mu^+ \to e^+e^-e^+$



- Mu3e (PSI)

<1.0x10^-12 @90% CL
SINDRUM, 1988

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



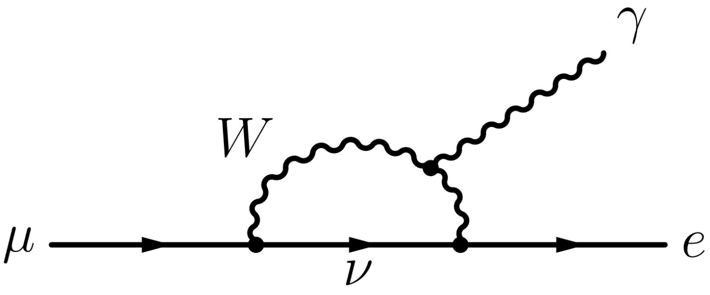
- DeeMe (J-PARC)
- **COMET (J-PARC)**
- Mu2e (FNAL)
- Mu2e-II (FNAL)
- PRISM/PRIME, FNAL AMF

<7x10^-13 @Au, 90% CL
SINDRUM-II 2006

Other searches

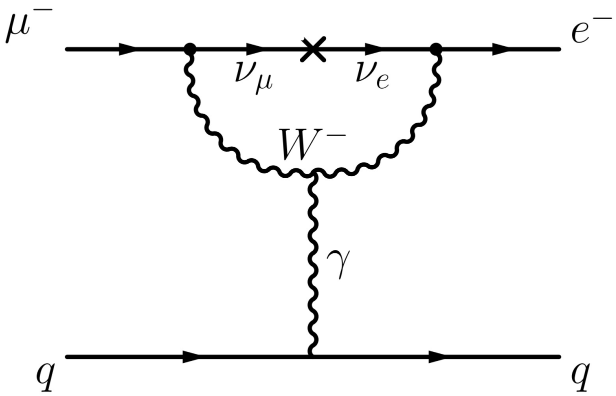
- $\mu^- N \to e^+ N'$
- $\mu^- \to e^- X$
- $\mu^- e^- \to e^- e^-$
- Muonium Oscillation

Very small possibility of CLFV in SM



$$\mathrm{BR}(\ell_1 \to \ell_2\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{j=1}^{3} U_{\ell_1 j}U^*_{\ell_2 j}\frac{m^2_{\nu_j}}{M^2_W}\right|^2$$

$$\cong \boldsymbol{\mathcal{O}(10^{-55} - 10^{-54})}$$

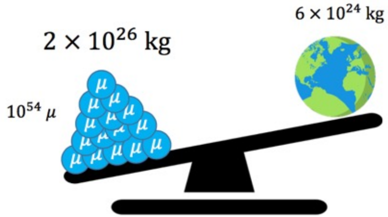


$$R_{\mu e} = \frac{\Gamma(\mu \to e)}{\Gamma(\mathrm{capture})}$$

$$\cong \mathrm{O}(\alpha)\times \mathrm{BR}(\mu \to e\gamma) \lesssim 10^{-55}$$

In SM, we need 30x more muon than the Earth.

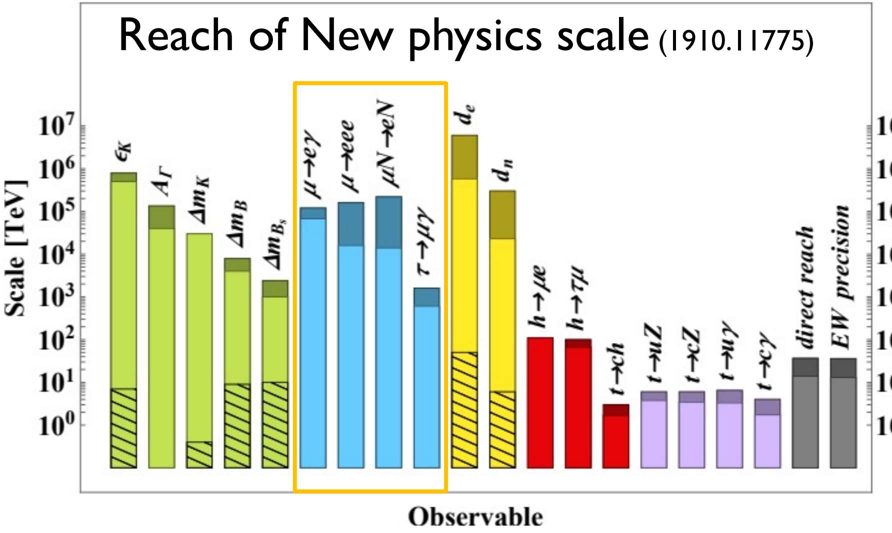
CLFV observation= Signature of New physics in BSM



How much sensitive to BSM

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0-\bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B\to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B\to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B\to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B\to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s\to\mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+\to\pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L\to\pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu\to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau\to\mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu+N\to e+N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

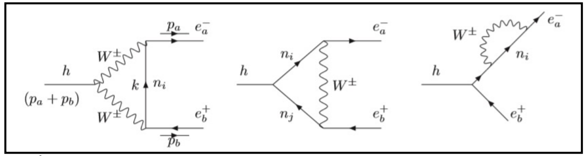
W. Altmannshofer et al., Nuclear Physics B 830, (2010)



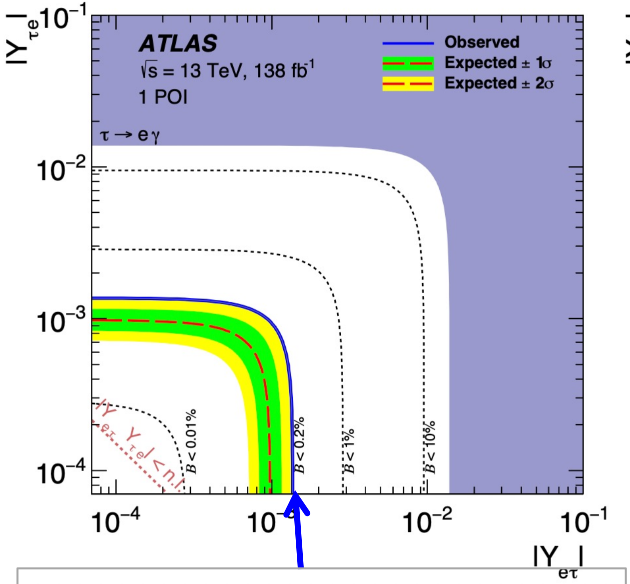
★★★	Large effects
★★	Visible but small
★	No sizeable effect

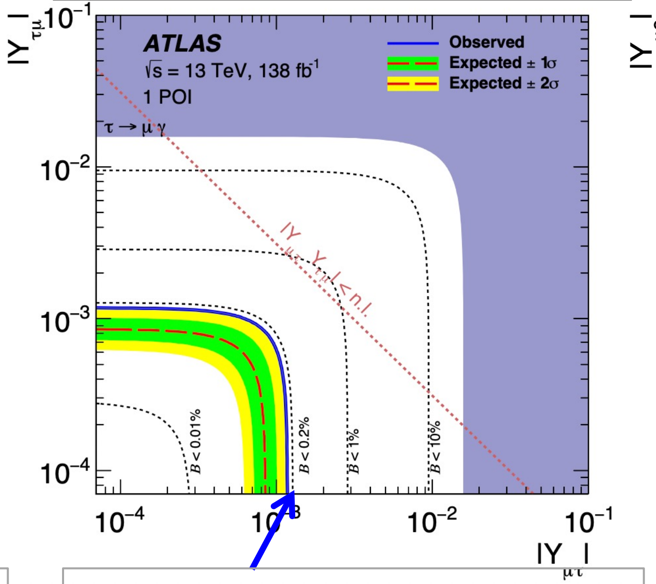
(Muon) LFV experiments are generally most sensitive to many BSM models, very high NP scale.
Note: All experiments are equally important to discriminate models

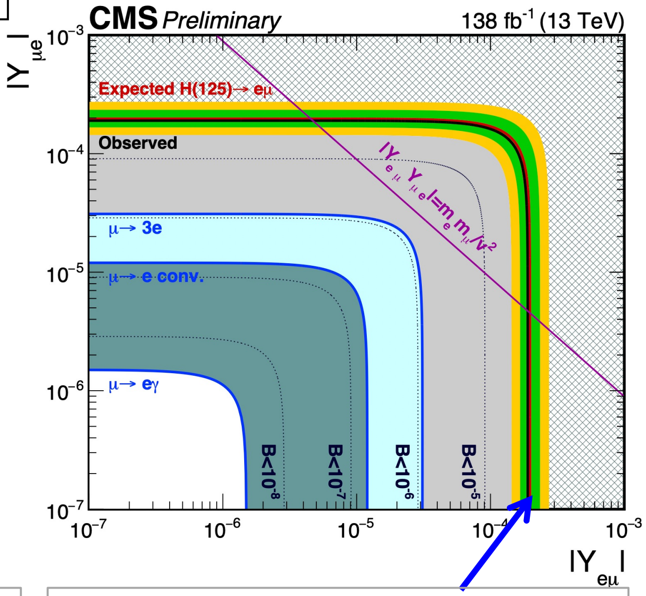
Higgs CLFV



(R.Harnik, et al., JHEP 03 (2013) 026,
ATLAS collab. JHEP 2307 (2023) 166,
CMS collab. CMS PAS HIG-22-002 (2023))







Br(H→eτ) <2.0x10^{-3}
(95% CL, ATLAS, 13TeV, 138fb^{-1},2023)

Br(H→μτ) <1.8x10^{-3}
(95% CL, CMS, 13TeV, 138fb^{-1},2023)

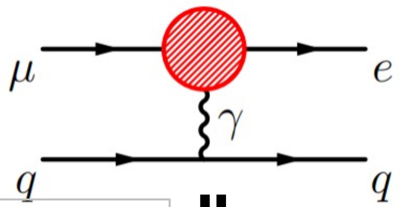
Br(H→eμ) <4.4x10^{-5}
(95% CL, CMS, 13TeV, 138fb^{-1},2023)

- CLFV via Higgs can be measured best in LHC, but, this is **not** the only BSM that CLFV experiments are sensitive to.
- **Muon LFV experiments can cover various BSM in much higher energy scale**

Dipole or Contact interactions

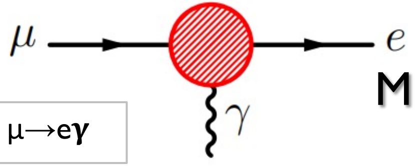
$$L_{CLFV} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L \gamma_\mu e_L \left(\sum_{q=u,d} \bar{q}_L \gamma_\mu q_L\right)$$

Dipole Interaction

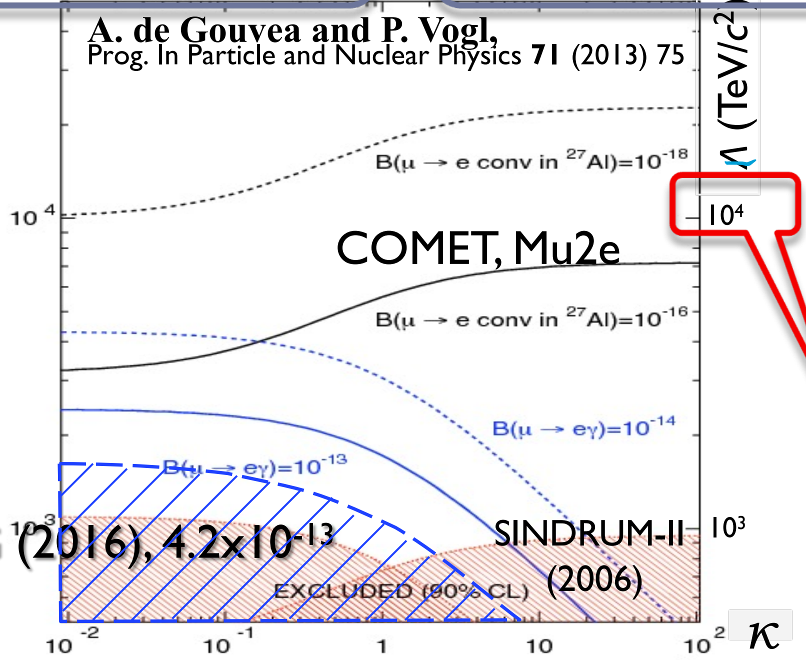


Muon conversion

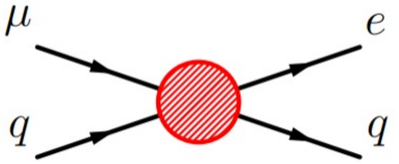
=



μ→eγ



Contact interaction



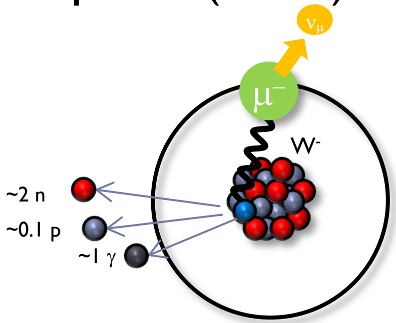
Probing O(10^4) TeV mass scale,

➔ Much higher energy scale than LHC

μ- in matter

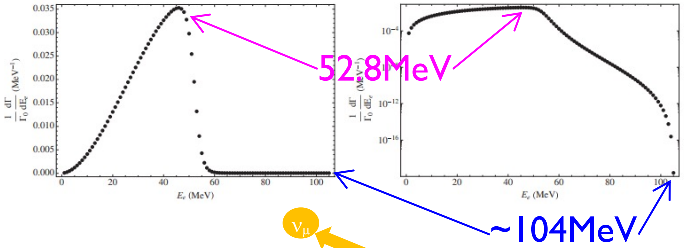
Muon Capture
(61% (Al))

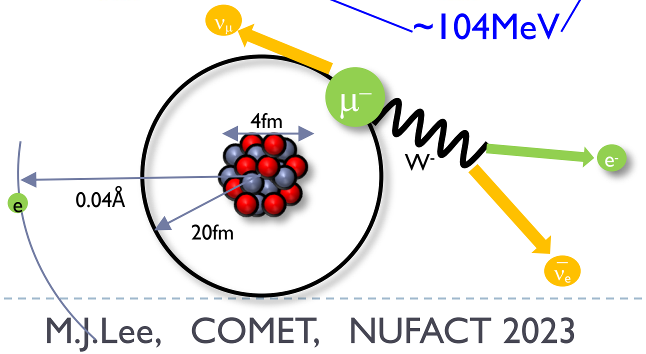
- $\mu^- + p \rightarrow \nu_\mu + n$
- Muon capture by nucleus
- BG hit source / Radiative Muon Capture (RMC) **BG**



Decay in orbit(DIO)
(39% (Al))

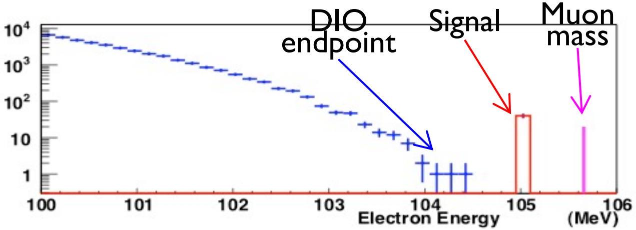
- $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$
- Bound muon decay
- Major **BG** source

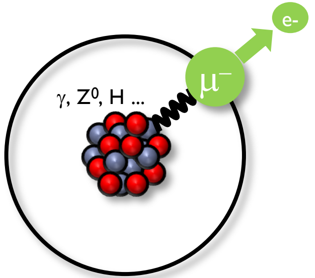




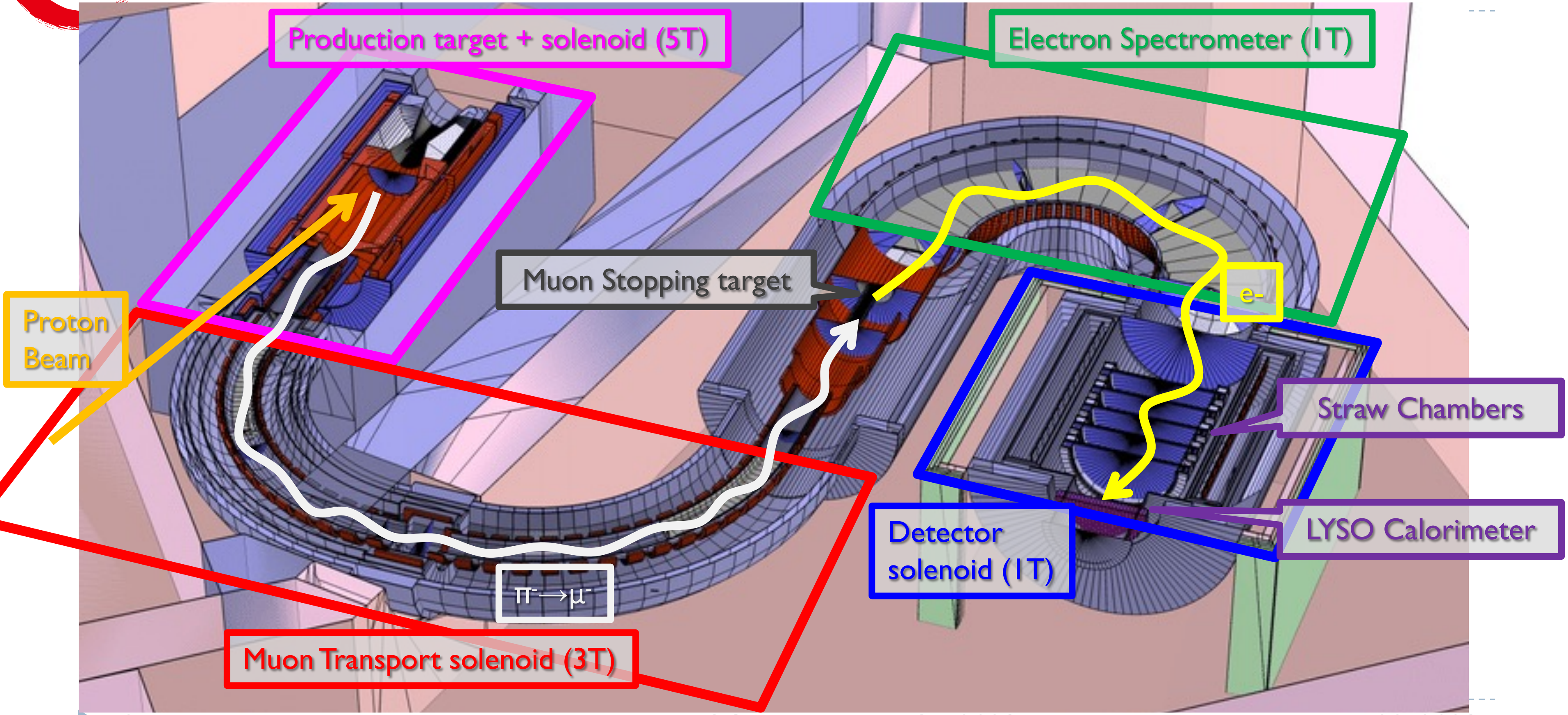
$\mu^- \rightarrow e^-$ conversion

- $\mu^- + N \rightarrow e^- + N$
- $E(e^-;Al) = m_\mu - E_{rec} - E_B$ = 104.97 MeV : **Signal**

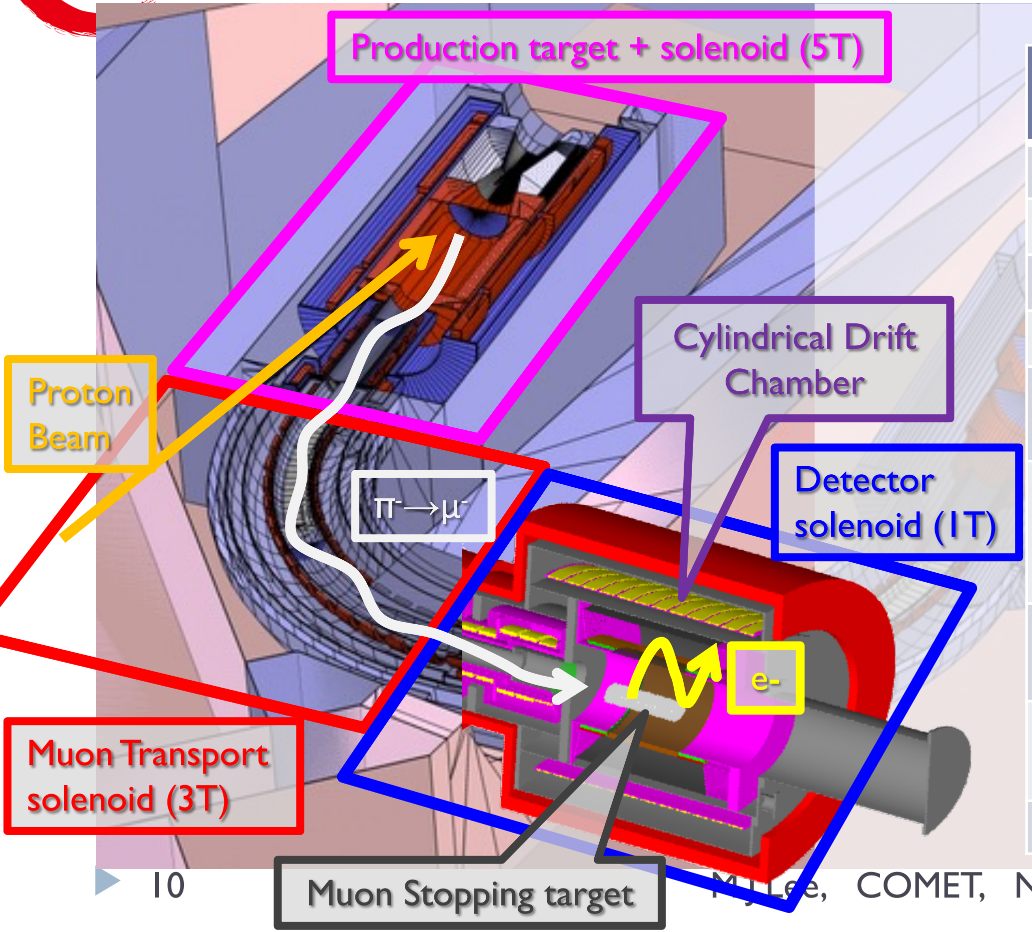




COMET (Phase-II) Experiment: for $O(10^{-18})$ SES



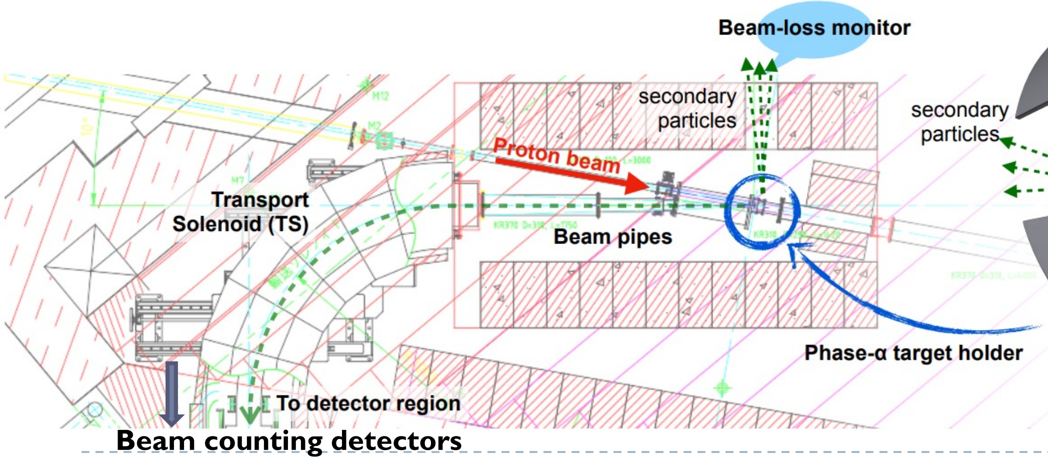
COMET Phase-I Experiment: for O(10^{-15}) SES

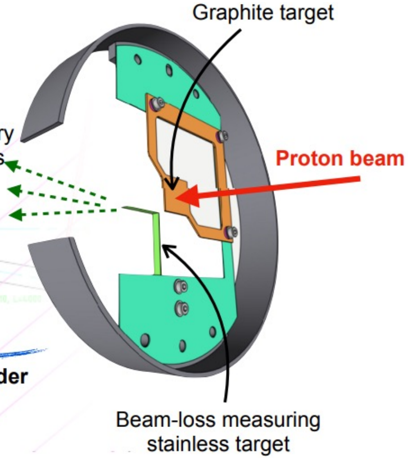


	COMET Phase-I	COMET Phase-II
E(Proton)	8 GeV	
P(Proton)	3.2 kW	56 kW
N (proton)	3.2×10^{19}	6.8×10^{20}
Proton Target	Graphite	Tungsten
Muon Target	Aluminum	Aluminum ?
Detector	Cylindrical Drift chamber	Straw + calorimeter
Sensitivity (90% CL)	7×10^{-15}	1.7×10^{-17} ~10^{-18}
DAQ start	FY2025	After Phase-I completion
DAQ Time (days)	~150	180 ~ 300

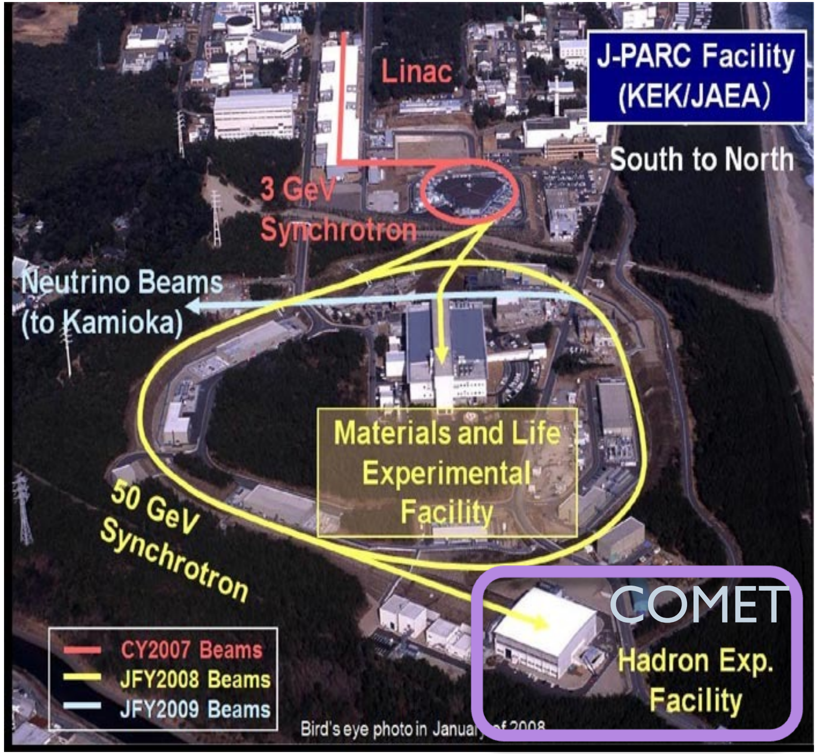
COMET Phase-α

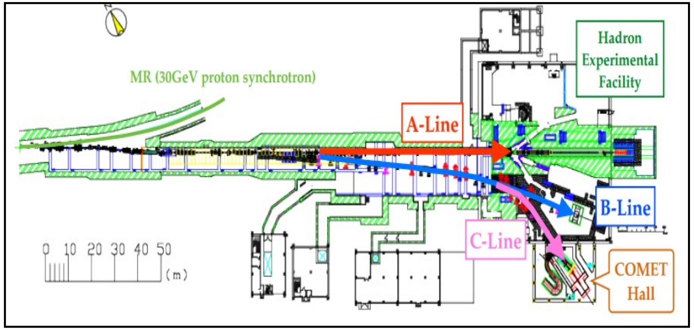
- A low beam-intensity run to study the beamline, in Feb-Mar 2023
- Measurement of the proton beam and π/μ backward production yield
- Details in Friday WG4 talk by Dr. Wu Chen





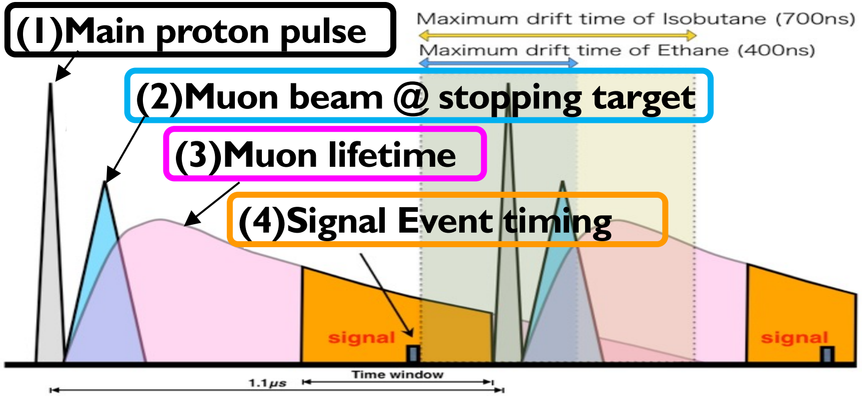
J-PARC facility / Beamline

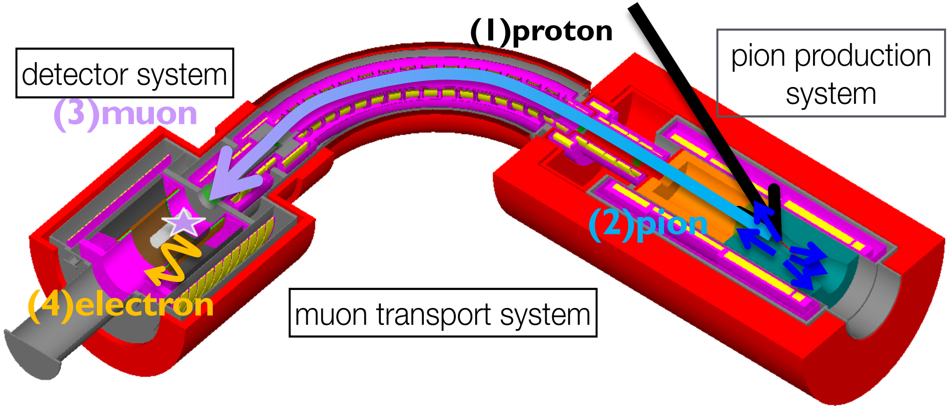


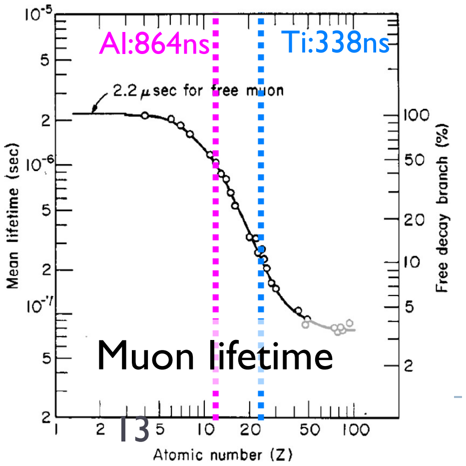


- J-PARC returned online after power supply upgrade
- Proton C1 Beamline is ready

Pulsed proton beam





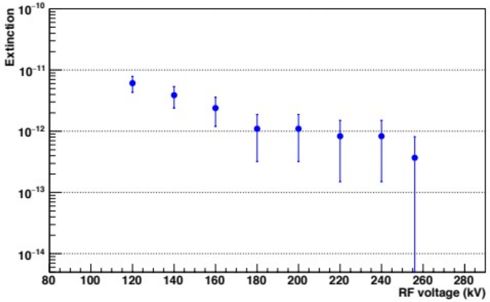


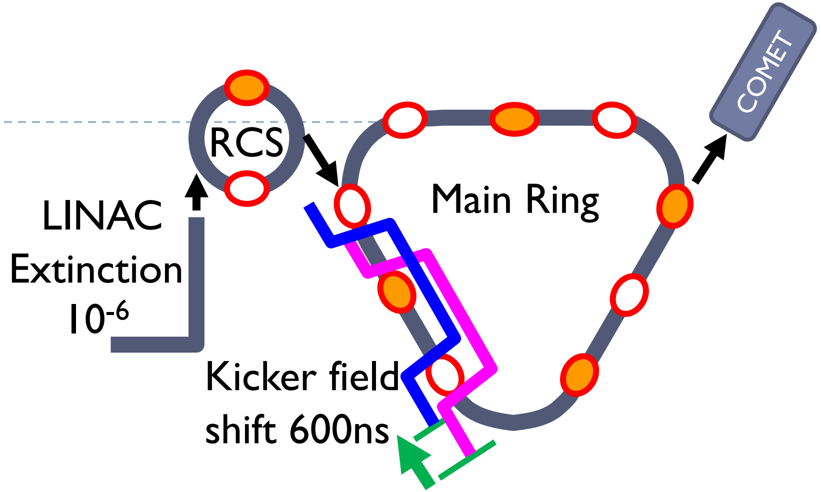
1. **Pulsed** protons arrive at production target, producing pions.
2. Muons(+pion) arrive at stopping target : **Prompt RPC BG events**
3. Captured muon processes with **finite lifetime.**
4. Some time after muon beam arrival, signal electron is measured, **avoiding prompt events.**

Pulsed proton beam + delayed signal timing window suppresses Radiative Pion Capture (**RPC**, $\pi^{\pm}N \rightarrow N'\gamma$) **BG**. **$10^{-10}$ extinction factor** required.

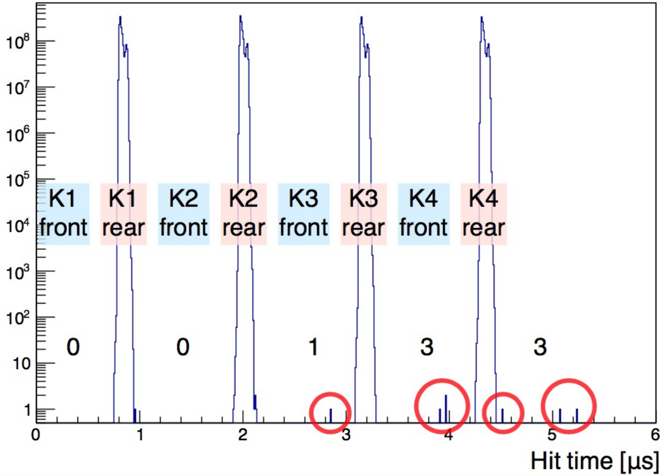
Extinction test results

Extinction
at MR proton beam dump
(8GeV)

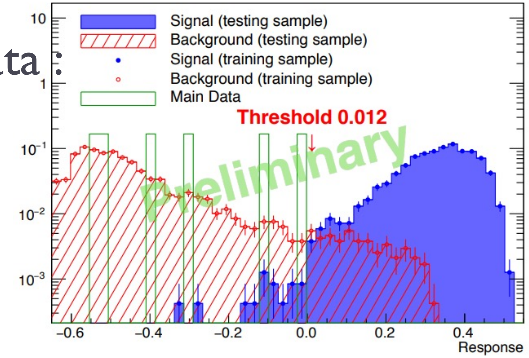




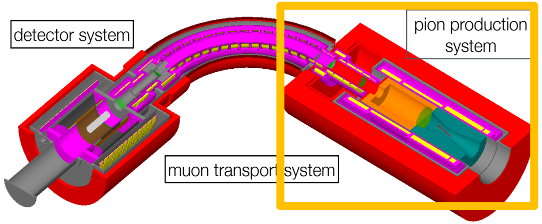
Extinction measurement
at hadron hall (2021)



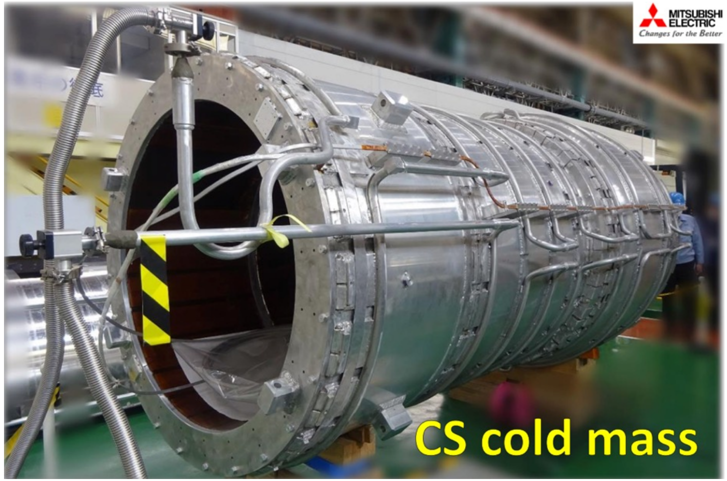
- Extinction measurement at hadron hall
  - 7 inter-bunch events at raw data : mostly accidental coincidence
  - Cut-based event selection retains 2 events : **9.3×10^{-11}**
  - BDT / MLP event selection retains 0 events : **3.2×10^{-11}**



Pion Capture Solenoid (PCS)

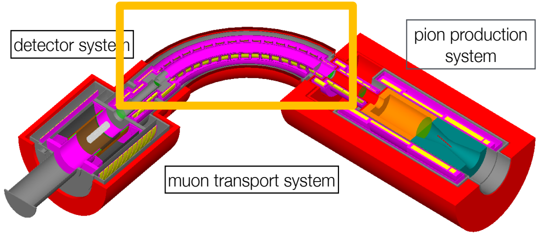


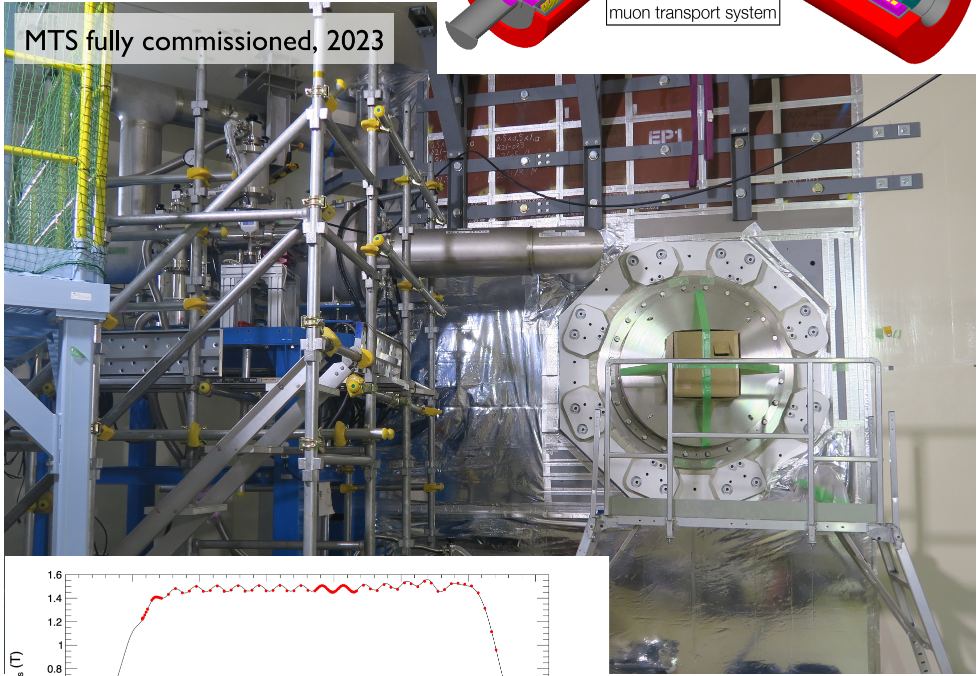
(Current PCS Area for Phase-α)



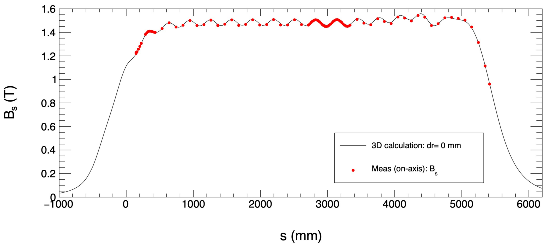
- Construction on going from 2020
- Inspection on CS coil performance and repair is underway
  - Finalize by early 2024

Muon Transport Solenoid

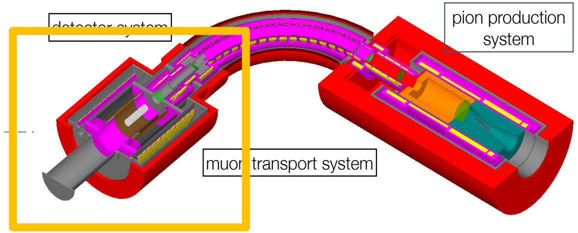




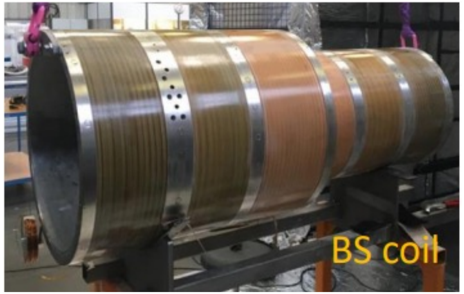
- MTS stable operation confirmed at 1.5T (solenoidal) + 70mT (dipole) field
  - No quench during 319 hr
  - Operated for phase-α DAQ
  - Cryogenic system operation also confirmed.
- Careful conditioning for 3T operation (210A) achieved
  - Improved support structure
  - More tests postponed later of 2023



Bridge / Detector Solenoids



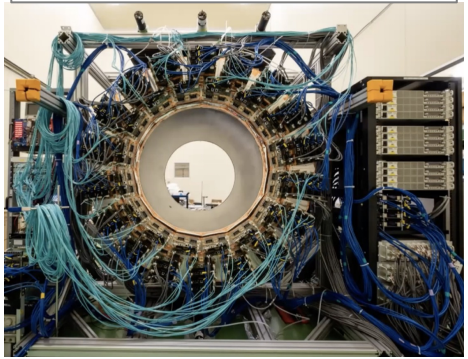
- DS coil and peripherals delivered June 2023.
- Excitation test within this year

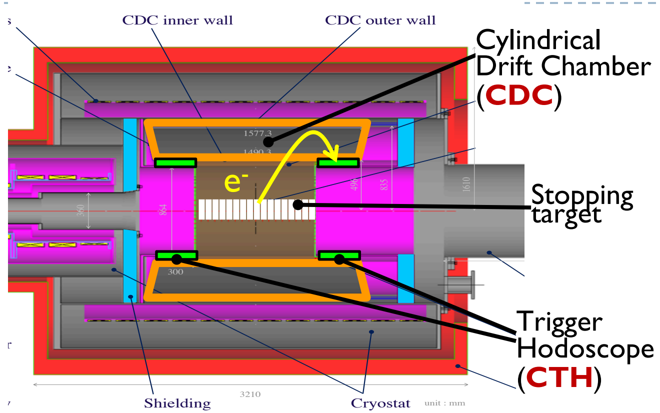


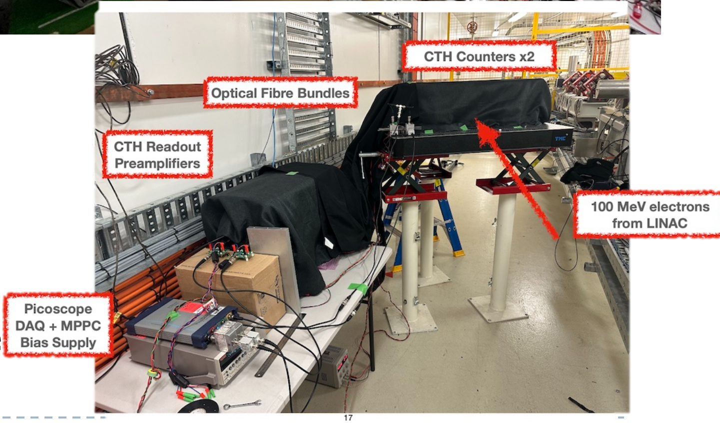
- BS magnet delivered March 2022

Main detector for Phase-I: CyDET(CDC+CTH)

Cylindrical Drift Chamber (2016, KEK)



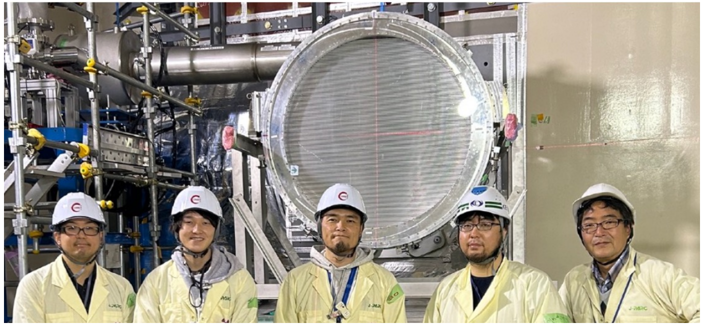


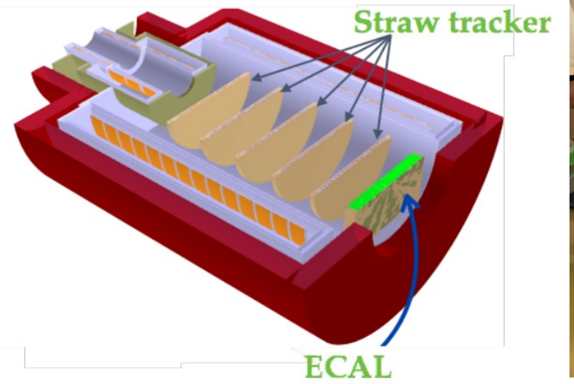


- **CDC**: All stereo-wire drift chamber, 20 layers, ~5000 sense wires, He:iC_4H_{10} = 9:1, HV=1850V
- Momentum resolution <200keV/c @ 105 MeV/c, spatial resolution 170um
- Rebuilding cosmic test setup underway in J-PARC
- **CTH** : 64-segmented two layered scintillators for trigger
- ~0.8 ns timing resolution. All scintillator delivered, module design upderway

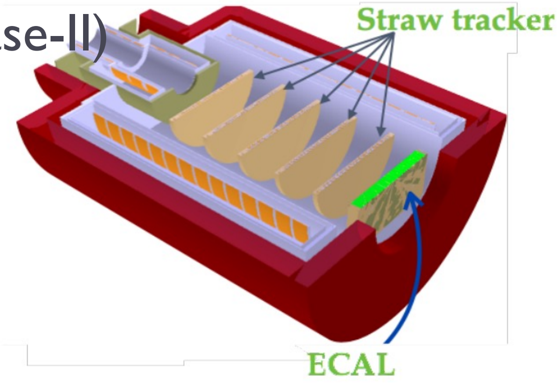
Straw Detector (Beam measurement and Phase-II)

- Detector for Phase-II experiment / Beam measurement in Phase-I (1/1000 beam power)
- Beam test with prototype achieved 150um spatial resolution, <200keV/c momentum resolution feasible.
- First station fully assembled and tested with Phase-α DAQ : issues on electronics were identified. Assembly of next stations underway
- Collaboration with CERN for new straw (t12μm / ϕ5mm) R&D for Phase-II

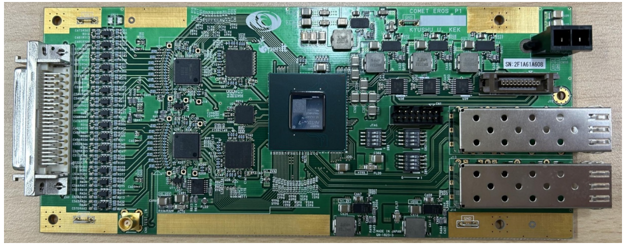




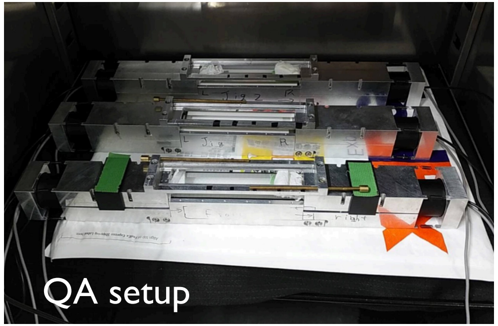
Calorimeter (Beam measurement and Phase-II)

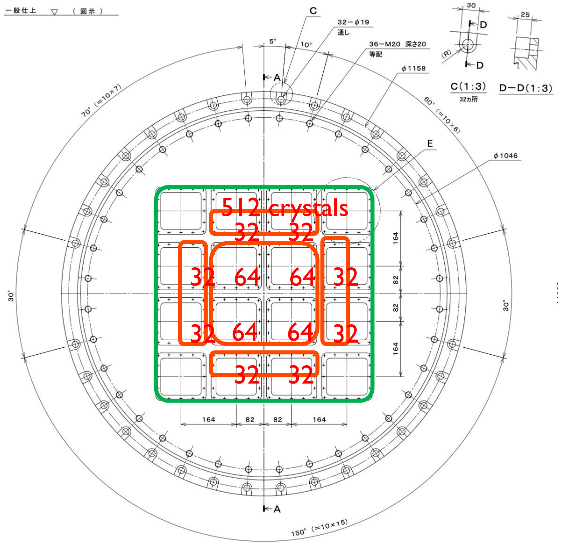


- ~1000 x LYSO crystal (20x20x120 mm) for measuring electron energy in Phase-II
- 512 crystals for Phase-I : >90% crystals acquired.
- Light readout – Hamamatsu APD S8864-1010 with 10x10 mm sensitive area
- Measured energy resolution – better 5% for the 105 MeV electrons
- "EROS" RO board with DRS-4 chip @ 1 GS/s – board under production / first real signal observed during Phase-α



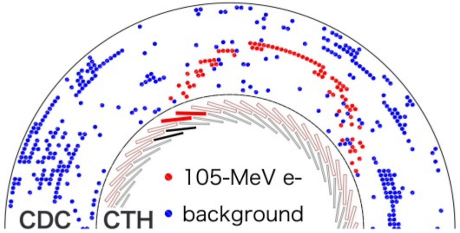
EROS board



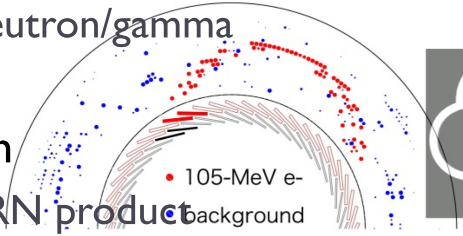


Trigger / DAQ

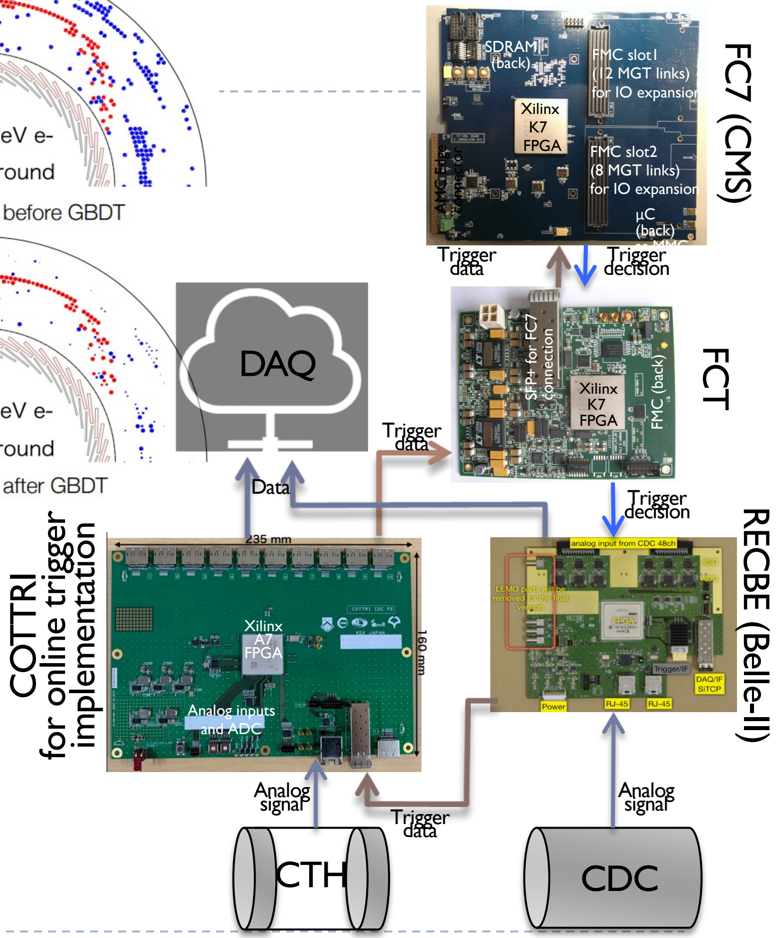
- High trigger rate (20-30 kHz) for DAQ
  - Mostly background hits
  - Beam electron, secondary from capture neutron/gamma
  - Online trigger suppress BG hits
- A configurable and flexible Trigger system
  - Central system based on commercial CERN product and a custom interface board
  - Ensuring commonality in interfacing with different systems.
- Online BG hit/event classification using charge and layer features
  - Trigger board implementation to the LUT of FPGA
  - Trigger rate reduced from 91 kHz to 13 kHz, 96% efficiency and 3.2μs latency.



(a) before GBDT

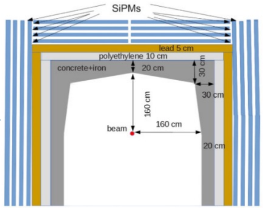


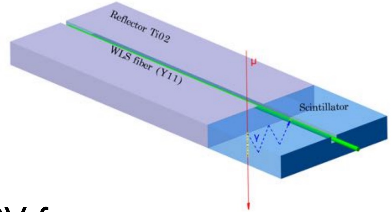
(b) after GBDT



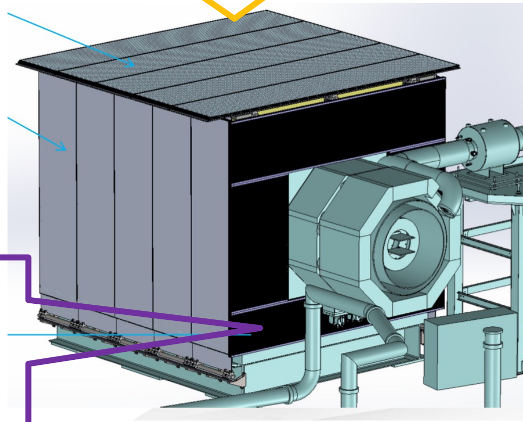
Cosmic Ray Veto

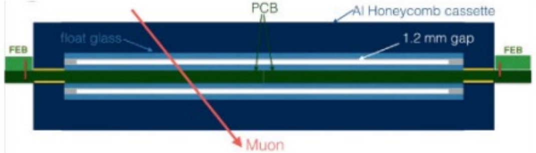
- To suppress Cosmic Ray muon to factor of 10^{-4}
- A bit delayed schedule. First scintillator module constructed in JINR and on the way to J-PARC





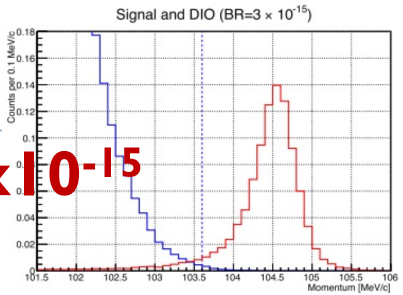
Four-layer scintillator CRV for CyDET coverage with SiPM readout 3/4 coincidence veto ~99.86%





Double gap Glass RPC for BS coverage
To cope with higher neutron radiation

Phase-I Sensitivity and Backgrounds

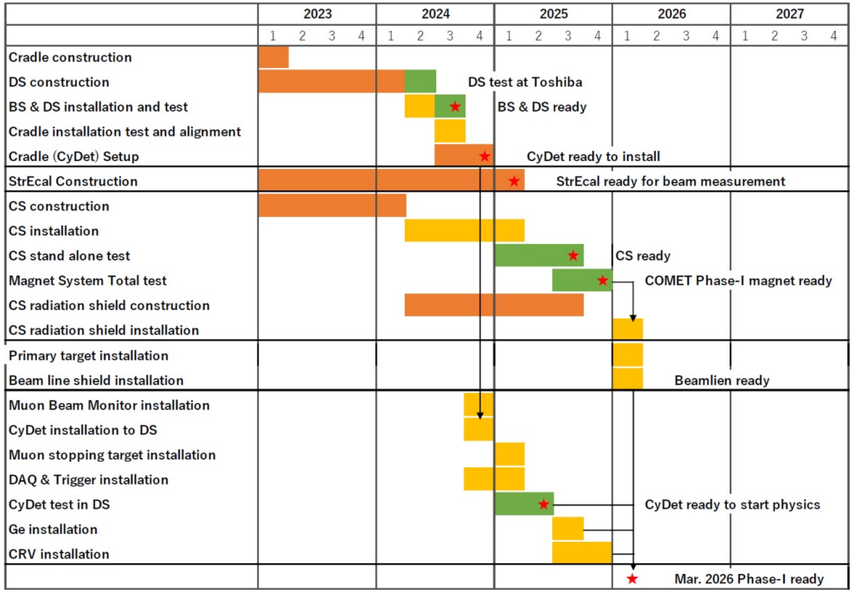


- COMET Phase-I Target single event sensitivity : **3×10^{-15}**
  - 100 times improvement from SINDRUM-II
  - Phase-II : $1.7 \times 10^{-17} \sim 10^{-18}$
- Net acceptance = **4.1%**
  - Online efficiency ~0.99
  - Geometric acceptance + track quality ~0.18
  - 103.6 MeV < p < 106MeV : 0.93
  - 700ns < t < 1170 ns : 0.3
- Background = **0.032**
  - DIO ~ 0.01 (dominant)
  - RPC ~ 0.003, Cosmic <0.01

Event selection	Value	Comments
Online event selection efficiency	0.9	Sect. 8.1.1
DAQ efficiency	0.9	
Track finding efficiency	0.99	Sect. 5.4
Geometrical acceptance + Track quality cuts	0.18	
Momentum window (ε_{mom})	0.93	$103.6\ \mathrm{MeV}/c < P_e < 106.0\ \mathrm{MeV}/c$
Timing window (ε_{time})	0.3	$700\ \mathrm{ns} < t < 1170\ \mathrm{ns}$
Total	0.041	

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
	Antiproton-induced backgrounds	0.0012
Others	Cosmic rays†	< 0.01
Total		0.032

Schedule / Summary



- COMET Phase-I Target single event sensitivity : **$3x10^{-15}$**
- DAQ start at FY2025
- Beamline ready, Solenoid construction / installation on going
- Critical detectors are mostly ready