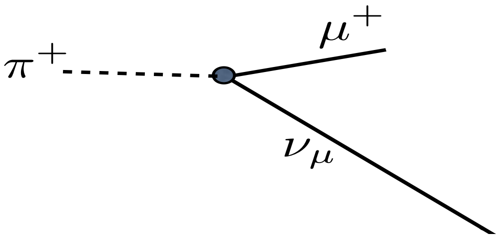
Search for Muon to Electron Conversion at J-PARC – COMET Experiment

MyeongJae Lee (Institute for basic science, Korea)
The 16th International Workshop on Tau Lepton Physics

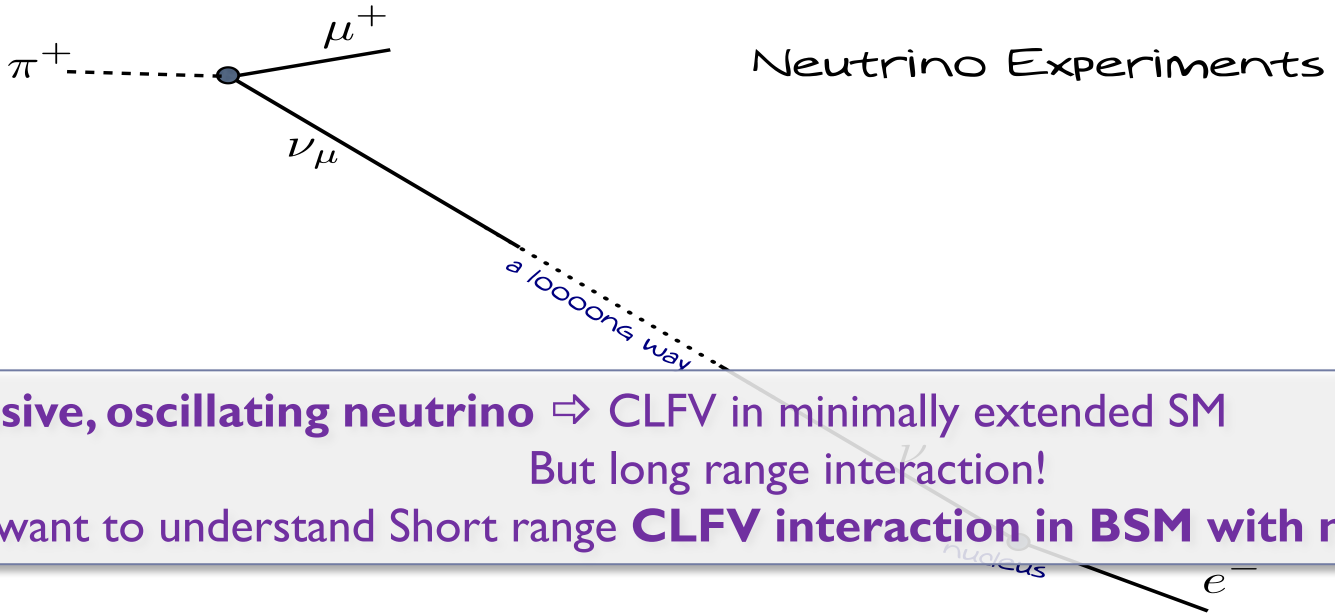
CLFV was Observed!



Neutrino Experiments

R.Harnik (FNAL), "CLFV theory", The Allure of Ultrasensitive Experiments (2014)

CLFV was Observed!



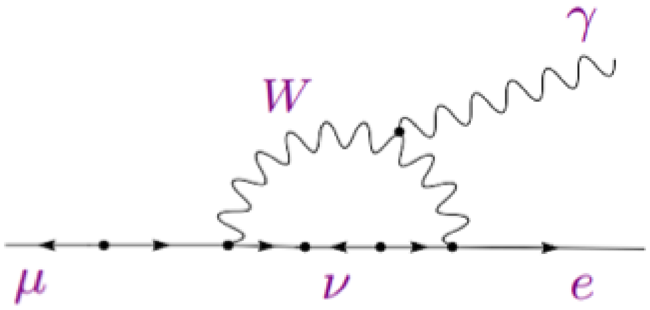
Massive, oscillating neutrino ⇨ CLFV in minimally extended SM

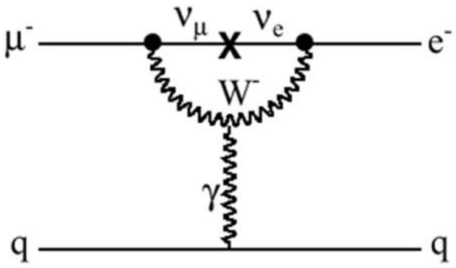
But long range interaction!

We want to understand Short range **CLFV interaction in BSM with muon**

R.Harnik (FNAL), "CLFV theory", The Allure of Ultrasensitive Experiments (2014)

Very small possibility of CLFV in SM

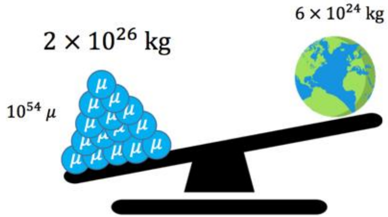




$$\mathrm{BR}(\ell_1 \to \ell_2\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{j=1}^{3} U_{\ell_1 j}U^*_{\ell_2 j}\frac{m^2_{\nu_j}}{M^2_W}\right|^2 \cong \mathcal{O}(10^{-55} - 10^{-54})$$

$$R_{\mu e} = \frac{\Gamma(\mu \to e)}{\Gamma(\text{capture})} \cong O(\alpha) \times \mathrm{BR}(\mu \to e\gamma) \lesssim 10^{-54}$$

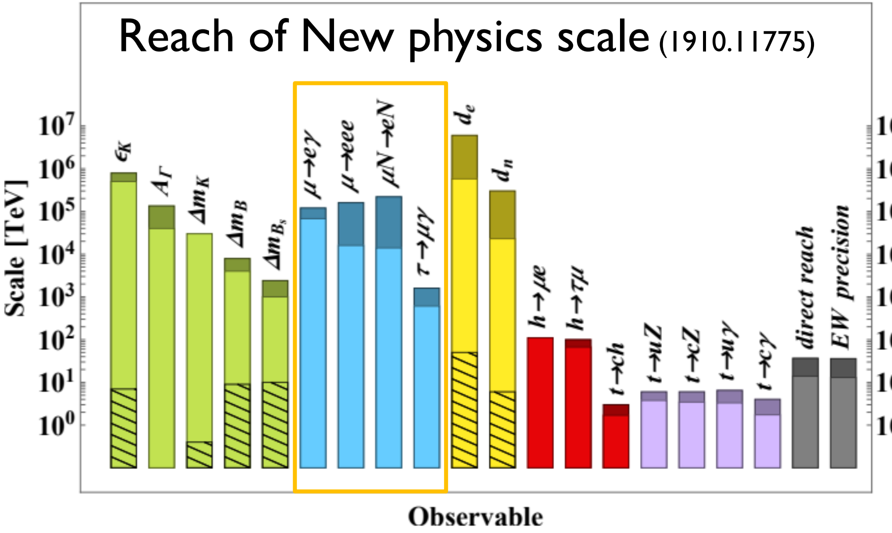
In SM, we need 30x more muon than the Earth.
CLFV observation= Signature of New physics in BSM



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	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

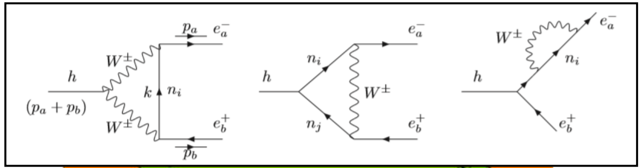
W.Altmannshofer et al., Nuclear Physics B 830, (2010)



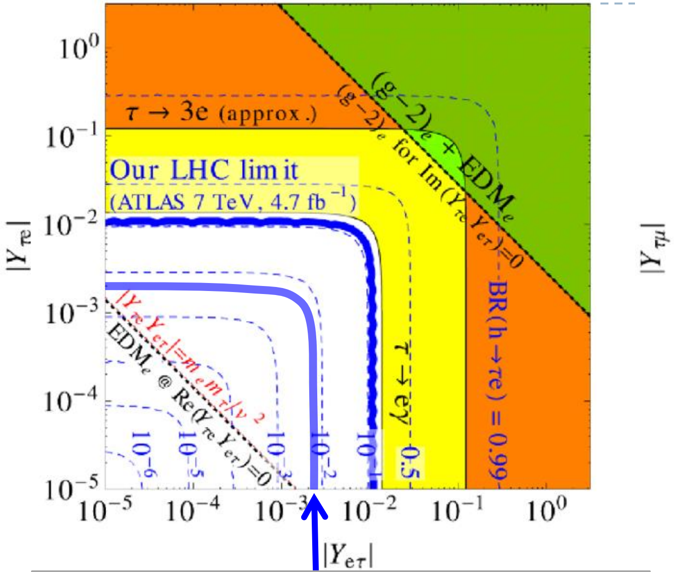
★★★	Large effects
★★	Visible but small
★	No sizeable effect

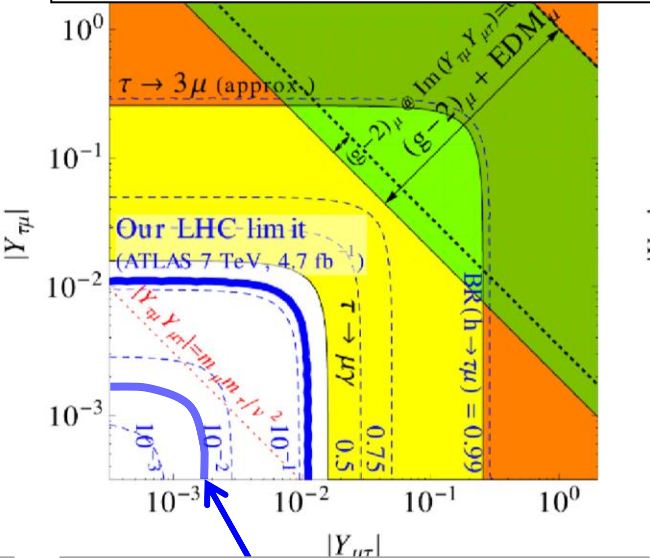
(Muon) LFV experiments are generally most sensitive to many BSM models, very high NP scale.
Note: All experiments are equally important to discriminate models

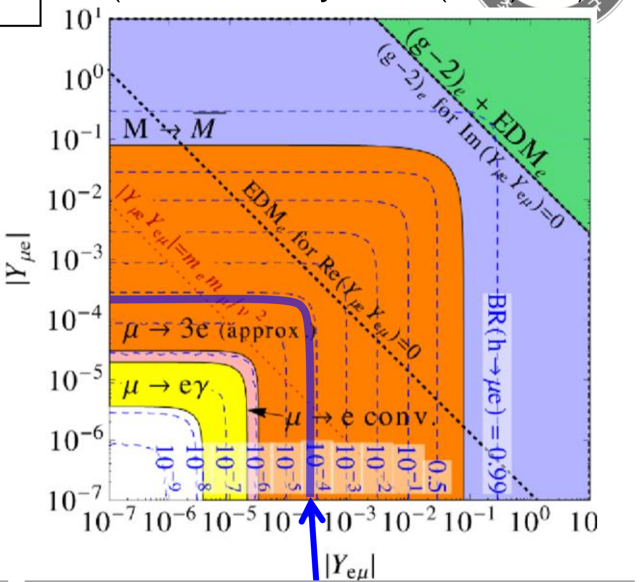
Higgs CLFV



(R.Harnik, et al., JHEP 03 (2013) 026)







<4.7x10^{-3}
(95% CL, ATLAS, 13TeV, 36.1fb^{-1}, 2020)

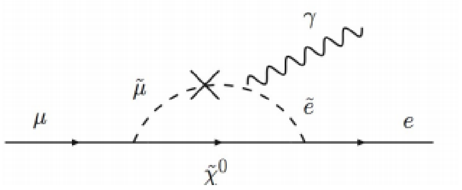
<2.5x10^{-3}
(95% CL, CMS, 13TeV, 35.9fb^{-1}, 2018)

<6.1x10^{-5}
(95% CL, ATLAS, 13TeV, 139fb^{-1}, 2020)

- 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**

Muon LFV

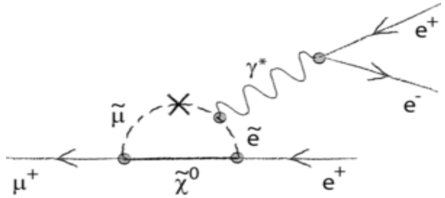
$\mu^+ \to e^+ \gamma$



- MEG
- MEG II (PSI)

<4.2×10^{-13} @90% CL
MEG, 2016

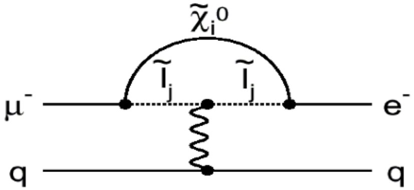
$\mu^+ \to e^+ e^- e^+$



- Mu3e (PSI)

<1.0×10^{-12} @90% CL
SINDRUM, 1988

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



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

<7×10^{-13} @Au, 90% CL
SINDRUM-II 2006

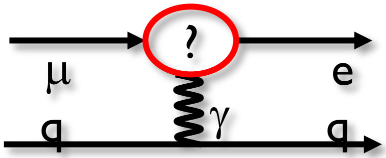
Other searches

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

Dipole or Contact interactions

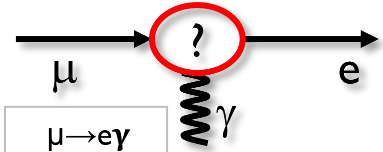
$$L_{CLFV} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\sum_{q=u,d}\bar{q}_L\gamma_\mu q_L\right)$$

Dipole Interaction

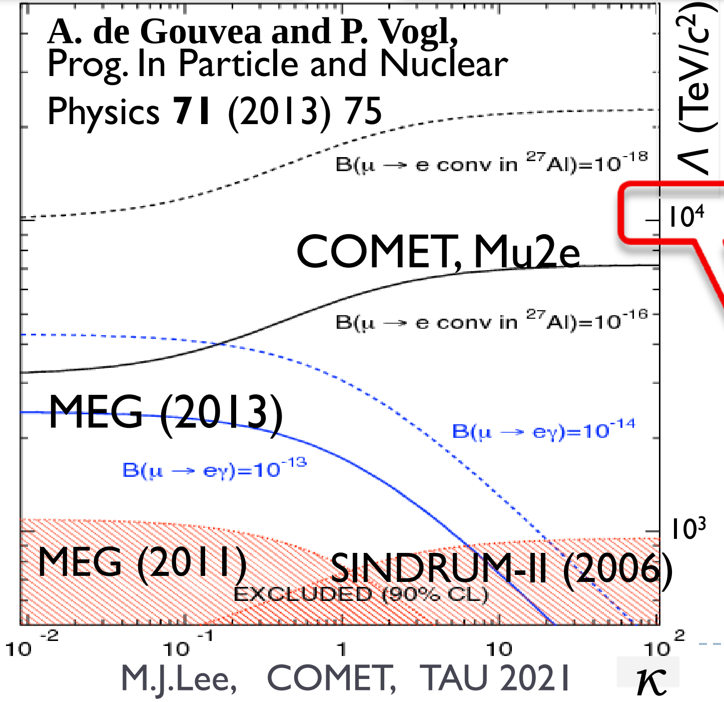


Muon conversion

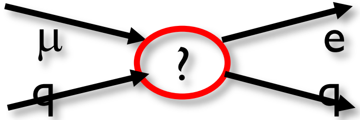
||



μ→eγ



Contact interaction



Probing O(10^4) TeV mass scale,

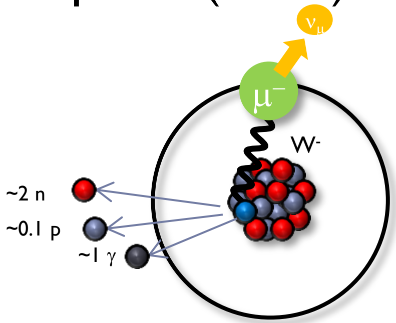
➔ Much higher energy scale than LHC

μ- in matter

Muon Capture

(61% (Al))

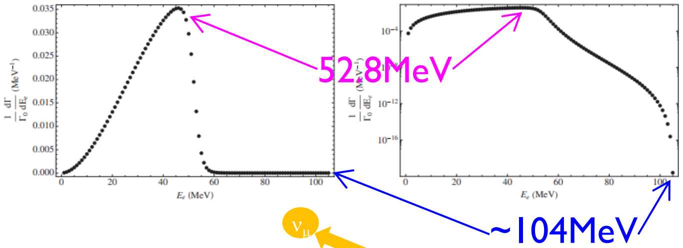
- $\mu^- + p \rightarrow \nu_\mu + n$
- Muon decay with nucleus
- BG hit source / Radiative Muon Capture (RMC) **BG**

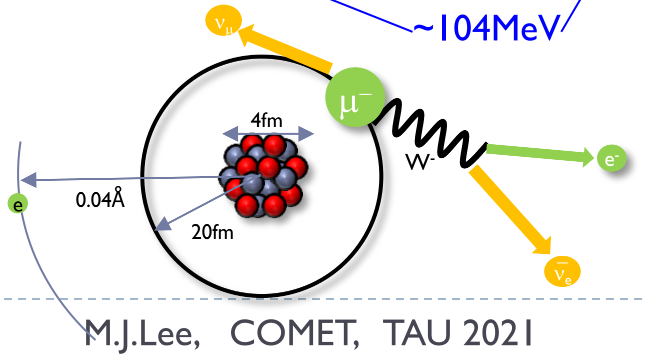


Decay in orbit(DIO)

(39% (Al))

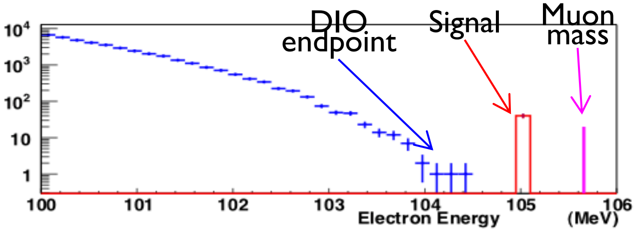
- $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$
- Bound muon decay
- Major **BG** source

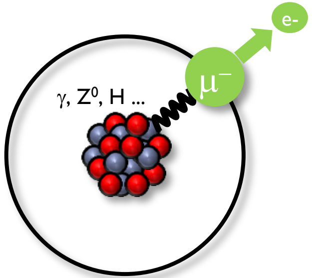




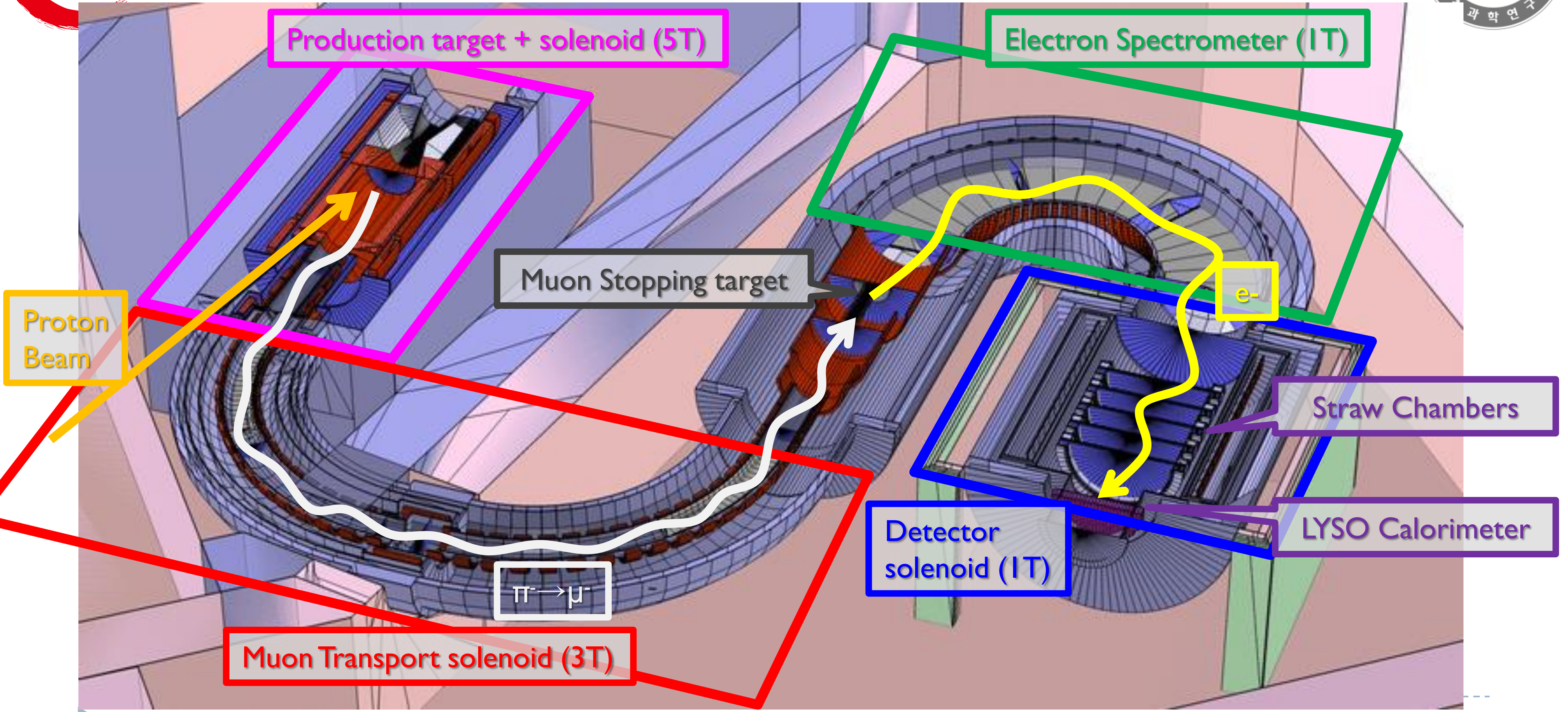
μ⁻→e⁻ conversion

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

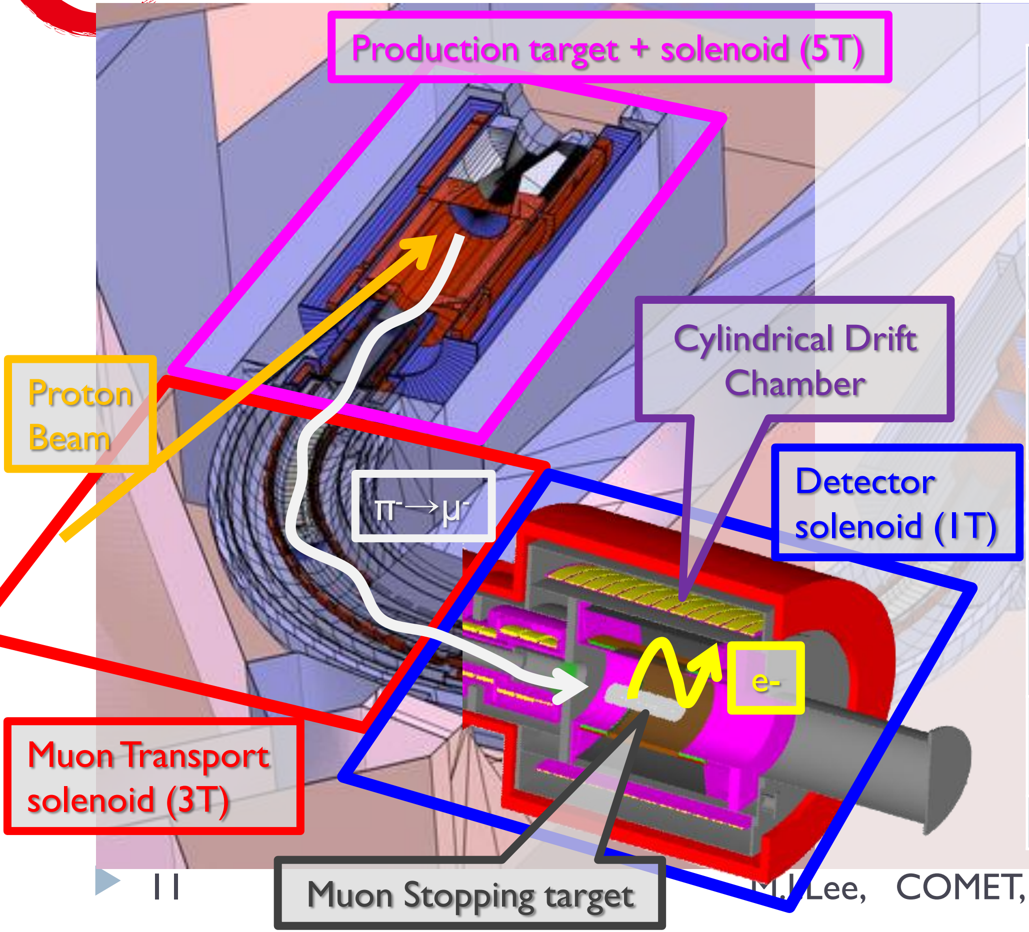




COMET (Phase-II) Experiment: for O(10^{-18}) SES

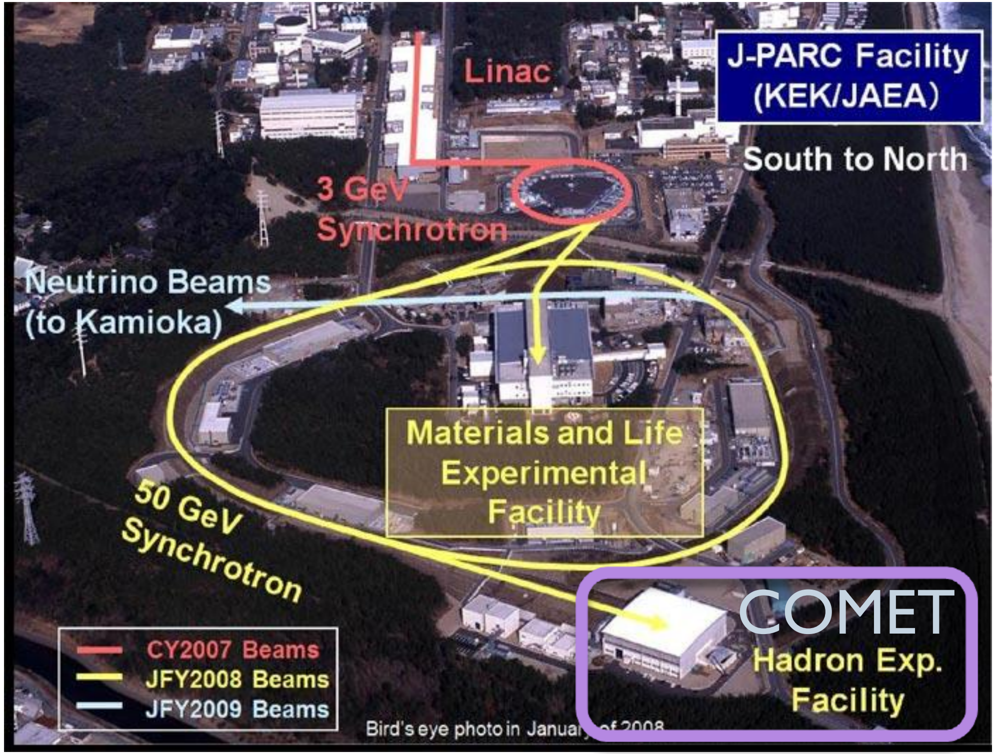


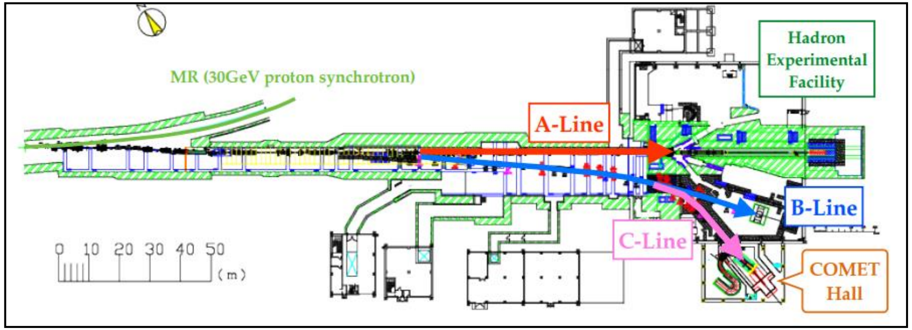
COMET Phase-I Experiment: for $O(10^{-15})$ SES



	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	Drift chamber	Straw + calorimeter
Sensitivity (90% CL)	7×10^{-15}	2.6×10^{-17} ~10^{-18}
DAQ start	2023 –	2025? –
DAQ Time (days)	~150	180 ~ 300

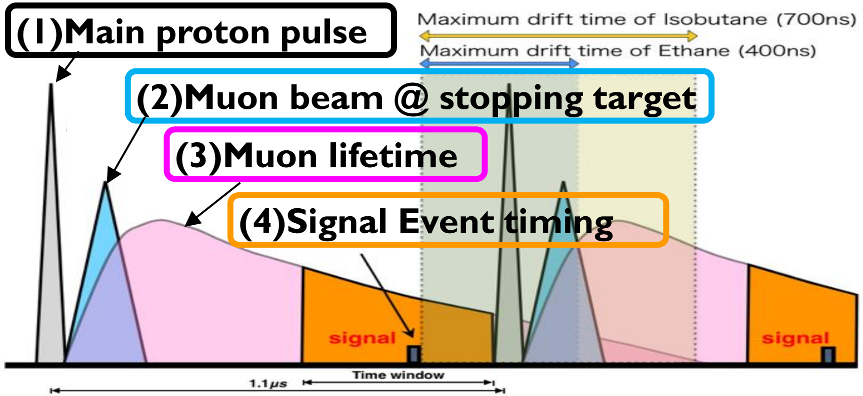
J-PARC facility / Beamline

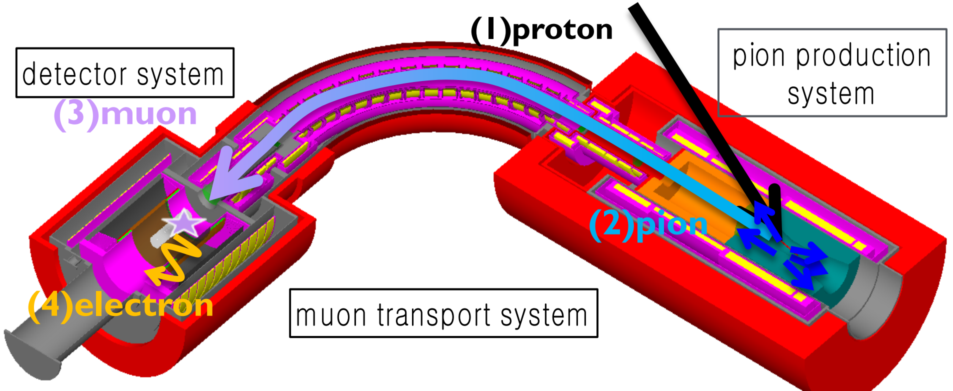


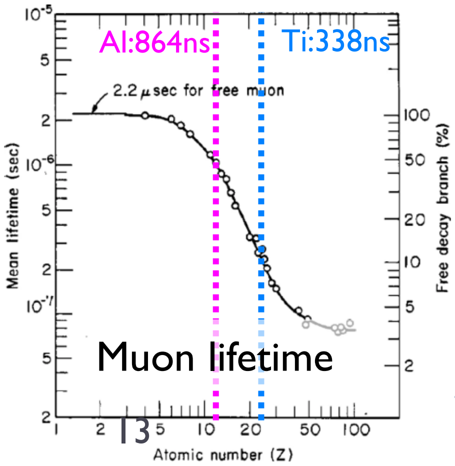


- J-PARC currently MR shutdowned for PS upgrade, until middle of 2022, for MW beam
- COMET beamline construction complete foreseen during shutdown

Pulsed proton beam





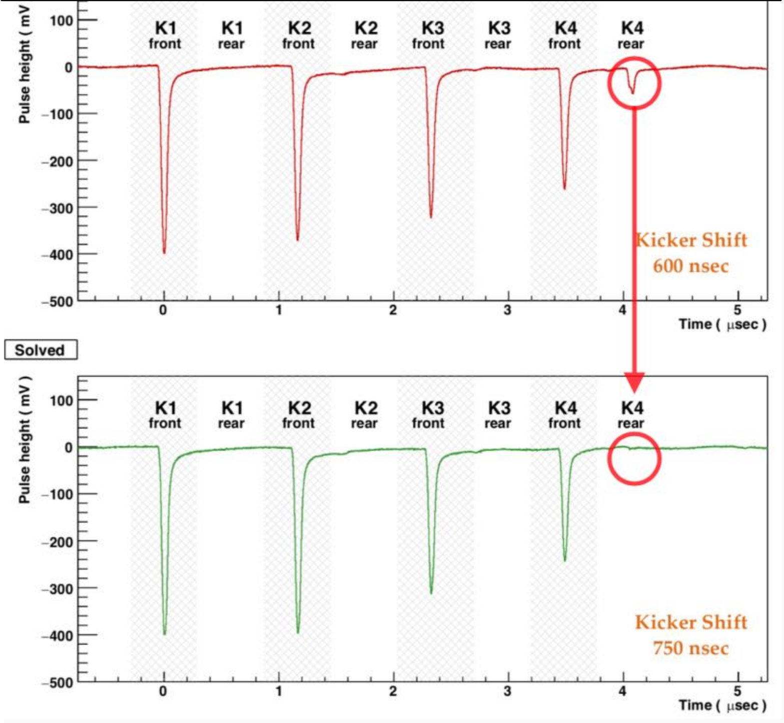


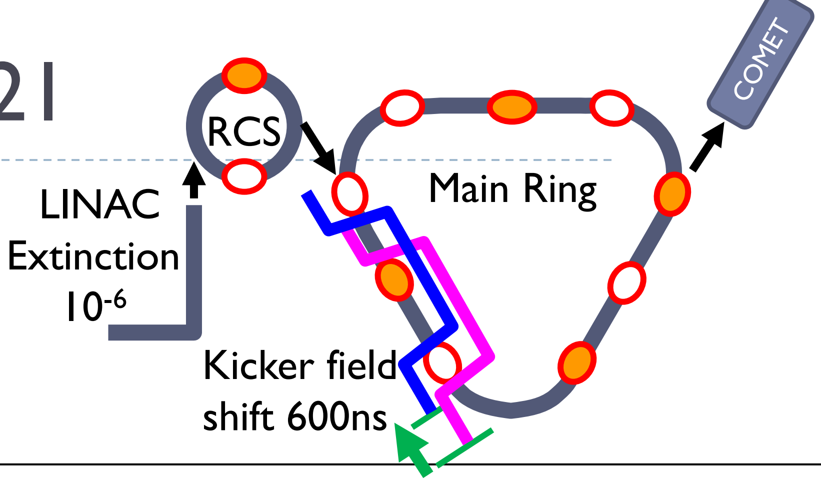
1. **Pulsed** protons arrive at production target, producing pions.
2. Muons(+pion) arrive at stopping target : **Prompt RPC BG events**
3. Captured muon processes with **finite lifetime.**
4. Some time after muon beam arrival, signal electron is measured, **avoiding prompt events.**

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 in 2019/21

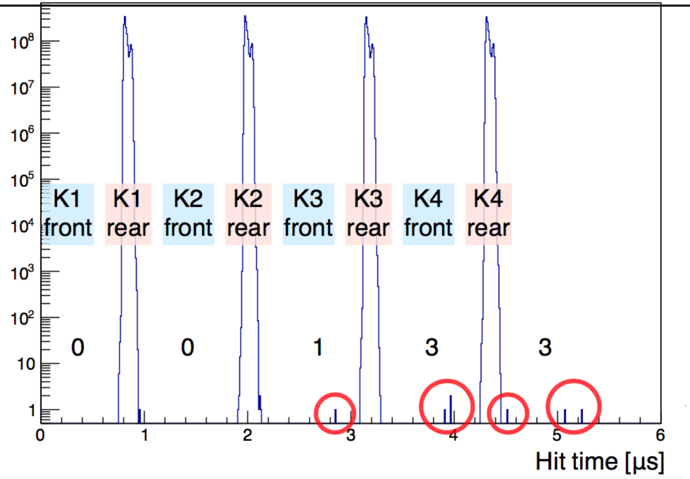
Measurement in neutrino beam dump





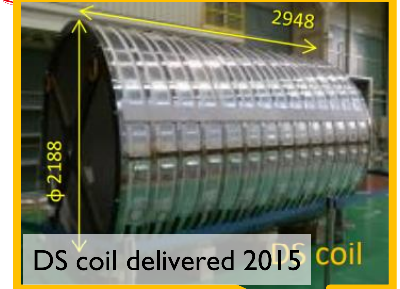
Measurement in Hadron hall

9.3×10^{-11} Extinction achieved (Preliminary)



H.Nishiguchi, IPAC2019
K.Noguchi, NuFACT 2021

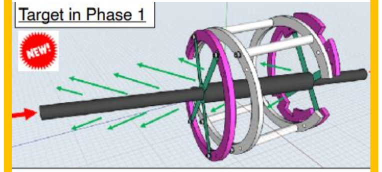
Solenoid magnet status



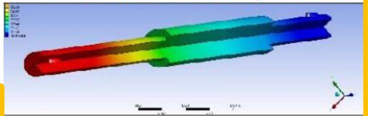
DS coil delivered 2015

BS coil delivered 2018

Phase-I Graphite target design done

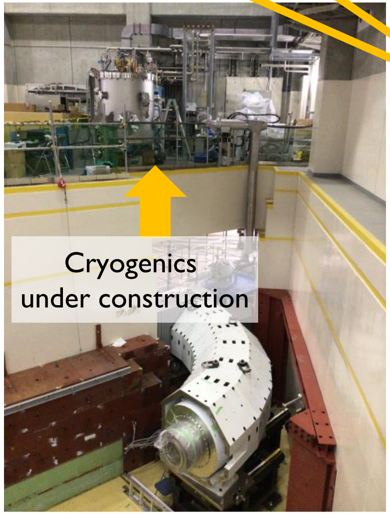


Graphite
Diameter: 26 mm and 40 mm, Length: 700 mm

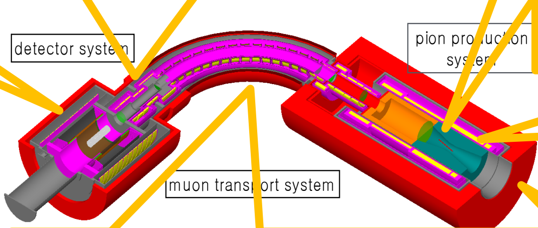


FEM simulation is completed. Max. temp. 245 degC.

CS cold-mass under construction, Ready by 2023



Cryogenics under construction



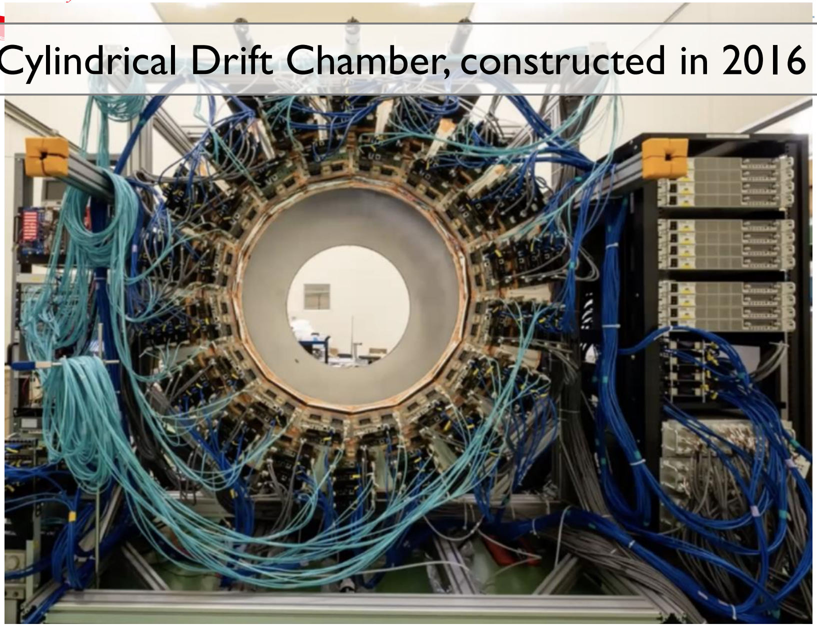
TS installed 2015, under test

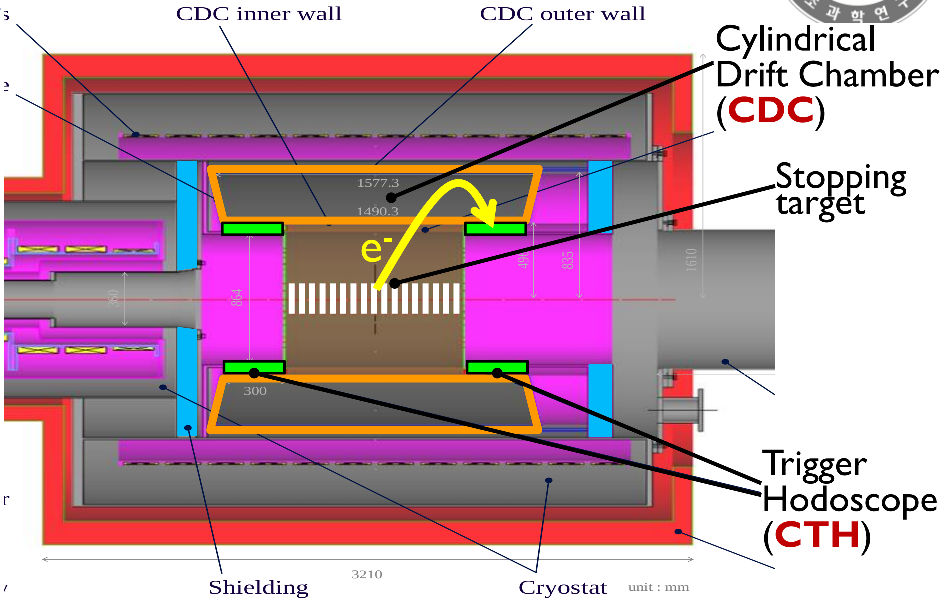
CS area, beam dump ready

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

C.Wu, NIMA v.1015 (2021)

Cylindrical Drift Chamber, constructed in 2016

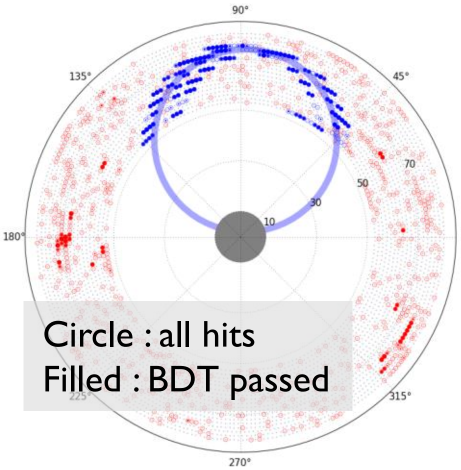




- **CDC**: All stereo-wire drift chamber, 20 layers, ~5000 sense wires, He:iC_4H_{10} = 9:1, HV=1850V
- Momentum resolution <200keV/c @ 105 MeV/c, spatial resolution 170um
- Cosmic test underway in KEK

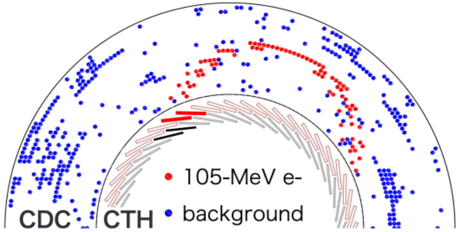
- **CTH** : 64-segmented two layered scintillators, providing trigger
- ~0.8 ns timing resolution

CDC BG Rejection, On/Offline, using **BDT**

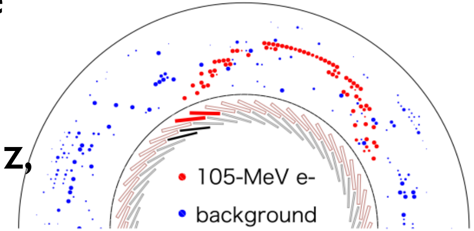


- **Offline** BG *hit* rejection 95%, signal eff. 99%
- Offline BG *event* rejection 95%, signal eff. 90%
- Using hit layer and hit energy deposition info.

- **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.

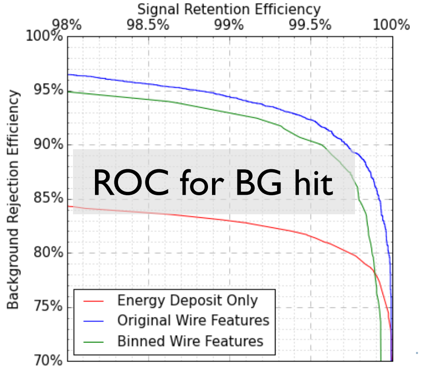


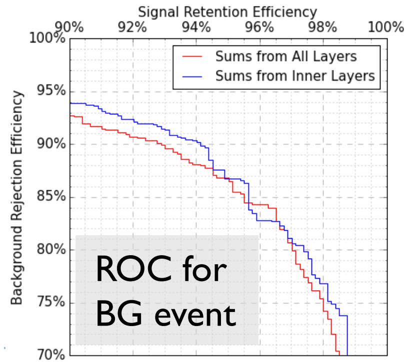
(a) before GBDT

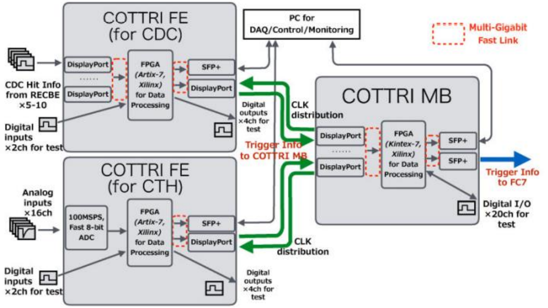


(b) after GBDT

Y.Nakazawa, IEEE-NS, v68 (2021)



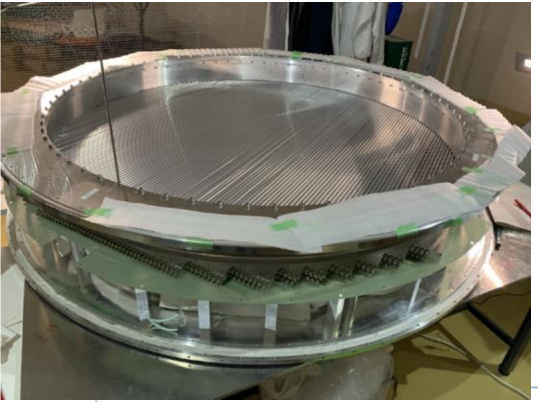


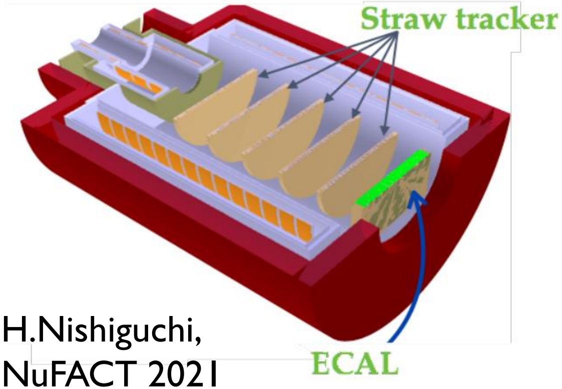


StrECAL (Straw+ECAL) / CRV (CosmicRay Veto)

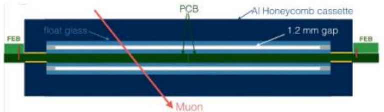
- Detector for Phase-II experiment / Beam measurement in Phase-I (1/1000 beam power)
  - 5 station of straw detectors+ ~2000 LYSO calorimeter
- Beam test with prototype achieved 150um spatial resolution, <200keV/c momentum resolution feasible.
- First full scale straw module assembled

- To suppress Cosmic Ray muon to factor of 10^{-4}
- Note: CDC can full-reconstruct Cosmic ray

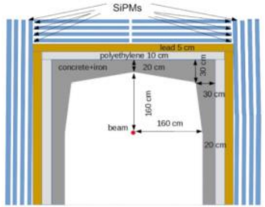




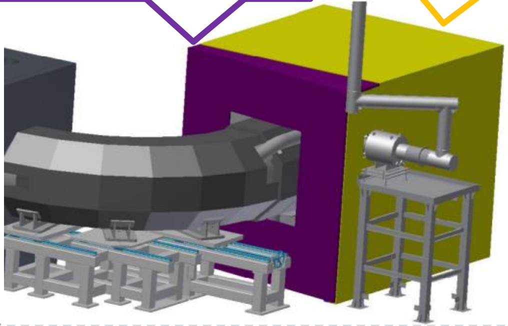
H.Nishiguchi, NuFACT 2021



Double gap Glass RPC for BS coverage



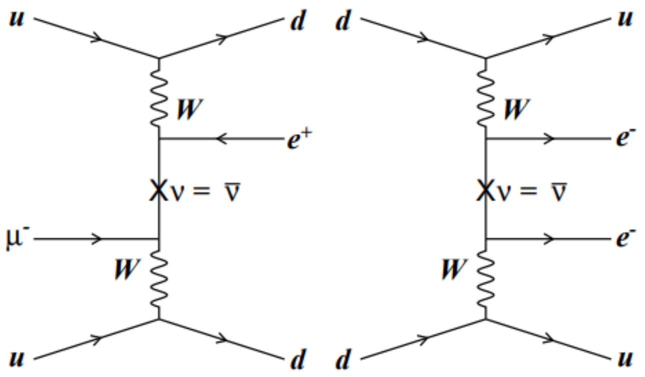
Four-layer scintillator CRV for CyDET coverage with SiPM readout



A new search: $\mu^- \to e^+$ in COMET Phase-I

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

- Similar process with $0\nu\beta\beta$ in eμ sector, Provides clues in LNV and Majorana ν
- Theoretical estimation :



$$\mathcal{R}^{\mu^- e^+} \equiv \frac{\Gamma(\mu^- + N(A,Z) \to e^+ + N'(A,Z-2))}{\Gamma(\mu^- + N(A,Z) \to \text{(All muon capture)})}$$

$$= 2.6 \times 10^{-22} \times \begin{Bmatrix} |\langle m_\nu \rangle_{\mu e}/m_e|^2 |\mathcal{M}_\nu|^2 & \text{(light neutrino)} \\ \left|\langle M_N^{-1} \rangle_{\mu e} m_p\right|^2 |\mathcal{M}_N|^2 & \text{(heavy neutrino)} \end{Bmatrix}$$

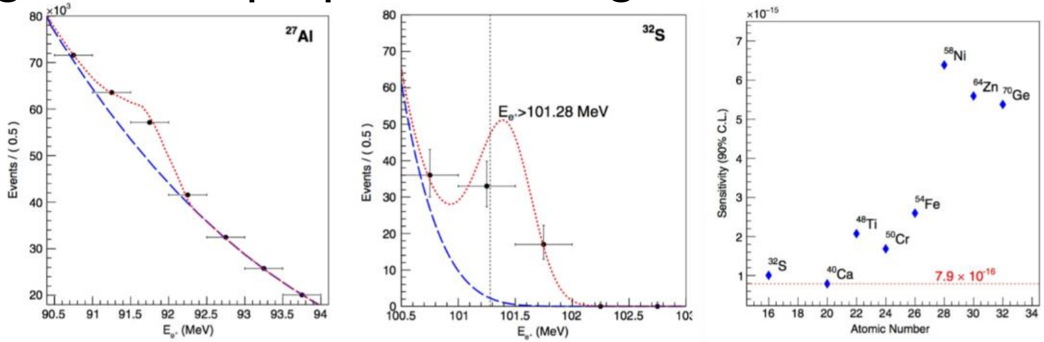
$$\begin{array}{rl} (0.008 - 1.7) \times 10^{-41} & \text{for a light neutrino, normal neutrino mass hierarchy,} \\ (0.05 - 6.7) \times 10^{-40} & \text{for a light neutrino, inverted neutrino mass hierarchy,} \\ \lesssim 3.8 \times 10^{-24} & \text{for a heavy neutrino.} \end{array}$$

(Note: Most recent measurement by SINDRUM-II (1998) with Ti : 1.7×10^{-12})

- Hard to beat $0\nu\beta\beta$ for (heavy) Majorana neutrino search, but observation imply:
  - Majorana neutrino ; Flavor effect suppressed in $0\nu\beta\beta$ but becomes dominant in eμ sector ; Even more complex interaction is responsible to neutrino mass

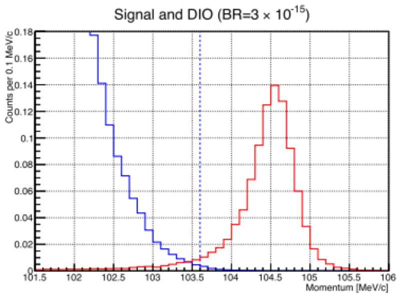
A new search: $\mu^- \rightarrow e^+$ in COMET Phase-I

- Experimentally simple but hard to achieve good sensitivity
  - By flipping charge. No DIO BG
  - RMC background dominates – Endpoint energy not well measured / understood
  - N(A,Z-2) may be excited (Giant resonance) – broader (O(10MV)) signal spectrum
  - **Although, COMET (and Mu2e) will be able to provide new opportunity for improved measurement**
- Experimental understanding of RMC / proper muon target choice are important
  - Replacing Al target to other nuclei may allow $O(10^4)$ sensitivity improvement



B.Yeo, PRD96 (2017)

Experiment Sensitivity of μ⁻→e⁻



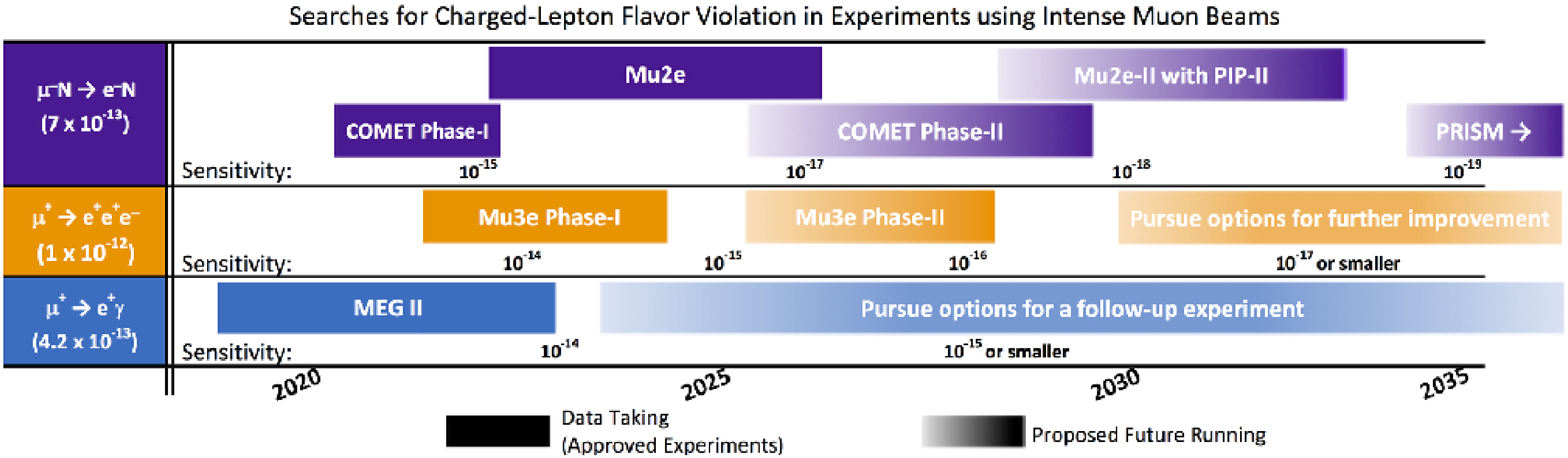
- COMET Phase-I Target single event sensitivity : **3×10^{-15}**
  - 100 times improvement from SINDRUM-II
  - Phase-II : 2.5×10^{-17} ~ 10^{-18}
- Net acceptance = **4.1%**
  - Online efficiency ~0.99
  - Geometric acceptance + track quality ~0.18
  - 103.6 MeV < p < 106MeV : 0.93
  - 700ns < t < 1170 ns : 0.3
- Background = **0.032**
  - DIO ~ 0.01 (dominant)
  - RPC ~ 0.003, Cosmic <0.01
- Schedule
  - Detector integration by 2023 summer
  - **Engineering run: end of 2023, followed by physics run**

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 MeV/c < P_e < 106.0 MeV/c
Timing window (ε_{time})	0.3	700 ns < t < 1170 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	~ 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

International Future Planning

A.Baldini et al., arXiv:1812.06540v1



Rich physics in near and long future for Muon LFV !