Status of COMET Experiment

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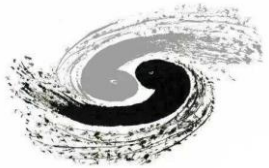
On behalf of the COMET collaboration

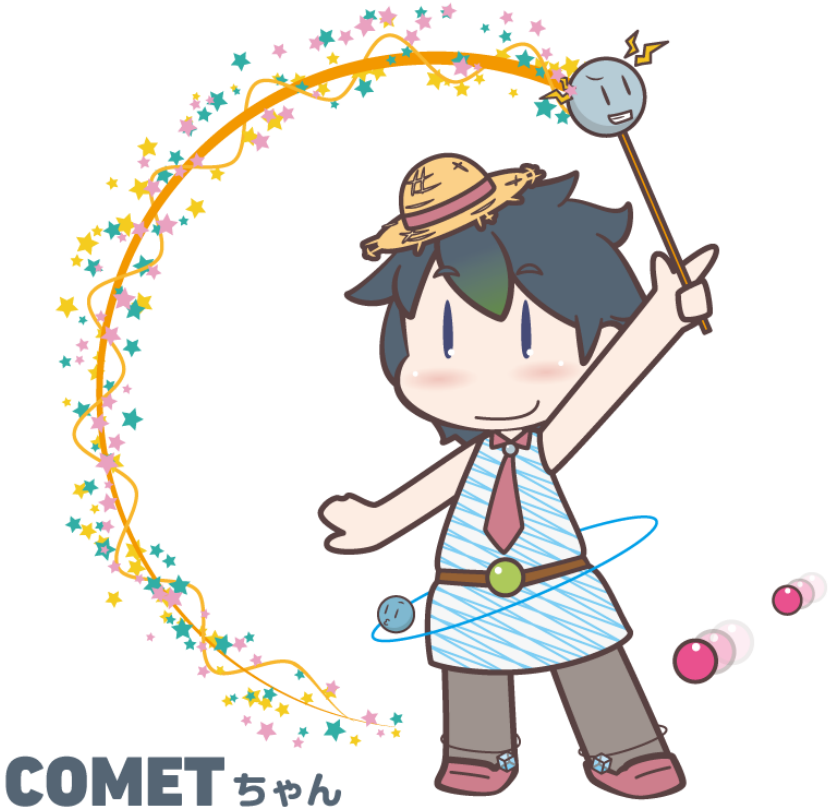
Institute of High Energy Physics, CAS



Outline

1. The COMET Experiment
2. Physics Motivation
3. Design of the COMET
4. Current Status of the COMET
5. Summary

The COMET Experiment

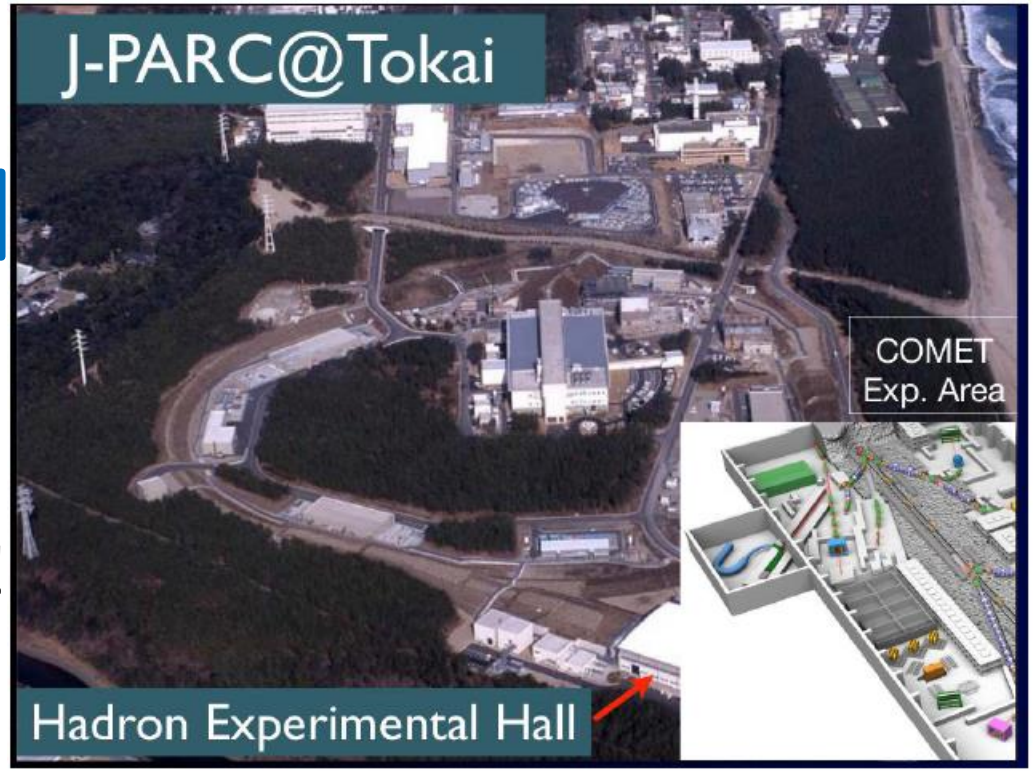


by higgstan.com

COherent Muon Electron Transition

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

- Experiment Target:
  $B(\mu^- + Al \rightarrow e^- + Al) = 2.6 \times 10^{-17}$ (S.E.S)
- This is **10000 times improvement!**
- Current world limit:
  $B(\mu^- + Au \rightarrow e^- + Au) < 7 \times 10^{-13}$
  given by SINDRUM II experiment (2006)
- Likely to get 100000 times improvement!
  still being optimized



The COMET collaboration

Oct 2018, COMET collaboration at Tbilisi

~200 members,
41 institutes from 17 countries

Still growing!

Physics Motivation

Charged Lepton Flavor Violation

The establishment of the Standard Model and the observation of Neutrino Oscillation worked-out very much in the particle physics. However there are still mysteries.

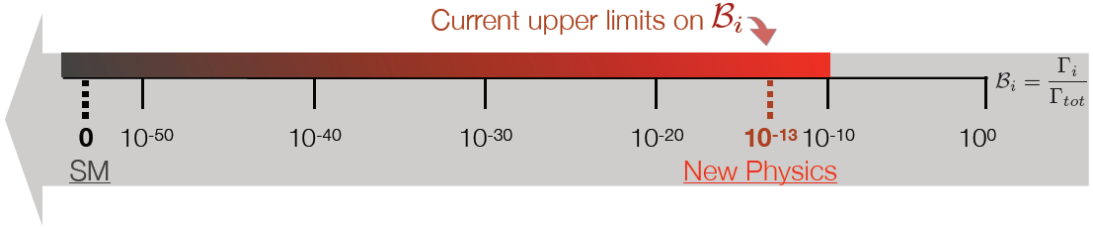
Process of CLFV

- Highly prohibited (O(<10^{-54})) in the SM

$$\frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu\nu)} \propto \left| \sum_i \frac{m_i^2}{m_W^2} U_{\mu i}^* U_{ei} \right|^2 \sim O(10^{-54})$$

small mass ratio of neutrino to weak boson

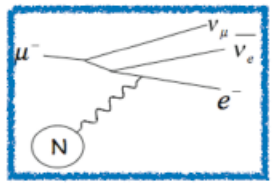
- No/less background from SM
- Very rare decays and not found yet!
- Clean field to search for new physics!



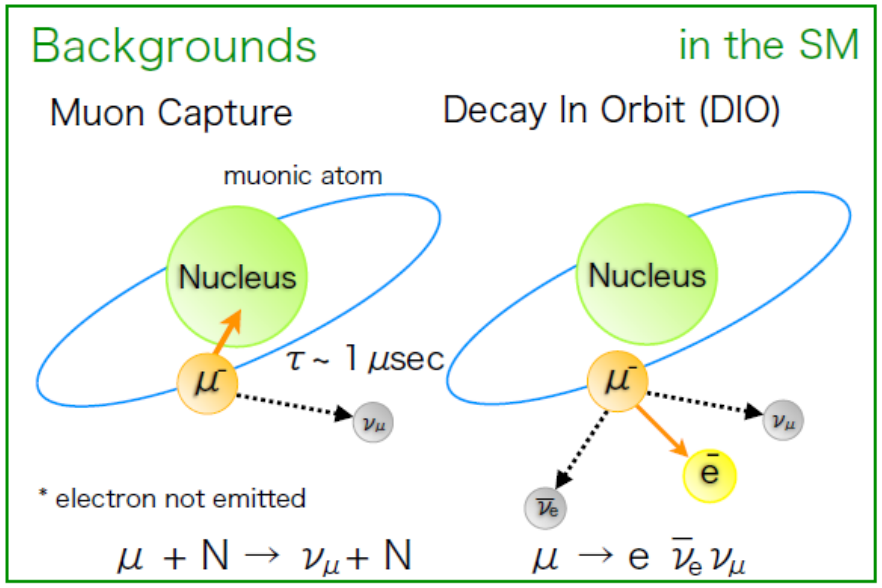
μ - e conversion

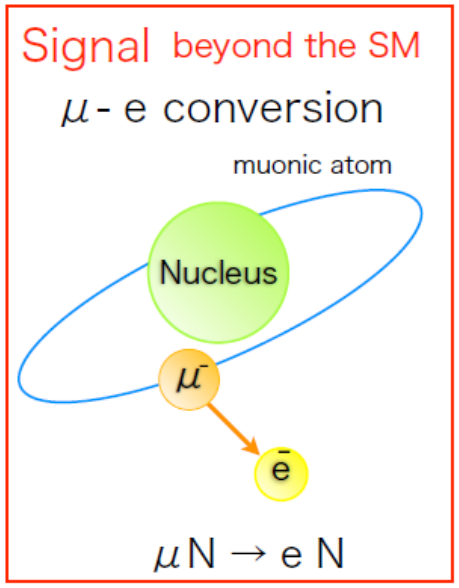
- Atomic capture of μ^-
  - Generate "muonic atom" by muon stopping at the target
- Measure emitted electron momentum from muonic atom
  - Decay in obit (DIO) is Michael edge up to 105 MeV
  - μ-e conversion signal is **mono-energetic ~105 MeV peak**
- Spectroscopic search for μ-e conversion

DIO Background

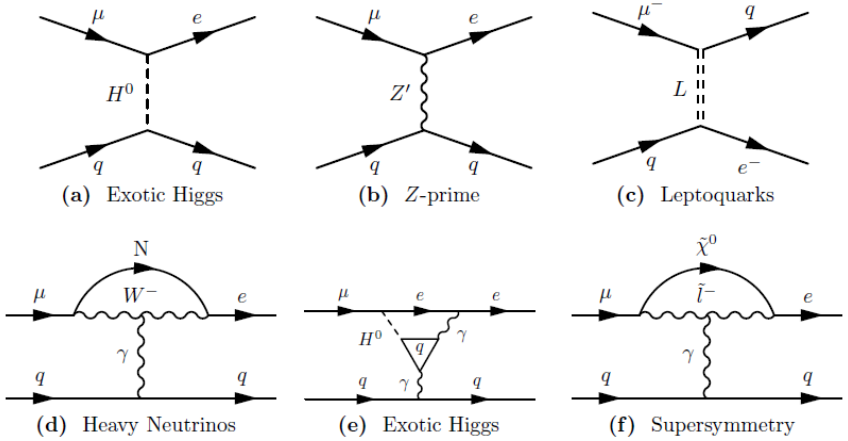


- $E_{\mu e}(Al) \sim m_\mu - B_\mu = 105MeV$
  - B_μ: binding energy of the 1s muonic atom

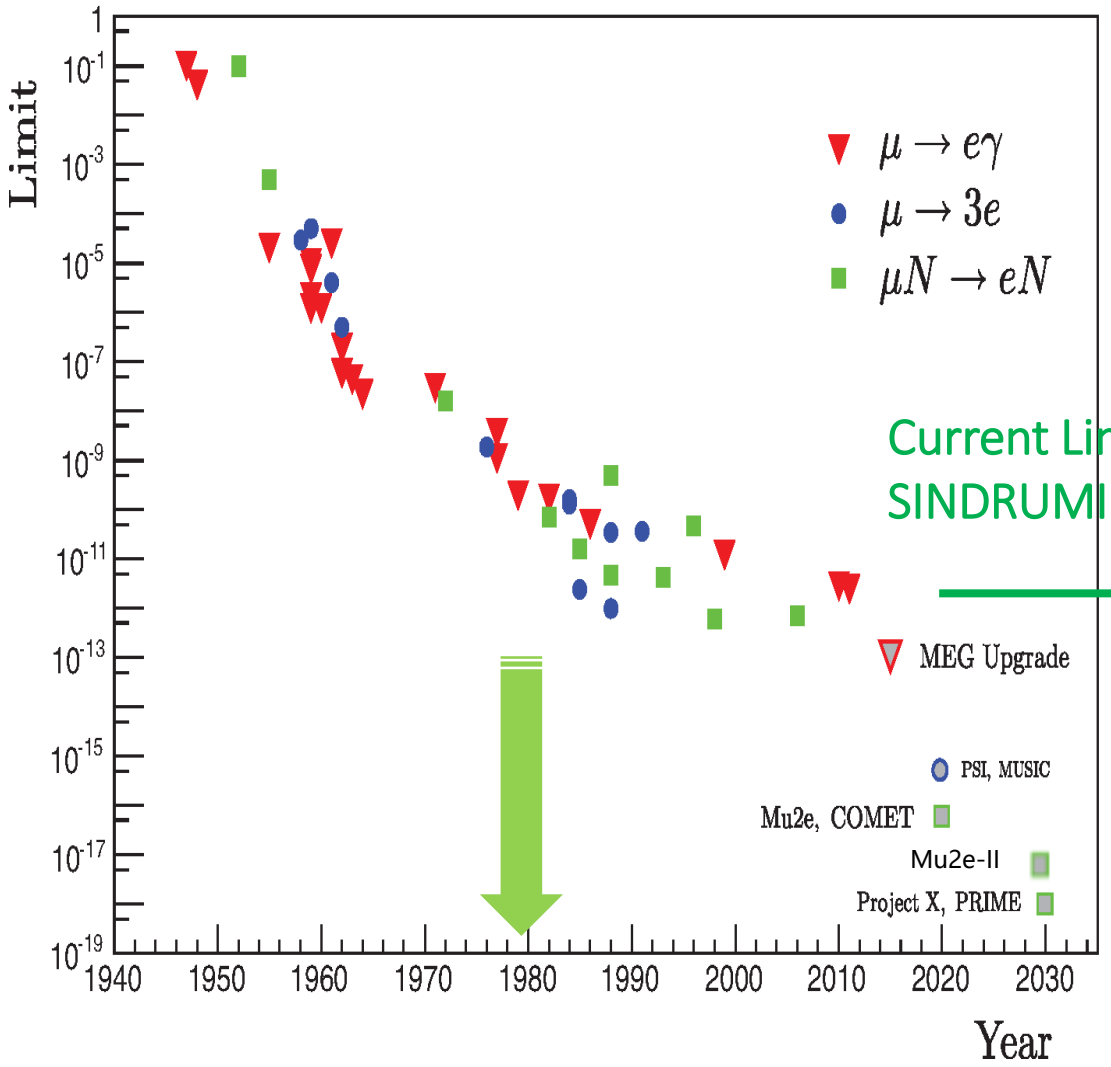




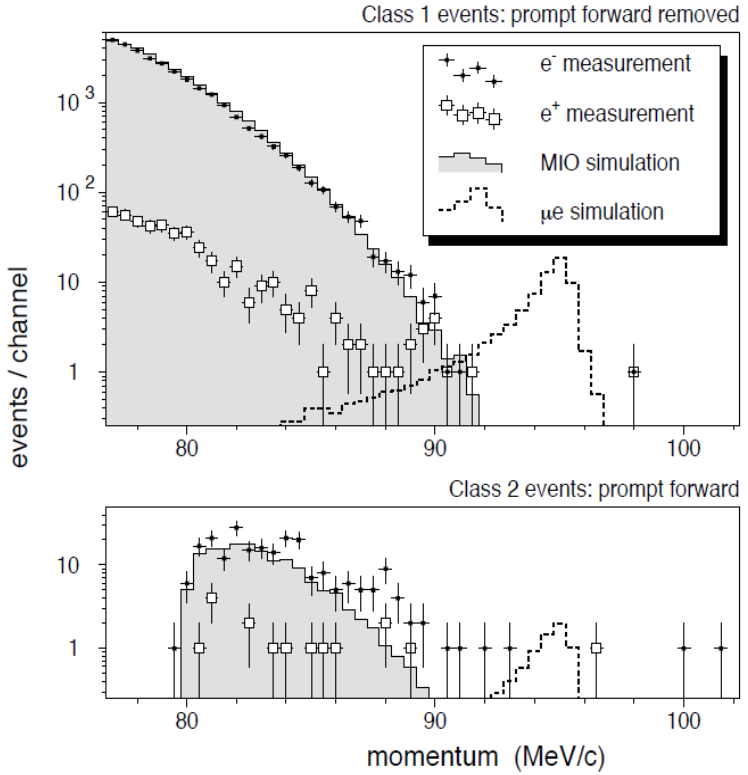
predicted branching ratio
$= 10^{-14} \sim 10^{-18}$



Search for Muon to Electron Conversion



Current Limit by SINDRUMII @ PSI



Eur.Phys.J. C47 (2006) 337-346

With a different design, > 4 orders of magnitude improvement is possible!

Design of the COMET

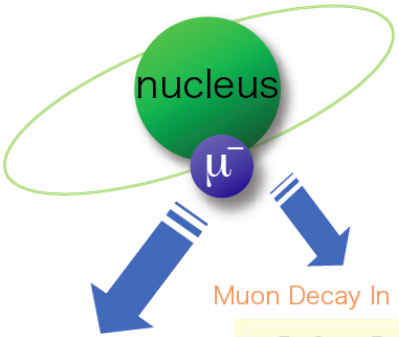
Background rejection (1)

- **Intrinsic physics background**

➢ Mostly from muon decay in orbit (DIO)

  - Calculated by Czarnecki with radiative correction. Branching ratio drops very quickly near end point
  - **Momentum resolution** required to be better than **200 keV/c**

1s state in a muonic atom

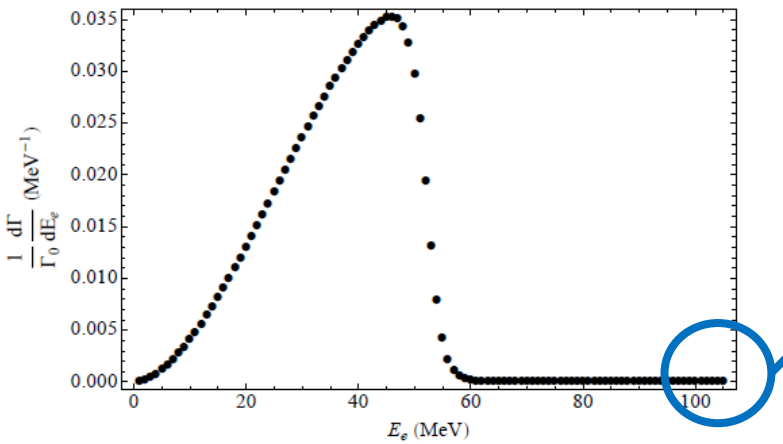


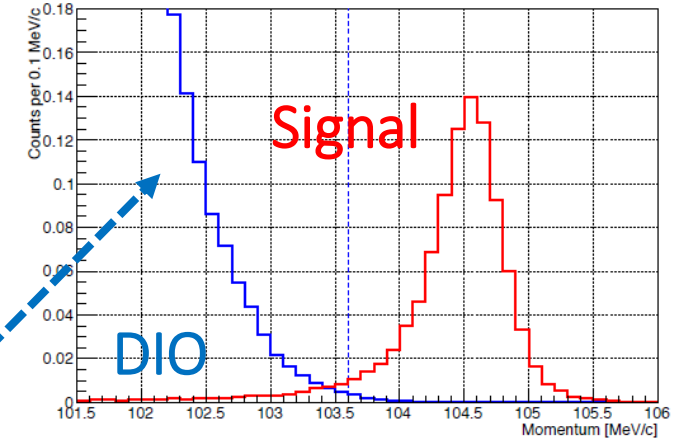
Muon Decay In Orbit

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

nuclear muon capture

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





Background rejection (2)

- **Beam related background**

➢Energetic particles in beam with E>100MeV

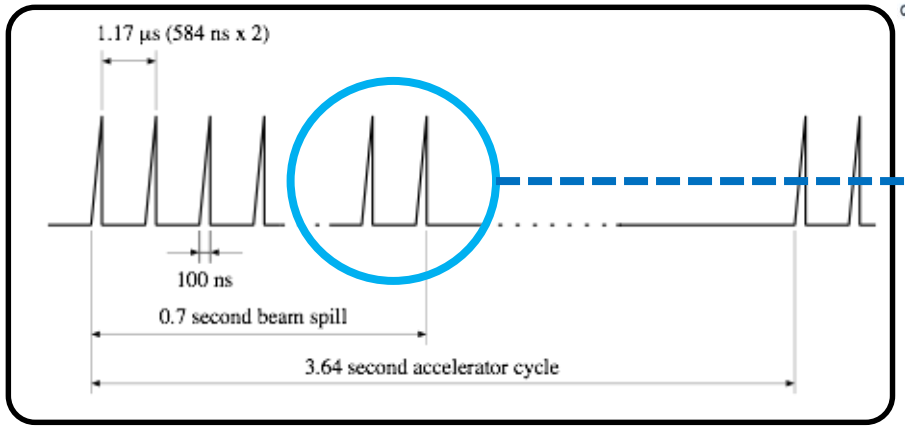
- Radiative pion capture, π^- (A,Z) → (A,Z-1) γ, γ → e^+ e^-
- Muon decay in flight, p_μ > 75 MeV/c
- Anti-proton induced, etc.

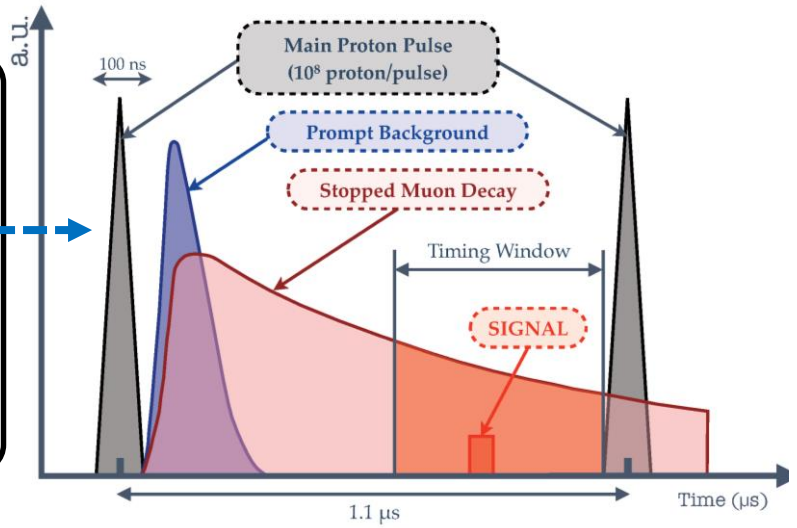
- Long muon beam line
- Can be suppressed by **pulse beam** and a **delayed measurement window (~700 ns)**
- Some due to leaked proton. Proton extinction factor required to be < 10^{-10}

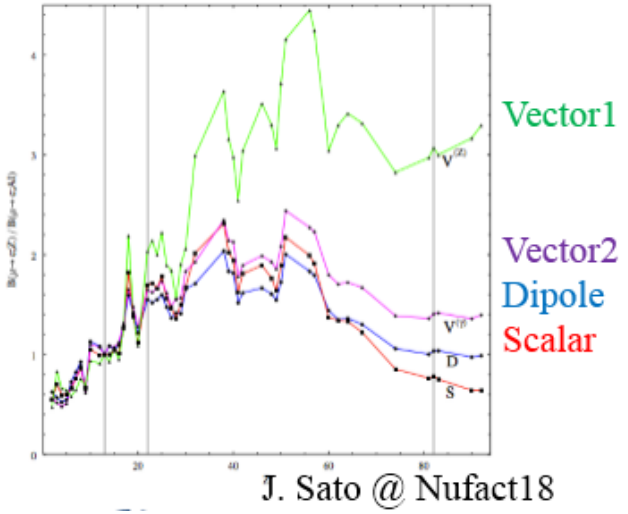
Material of muon stopping target

- Heavier nucleus has large overlap with muon wave function
- Lighter nucleus has longer life time of muon in muonic atoms
- **Aluminum** stopping target will be used in COMET

  τ_μ in Al ~ 0.9μsec

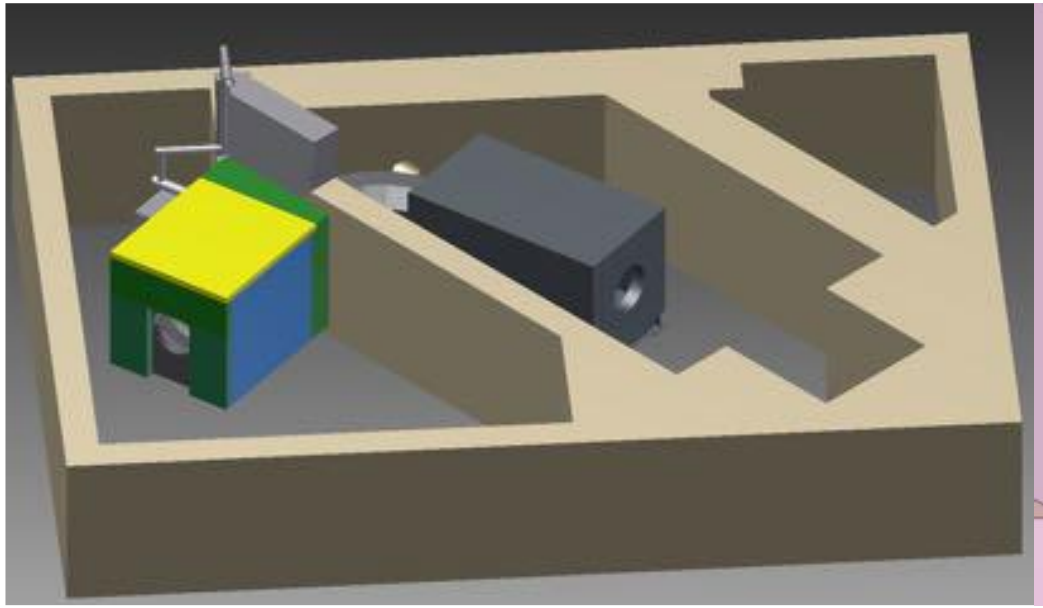


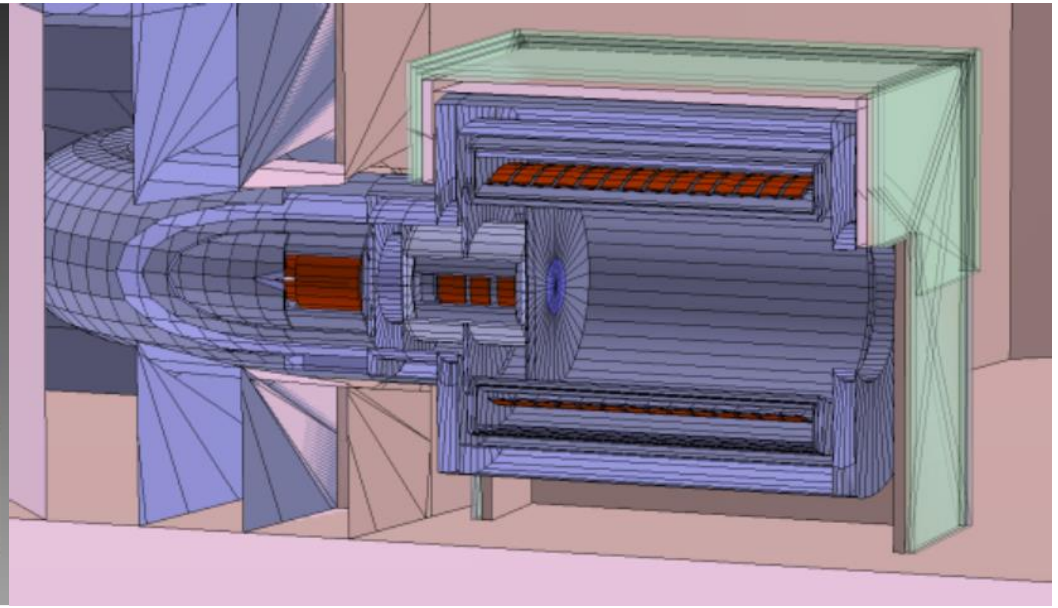




Background rejection (3)

- Cosmic ray background

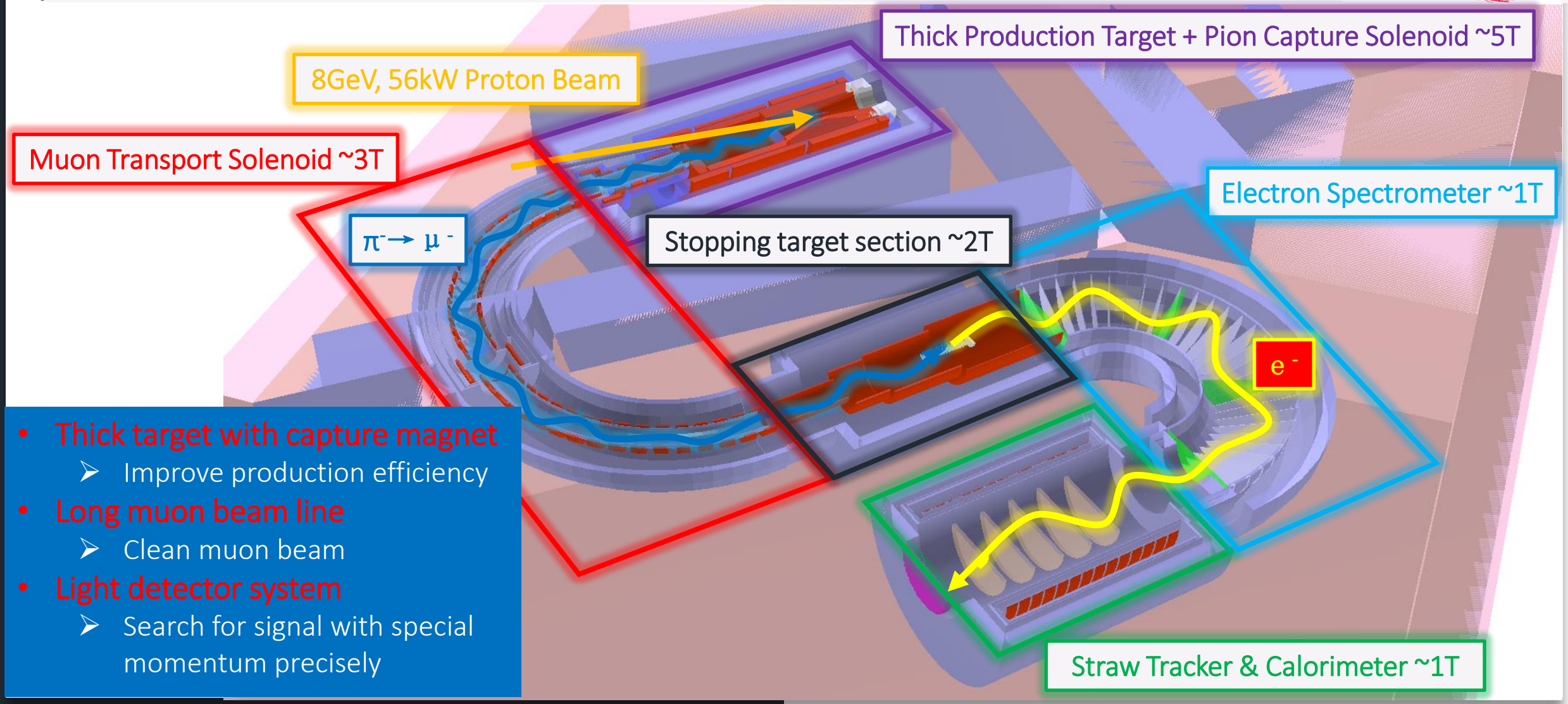




➢ Cosmic rays may create e^- in signal region that come into a detector and make trigger.

- To avoid these CR induced BG, target and detector region have to be covered by veto counters.
- Required performance: CRV inefficiency ~ 10^{-4}
- CR background ∝ data taking time (shorter running time with higher beam intensity is better)

Overview



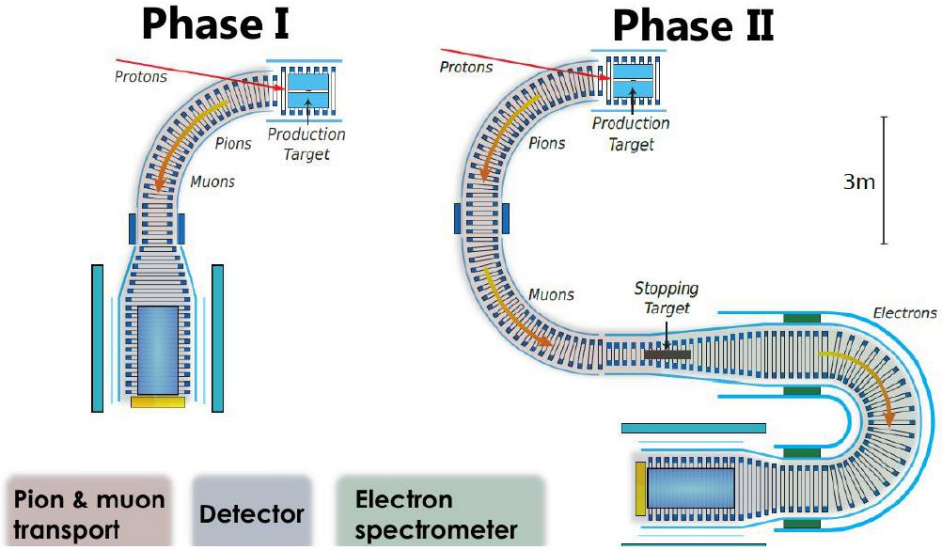
- Thick target with capture magnet
  - Improve production efficiency
- Long muon beam line
  - Clean muon beam
- Light detector system
  - Search for signal with special momentum precisely

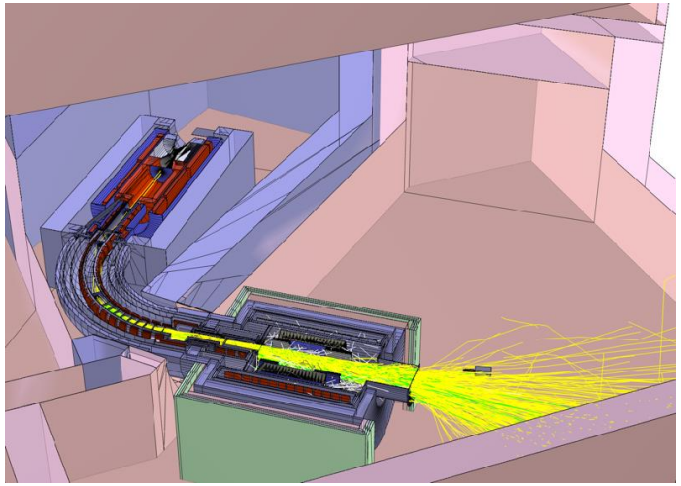
Staged plan of COMET

COMET Phase-I, 5 months data taking

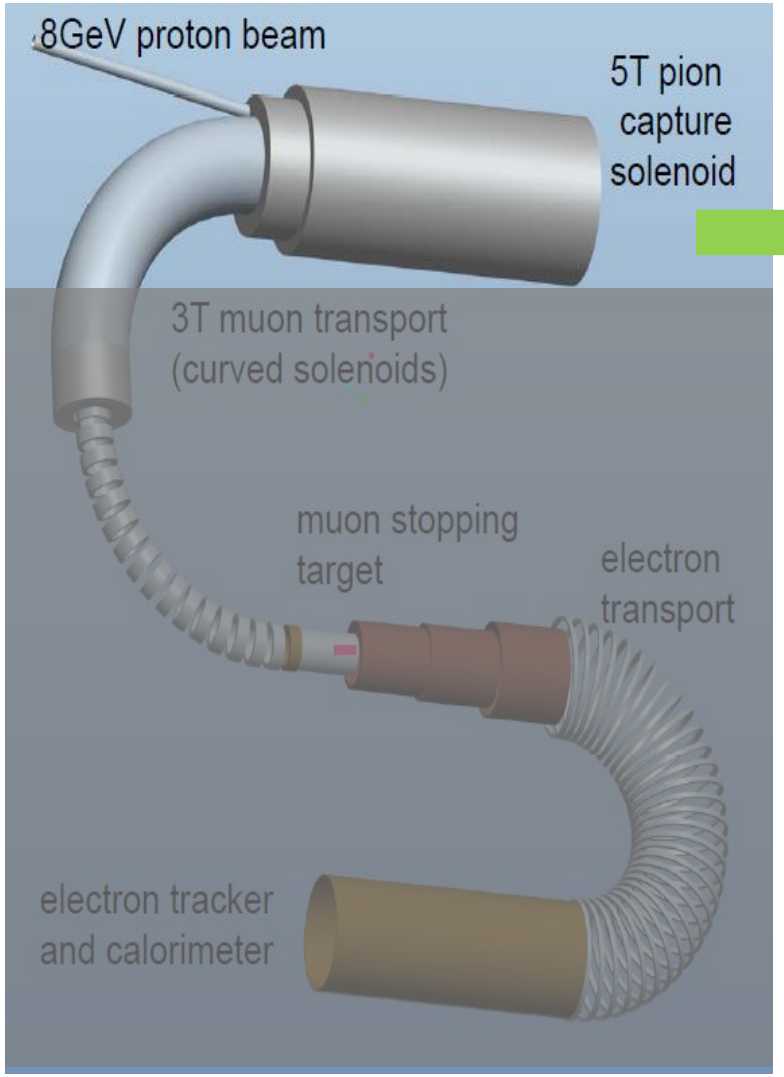
Proton beam: 8 GeV, 0.4 mA, 3.2 kW

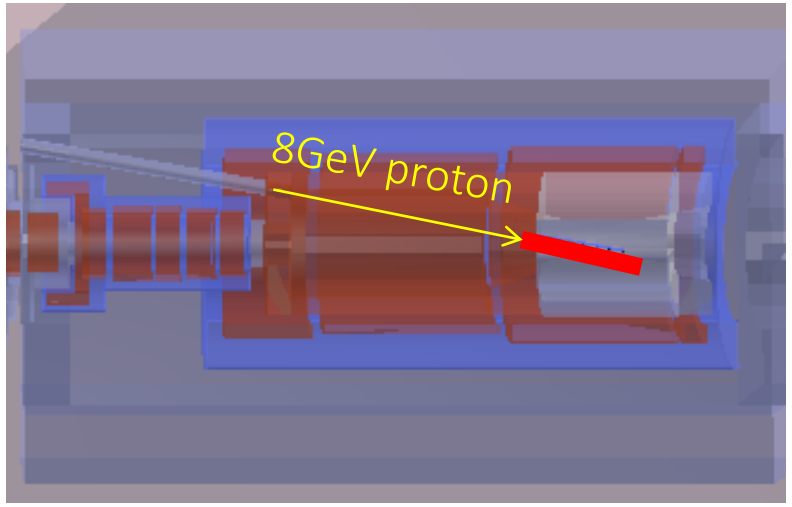
- Search for $\mu - e$ conversino with cylindrical detector (CyDet) with:
  S.E.S. = 3×10^{-15}
  (2 orders of magnitude improvement).
- Directly measure the muon beam with prototypes of Phase-II detector.
  - Very useful to guide Phase-II





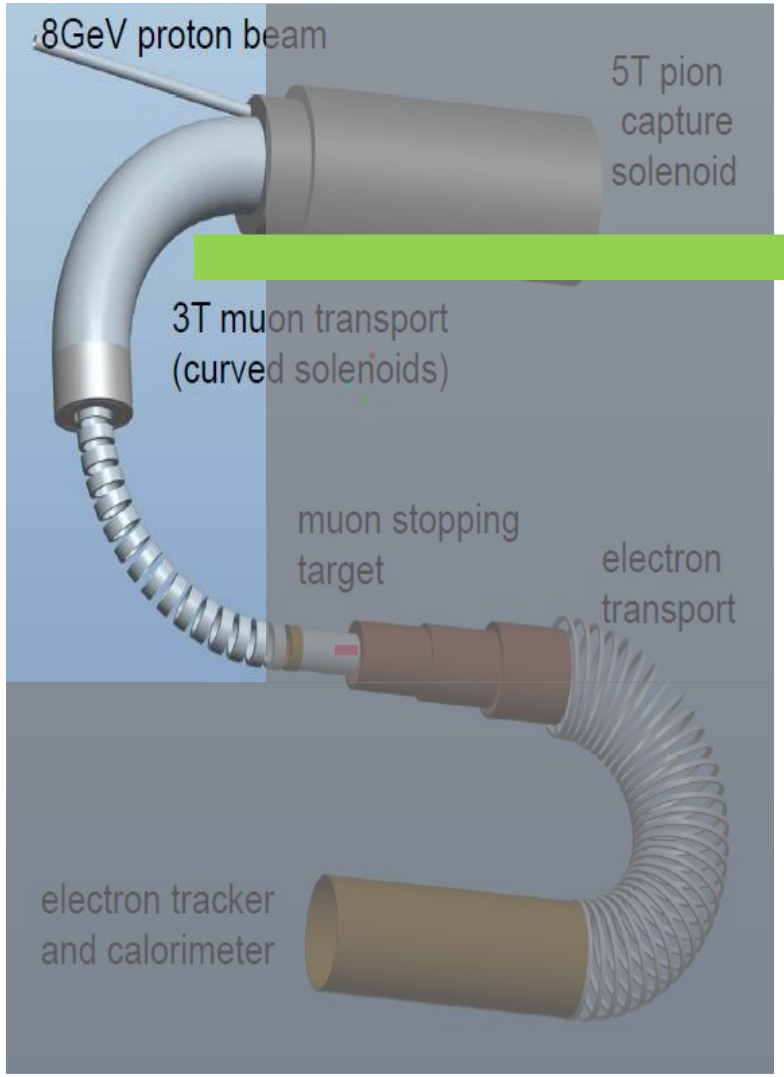
Production target and the capture magnet





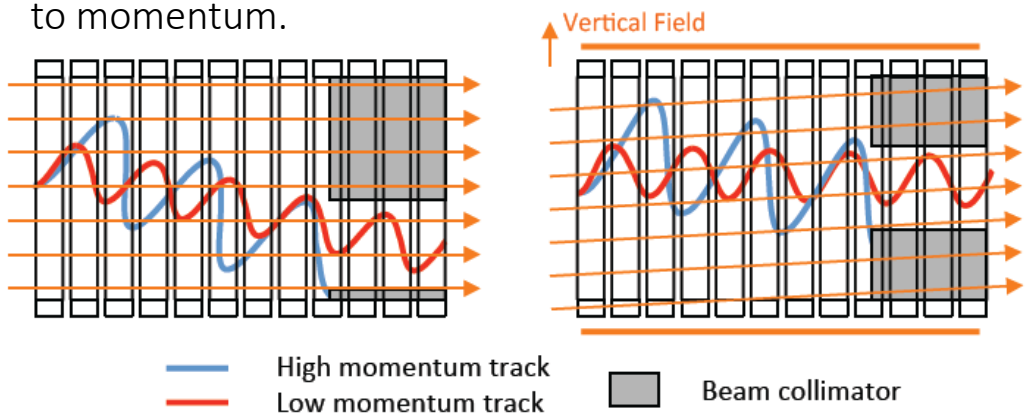
- 8 GeV 56 kW proton beam
- Thick target with 1~2 hadron interaction length
- Powerful capture magnet: 5 T
  - Large inner bore to fit in the shielding
  - Adiabatic decreasing field: focusing and mirroring
- Expected muon yield: 10^{11} muon/sec! (10^{8} @ PSI)

Transportation solenoid



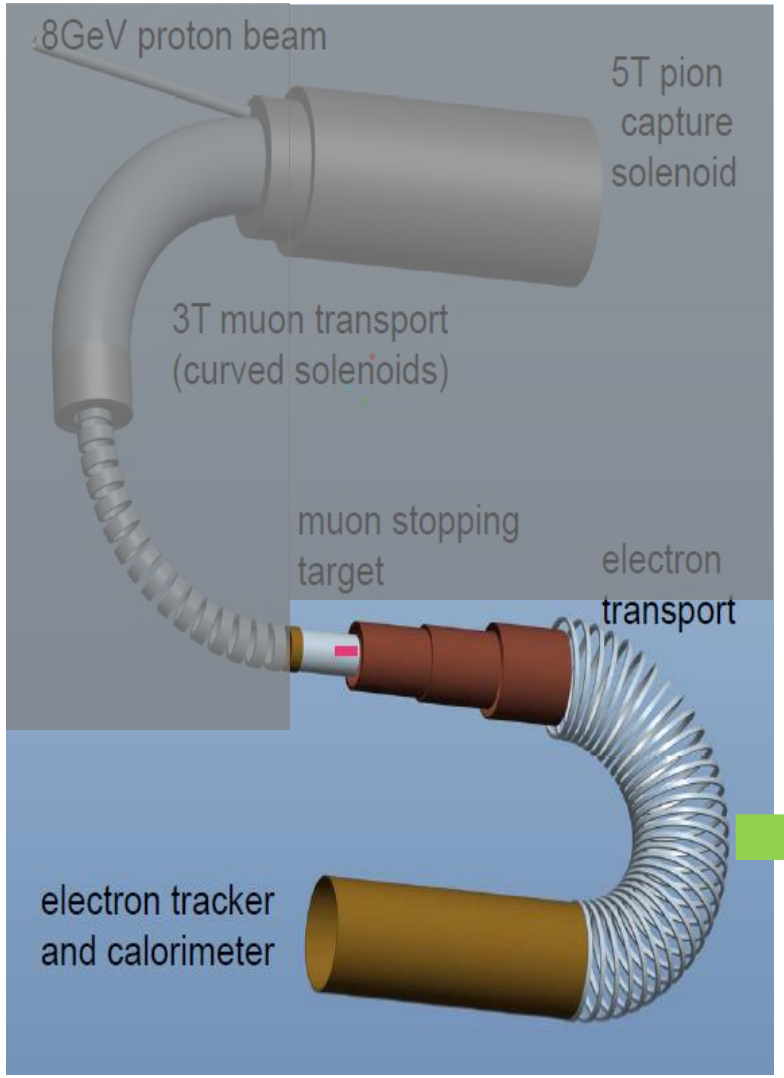
Drift vertically, proportional to momentum.

Vertical field as “correction”

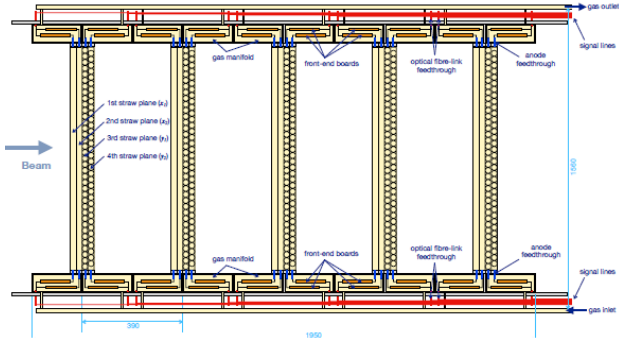


- Use C shape curved solenoid
  - Beam gradually disperses
    - Charge & momentum
  - Dipole field to pull back muon beam
    - Can be used to tune the beam
  - Collimator placed in the end
    - Utilize the dispersion in 180 degrees

Stopping target and detector system

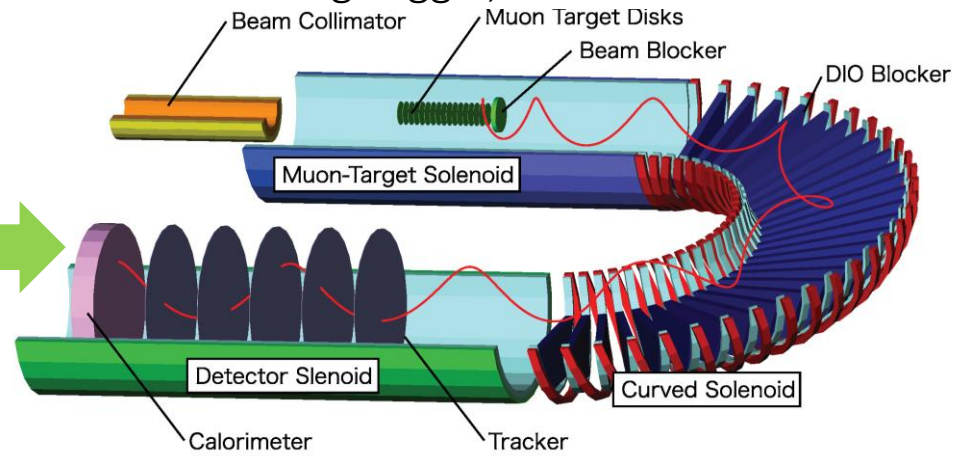


- Use straw tracker to measure the momentum
  - Really light: put in vacuum, 12 micro meter thin straw



Tracker with Straw-tubes
- Operational in vacuum in 1T
- Δp = 150~200 keV/c (for p=105 MeV/c)
- Straw tube
  - 20 μm thick, 9.75 mm diameter for Phase-I
  - 12 μm thick, 5 mm diameter for Phase-II
- More than 5 stations (xx'yy'>5)
- Ar:C_2H_6 (50:50)

- Electromagnetic calorimeter
  - Providing trigger, TOF and PID



- 1,920 LYSO crystals
  - 2×2×12 cm (10.5 radiation length)
- ΔE/E = 5% (for E=105 MeV)
- 40-ns decay time
- APD + read-out(EROS)

Physics Sensitivity

COMET Phase-II, One year data taking, 8 GeV, 7 mA, 56 kW proton beam

- Search for $\mu - e$ conversion with S.E.S. = 2.6×10^{-17} (4 orders of magnitude improvement)
- Further optimization on the way
  - Likely to improve sensitivity by factor of 10 ($\mathcal{O}(10^{-18})$)
  - with the same beam power and beam time
  - More muons with in-depth optimization of target
  - Higher acceptance after redesigning of collimator

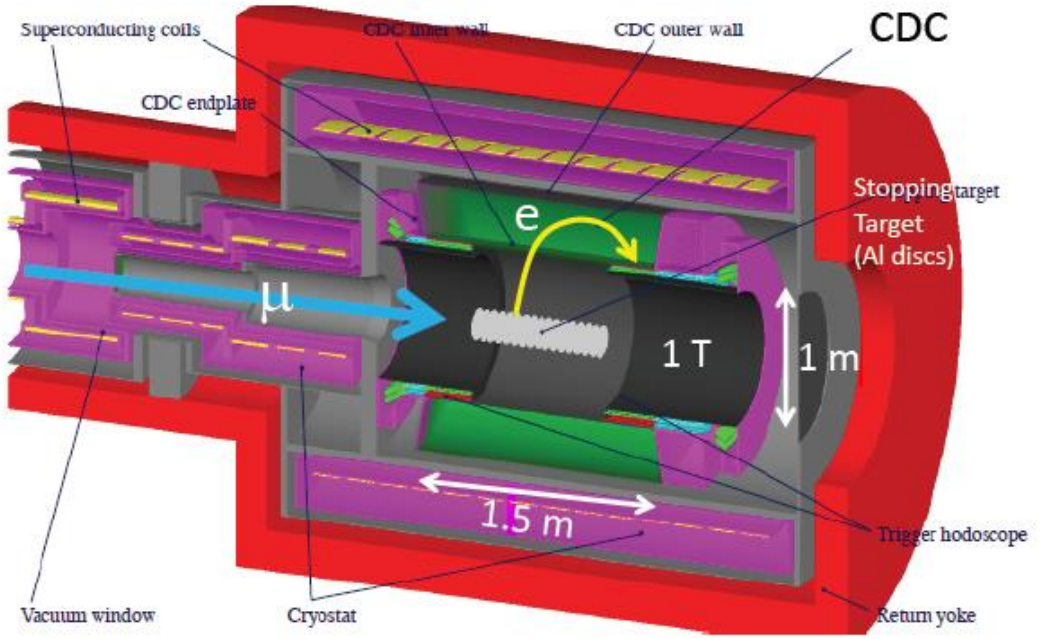
Event selection	Value
Online event selection efficiency	0.9
DAQ efficiency	0.9
Track finding efficiency	0.99
Geometrical acceptance + Track quality cuts	0.18
Momentum window ($\varepsilon_{\mathrm{mom}}$)	0.93
Timing window ($\varepsilon_{\mathrm{time}}$)	0.3
Total	0.041

Parameter	Phase-I	Phase-II
Bending	90^0 (beam)+0^0(detector)	180^0 (beam)+180^0(detector)
Beam power	3.2 kW (8 GeV)	56 kW (8 GeV)
Running time	$9.5 \cdot 10^6$ sec	$2 \cdot 10^7$ sec
POT	$3.2 \cdot 10^{19}$	$8.5 \cdot 10^{20}$
Stopped muons on target	$1.5 \cdot 10^{16}$	$2 \cdot 10^{18}$
S.E.S.	$3.1 \cdot 10^{-15}$	$2.6 \cdot 10^{-17}$

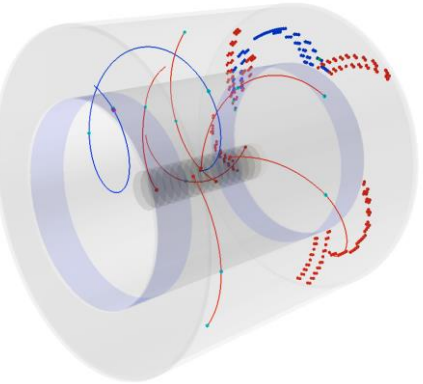
Cylindrical Detector (CyDet)

Specially designed for Phase-I. Consists of:

- Cylindrical trigger hodoscope (CTH):
  - Two layers: plastic scintillator for trigger time and Cerenkov counter for PID.
  - Finemesh PMT readout
  - 4-fold coincidence trigger
- Cylindrical drift chamber (CDC):
  - 20 stereo layers: z information with few layers' hits
  - Helium based gas: minimize multiple scattering.
  - Large inner bore: to avoid beam flash and DIO electrons.
  - Momentum resolution: 200 keV/c (for p=105 MeV/c)
- Stopping target
  - Aluminum target with 17 disks
  - 100-mm radius, 0.2-mm thickness, 50-mm spacing.



Aluminum target disks



Monte Carlo study of COMET Phase-I

- The optimization of COMET Phase I is finished. Detailed performance is estimated with Monte Carlo studies. TDR was published on arXiv (arXiv:1812.09018 [physics.ins-det])
- Sensitivity:
  - Total acceptance of signal is 0.041.
  - Can reach $\mathbf{3 \times 10^{-15}}$ SES in 150 days.

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

$$B(\mu^- + Al \to e^- + Al) = 3 \times 10^{-15} \quad (\mathrm{S.E.S})$$
$$B(\mu^- + Al \to e^- + Al) < 7 \times 10^{-15} \quad (90\% C.L.)$$

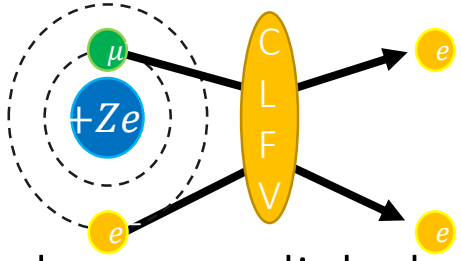
- Background:
  - With 99.99% CRV total expected BG is 0.032
- Trigger rate:
  - Average trigger rate ~10kHz (after trigger with drift chamber hits)

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.

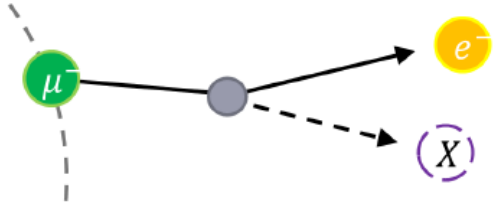
Other Physics Topics on COMET

- $\mu^- N_Z \rightarrow e^+ N_{Z\text{-}2}$: Lepton number violation (LNV)
  - Current limits: $\mu^- Ti \rightarrow e^+ Ca(gs) \leq 1.7 \times 10^{-12}$ Phys. Lett. B422 (1998)
    $\mu^- Ti \rightarrow e^+ Ca(ex) \leq 3.6 \times 10^{-12}$ Phys. Lett. B764 (2017)
  - Can improve with a proper target Phys. Rev. D96 (2017)
- $\mu^- e^- \rightarrow e^- e^-$: μ^- and e^- overlap proportional to Z^3



Phys. Rev. Lett. 105 (2010)
Phys. Rev. D93 (2016) 076006
Phys. Rev. D97 (2018) 015017

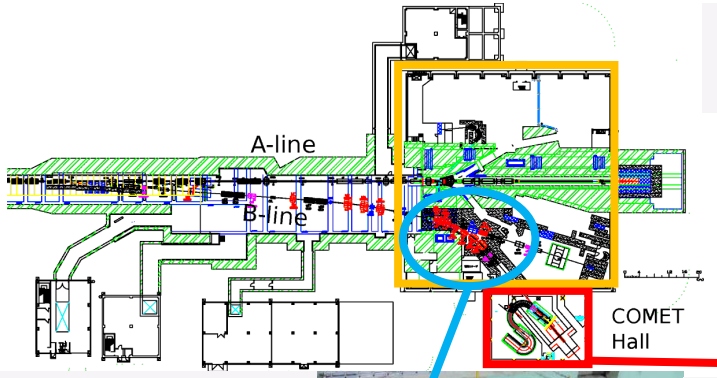
- $\mu^- \rightarrow e^- X$: X can be a new light boson, axion, etc.
  - feasibility being studied in COMET



Phys. Rev. D79. 055023 (2009)
Phys. Rev. D84. 113010 (2011)

Current Status of the COMET

COMET Facility



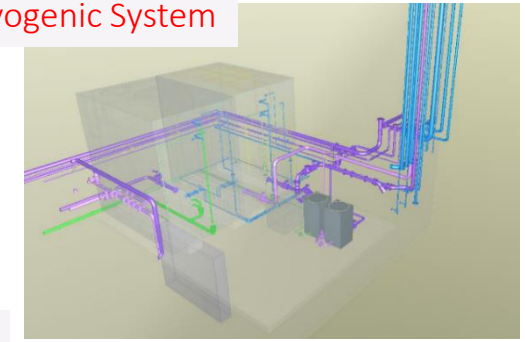
COMET Experimental Hall
Constructed in 2015

Installation Yard in 2015

Beam separation
Wall completed in 2018

Experiment Room in 2019

Cryogenic System

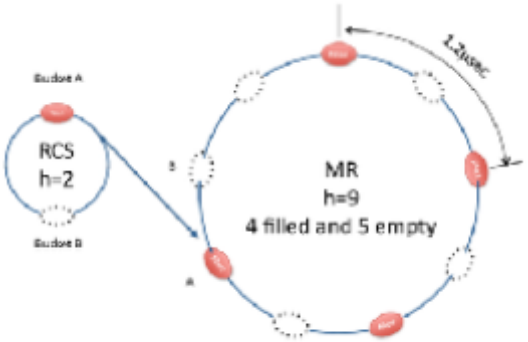


2 magnets will be moved to Hadron Hall

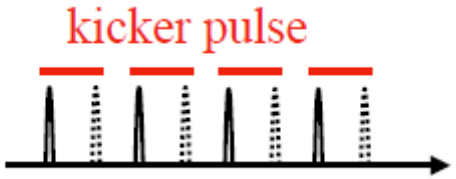
- Experimental Hall building completed
- Cryogenic system under construction
- Proton beamline will be ready this year
  - Shield wall & power station completed. 2 more magnets to be located soon.

Proton beam from J-PARC MR

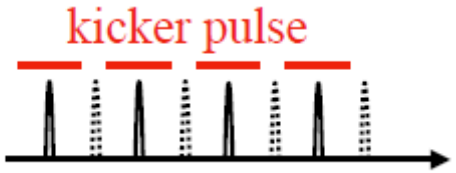
- To make the proton extinction factor $< 10^{-10}$
  - Shift the kicker phase by half period to avoid residual protons in the empty bucket.



Normal

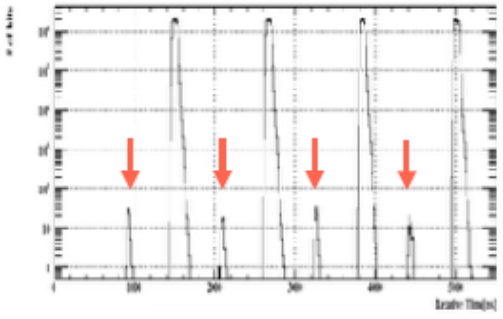


COMET shift kicker timing

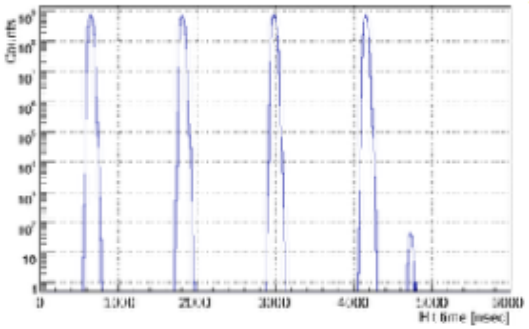


- Measurement at Hadron Hall MR using 8 GeV proton beam, Slow extraction

Normal

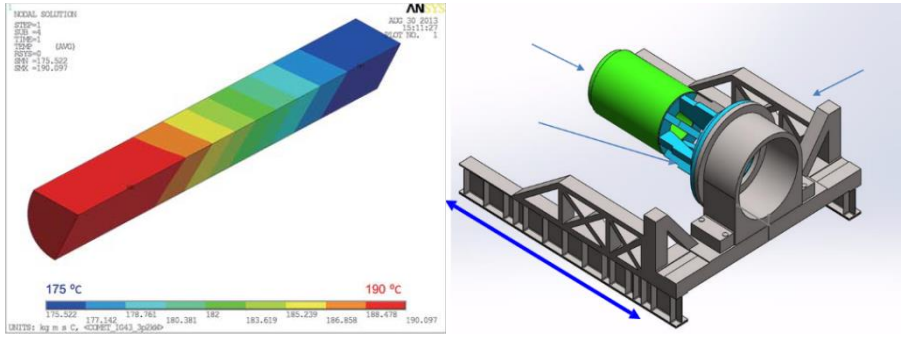


shift kicker by 600 nsec (half bunch)

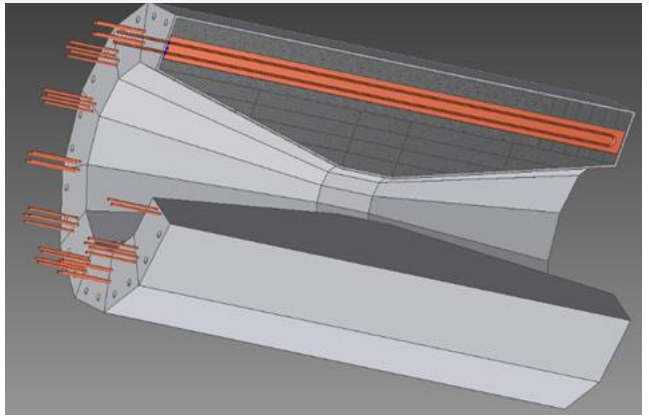


Extinction factor
$< 6\times10^{-11}$ achievable

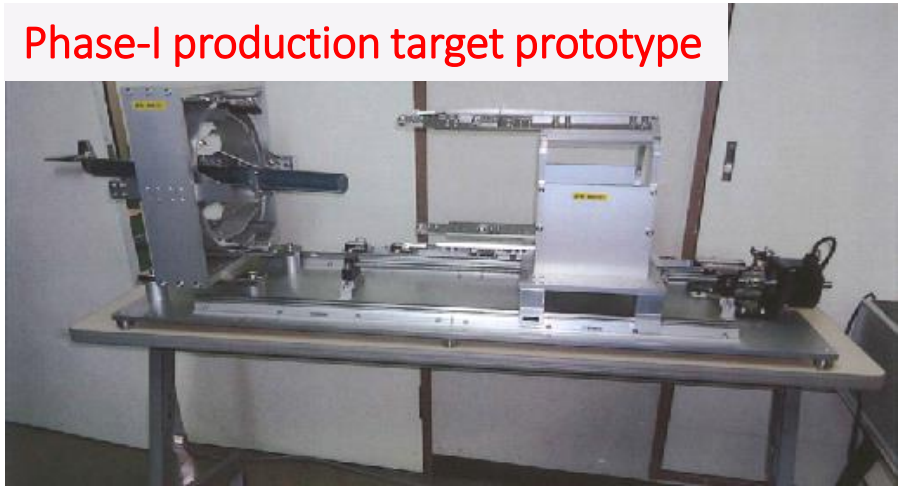
Production Target System



Tungsten shielding with water cooling

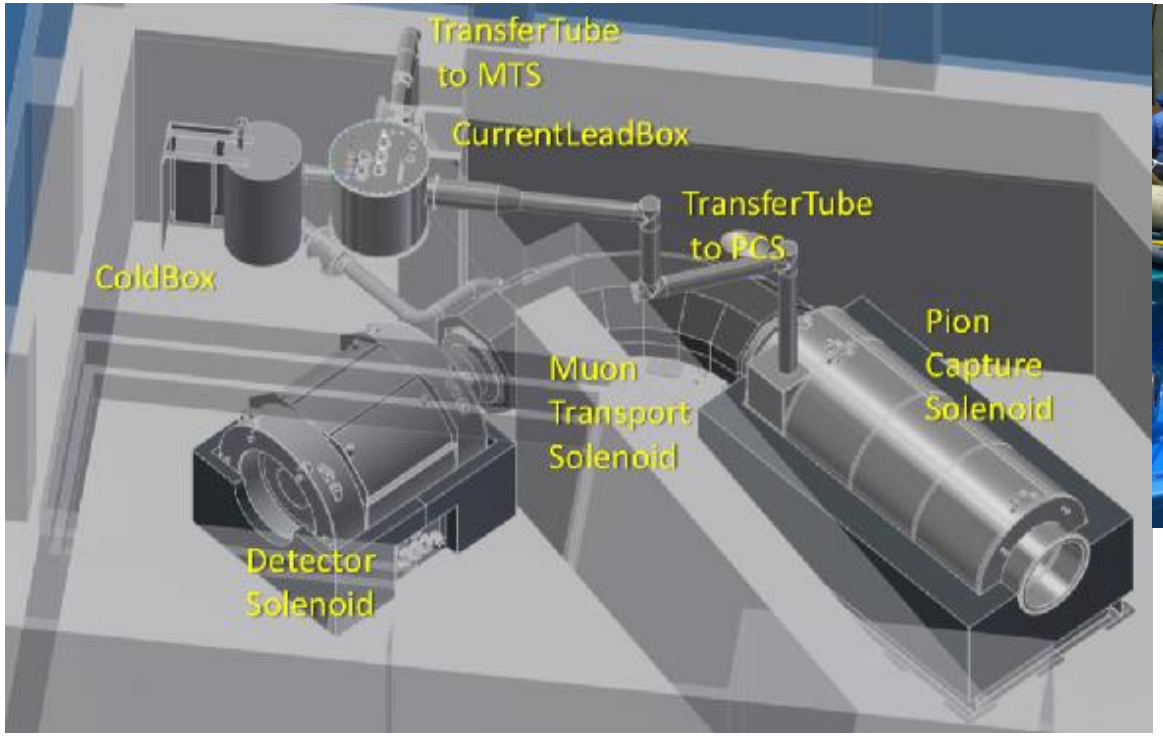


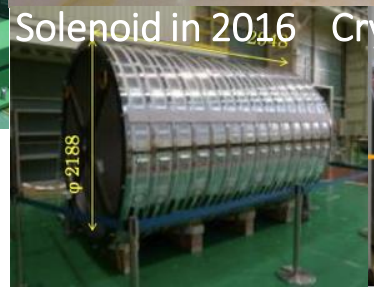
Phase-I production target prototype



- Phase-I graphite target (IG-43) can be cooled under radiation with 3.2 kW beam.
- Remote handling and cask design of target is in progress.
- Shielding blocked with water cooling is being designed.

Solenoids



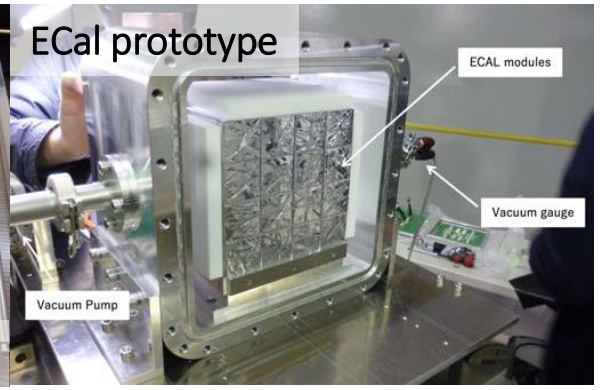


- Capture solenoid
  - Last coil under winding.
- Transport solenoid
  - Installed and ready for cryogenic test.
- Bridge & detector solenoid
  - DS coil and cryostat ready. BS coil delivered.
- Cryogenic system:
  - Refrigerator test completed.
  - Helium transfer tube in production.

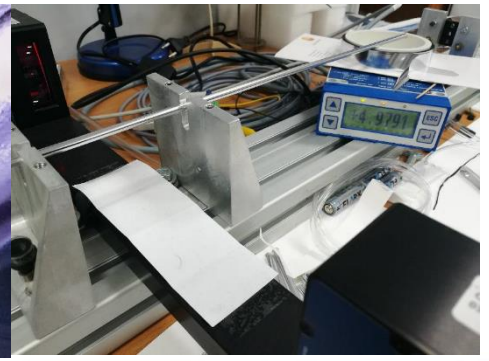
StrEcal

- Straw tube detector
  - Finished vacuum test with 20 um straw tubes.
  - Mass production for Phase-I finished.
  - Tested with 100 MeV electron beam. 150 um spatial resolution achieved.

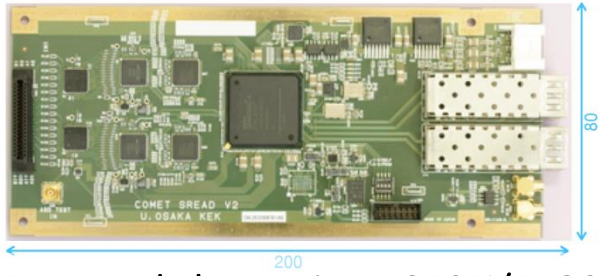
Straw tube prototype



- R&D of Straw tube
- 12 micro meter thin straw produced for Phase-II!
- Diameter 5 mm
  - 1 bar overpressure straw tube diameter measurement shows 0.1 um accuracy.
- Over pressurization test holding more then 4 bar



- 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.

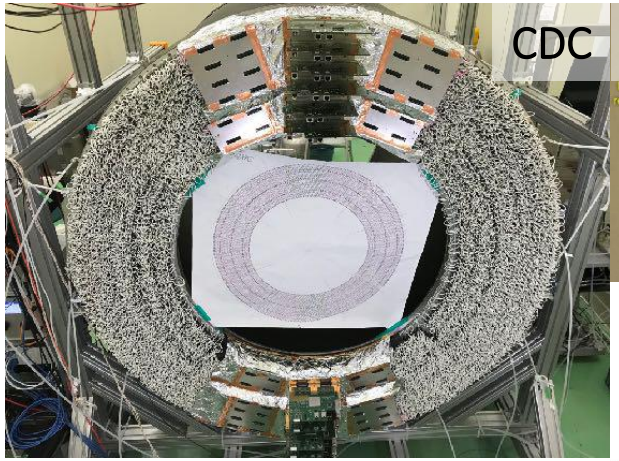


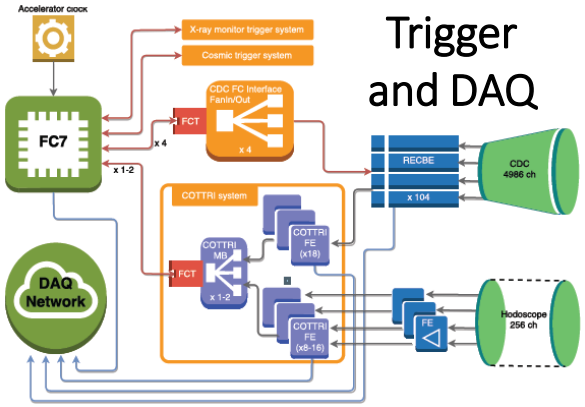
Front end electronics: ROESTI/EROS

CyDet (Phase-I)

- Cylindrical Drift chamber (CDC)
  - Prototype tests finished in 2015. 150 um 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.

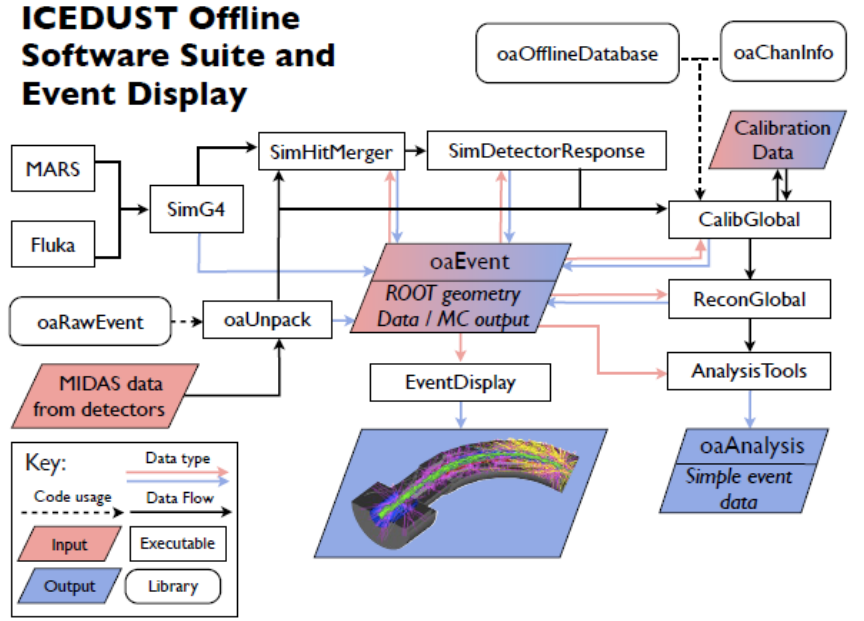




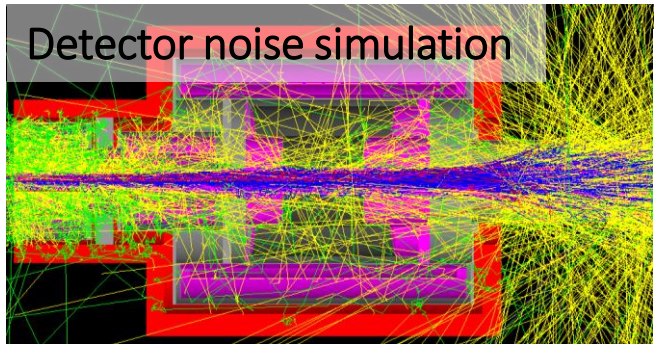
Trigger and DAQ

Software

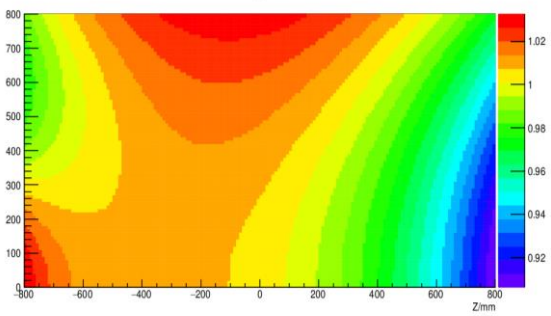
- Development of frame “ICEDUST”
  - Based on ND280 framework
  - Almost ready, still being implemented more
- Optimizing design using MC simulation
  - Simulation of production target, translation, magnetic field, collimator, stopping target, detector shield ……
  - Mass MC events generation is ongoing for more higher statistic study



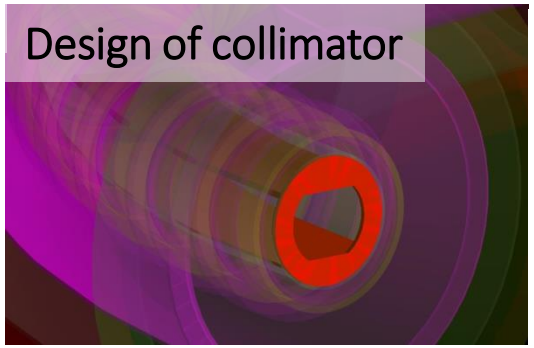
Detector noise simulation



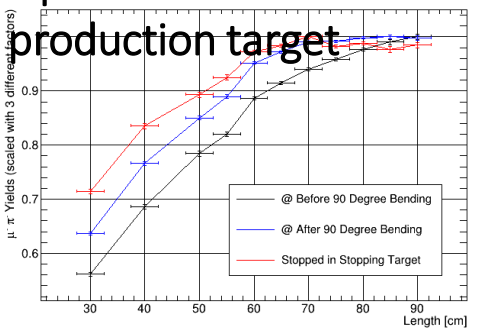
Calculation of magnetic field



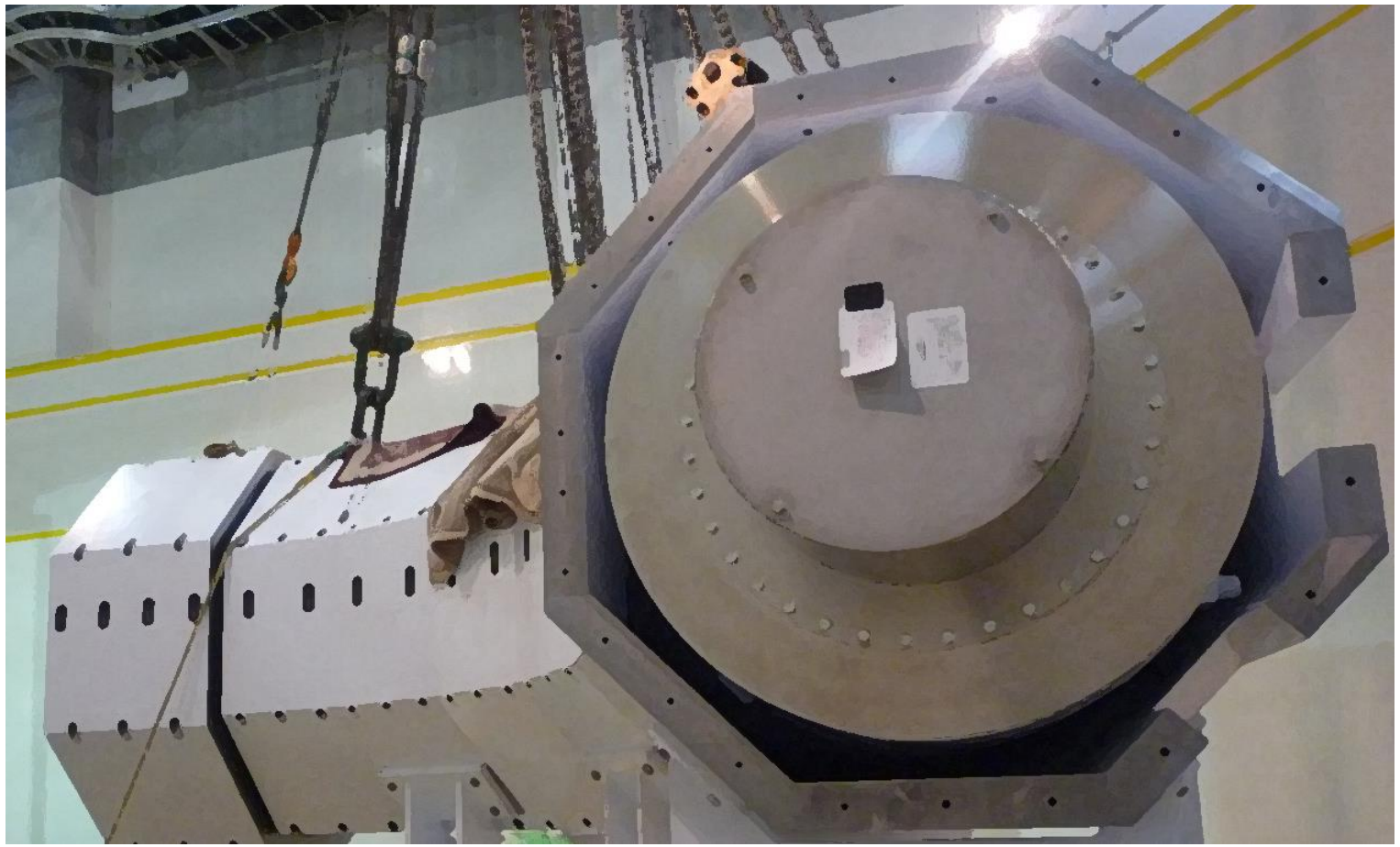
Design of collimator



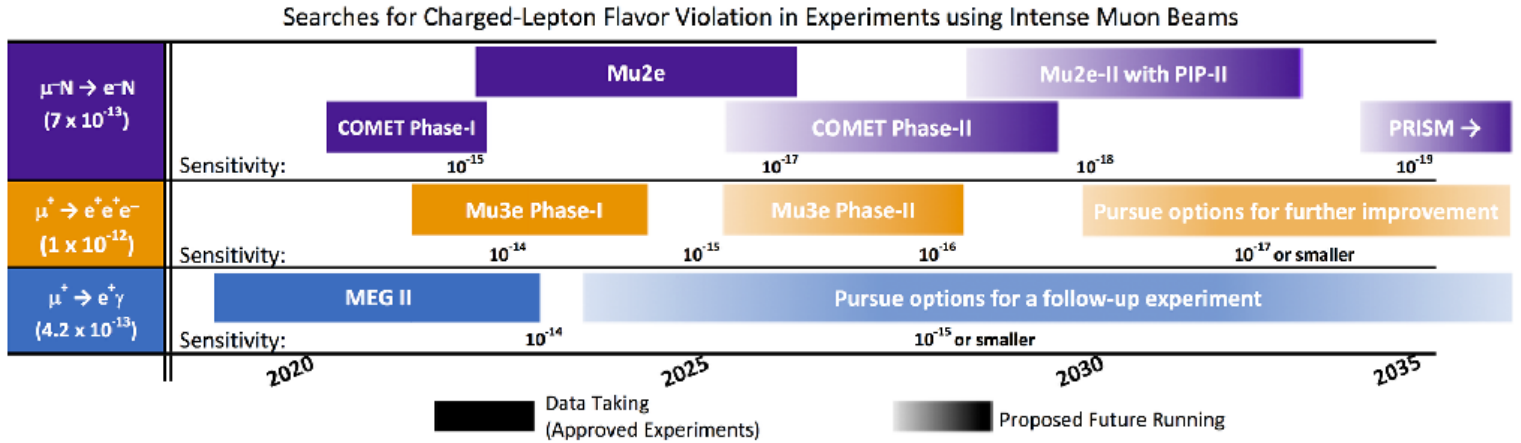
Optimization of production target



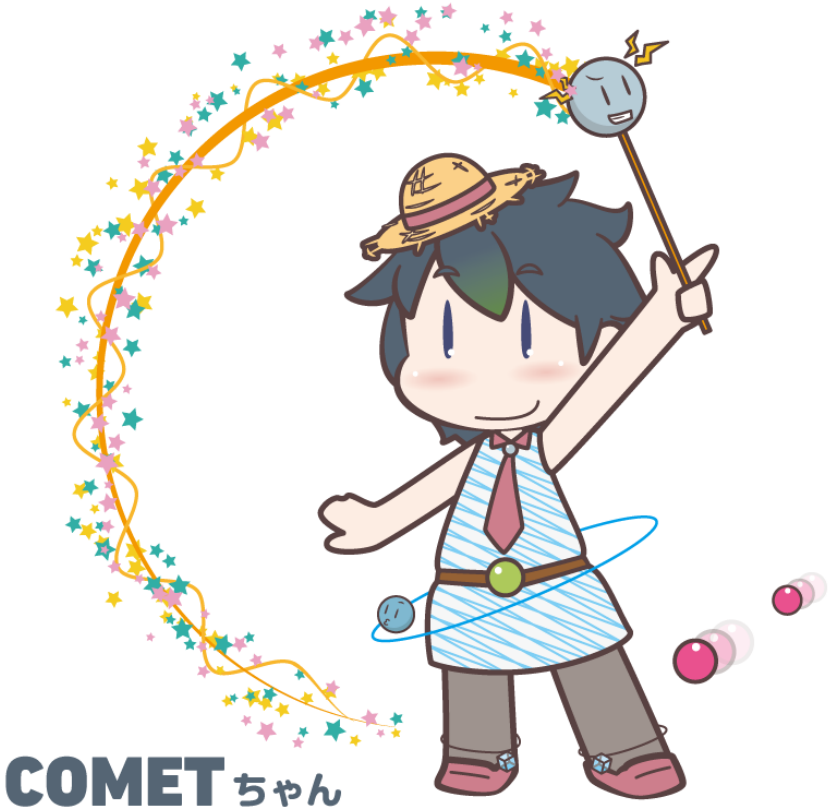
Summary



- COMET is an experiment at J-PARC searching for muon to electron process.
  - Aims at S.E.S = 2.6×10^{-17} (4 orders of magnitude improvement) with 1 year beam time using 56 kW 8 GeV proton beam.
  - With the same beam power, **10** times better sensitivity ($\mathcal{O}(10^{-18})$) is likely and optimization is on the way.
- COMET will be carried out in two phases and Phase-I is under construction.
  - Aims at S.E.S = 3×10^{-15} (2 orders of magnitude improvement) with 150 days beam time using 3.2 kW 8 GeV proton beam.
  - Will directly measure the muon beam.
- COMET Phase-II R&D study is on going and will be adjusted based on Phase-I result.



Backup



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