Introduction of the COMET Experiment

Zhang Yao

On behalf of the COMET collaboration
Institute of High Energy Physics, CAS

Outline

- cLFV and Muon to electron conversion
- The COMET experiment
- BINP and IHEP group in COMET
- Summary

Charged Lepton Flavor Violation(cLFV)

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.

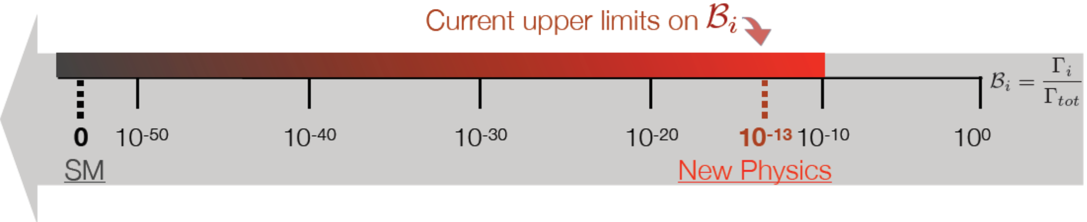
Process of CLFV

- 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

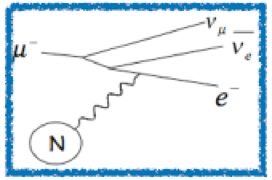
- **No/less background** from SM
- Very rare decays and **not found yet!**
- Clean field to search for new physics!



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

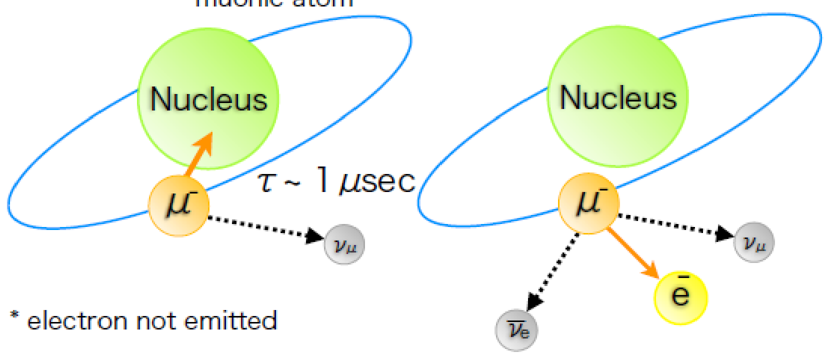
DIO Background



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

Backgrounds in the SM

Muon Capture — Decay In Orbit (DIO)

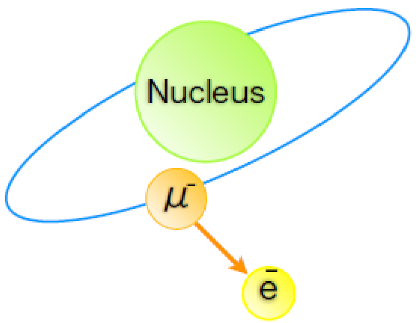


* electron not emitted

$\mu + N \rightarrow \nu_\mu + N$ — $\mu \rightarrow e\ \bar{\nu}_e \nu_\mu$

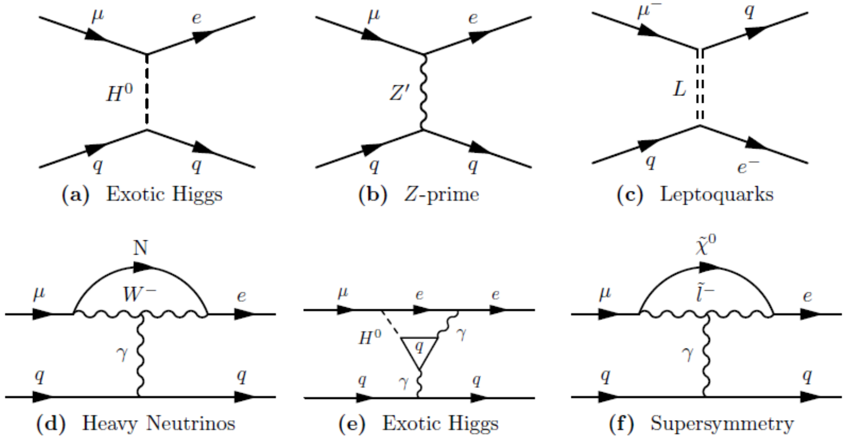
Signal beyond the SM

μ - e conversion

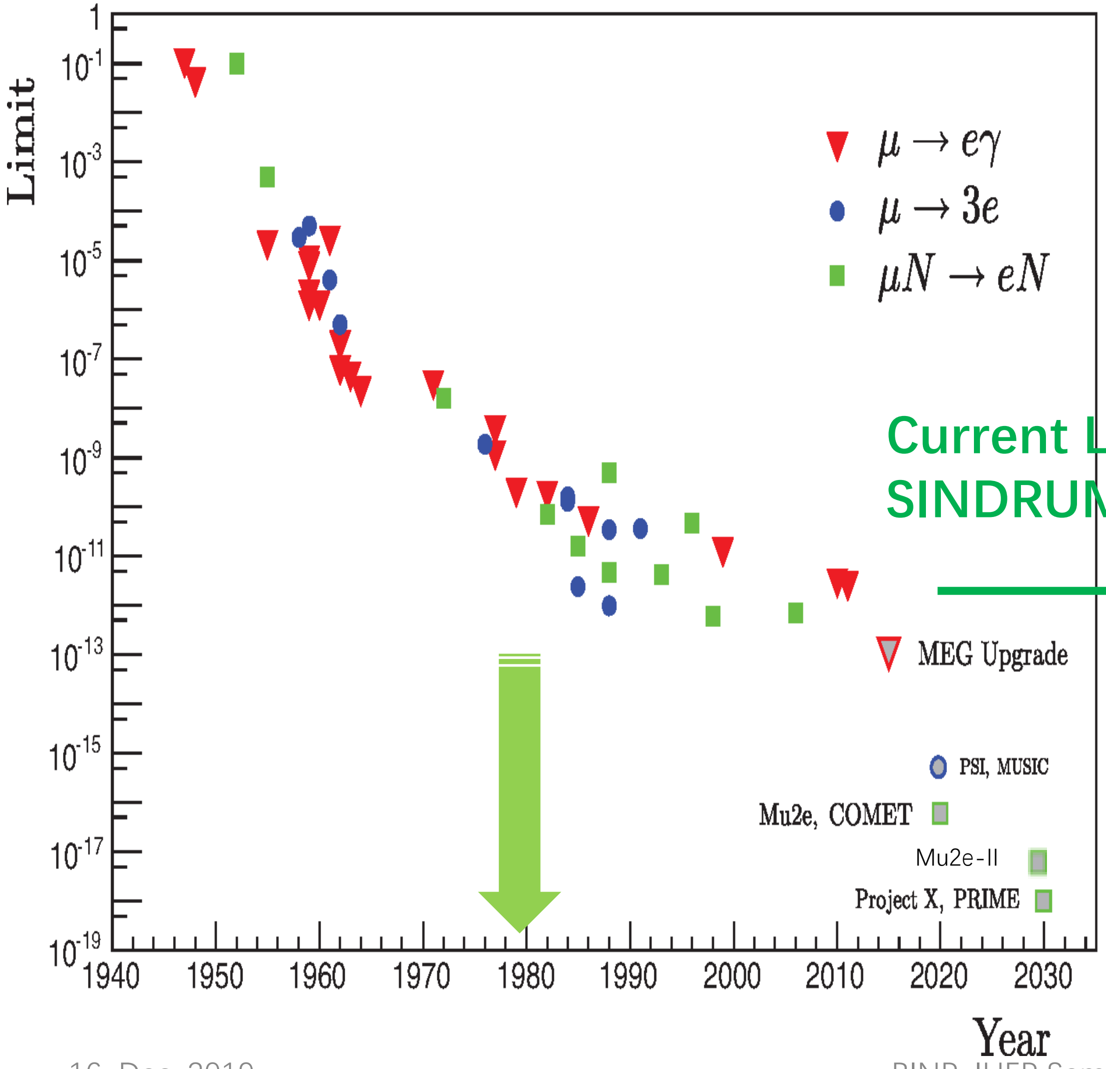


$\mu N \rightarrow e N$

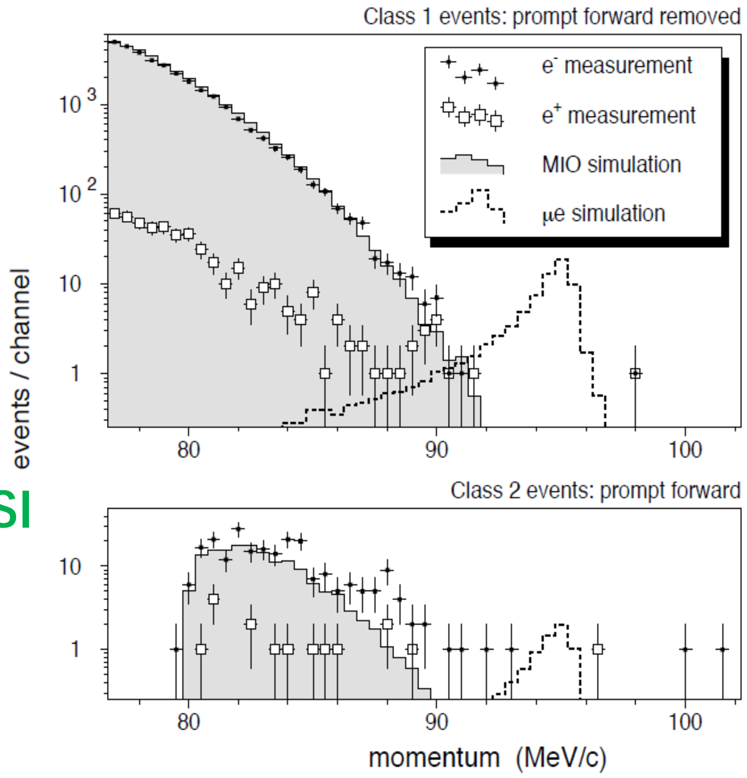
predicted branching ratio
$= 10^{-14} \sim 10^{-18}$



Search for μ - e Conversion



Current Limit by SINDRUMII @ PSI



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

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

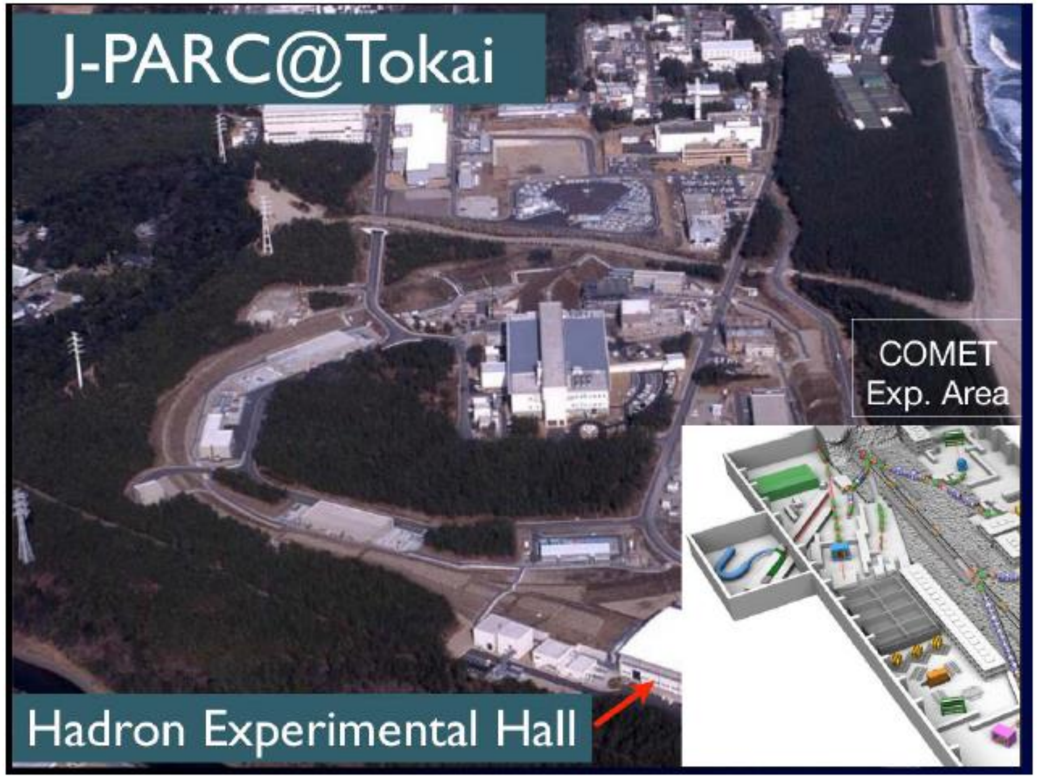
COherent Muon Electron Transition(COMET)

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

- Experiment Target:
  $B(\mu^- + Al \rightarrow e^- + Al) = 2.6\times10^{-17}$ (S.E.S)
- This is **10000 times improvement!**
- Current world limit:
  $B(\mu^- + Au \rightarrow e^- + Au) < 7\times10^{-13}$
  given by SINDRUM II experiment (2006)
- Likely to get 100000 times improvement!
  still being optimized

$$SES = Br(\mu^- + Al \rightarrow e^- + Al) = \frac{1}{N_\mu \cdot f_{cap} \cdot f_{gnd} \cdot A_{\mu-e}}$$

$f_{cap} = 0.61$ (Al), fraction of muon capture
$f_{gnd} = 0.9$ is the fraction of μ−e conversion to the ground state in the final state
$A_{\mu-e} = 0.041$ is the signal acceptance
N_μ is the number of muons stopping in the muon target



The COMET collaboration

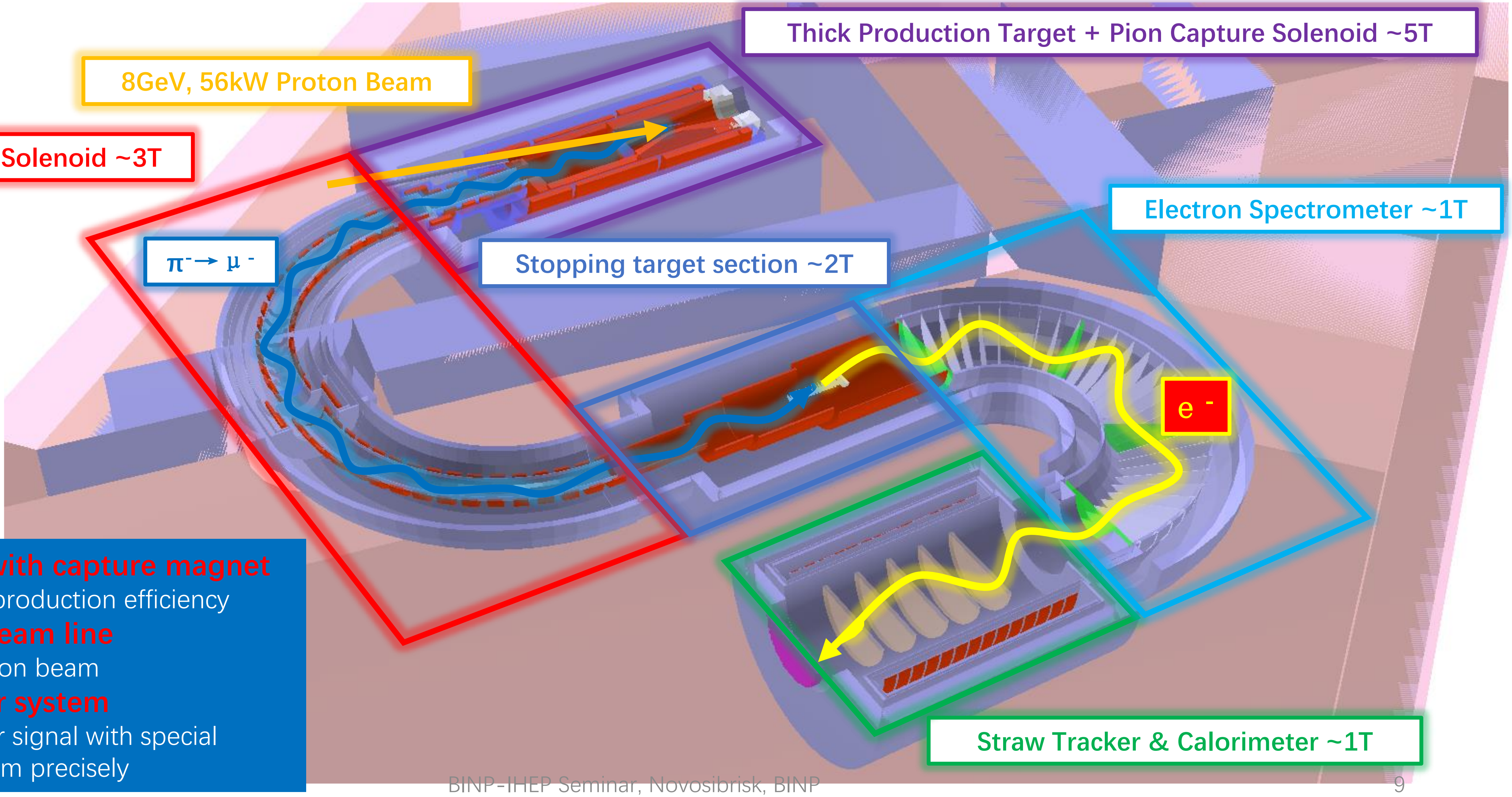
Oct 2018, COMET collaboration at Tbilisi

~200 members,
41 institutes from 17 countries

Still growing!

Design of the COMET

Overview



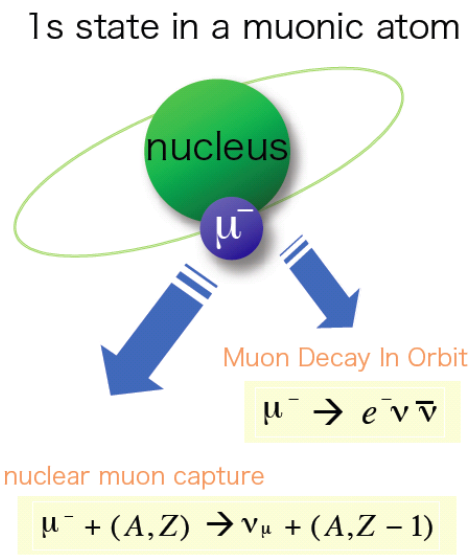
- Thick target with capture magnet
  - Improve production efficiency
- Long muon beam line
  - Clean muon beam
- Light detector system
  - Search for signal with special momentum precisely

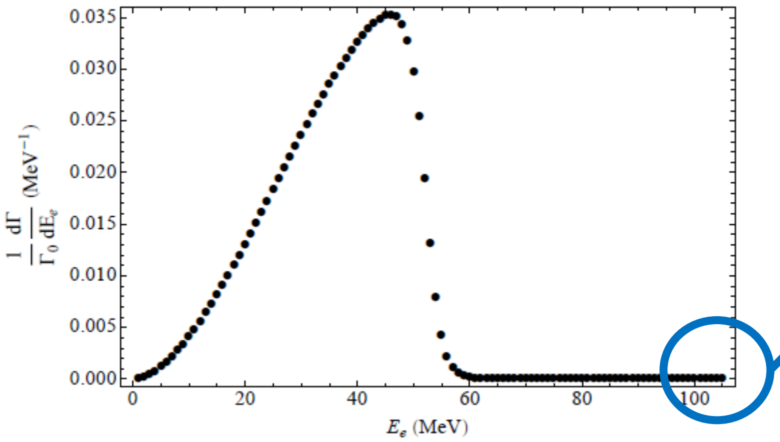
Background rejection (1)

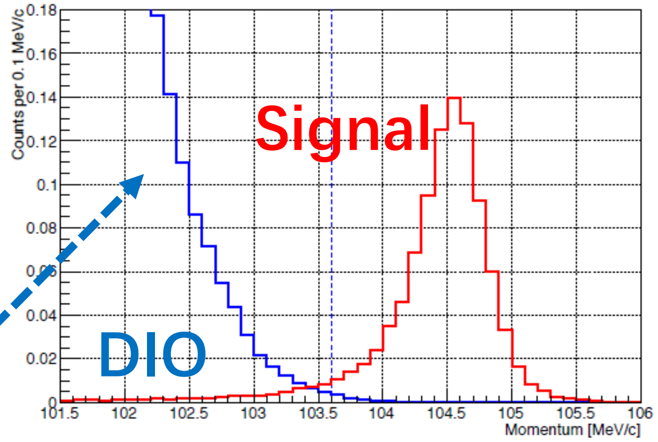
- **Intrinsic physics background**

➢ 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**







Background rejection (2)

- **Beam related background**

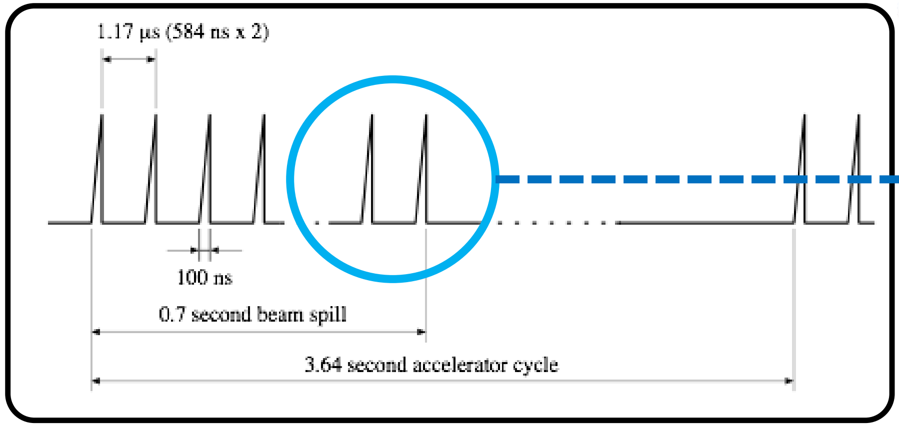
➢ Energetic particles in beam with E>100MeV

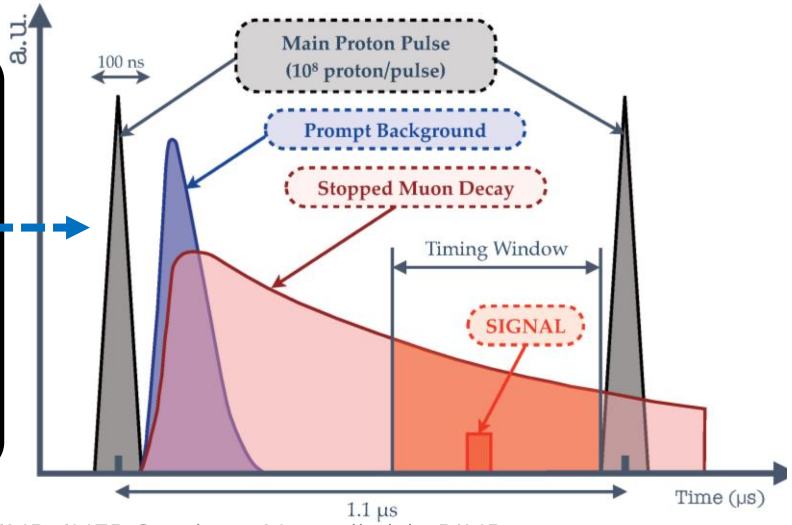
- Radiative pion capture, π^- (A,Z) → (A,Z-1) γ, γ → $e^+ e^-$
- Muon decay in flight, p_μ > 75 MeV/c
- Anti-proton induced, etc.

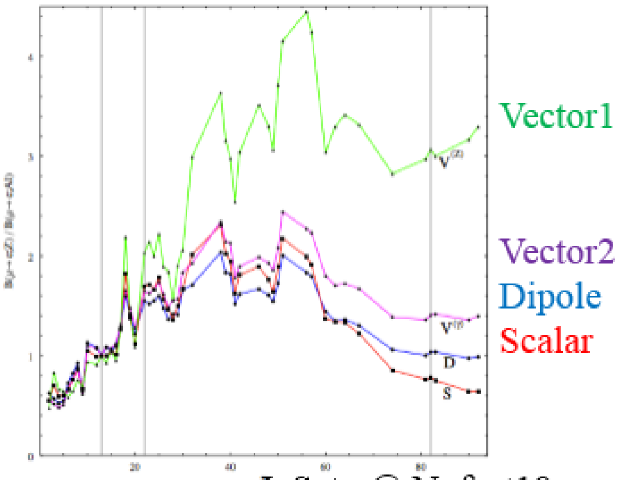
- Long muon beam line
- Can be suppressed by **pulse beam** and a **delayed measurement window (~700 ns)**
- Some due to leaked proton. Proton extinction factor required to be < 10^{-10}

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



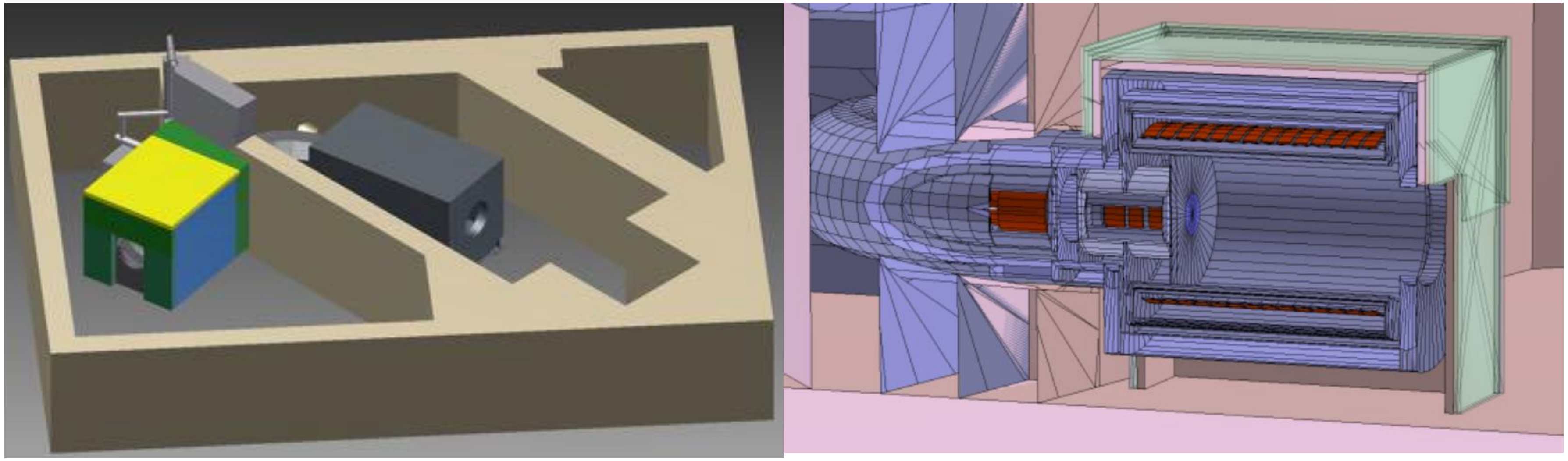




J. Sato @ Nufact18

Background rejection (3)

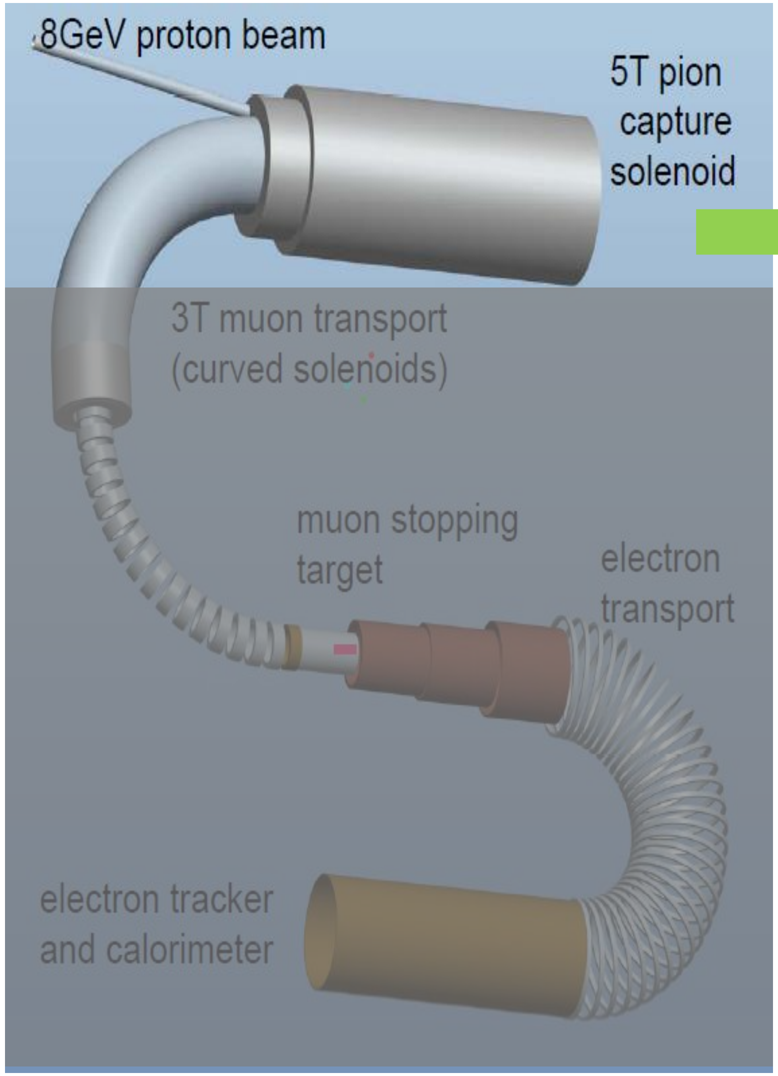
- Cosmic ray background

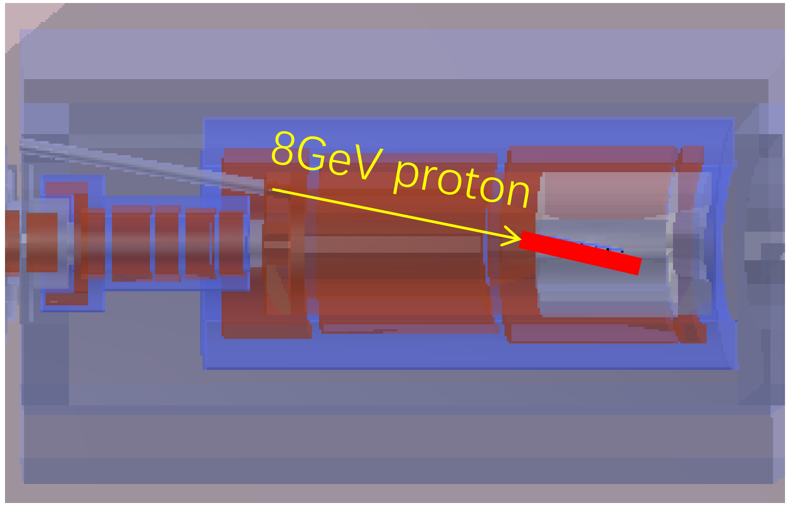


➢ Cosmic rays may create e^- in signal region that come into a detector and make trigger.

- 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)

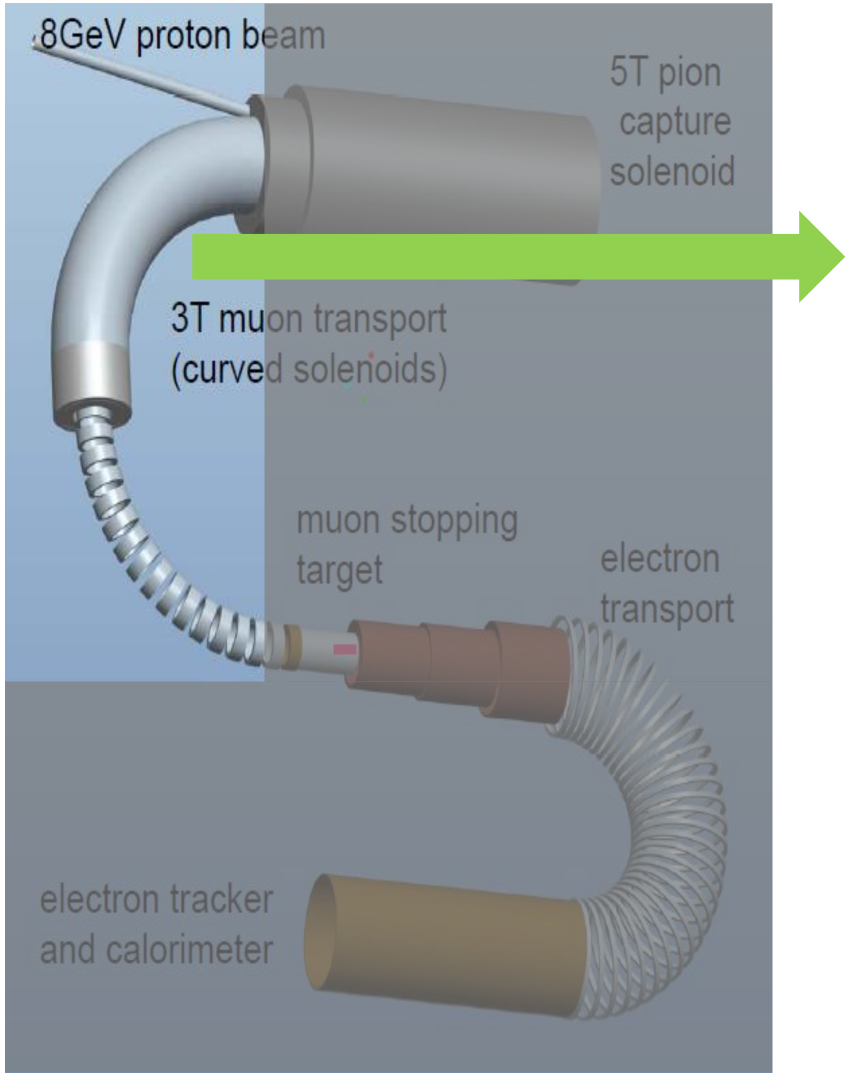
Production target and the capture magnet



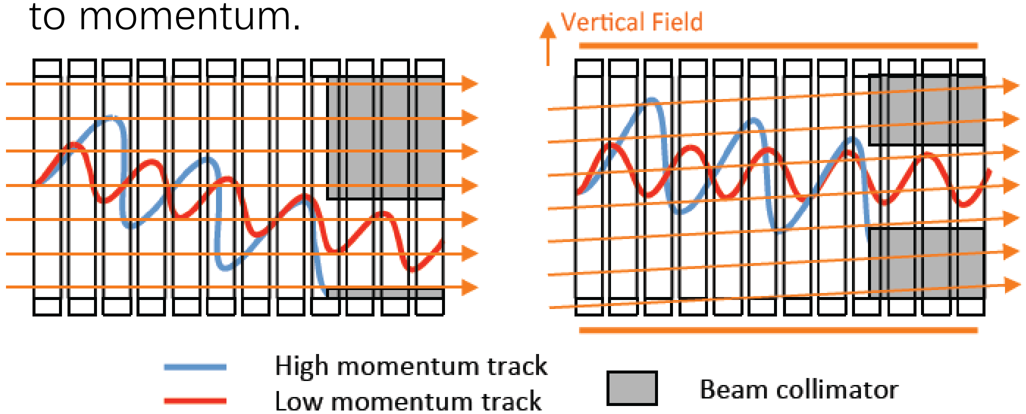


- 8 GeV 56 kW proton beam
- Thick target with 1~2 hadron interaction length
- Powerful capture magnet: 5 T
  - Large inner bore to fit in the shielding
  - Adiabatic decreasing field: focusing and mirroring
- Expected muon yield: 10^{11} muon/sec! $(10^8\ @\ PSI)$

Transportation solenoid

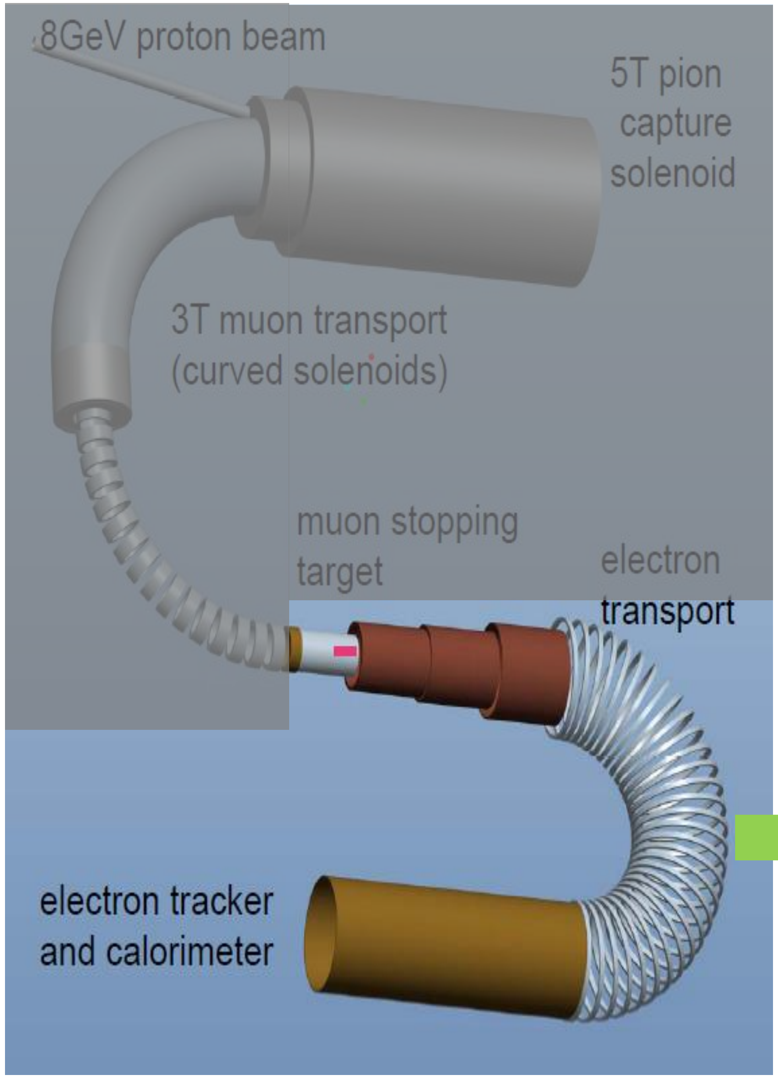


Drift vertically, proportional Vertical field as "correction" to momentum.

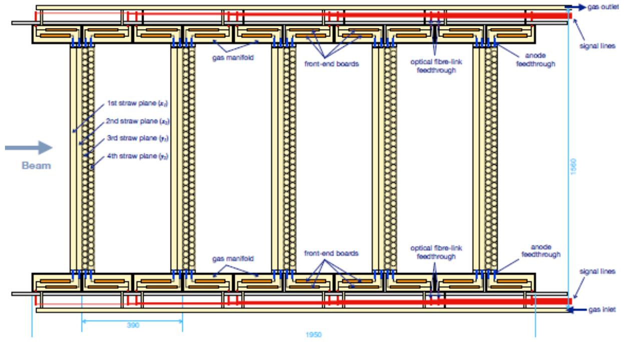


- Use **C shape** curved solenoid
  - Beam gradually disperses
    - Charge & momentum
  - Dipole field to pull back muon beam
    - Can be used to tune the beam
  - Collimator placed in the end
    - Utilize the dispersion in 180 degrees

Stopping target and detector system

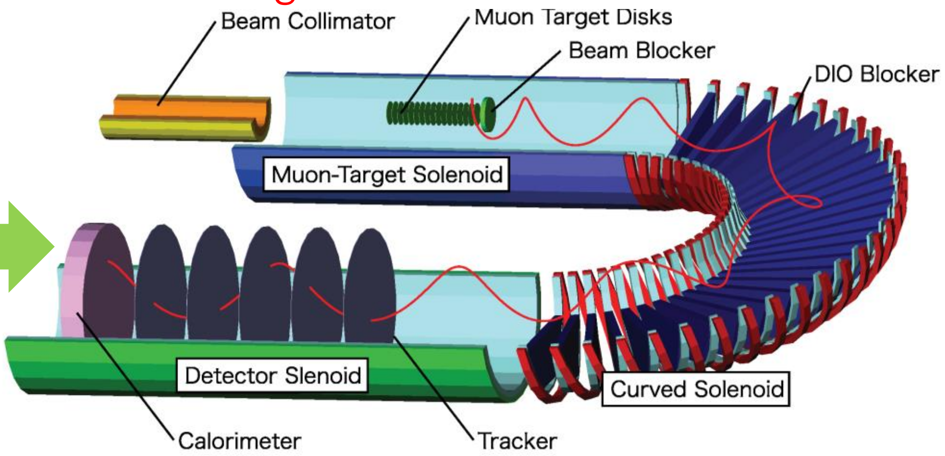


- Use straw tracker to measure the momentum
  - Really light: put in vacuum, **12 micro** meter thin



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



- 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

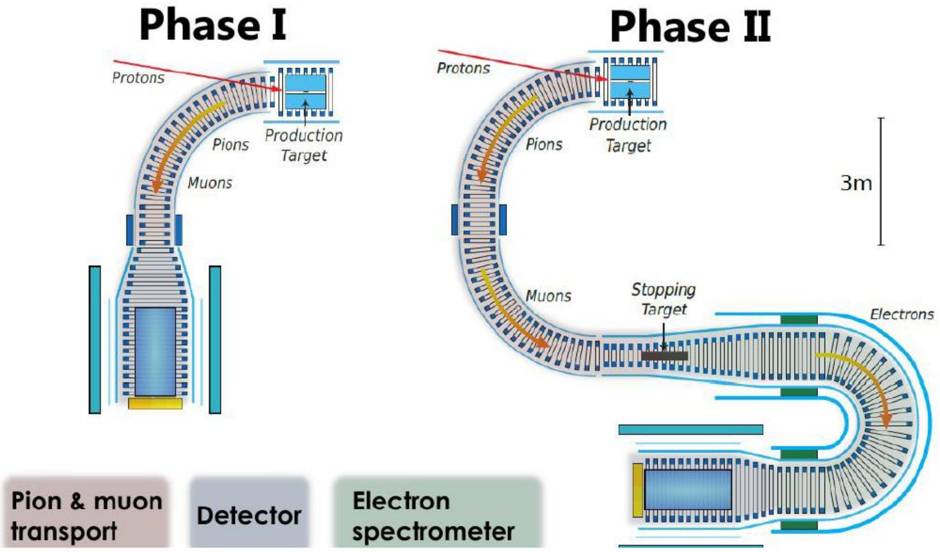
Event selection	Value
Online event selection efficiency	0.9
DAQ efficiency	0.9
Track finding efficiency	0.99
Geometrical acceptance + Track quality cuts	0.18
Momentum window (ε_{mom})	0.93
Timing window ($\varepsilon_{\text{time}}$)	0.3
Total	0.041

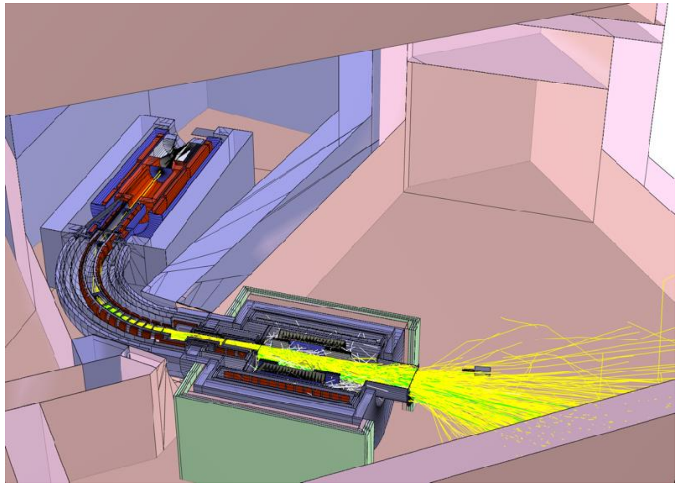
Parameter	Phase-I	Phase-II
Bending	90^0 (beam)+0^0(detector)	180^0 (beam)+180^0(detector)
Beam power	3.2 kW (8 GeV)	56 kW (8 GeV)
Running time	$9.5 \cdot 10^6$ sec	$2 \cdot 10^7$ sec
POT	$3.2 \cdot 10^{19}$	$8.5 \cdot 10^{20}$
Stopped muons on target	$1.5 \cdot 10^{16}$	$2 \cdot 10^{18}$
S.E.S.	$3.1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

Staged plan of COMET

COMET Phase-I, 5 months data taking
Proton beam: 8 GeV, 0.4 mA, 3.2 kW

- Search for $\mu - e$ conversion 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

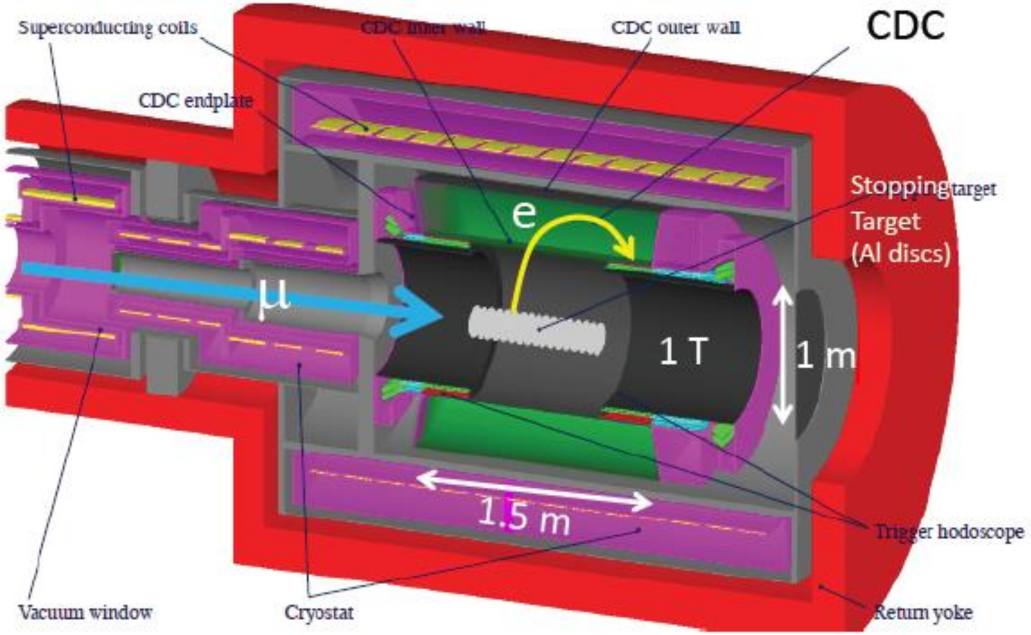




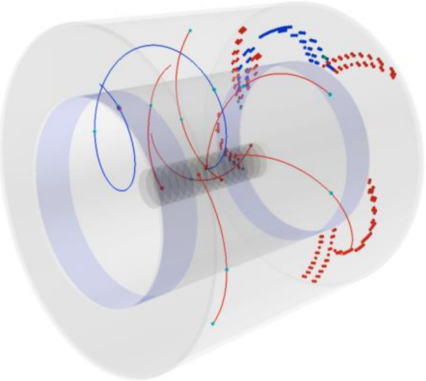
Cylindrical Detector (CyDet) for Phase-I

Specially designed for Phase-I. Consists of:

- Cylindrical trigger hodoscope (CTH):
  - Two layers: plastic scintillator for trigger time ar Cerenkov counter for PID.
  - Finemesh PMT readout
  - 4-fold coincidence trigger
- Cylindrical drift chamber (CDC):
  - 20 stereo layers: z information with few layers' h
  - 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 **3×10^{-15} SES in 150 days**.

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

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

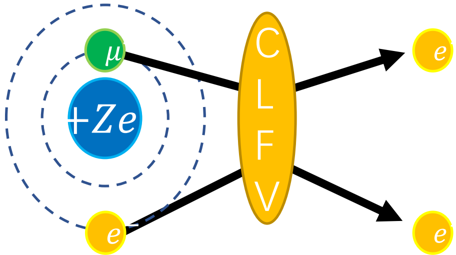
- Background:
  - With 99.99% CRV total expected BG is 0.032
- Trigger rate:
  - Average trigger rate ~10kHz (after trigger with drift chamber hits)

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.

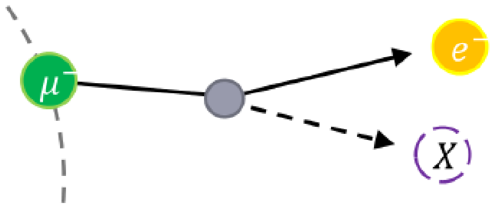
Other Physics Topics on COMET

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



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

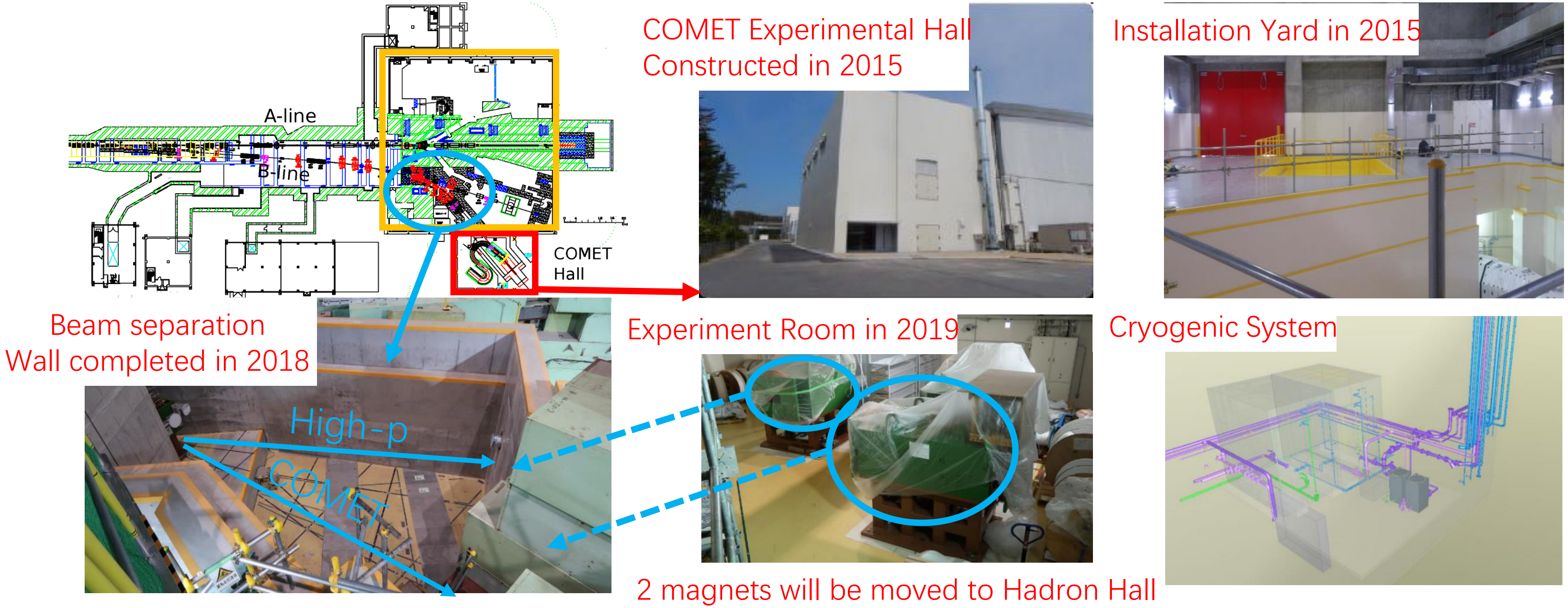
- $\mu^- \to e^- X$: X can be a new light boson, axion, etc.
  - feasibility being studied in COMET



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

Current Status of the COMET

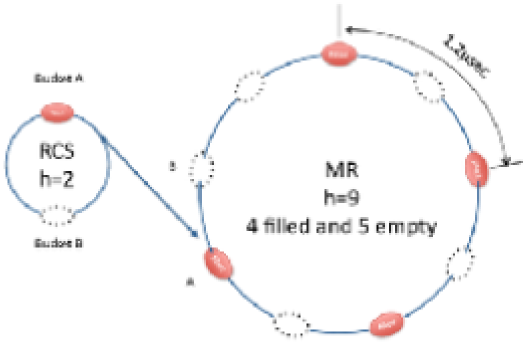
COMET Facility

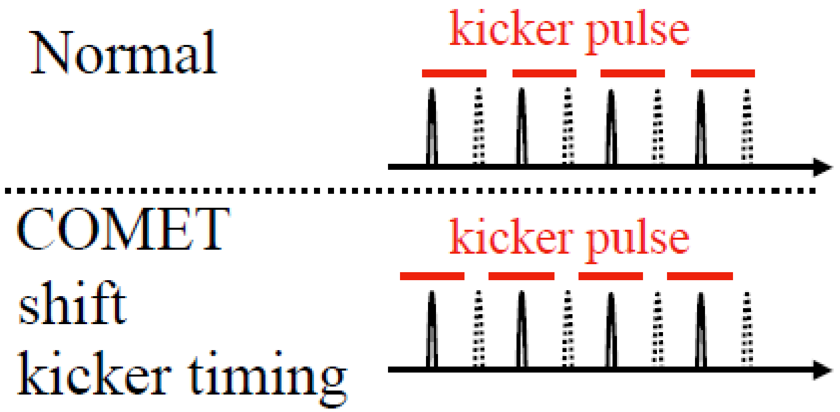


- Experimental Hall building completed
- Cryogenic system under construction
- Proton beamline will be ready this year
  - Shield wall & power station completed. 2 more magnets to be located soon.

Proton beam from J-PARC MR

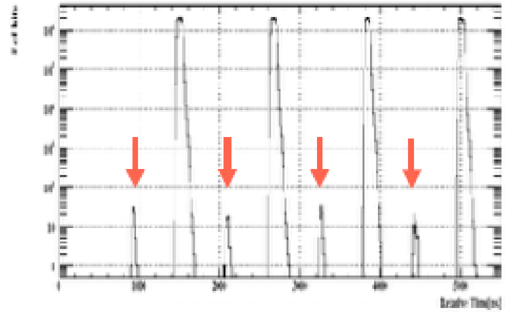
- To make the proton extinction factor $< 10^{-10}$
  - Shift the kicker phase by half period to avoid residual protons in the empty bucket



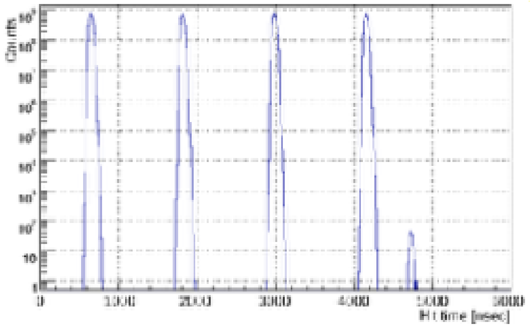


- Measurement at Hadron Hall MR using 8 GeV proton beam, Slow extraction

Normal

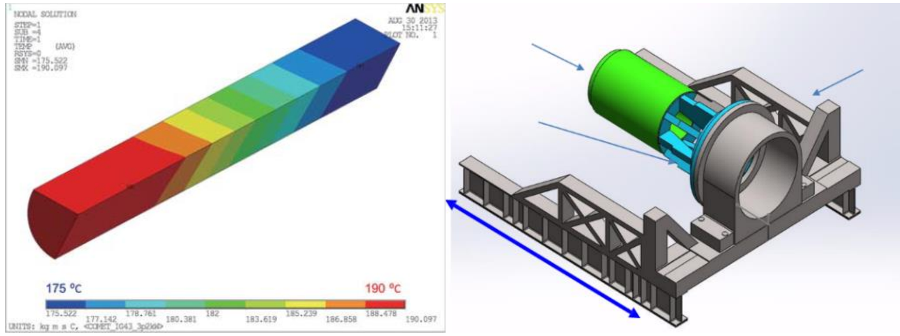


shift kicker
by 600 nsec
(half bunch)

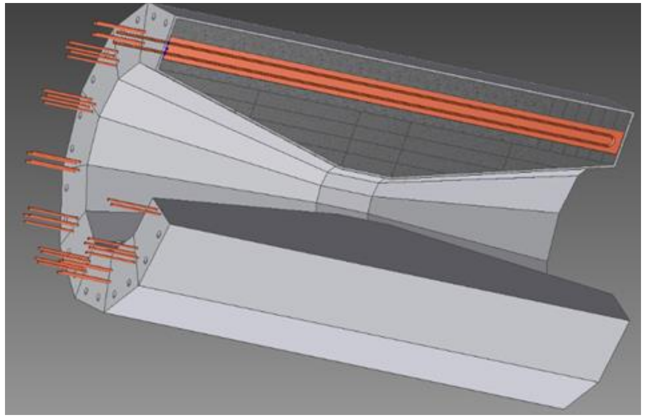


Extinction factor $< 6\times10^{-11}$ achievable

Production Target System



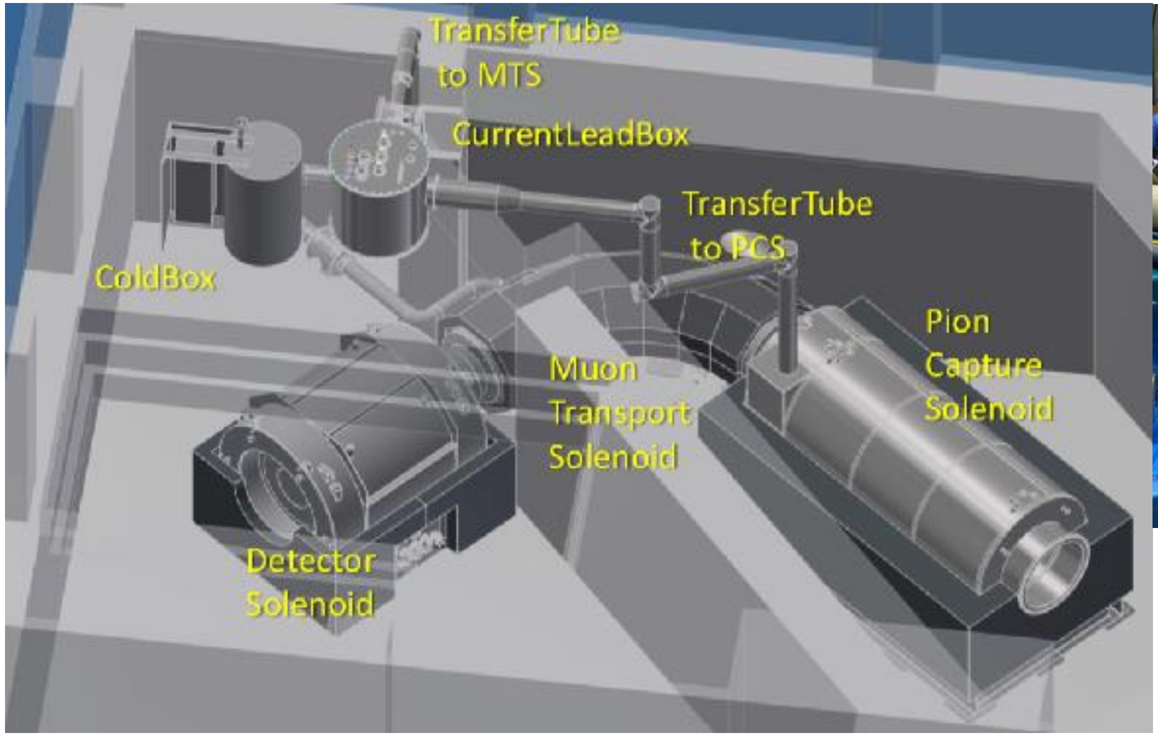
Tungsten shielding with water cooling

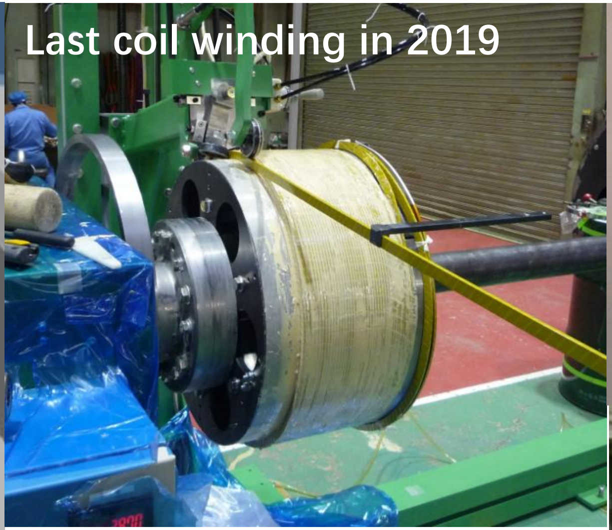


Phase-I production target prototype

- 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



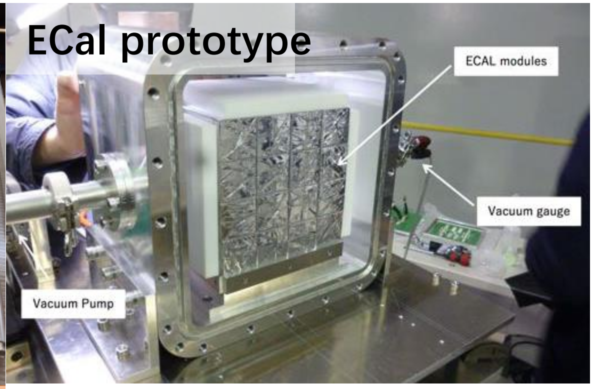


- Capture solenoid
  - Last coil under winding.
- Transport solenoid
  - Installed and ready for cryogenic test.

- Bridge & detector solenoid
  - DS coil and cryostat ready. BS coil delivered.
- Cryogenic system:
  - Refrigerator test completed.
  - Helium transfer tube in production.

StrEcal

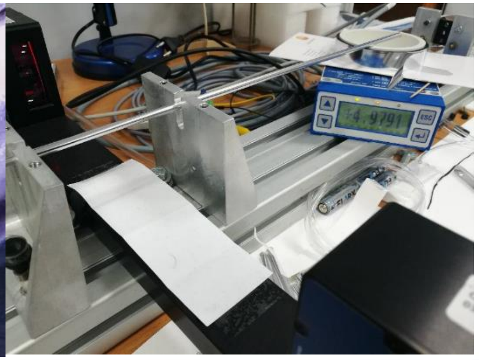
- Straw tube detector
  - Finished vacuum test with 20 um straw tubes.
  - Mass production for Phase-I finished.
  - Tested with 100 MeV electron beam. 150 um spatial resolution achieved.



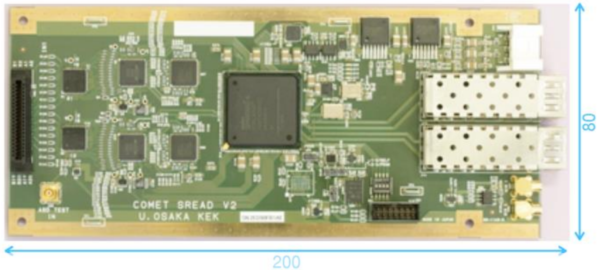
ECal prototype

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



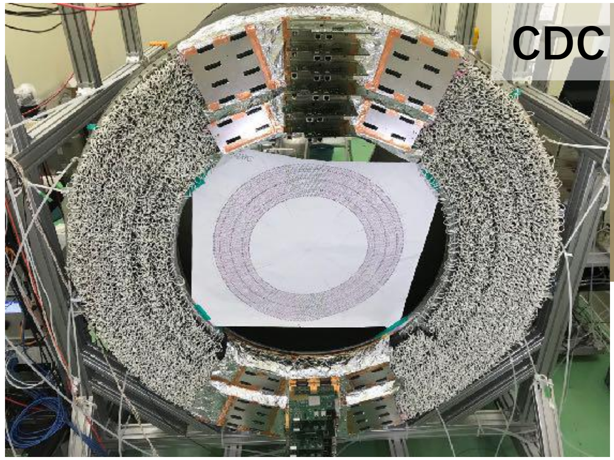
- Electromagnetic calorimeter
  Tested GSO and LYSO. Preliminary resolutions are 5.7% and 4.6% for each. LYSO chosen as final option.
- Front end electronics
  Finished designing (ROESTI/EROS) based on DRS4 with GHz sampling rate. Radiation tests results published.

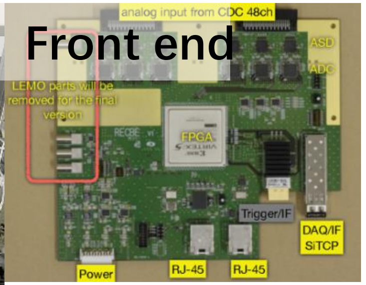


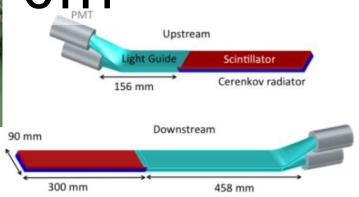
Front end electronics: ROESTI/EROS

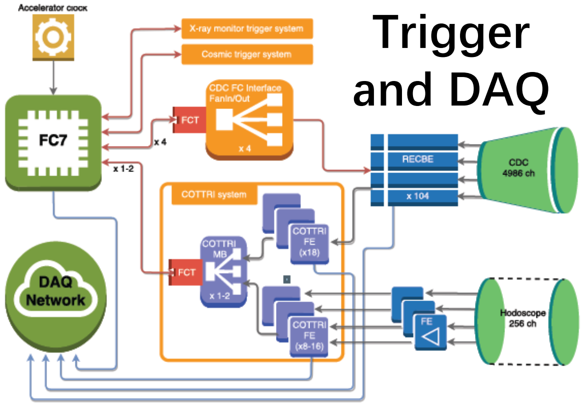
CyDet (Phase-I)

- 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.





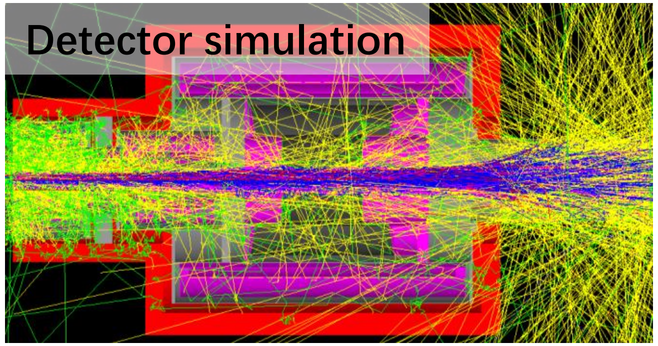


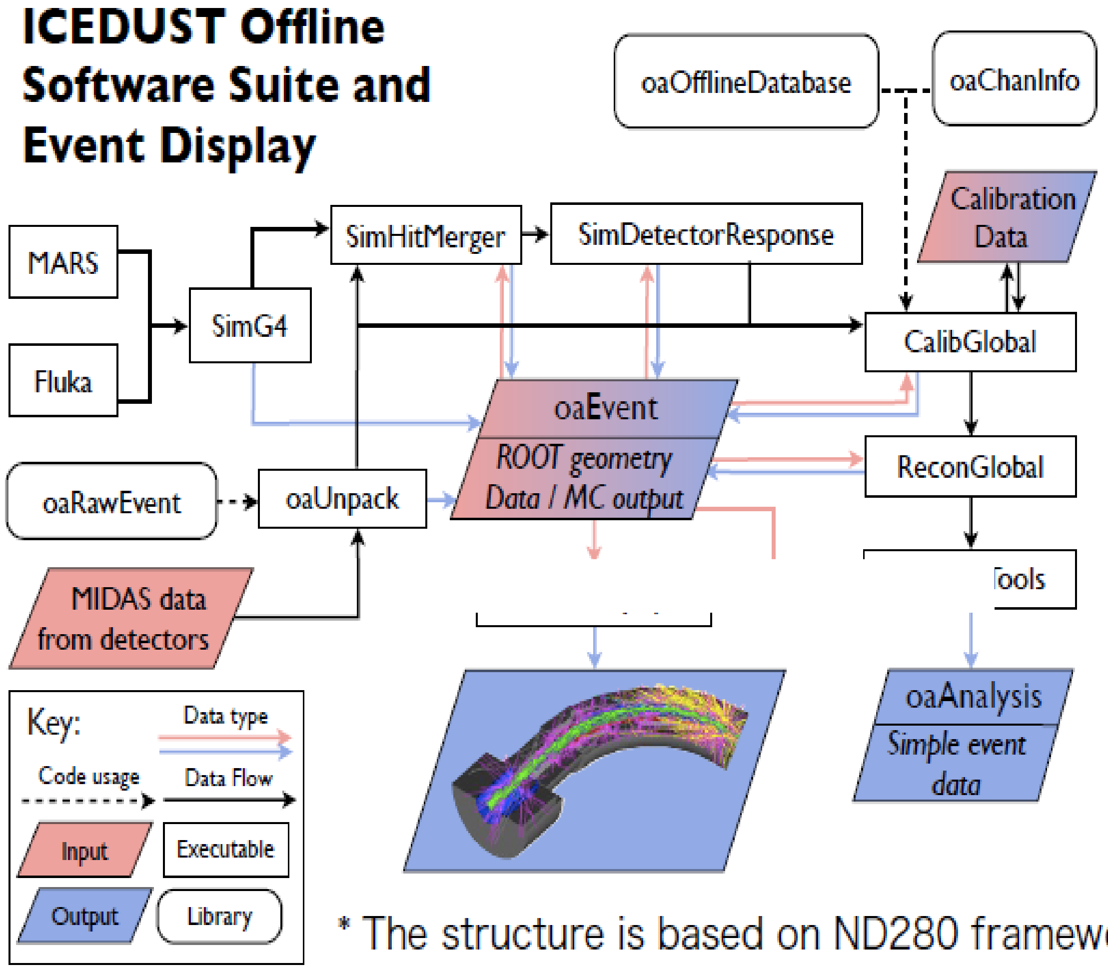


- Trigger system
  Cylindrical trigger hodoscope (CTH) under mechanical design.
  Trigger logic and trigger board design finished. Communication tests with FCT-FC7 trigger system is on going.

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



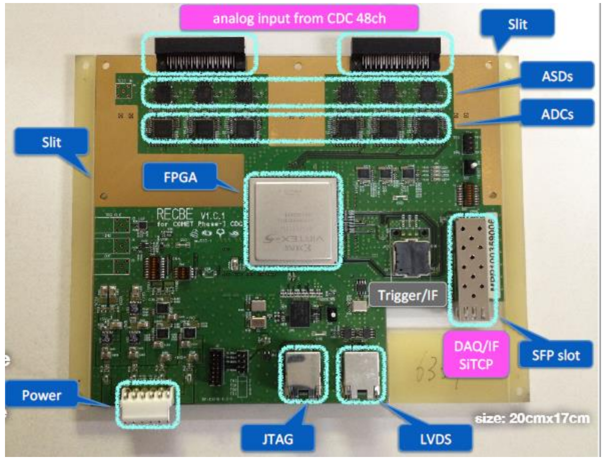


* The structure is based on ND280 framewo

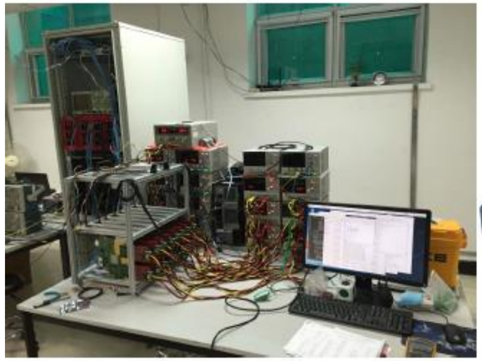
Contribution of Chinese Group
--- Production of drift chamber readout

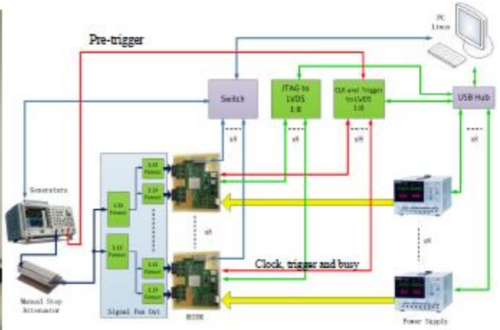
- The production of 128 readout board – RECBE has finished by IHEP, China in 2015
  - The design is based on BELLE-II CDC readout board
  - 48 input channels
  - TDC Time resolution: 1 nsec
  - ADC Sampling rate : 30 MHz
- A performance test, threshold scanning and aging test have been done

128 pcs RECBE in the dry box



COMET-CDC readout board

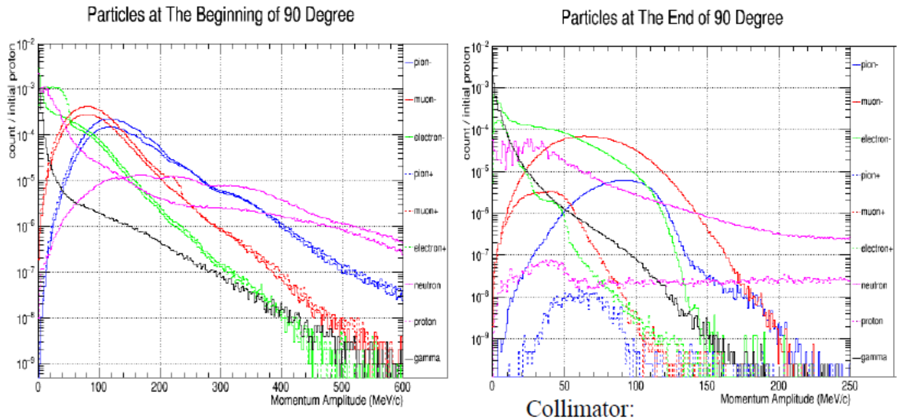




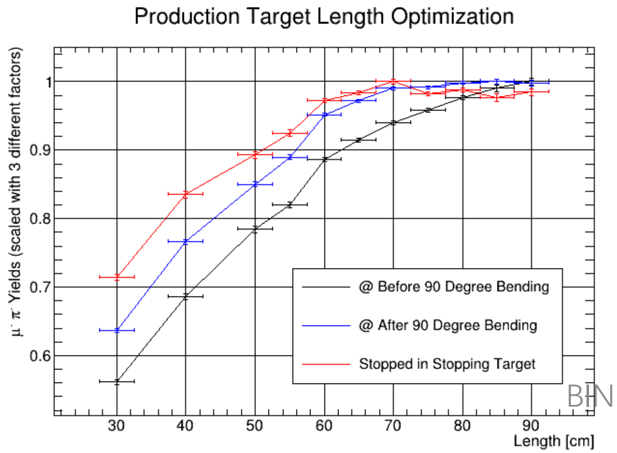
Automatic Test System

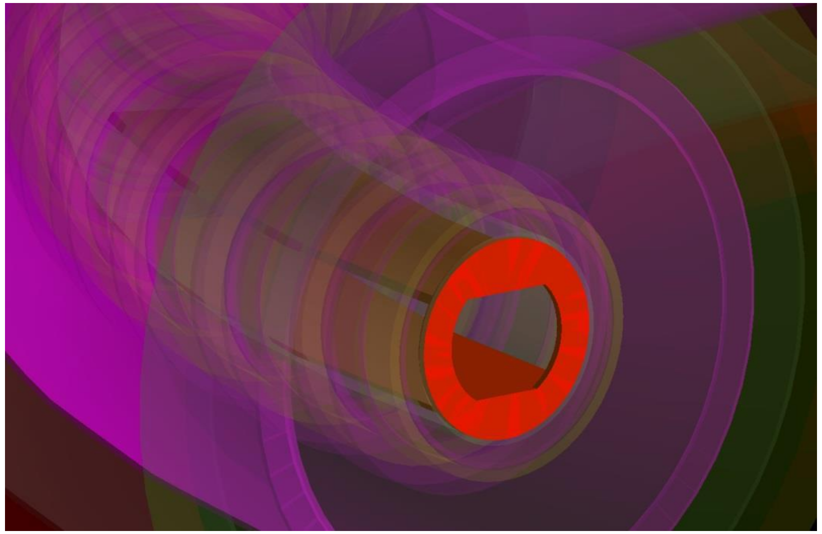
Contribution of Chinese Group
--- Phase-I design optimization

- Beam simulation
- Experiment optimization
  - Production target, Collimator ,CTH
- Sensitivity and Backgrounds
  - Muon decay in orbit (DIO)
  - Radiative muon capture (RMC)
  - Radiative pion capture (RPC)
  - anti-proton
  - Other beam related backgrounds



Collimator:
Vertical option





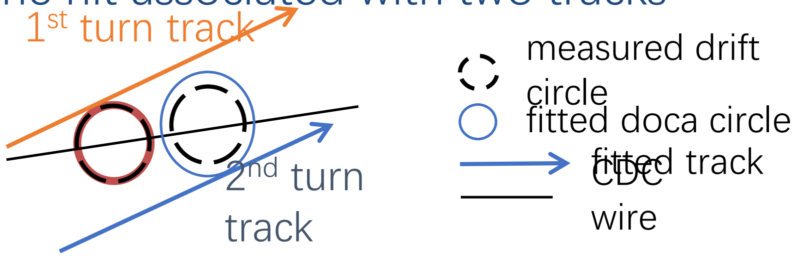
Collimator after optimization

Contribution of Chinese Group
--- Offline software development and analysiss

- Drift chamber track finding and track fitting
  - Line circle combinational track finding
  - Multi-turn track fitting based on genfit2
- Magnetic filed calculation
- Mass production on Tianhe2 super computer

weighted measurement for multi-turn tracks

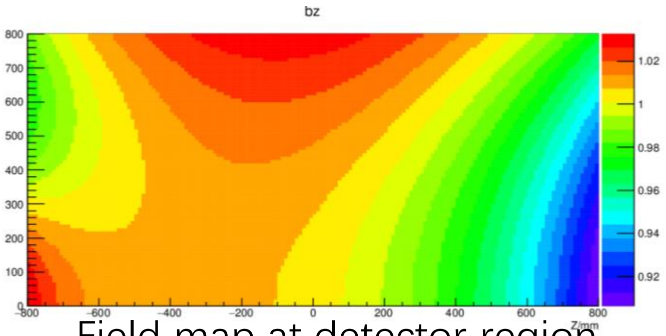
one hit associated with two tracks



The possibility of hit *i* assigned to track *j* is defined as matrix Φ

$$(\Phi)_{ij} = \varphi_{ij} = \varphi(y_i; Hx_j, V_i),$$

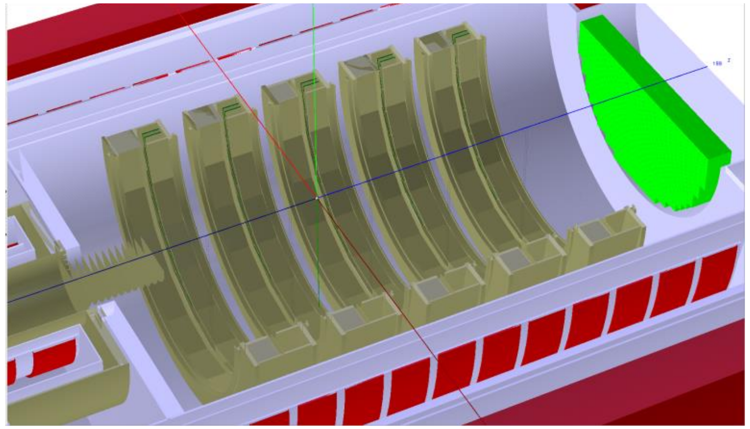
Assignment weight of hit i to track j $p_{ikj} = \dfrac{\varphi_{ikj}}{\sum_l \sum_\alpha \varphi_{i\alpha l} + c}.$

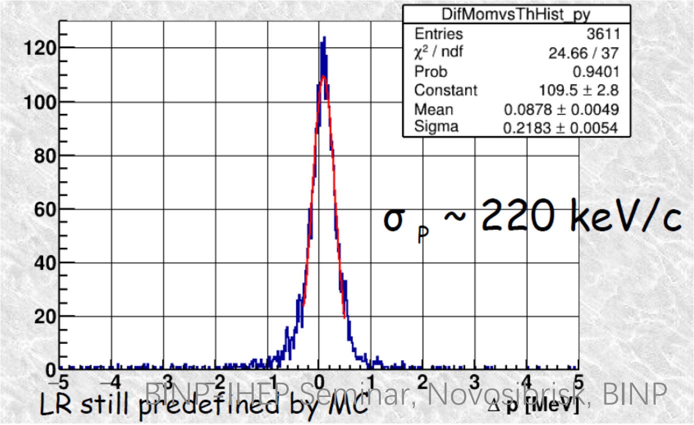


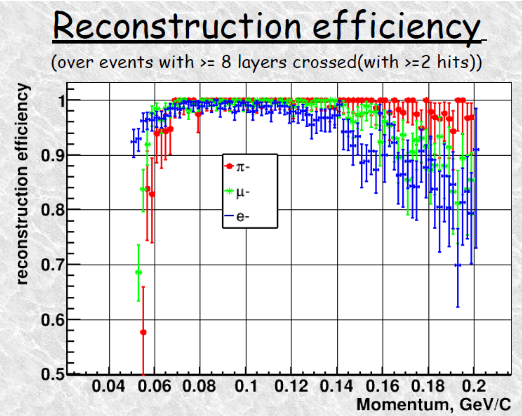
Field map at detector region

Contribution from BINP
--- ECAL electronics and straw tracking etc.

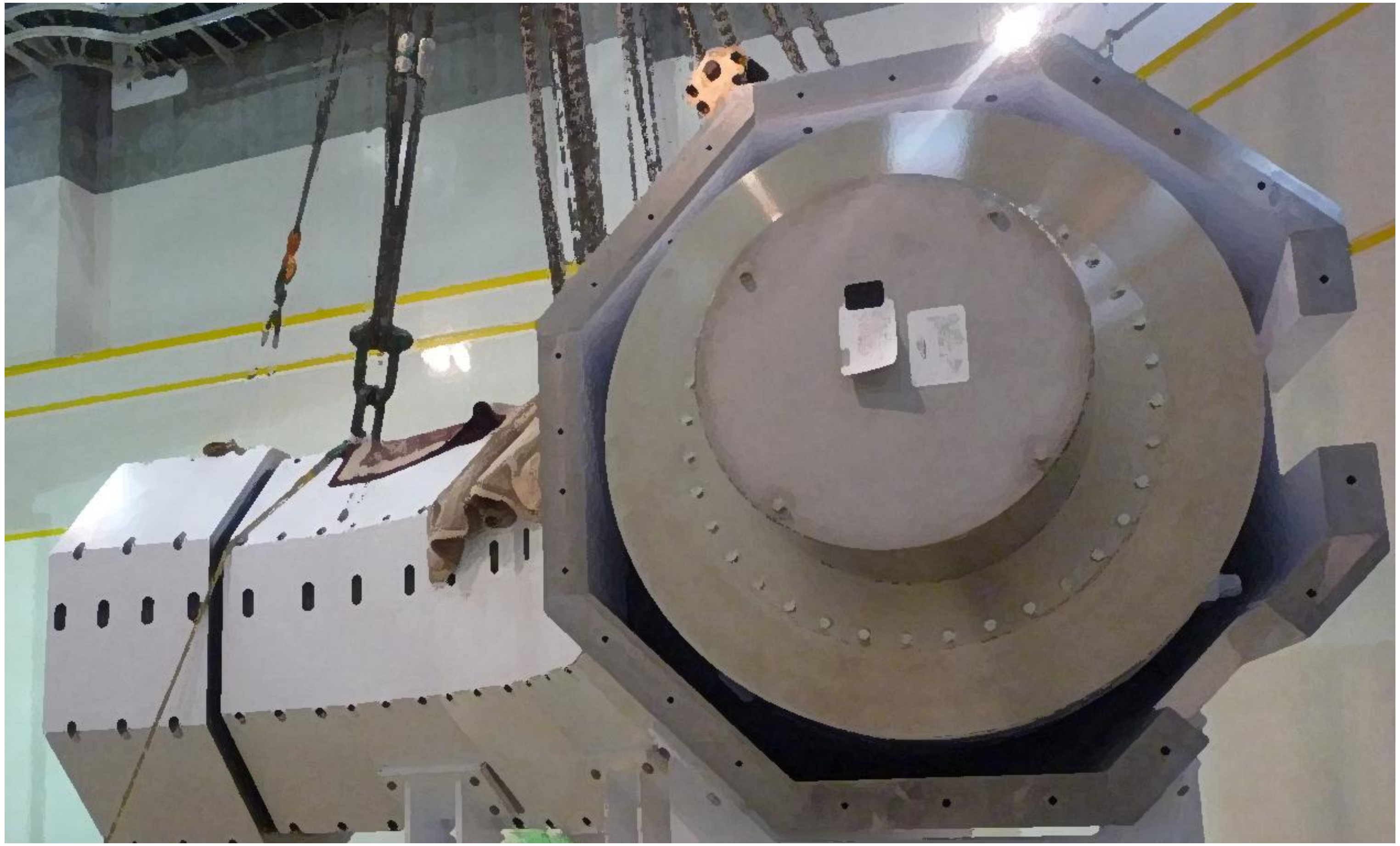
- Y. Yudin, L. Epshteyn, R. Akhmetshin, L. Epshteyn, D. Grigoriev, V. Kazanin
  - ECAL electronics
  - ECAL trigger
- Fedor Ignatov
  - Track finding in the Straw Tracker







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.