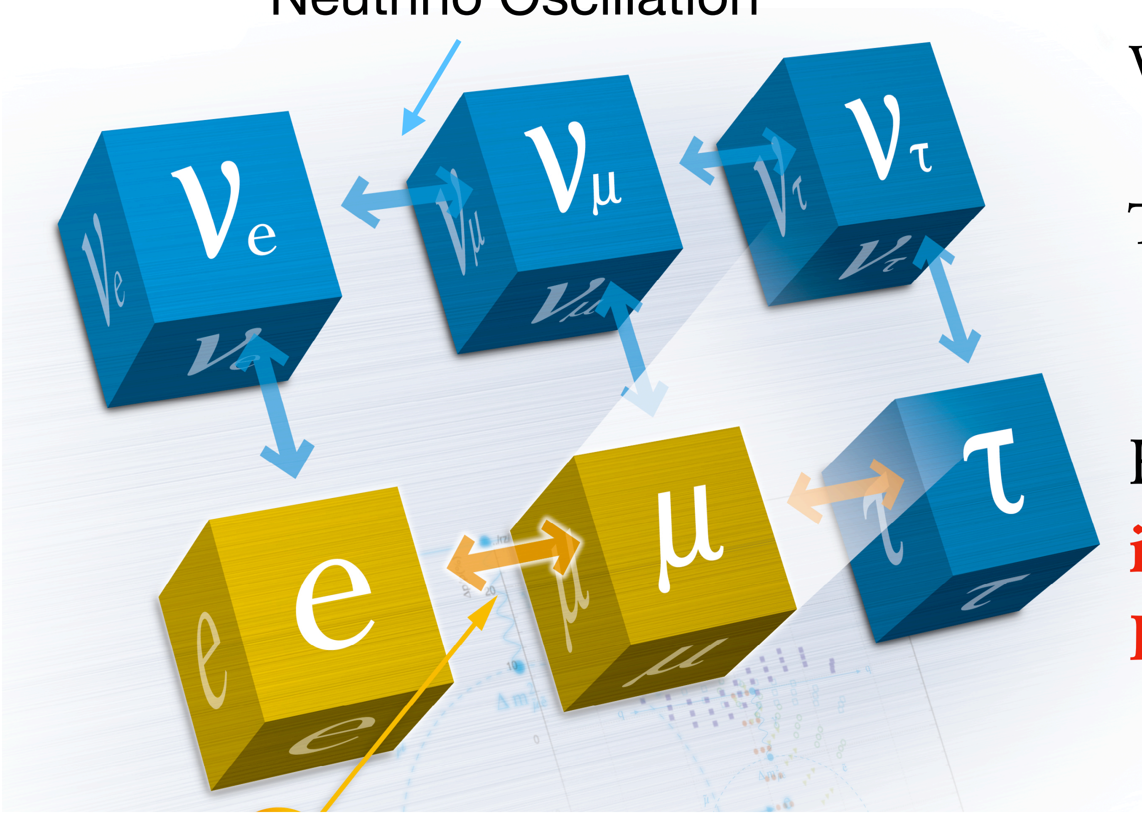
Status of the COMET experiment

Manabu MORITSU (KEK)
On behalf of the COMET Collaboration

20th Workshop on Neutrinos from Accelerators (NUFACT2018)
13th Aug., 2018, Virginia Tech, Blacksburg

Lepton flavor violation (LFV)



We already know that lepton flavor is no longer conserved

- ✓ neutrino oscillation, non-zero m_ν

The conservation law was just an empirical law

- ✓ without any symmetry behind

However,
in the charged lepton sector,
LFV has never been observed yet…

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

small mass ratio of neutrino to weak boson

Since the SM contribution is negligibly small,
observation of the CLFV indicates a clear evidence of **New Physics**.

Charged LFV in muons

- $\mu^+ \to e^+ \gamma$
- $\mu^+ \to e^+ e^+ e^-$
- $\mu^- N \to e^- N$ (μ-e conversion)

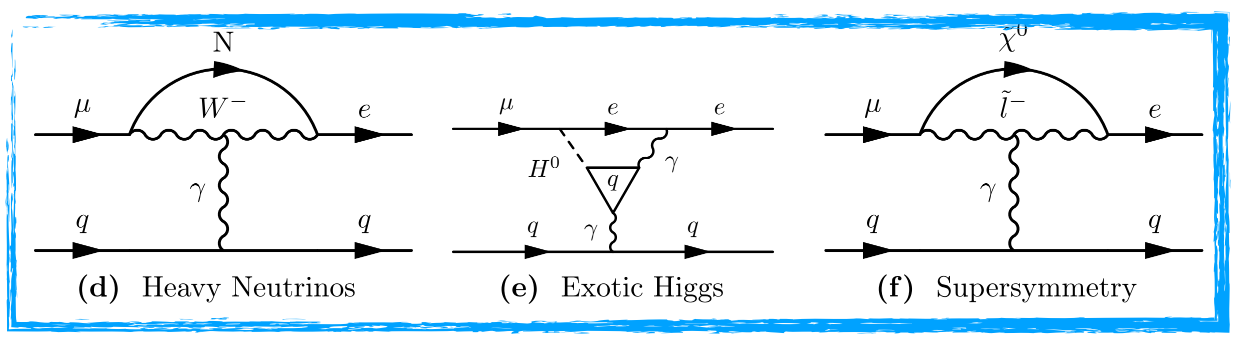
Effective Lagrangian

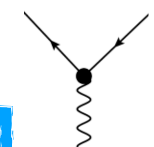
$$\mathcal{L} = \frac{1}{1+\kappa}\frac{m_\mu}{\Lambda^2}\bar{\mu}_R \sigma^{\mu\nu} e_L F_{\mu\nu} + \frac{\kappa}{1+\kappa}\frac{1}{\Lambda^2}(\bar{\mu}_L \gamma^\mu e_L)(\bar{q}_L \gamma_\mu q_L)$$

Photonic 4-fermion

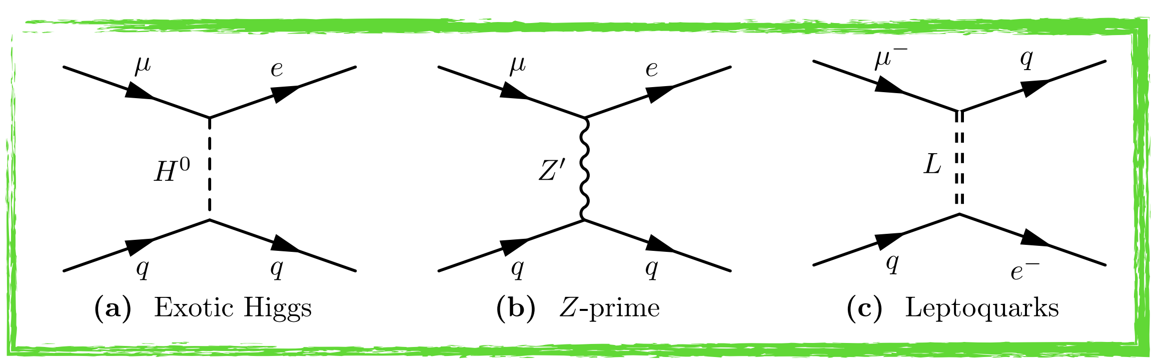
New Physics contributions

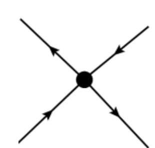
Photonic (dipole) term

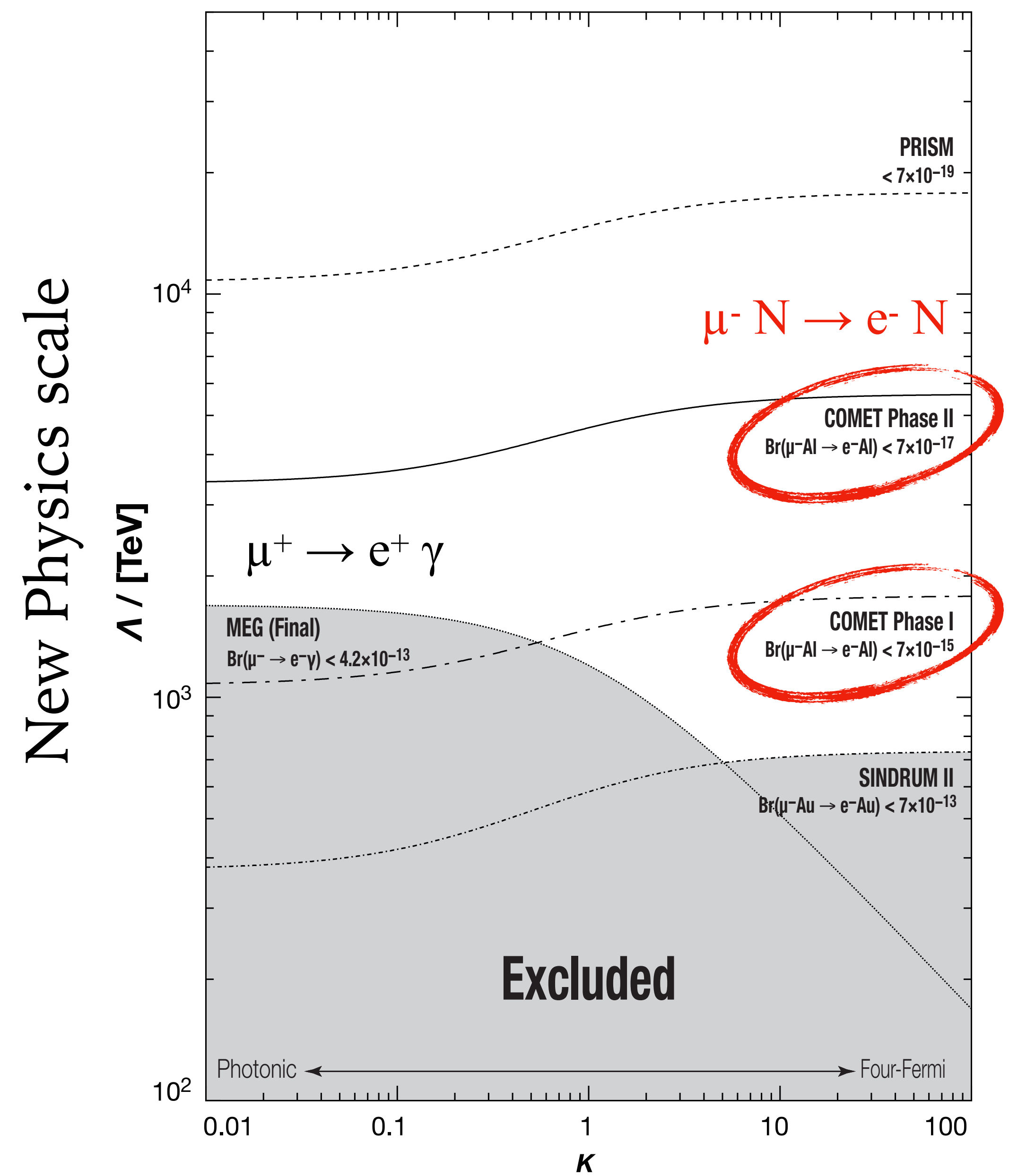




4-fermion (contact) term







Photonic ← → 4-fermion

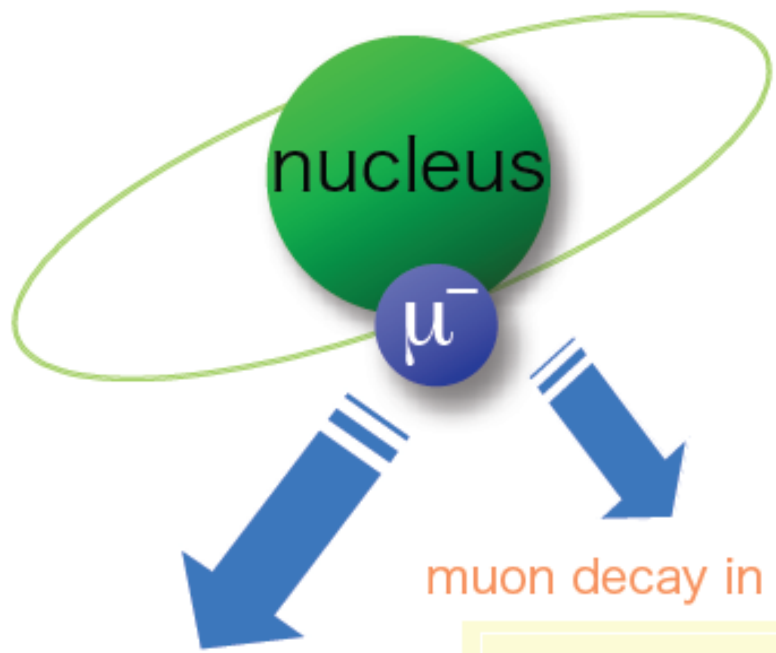
✓ *Different measurements are complementary.*

✓ *μ-e conversion is sensitive to both contributions.*

Muon-to-electron conversion

Fate of muonic atom

1s state in a muonic atom



muon decay in orbit (39% in Al)

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

nuclear muon capture (61% in Al)

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

μ-e conversion

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

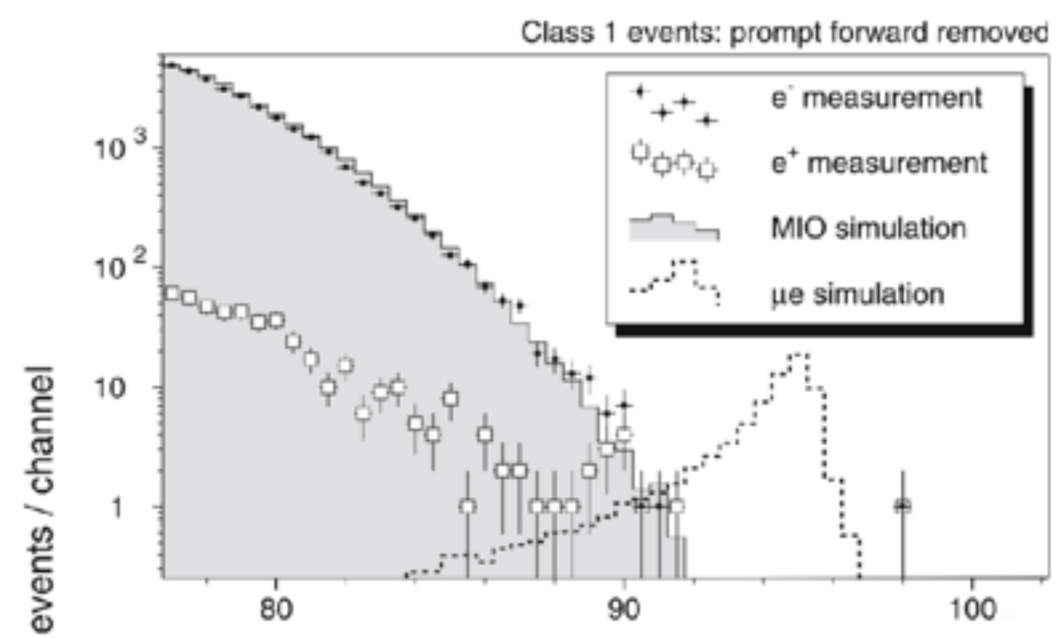
single mono-energetic electron

$$E_{\mu e} = m_\mu - B_\mu - E_{\rm rec} = 104.97 \text{ MeV for Al}$$

Current upper limit

SINDRUM-II, EPJ C47, 337 (2006)

Br(μ^- Au → e^- Au) < **7 x 10^{-13}**



Background rejection

① Decay-in-orbit → Detector

② Beam-related prompt BG → Beam

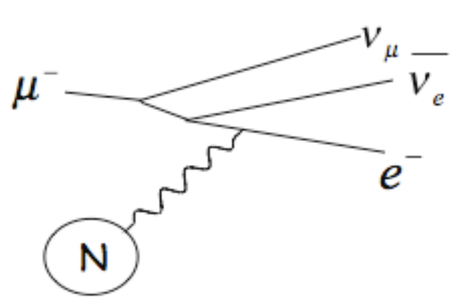
③ Cosmic-ray induced → Veto

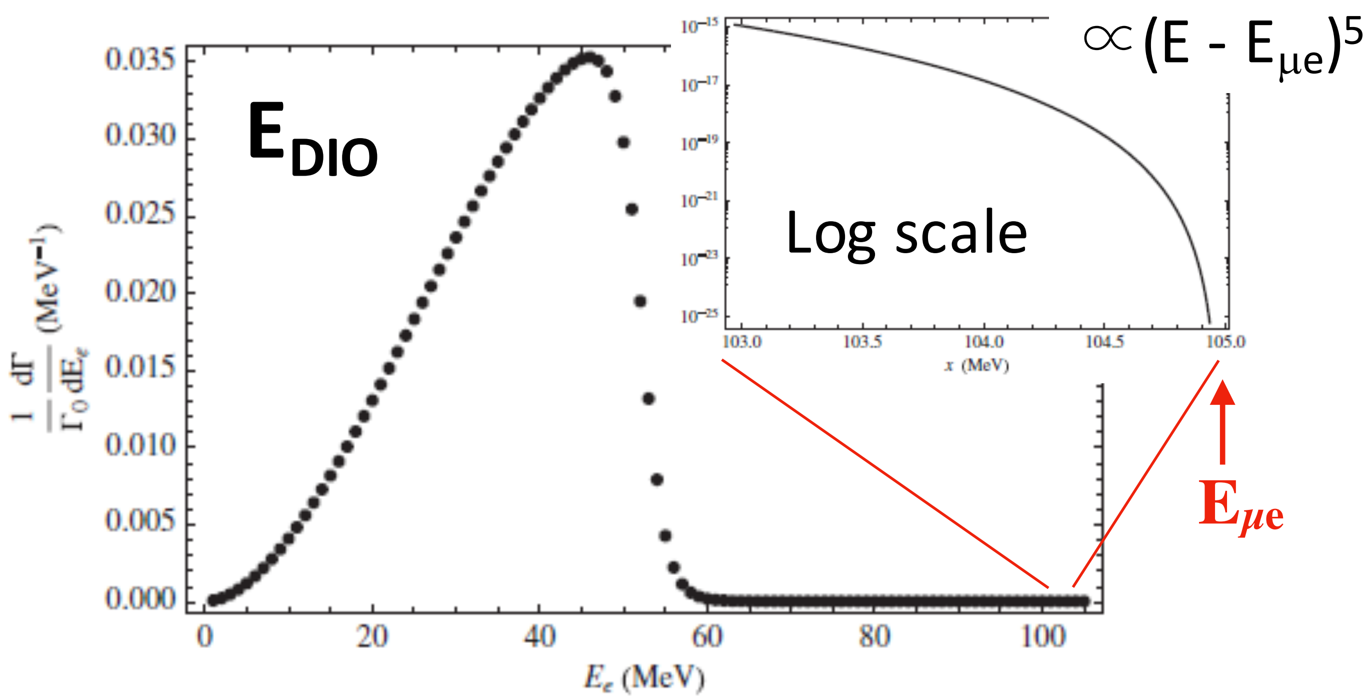
Background rejection (1)

① Decay-in-orbit → Detector resolution

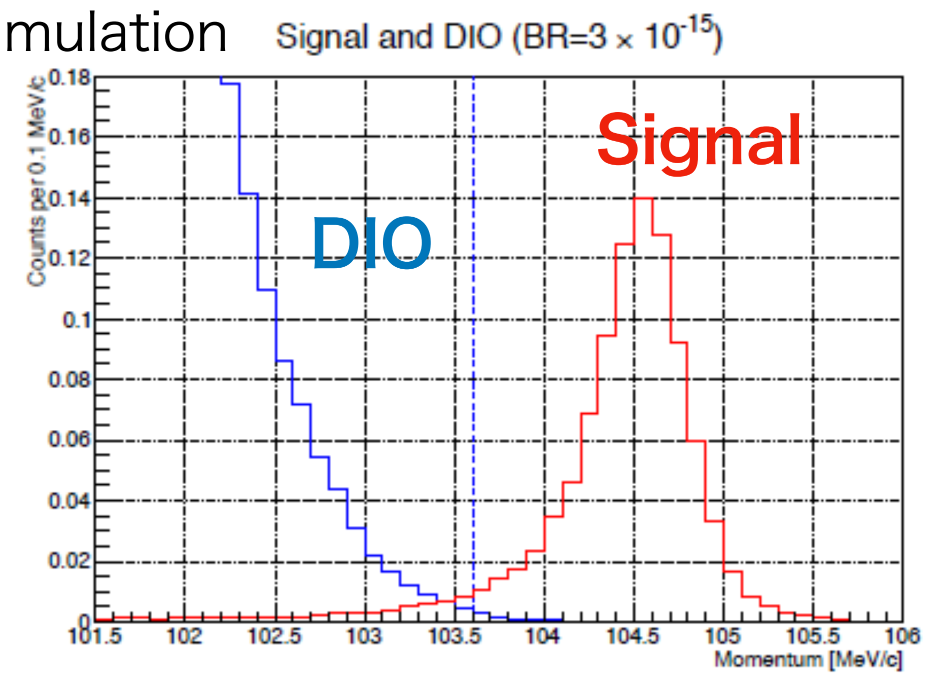
Intrinsic physics background

Muon decay in orbit





Simulation



Required momentum resolution

$\Delta p < 200$ keV/c

for 105 MeV/c electrons

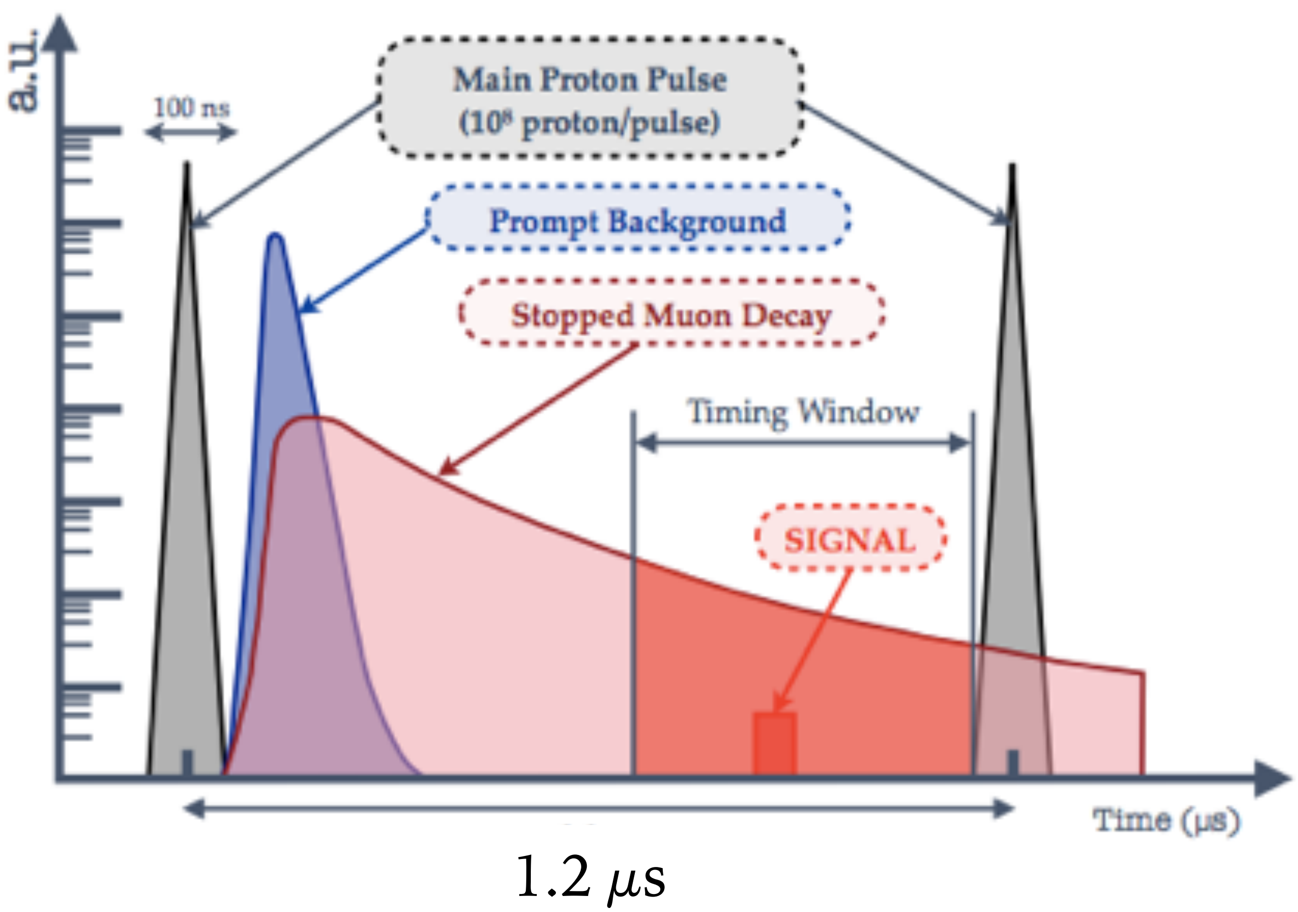
Background rejection (2)

② Beam-related prompt BG → Pulsed Beam

muon beam is contaminated by a lot of pions, and the momentum is spreading in a wide range.

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

} correlated with beam timing



Cf.) τ_μ(Al) = 0.9 μsec

✓ Long muon beam line
- reduce π contami.

✓ Pulsed beam
- prompt vs. delayed

➡ Delayed-timing measurement

Lifetime of the muonic atom should be comparable to the pulse interval

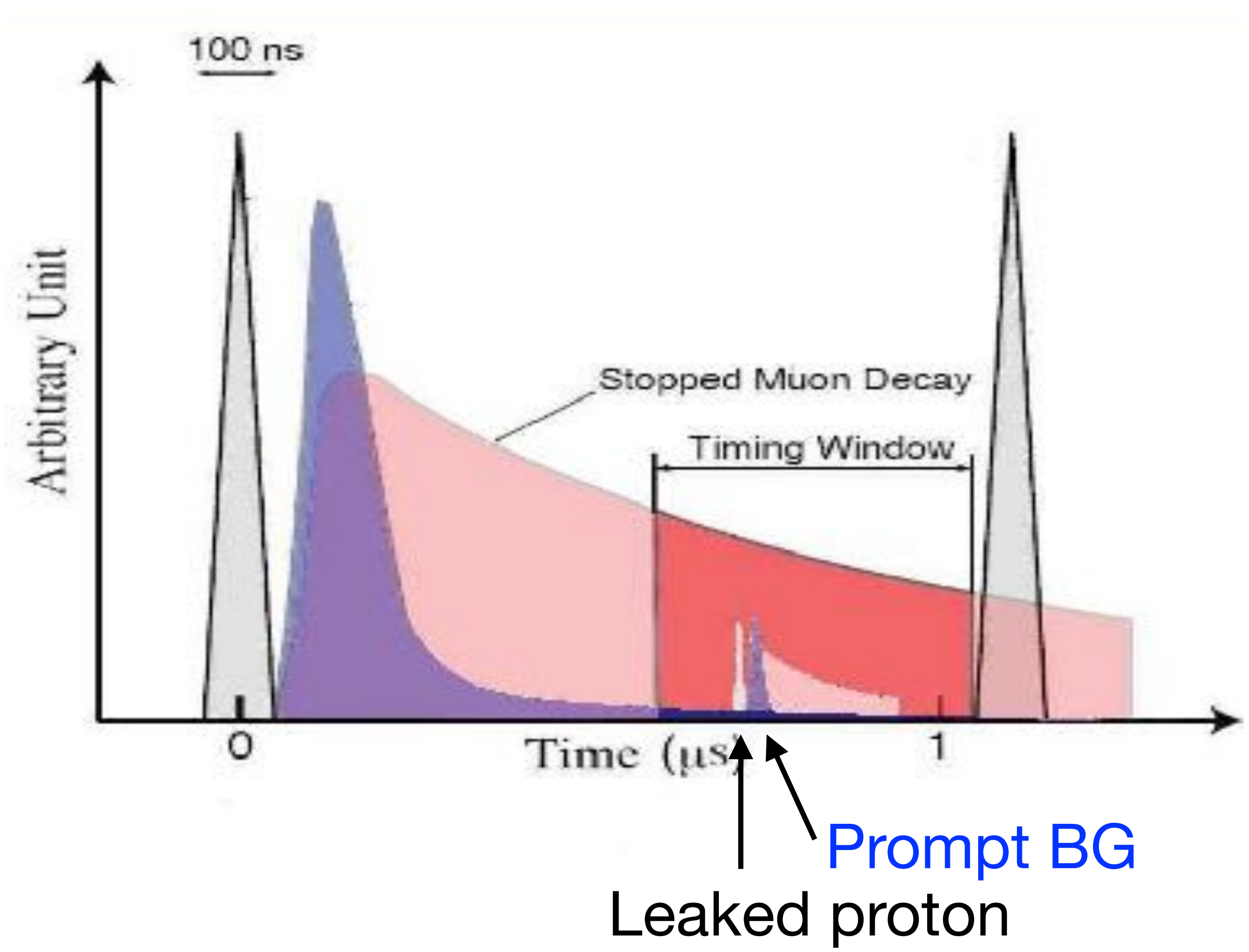
Background rejection (2)

② Beam-related prompt BG → Pulsed Beam

muon beam is contaminated by a lot of pions, and the momentum is spreading in a wide range.

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

} correlated with beam timing



✓ Long muon beam line
- reduce π contami.

✓ Pulsed beam
- prompt vs. delayed

➡ Delayed-timing measurement

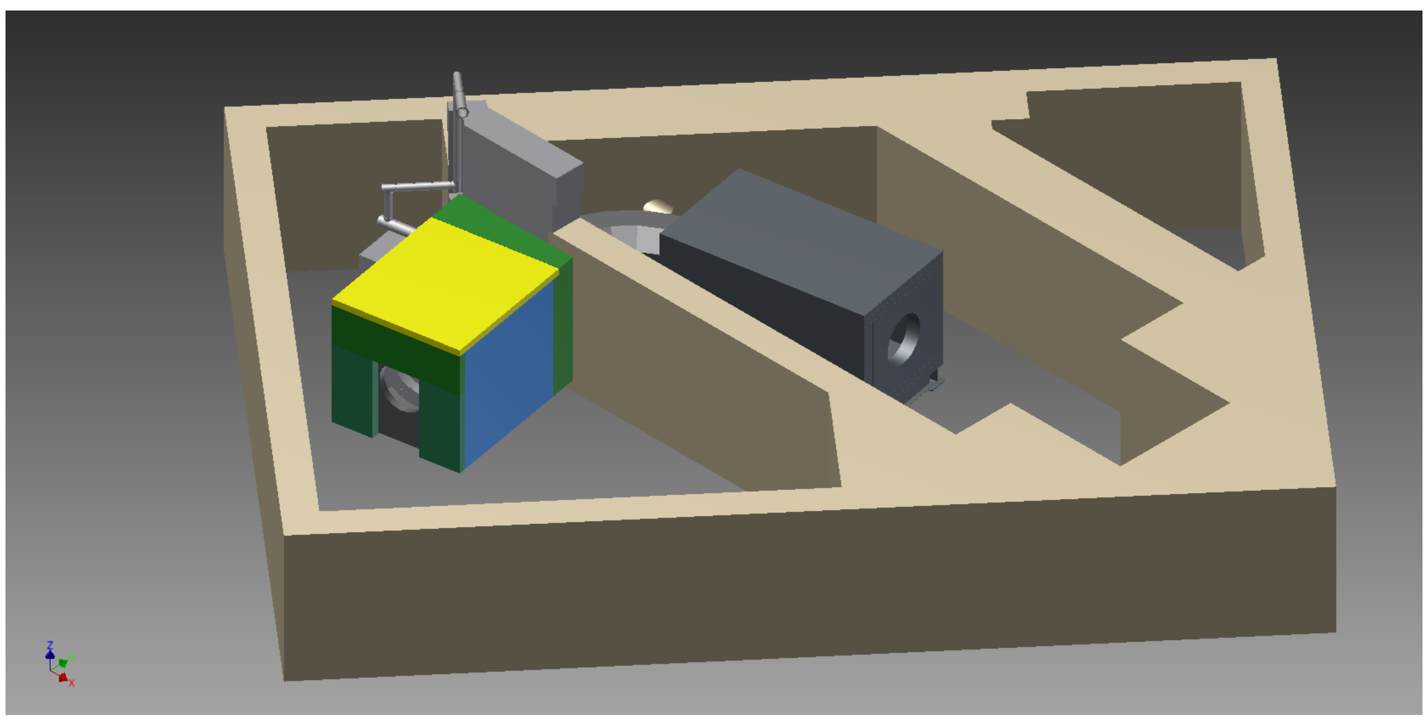
✓ Extinction factor $<10^{-10}$

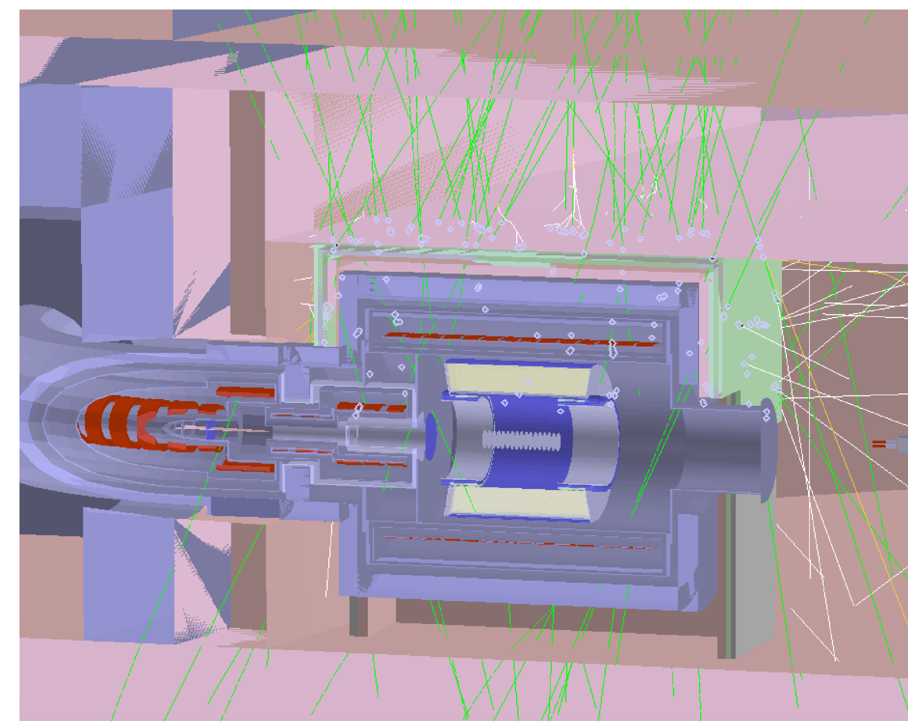
$$R_{ext} = \frac{\text{\# of protons in between pulses}}{\text{\# of protons in pulses}}$$

Leaked protons are dangerous to make the beam BG in the timing window.

Background rejection (3)

③ Cosmic-ray induced → Veto





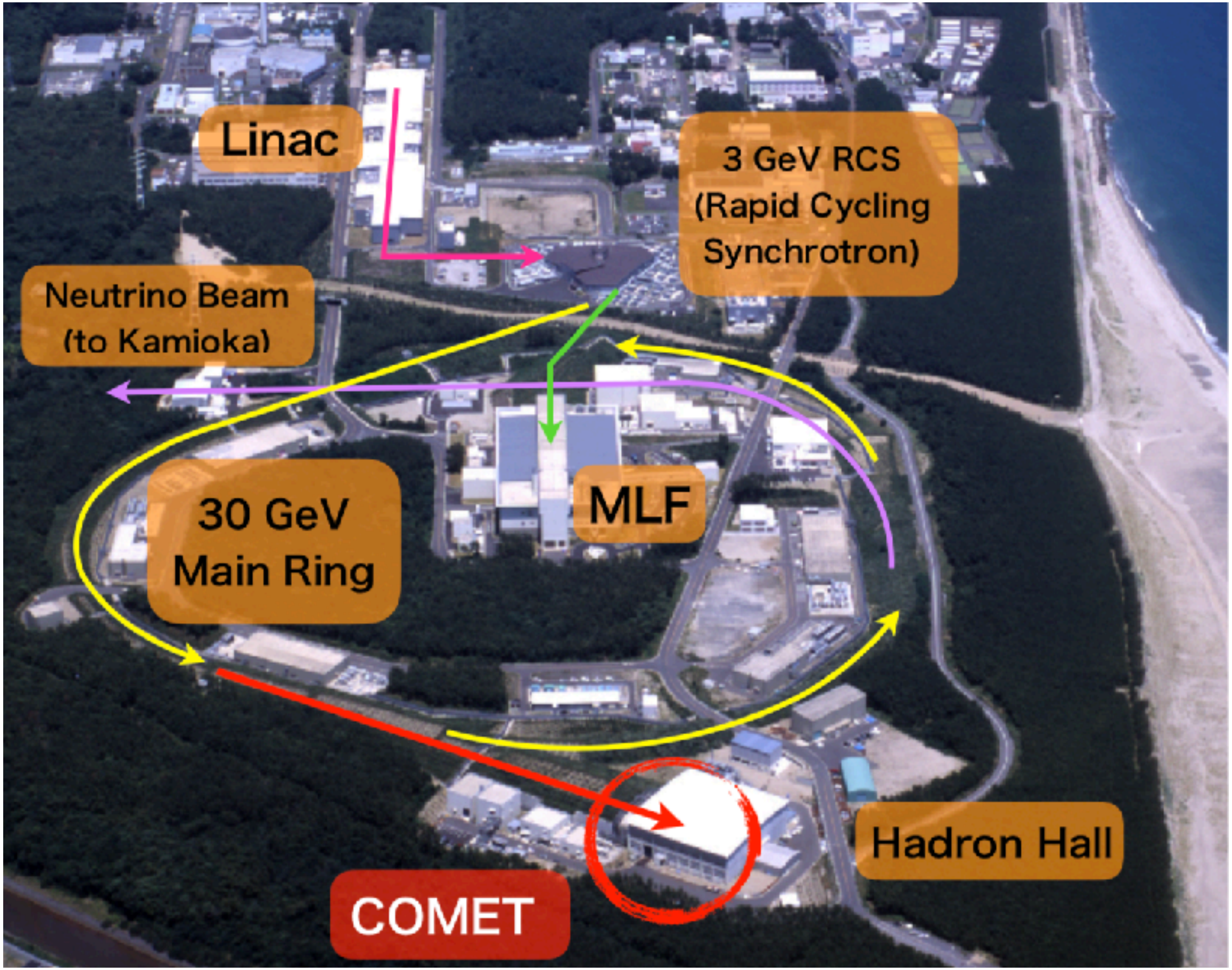
- Cosmic rays may create 105-MeV electrons that come into a detector and make trigger.
- To avoid these CR induced BG, detector region have to be covered by veto counters.
- Required performance: **CRV inefficiency ~ 10^{-4}**
- CR background ∝ data taking time (→ shorter running time with higher beam intensity is better)

The COMET Experiment


Collaboration Meeting @ Osaka, 2018/Jan

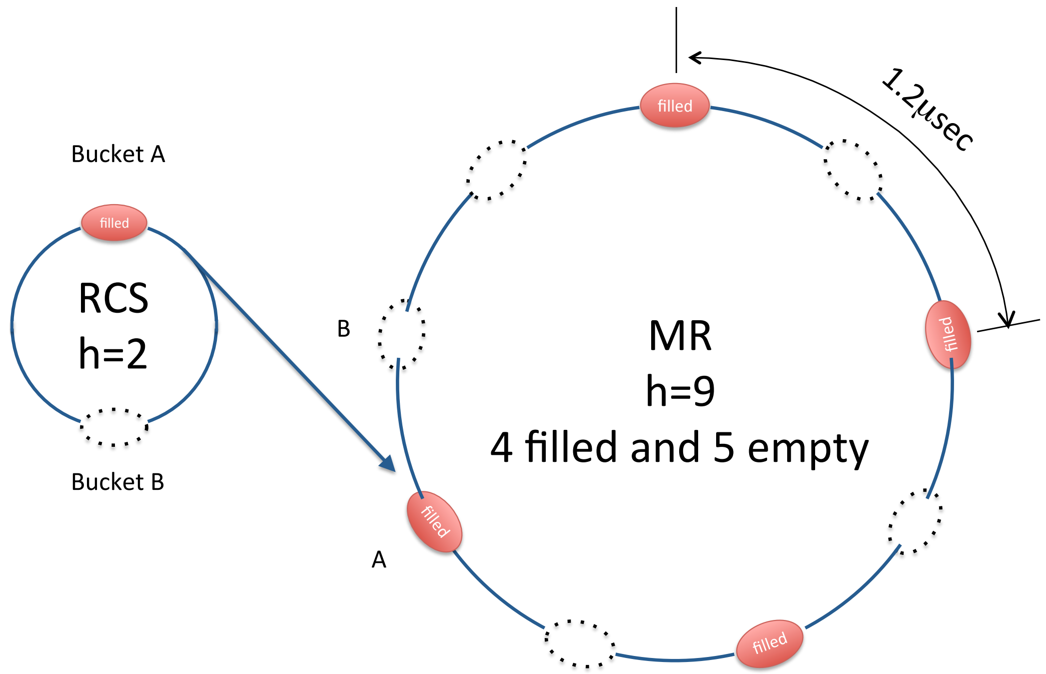
~200 collaborators,
41 institutes, 17 countries

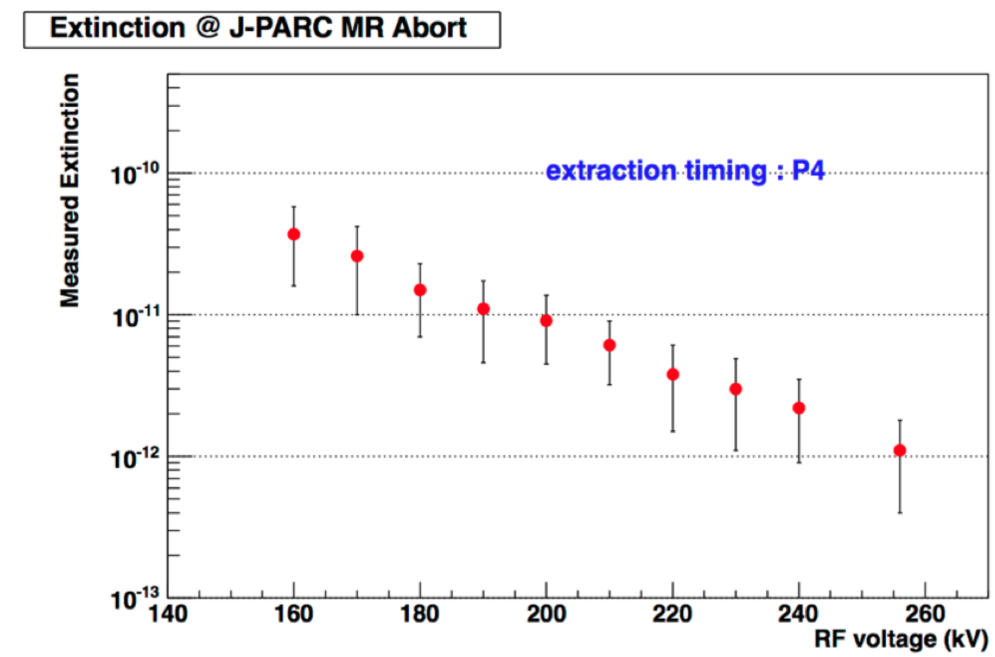
Accelerator



Proton beam for COMET

Cf.) Requirement < 10^{-10}

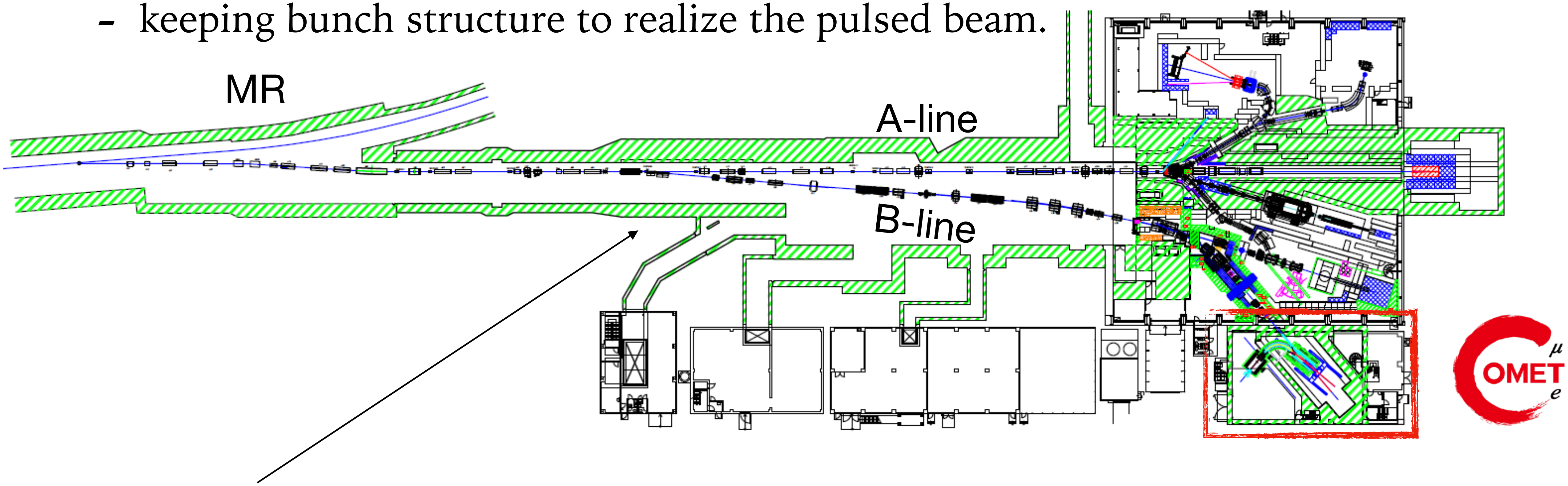


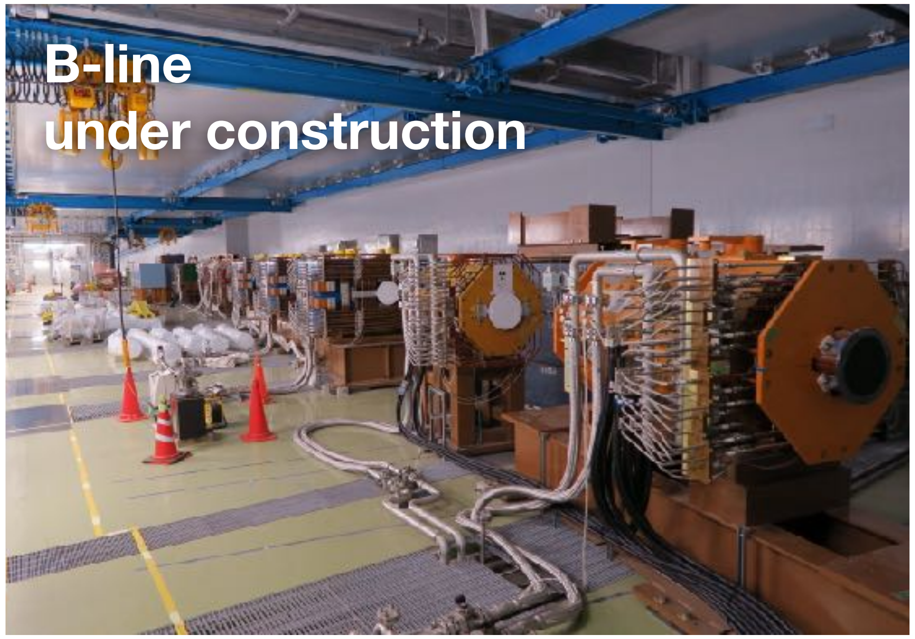


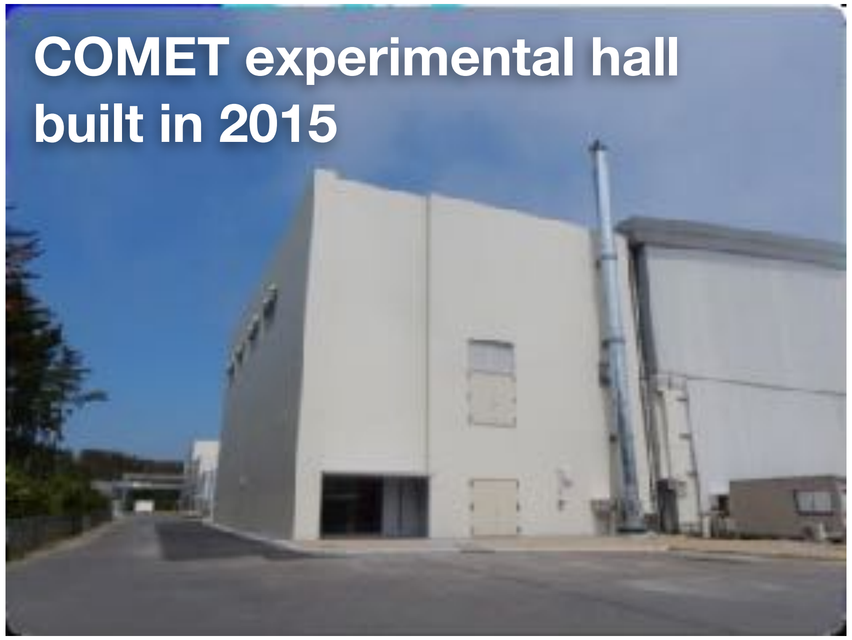
- **COMET dedicated operation**
  - Energy: 8 GeV
  - Pulsed beam: 1.17-μsec interval
  - 3.2 kW for Phase-I
  - 56 kW for Phase-II
- **Obtained Extinction**
  - = $\mathbf{10^{-12} \sim 10^{-11}}$ @ FX abort
  - Good enough for COMET

Beam line

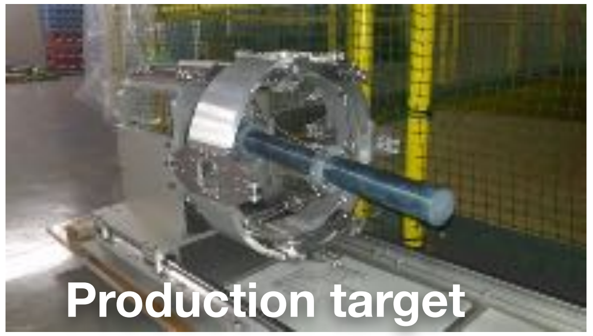
- New beam line & experimental hall were constructed.
- Bunched Slow Extraction (BSX)
  - keeping bunch structure to realize the pulsed beam.







High-intensity muon source

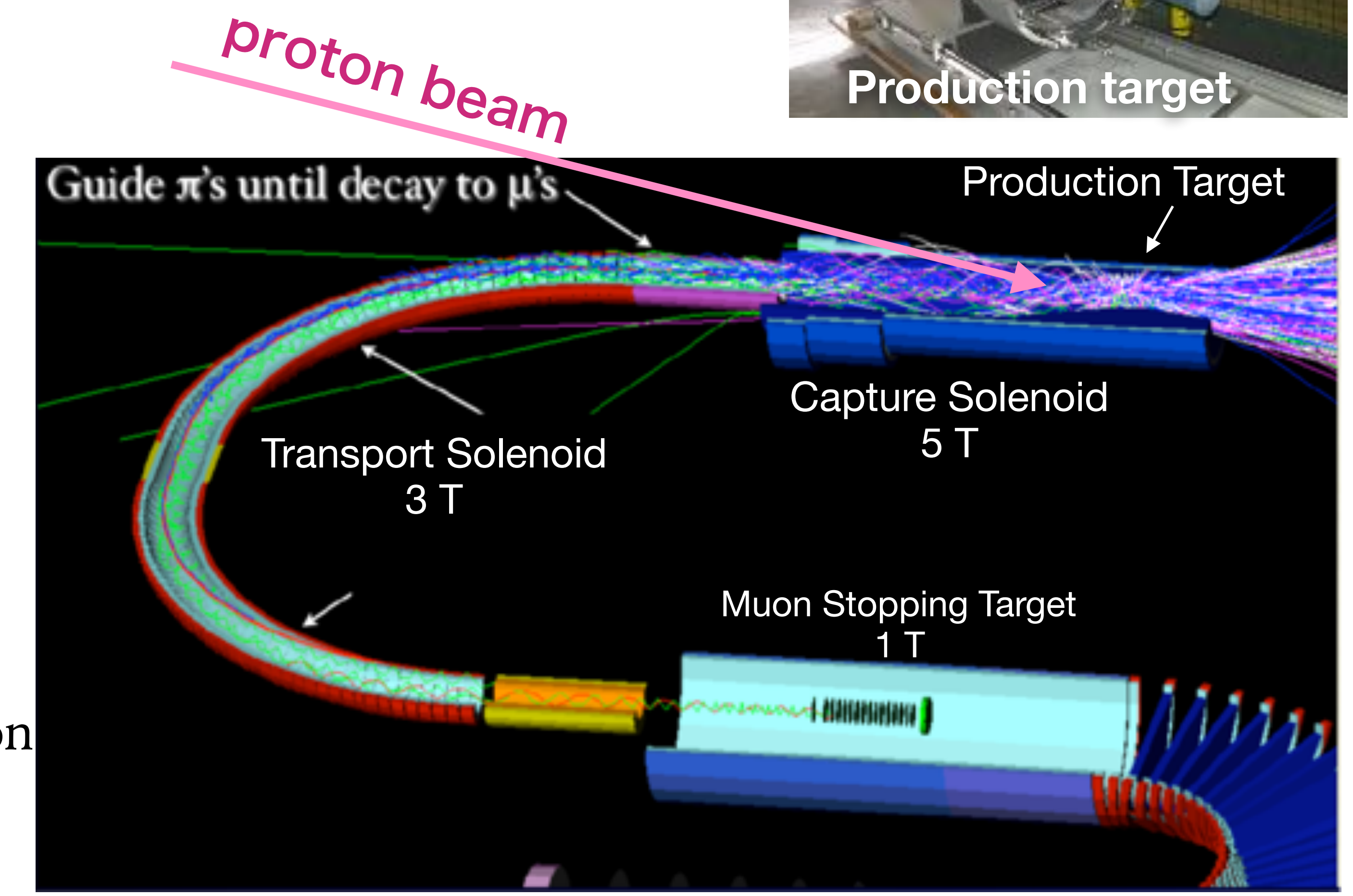


Powerful muon source is mandatory !!

To achieve 10^{-17} sensitivity,

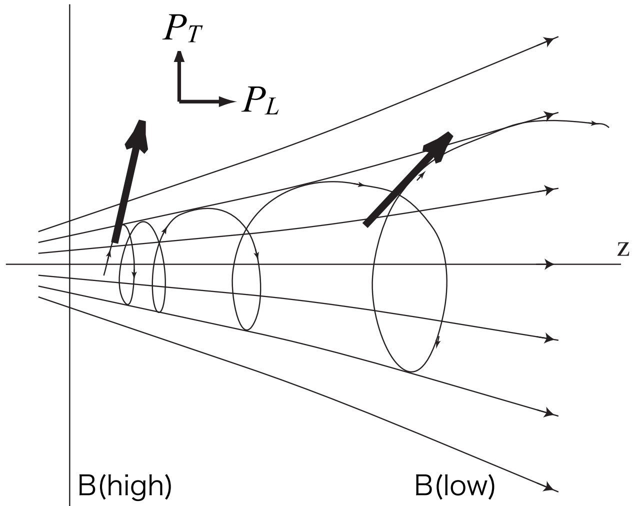
~10^{11} muons/sec

(with 10^7 sec running time.)



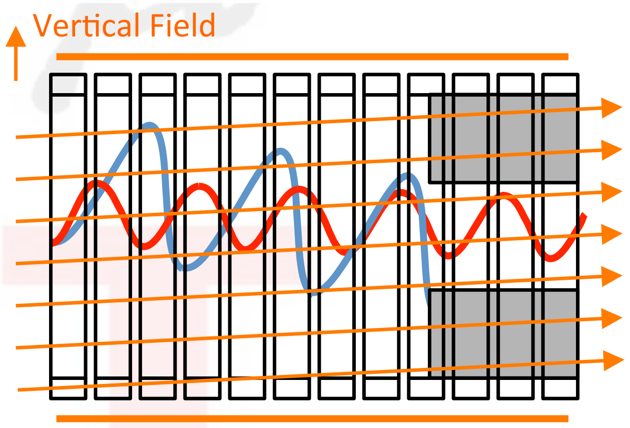
- Long production target
- Capture solenoid
  - Backward generated pion → muon
- Curved Transport solenoid
  - Vertical drift → Momentum & charge selection

Capture solenoid



gradient magnetic field

Transport solenoid

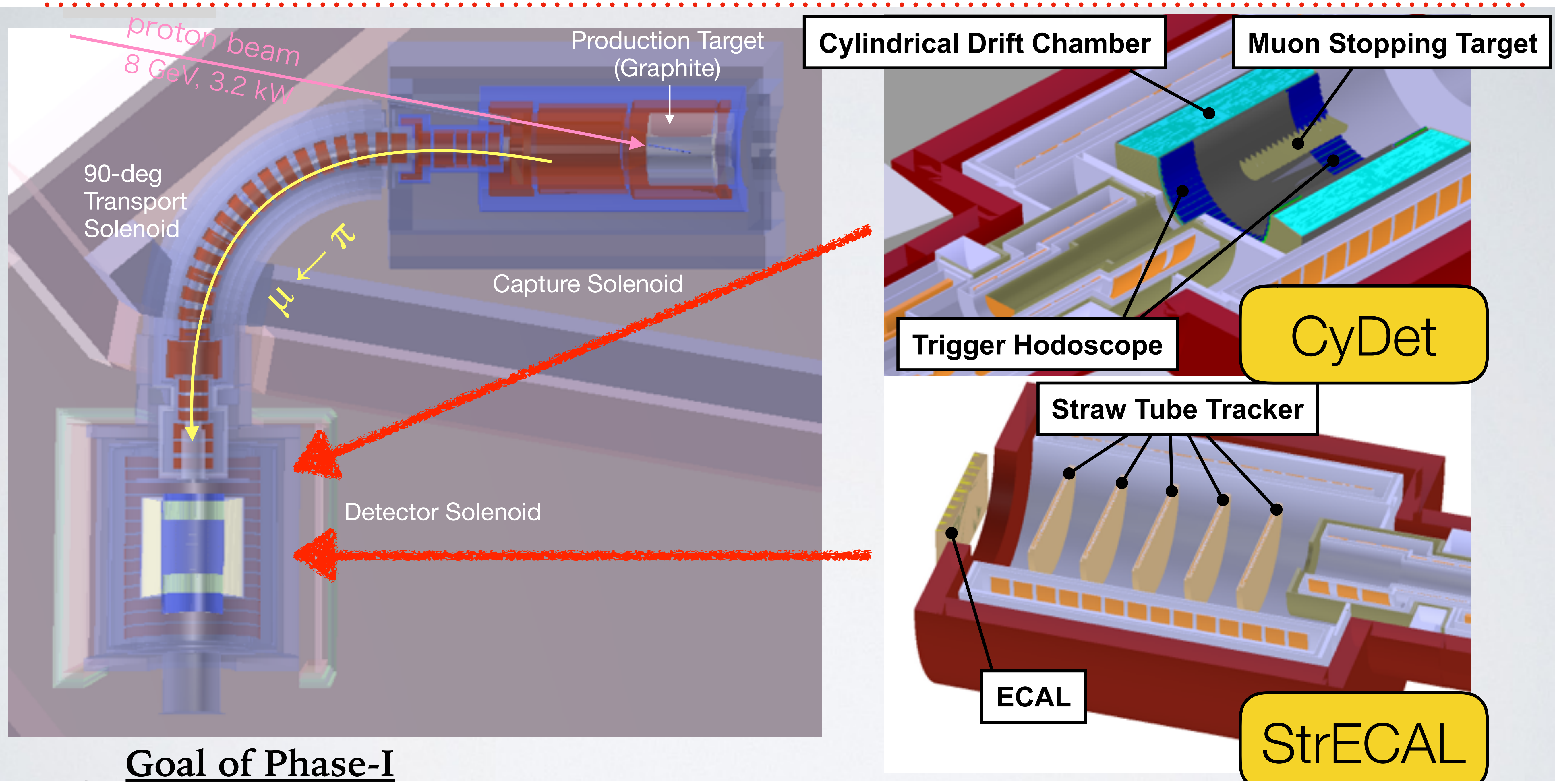


$$D = \frac{1}{qB}\left(\frac{s}{R}\right)\frac{p_L^2 + \frac{1}{2}p_T^2}{p_L},$$

Demonstrated at MuSIC

MuSIC @ RCNP, Osaka U

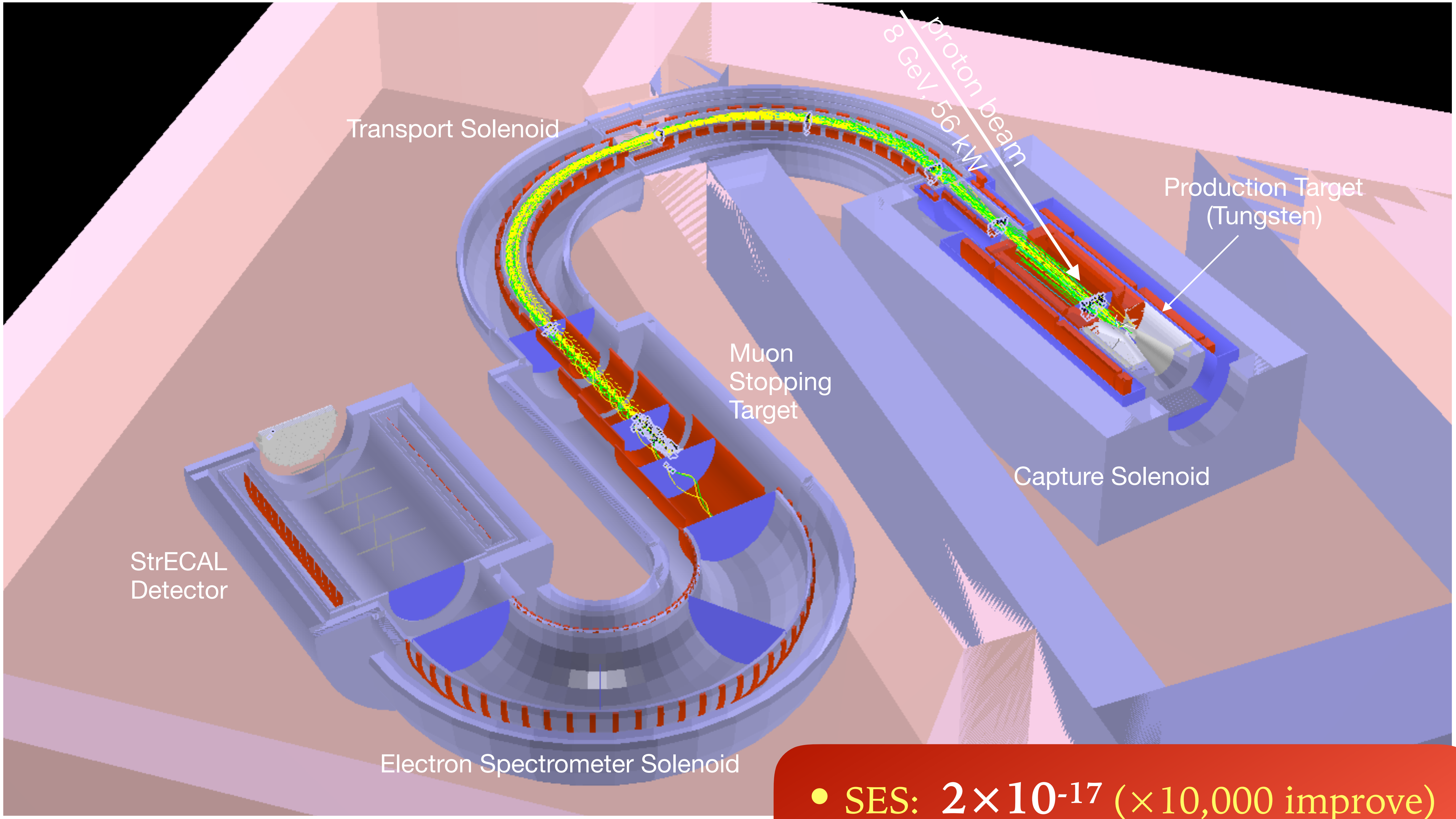
COMET Phase-I



Goal of Phase-I

- **Physics measurement** → **CyDet**
  - μ-e conversion search, SES: 3×10^{-15} (×100 improve), 150 days running
- **Beam measurement** → **StrECAL**
  - to understand beam quality and background (PID, momentum, timing)

COMET Phase-II

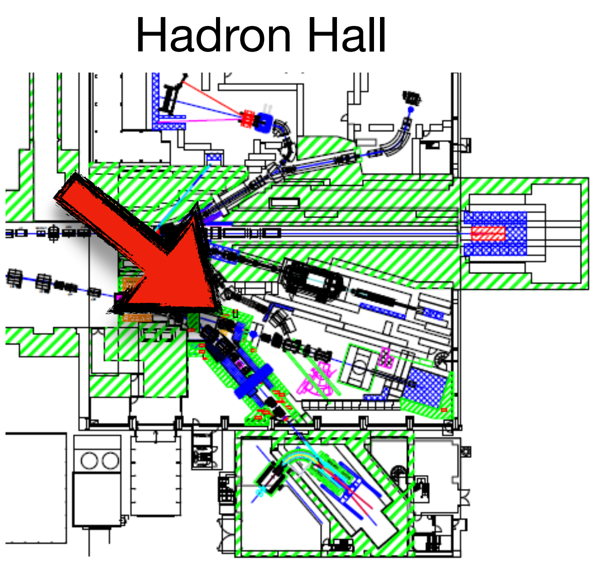


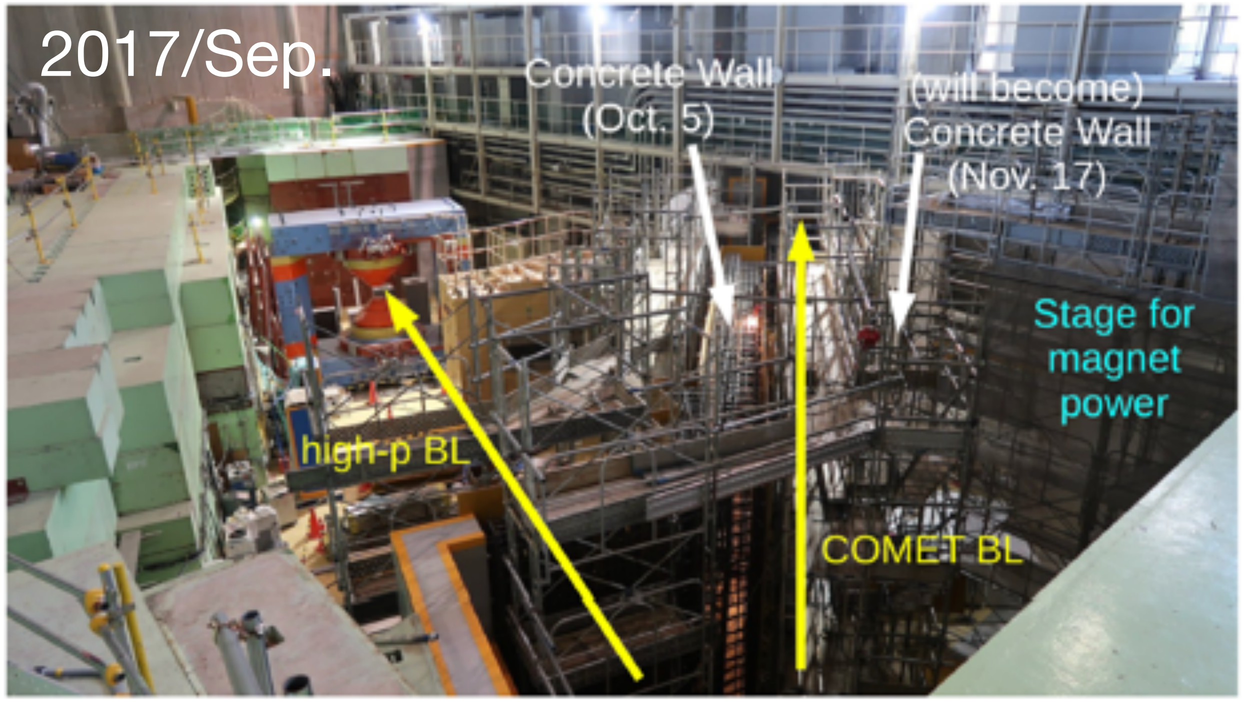
- SES: 2×10^{-17} (×10,000 improve)
- Beam: 56 kW
- 1 year running

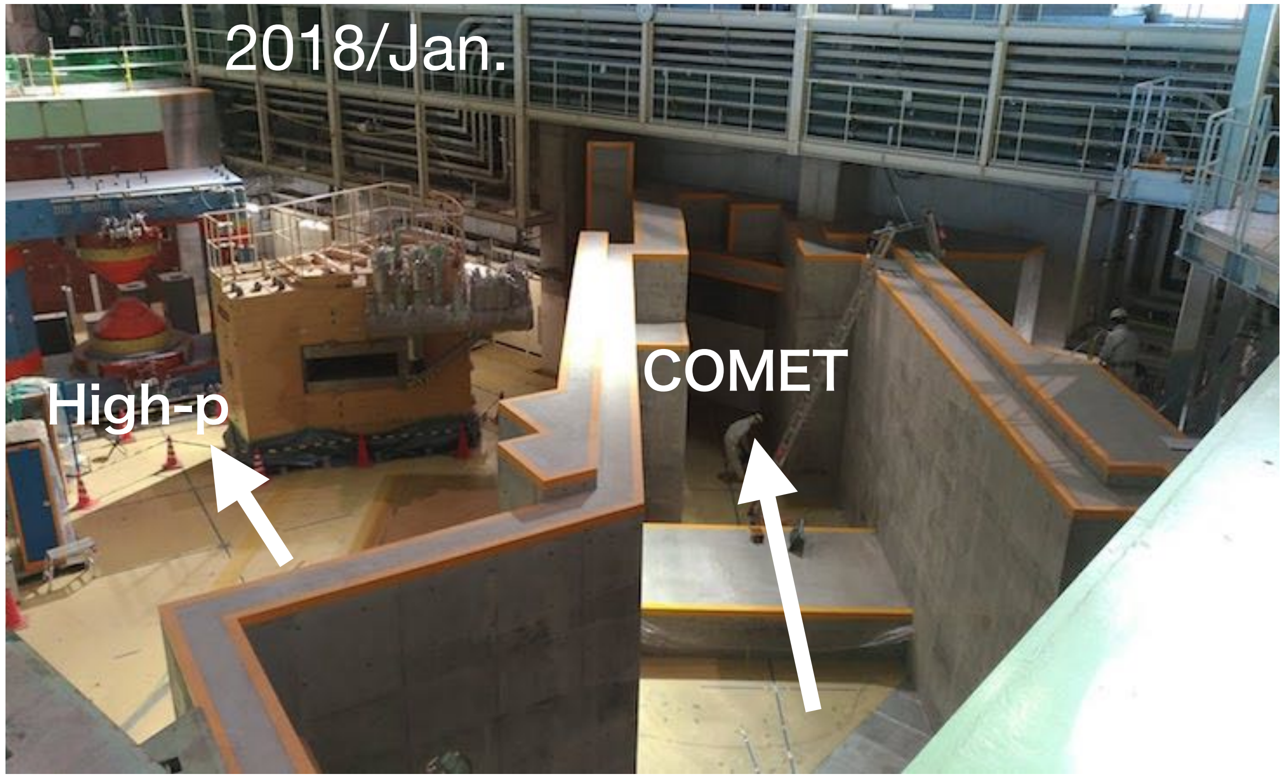
Recent Status

Beam line construction

View from here

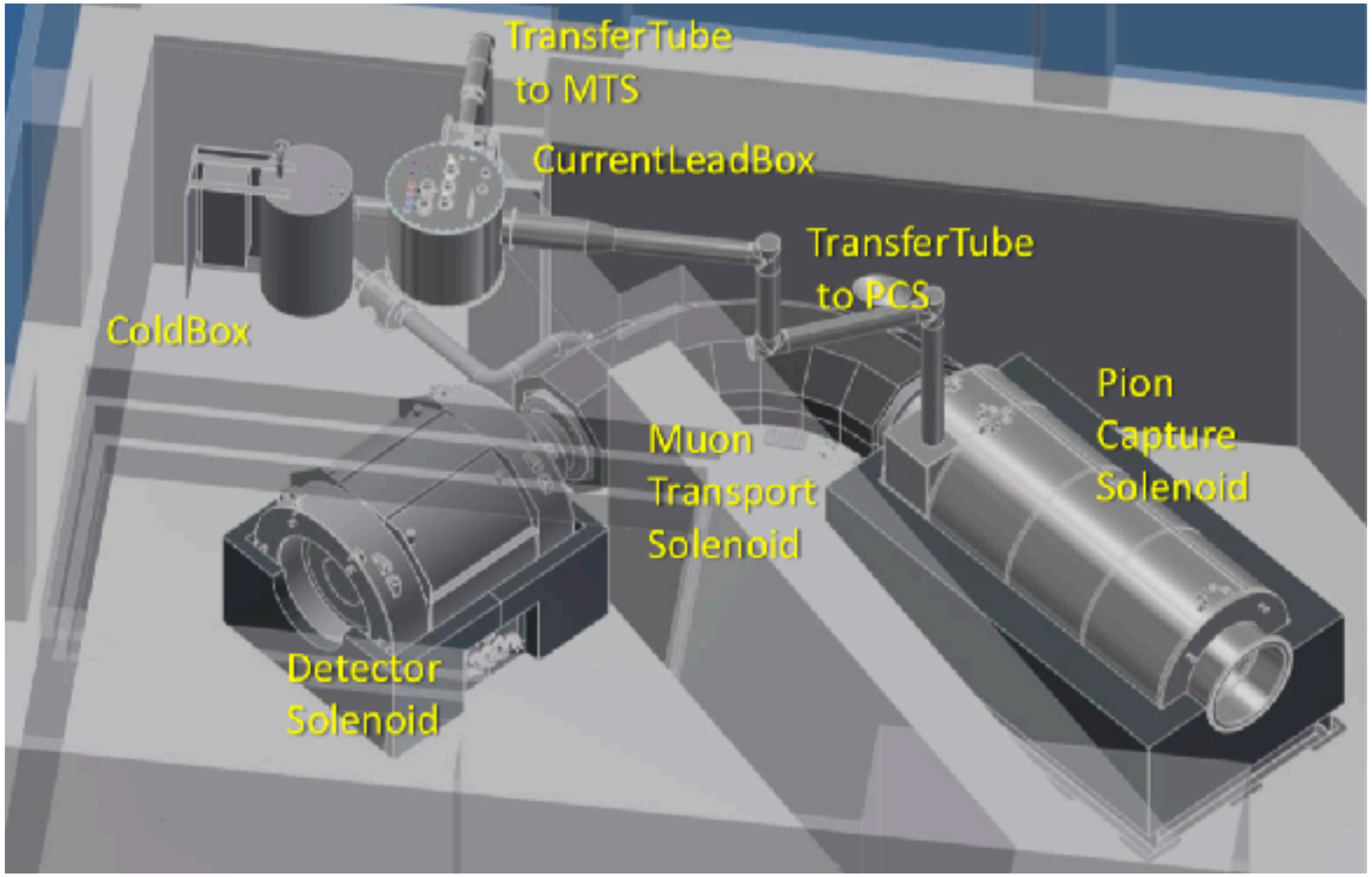


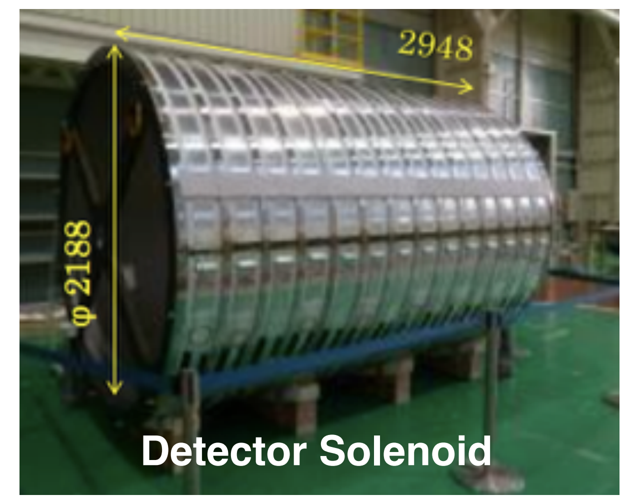




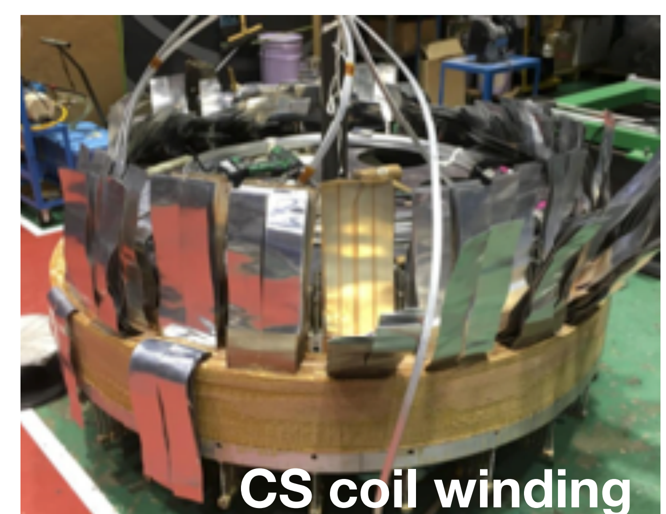
Beam line wall construction was completed.

Solenoid magnet status



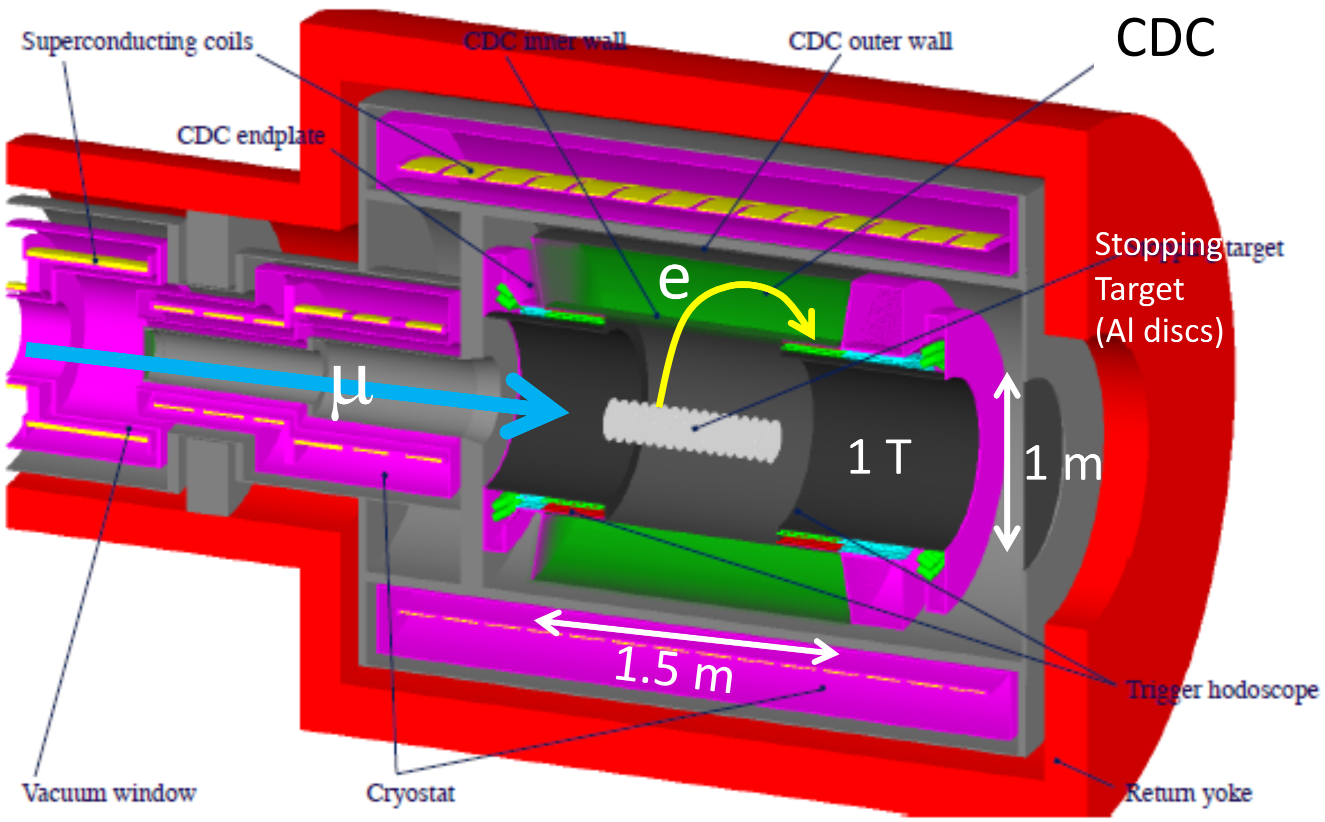


- **Capture solenoid:**
  - Coil winding & cold mass assembly in progress. Cryostat design ongoing.
- **Transport solenoid:**
  - Installed and ready for cryogenic test
- **Bridge & Detector solenoids:**
  - DS coil ready. Cryostat design in progress.
- **Cryogenic System:**
  - Refrigerator test completed. Helium transfer tube in production



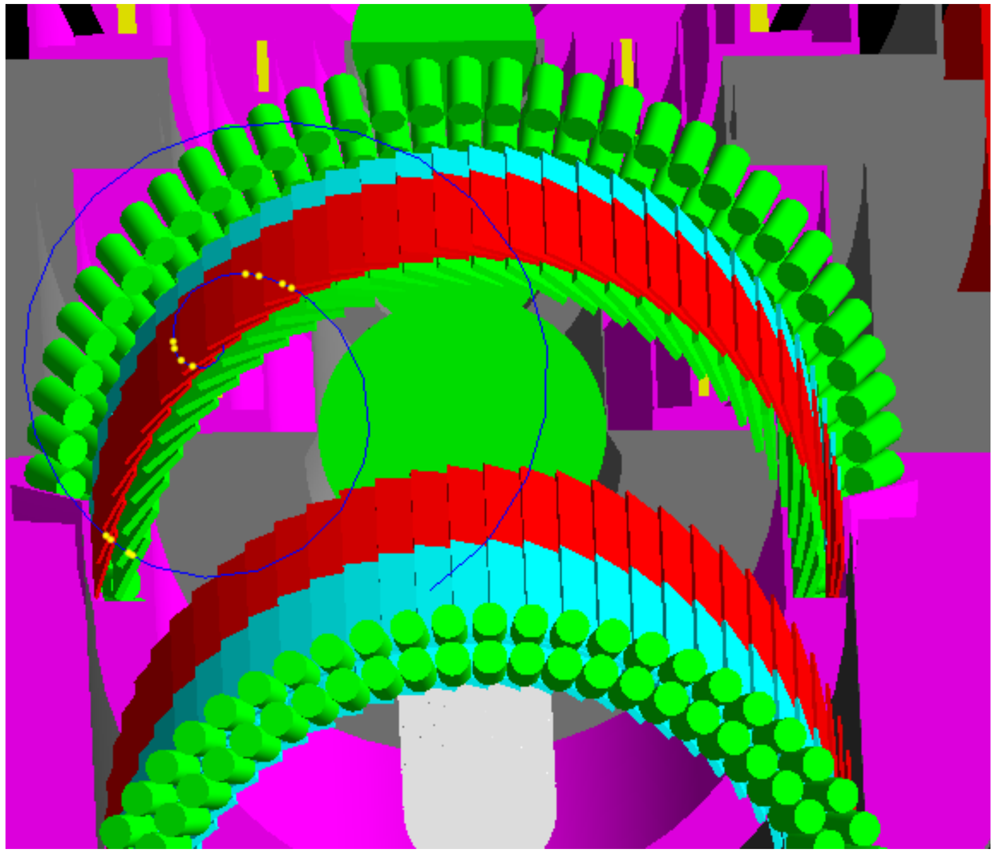
CyDet system

Detector for μ-e search in Phase-I



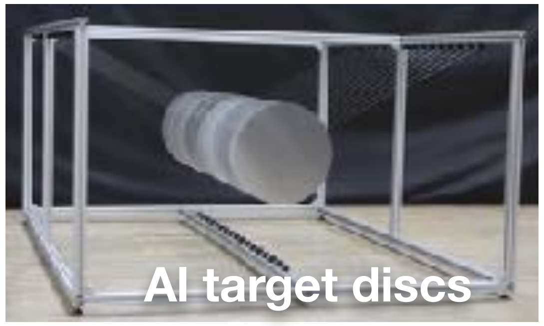
CDC (Cylindrical Drift Chamber)

- electron tracking in 1 T
- Δp = 200 keV/c (for p=105 MeV/c)
- Low-mass chamber
  - He:i-C_4H_{10} (90:10)
  - 0.5-mm CFRP inner wall
  - Al field wire, 126μm, 4986
  - Au-W sense wire, 25μm, 14562
- Alternating all stereo layer
  - 20 layers, $\pm$64~75 mrad



CTH (Cylindrical Trigger Hodoscopes)

- Scintillator & Acrylic Cherenkov
- Finemesh PMT readout
- 4-fold coincidence trigger

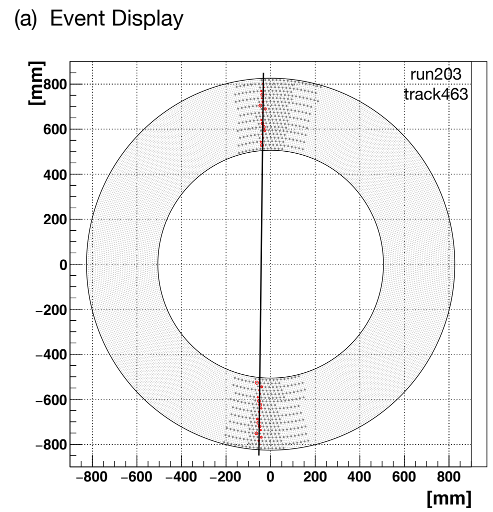


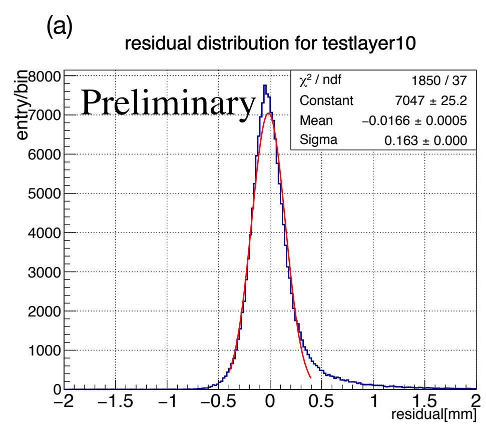
Stopping Target

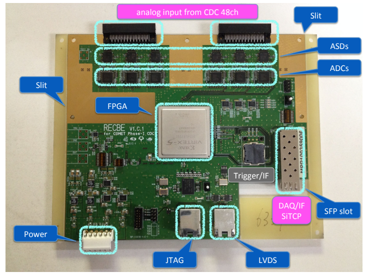
- Al target consists of 17 discs
- 100-mm radius, 0.2-mm thickness, 50-mm spacing.

CyDet status

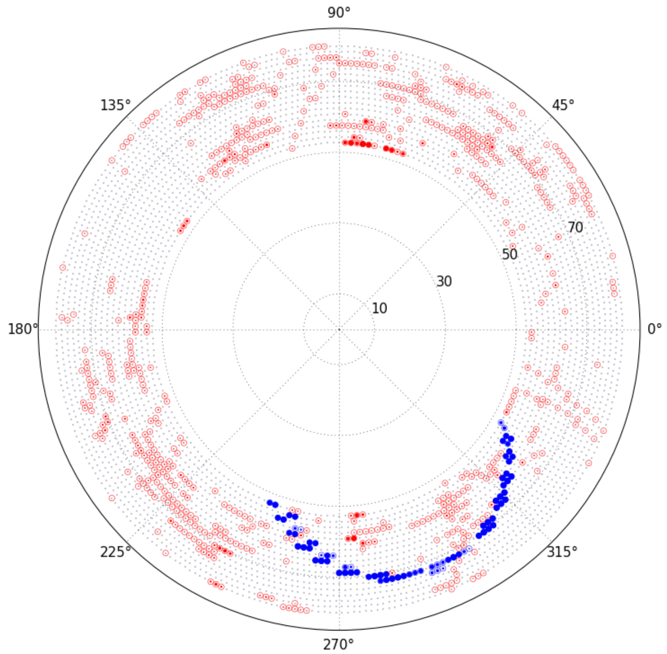
CDC cosmic-ray test is ongoing in KEK.
Good performance was obtained.





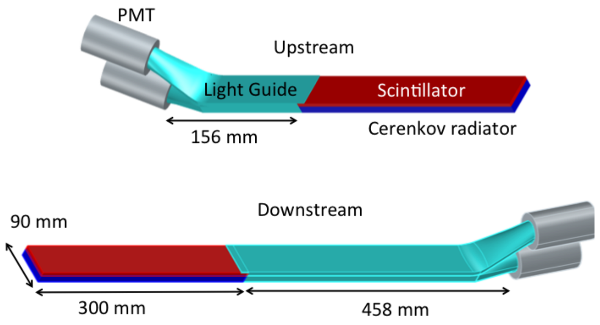


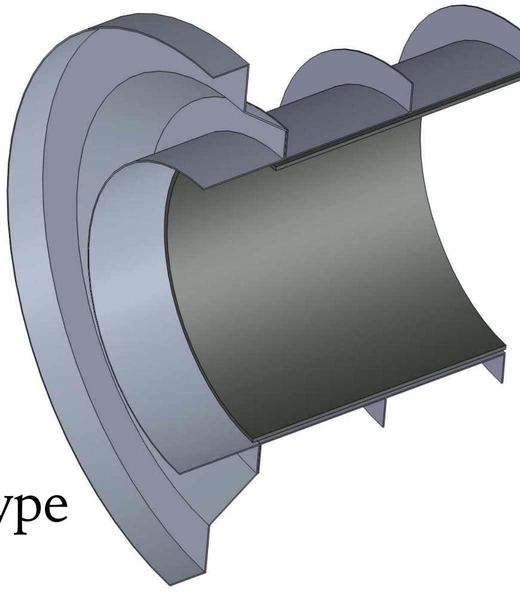
All 120 CDC FE boards were fabricated, and QA was finished in IHEP.



High-level track trigger

- Software-level algorithm was already established.
- can reduce background hits into 1/20 while retaining 99% of signals.

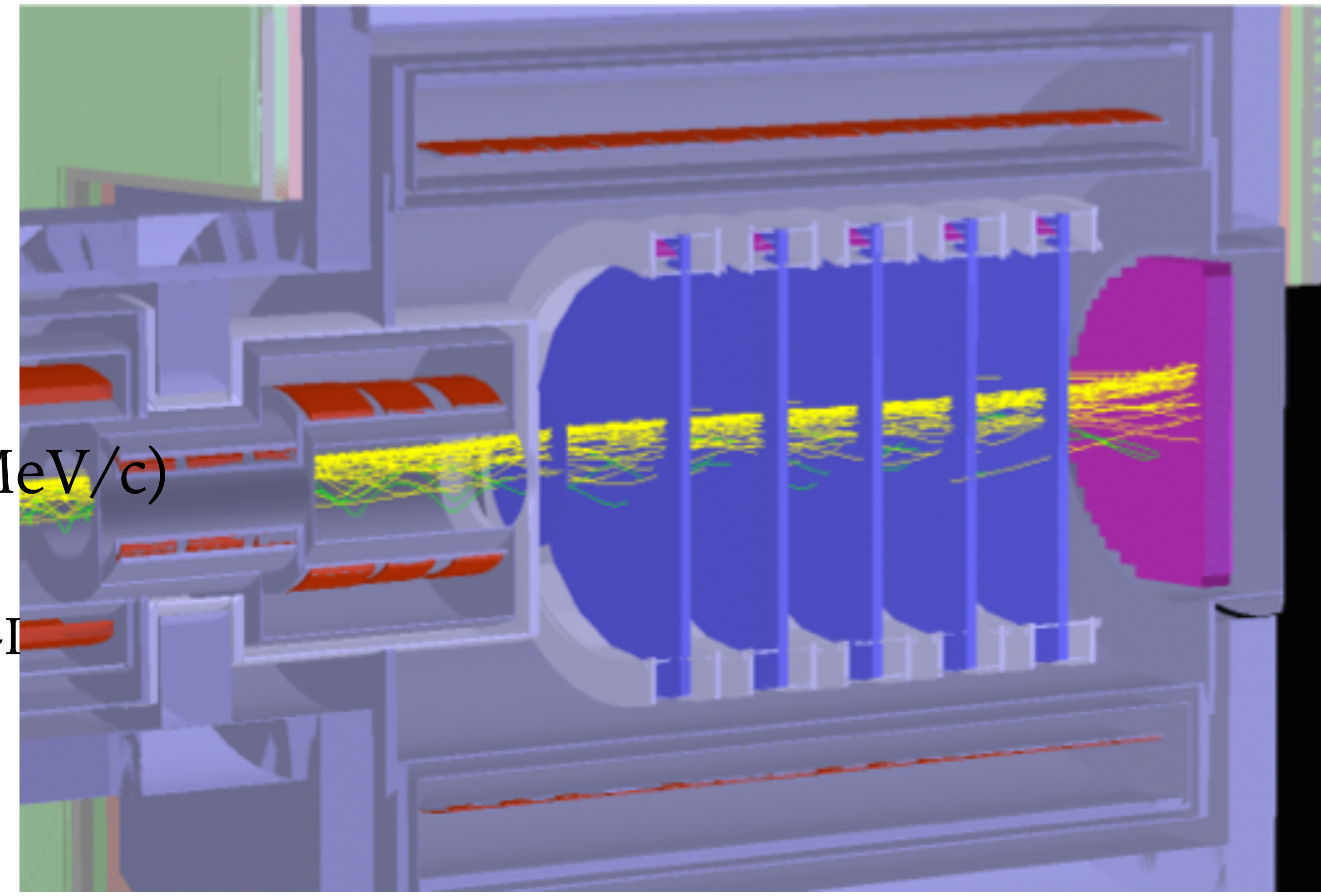




CTH structure prototype is under construction.

StrECAL system

Detector for beam measurement in Phase-I,
and μ-e search in Phase-II



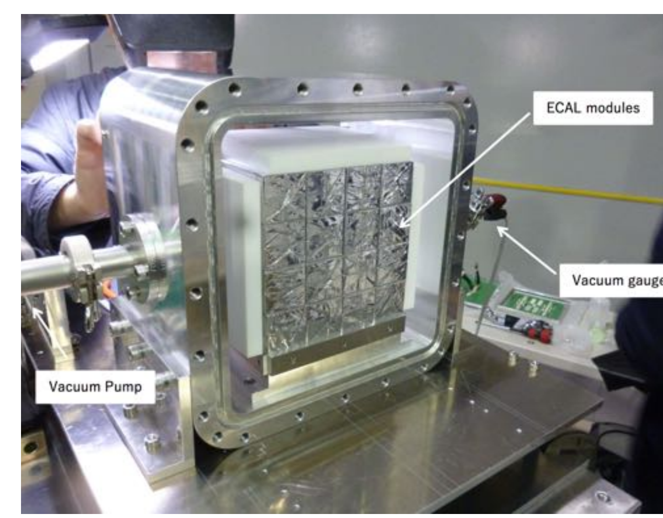
Straw Tube Tracker

- Operational in vacuum in 1 T
- 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
- 5 stations (xx'yy'×5)
- Ar:C_2H_6 (50:50)

Electron Calorimeter

- 1,920 LYSO crystals
  - 2×2×12 cm (10.5 radiation length)
- $\Delta E/E$ = 5% (for E=105 MeV)
- 40-ns decay time
- APD readout

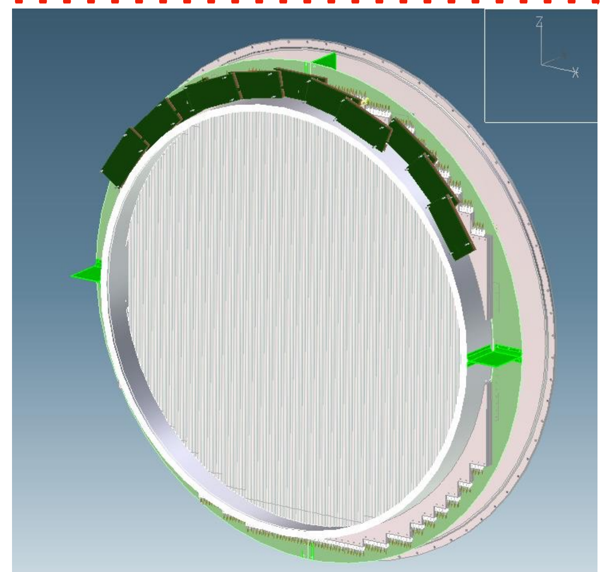
Straw Tracker prototype



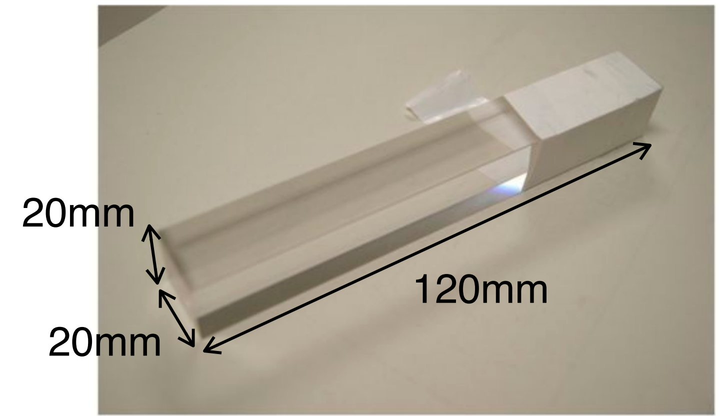
ECAL prototype

StrECAL status

Straw tube production for Phase-I was completed.

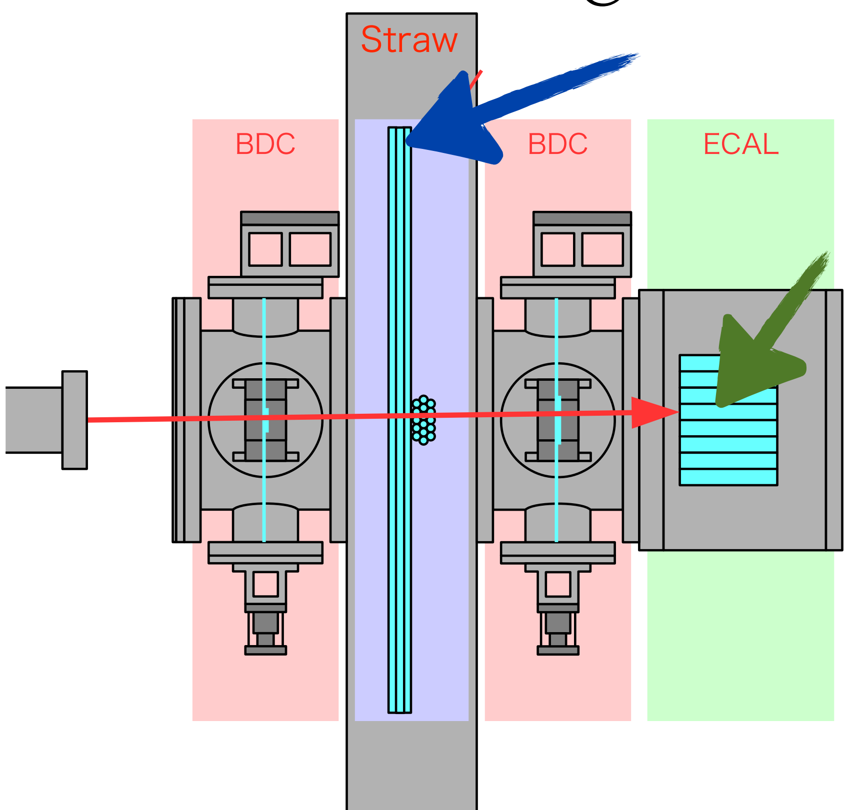


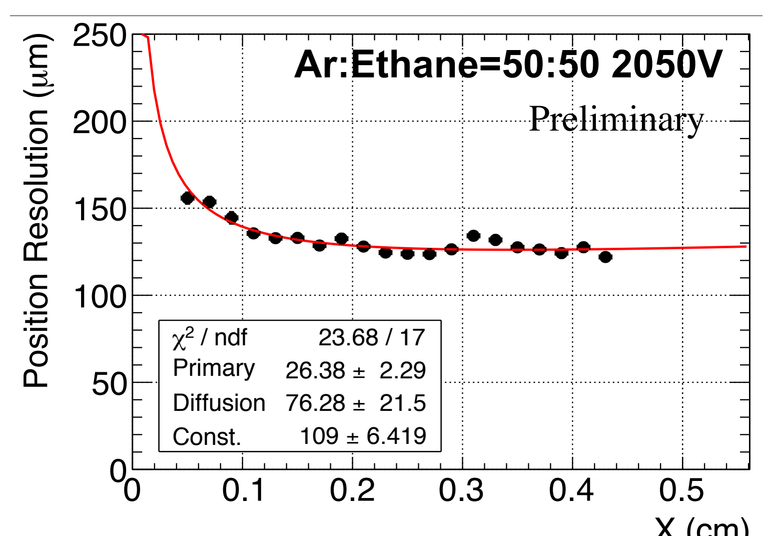
Thermal study of FE in gas manifold was carried out.
Straw station assembly will start soon.



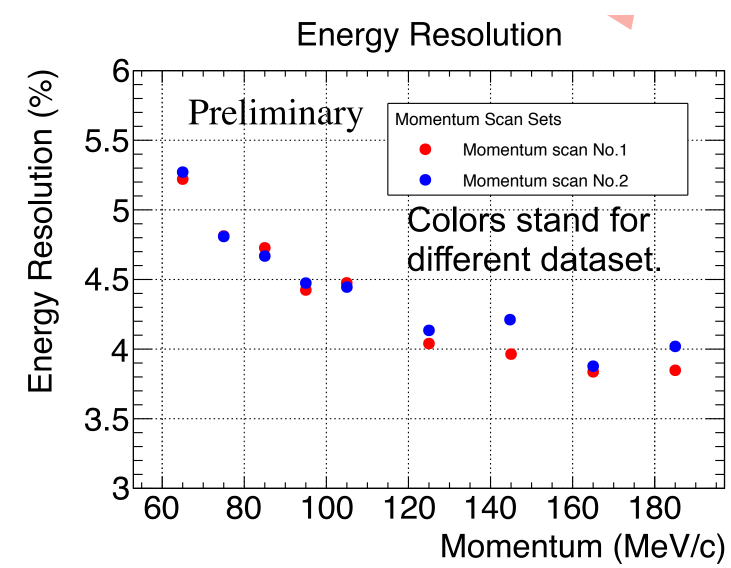
Buying procedure of ~500 LYSO for Phase-I is ongoing.

StrECAL Beam Test @ 2017





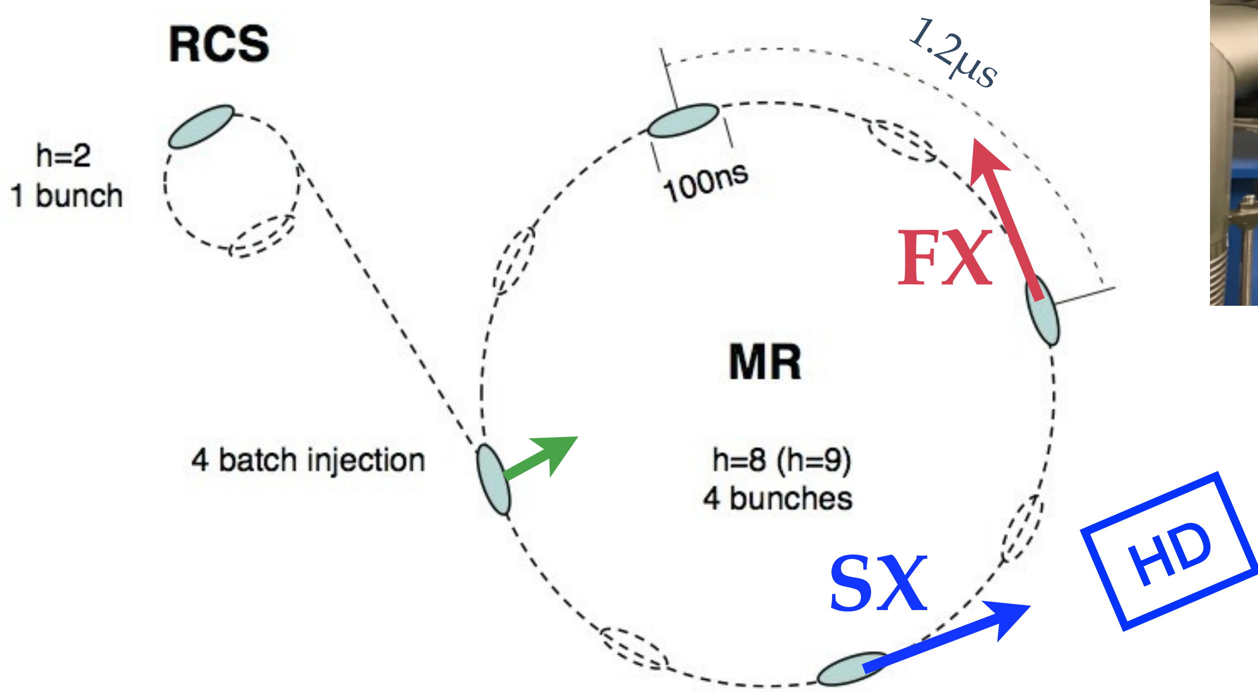
Straw:
position resolution < 150 μm

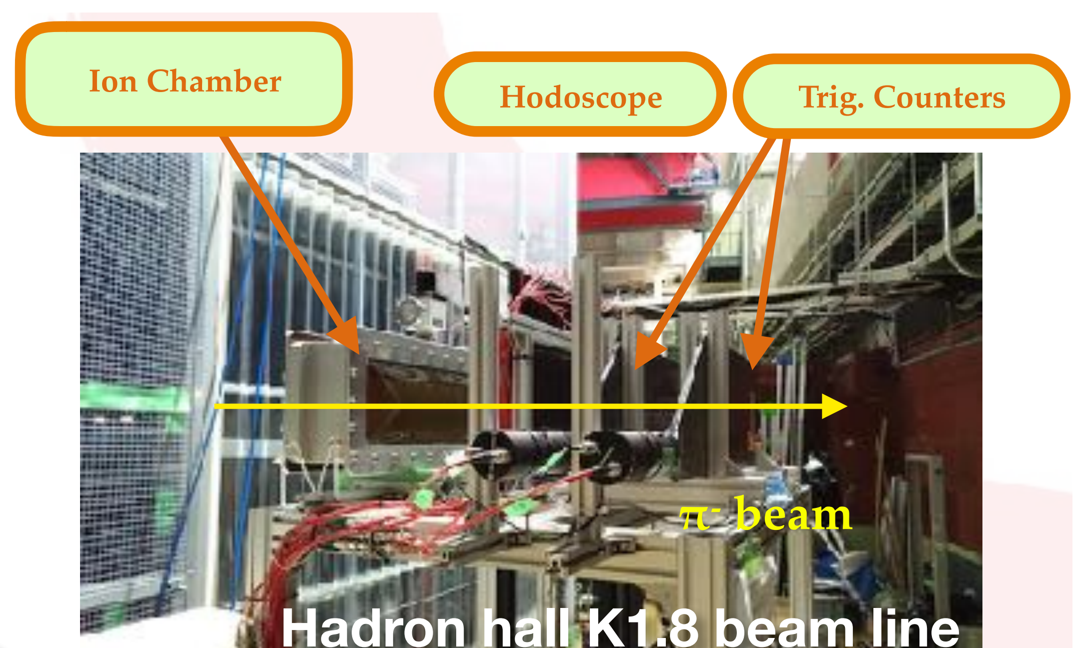


ECAL:
$\Delta E/E < 4.4\%$ @ 105 MeV

8 GeV test & Extinction measurement

8-GeV operation & extinction measurement were done at J-PARC in Jan.-Feb., 2018.





- Campaign was successfully carried out.
- Extinction was measured by both FX & SX.
  - ✓ First trial of 8 GeV Bunched SX.

See Hajime Nishiguchi's talk on Friday

Sensitivity and Background

Sensitivity

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 ($\varepsilon_{\rm mom}$)	0.93
Timing window ($\varepsilon_{\rm time}$)	0.3
Total	0.041

$103.6 < p_e < 106.0$ MeV/c

$700 < t_e < 1170$ ns

@ Phase-I

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

= 3×10^{-15}

Number of muons stopped inside targets

Fraction of μ-e conversion to the ground state = 0.9

Fraction of muons to be captured by Al target = 0.61

$N_\mu = 1.5\times10^{16}$ → **150 days by 3.2 kW**

@ Phase-II

1 year by 56 kW

+ Tungsten production target
+ 180◦ Transport Solenoid
+ Electron Spec. Solenoid

S.E.S **= 2×10^{-17}**

Background estimation

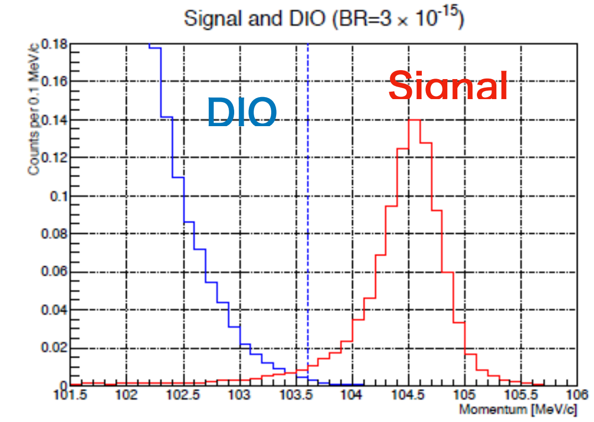
Detector

Beam

CR

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.



$103.6 < p_e < 106.0$ MeV/c

Assuming
$R_{ext} = 3\times10^{-11}$

$700 < t_e < 1170$ ns

@ Phase-I

BG is small enough

@ Phase-II

BG is still less than 1 by simulation

to be confirmed by Phase-I Beam Measurement

Summary & Prospects

- COMET aims to search for μ-e conversion with sensitivity of 3×10^{-15} / 2×10^{-17} at Phase-I / II.
- Detector & beam line preparation is intensively in progress.
- **Detector will be ready in 2019 for Phase-I, and commissioning will start soon after completing the beam-line construction.**
- Phase-II study is also in progress. We are able to optimize the Phase-II parameters based on the coming Phase-I results.

Backup

Summary of COMET Phase-I / II

	Phase-I	Phase-II #
Proton Beam Power	3.2 kW (8 GeV×0.4 μA)	56 kW (8 GeV×7 μA)
# of protons / acc. cycle	6.2×10^{12} / 2.48 sec	1.1×10^{14} / 2.48 sec
DAQ time	1.26×10^{7} sec (146 days)	2.0×10^{7} sec (231 days)
Total protons on target	3.2×10^{19}	9.0×10^{20}
# of muons stop / proton	4.7×10^{-4}	1.6×10^{-3}
Total muons stop	1.5×10^{16}	1.4×10^{18}
Detector Acceptance+Efficiency	0.041	0.057
S.E.S.	**3.0×10^{-15}**	**2.0×10^{-17}**
# of BG	0.032	< 1

Phase-II parameters are tentative, more improvement under study

Related (byproduct) measurements

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

B.Yeo, Kuno, MJ.Lee, Zuber, PRD96, 075027 (2017)

- Lepton Number Violation process.
- Target nucleus mass relation is required: $M(A,Z-2) < M(A,Z-1)$,
  - to eliminate radiative muon capture BG
- 10,000× sensitivity improvement is possible.
- Promising isotopes: ^{40}Ca, ^{32}S

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

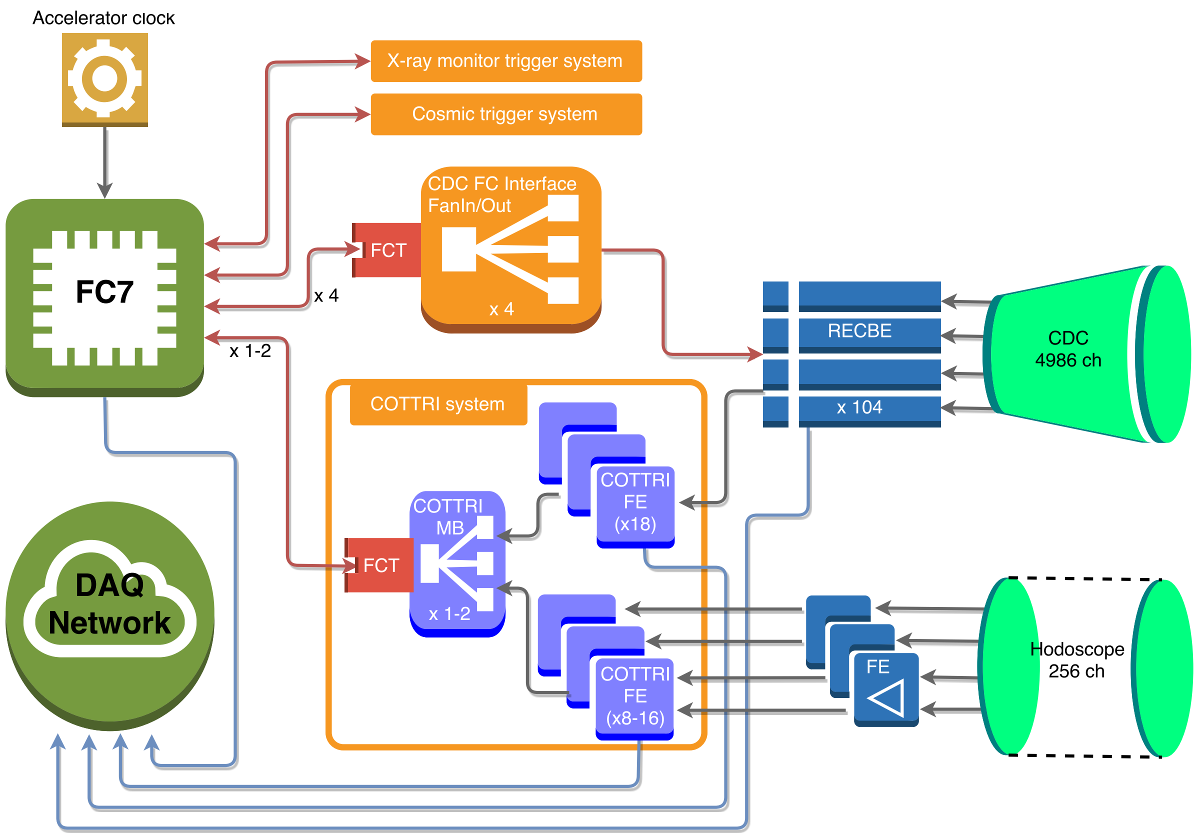
Koike, Kuno, J.Sato, Yamanaka, PRL105, 121601 (2010).
Uesaka, Kuno, J.Sato, T.Sato, Yamanaka, PRD93, 076006 (2016), PRD97, 015017 (2018).

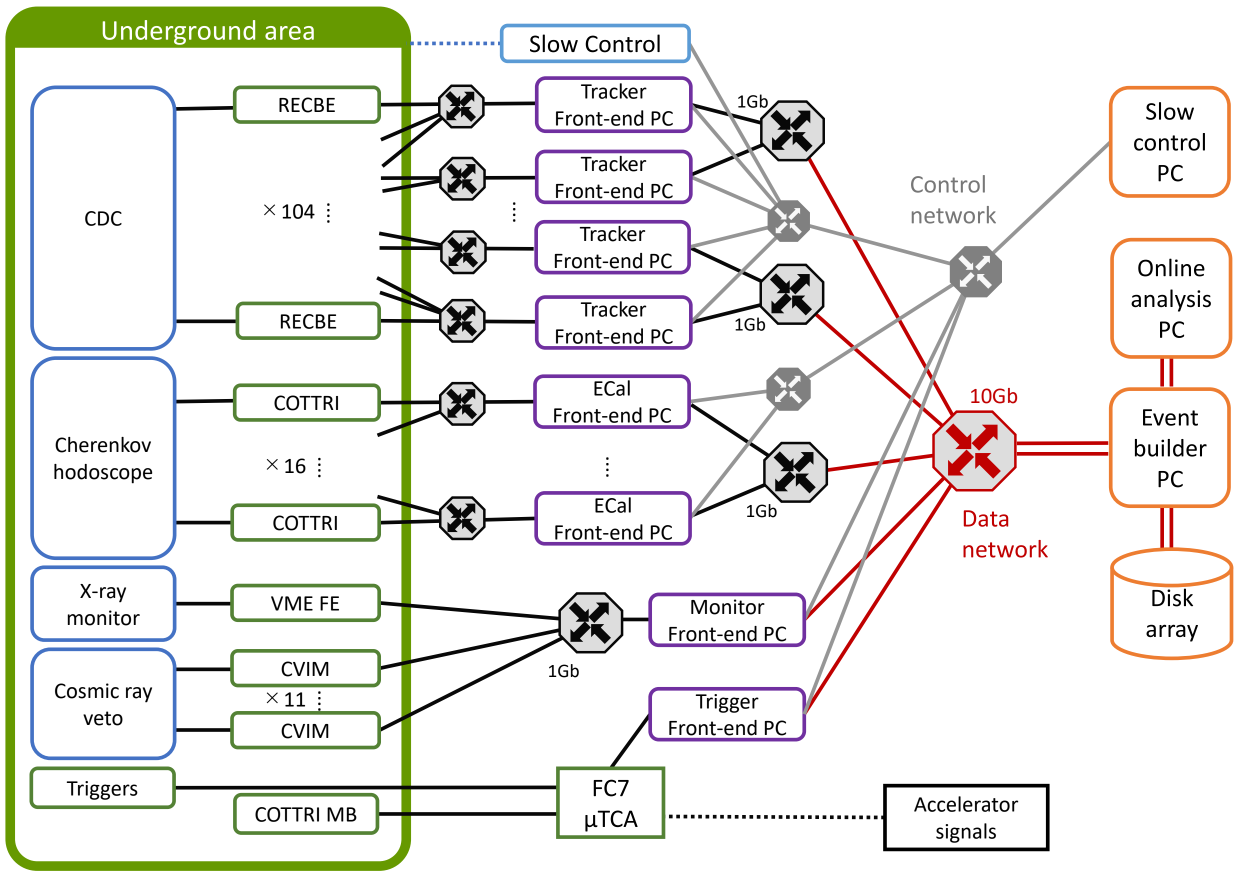
- The Coulomb attraction from the nucleus in a heavy muonic atom leads to significant enhancement in its rate.
- Z dependence could be used to distinguish interaction types.

Joe Sato's talk on Friday

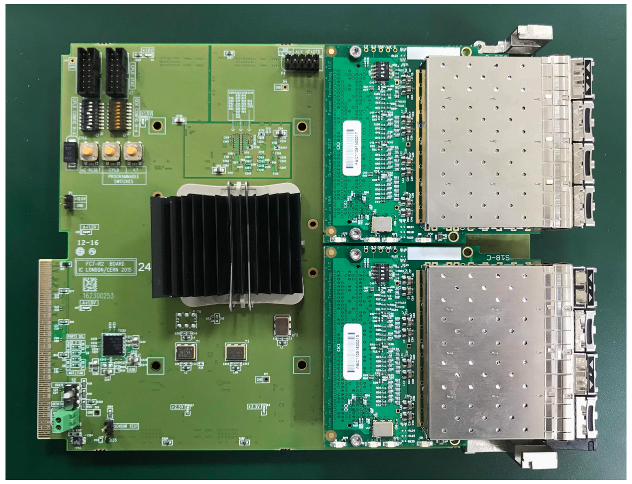
Feasible in Phase-I

Trigger & DAQ

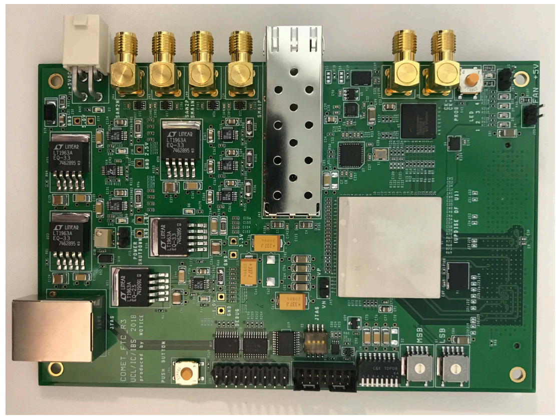




FC7



FCT



I/F board for FCT & RECBE

Cosmic-Ray Veto detector

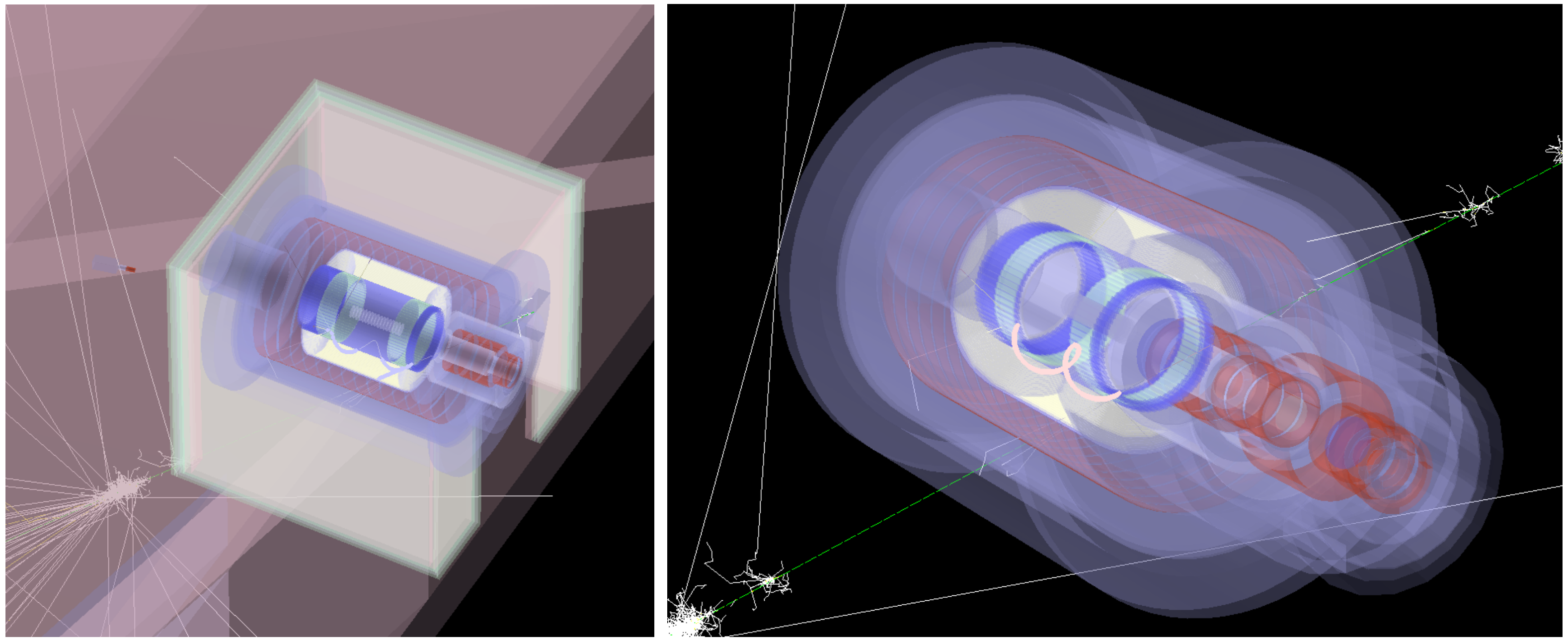
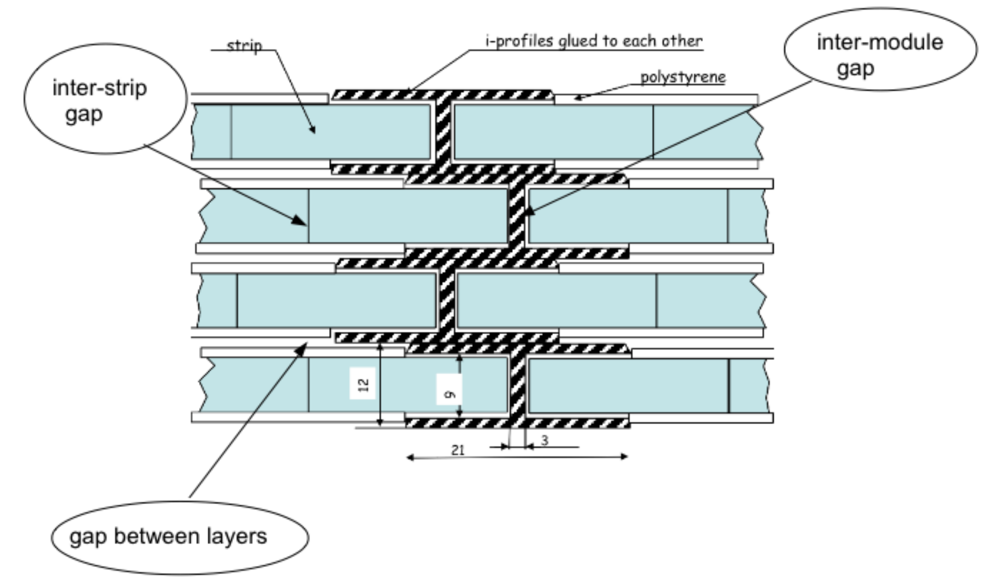


Figure 12.20: *One of the cosmic ray events which escapes the detection by the CRV and enters the BS region, creating an electron reaching the CDC. The same event shown for the whole detector region (left) and a zoomed view (right).*



CRV strip layout

CRV inner shield