# Searching for Muon to Electron Conversion with the COMET Experiment

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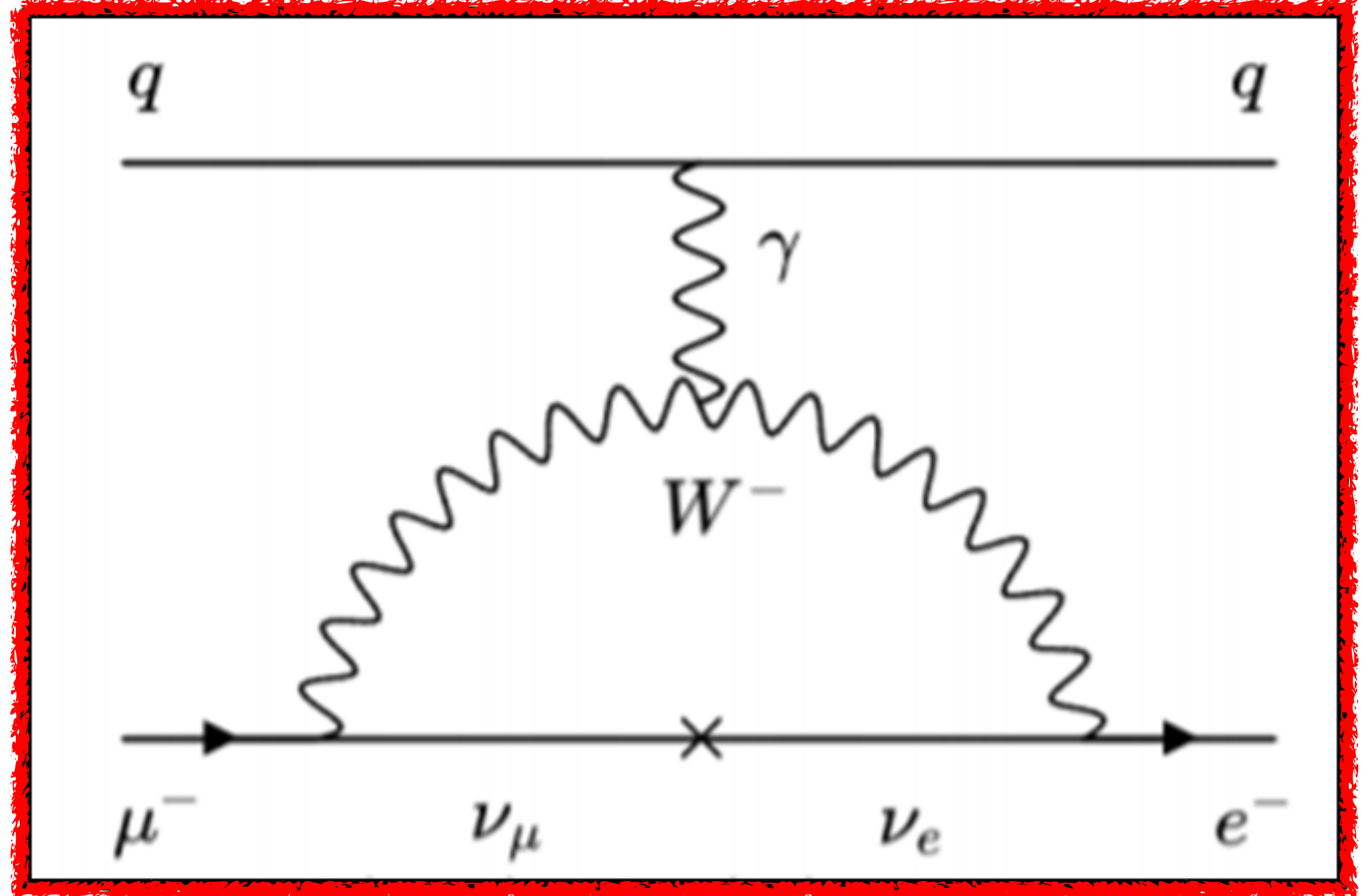
On behalf of the COMET collaboration

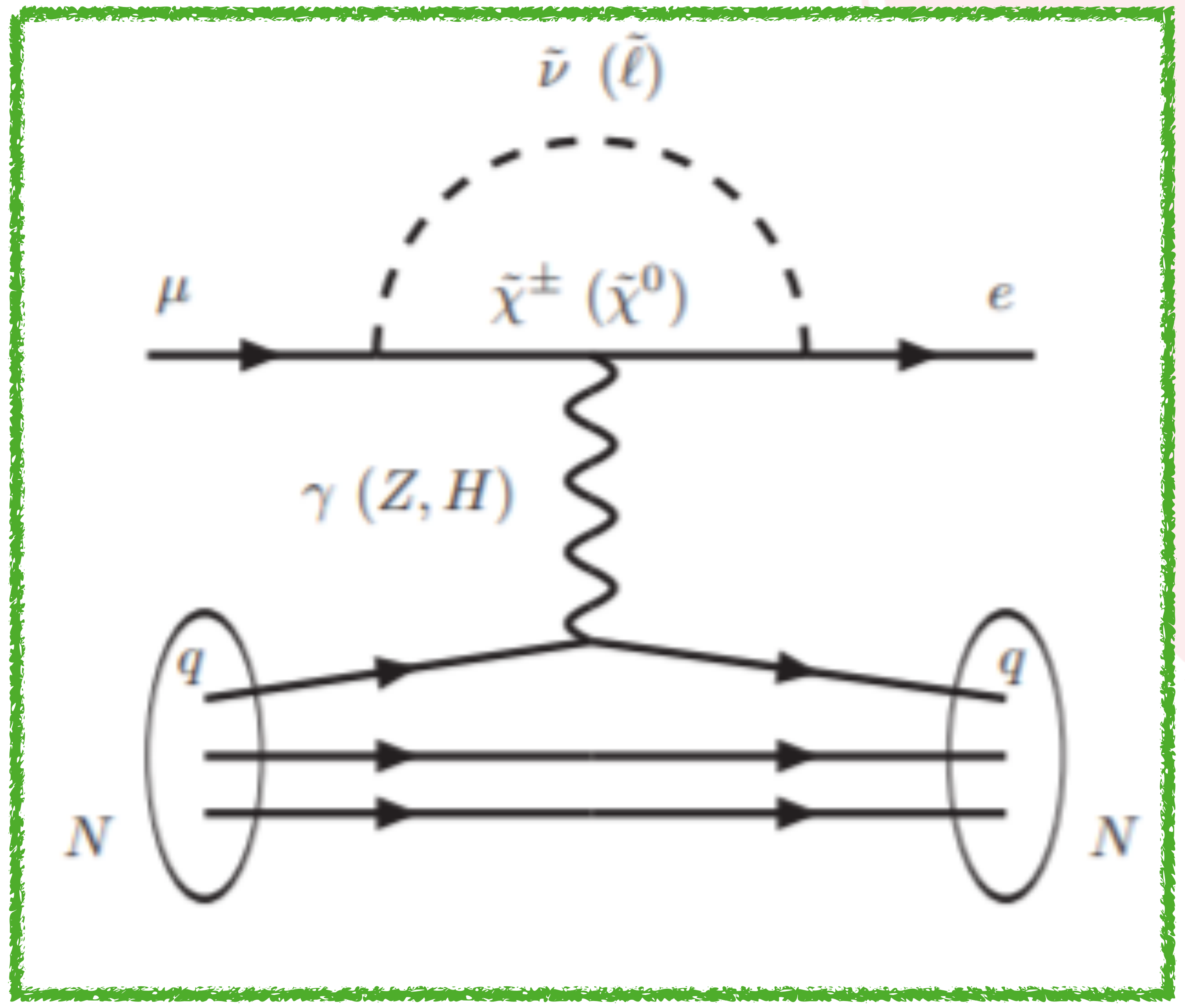
*NuFact22 @ Salt Lake City, July 30 - August 6th 2022*

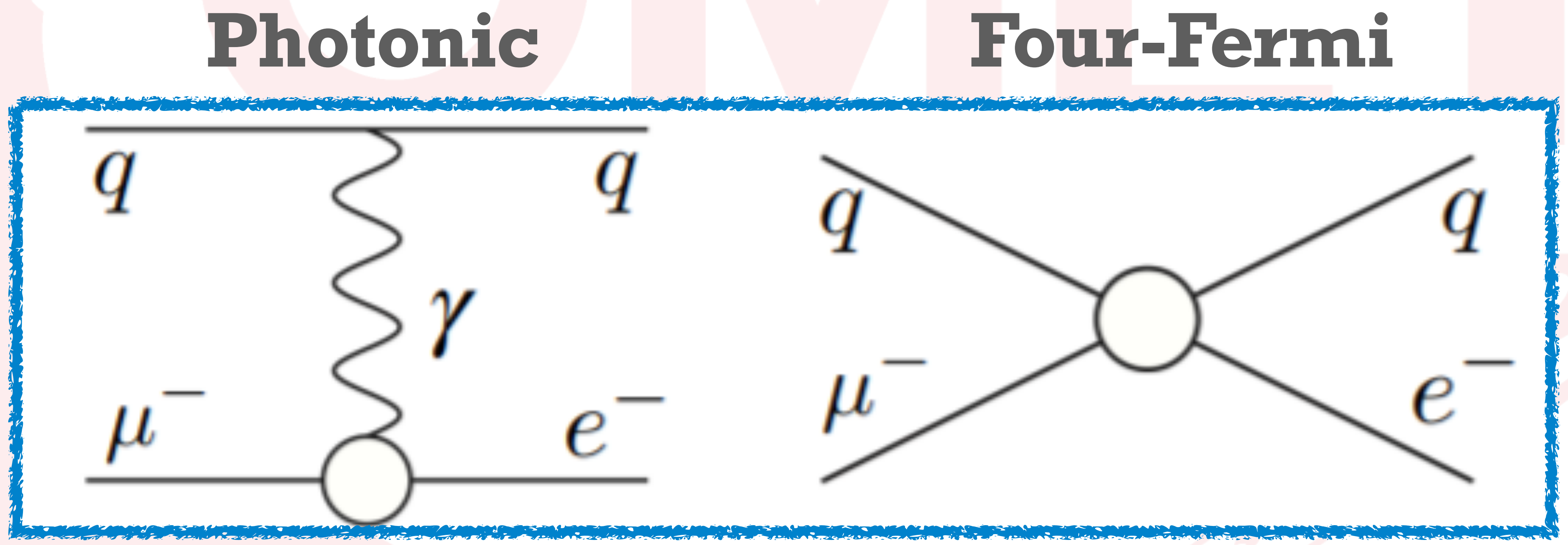
# Charged Lepton Flavour Violation

- Flavour violation in quark and neutrino sectors but not observed in charged leptons:
  - SM physics = unobservable branching ratio for CLFV processes
  - Observation of CLFV (such as $\mu \to e$) = **clear signal for new physics!**
- Dipole + contact operators in effective field theories
- Probe new physics well beyond collider energy scales ($\Lambda$)
- Many specific BSM models (SUSY, leptoquark, Z')

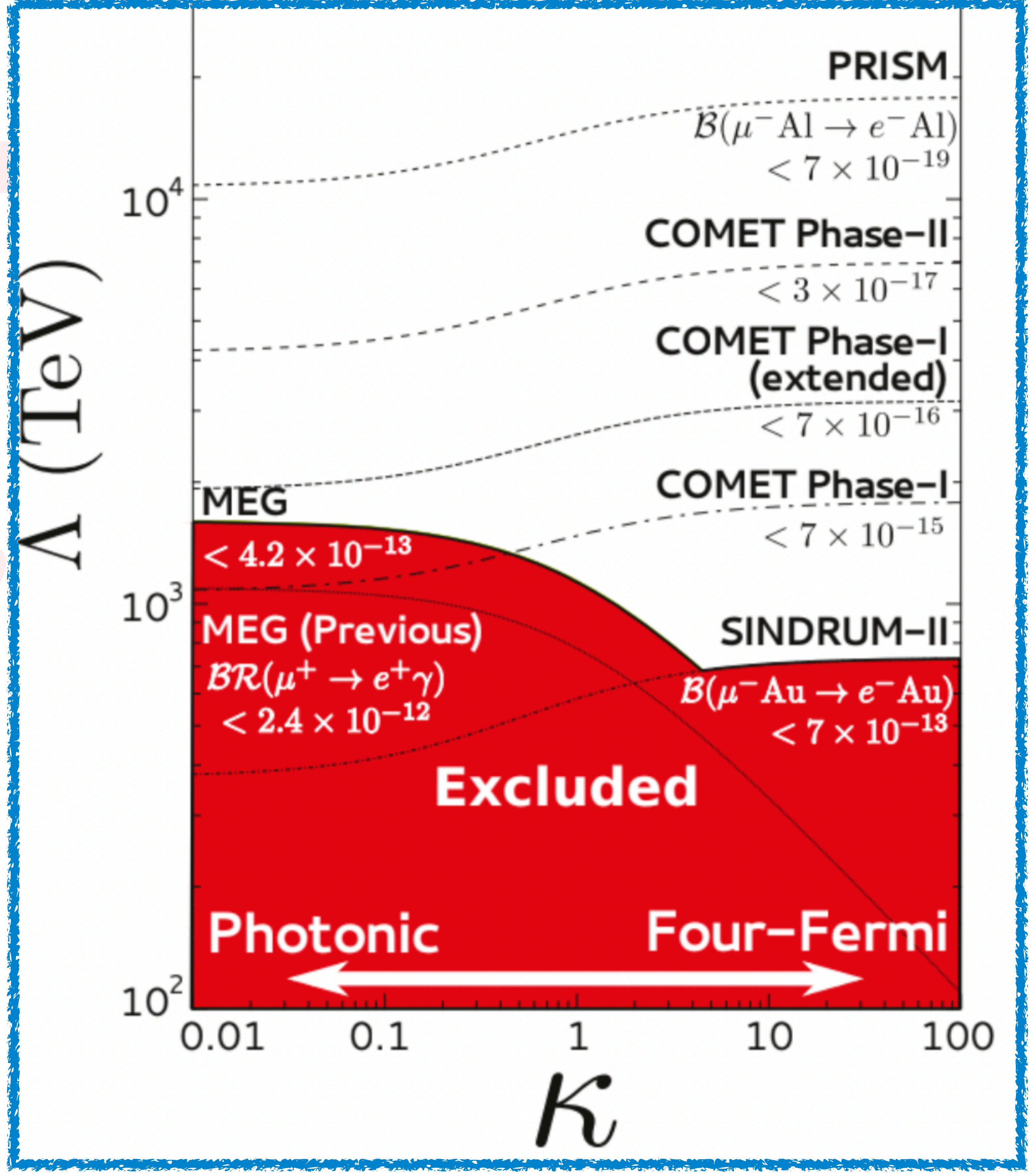



$$BR(\mu \to e) \approx \mathcal{O}(10^{-55})$$



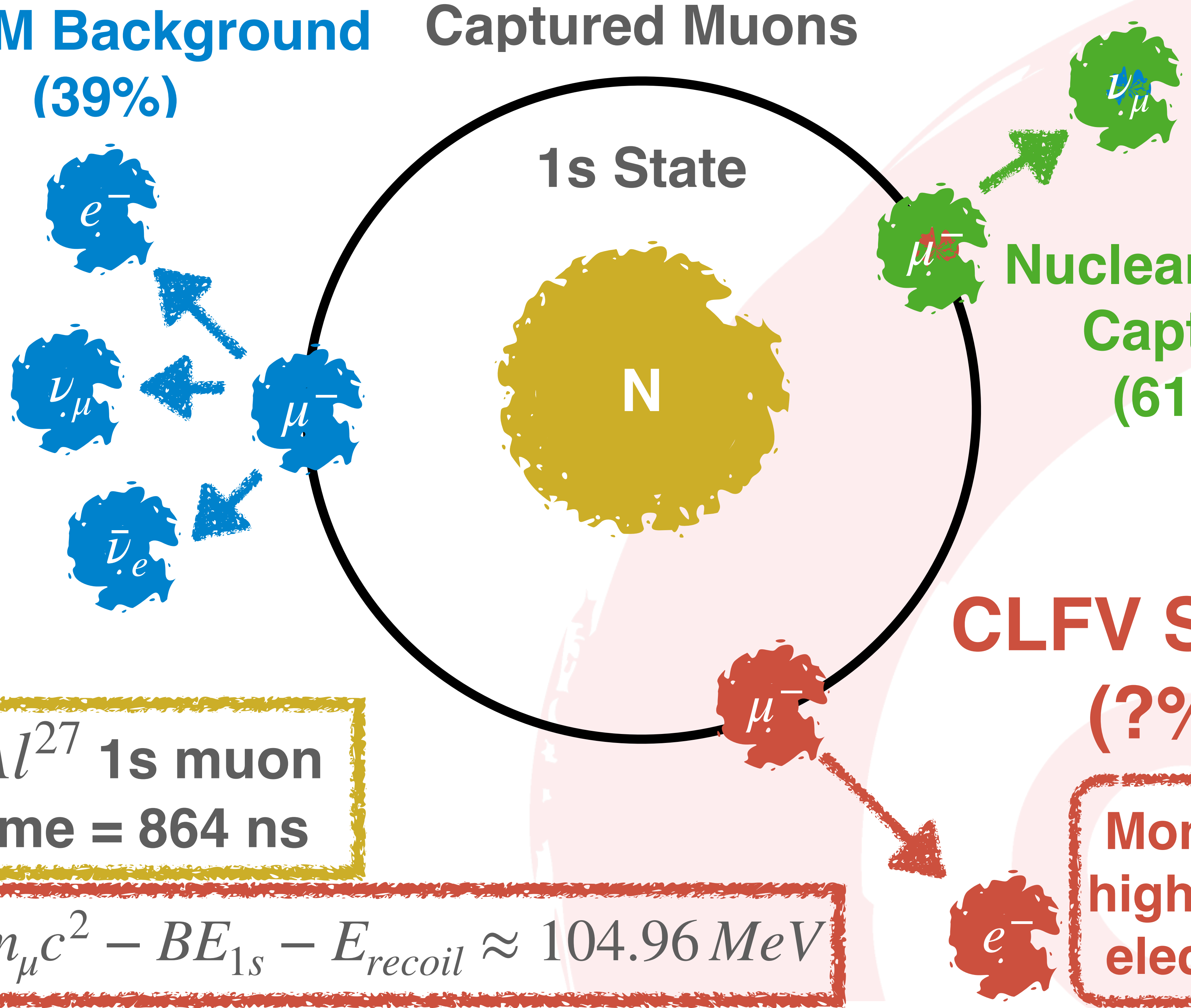

$$\mathcal{L} = \frac{1}{\kappa+1}\frac{m_\mu}{\Lambda^2}(\bar{\mu}_R\sigma^{\mu\nu}e_L F_{\mu\nu}) + \frac{\kappa}{\kappa+1}\frac{1}{\Lambda^2}(\bar{\mu}_R\gamma^\mu e_L)(\bar{q}_L\gamma_\mu q_L) + h.c.$$



# Muon to Electron Conversion $(\mu^- + N \rightarrow e^- + N)$

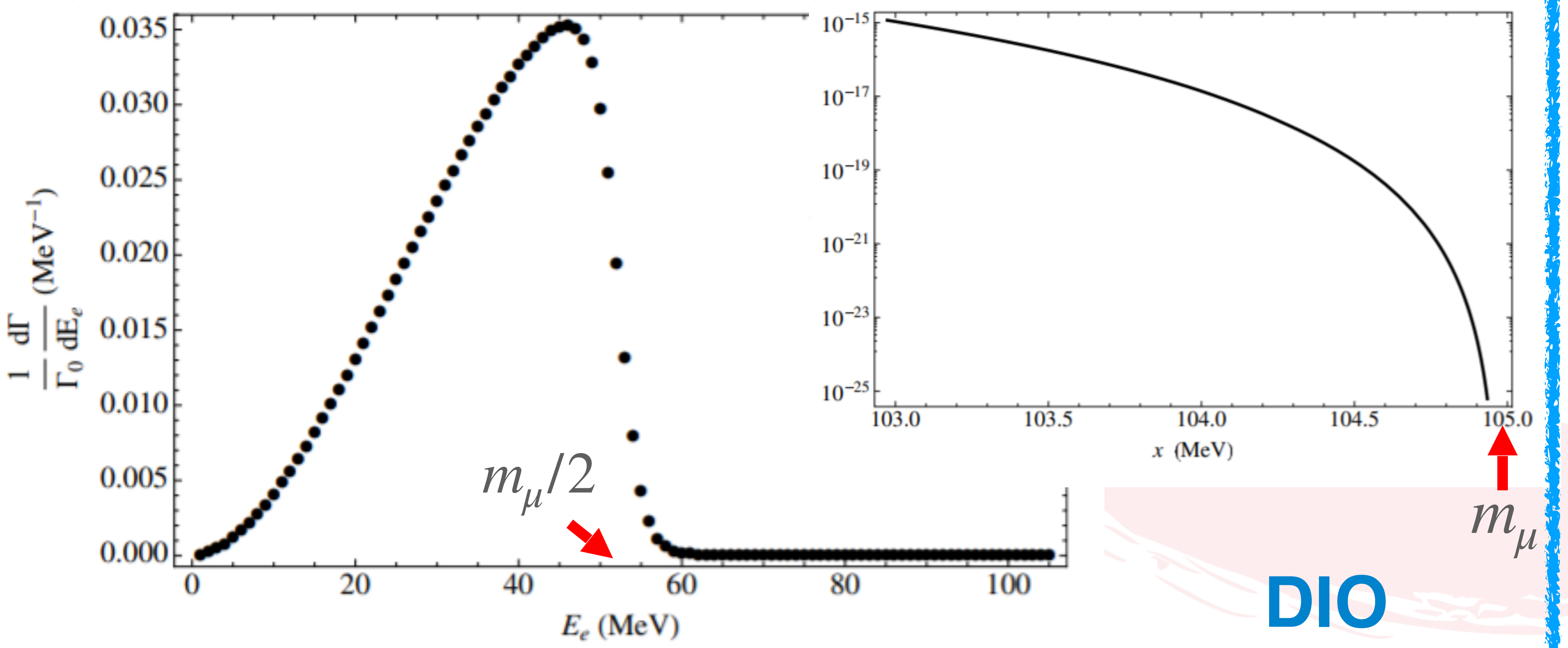
DIO SM Background (39%)

Captured Muons




N = $Al^{27}$ 1s muon lifetime = 864 ns

$E_e = m_\mu c^2 - BE_{1s} - E_{recoil} \approx 104.96\, MeV$




Spectra: A. Czarnecki, X.G. i Tormo, and W.J. Marciano, Phys. Rev. D, 84, 013006

## Some Present Upper Limits (SINDRUM II)

| Year | CR Bound (90% CL) | Nucleus |
|---|---|---|
| 2006 | $7.0 \times 10^{-13}$ | Au |
| 1998 | $6.1 \times 10^{-13}$ | Ti |
| 1996 | $4.6 \times 10^{-11}$ | Pb |

**The next generation of experiments (COMET, Mu2e) will push sensitivity to $\mathcal{O}(10^{-17})$**

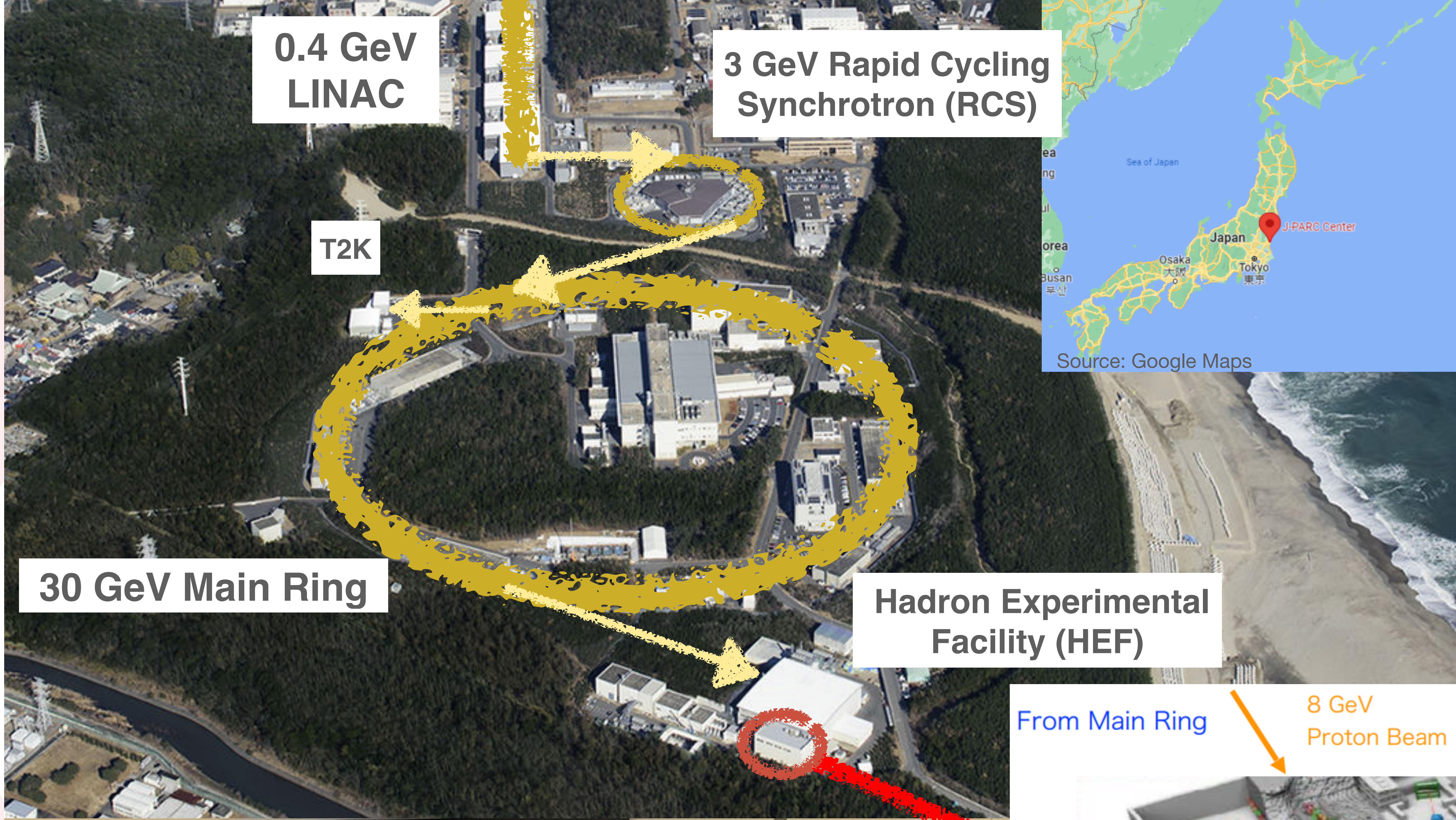
Sources: *A search for μ-e conversion in muonic gold*, The SINDRUM II Collaboration, Eur. Phys. J. C 47 (2) 337-346 (2006)
Wintz P. et al. SINDRUM II Collaboration, Proceedings of the First International Symposium on Lepton and Baryon Number Violation (1998)
Honecker W. et al. (SINDRUM II Collaboration), Phys. Rev. Lett., 76 (1996) 200.

## Strategies needed for improving $\mu \rightarrow e$ experimental sensitivity

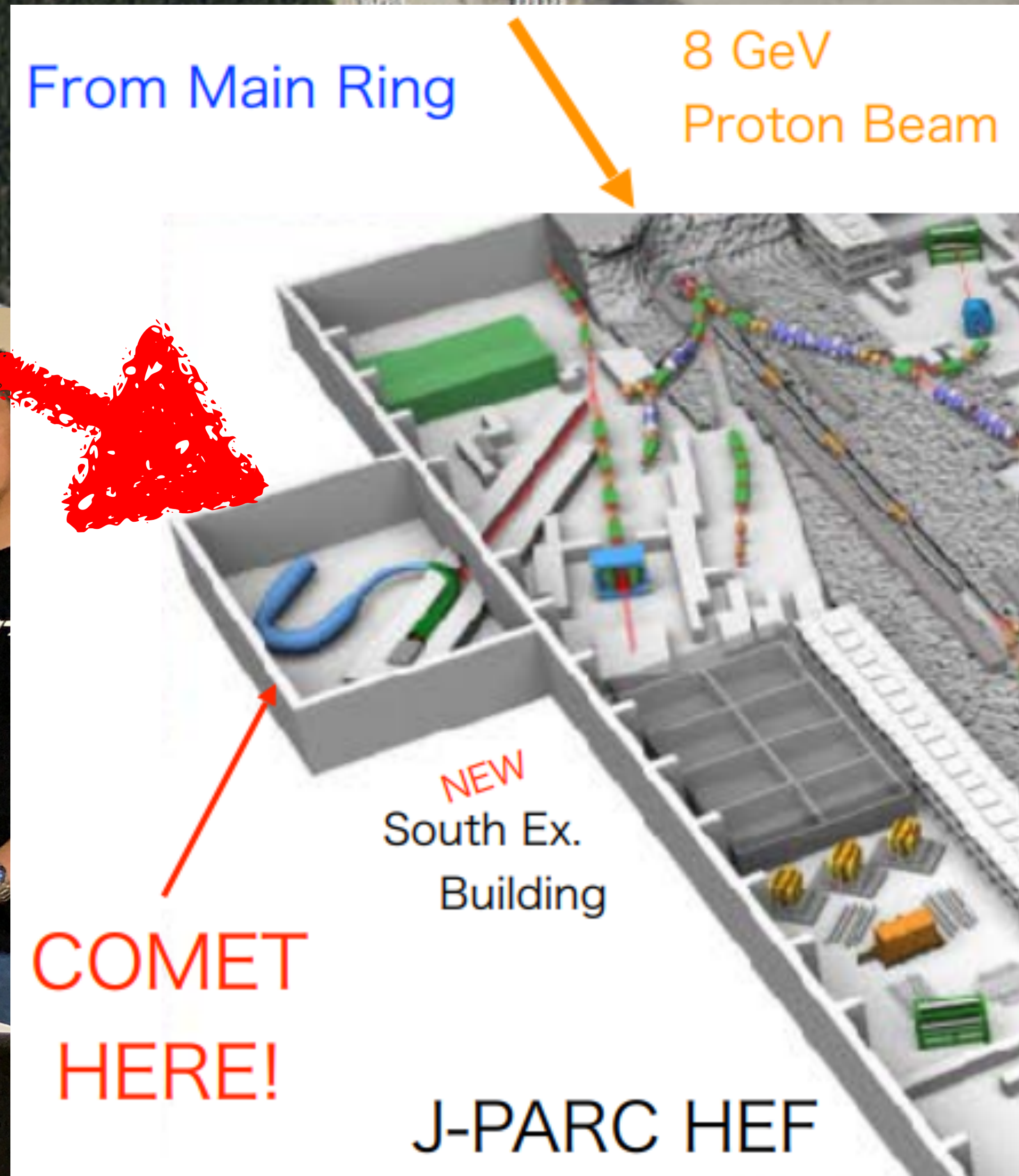
- Excellent momentum resolution (< **200 keV/c**) → Separation of decay in orbit (DIO) from signal
- High statistics
- Background suppression → Beam related backgrounds via **pulsed muon beam**, atmospheric muons via veto detector, etc

# The COMET Experiment

- COMET (**Co**herent **M**uon to **E**lectron **T**ransition) Experiment is searching for $\mu^- + Al \rightarrow e^- + Al$ with increased sensitivity
- 200+ members over 48 institutes in 18 countries
- Construction happening Hadron Hall at J-PARC in Tokai, Japan



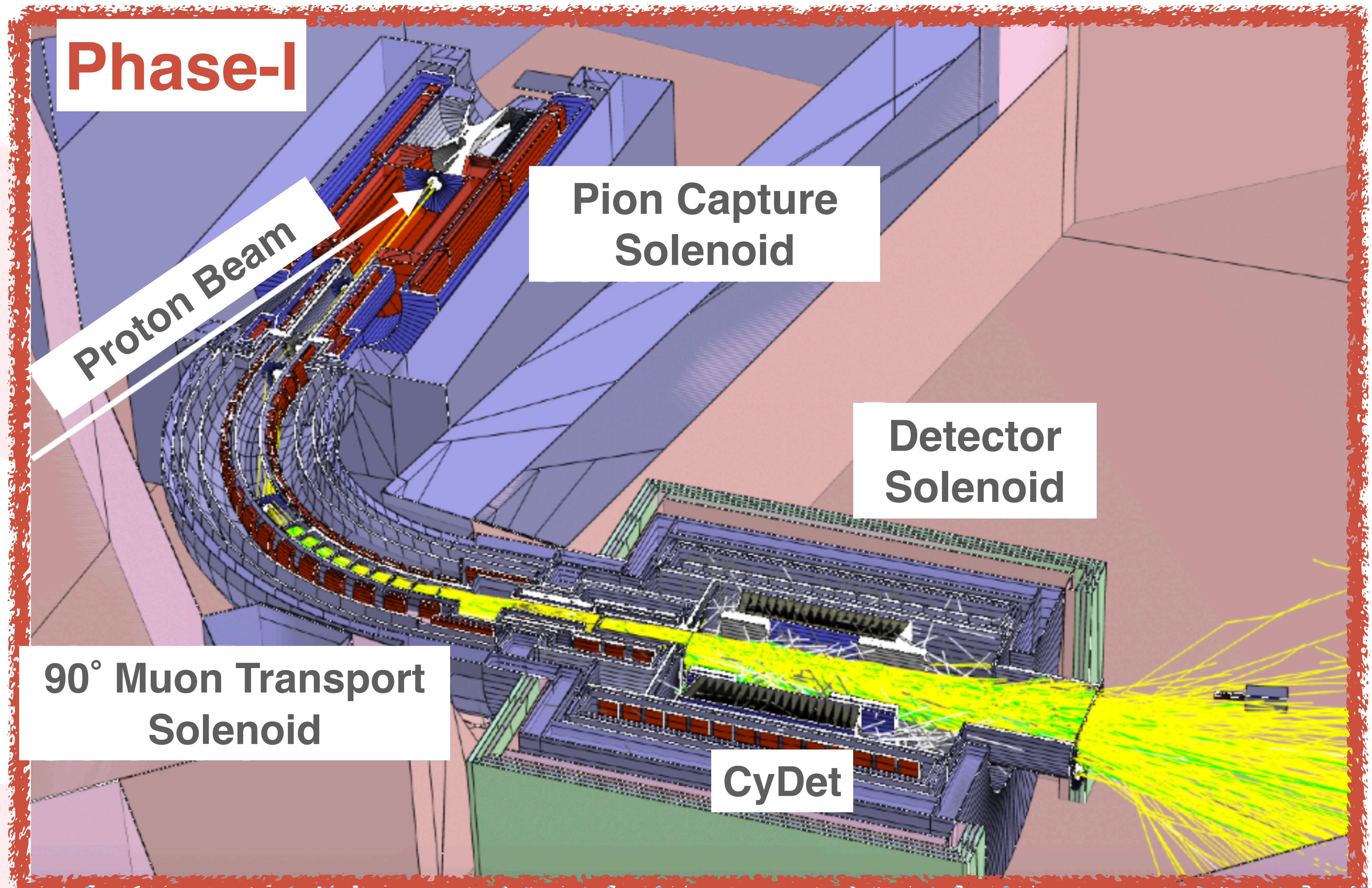


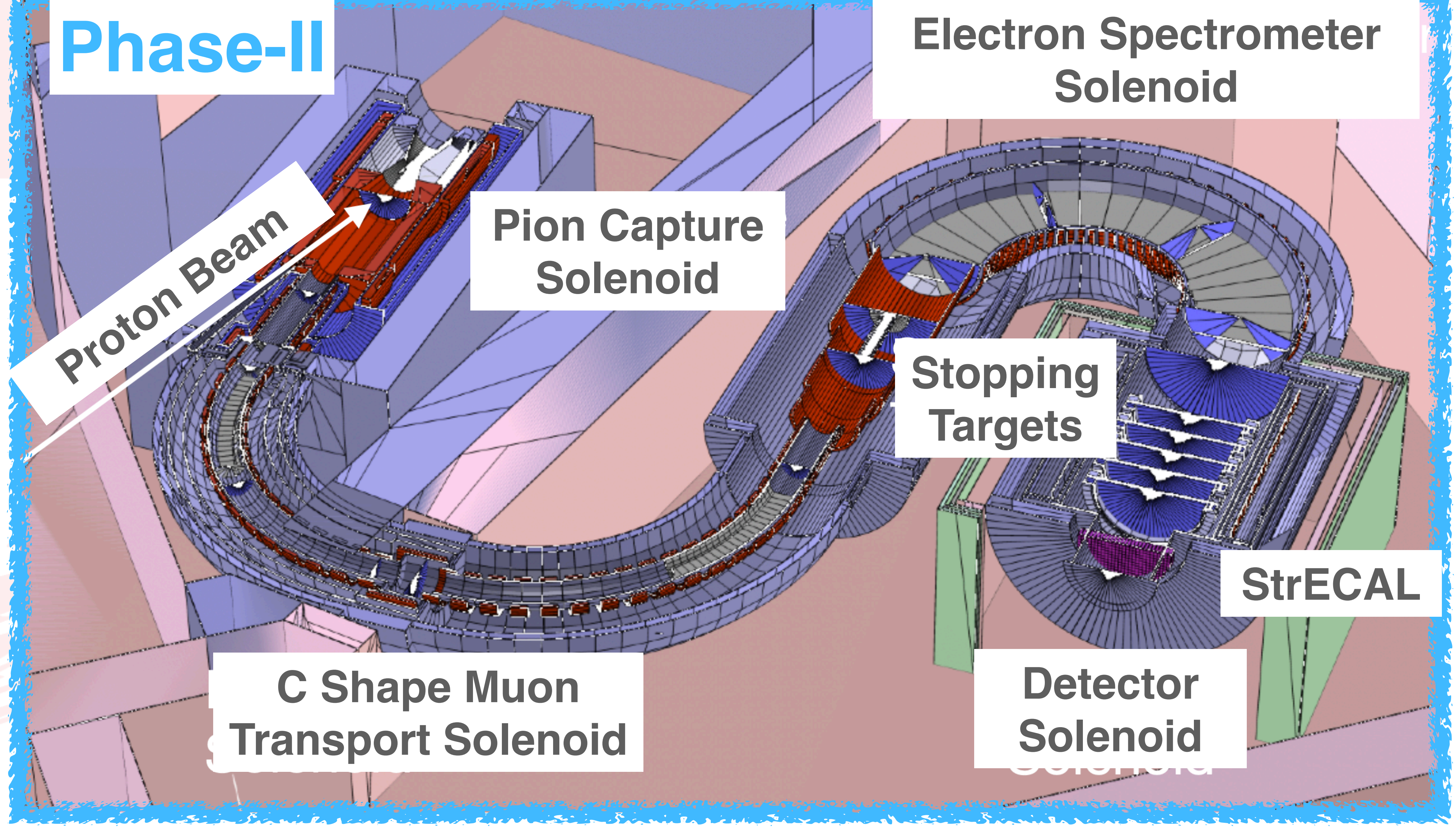


# The COMET Experiment

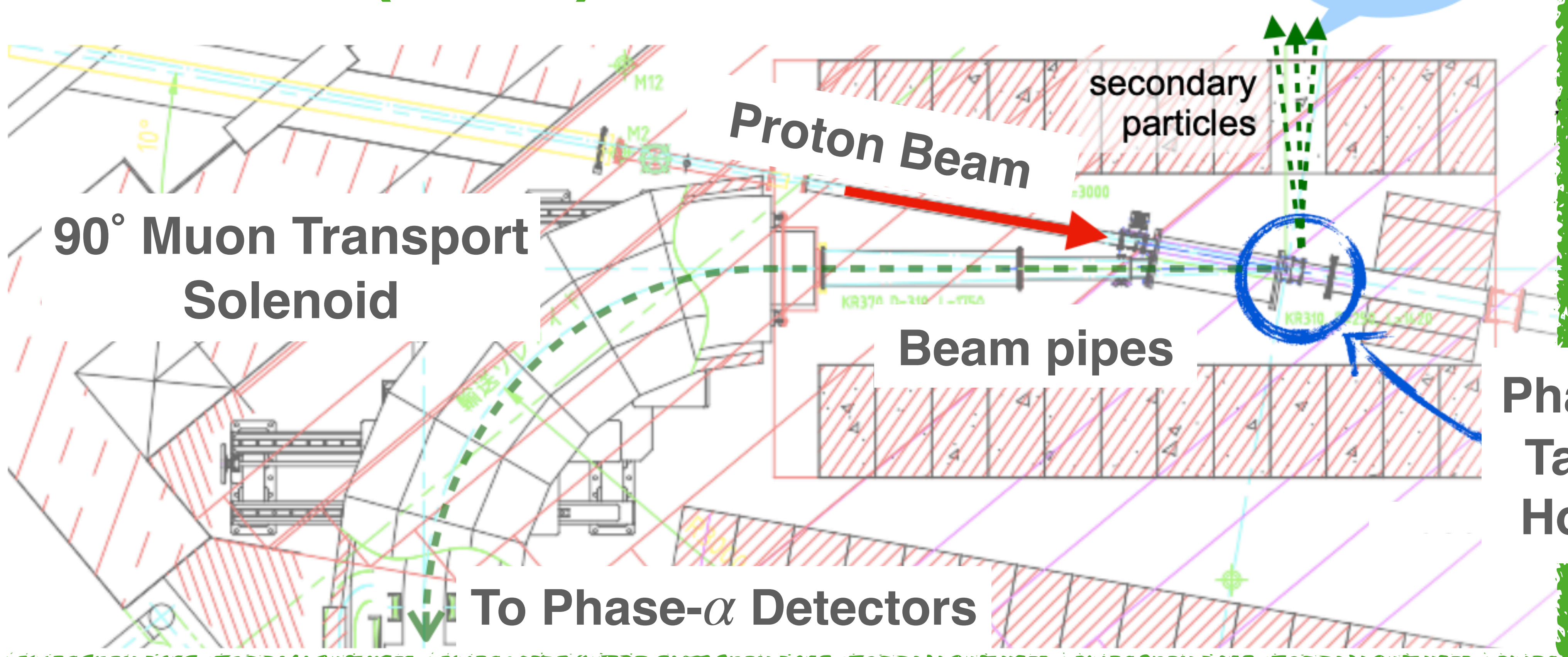
Staged Approach

| | Phase-I (2024) | Phase-II |
|---|---|---|
| SES | $3.1 \times 10^{-15}$ | $1.4 \times 10^{-17}$ |
| Proton Beam | 8 GeV (3.2 kW) | 8 GeV (56 kW) |
| Transport Solenoid | 90˚ bend | C-shape |
| Stopped Muons | $1.5 \times 10^{16}$ | $1.6 \times 10^{18}$ |
| Runtime | 150 days | 260 days |
| Detectors | CyDet (physics)<br>StrECAL (beam + background) | StrECAL (physics) |



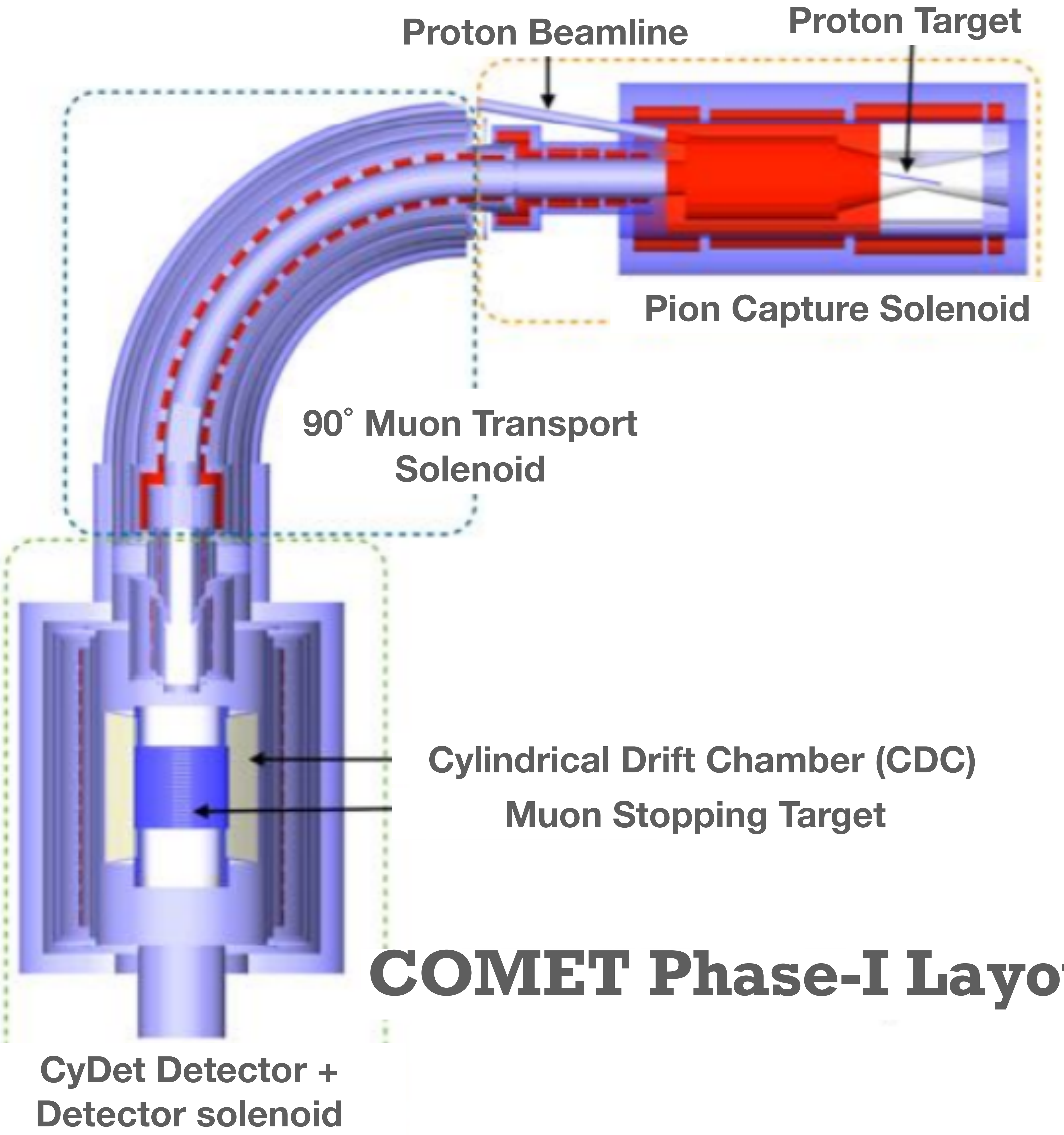

## Phase-$\alpha$ (2023)




Initial low intensity beam run

# Phase-I Overview

- 150 days of data collection beginning in **2024**
- Single event sensitivity = $3.1 \times 10^{-15}$
- Important design factors to improve sensitivity:
  - ➢ Intense muon beam - $\mathcal{O}(10^{18})$ muons produced → results in ~ $1.2 \times 10^{9}$ **muons stopped per second**!
  - ➢ **Pulsed beam structure** excludes prompt backgrounds → Al stopping target works with $\mathcal{O}(1\ \mu s)$ bunch intervals
  - ➢ Momentum selection in **curved solenoid** with optimised **dipole fields**




**COMET Phase-I Layout**

# Phase-I Sensitivity Expectations

Single event sensitivity expected in Phase-I:

$$B(\mu^- + Al \rightarrow e^- + Al) = \frac{1}{N_\mu \times f_{cap} \times f_{gnd} \times A_{\mu-e}} = 3.1 \times 10^{-15}$$

$N_\mu = 1.5 \times 10^{16}$: muons stopped in target

$f_{gnd} = 0.9$: fraction of muons transitioning to ground state

$f_{cap} = 0.61$: fraction of stopped muons captured

$A_{\mu-e} = 0.041$: acceptance of $\mu - e$ signal

Table 13: Factors contributing to the $\mu - e$ conversion signal acceptance value.

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

**Phase-I $\mu - e$ conversion signal acceptance factors**

| 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 | $\leq 0.0038$ |
| | Radiative pion capture | 0.0028 |
| | Neutrons | $\sim 10^{-9}$ |
| Delayed beam | Beam electrons | $\sim 0$ |
| | Muon decay in flight | $\sim 0$ |
| | Pion decay in flight | $\sim 0$ |
| | Radiative pion capture | $\sim 0$ |
| | Antiproton-induced backgrounds | 0.0012 |
| Others | Cosmic rays† | $< 0.01$ |
| Total | | 0.032 |

† This estimate is currently limited by computing resources.

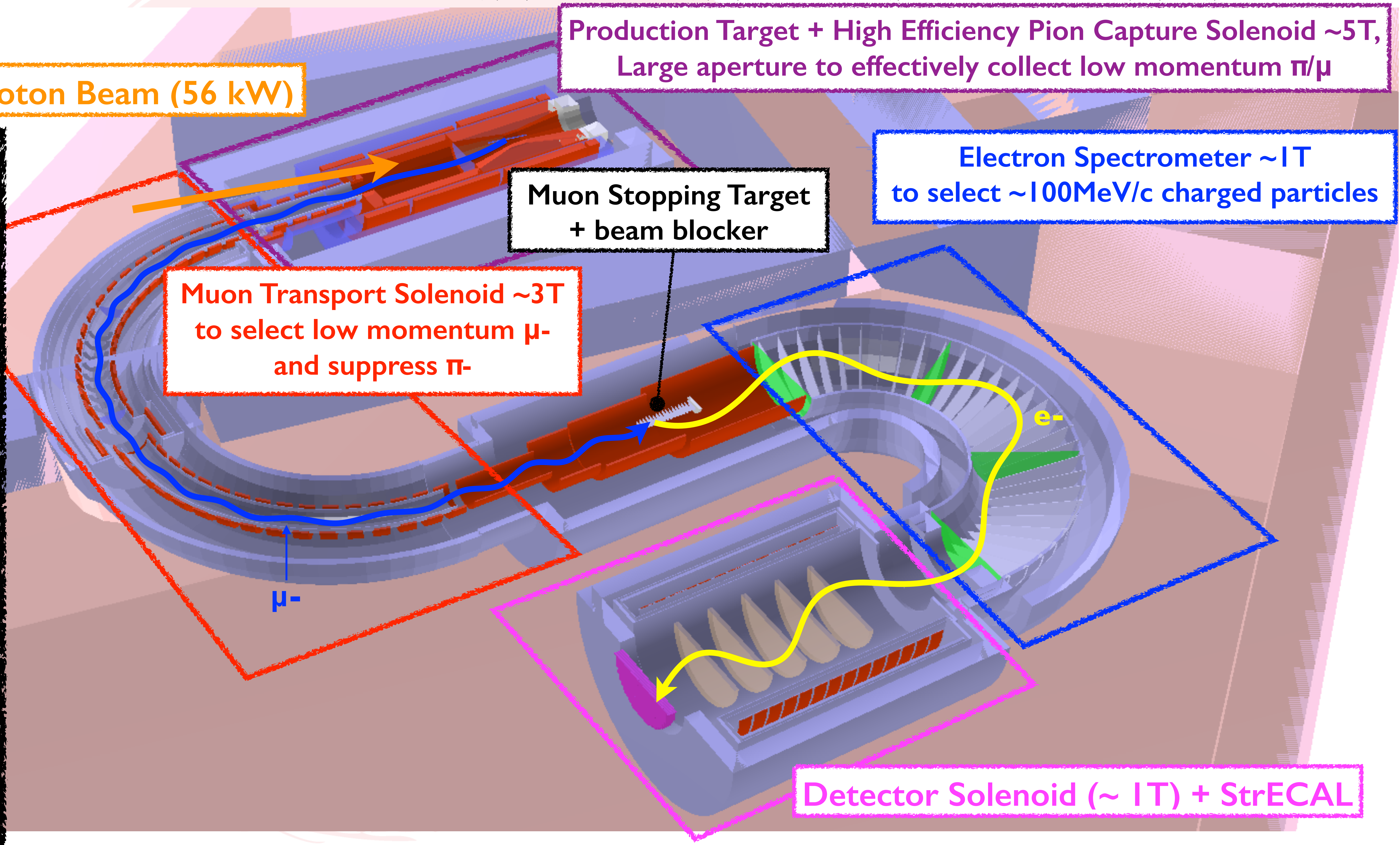
**Phase-I background events**

# Phase-II Overview

- To begin following Phase-I with 260 days running time
- Single event sensitivity further improved to $1.4 \times 10^{-17}$

Further design factors to improve sensitivity over Phase-I:

- ➢ **C-shaped muon transport solenoid** → further suppression of beam background over Phase-I
- ➢ Additional curved **Electron Spectrometer** → suppression of DIO + beam background
- ➢ **StrECAL detector** → all in vacuum + almost full 2π coverage



# Phase-II Sensitivity Expectations

Single event sensitivity expected in Phase-II (recently studied by K.Oishi, PhD Thesis, 2021)

$$B(\mu^- + Al \to e^- + Al) = \frac{1}{(I_p/e) \times t_{run} \times R_{\mu/p} \times \mathscr{B}_{capture} \times A_{\mu-e}} = 1.4 \times 10^{-17}$$

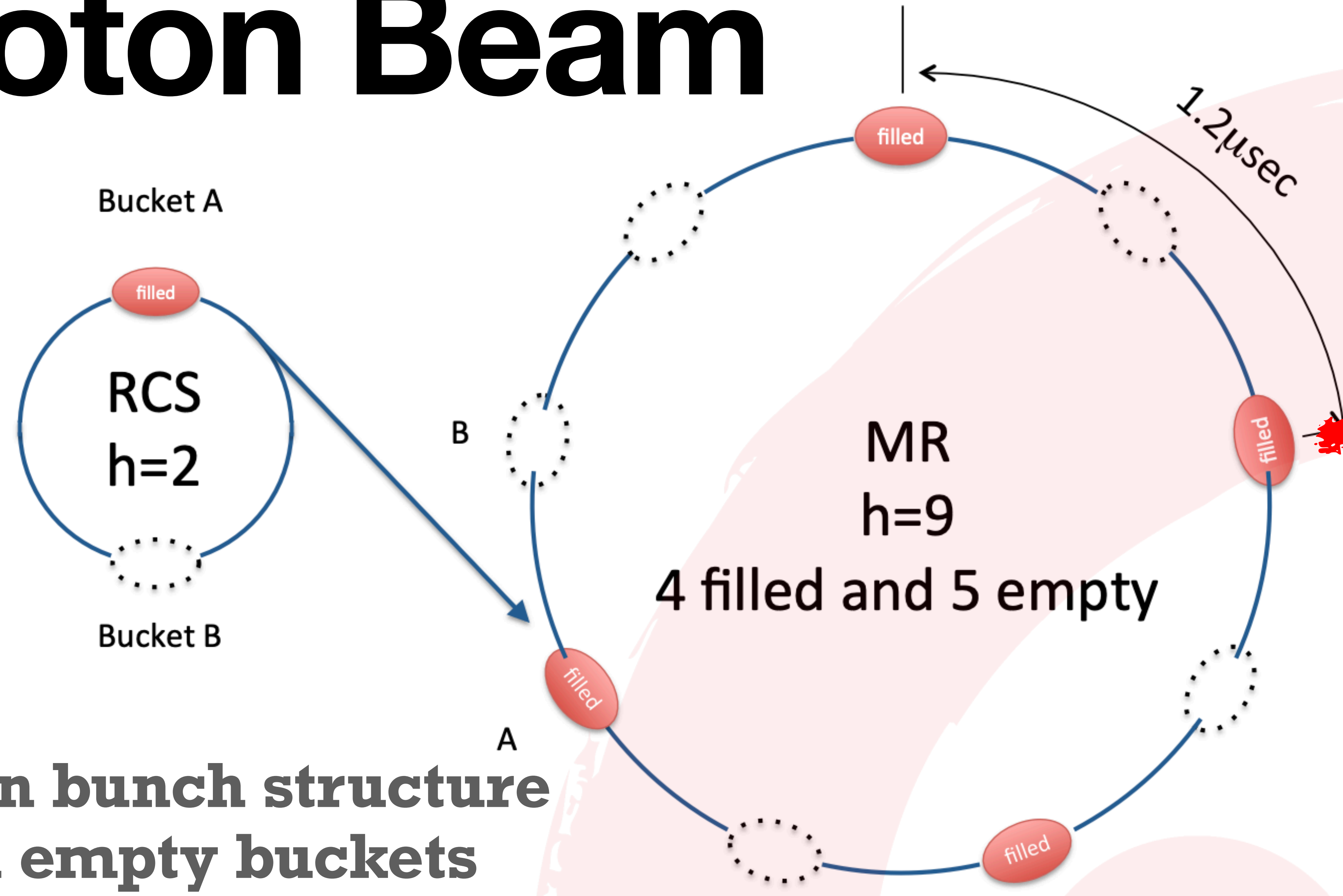
**Phase-II $\mu - e$ conversion sensitivity factors**

| Parameter | Value | Comments |
|---|---|---|
| $I_p$ | 7 $\mu$A | 8 GeV proton beam current in the Phase-II beam |
| $t_{run}$ | $2 \times 10^7$ sec | One-year live time of the data taking |
| $R_{\mu/p}$ | $3.8 \times 10^{-3}$ | Muon stopping rate per POT |
| $\mathscr{B}_{capture}$ | 0.61 | Branching ratio for muon capture in Aluminum |
| $A_{\mu\text{-}e}$ | 0.034 | Total signal acceptance |

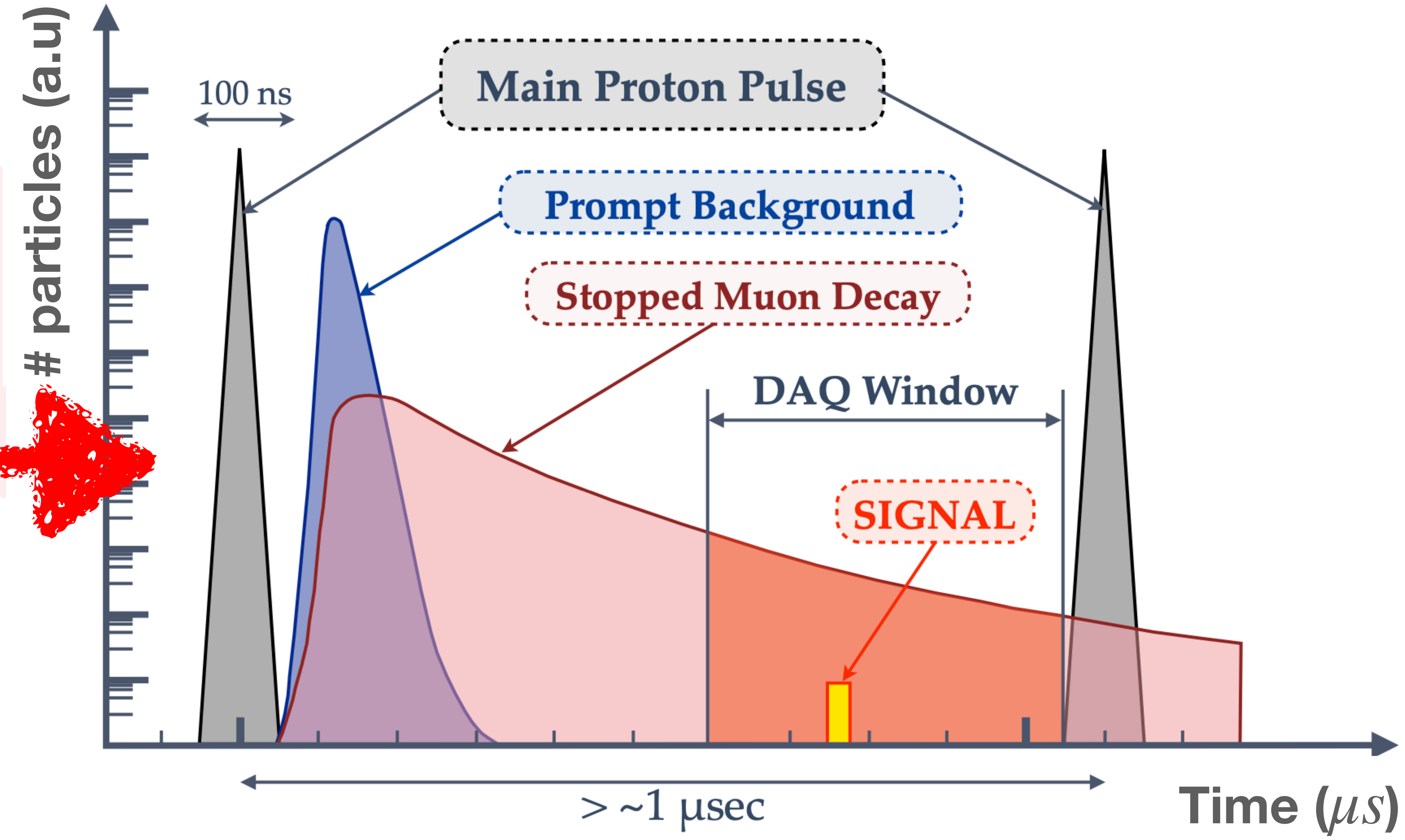
| Acceptance | Value | Comments |
|---|---|---|
| **(1) Geometrical acceptance** | **0.18** | |
| **(2) Trigger and DAQ acceptance** | **0.43** | |
| Timing window acceptance | 0.49 | $600 < t < 1200$ nsec |
| Energy threshold acceptance | 0.97 | $E > 70$ MeV |
| DAQ efficiency | 0.90 | |
| **(3) Reconstruction efficiency** | **0.77** | Chapter 7 |
| ECAL reconstruction | 0.92 | Section 7.2.6 |
| Straw tracker reconstruction | 0.84 | Section 7.3.6 |
| **(4) Quality cut efficiency** | **0.94** | Section 7.4 |
| The number of hits in the track | 0.96 | $N_{hits} \geq 12$ |
| p-value of the track fitting | 0.98 | p-value > 0.001 |
| $E/p$ | 1.00 | $0.985 < E/p < 1.015$ |
| **(5) Momentum cut acceptance** | **0.62** | 104.2 MeV/$c$ < p < 105.5 MeV/$c$ |
| *Total of (3)–(5)* | *0.45* | |
| **Total acceptance** | **0.034** | |

**Phase-II $\mu - e$ conversion signal acceptance factors**

# Proton Beam




**Proton bunch structure via empty buckets**

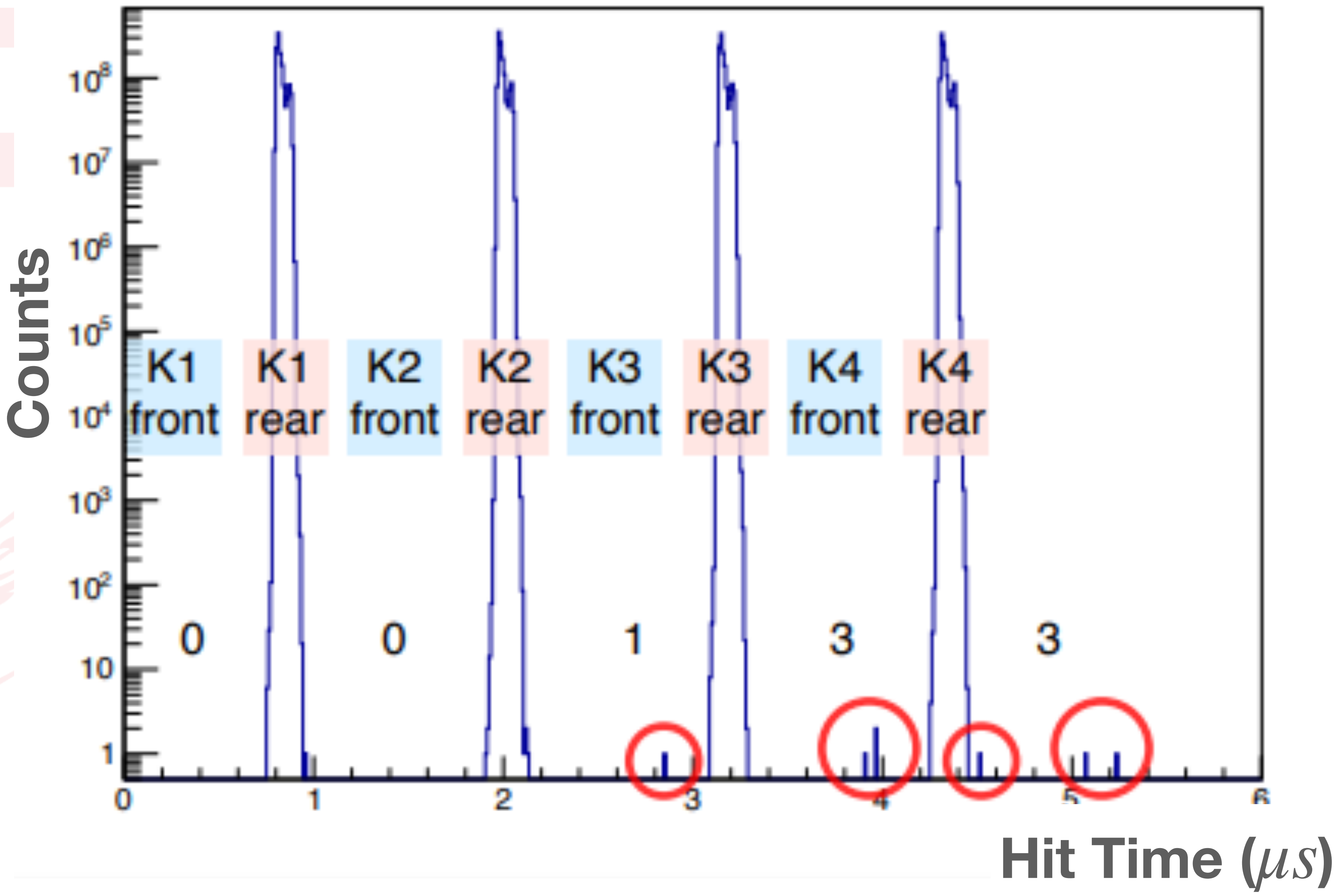



**Pulsed beam structure avoids majority prompt beam backgrounds**

- **Pulsed beam structure** in both phases

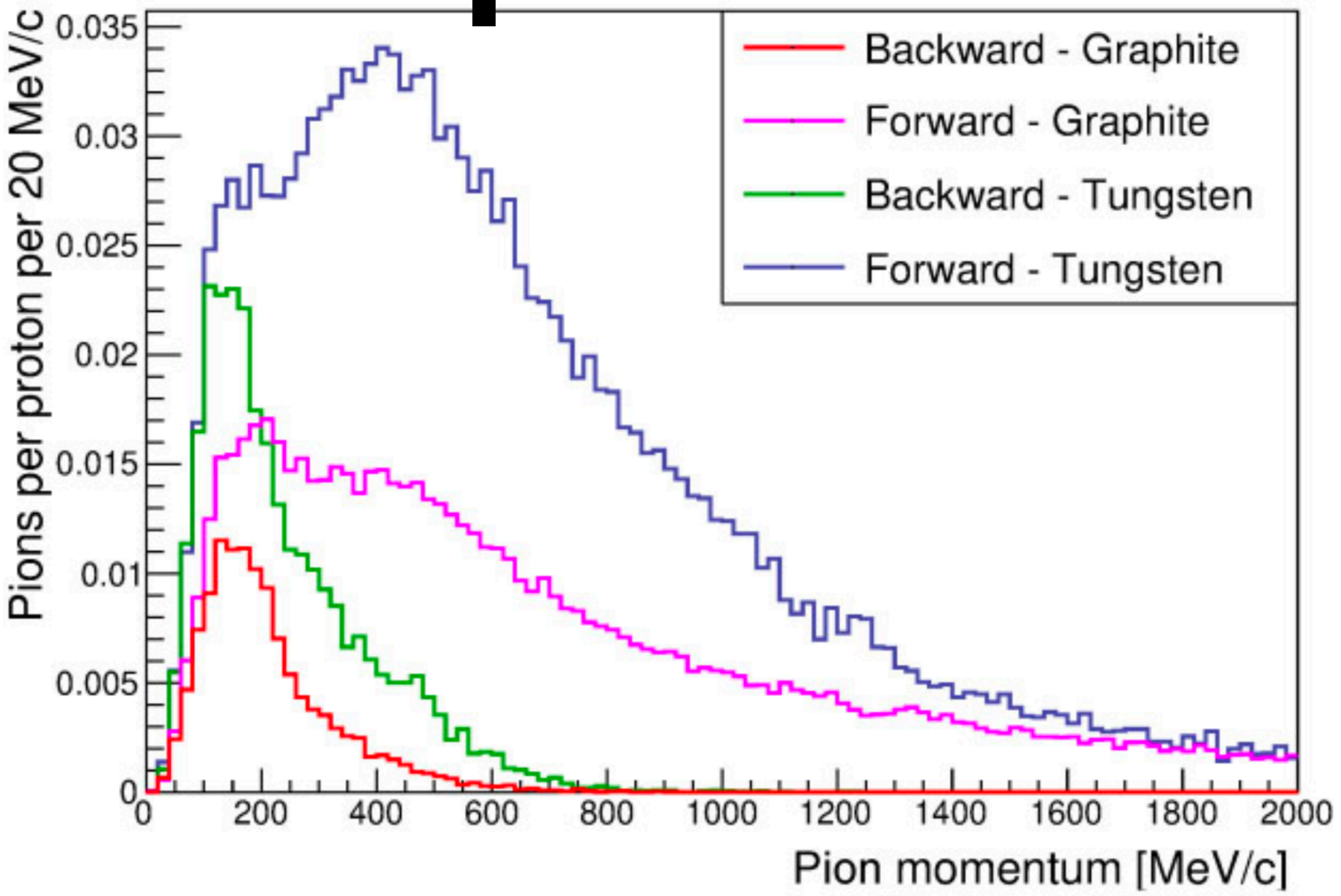
  Phase-I: 8 GeV (3.2 kW) Phase-II: 8 GeV (56 kW)

- Beam commissioning recently performed with $\mathcal{O}(10^{10})$ statistics
  - 7 interbunch counts determined to be background from analysis
  - $\mathcal{O}(10^{-10})$ extinction protons (90% C.L.) **meets Phase-I requirements** - further measurements in Phase-$\alpha$

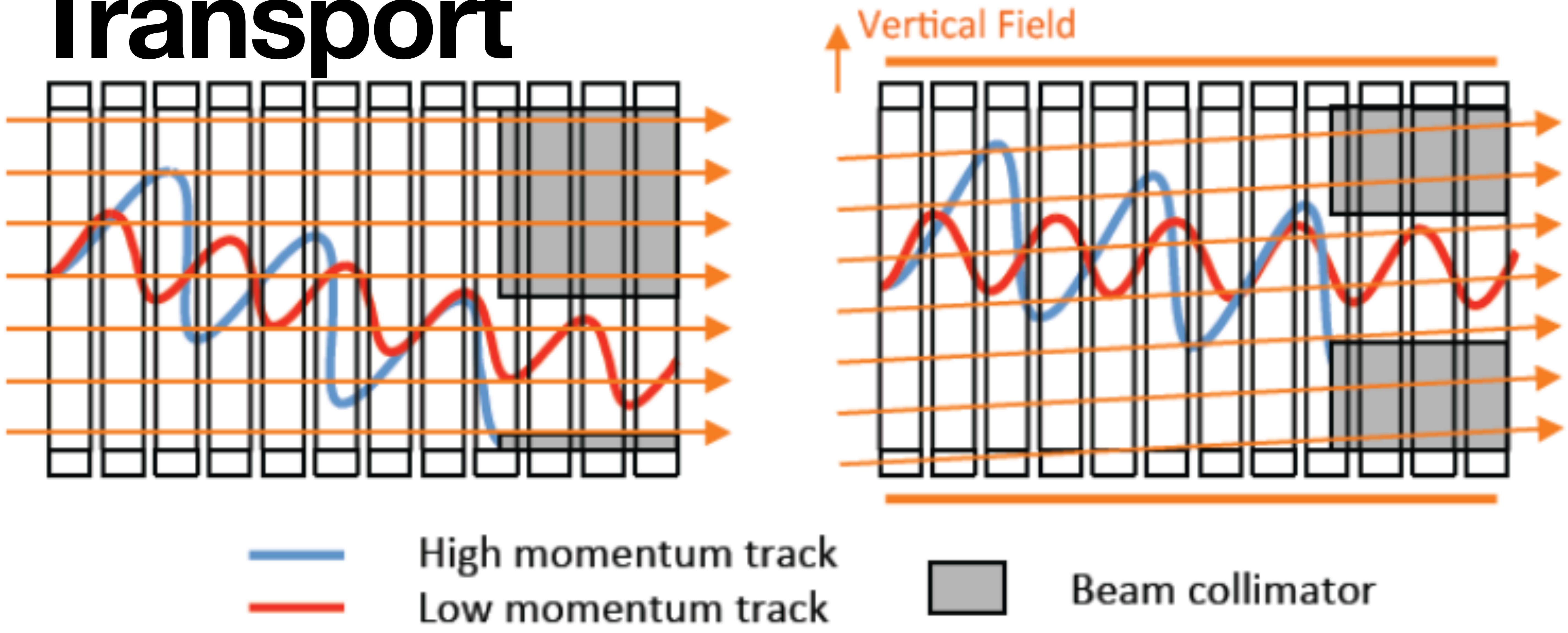



**8 GeV beam commissioning**

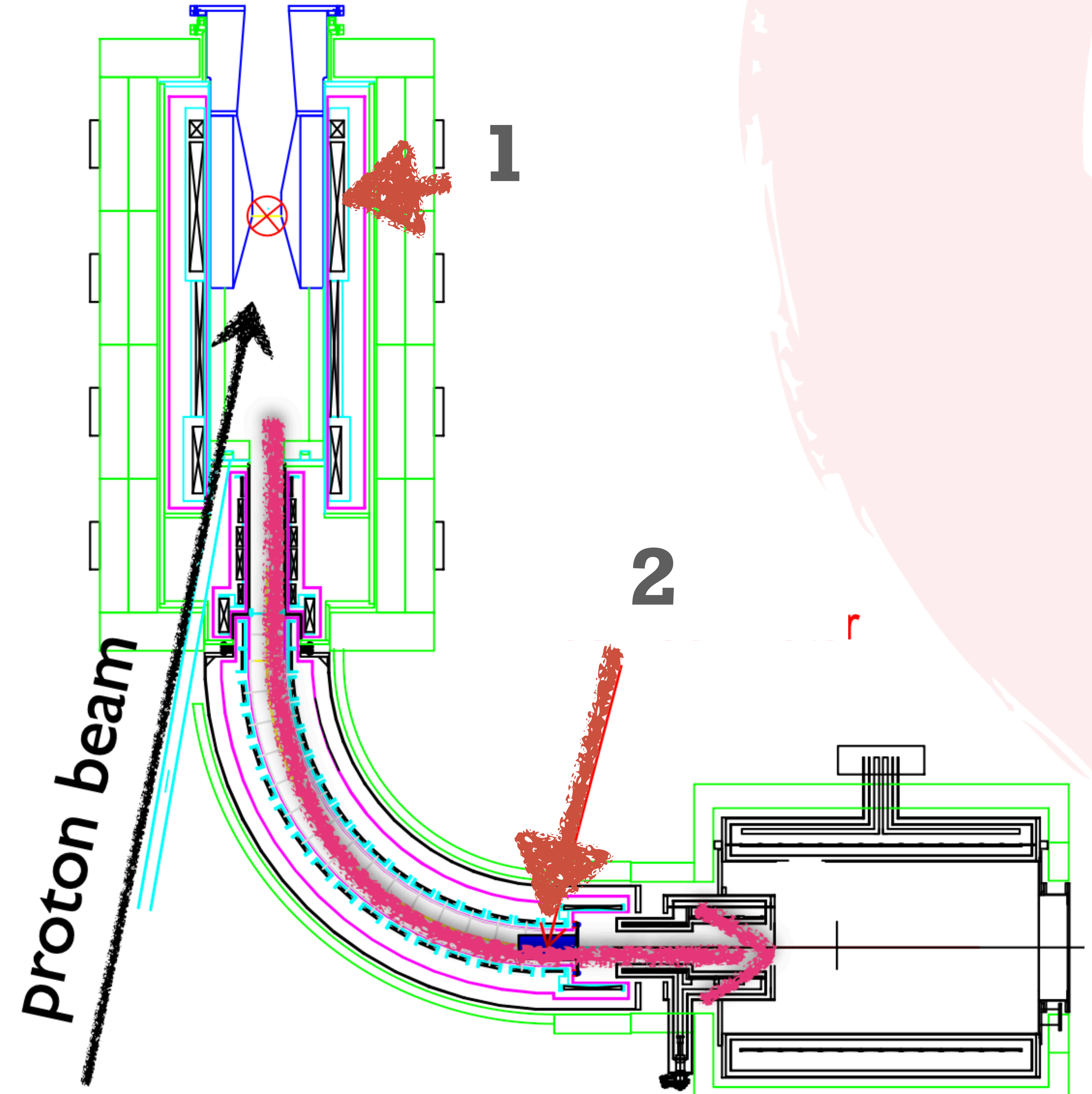
# Pion Capture and Muon Transport




**1: Pion yields for graphite and tungsten targets**




**2: Compensating field and collimators at end of transport solenoid**




- Graphite pion production target used in Phase-I, with 5 T capture solenoid.
  → **Upgraded to tungsten for Phase-II**
- Pions decay within curved transport solenoid delivering intense muon beam to stopping targets.
  → **Phase-I uses 90˚ curved solenoid, upgraded to full C-shape for Phase-II**
- Muons follow helical trajectory through curved transport solenoid
  →**Additional dipole field used to compensate for this drift**
- **Collimators optimised** to select for **low momentum** muons

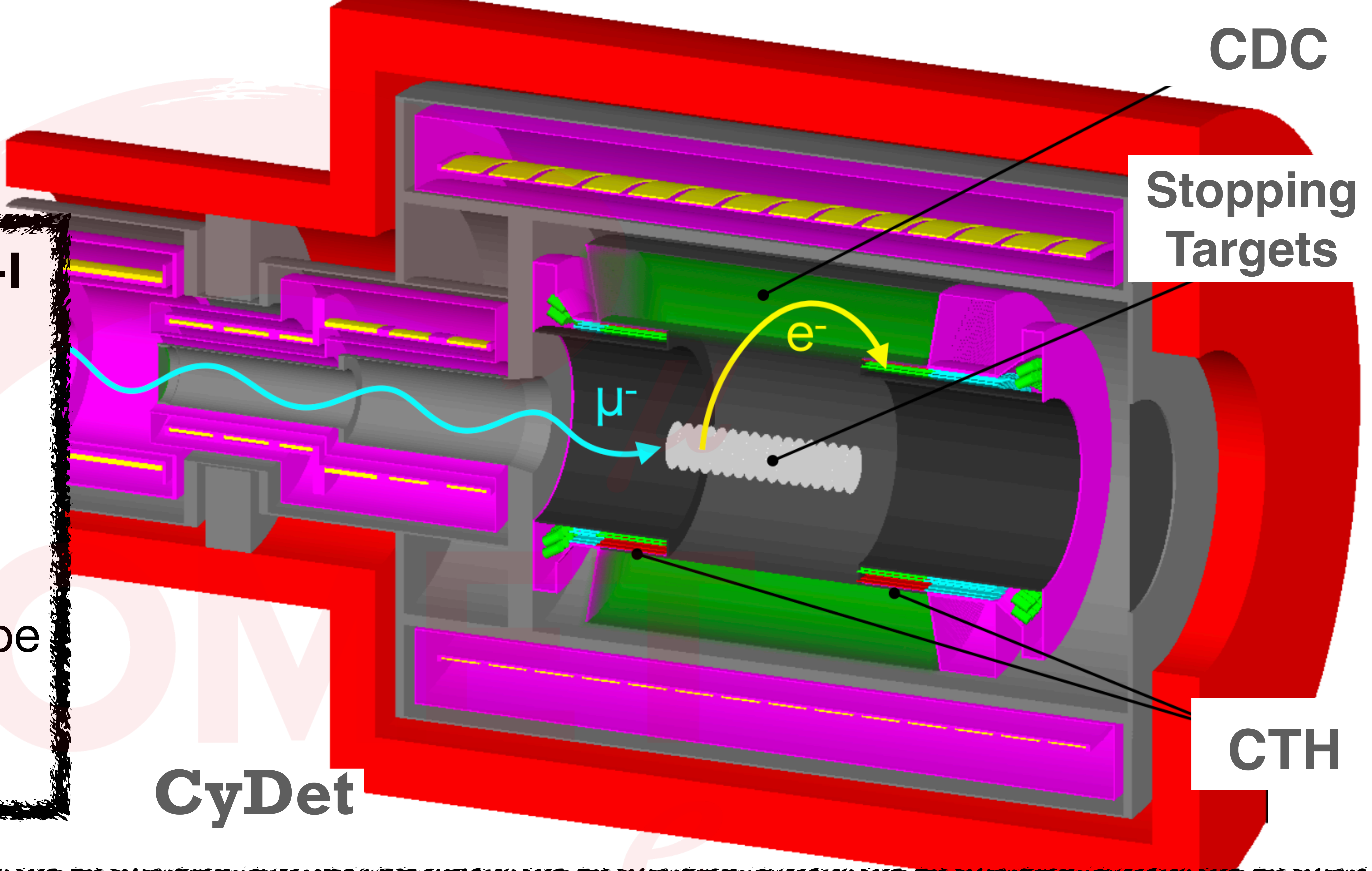
# CyDet Detector

(**Cy**lindrical **Det**ector)

Main physics detector for **Phase-I**

Two major detector components:

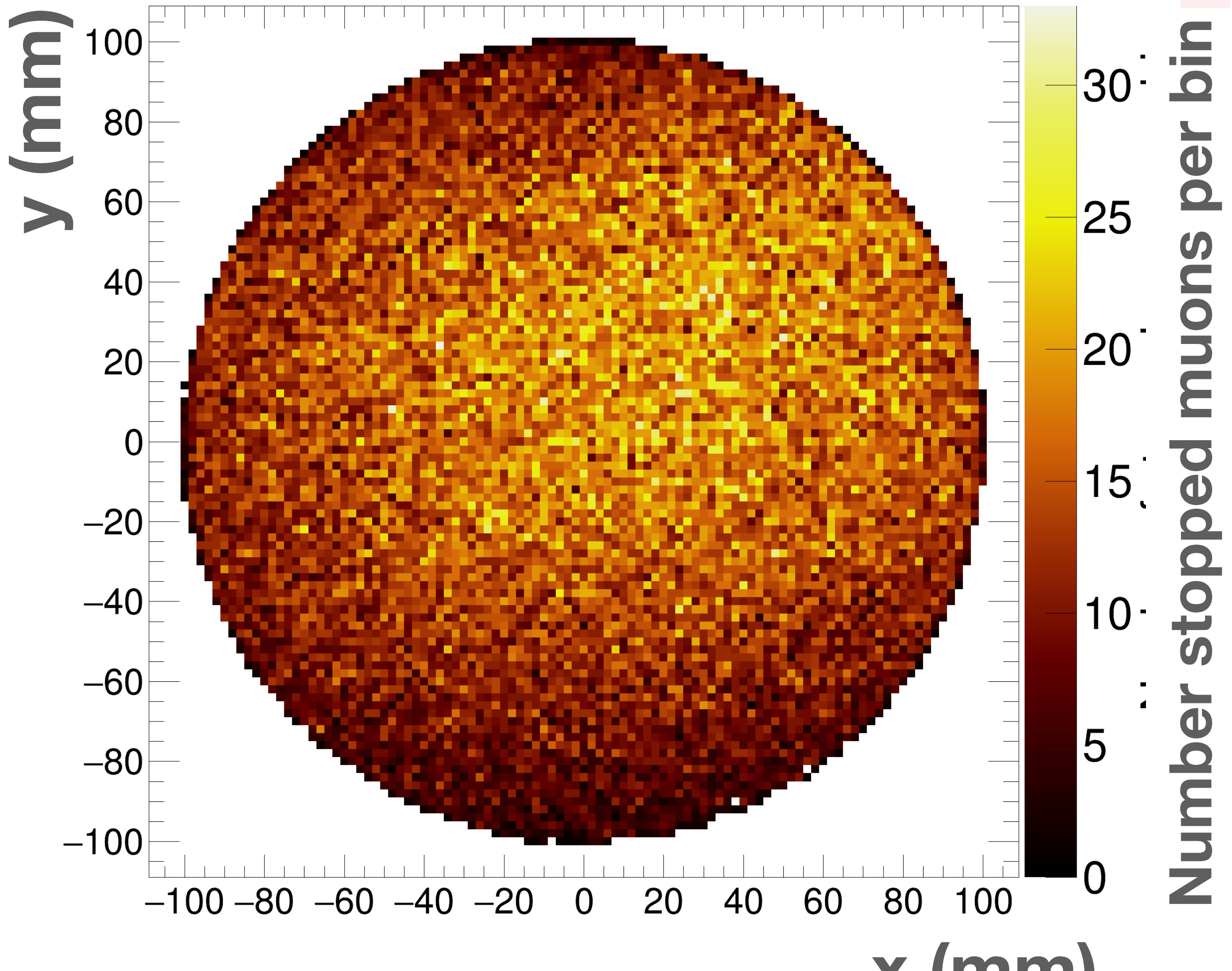
- Cylindrical Drift Chamber (**CDC**) - **tracking** and **momentum** information
- Cylindrical Trigger Hodoscope (**CTH**) – selective for **high momentum** particles, provides **timing** information



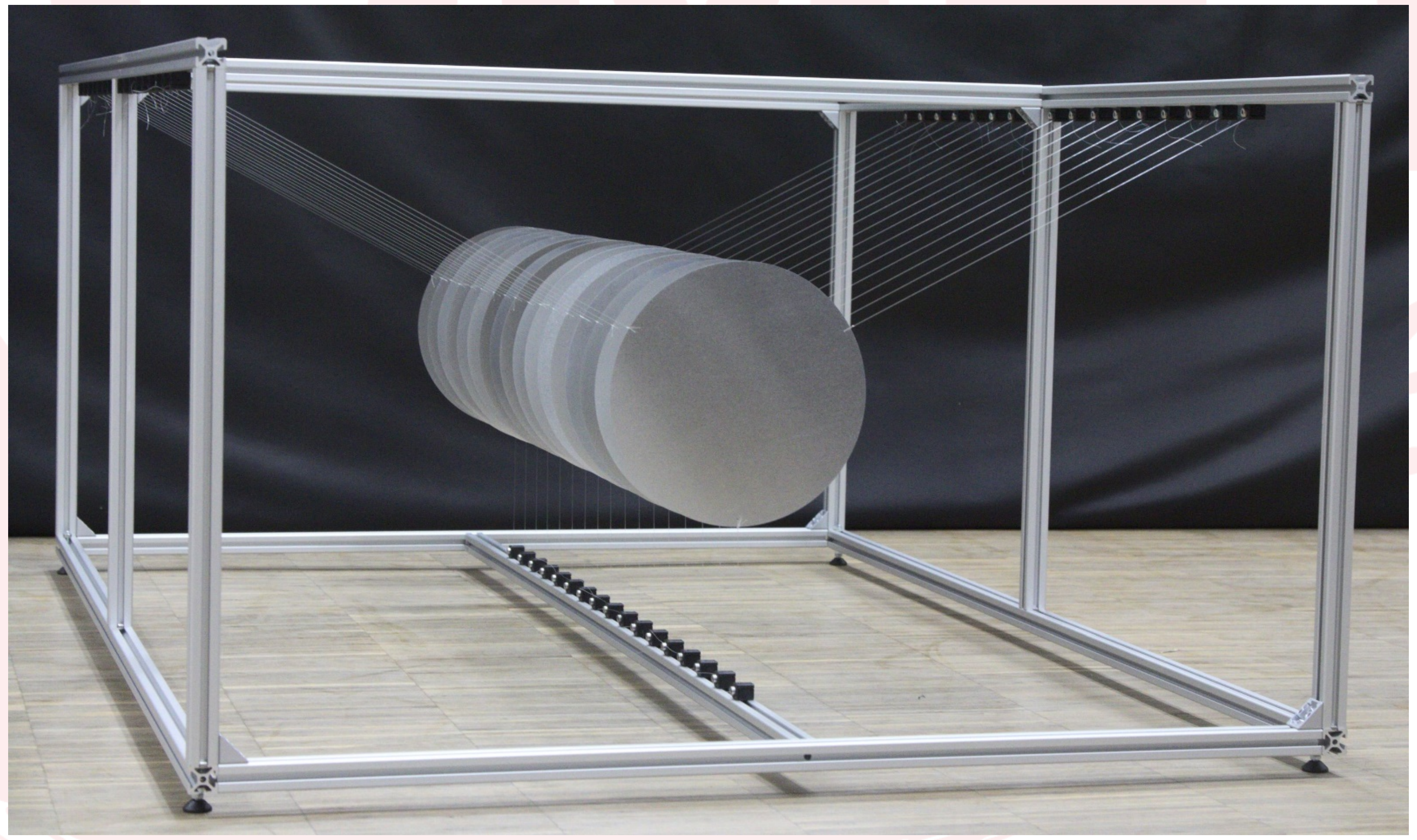

- Surrounded by **1 T magnetic solenoid** – charged particles follow helical trajectory towards ends
- **High radiation levels** expected in detector region
  - $10^{12}\ n_{eq}/cm^2$ neutrons, 1 kGy gamma rays

# Stopping Targets

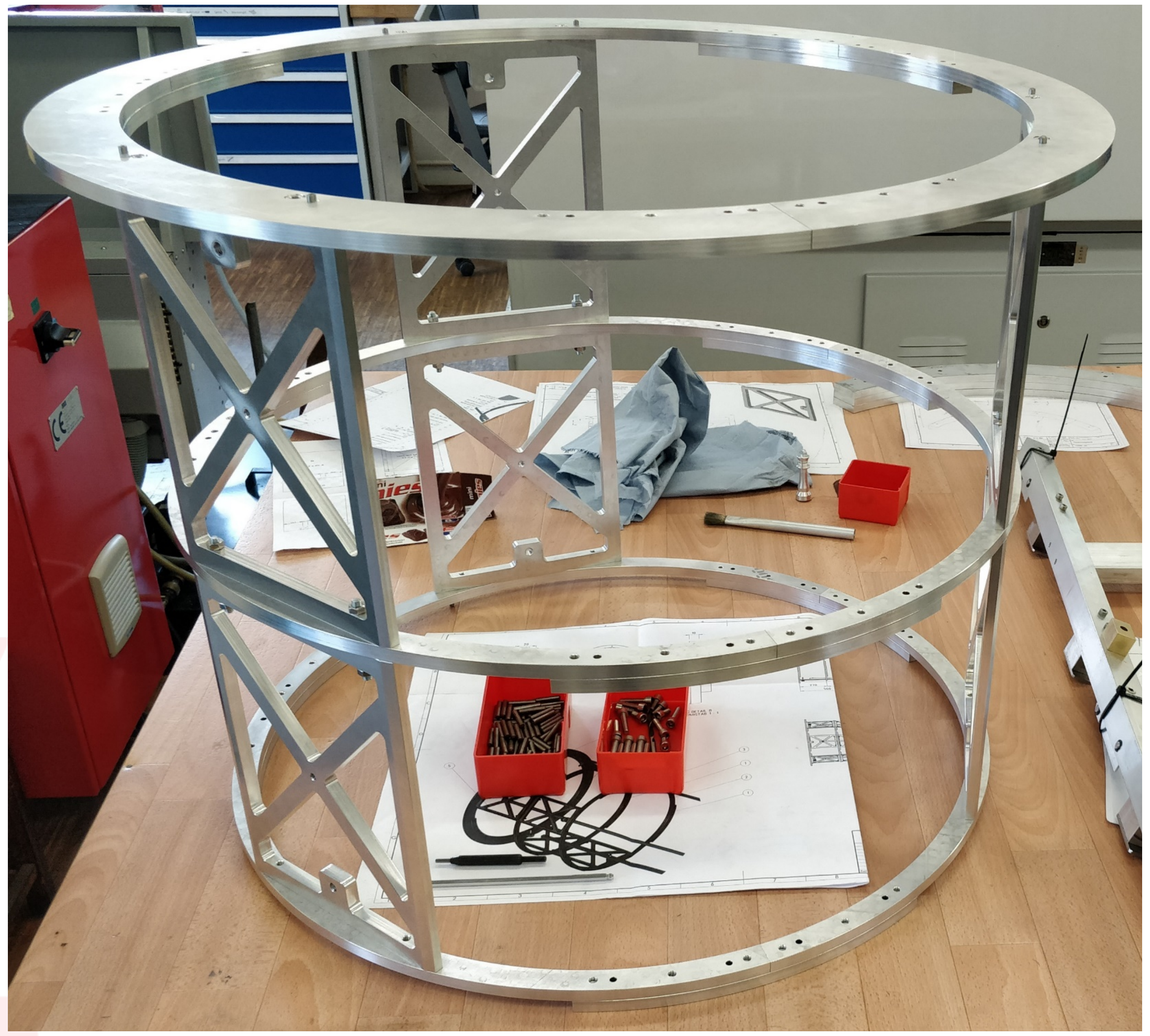
- **17 aluminium disks** (100 mm radius, 200 $\mu$m thickness) at centre of detector region
- Muons from transport solenoid captured by aluminium stopping targets
- Al provides good tradeoff between **muon capture rate, DIO endpoint tail and lifetime** (864 ns)
- Production of stopping target holder prototype currently underway

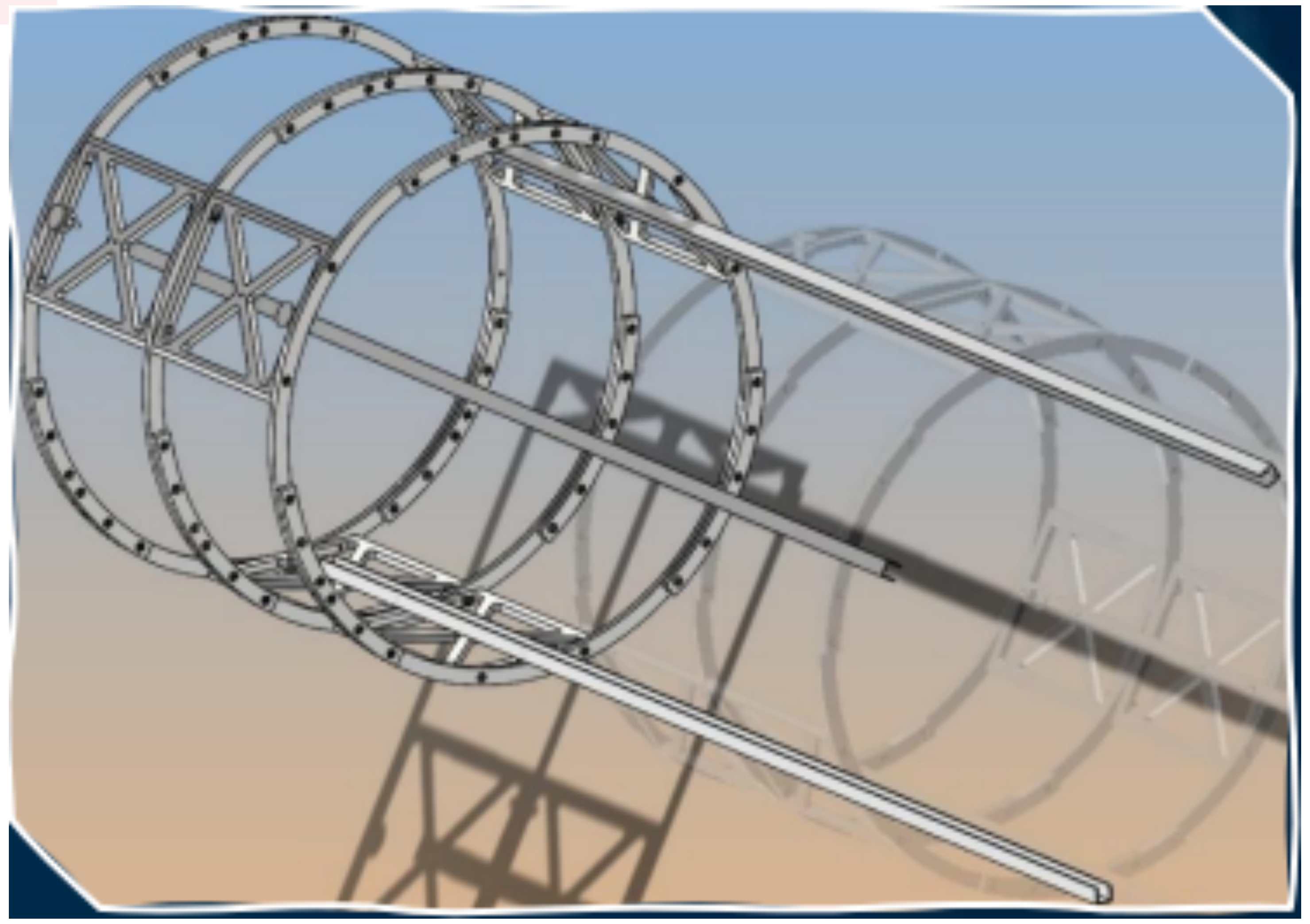



**Phase-I stopped muon distribution**



**Mock up target holder**

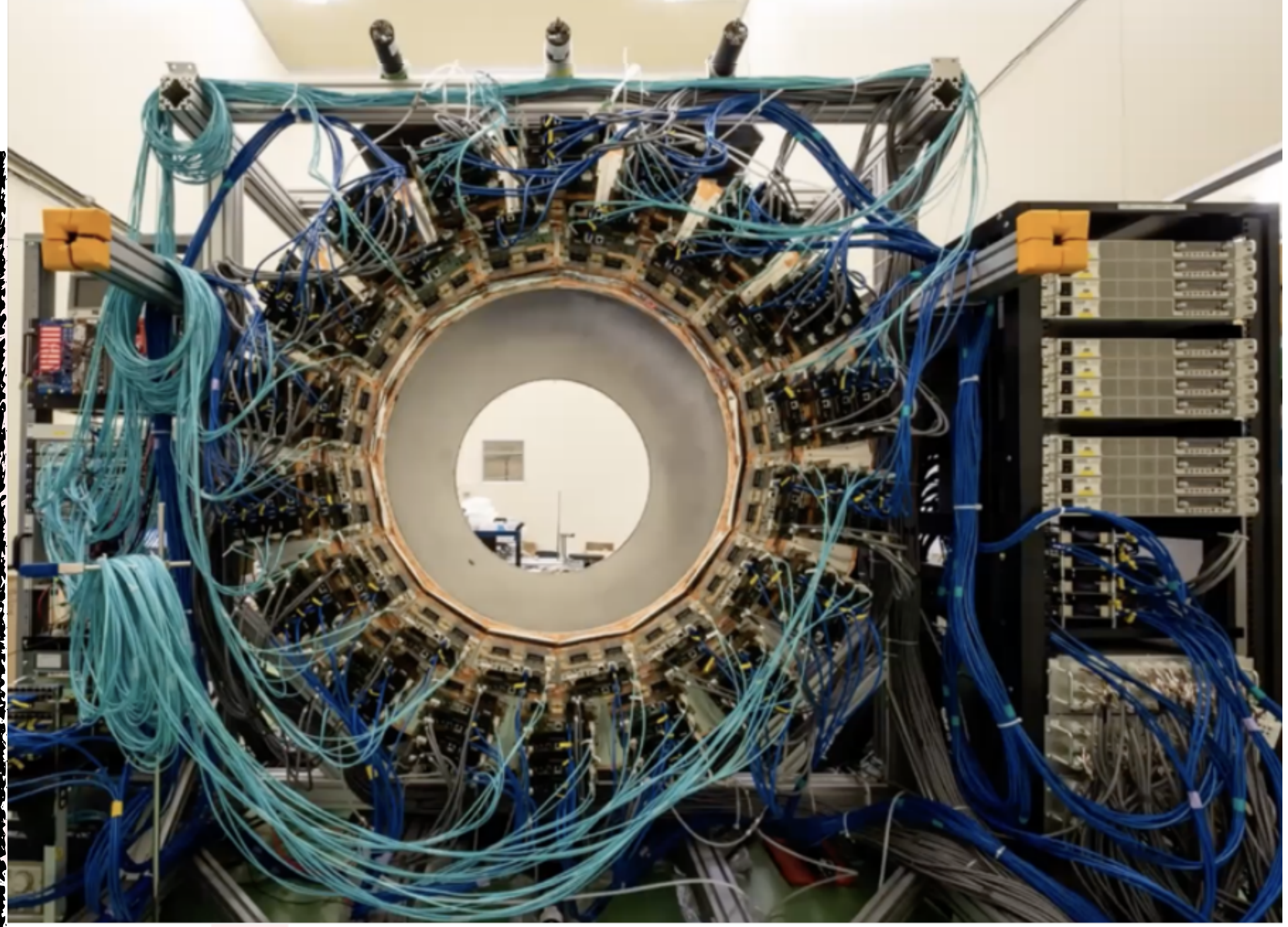




**Phase-I stopping target holder prototype progress and design**

# CDC (<u>C</u>ylindrical <u>D</u>rift <u>C</u>hamber)

- **20 concentric layers** with alternating positive and negative **stereo angles** (4986 sense wires + 14562 field wires)
- **Large inner radius** suppresses DIO electrons reaching sense layers
- Signal electrons **contained** within CDC for better momentum resolution
- Better than **200 keV/c momentum resolution** for signal electrons
- Completed in 2016, read out and testing since 2019, scheduled to be moved on site to J-PARC early August



CDC cosmic ray testing

CDC front end electronics cooling tests

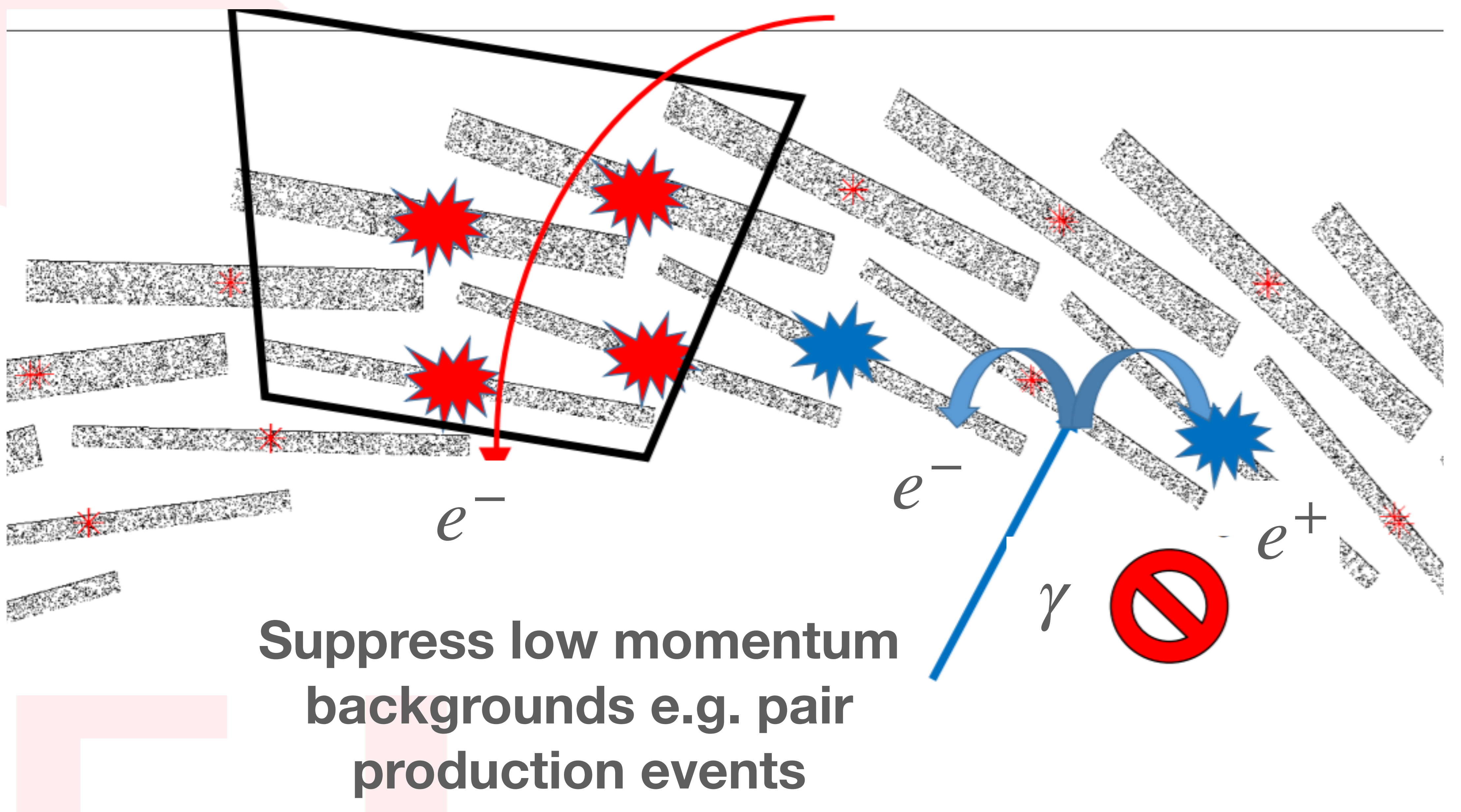
**Some select CDC parameters**

| | |
|---|---|
| Gas | He:i$C_4H_{10}$ (90:10) |
| Layers | 20 (2 guard layers) |
| Sense Wires | 25 $\mu$m, gold-plated tungsten |
| Field Wires | 126 $\mu$m, pure Aluminium |
| Inner wall (radius) | 496 mm |
| Stereo layers | +- 70 mrad (alternate) |

# CTH (Cylindrical Trigger Hodoscope)

- Important for suppressing many backgrounds and providing better **timing information** for signal measurements
- **2 x 64 concentric scintillator counter rings** at either end of CDC each with MPPC for readout
- **Tilted** support structure optimised for signal acceptance
- Time resolution requirement **better than 1 ns**
- 5-10 m **optical fibre readout** used to remove MPPC from **highest radiation levels**

## Main Principle: 4-fold coincidence

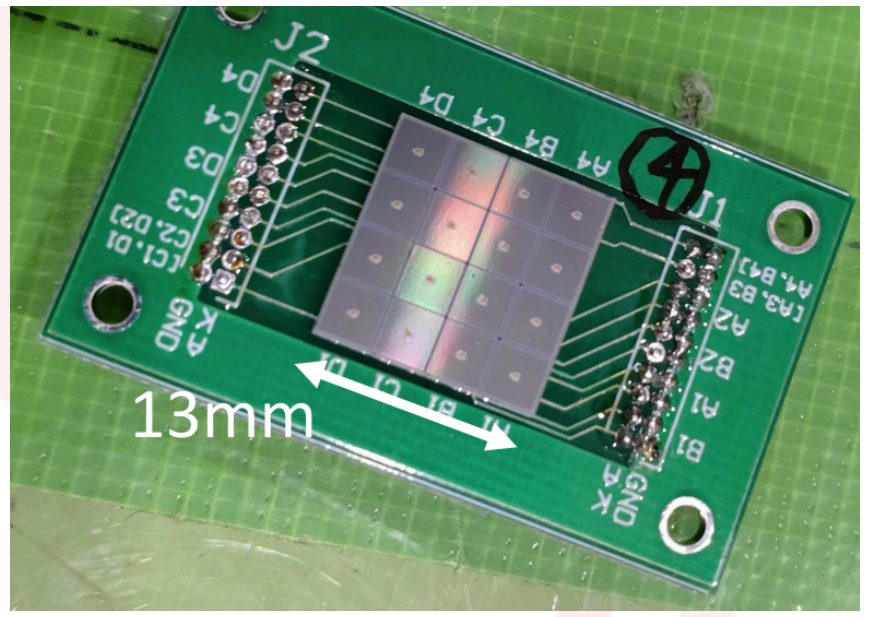



## Current Counter Design

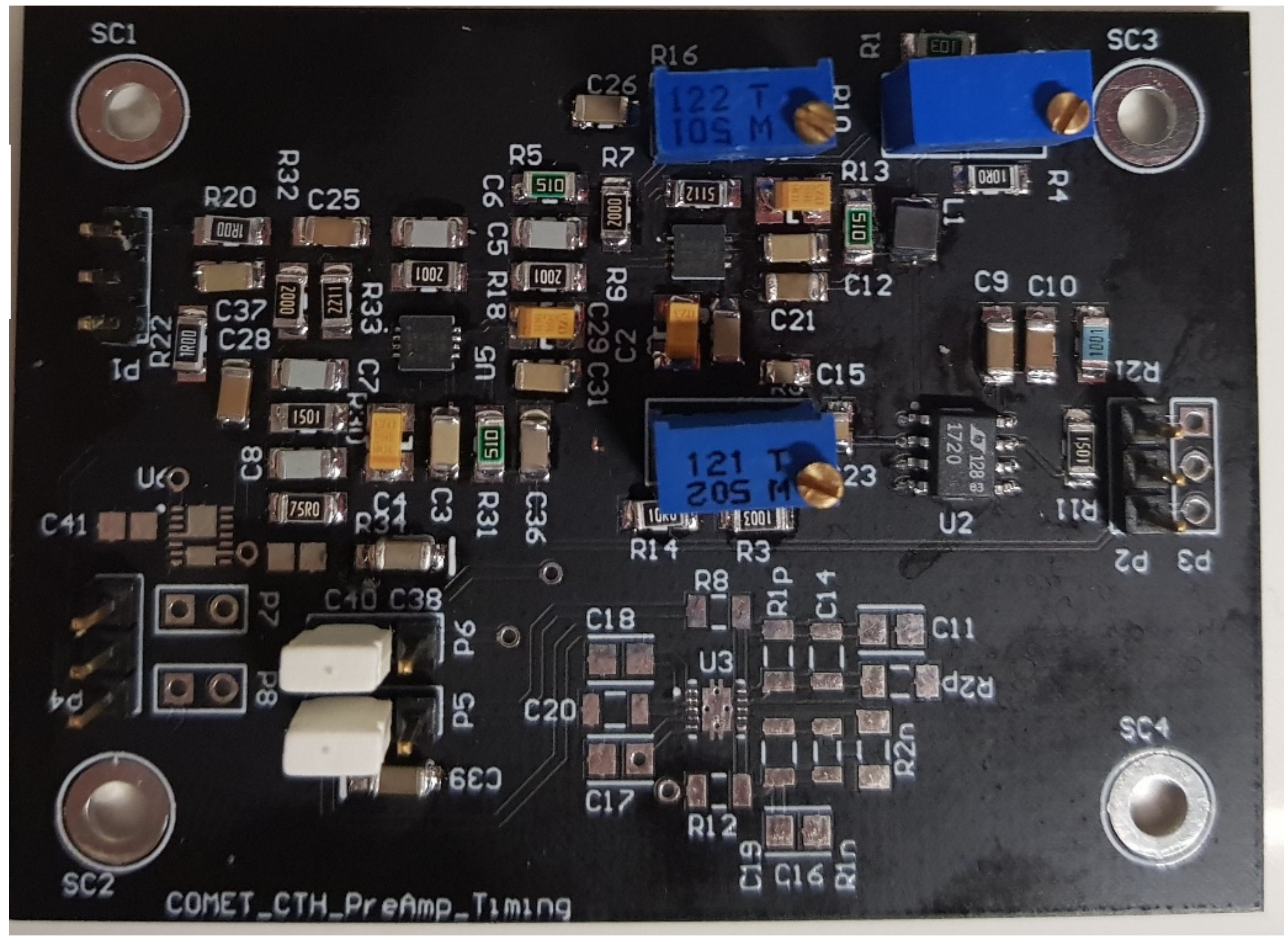
# CTH (Cylindrical Trigger Hodoscope)

- Prototype evaluation ongoing - photon yield, timing resolution, preliminary beam tests with 100 MeV electrons
- First prototypes of readout electronics being evaluated
- MPPC cooling and neutron irradiation test performed recently
- Construction in early 2023

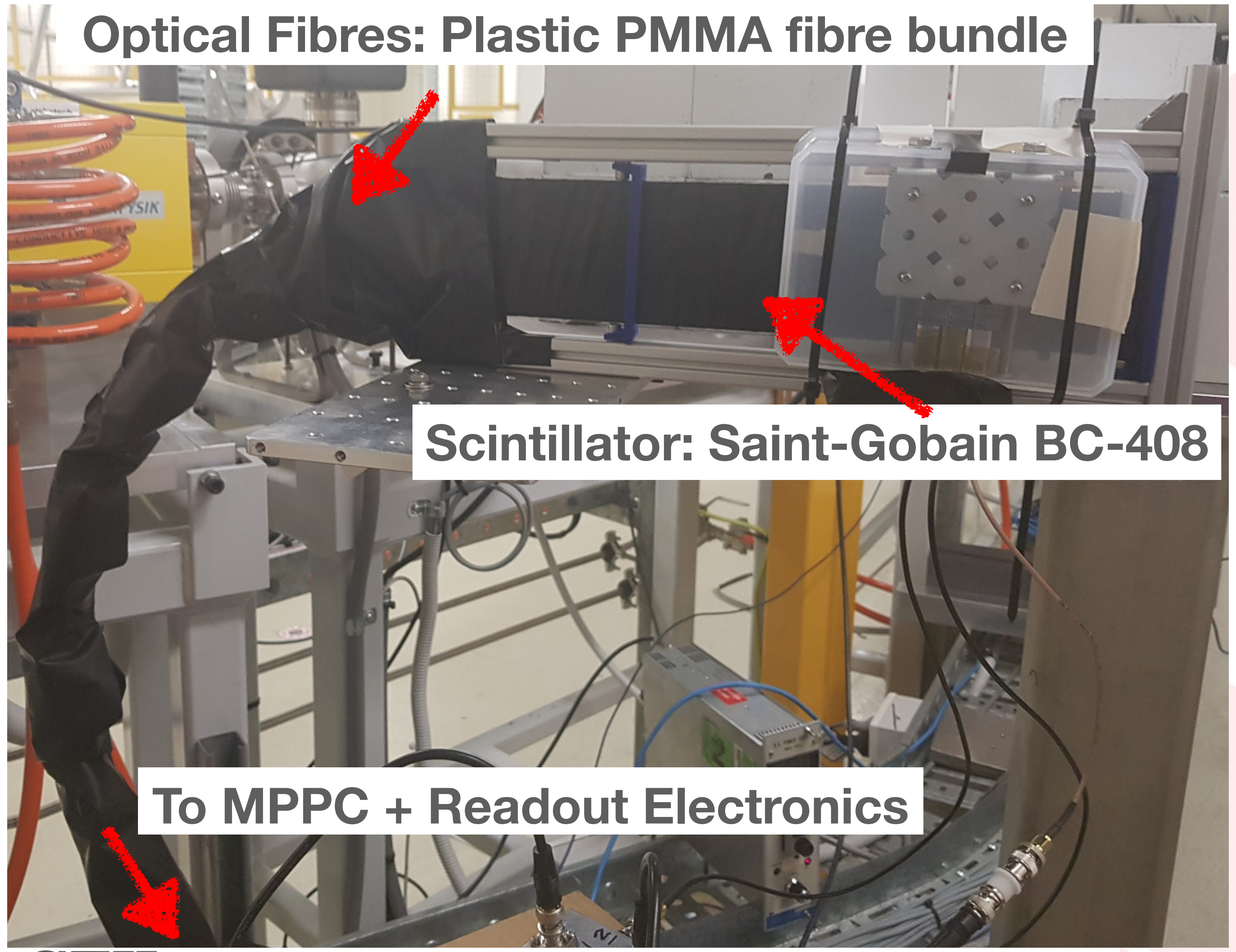
Hamamatsu S14161-3050HS-04



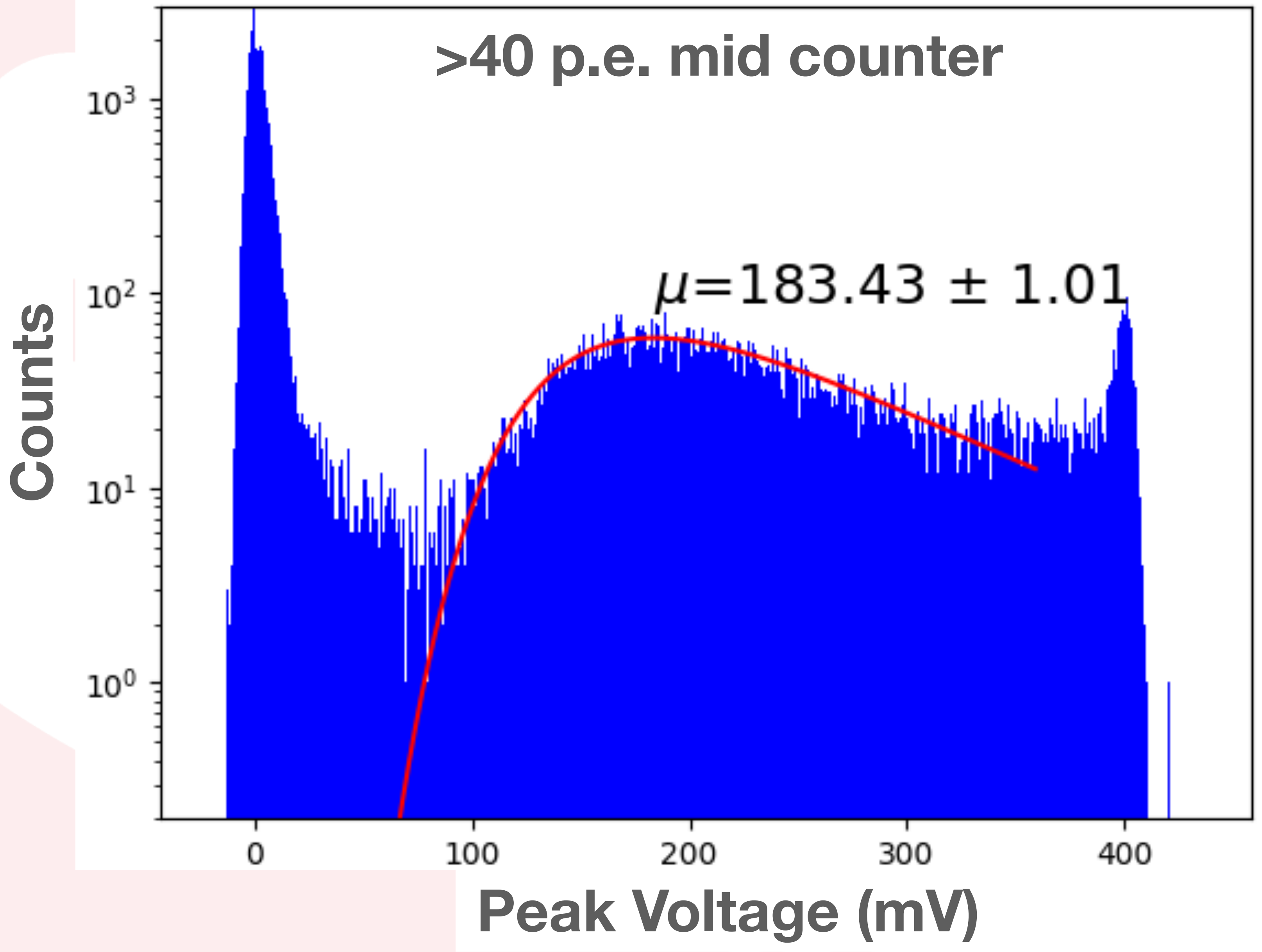

MPPC PCB



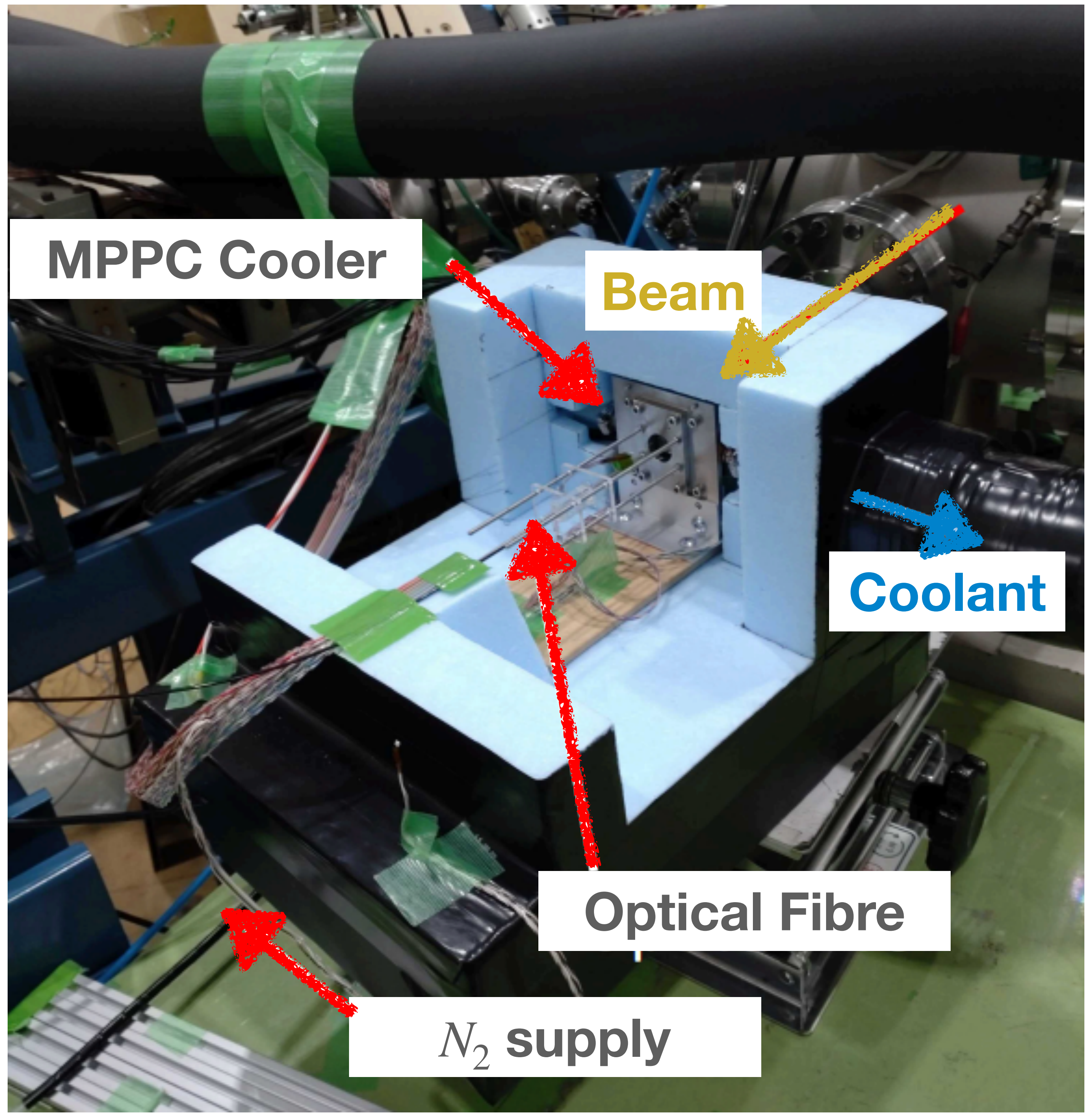

Prototype Readout Electronics




CTH counter prototype test at Australian Synchrotron



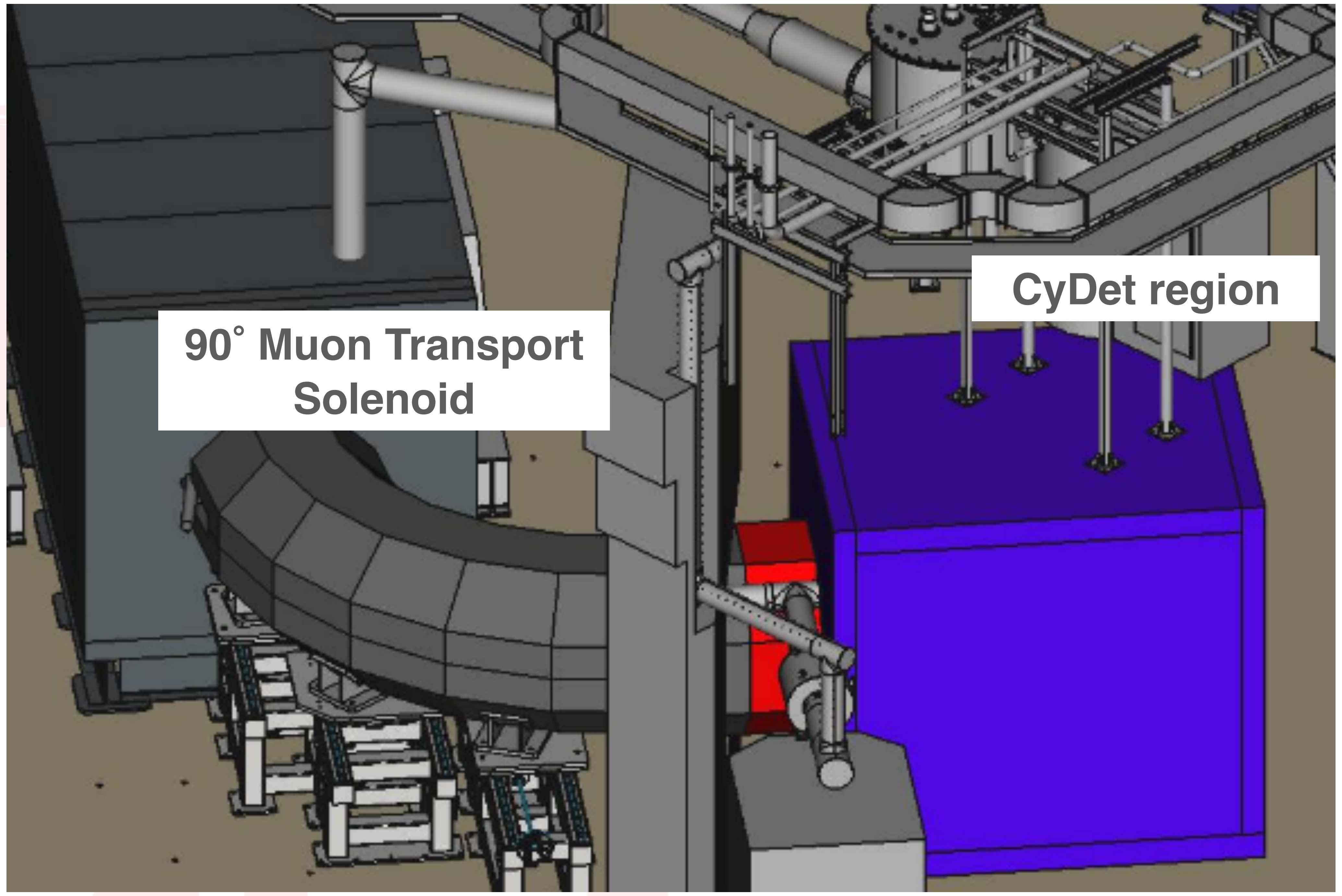

Cosmic ray photon yield measurement



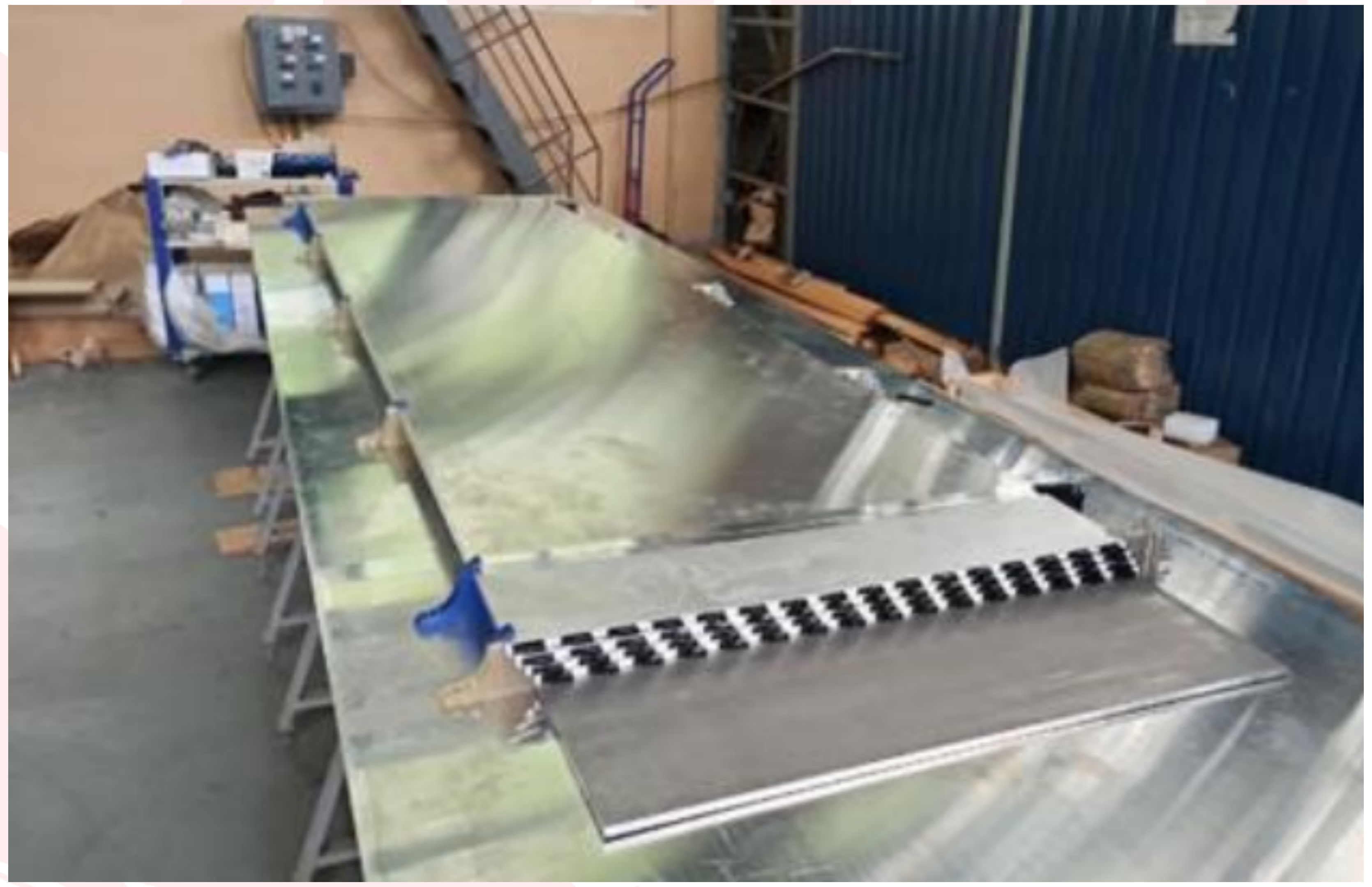

MPPC cooling prototype at irradiation tests

# CRV (Cosmic Ray Veto)

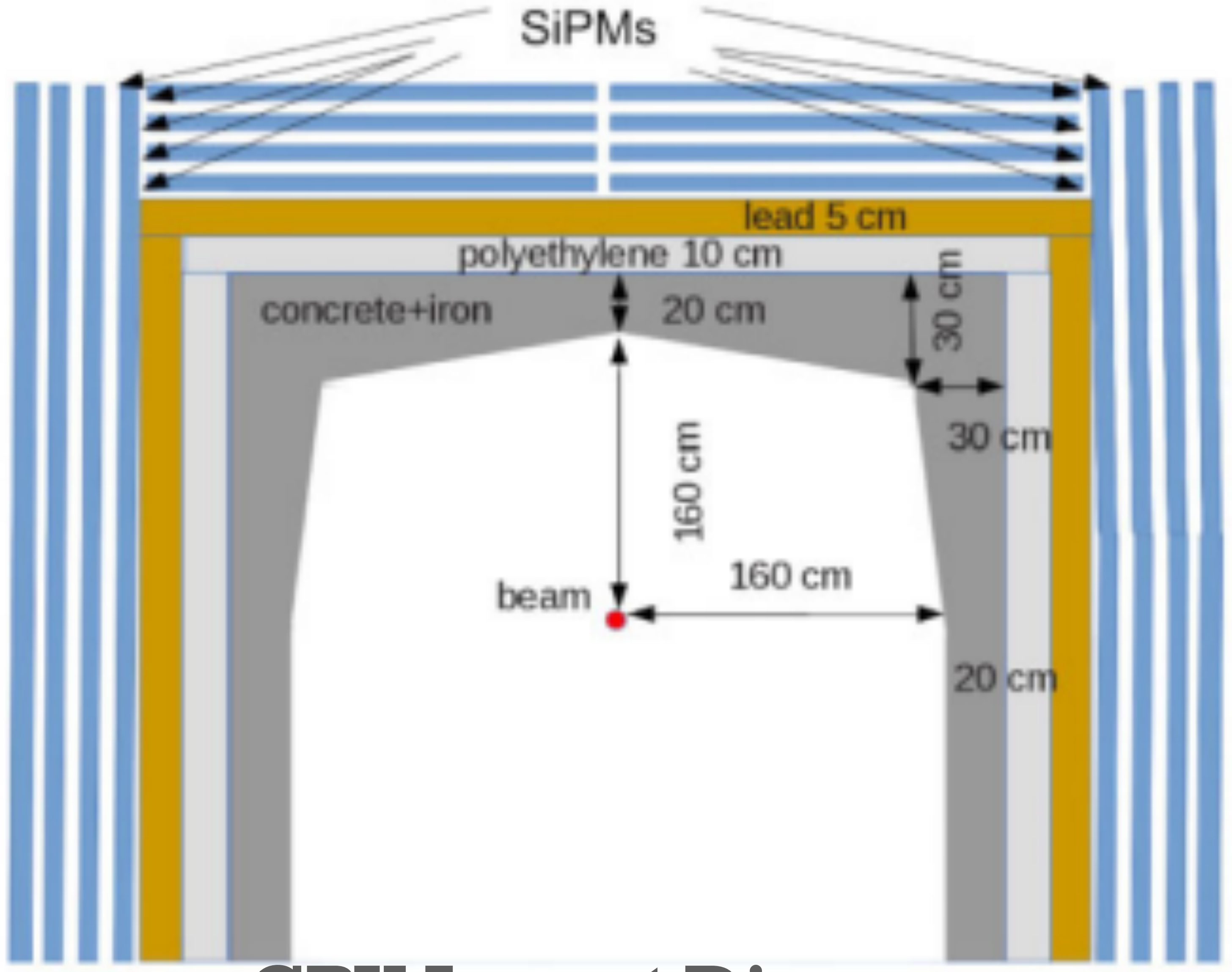
- Necessary to exclude **atmospheric muons**
- Cosmic Ray Veto (**CRV**) detectors used in Phase-I and Phase-II
- Phase-I coverage includes **CDC** and **bridge solenoid** (at end of muon transport solenoid)
- Requires **99.99%** efficiency and less than **5%** dead time
- Active and passive shielding
- First module constructed




Phase-I CRV Geometric Coverage



CRV Left Side Module



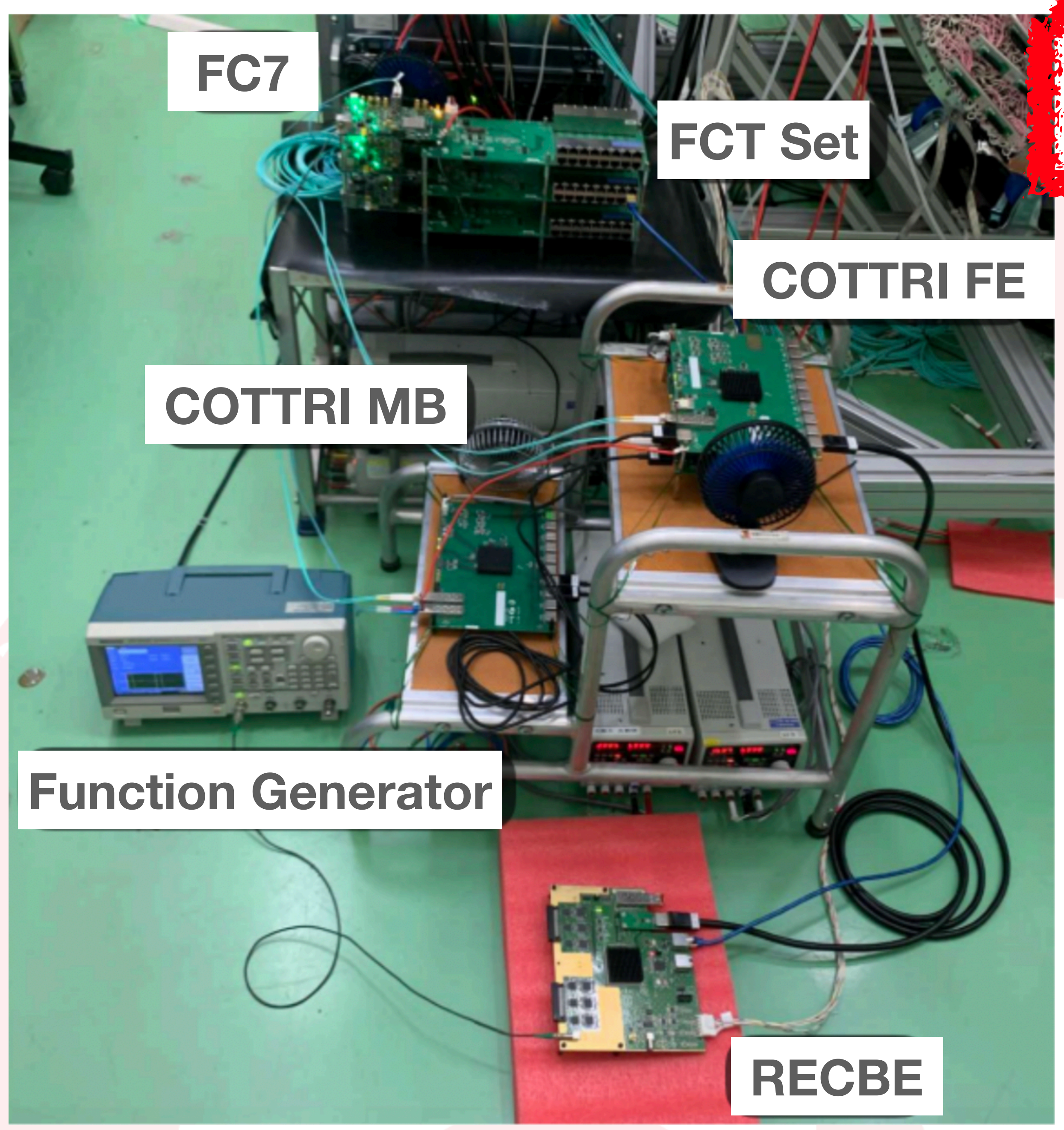

CRV Layout Diagram

# Trigger/DAQ System

- Trigger rate suppressed to **13 kHz** with **96%** efficiency and **3.2** $\mu s$ latency using GBDT hit classification

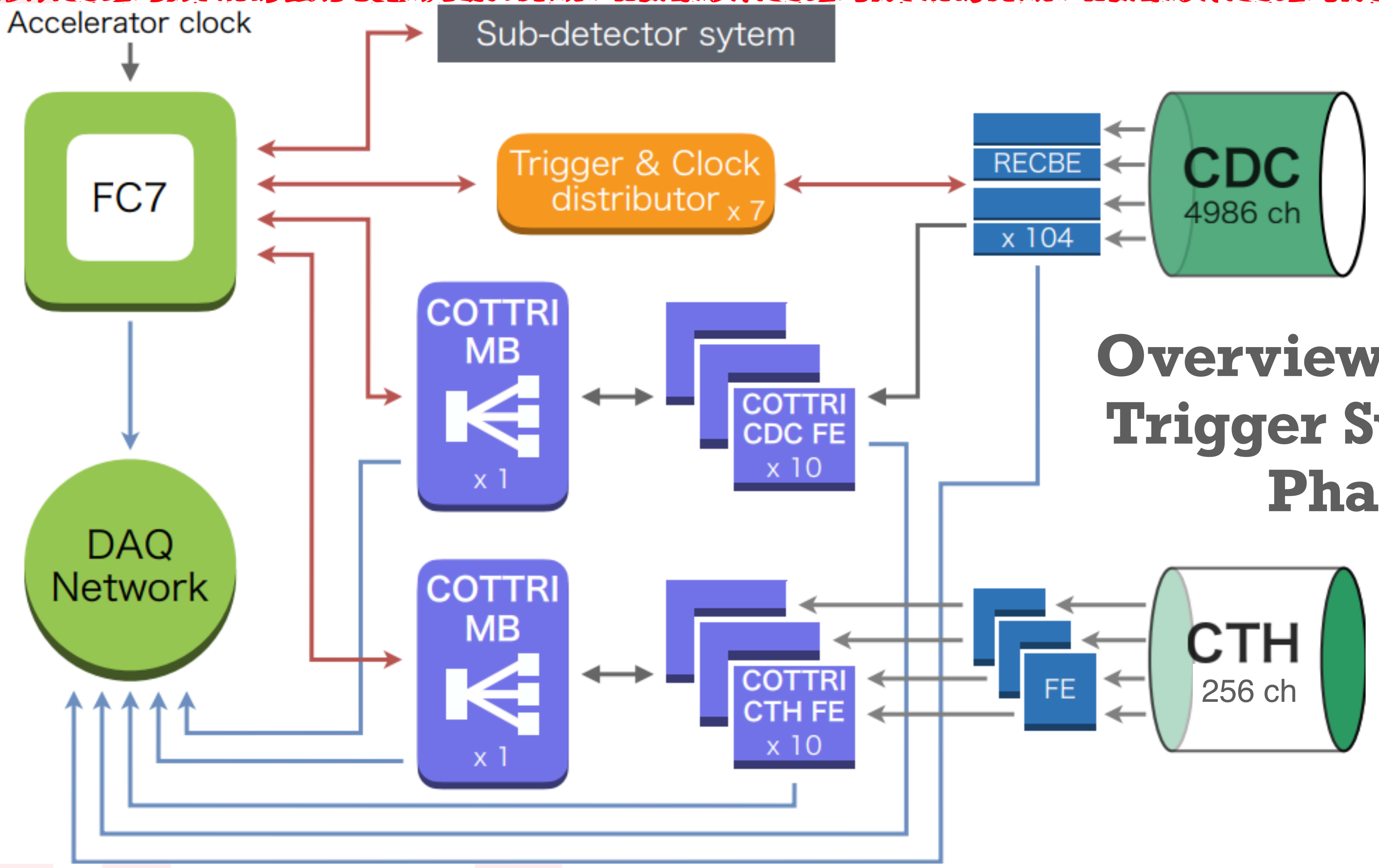
- More machine learning based systems are currently being explored for further improvements

- MIDAS based DAQ system with total throughput of **1 GB/s**

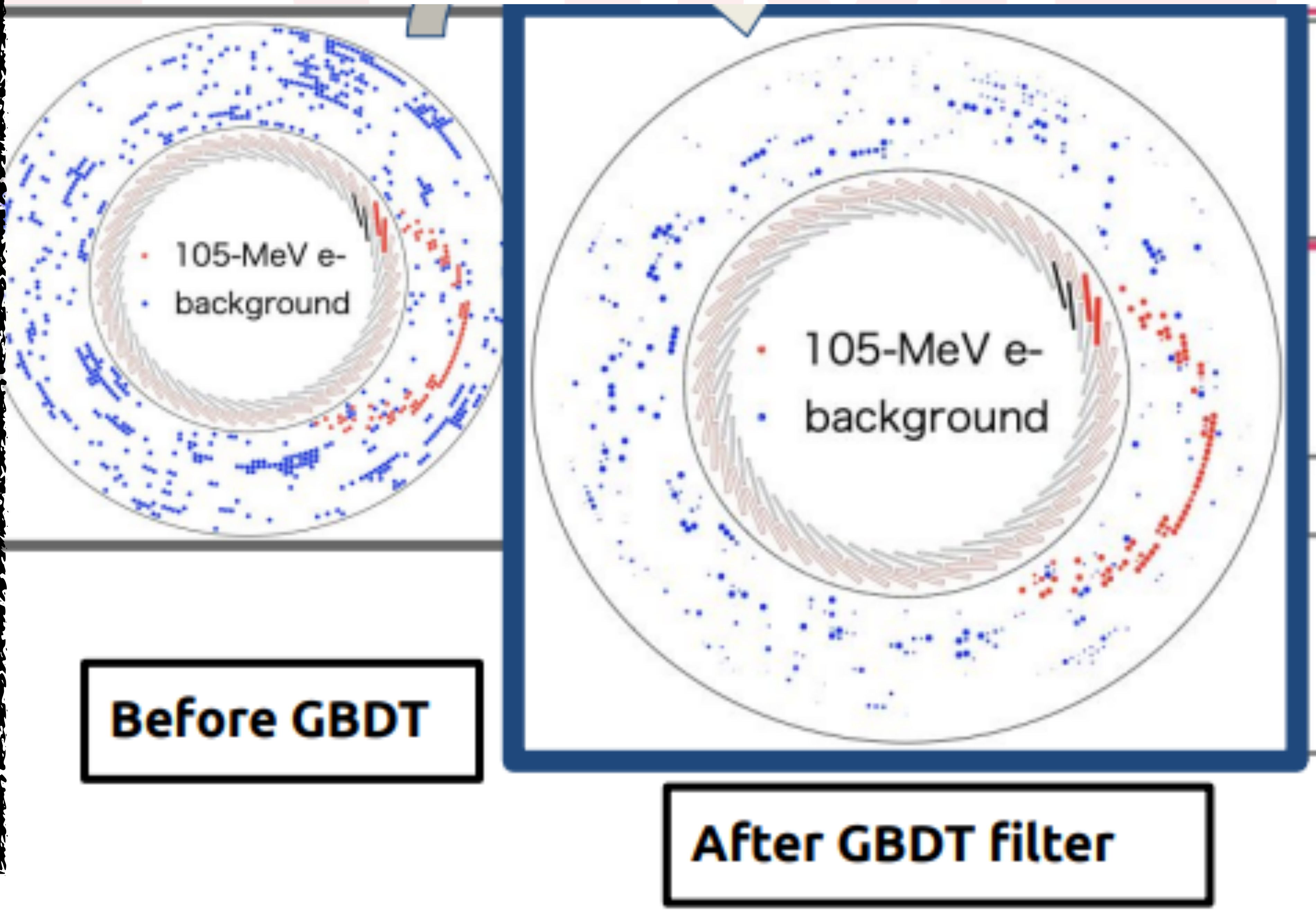


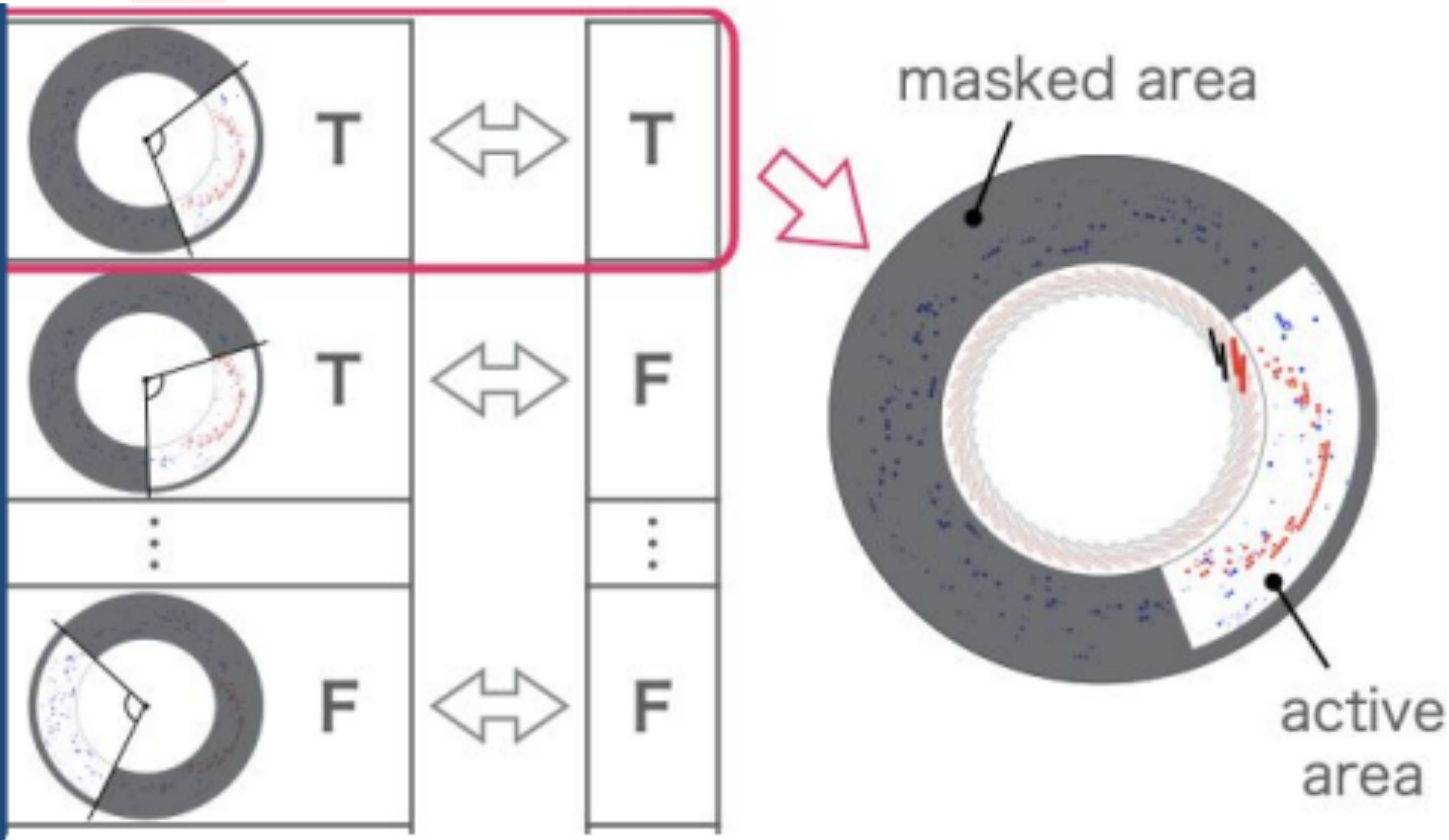

**Preliminary chain test of trigger system**

**More details in Yuki Fujii's talk on Friday (WG4+6)!**




**Overview of CyDet Trigger System for Phase-I**



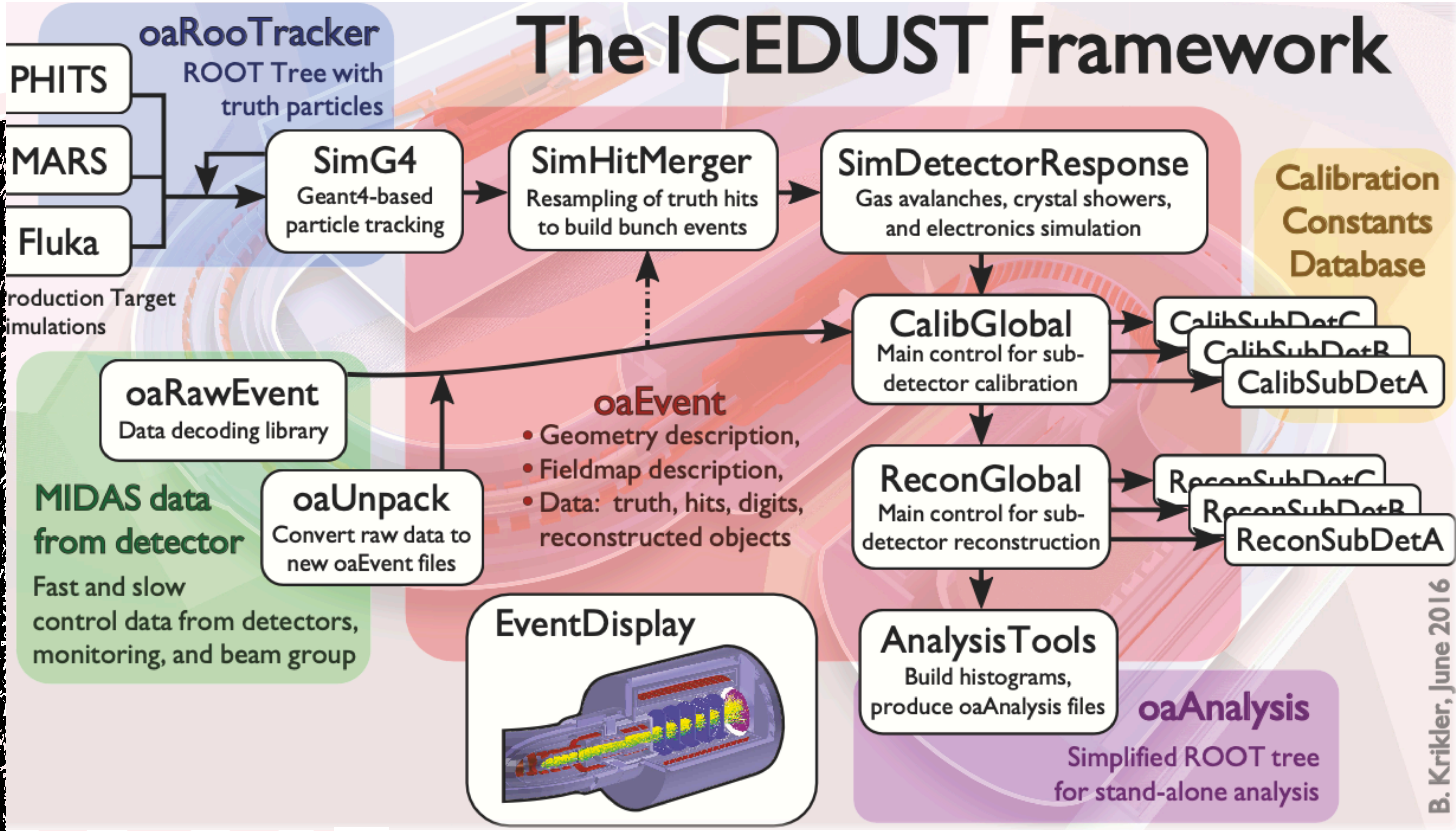

**Online GBDT hit classification**

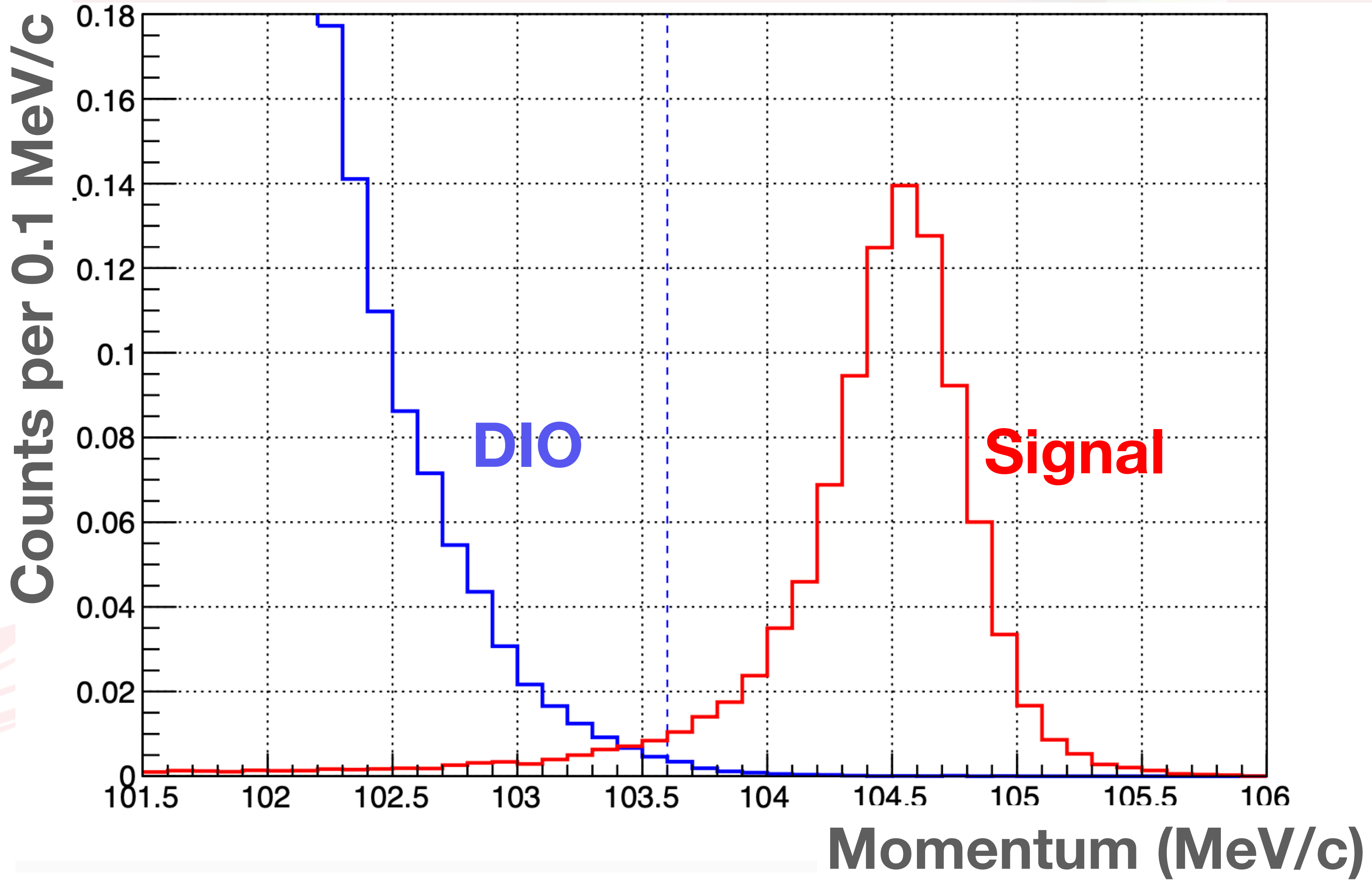
# Software

- COMET uses offline software framework called **ICEDUST**
  - Based on ND280 detector software framework from T2K experiment
  - Full physics simulation with realistic geometry and magnetic field implementation
  - Calibration, reconstruction and analysis

- Currently progressing on **sixth mass production** of simulation data

- Offline reconstruction and tracking work also ongoing

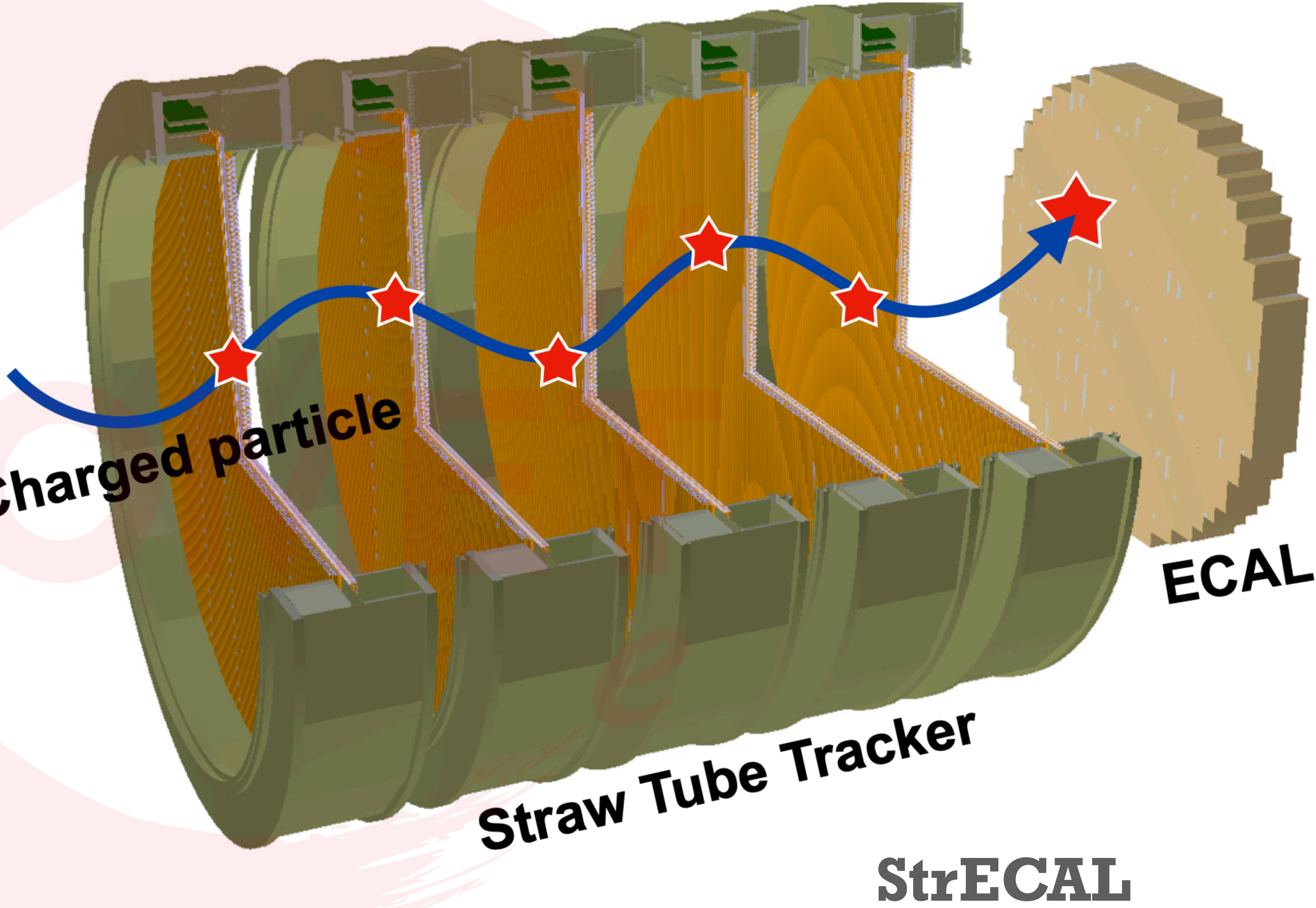



Phase-I Reconstructed Momentum Distribution

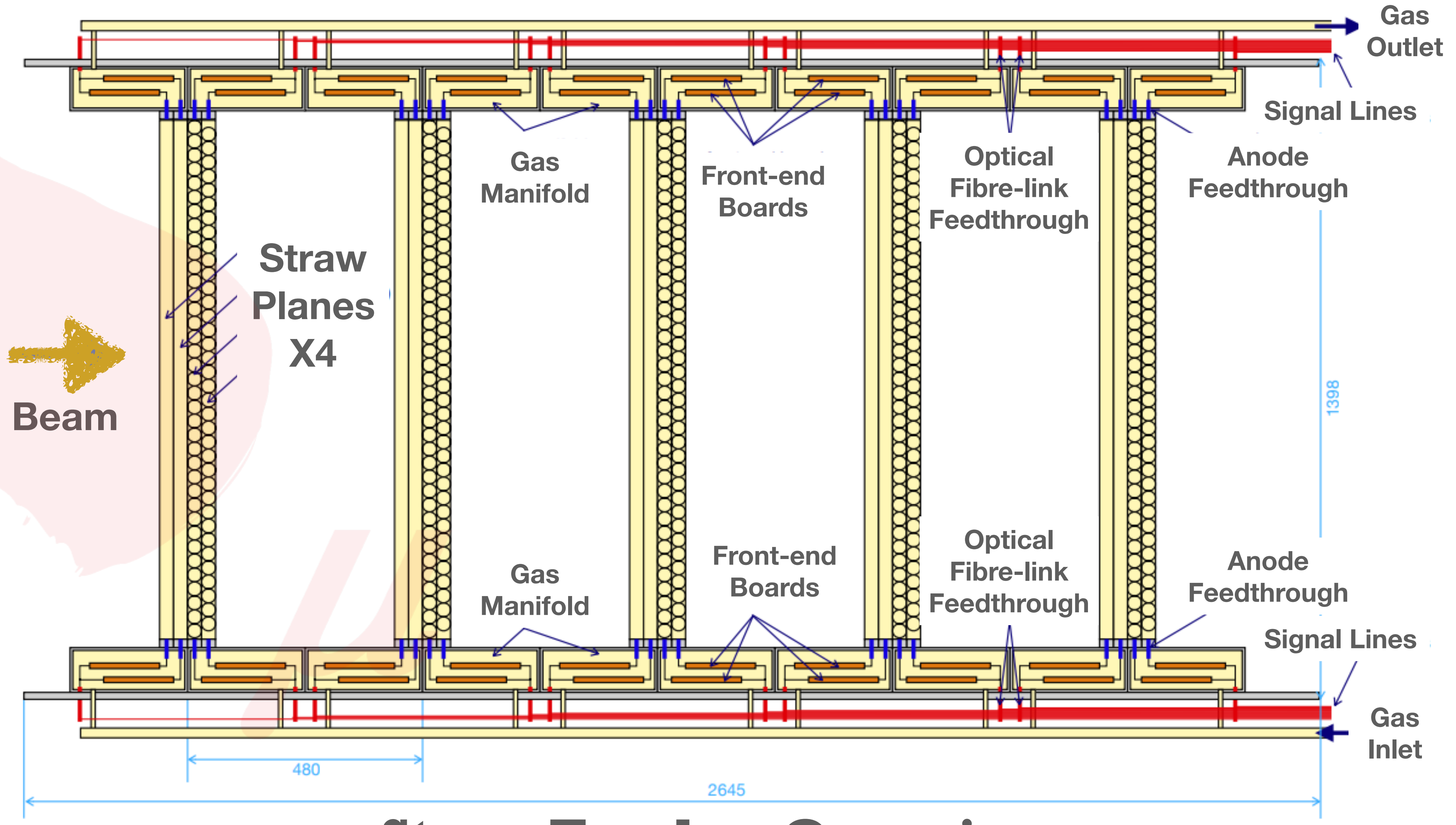
# StrECAL Detector

- **Str**aw tube tracker (momentum) **E**lectromagnetic **cal**orimeter (energy, timing + position)
- Main physics detector for **Phase-II**
- Will perform **beam + background measurement** in Phase-I – construction to be completed end of 2023

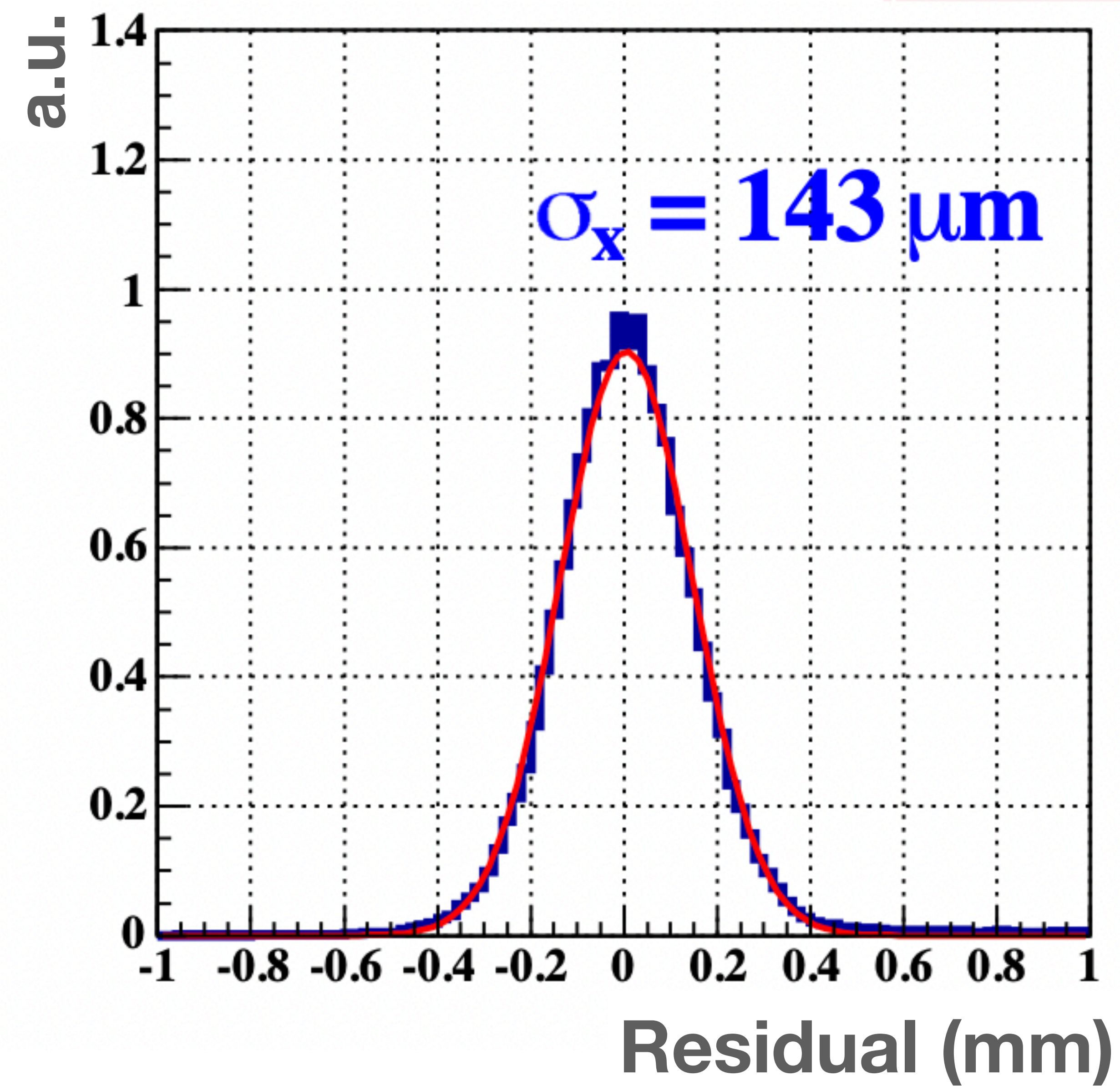


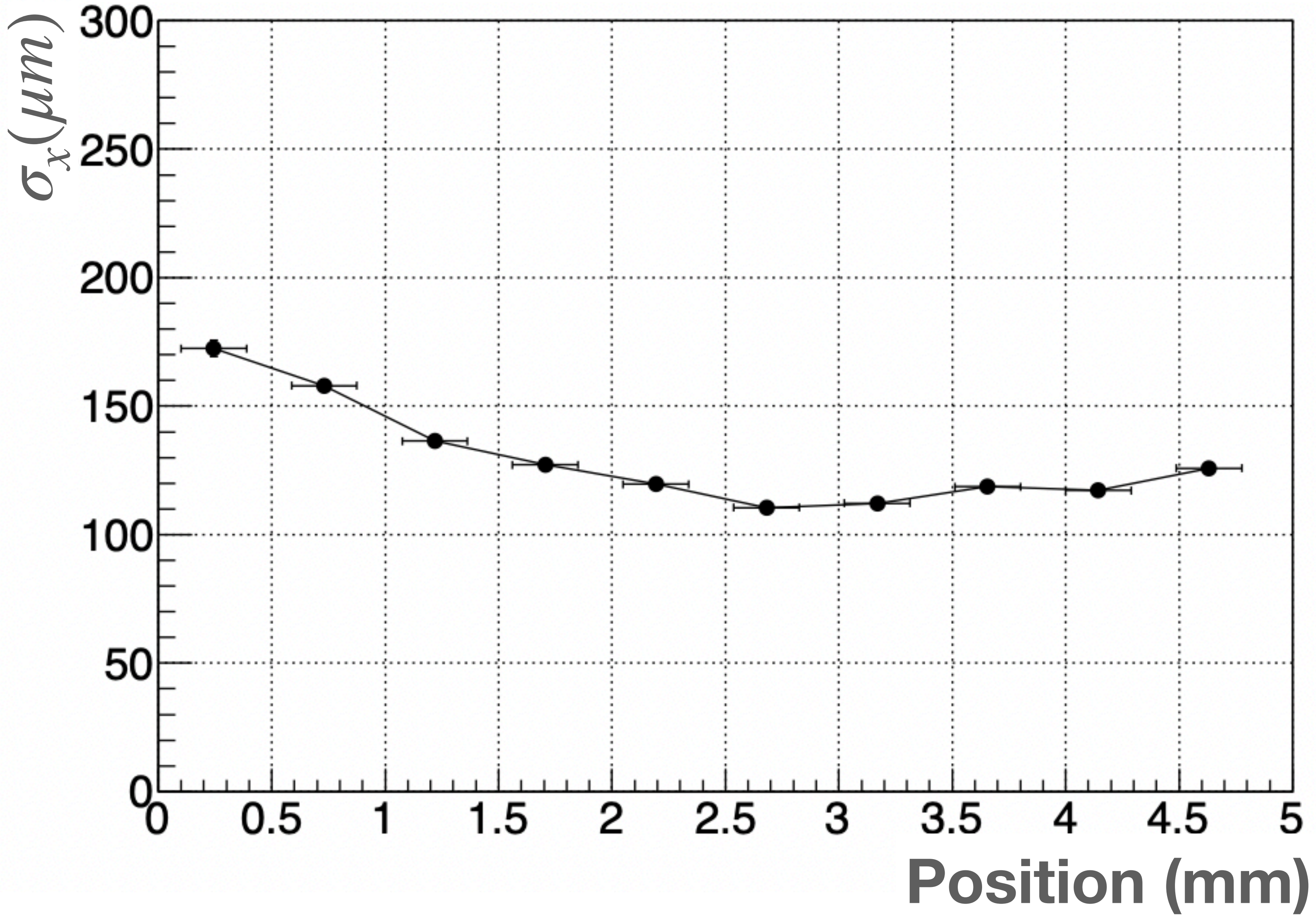
# StrECAL: Straw Tracker

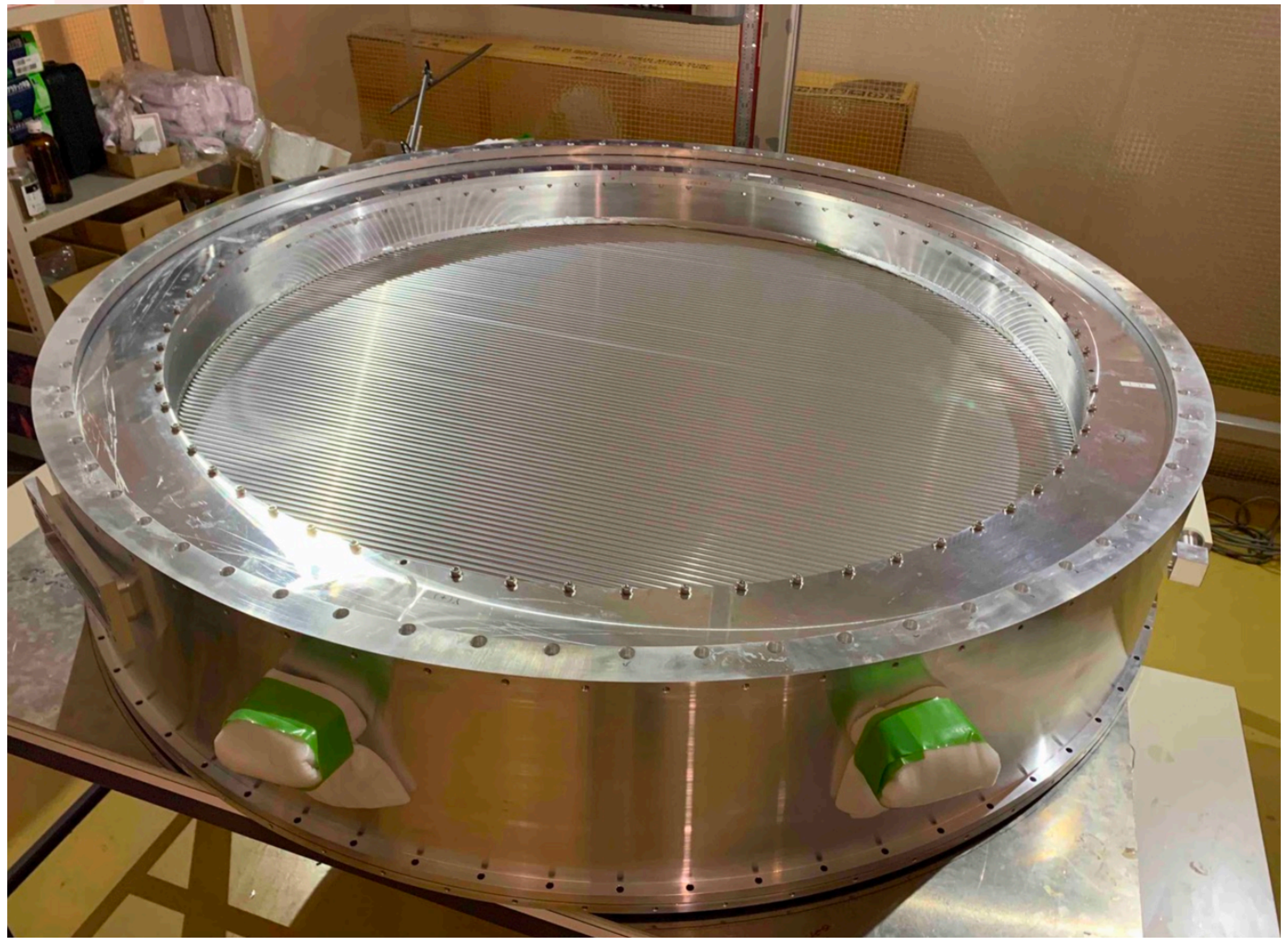
- 5 straw stations with 4 straw planes (2 in x-plane, 2 in y-plane)
- Phase-I: **20** $\mu m$ mylar + 70 nm Al thickness, **9.8** $mm\phi$ straws
  Phase-II: **12** $\mu m$ mylar + 70 nm Al thickness, **5.0** $mm\phi$ straws
- Ar:Ethane (50:50) gas used
- Averaged spatial resolution less than $150\ \mu m$ →better than **200 keV/c resolution**
- Currently one Phase-I straw station completed and second in progress




Straw Tracker Overview

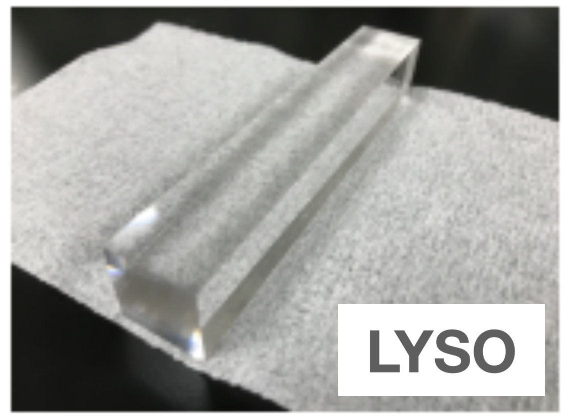


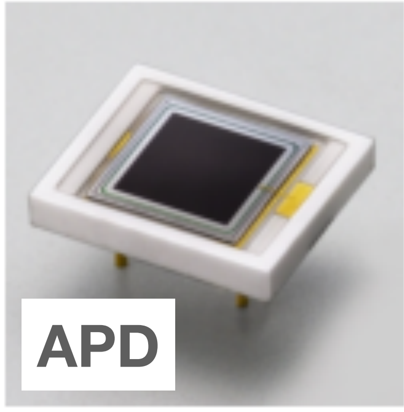



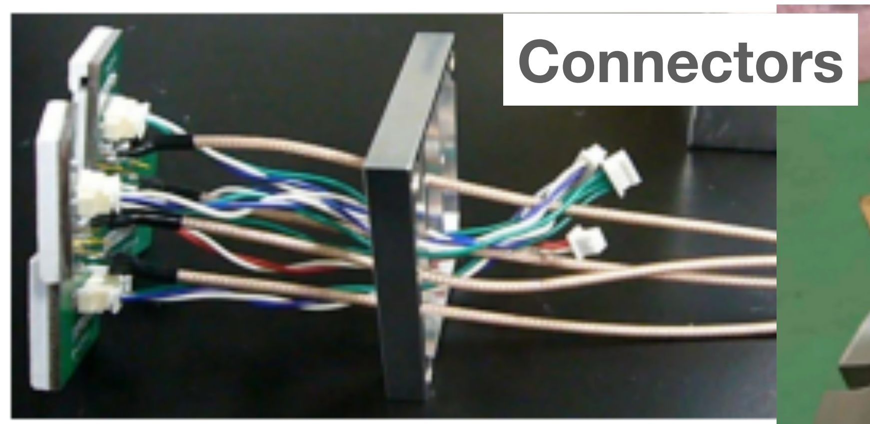



First Completed Straw Station

# StrECAL: ECAL

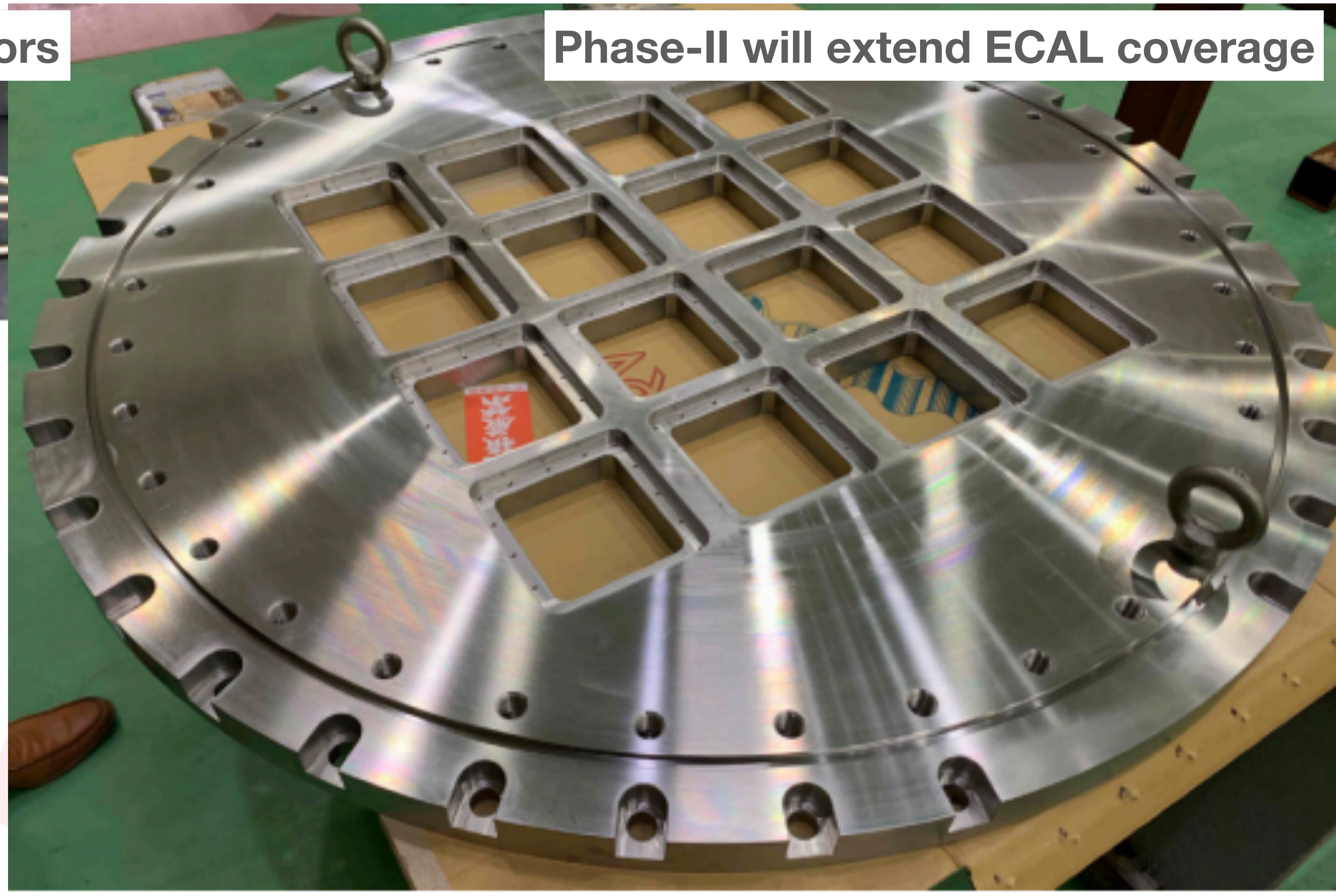


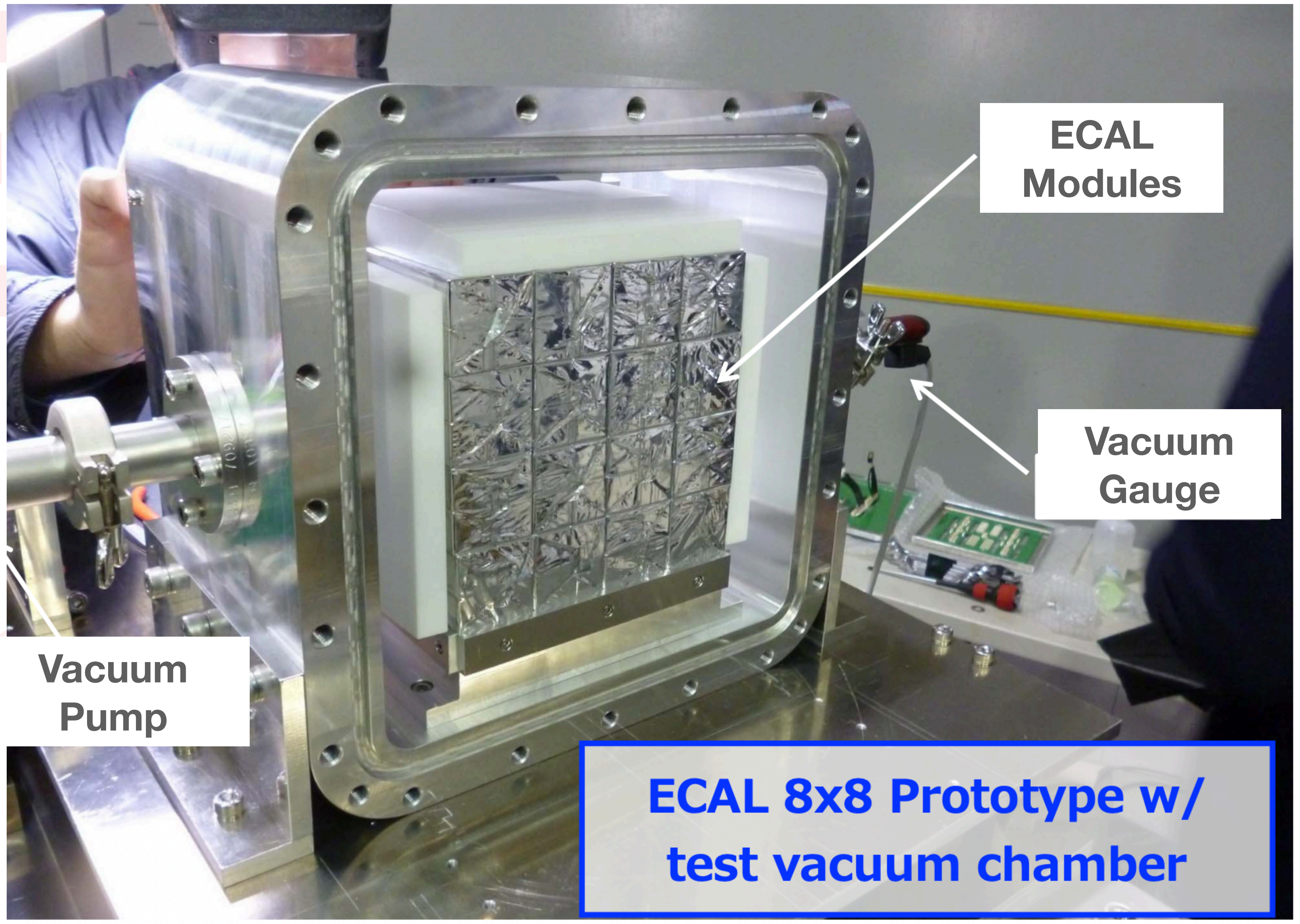




**ECAL Components**

- Designed for good **timing, position and energy resolution** in 1 T magnetic field
- Uses **LYSO** crystals and silicon **APDs**
- 105 MeV electron prototype tests **meet requirements**:
  $\sigma_E/E = 4\,\%$
  $\sigma_x = 0.6\ cm$
  $\sigma_t = 0.5\ ns$
- ECAL Phase-I support structure complete, crystal installation and detector construction to begin as well as readout electronics production
- Phase-II structure extends LYSO crystal coverage

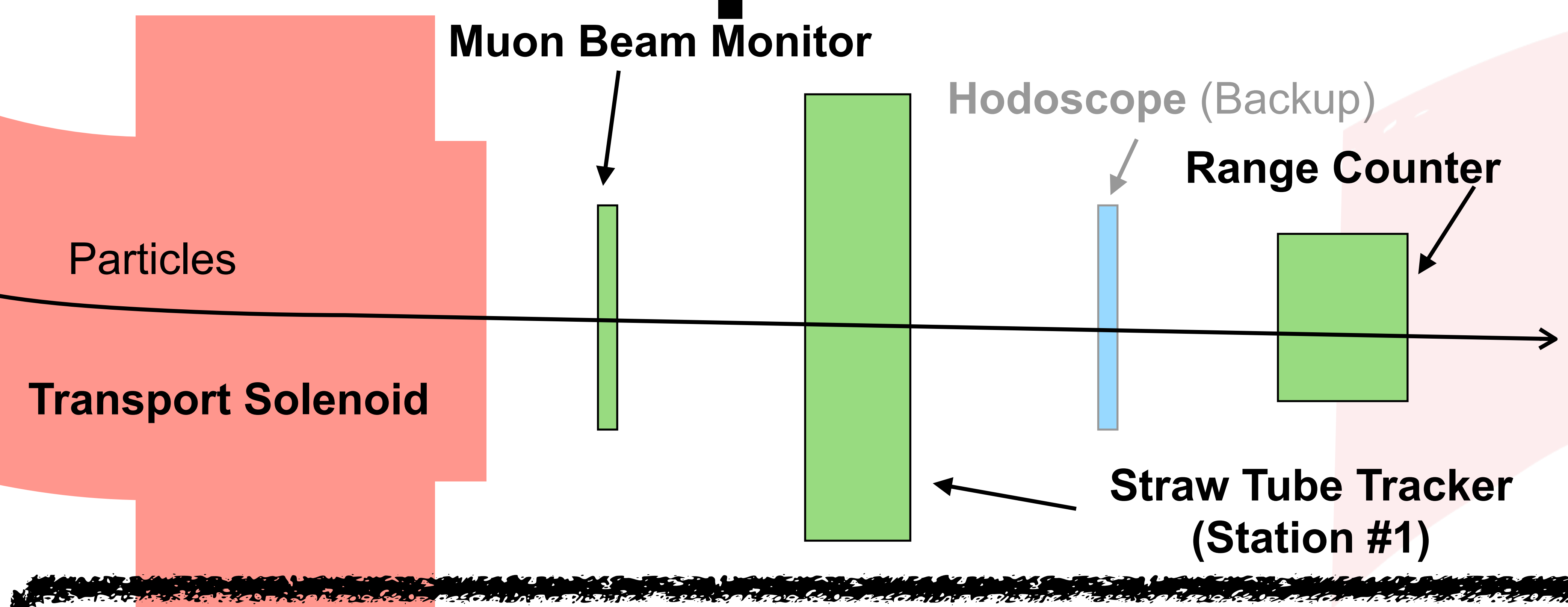



**Phase-I ECAL Support Structure**

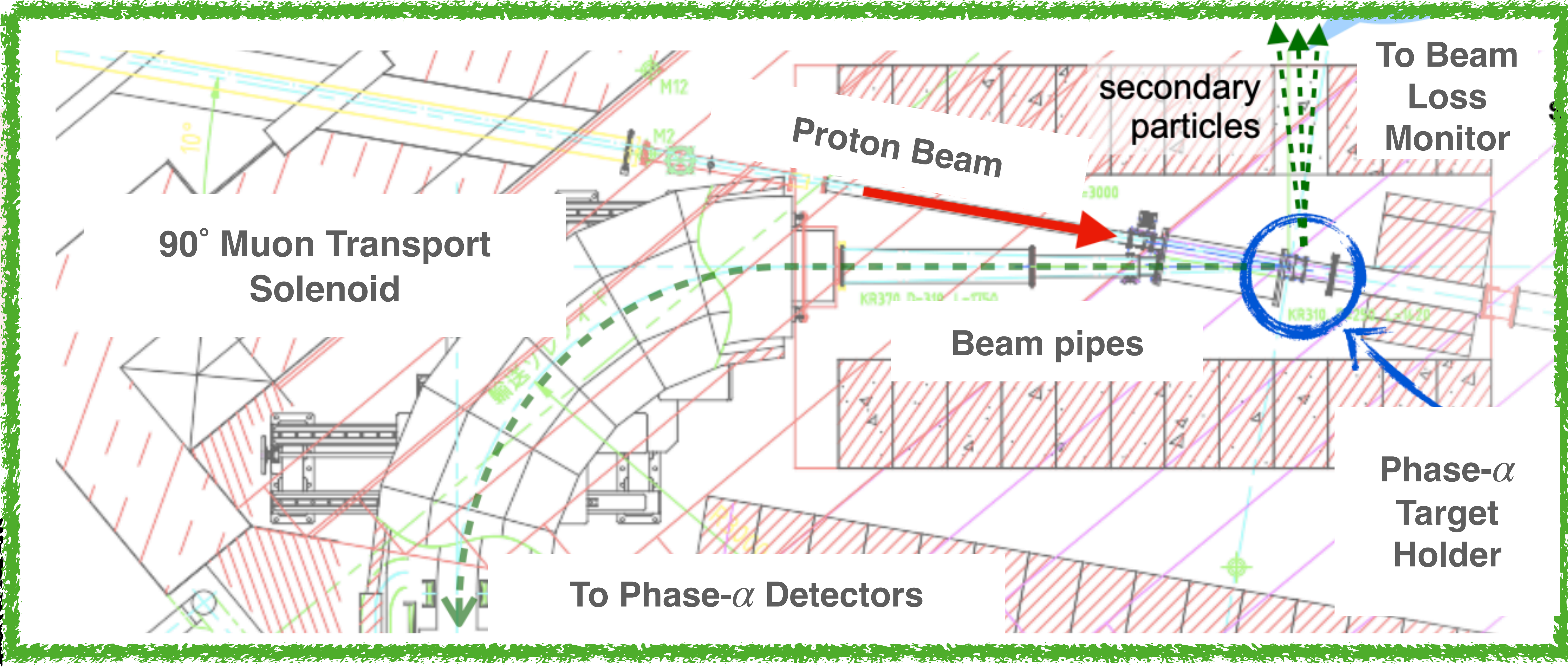


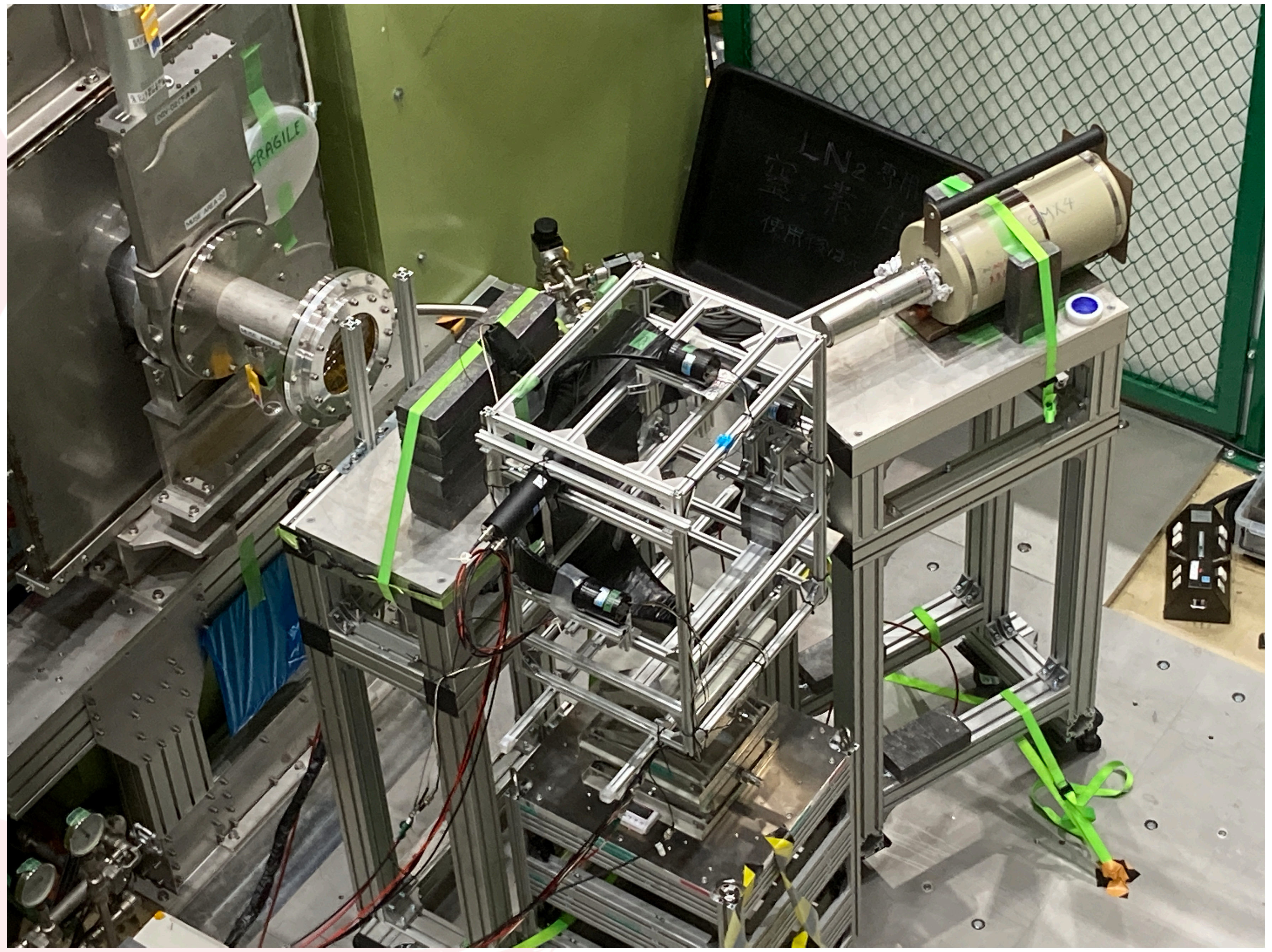

**ECAL Prototype Detector**

# Phase-Alpha

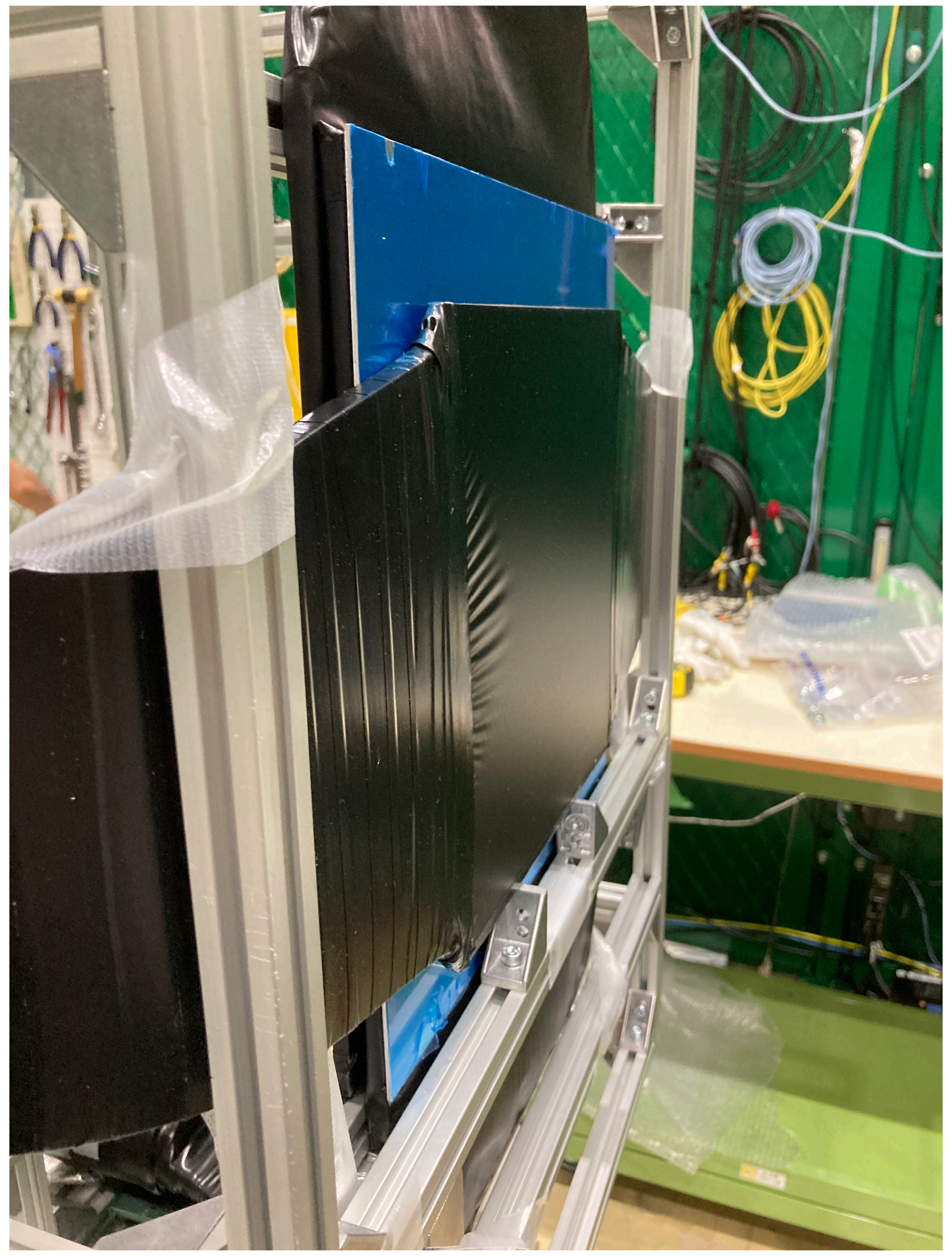



- Low intensity beam run in **2023** taking advantage of **proton beam facility being almost ready**
- **Aims of Phase-$\alpha$:**
    - Proton beam commissioning and further extinction measurements
    - Properties of COMET muon beam
    - Pion yield/cross section and secondary particles measurements
    - Validation of simulations
    - Transport solenoid selection capabilities
- Beam test for Phase-$\alpha$ detectors was performed in July



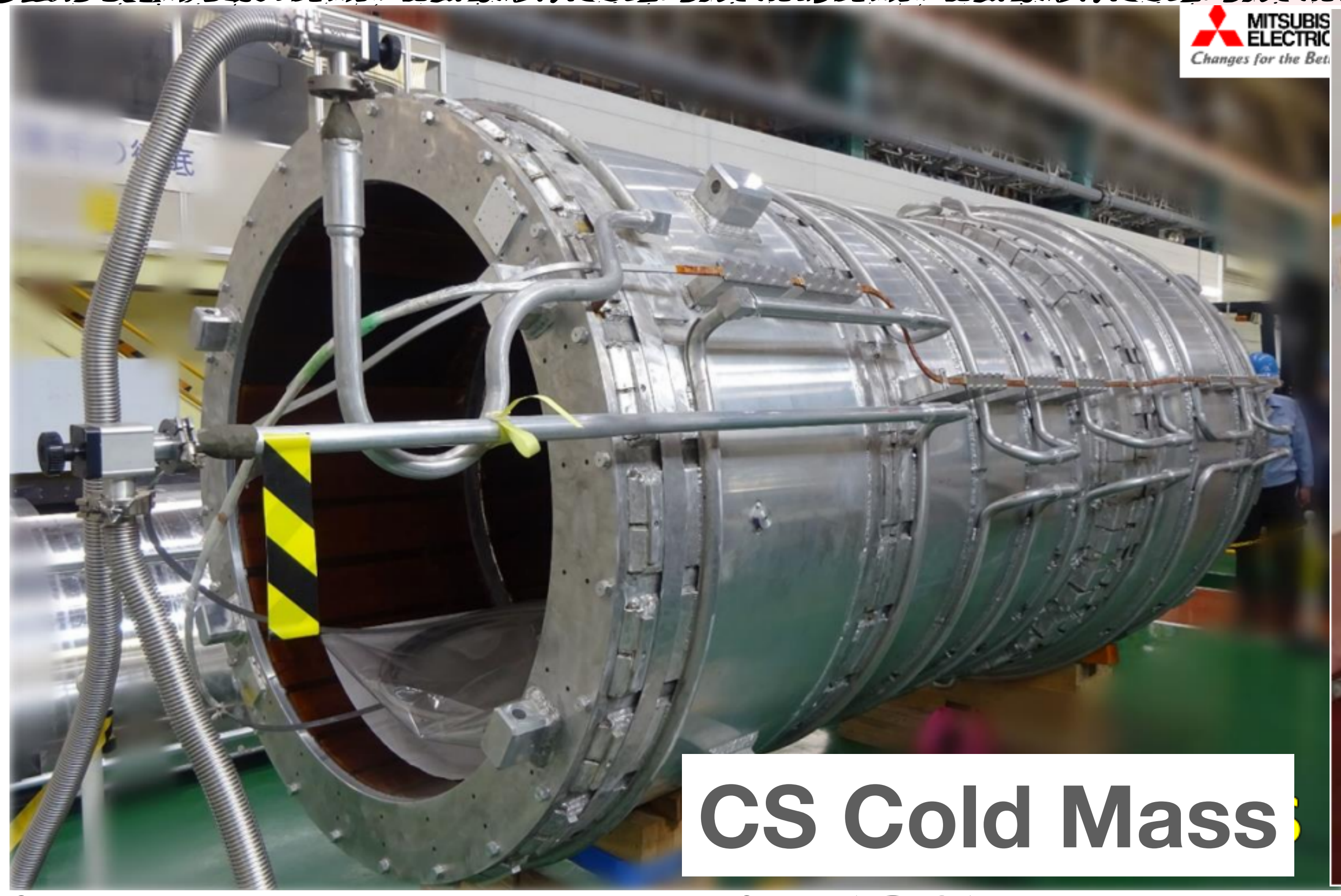
Beam Test in July 2022

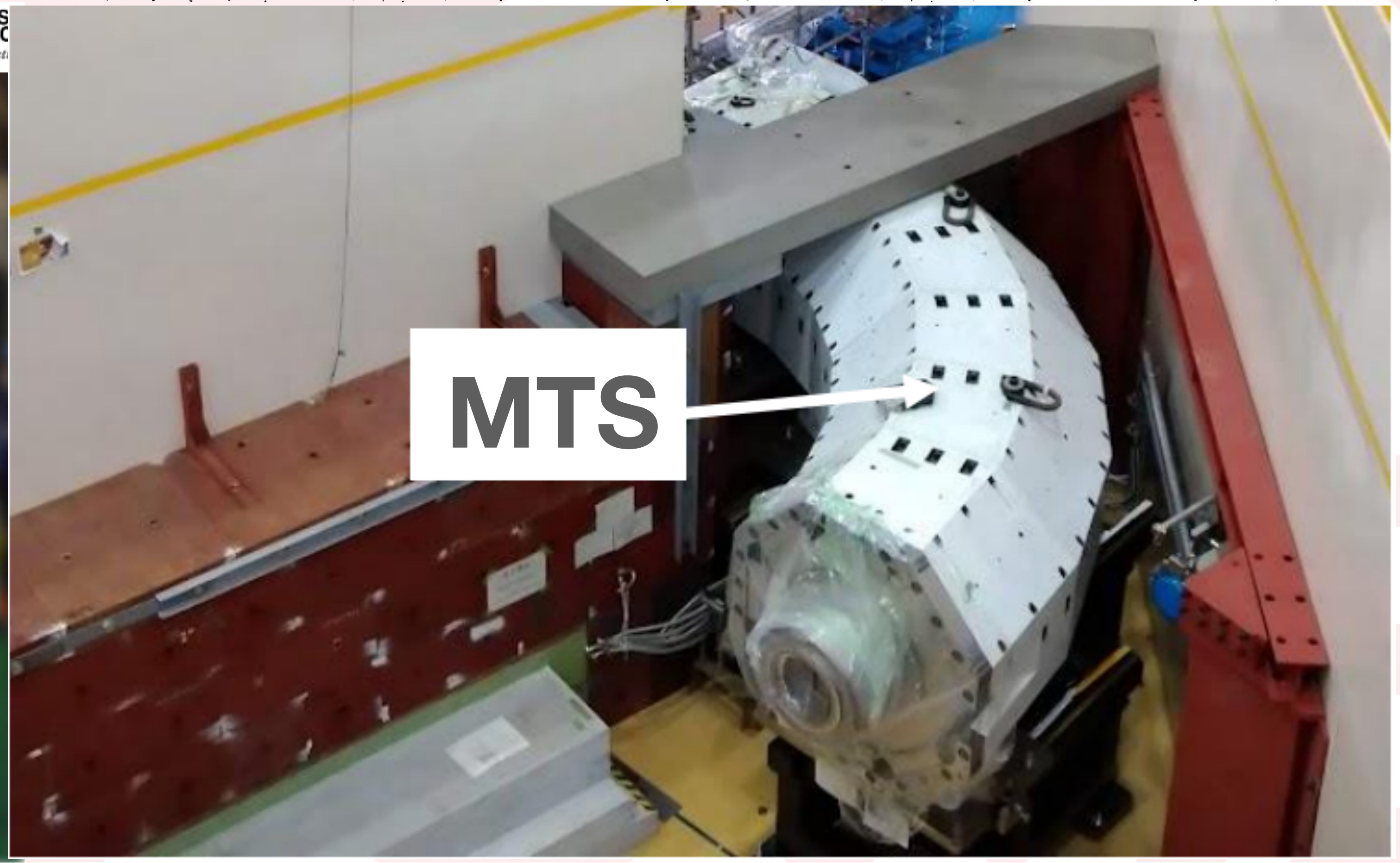


Range Counter Prototype at Beam Test

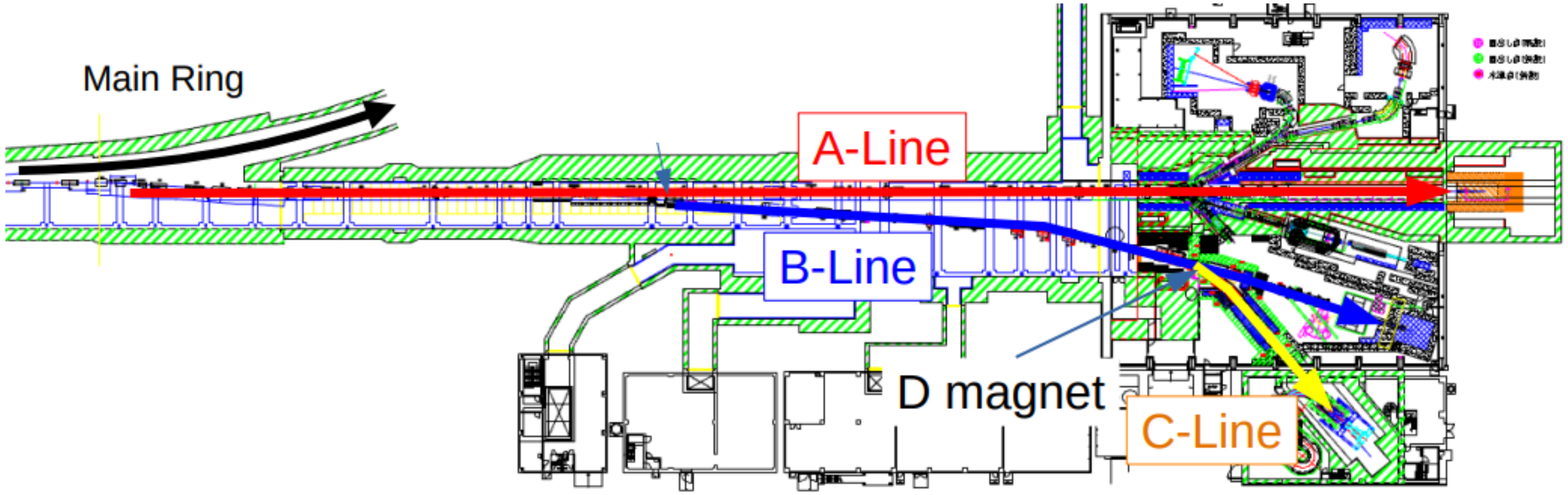
# Facility and Magnets

- C-Line under construction for COMET – **beamline up to Hadron Hall** (location of COMET) **completed**
- Muon Transport Solenoid first cooling and excitation test performed recently
- Preparation for pion capture solenoid assembly ongoing




**Pion capture solenoid (CS) cold mass and muon transport solenoid (MTS)**



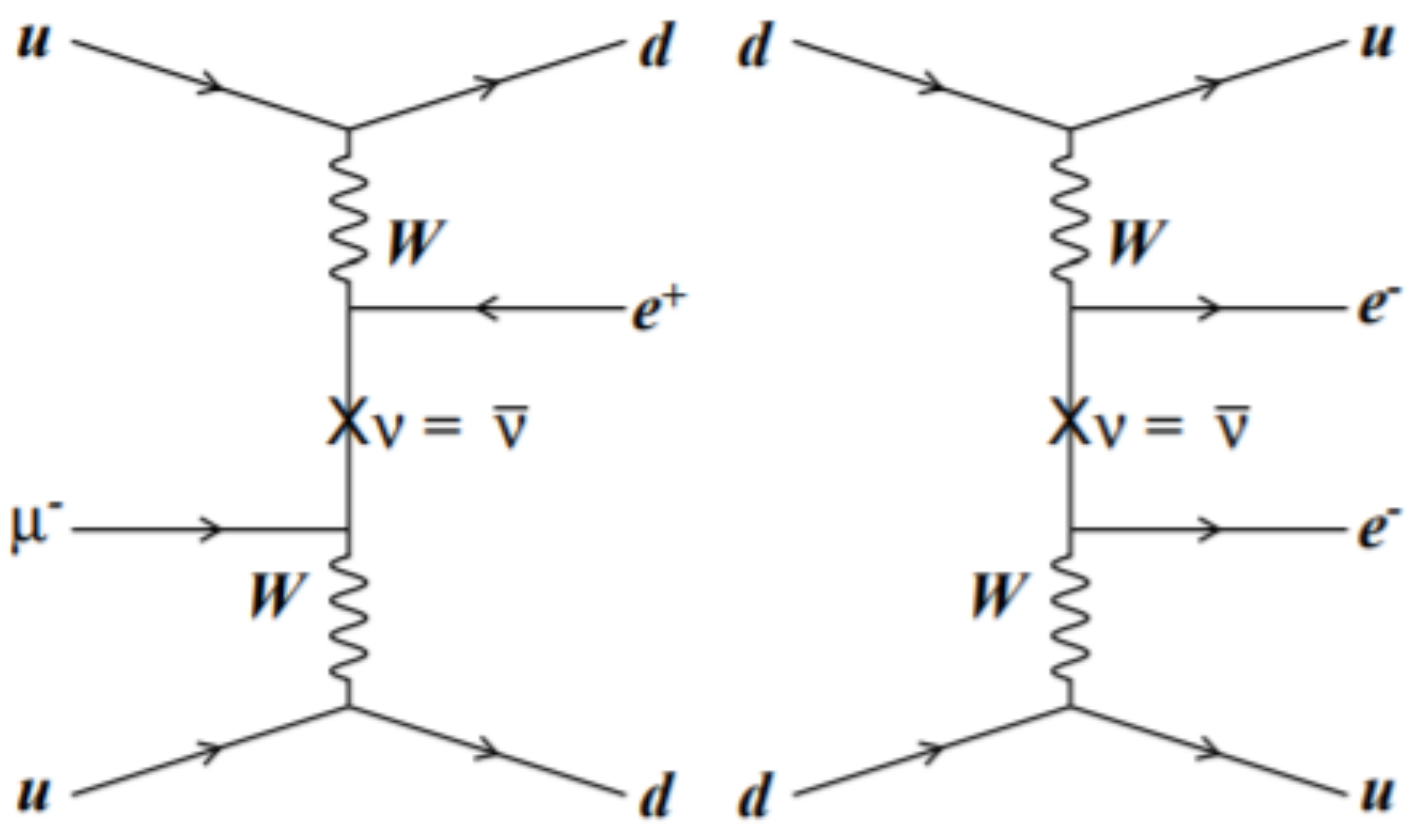

**J-PARC Facility Layout - COMET located at end of C-Line**

**Almost ready for Phase-$\alpha$**

**C-Line beamline equipment in Hadron Hall installed**

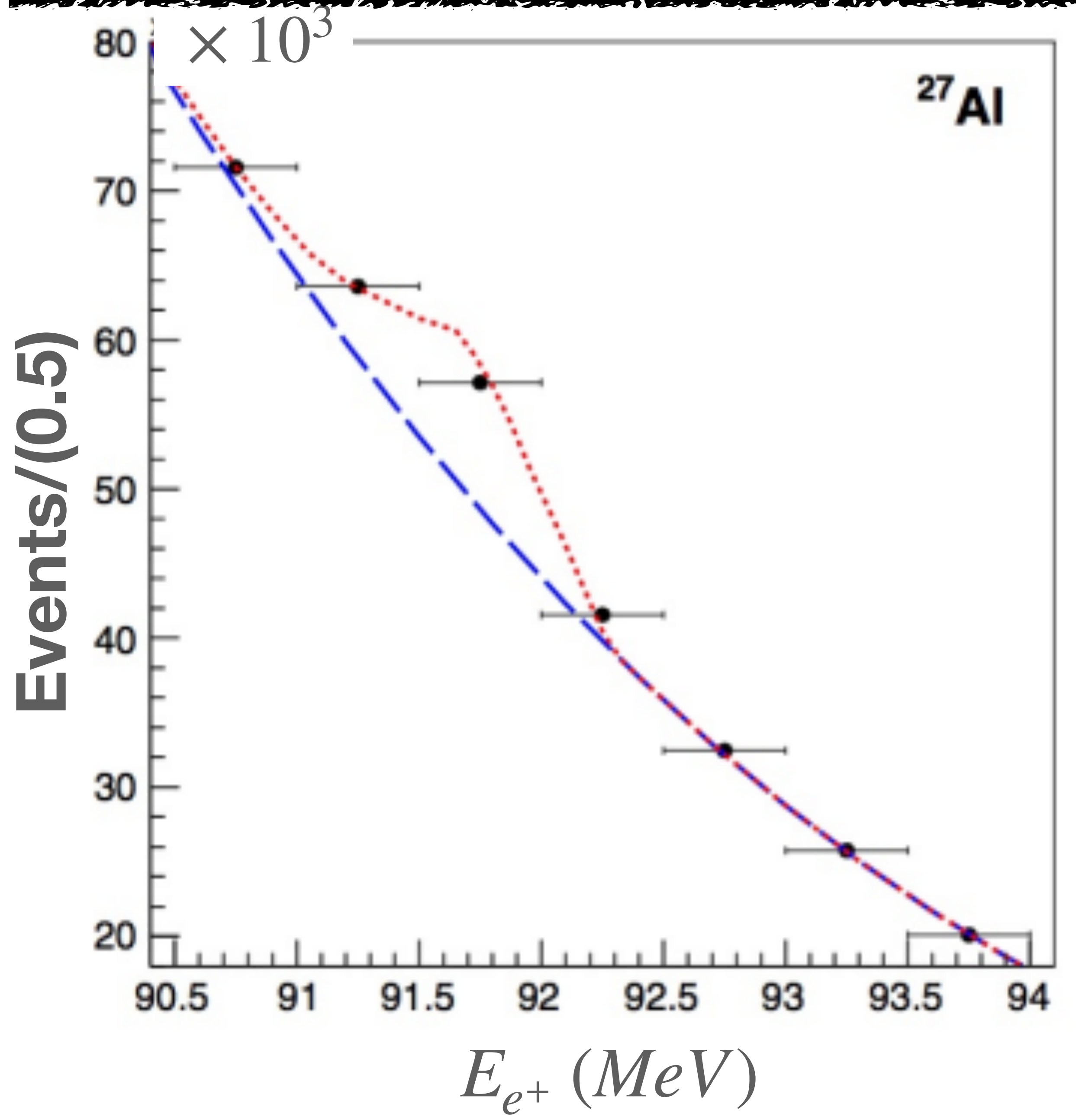
# Muon to Positron Conversion

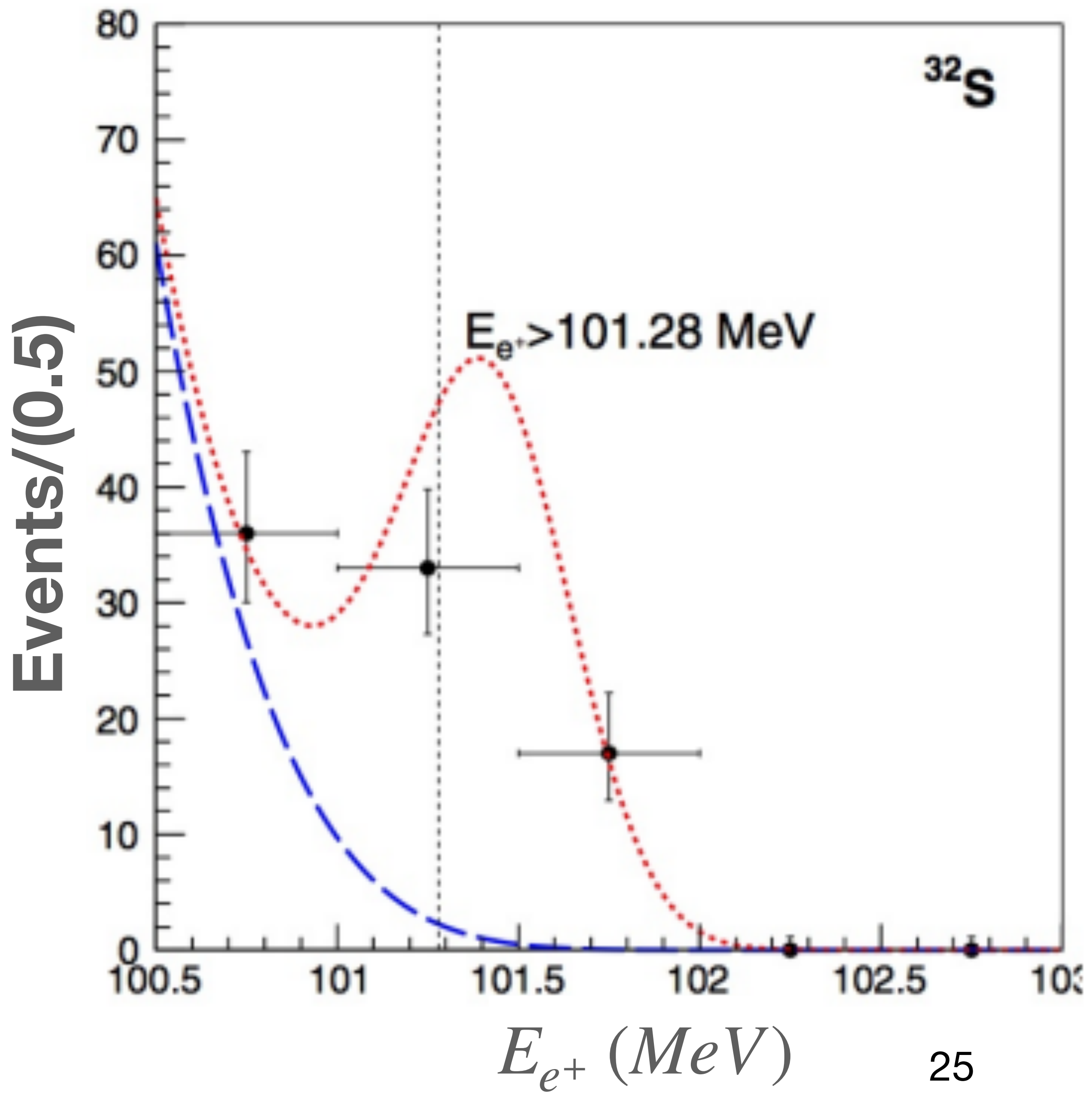
- COMET can also be **sensitive to additional physics**
- **Positron conversion** search complementary to $0\nu\beta\beta$ search
- Could be facilitated by addition of Majorana neutrinos or exchange of SUSY particles
- Current work being made on precise measurement of **radiative muon capture** photon spectrum plus simulation work on choice of **stopping target material**

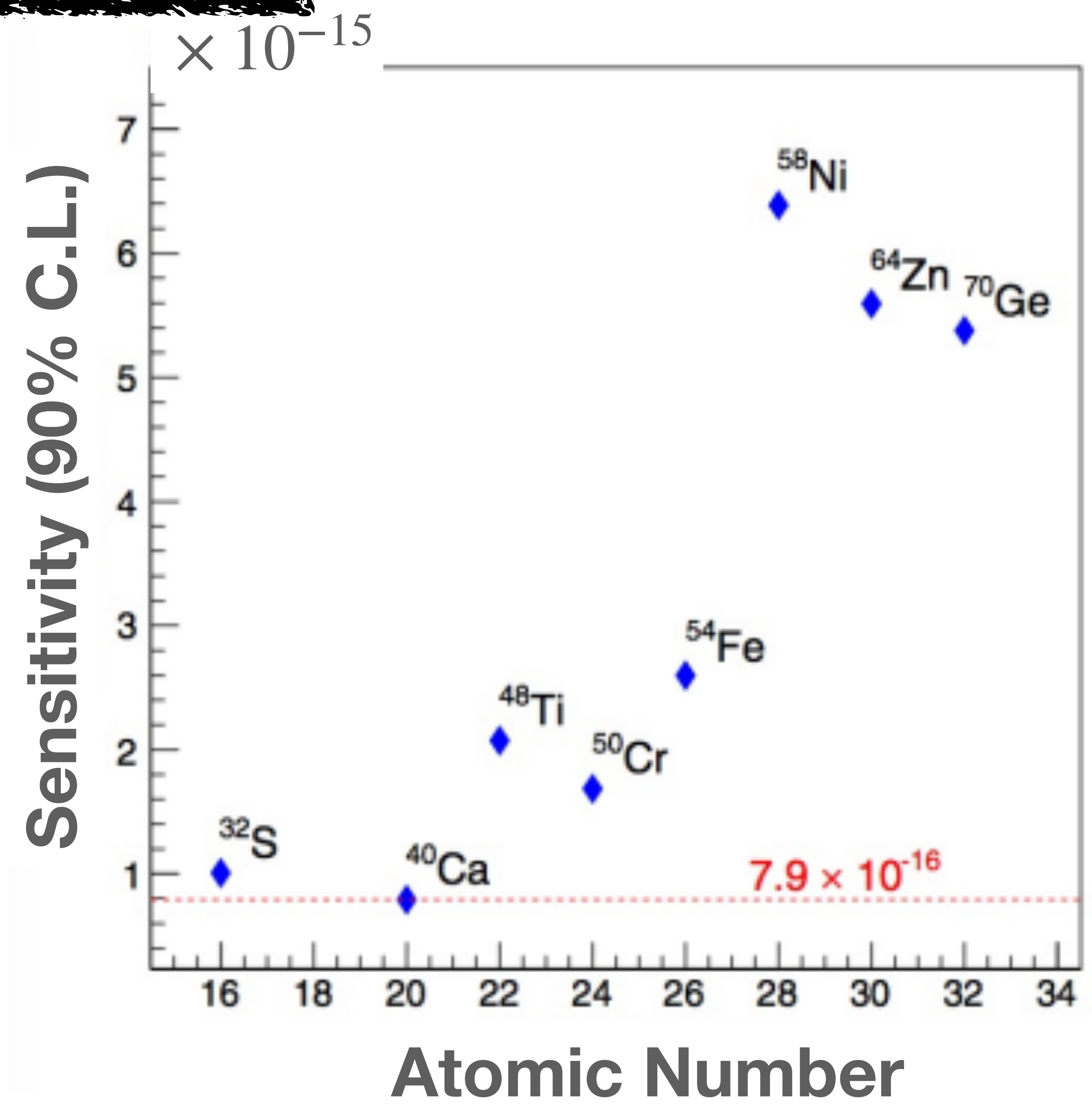



**Muon positron conversion and $0\nu\beta\beta$ diagrams**

Source: MJ.Lee an M.Mckenzie, *Muon to positron conversion*, arXiv:2110.07093



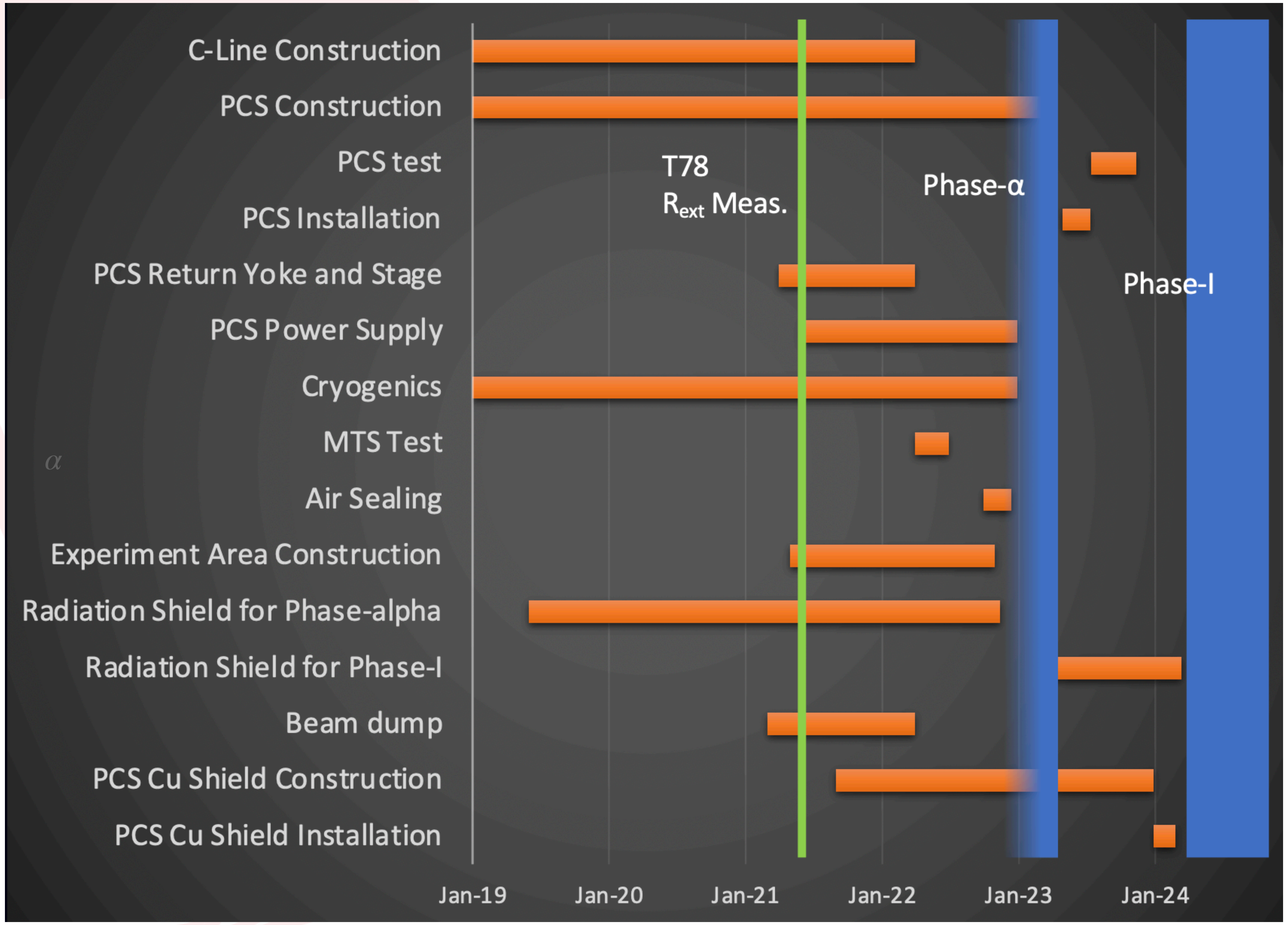




**Energy spectrum and sensitivity for muon positron conversion with different targets**

Source: MJ.Lee et al. *Search for Muon to Positron Conversion in $\mu^- \rightarrow e^-$ Conversion Experiments*, SnowMass2021-Letter of Interest

# Timeline

- All key facility and detectors on schedule for Phase-$\alpha$ (**2023**) and Phase-I (**2024**)
- Facility beamline to be ready for Phase-$\alpha$ (**2022**)
- Phase-I detectors:
  - CyDet - CDC moving to J-PARC (**2022**) and CTH construction (**2023**)
  - Phase-I StrECAL (**2023**)
  - CRV (**2023**)
- Phase-II following on from Phase-I, R&D efforts progressing now




**Facility timeline in lead up to Phase-$\alpha$ and Phase-I**

# Summary

## Thanks for listening!

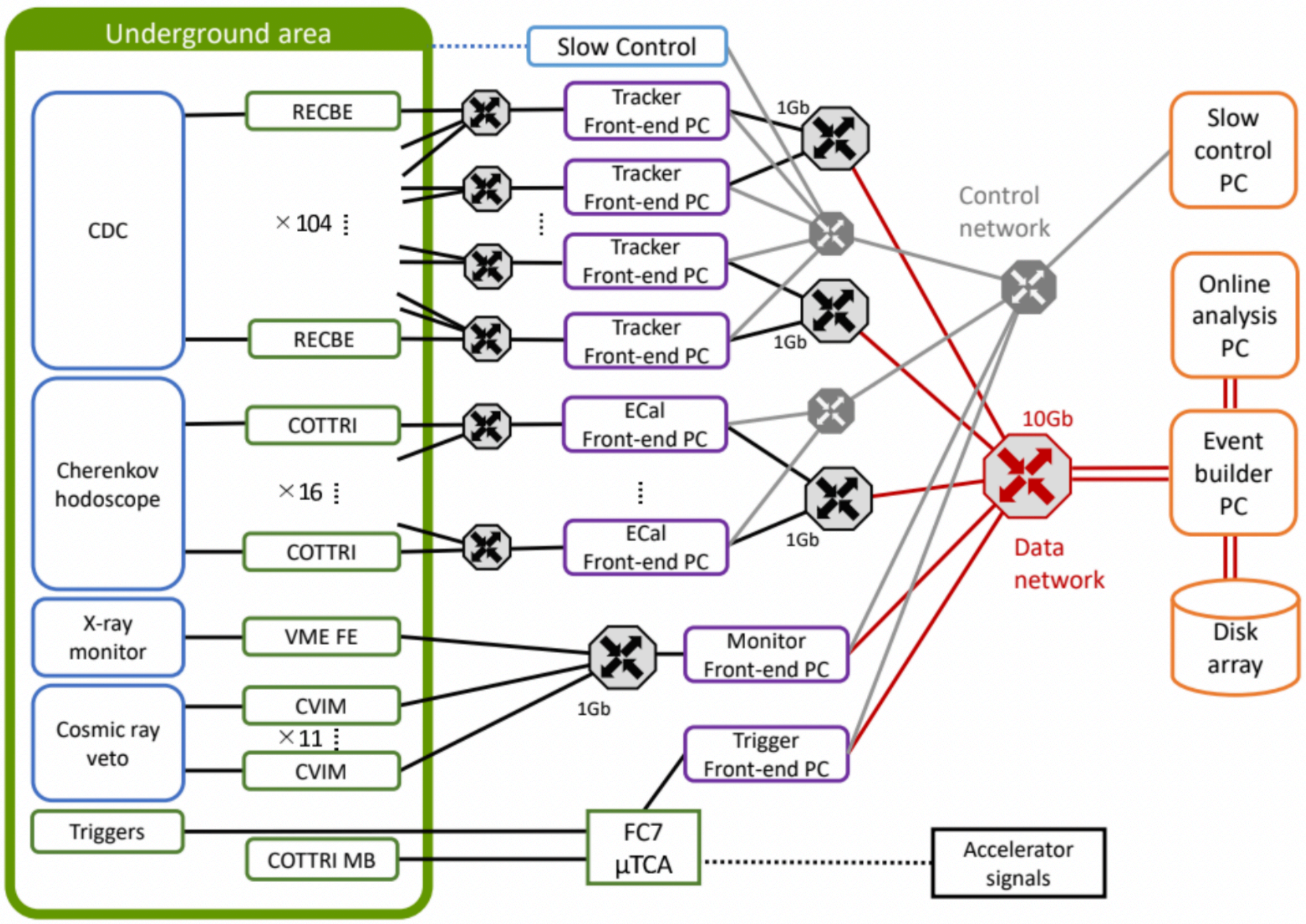
- The **COMET experiment** is searching for $\mu^- + Al \to e^- + Al$ with **increased sensitivity** using a staged approach.
- **Phase-I** will start physics run in **2024** with sensitivity of $3.1 \times 10^{-15}$
- **Phase-II** will begin shortly after Phase-I **increasing sensitivity** to $1.4 \times 10^{-17}$
- **Phase-$\alpha$ low intensity beam run** will begin at the start of **2023**, an important milestone in preparing for physics data collection!

**Recent Progress Recap**

- **COMET proton beamline** (C-Line) **almost completed**, on schedule for Phase-$\alpha$
- **Beam tests** in preparation for **Phase-$\alpha$ completed**
- **Phase-I detectors** all on schedule for **2024**
- **Sixth mass production** from COMET software group currently **progressing**

# Backup Slides

# DAQ Outline




Overview of DAQ System for Phase-I