A Cylindrical Trigger Hodoscope System for the COMET phase-I experiment

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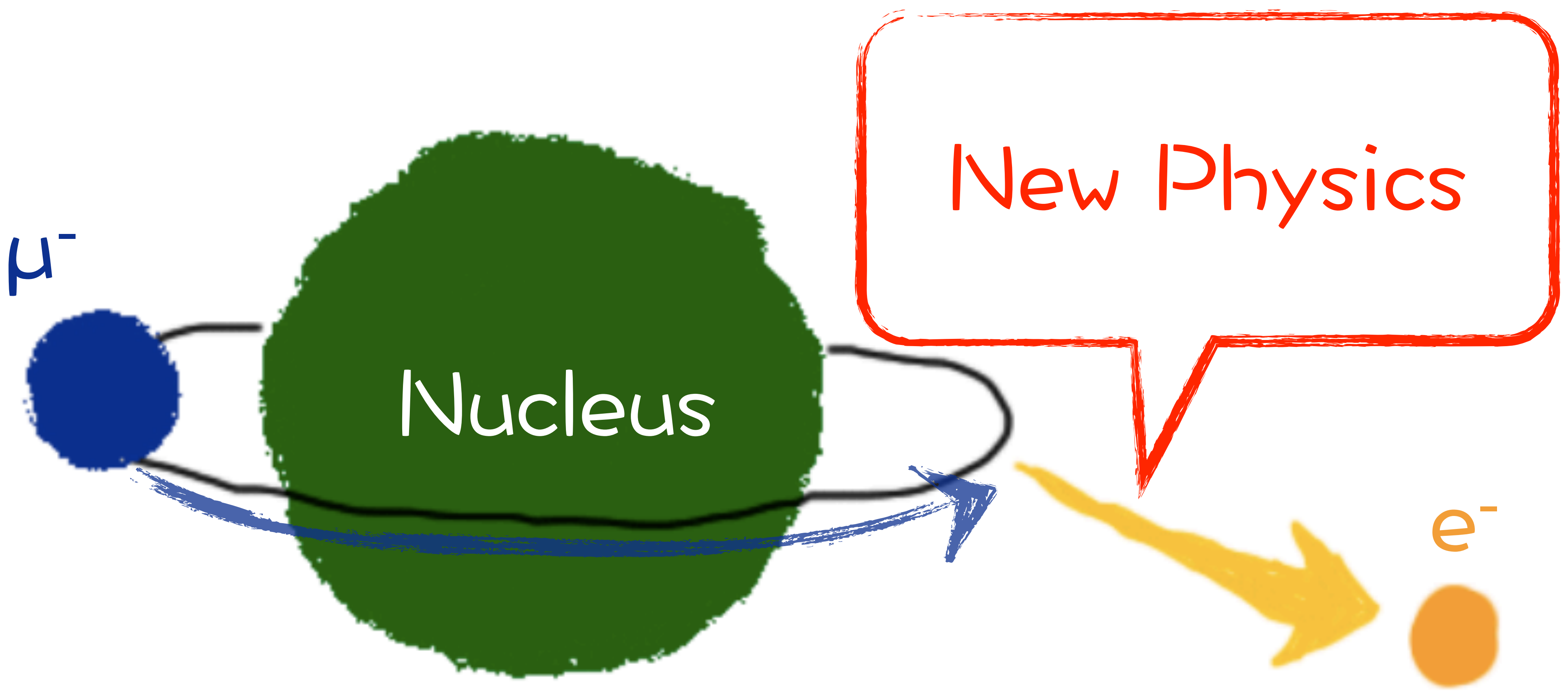
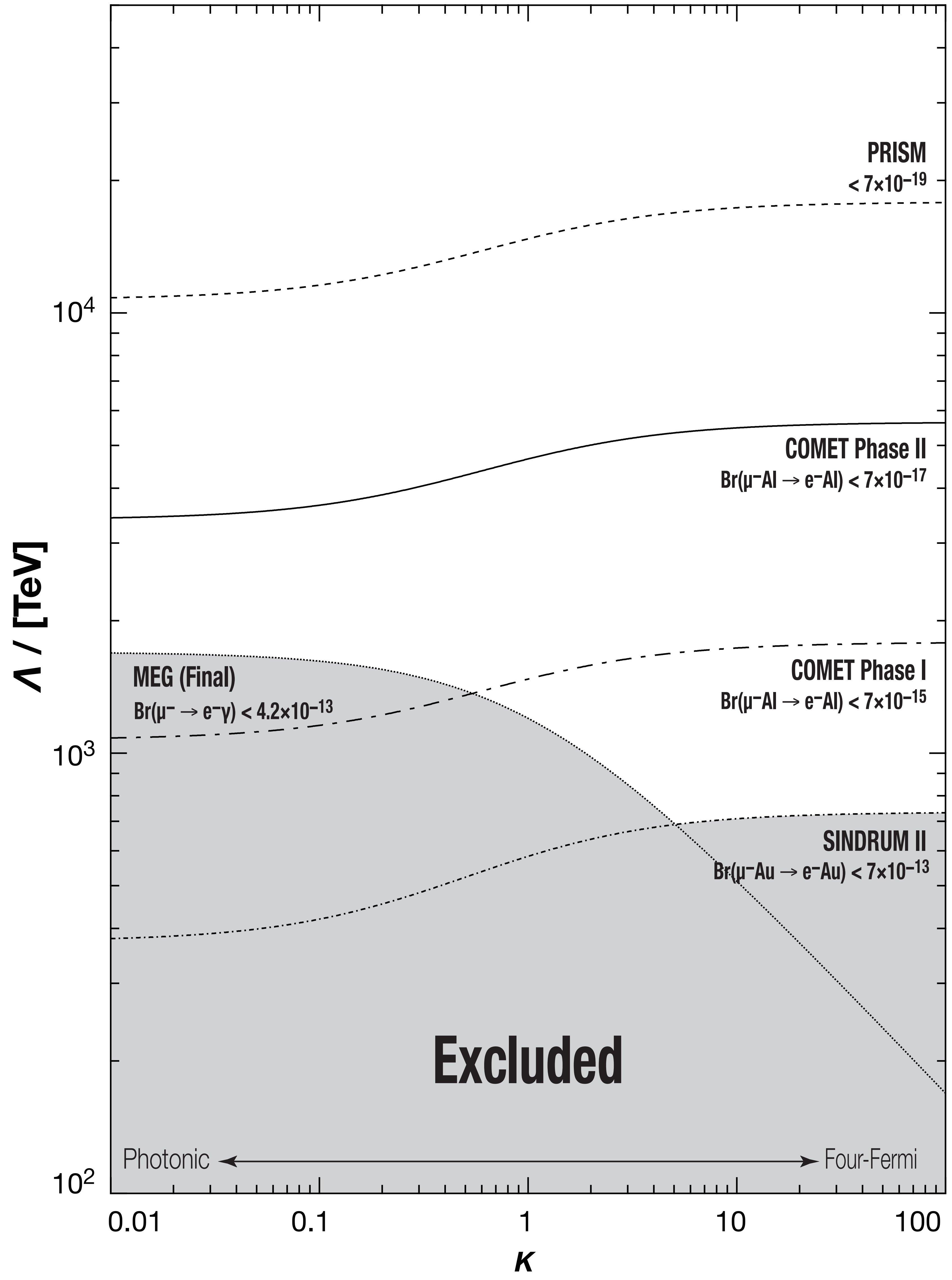
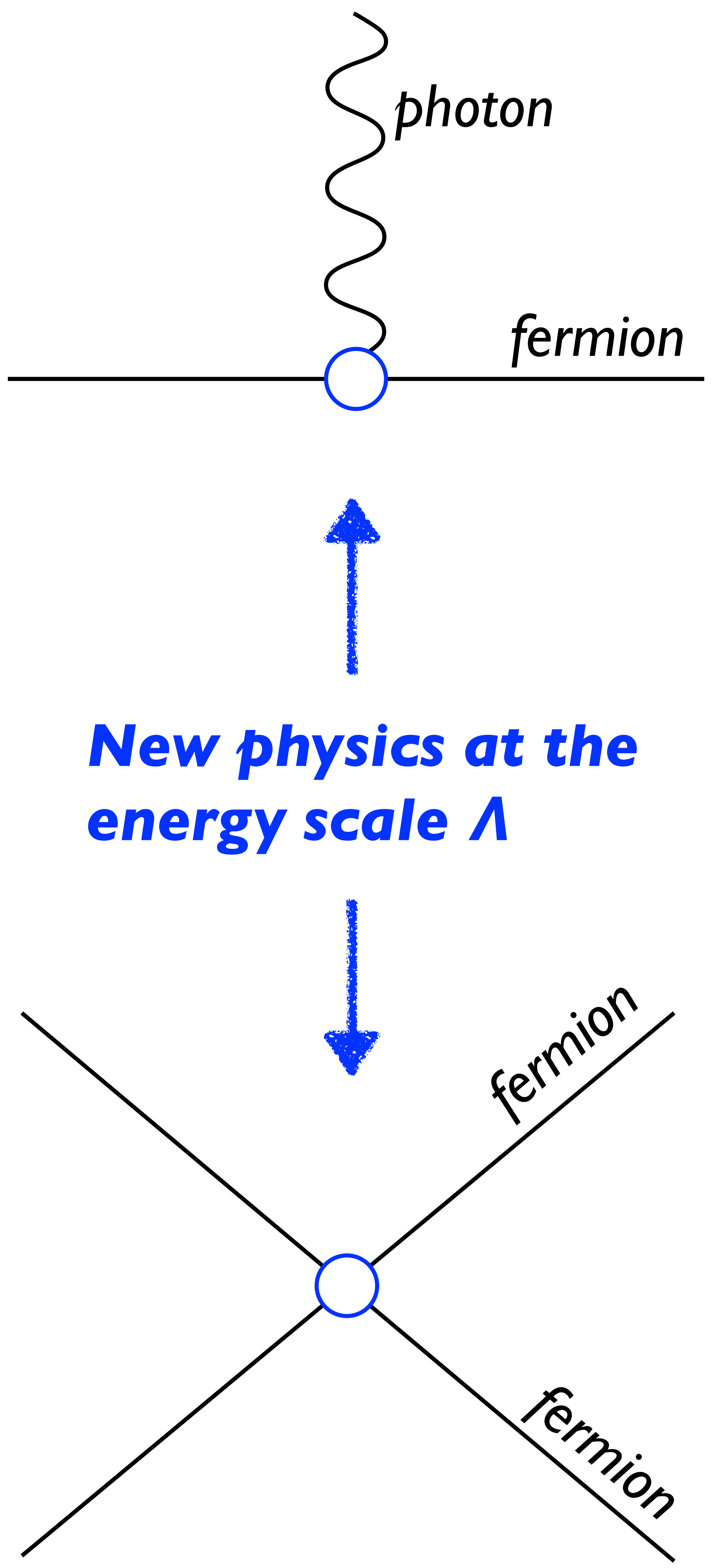
The muon-to-electron conversion

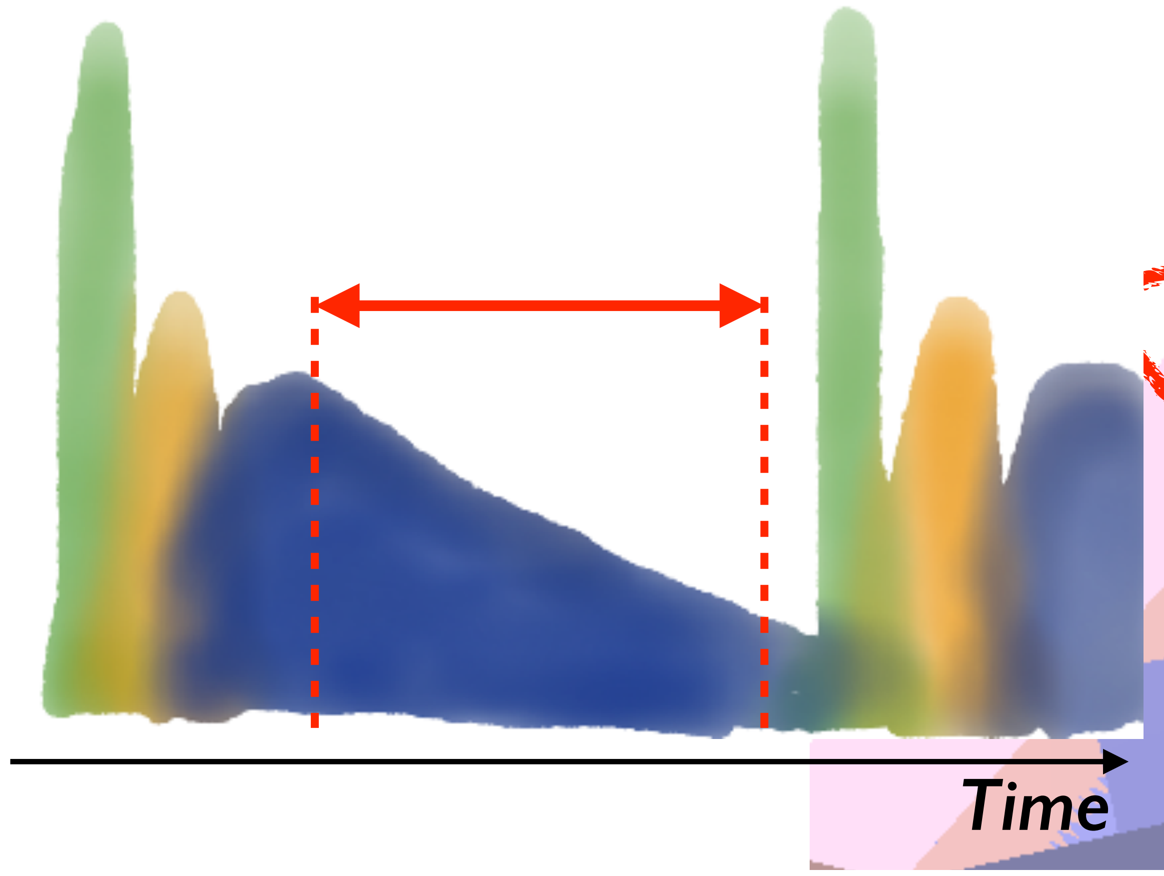
- One of the Charged Lepton Flavour Violation (CLFV) processes detectable if only the BSM exists
- Indirectly sensitive to the energy scale of new physics higher than 100 TeV
- The current 90% C.L. upper limit is 7×10^{-13} @Au set by SINDRUM II

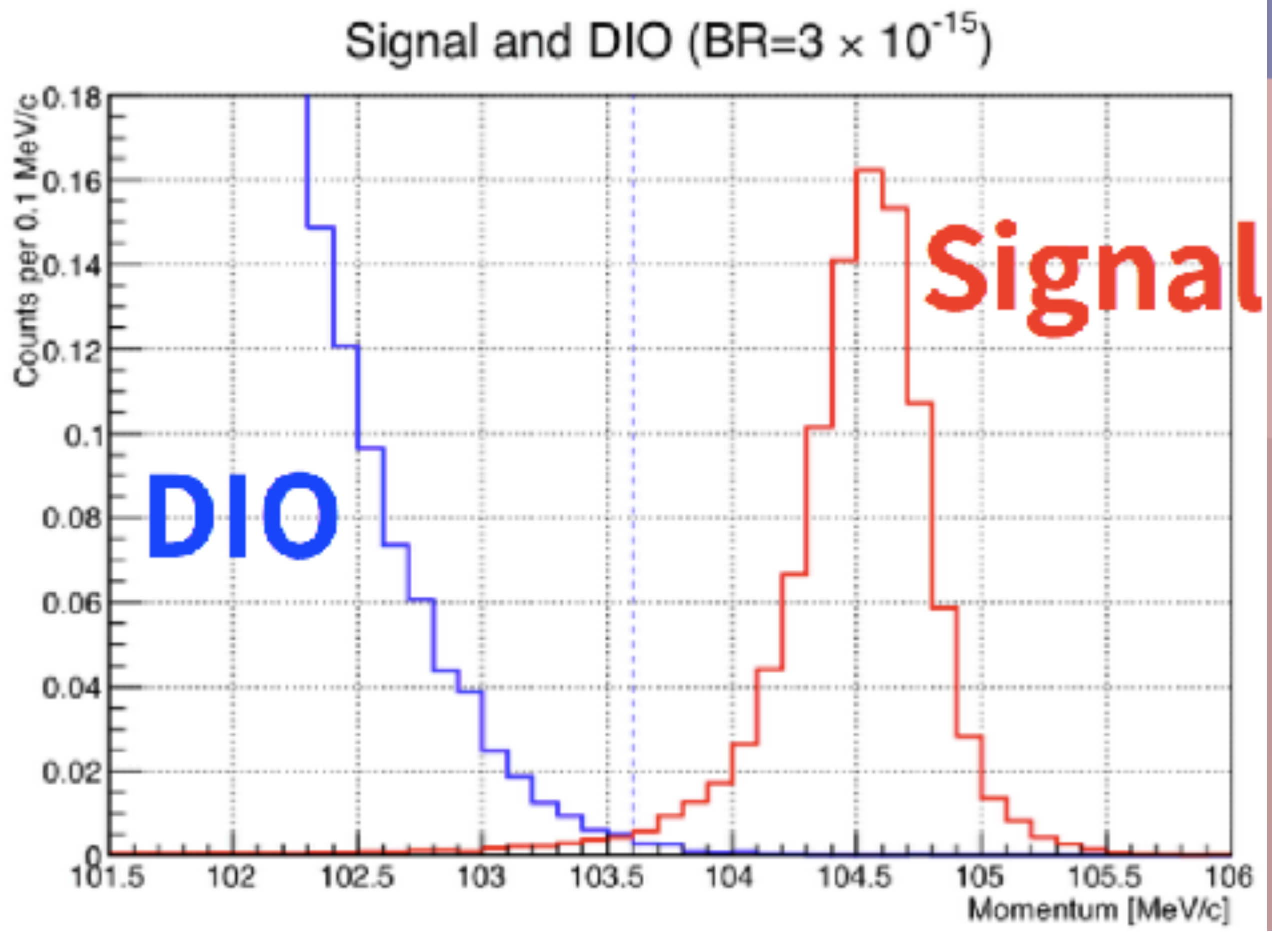


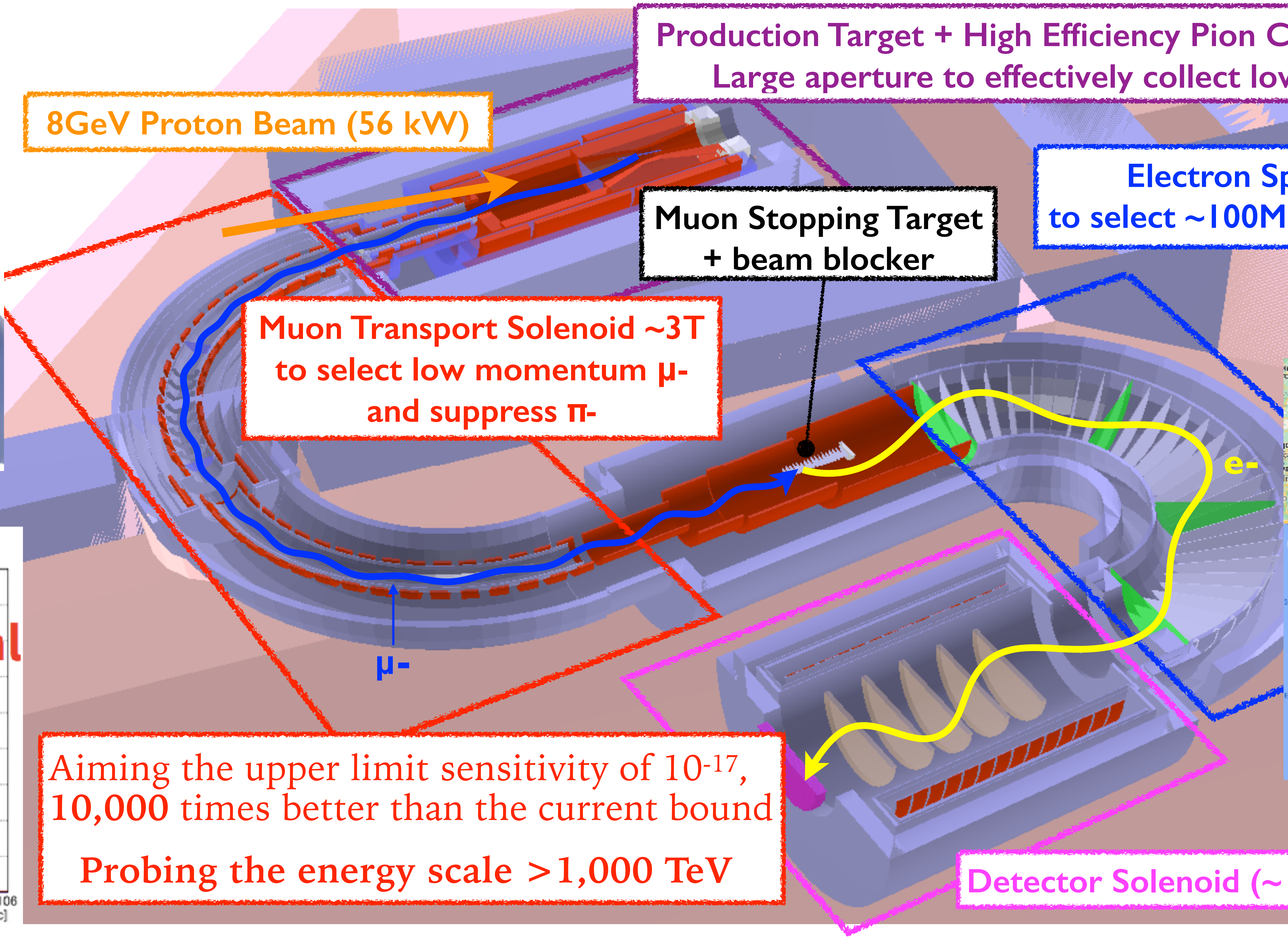


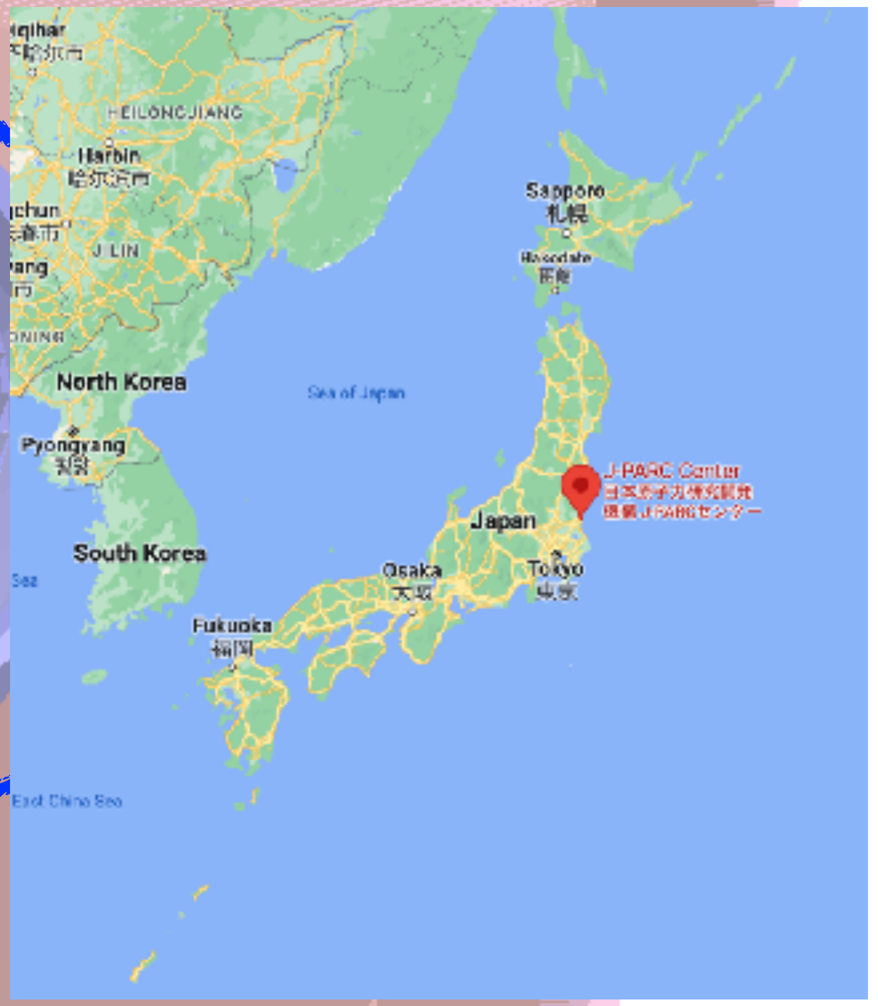


The COMET Experiment @J-PARC





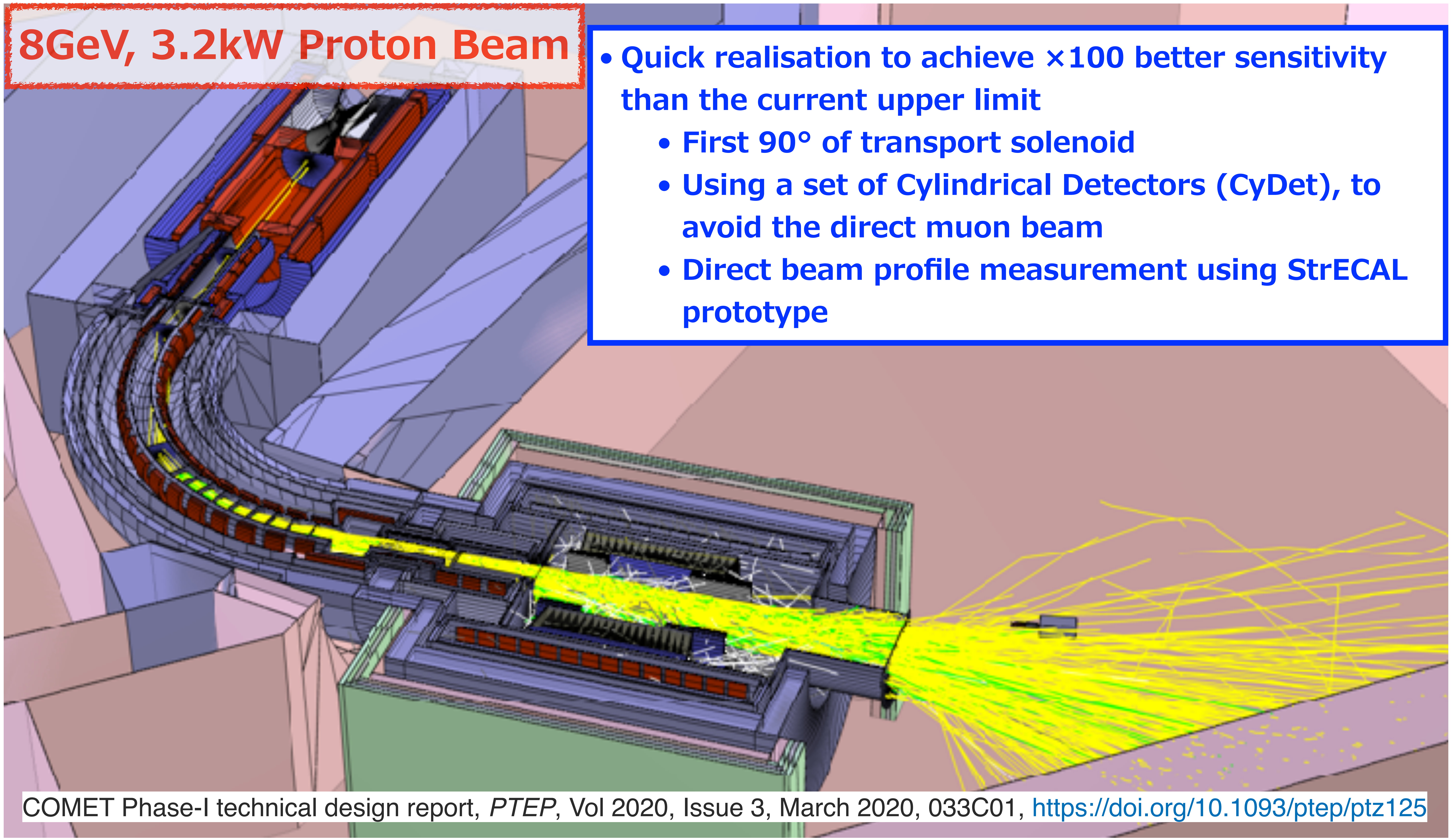




Aiming the upper limit sensitivity of 10^{-17},
10,000 times better than the current bound

Probing the energy scale >1,000 TeV

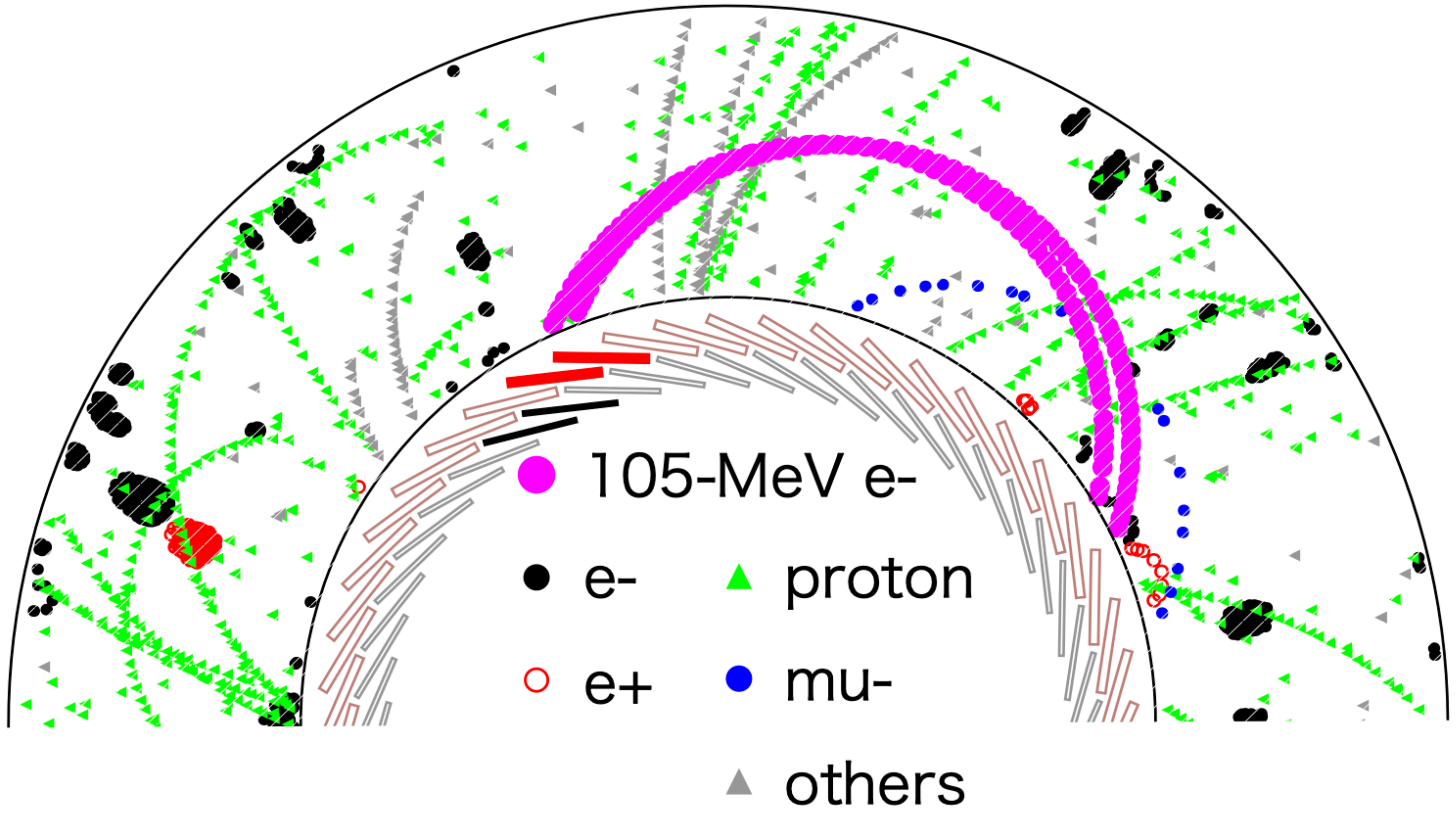
COMET Phase-I

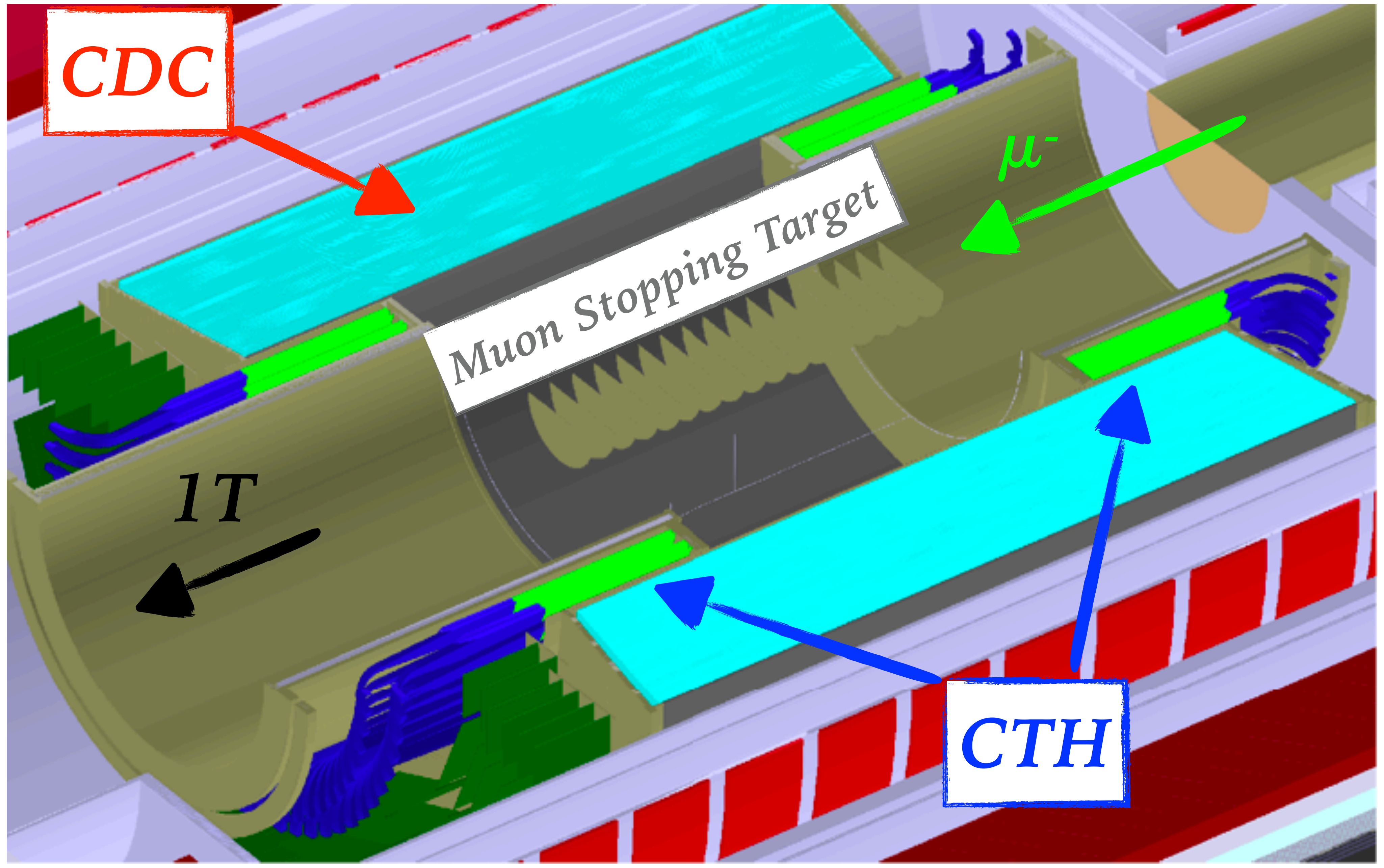


- Quick realisation to achieve ×100 better sensitivity than the current upper limit
  - First 90° of transport solenoid
  - Using a set of Cylindrical Detectors (CyDet), to avoid the direct muon beam
  - Direct beam profile measurement using StrECAL prototype

COMET Phase-I technical design report, *PTEP*, Vol 2020, Issue 3, March 2020, 033C01, https://doi.org/10.1093/ptep/ptz125

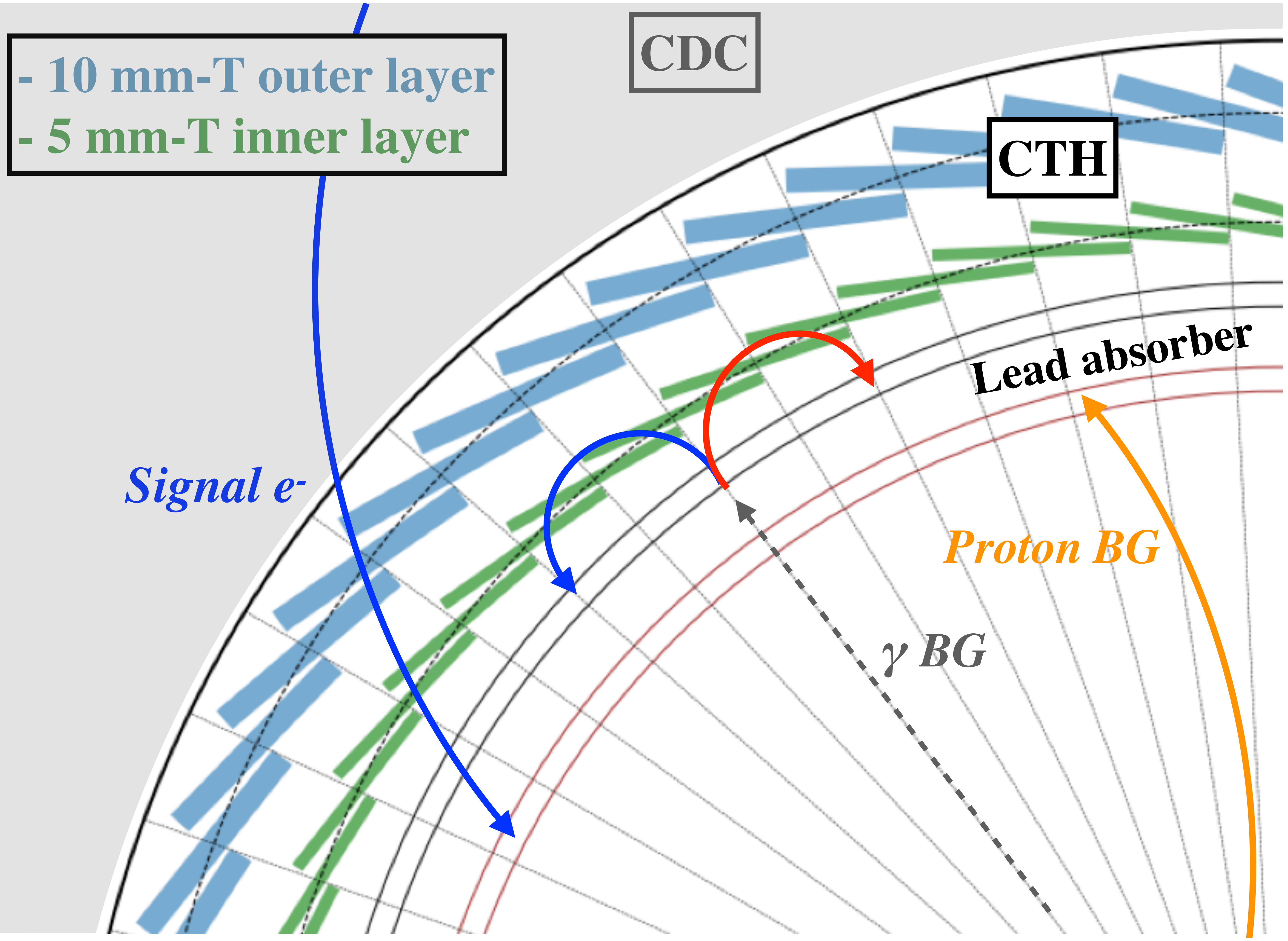
Cylindrical Detector (CyDet)





- Cylindrical Drift Chamber (CDC)
  - ~5k sense wires for momentum measurement with 200 keV/c momentum resolution
- Cylindrical Trigger Hodoscope (CTH)
  - Precise timing measurement (better than 1 ns) and generate a primary trigger signal
  - Monash group is leading the detector development

Cylindrical Trigger Hodoscope



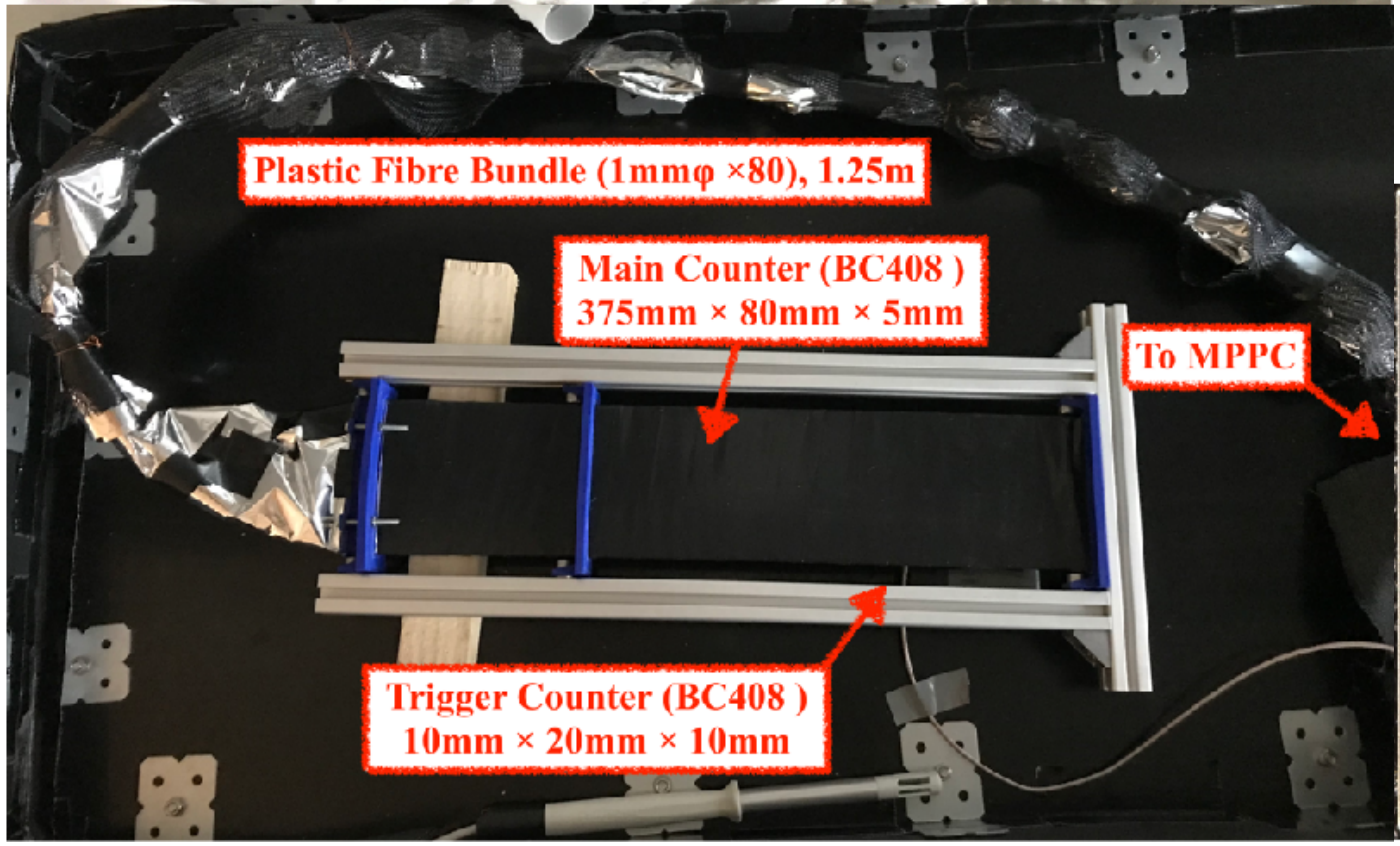
- Select the signal-like high momentum electrons while suppressing other low momentum/heavier particles
  - Thick inner absorber + Four fold coincidence with two concentric layers
- Measure the electron arrival timing as precise as 1 ns
  - Use fast plastic scintillators (BC-408)
- Operational under the high radiation environment + 1 T magnetic field
  - 1 kGy gamma dose + 10^{12} n/cm^2 neutrons

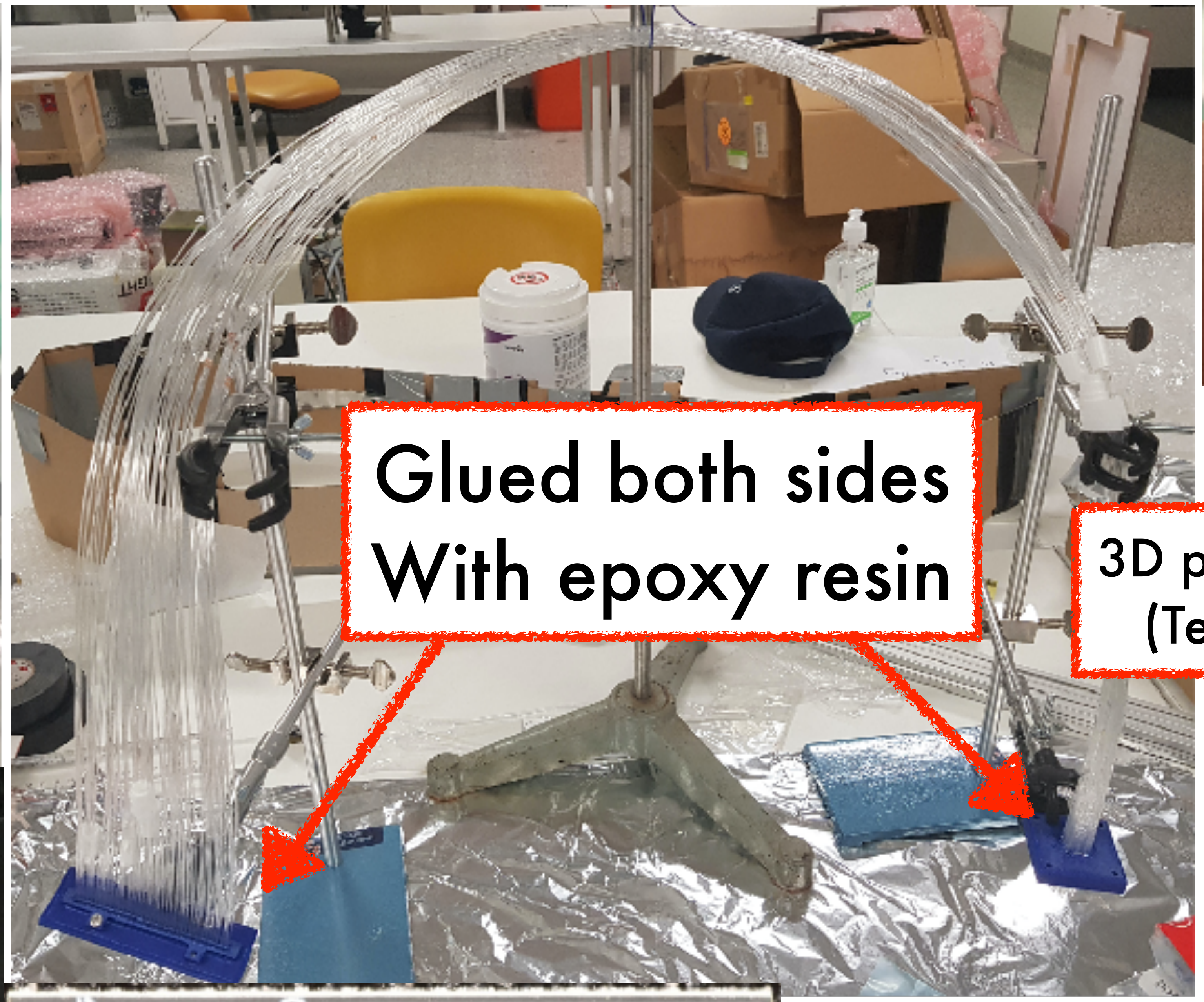
Fibre bundle + SiPM readout

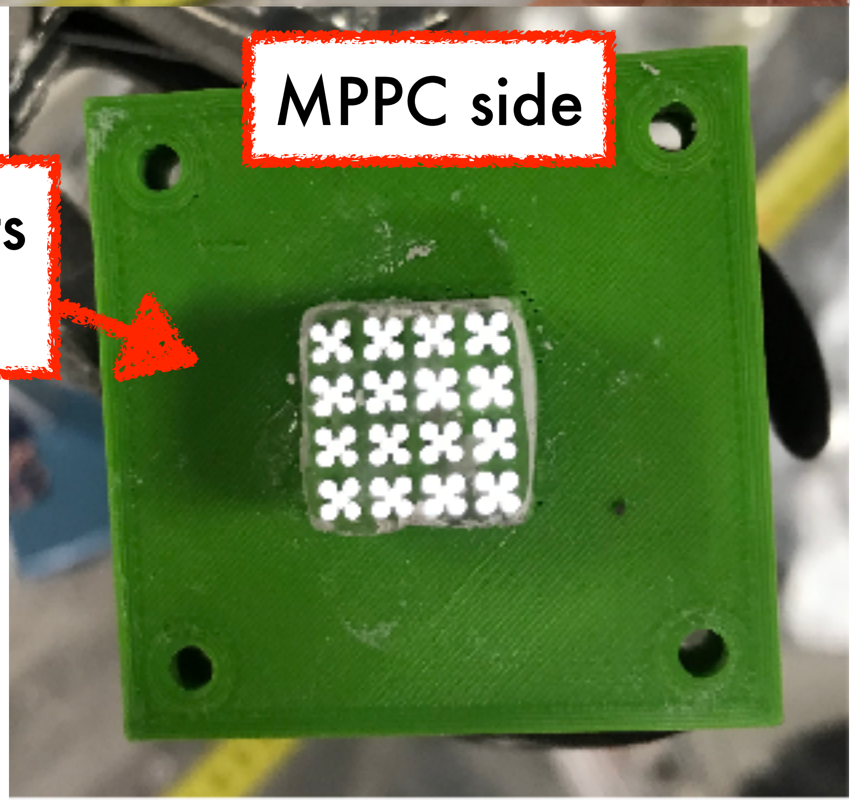
	Performance	Magnetic field	Radiation tolerance	Cost
SiPM	★★★	★★★	★	★★★
PMT	★★★	★	★★	★

- Having sensors inside the detector solenoid is quite difficult due to the high radiation dose
- Expected dose level is 1-2 orders lower outside the DS by introducing a thick neutron shielding box
  - Photon extraction using optical fibres enables to use cheaper photo sensors such as silicon photomultipliers (SiPMs)
  - Better accessibility to the sensors for easier maintenance/replacement
  - Cons; Lower light yield due to the longer photon transferring ➡ need the R&D

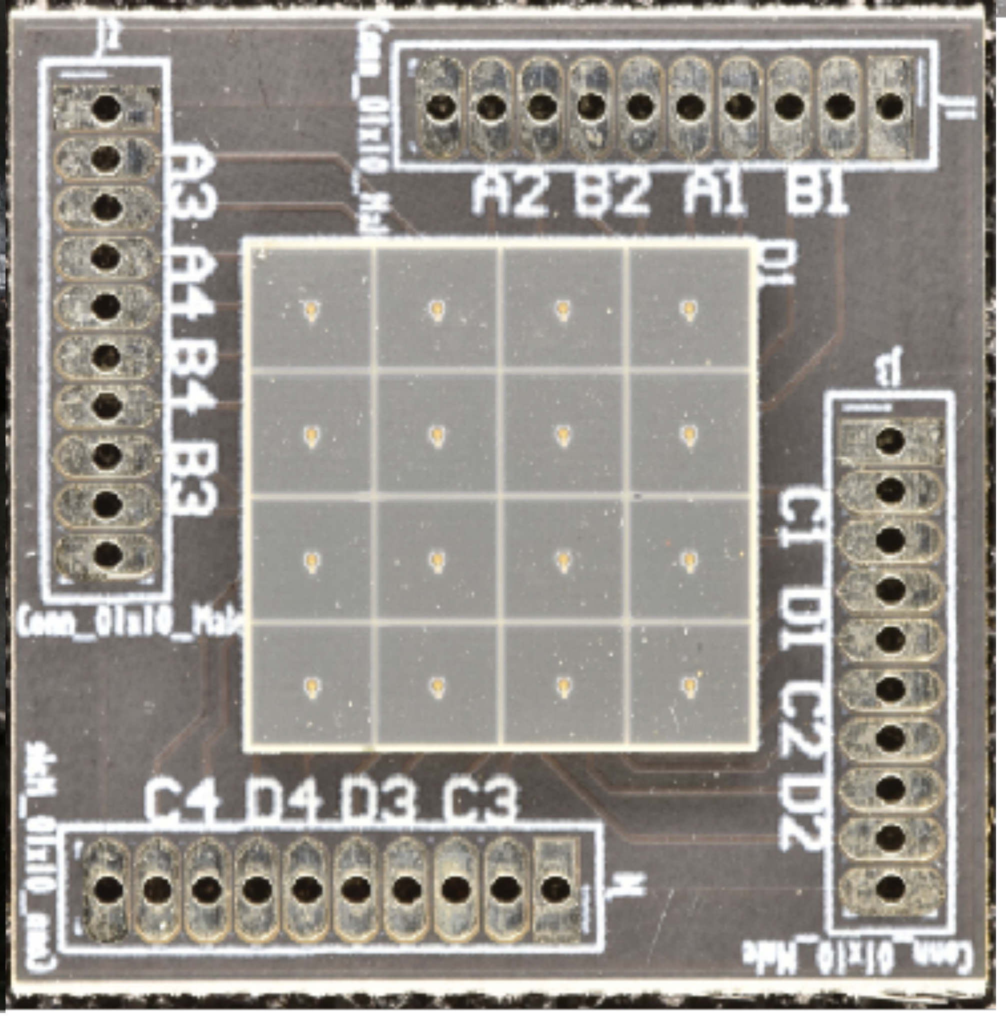
A Small Prototype







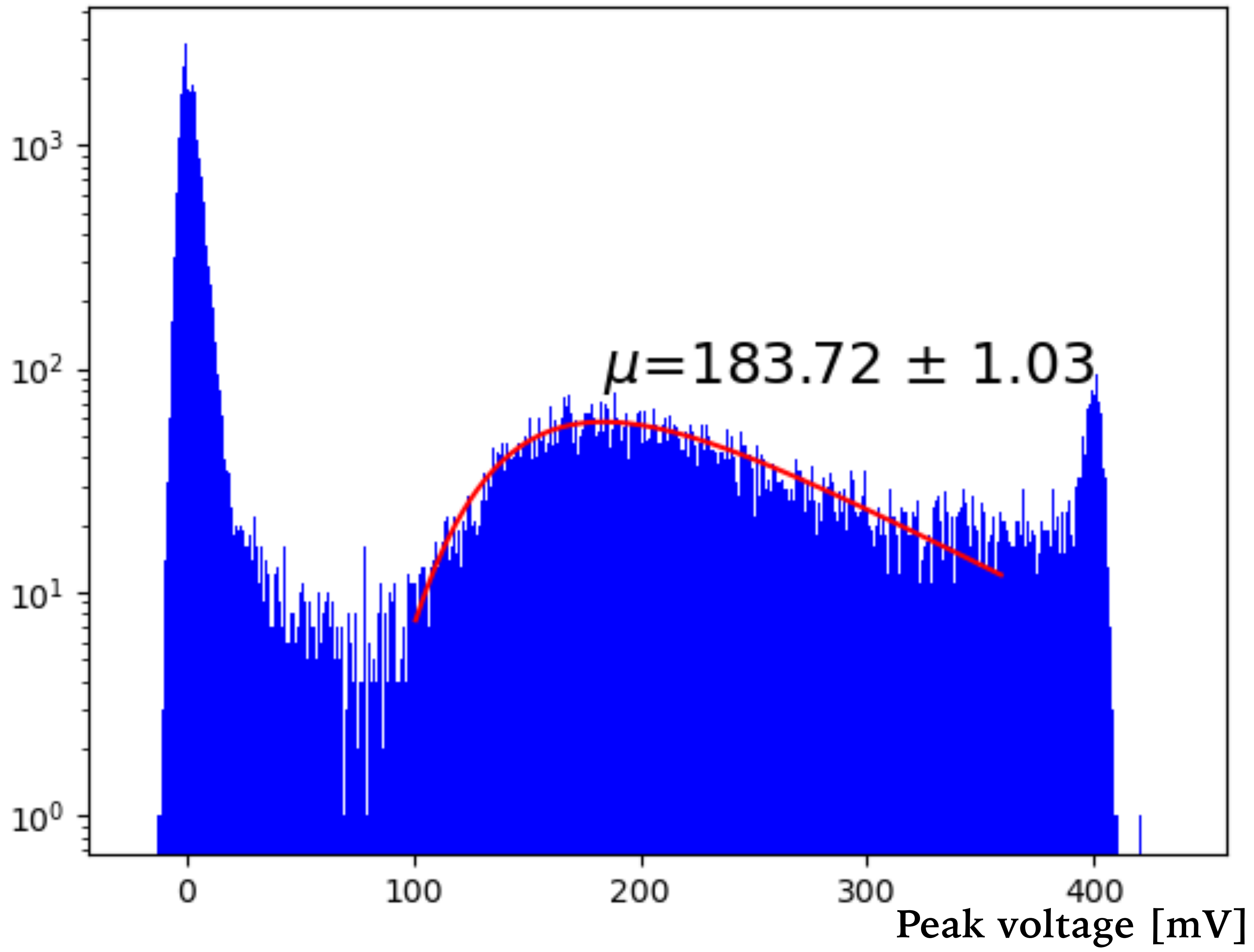
3D printed parts
(Temporary)

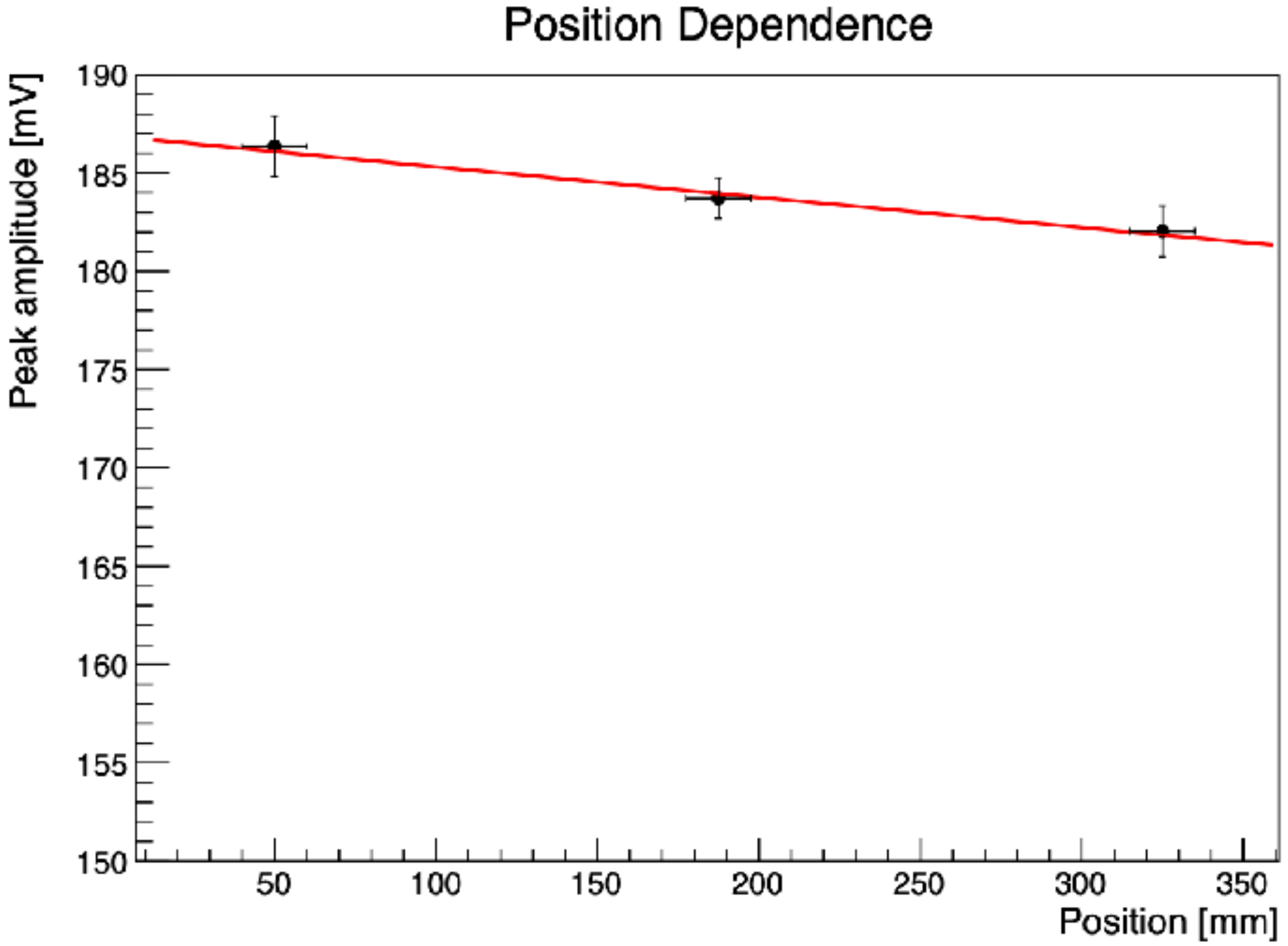


- A small prototype to prove the performance and improve the final design
  - A 1:1 scale plastic scintillators
  - The baseline large area SiPM (Hamamatsu S14161-3050HS)

Light Yield

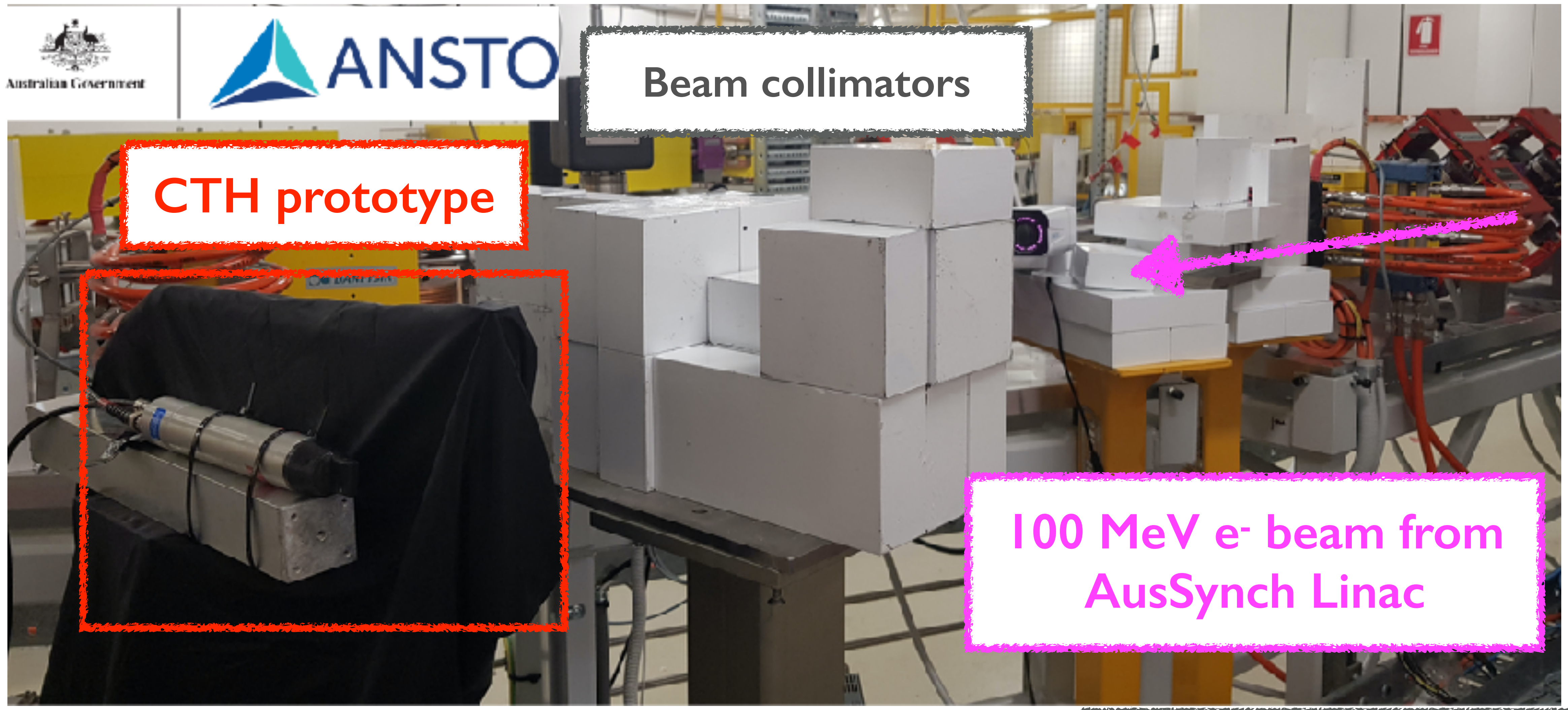
Peak voltage distribution at the centre of the counter

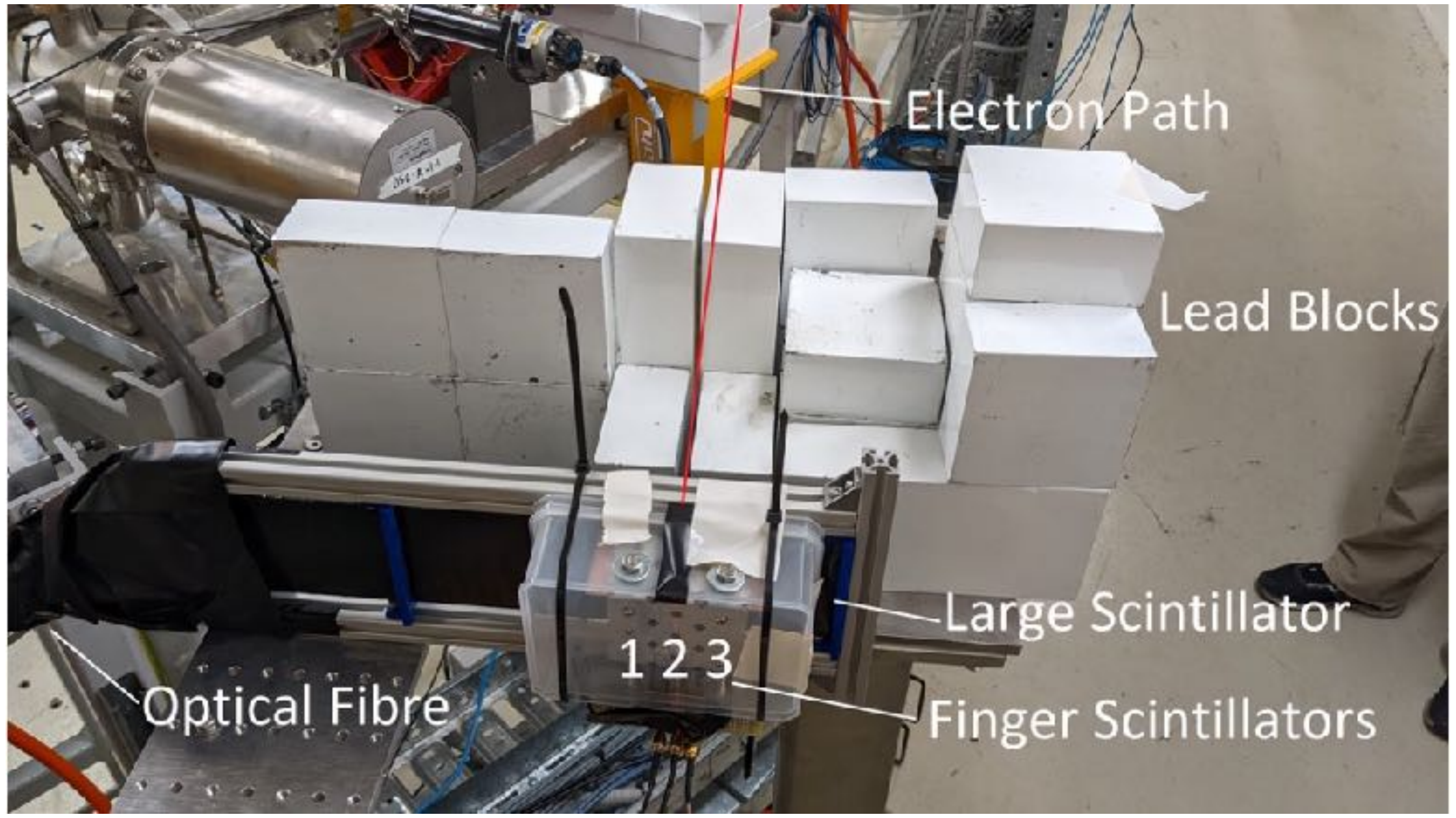


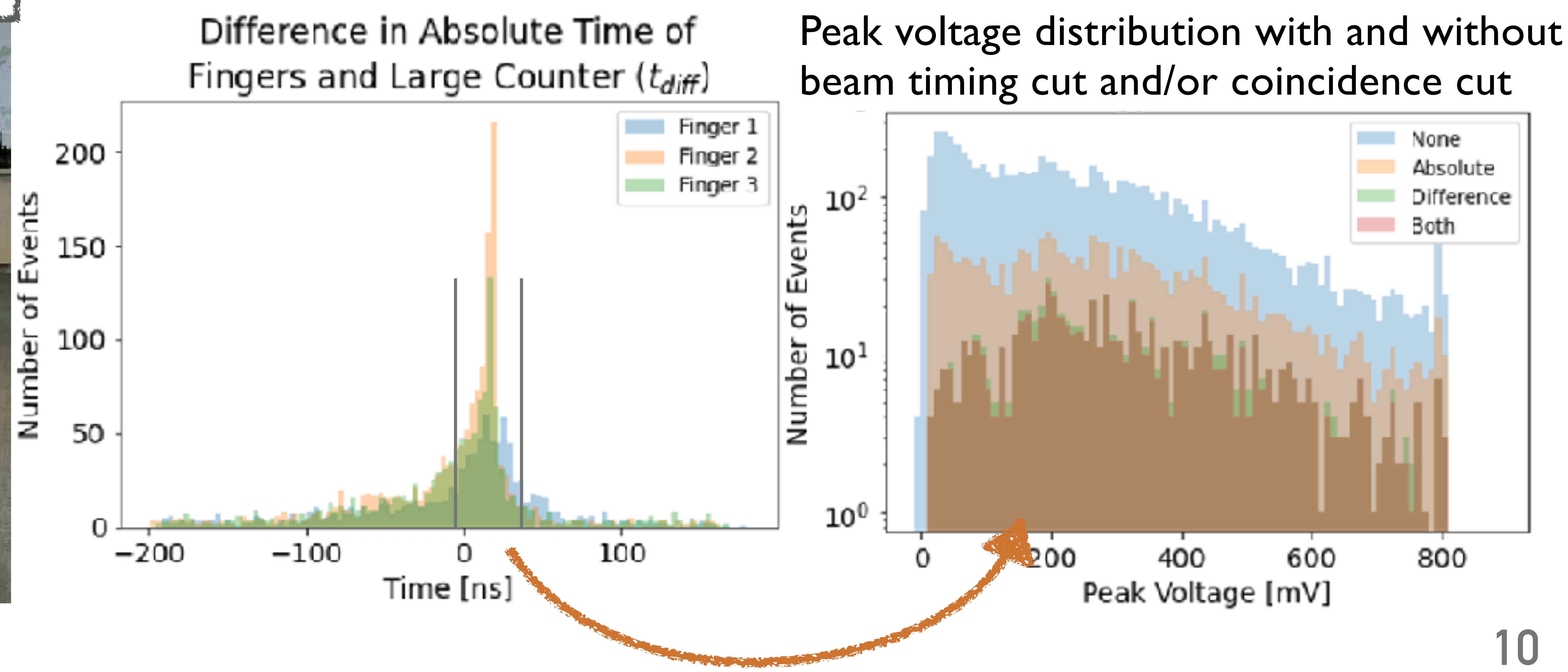


- The light yield was measured with a small prototype using the Sr-90 checking source and the trigger counter
  - Measured peak voltage 180 mV, 1 p.e. peak = 4.2 mV ➡ 42 p.e. for the minimum ionisation
  - No strong position dependence was observed as expected

Beam Tests @ Australian Synchrotron



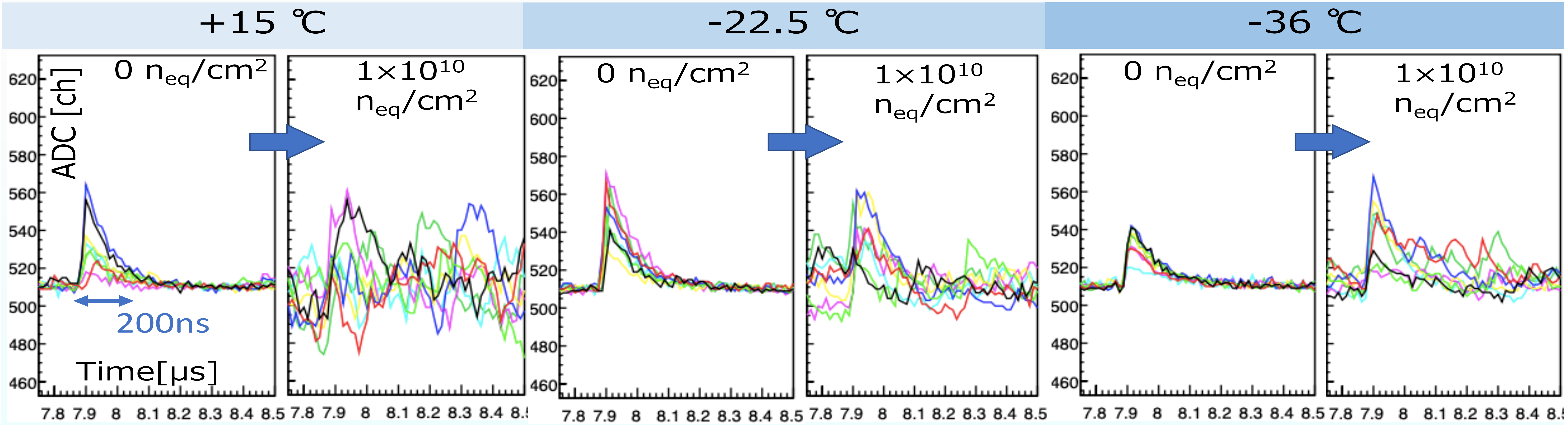




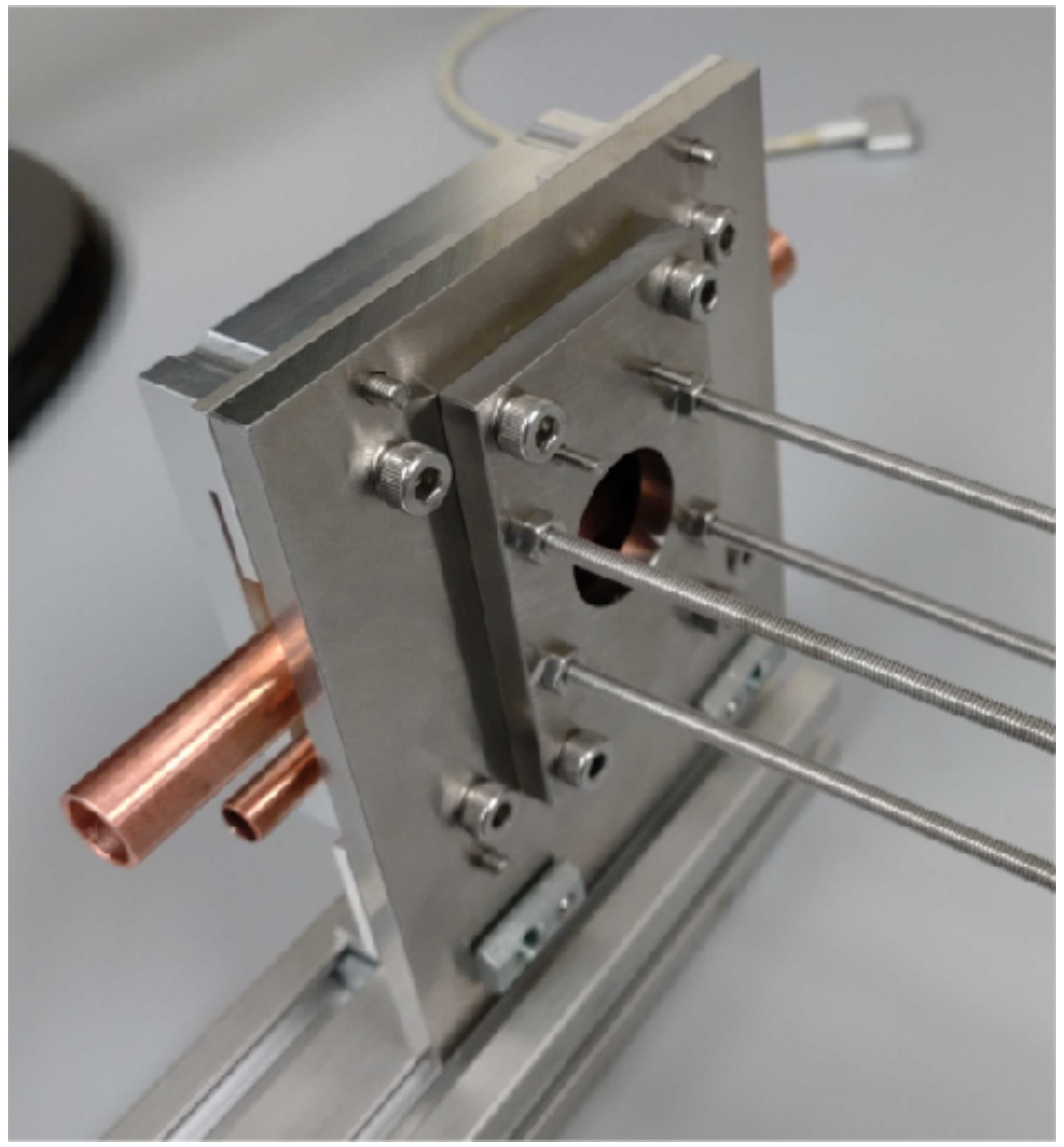
Irradiation Tests

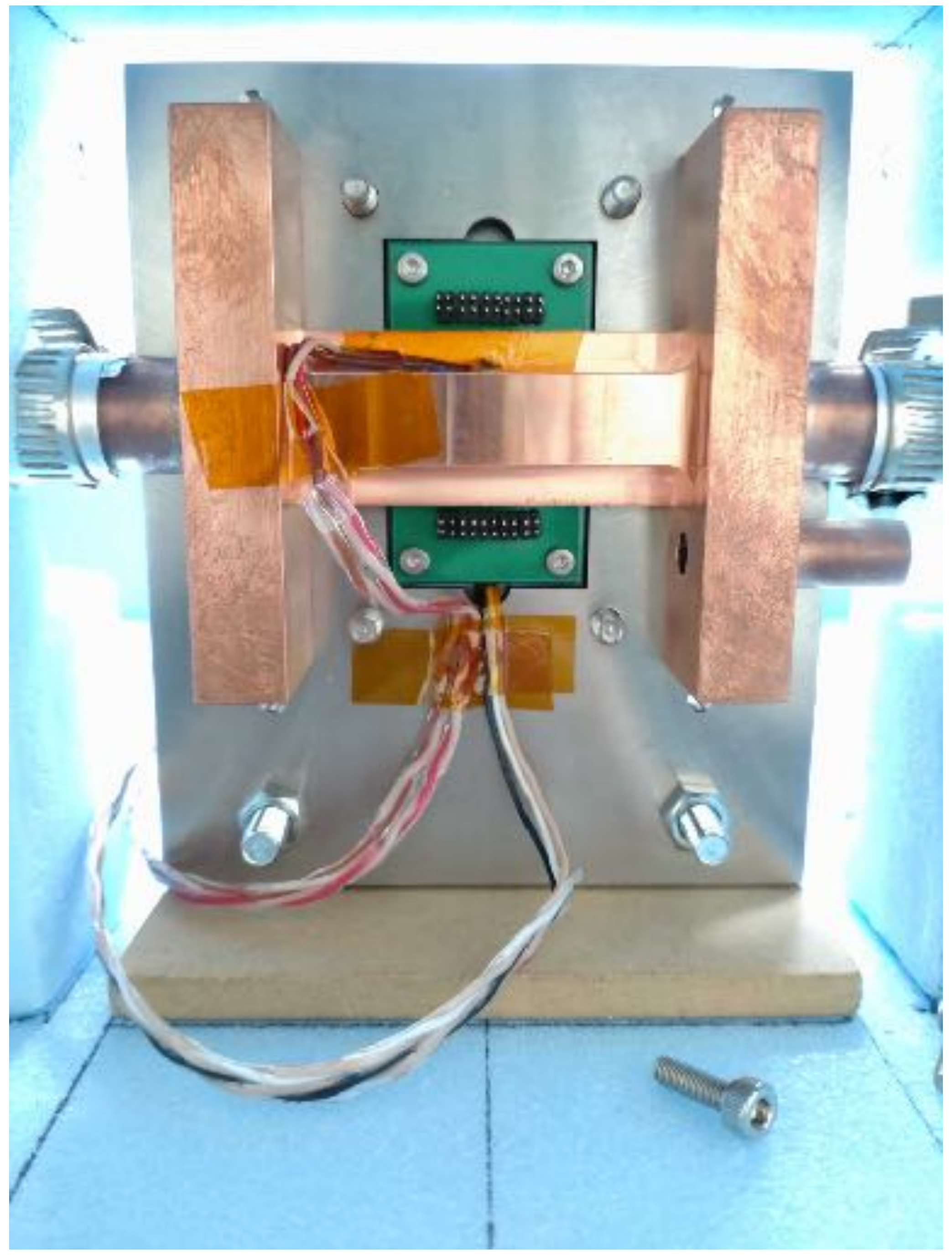
- SiPM system irradiated up to 10^{11} neutrons/cm^2 w/ and w/o cooling
  - Found that SiPM is operational up to 10^{10} neutrons/cm^2 assuming more than 25 photo electrons from the signal electrons
  - Cooling down to -35°C is mandatory to reduce the dark current due to the thermal electrons
- Plastic Scintillator and plastic optical fibres irradiated up to 1 kGy gamma dose
  - Roughly 20% light yield drop is expected @1 kGy
  - Photon transmittance + attenuation length degrade ~10%

Sample waveforms for a SiPM single channel with ~10 p.e. LED signal



SiPM Cooling System





- SiPM cooling system is being developed with Osaka and Kyushu Universities
- A single channel cooling system achieved -36°C with a chiller and alcohol coolant at -40°C
- New prototype with 16 channels will be produced this year

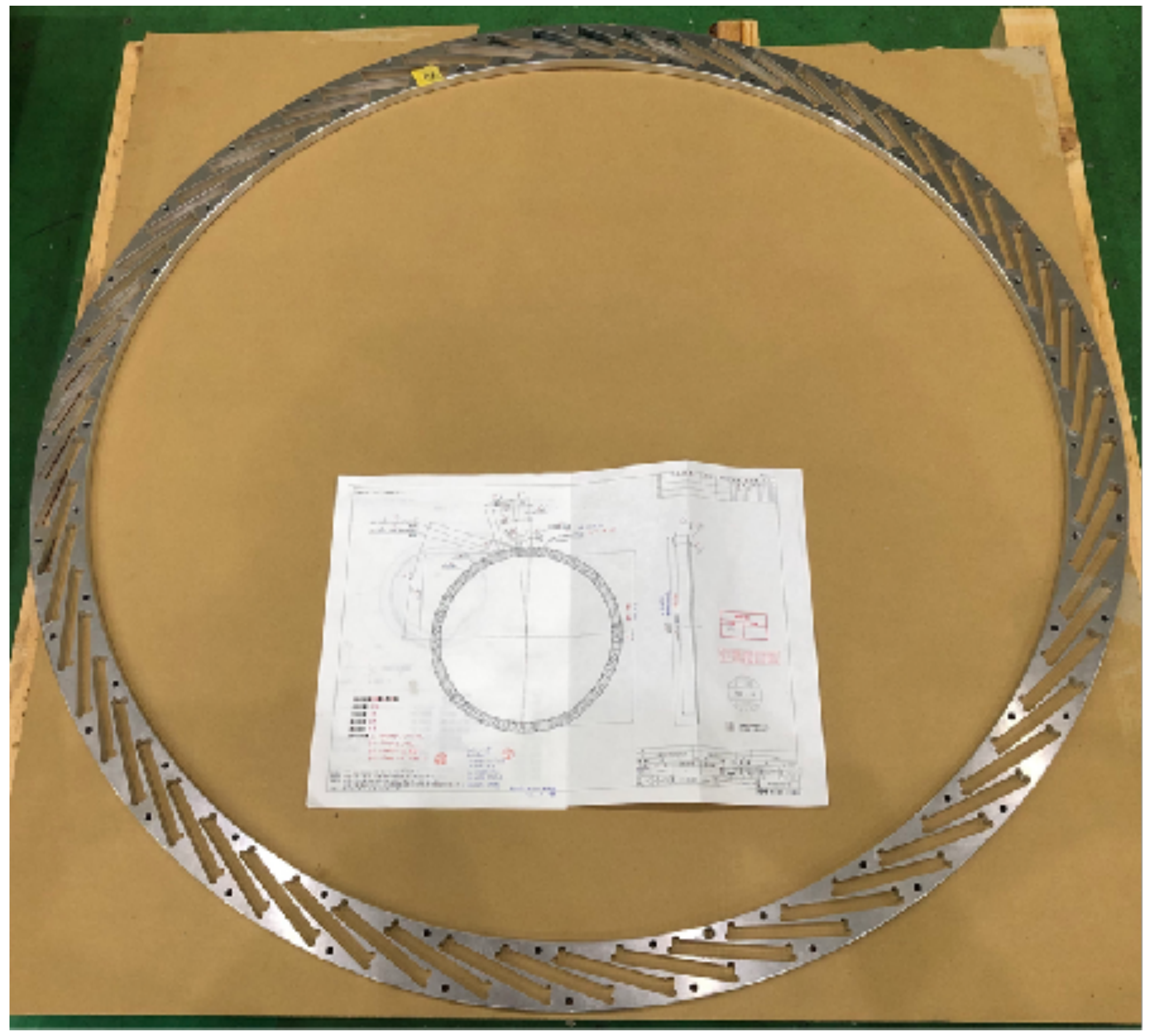
Readout electronics

- We have developed both analog and digital electronics for CTH at Monash
  - SAM provides the energy signal with a longer shaping (FWHM ~50ns) and sharper timing signal (FWHM ~20 ns)
  - COTTRI digitise both energy and timing signal and send the info to DAQ PC and downstream trigger system

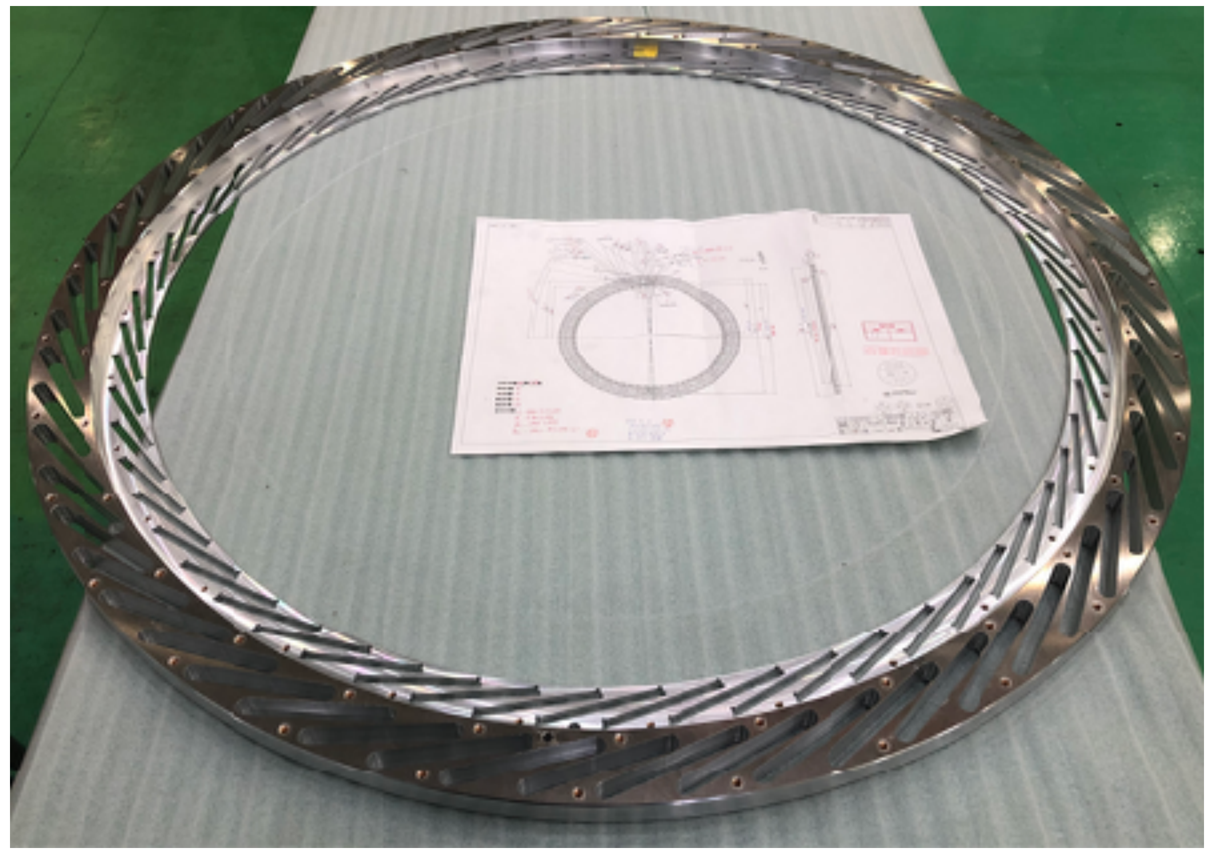
SAM (Summing Amplifier Module) ×256

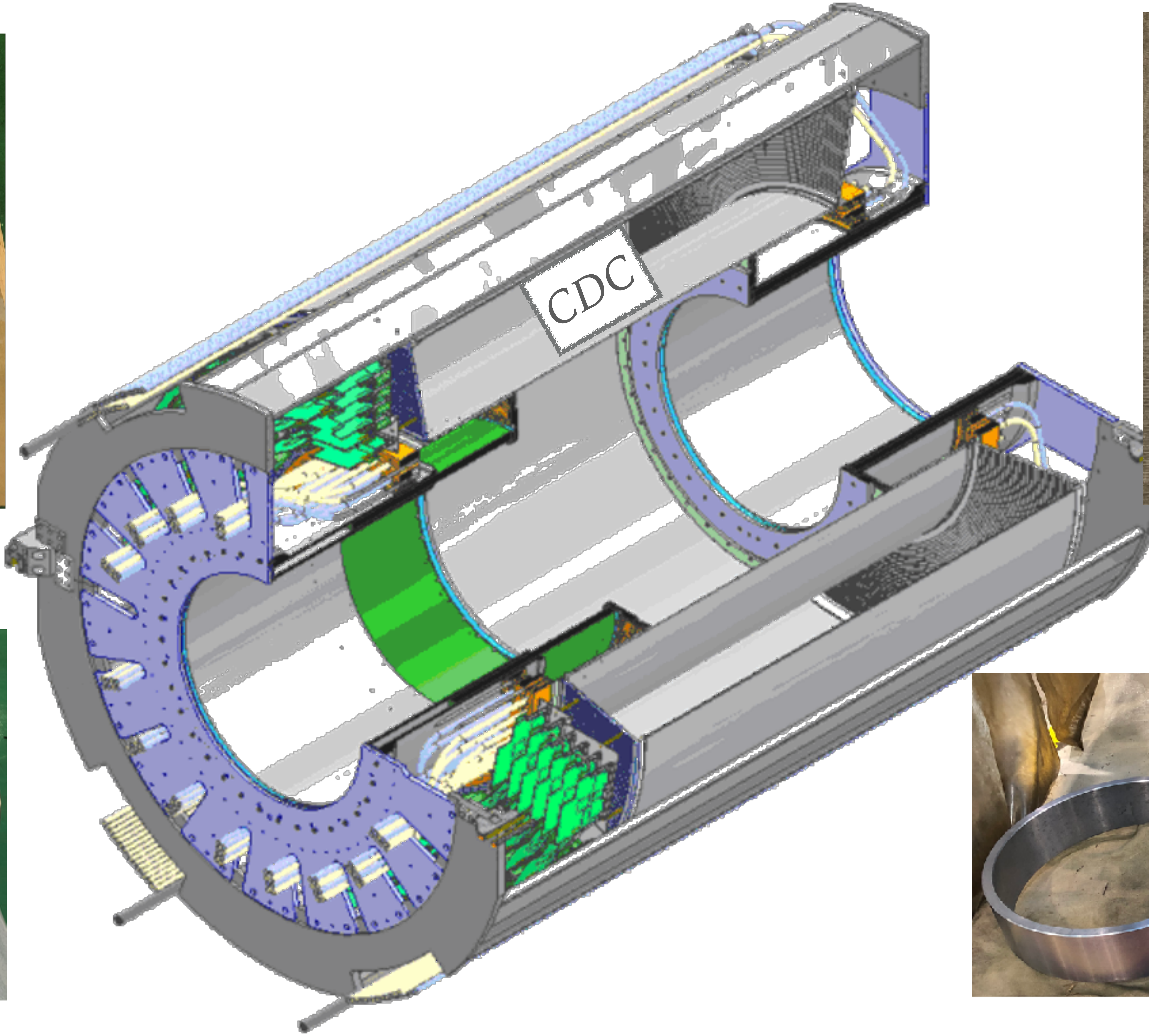
COTTRI (COmeT TRIgger) board ×12

Support Structure



Mid counter supports

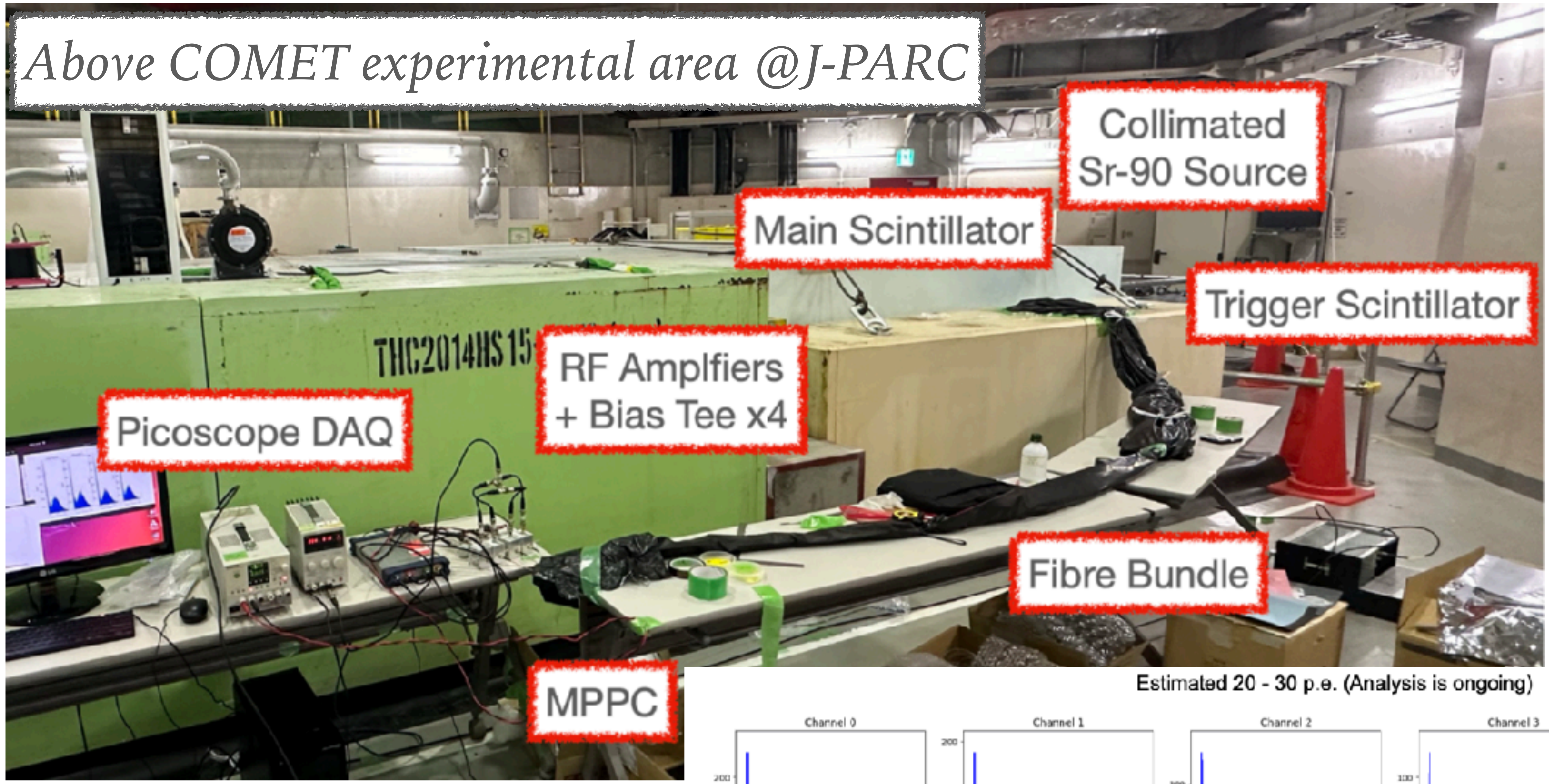


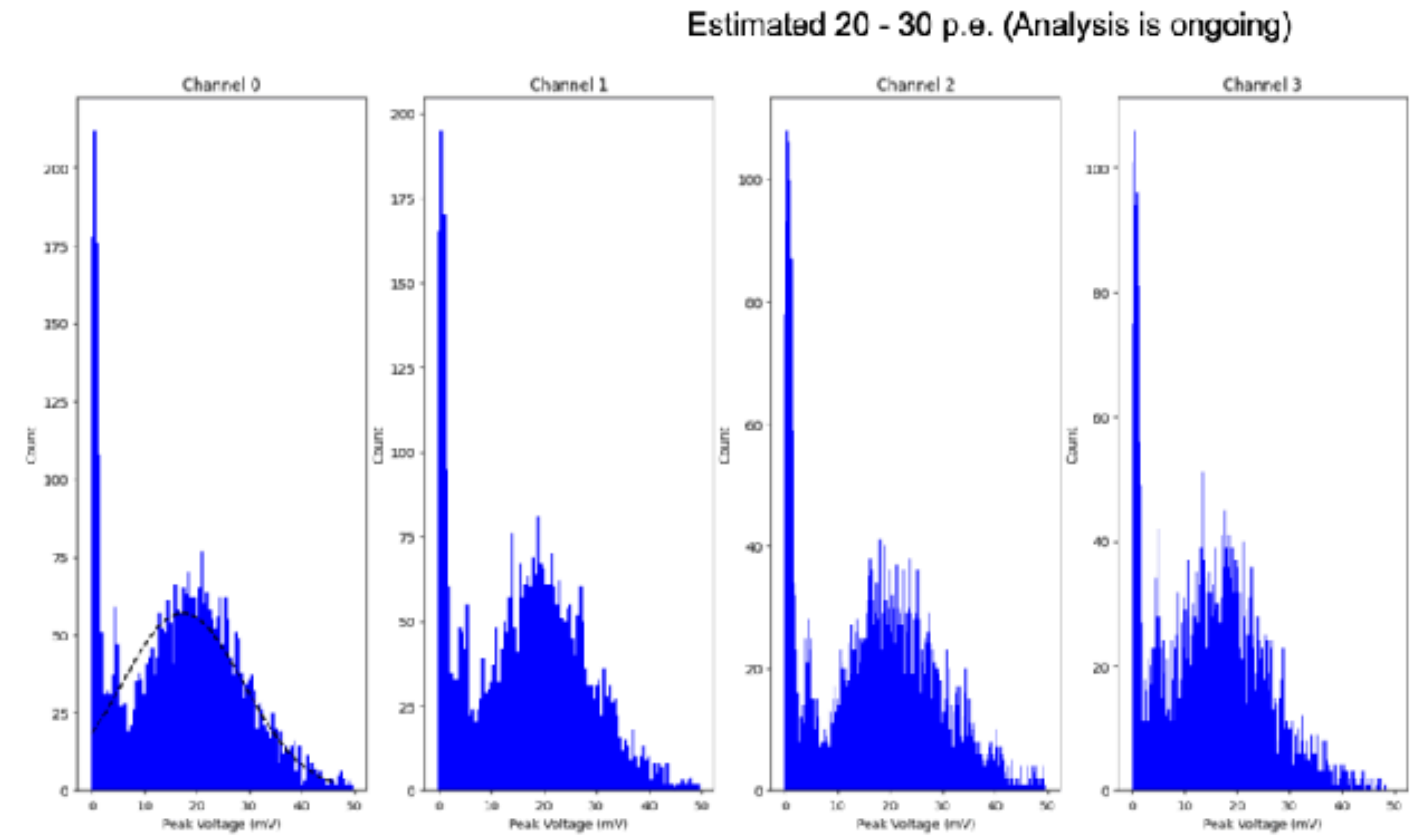


End counter support

Lead absorbers

Real Scale Prototype





- A first real scale fibre readout prototype was built and tested with a counter and Sr-90 at J-PARC in the last month
  - The data analysis is still ongoing
  - Many feedback to improve the construction procedure were found

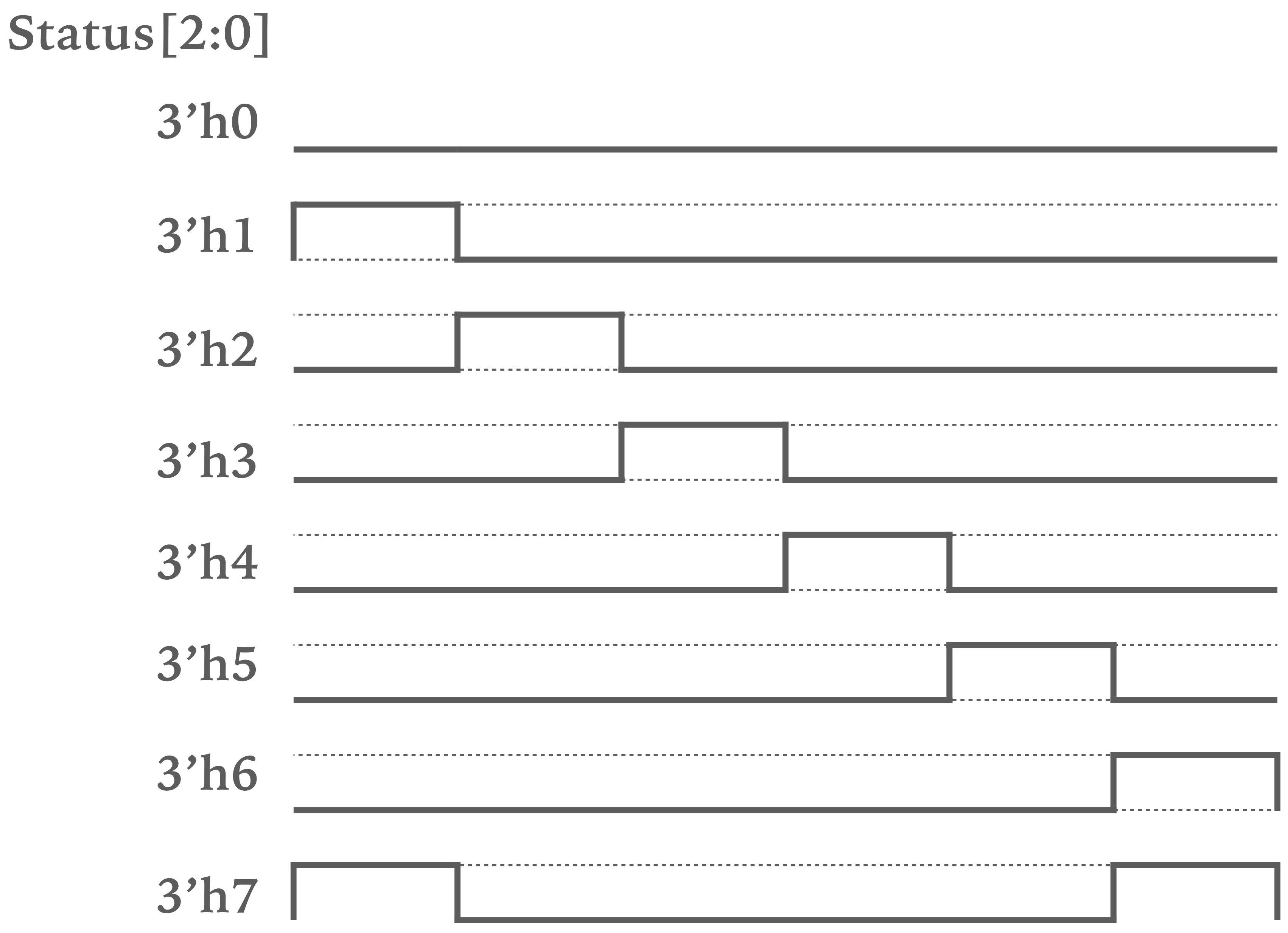
Summary & Prospects

- The COMET experiment aims to search for the μ-e conversion with upper limit sensitivities of 10^{-15} and 10^{-17} in Phase-I and Phase-II respectively
- Monash group is leading the prototyping and construction of the CTH detector system in COMET Phase-I
- Most of R&D items have been completed, and the prototype detectors satisfy our requirements (radiation hardness, timing and light yield)
  - Including the test beam measurement @Linac of Australian Synchrotron
- The detector construction will begin in this year 2023

CTH FEB – MB communication

- Trigger data format from FEB to MB (tentative version)
  - Send 3-bit hit status×24 (+parity bits) to COTTRI MB every 25 ns using MGT

Ch0	Ch1	Ch2	…	Ch23
data[2:0]	data[2:0]	data[2:0]	…	data[2:0]
data[2:0]	data[2:0]	data[2:0]	…	data[2:0]
data[2:0]	data[2:0]	data[2:0]	…	data[2:0]



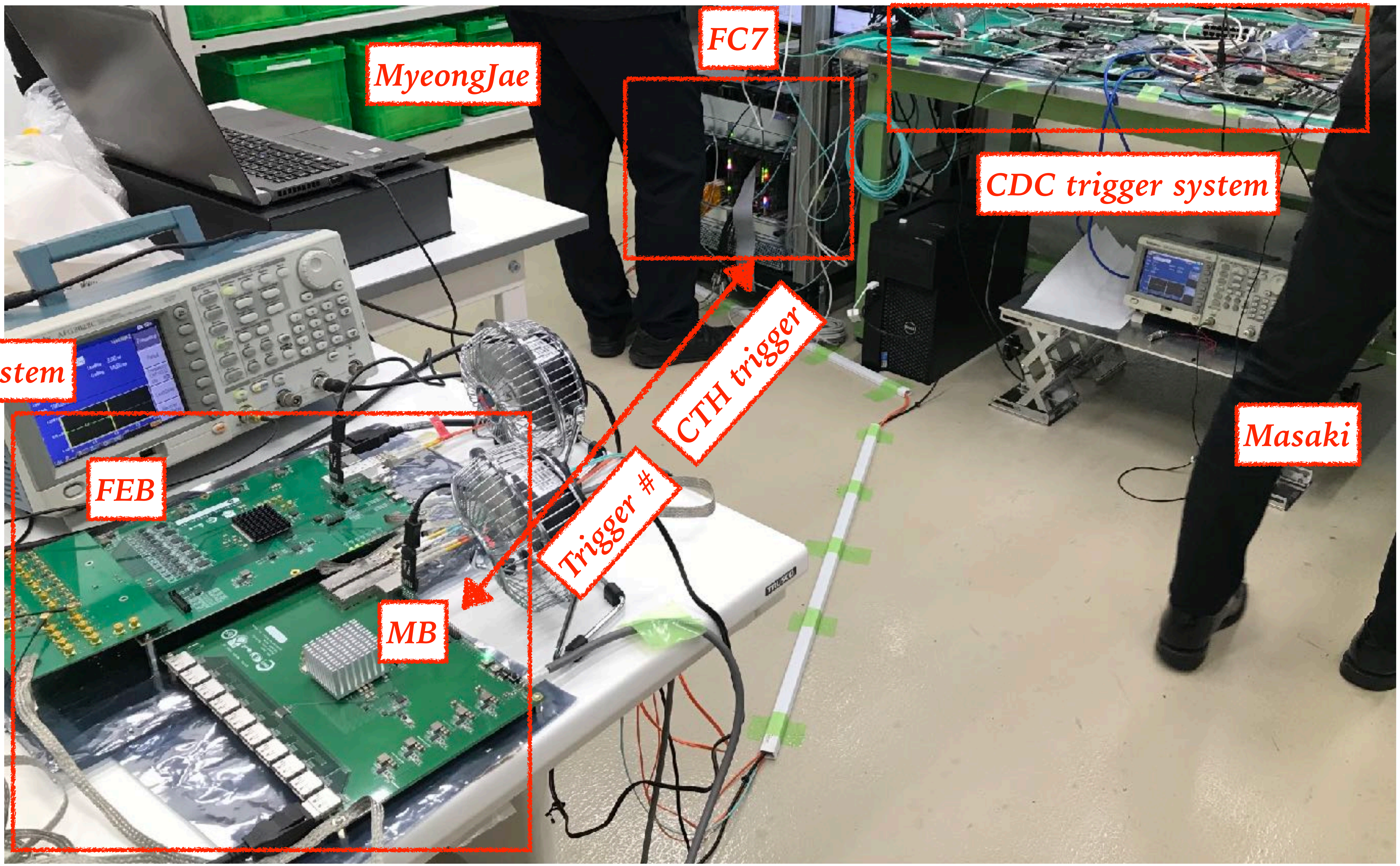
Trigger timing resolution = 4.17 ns (240 MHz)

➡ Coincidence time window will be ± 4.17 ns for triggering

Can separate pile-ups with a time gap farther than ~20 ns

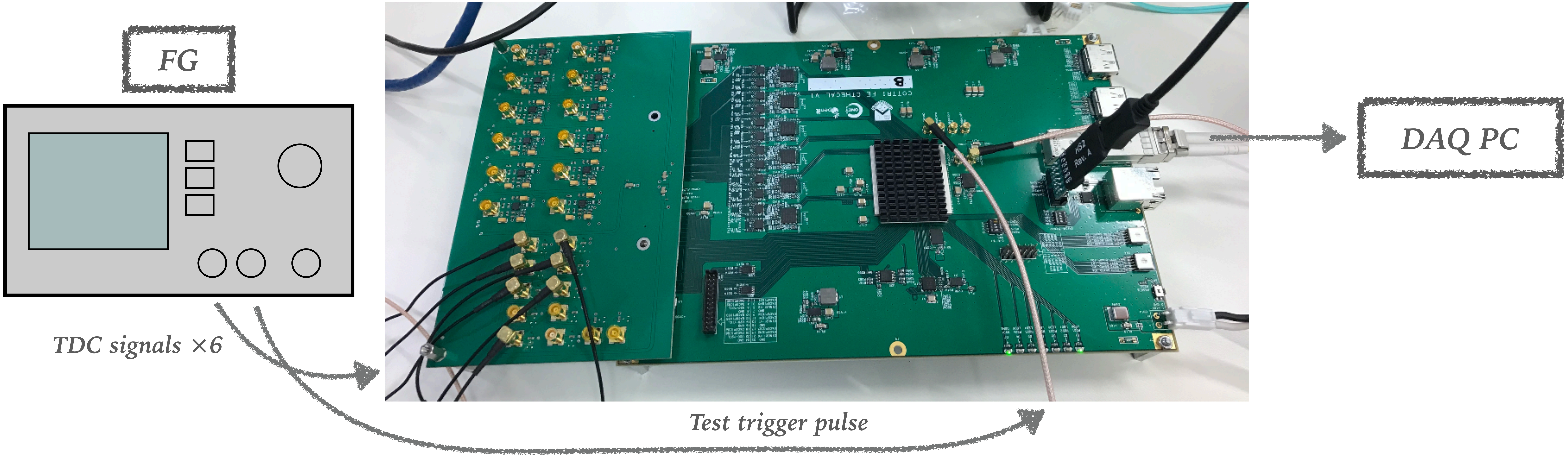
MB performs coincidence based on this hit information & send it to FC7

Trigger chain test



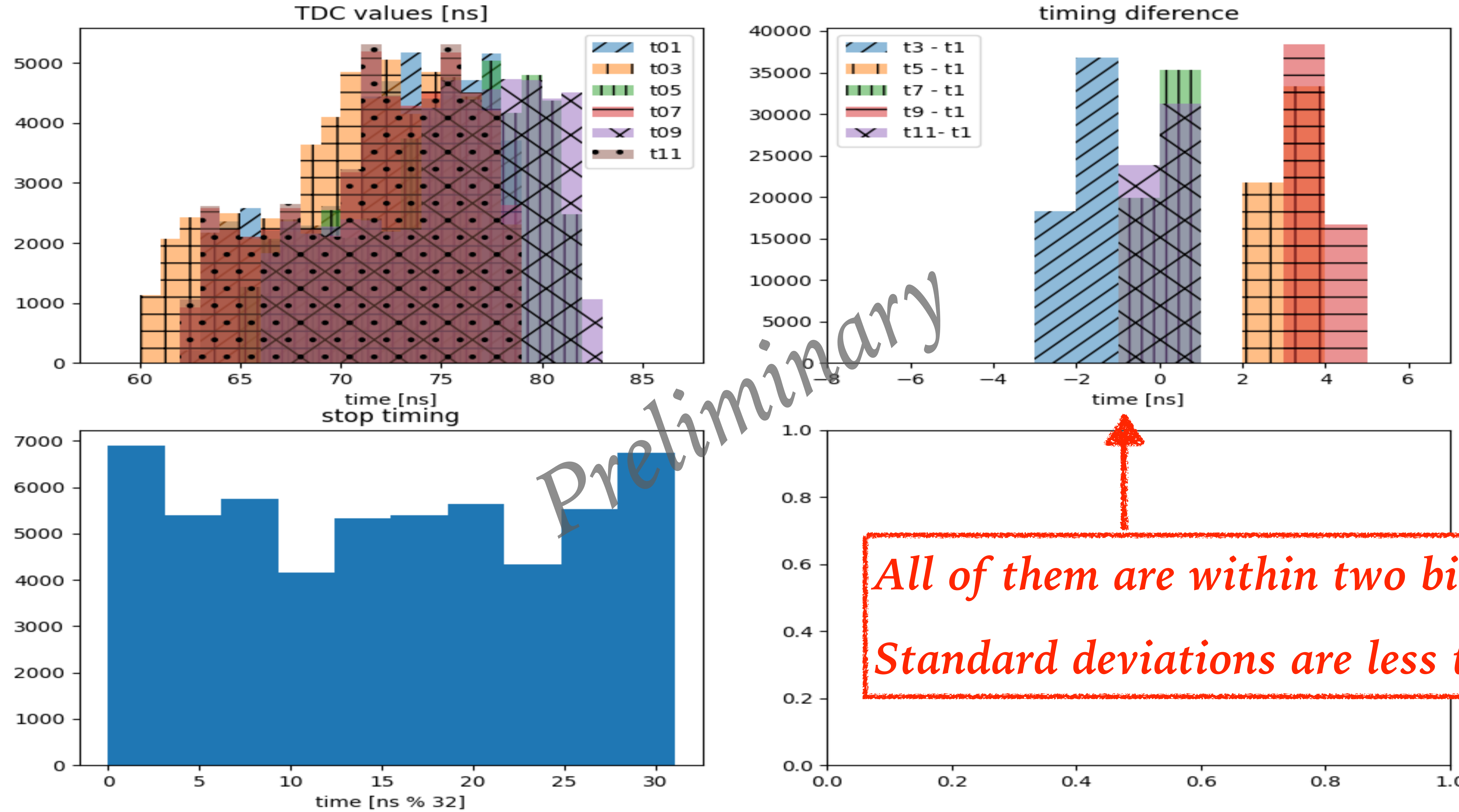
TDC implementation

- The basic algorithm almost same as RECBE
- Four 240 MHz clocks with different phases to realise 1.04 ns periodic 3-bit counters + hit-flag to be stored with 120 MHz clock
  - Possible upgrade into 0.52 ns cycle by implementing four more phases if needed
  - Tested @Monash with the smallest setup



TDC data (Simple DAQ monitor)

TDC data



All of them are within two bins,

Standard deviations are less than 0.5 ns

COTTRI CTH Hardware Status

- All basic functionalities verified → Ready for the final production
- Almost all parts already secured to produce 13 additional FEBs
  - Start final production in April
- Two COTTRI CTH MBs already produced thanks to MyeongJae
  - Full chain trigger test to be expected in this year!