Searching for muon to electron conversion in COMET

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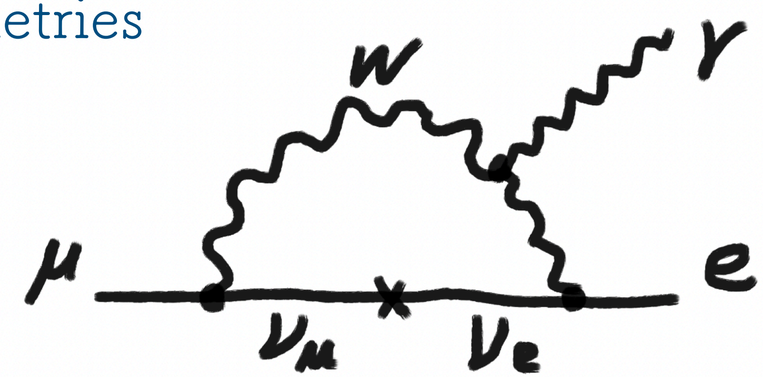
WIN 2025 @ University of Sussex

Science & Technology Facilities Council | UK Research and Innovation

Charged Lepton Flavour Violation (CLFV)

- **$\mu \to e\gamma$, $\mu \to eee$, $\mu N \to eN$, $\tau \to \mu\gamma$, etc..**
- Forbidden in the SM, although unrelated to any Gauge symmetries
  - An accidental conservation due to the GIM suppression
- Neutrinos oscillate and it is BSM!
  - Dirac or Majorana? How so tiny, Seesaw?
  - However, the CLFV is negligibly small in minimum ν SM:



$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \sum_i \left| U_{\mu i} U_{ei} \frac{\Delta m_i^2}{M_W^2} \right|^2 \sim 10^{-54}$$

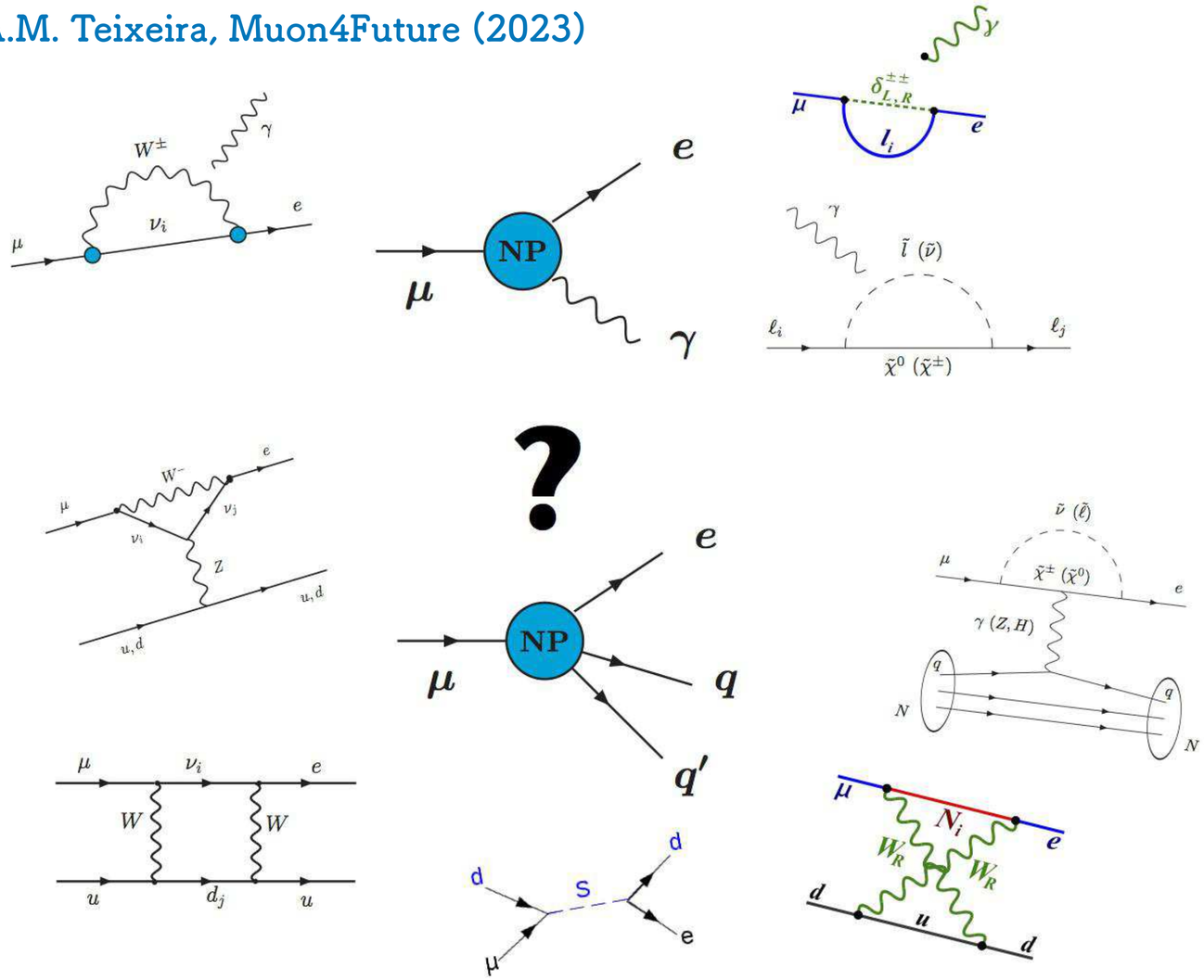
  ↔ Significant enhancement in many BSMs = free from SM background

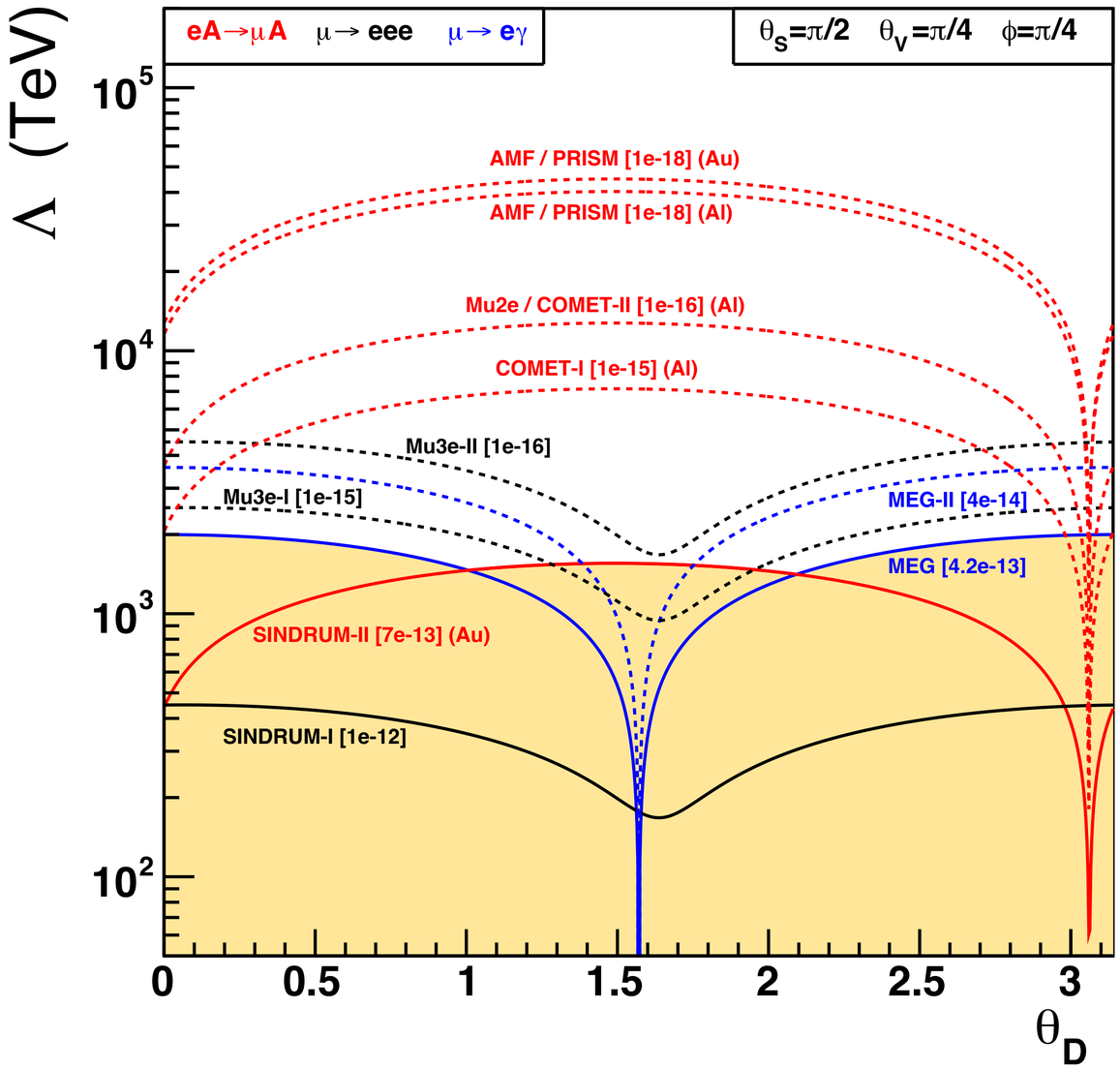
  - **CLEAR EVIDENCE of new physics if discovered!**

CLFV in new physics

CLFV channels are complementary and all sensitive to new physics energy scale (Λ) up around **O(10$^{3-4}$) TeV**

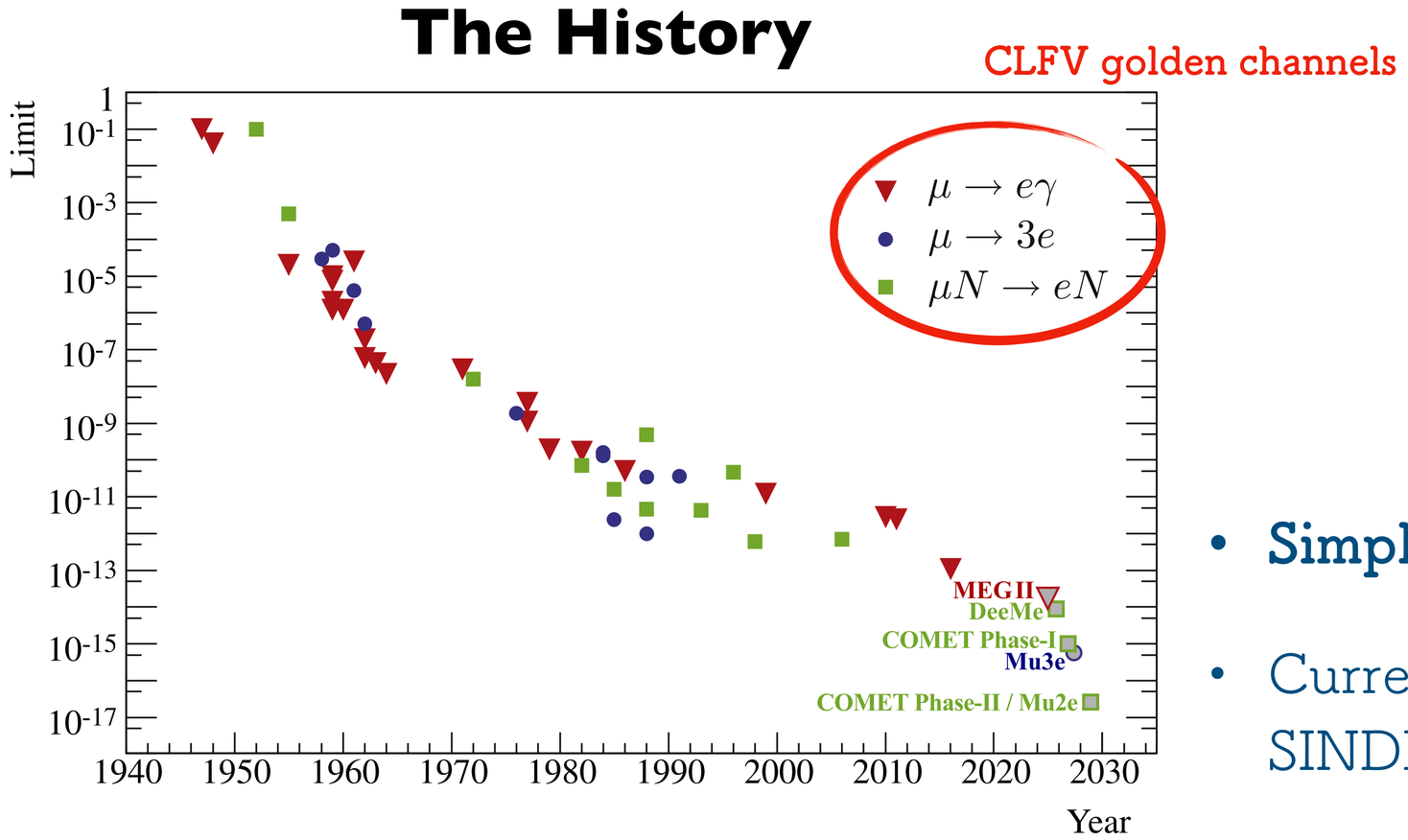
A.M. Teixeira, Muon4Future (2023)

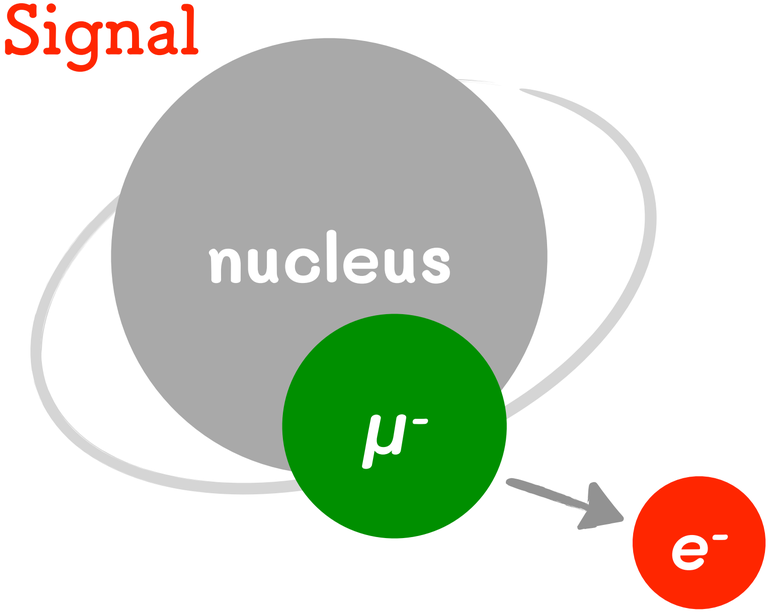




Y. Fujii, June 2025, WIN2025

μ-e conversion

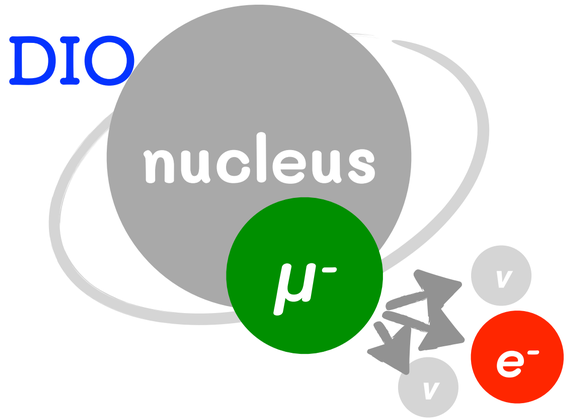


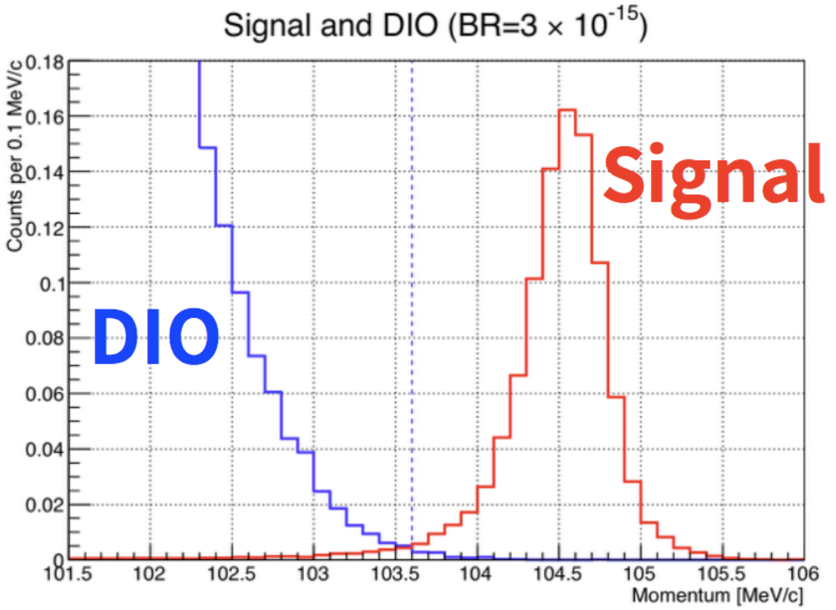


$$E_e \approx M_\mu - B_{\mu,\mathrm{Al}} - E_{\mathrm{recoil,Al}} \approx 105\mathrm{MeV}/c$$

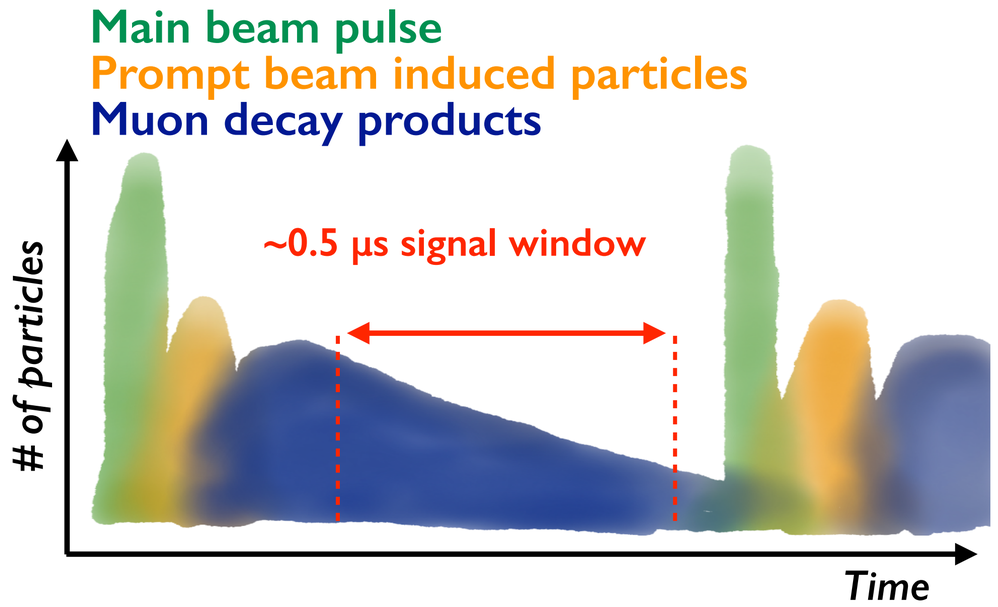
- **Simple final state**
- Current upper limit: 7×10^{-13} @90% C.L. by SINDRUM II
- Sensitive to tree diagrams involving a quark, such as Z', compared to other processes

Backgrounds





- **Physics background**
  - Michel decay on an orbit (DIO: Decay In Orbit)
    → **precise momentum measurement**
- **Beam induced backgrounds**
  - In-flight decays of π /μ → **avoid prompt timing**
  - Anti-protons → **use low energy proton beam**
- **Cosmic-ray induced background**
  - Either direct $\mu^{\pm}$ or in-direct $e^{\pm}$ → **offline veto**



COMET Overview
(COherent Muon-to-Electron Transition)

8 GeV proton beam

Pion production target + capture solenoid (max 5 T)

Muon stopping target

Electron transport spectrometer ~1 T

e-

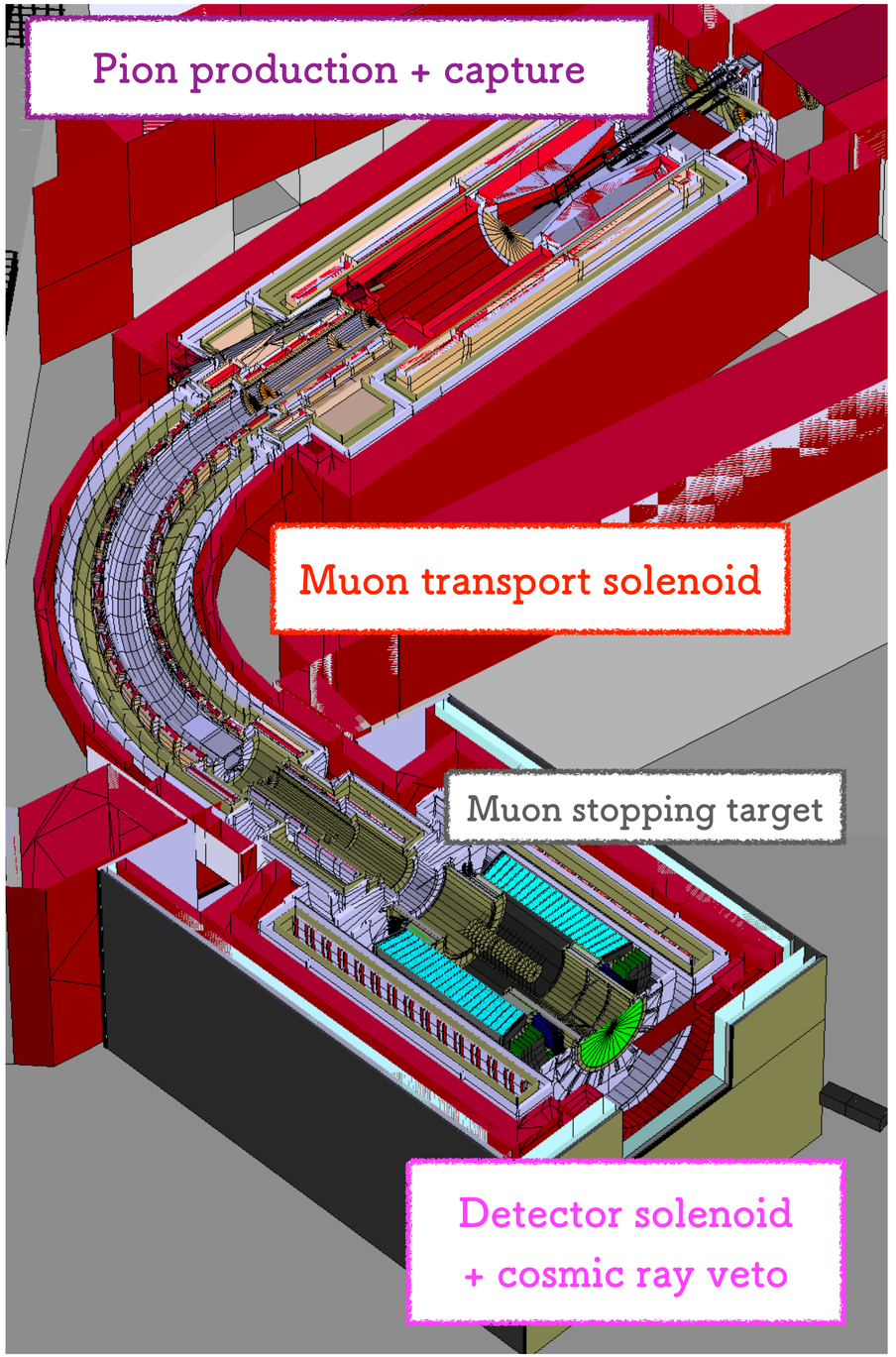
μ^-

Curved muon transport solenoid
Max 3 T + dipole ~0.05 T

Detectors + Solenoid ~1 T
+ Cosmic-ray veto

COMET Phase-I

- **Robustness**
  - μ-e search at the end of 1/2 MTS for early realisation
  - Direct beam measurement at the first half of MTS allowing data-driven design re-optimisations for Phase-II
  - Better understanding on backgrounds
- **Physics**
  - An O(10^{-15}) sensitivity still achievable; **100** times better than the current upper limit
  - Allow to study different physics, e.g. $\mu^- N(A, Z) \rightarrow e^+ N'(A, Z-2)$

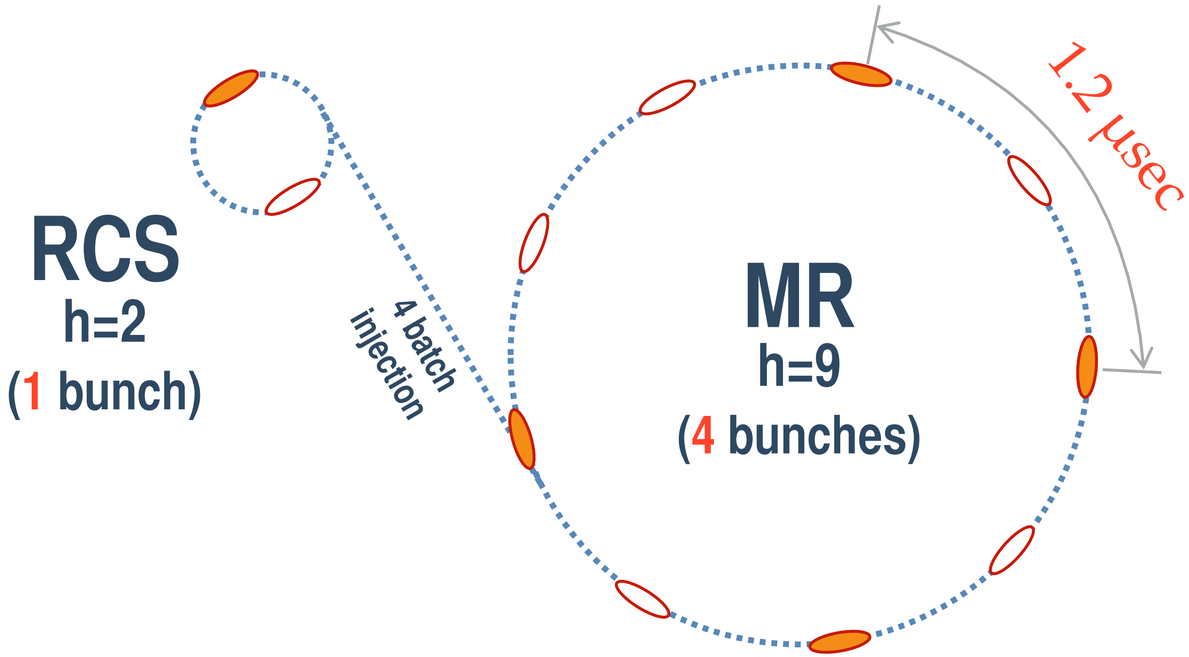


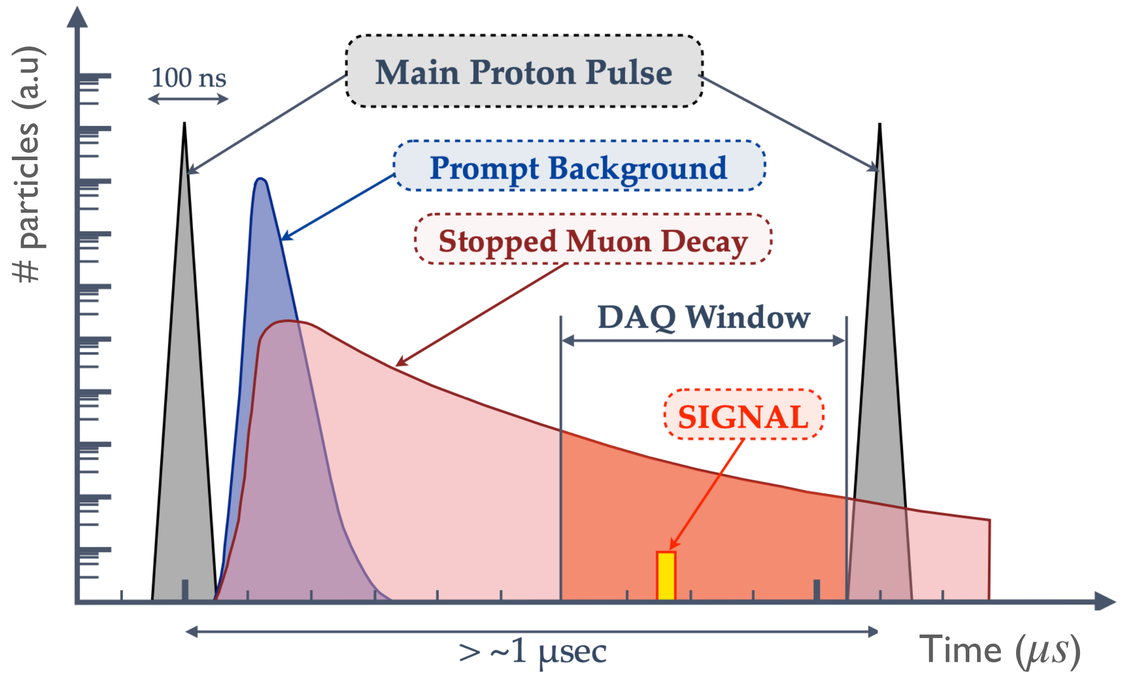
Proton beam

- Accelerated to 8 GeV by the Main Ring (MR) synchrotron @ J-PARC ↔ 30 GeV in the normal MR operation
  - 8 GeV, 3.4 kW (56 kW) for Phase-I (Phase-II)

    → O($10^{12–13}$) POT/sec
  - 1.2 μs time intervals by emptying 1/2 beam harmonics at the rapid cycler synchrotron (RCS)
- Extremely clean pulsed beam is required

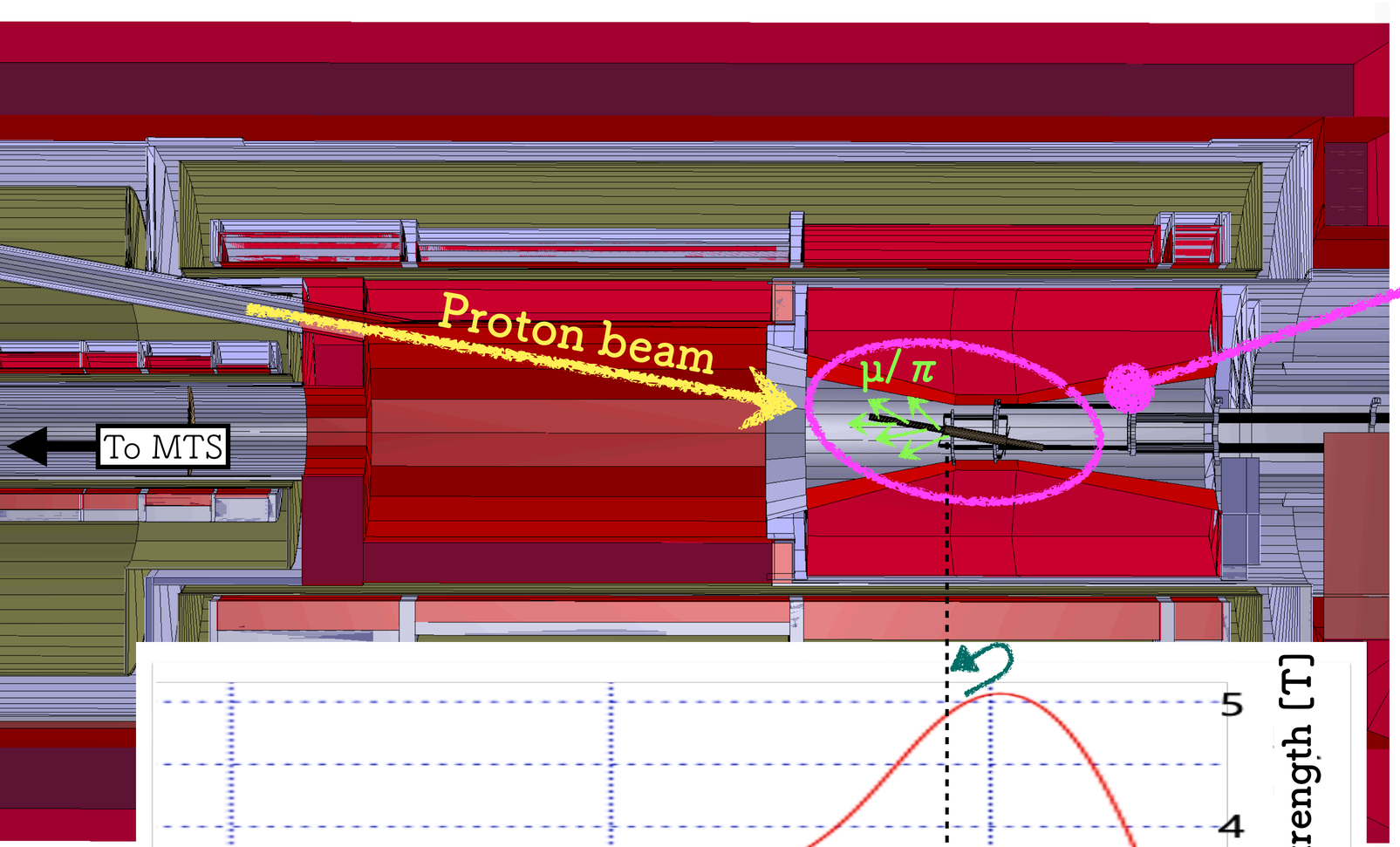
  → Residual protons fraction < **10^{-10}** w.r.t the #protons in a main bunch already achieved

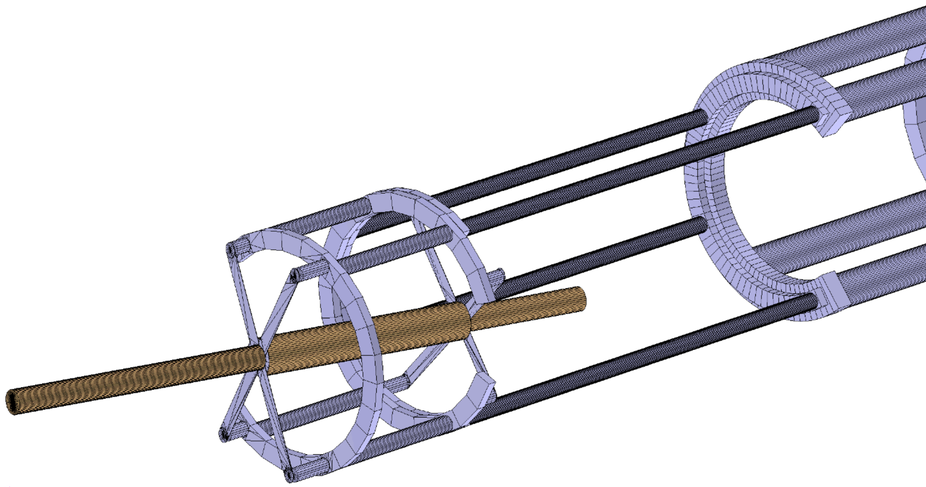




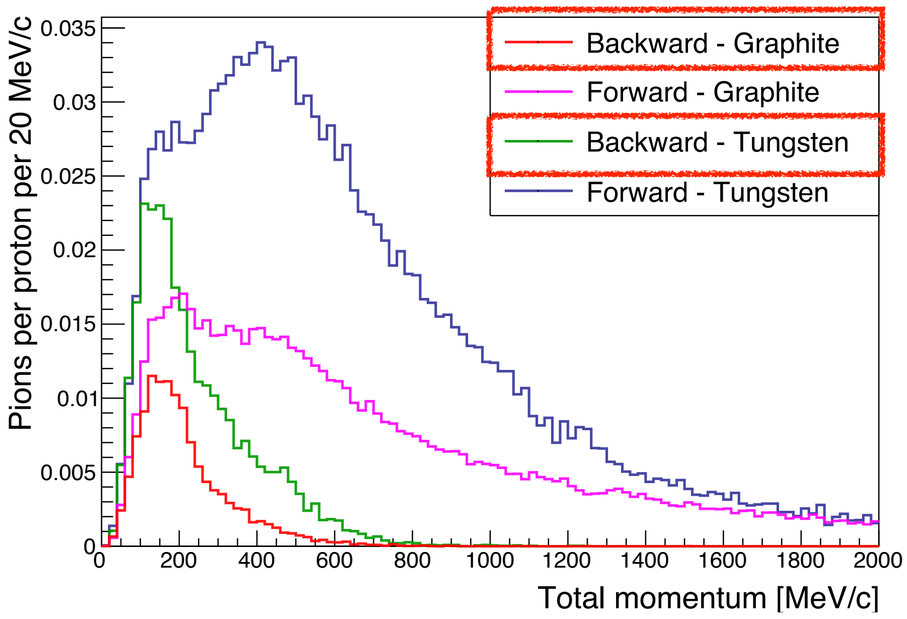
K. Noguchi, et al., Proc. of Sci., 402 (2022)

Pion production & capture



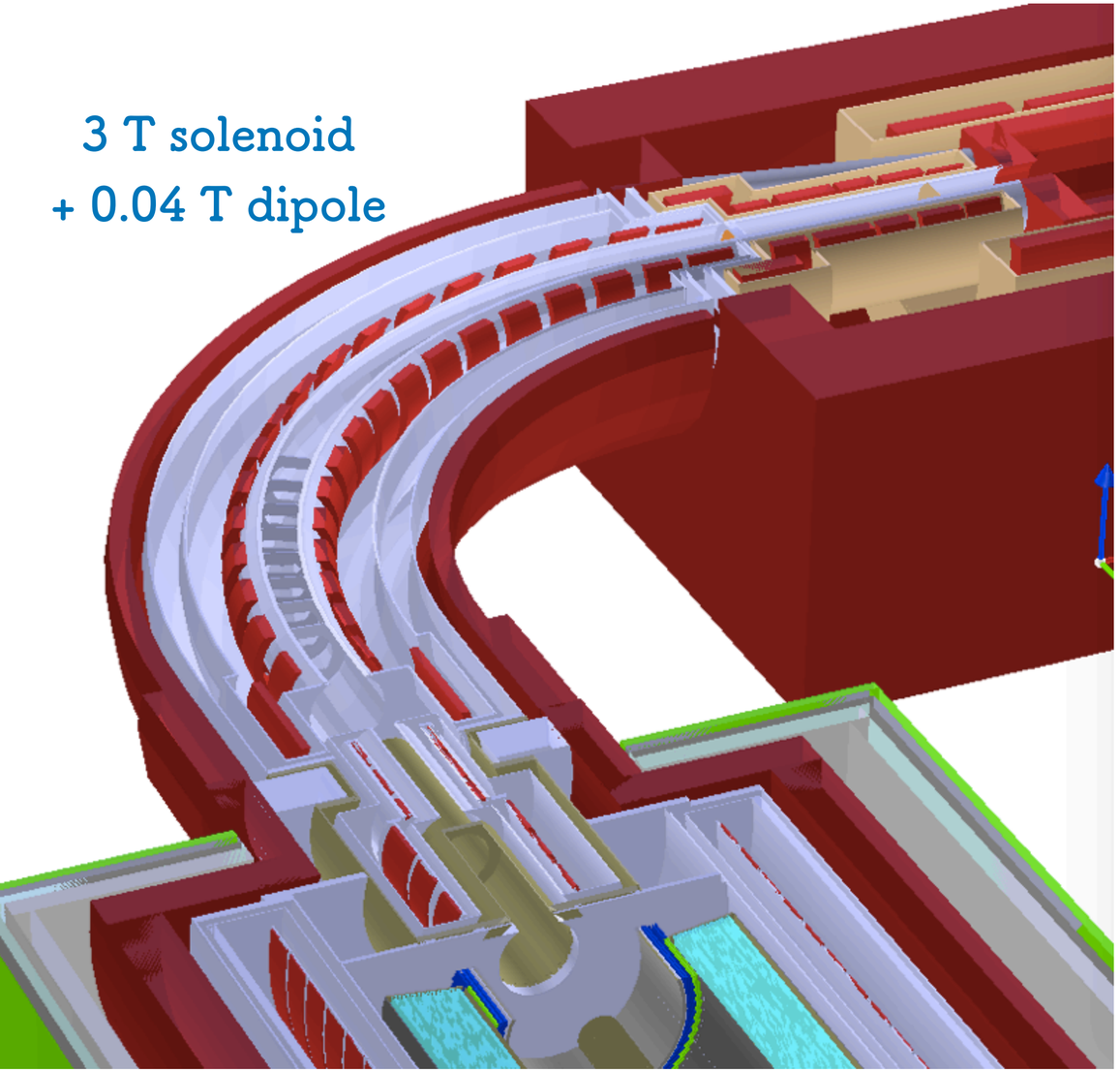


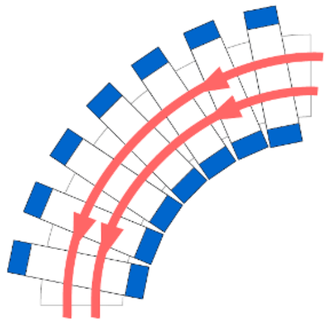
Graphite (Tungsten) pion production target for Phase-I (Phase-II)



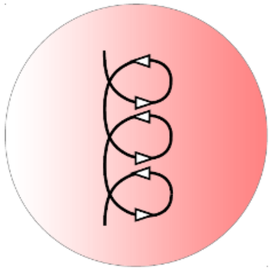
Muon beam

3 T solenoid
+ 0.04 T dipole



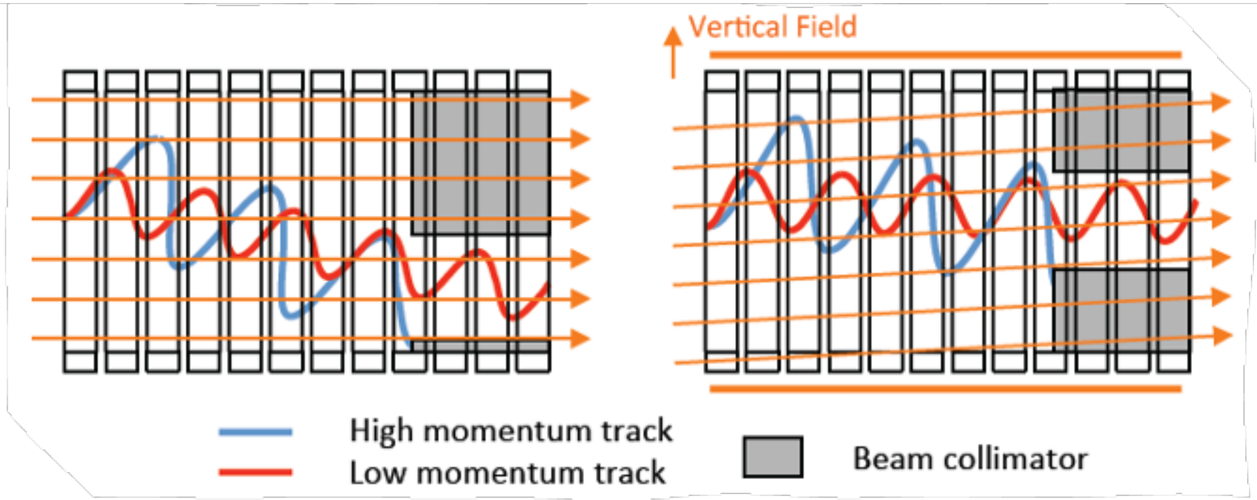


- Radial gradient in magnetic field
- Cylindrical field lines



Circular motion about a drifting centre:

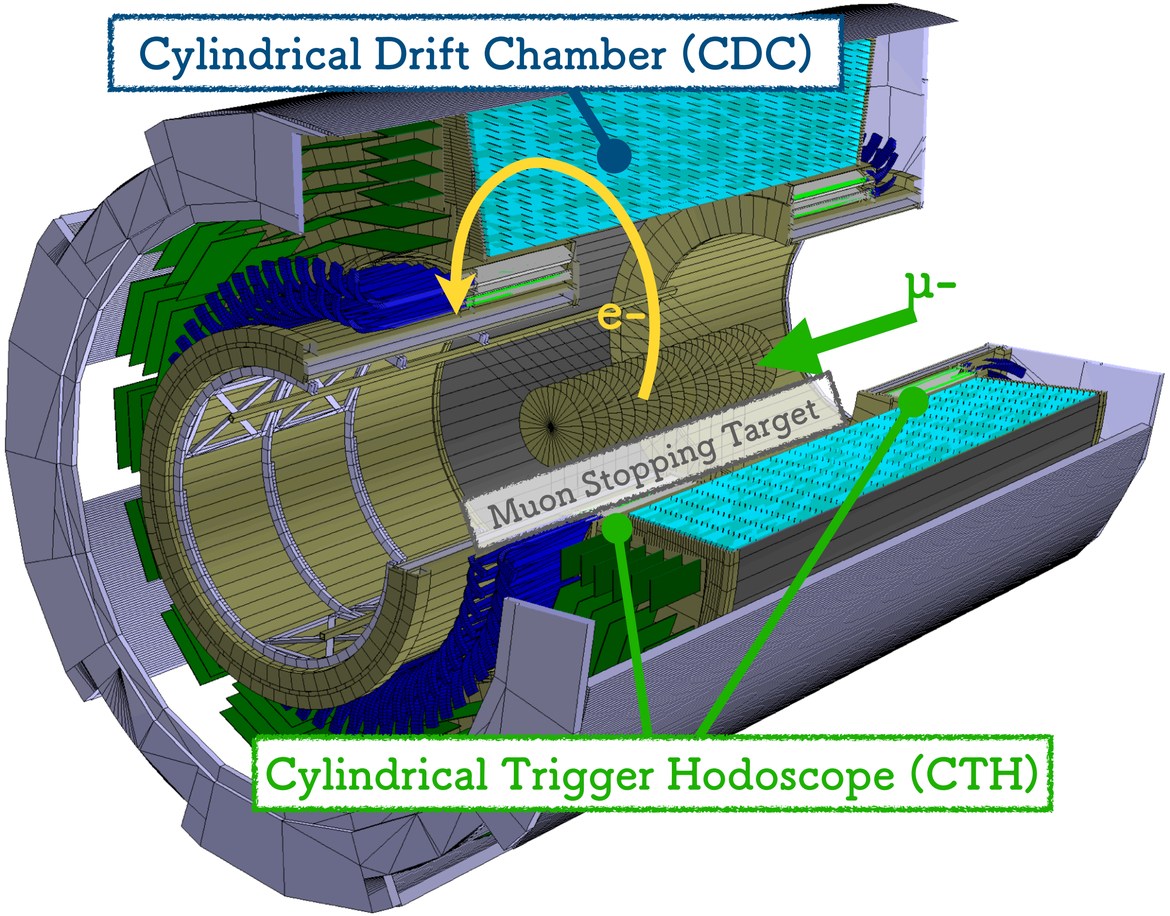
$$D \propto \frac{p}{qB} f(\theta)$$

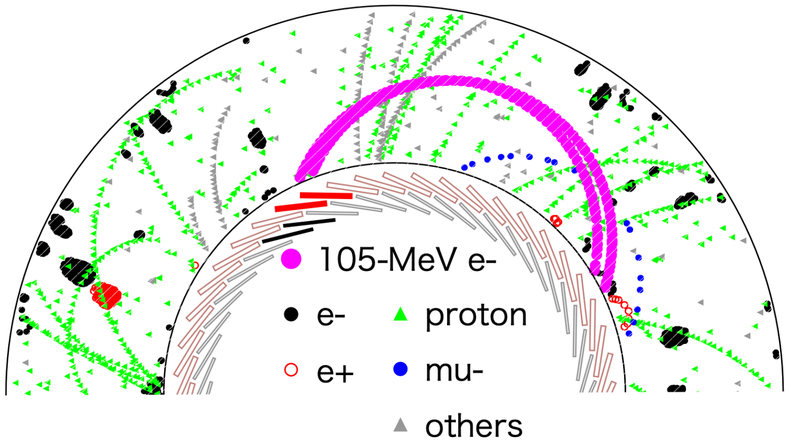


- Most pions decay before reaching the detector region
- Positive / high-p particles are filtered due to the vertical drifting while travelling inside the curved solenoid field
- Additional dipole field to adjust low-p μ^- around the centre

CyDet (1)

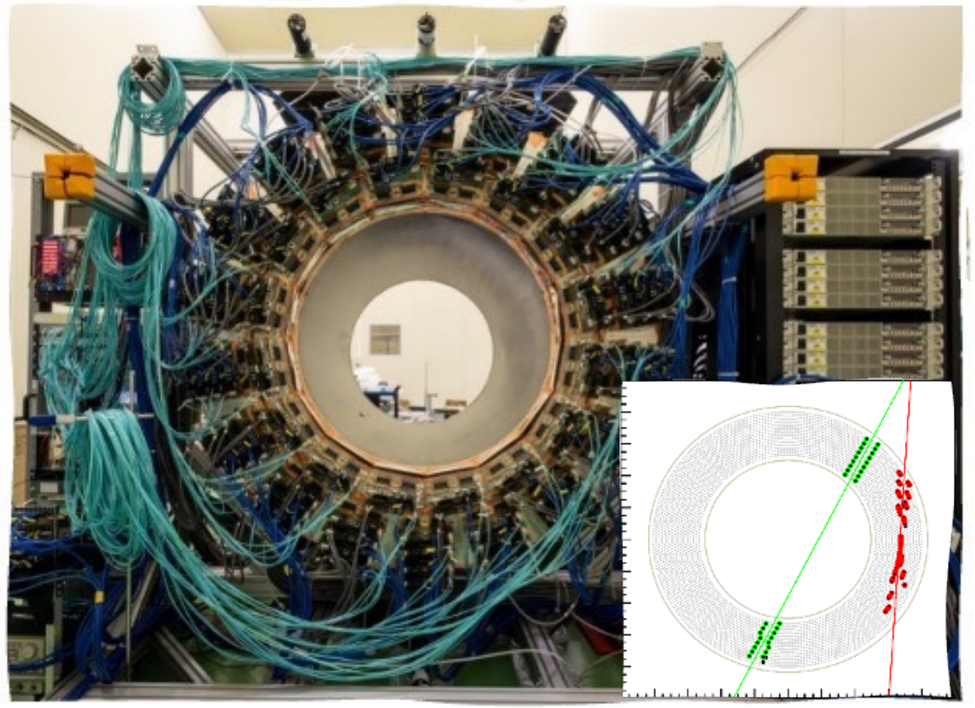
- Surrounding the muon stopping target discs to avoid high intensity beam and the majority of DIO electrons
  - Yet to be high hit rate + high radiation environment (**1 kGy, 10^{12} n/cm^2**)
- **Requirements**
  - Momentum resolution: <**200 keV/c** in σ
  - High hit rate tolerance: **O(1) MHz** / channel
- **Cylindrical Drift Chamber (CDC)**
  - Momentum reconstruction
- **Cylindrical Trigger Hodoscope (CTH)**
  - Timing reconstruction, primary trigger generation





CyDet (2)

- **Cylindrical Drift Chamber (CDC)**
  - Full stereo wire drift chamber, 20 layers, ~5k sense wires
  - 0.5 mm^t CFRP inner wall + helium based gas mixture (He:iso-C_4H_{10} = 9:1) to minimise the multiple scattering
  - Average **spatial resolution of <200 μm achieved** → σ_p ~200 keV/c
  - Full readout tests, gas system and DAQ tests are ongoing at J-PARC

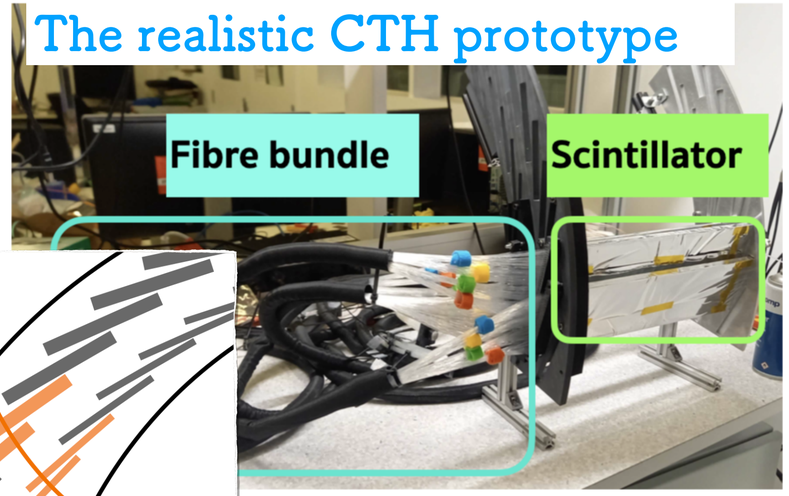


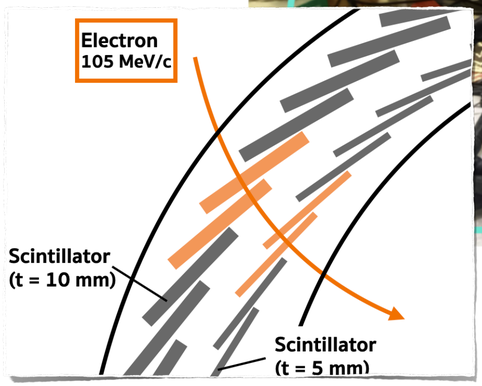
A. Sato, et al., Nucl. Instrum. Methods Phys. Res. A, 1069 (2024), 169926

- **Cylindrical Trigger Hodoscope (CTH)**
  - Timing measurement <1 ns & Four-fold coincidence to suppress accidental trigger rate <**100 kHz**
  - Silicon photomultipliers will be installed outside of the detector solenoid to avoid the high radiation environment
  - W/ the realistic prototype, <**1 ns time resolution was obtained** and the particle identification capability was tested

Y. Fujii, et al., Nucl. Instrum. Methods Phys. Res. A, 1067 (2024), 169665

The realistic CTH prototype





Phase-I expected sensitivity & BGs

$$\mathcal{B}(\mu^- N \to e^- N)\big|_{Al} = \frac{1}{N_\mu \cdot f_{cap} \cdot f_{gnd} \cdot A_\mu} \approx 3 \times 10^{-15}$$

N_μ : #of stopped μ^-, **1.5×10^{16}**, exp. @ 150 days,

f_{cap} : fraction of stopped μ^- captured, 0.61, theory,

f_{gnd} : fraction of μ^- bound to ground state, 0.9 theory,

A_μ : acceptance of μ-e signal, 0.041, exp..

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

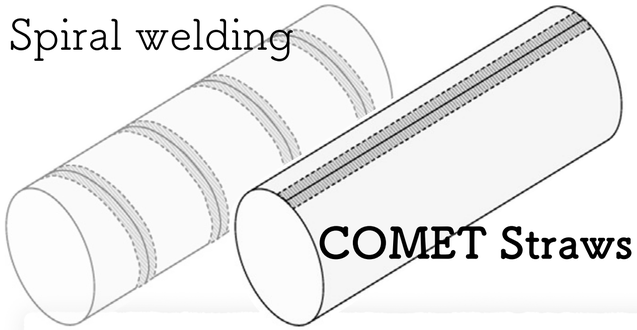
Type	Background	Estimated events
Physics	Muon decay in orbit	0.01
	Radiative muon capture	0.0019
	Neutron emission after muon capture	< 0.001
	Charged particle emission after muon capture	< 0.001
Prompt Beam	* Beam electrons	
	* Muon decay in flight	
	* Pion decay in flight	
	* Other beam particles	
	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

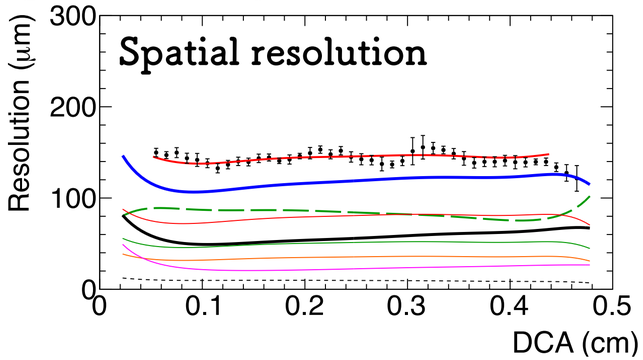
† This estimate is currently limited by computing resources.

The COMET Collaboration, et al., Prog. Theor. Exp. Phys. 2020 (3) (2020), 033C01.

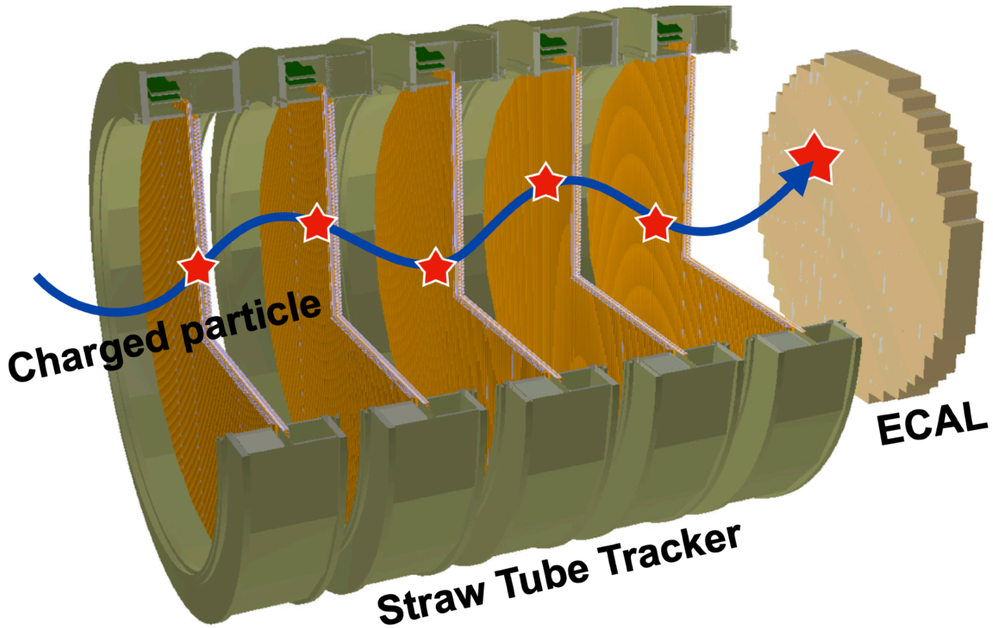
Other detectors

Spiral welding

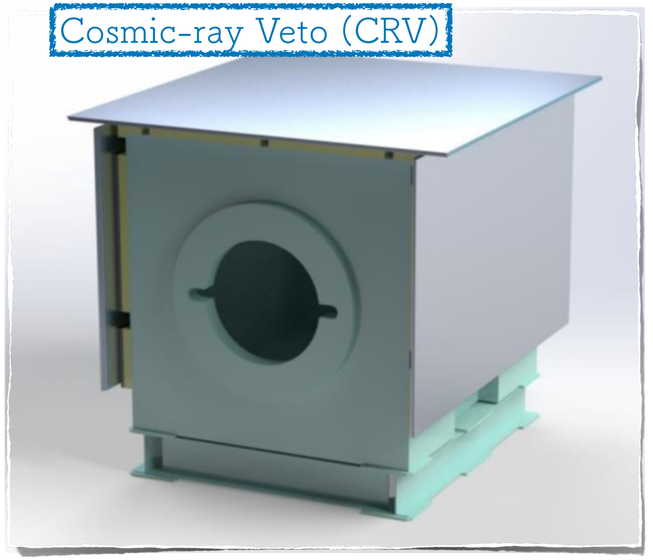


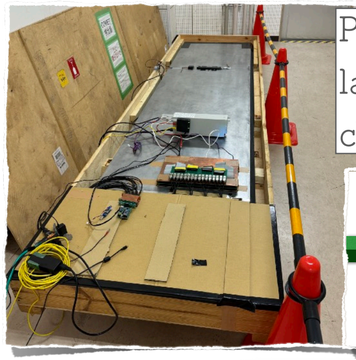


Phase-I beam measurement detectors
= Phase-II prototype detectors

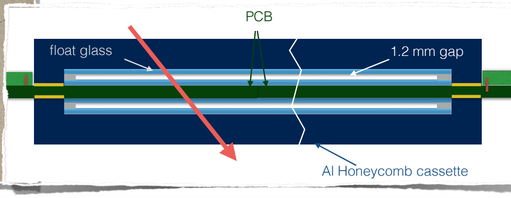


Cosmic-ray Veto (CRV)

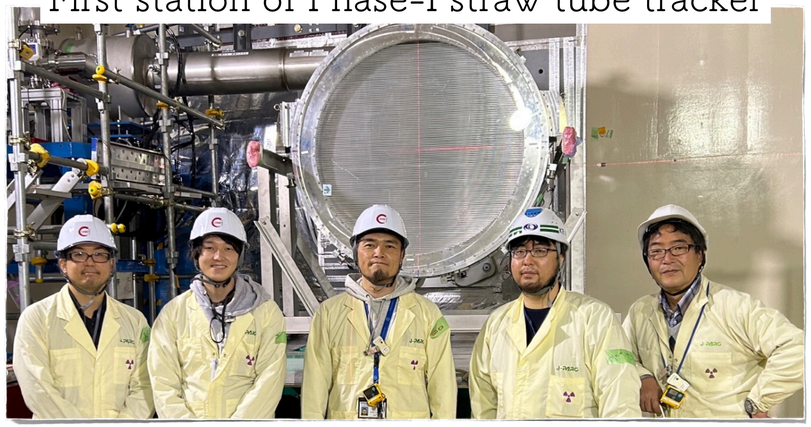




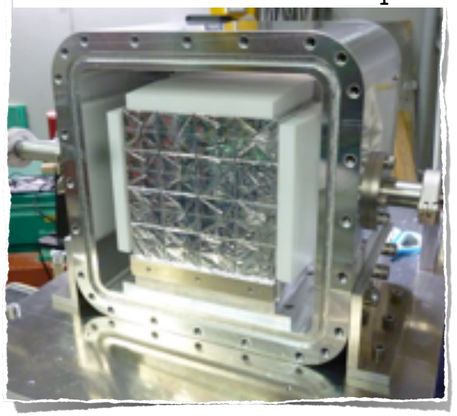
Plastic scintillators for Top & lateral sides, Resistive plate chambers for front/back sides

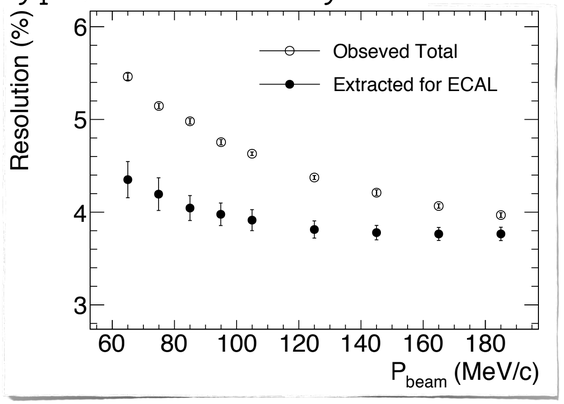


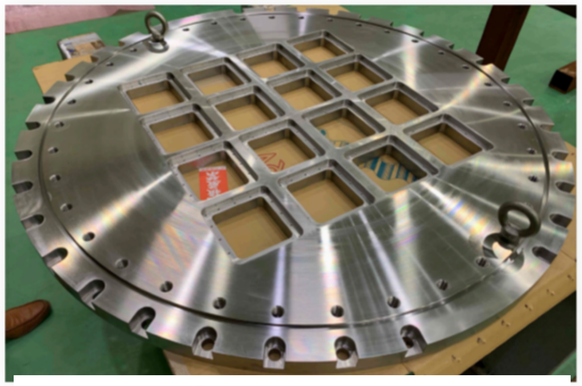
First station of Phase-I straw tube tracker



Electron calorimeter prototype, 4x4 LYSO crystals





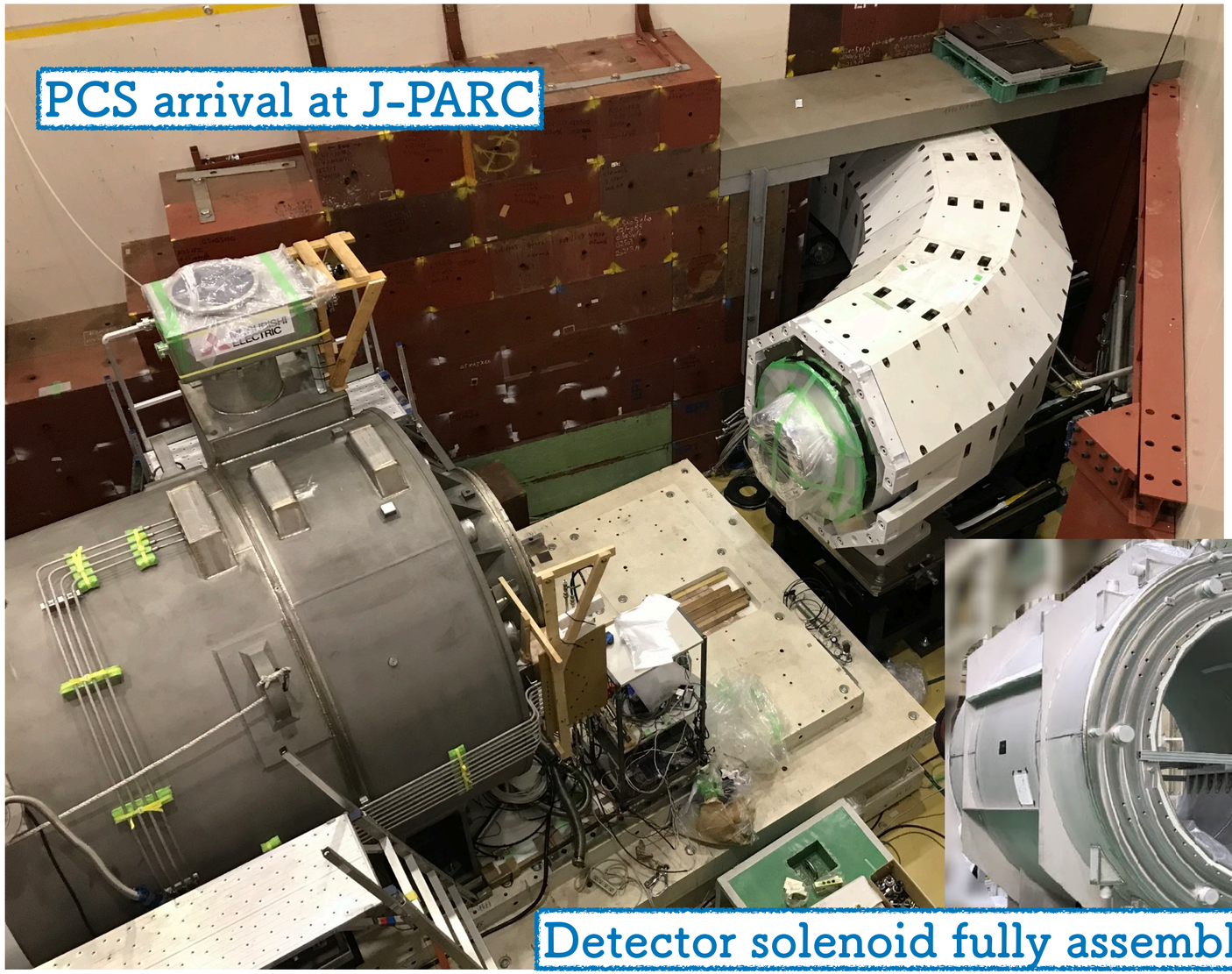


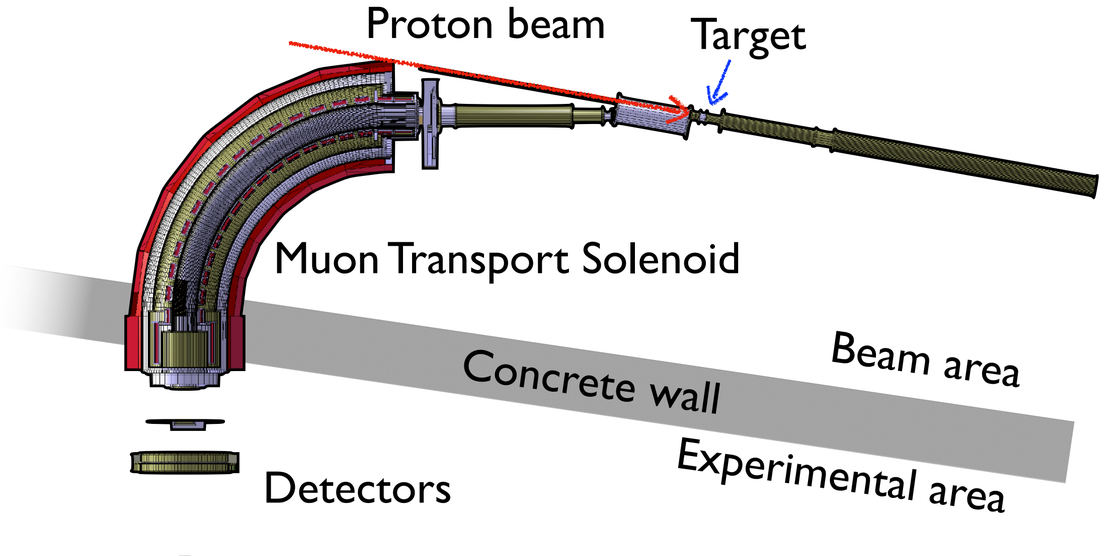
Phase-I ECAl support structure

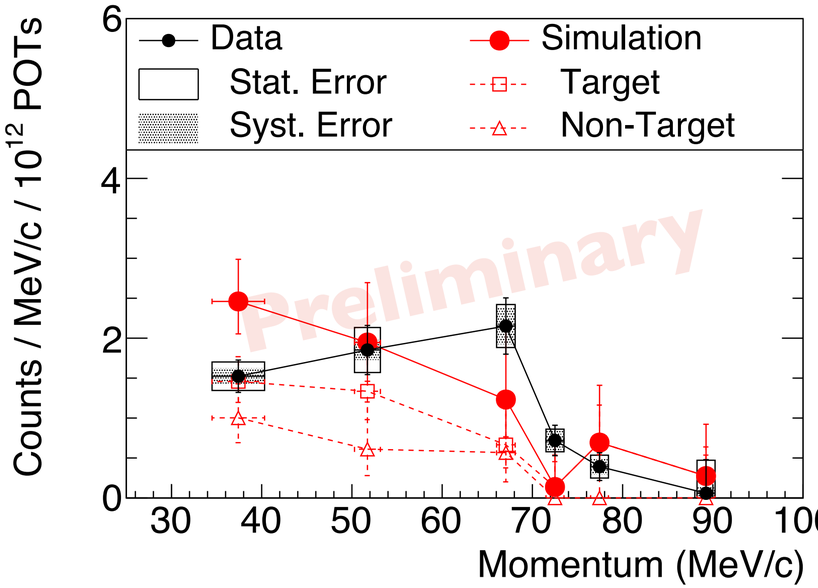
H. Nishiguchi, et al., Nucl. Instrum. Methods Phys. Res. A, 958 (2020) 162800

Recent Highlights

Analysis results of the first MTS commissioning w/ 8 GeV proton beam (COMET Phase-α) to be published soon





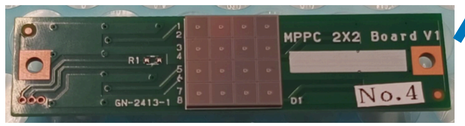


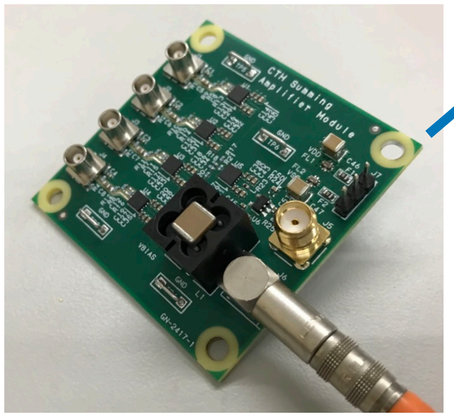
Summary

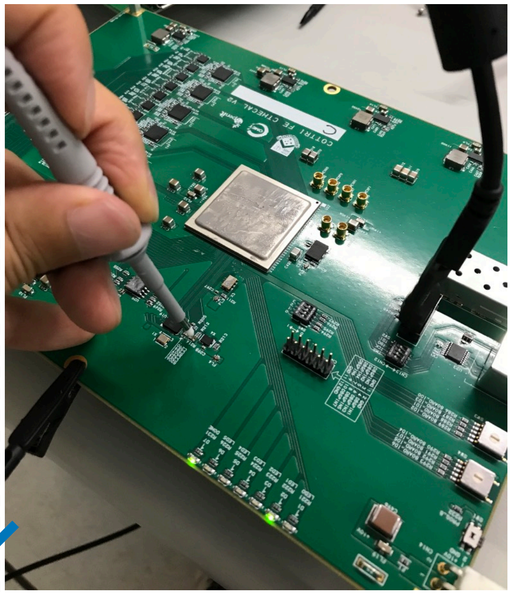
- COMET searches for μ-e conversion with the sensitivities **100 (10,000)** times better than the current upper limit in Phase-I (Phase-II)
  - **Clear sign of new physics if discovered** or stringent limit on new physics models
  - Model parameters can be constrained by combining other CLFVs / different muonic atoms
- Phase-I preparations are ongoing
  - Muon beam transportation was demonstrated in COMET Phase-α, the results to be published soon
  - **All muon beam-line magnets have been constructed** and installation is ongoing
  - Almost all detectors are in construction / installation stages
  - Expected to start in 2026-2027 with low intensity beam at the beginning

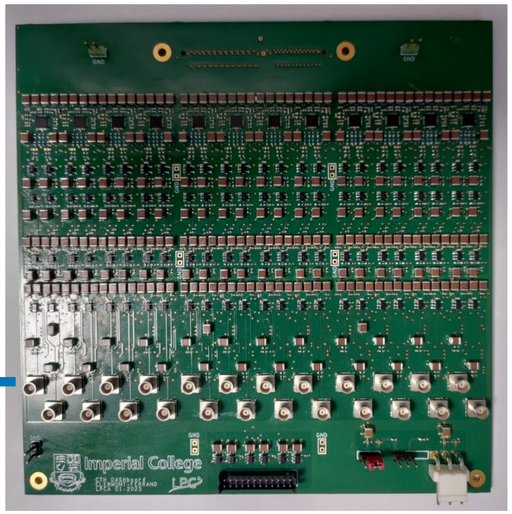
Back up

CTH readout









シンチレーション光

放射線遮蔽

冷却システム

光センサー
(Silicon Photomultiplier: SiPM)
×256

アナログ電気信号

前段増幅器SAM
(Summing Amplifier Module)
×256

アナログ電気信号×24ch

後段整形・弁別回路DASH
(Discriminating And SHaping)
×12

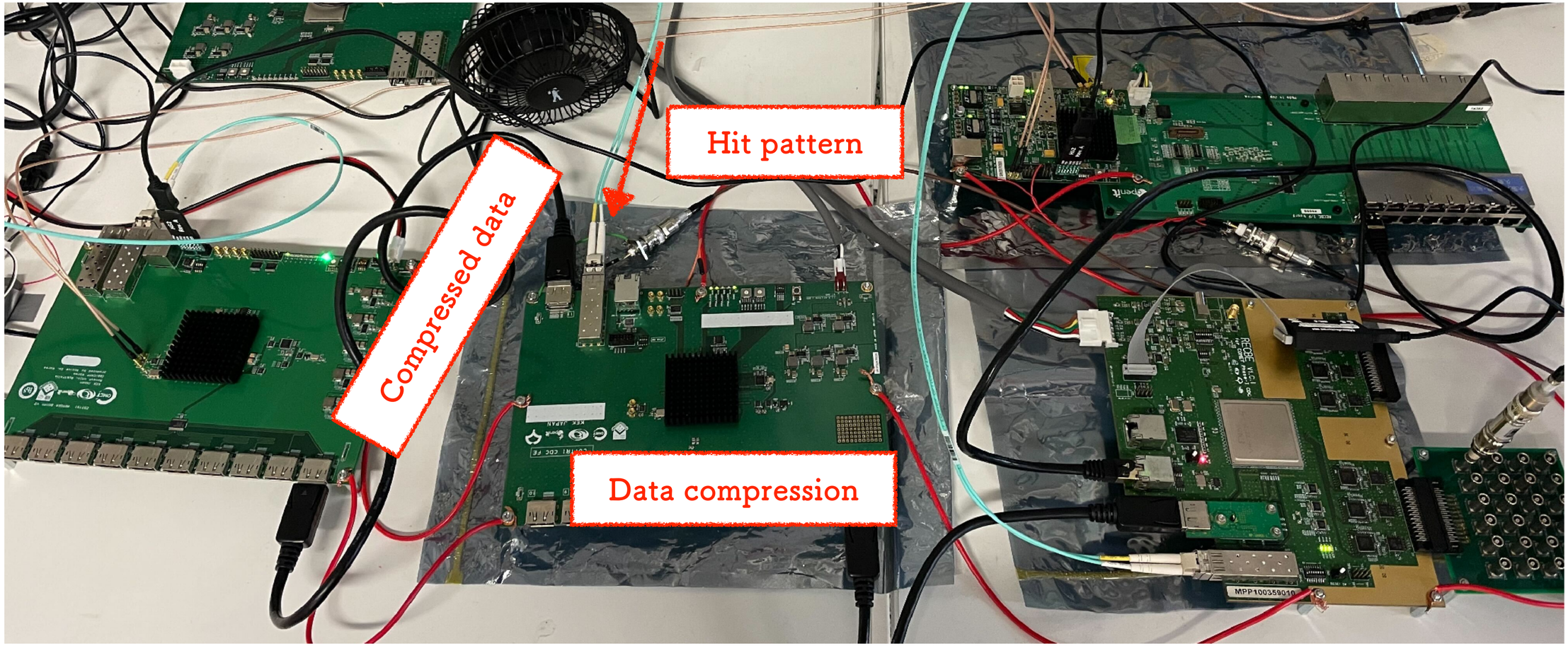
アナログ+デジタル信号
×24

トリガー・読出し回路COTTRI
(COmeT TRIgger)
×12

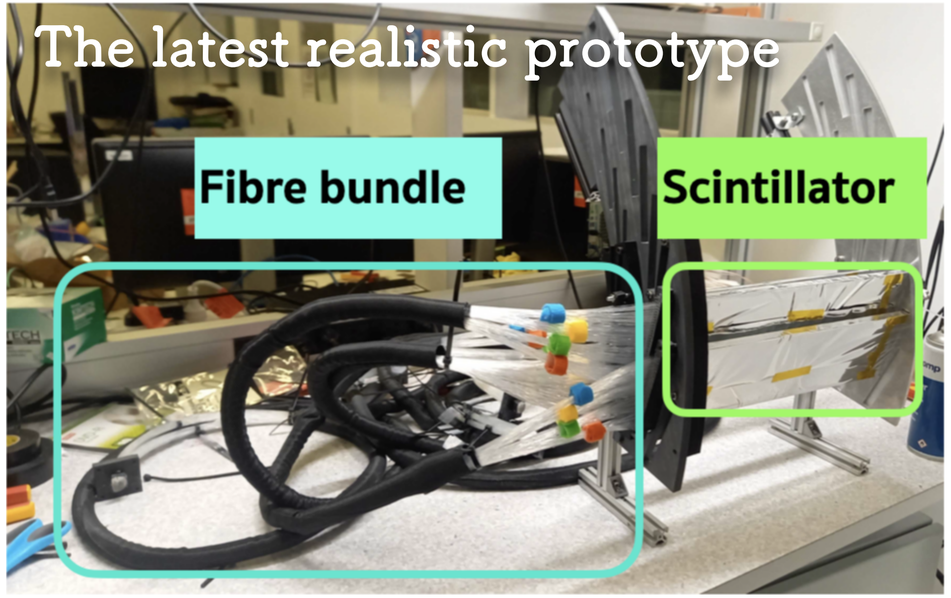
デジタル信号

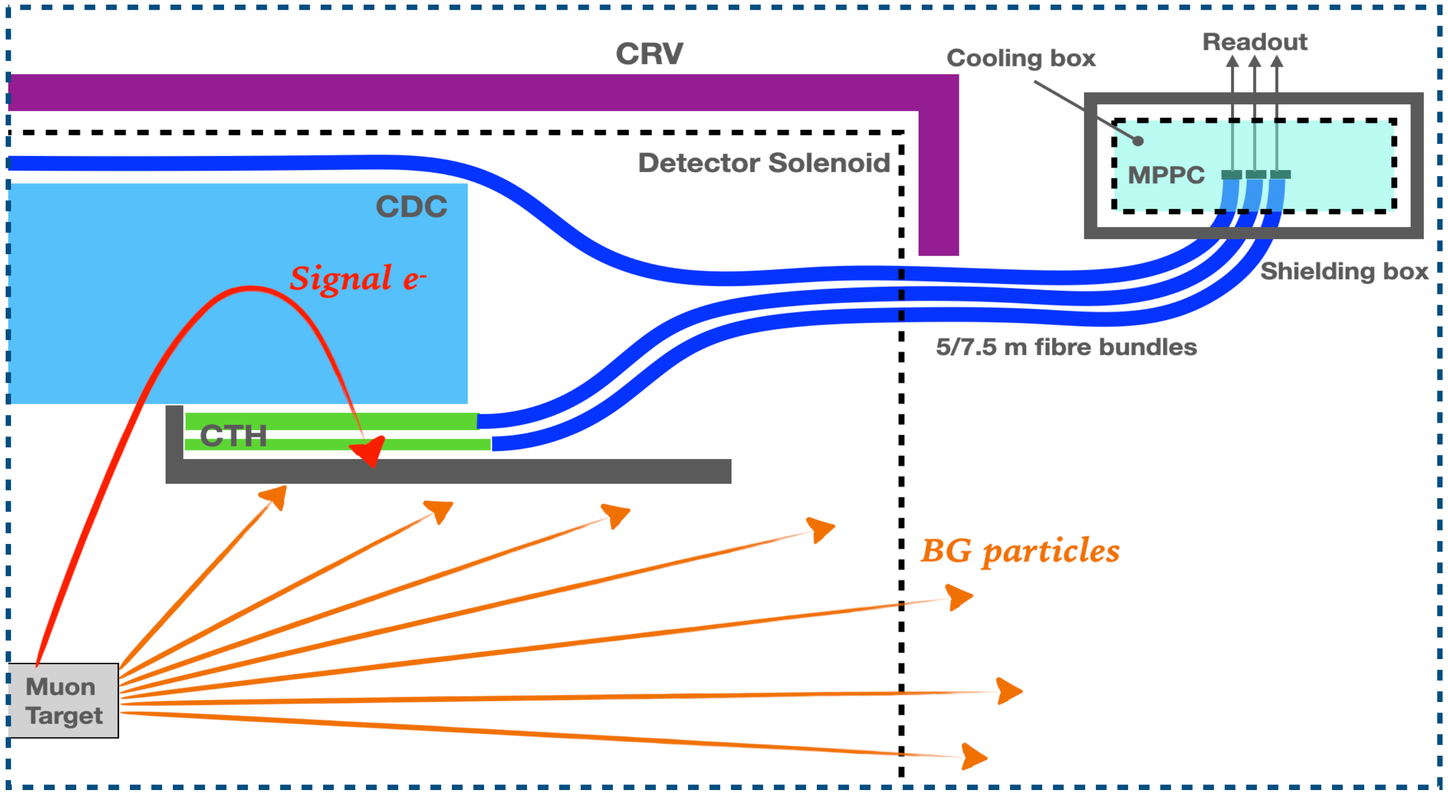
後段トリガー回路・データ取得PCへ

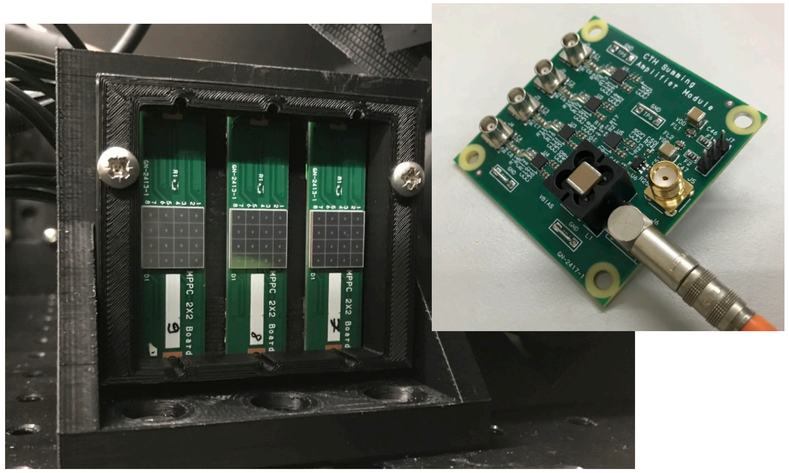
CDC trigger & readout boards



CTH

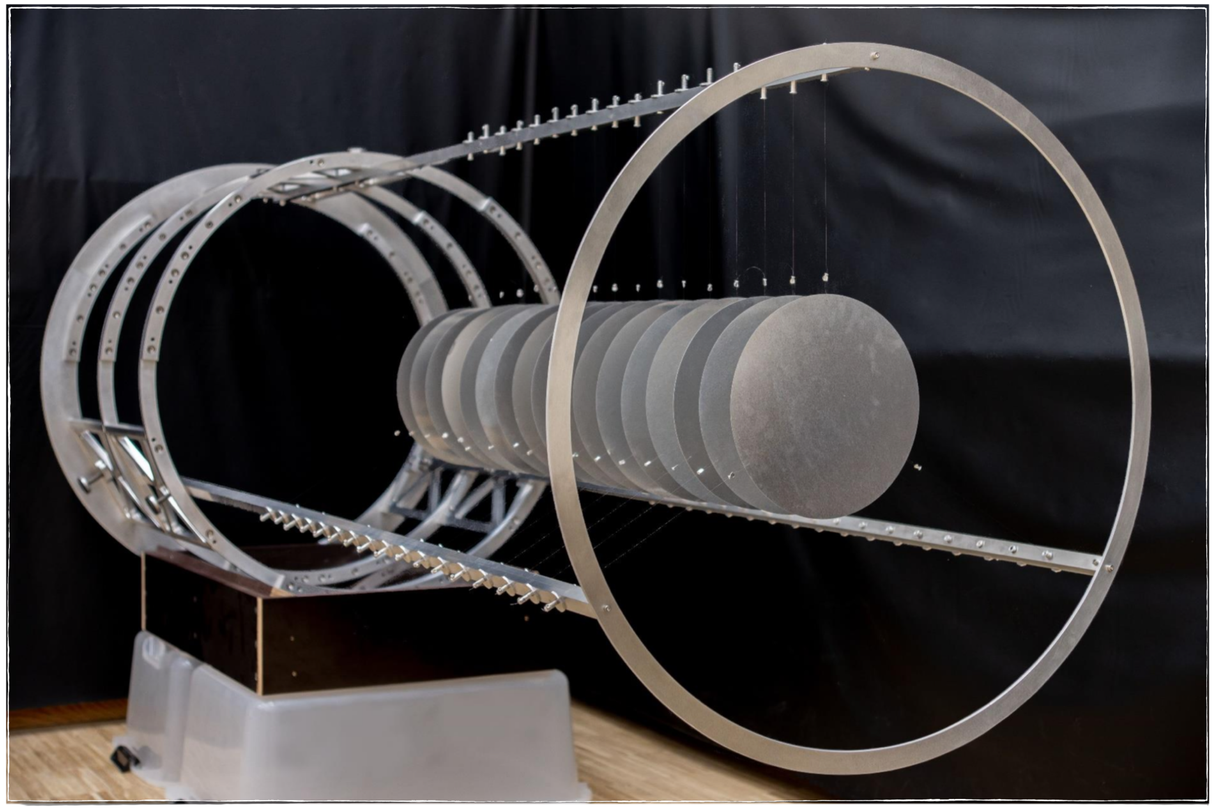

The latest realistic prototype
Fibre bundle
Scintillator


CRV
Cooling box
Readout
Detector Solenoid
MPPC
CDC
Signal e-
Shielding box
5/7.5 m fibre bundles
CTH
BG particles
Muon
Target

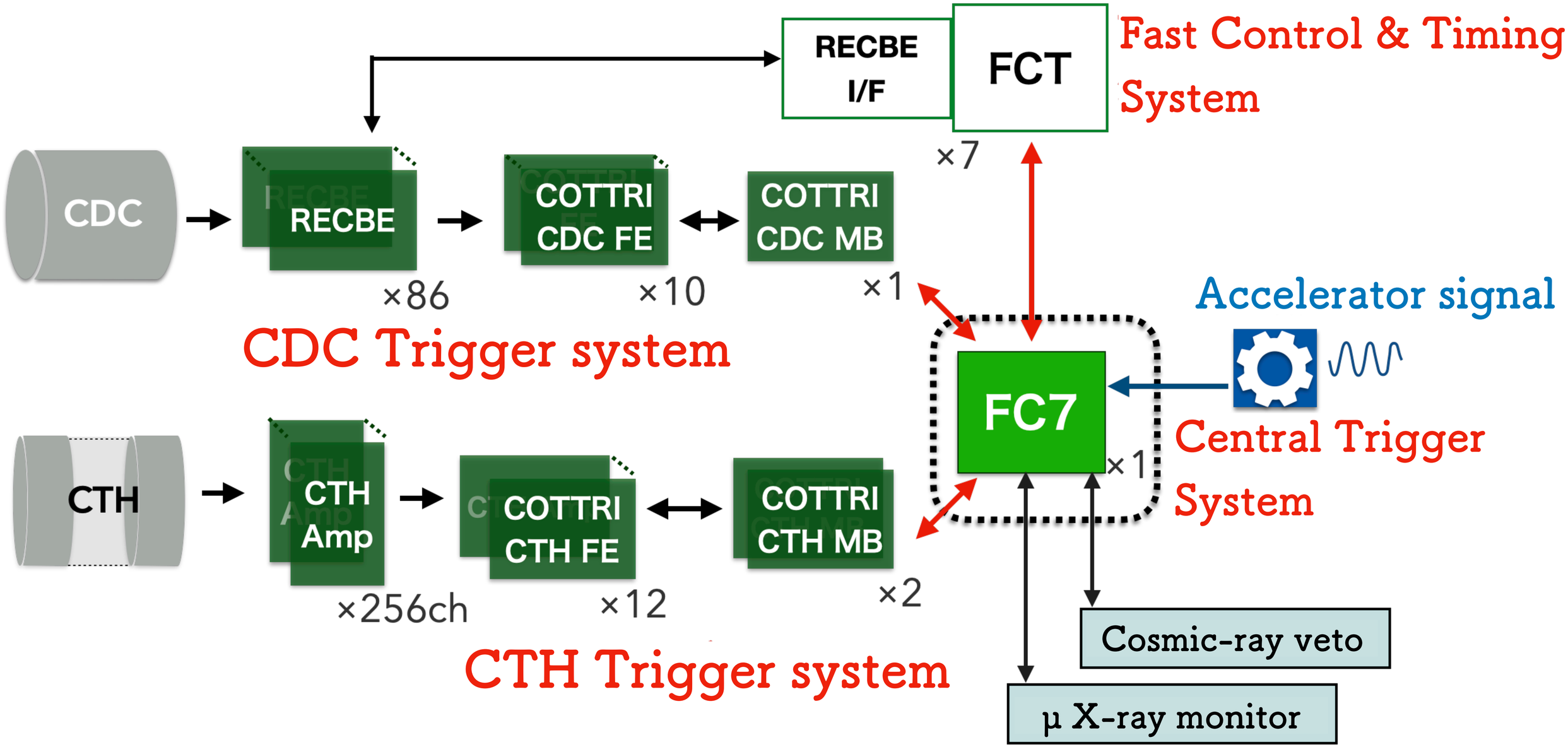


Muon stopping target

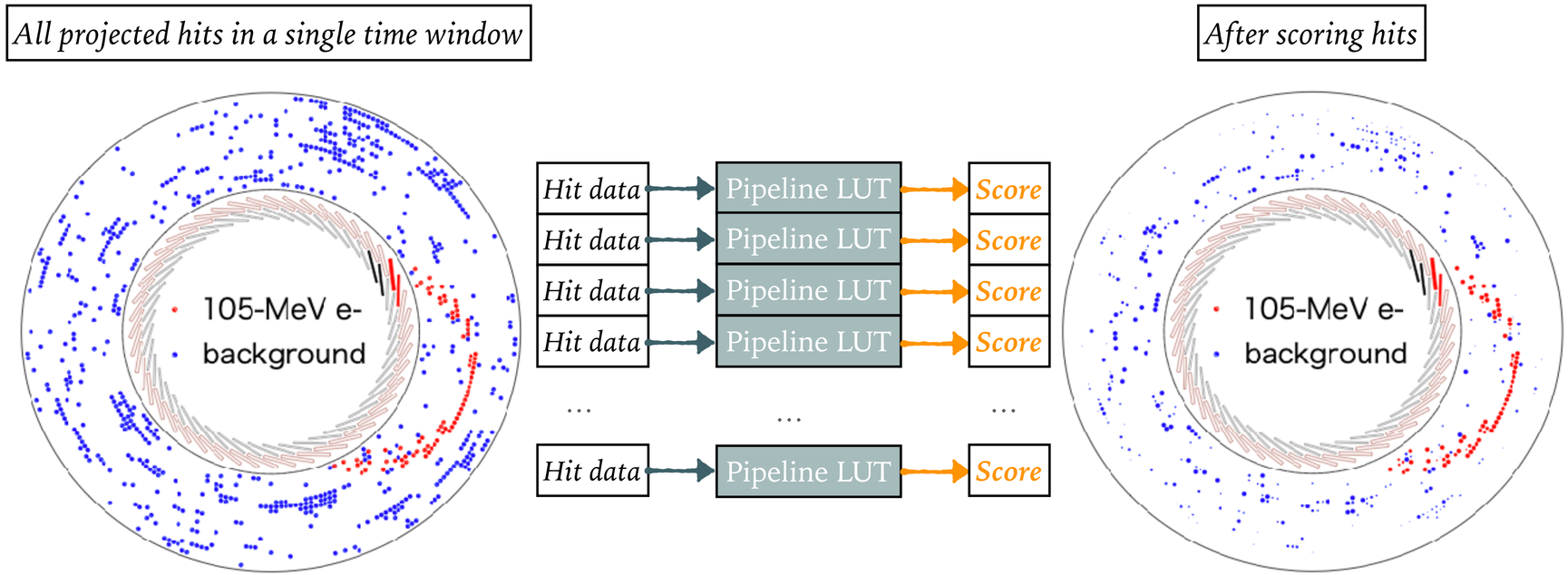
- 17 aluminium discs, 0.2 mm^t each
- Possible upgrade to increase number of discs and/or using 0.1 mm^t discs

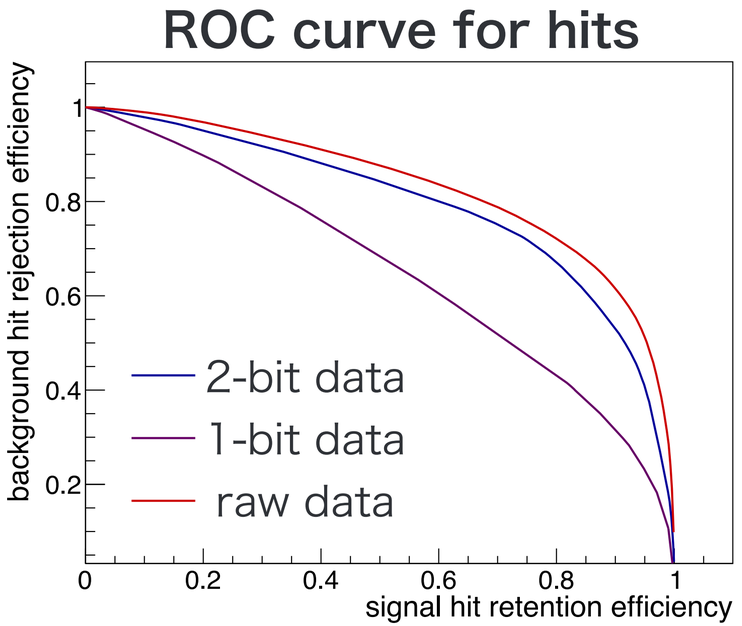


CyDet online trigger system



ML based online trigger scheme





- CTH 4重同時計測による100 kHzのトリガー信号をさらに1/10にする必要があるため, CDCの情報をトリガーに加える
- 以下のアルゴリズムをFPGA (Field Programmable Gate Array)内部に飛跡トリガー回路として実装する
  - 信号/雑音ヒットの特徴量(電荷, 分布)を利用しBoosted Decision Treeによるヒット分類
  - BDT後のスコア分布を入力にした深層学習モデルによる信号/雑音の事象弁別
- 上記どちらも実際に簡易モデルをFPGA上にプログラムして動作実証済み
  - 現在は大統計MCを用いたモデルの最適化を進めている

Far future plans

- Aiming O(10^{-17}) sensitivity w/ Straw-tube tracker+ECAL put inside the vacuum
  - C-shaped MTS and additional electron spectrometer as already shown
- PRISM/PRIME
  - Muon storage ring with phase rotation w/ an FFAG technique