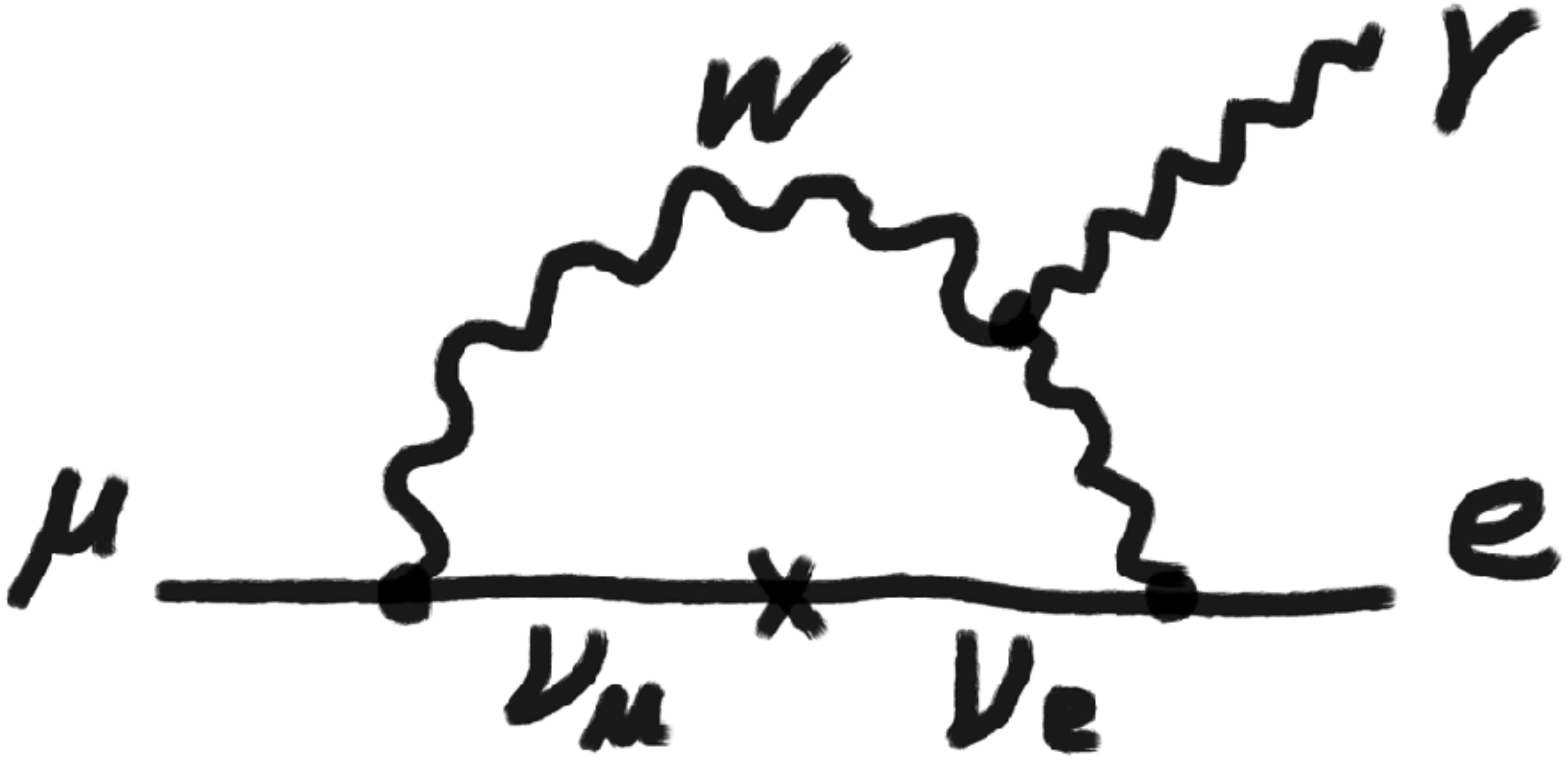
CLFV Search in COMET

Yuki Fujii for COMET
Monash University
New Frontiers in Lepton Flavor
16th May 2023, Pisa

Muon Charged Lepton Flavour Violation (CLFV)



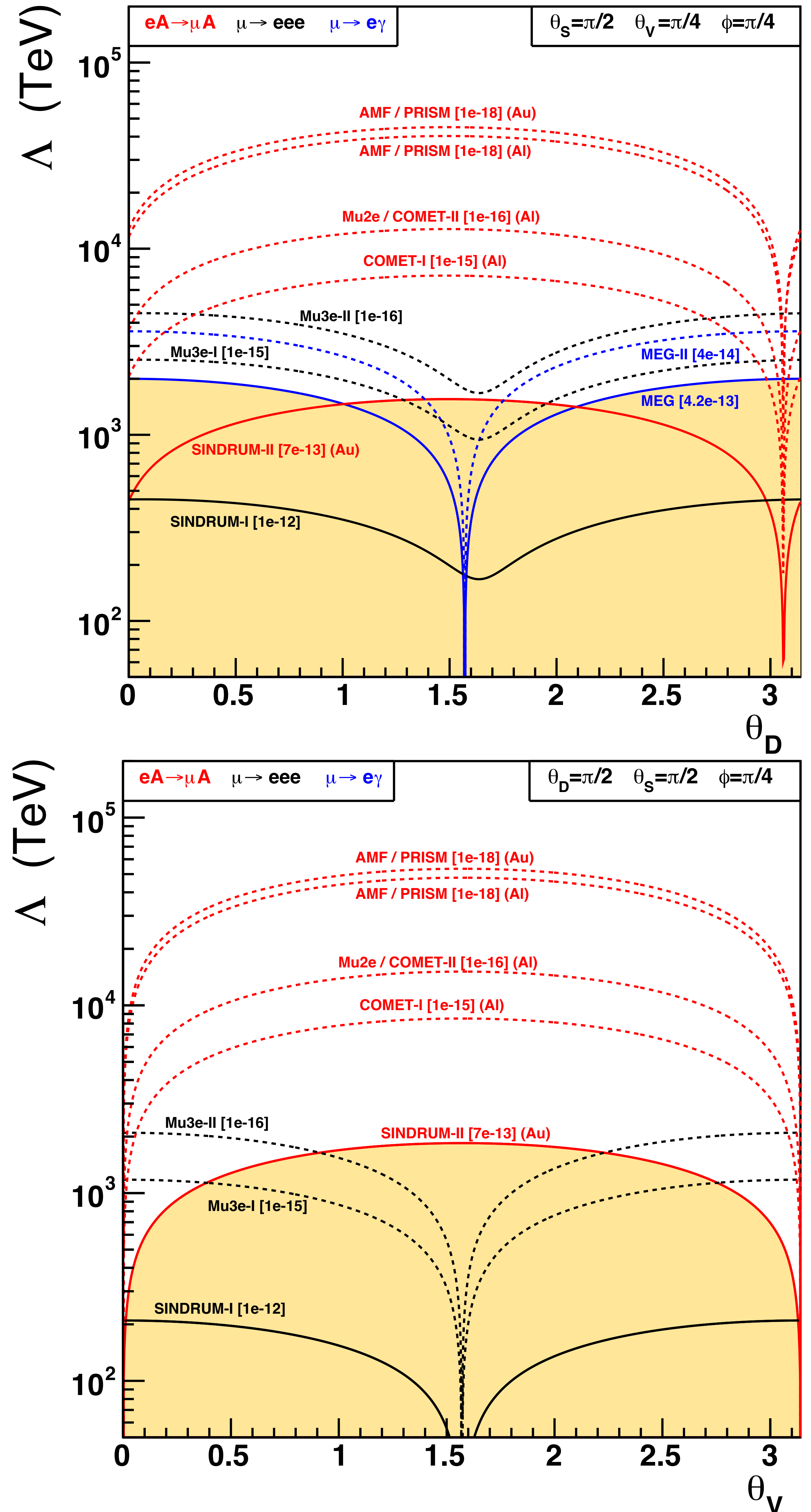
$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_i U^{\dagger}_{\mu i}U_{ei}\frac{m^2_{\nu_i}}{m^2_W}\right|^2 \approx 10^{-54}$$

$$\approx CR(\mu^- N \to e^- N)$$

- ➤ No CLFV processes in the Standard Model
- ➤ Massive neutrinos induce CLFV processes via neutrino oscillations
    - ➤ Already new physics beyond the Standard Model but as tiny as almost undetectable
- ➤ **Clear sign of the new physics if discovered**

CLFV in EFT

- Searches for CLFV processes indirectly probing Λ_{NP} > *1 PeV* new physics scale
  - ⇔ Ultra large Moon collider, ***14 PeV pp*** (arXiv:2106.02048)
- Complementary searches available with different muon CLFV modes (mainly *μ→eγ*, *μ→eee*, ***μN→eN***)
  - Current upper bound; 7×10^{-13} @Au, 90%C.L. by SINDRUM II
  - COMET aims to search for a *μ-e* conversion with **100/10,000** times better sensitivity

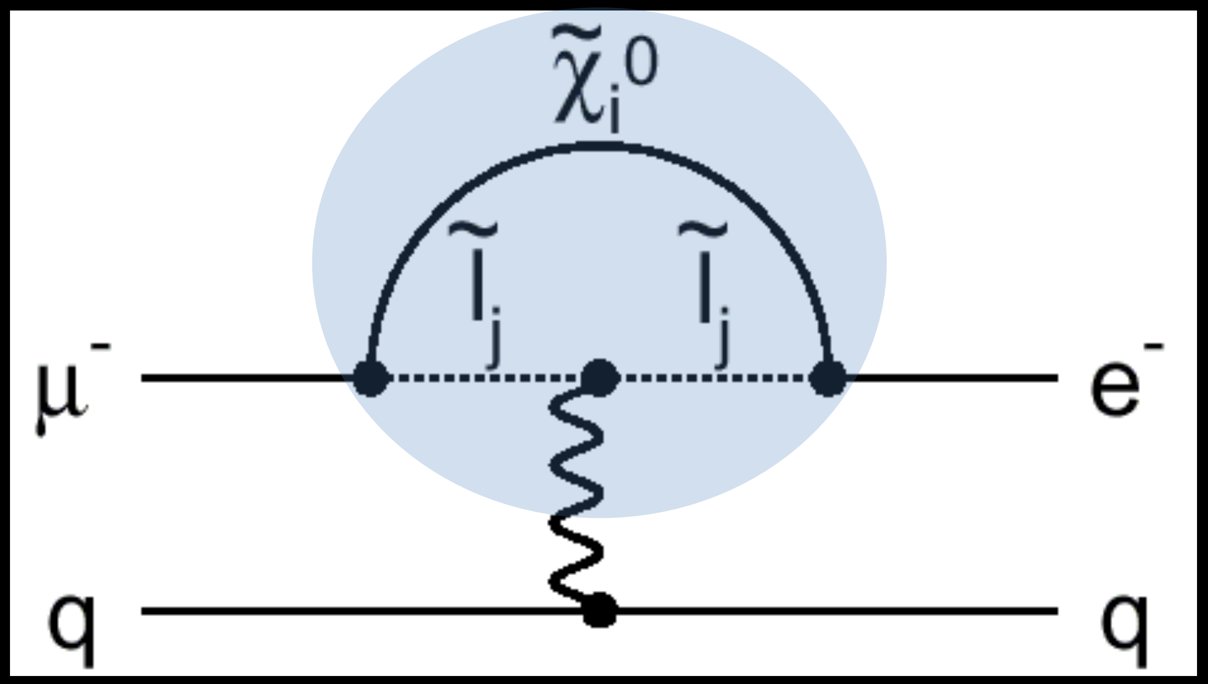


S. Davidson and B Echenard, arXiv:2204.00564

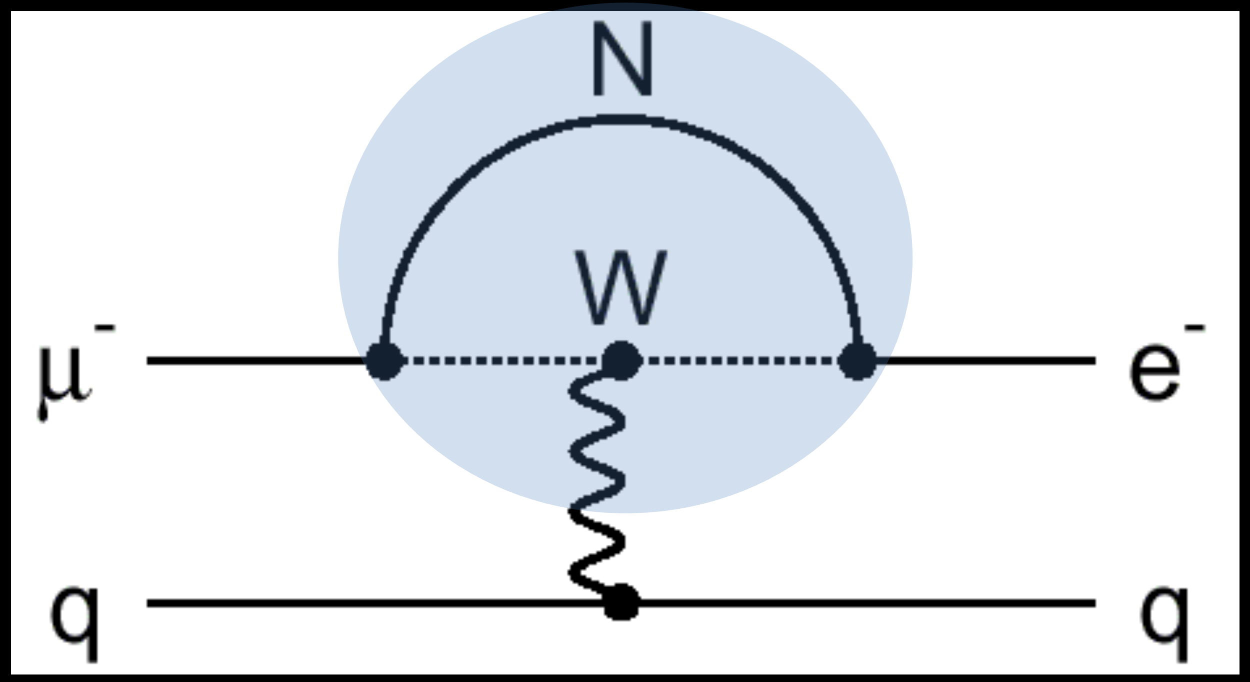
μ-e conversion in BSM

Loops

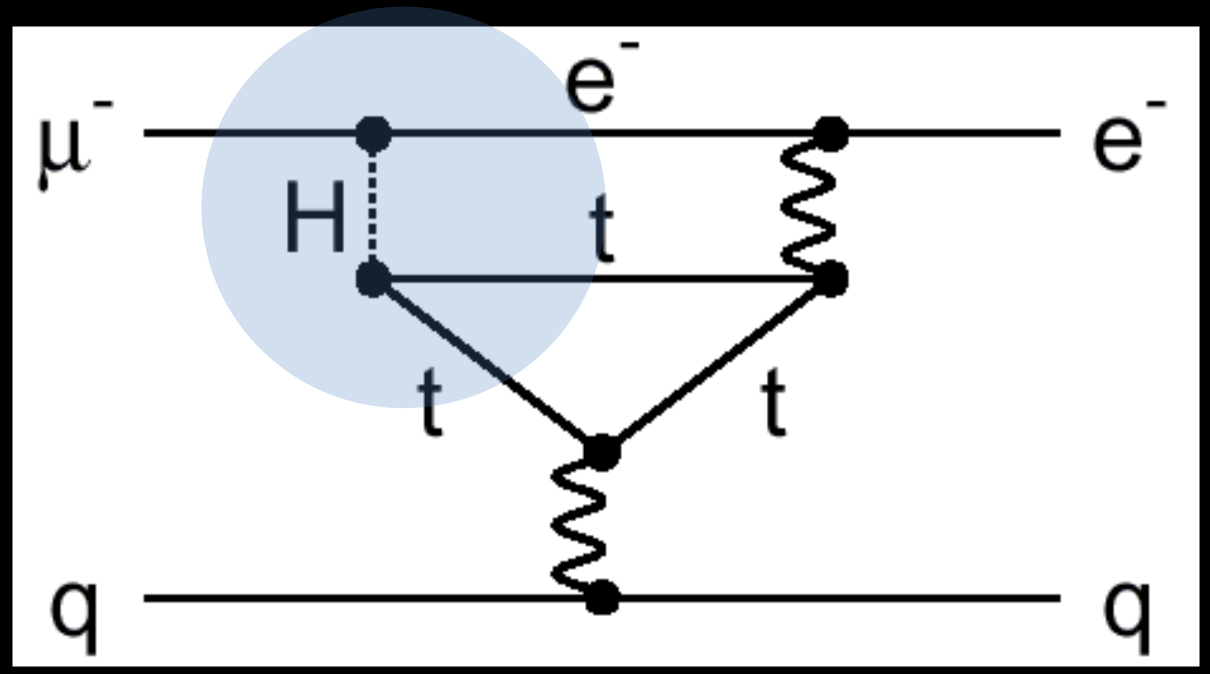
Supersymmetry



Heavy neutrino

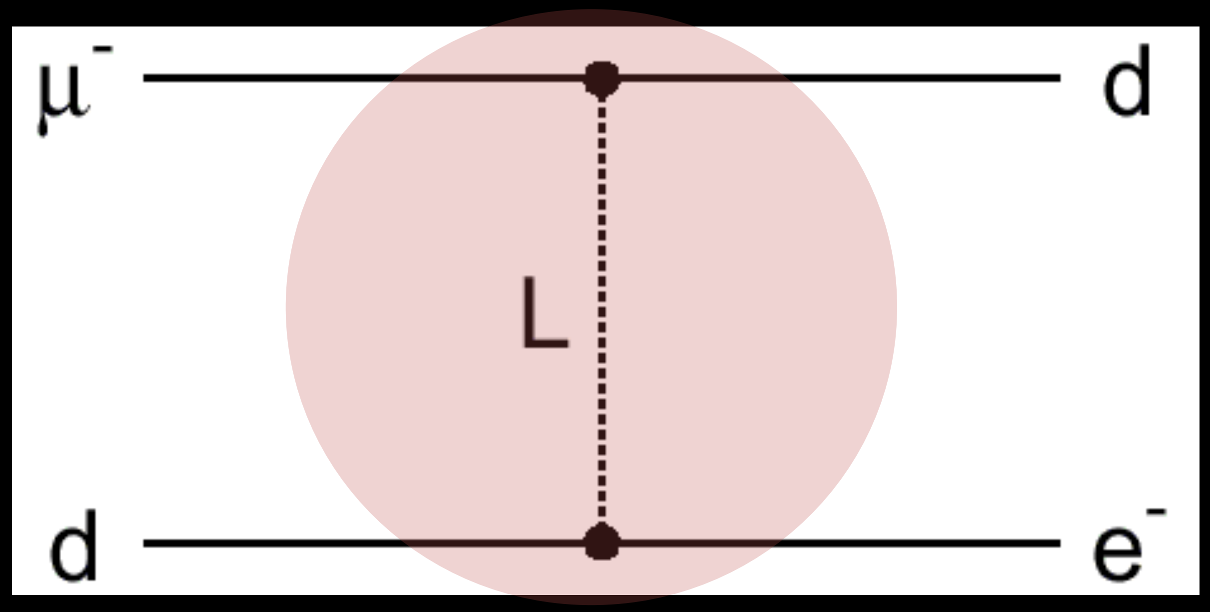


Two Higgs doublet

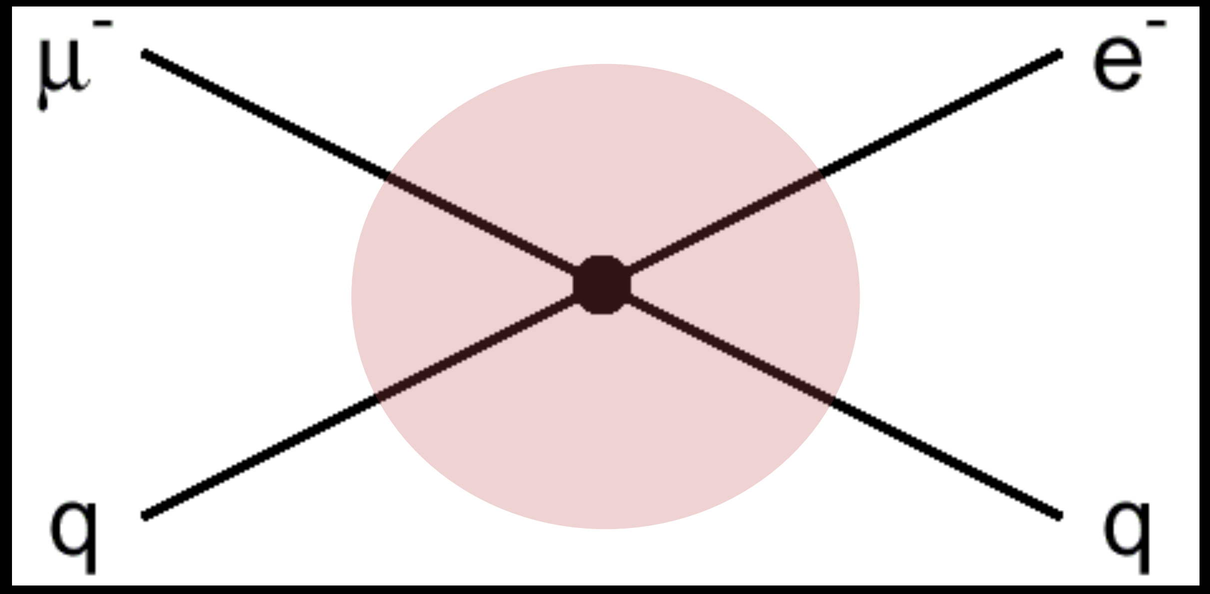


Contact interaction

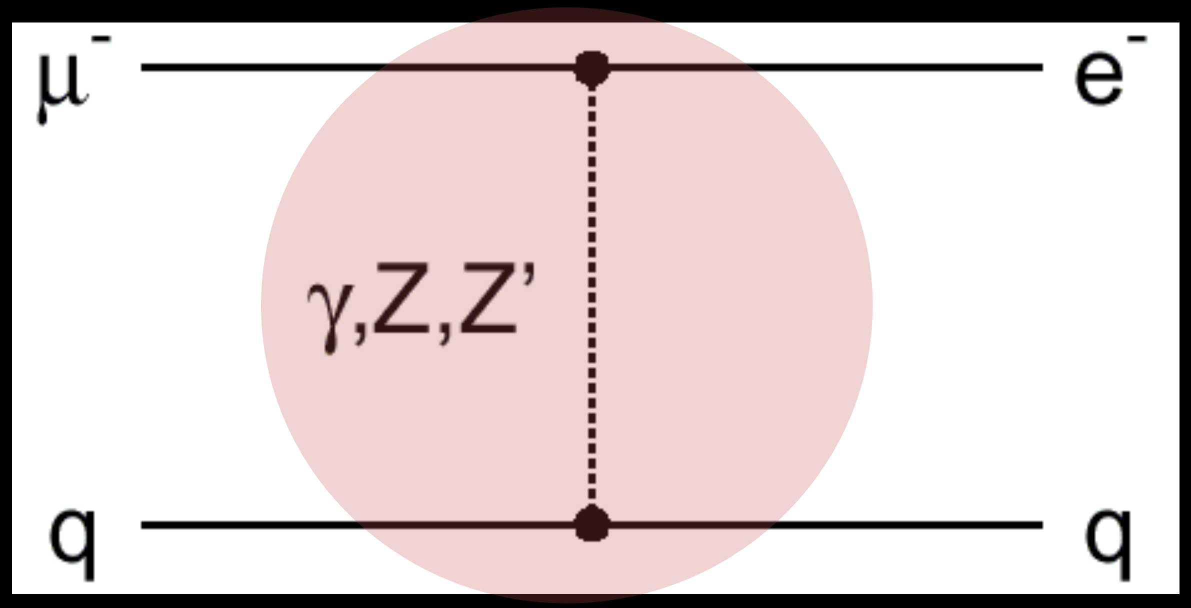
Leptoquarks



Compositeness



New heavy bosons / anomalous coupling

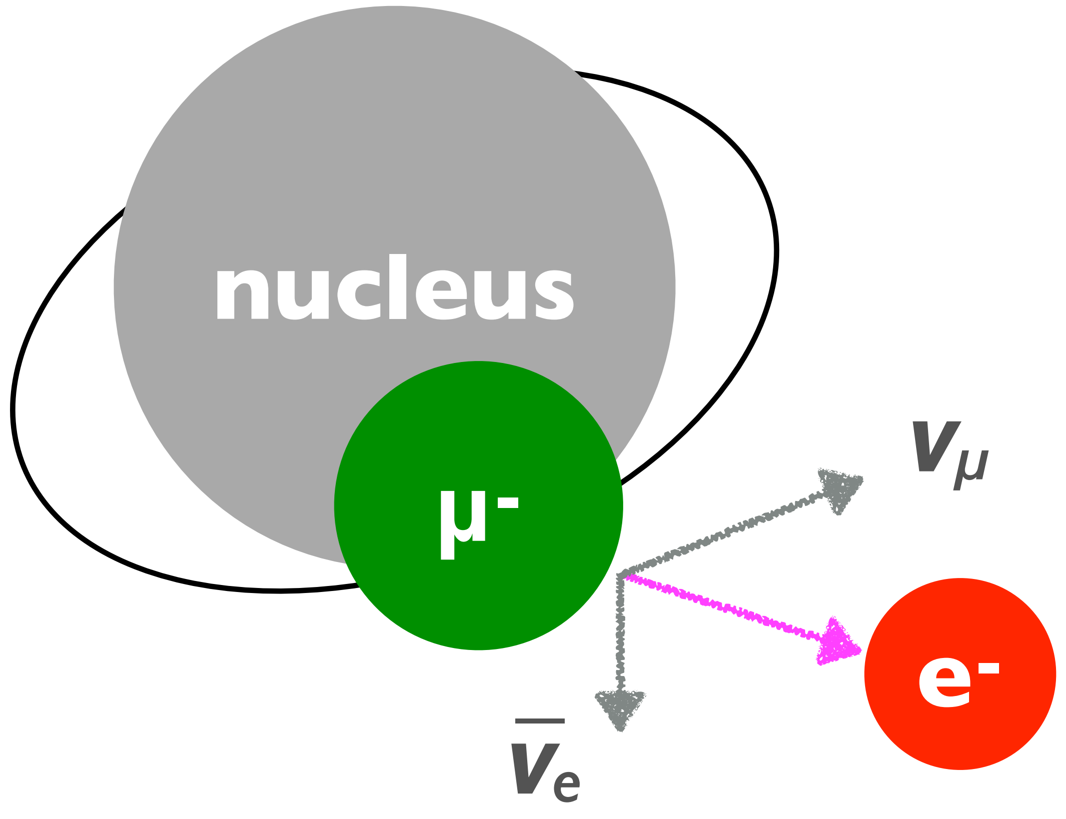


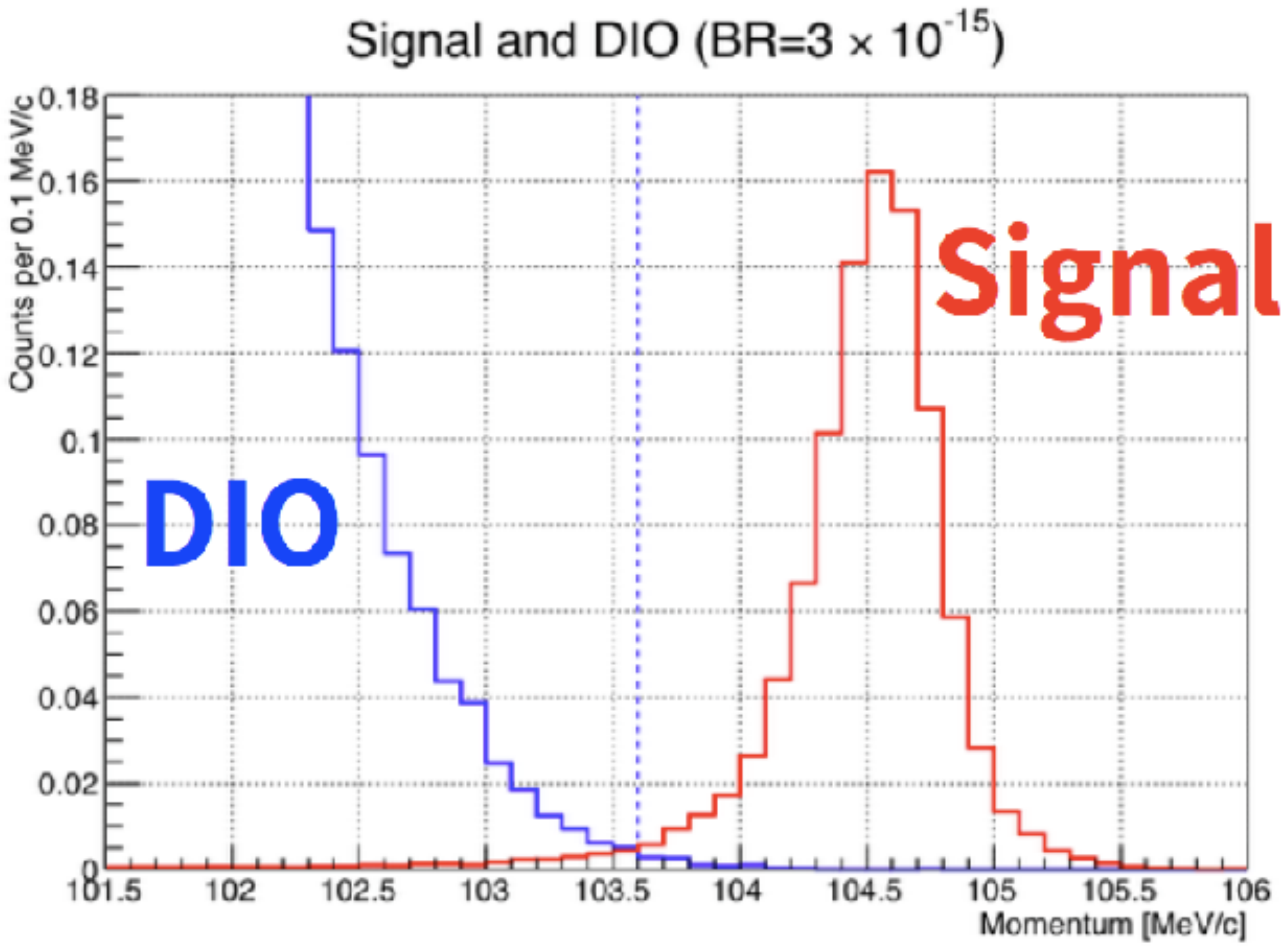
Different interactions generate different processes → complementary searches unveil the BSM structure

S. Davidson and B Echenard, Rare processes and Precision Frontier kick-off meeting (2020)

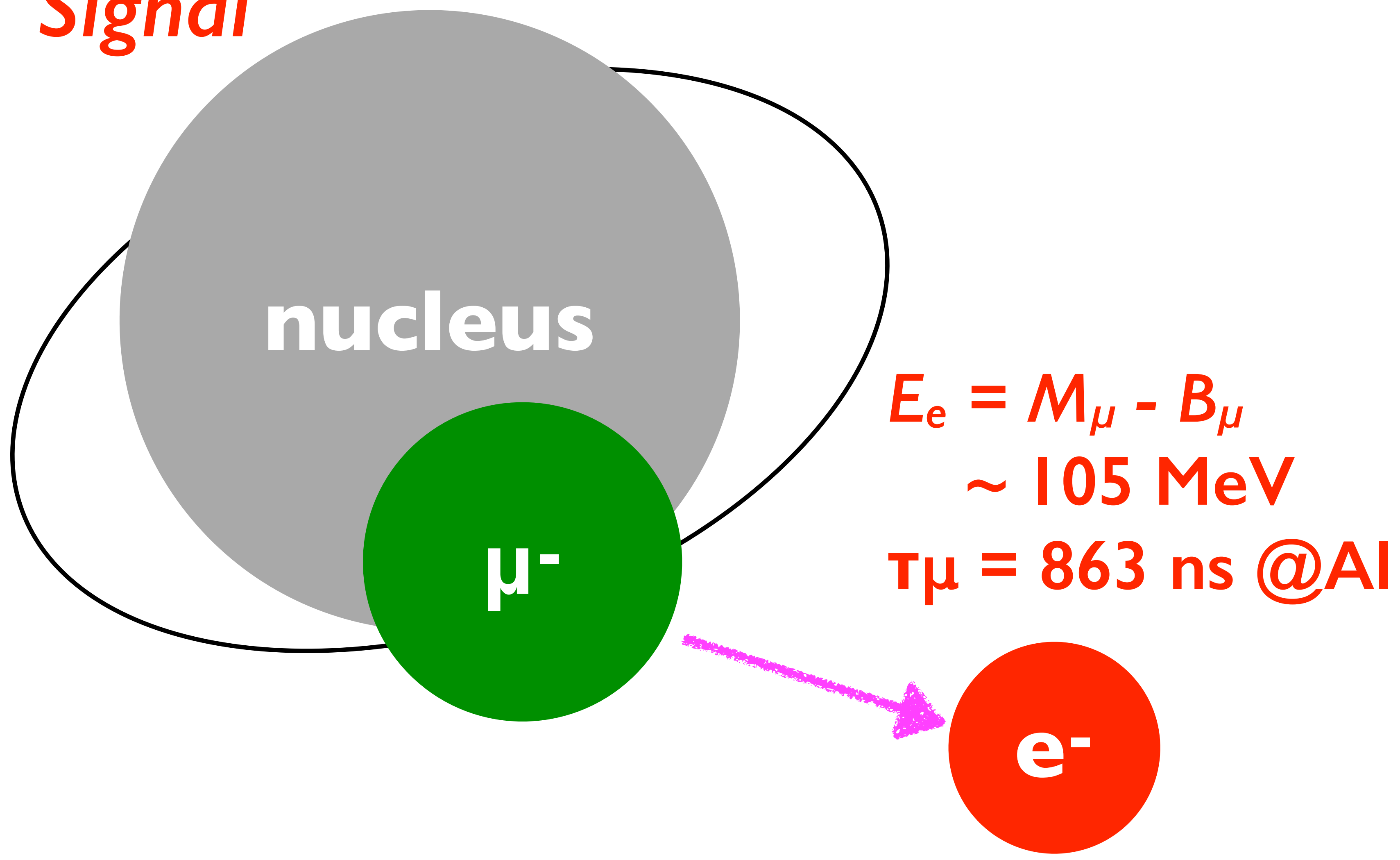
Signal and Backgrounds

Decay In Orbit (DIO)





Signal



$E_e = M_\mu - B_\mu$

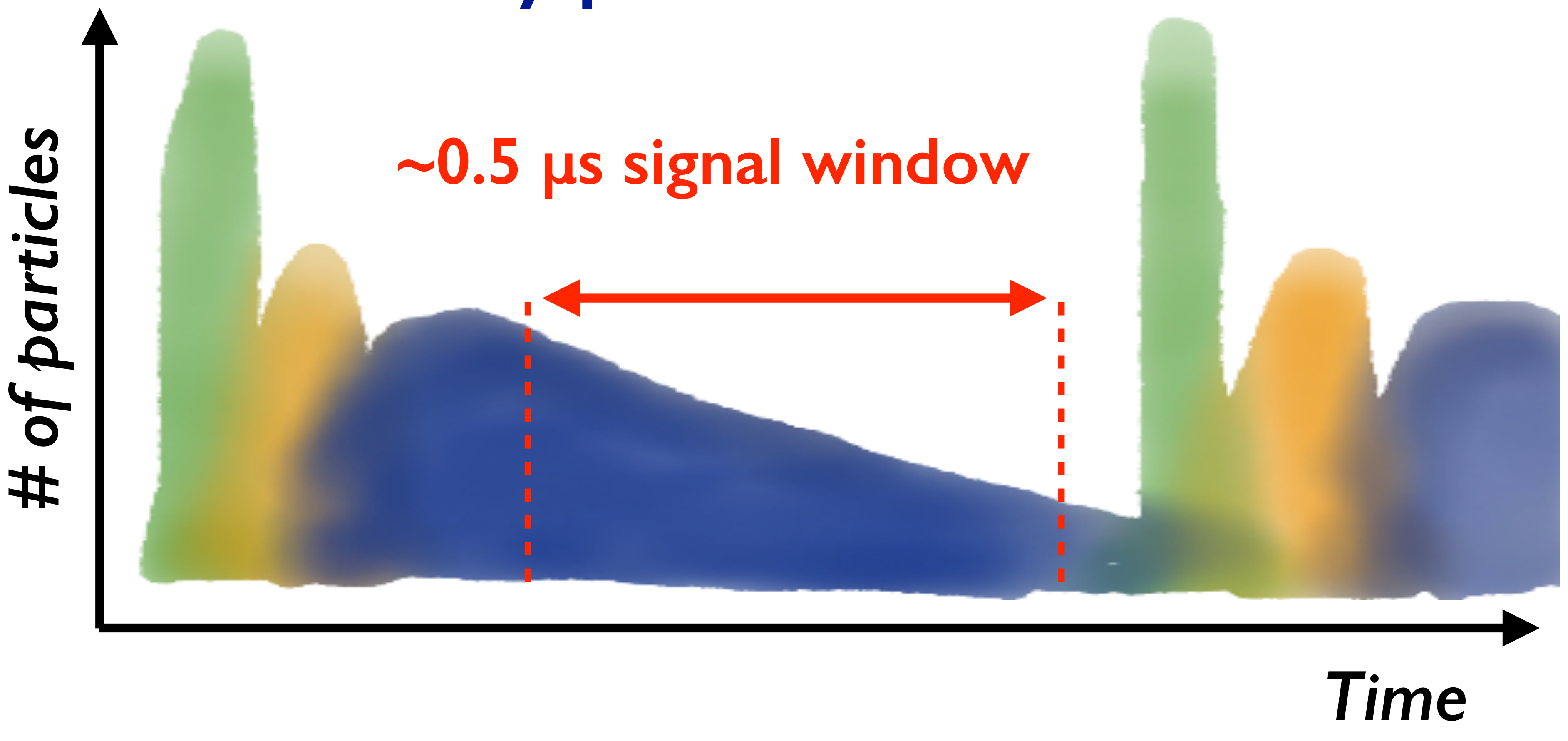
~ 105 MeV

τμ = 863 ns @Al

Main beam pulse

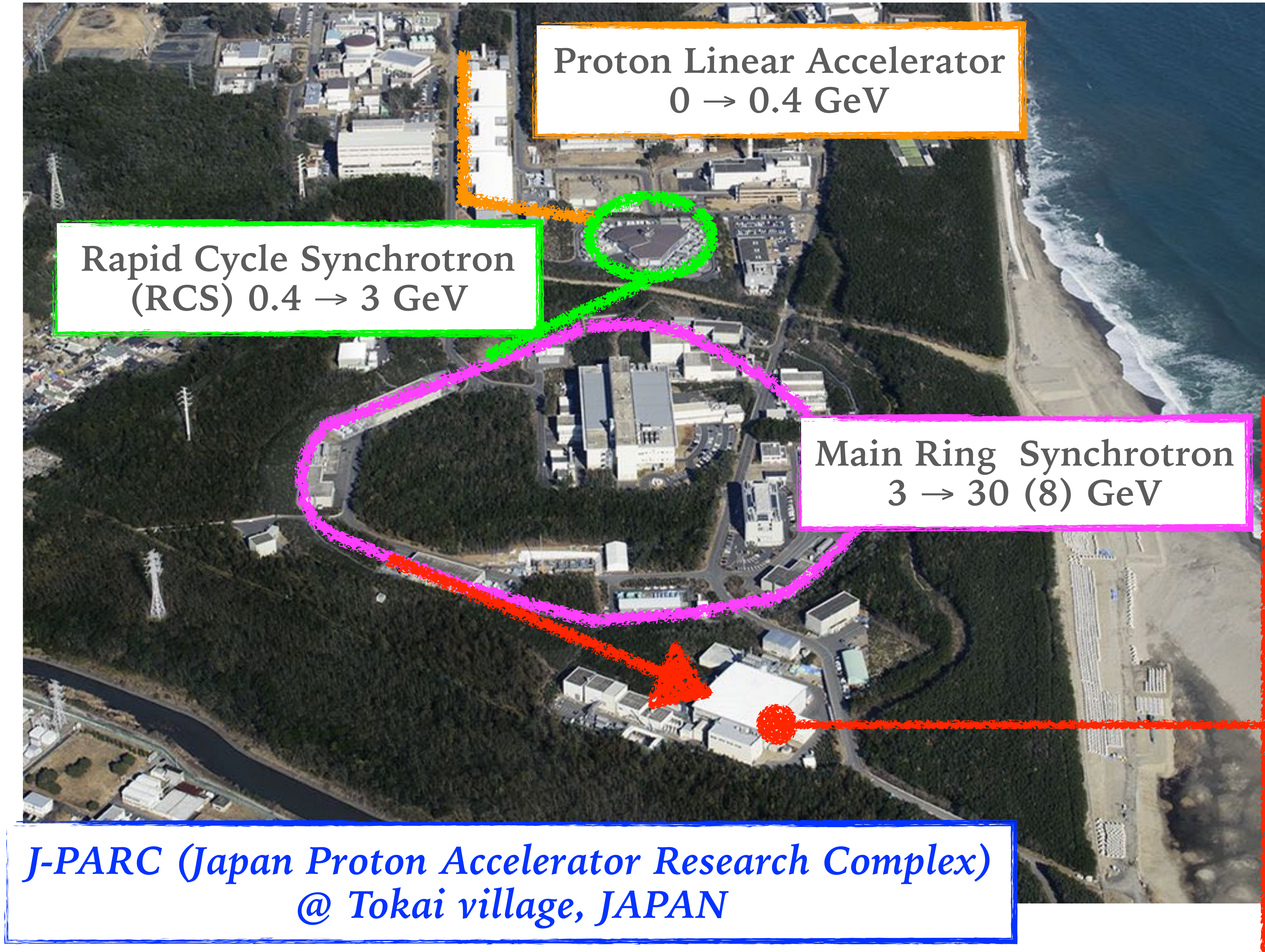
Prompt beam induced particles

Muon decay products



- ➤ Single electron with a mono-energy of ~105 MeV
  - ➤ No accidental coincidence
  - ➤ **sensitivity ∝ beam intensity ➡ more & more muons!**
- ➤ Pulsed-beam + delayed time window to sweep out all beam prompt backgrounds

COMET Experiment @J-PARC



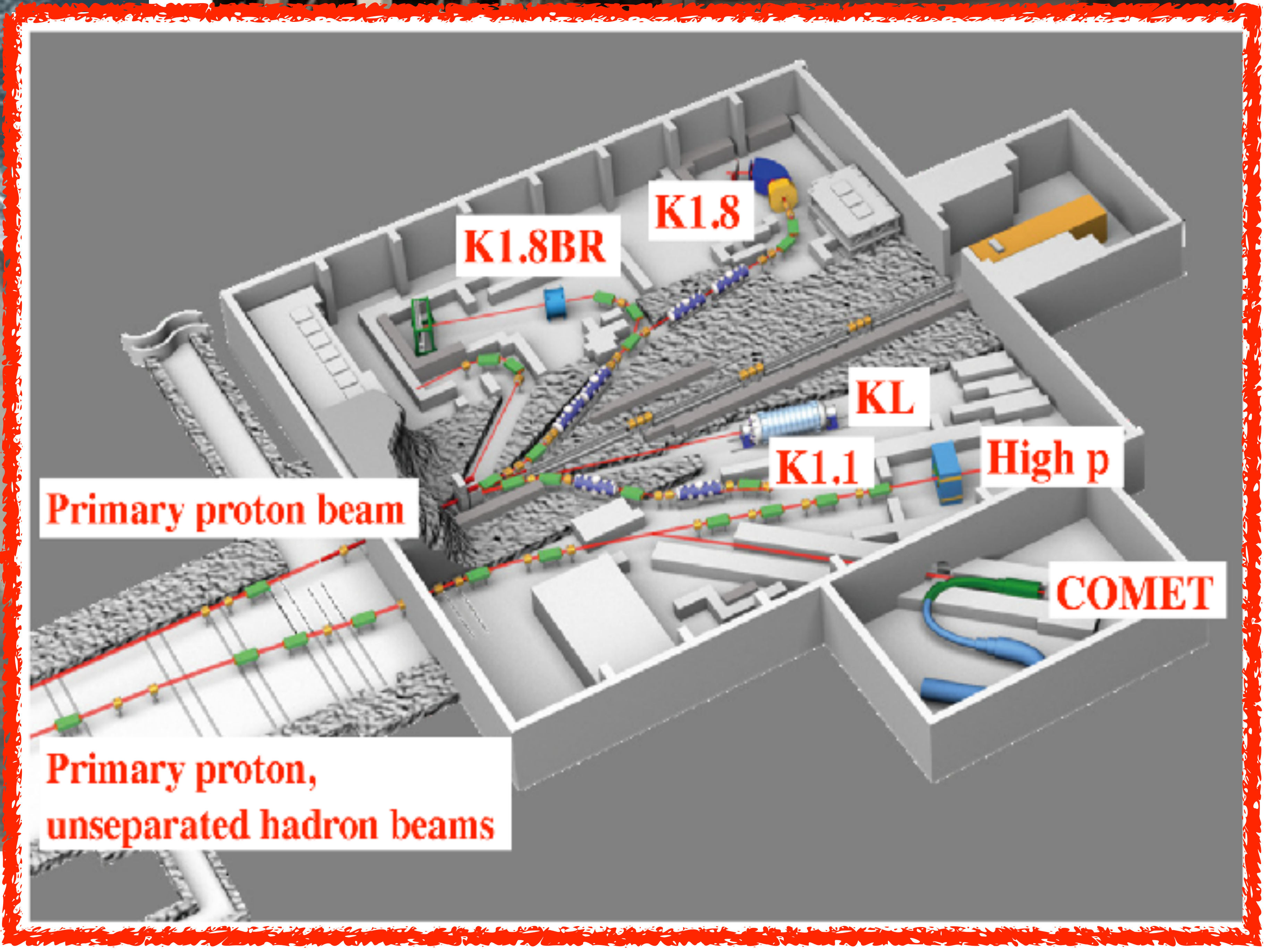
Proton Linear Accelerator
0 → 0.4 GeV

Rapid Cycle Synchrotron
(RCS) 0.4 → 3 GeV

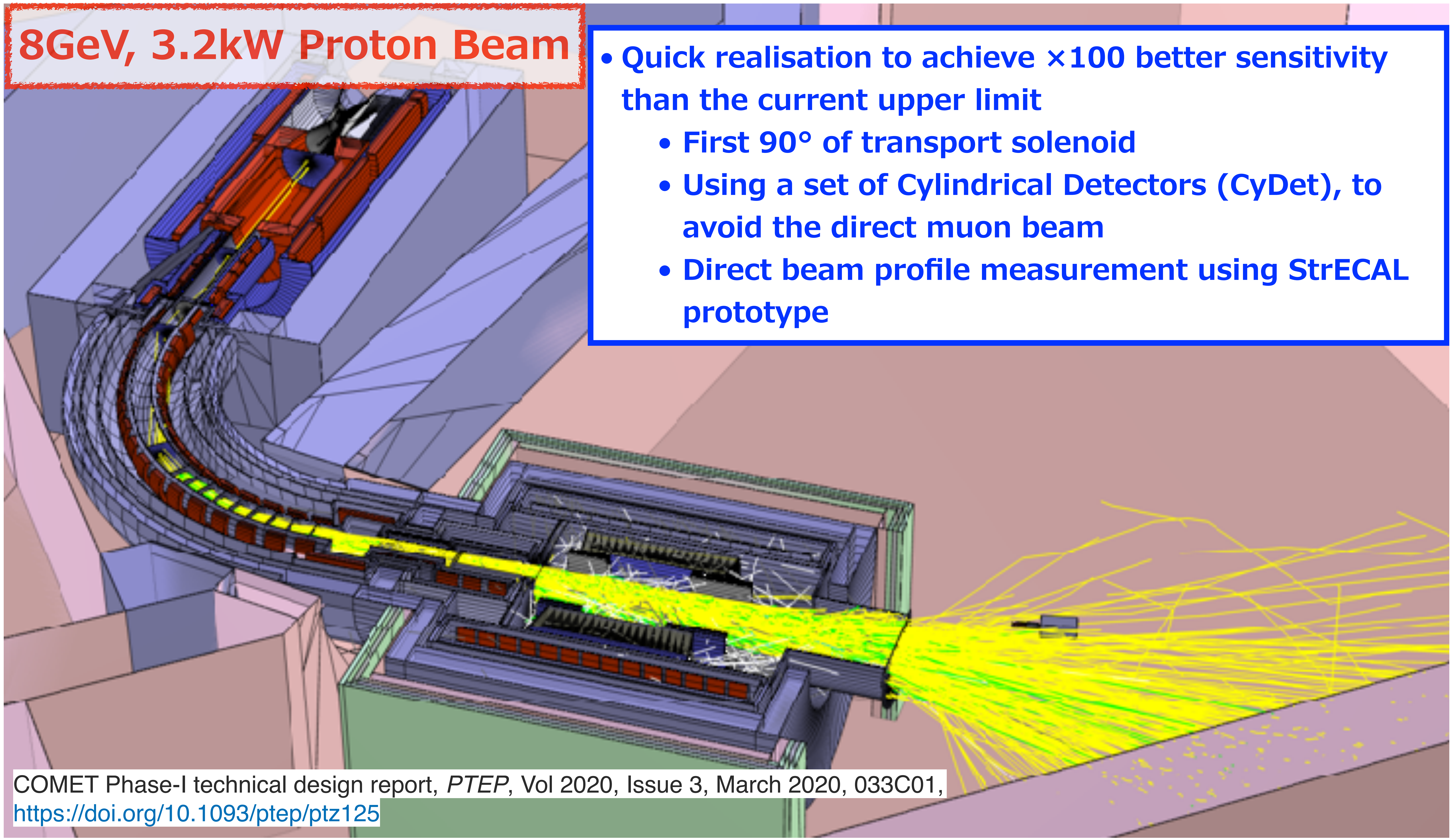
Main Ring Synchrotron
3 → 30 (8) GeV

J-PARC (Japan Proton Accelerator Research Complex)
@ Tokai village, JAPAN

>200 researchers



COMET Phase-I - Overview -

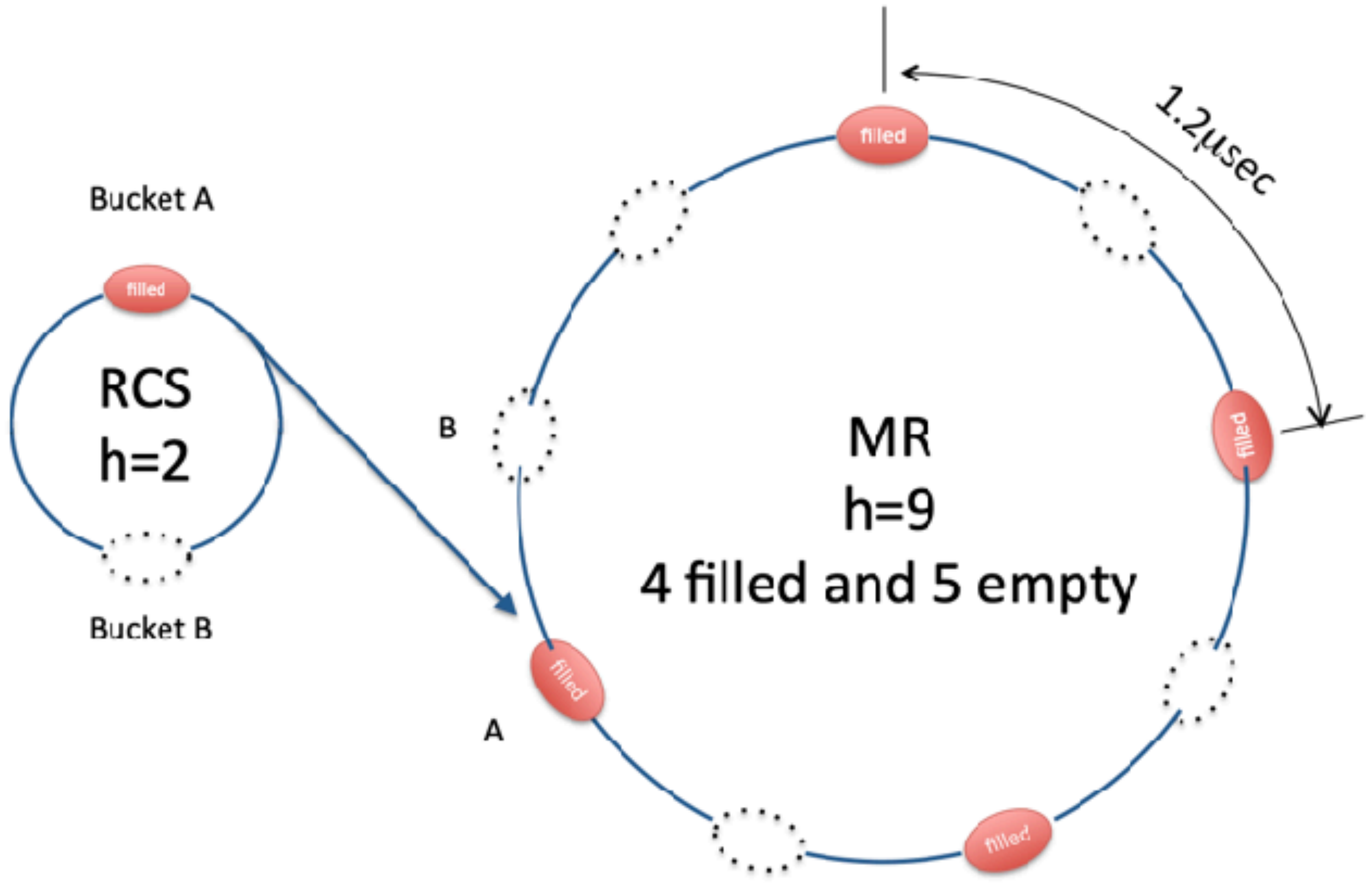


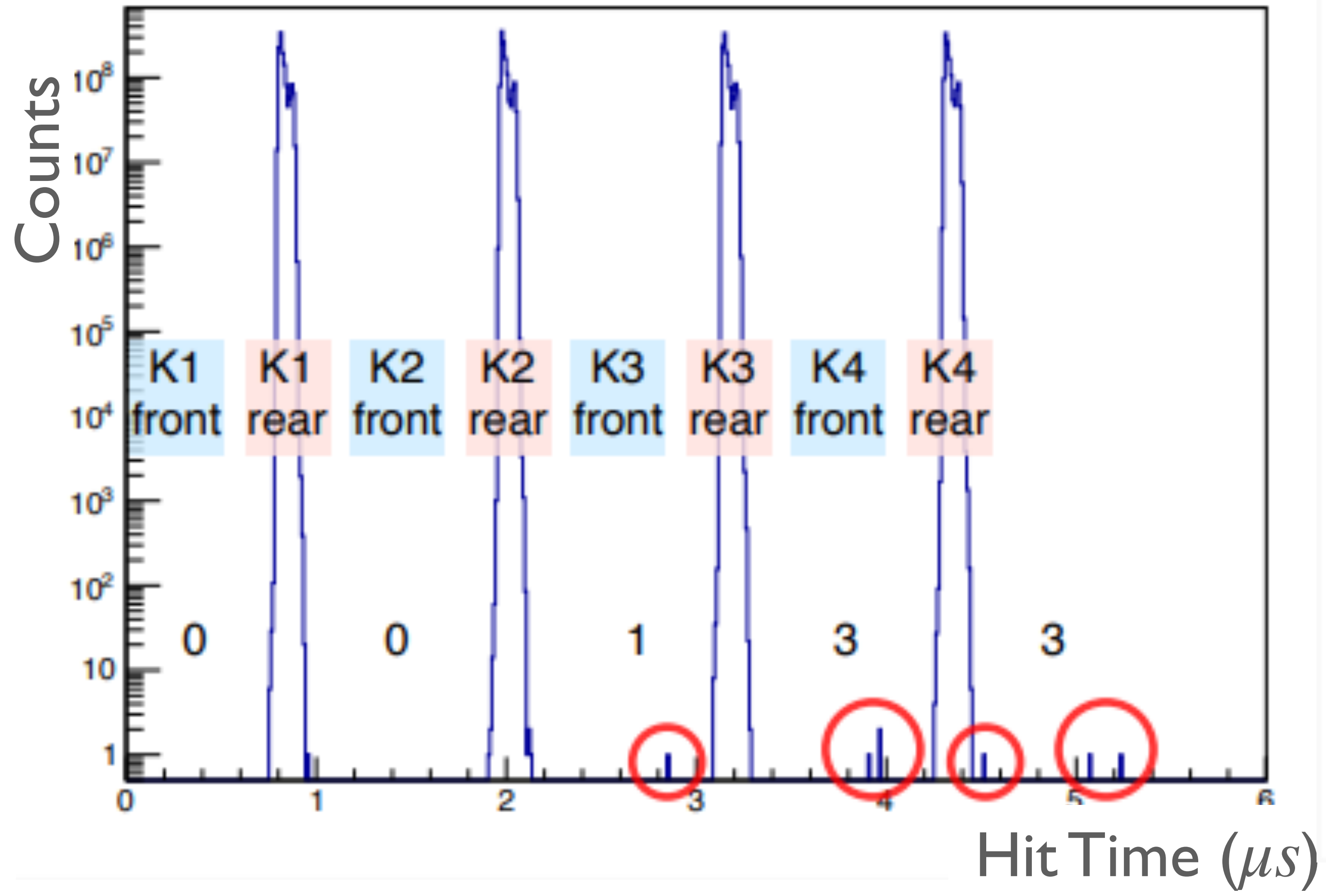
8GeV, 3.2kW Proton Beam

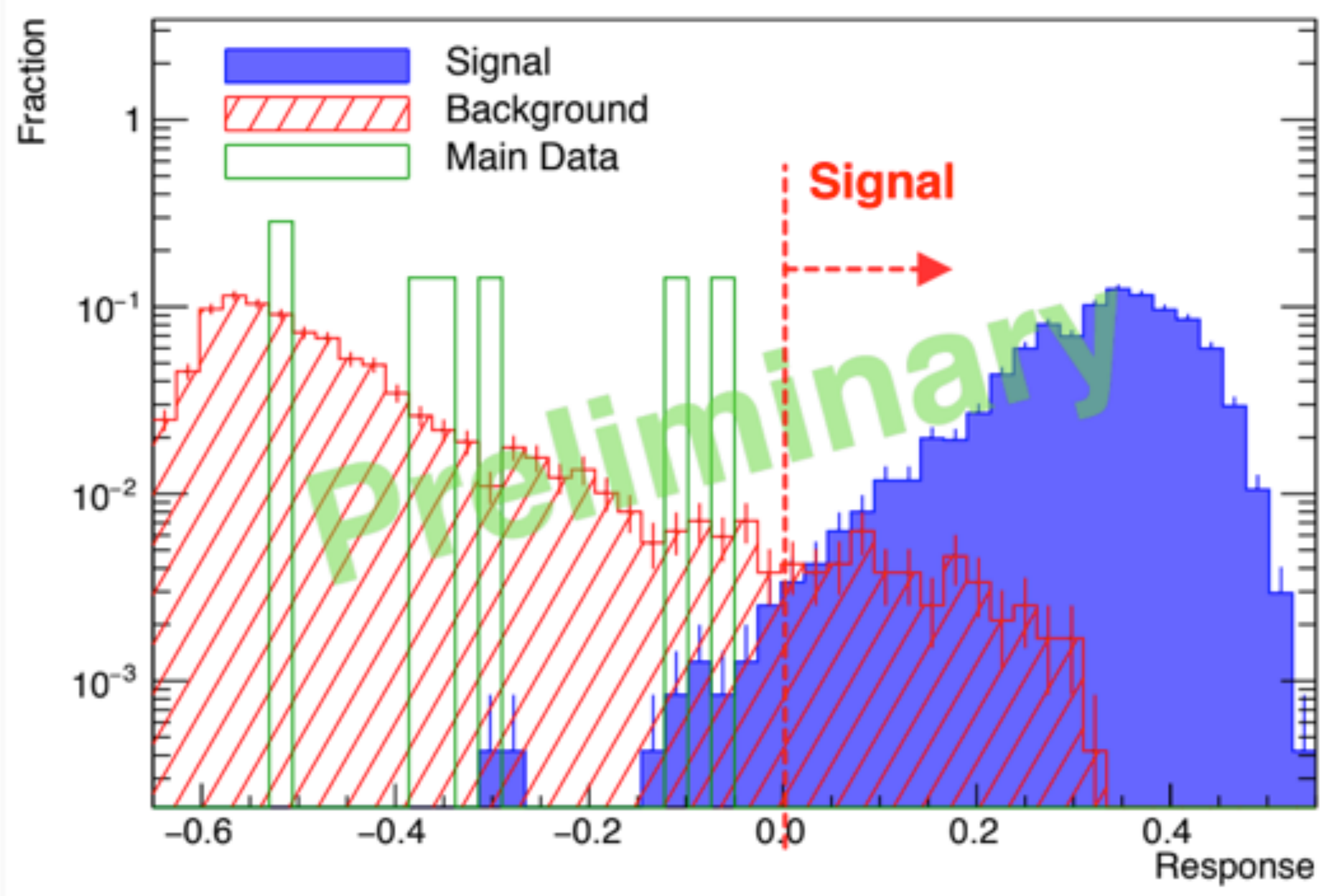
- **Quick realisation to achieve ×100 better sensitivity than the current upper limit**
  - **First 90° of transport solenoid**
  - **Using a set of Cylindrical Detectors (CyDet), to avoid the direct muon beam**
  - **Direct beam profile measurement using StrECAL prototype**

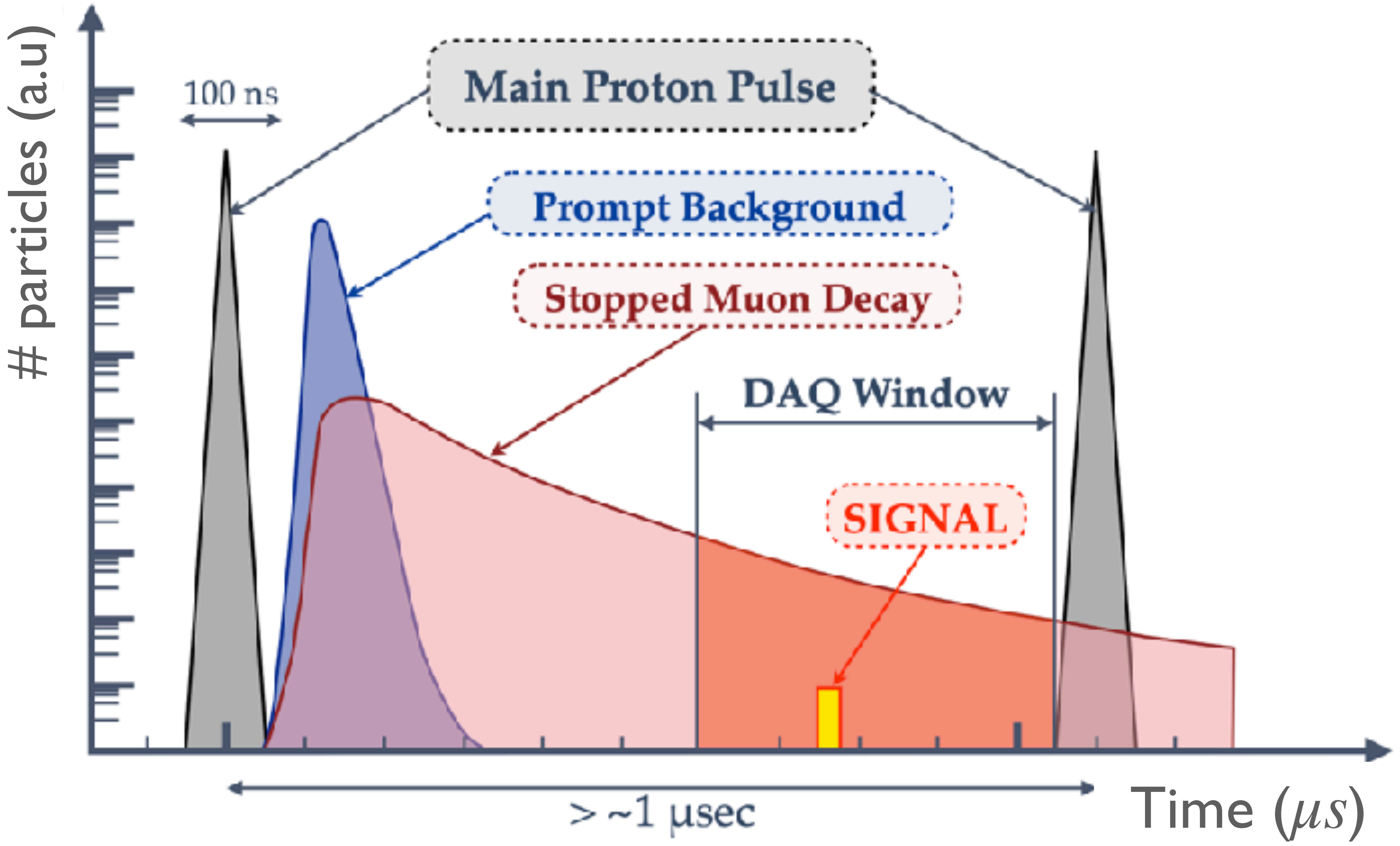
COMET Phase-I technical design report, *PTEP*, Vol 2020, Issue 3, March 2020, 033C01, https://doi.org/10.1093/ptep/ptz125

COMET Phase-I ~Proton beam~









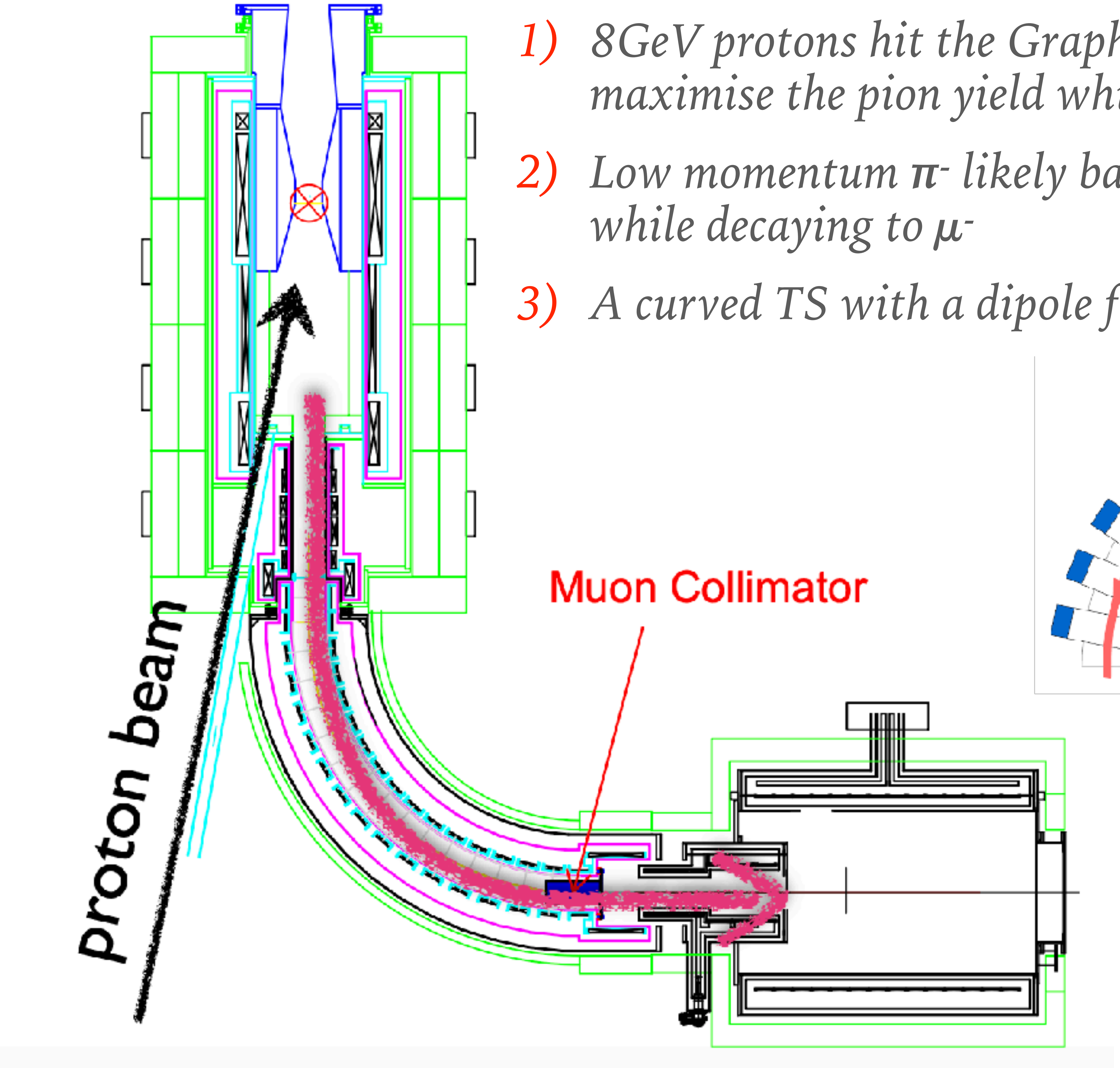
Bunched-slow extraction @8GeV has been well studied at J-PARC hadron hall and high quality bunched beam was obtained

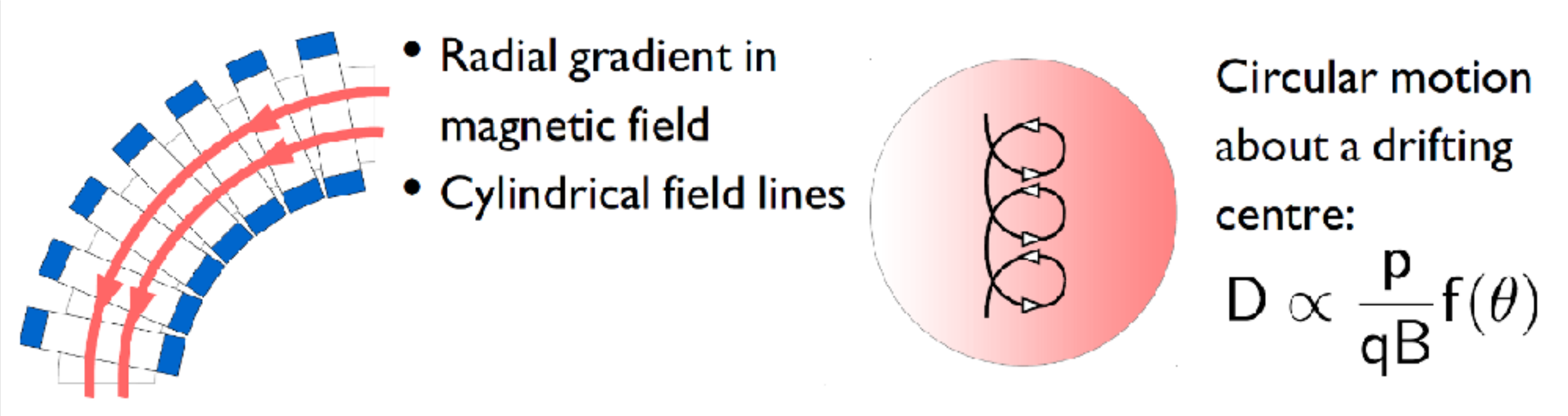
All events between pulses are most probably “accidental BG” (≠single particle from the beam)

→ $R_{\text{Extinction}} < 10^{-11}$ (K. Noguchi *et.al.* NuFact2021)

COMET Phase-I ~Muon beam~

1) *8GeV protons hit the Graphite target and produce secondary pions (Energy chosen to maximise the pion yield while preventing anti-protons)*
2) *Low momentum π^- likely back scatter and direct to the muon transportation solenoid (TS) while decaying to μ^-*
3) *A curved TS with a dipole field to select low momentum negative particles*

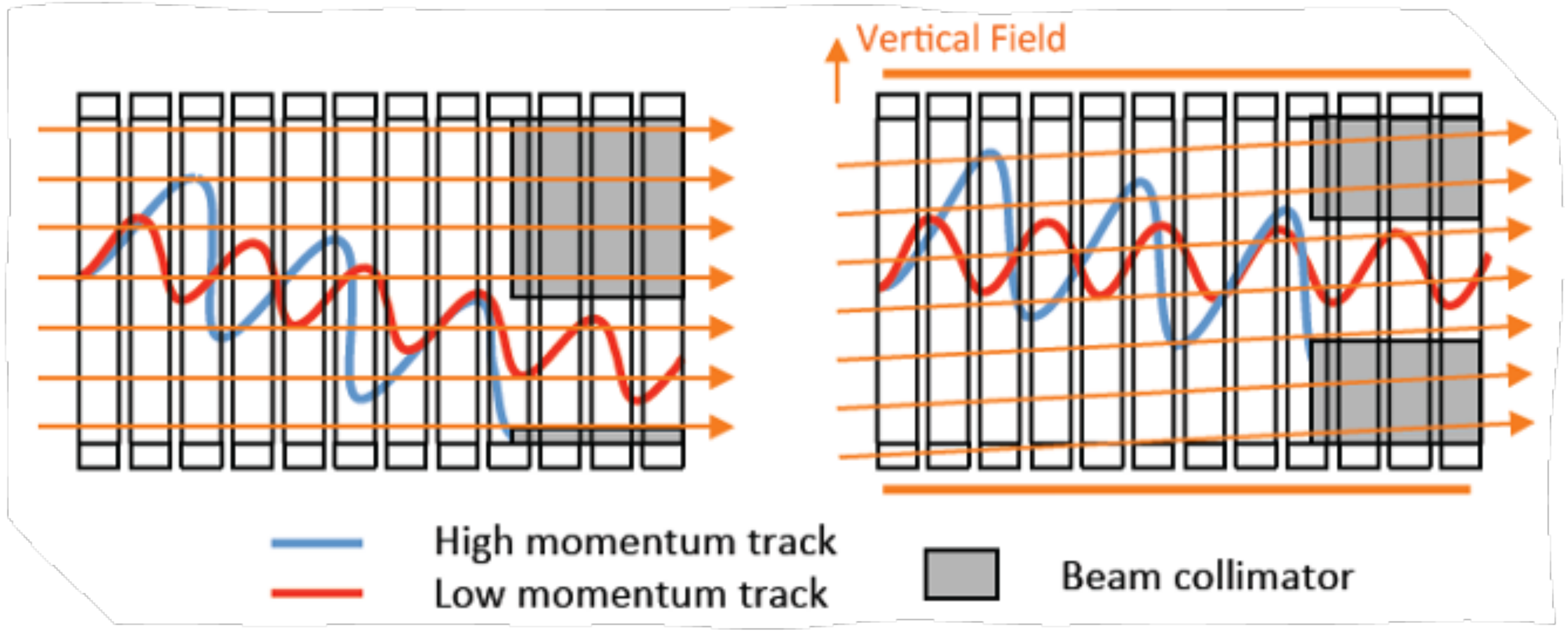




- Radial gradient in magnetic field
- Cylindrical field lines

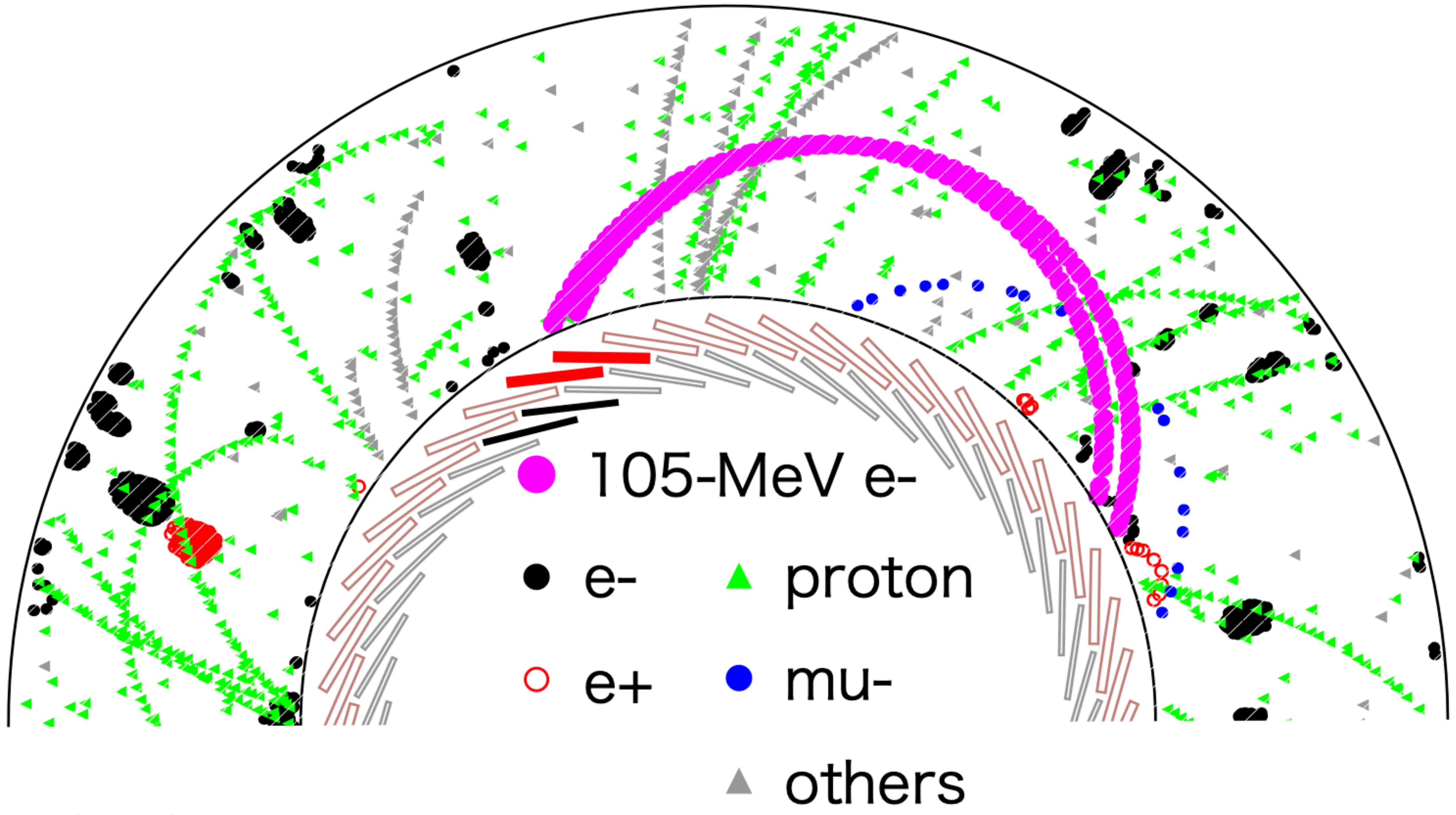
Circular motion about a drifting centre:

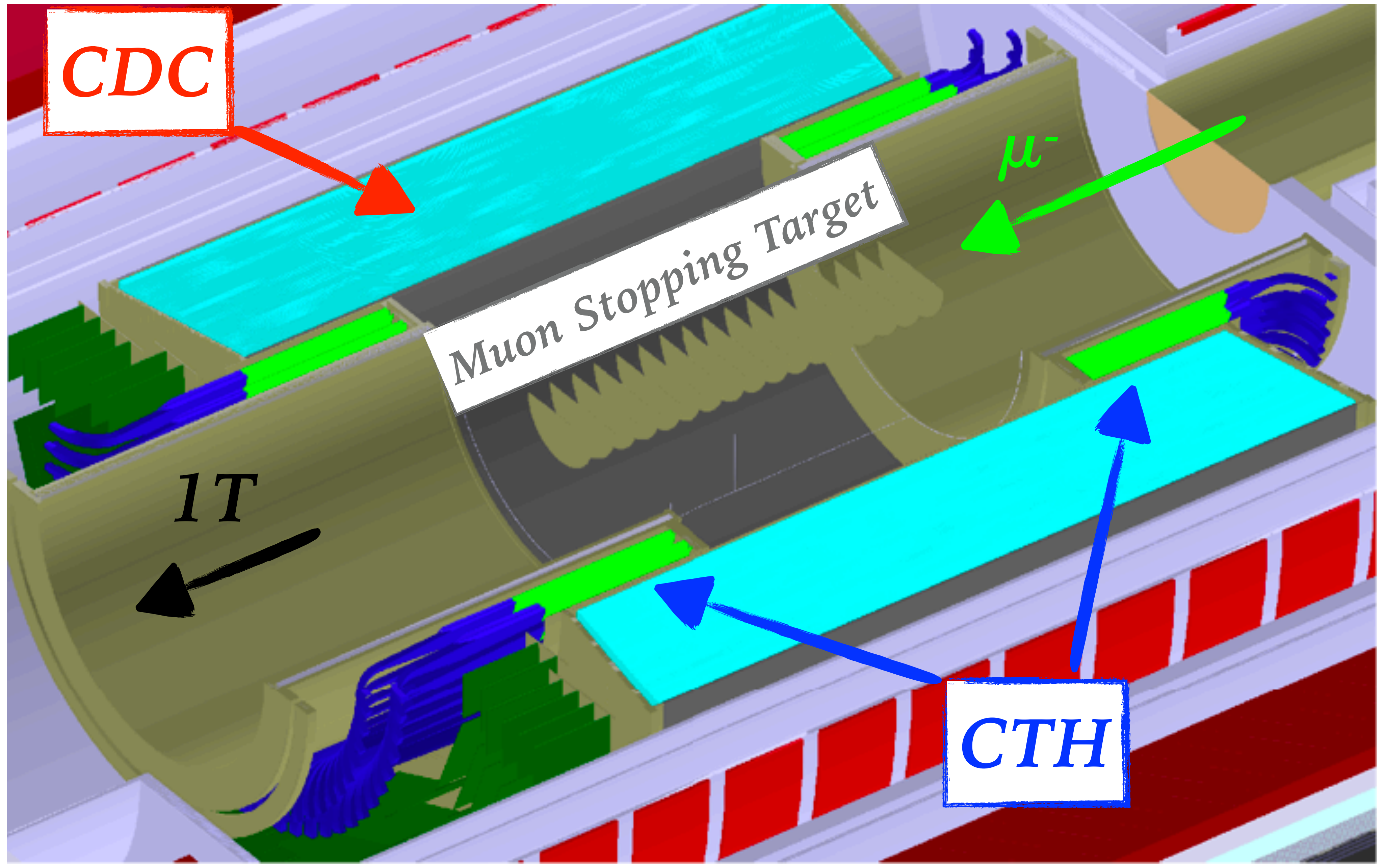
$$D \propto \frac{p}{qB} f(\theta)$$



Yuki Fujii, New Frontiers in Lepton Flavor, Pisa, Italy, 2023

COMET Phase-I ~CyDet~

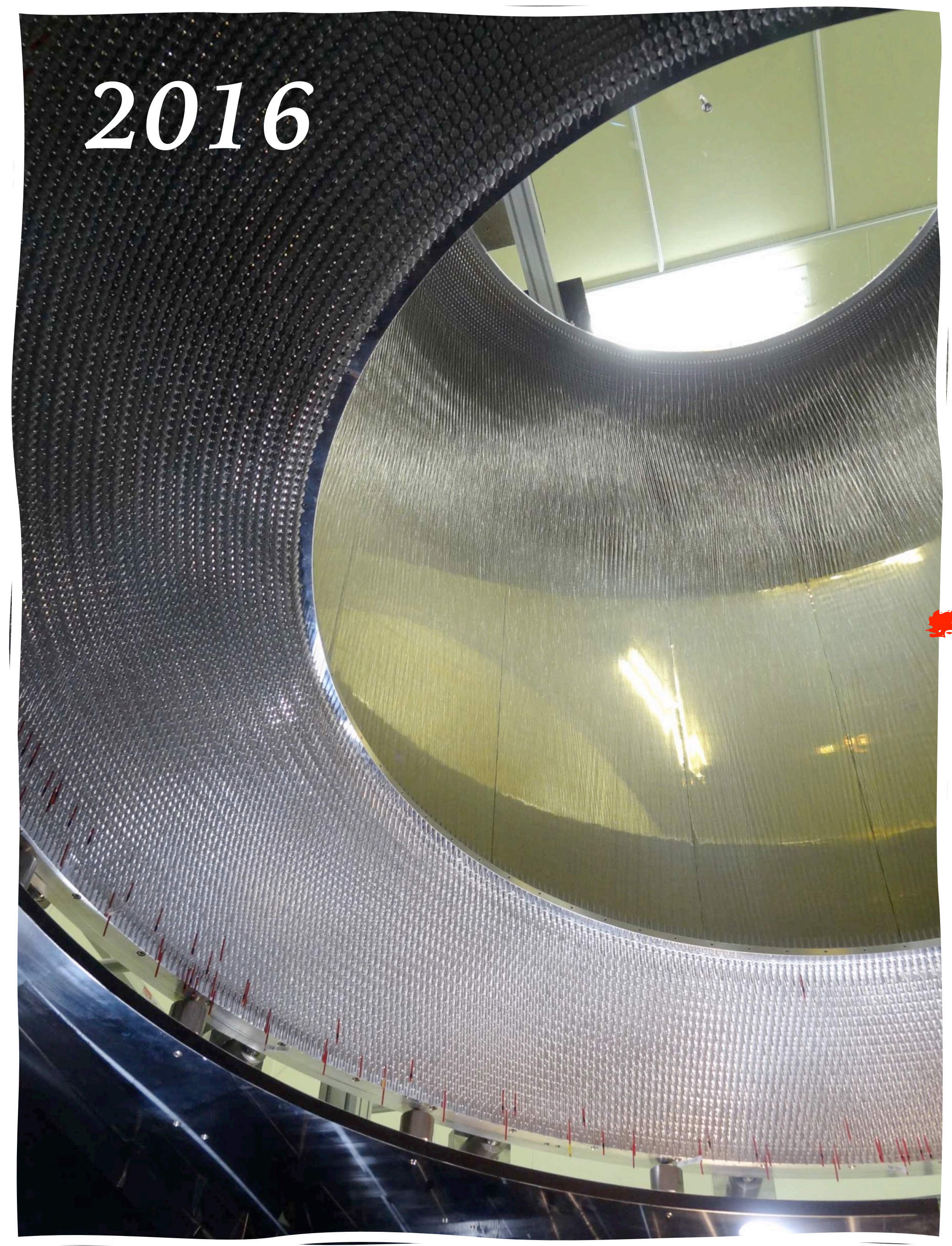


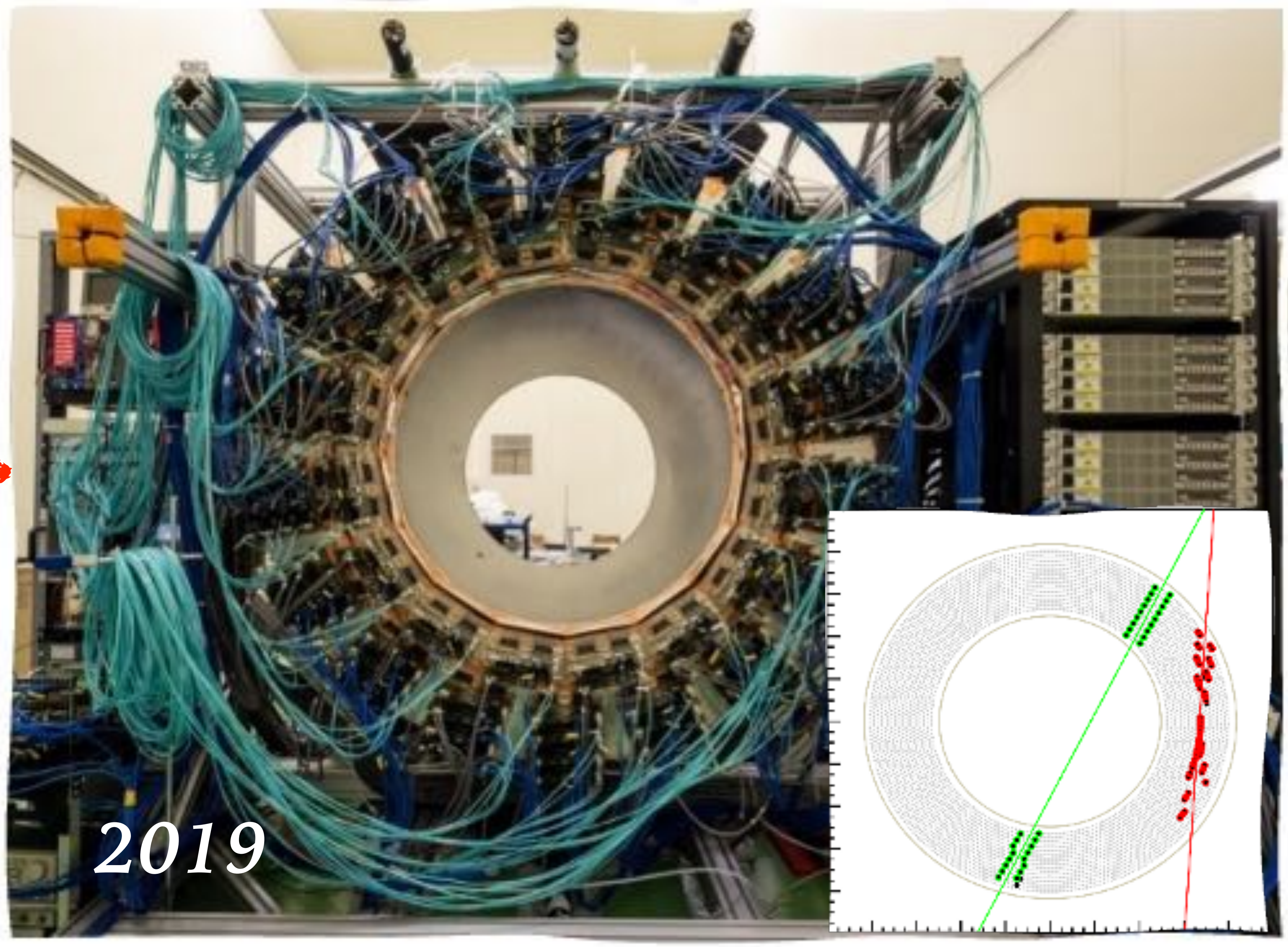


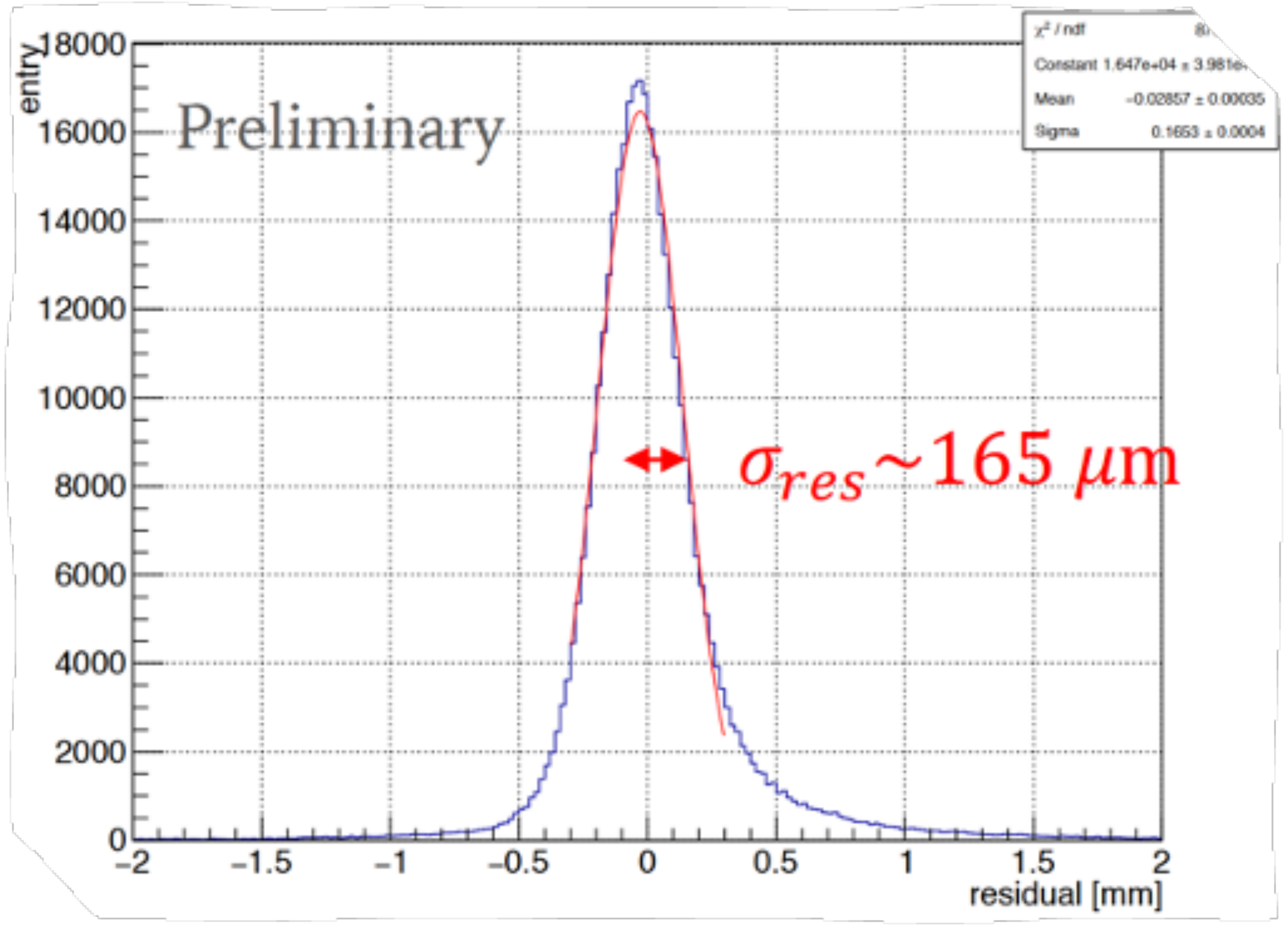
- CDC
  - ~5,000 wires, 20 stereo layers for momentum measurement, He:iC_5H_{10}=90:10, typical drift time <400ns
  - Signal electrons' trajectories fully contained inside the volume
- CTH
  - 2 layers of 64 segmented plastic scintillator rings at both ends of CDC for the timing measurement
  - Suppress accidental events and low momentum particles by taking four-fold coincidence

COMET Phase-I ~CDC~

- All stereo-angle wire cylindrical drift chamber to measure the momentum of incoming charged particle
- Following the wiring completion in 2016, the full channels readout tested in 2019 → almost ready for the installation



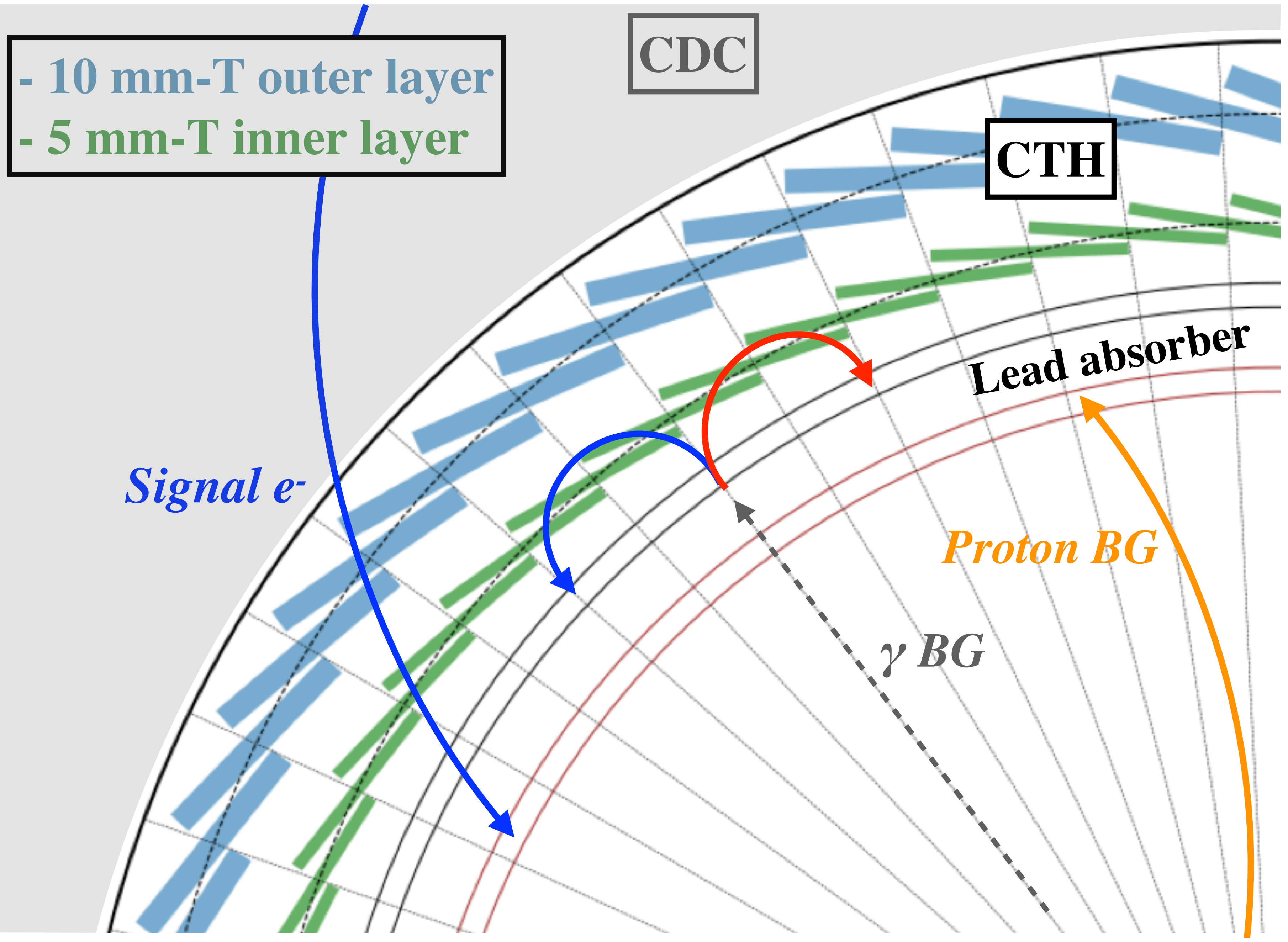




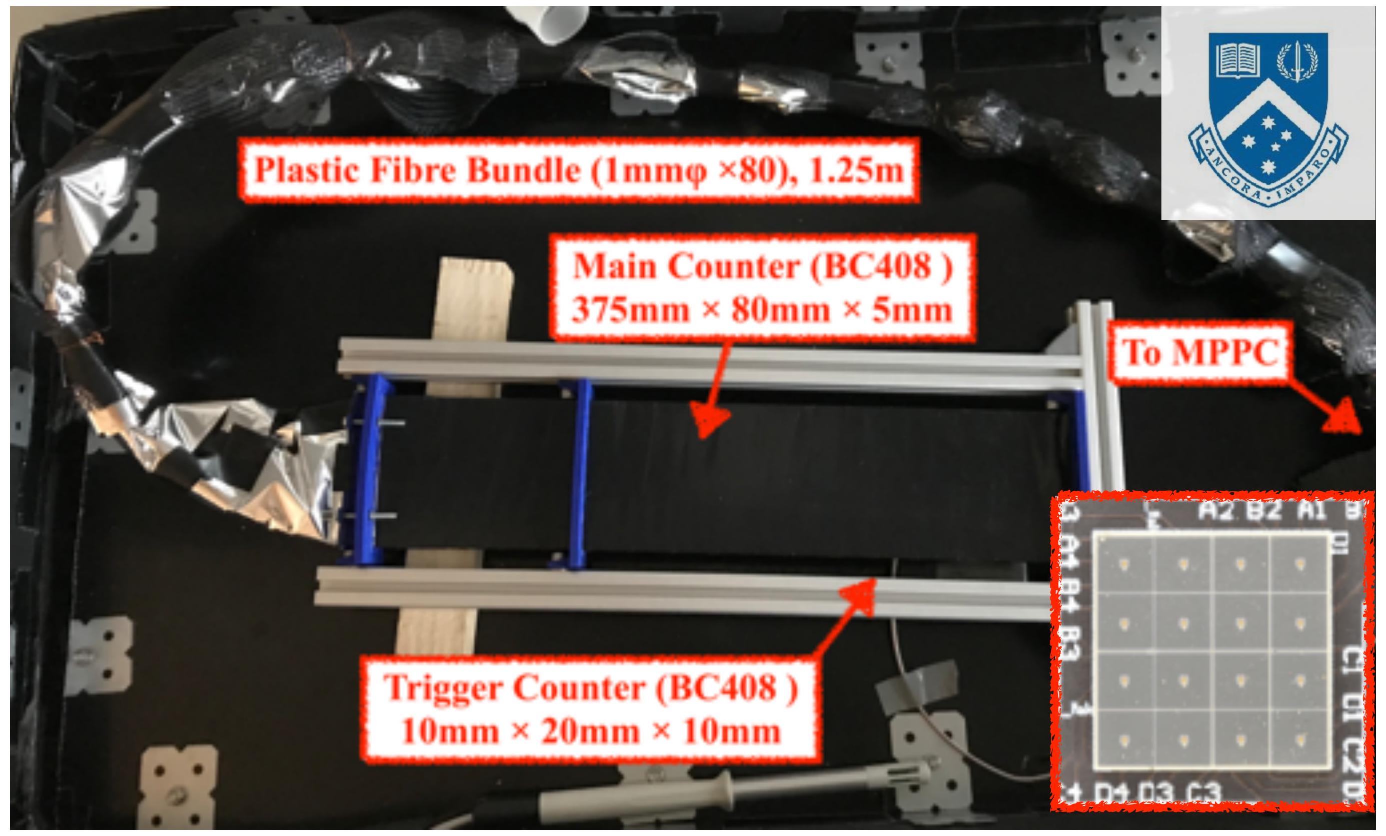
C. Wu, *et.al.* DOI:10.1016/j.nima.2021.165756

COMET Phase-I ~CTH~

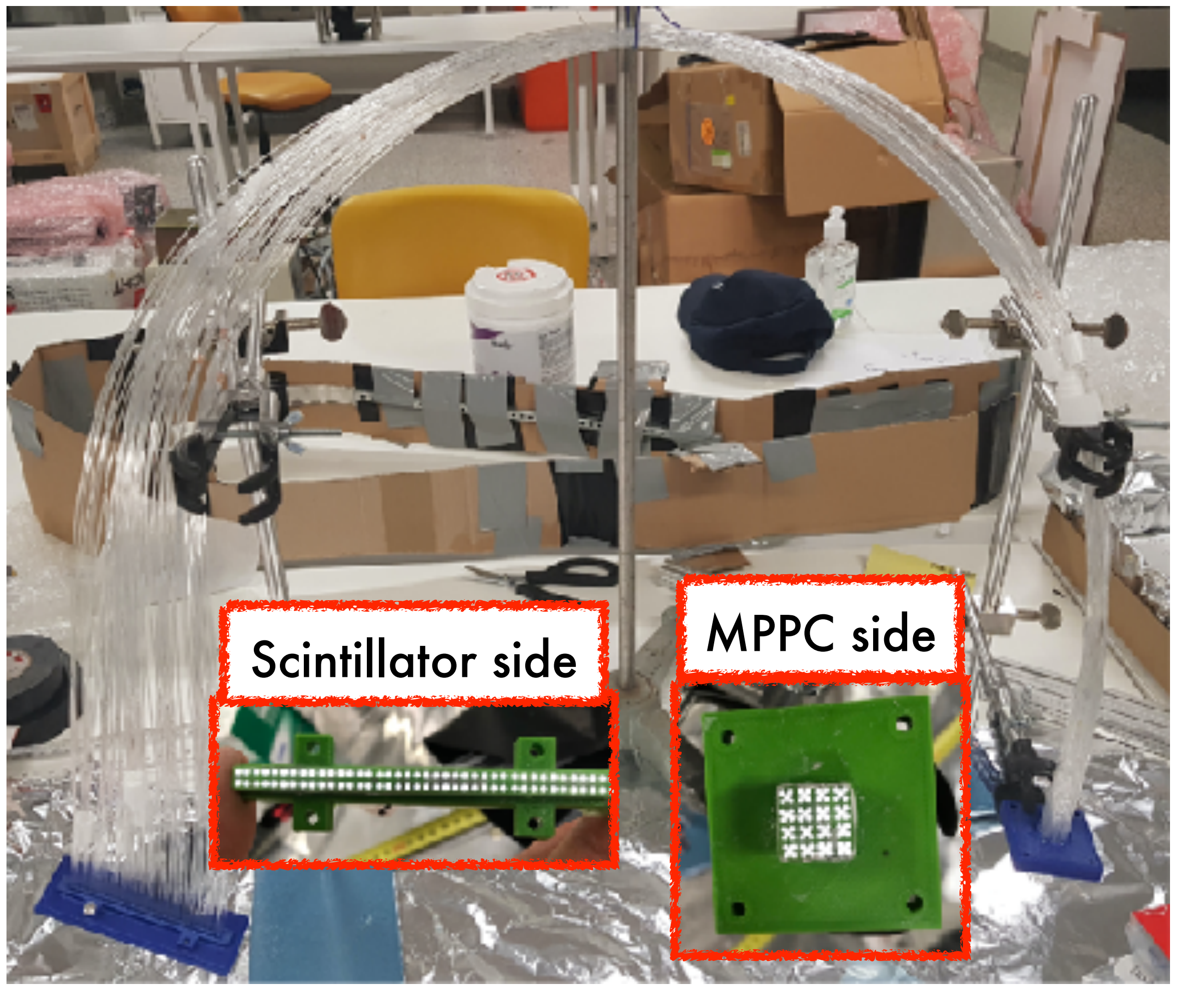
- Four fold coincidence for better timing determination & less accidental events ⇔ the rate of e+/e- <10MeV is as high as 1-10 MHz
  - After 4-fold coincidence, the rate become less than 100 kHz (based on simulation studies)
  - Photon extraction with fibre bundles to use inexpensive commercial SiPMs



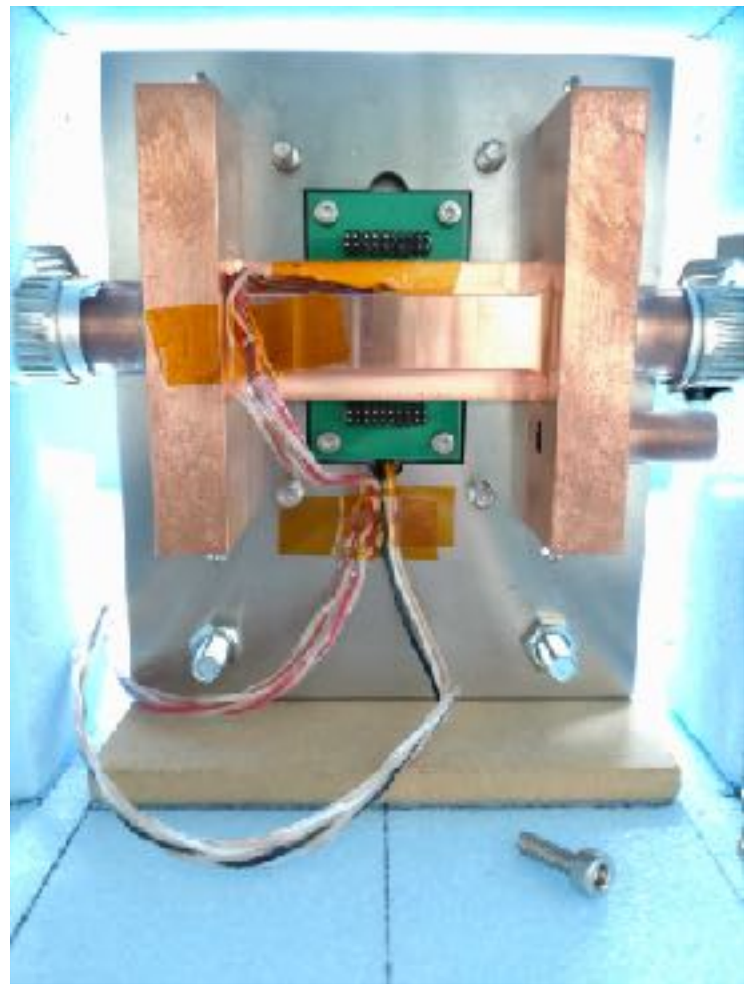
Y. Fujii, *et.al.* DOI:10.5281/zenodo.6781368



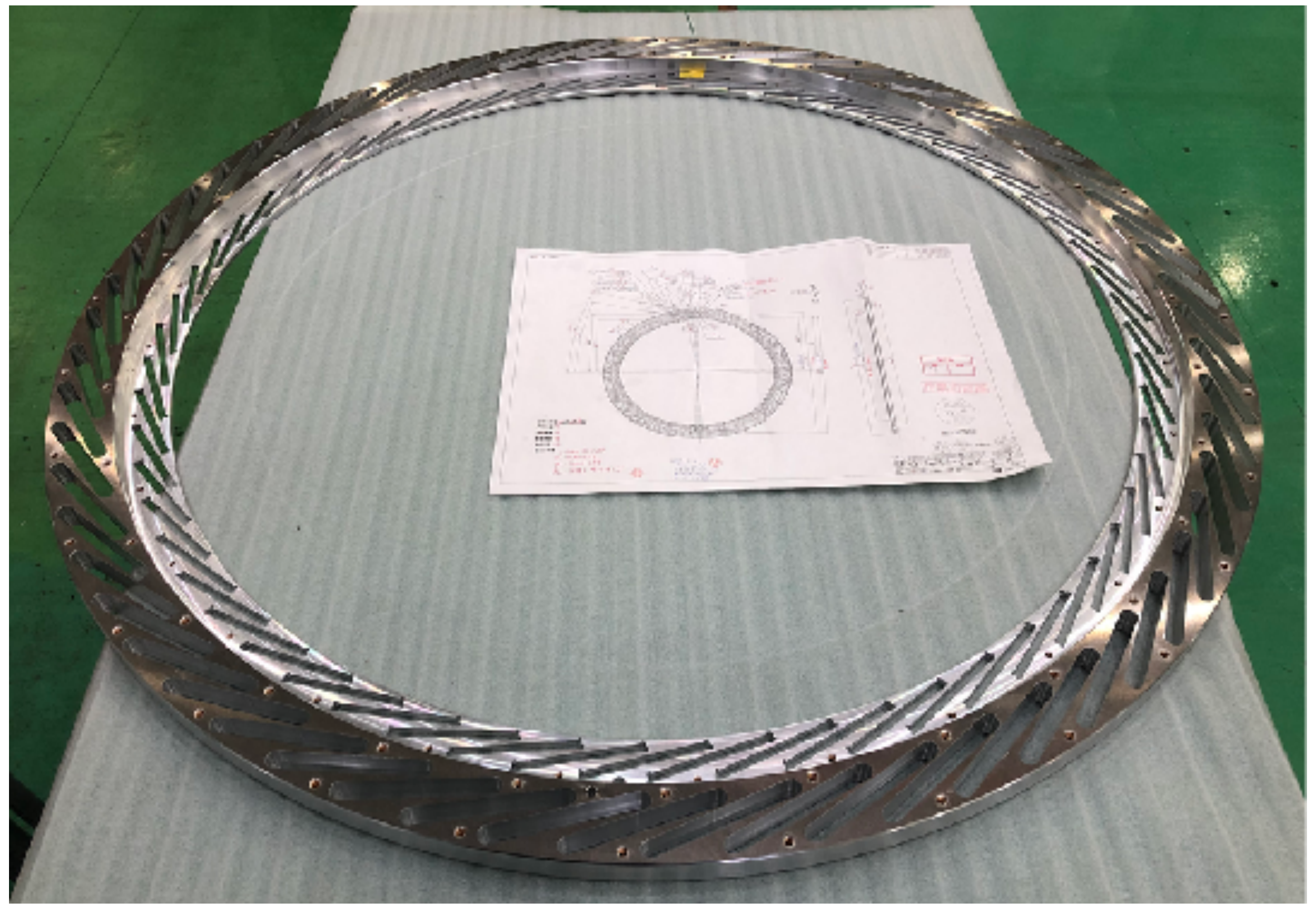
CTH counter + fibre prototype constructed and tested @Monash



Fibre bundle prototype

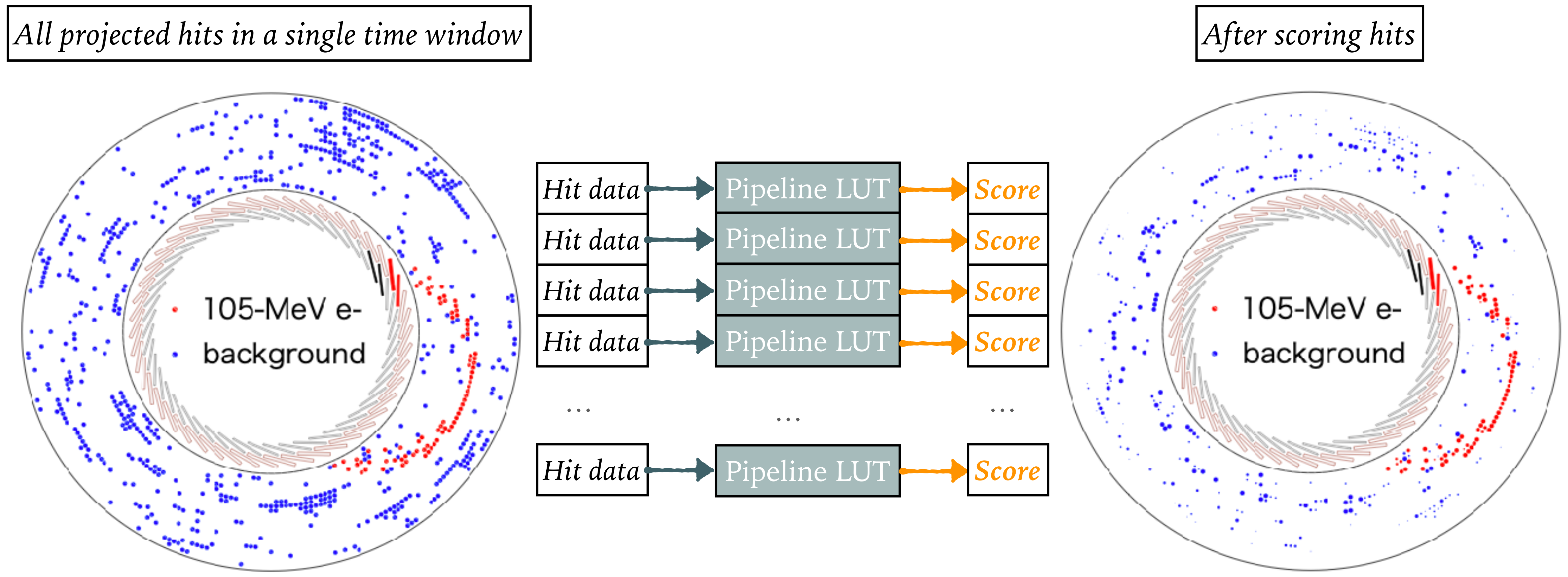


MPPC cooling system to achieve ~ -40°C

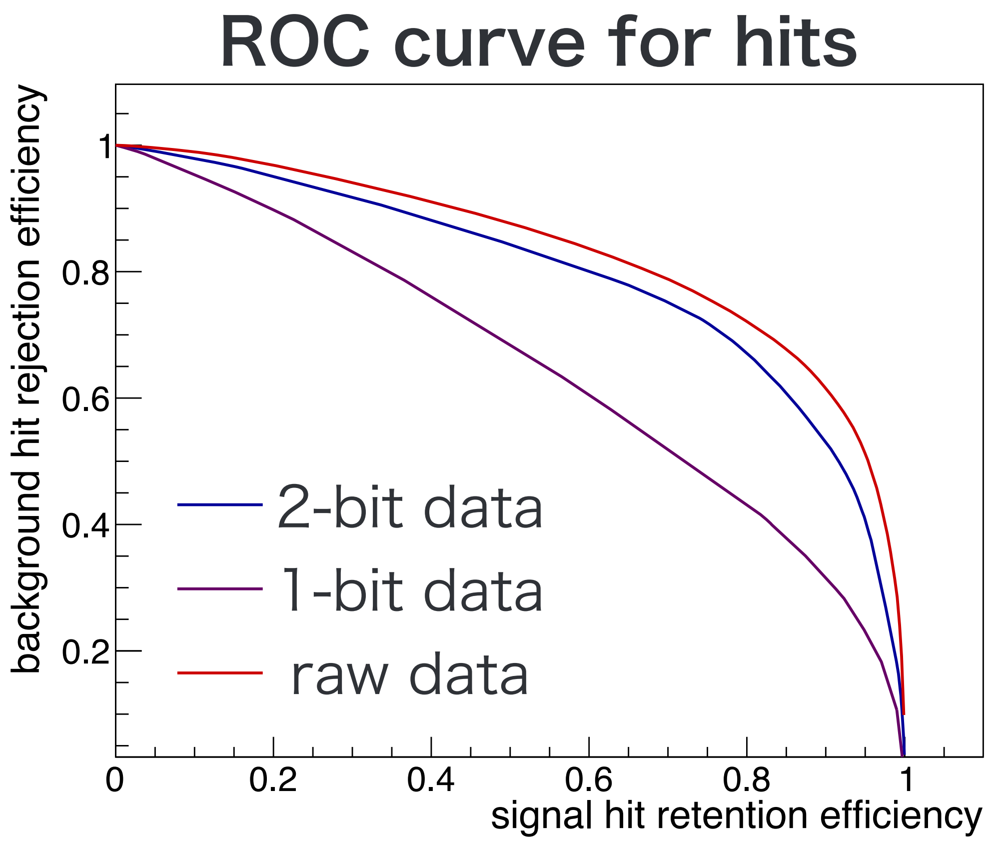


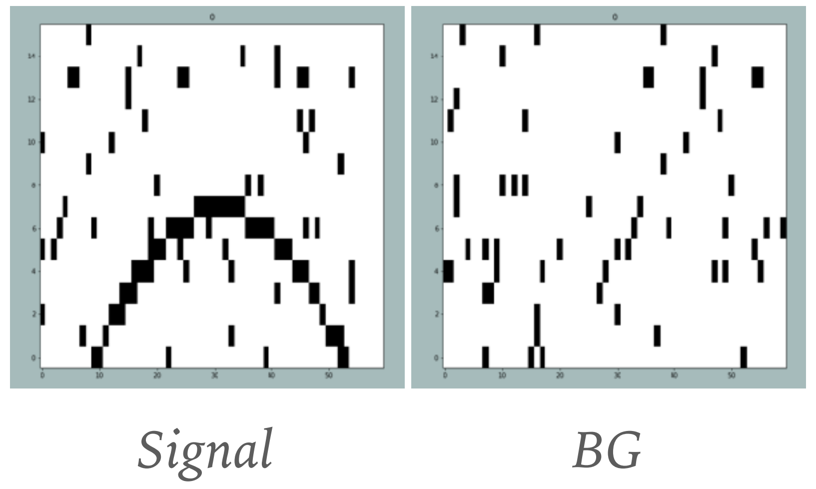
CTH Counter supporting structure

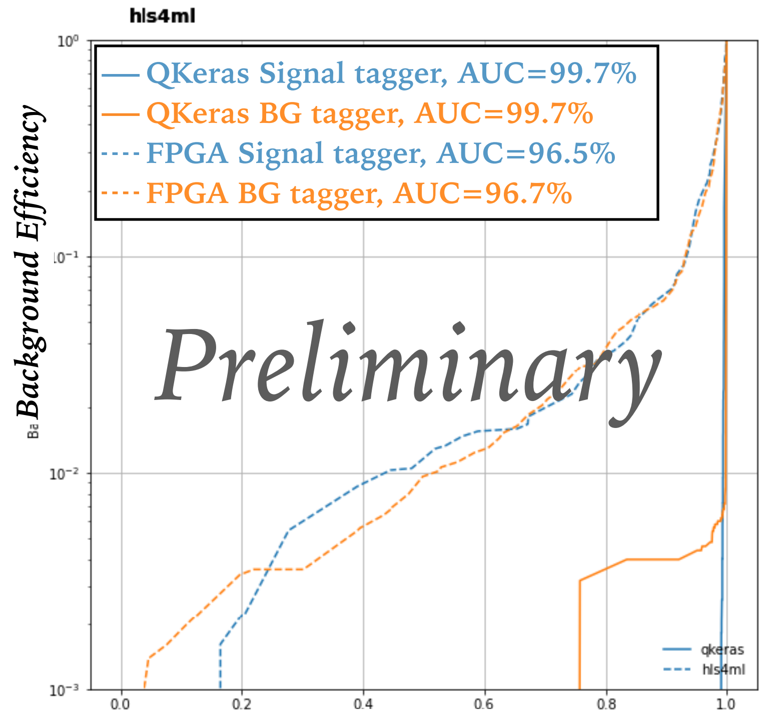
COMET Phase-I ~CyDet trigger~



Y. Nakazawa's PhD thesis

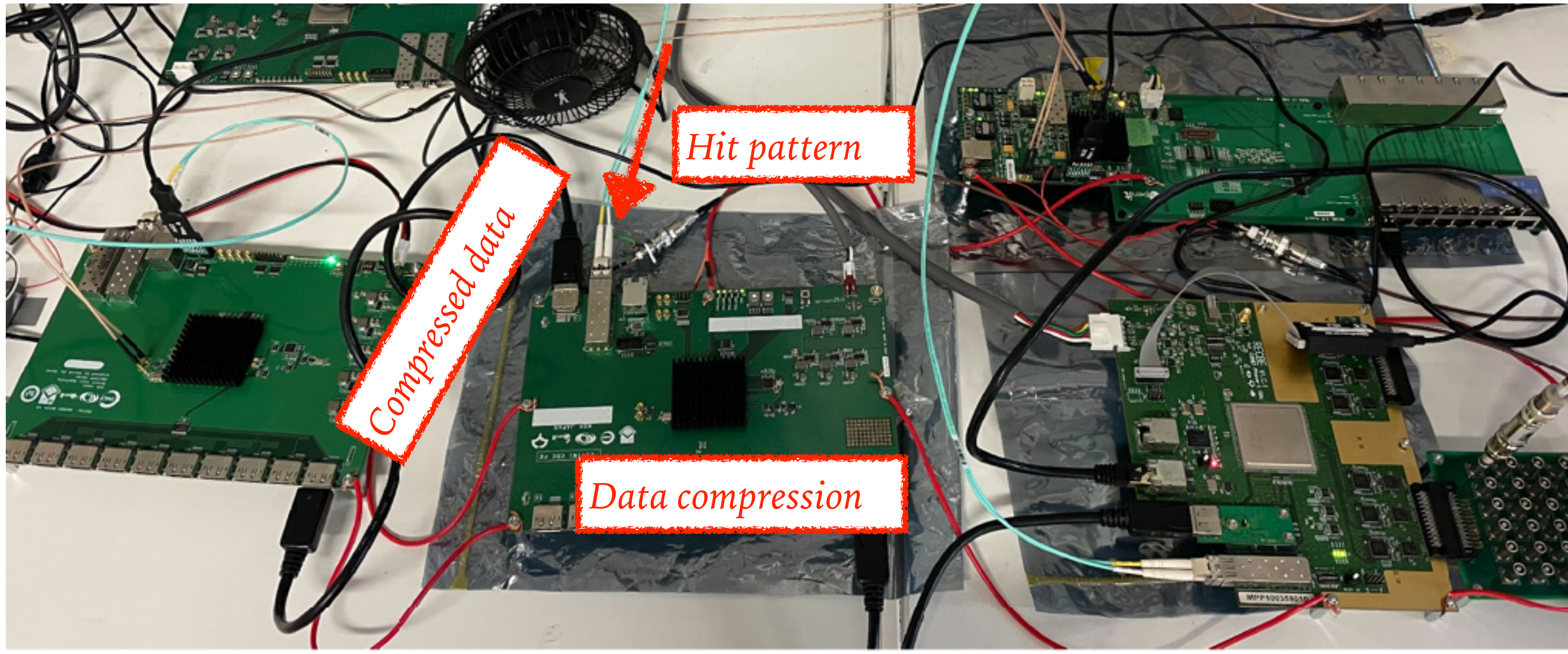






Using mock data and real FPGA boards, 120 ns latency achieved without losing too many signals

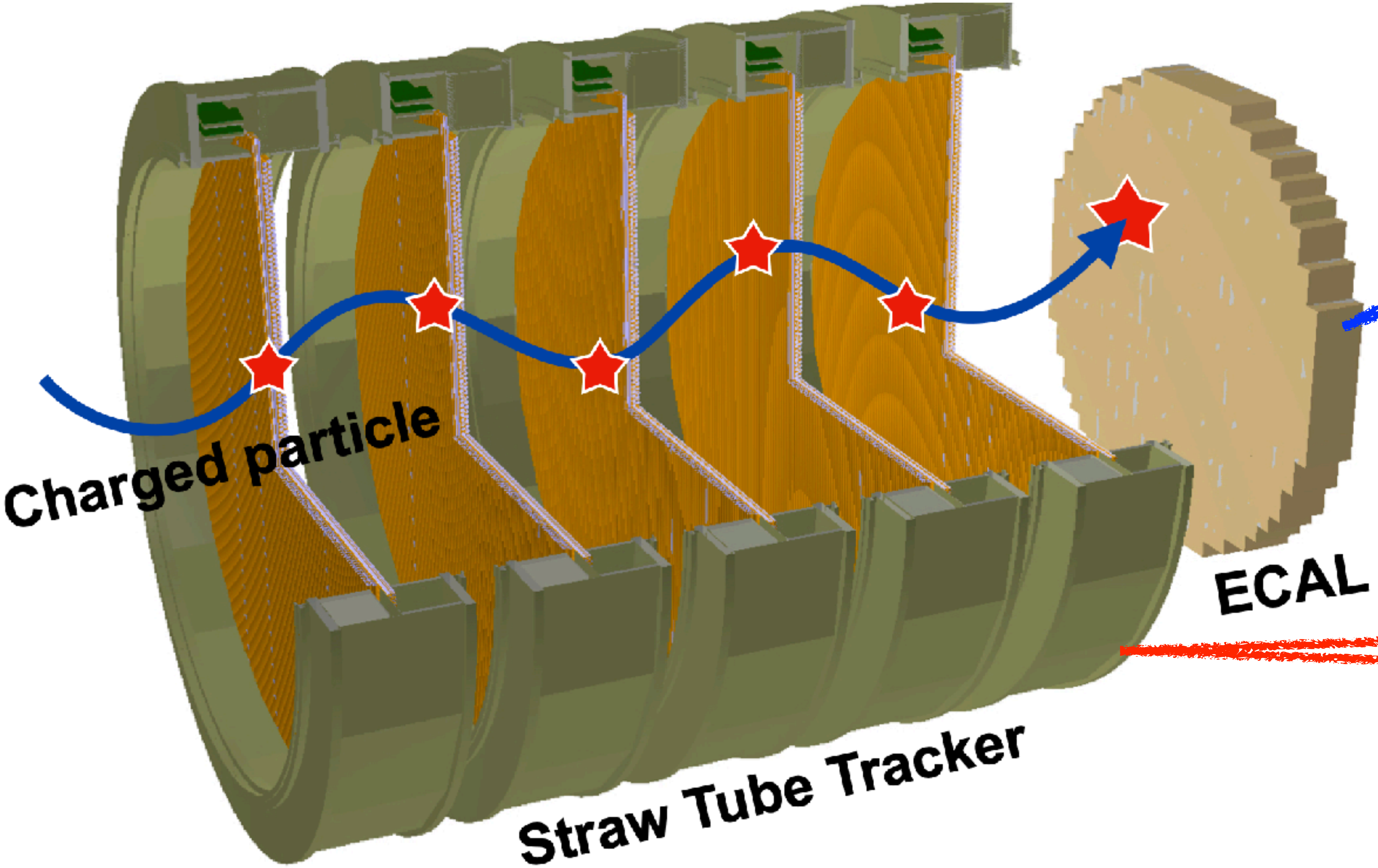
- Further trigger rate suppression by using the CDC hit information @FPGA level to achieve the trigger rate less than 13 kHz with the maximum signal efficiency
  - Many BG hits deposit larger energy than signal ones without helix pattern contained inside the CDC
  - GBDT for hit classification to reduce the BG-like hits
  - Neural network based event classification trigger is being developed for further BG trigger suppression



Y. Fujii, M. Miyataki et.al. NuFact 2023

COMET Phase-I ~StrECAL~

Direct beam measurement with Phase-II prototype detectors



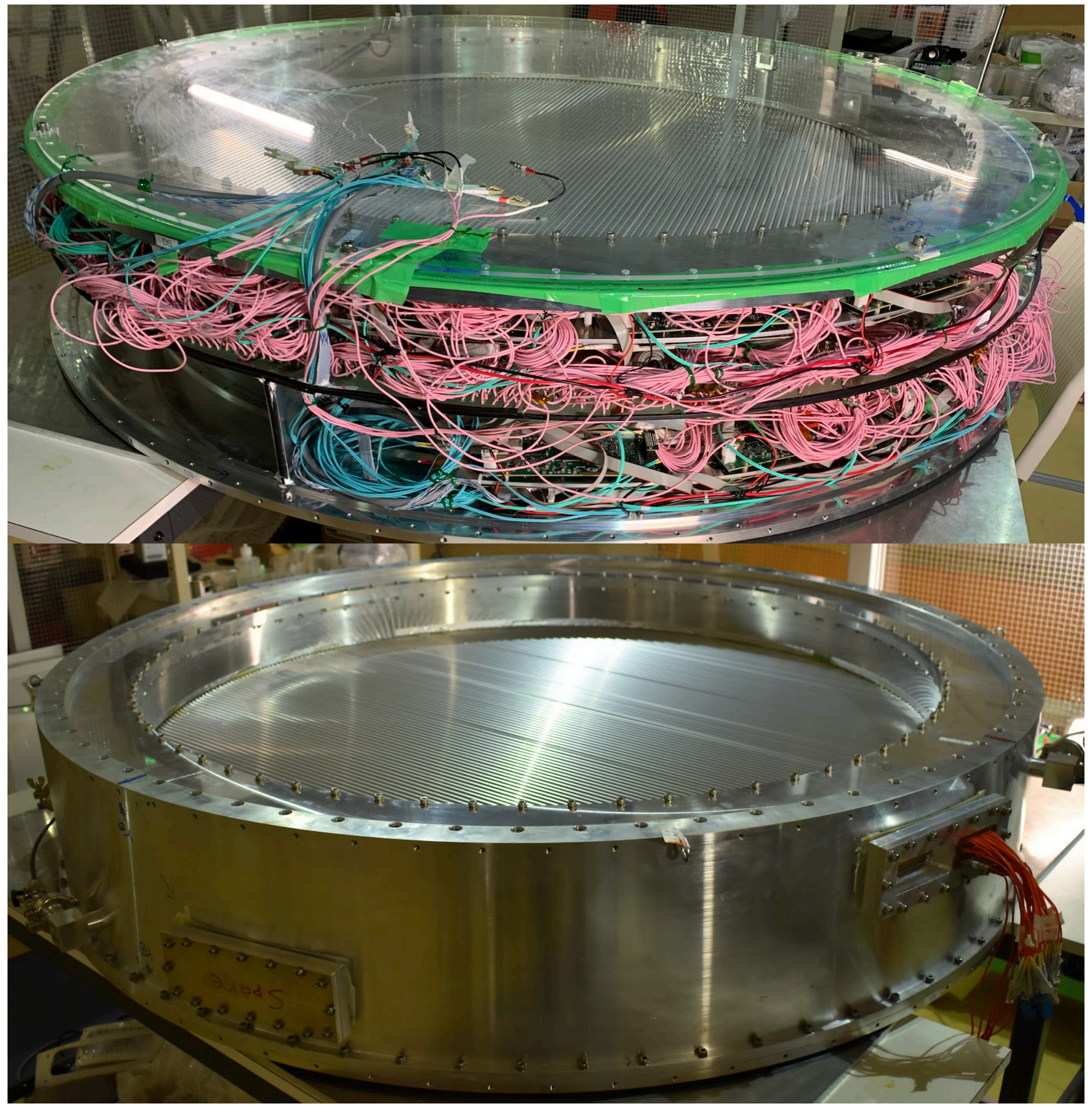
LYSO crystals
- Full energy absorption
- Fast time response

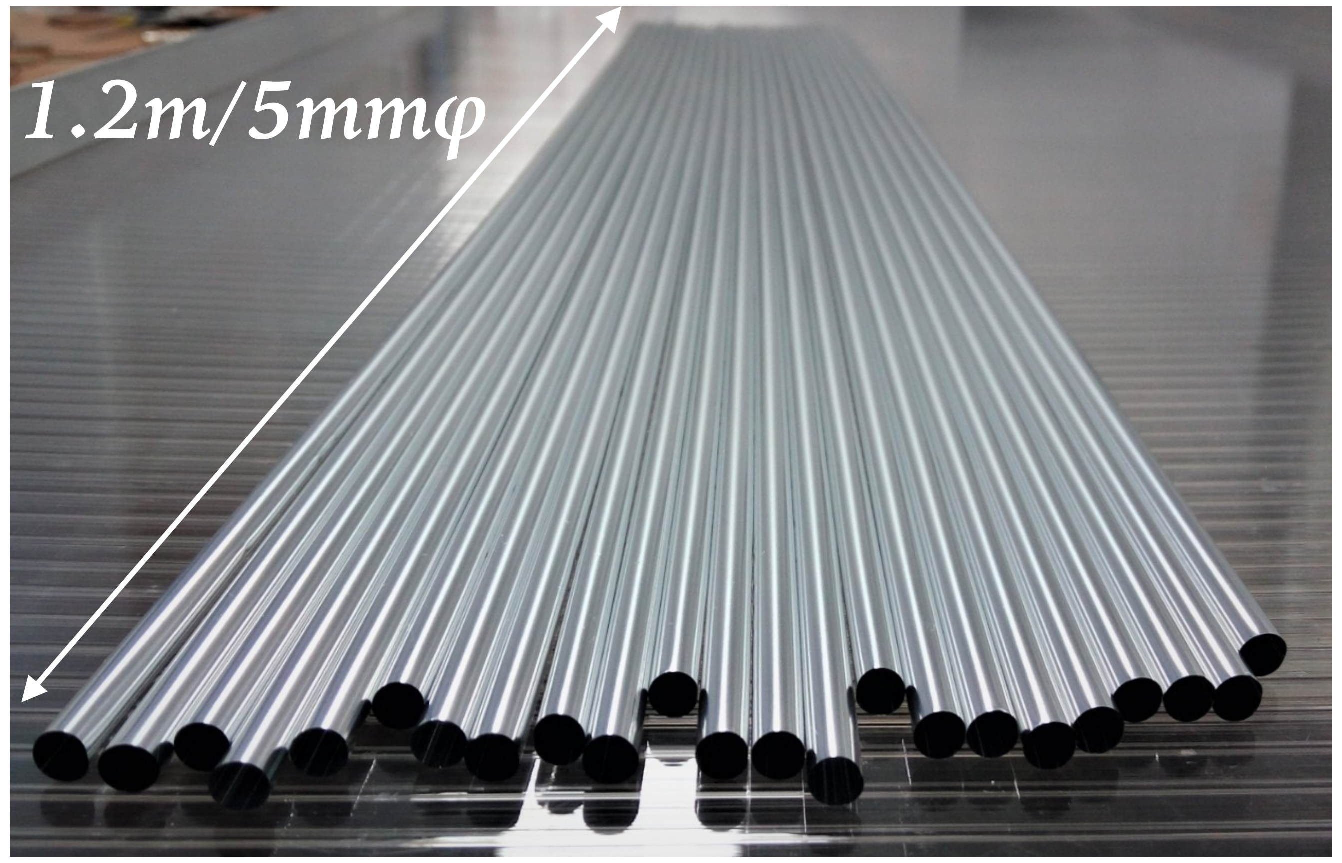
APD readout (space & radiation tolerance)

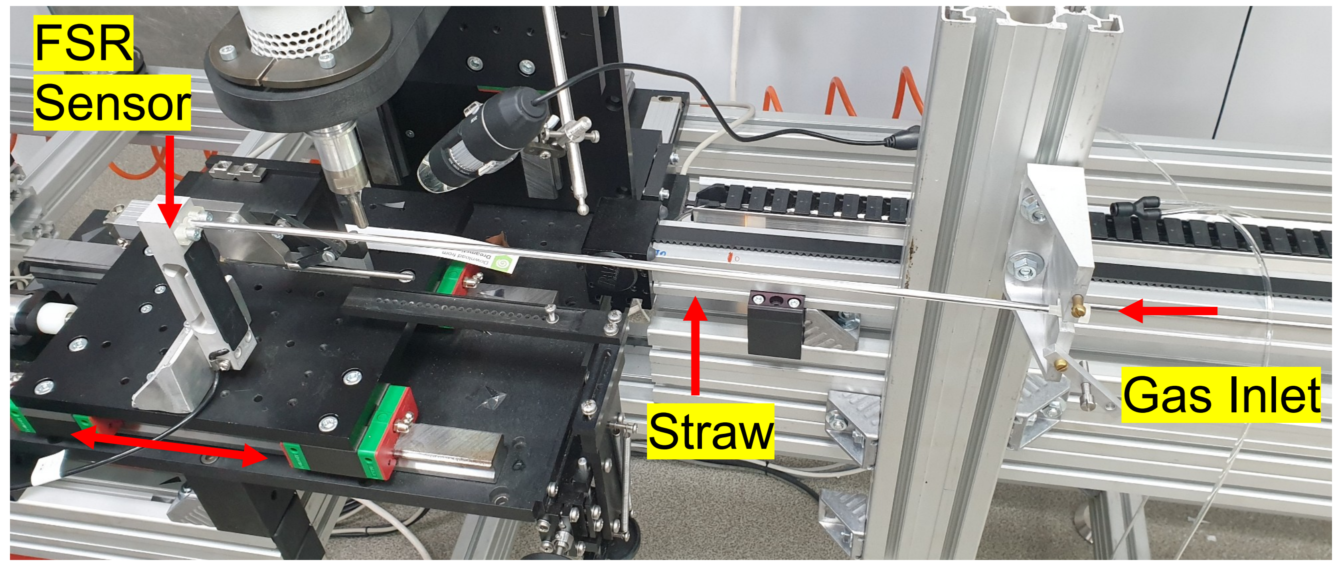
5 or more Straw stations
- Each station consists of 2 horizontal and 2 vertical layers
- Vacuum tight ultra thin straw tubes

COMET Phase-I ~Straw Tracker~

- The 1st full channel straw station constructed for COMET Phase-α/Phase-I beam measurements
  - Made of Aluminised mylar 20μmT, 10mmφ tolerate the 1 atm pressure difference, filled with Ar:Ethane 50:50
  - Expected $\sigma_p \sim 180$ keV/c
- Besides, 12μmT, 5mmφ straws have been developed and being tested, $\sigma_p \sim 150$ keV/c essential to achieve the aiming sensitivity in Phase-II

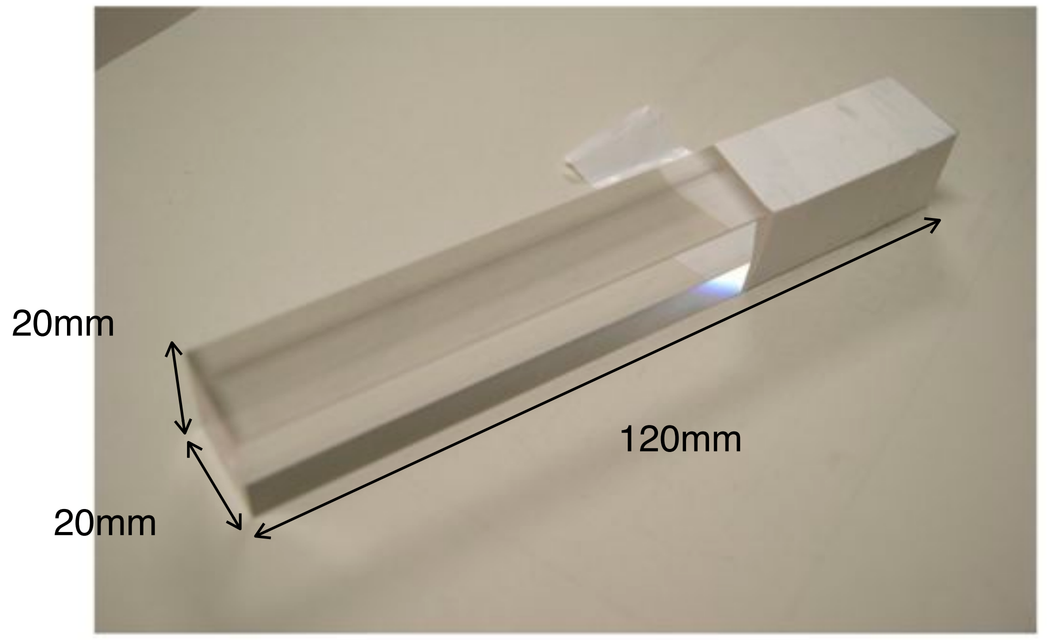


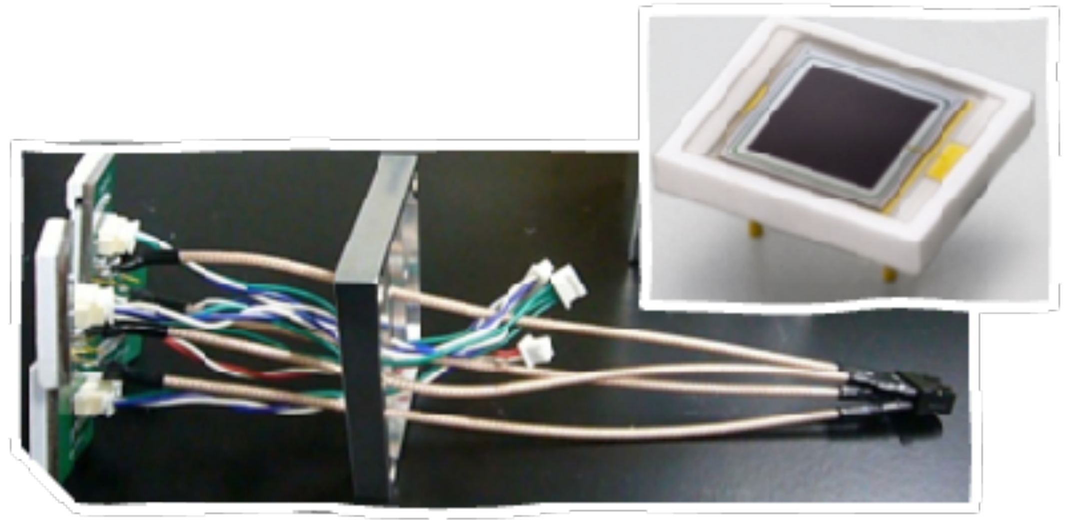


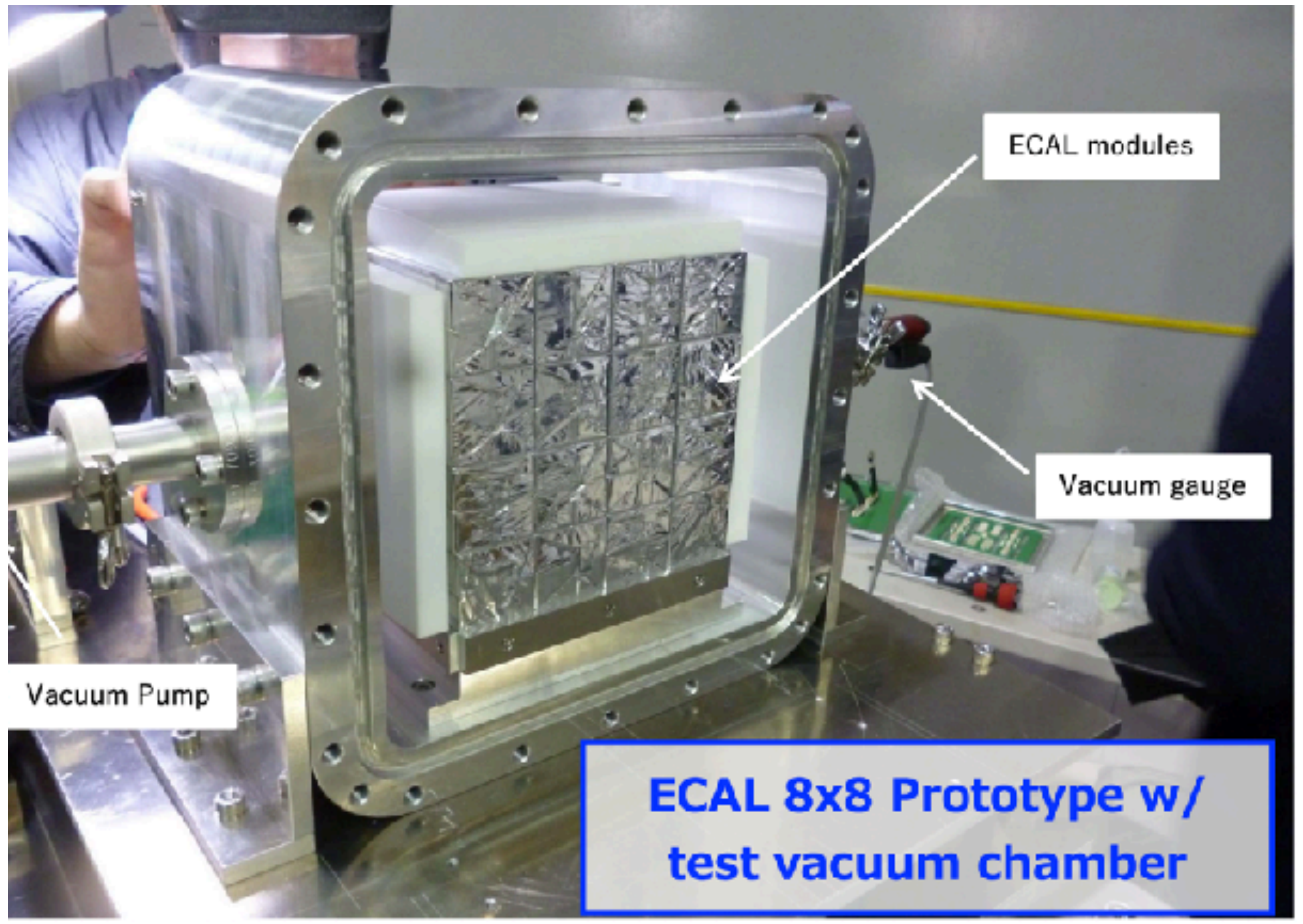


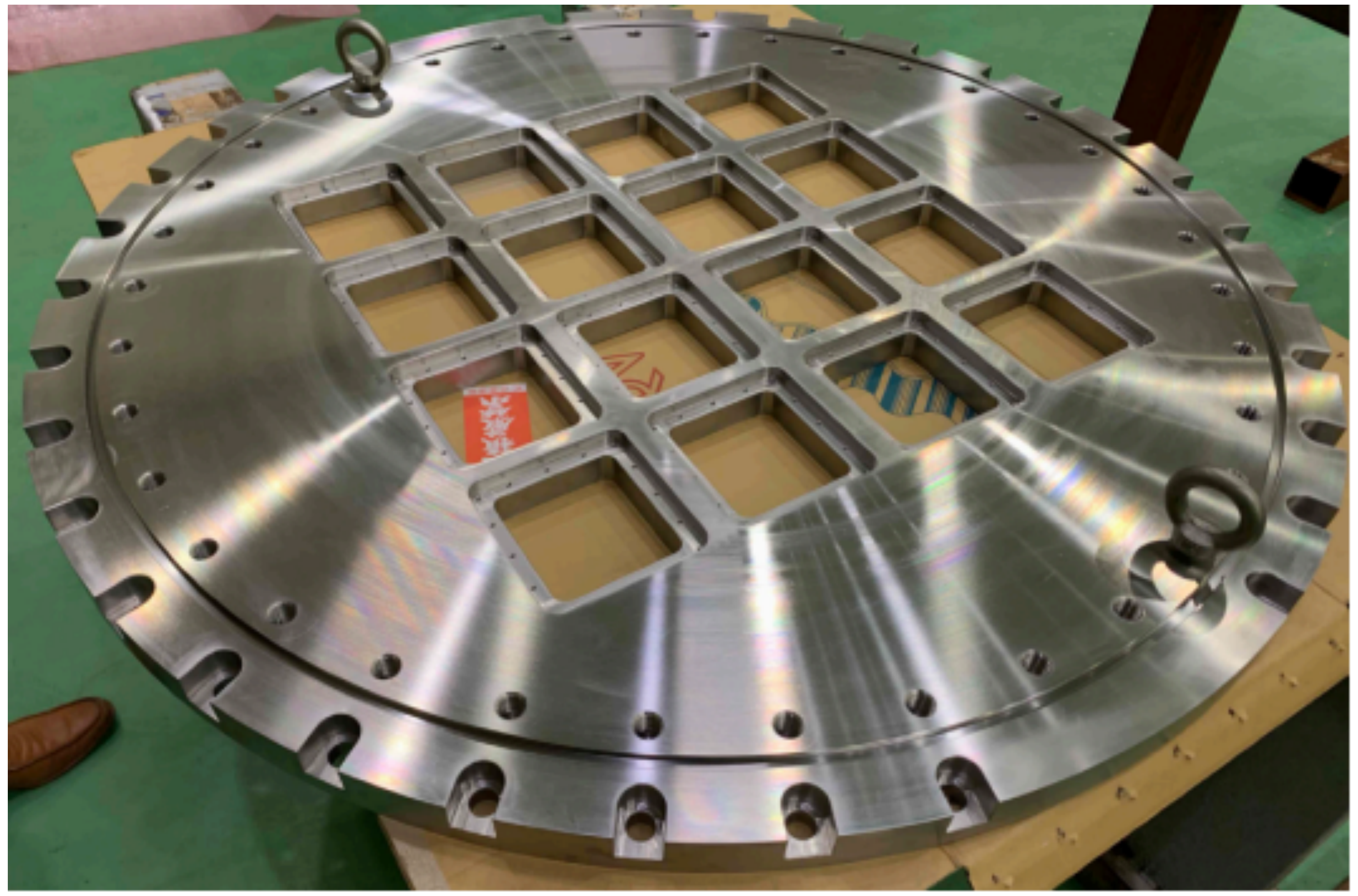
COMET Phase-I ~Electron Calorimeter~

- Measure the electron arrival time with good energy resolution
- Energy resolution better than 5% @100 MeV e^-, $\sigma_t \sim 0.5$ ns, $\sigma_{X/Y} \sim$ 6mm, all validated in the test beam measurement
- LYSO 64 × 16 modules to be installed in the Phase-I
  - In Phase-II it'll be scaled up to 5,000 for ~1.5 mφ coverage with smaller gaps

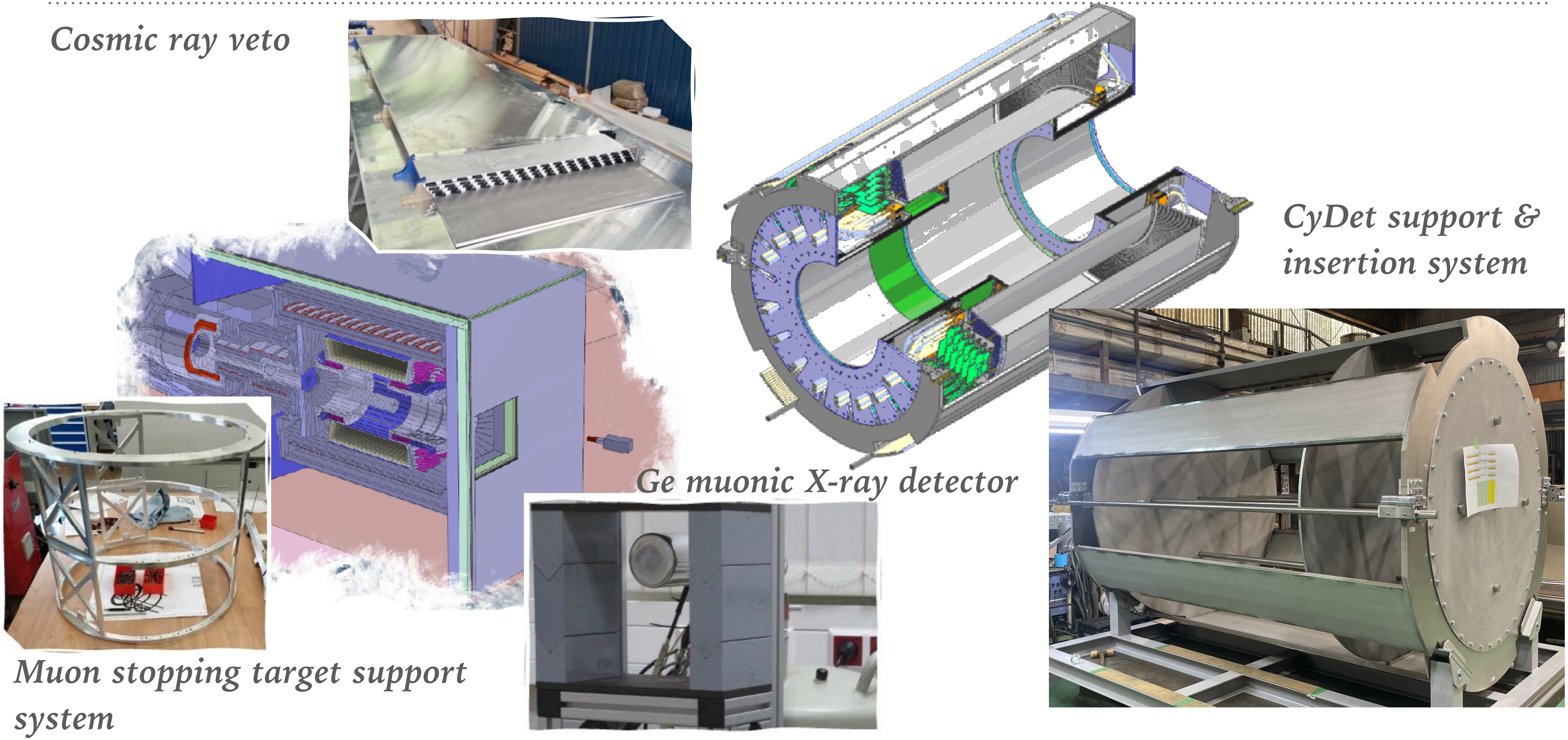








COMET Phase-I ~Other Systems~



Cosmic ray veto

CyDet support & insertion system

Ge muonic X-ray detector

Muon stopping target support system

COMET Phase-I ~Expected Sensitivity~

$$\mathscr{B}(\mu^- N \to e^- N)|_{Al} = \frac{1}{N_\mu \cdot f_{cap} \cdot f_{gnd} \cdot A_{\mu-e}} = 3.0 \times 10^{-15}$$

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..

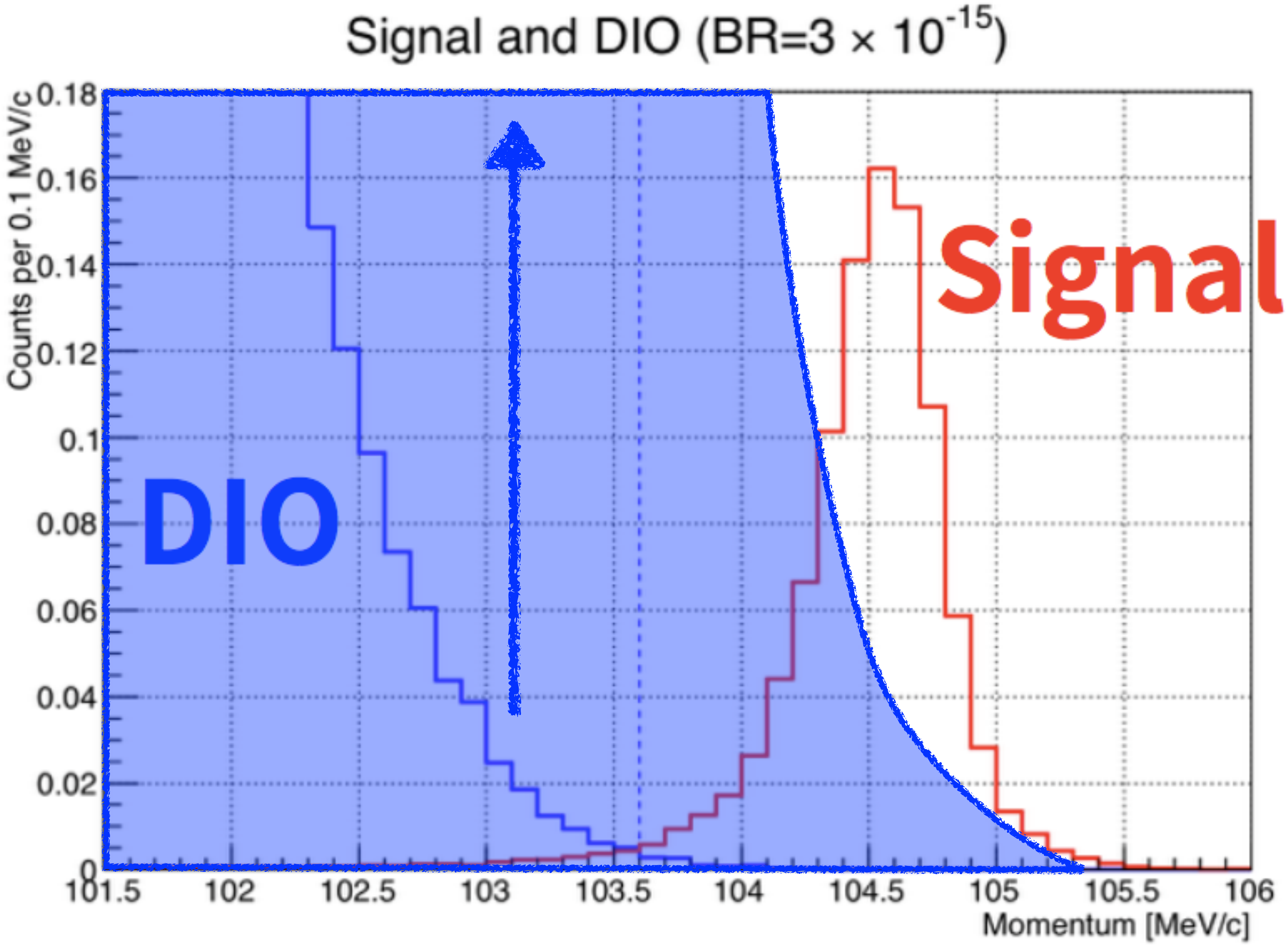
Item	Value	Comment
Acceptance	0.2	Fixed
Trigger/DAQ efficiency	0.8	Subject to change
Track finding efficiency	0.99	SC
Track selection	0.9	SC
Momentum window	0.93	103.6 MeV/c < p < 106.0 MeV/c
Timing window	0.3	700 < t < 1170 ns, SC
Total	0.04	At least 25% error

COMET Phase-I ~Background~

Type	Background	Estimated events
Physics	Muons decay in orbit	0.01
	Radiative muon campture	0.0019
	Neutron emission after muon capture	< 0.001
	Charged particle emission after muon capture	< 0.001
Prompt beam	Beam electrons, μ/π decay-in-flight, others	Total < 0.0038
	Radiative pion capture	0.0028
Delayed beam	↑ from delayed proton beam	Negligible
	Antiproton induced background	0.0012
Others	Cosmic rays (computationally limited)	< 0.01
Total		**< 0.032**

➡ *COMET Phase-I is almost BG free, sensitivity is only limited by the cost of radiation shielding and detector's rate capabilities!*

COMET Phase-II ~Concept~



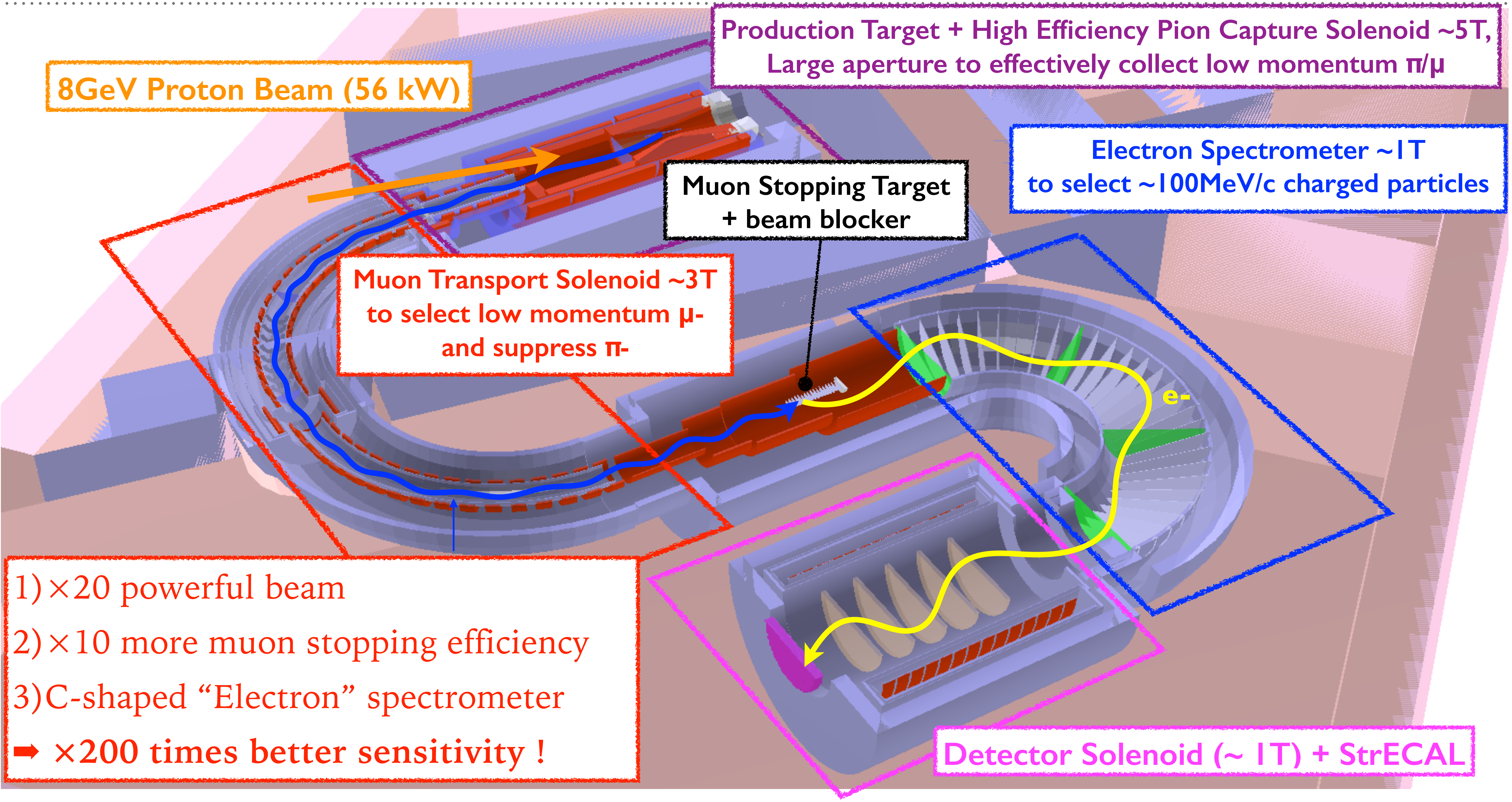
×100 Sensitivity means ×100 background particles

- DIO background suppression is essential
  - Better momentum resolution ≒ less materials
  - Higher pile-up situation

Smaller diameter straw-tubes with thinner wall

Additional electron spectrometer to reduce lower momentum DIOs

COMET Phase-II



8GeV Proton Beam (56 kW)

Production Target + High Efficiency Pion Capture Solenoid ~5T,
Large aperture to effectively collect low momentum π/μ

Electron Spectrometer ~1T
to select ~100MeV/c charged particles

Muon Stopping Target
+ beam blocker

Muon Transport Solenoid ~3T
to select low momentum μ-
and suppress π-

Detector Solenoid (~ 1T) + StrECAL

1) ×20 powerful beam

2) ×10 more muon stopping efficiency

3) C-shaped "Electron" spectrometer

➡ **×200 times better sensitivity !**

Yuki Fujii, New Frontiers in Lepton Flavor, Pisa, Italy, 2023

COMET Phase-II ~Sensitivity~

$$\mathscr{B}(\mu^- N \to e^- N)|_{Al} = \frac{1}{N_\mu \cdot f_{cap} \cdot f_{gnd} \cdot A_{\mu-e}} = 1.4 \times 10^{-17}$$

N_μ : #of stopped μ^-, **3.3×10^{18}**, exp. @ 230 days,

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

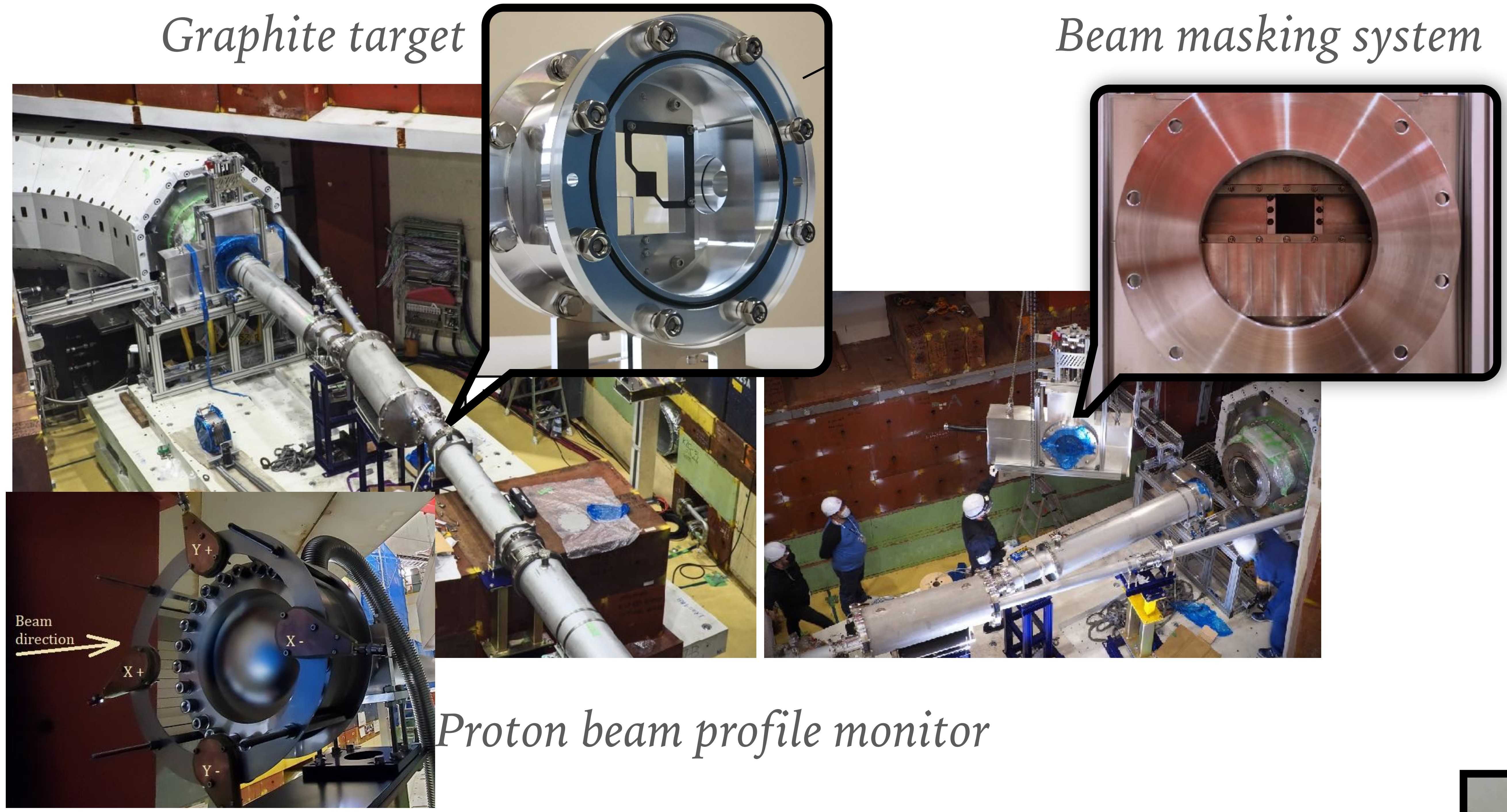
f_{gnd} : fraction of μ^- bound to ground state, 0.9 theory,

A_μ : acceptance of μ-e signal, **0.036**, exp..

Item	Value in P-I	Value in P-II	Comment
Acceptance	0.2	**0.18**	Fixed
Trigger/DAQ efficiency	0.8	**0.87**	Subject to change
Track reconstruction efficiency	0.99	**0.77**	SC
Track selection	0.9	**0.94**	SC
Momentum window	0.93	**0.62**	104.2 MeV/c < p < 105.5 MeV/c
Timing window	0.3	**0.49**	600 < t < 1170 ns, SC
Total	0.04	**0.034**	At least 25% error

K. Oishi, PhD thesis in 2020

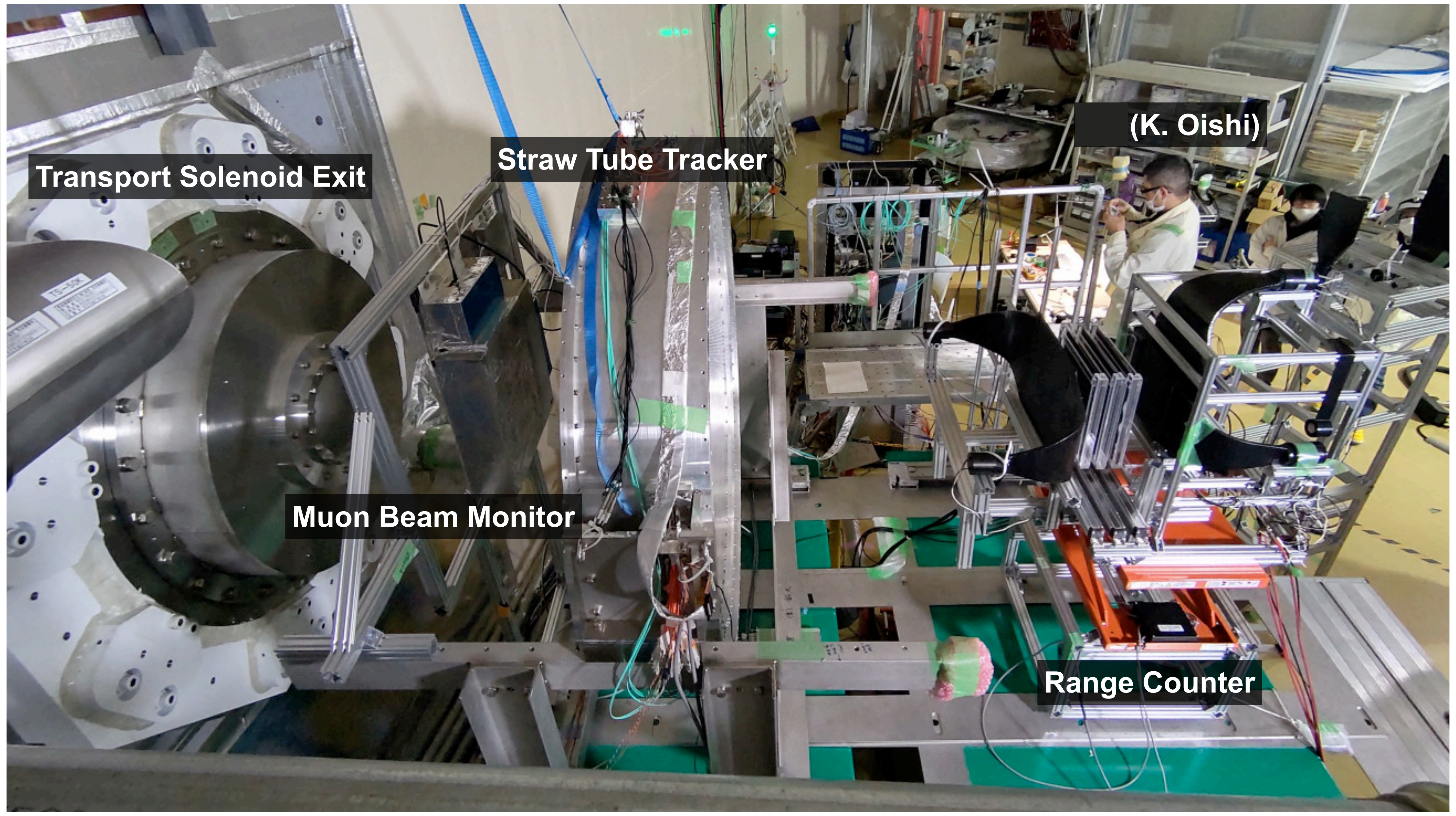
Phase-α



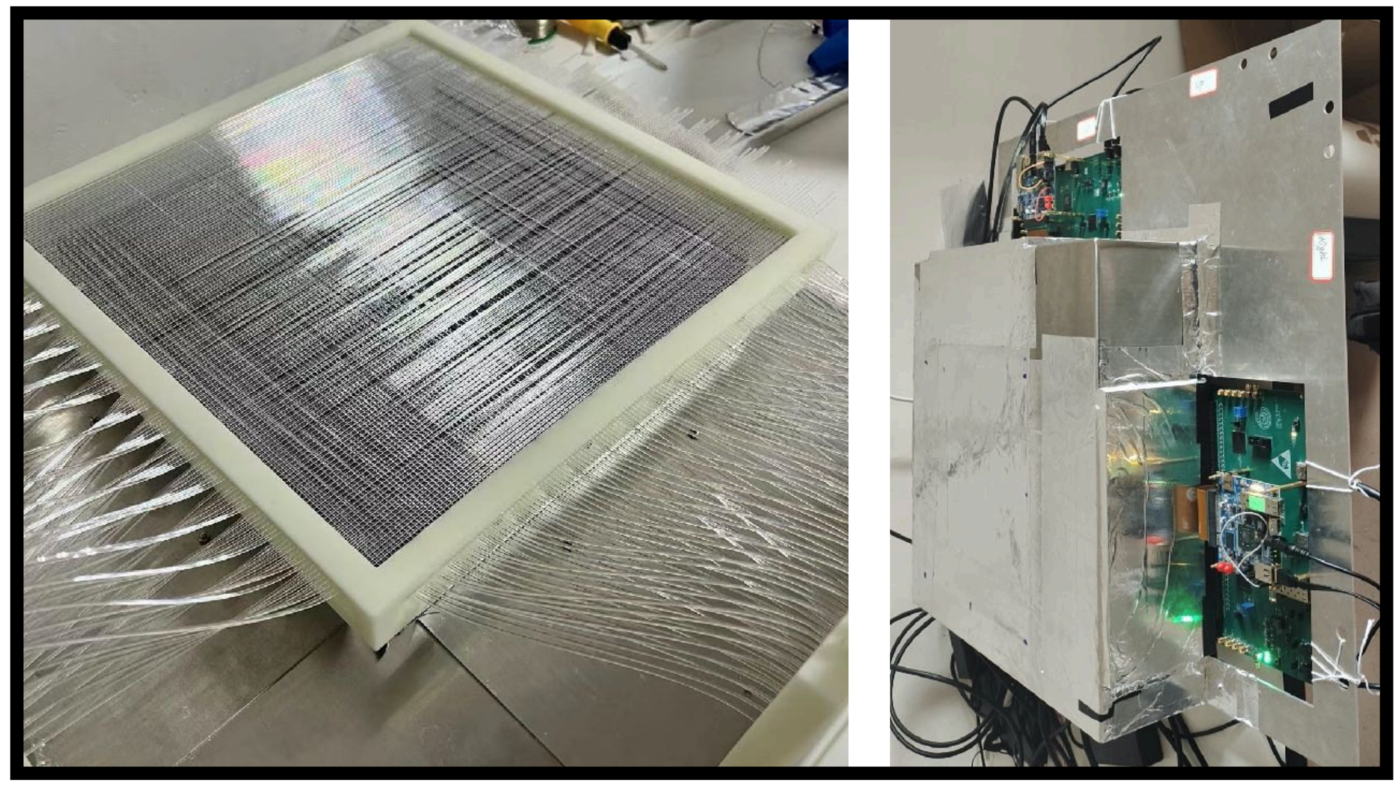
Graphite target

Beam masking system

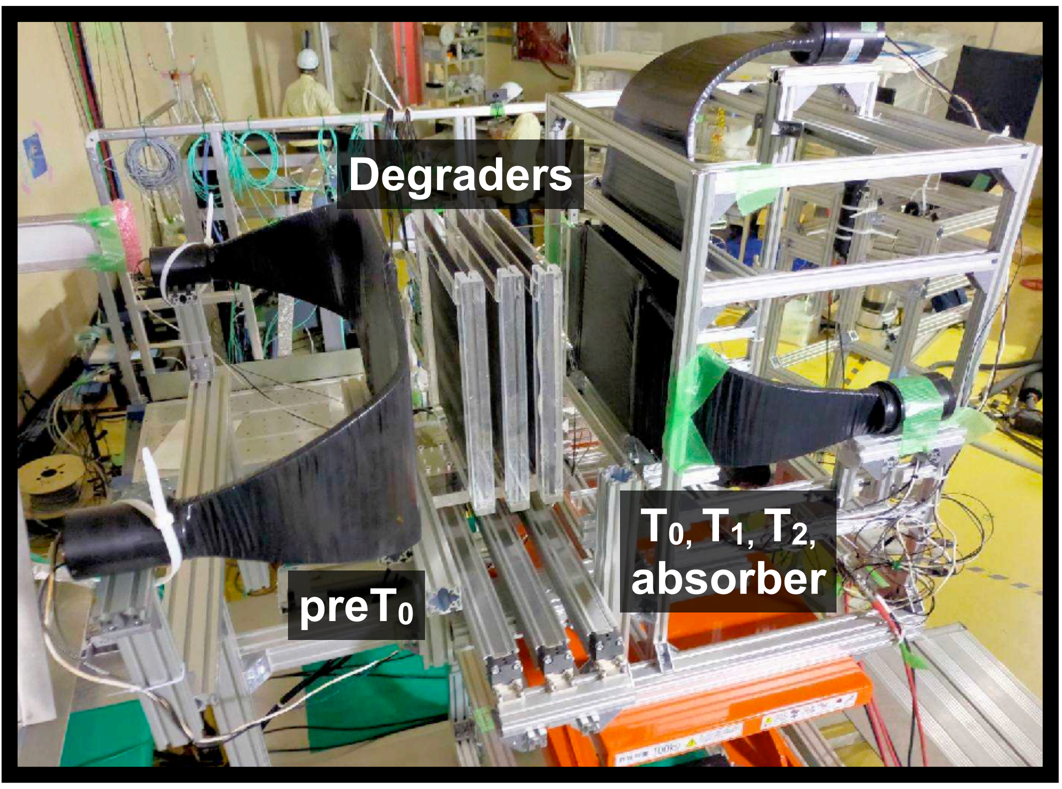
Proton beam profile monitor



- After C-line completion at J-PARC hadron facility, temporary graphite target and muon beam measurement detectors were installed
  - COMET phase-α w/ very low intensity to study the beam profile before/after the TS

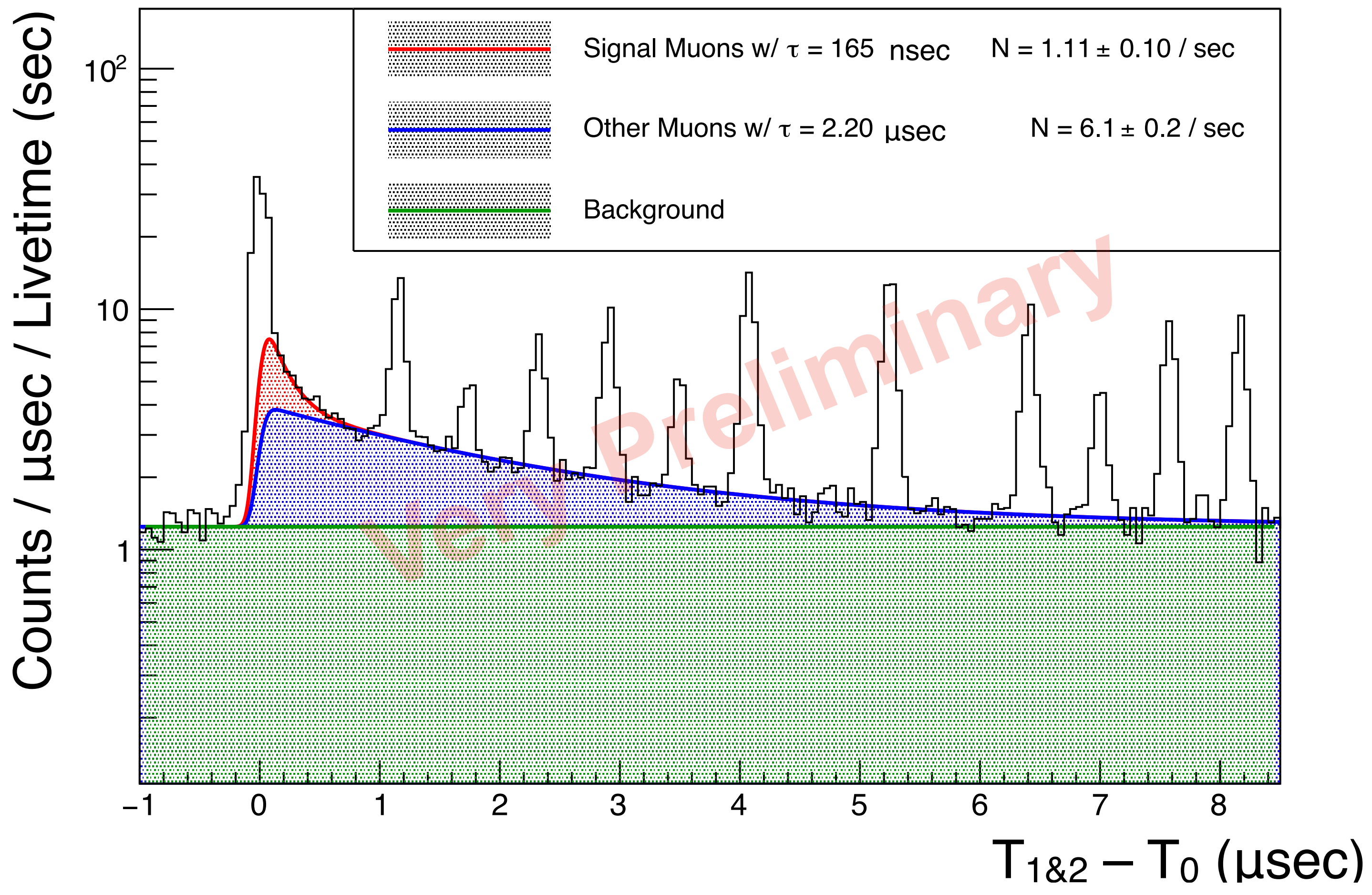


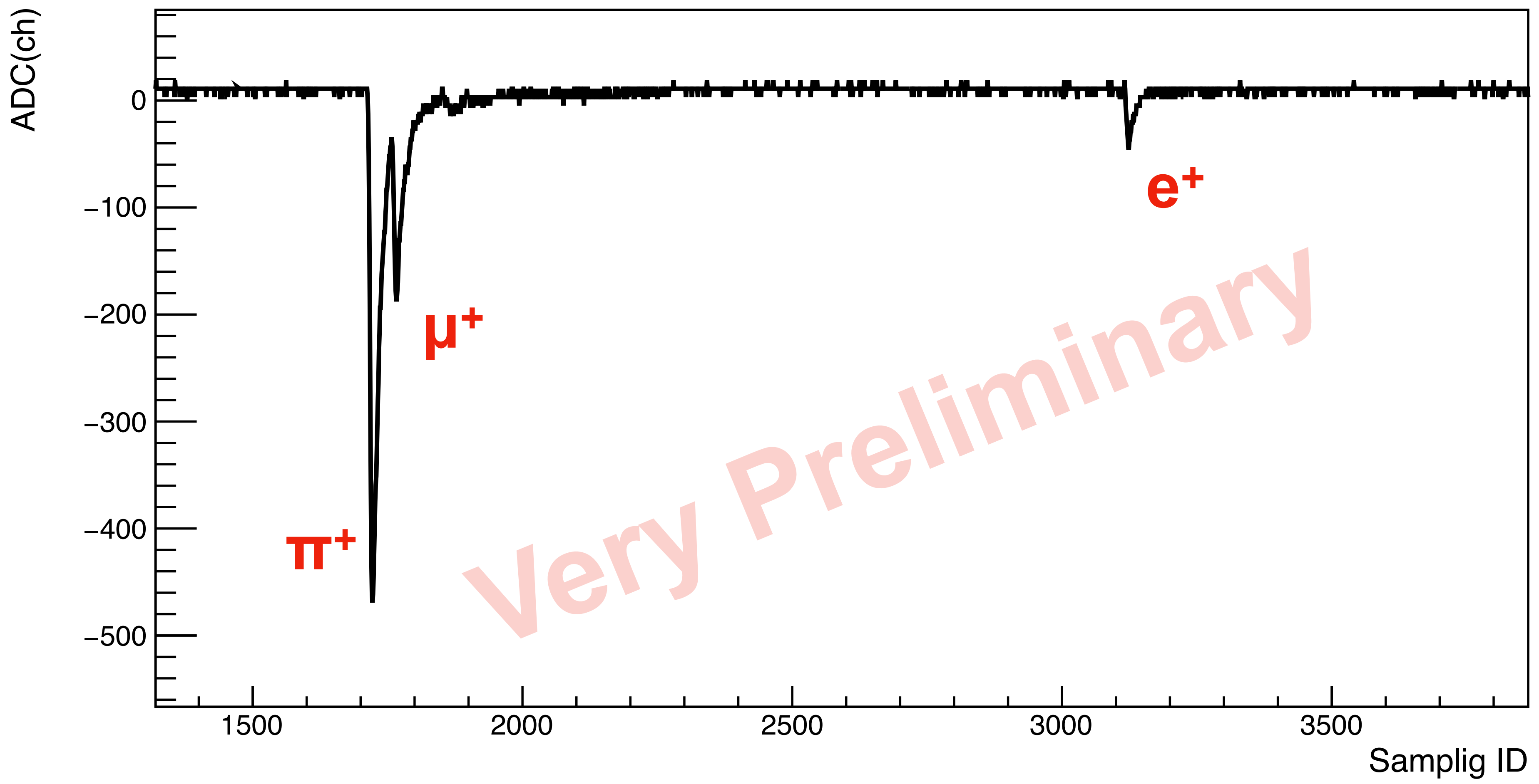
Muon position/timing detector



Range counter

Phase-α





Hadron experimental facility "C-line" is completed

- J-PARC news article 17th March

- **The first muon beam was delivered to the COMET experimental area!**
  - Clear pulse structure + muon decay time structure were observed
  - Some π^+ decay chain candidate events were seen
  - Detailed analysis is ongoing and possibility for taking the further beam profiling data early this year

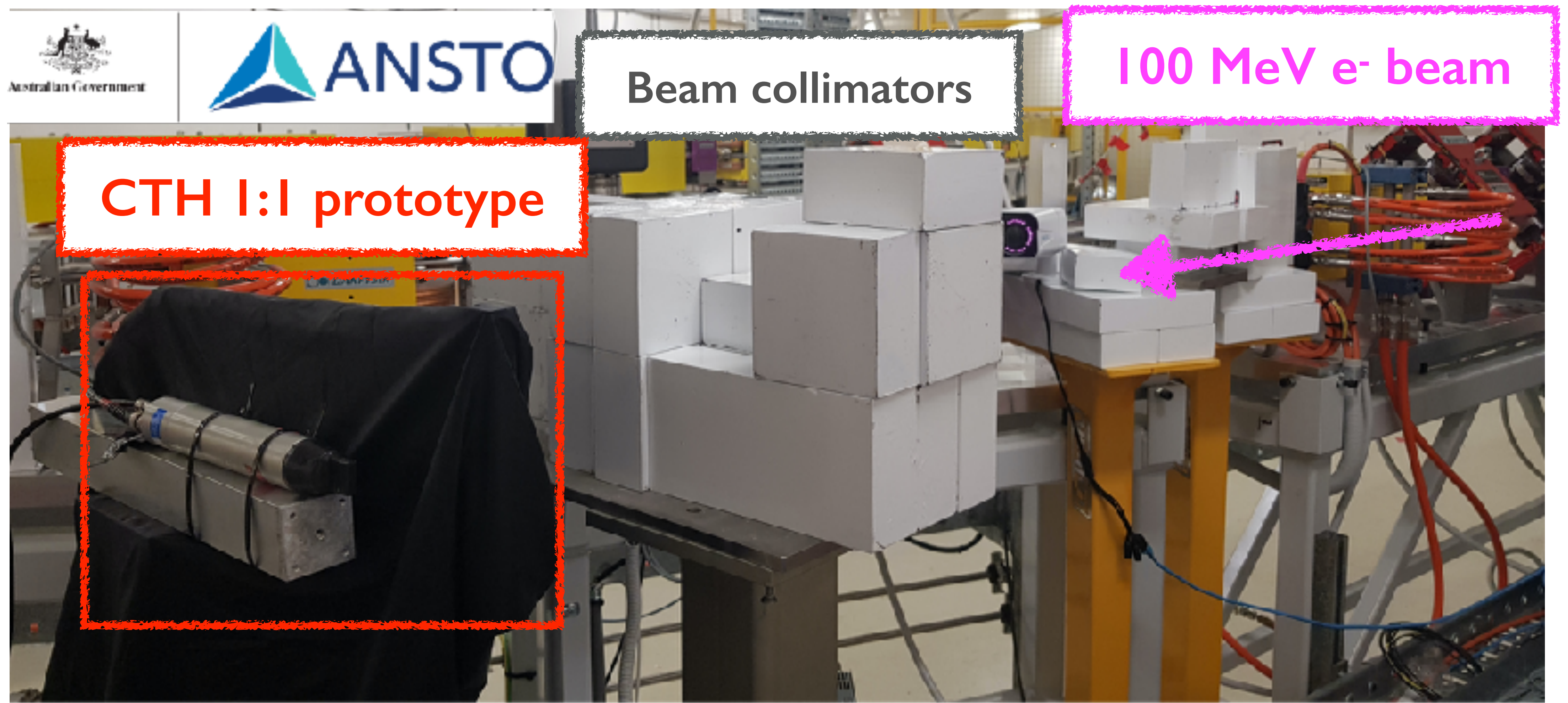
Summary & Prospects

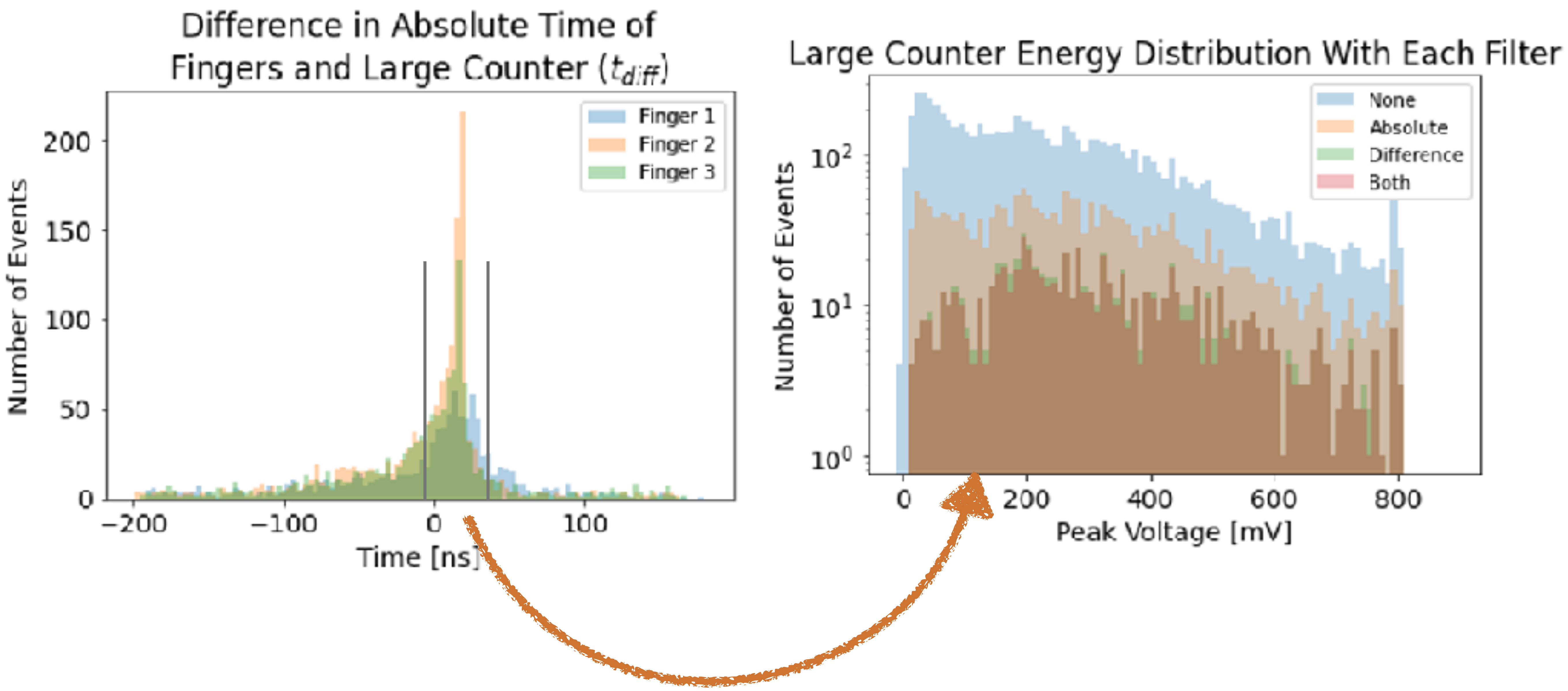
- COMET searches for the μ-e conversion with the world's best sensitivity, 10^{-15} and 10^{-17} in its Phase-I and Phase-II
- Many things are ongoing to start the physics run in 2024/2025
- Recent phase-α experiment proved the low-p muon transportation scheme with a curved solenoid
- More to come in next few years, stay tuned!

Thank You

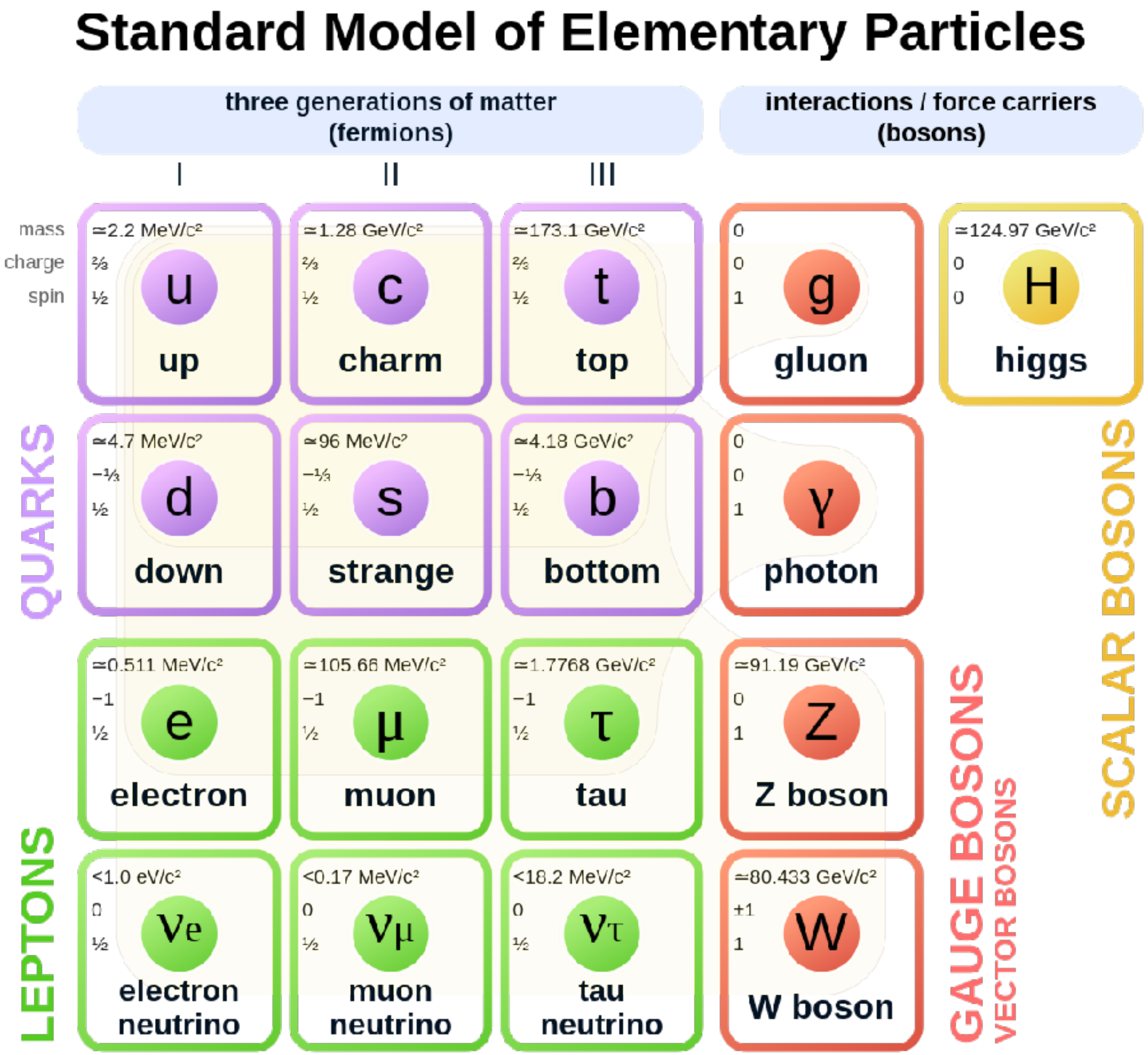
The Kangaroo Sanctuary / Facebook

COMET Phase-I – Monash Activities –





What is CLFV?

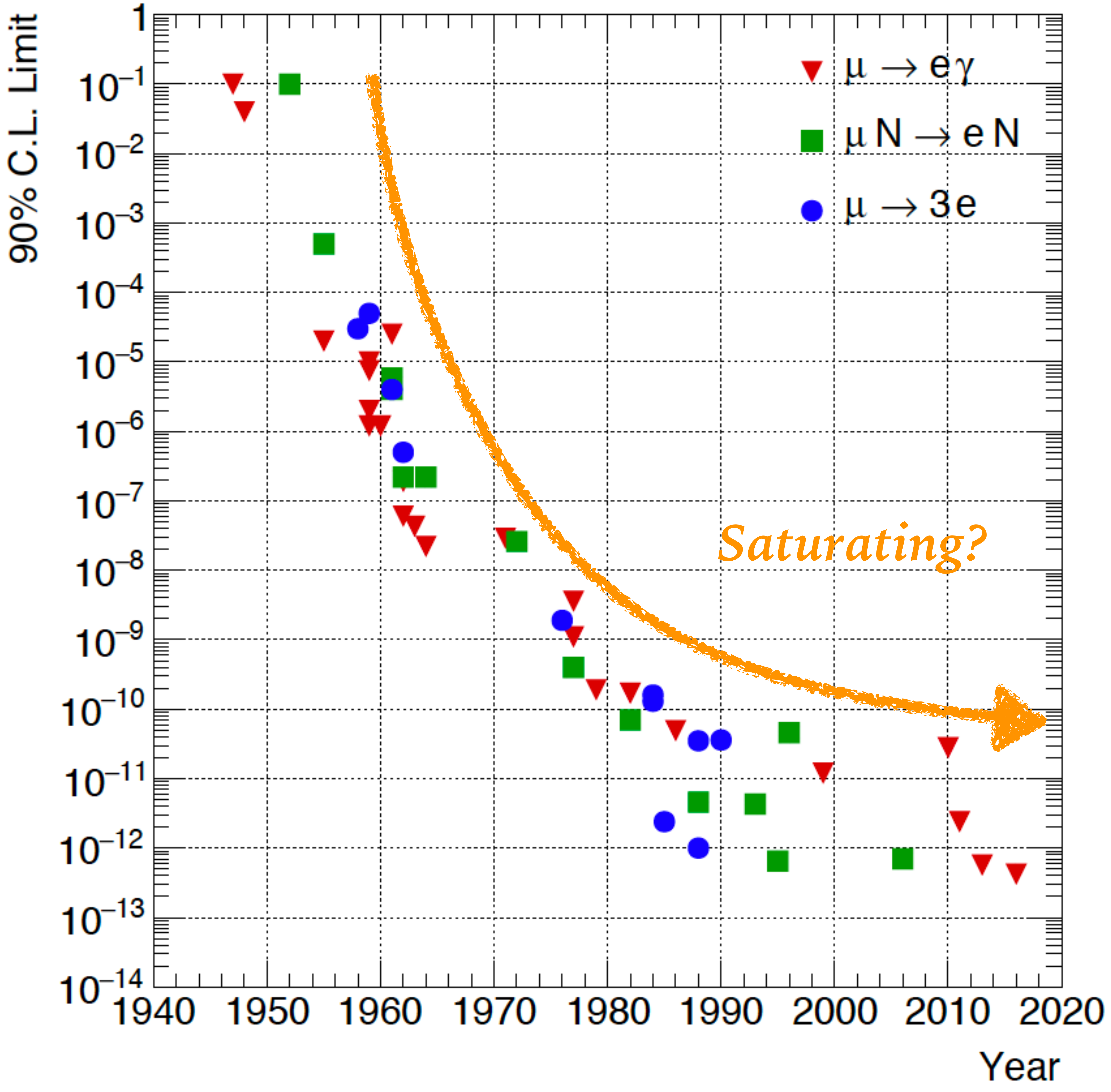


Wikipedia

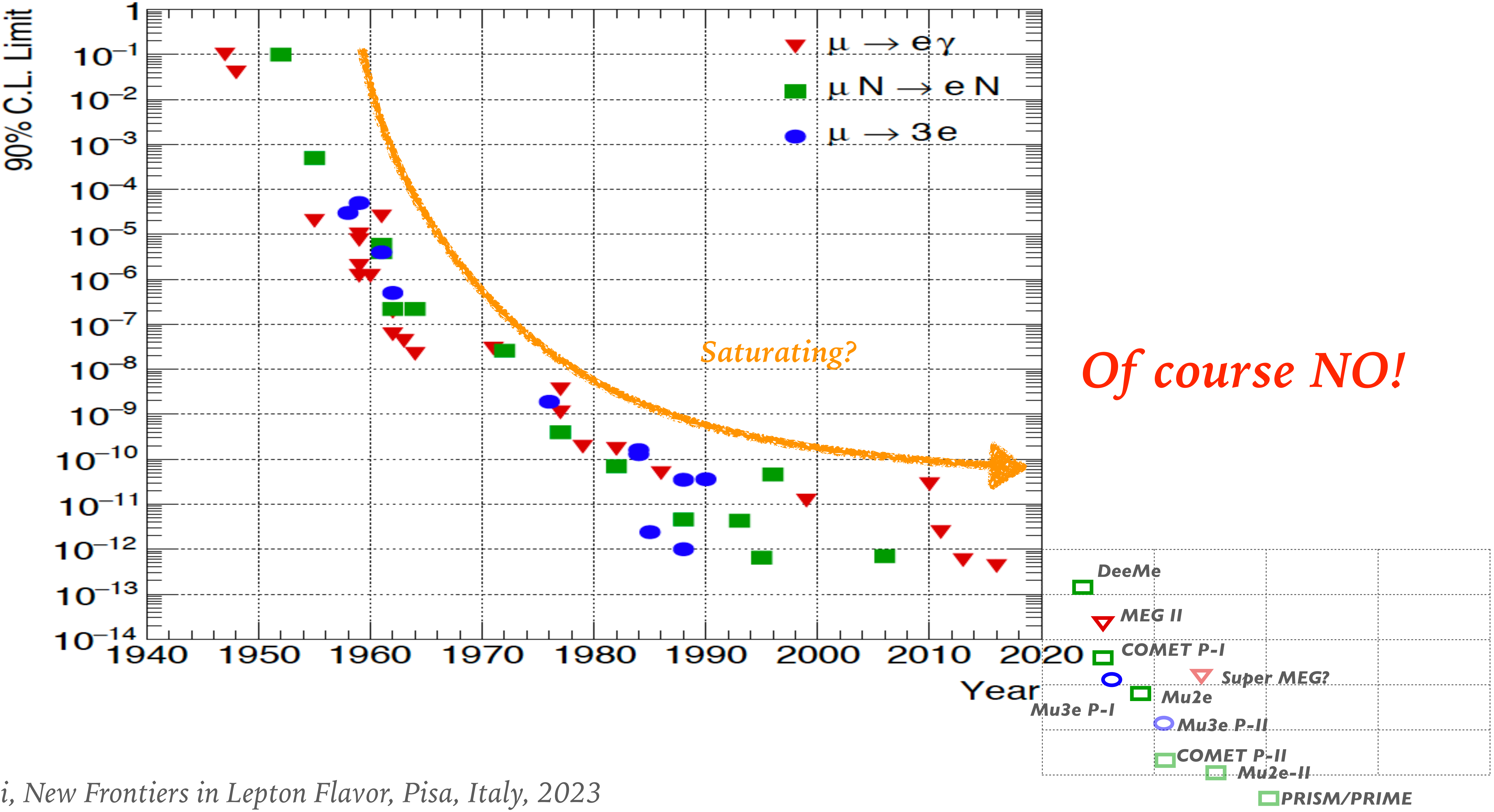
- Modern Particle Physics
  - Based on the beautiful symmetries and conservation laws → eventually broken
  - Forces are nicely unified → but no gravity
  - No dark matters, neutrino masses, *etc*…
- We know
  - Quarks mix (CKM matrix)
  - Neutrinos mix (PMNS matrix)
- So why don’t charged leptons mix?
  - Charged Lepton Flavour Violation (CLFV)

CLFV History

- Muons were discovered in 1936 accidentally
  - *“Who ordered that?” — I. I. Rabi*
  - Dawn of the flavour physics
- Current upper limits (for muons = golden channels @90% C.L.)
  - $BR(\mu^+ \to e^+e^+e^-) < 1.0 \times 10^{-12}$ by SINDRUM @PSI, Nucl. Phys. B 299 (**1988**)
  - $CR\ (\mu^- N \to e^- N)|_{Au} < 7.0 \times 10^{-13}$ by SINDRUM II @PSI, Eur. Phys. J. C 47 (**2006**) 337
  - $BR(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$ by MEG @PSI, Eur. Phys. J. C 76 (**2016**) 434



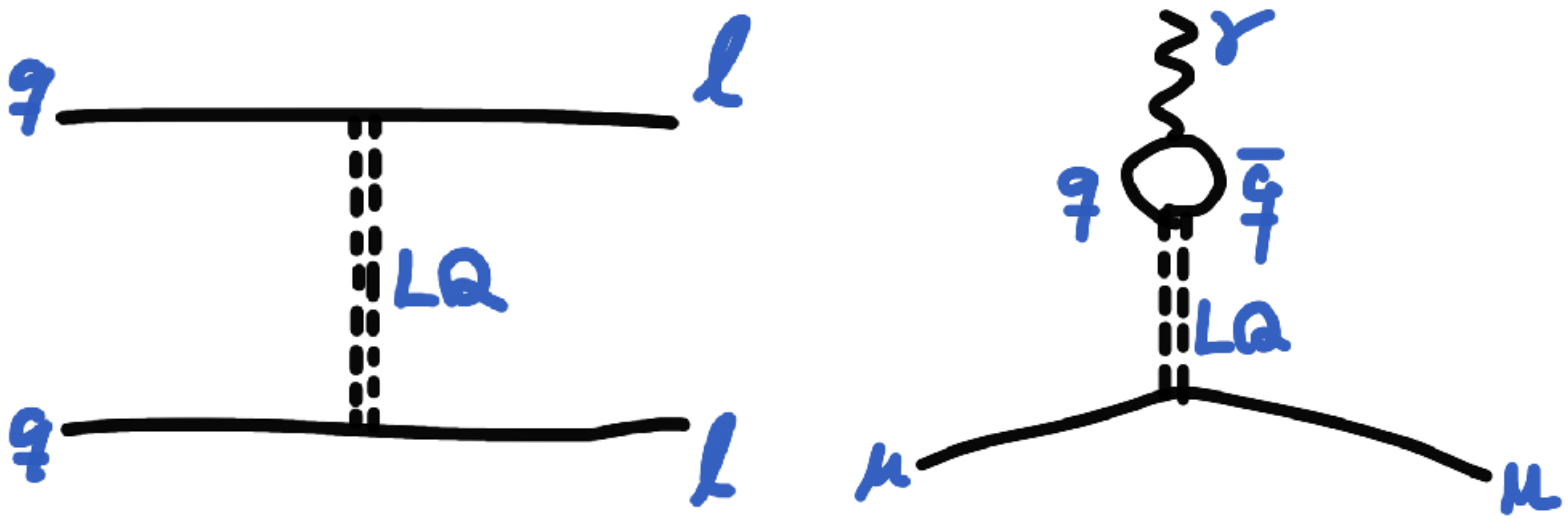
Future Prospects (from my optimistic view)

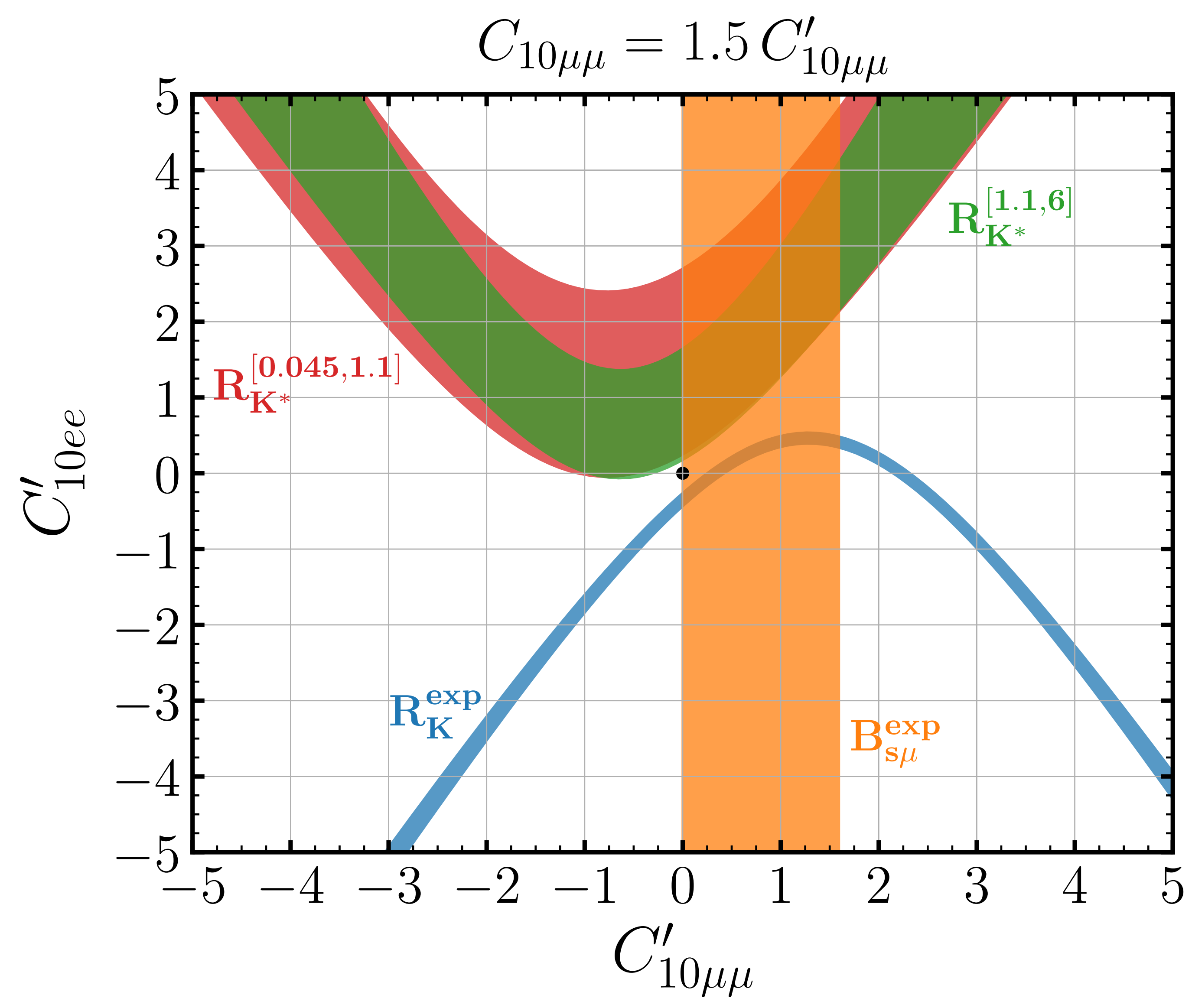


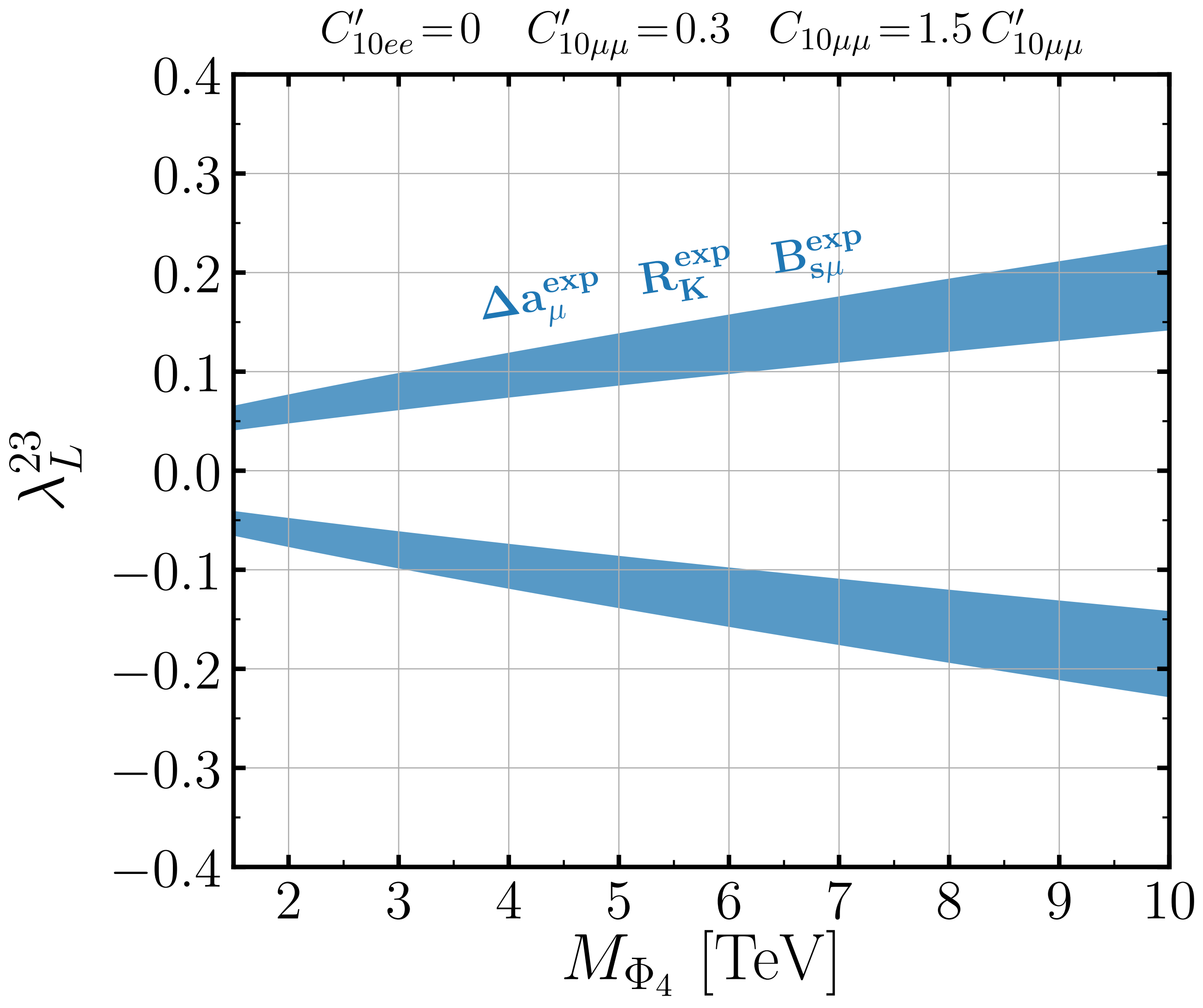
Of course NO!

CLFV and Leptoquarks

- LQ can simultaneously explain both;
  - Recent B physics anomalies
  - Long standing g-2 anomaly







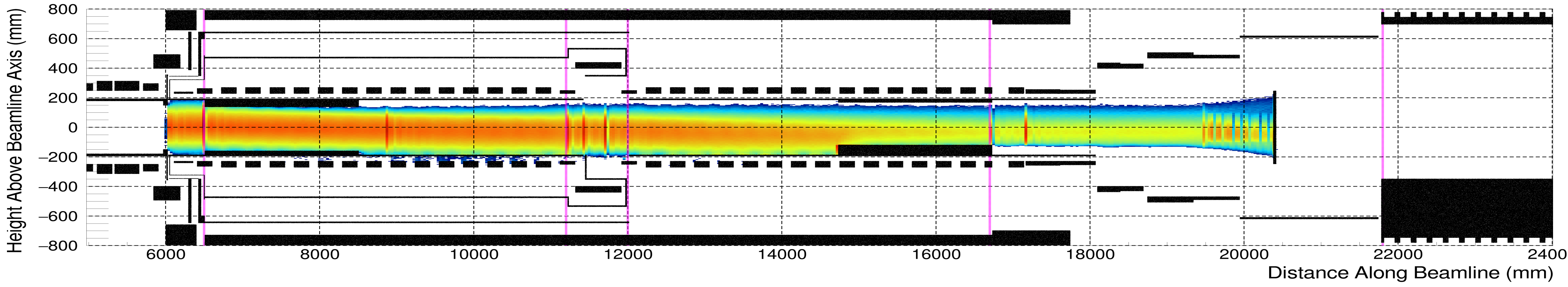
Left plot; Scalar LQ, Φ4 satisfies all b

Right plot; Allowed region from g-2 results

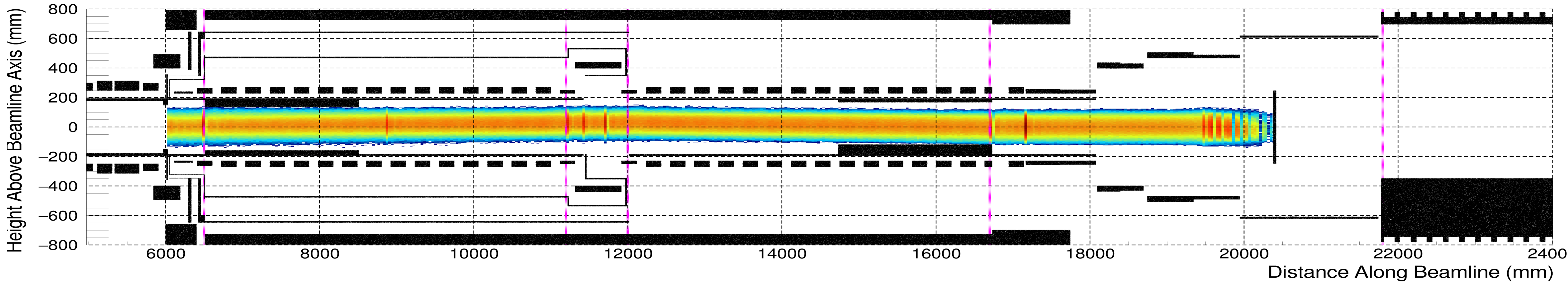
anomalies All 1σ band

→ all of them somehow satisfied

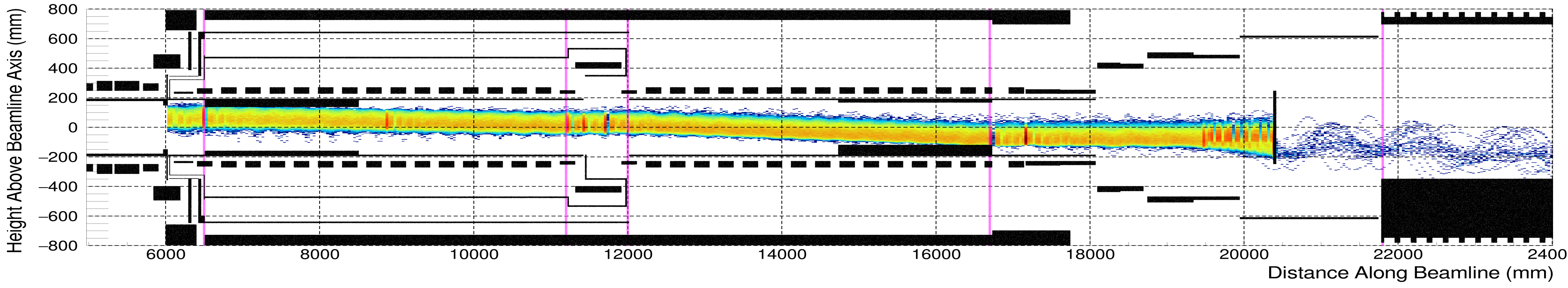
P.F. Perez, et.al. arXiv:2104.11229



(a) All Muons



(b) Stopped Muons



(c) Muons with $p > 70$ MeV/c around the stopping target