SUB-Millicharge ExperimenT (SUBMET)

Search for sub-millicharged particles at J-PARC

Hoyong Jeong (Korea University) on behalf of the SUBMET collaboration

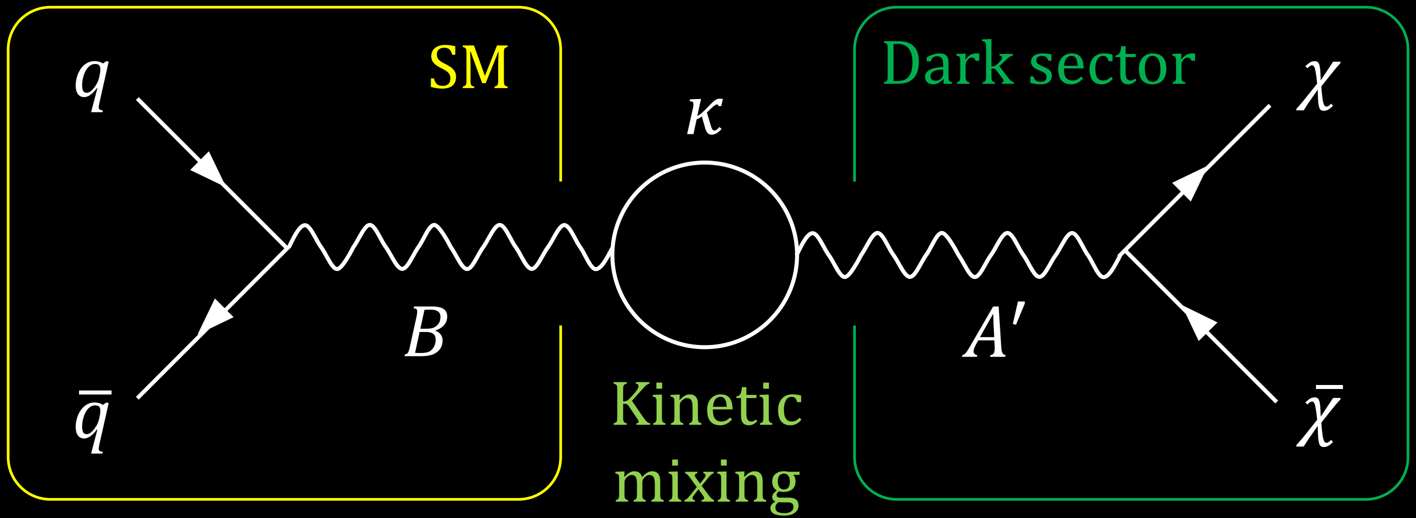
July 1st 2024

LLP2024: Fourteenth workshop of the Long-Lived Particle Community

Motivation

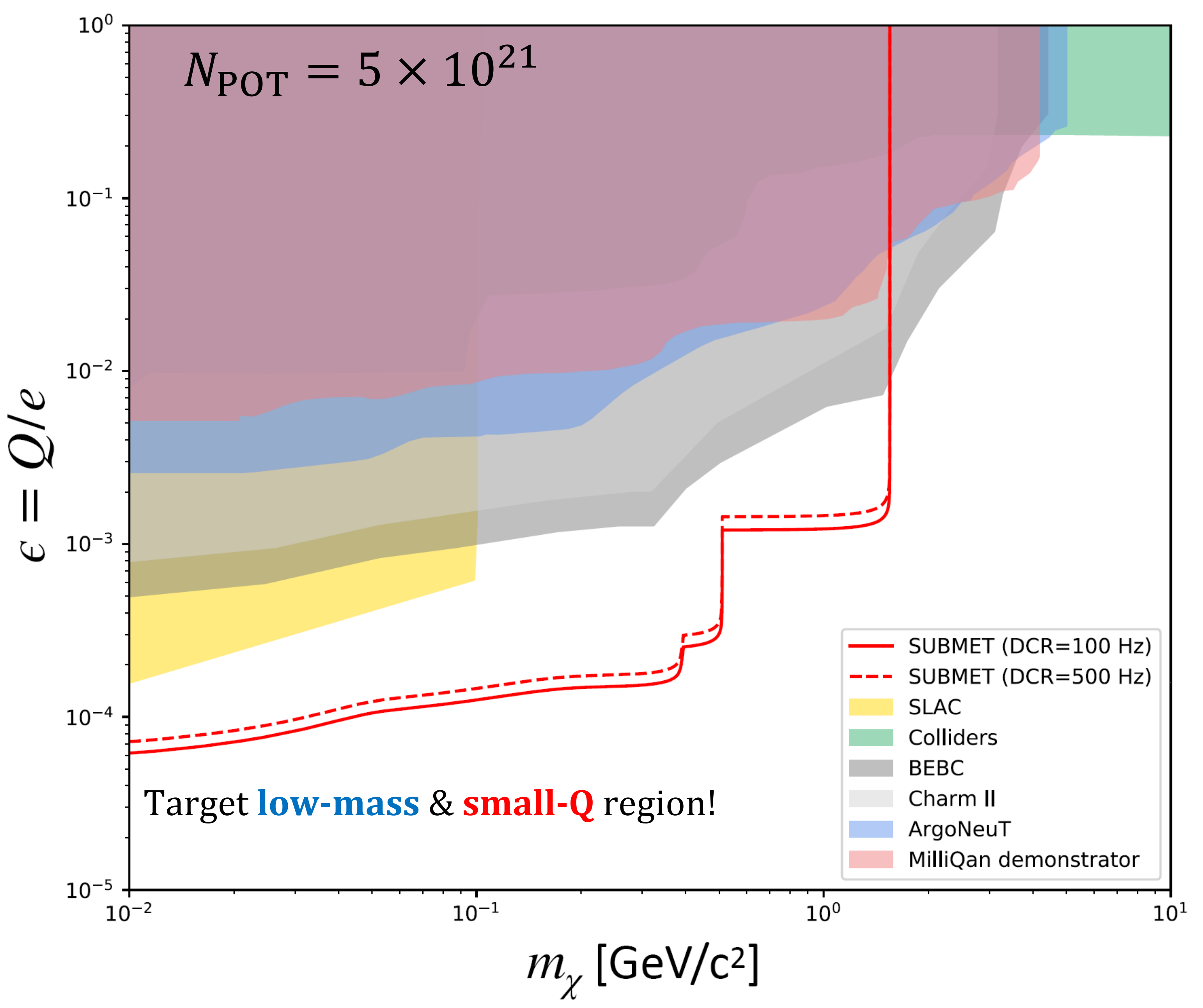
$$\mathcal{L}_{\text{dark sector}} = -\frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\chi}(\partial\!\!\!/ + ie'A\!\!\!/' + iM_{\text{mCP}})\chi - \frac{\kappa}{2}A'_{\mu\nu}B^{\mu\nu}$$

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\chi}(\partial\!\!\!/ + ie'A\!\!\!/' + i\boldsymbol{\kappa e'}B\!\!\!/ + iM_{\text{mCP}})\chi$$



New fermion (χ) can have a small EM charge: milli-charged particle.

"Kinetic mixing with a new massless 'dark' boson **can provide the link between SM and a hidden/dark sector**." (Holdom, 1985)



Largely yet unexplored region:

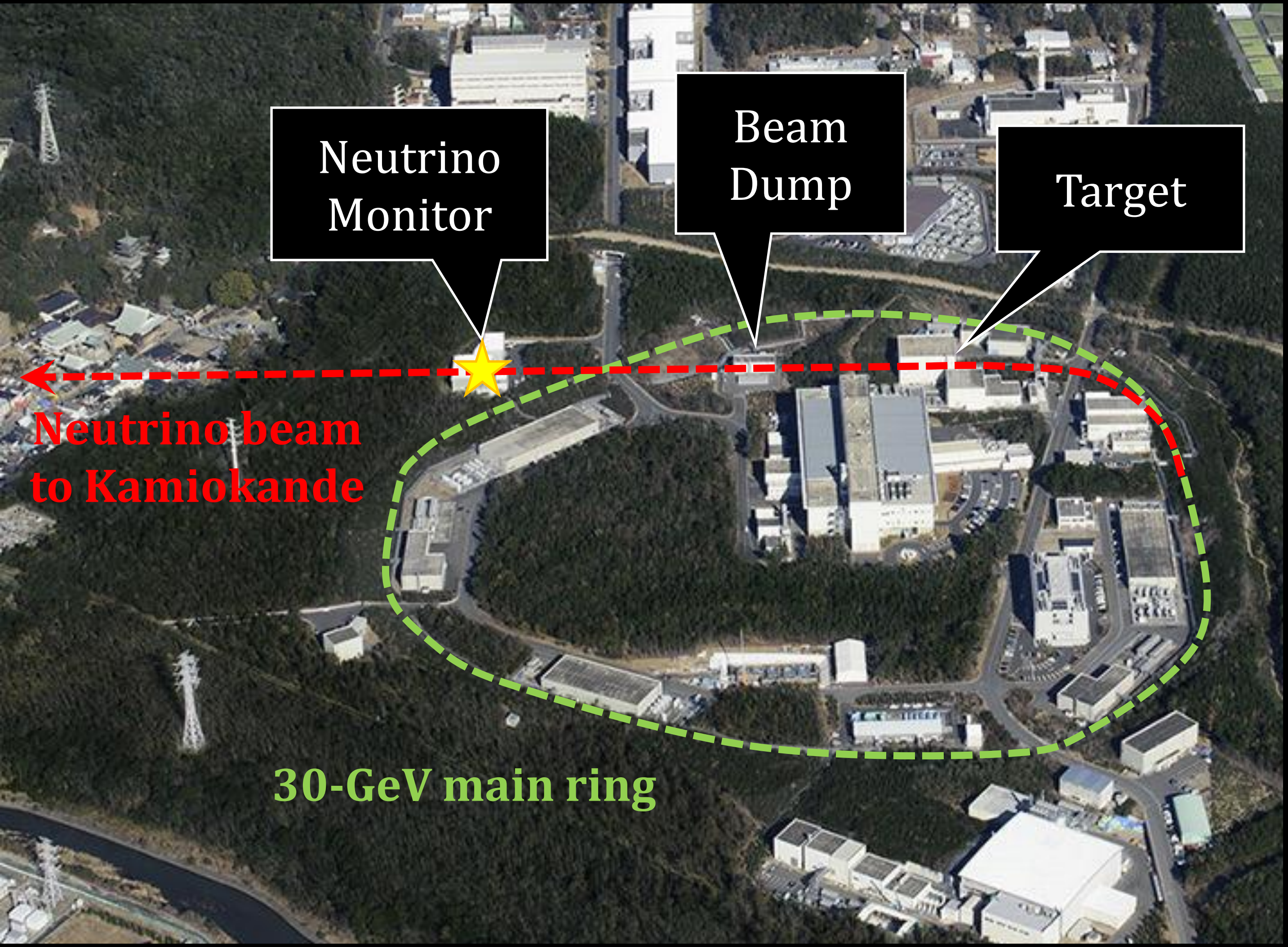
$Q < 2 \times 10^{-4} e$

and

$Q < 10^{-3} e, m_\chi > 0.1\ \mathrm{GeV/c^2}$

Scintillator-based detector using proton fixed-target collisions at J-PARC (inspired by milliQan experiment)

From https://j-parc.jp/c/en/about/outline.html



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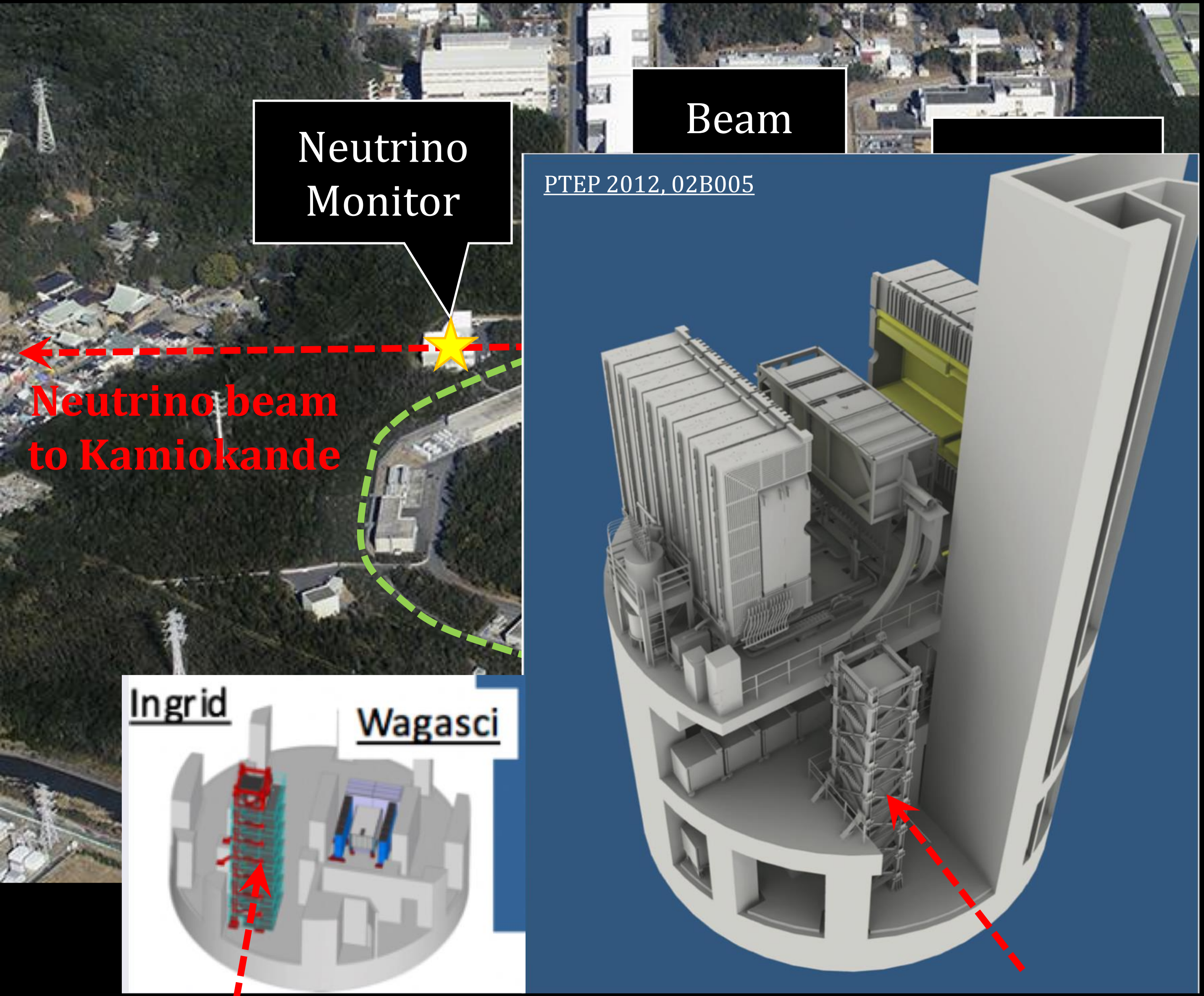

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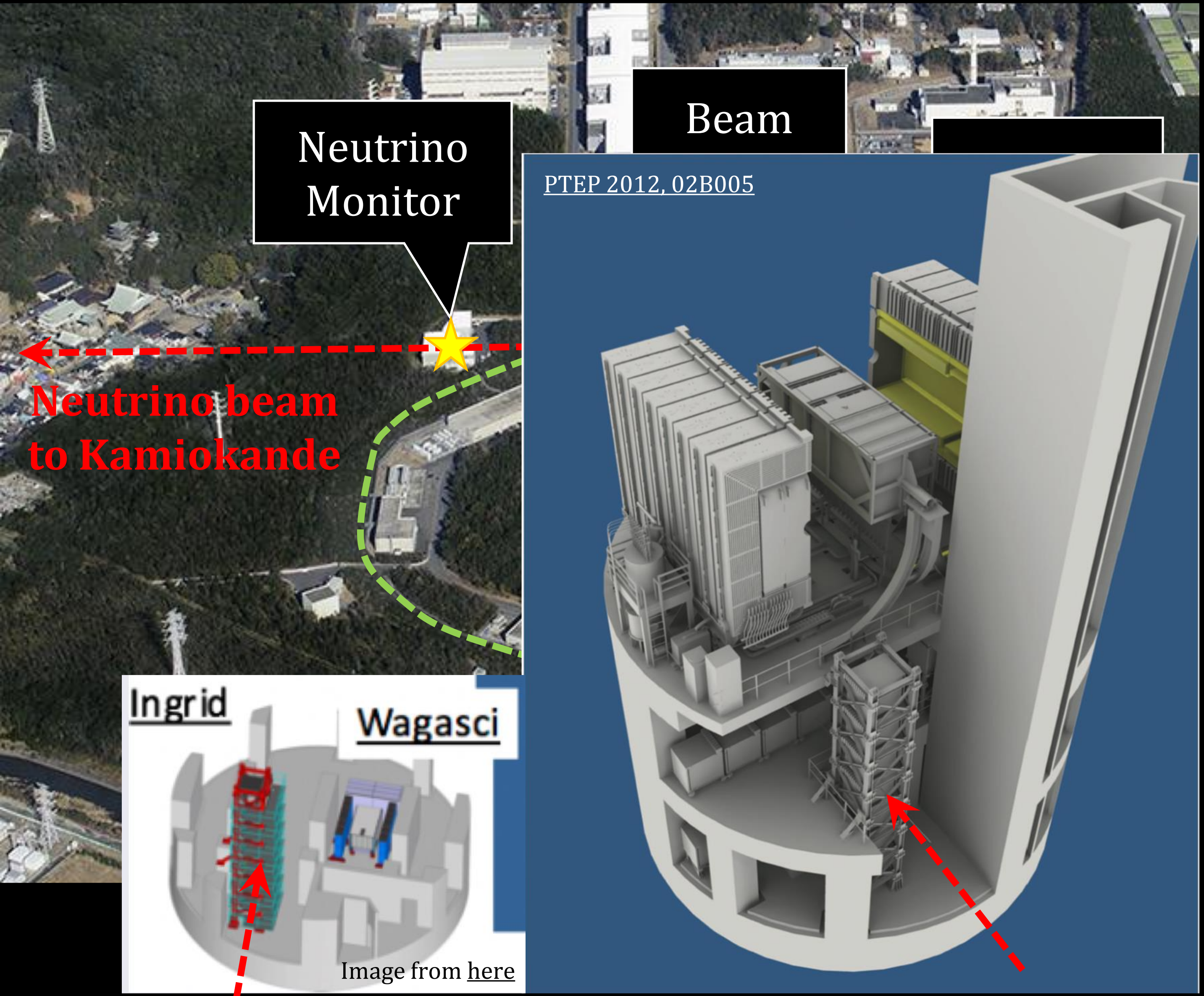
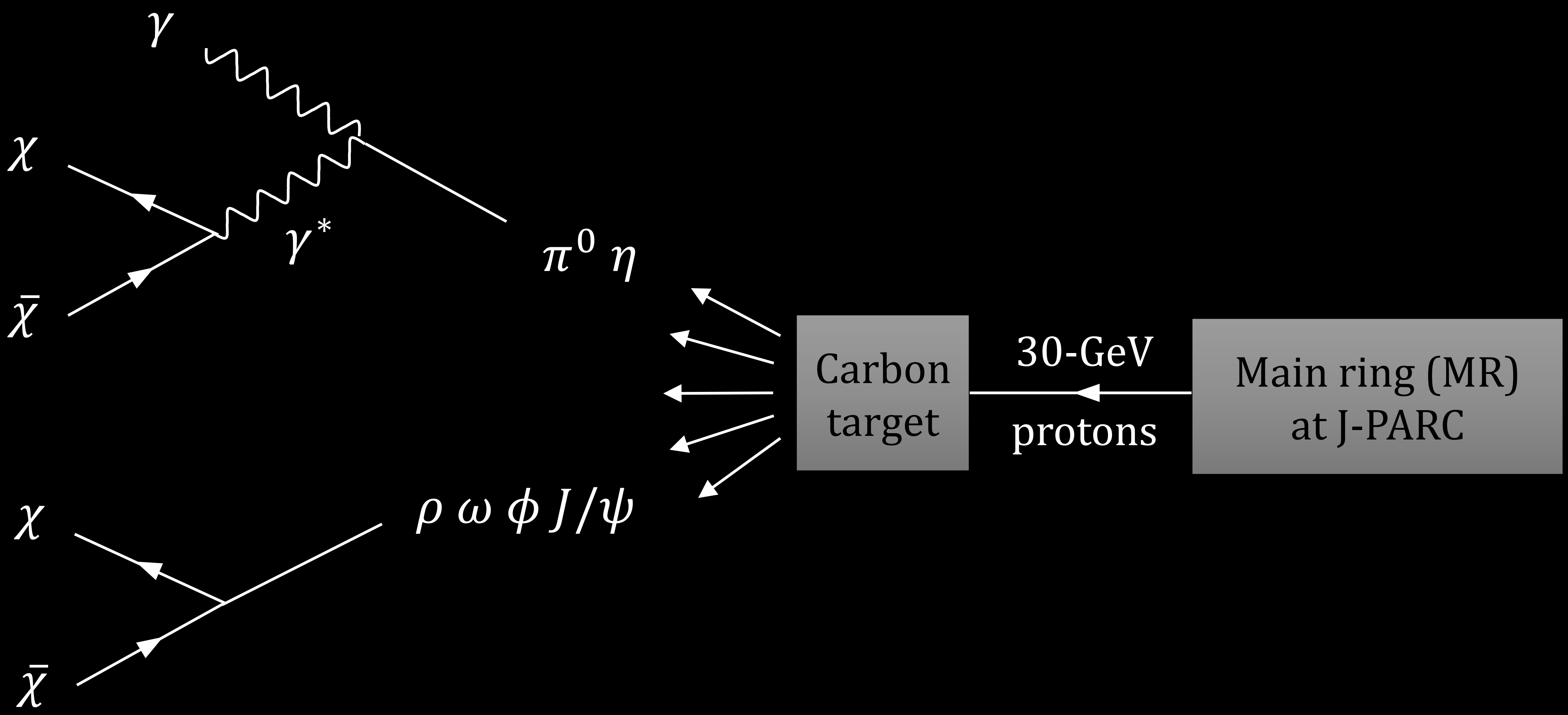
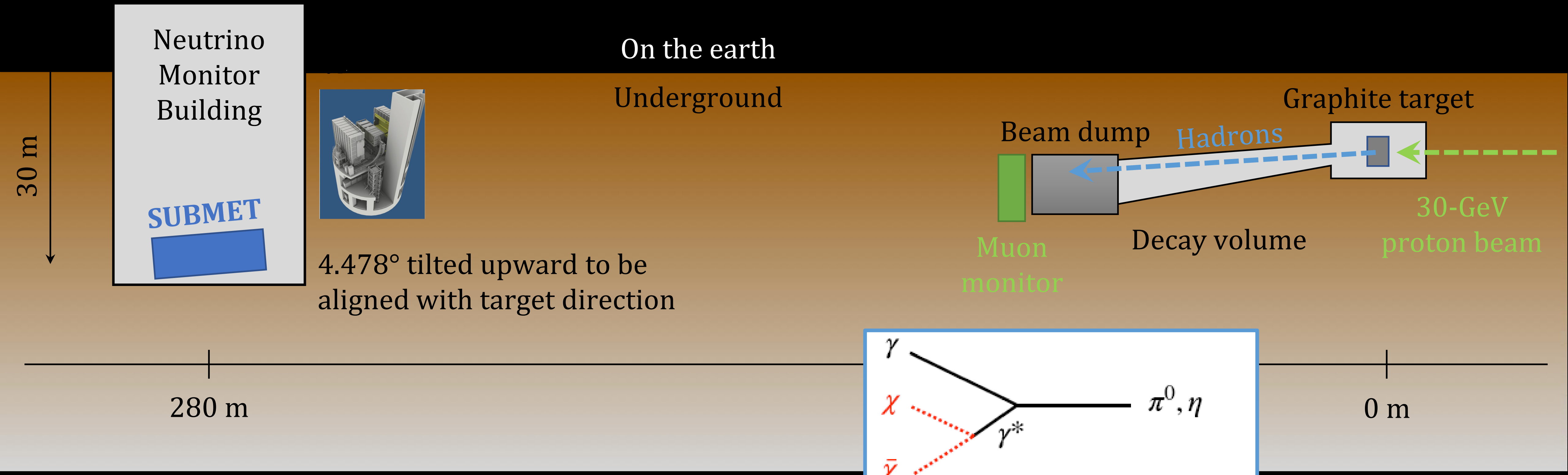
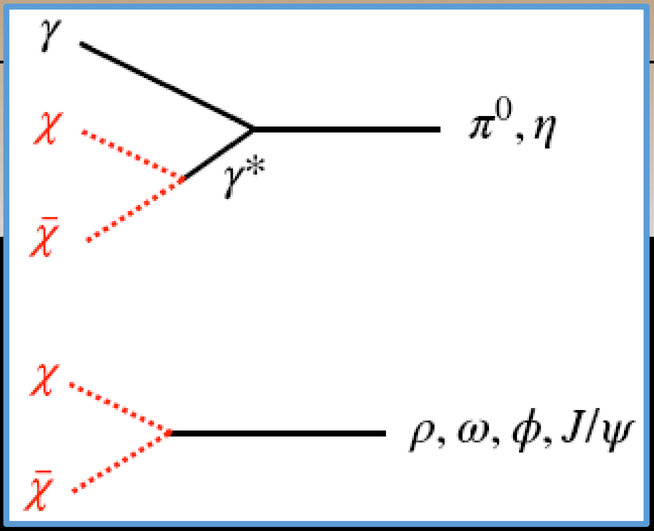


1 m × 4 m at B2
is secured for the
experiment.


γ
χ
γ^*
$\bar{\chi}$
π^0 η
χ
$\bar{\chi}$
ρ ω ϕ J/ψ
Carbon target
30-GeV
protons
Main ring (MR) at J-PARC

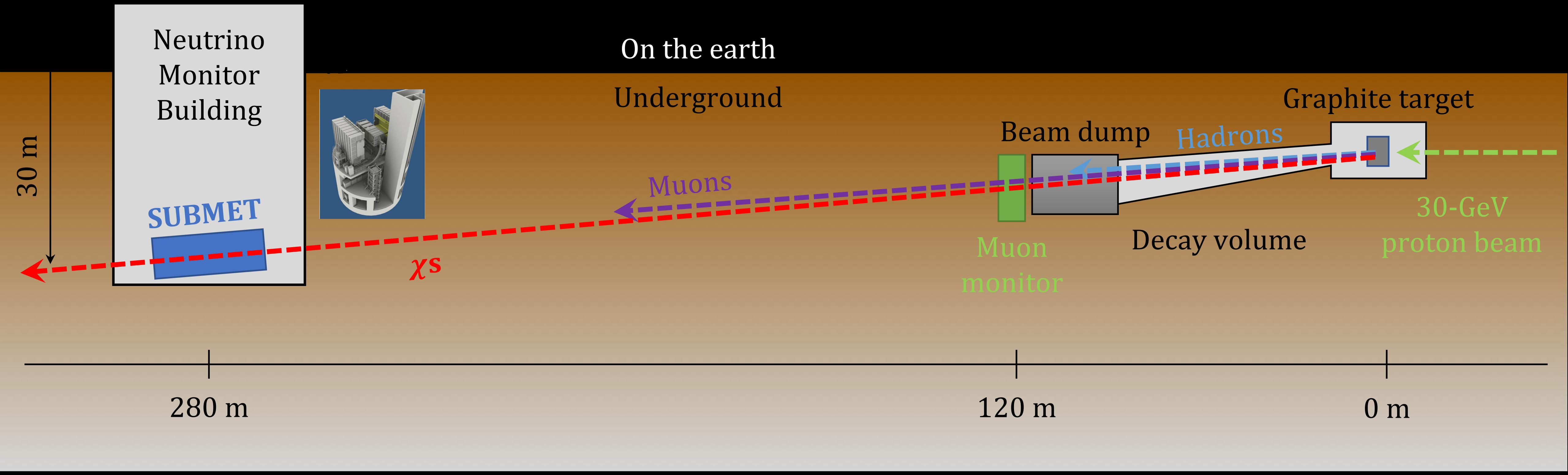
Basic Idea of χ Detection





➢ Protons hit the target and produce hadrons.

Basic Idea of χ Detection



- Hadrons stop in the Beam Dump.
- Muons lose the entire energy in sand (5 MeV/cm) before reaching NM building.
- χs reach the detector. (Energy loss for χs with $q = 10^{-3}e$ is < 0.1 MeV.)

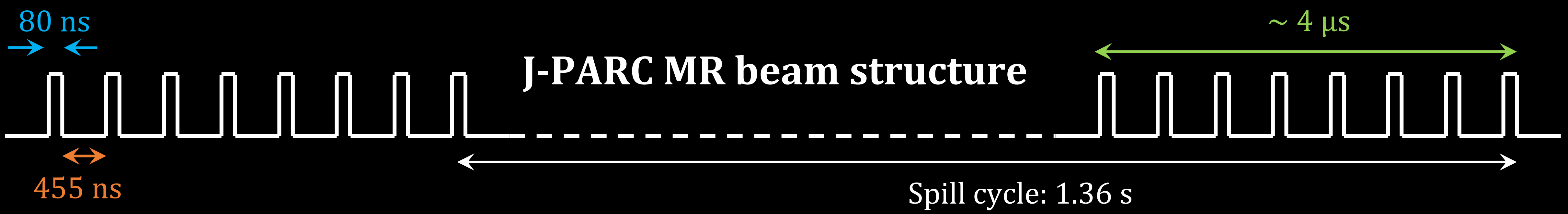
Backgrounds

PMT dark current and external radiation (major): Measured in the lab and at the experimental site

Beam-induced backgrounds: Expected to be minor

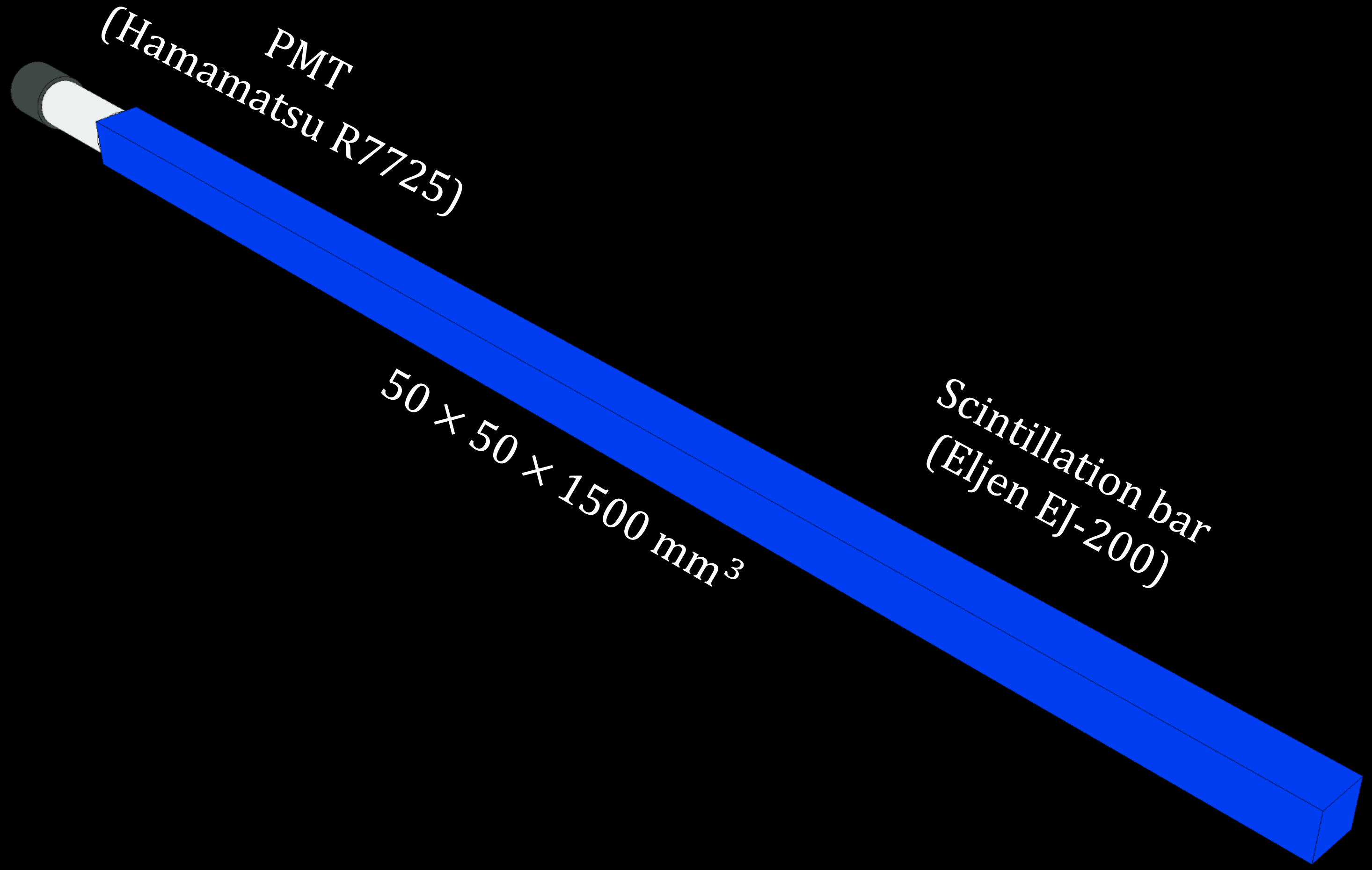
Cosmic backgrounds: Negligible based on GEANT4 simulation

- In the estimation of background, use 1.3 μs (0.16 μs × 8 bunches) per spill as a signal region
  - χs travel at $\sim c$, so 2σ of the bunch width (160 ns) should capture most of them



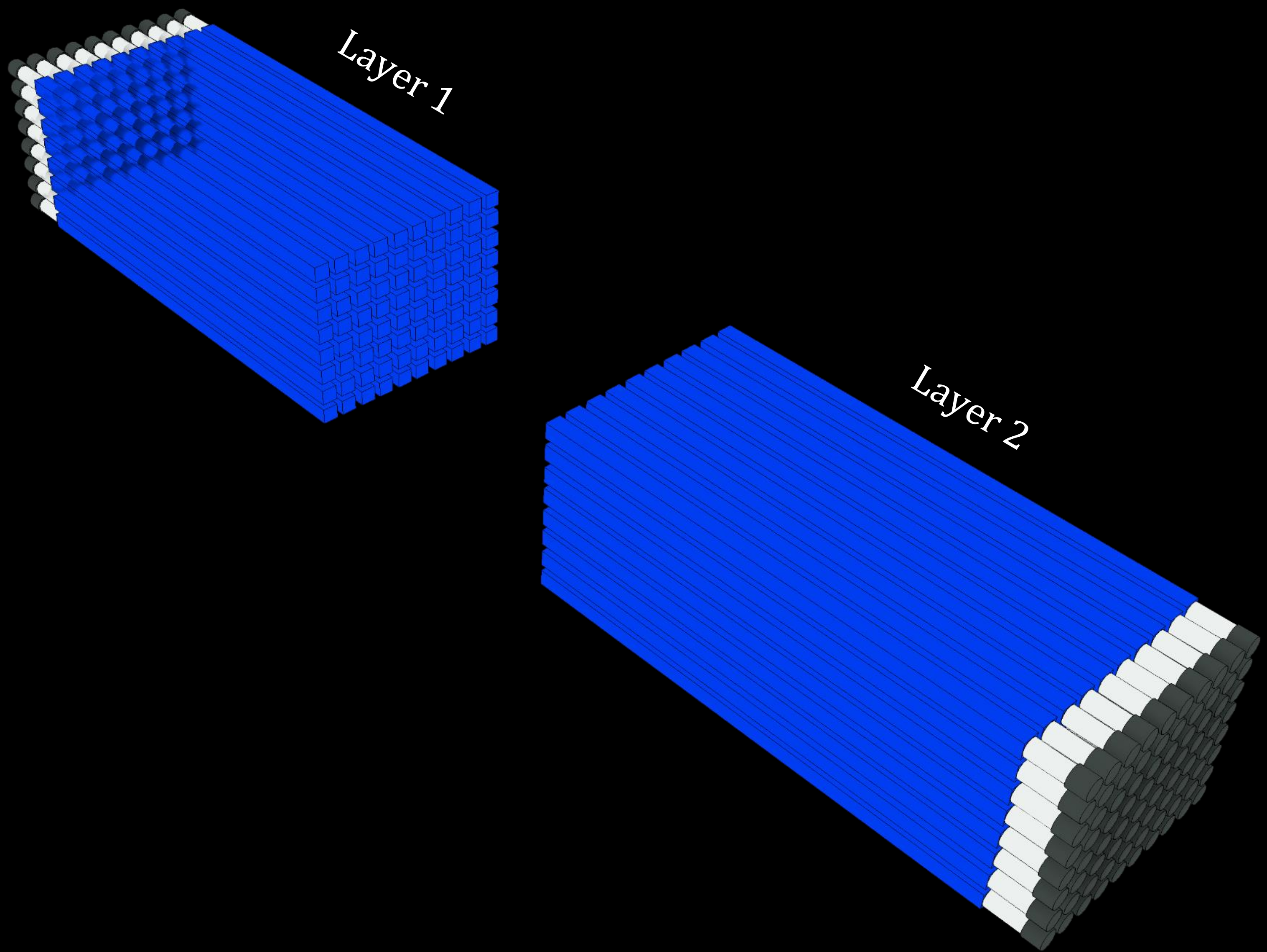
- Assume that data-taking period/year is 4 months; live time is **~ 50 sec** for 3 years

Overview of Detector Design



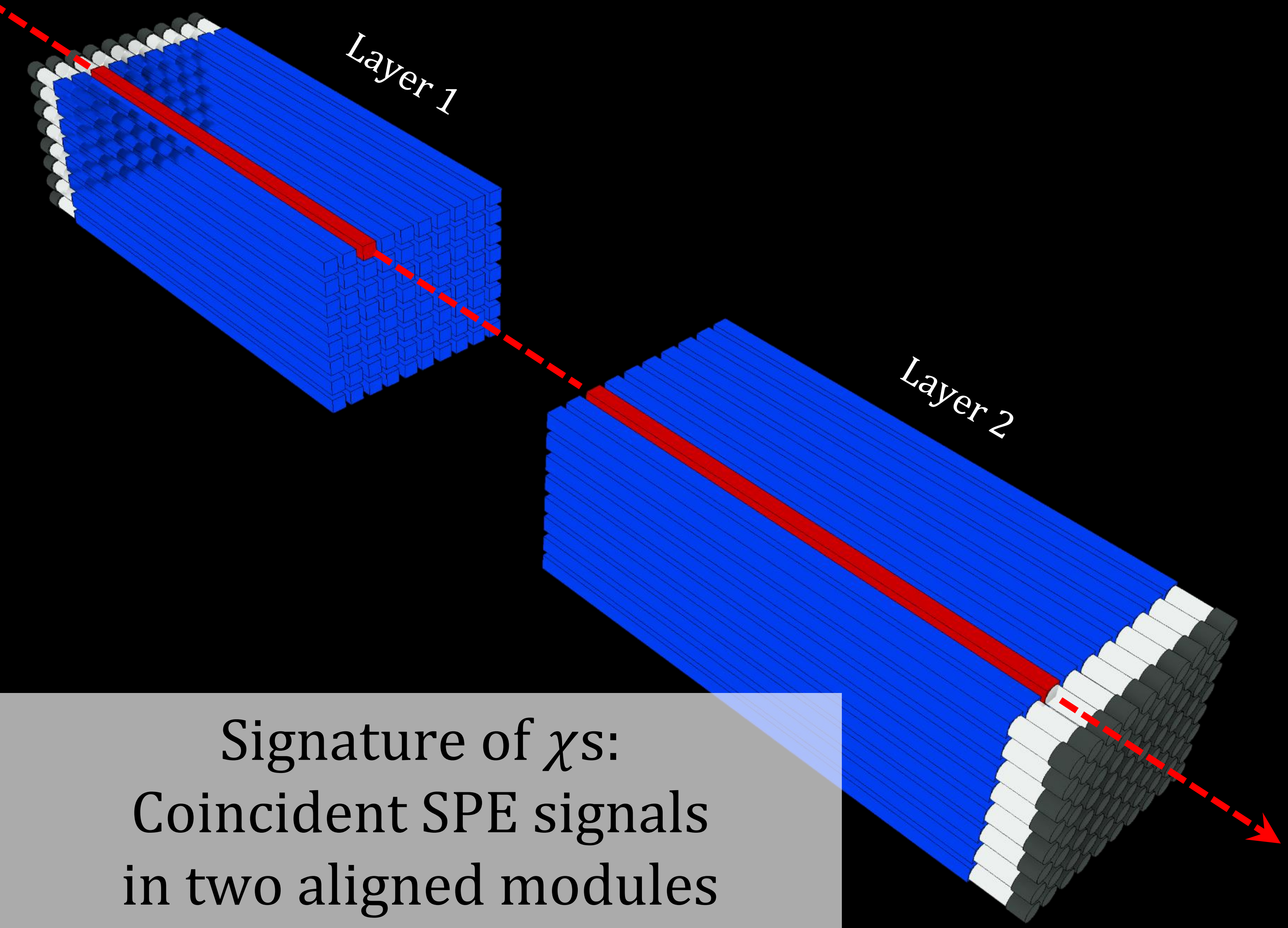
- Use **long** (1.5 m) scintillator bars so that χs with small charge can produce photons
  - For small ϵ, detect single photons

Overview of Detector Design



- ➢ Use **long** (1.5 m) scintillator bars so that χs with small charge can produce photons
  - For small ϵ, detect single photons
- ➢ **Stack** (10×8) scintillators to increase total volume
- ➢ Use **two layers** to control backgrounds

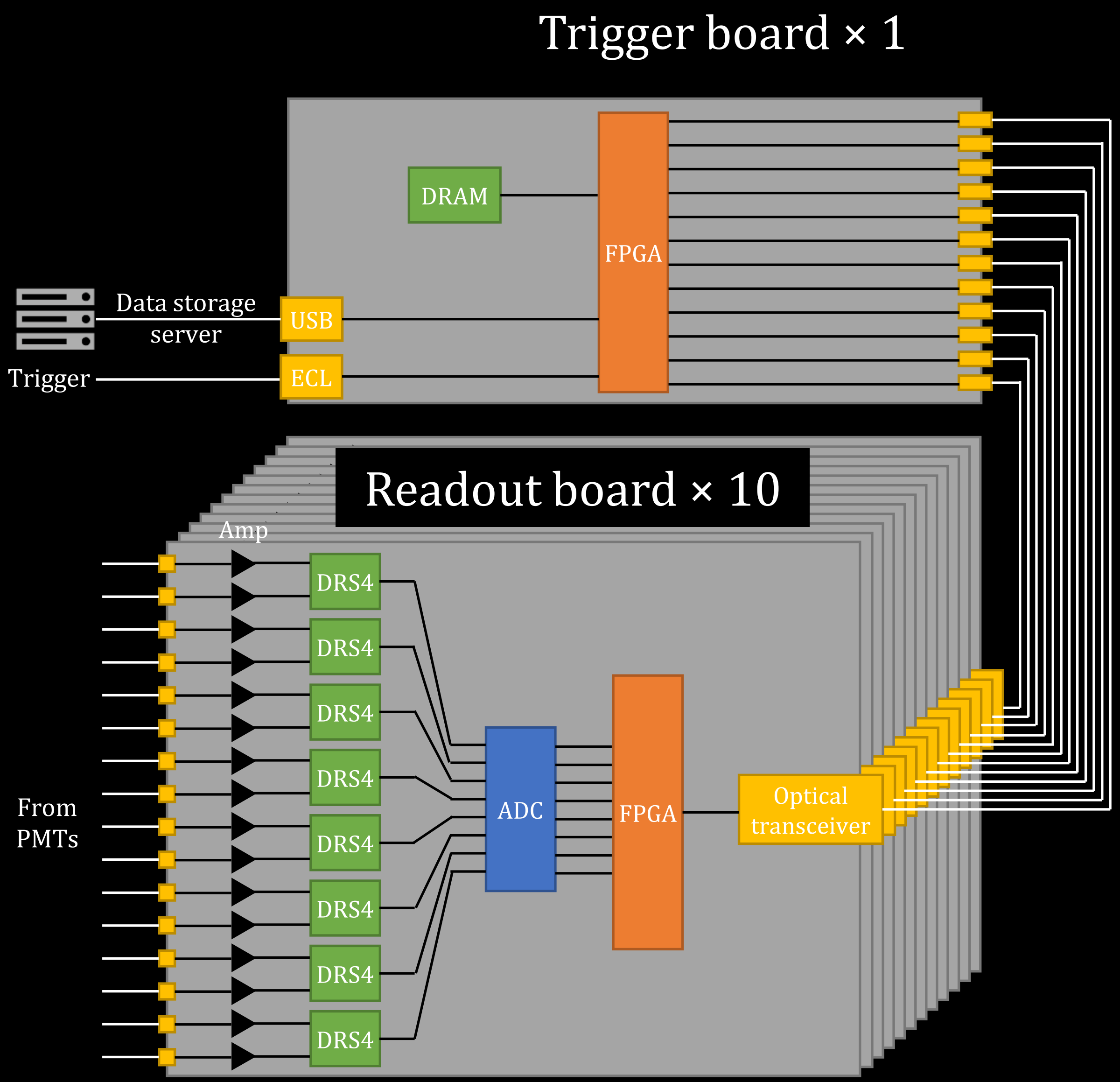
Overview of Detector Design



- Use **long** (1.5 m) scintillator bars so that χs with small charge can produce photons
  - For small ϵ, detect single photons
- **Stack** (10×8) scintillators to increase total volume
- Use **two layers** to control backgrounds
- **Align** the two layers such that a goes through them

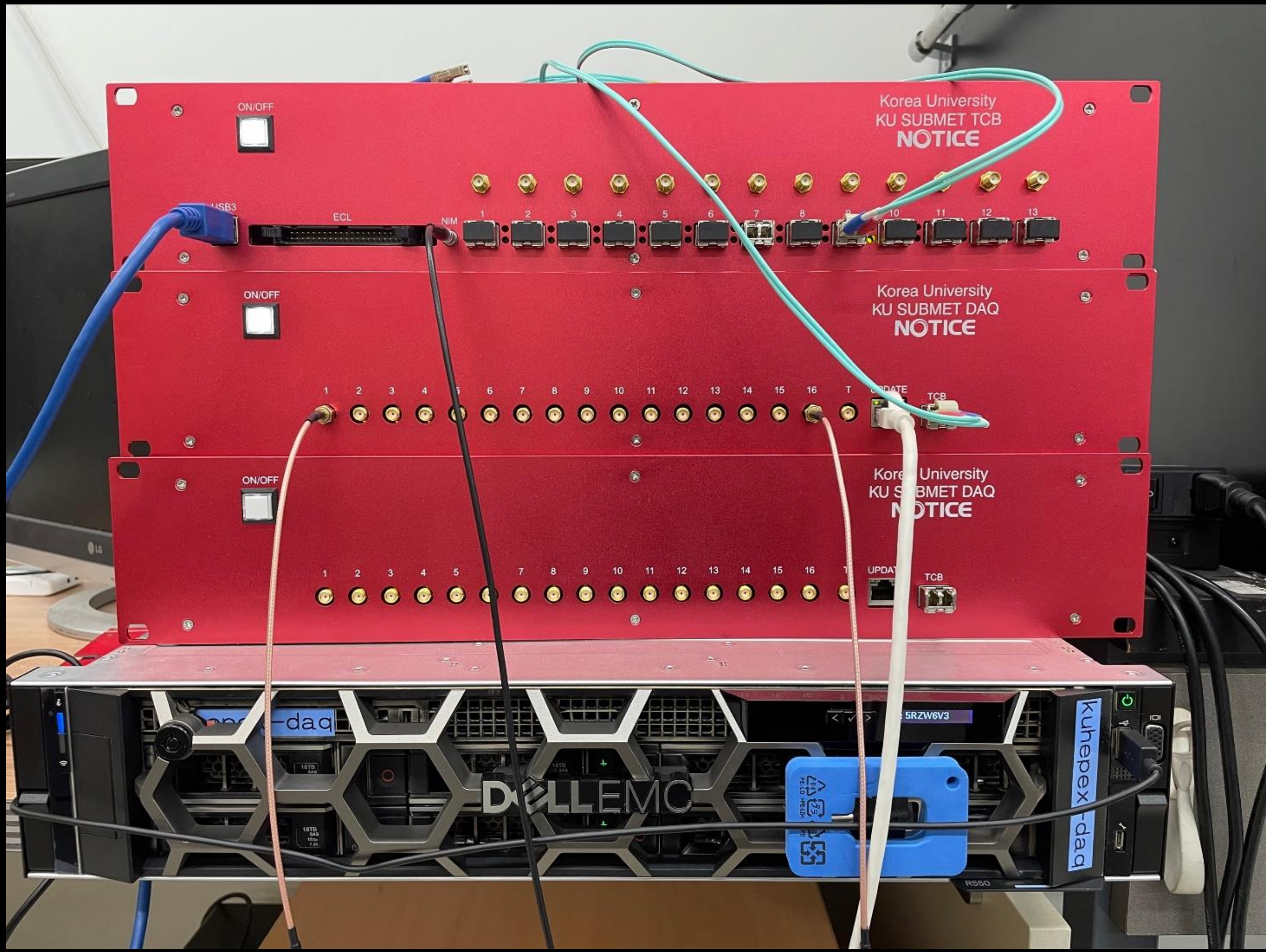
Signature of χs:
Coincident SPE signals
in two aligned modules

Readout

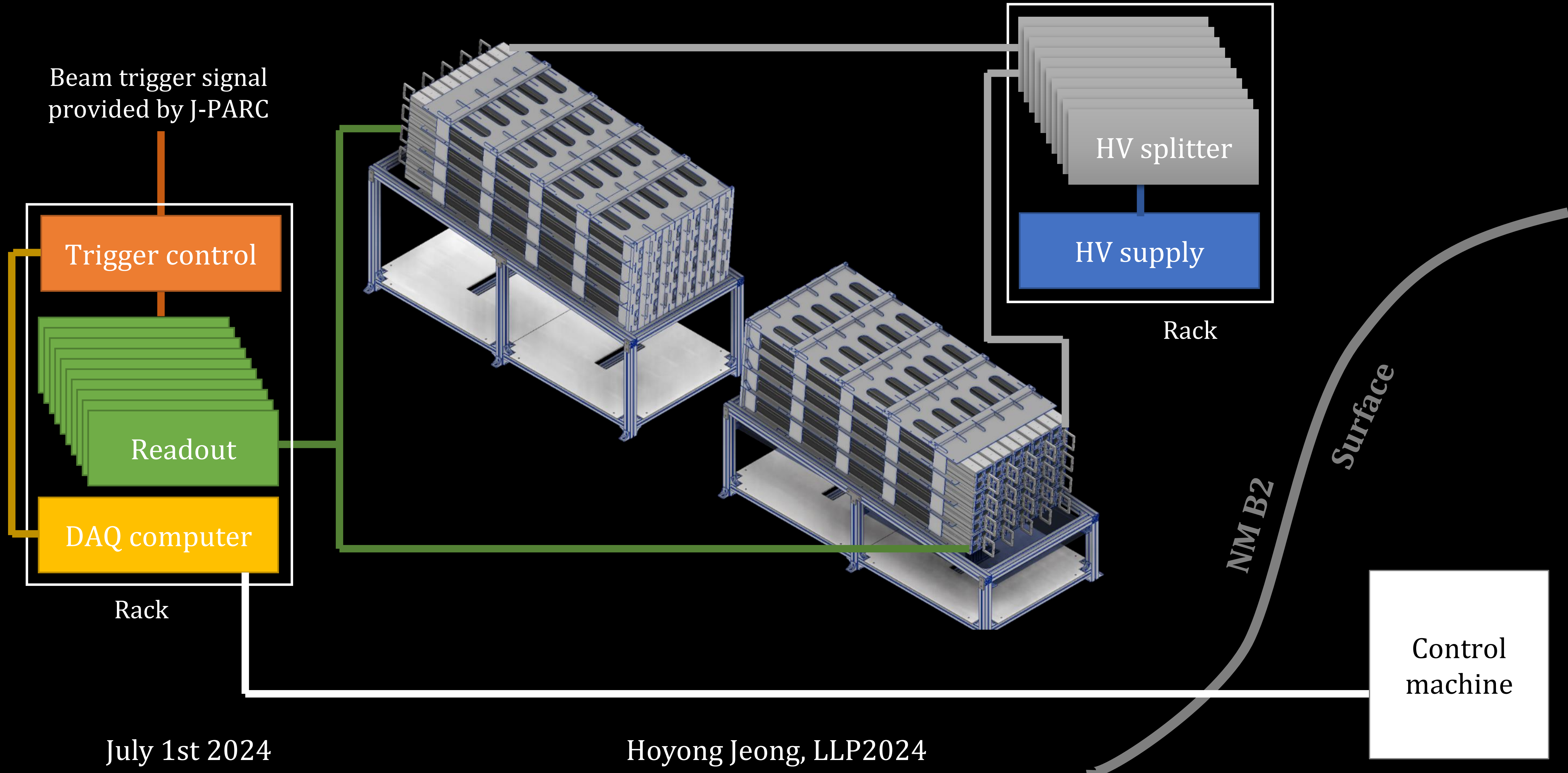


Sensitive and fast enough to detect single photo-electric (SPE) signal (~ 50 mV, ~ 20 ns)

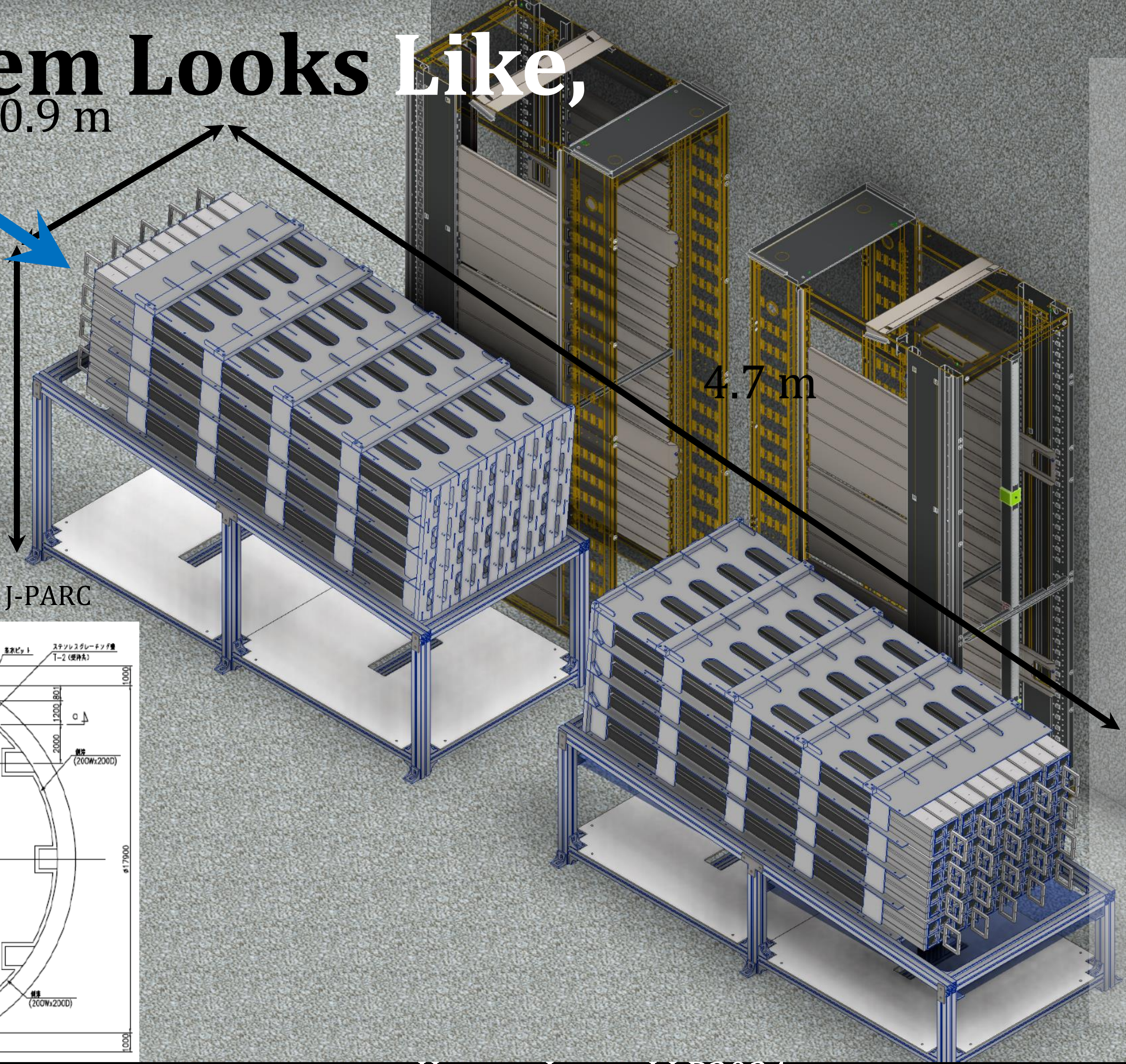
DAQ: Custom **DRS4**-based readout systems



Overview of Detector Design

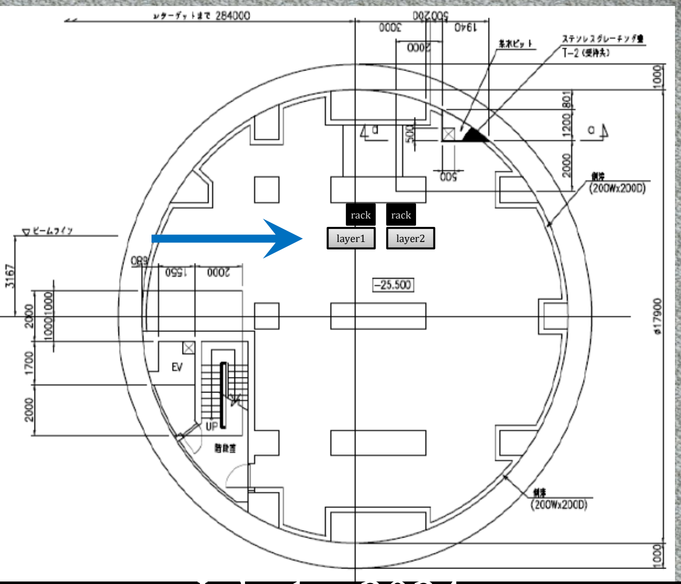


Full System Looks Like,



- 1,000 kg
- 2,450 pieces
- 160 modules (PMTs + Scints)
- 2 racks
- 10 readout boards
- 1 trigger boards
- 1 DAQ server
- 10 HV splitters
- 1 HV supply
- 160 signal cables (total length 1.2 km)
- 160 HV cables (total length 1.2 km)
- 72 HV short cables (total length 0.2 km)

Neutrino Monitor building, J-PARC

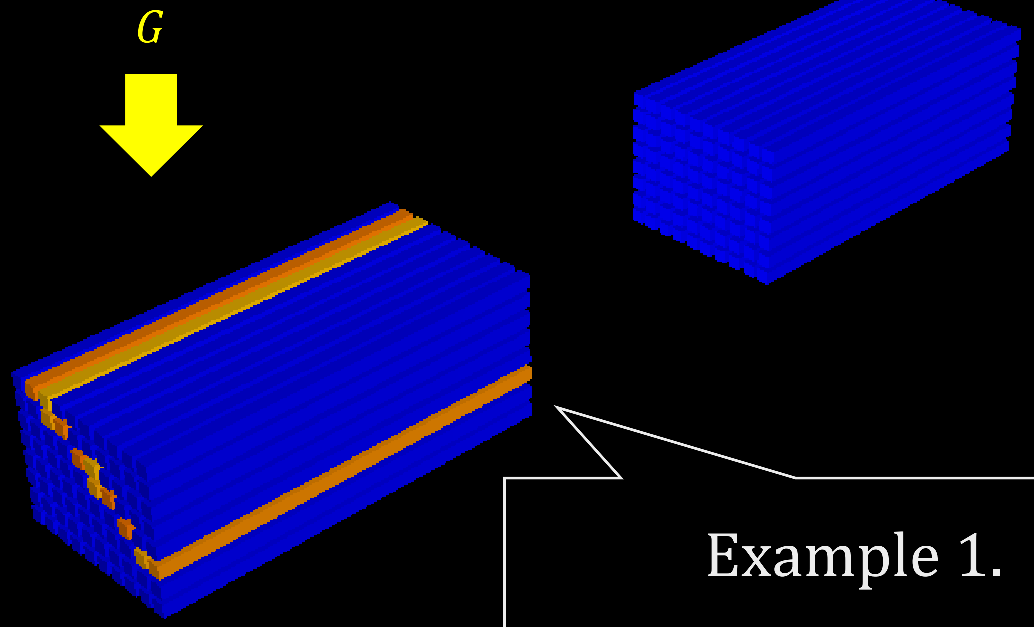


Full system test in Korea,
before going to J-PARC.
(April 2024)

Cosmic Run

- ➢ Run configuration
  - 10 Hz external periodic triggering
  - 12 hours = 432,000 triggered events
  - 1300 V applied to all modules
  - All 160 channels on
- ➢ Cosmic track selection
  - Pulses in a same time window
  - Pulse height more than 0.56 V
  - At least 7 hits in a row
- ➢ Result
  - 279 events detected

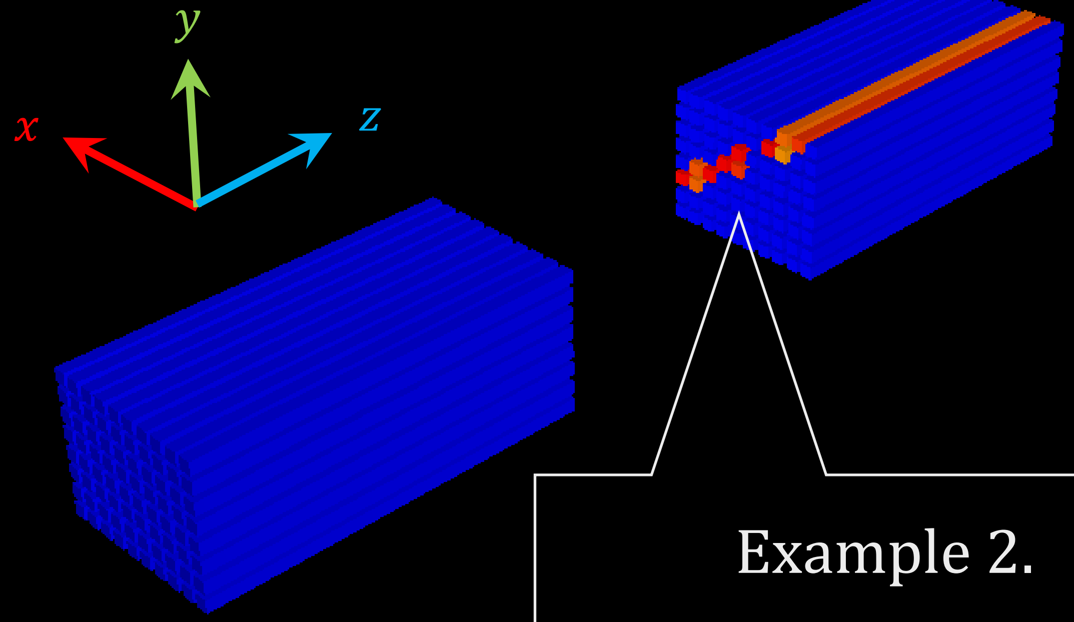
Cosmic Event Visualization



Example 1.

A track

passing through **layer1**



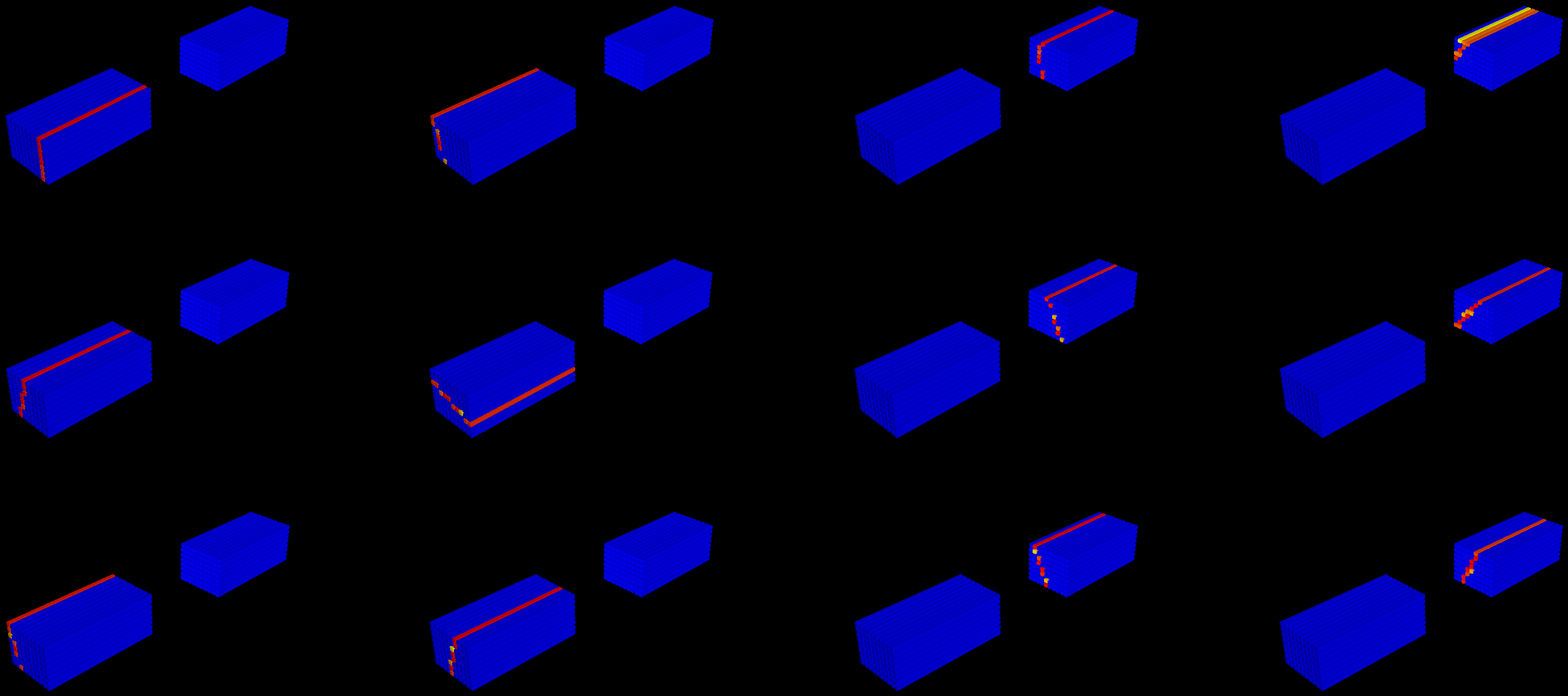
Example 2.

A track

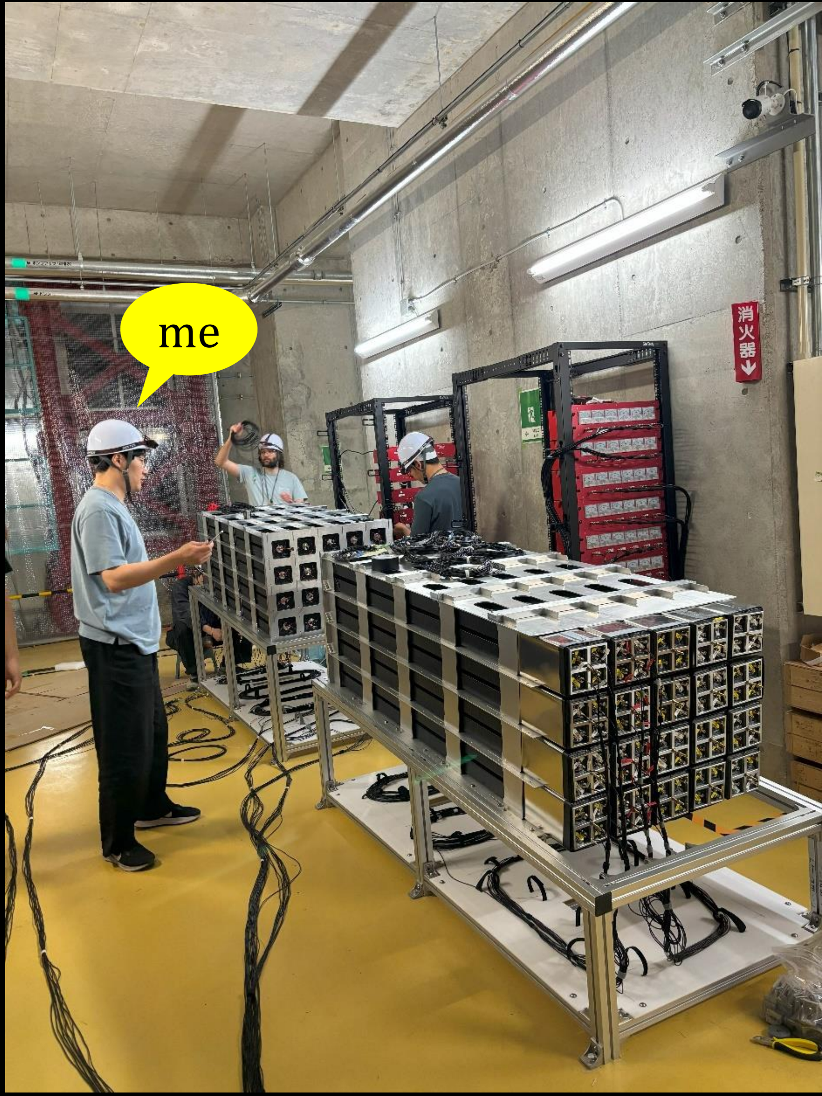
passing through **layer2**

(Color scale: 17 V·ns to 68 V·ns in pulse area)

More Events



Installation Photos in J-PARC



History of SUBMET

Letter of Intent: Search for sub-millicharged particles at J-PARC

Suyong Choi[1], Jeong Hwa Kim[1], Eunil Won[1], Jae Hyeok Yoo[1], Matthew Citron[2], David Stuart[2], Christopher S. Hill[3], Andy Haas[4], Jihad Sahili[5], Haitham Zaraket[5], A. De Roeck[6], and Martin Gastal[6]

[1]Korea University, Seoul, Korea
[2]University of California, Santa Barbara, California, USA
[3]The Ohio State University, Columbus, Ohio, USA
[4]New York University, New York, New York, USA
[5]Lebanese University, Hadeth-Beirut, Lebanon
[6]CERN, Geneva, Switzerland

LOI

Abstract

We propose a new experiment sensitive to the detection of millicharged particles produced at the 30 GeV proton fixed-target collisions at J-PARC. The potential site for the experiment is B2 of the Neutrino Monitor building, 280 m away from the target. With $N_{POT} = 10^{22}$, the experiment can provide sensitivity to particles with electric charge $3 \times 10^{-4} e$ for mass less than 0.2 GeV/c^2 and $1.5 \times 10^{-3} e$ for mass less than 1.6 GeV/c^2. This brings a substantial extension to the current constraints on the charge and the mass of such particles.

Proposal: Search for sub-millicharged particles at J-PARC

SUB-Millicharge ExperimenT (SUBMET)

Sungwoong Cho[1], Suyong Choi[1], Jeong Hwa Kim[1], Eunil Won[1], Jae Hyeok Yoo[1], Claudio Campagnari[2], Matthew Citron[2], David Stuart[2], Christopher S. Hill[3], Andy Haas[4], Jihad Sahili[5], Haitham Zaraket[5], A. De Roeck[6], and Martin Gastal[6]

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Proposal

Abstract

We propose a new experiment searching for sub-millicharged particles (χs) using 30 GeV proton fixed-target collisions at J-PARC. The detector is composed of two layers of stacked scintillator bars and PMTs and is proposed to be installed 280 m from the target. The main background is a random coincidence between two layers due to dark counts in PMTs, which can be reduced to a negligible level using the timing of the proton beam. With $N_{POT} = 5\times10^{21}$ which corresponds to running the experiment for three years, the experiment provides sensitivity to χs with the charge down to $6 \times 10^{-5} e$ in $m_\chi < 0.2$ GeV/c^2 and $10^{-3} e$ in $m_\chi < 1.6$ GeV/c^2. This is the regime largely uncovered by the previous experiments.

Technical Design Report

E83: Search for sub-millicharged particles at J-PARC

SUB-Millicharge ExperimenT (SUBMET)

Sungwoong Cho[1], Suyong Choi[1], Seokju Chung[1], Hoyong Jeong[1], Hyunki Moon[1], Eunil Won[1], Jae Hyeok Yoo[1], Matthew Citron[2], Claudio Campagnari[3], Jeong Hwa Kim[3], Ryan Schmitz[3], David Stuart[3], Christopher S. Hill[4], Andy Haas[5], Ayman Youssef[6], Ahmad Zaraket[6], Haitham Zaraket[6], A. De Roeck[7], and Martin Gastal[7]

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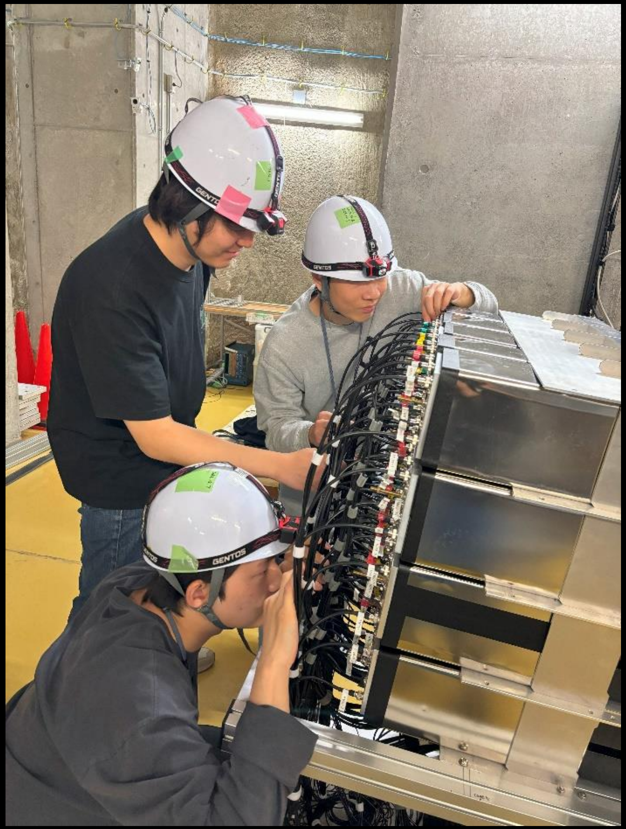
[7]CERN, Geneva, Switzerland

TDR

2020	2021	2022	2023

- LOI submitted in summer 2020
- Proposal submitted in summer 2021 (32nd PAC meeting)
- Stage-I approval April 2022
- TDR submitted Nov 2022
- FIFC meeting Dec 2022
- Request for stage-II approval in Jan 2023 (35th PAC meeting)

This Year,



NOW

6/4 ~

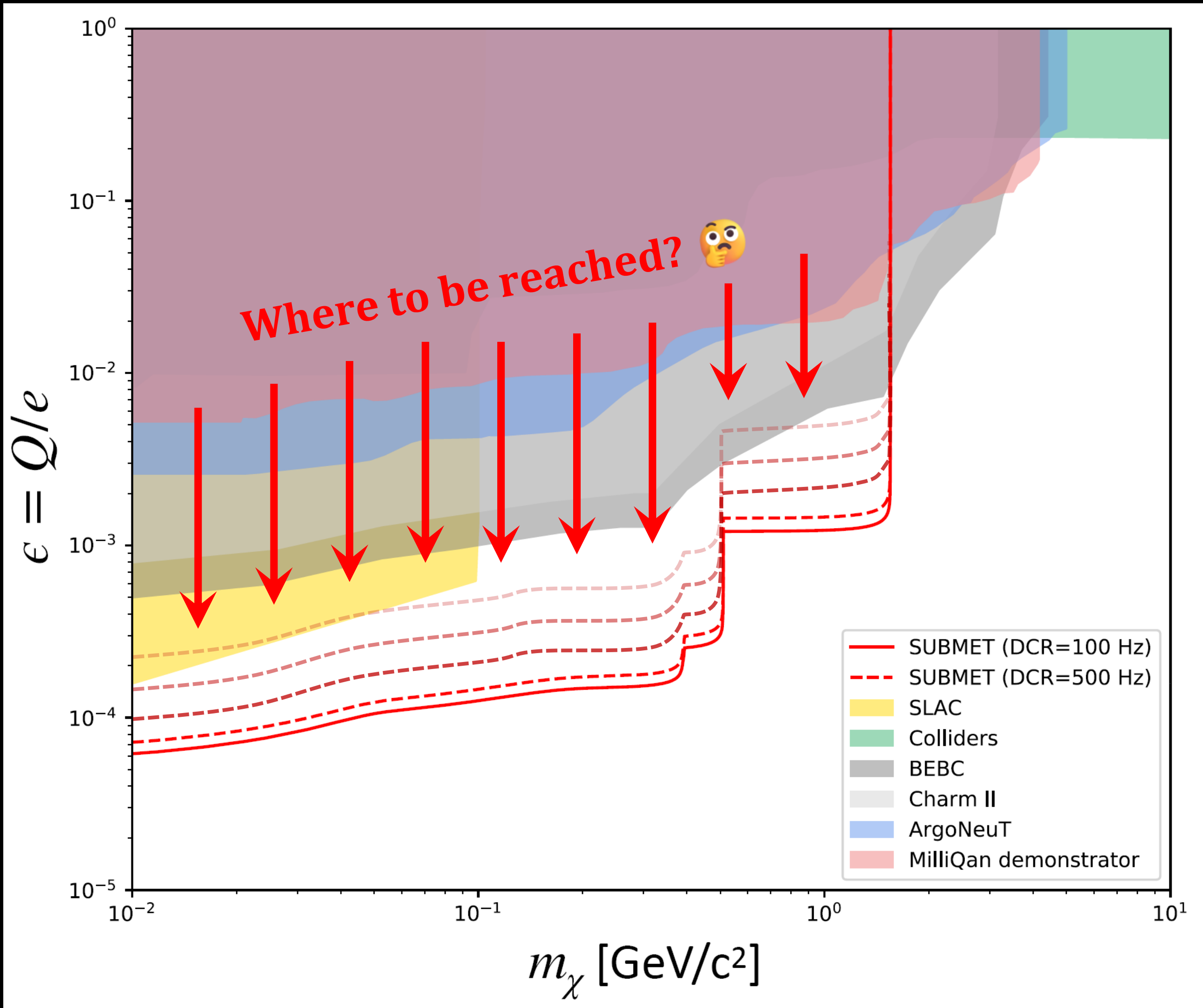
Mar 2024 | Apr 2024 | May 2024 | Jun 2024

- **Mar 2024:** Finalize detector R&D, fabrication
- **Apr 2024:** Full system test in Korea, Shipping to Japan
- **May 2024:** Installation, Commissioning
- **Jun 2024:** Data taking

J-PARC ν Beam Operation In June

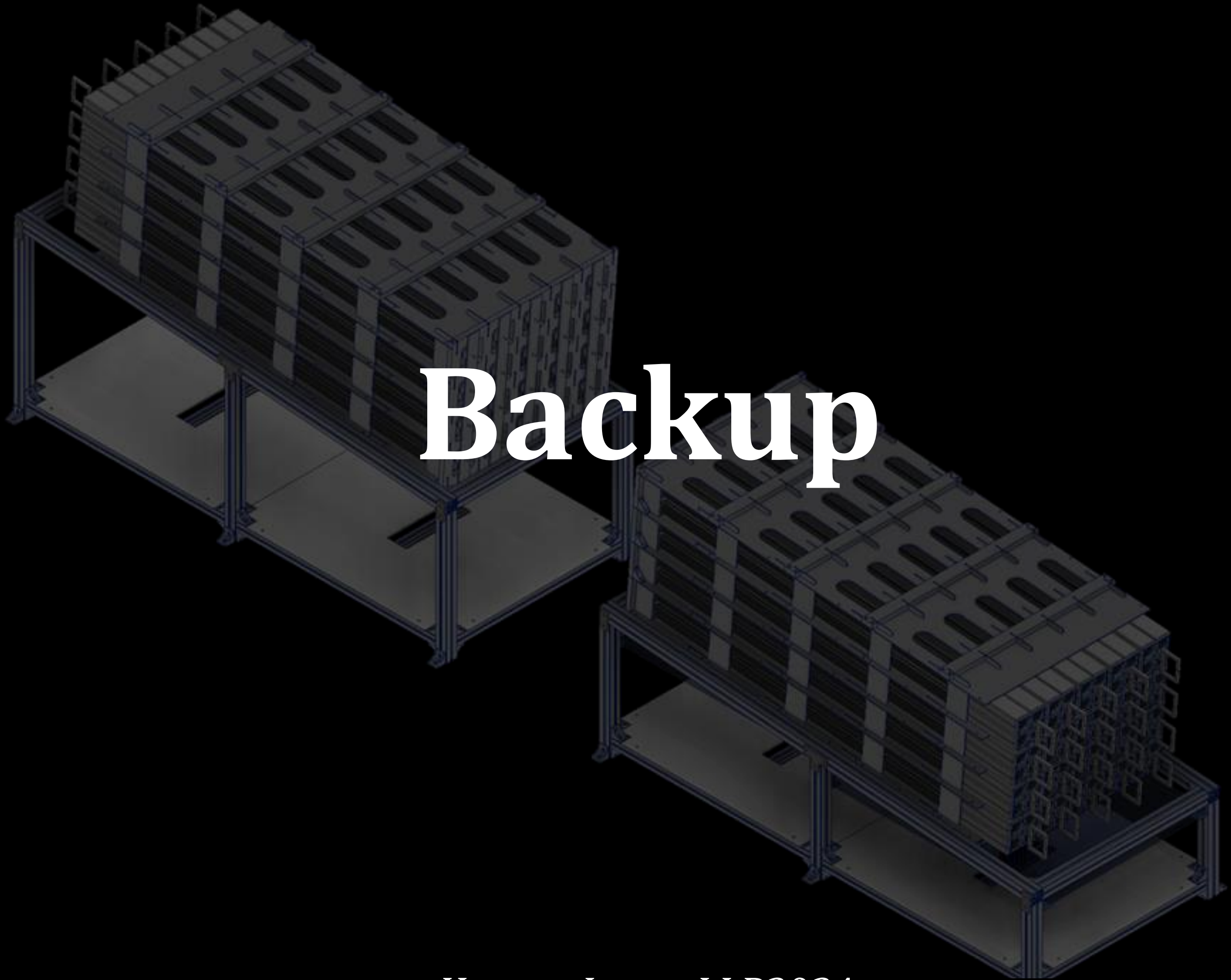
- Data-taking result
  - **Full system working w/o problem**
  - 4th ~ 28th in June ~~~ 4th in July~~
  - ~ 900k triggered events
  - Live time ~ 4 sec
  - About **8%** of goal statistics

Data analyzed soon.
Stay Tuned!



Thank you

Backup



The Team

Sungwoong Cho
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Hoyong Jeong
Hyunki Moon
Changhyun Seo
Eunil Won
Jae Hyeok Yoo

Claudio Campagnari
Jeong Hwa Kim
David Stuart
Ryan Schmitz

Matthew Citron
Juan Salvador Tafoya Vargas*

Christopher S. Hill
Collin Zheng*
Ryan De Los Santos*

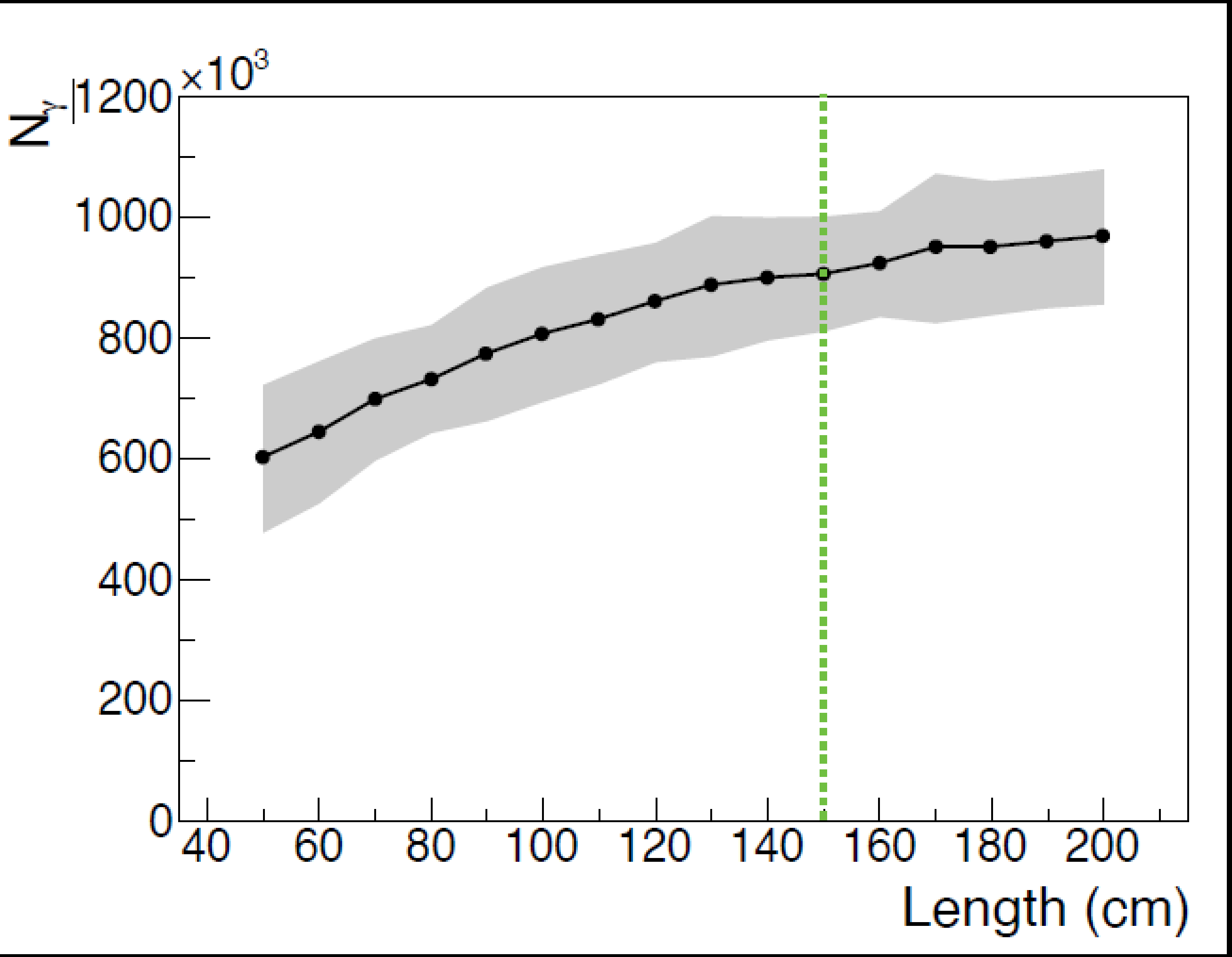
Andy Haas

Jihad Sahili
Ayman Youssef
Ahmad Zaraket
Haitham Zaraket

Albert De Roeck
Martin Gastal

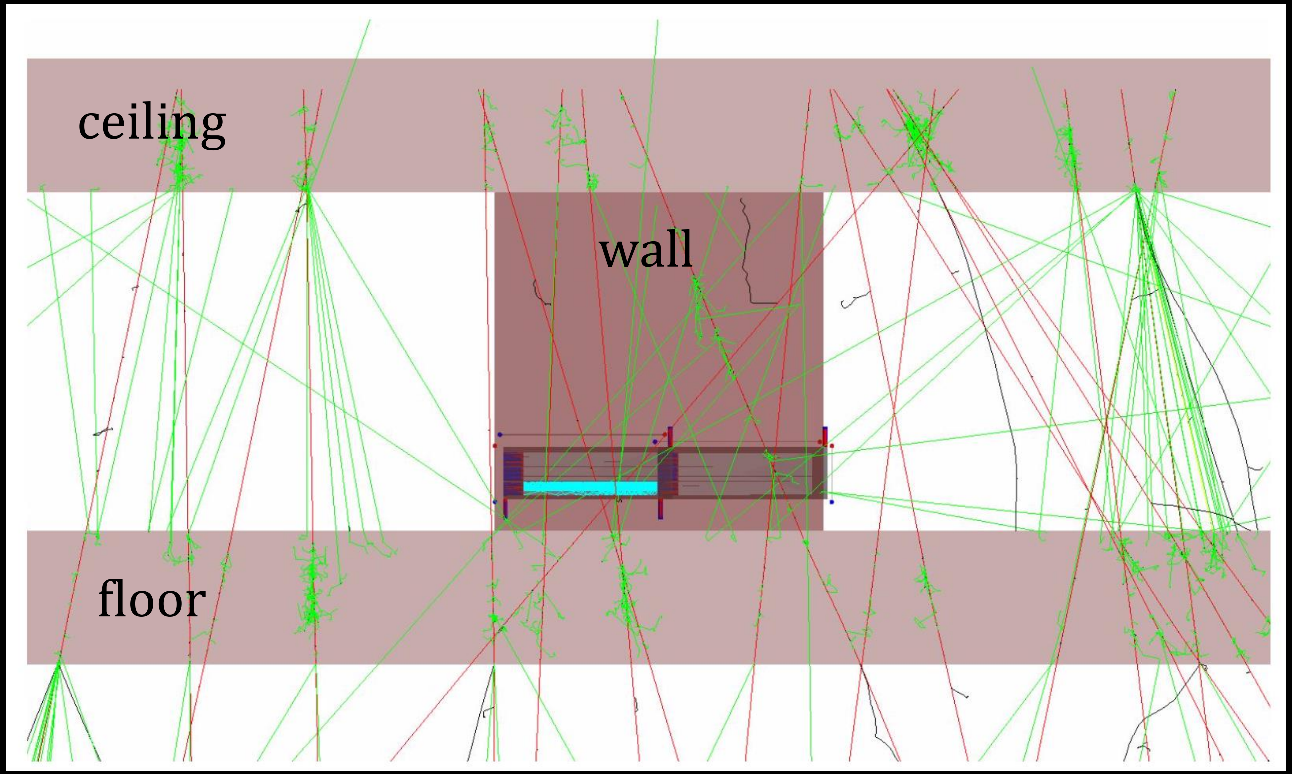
* Special thanks

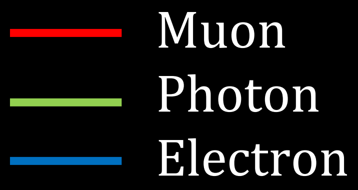
Optimization of Module Design



- Width of the scintillator bars (50 mm × 50 mm) determined by the size of the PMTs
- Length of the scintillator bars determined by spatial constraint and GEANT4 study
  - Due to spatial constraint, the max allowed length is about 1500 mm
  - Count the number of photons (N_γ) produced by a through-going muon as a function of bar length
  - Not much increase above 1500 mm, so 1500 mm has been chosen as the bar length

Cosmic Background

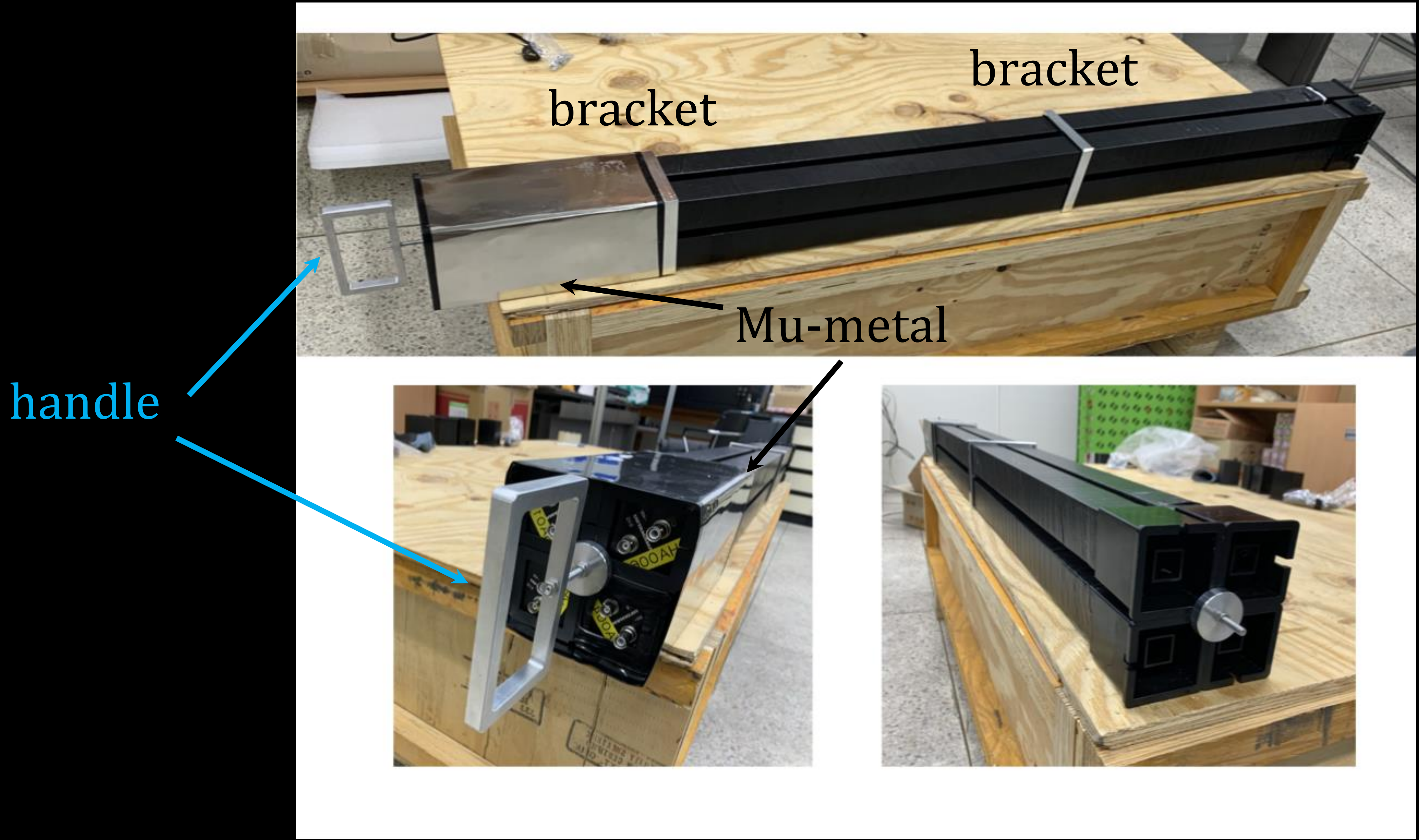




N_{PE}	Background Prediction
≤ 1	0.002
≤ 2	0.06
≤ 3	0.1
≤ 4	0.022
≤ 5	0.034

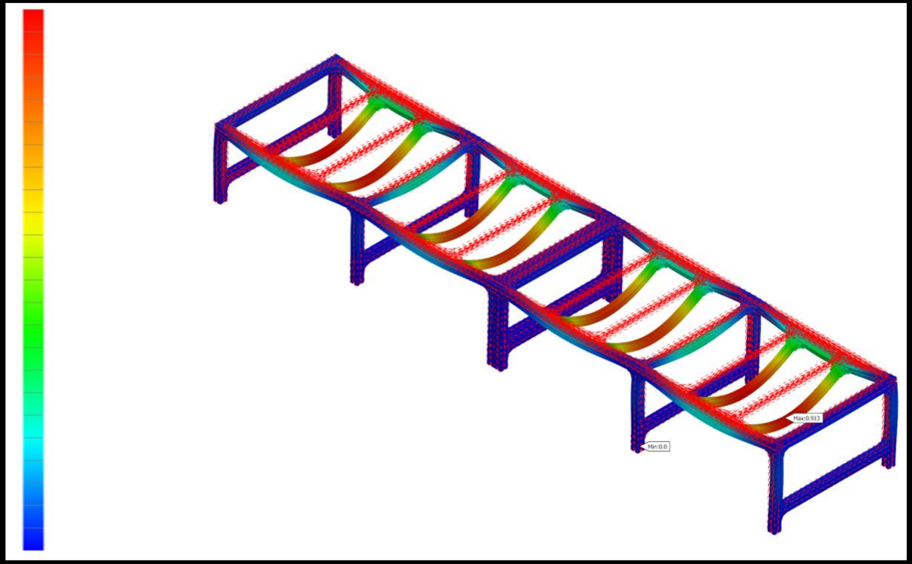
- Muons going through SUBMET can be tagged/rejected by panels
- They can interact with the material around the detector and generate shower of particles including low energy photons
  - If they hit two layers at the same time, they can mimic the signature of a χ
- Performed GEANT4 simulation to estimate this contribution
  - Used rate on the surface ($1\ /\text{cm}^2 \cdot \text{min}$), generated 12 m × 12 m grid of muons, number of muons corresponds to data taking for 20 years
- As the table shows, predictions is **< 0.1 for 3 years**

Detector components: Supermodule

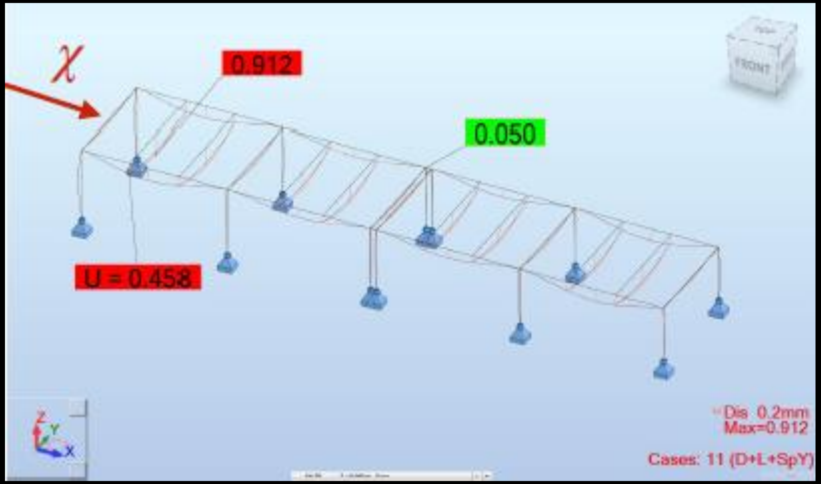


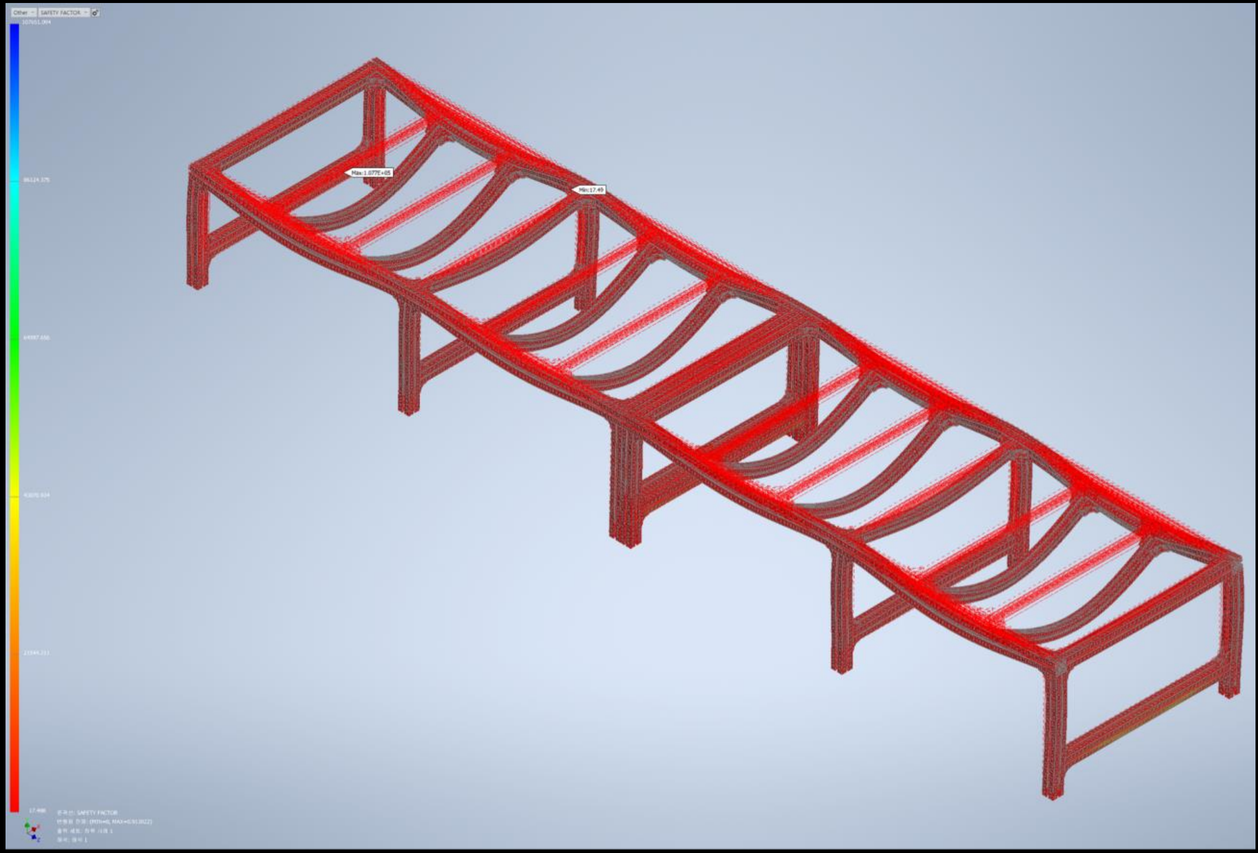
Test on the Mechanics

static



seismic





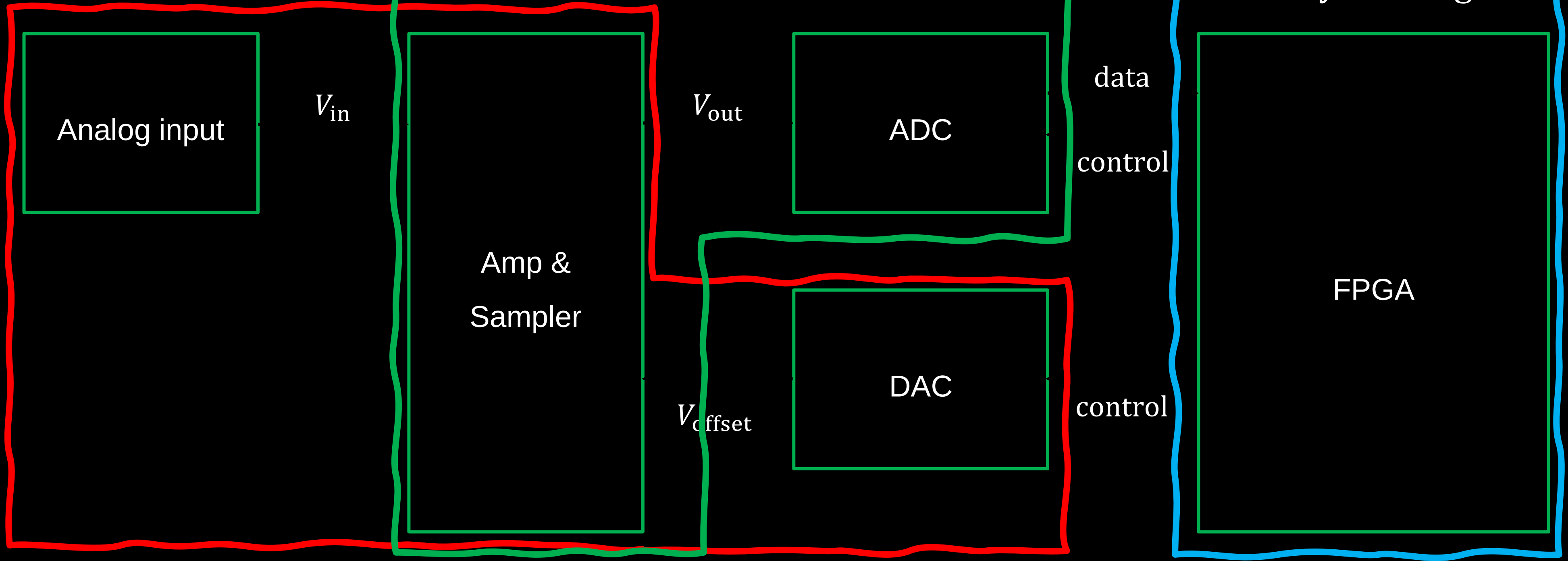
Checked stress and safety factor in FEM analysis

- Maximum stress: 200 MPa
- Minimum safety factor: 17.49

DAQ Electronics Diagram

- 1024 cells × 8 chs in DRS4
- Two input channels per DRS4
- 820 MHz sampling
- 33 MHz readout
- LVDS dynamic range : 2 V
- 12-bit for one cell

- Send TRG+CLK
- Adjustable time window through sampling rate control
- Delay TRG signal

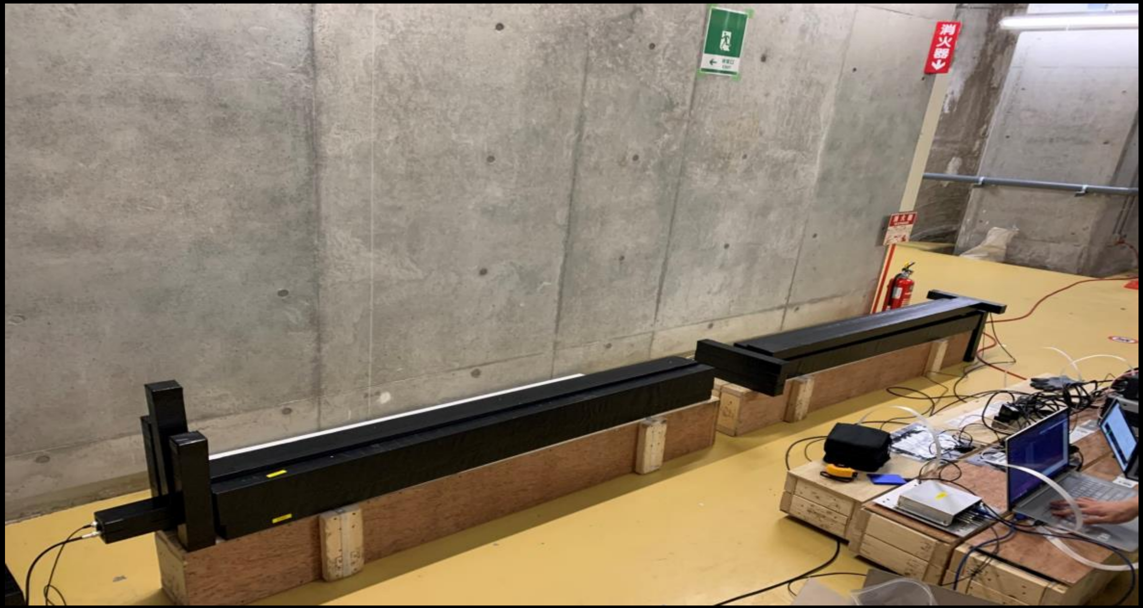


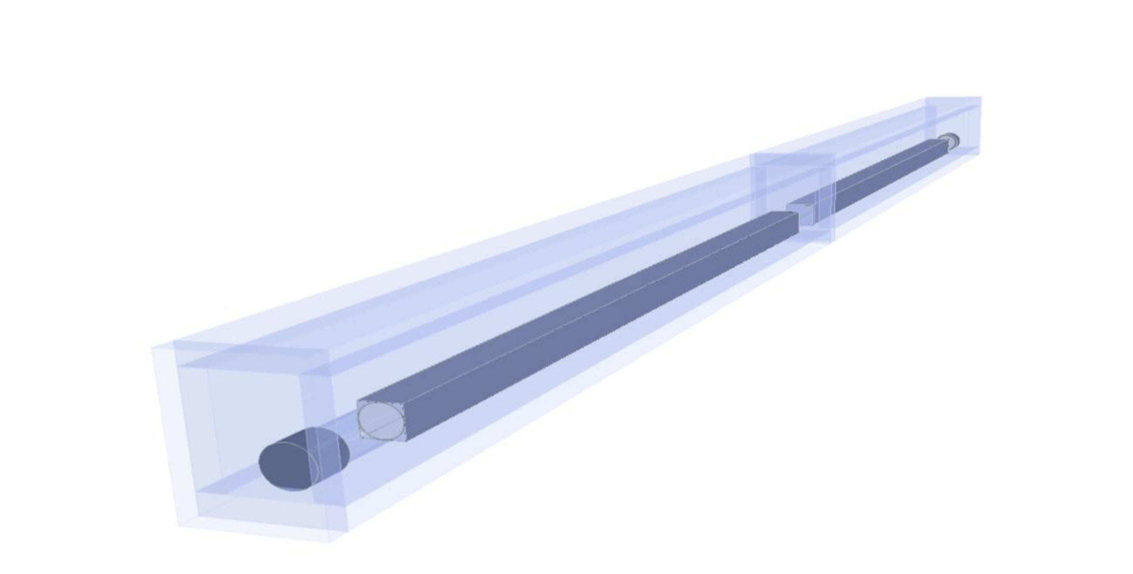
HV Supply Monitoring

▲ Web controller panel

- ➢ The voltage and current of individual channels are plotted in real-time through online.
- ➢ The numerical value of the target voltage and the channel state are combined into the upper panel, being indicated with a color palette.

Background Measurement

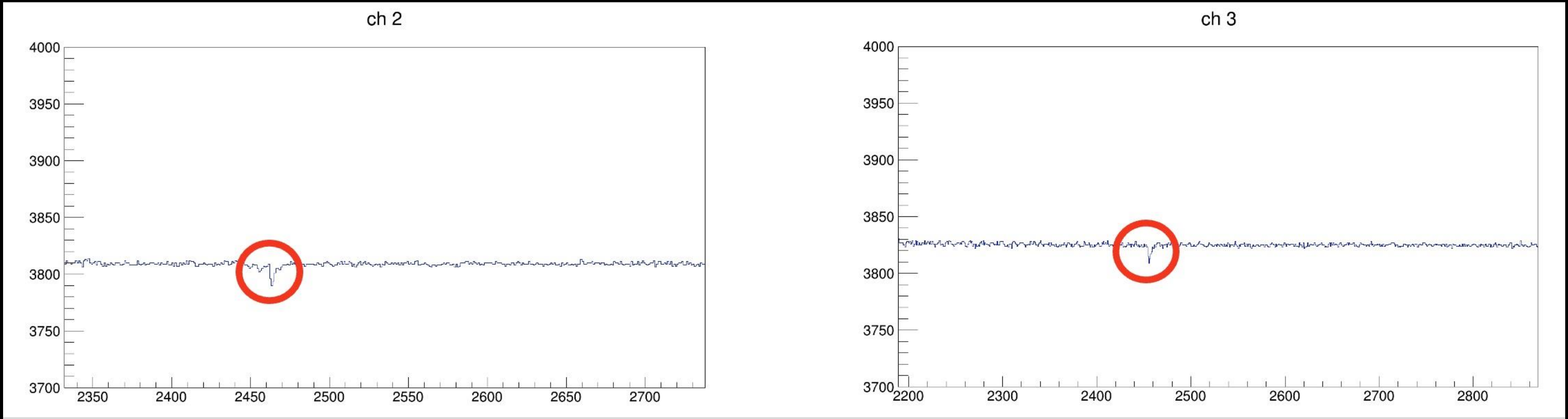




- ➢ Radiation from the structures of the building can generate pulses that are indistinguishable from the pulses due to χs
- ➢ Since the condition of such radiation strongly depends on the environment, we measured the rate at the detector site

- ➢ Pair of modules shielded by other scintillators
- ➢ Recorded total of 12M events, corresponding to ~63 s of live time (data taking for 4 years)

Background Measurement

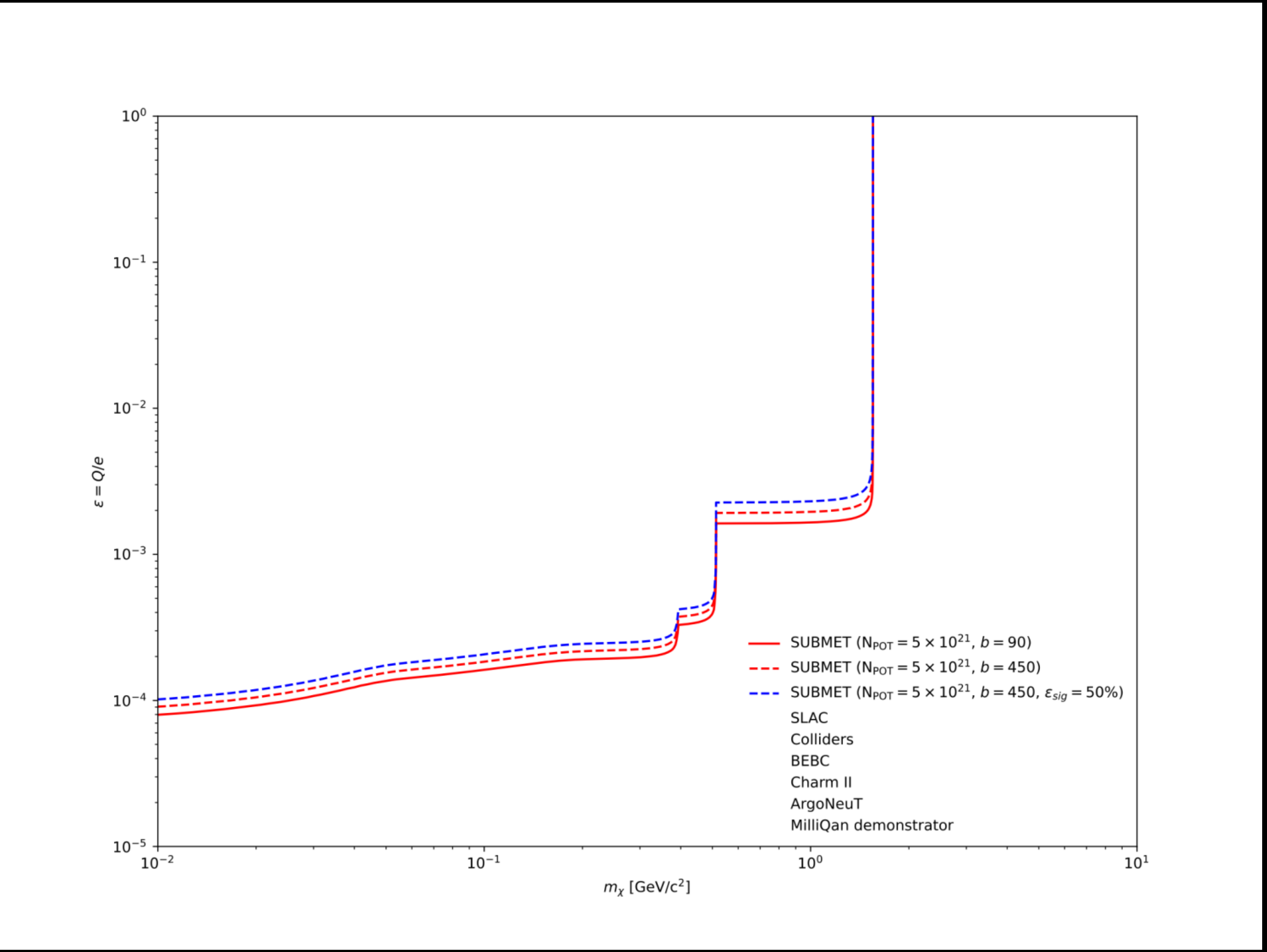


➢ Applied following cuts to select events
- Pulse height : 5.8 mV < Vpulse < 30 mV
- Pulse width : $\Delta t_{width} < 7$ ns
- Remove events with a large number of afterpulses: Npulse < 3
- Coincidence time window: $\Delta t_{pulse} < 20$ ns

➢ 1 background events out of 12M events

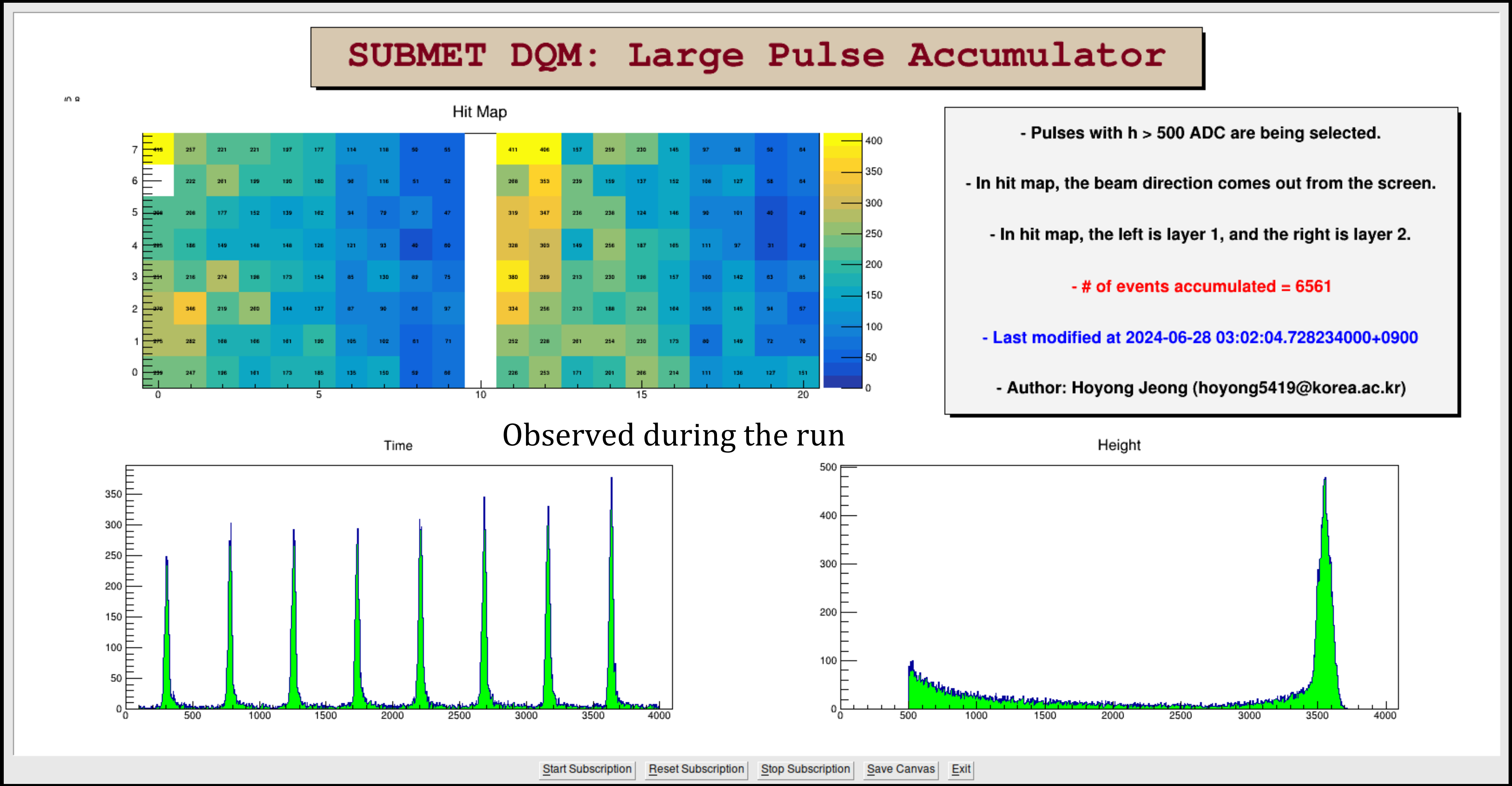
➢ 1×80/4 /2 = 10 background events per year (80 pair of modules, time ordering)

Detector Performance



- Exclusion limit using bkg = 90 and bkg =450, $N_{\mathrm{POT}} = 5 \times 10^{21}$
- Even with 5 times more backgrounds, only minor change in sensitivity due to rapid drop in signal acceptance. $(N_{signal} \propto \varepsilon^6)$

Bunch Structure



Observed during the run

SPE Pulse Finding

[Motivation] In case of fluctuating baseline, how to estimate baseline level in spite of the presence of signals?

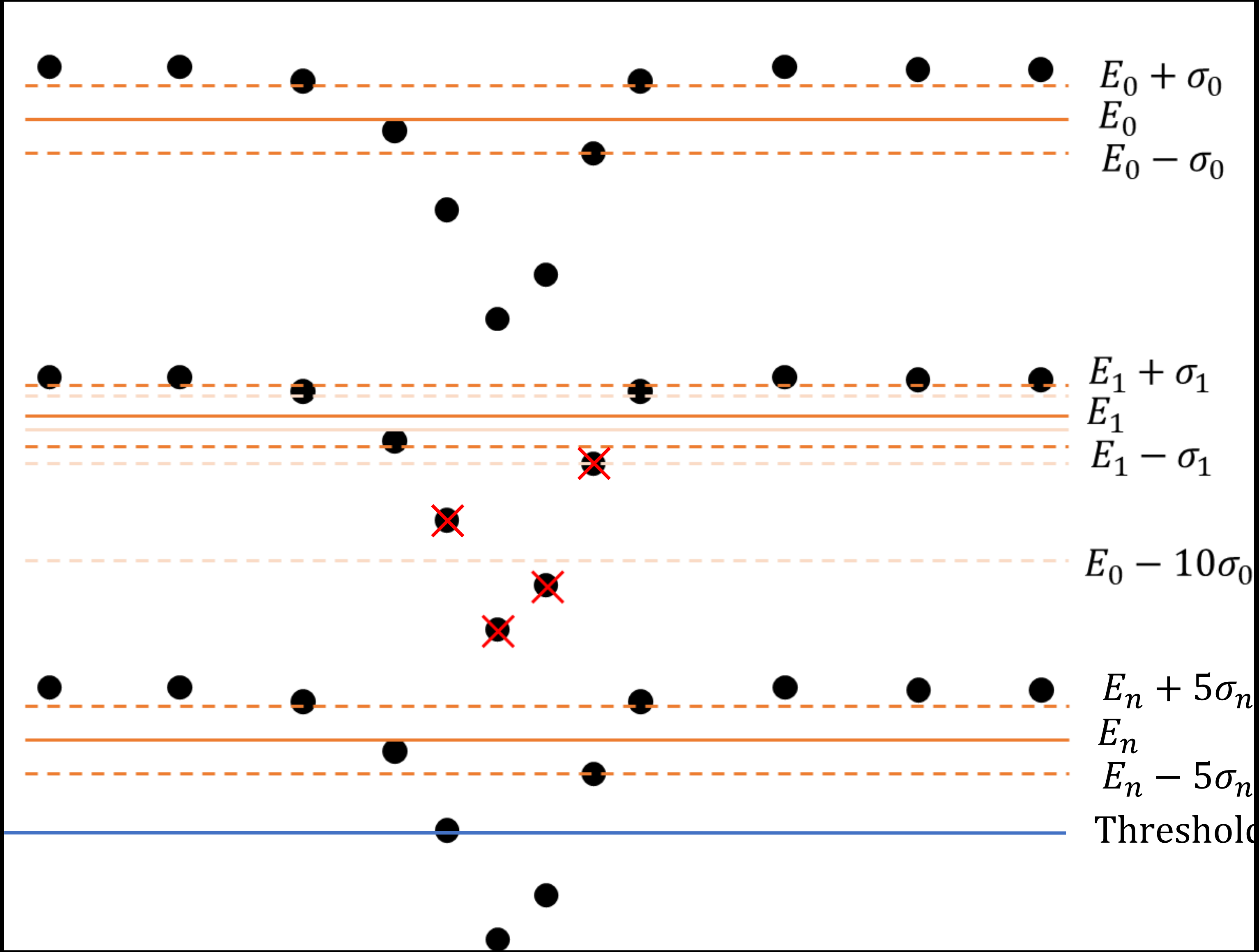
Step 1. Calculate E_0, σ_0

Step 2. Exclude points outside of $E_0 \pm 5\sigma_0$ and their neighbors when calculating E_1, σ_1.

Step 3. Iterate until every points are inside of $E_n \pm 5\sigma_n$

Step 4. Series $\{E_0\ E_1, E_2, \dots\}$ may converge to pedestal level.

Step 5. Find the point that exceeds the threshold.



Raw Data Structure

➢ 4,096 × 16 bits = 65,536 bits for each channel

- 131,072 bytes for each board per event
- among 16 bits, only 12 bits are used to reduce memory usage

➢ first 2 × 2 bytes × 16 channels = 64 bytes are reserved for header

- data length, board id, beam spill number, triggered time, trigger count in trigger / readout board, PLL lock status

```
00000000: 0000 0200 0166 6600 b300 5a82 ac00 0000
00000010: 0000 0000 b800 5a82 ac00 0000 0000 0000
00000020: b200 b00c b20c b204 b004 b204 b204 b204
00000030: ff00 0000 0000 0000 0000 0000 0000 0000
00000040: 026e ce6d 162e 202e 111e 051e 354e 2a4e
00000050: 1b6e fd6d 1c4e 004e 193e fd3d 213e 183e
00000060: 000e c80d 180e 1f0e 0f0e 000e 350e 2a0e
00000070: 1a0e fe0d 190e 010e 190e fd0d 1f0e 180e
00000080: 010e c60d 160e 210e 0d0e 030e 330e 290e
00000090: 1c0e fb0d 190e 000e 170e fc0d 1e0e 160e
```

64 bytes of header
Data corresponding to t = 0, 1 are removed

32 bytes of ADC for each sampling