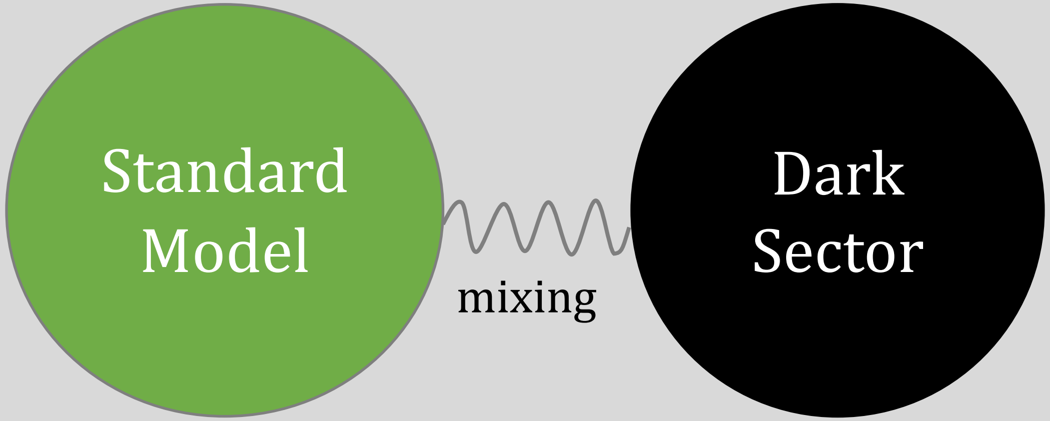
Search for sub-millicharged particles at J-PARC

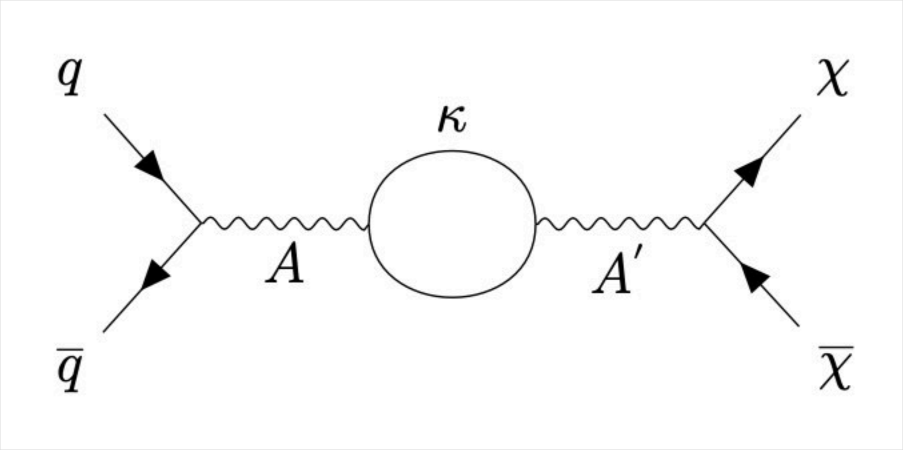
Changhyun Seo (Korea University) on behalf of the SUBMET Collaboration

The 16th Particle Physics and Cosmology conference (PPC), June 12 – 16, 2023,

Institute for Basic Science in Dajeon, Korea

Motivation



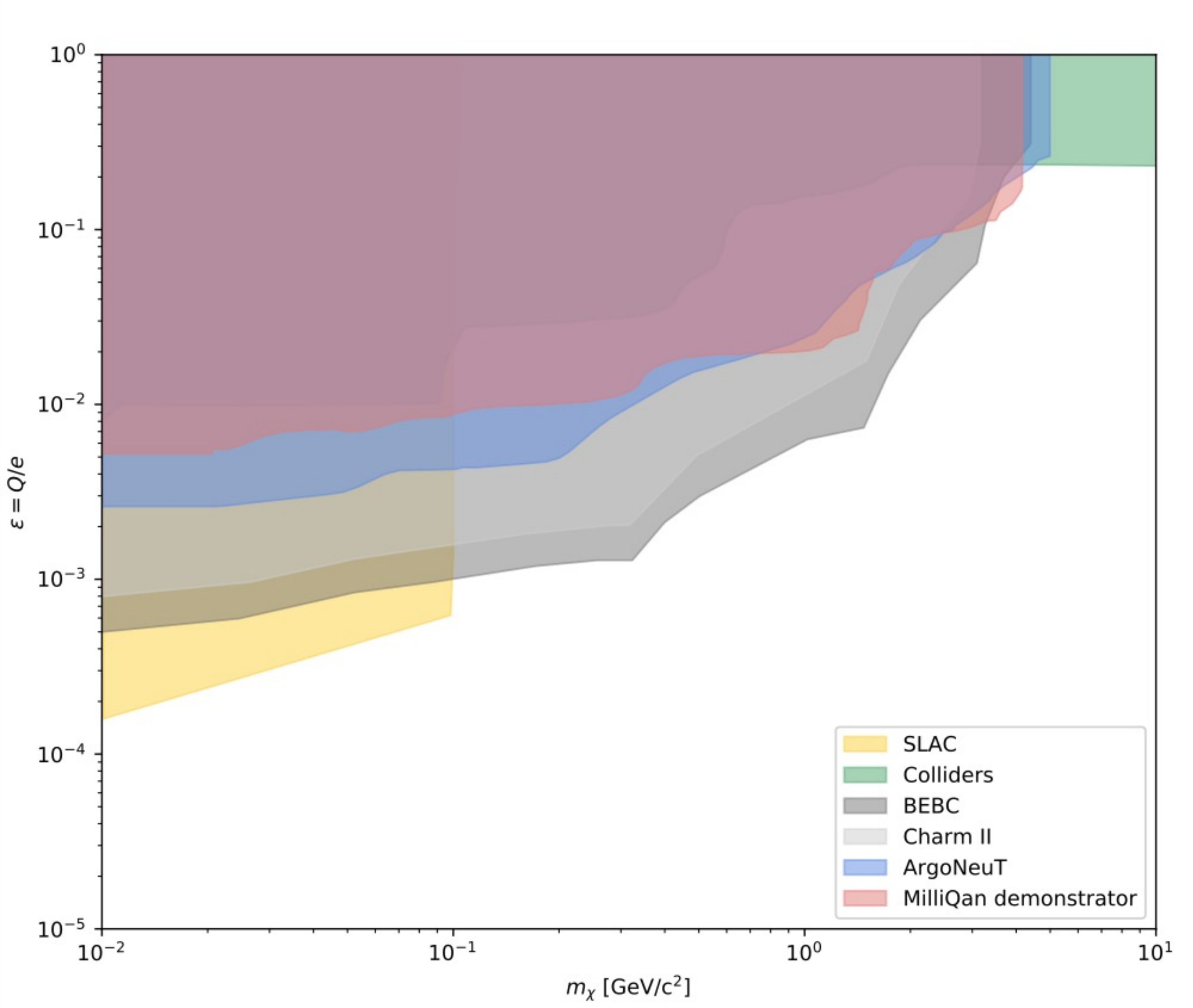


- Electric charge quantization is a long-standing question in particle physics.
- There are no strong motivation for charge quantization
- Well-motivated Dark-sector models have been proposed that there can be millicharged-particles.
- One mechanism to produce millicharged particles is introducing an extra U(1) in dark sector with massless dark-photon (A') and dark-fermion (χ)
- A' and A can kinetically mix (size of mixing κ)
- Charge of χ is proportional to mixing (κ)

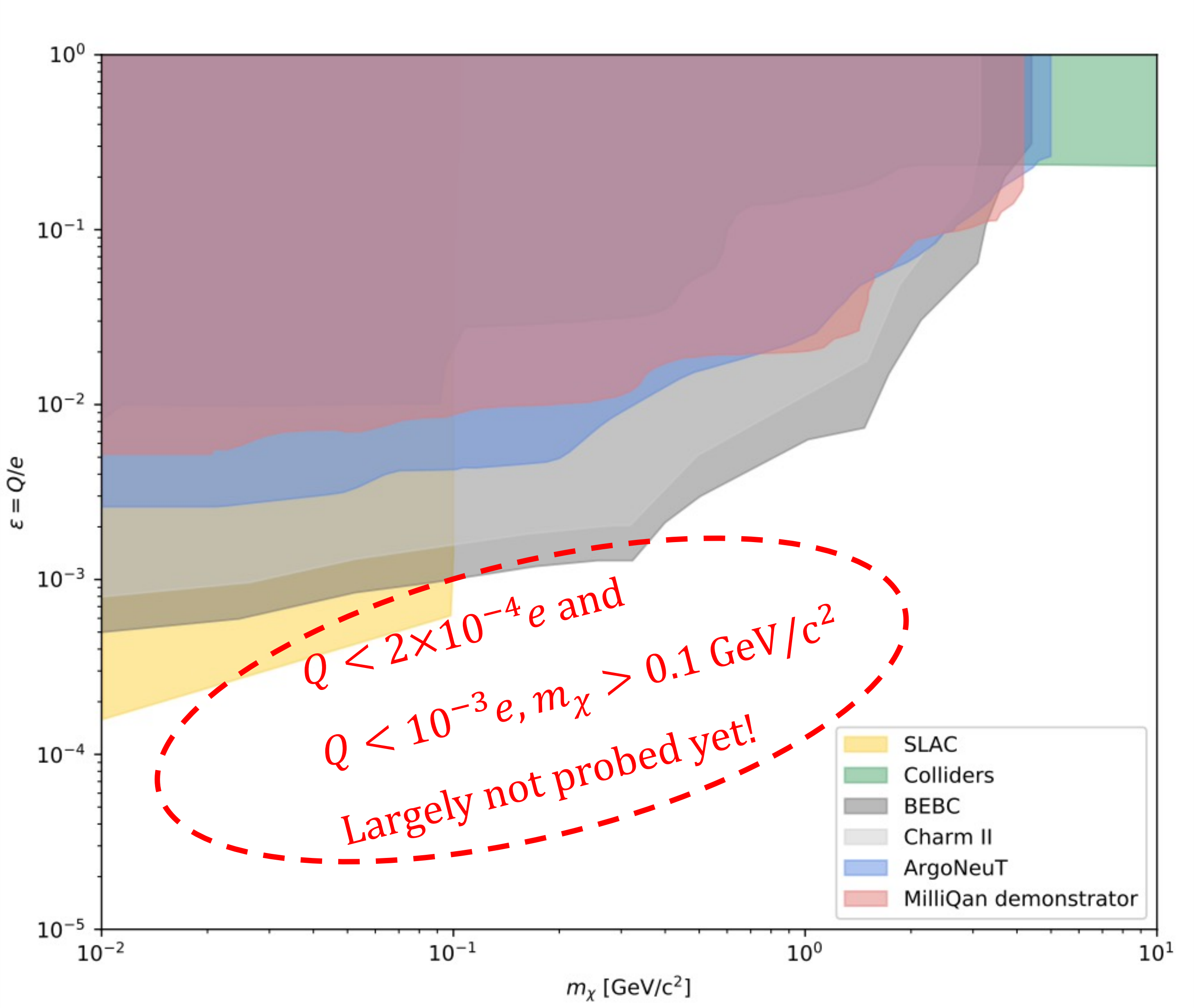
$$\mathcal{L}_{\text{dark sector}} = -\frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\chi}(\partial\!\!\!/ + ie'A\!\!\!/' + iM_{\text{mCP}})\chi - \frac{\kappa}{2}A'_{\mu\nu}A^{\mu\nu}$$

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

Current research

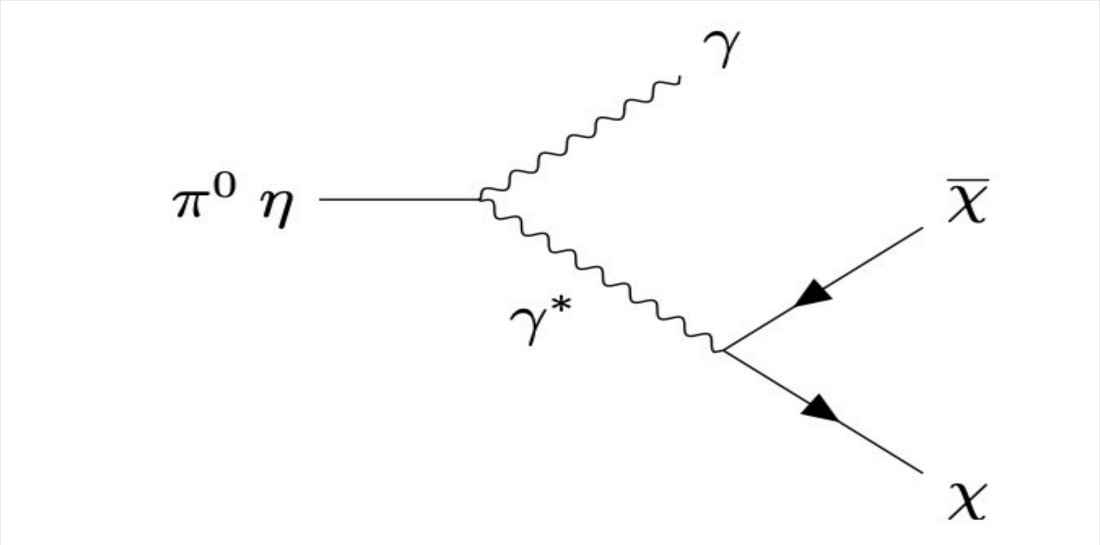


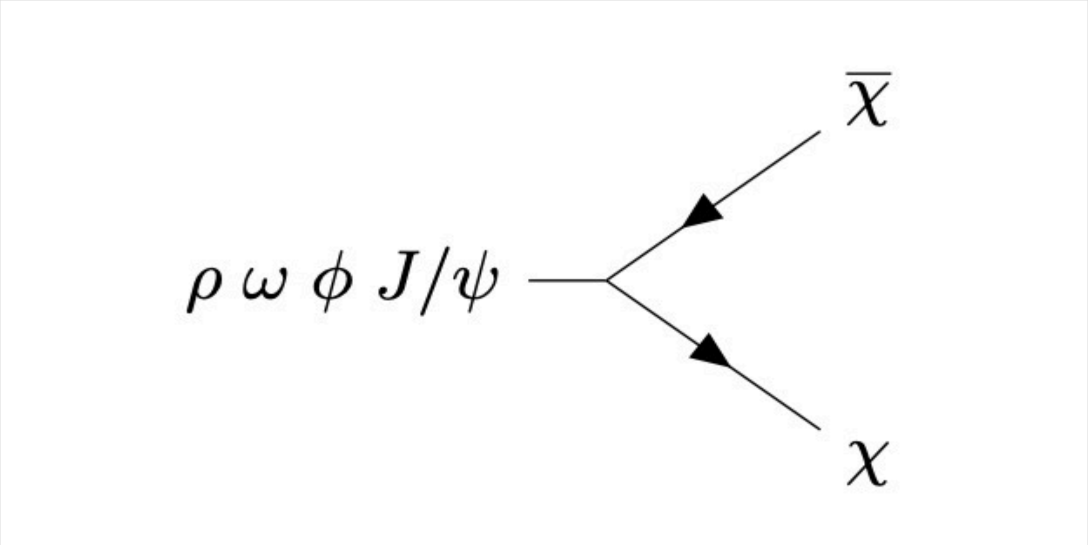
Current research



- **SUB-M**illicharge **E**xperimen**T** (SUBMET): new experiment targeting small charge & low mass region.
- Scintillator-based detector using proton fixed-target collisions at J-PARC

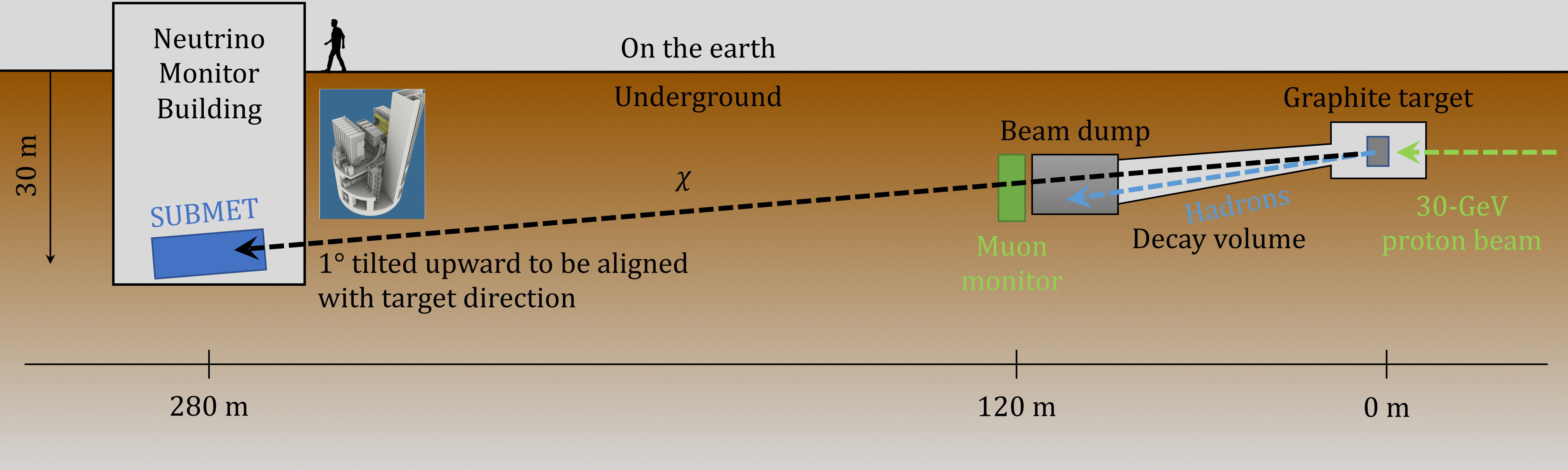
Production of millicharged particles





- At proton fixed-target collisions at J-PARC (Japan Proton Accelerator Research Complex) χs can be produced from the decay of π^0, η, ρ, ω, ϕ and J/ψ neutral mesons.
- Light mesons (π^0, η) decay through a photon , while heavy mesons (ρ, ω, ϕ and J/ψ) decay to a pair of χ s directly.

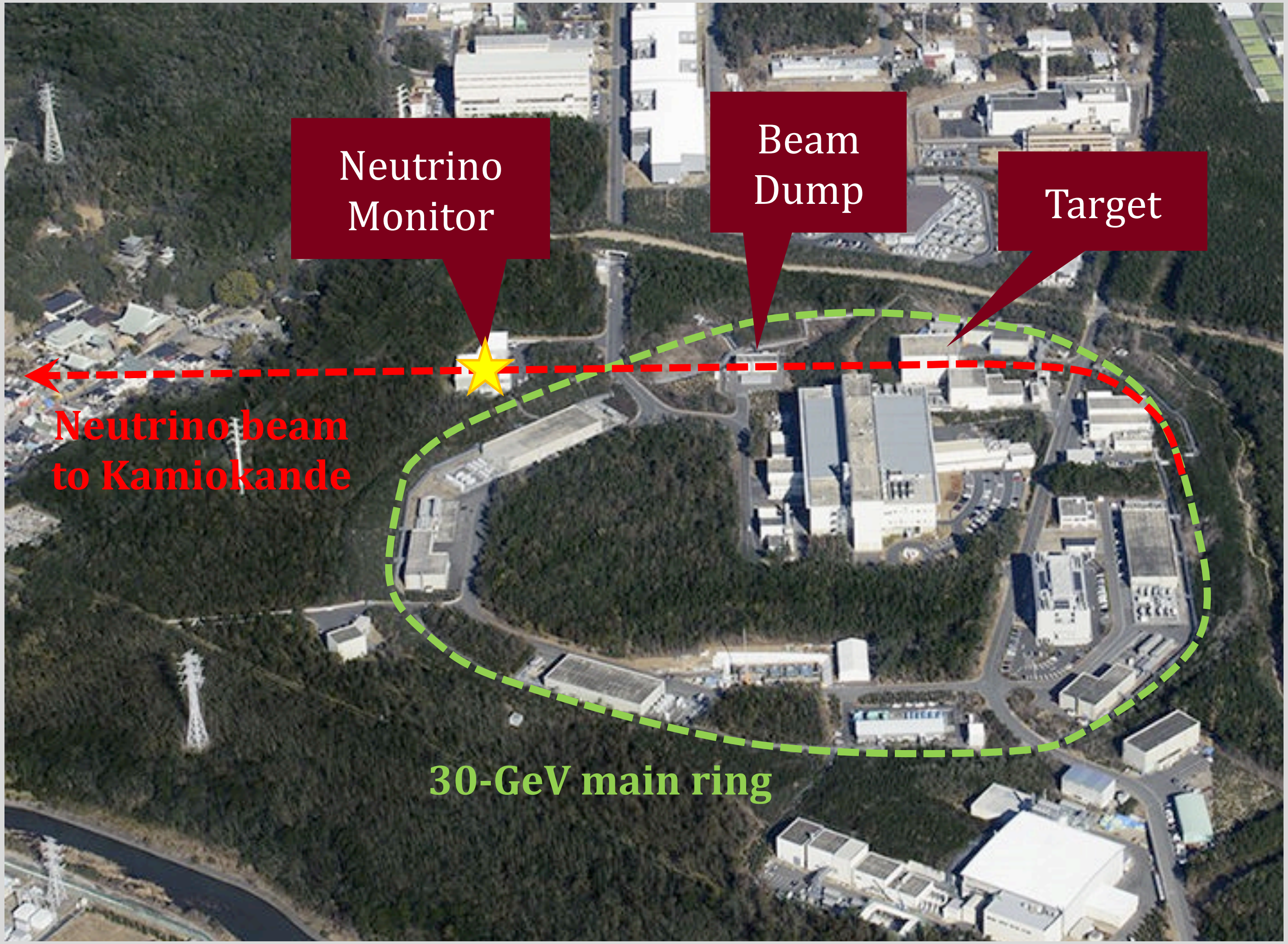
Basic Idea of detecting χs



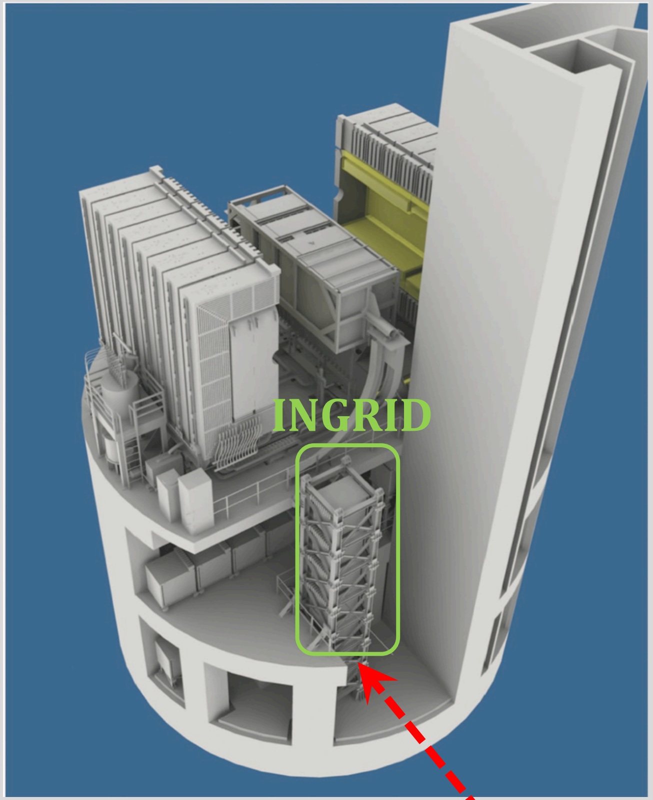
- Protons hit the target and hadrons are produced.
- Hadrons stop in the Beam Dump.
- Muons are identified by the muon monitor and lose the entire energy in sand (5 MeV/cm) before reaching NM building.
- χs reach the detector. (Energy loss for χs with $q = 10^{-3}e$ is < 0.1 MeV.)

Experimental site

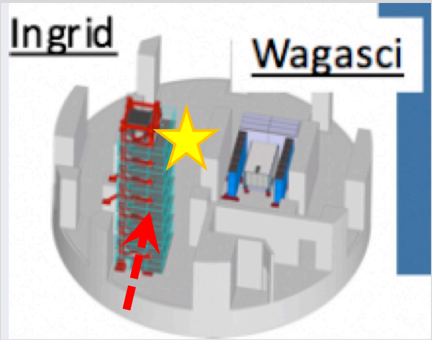
From https://j-parc.jp/c/en/about/outline.html



From PTEP 2012, 02B005



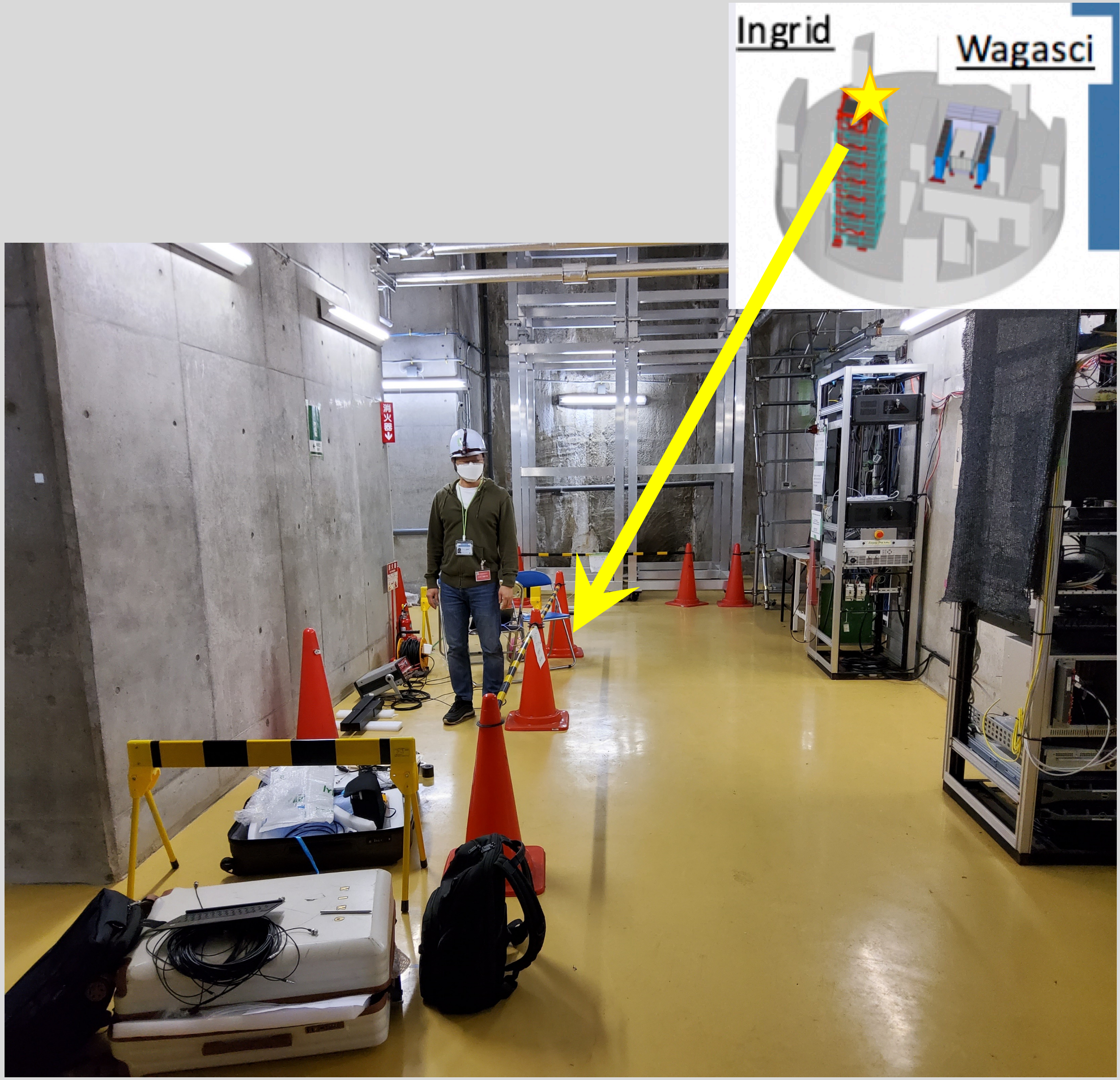
ν **beam**



From https://indico.phys.vt.edu/event/34/contributions/708/attachments/581/746/HallsjoMIND.pdf

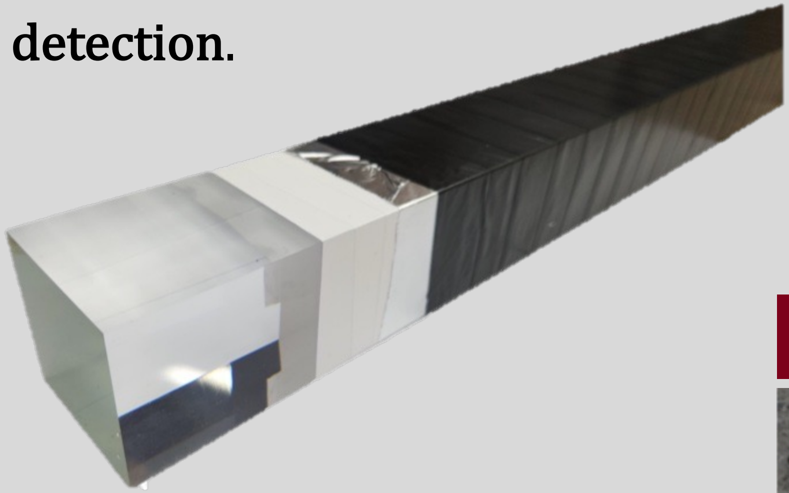
Experimental Site

- Our experimental site is on the bottom floor (~ 30 m underground) of the Neutrino Monitor (NM) building.
- **1 m×4 m** for the detector itself
- Power, network, and beam-related trigger signal are available.
- We visited the site and checked environment in May 2022.



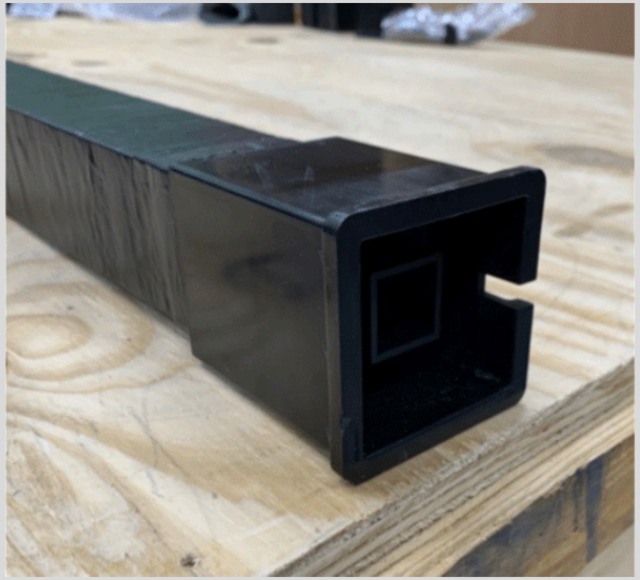
Detector concept

- χs goes through a scintillator bar and produce photons by ionization.
- Use long scintillator bars to enhance the production of photons by χs inside.
- For small Q $(10^{-3}e)$, it becomes **single-photon detection**.



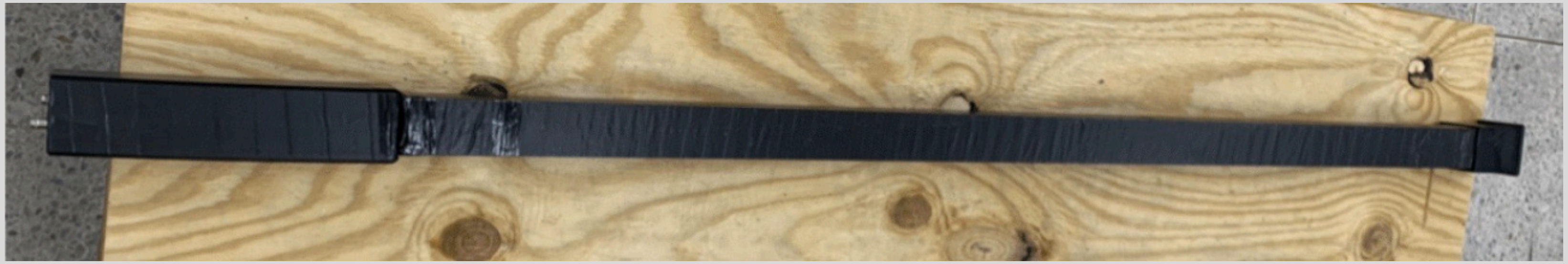
▲ A scintillator bar wrapped with teflon + Al foil + insulating tape

▲ PMT support



▲ LED support

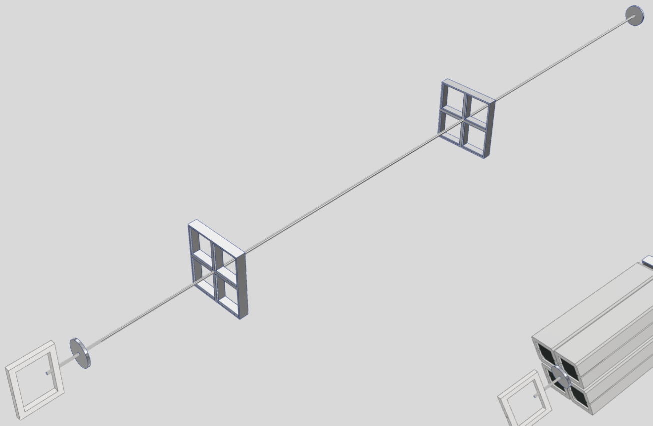
Module = PMT + scintillator + plastic supports

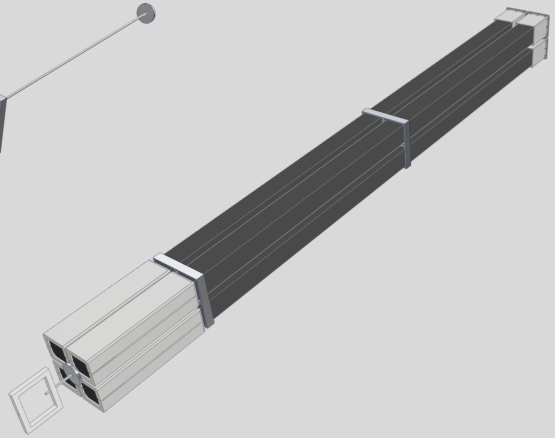


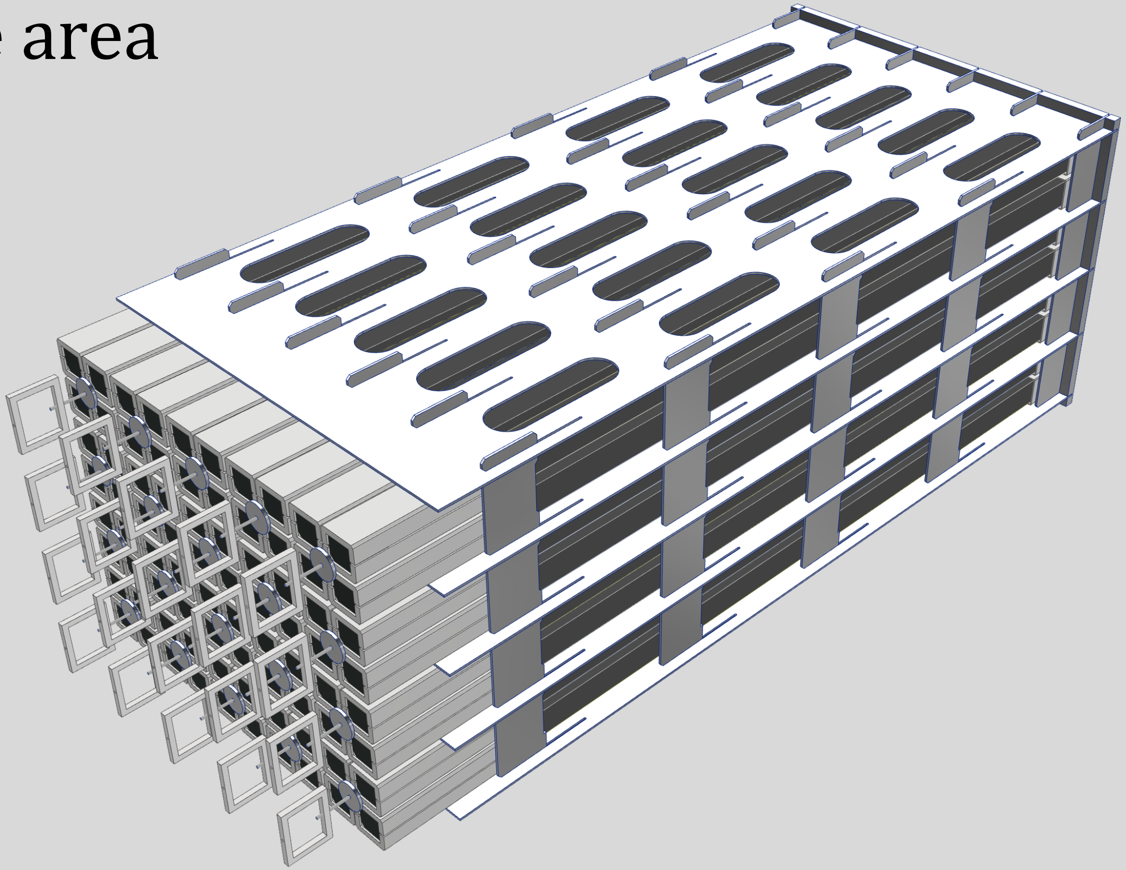
Detector concept

- ➢ Stack scintillators to increase coverage area

Supermodule = mechanical support + 4 × module





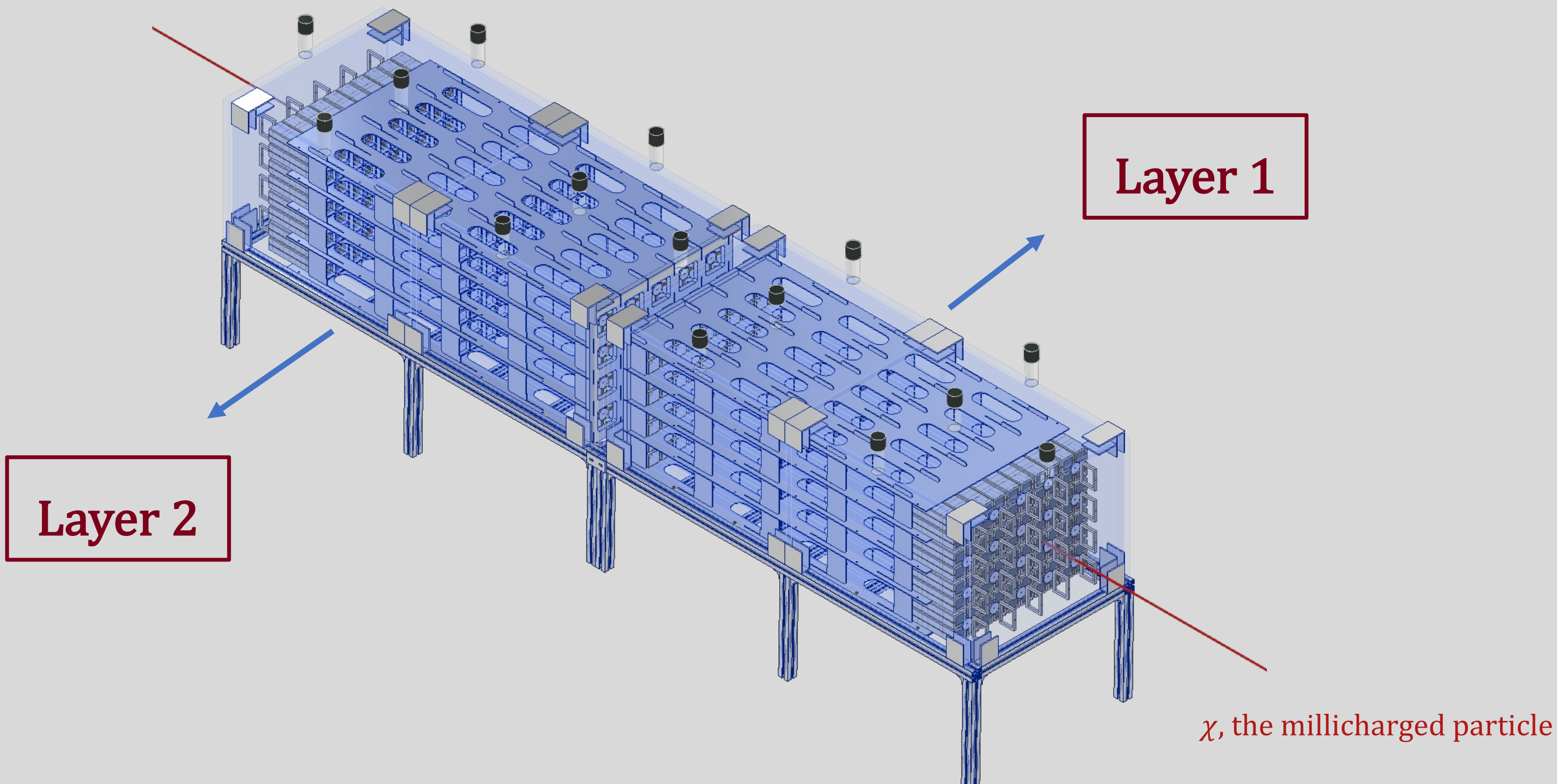


▲ 1 Layer

5 ×4 supermodules assembled

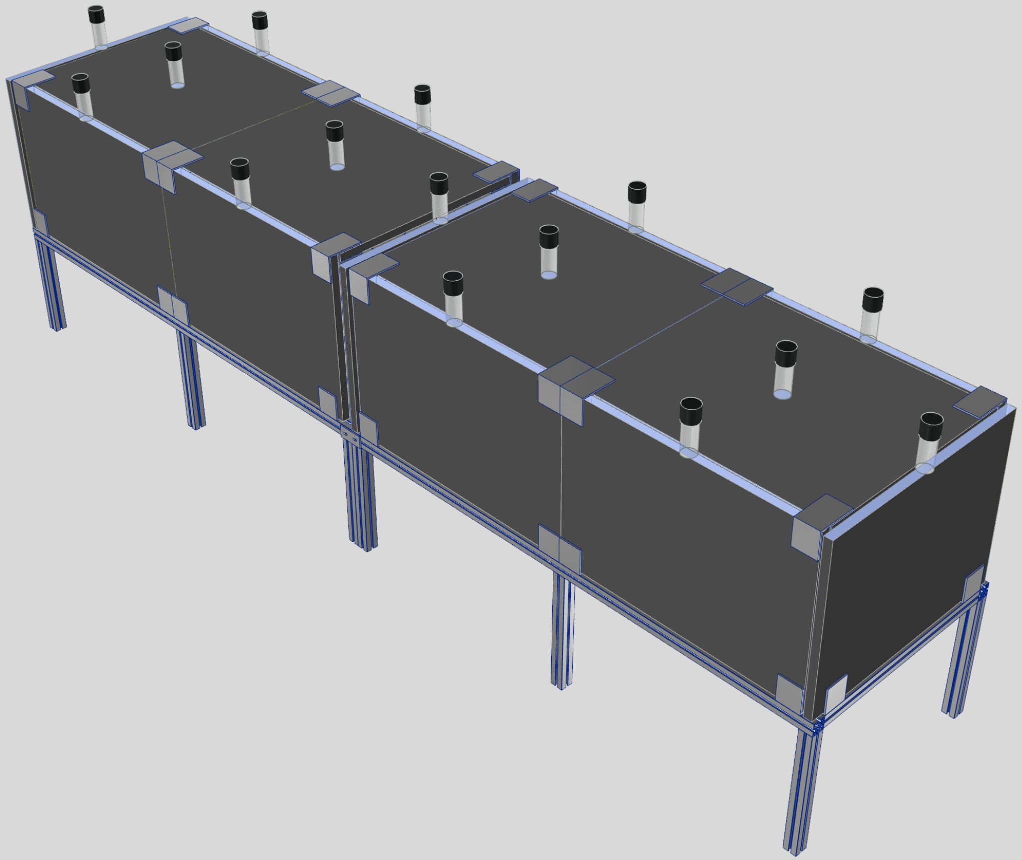
Detector concept

- Use **two layers** and align the two layers such that a χ goes through both of them for a small time interval ($\Delta t{\sim}20$ ns) at a speed of light.
- Require small time interval ($\Delta t{\sim}20$ ns) between hits in the two layers and use the timing of proton beam.
  - **They help reduce backgrounds significantly.**



Full Mechanics Overview

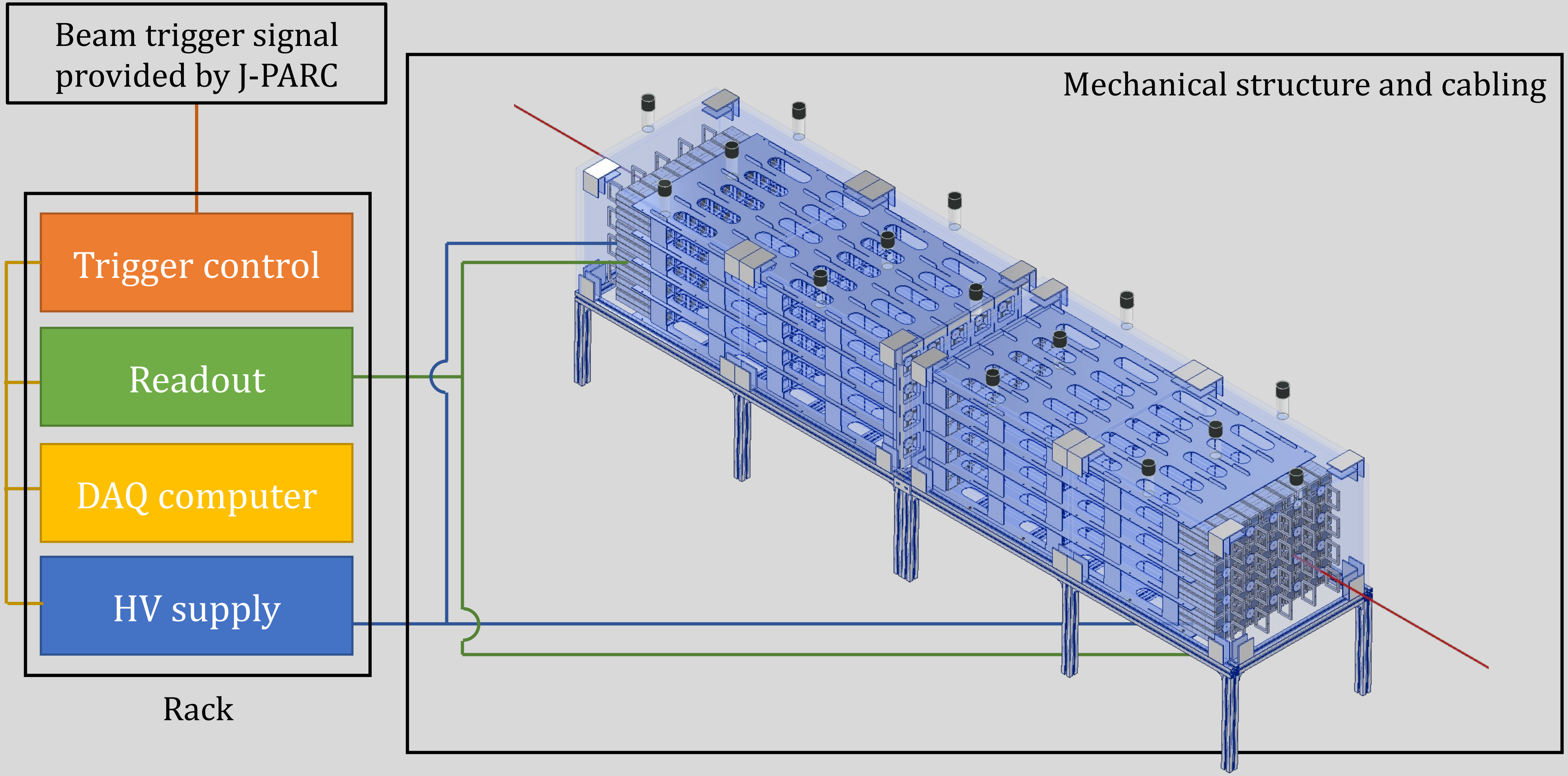
- The SUBMET detector is surrounded by "veto panels" (scintillator + PMT).
- The veto panels can tag cosmic events and veto them.
- We used a wooden panel with a similar size as the scintillator panel for testing purposes.



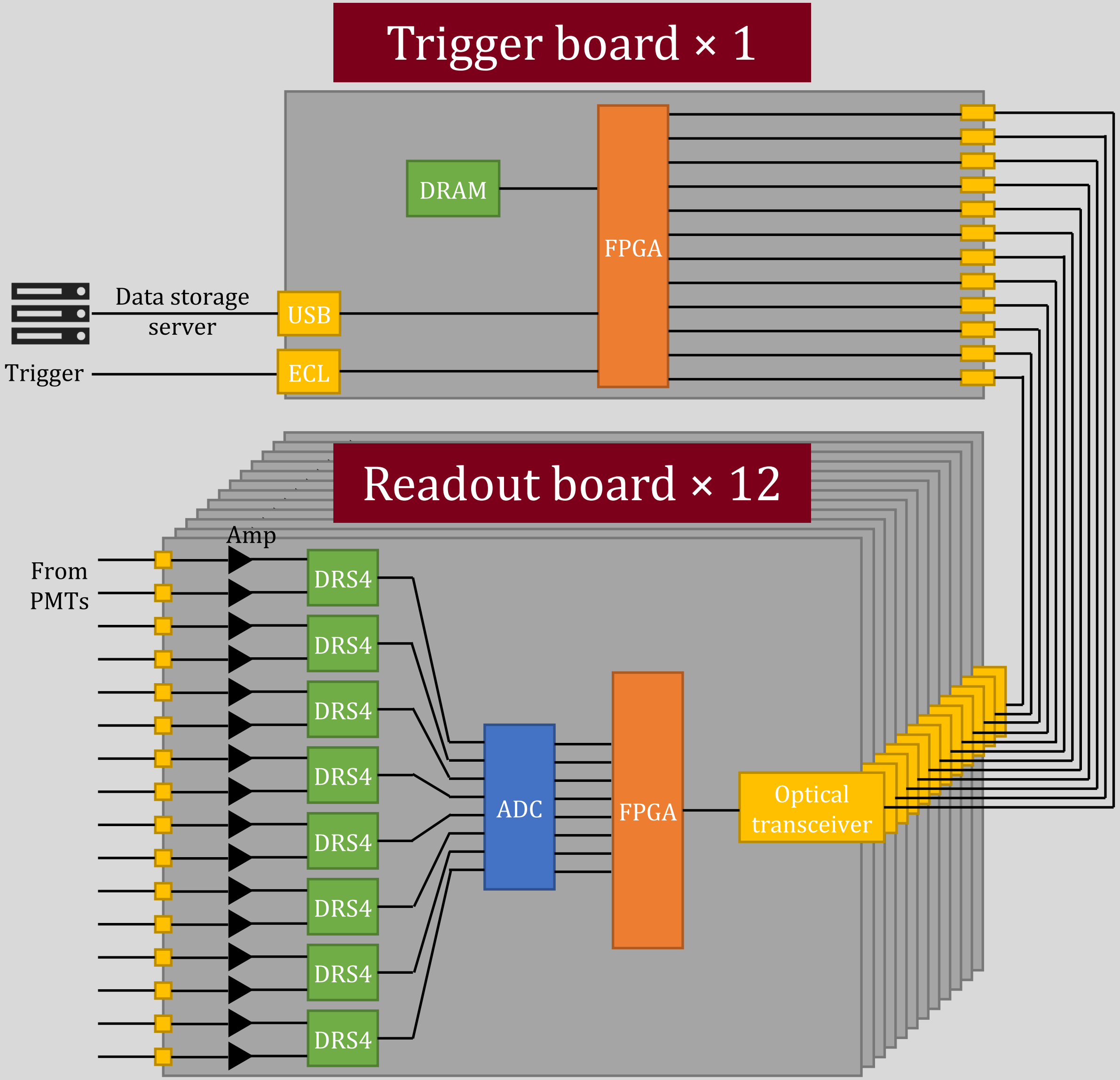
▲ Full SUBMET detector (CAD image)

▲ One layer of SUBMET detector

Detector System



Full-scale DAQ system



Requirements

- Precision :

  O(~mV) precision to detect single-photon events

- Time window :

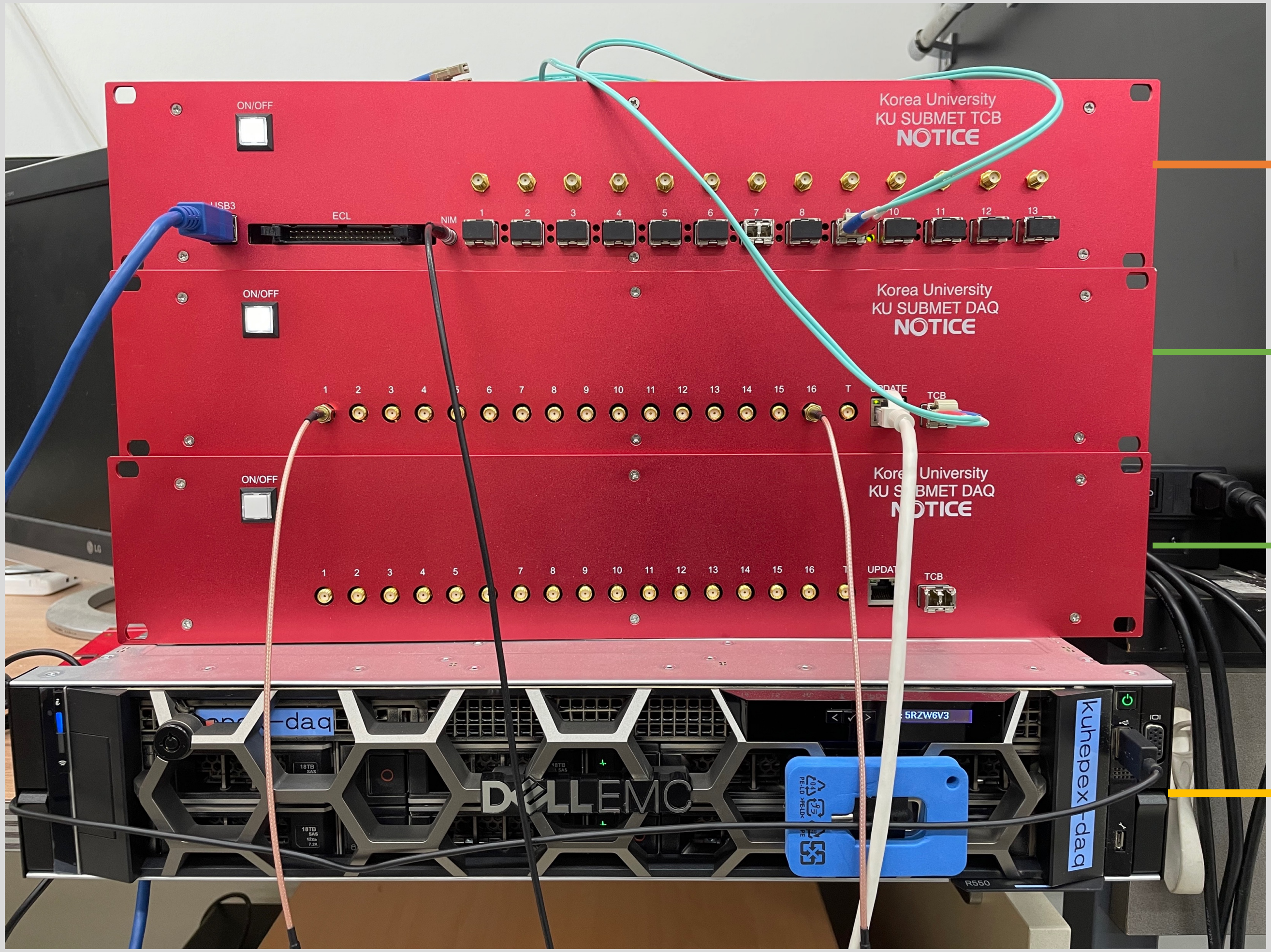
  ~ 5 μs to record events from all proton bunches

- Stability in long time running :

  ~ 3 years run

- Prototype board is fabricated and tested

Full-scale DAQ system



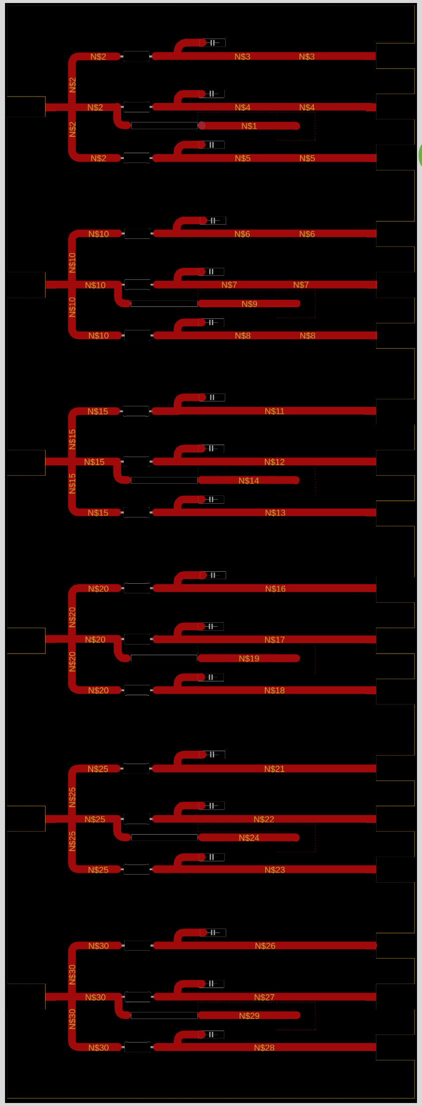
Trigger board

2 Readout boards

DAQ computer

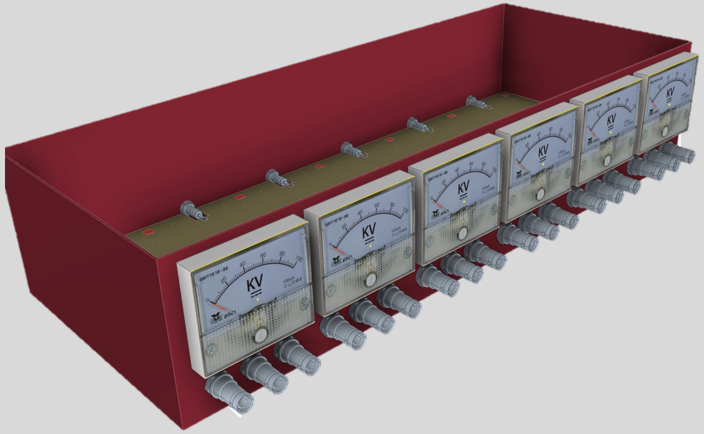
HV (High Voltage) supply

1 Input



3 Outputs

▲ CAEN SY5527 HV supply front (left) & AG7236SN rear (right) view



▲ HV splitter

- ➢ SUBMET uses **CAEN SY5527** HV supply (72 channels) to power PMTs
- ➢ It does not have enough channels to supply HV to 192 PMTs.
- ➢ Solution: Design a splitter that can multiply number of output channels by factor of 3.

HV Supply: Monitoring

▲ Rear view of HV supply

▲ 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 sources

- χs that reach the detector will go through the two layers in a $\sim$ 20 ns time window producing a coincidence signal
- For the charge below $Q \sim O\,(10^{-3}$ e), a single photon is produced in each layer

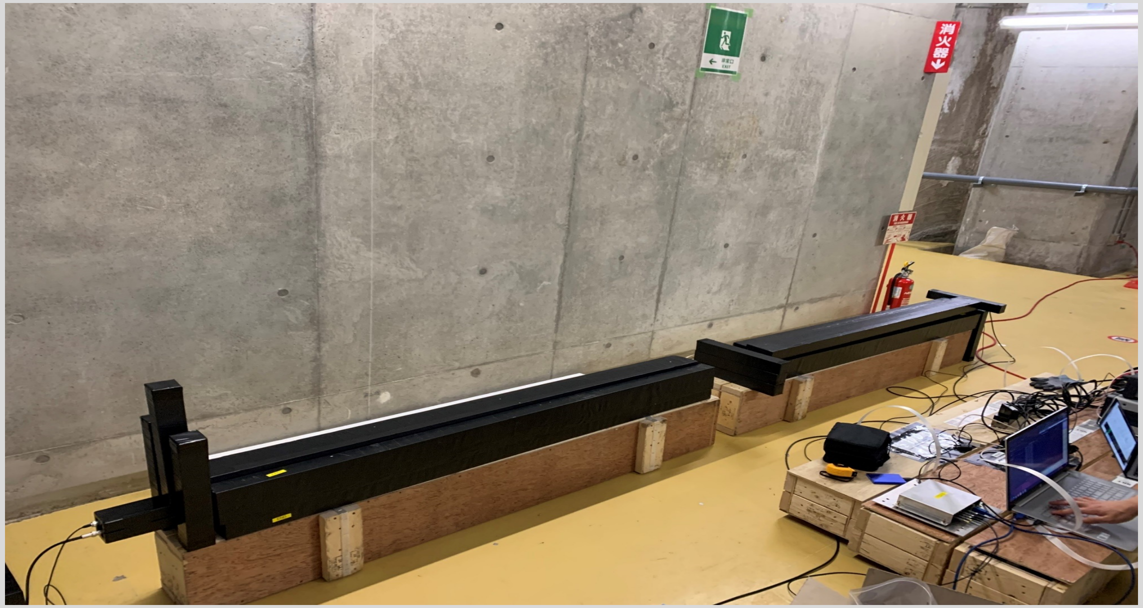
  Any source that can produce coincidence single photon signals will be a potential background source
- Expected background sources

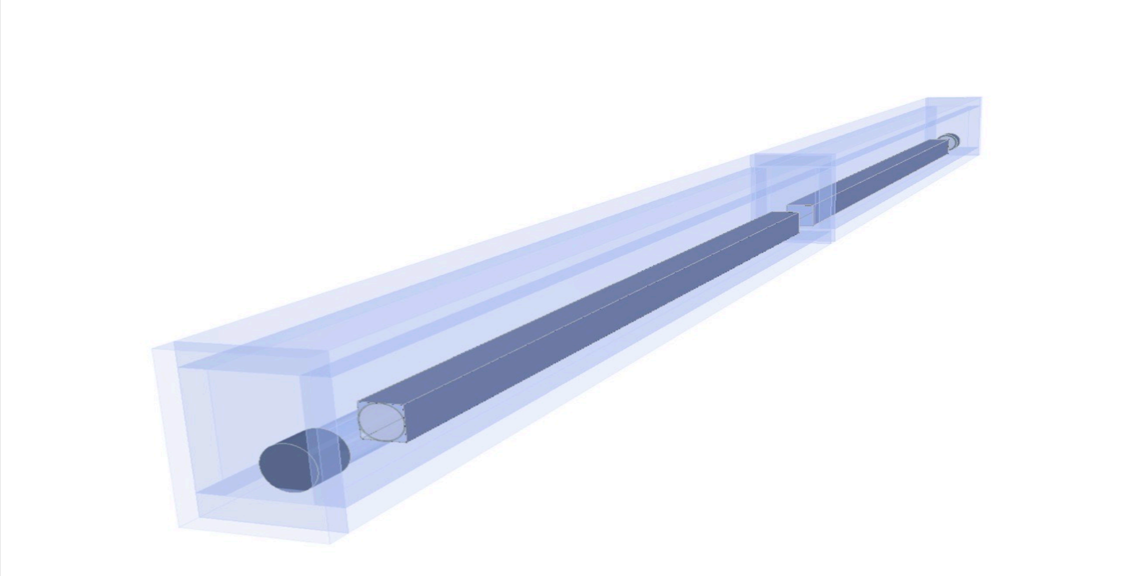
  1). PMT dark current and external radiation (major): measured in the lab and at the experimental site

  2). Beam-induced backgrounds

  3). Cosmic backgrounds (negligible in Geant4 simulation)

PMT dark current and external radiation

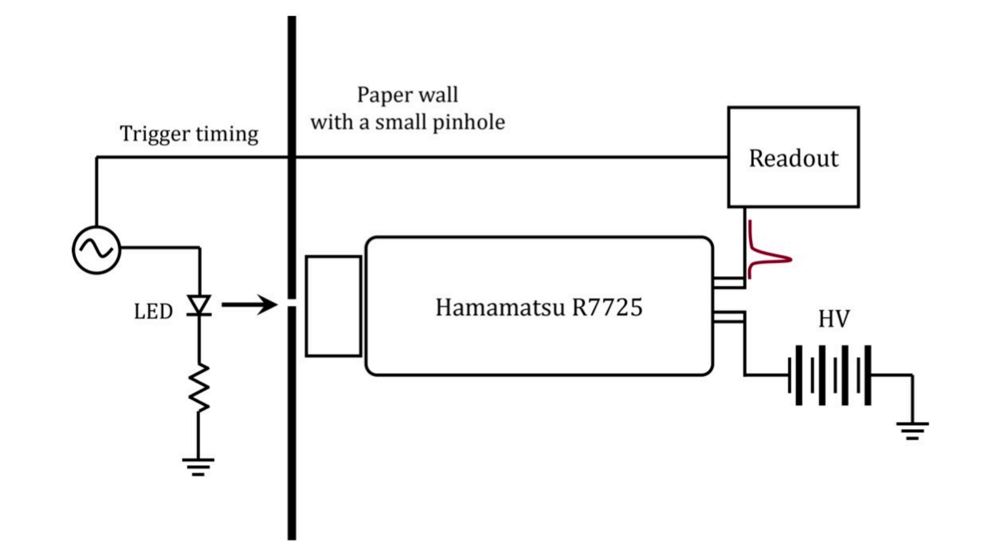


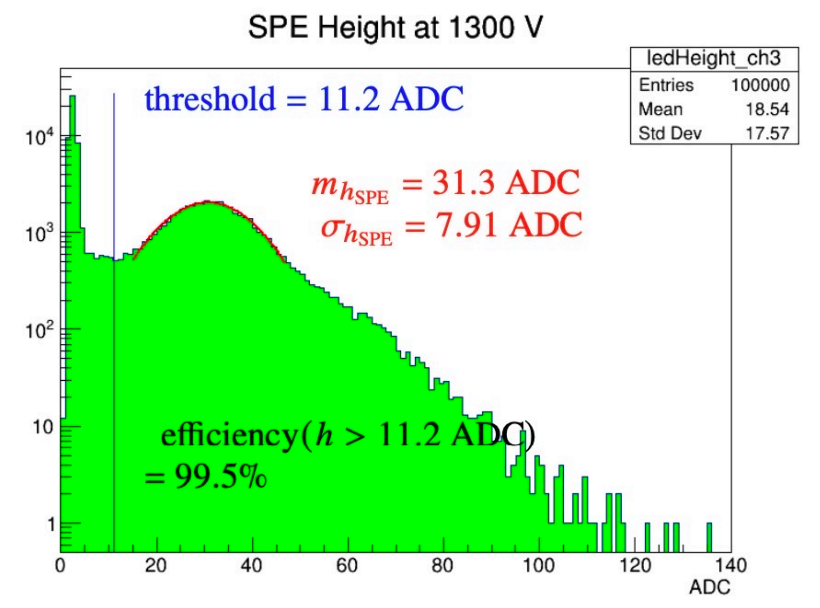


- Radiation from the structures of the building can generate pulses that are indistinguishable from the pulses due to χs
- Since the condition of such radiation strongly depends on the environment, we measured the rate at the detector site

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

Identifying single photoelectron pulses

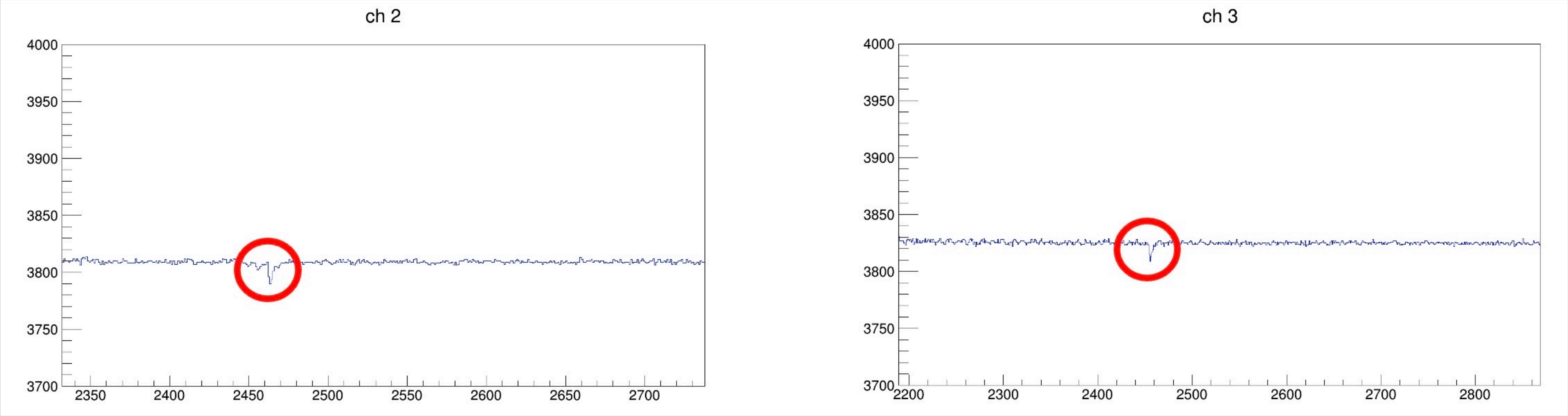




- Before estimating the background events, the detector must identify single photoelectron (SPE) signals.
- One way to achieve this is by illuminating the photocathode of an PMT with a dim LED light and measuring the typical pulse height of the resulting SPE pulses.
- By conducting LED testing, we were able to establish a selection cut for SPE events.

  SPE Pulse height : 20 ADC < V_{pulse} < 50 ADC

PMT dark current and external radiation



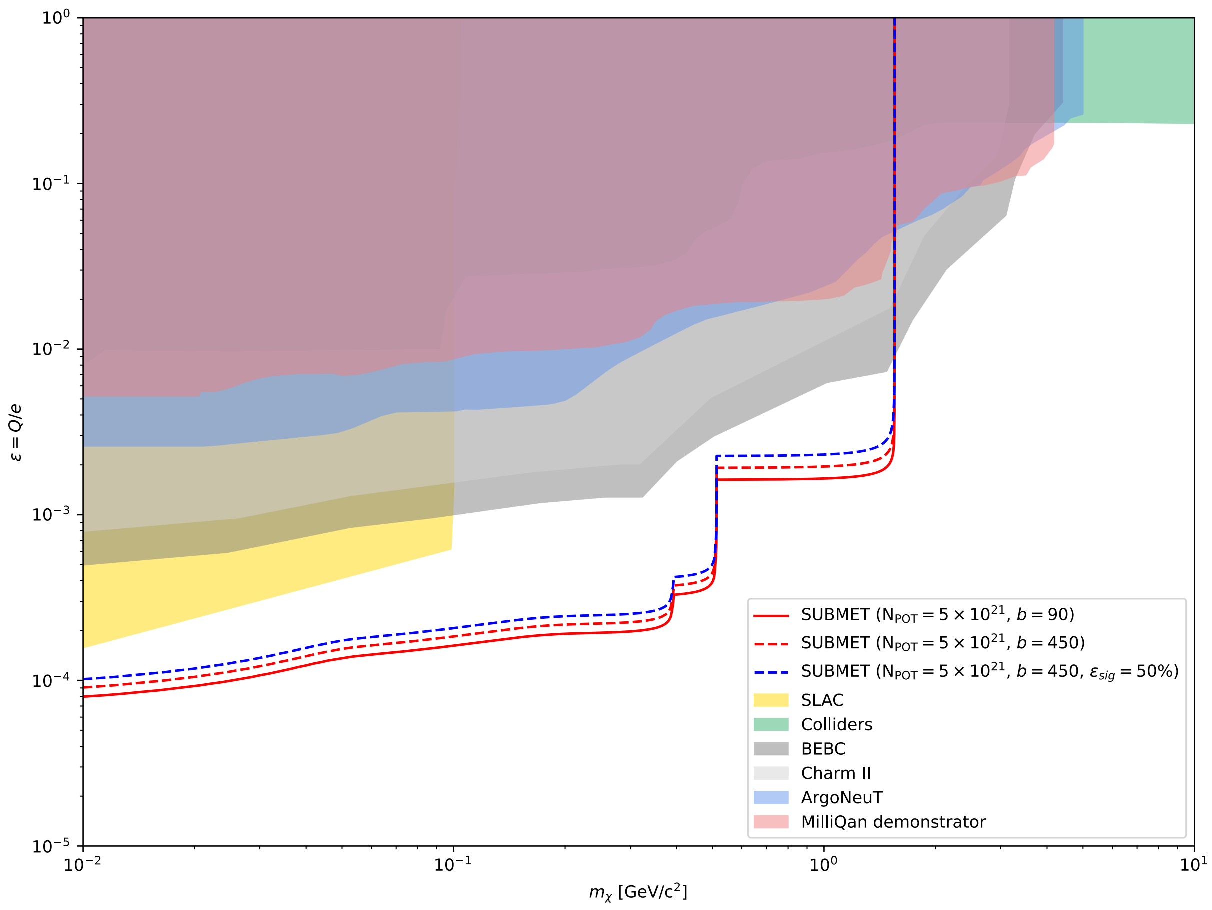
- Applied following cuts to select events
  - Pulse height : 5.8 mV < Vpulse < 30 mV
  - Pulse width : Δt_{width}< 7 ns
  - Remove events with a large number of afterpulses:

    Npulse < 3
  - Coincidence time window: Δt_{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)

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. $(N_{signal} \propto \varepsilon^{6})$

Summary and Future Step

- SUBMET can provide unique opportunity to probe small charge & low mass (m_χ < 1.6 GeV) millicharged particles.
- Finished **mechanics design** of the whole detector structure.
- Based on the prototype board study, the **full-scale DAQ boards** have been designed and tested.
- Visited J-PARC in Nov 2022 to study beam-off **background**.
- TDR submitted and awaiting **stage-II approval**

- As soon as stage-II status is granted, we plan to start detector installation and explore the unexplored regime!

Back-up

Where We Are

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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[4]*New York University, New York, New York, USA*
[5]*Lebanese University, Hadeth-Beirut, Lebanon*
[6]*CERN, Geneva, Switzerland*

Proposal

Abstract

We propose a new experiment searching for sub-millicharged particles (χ_s) 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 χ_s 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)

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[1]*Korea University, Seoul, Korea*
[2]*University of California, Davis, California, USA*
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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 2022 (35th PAC meeting)

Software : 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 $\{E_0\ E_1, E_2, \ldots\}$ may converge to pedestal level.

Step 5. Find the point that exceeds the threshold.