# Search for millicharged particles at J-PARC

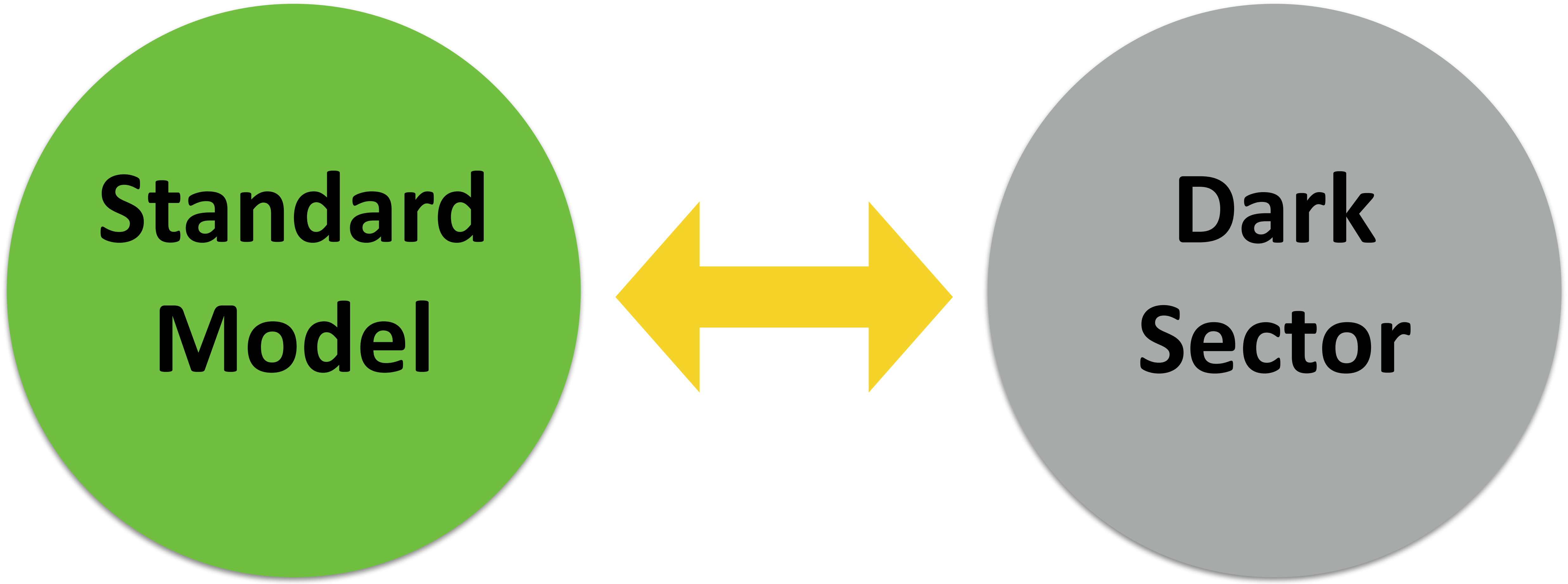
## *SUB-MillichargeExperimenT (SUBMET)*

Jae Hyeok Yoo (Korea University) on behalf of the SUBMET collaboration

06/20-22/2022

Phase II ND Workshop (Imperial College London)

# Motivation

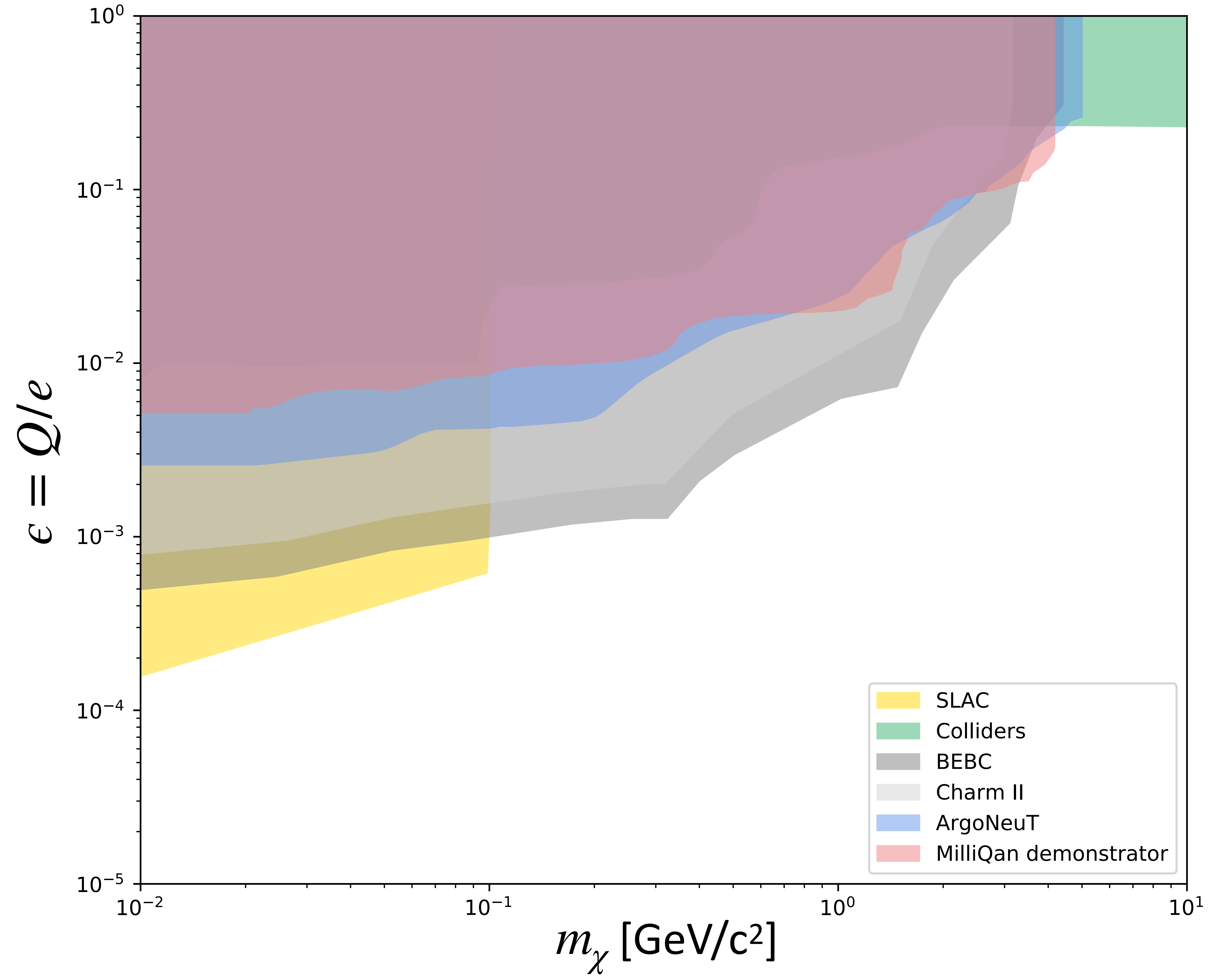



$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} A'_{\mu\nu} A'^{\mu\nu}$$
$$+ i\bar{\chi} \left( \partial\!\!\!/ + ie' A\!\!\!/' + i\kappa e' B\!\!\!/ + iM_{\rm mCP} \right) \chi$$

Kinetic mixing between $A'$ and SM photon $B$ results in fractional charge ($\kappa e'$) for $\chi$

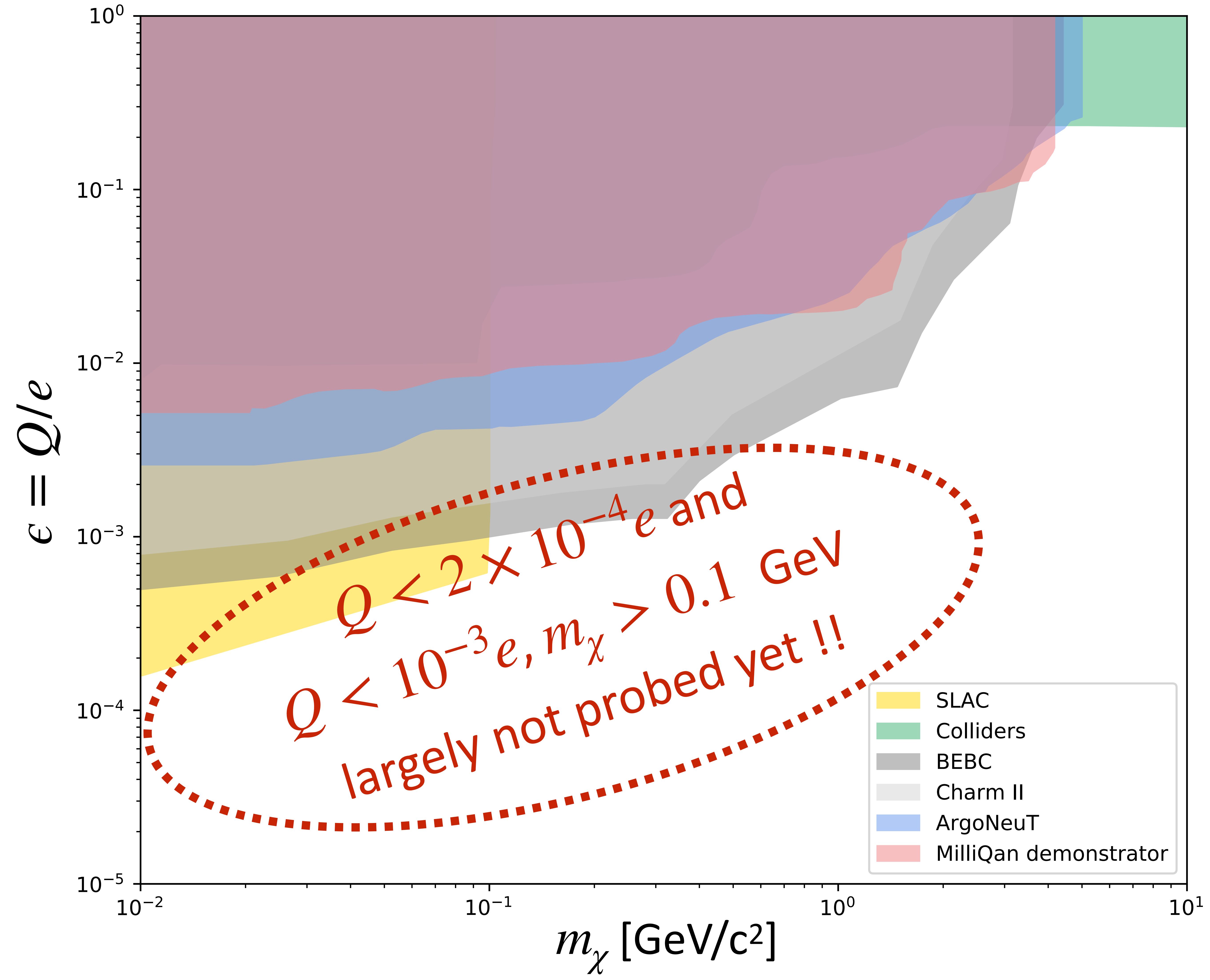
- Quantization of electric charge is a long-standing question in physics
- Well-motivated dark-sector models have been proposed to predict the existence of millicharged particles ($\chi$s) while preserving the possibility for unification
- One possibility is to assume new dark sector U(1) with massless dark-photon ($A'$) and massive dark-fermion ($\chi$)

# Current reach

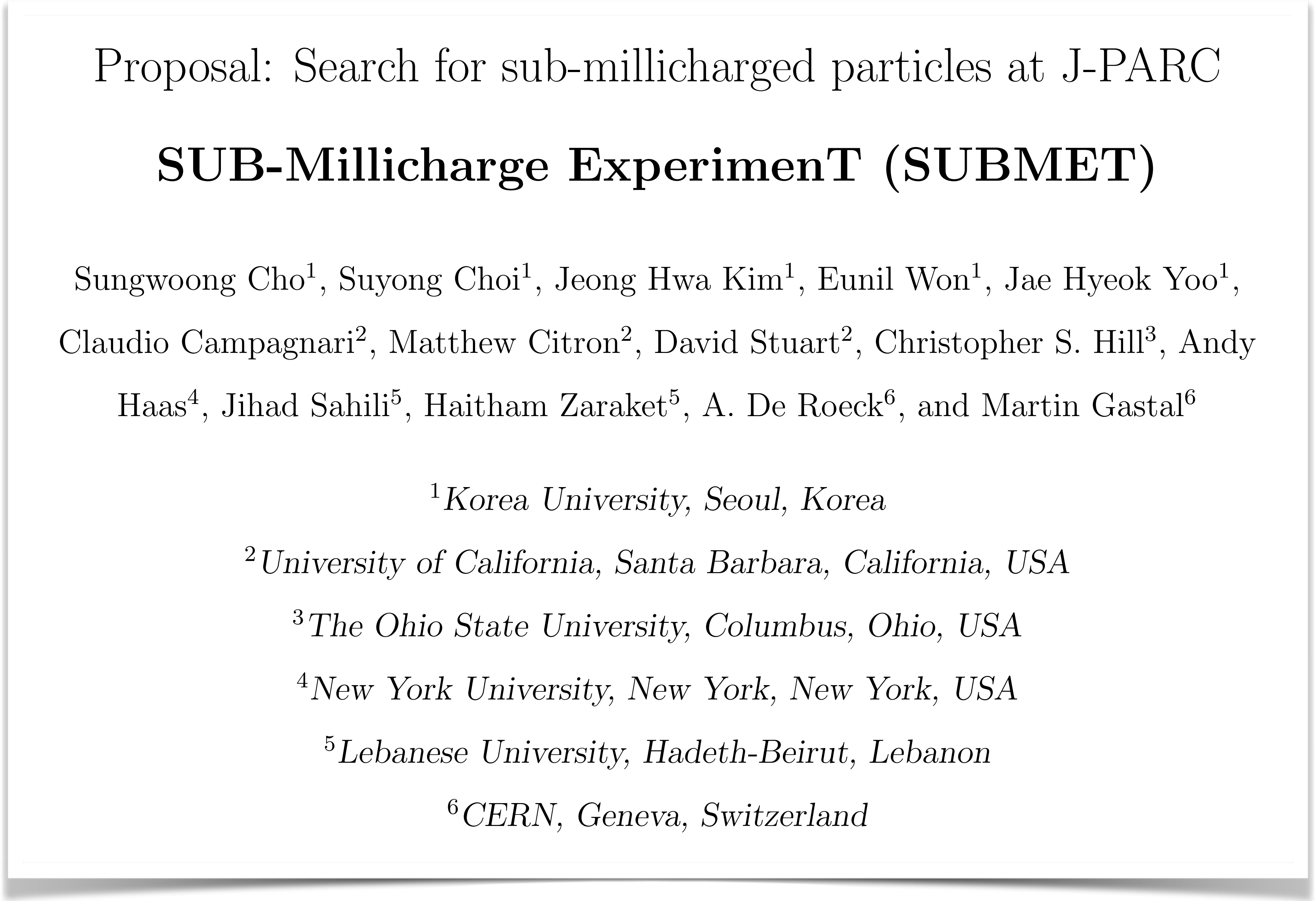



- Various searches for millicharged particles so far

# SUBMET: SUB-Millicharge ExperimenT




- Scintillator-based detector using proton fixed-target collisions at J-PARC (inspired by milliQan experiment)
- Target low-mass and small-Q region


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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[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*

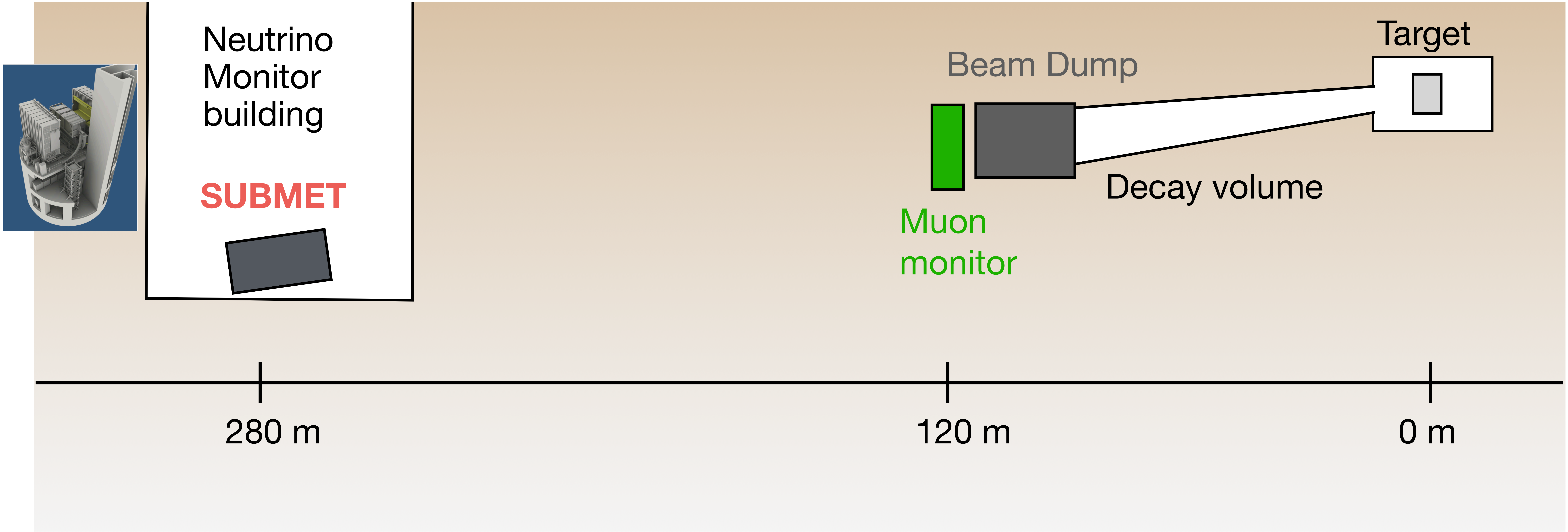
[6] *CERN, Geneva, Switzerland*

# J-PARC complex

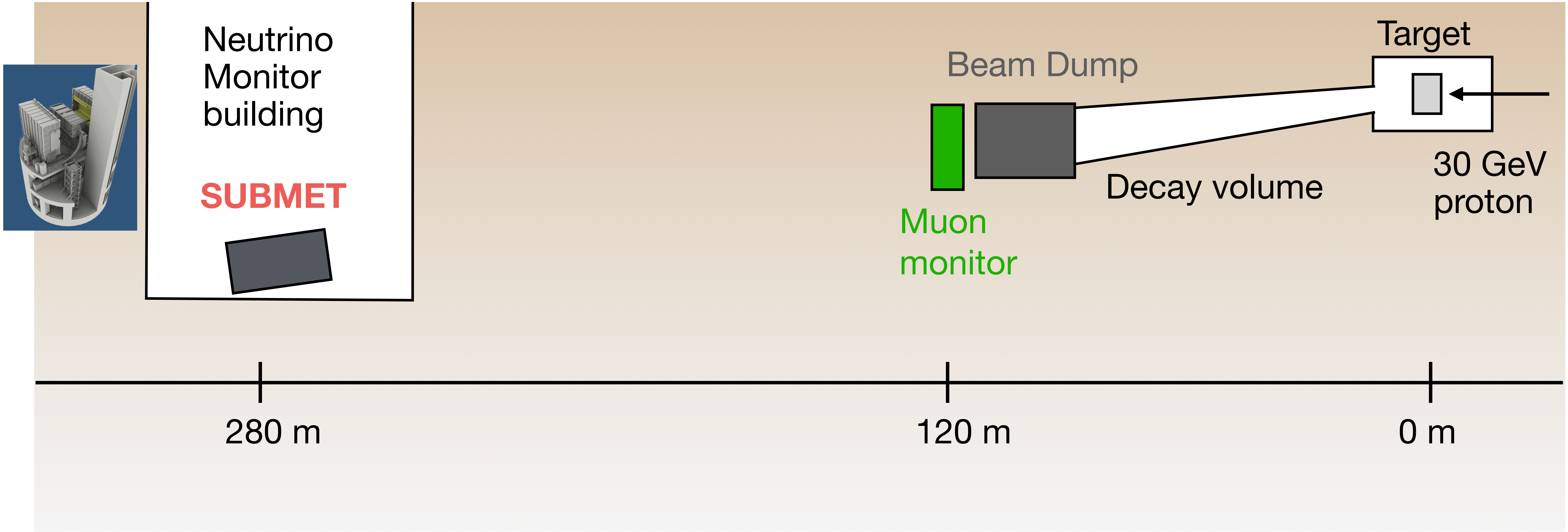
# Experimental site

# Experimental site

# Basic idea of detecting $\chi$s

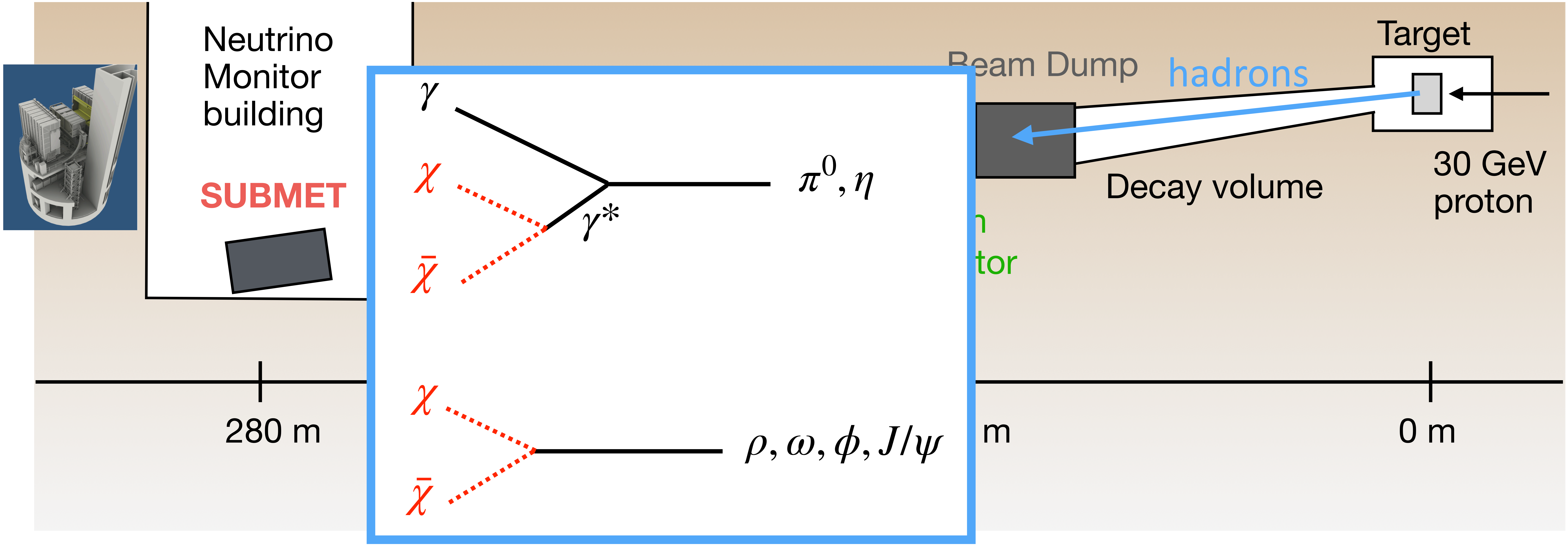


# Basic idea of detecting $\chi$s



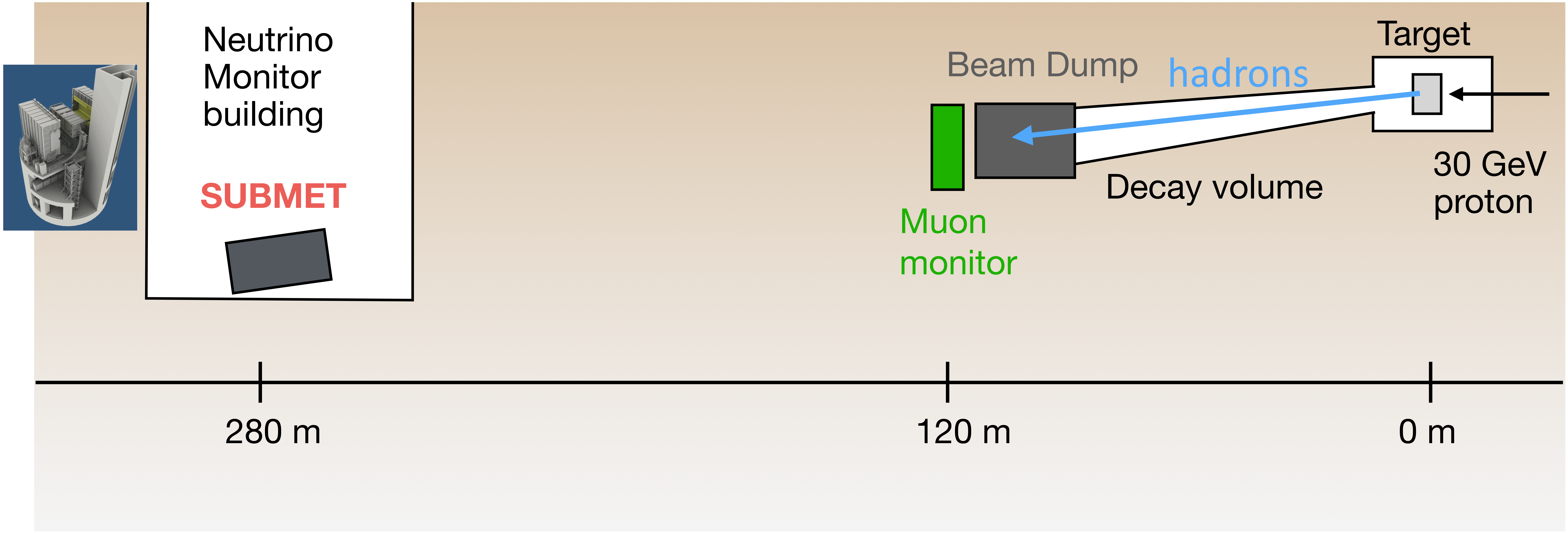

Protons hit the target and produce hadrons

# Basic idea of detecting $\chi$s



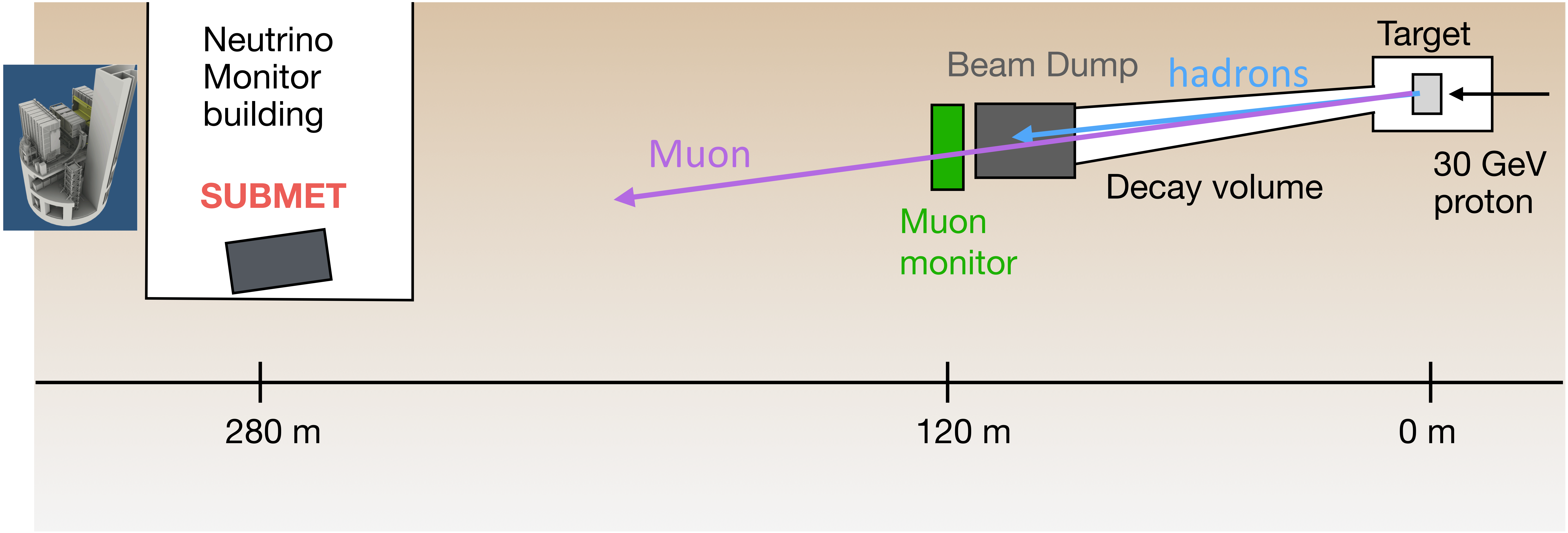

Millicharged particles are produced from the decay of neutral mesons

# Basic idea of detecting $\chi$s



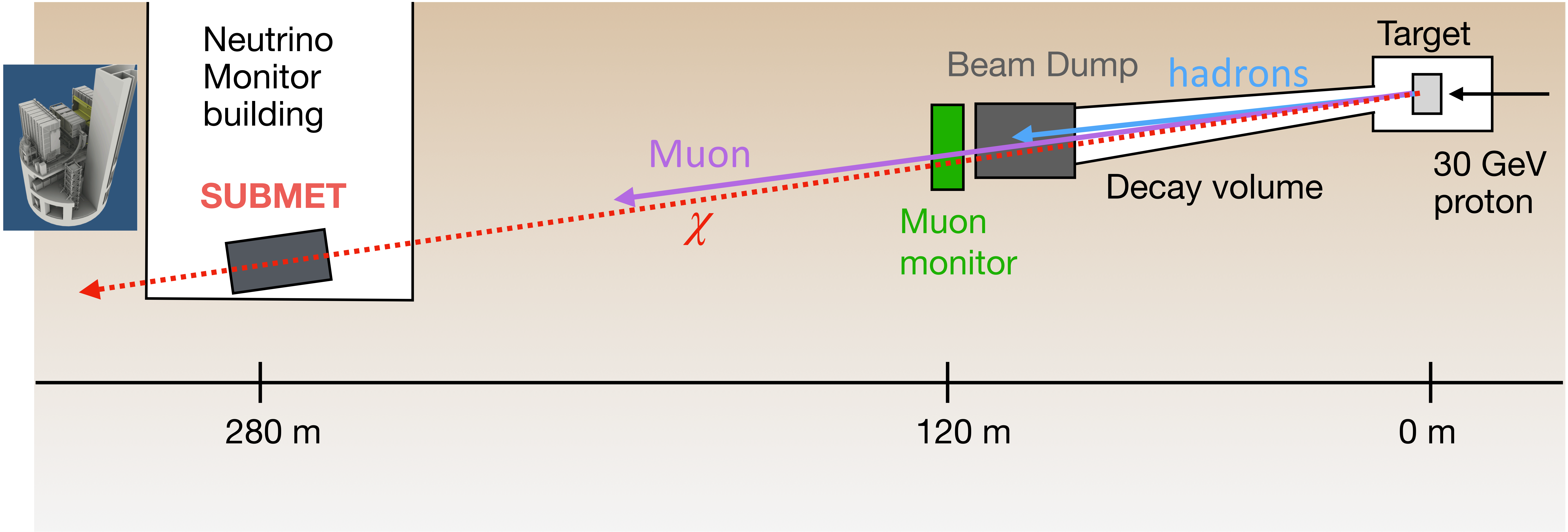

Hadrons stop in the Beam Dump

# Basic idea of detecting $\chi$s




Muons pass the Beam Dump, but lose the entire energy in sand (5 MeV/cm) before reaching the Neutrino Monitor building

# Basic idea of detecting $\chi$s

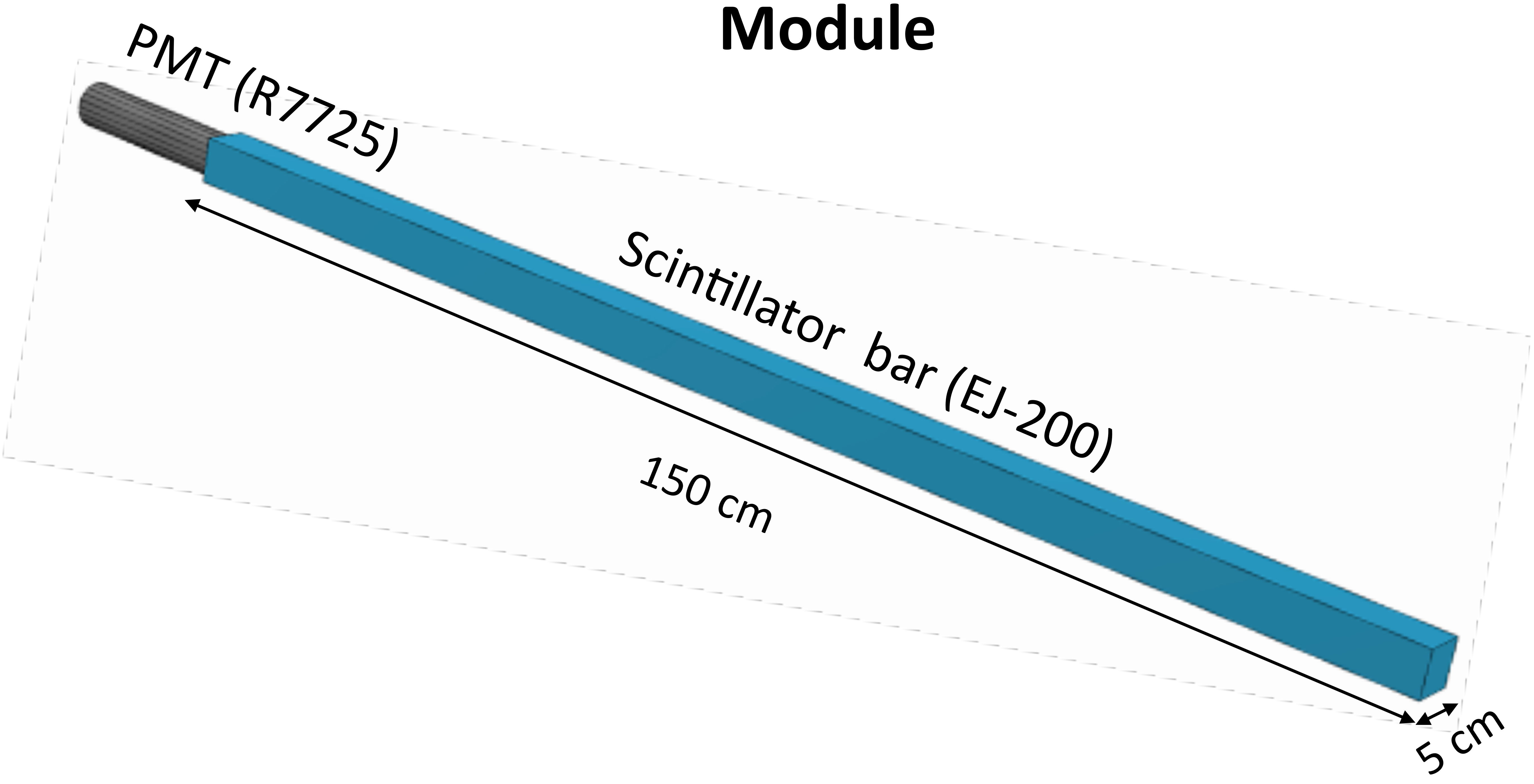



Only $\chi$s (and neutrinos) reach the detector

(energy loss for $\chi$s with $Q = 10^{-3}e$ is <0.1 MeV )

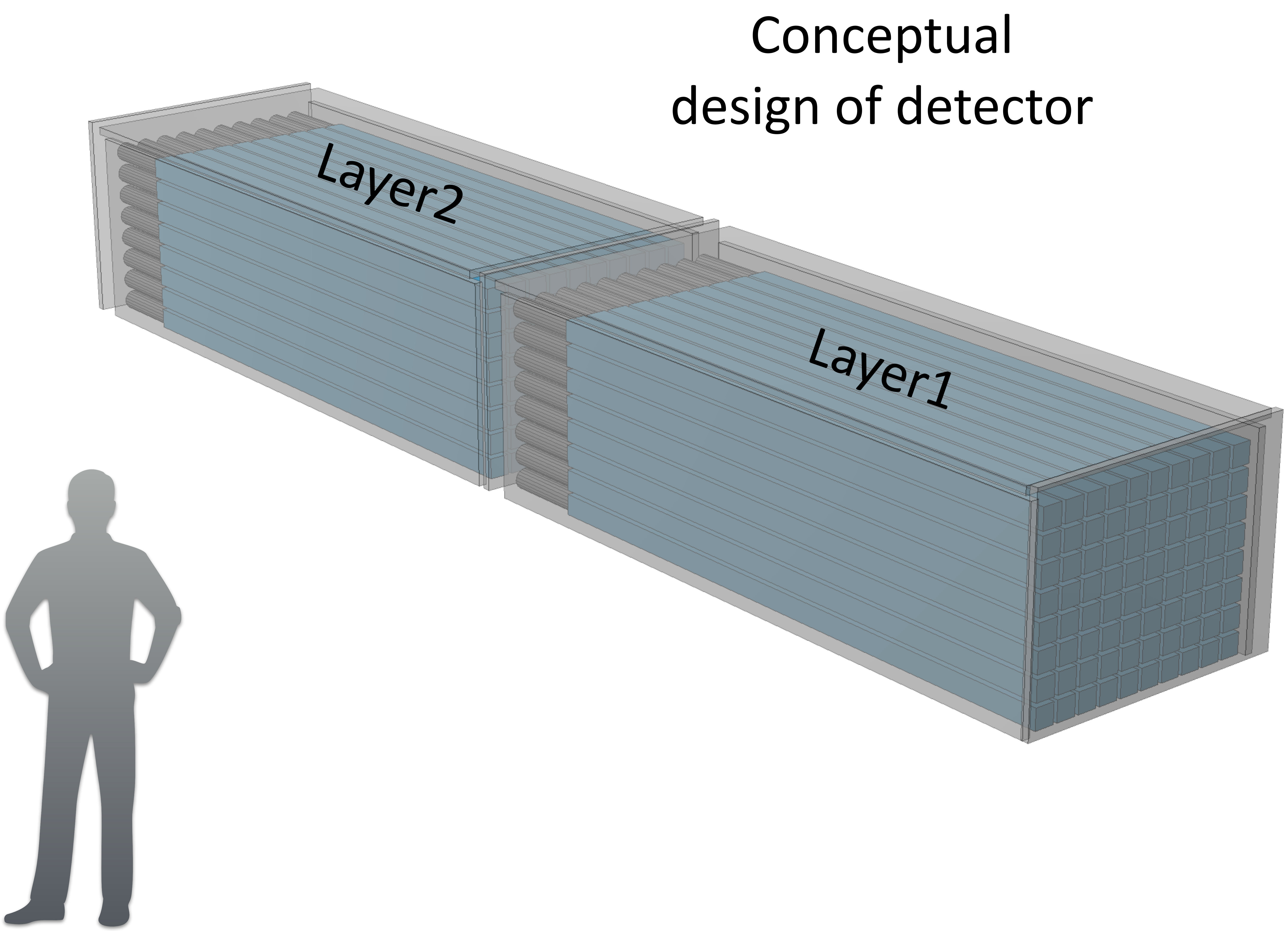
# Overview of detector design

**Module**



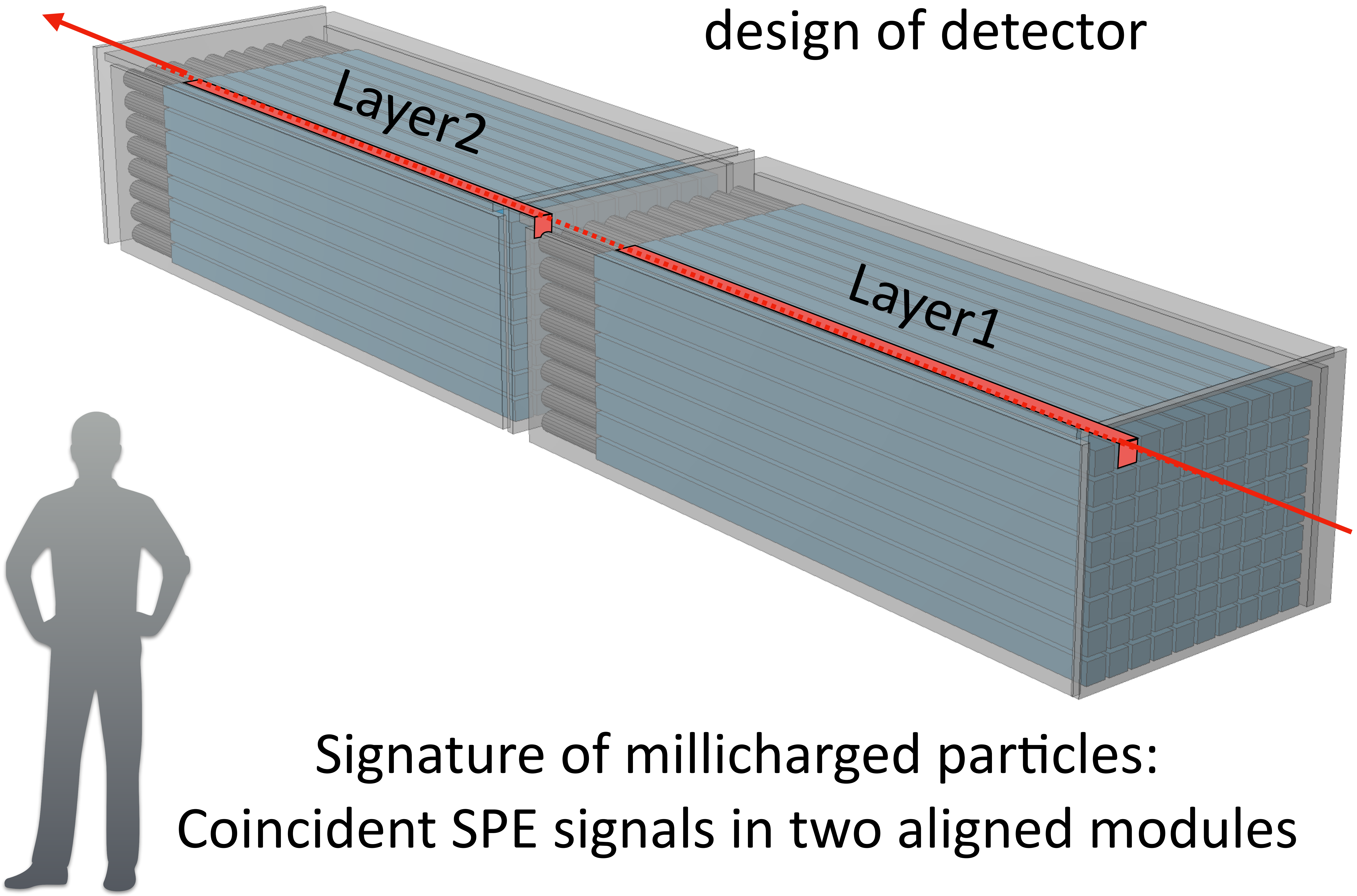

- Use long (1.5 m) scintillator bars so that $\chi$s with small change can produce photons
  - For small $\epsilon$, detect single photons

# Overview of detector design




- Use long (1.5 m) scintillator bars so that $\chi$s with small change can produce photons
  - For small $\epsilon$, detect single photons
- Stack (10x8) scintillators to increase total volume and use two layers to control backgrounds

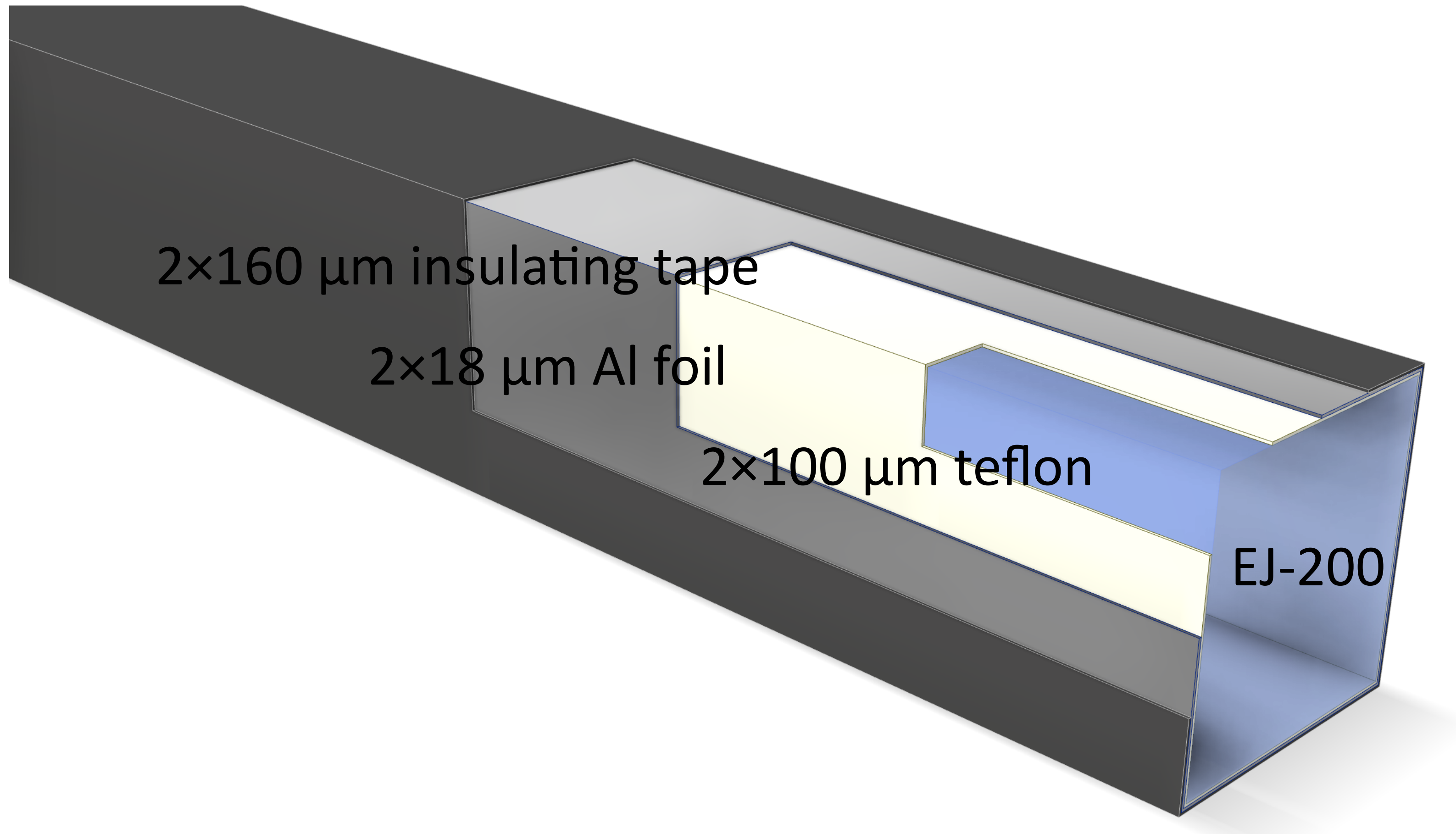
# Overview of detector design




Signature of millicharged particles:
Coincident SPE signals in two aligned modules

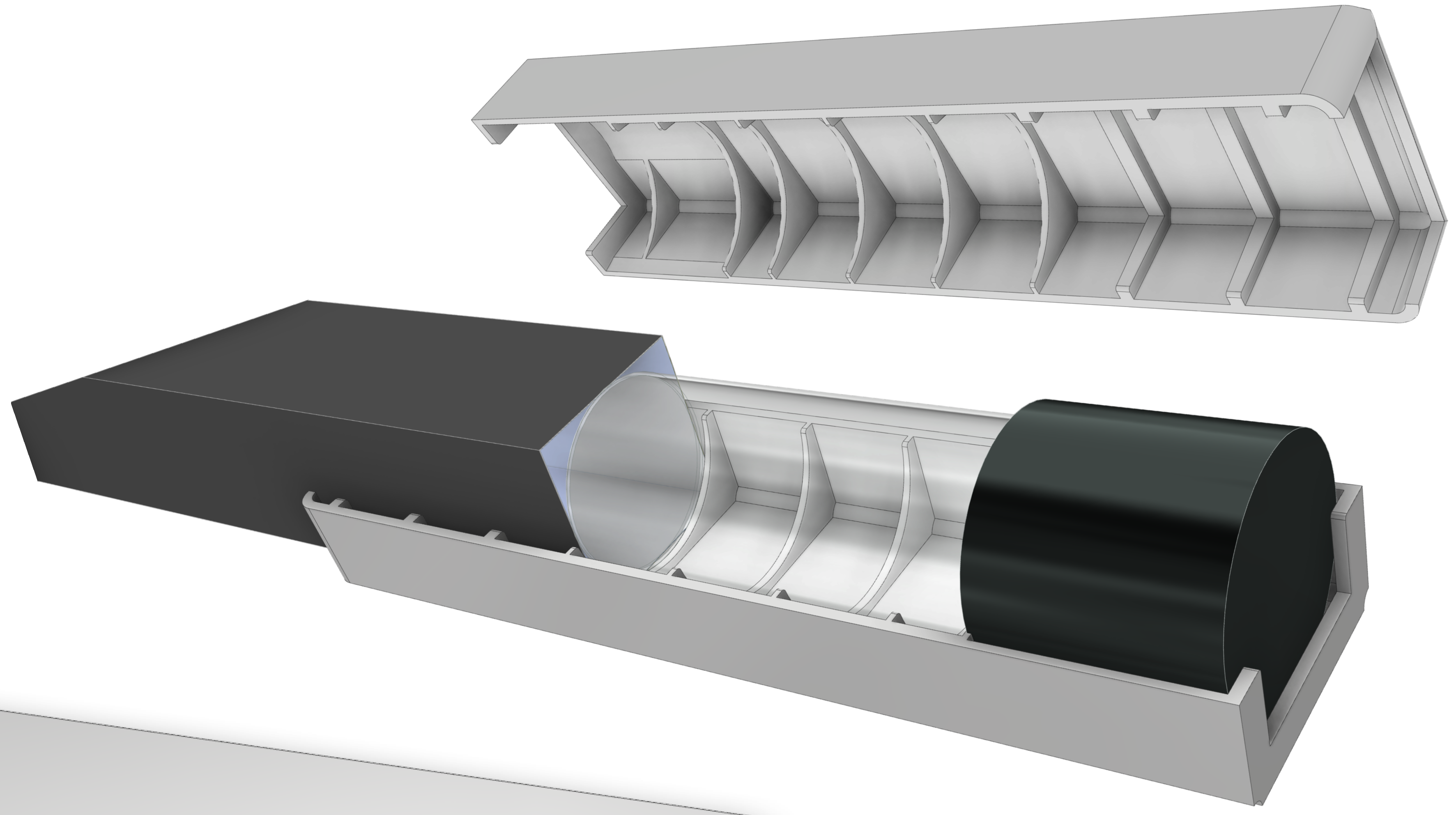
- Use long (1.5 m) scintillator bars so that $\chi$s with small change can produce photons
  - For small $\epsilon$, detect single photons
- Stack (10x8) scintillators to increase total volume and use two layers to control backgrounds
- Align the two layers such that a $\chi$ goes through them
- Cover them with scintillator panels to tag/reject external radiation/cosmic muons

# Detector components: module

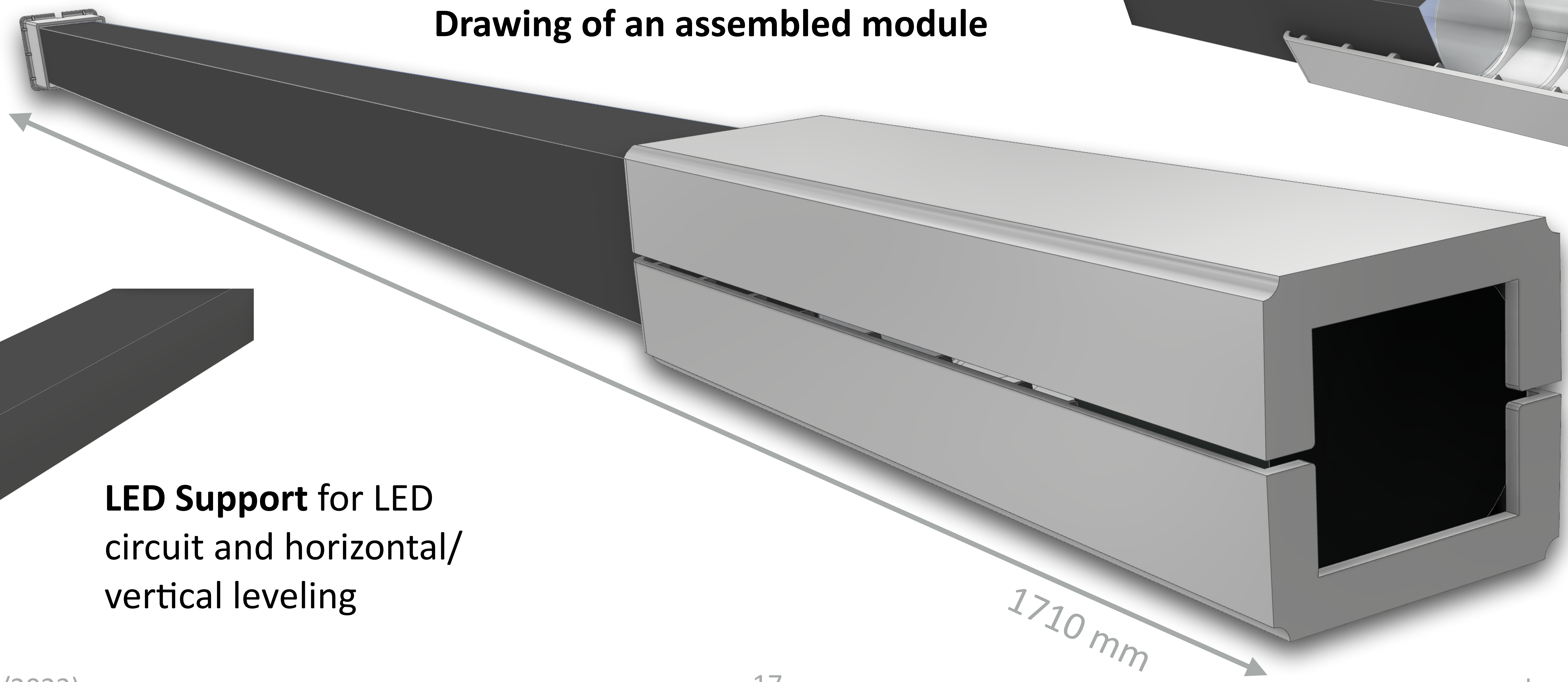


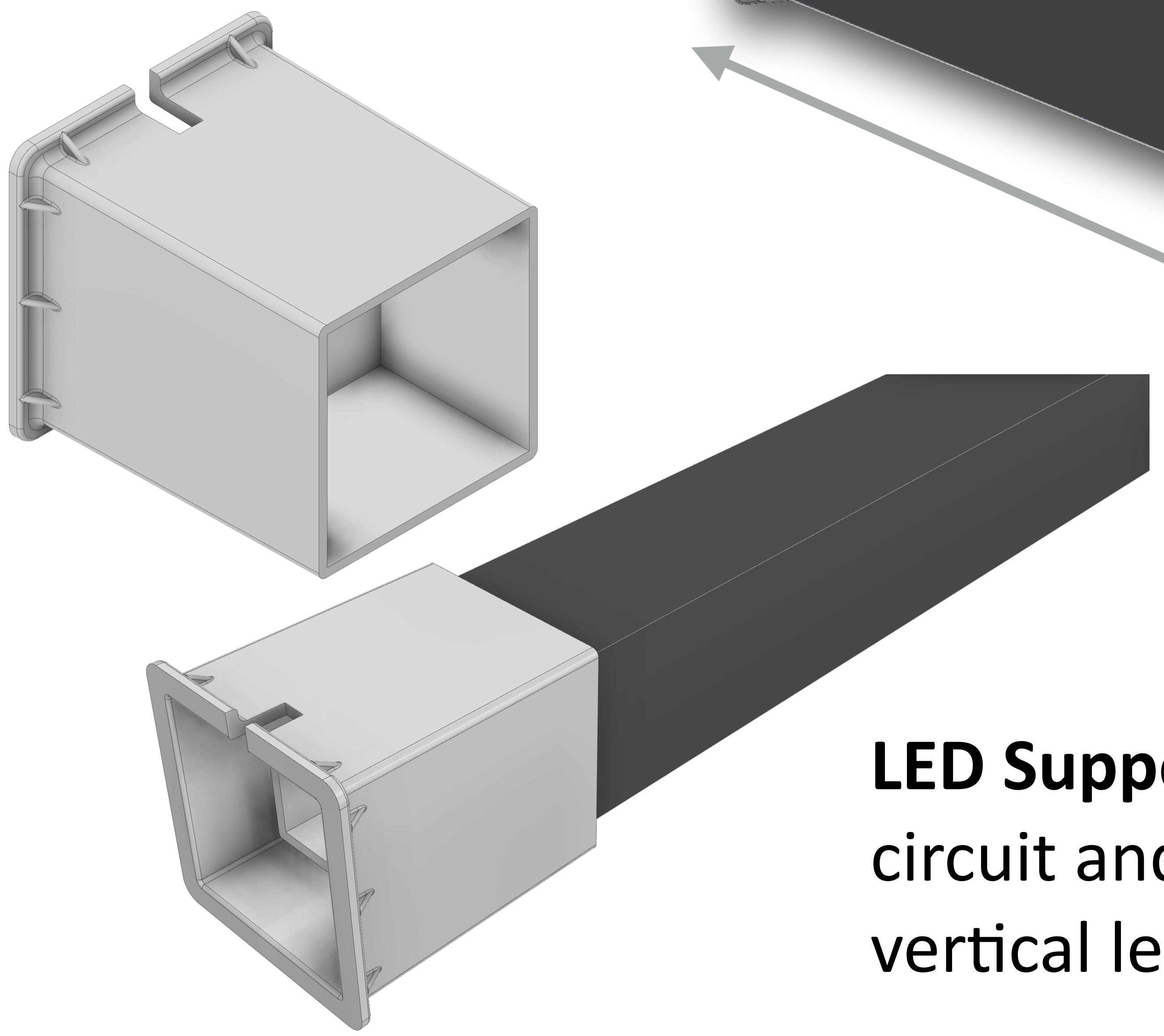

How a **scintillator** bar is **wrapped**
(teflon + Al foil + insulating tape)

**PMT support** for coupling between PMT and scintillator



**Drawing of an assembled module**



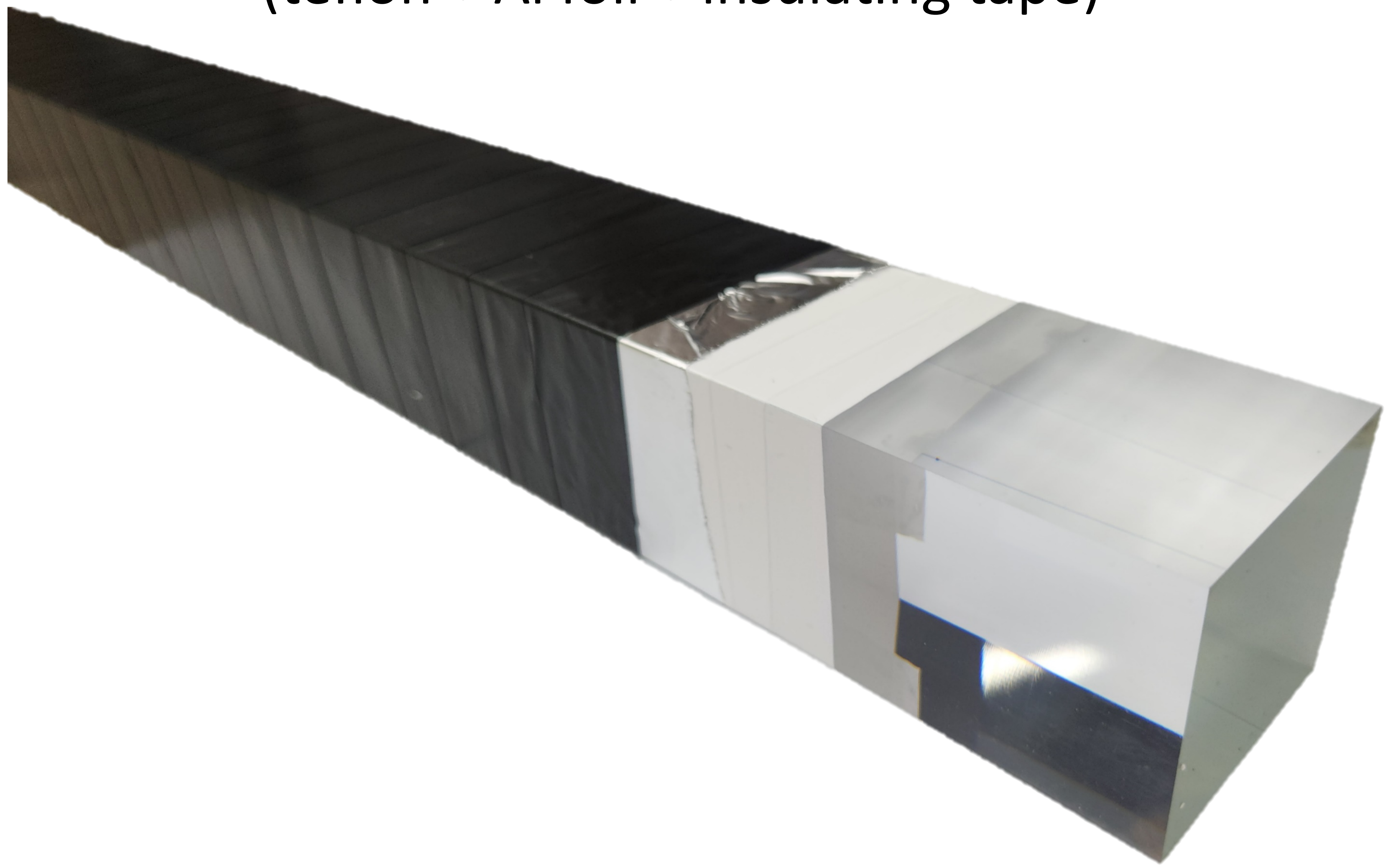



**LED Support** for LED circuit and horizontal/ vertical leveling

# Detector components: module

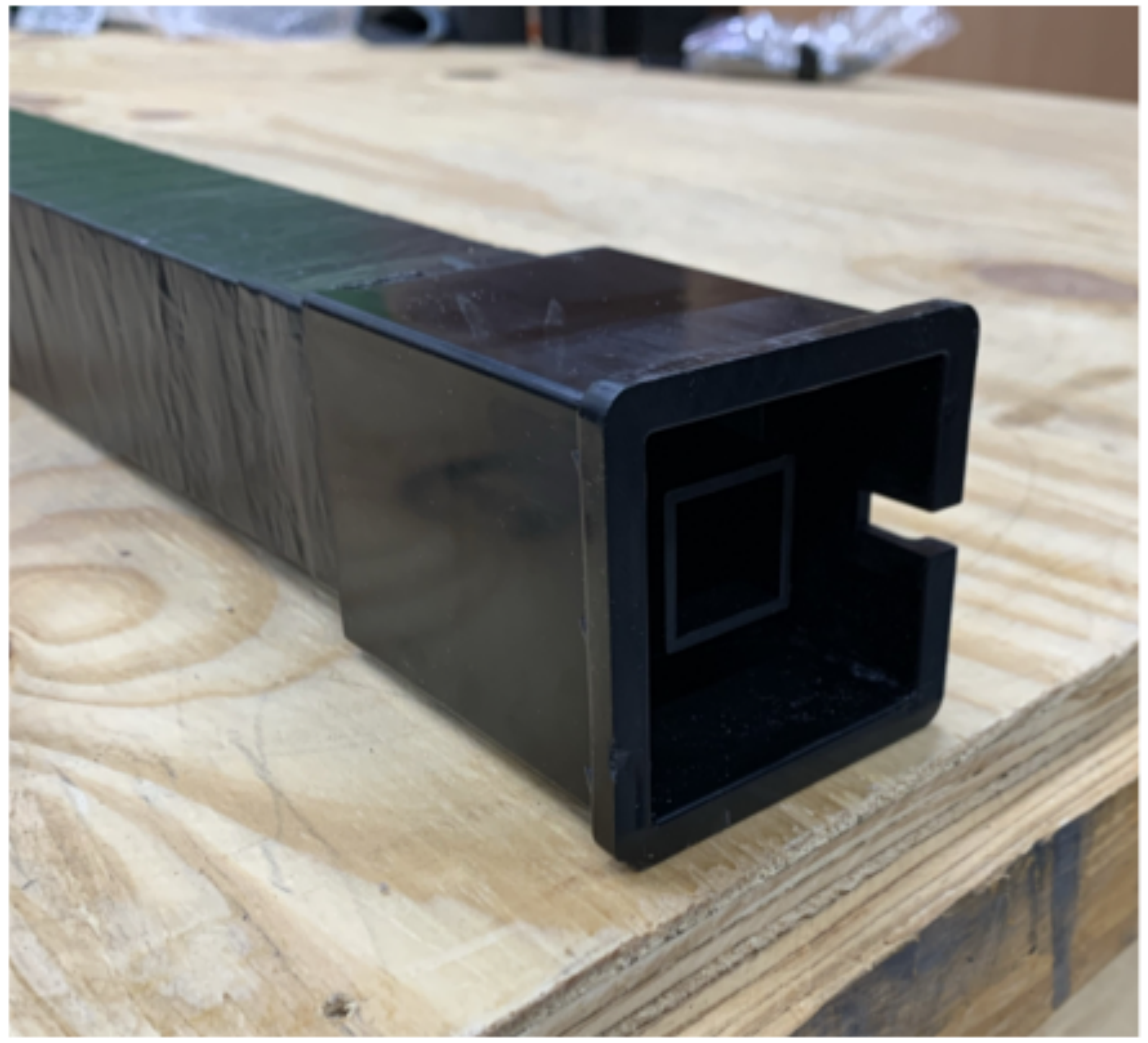
How a **scintillator** bar is **wrapped**

(teflon + Al foil + insulating tape)



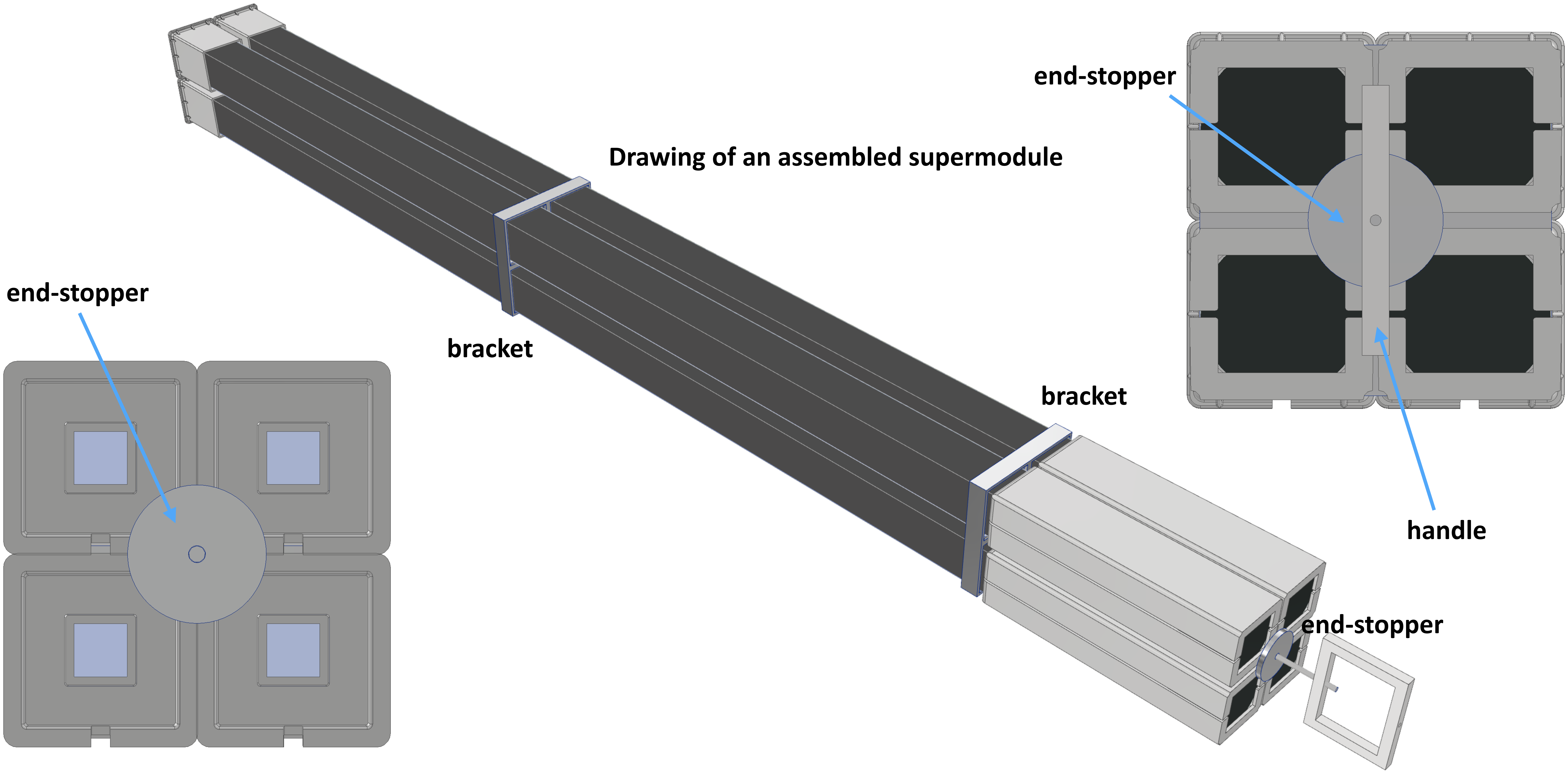
**An assembled module**

**PMT support** for coupling between PMT and scintillator

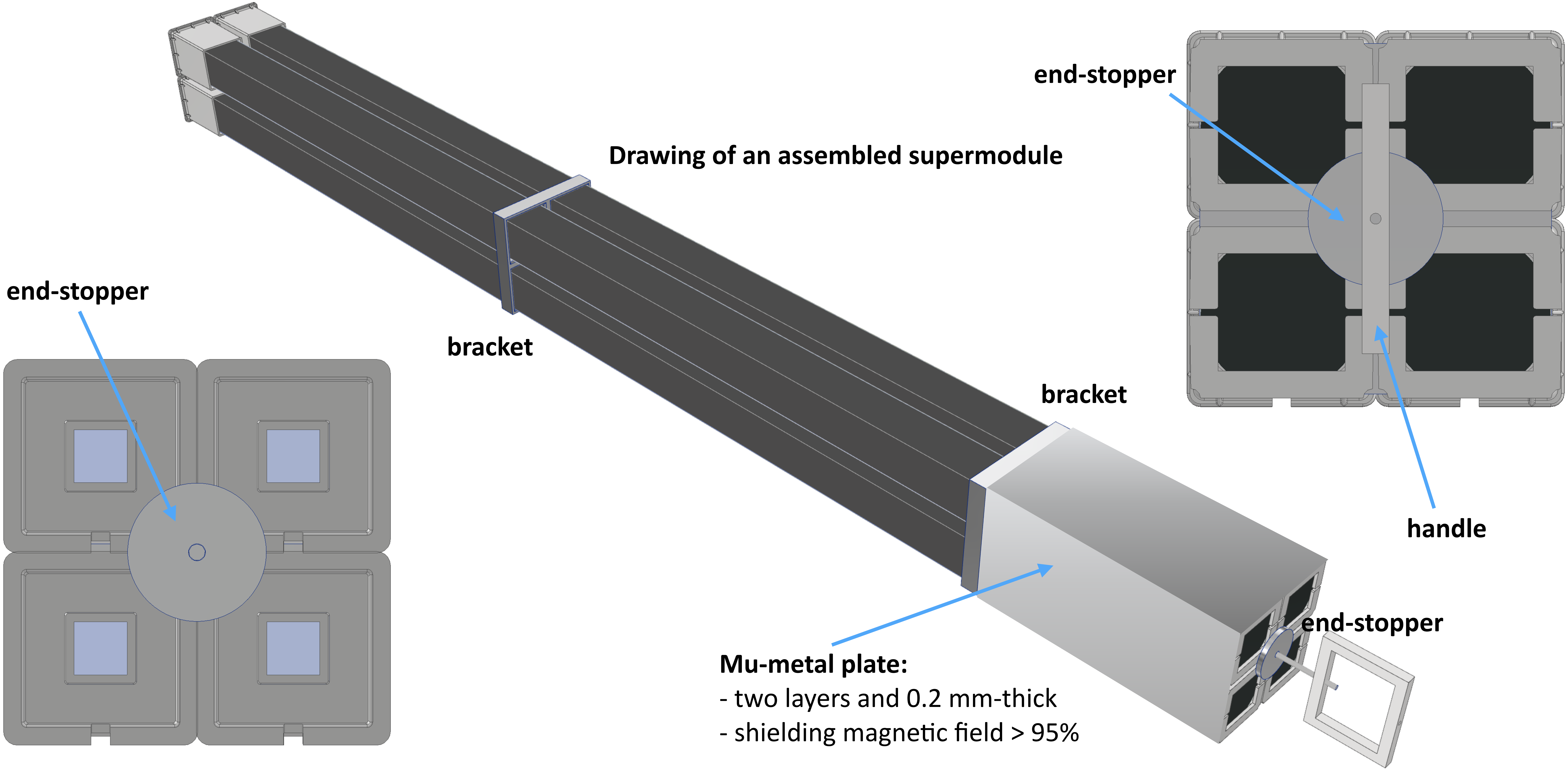


**LED Support** for LED circuit and horizontal/vertical leveling

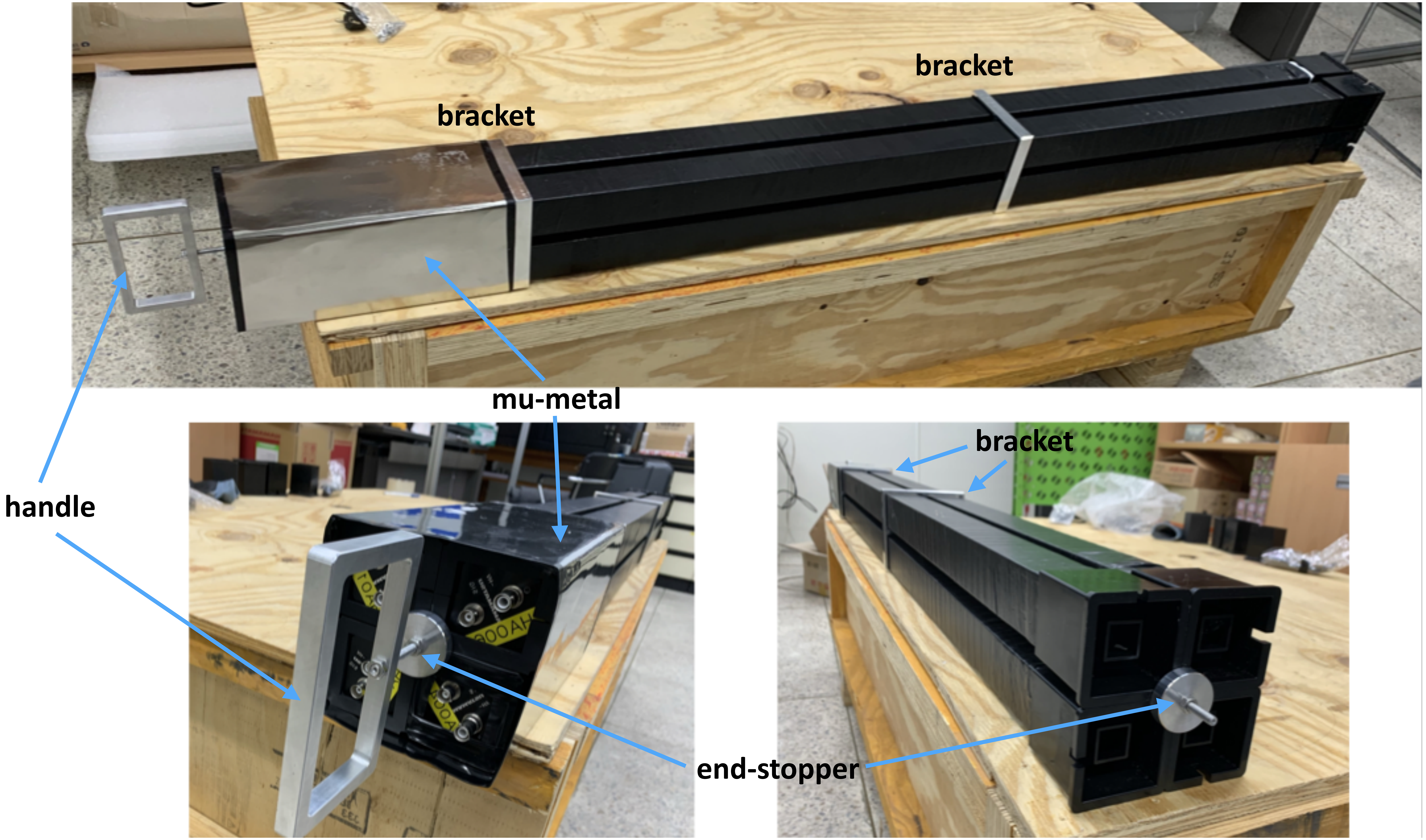
# Detector components: supermodule



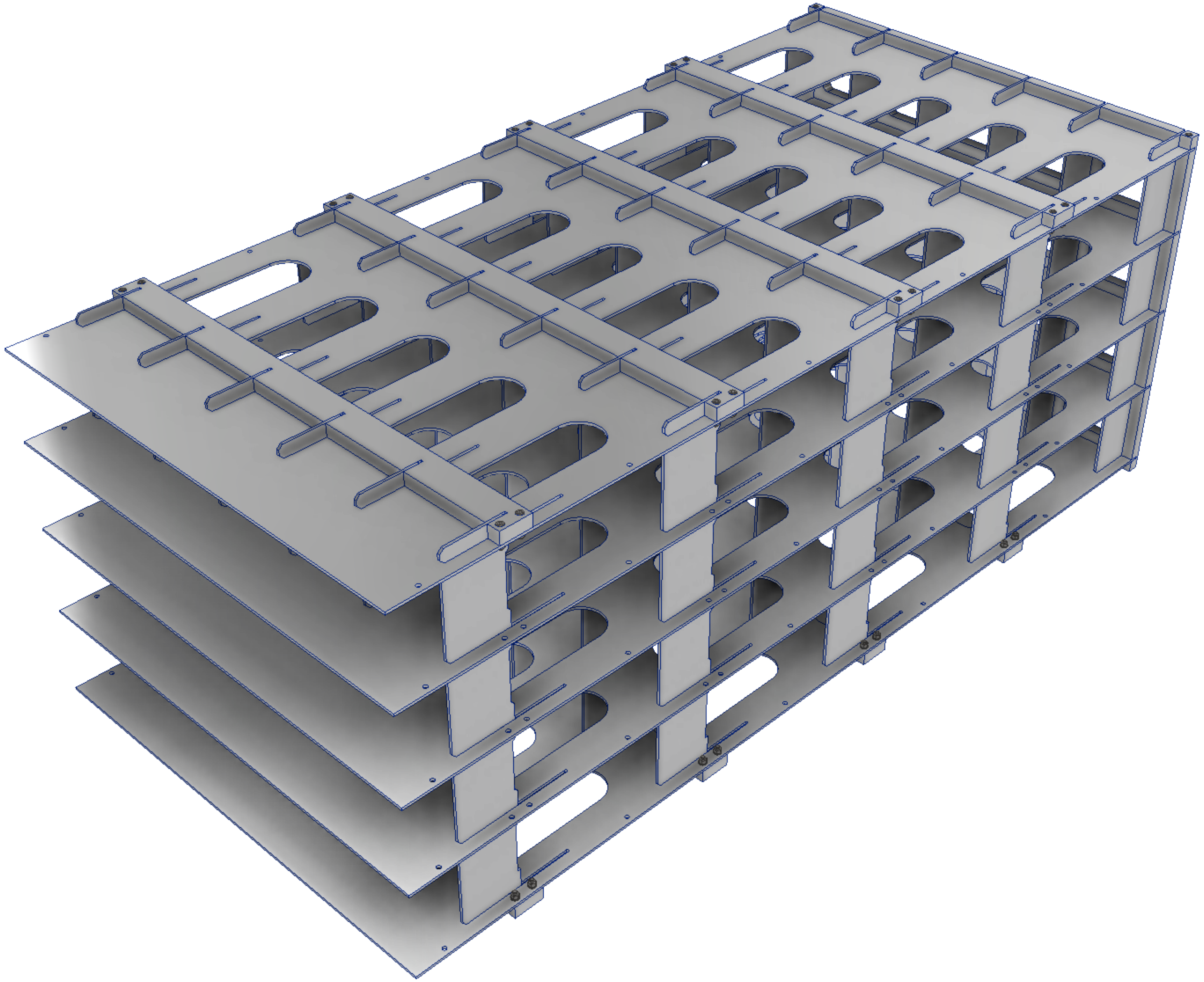
# Detector components: supermodule



# Detector components: supermodule



# Detector components: Cage



- **Cage**: a structure that holds twenty (5 × 4) supermodules
- 1 cage per layer
- Made of aluminum
- 4 main parts
  - end-cap
  - vertical plate
  - horizontal plate
  - cage-cap

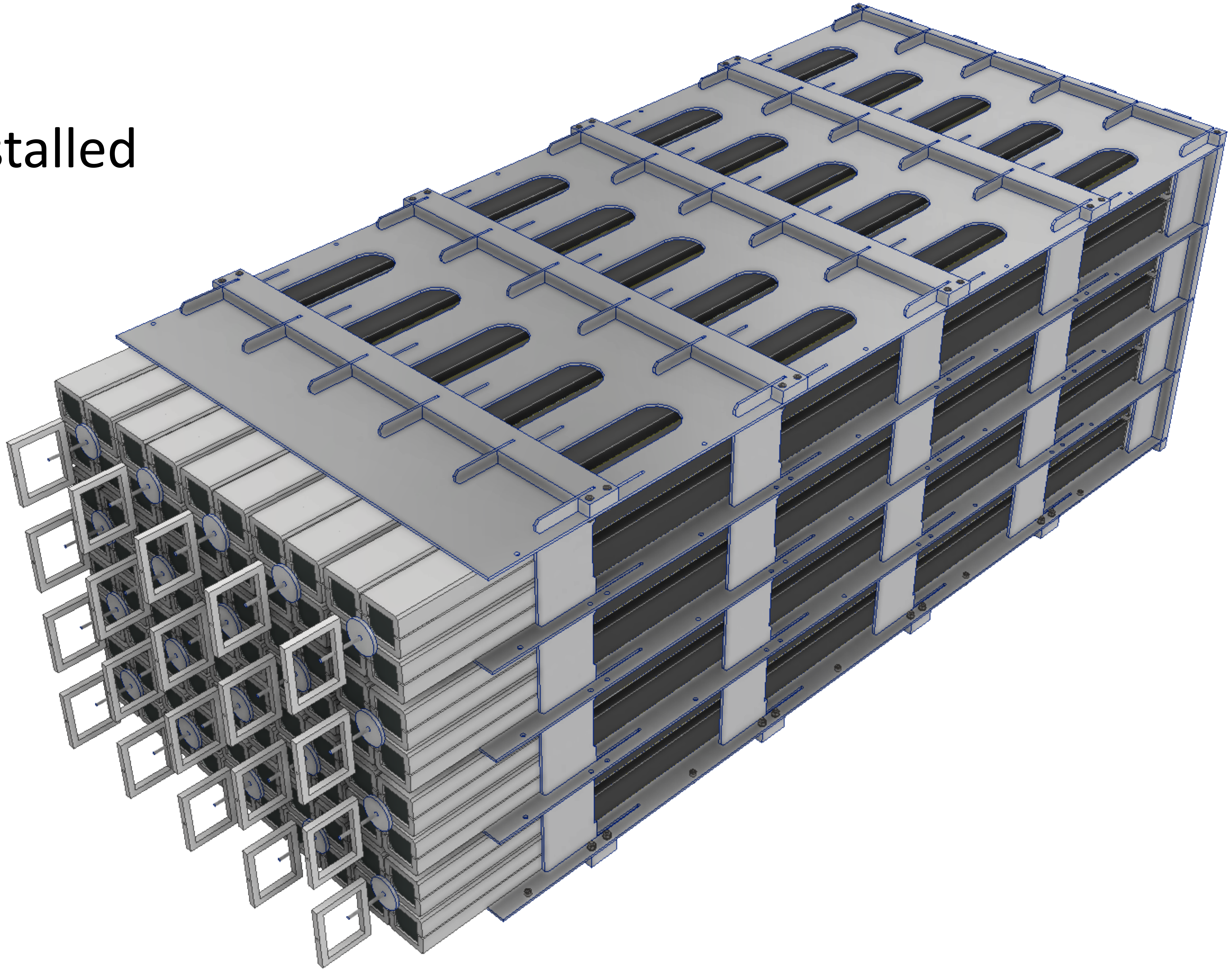
# Detector components: Cage

## With supermodules installed

Dimensions are

$1850 \times 764 \times 620\ mm^3$

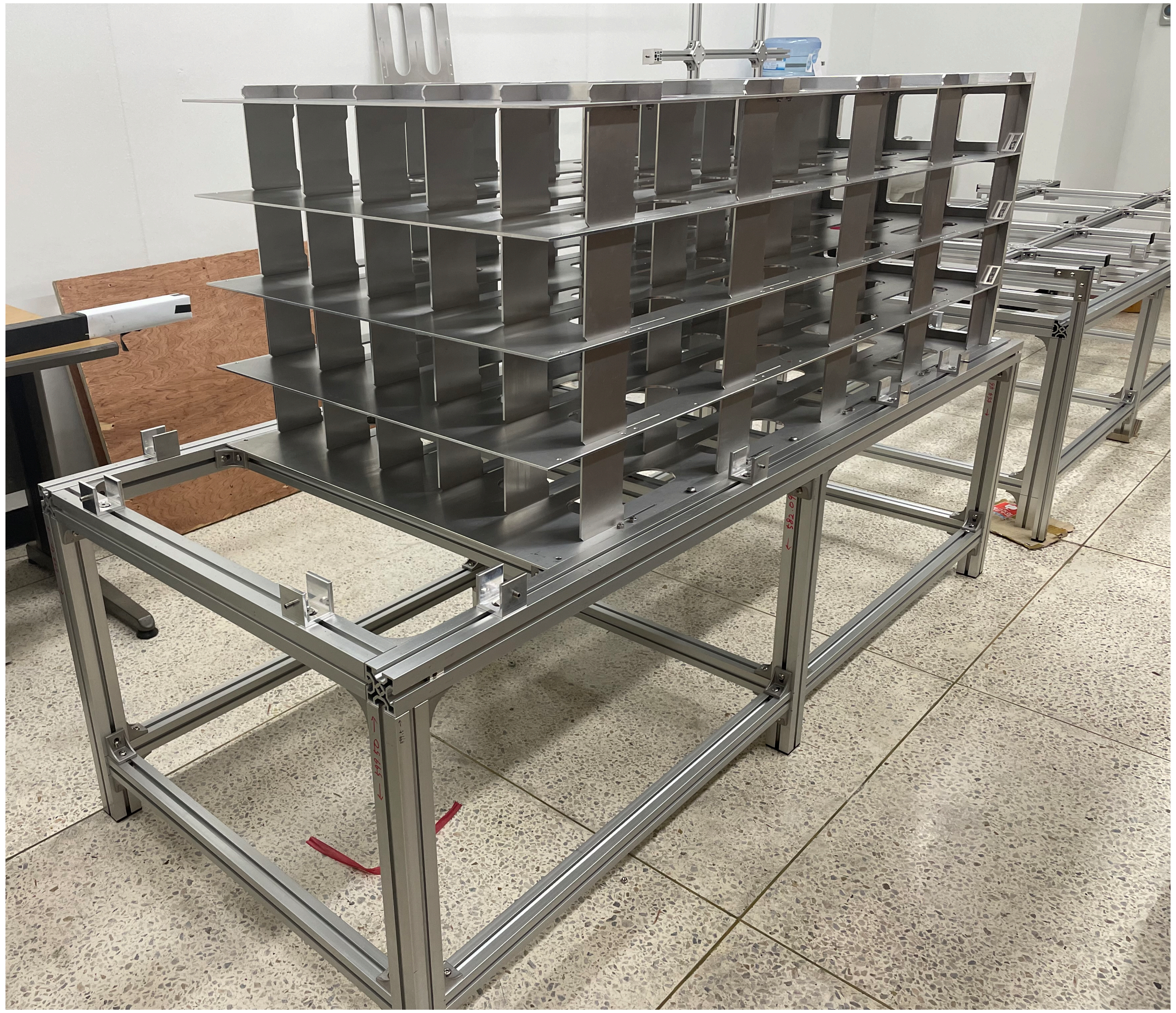
total weight: ~430 kg

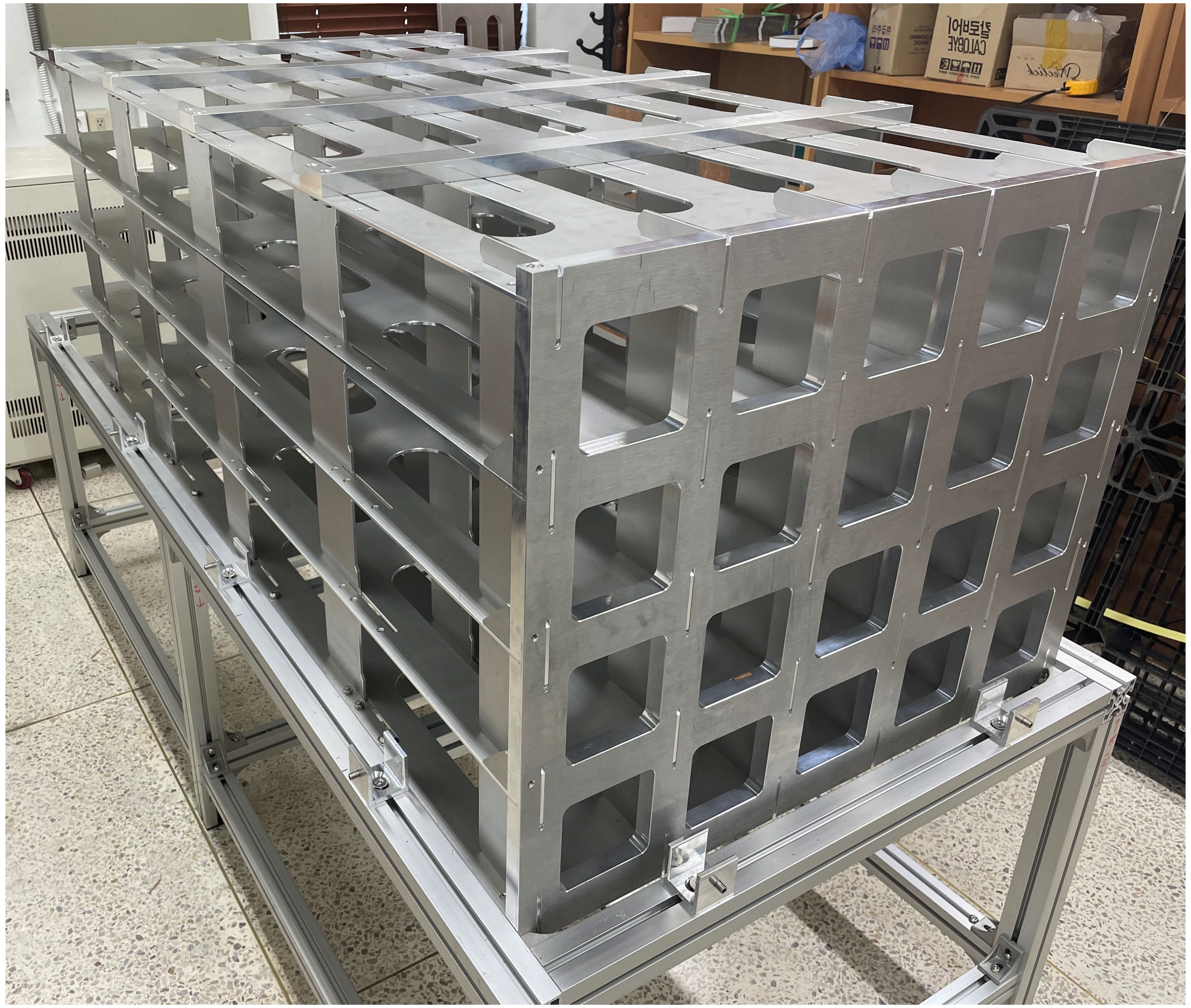


# Detector components: Table


- **Table**: a structure that provides some distance from the floor and align the detector axis to point the target
- Made of 4040 and 5050 aluminum profiles
- Tilted by 1 degree wrt floor

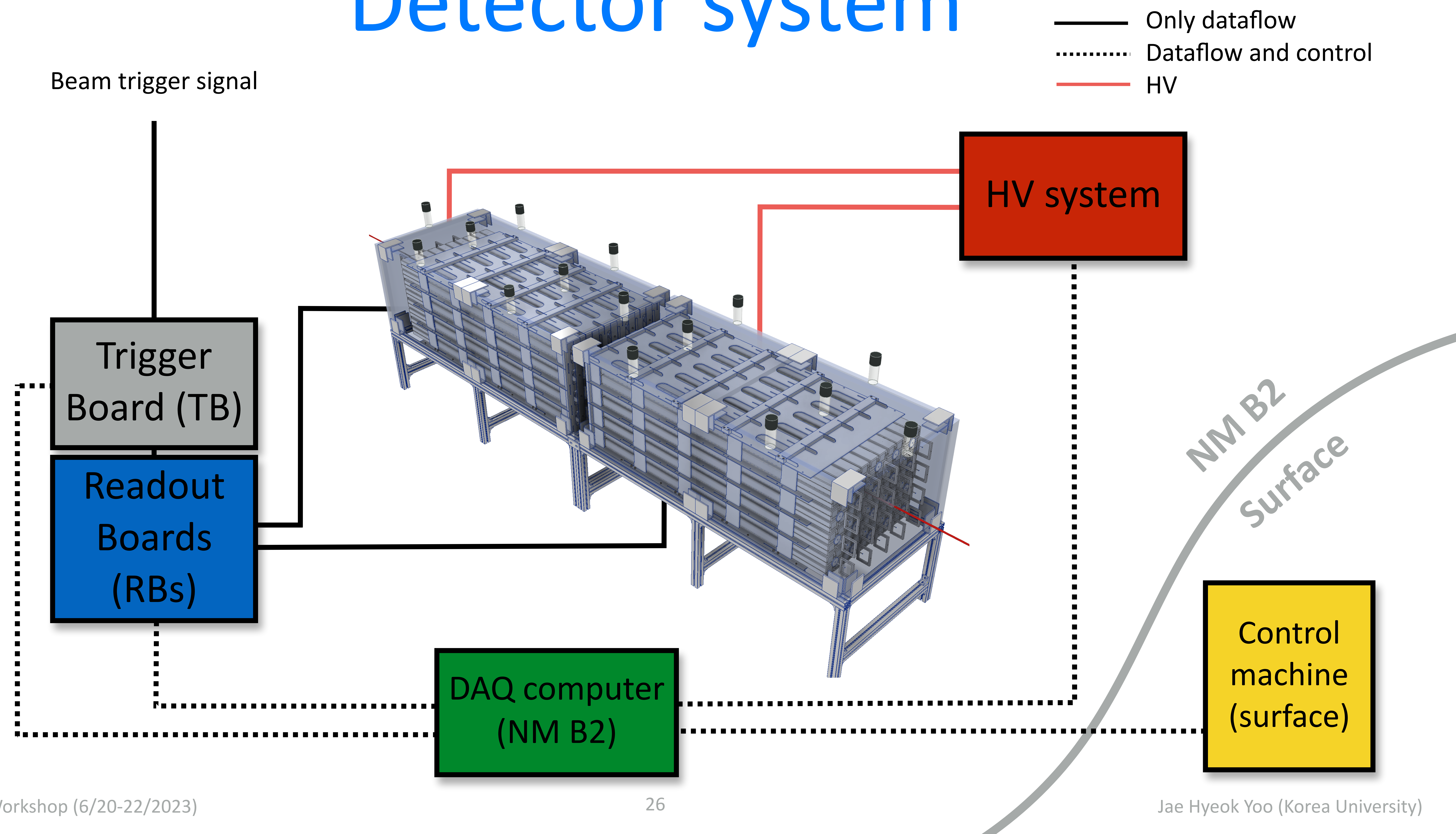
# Detector components: Cage + Table





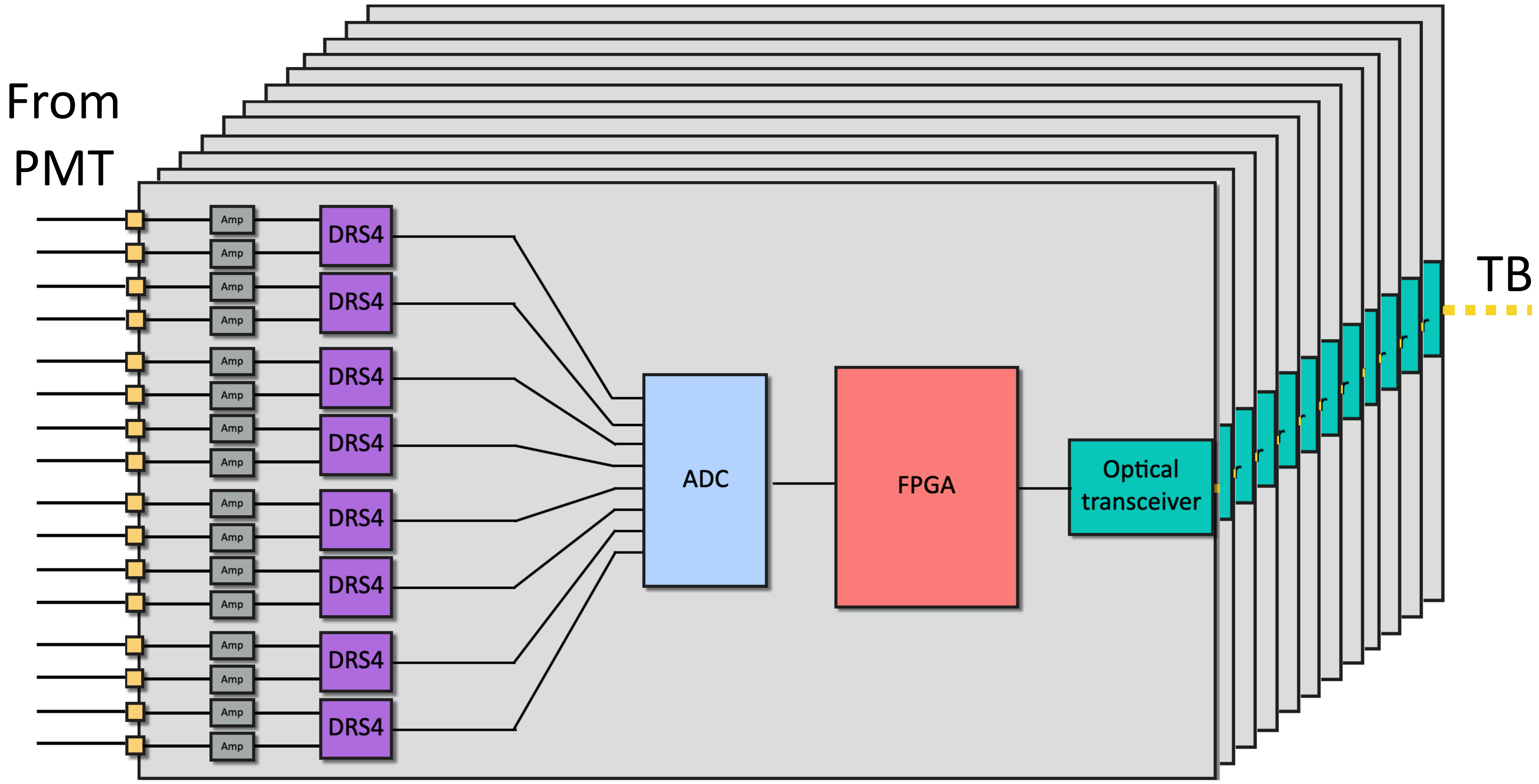
Stability of mechanics confirmed by static and dynamic weight simulations (results in the backup)

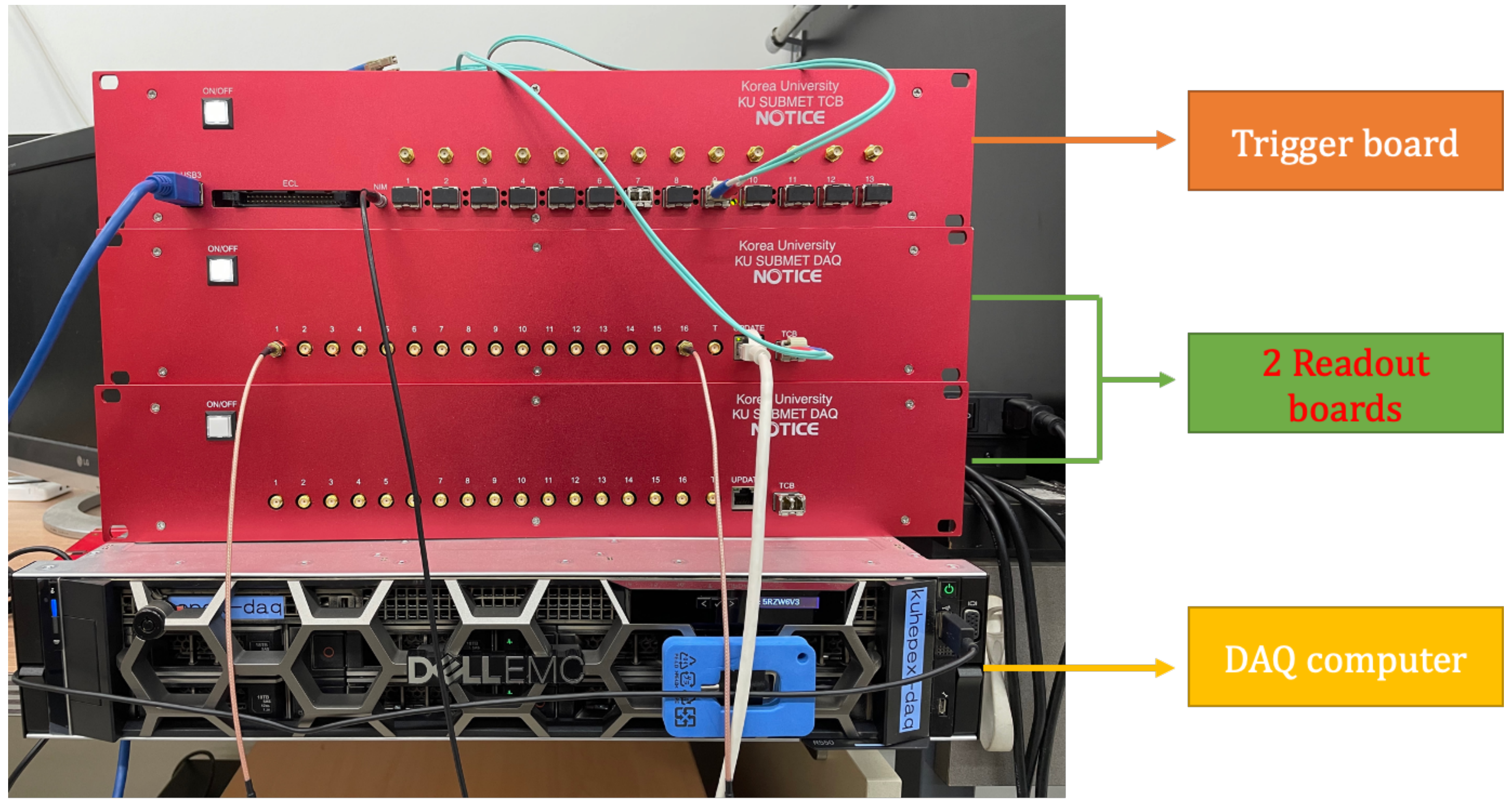
# Detector system



# Detector system

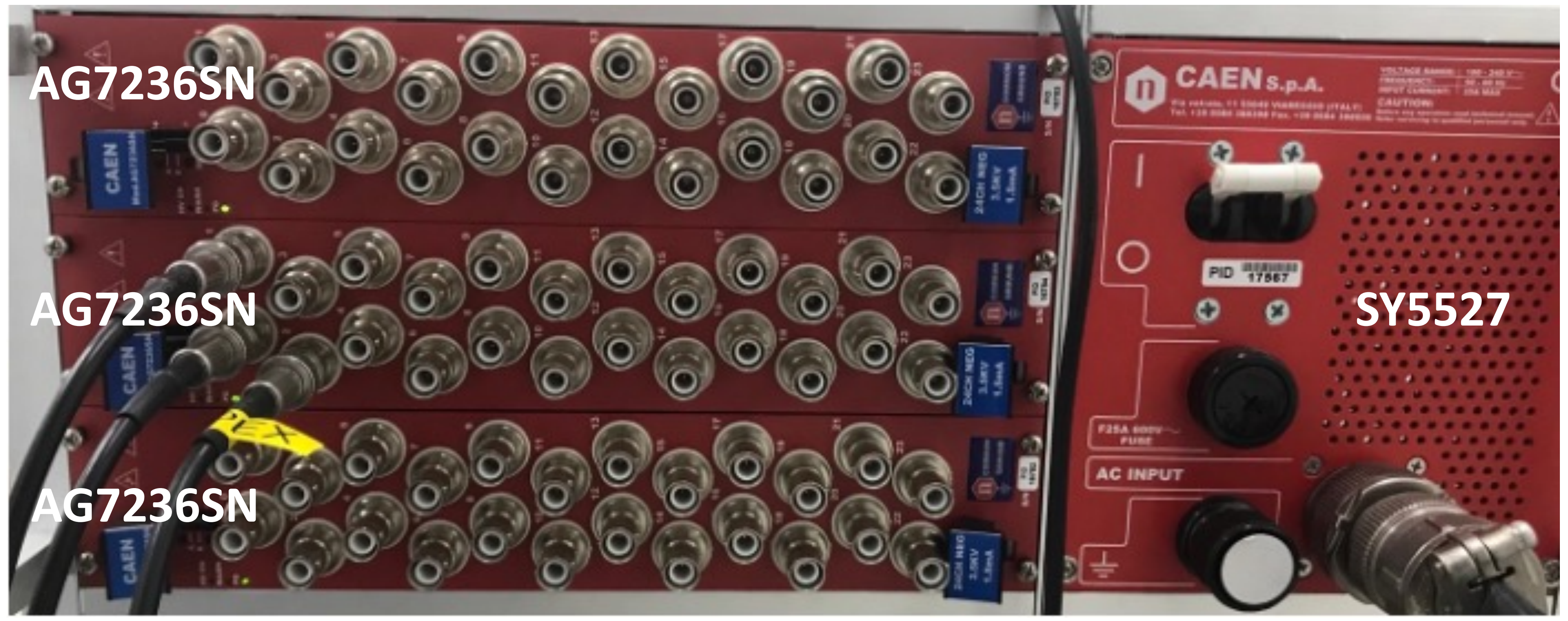
# Readout Boards




- Requirements
  - $O(\sim$ mV$)$ precision to detect SPE signal
  - $> 0.5$ GHz sampling rate to identify SPE signal
  - $> 5$ µs acquisition window for sampling a full spill (use beam trigger)
- Design: cascade 4 channels of a DRS4 chip to achieve 0.7 GHz sampling rate and $\sim 6$ µs acquisition window
  - Tested with a 4-ch prototype board
- Plan to use twelve 16-channel boards (max 192 channels)

# HV system



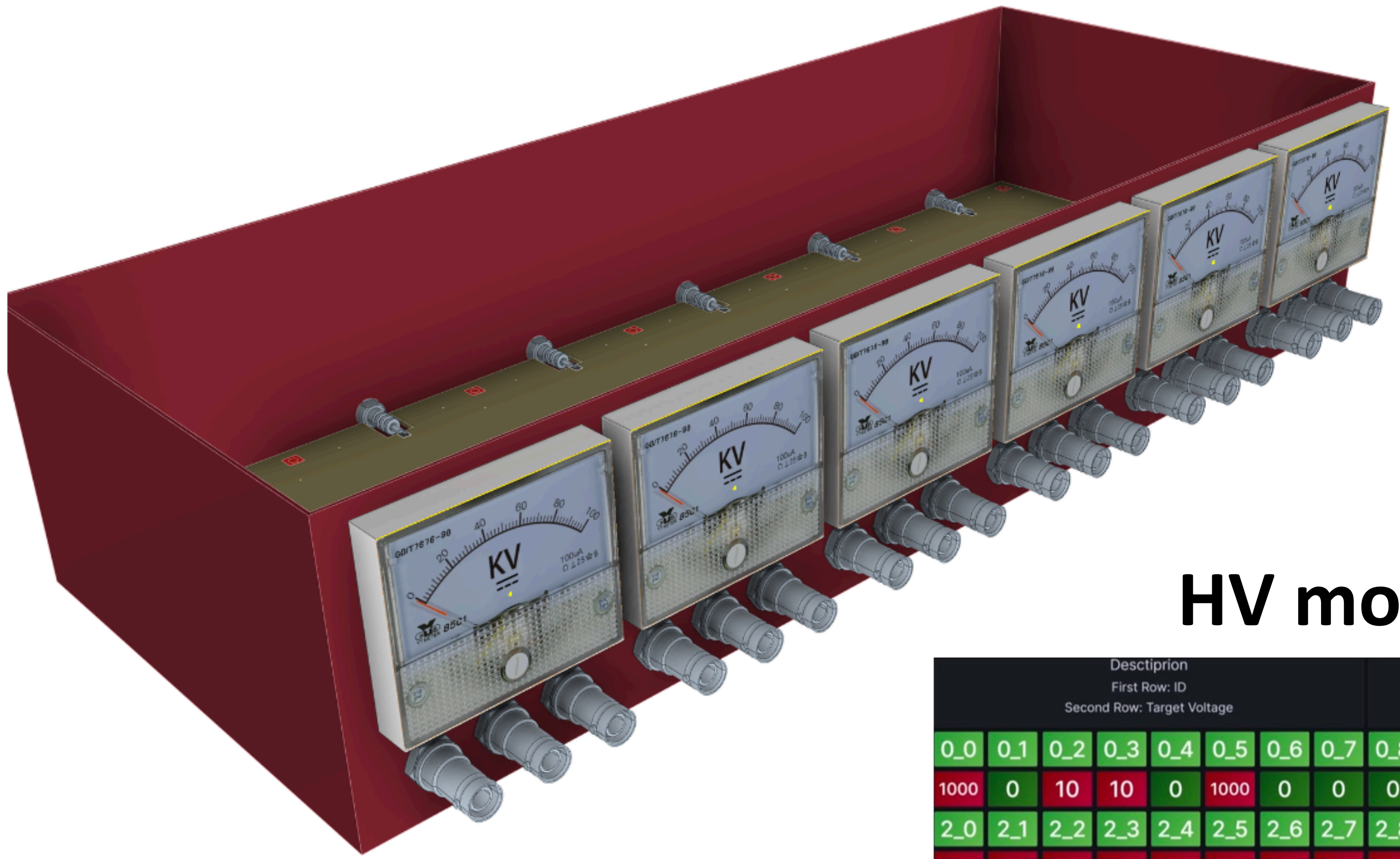



Illustration of a splitter box

HV monitoring & control


- High Voltage (HV) is supplied to the PMTs by CAEN AG7236SN cards in the CAEN SY5527 frame
  - Each AG7236SN board has 24 output channels and max current and voltage per channel are 1.5 mA and 3.5 kV, respectively
- Since the typical current per PMT is ~300 mA at the operating voltage, one channel can serve up to 4-5 PMTs
  - We feed HV to 3 PMTs from one AG7236SN channel using a HV splitter
- One splitter box takes 6 HV inputs and feeds 18 PMTs
- Developed HV monitoring/control system

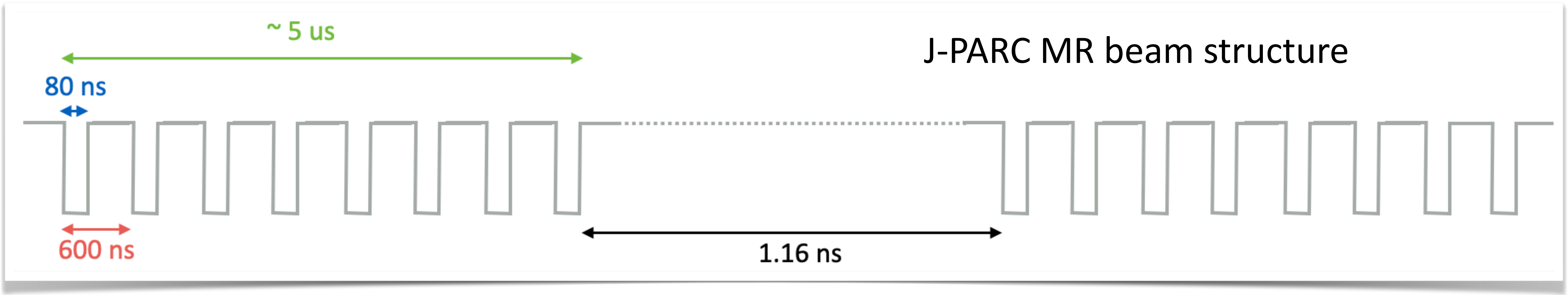
# Backgrounds

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

**Beam-induced backgrounds:** expected to be minor

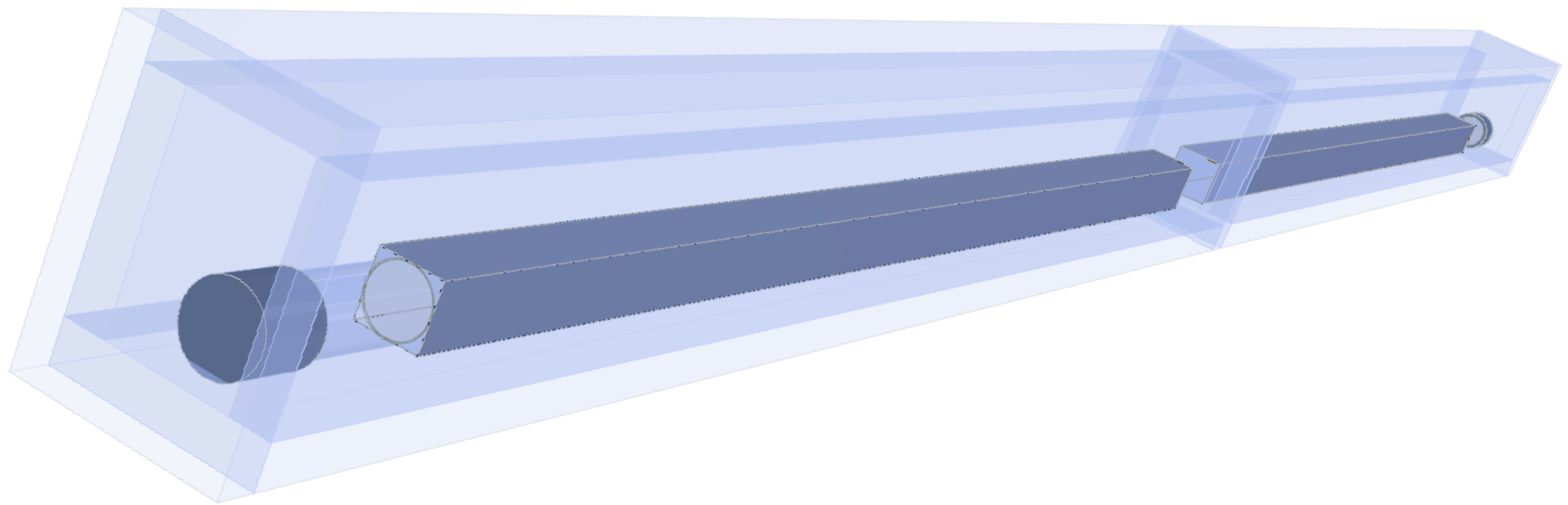
**Cosmic backgrounds:** negligible based on Geant4 simulation

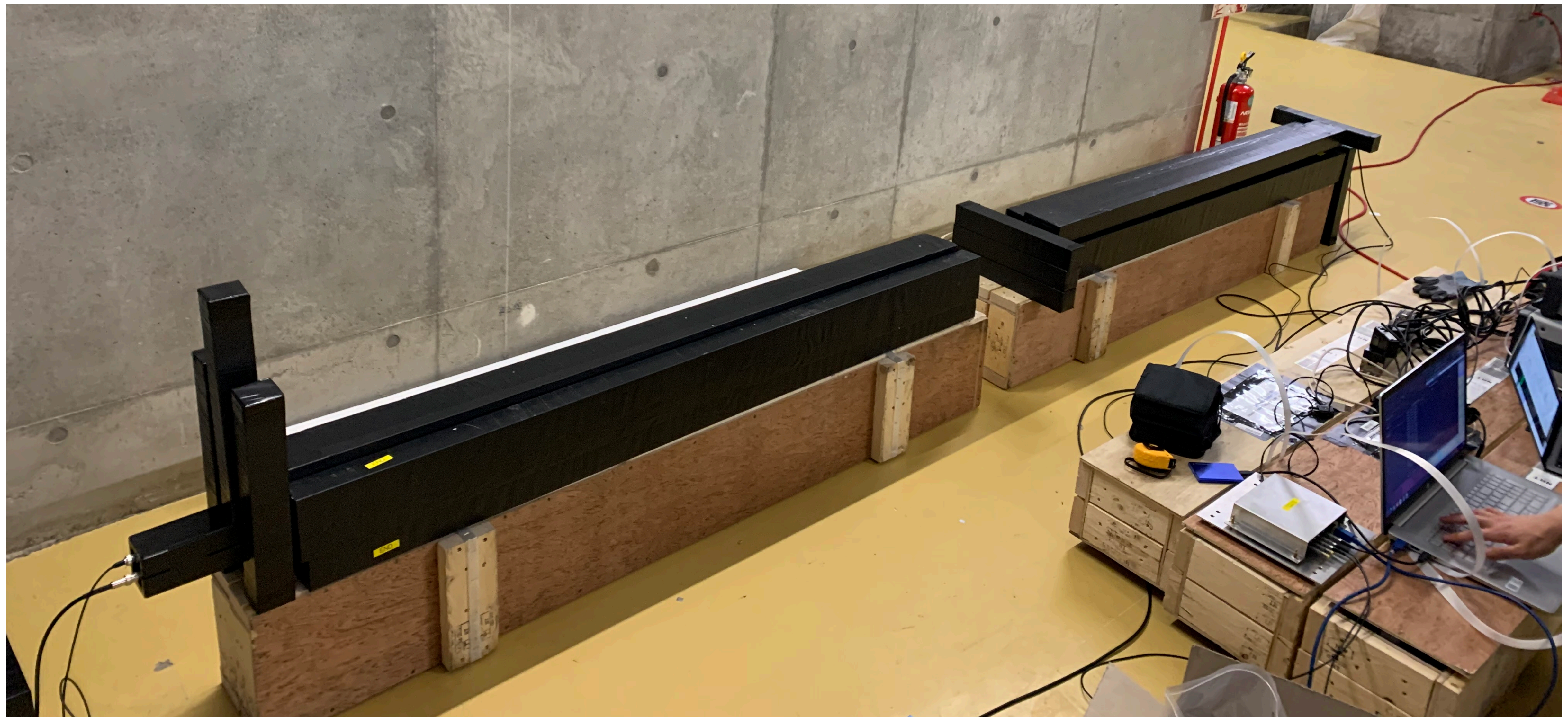
- In the estimation of background, use 1.3 µs (0.16 µs x 8 bunches) per spill as a signal region
  - $\chi$s travel at $\sim c$, so $2\sigma$ of the bunch width (160 ns) should capture most of them




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

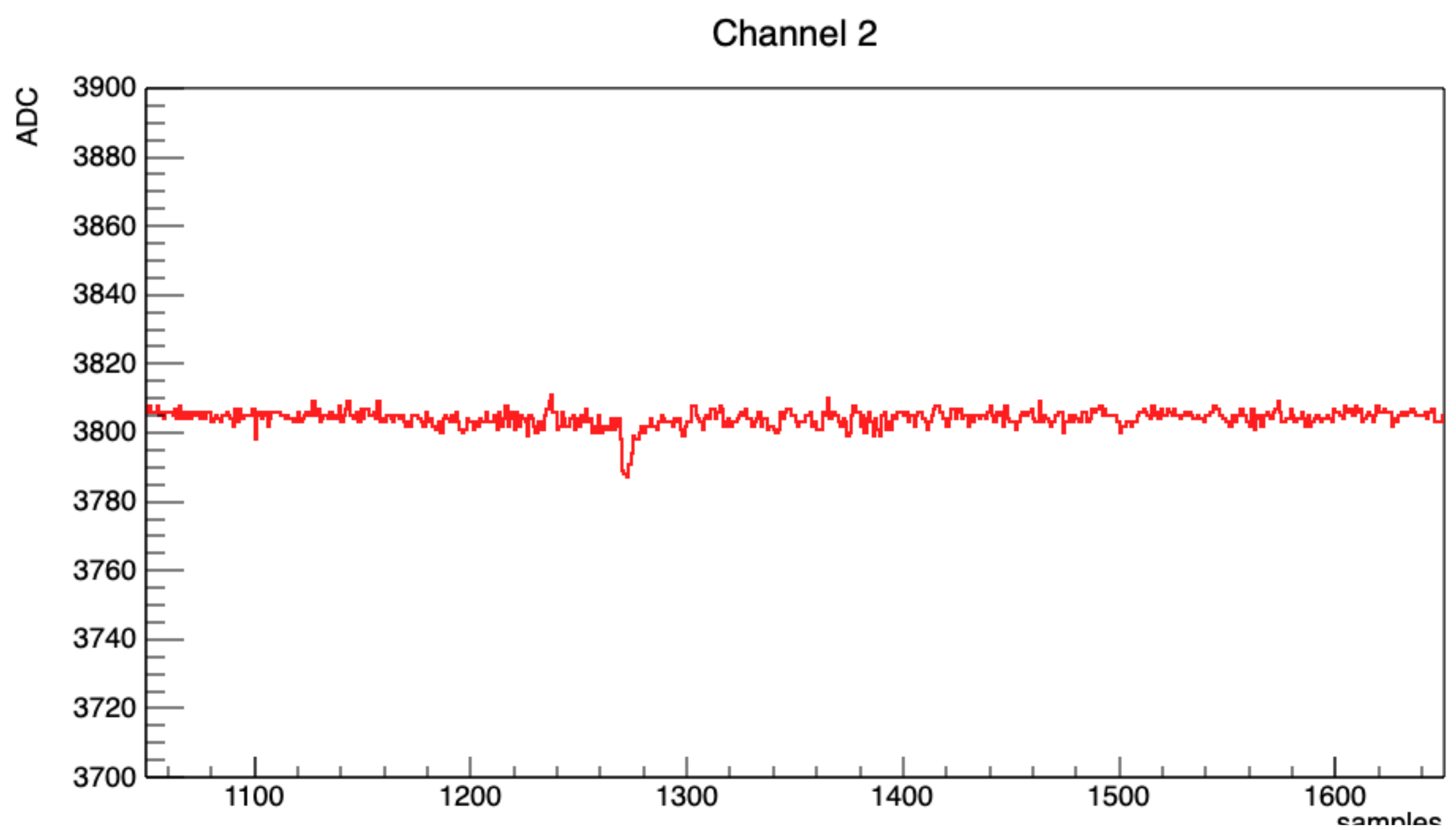
# External radiation + PMT dark current

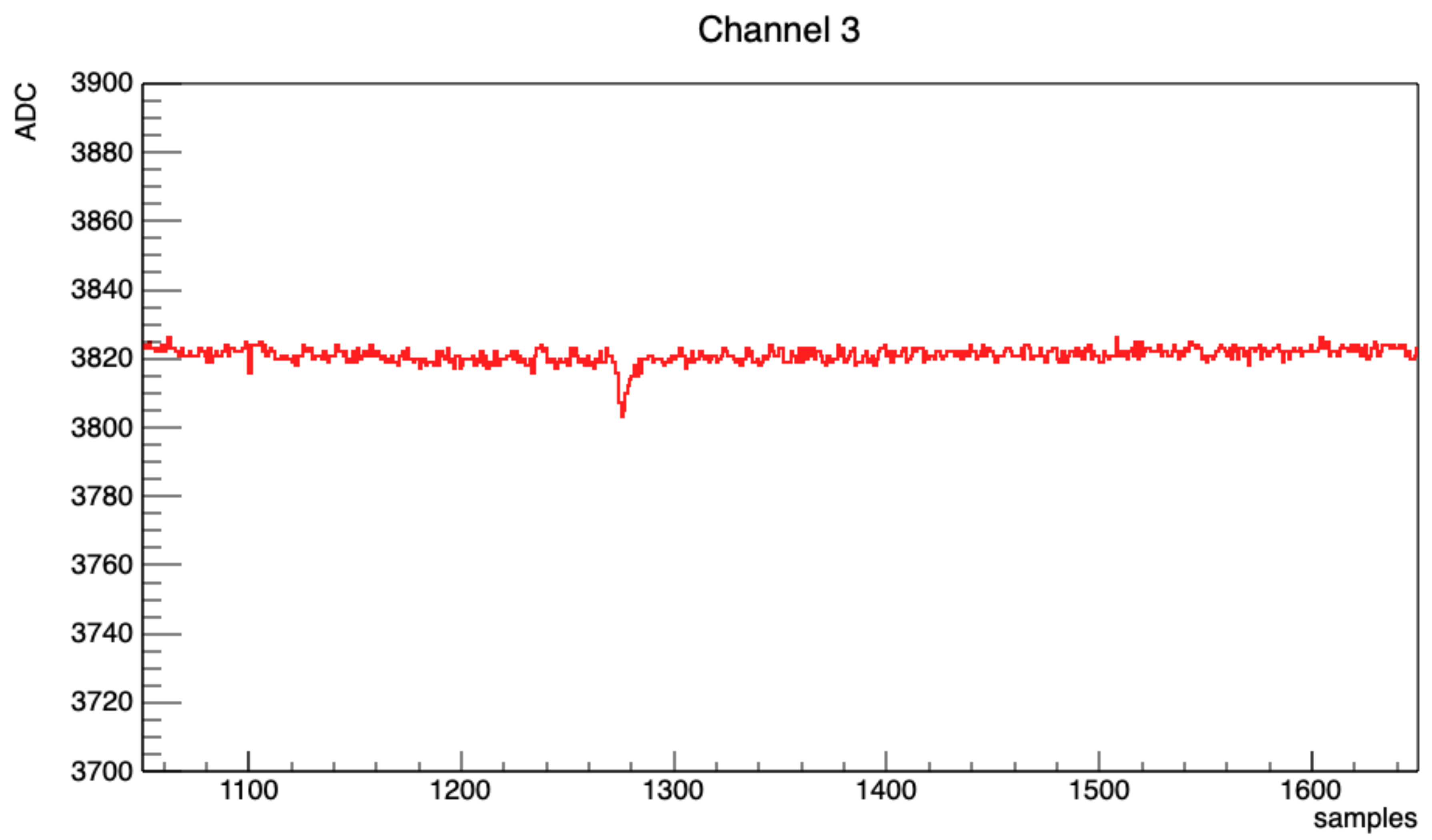




- Radiation from the structures of the building can generate pulses that are indistinguishable from the pulses due to $\chi$s
- In particular, if the radiation from the same source produces a single photon signal in the two modules that are aligned, the time difference between them can be small enough to be identified as a $\chi$ signal
- Since the condition of radiation strongly depends on the environment, we measured the rate at the detector site

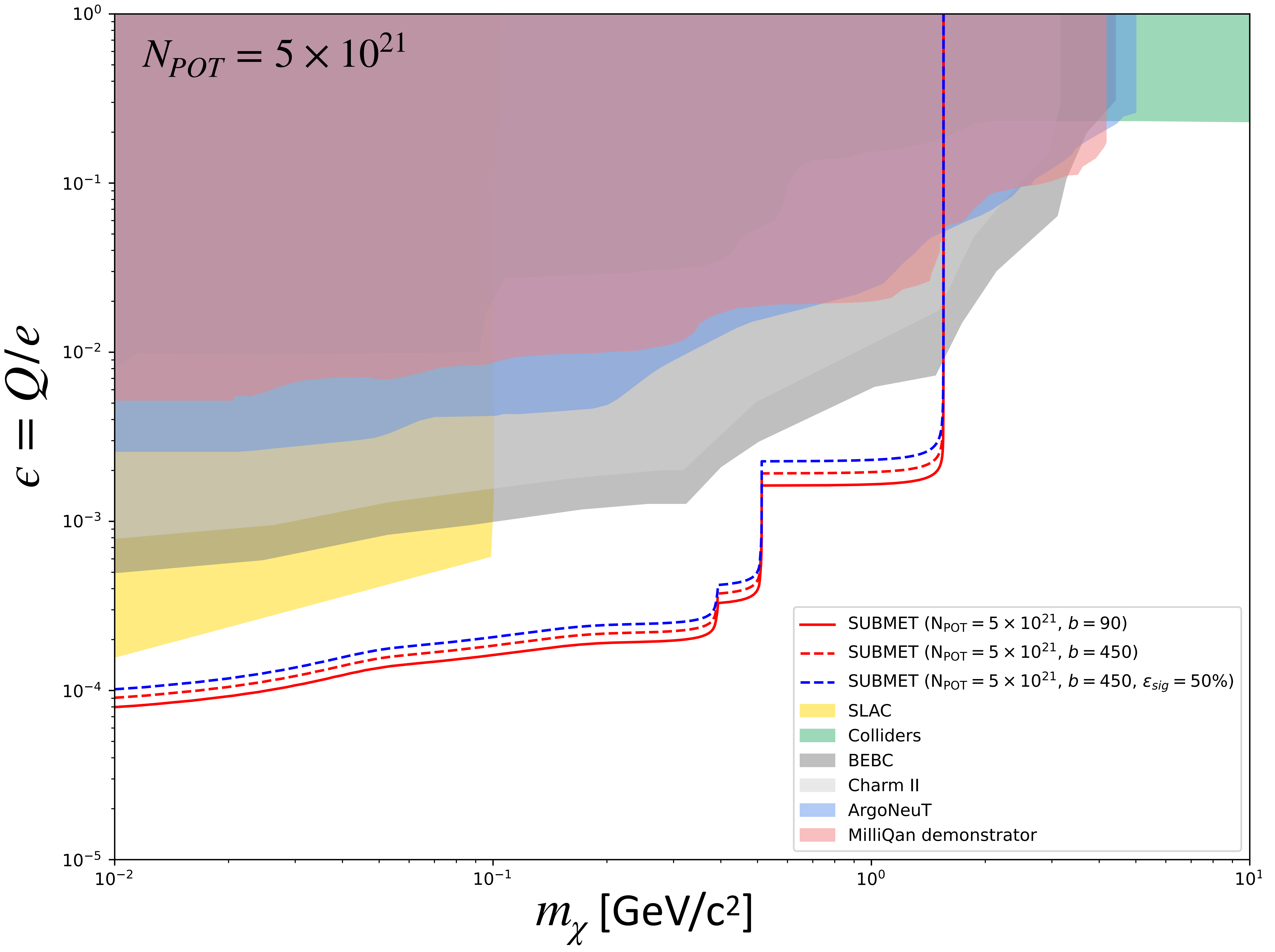
# External radiation + PMT dark current




- Applied following cuts to select events
  - SPE selection: $20 < V_{pulse} < 50$ ADC, pulse width < 7 samples (10 ns)
  - Remove events with a large number of afterpulses: $N_{pulse} \leq 2$
  - Coincidence time window: $\Delta t < 14$ samples (20 ns)
- Results
  - Total number of events recorded: 12M
    - This corresponds to 4 years of data
  - Number of events that passed the cuts: 1
    - There are 80 pairs of modules
  - Use directionality of the beam (factor of 2 reduction)
  - Expected number of backgrounds ($b$): 30 events for 3 years

# Sensitivity of SUBMET




3 scenarios have similar performance due to the steep drop of $N_{signal}$ in sub-millicharge regime ($N_{signal} \propto \epsilon^6$)

# History of SUBMET (E83)

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]

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[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

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[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*


Proposal


**Abstract**

We propose a new experiment searching for sub-millicharged particles ($\chi$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 $N_{POT} = 5 \times 10^{21}$ which corresponds to running the experiment for three years, the experiment provides sensitivity to $\chi$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

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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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[6]*Lebanese University, Hadeth-Beirut, Lebanon*
[7]*CERN, Geneva, Switzerland*


TDR

FIFC meeting Dec 2022

| 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|

LOI submitted in summer 2020

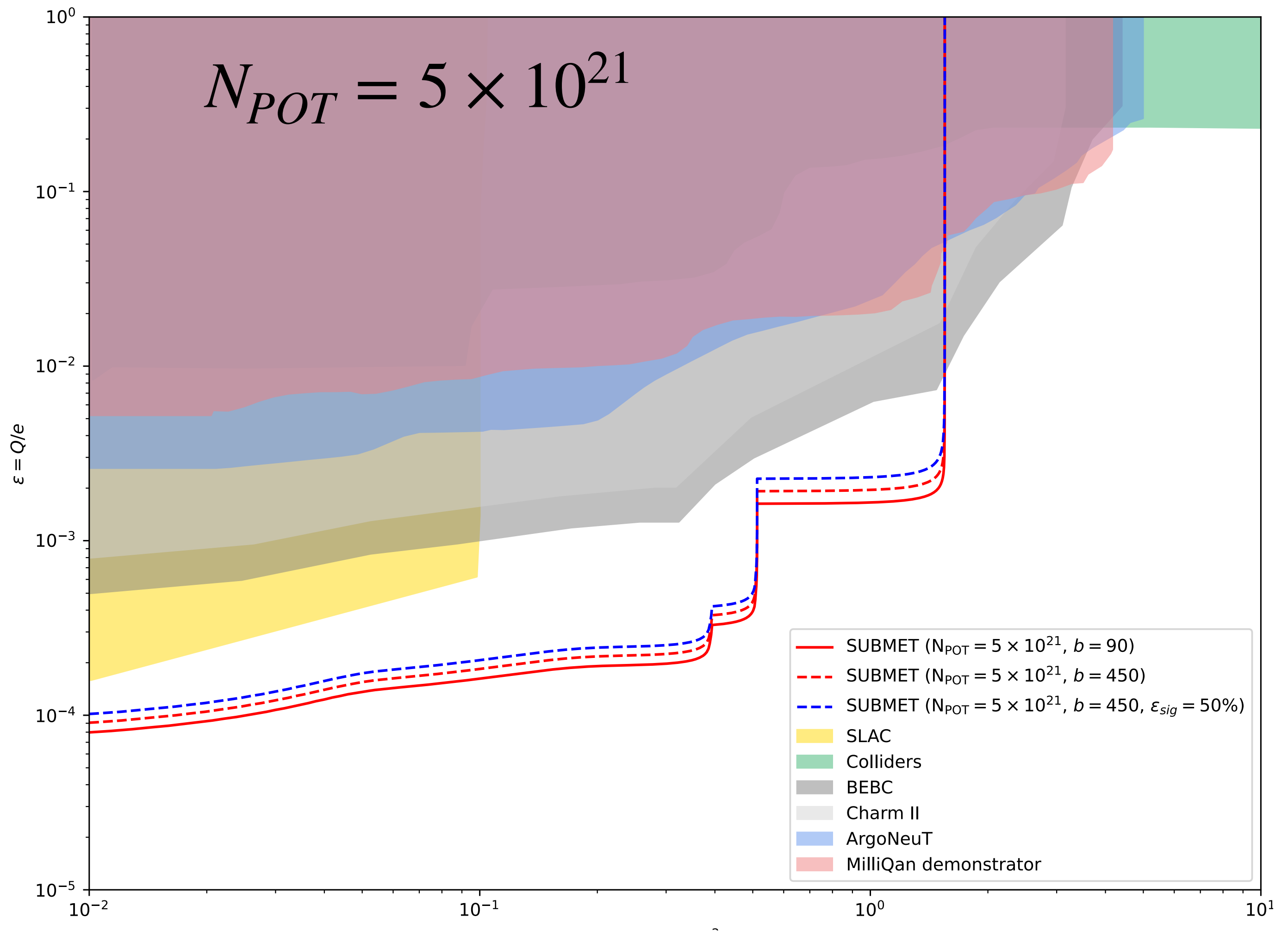
Proposal submitted in summer 2021 (32nd PAC meeting)

Stage-I approval April 2022

TDR submitted Nov 2022

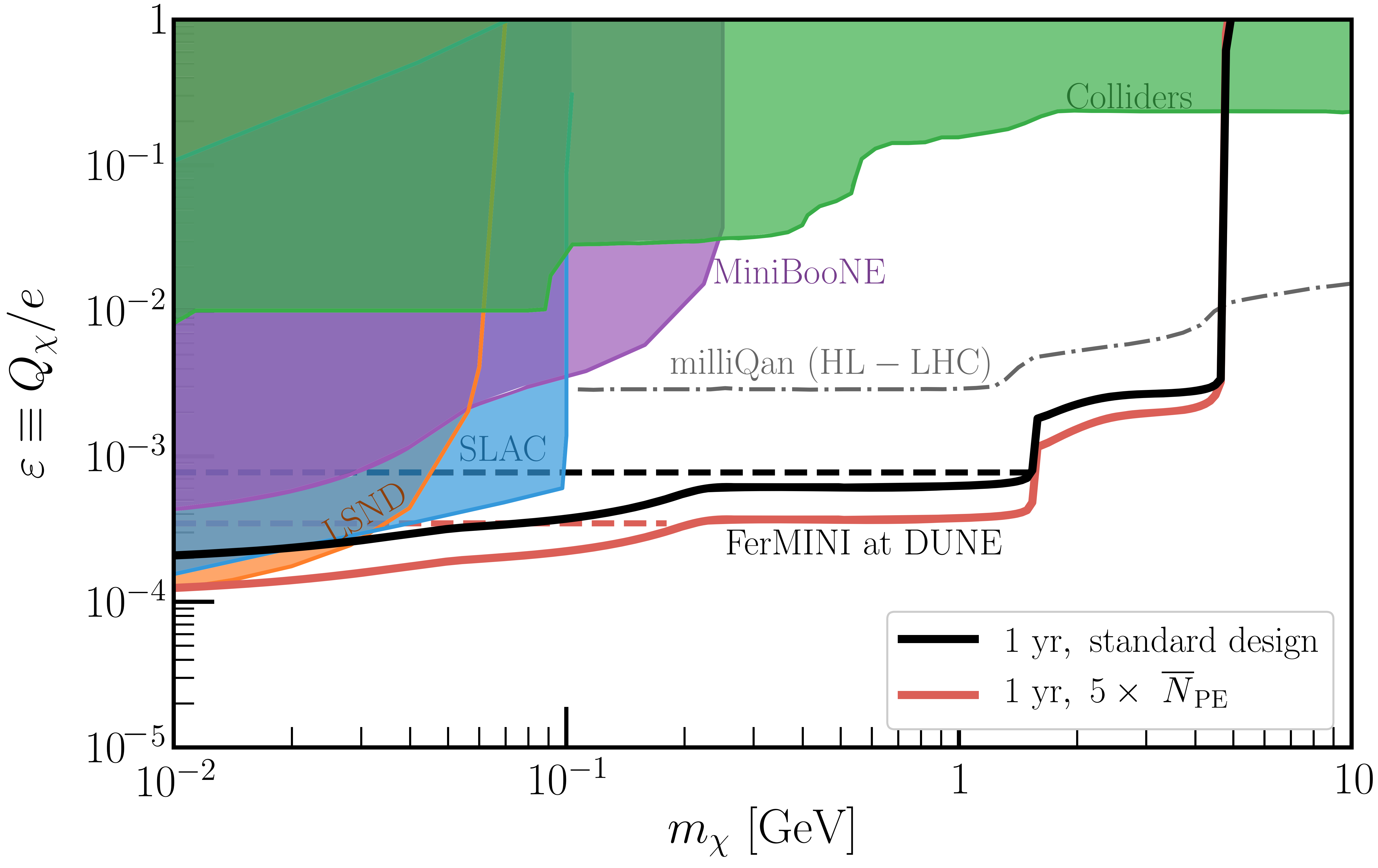
Request for stage-II approval Jan 2023

# Summary and outlook




- SUBMET can provide unique opportunity to probe small-charge and low-mass ( $m_\chi < 1.6$ GeV) millicharged particles
- Tested design of the detector: no major issues found
- Measured the rate of the major background on site
- Currently, testing and assembling the modules before installation, and studying the performance of the full-scale readout system
- Outlook: after receiving Stage-II approval and performing full-scale detector test in Korea, plan to install the detector in J-PARC and start exploring the unexplored regime!

# Millicharged particle search at DUNE ND site




- There is already an idea
  - Kevin Kelly, and Yu-Dai Tsai, *FerMINI*, PRD 100, 015043 (2019)
  - Detector has 3 layers
- Requiring coincidence between layers is the main method of background suppression: more layers → less backgrounds
- But, detection efficiency for $\epsilon < 10^{-3}$ is proportional to $\epsilon^2$, so adding more layers significantly degrades sensitivity
- SUBMET uses beam-timing as an additional handle to control backgrounds (beam is not continuous, but comes in like a pulse)
- What is the DUNE beam structure like?

# Backup

# The team

Sungwoong Cho
Suyong Choi
Jeong Hwa Kim
Eunil Won
Jae Hyeok Yoo
Hoyong Jeong
Hyunki Moon

Claudio Campagnari
Matthew Citron
David Stuart
Ryan Schmitz

Christopher S. Hill

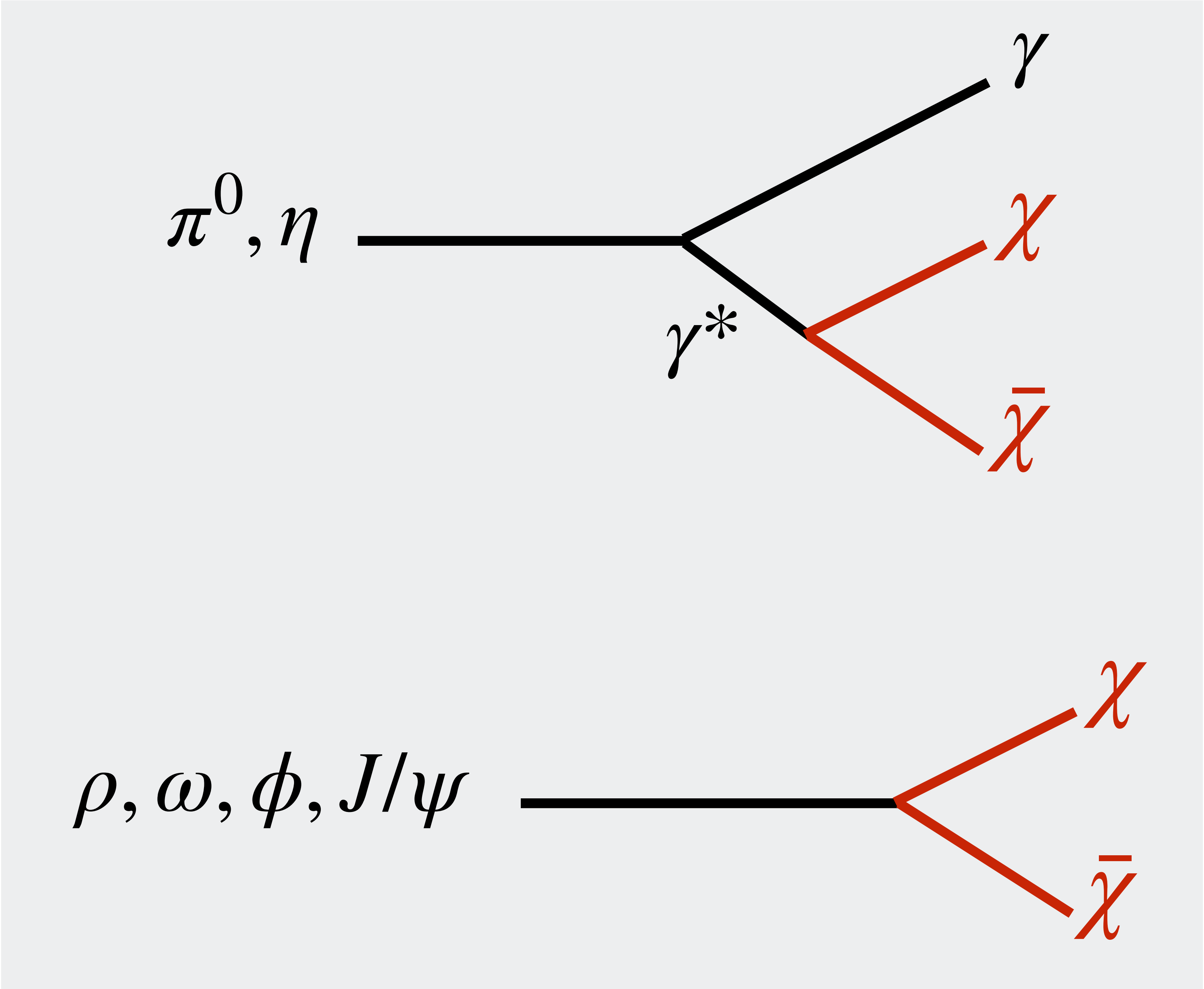
Andy Haas

Jihad Sahili
Haitham Zaraket

Albert De Roeck
Martin Gastal

# Production of $\chi$s

- $\chi$s can be produced from the decay of neutral mesons
  - $\pi^0, \eta$ through a photon
  - $\rho, \omega, \phi,$ and $J/\psi$ directly to $\chi\bar{\chi}$
- In both cases, $m_\chi$ up to $m_{meson}/2$ is allowed
- Number of $\chi$s produced at the proton-target collisions is proportional to

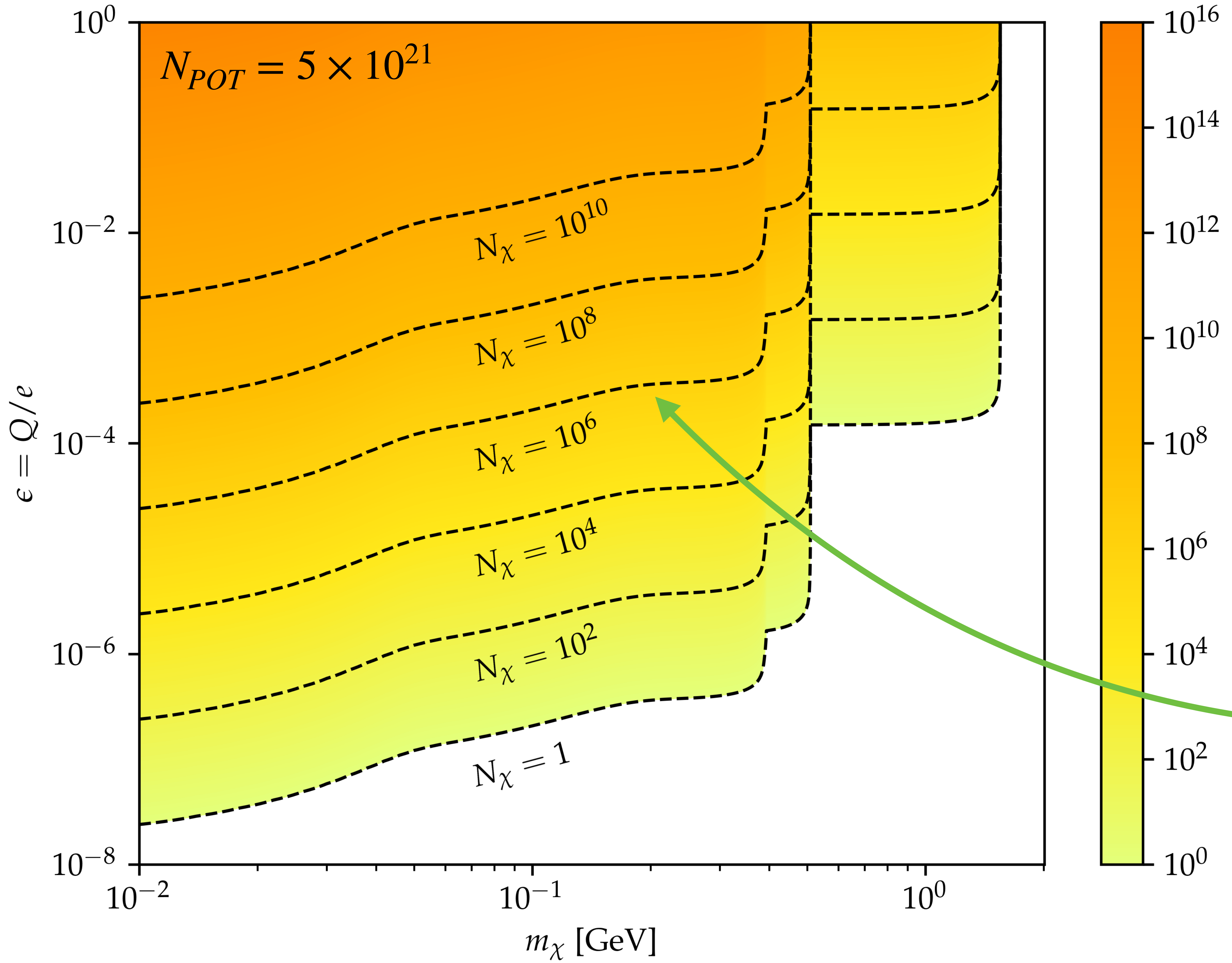



$$c_{meson}\epsilon^2 N_{POT} \times f\left(\frac{m_\chi^2}{m_{meson}^2}\right)$$

$c_{meson}$: number of mesons produced per proton-on-target (POT)
$\epsilon$: $Q/e$ where $Q$ is the charge of $\chi$ and $e$ is the electron charge
$N_{POT}$: total number of POT
$f$: phase space related integral that depends on $m_\chi$ and $m_{meson}$

- Values of $c_{meson}$ for each meson are estimated from Pythia simulation and validated by comparison with measurements

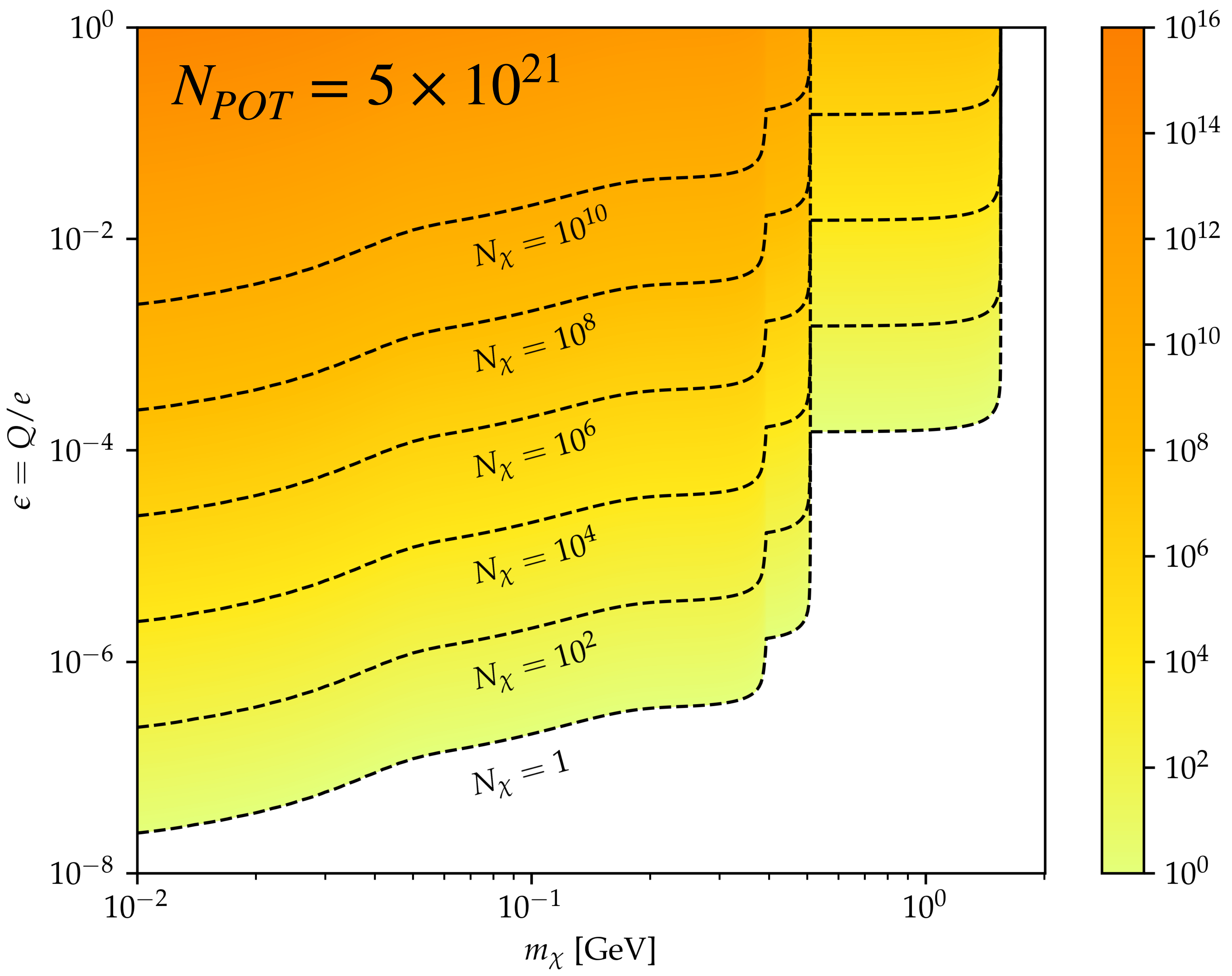
# Production of $\chi$s




- Expected number of $\chi$s that reach $0.5 \times 0.5$ m² detector area ($N_\chi$) in $N_{POT} = 5 \times 10^{21}$
- Material effect/detection efficiency not included
- Dependence on $m_\chi$ due to production of mother mesons (Note that $m_\chi \leq \frac{m_{meson}}{2}$)
- Expect $\sim 10^6$ $\chi$s where the exclusion limit is placed

# Production → detection

Number of $\chi$s that reach the detector ($N_\chi$)



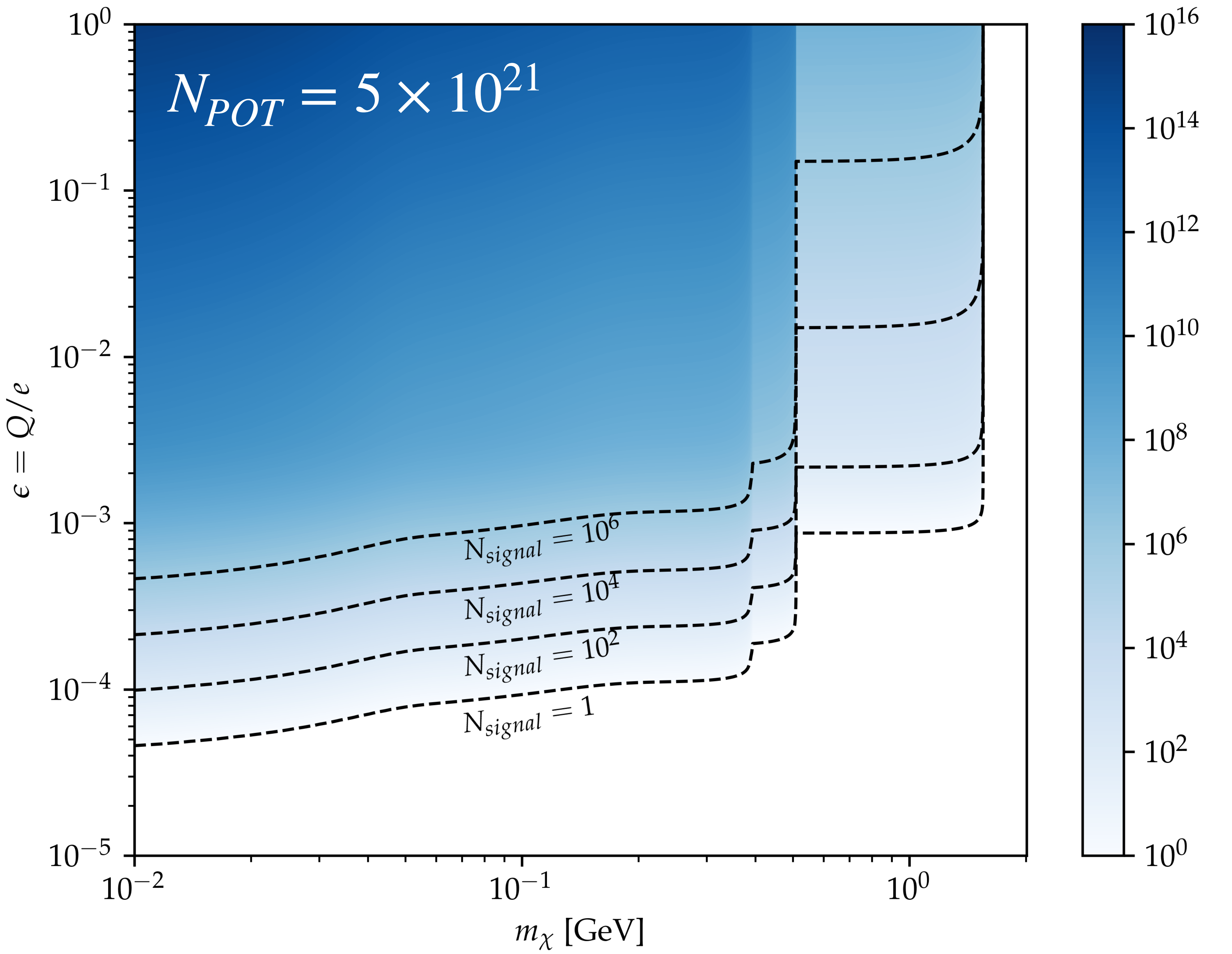

Detection efficiency $P$

2 = number of layers

$$P = (1 - e^{-N_{PE}})^2$$

Used PMT QE = 30%

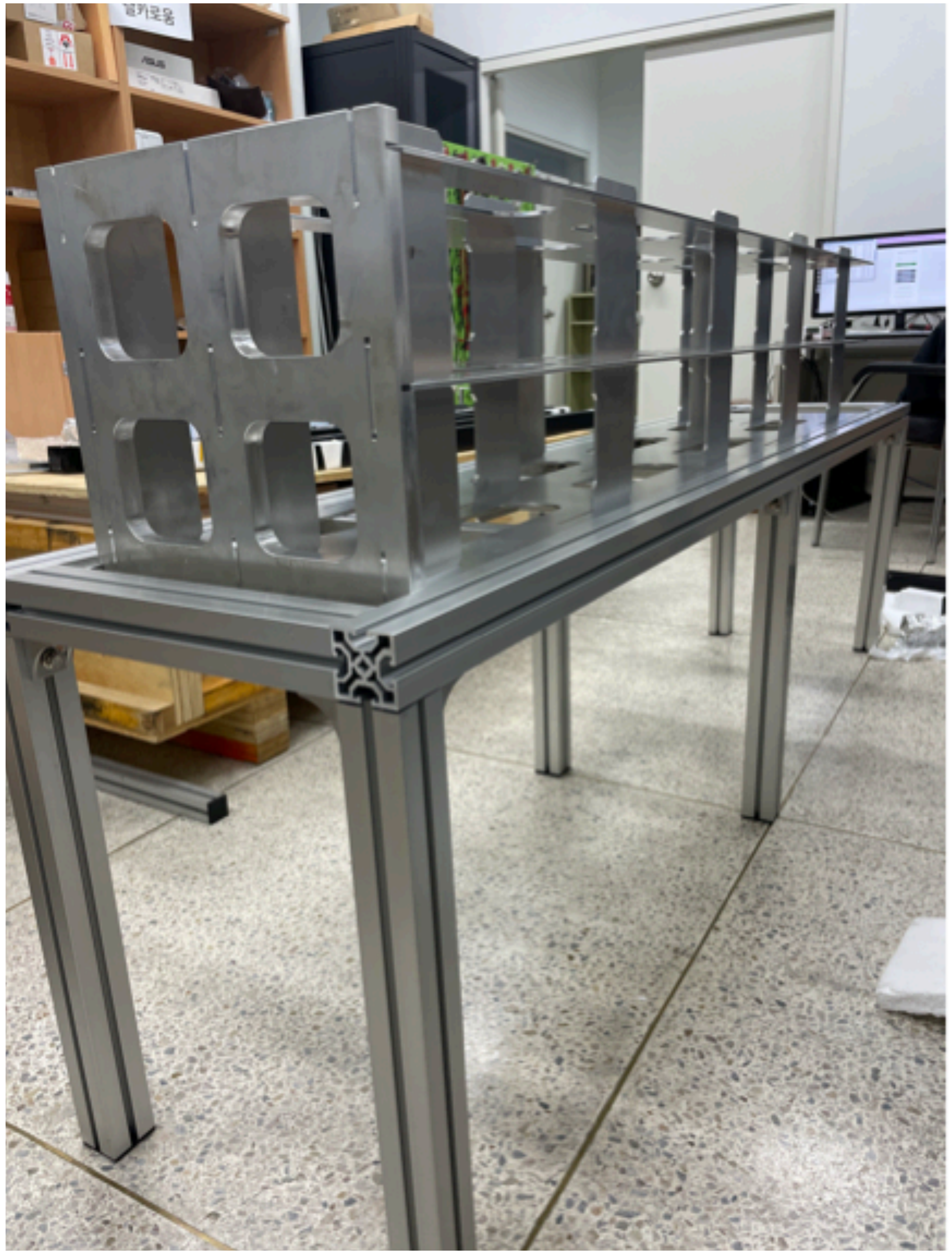
Number of $\chi$s detected by SUBMET ($N_{signal}$)

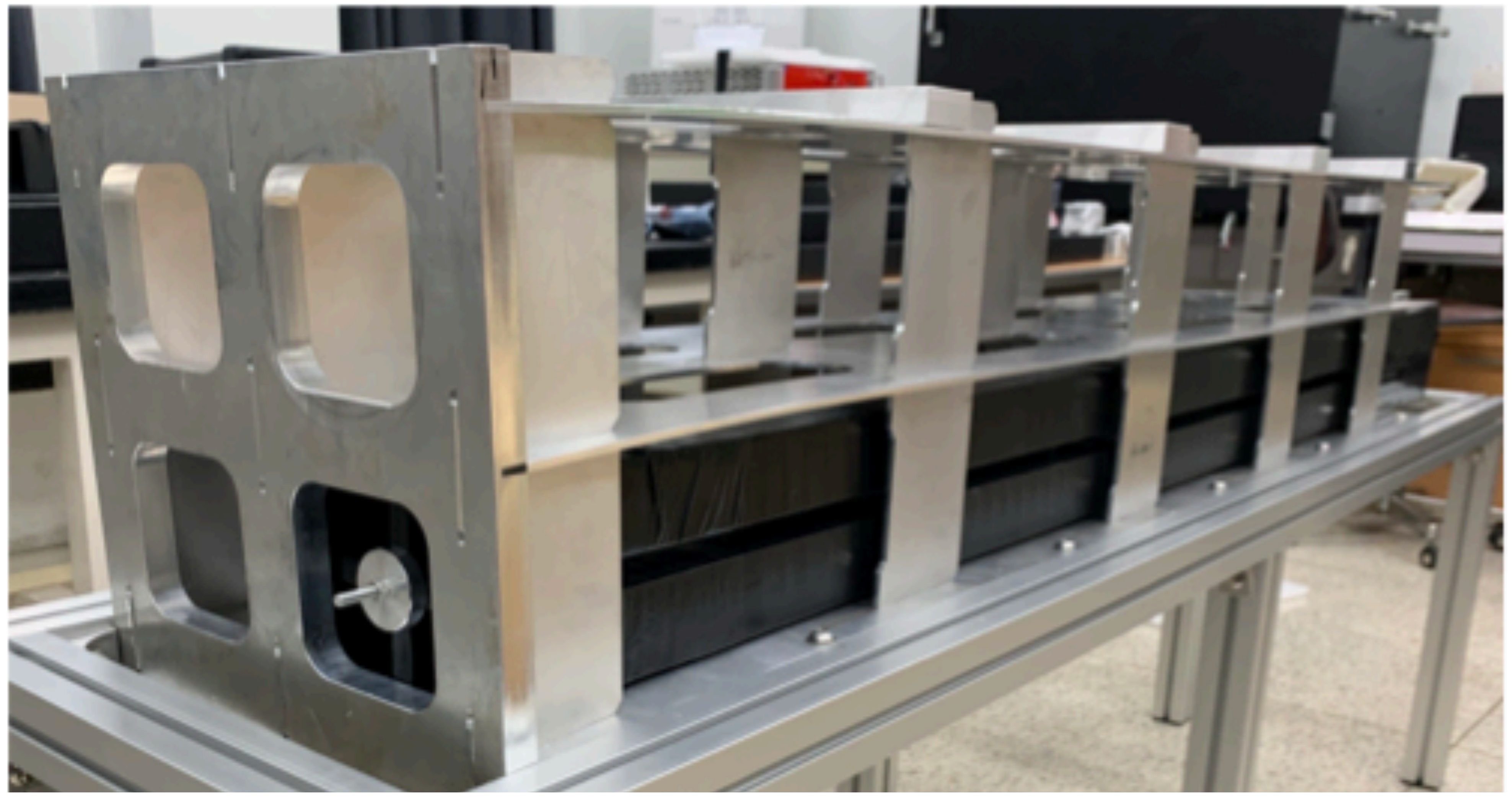



Very steep drop in $\epsilon < 10^{-3}$

→ in this regime, $N_{signal} \propto \epsilon^6$

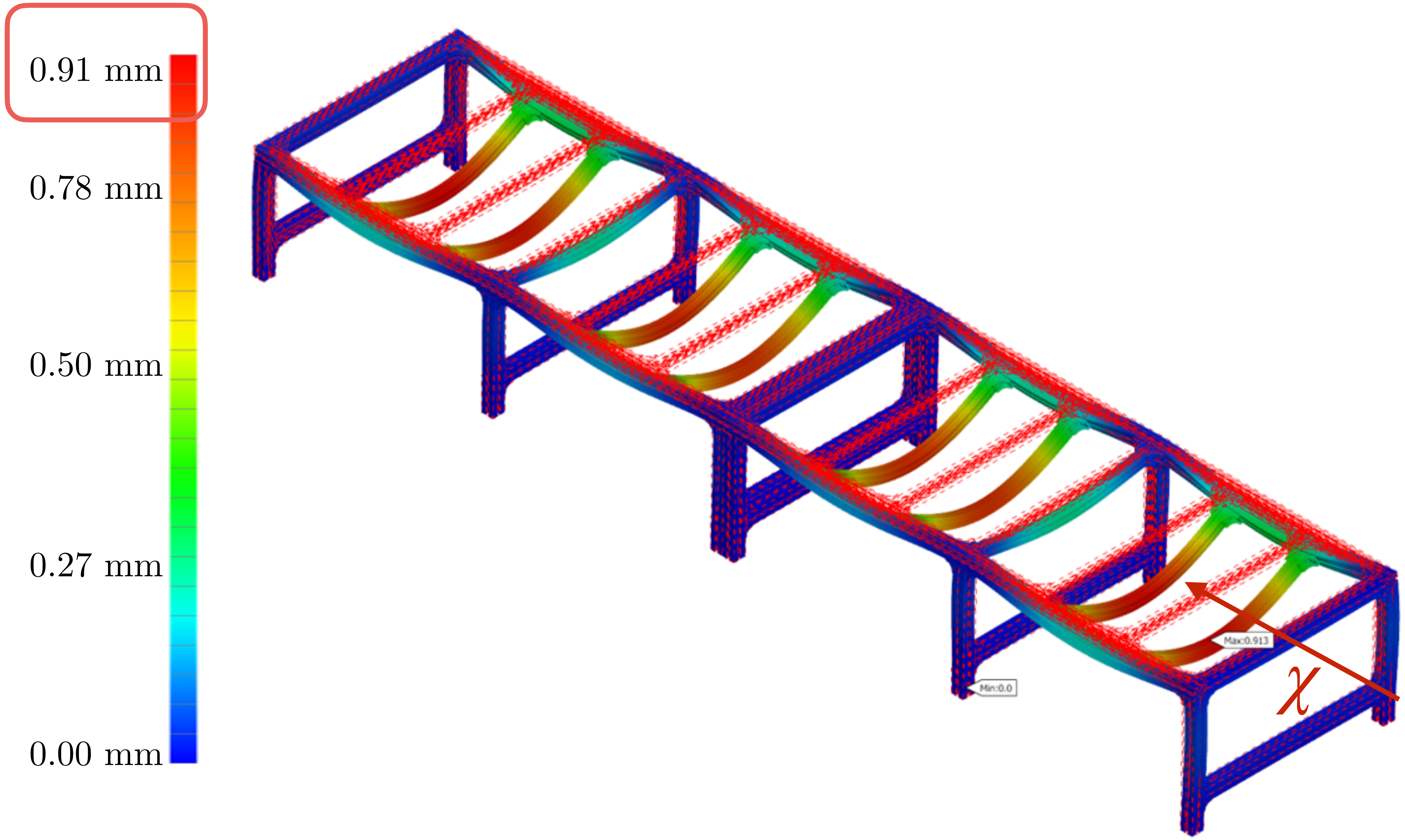
# Testing detector design: prototype





- A prototype layer for 2×2 supermodules has been constructed
- Cage attached on the Table
- A supermodule nicely fit in the Cage

# Testing detector design: static analysis




A static analysis has been performed to evaluate the maximum displacement of Table segments

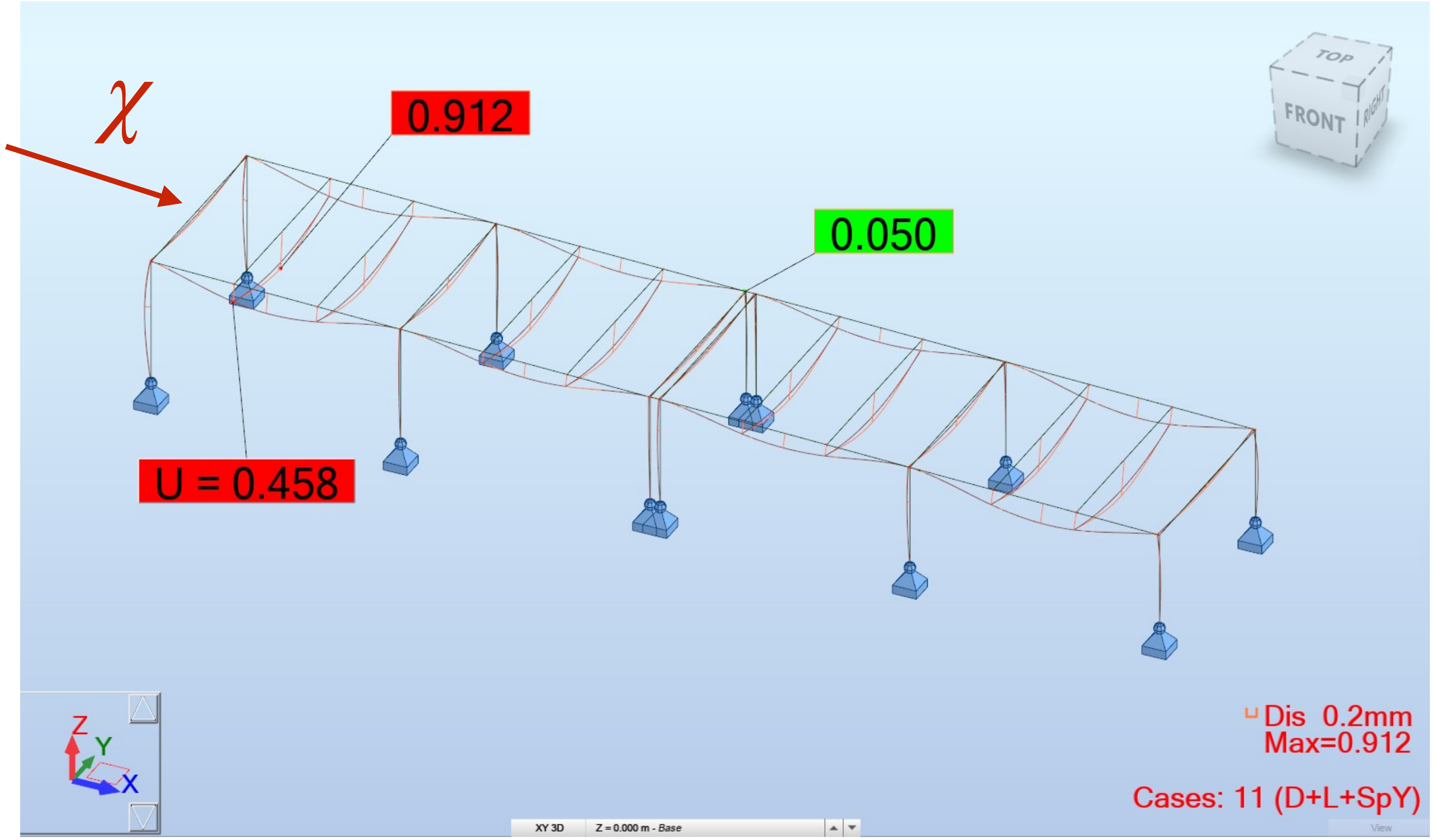
- Used Autodesk Inventor Professional 2023

Configuration

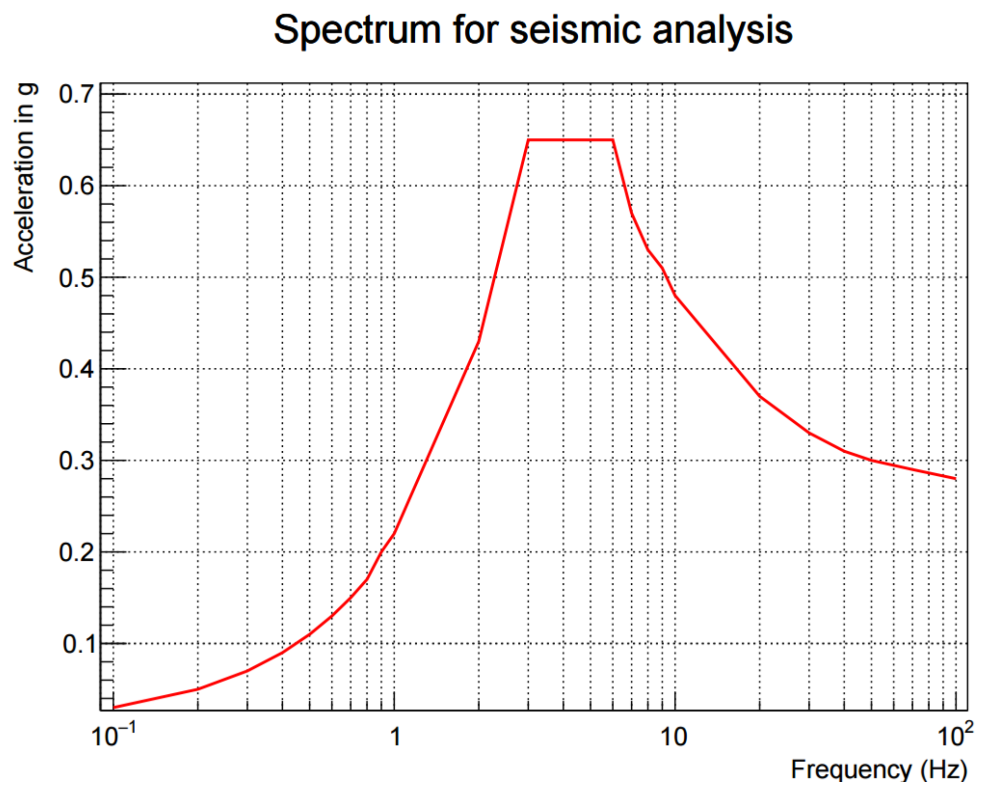
- Dead load: total weight of Table1/2
- Live load: 10000 N

Result: **maximum displacement is < 1 mm**

# Testing detector design: seismic analysis

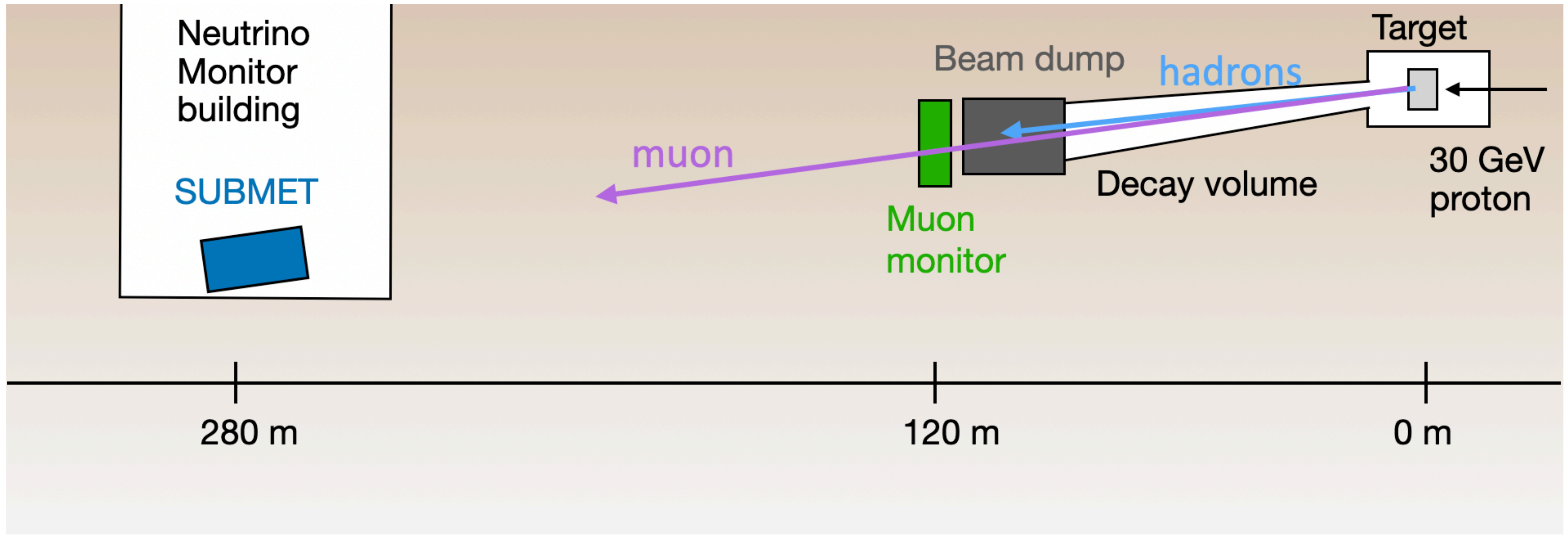



- A seismic spectrum taken into account in addition to the gravity load
  - Used Autodesk Robot Structural Analysis Professional 2023
- Spectrum




- Configuration
  - Same as static analysis + spectral in the Y-direction
  - Also tested spectral in other directions
- Result: maximum displacement < 1 mm

# Backgrounds (beam-related)



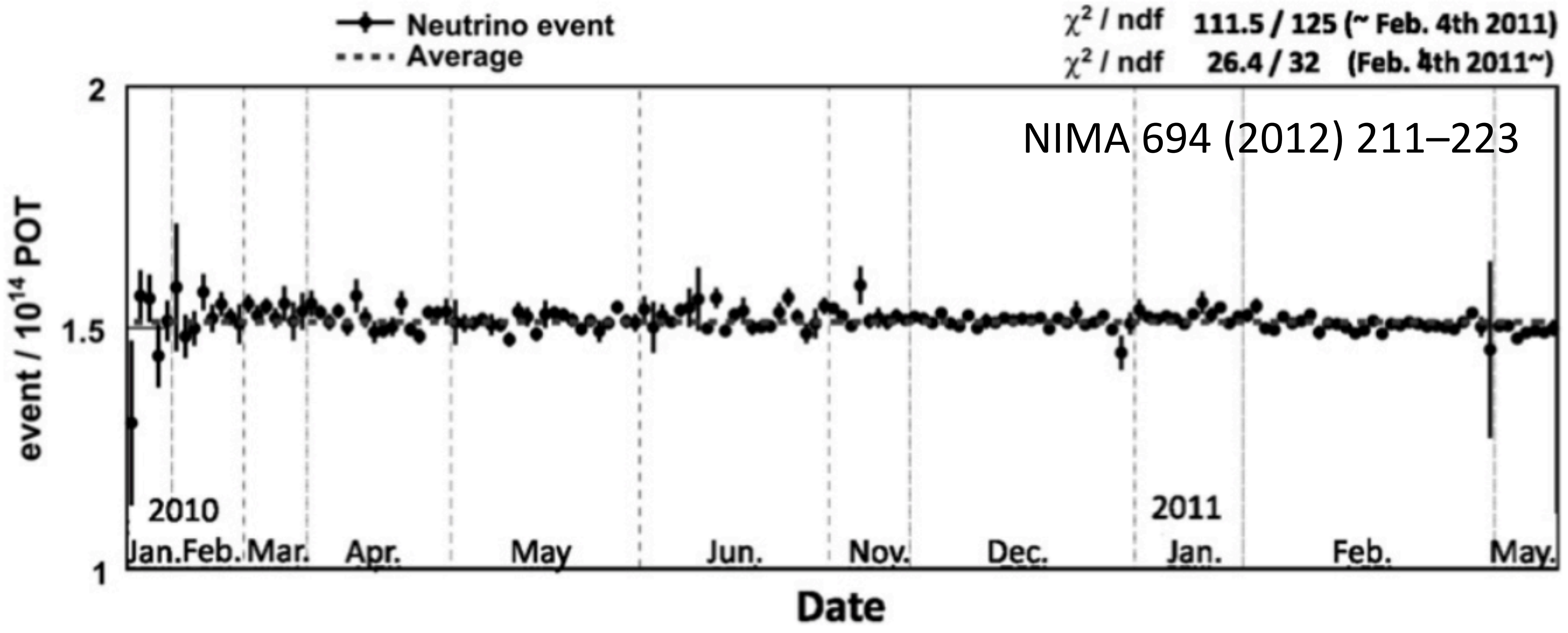
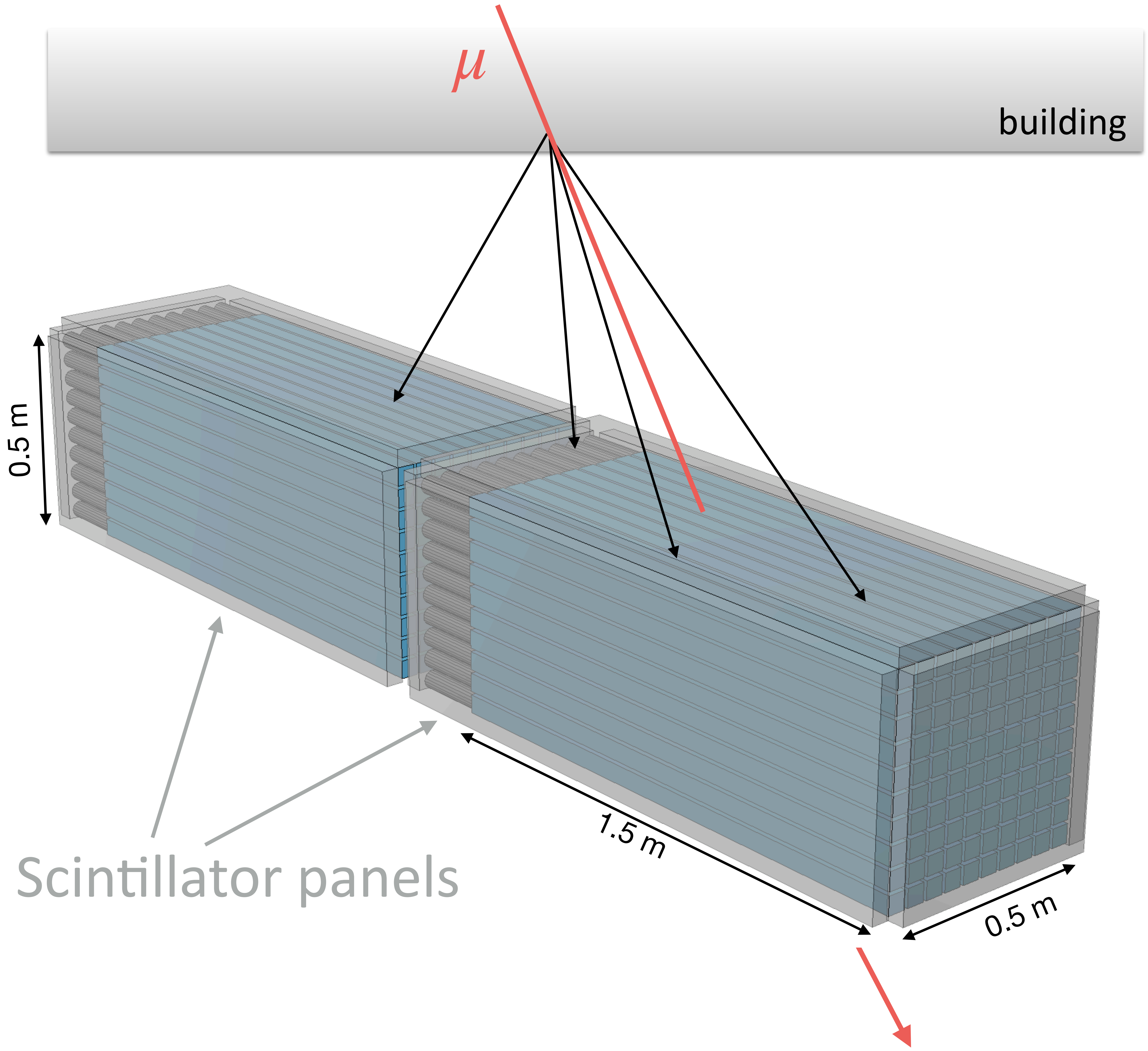




**Fig. 24.** Daily event rate of the neutrino events normalized by protons on target.

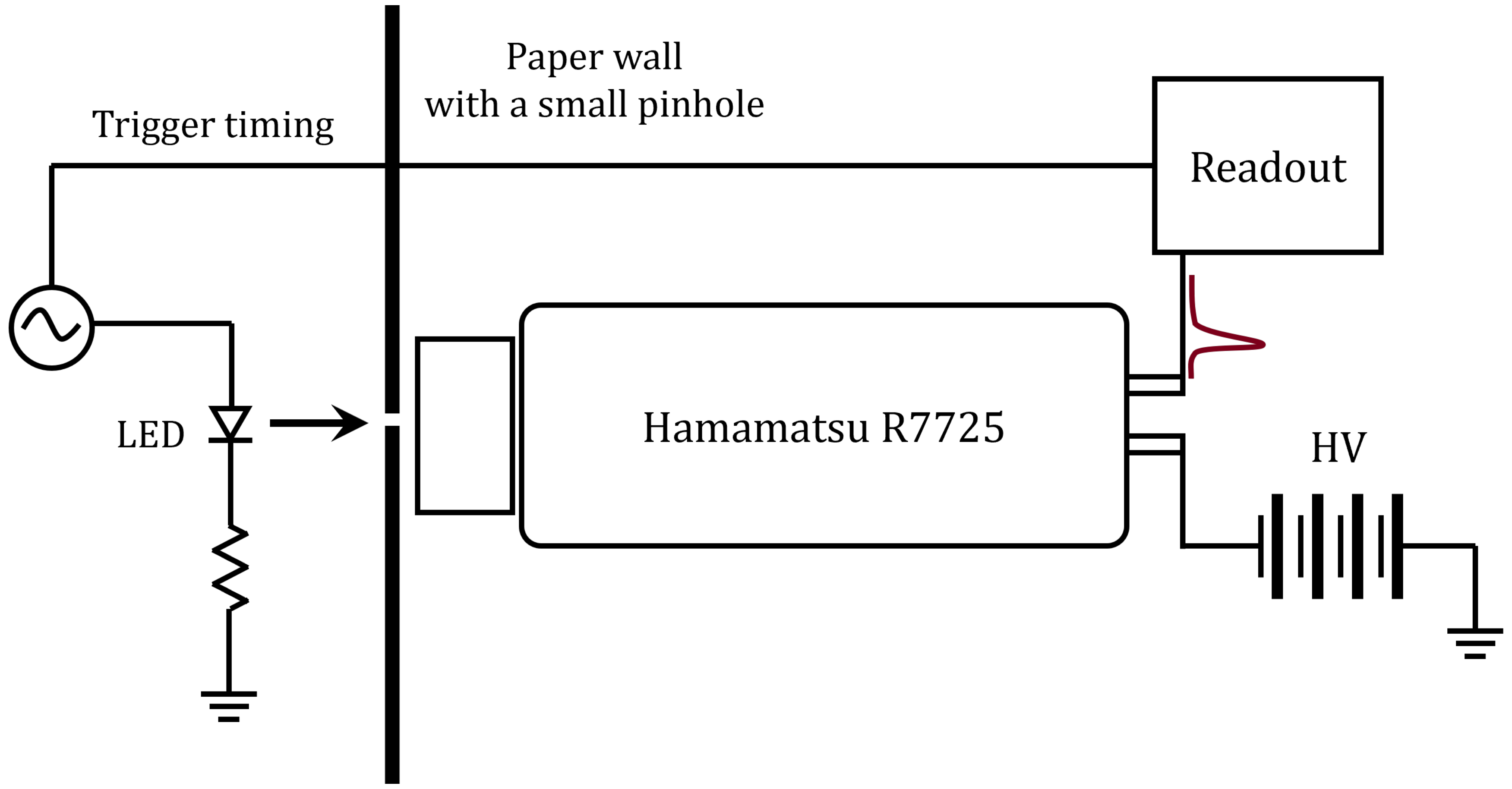
- Muons from hadron decays do not reach detector due to energy loss
- Neutrino interactions with scintillator
  - Refer to the measurements by INGRID: $8\times10^{7}$ for $N_{POT} = 5\times10^{21}$
  - Iron: denser material → upper bound
  - Considering volume difference (1/50) and requiring coincidence, the rate becomes negligible
- Muons from interactions between neutrinos and the material of the building can be identified/rejected by installing scintillator plates in front of the detector

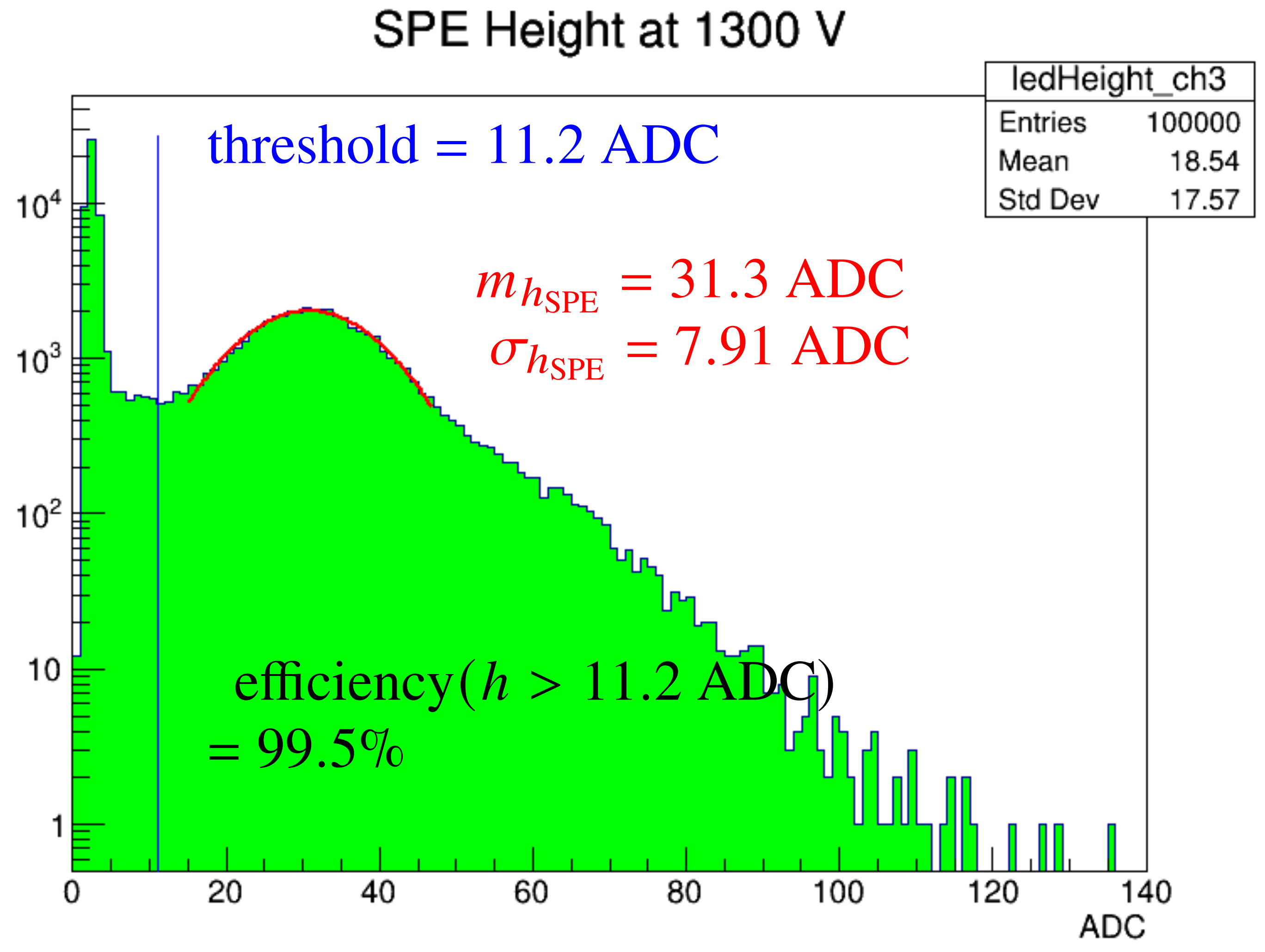
# Backgrounds (cosmic muons)

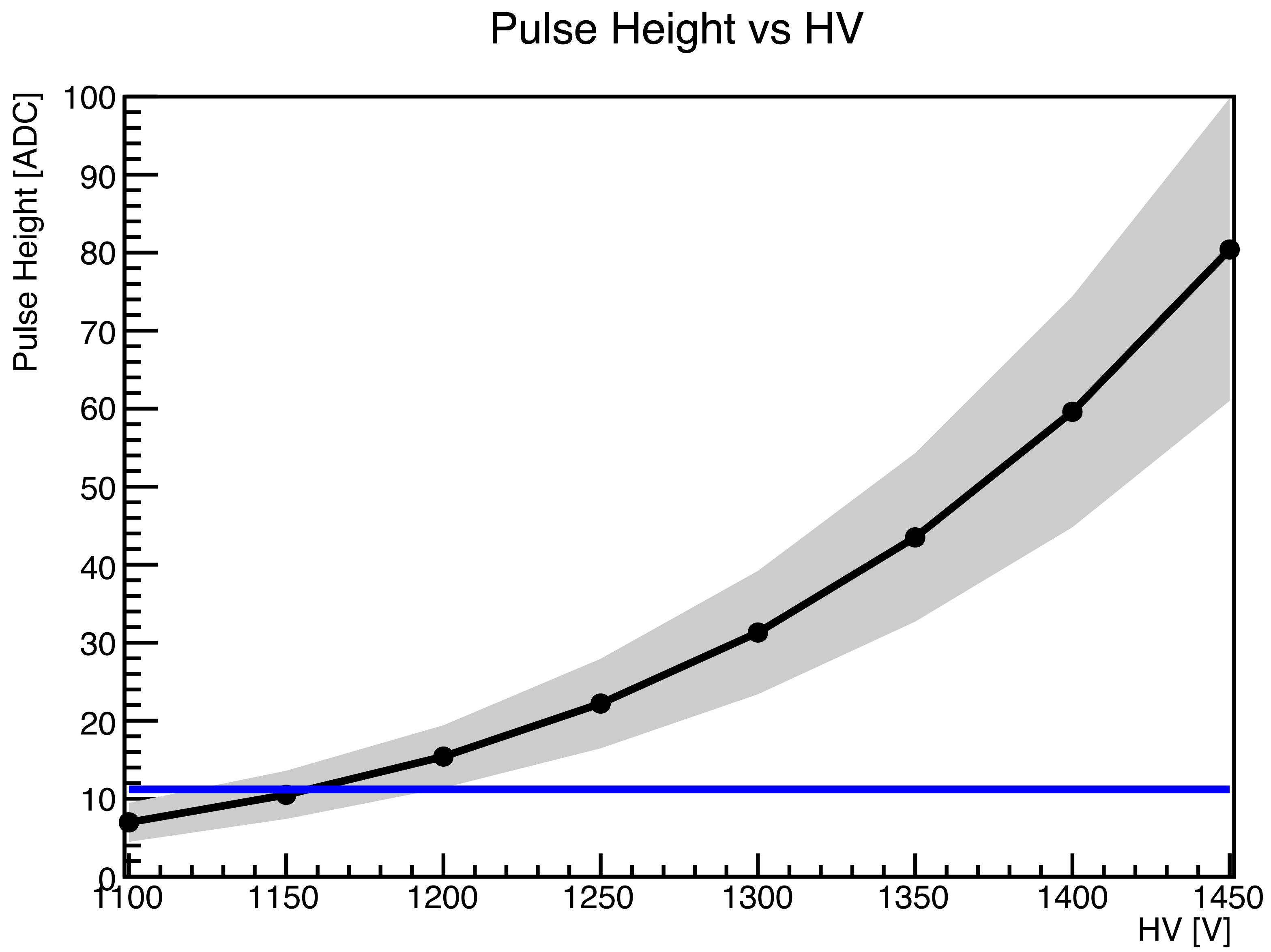


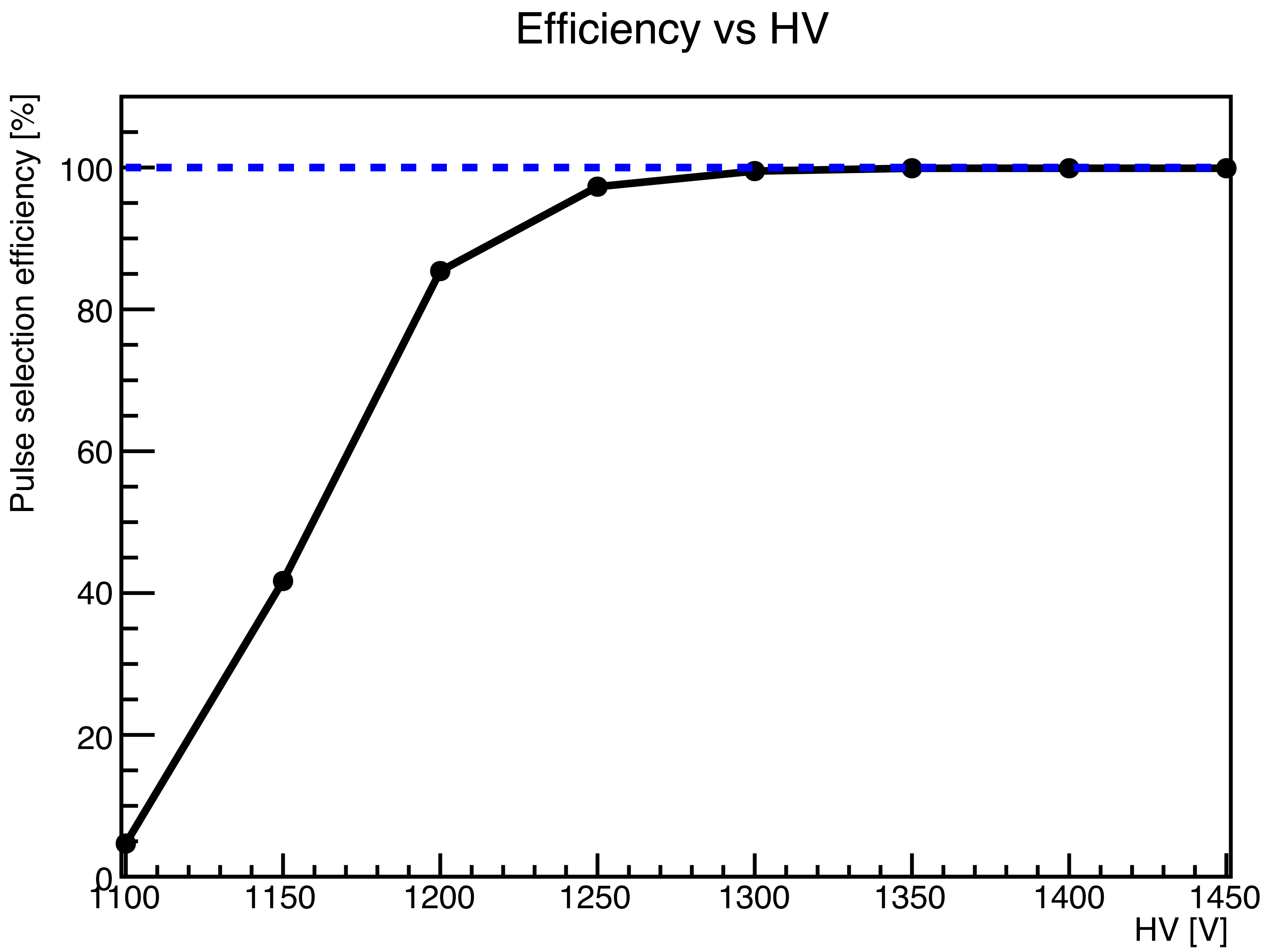

- Shower produced by cosmic muons hitting the structure of the building
  - Shower particles can hit both layers at the same time
  - Typically large number of hits and larger energy deposits
- Can be rejected by scintillator panels covering top/sides or using the outermost bars
- Precise measurement should be performed *in situ*

# SPE detection efficiency

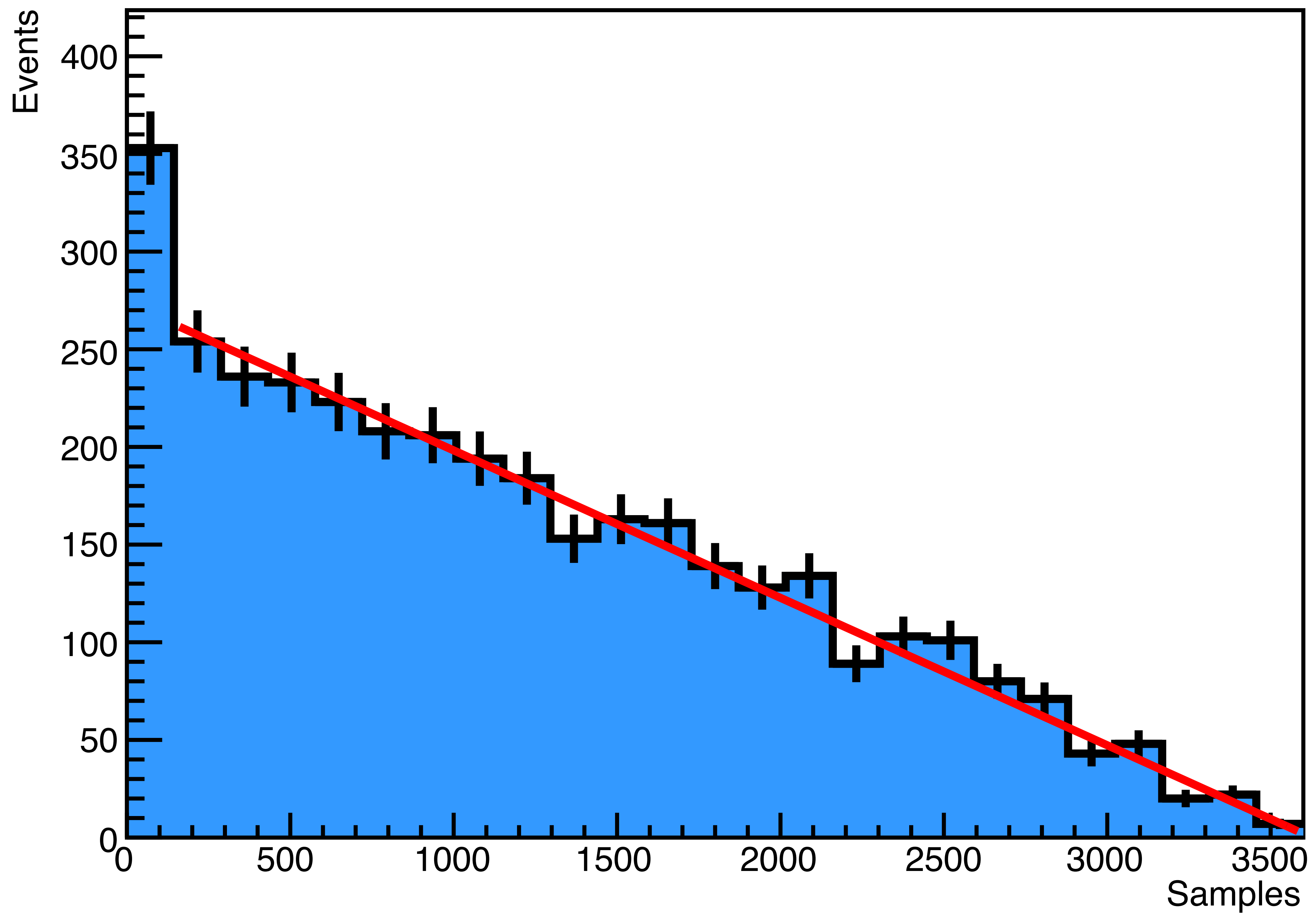


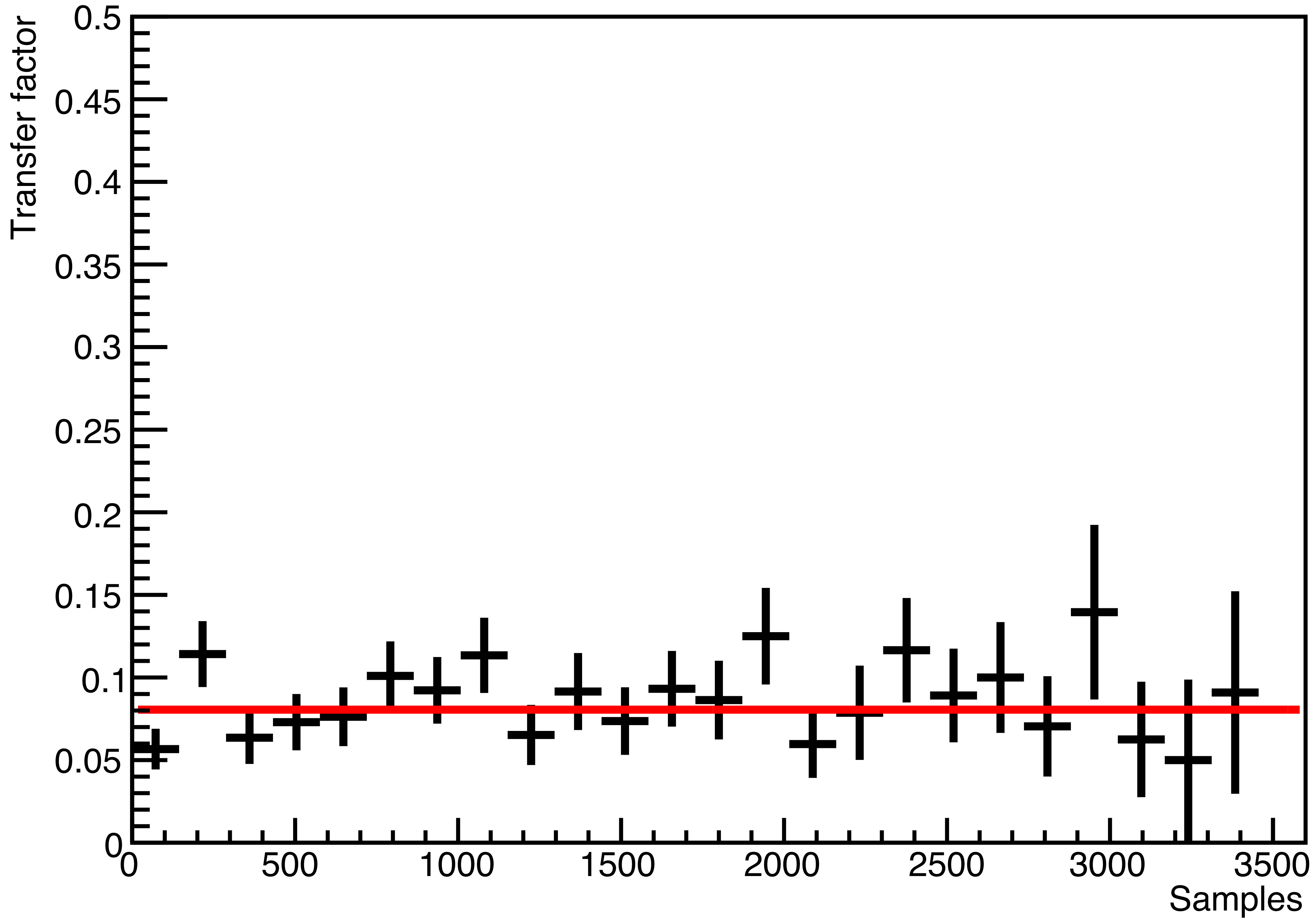



# Prediction for random backgrounds




(Left) Distribution of $\Delta t$ between two channels. The result of a linear fit is represented by a red line. (Right) Transfer factor as a function of $\Delta t$. The red line corresponds to the fit with a horizontal line.