Performance of the Dual-Readout Calorimeter for Low-Energy Electromagnetic Particles

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Department of Physics, Yonsei Univ.

Sungwon Kim

on behalf of the Korea Dual-Readout Calorimeter collaboration

CALOR2024 @ Tsukuba

23 May 2024

2023 Test beam with DRC at CERN

- Korea DRC collaboration had **test beam** (TB) in **2023** with 50cm **DRC** module at CERN east area **T9**
- Take data with **low energy** (1~5 GeV) **positron** beam
- Measured EM energy resolution & linearity, tower uniformity and response change of the tower
- **First result** to measure EM performance of DRC with beam with **energy below 6 GeV**
- Also **first result** using DRC with the **projective geometry**

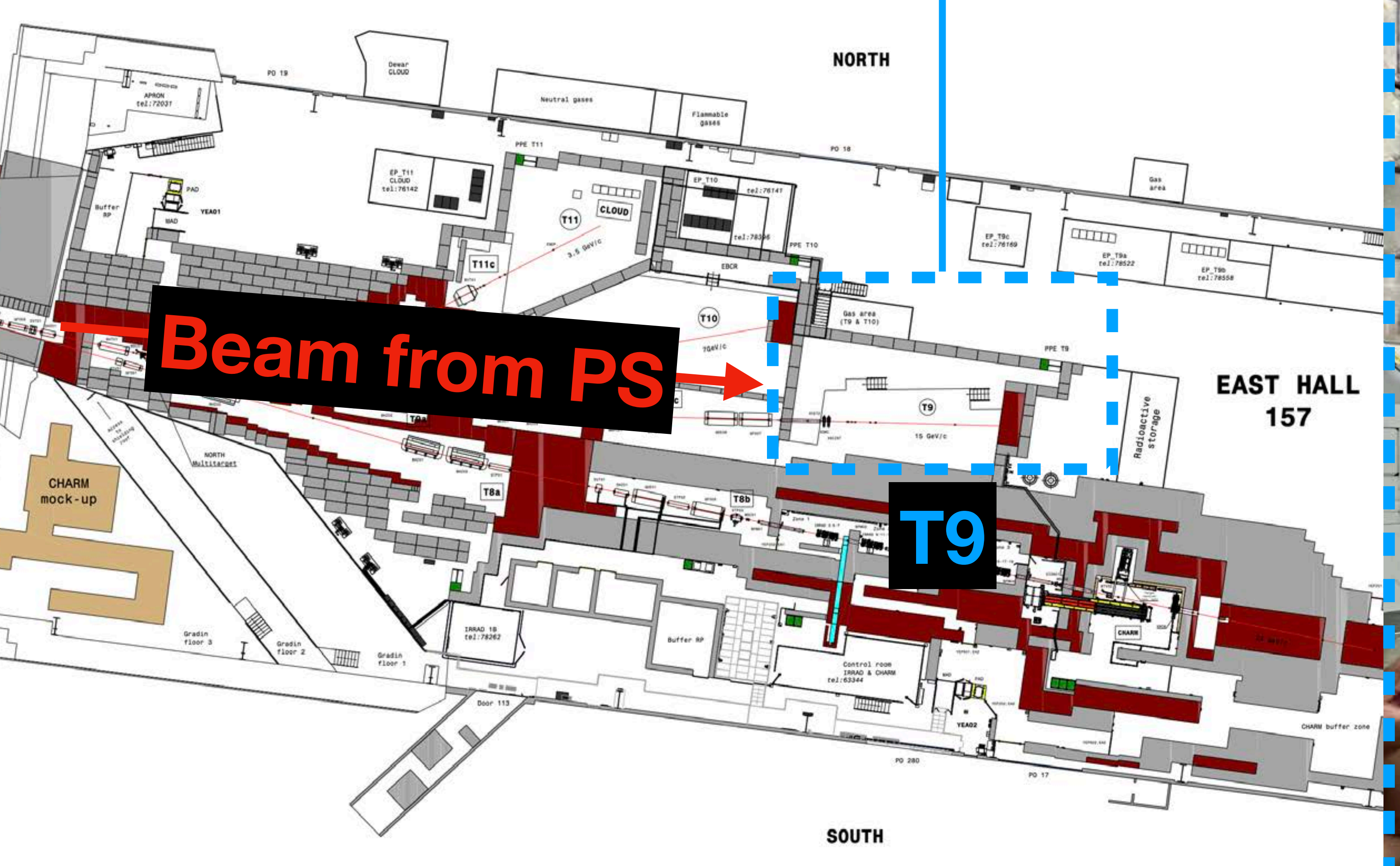


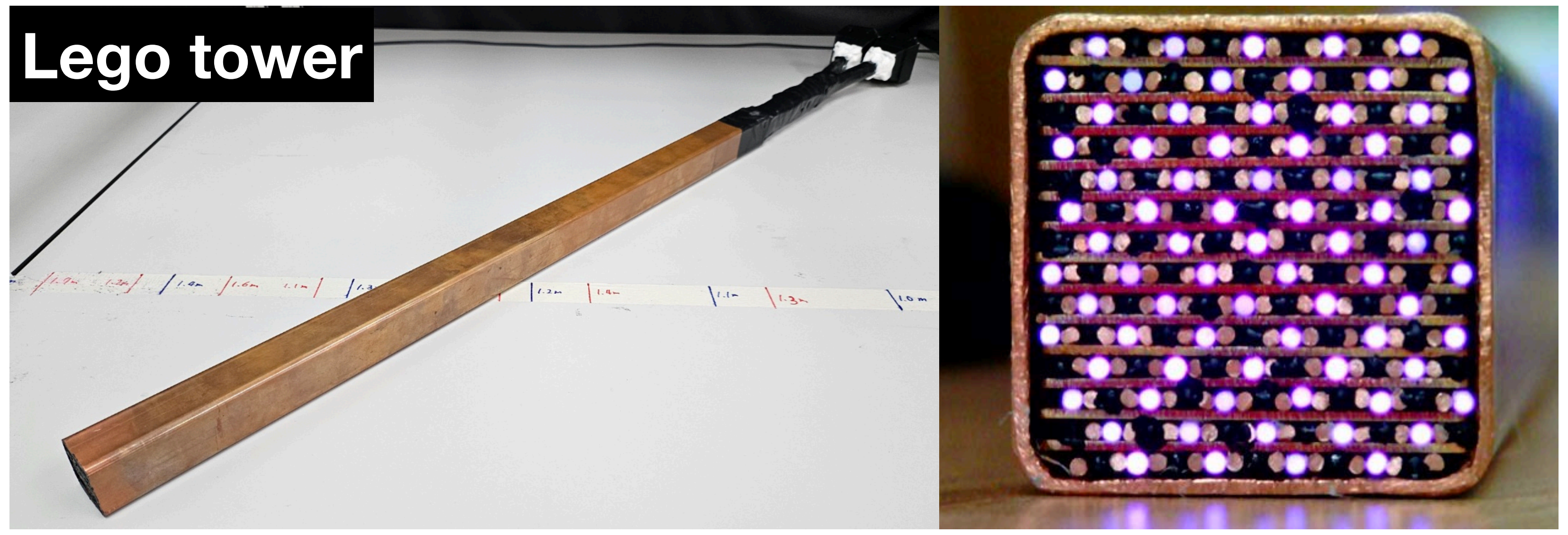
Figure ref

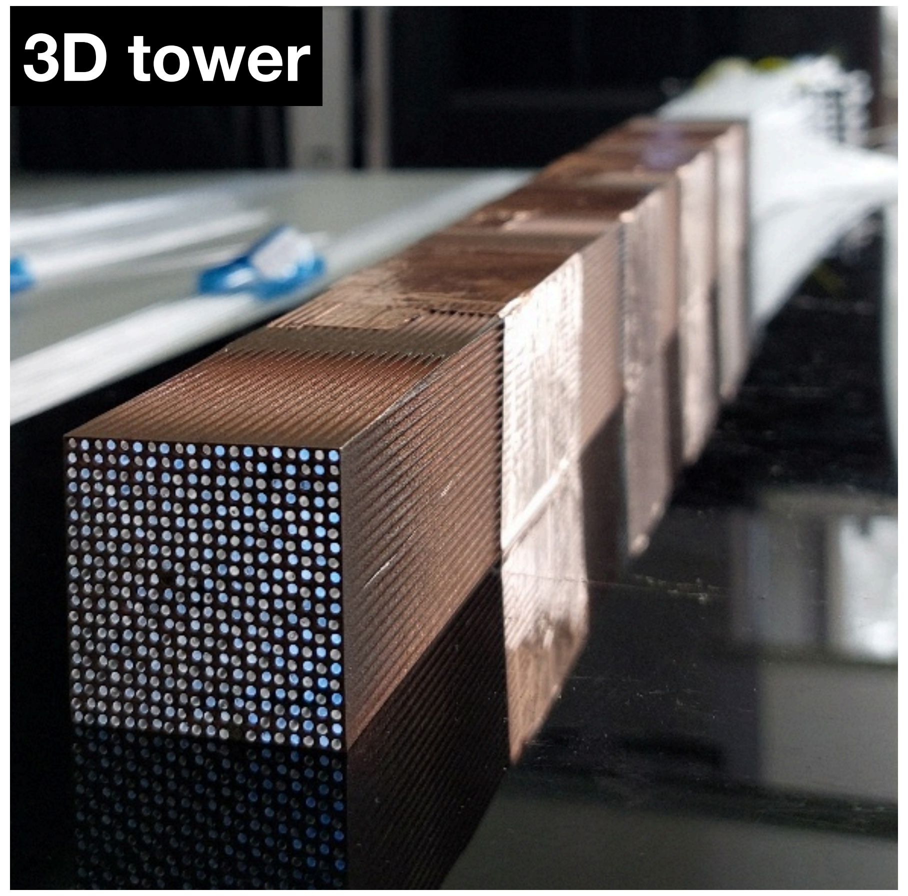
The T9 experimental hall

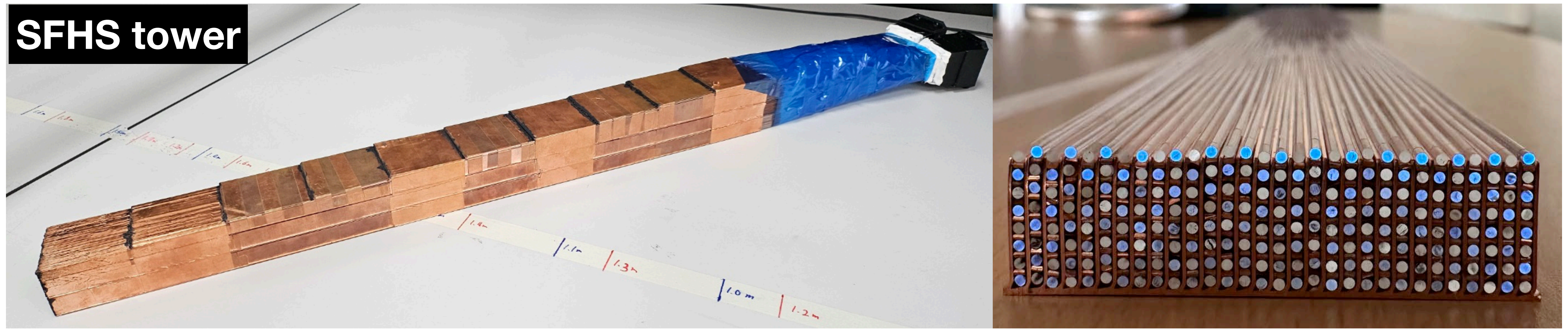
50 cm DRC module

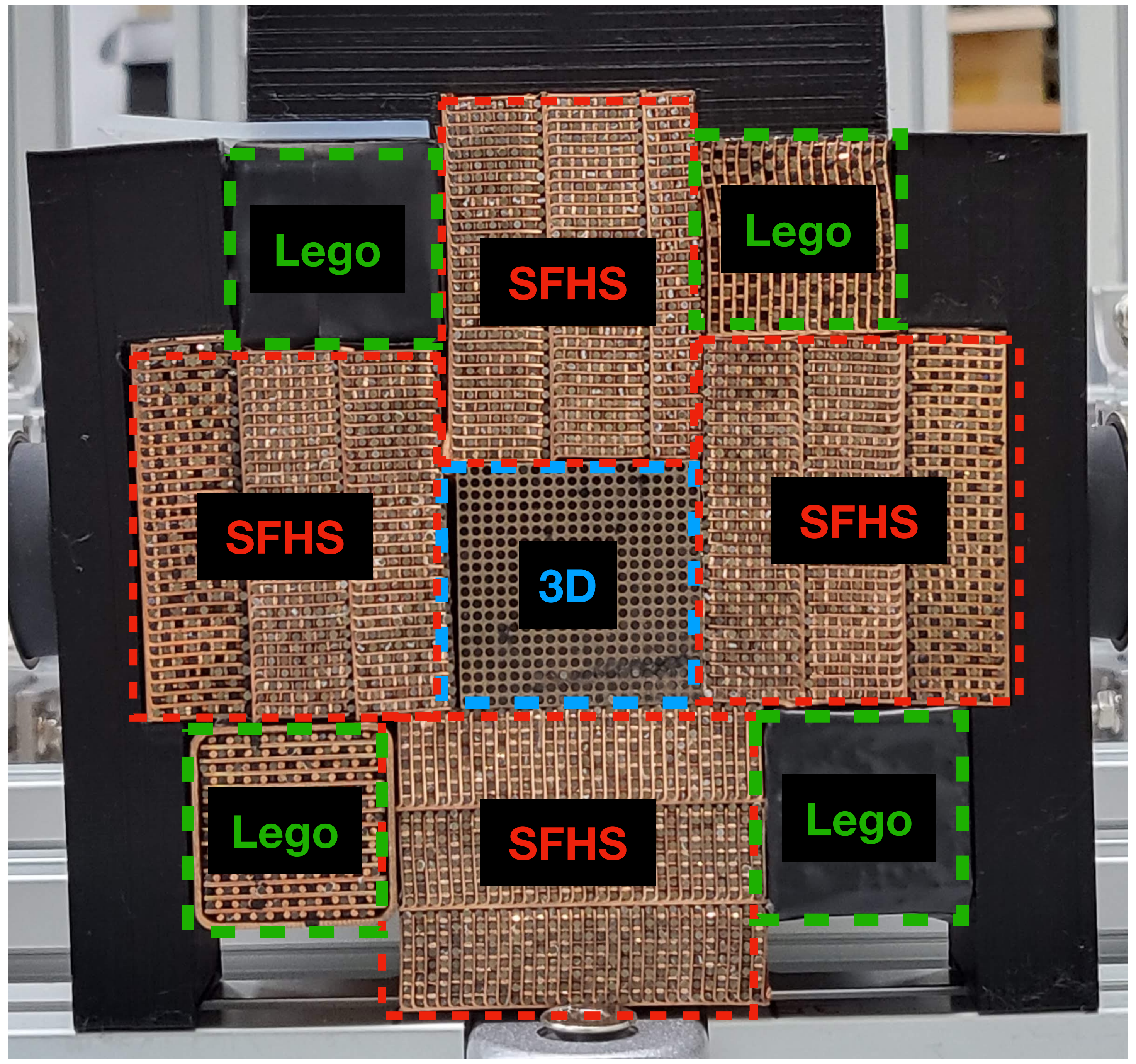
The DRC module used for TB

- DRC has **modular structure** : Consists of total **9 towers** with **3 different copper forming technique**
  - **3D** : 3D-printed copper block, fiber inserted inside the holes
  - **Lego** : Square shaped copper pipe, fibers inserted inside the pipe
  - **Skiving Fin Heatsink (SFHS)** : Copper block made with skiving machine, fiber inserted between fins
- **Scintillation(S.)** and **Cherenkov(C.) fibers** are installed inside the copper absorber









Upstream view of DRC module

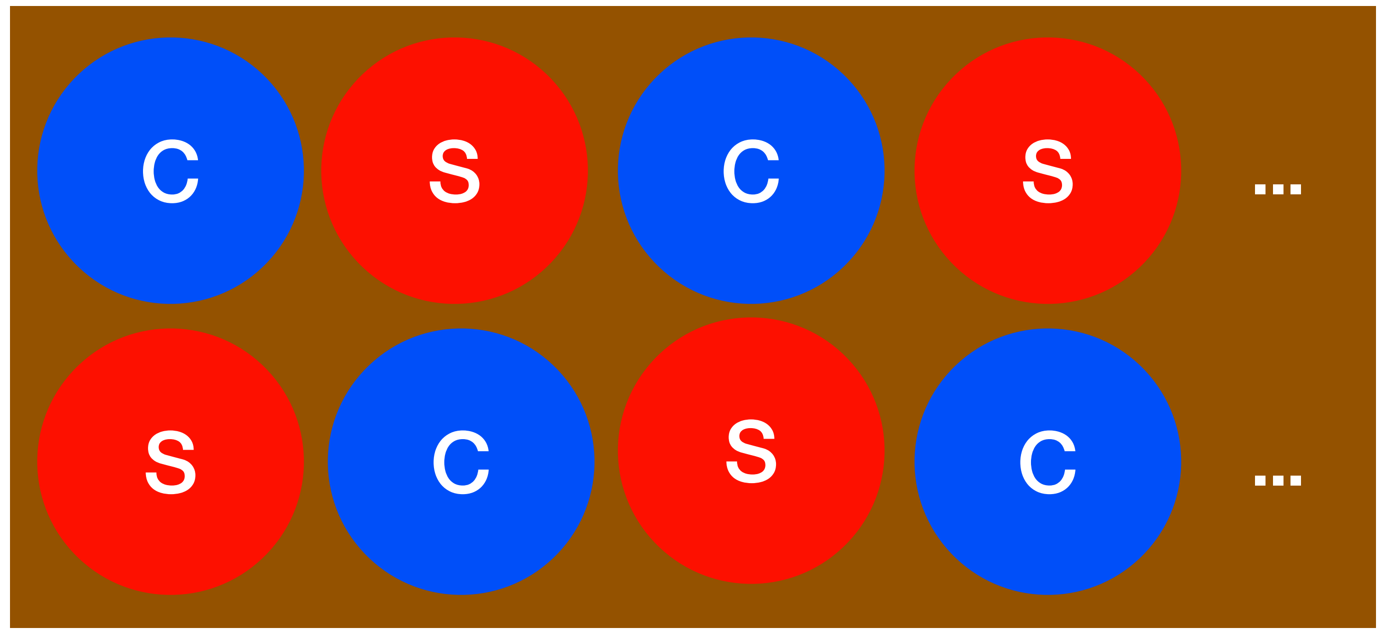
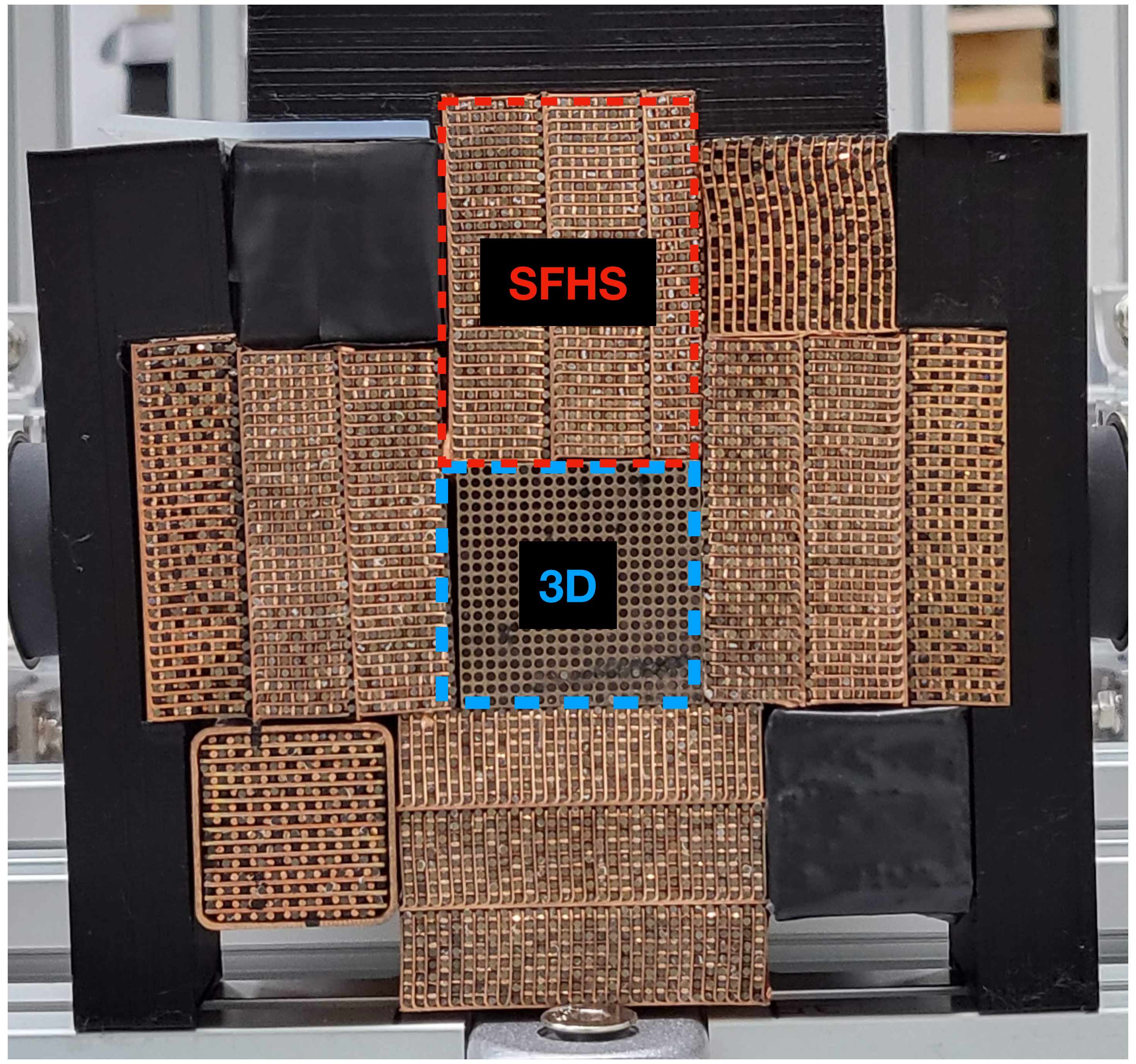


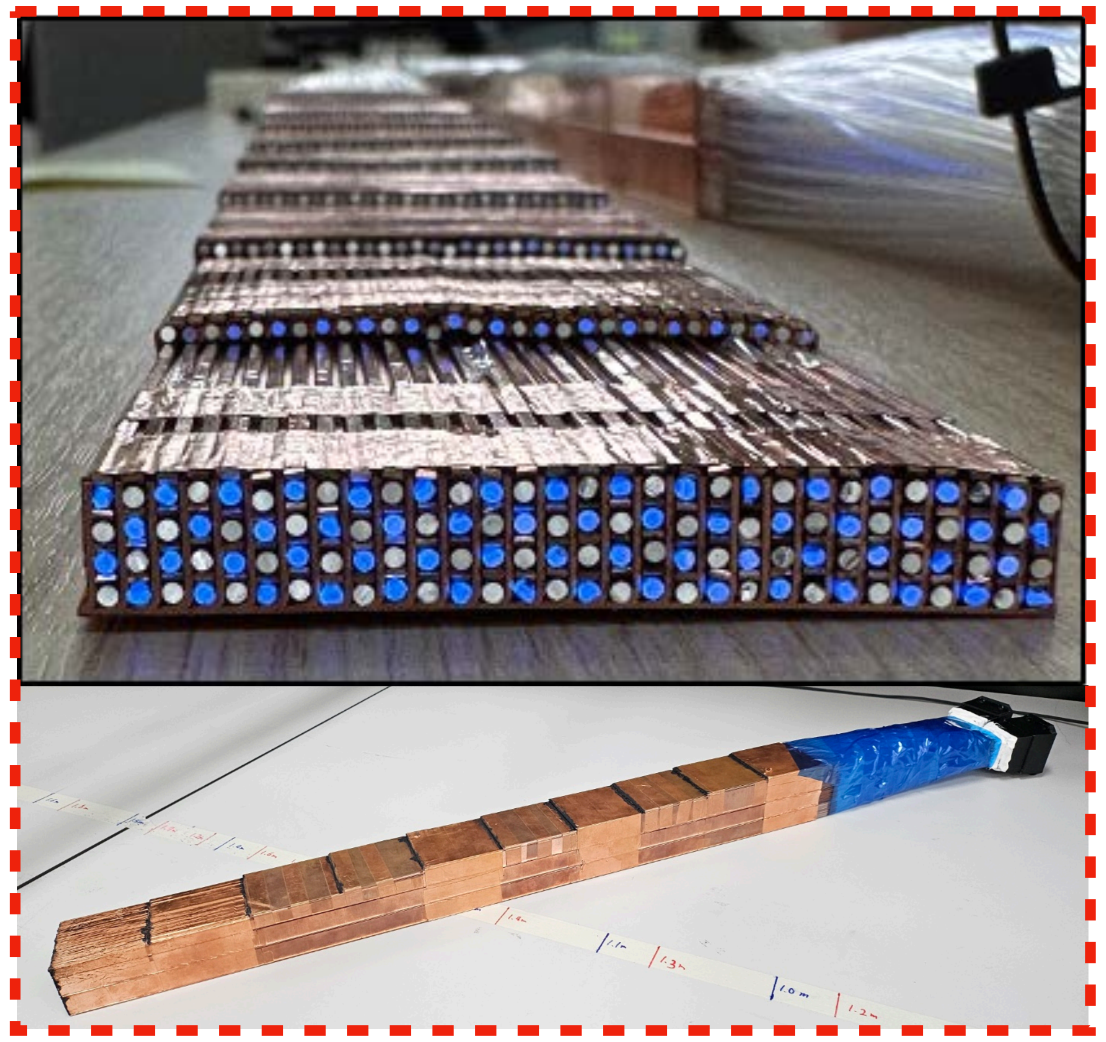
Diagram of the optical fibers alternatively installed in the copper absorber

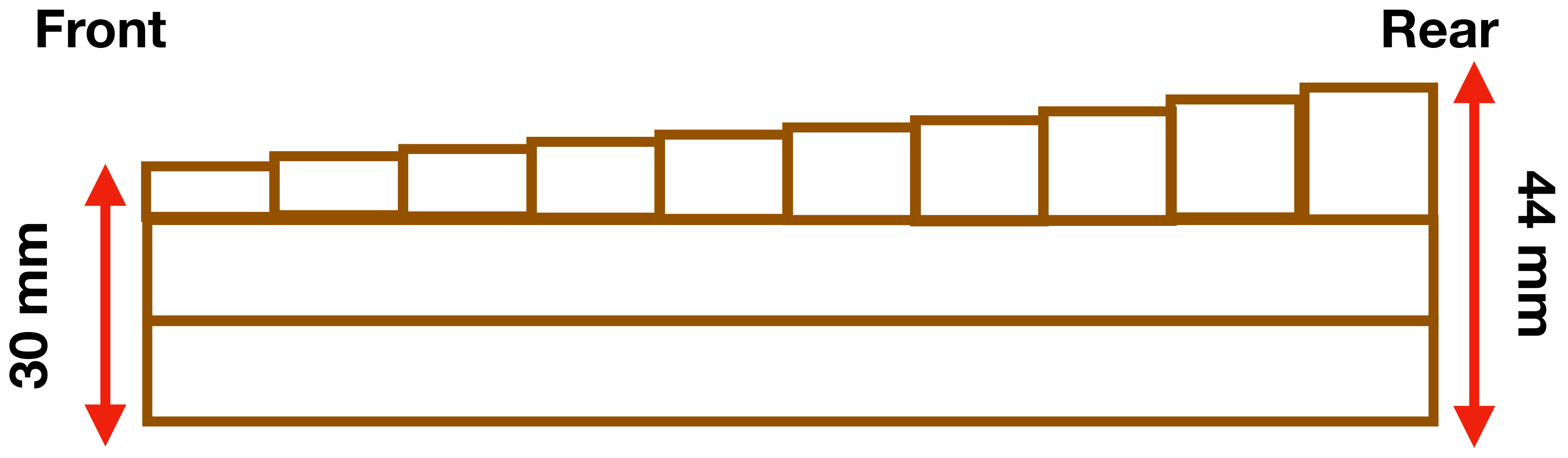
The DRC module used for TB

- The 3D and SFHS (top) tower has **projective geometry**
- **3D tower** front side has size of $3 \times 3\ \mathrm{cm}^2$, while the rear side shows $4.5 \times 4.5\ \mathrm{cm}^2$
- **Top SFHS tower** has stair-like geometry with height of $3\ \mathrm{cm}$ for the front side and $4.4\ \mathrm{cm}$ for the rear side

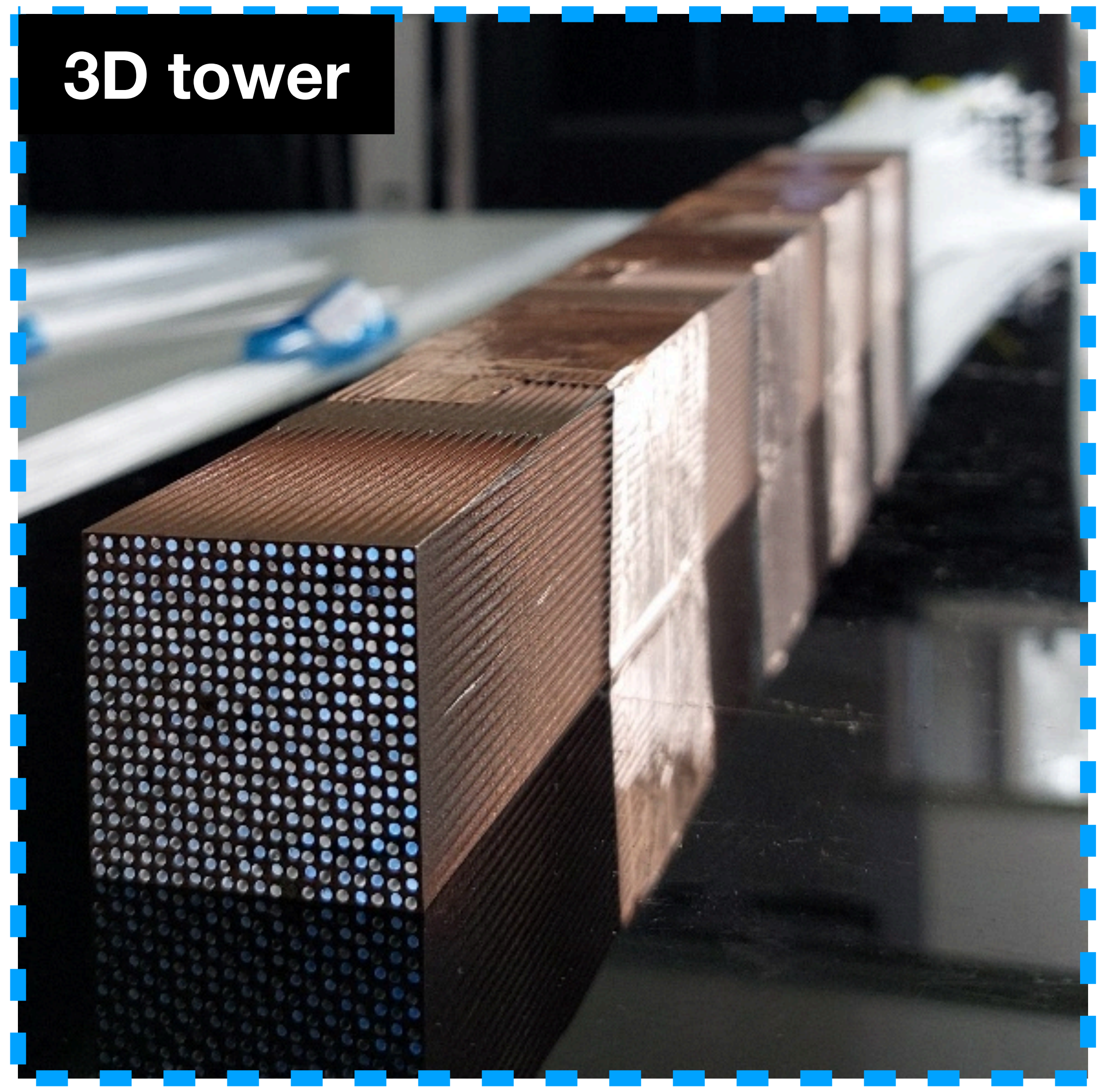


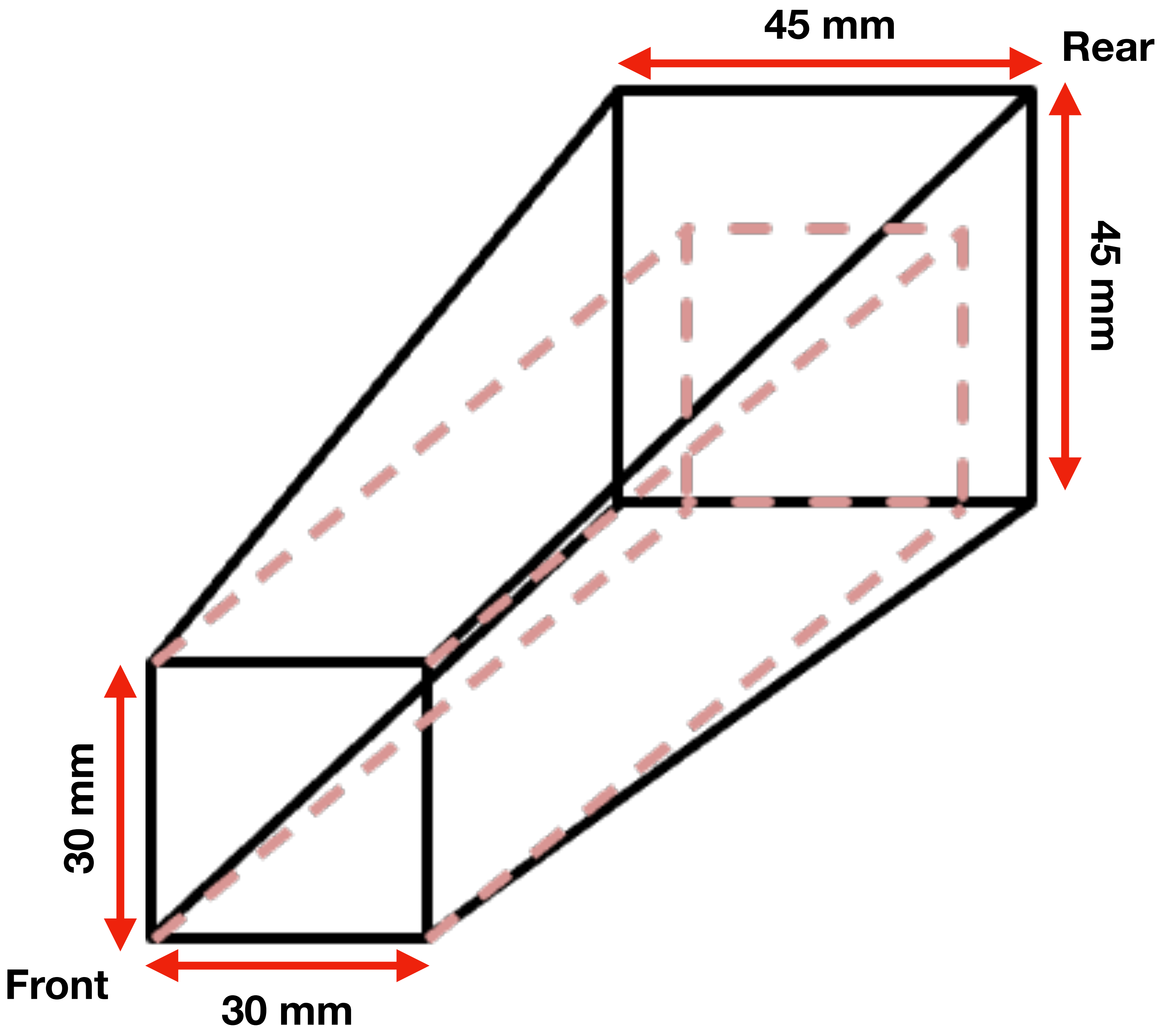
Upstream view of DRC module





Side view of the SFHS tower

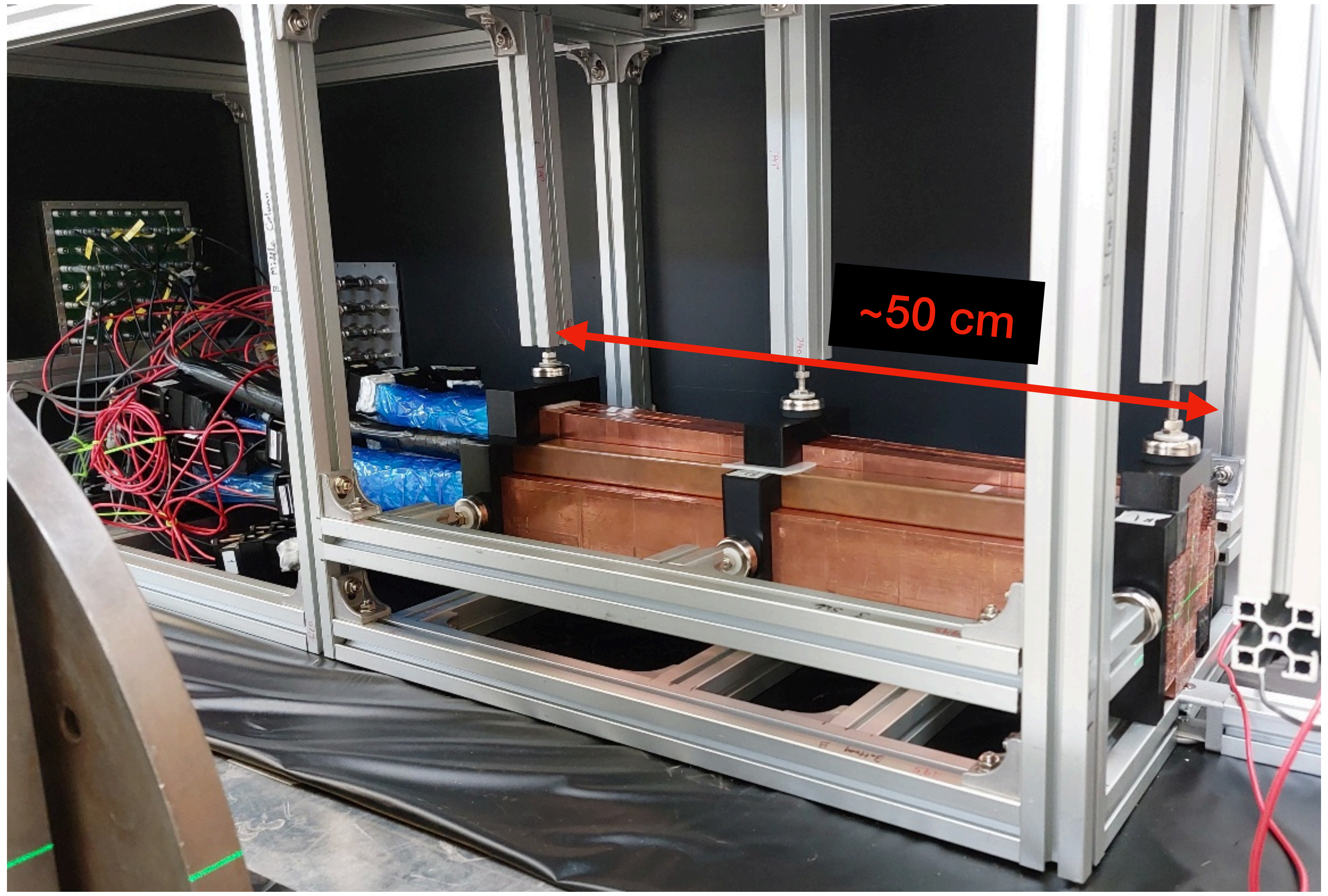




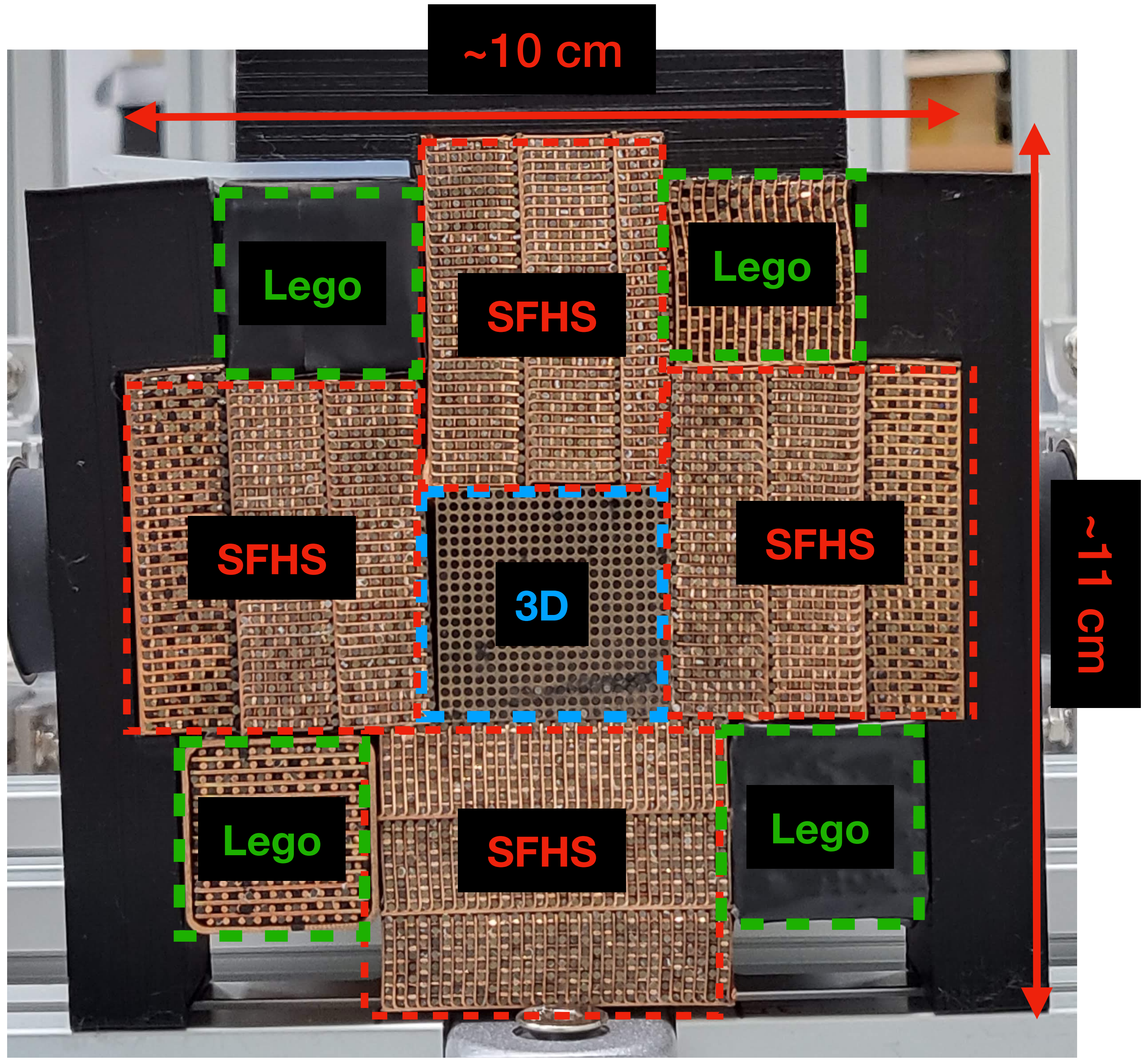
Dimensions of the 3D tower

The DRC module used for TB

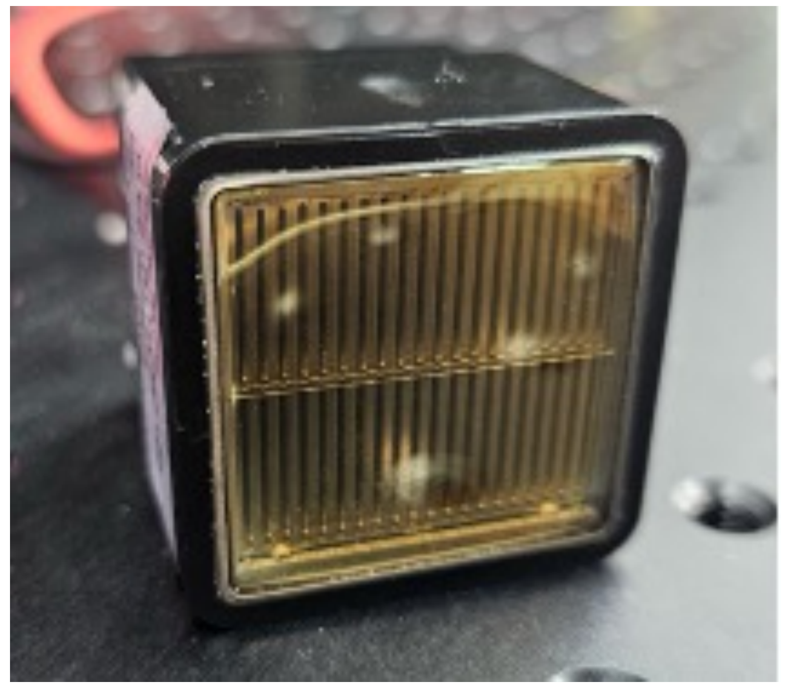
- DRC has **50 cm** length (~ 25 χ_0), front side cross section of $10 \times 11\ \mathrm{cm}^2$ (~ 2.5 Moliere radii)
- Dimensions corresponds to **~99 % longitudinal** shower containment, **~95 % lateral** shower containment
- Readouts : **MCP-PMT and PMT** for 3D tower, **PMT** for others
- Detector, readouts supported with aluminum profile specially designed for the TB



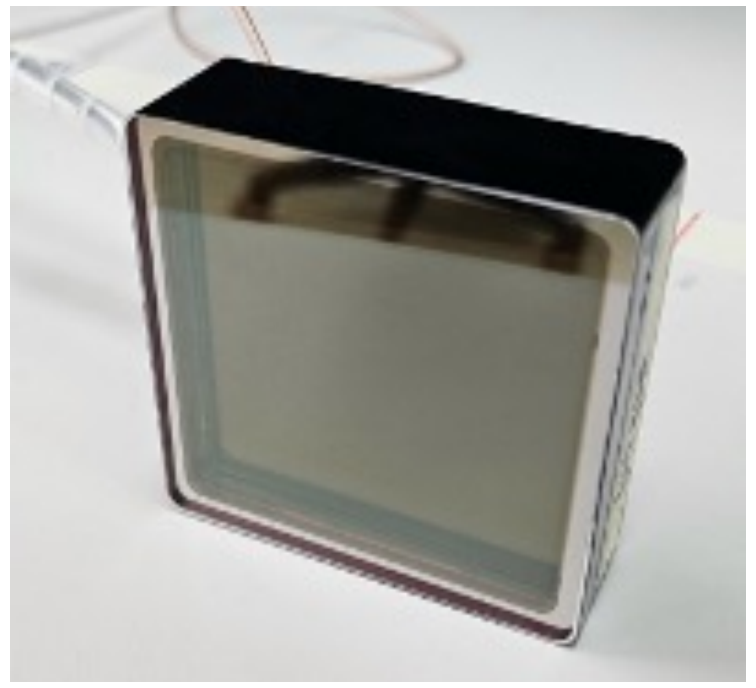
Side view of DRC module



Upstream view of DRC module



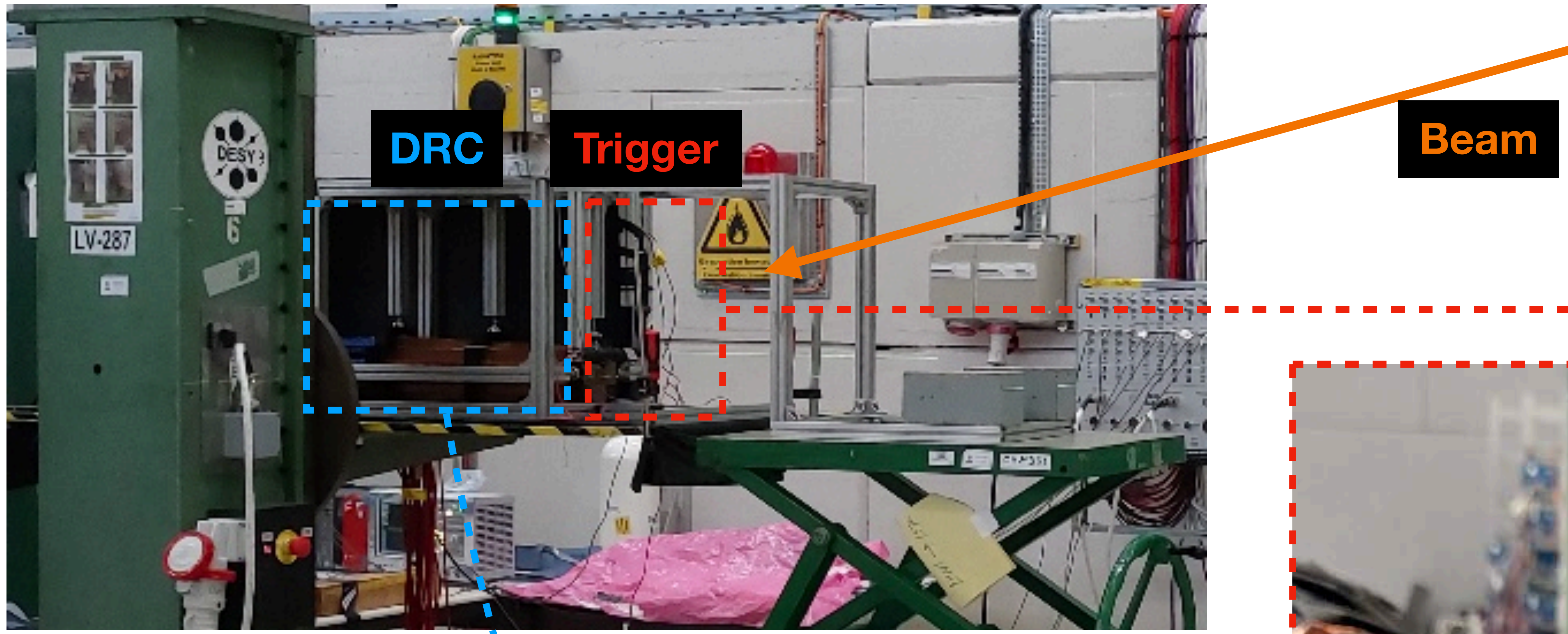
PMT

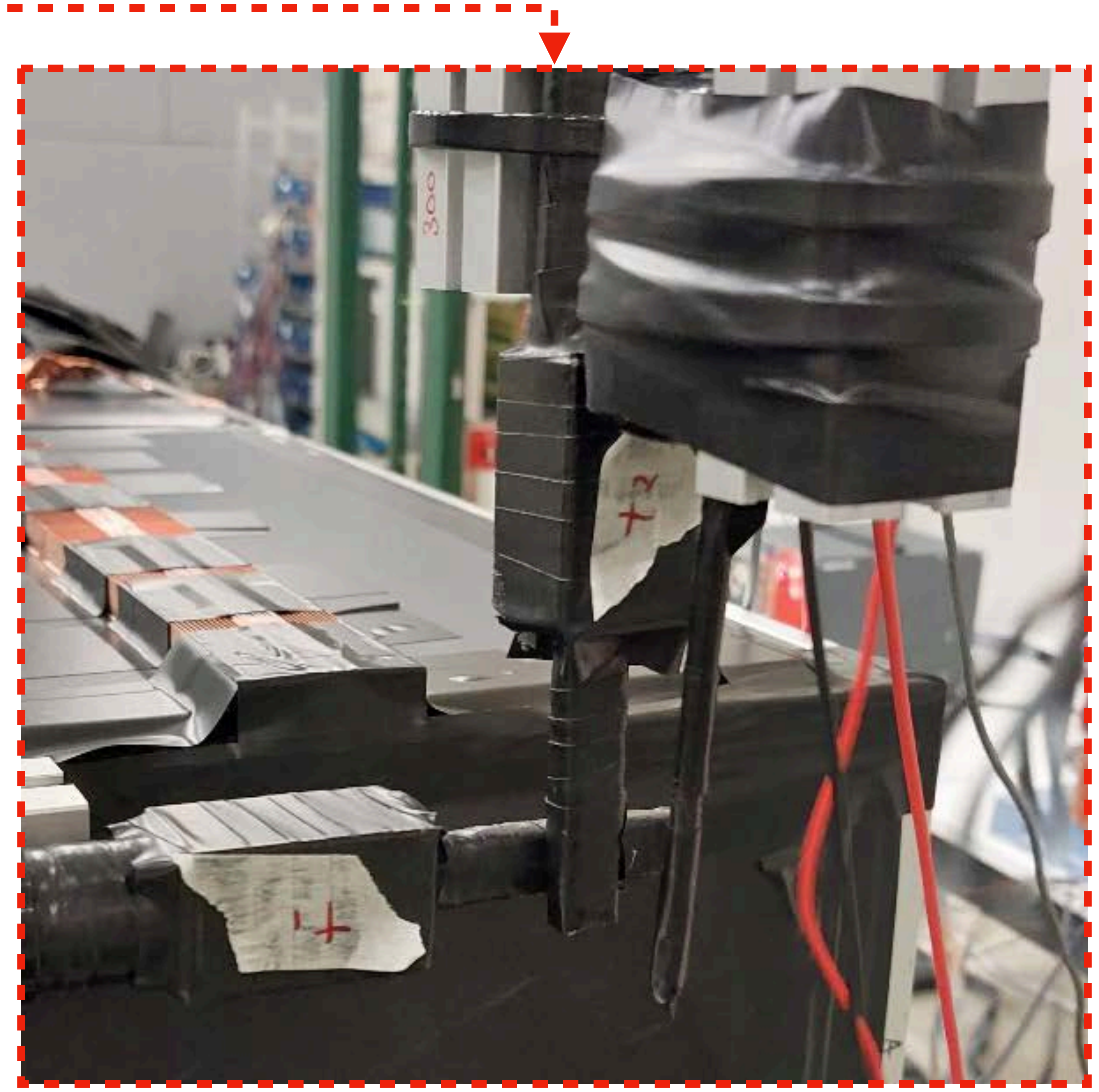


MCP-PMT

Experimental setup

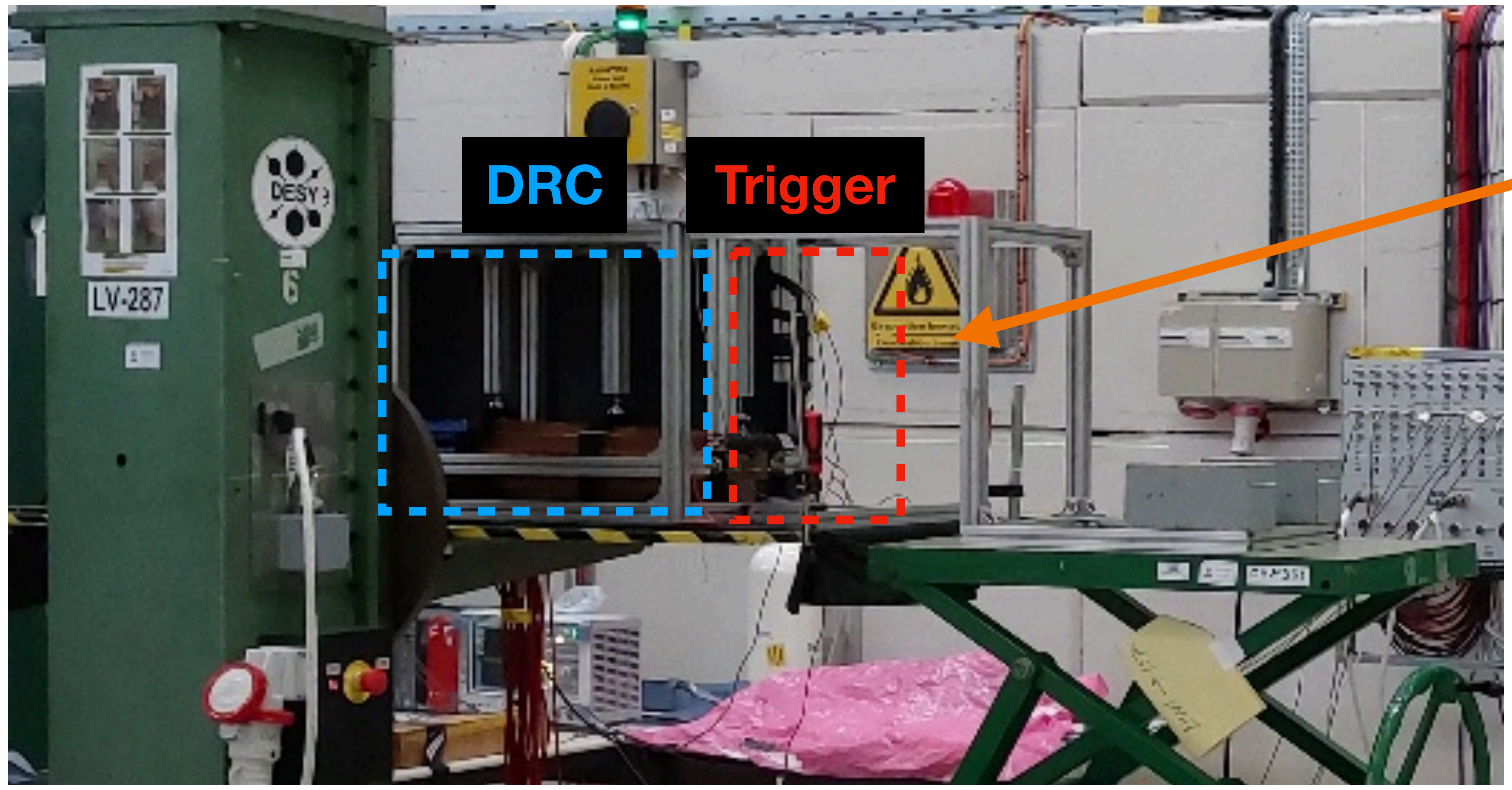
- Hardware setup : Beam line → Cherenkov counters → Triggers → DRC → DAQ → DAQ PC
- **Trigger detectors** : Used 2 (or 3) **scintillation detectors** to create **trigger** signal
- Trigger detectors has cross section of $1 \times 1\ \mathrm{cm}^2$ (or $0.2 \times 1\ \mathrm{cm}^2$ when using 3 triggers)





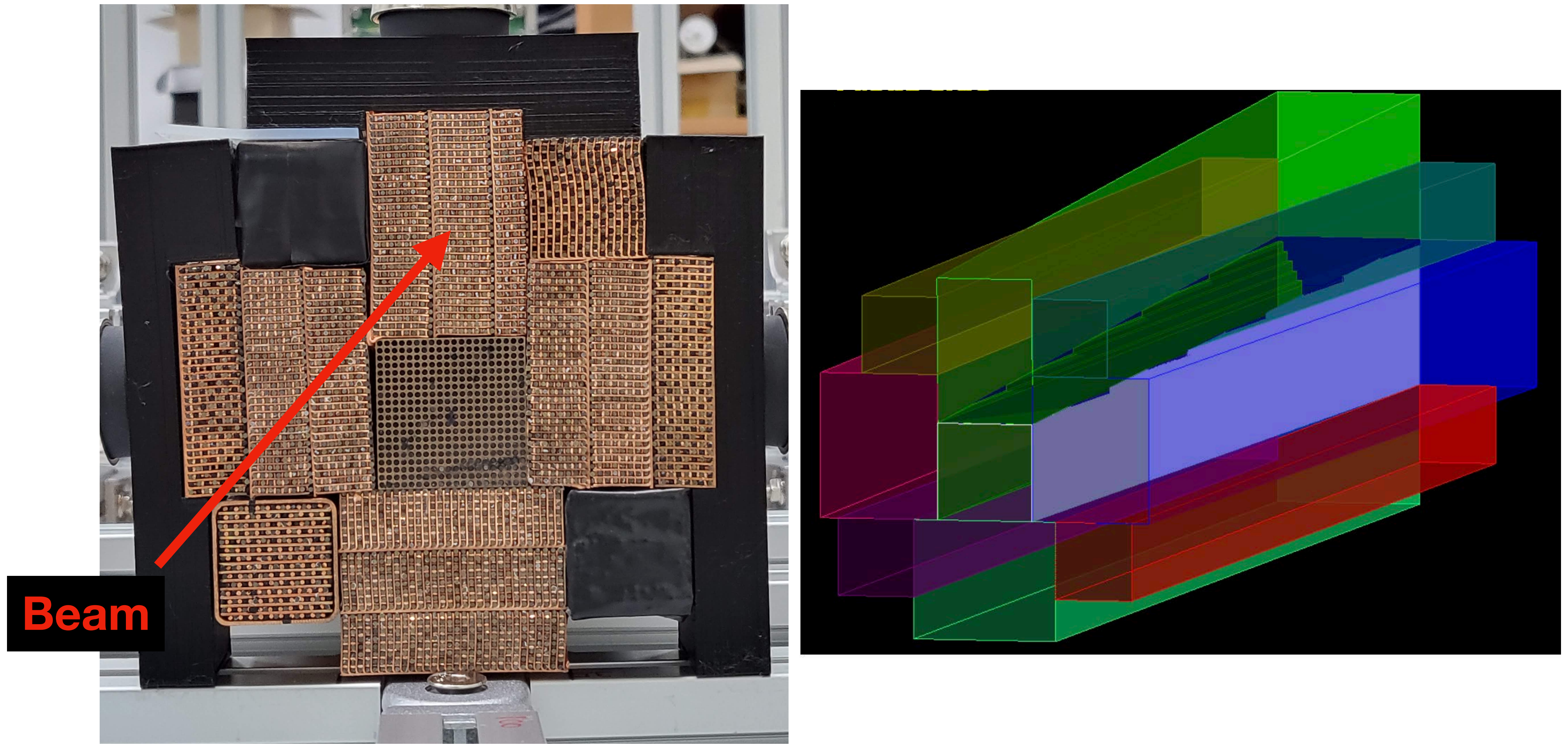
Experimental setup

- Hardware setup : Beam line → Cherenkov counters → Triggers → DRC → DAQ → DAQ PC
- **DAQ** : Digitizes the signals from readouts using **DRS4** chip, store the data in DAQ PC
- DAQ installed far behind DRC to avoid radiation damage

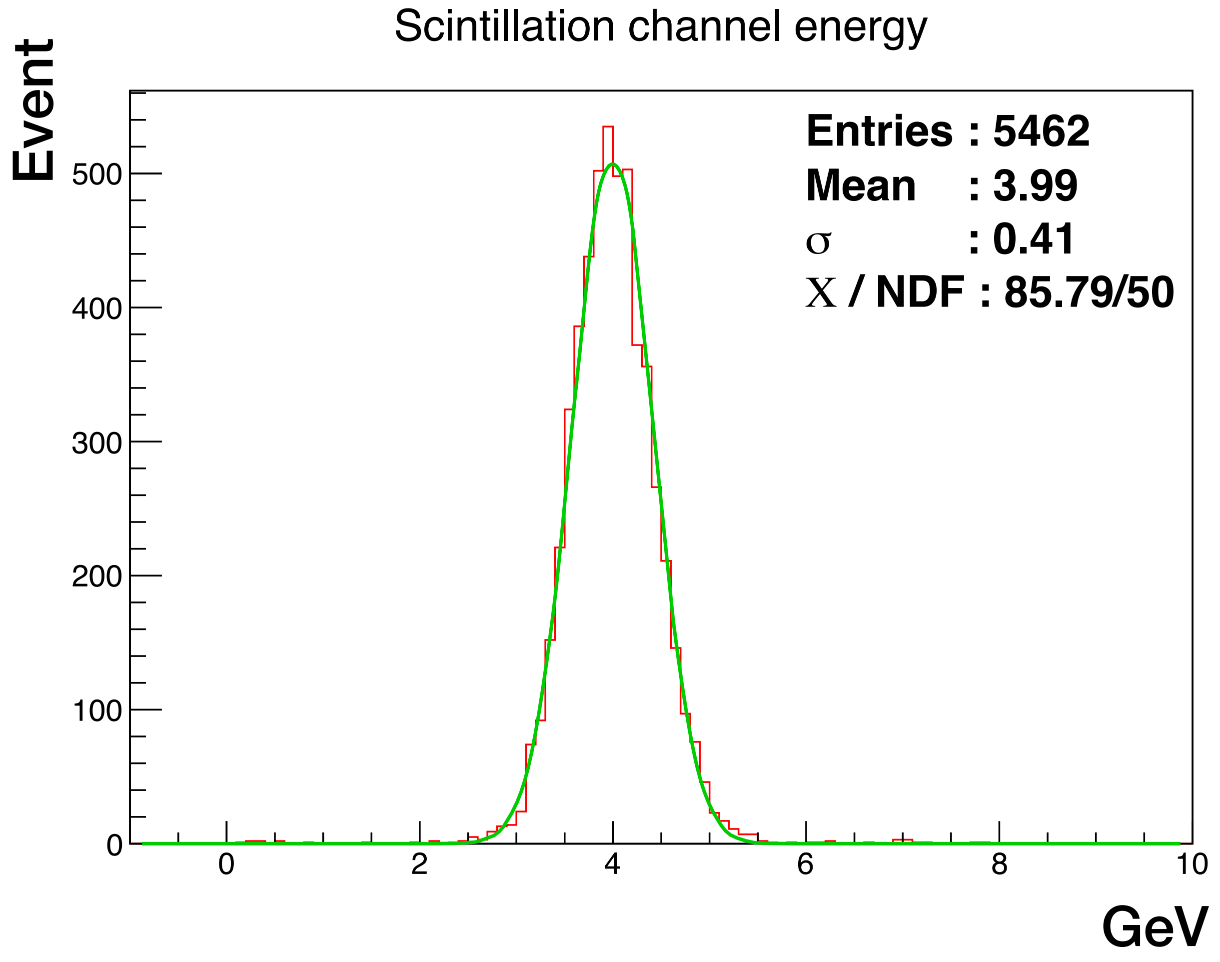


Test beam data analysis procedure

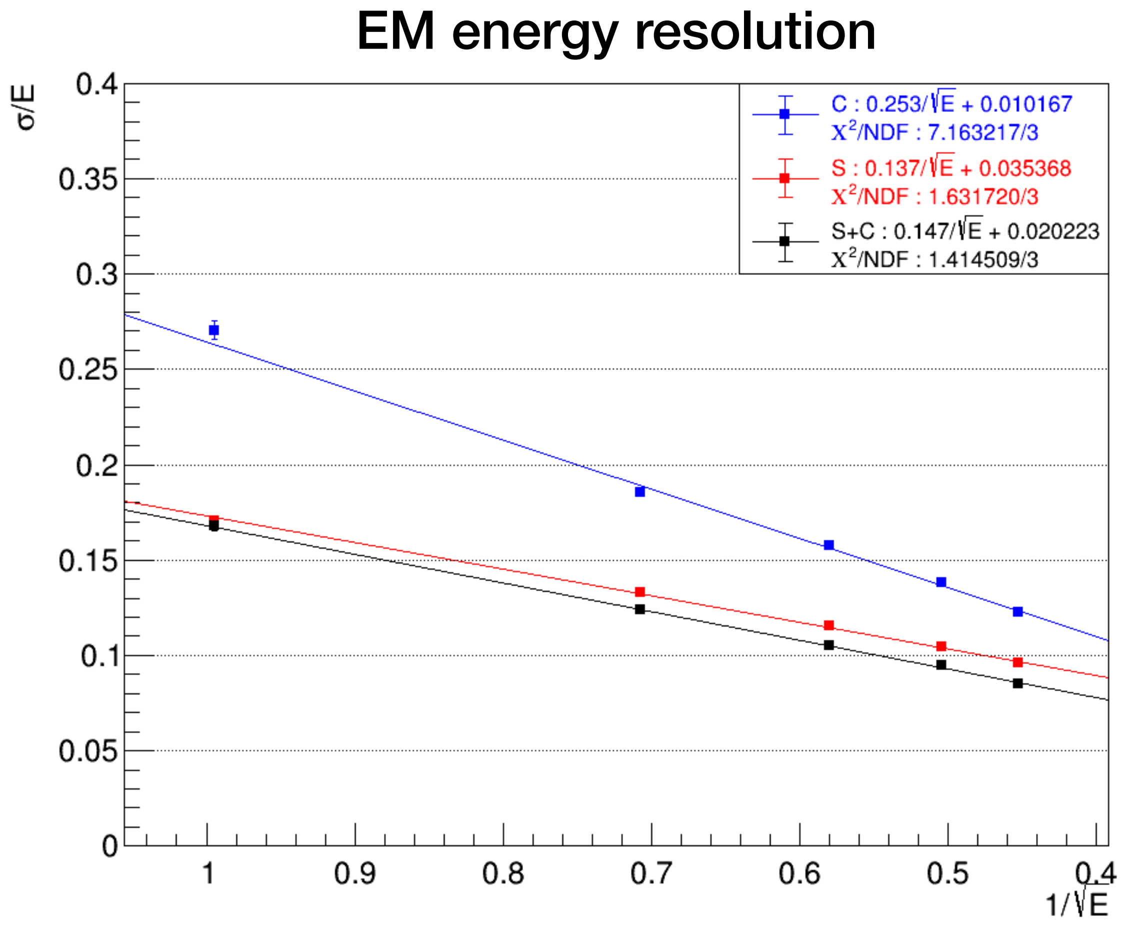
- Using the DRC module and HW setup, took data with **positron beam** with energy of **1, 2, 3, 4, 5 GeV**
- The data analysis procedure
    1. **Calibrate** the DRC towers to measure the energy using the data and Geant4 simulation
    2. **Measure** the **energy** of the particle beam
    3. Extract the **EM energy performances** of the DRC



1. Calibrate the DRC towers with help of Geant4 simulation



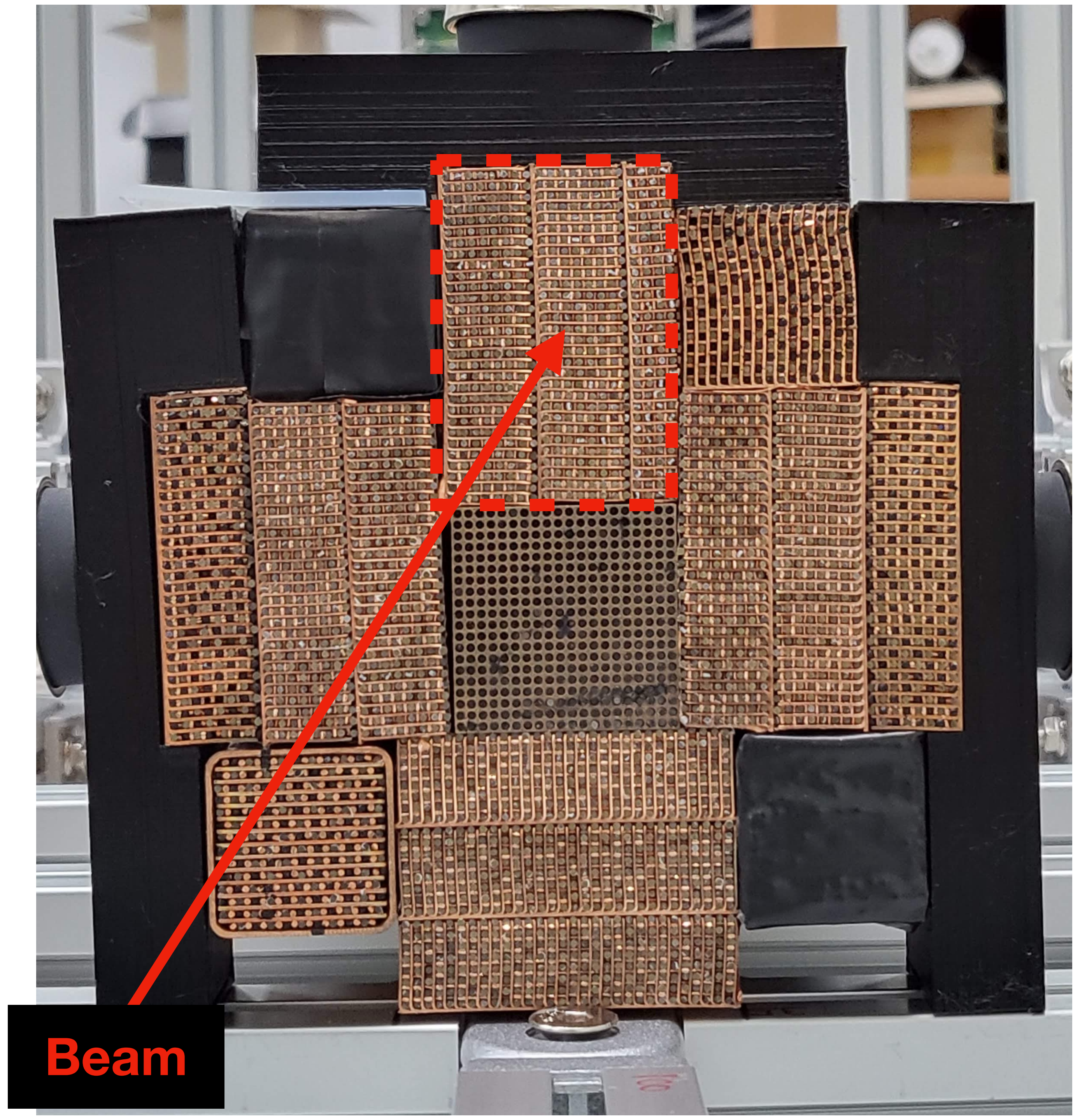
2. Measure the positron beam energy



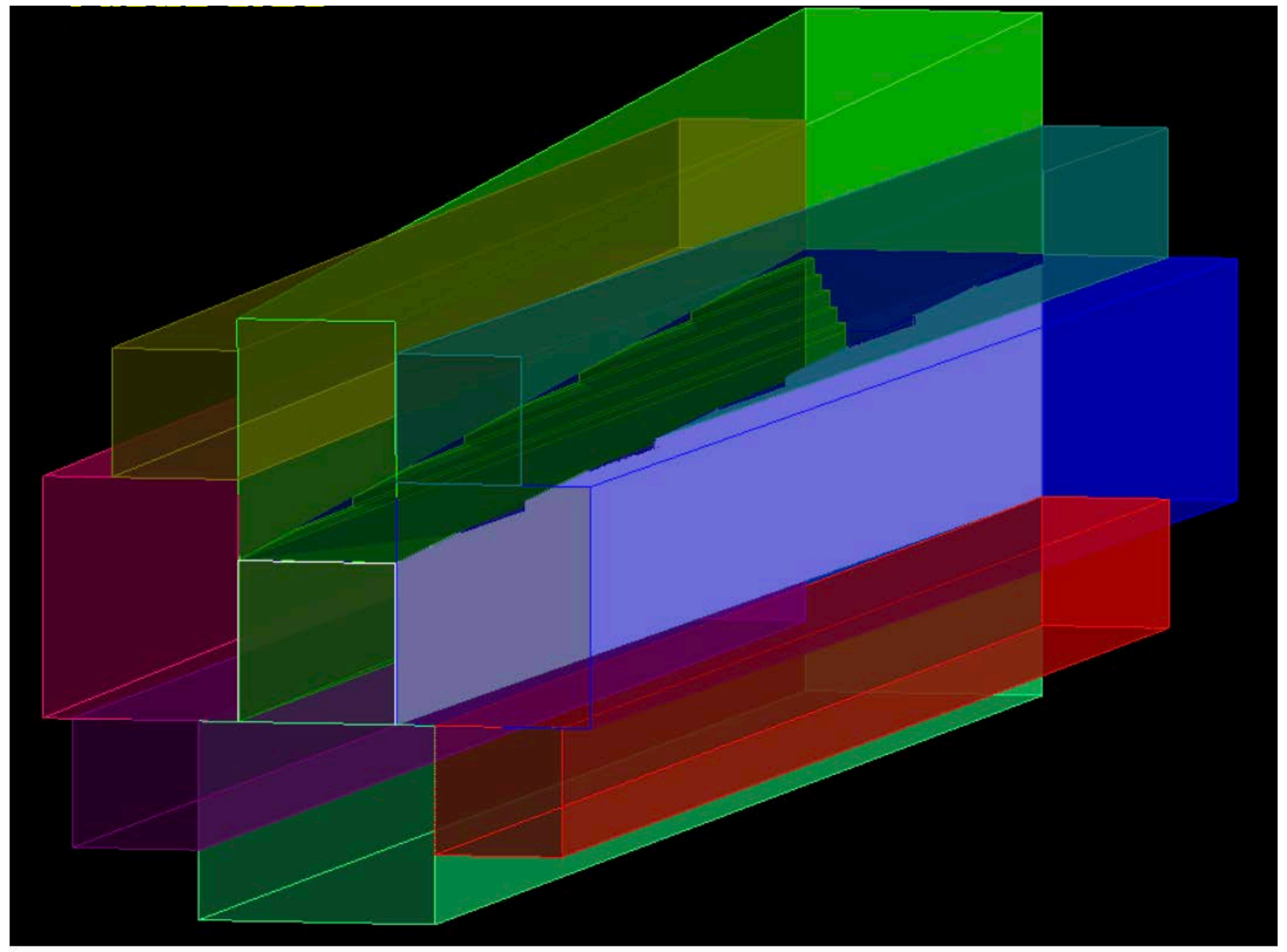
3. Extract EM performances

DRC calibration

- The DRC towers are **calibrated** to measure the beam energy
- Tower's **ADC response** measured using the **4 GeV e^+ beam** shoot to its center
- **Calibration constant** calculated by using expected energy deposit obtained with **simulation**
- $Calib.Const. \times ADC\ count = Beam\ energy\ (4\ GeV) \times E\ deposit\ fraction$

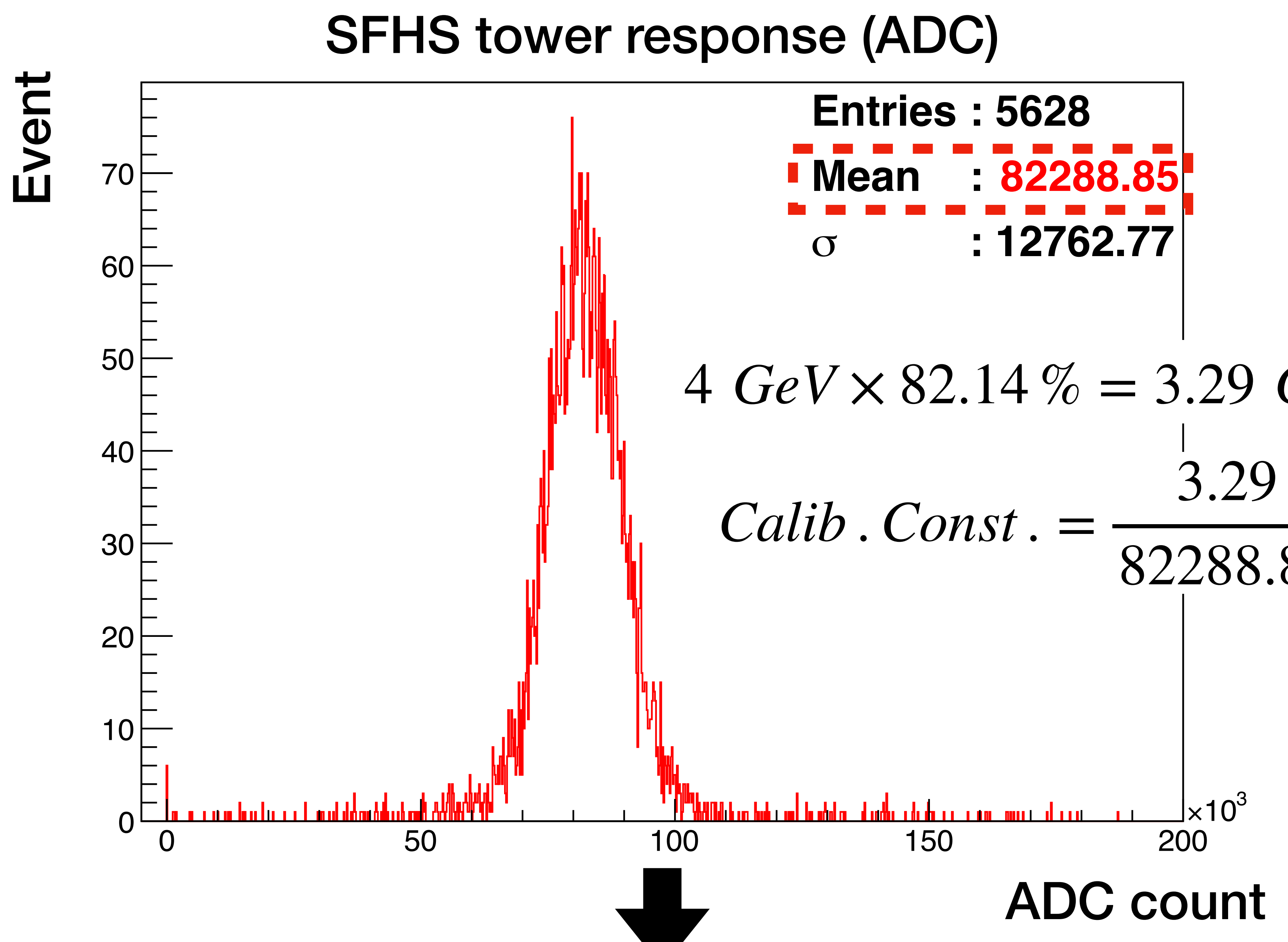


Beam shoot to the center of the tower to be calibrated (ex. SFHS tower)



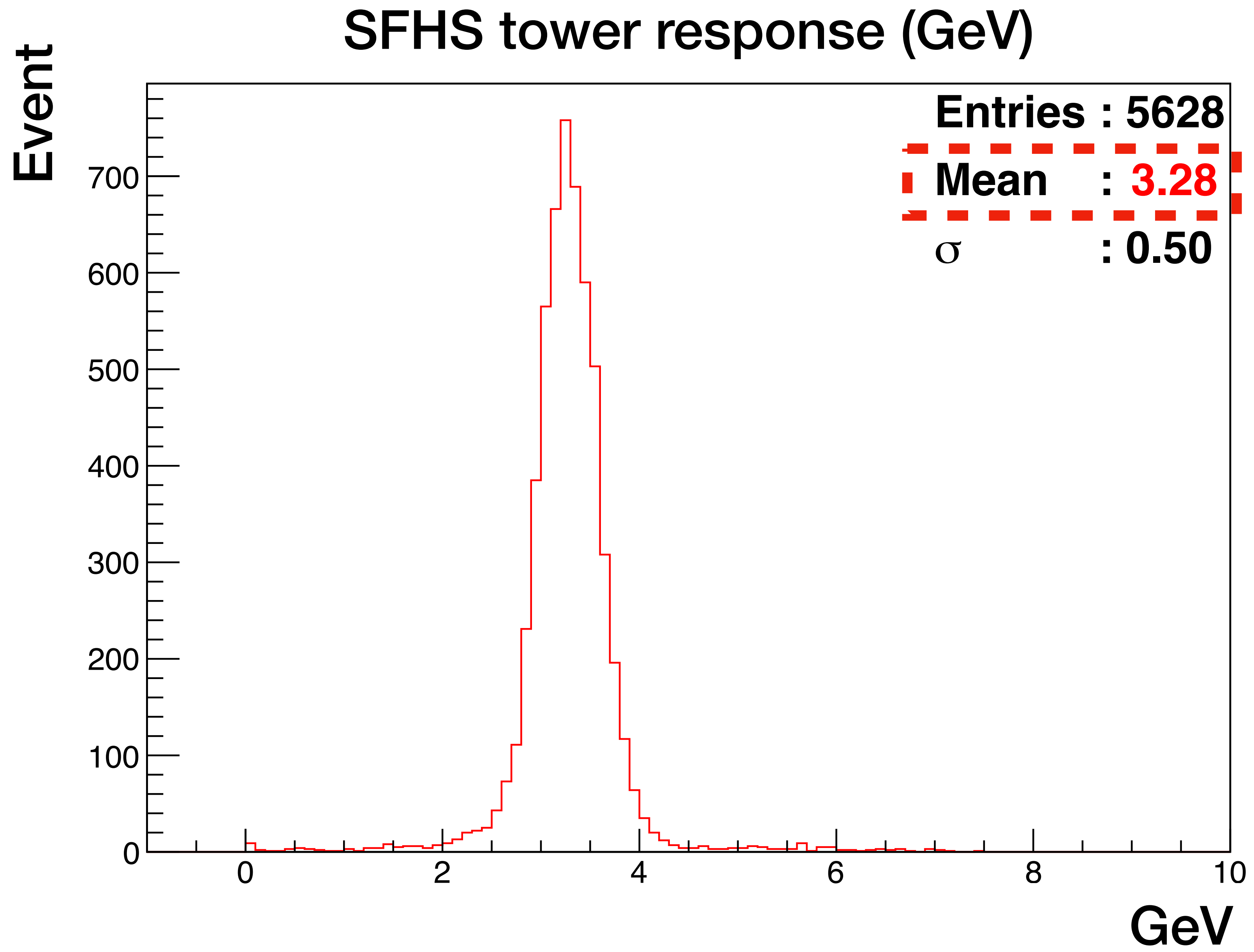
Target tower	Ch	E deosit
HW	S	82.14
	C	82.14
H1	S	82.36
	C	82.36
H2	S	82.32
	C	82.32

E deposit fraction calculated with Geant4 simulation



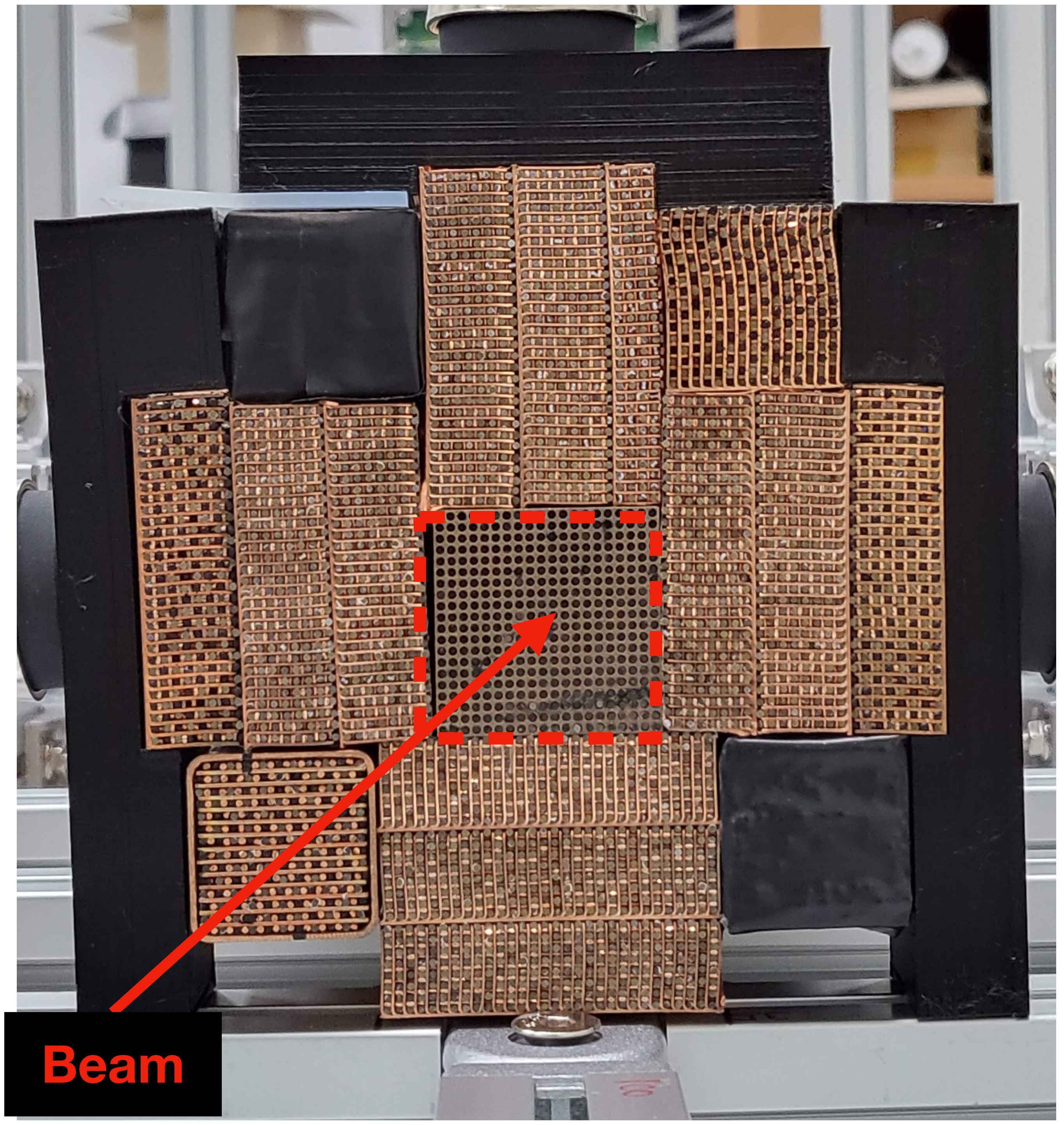
$$4\ GeV \times 82.14\,\% = 3.29\ GeV$$

$$Calib.Const. = \frac{3.29}{82288.85}$$

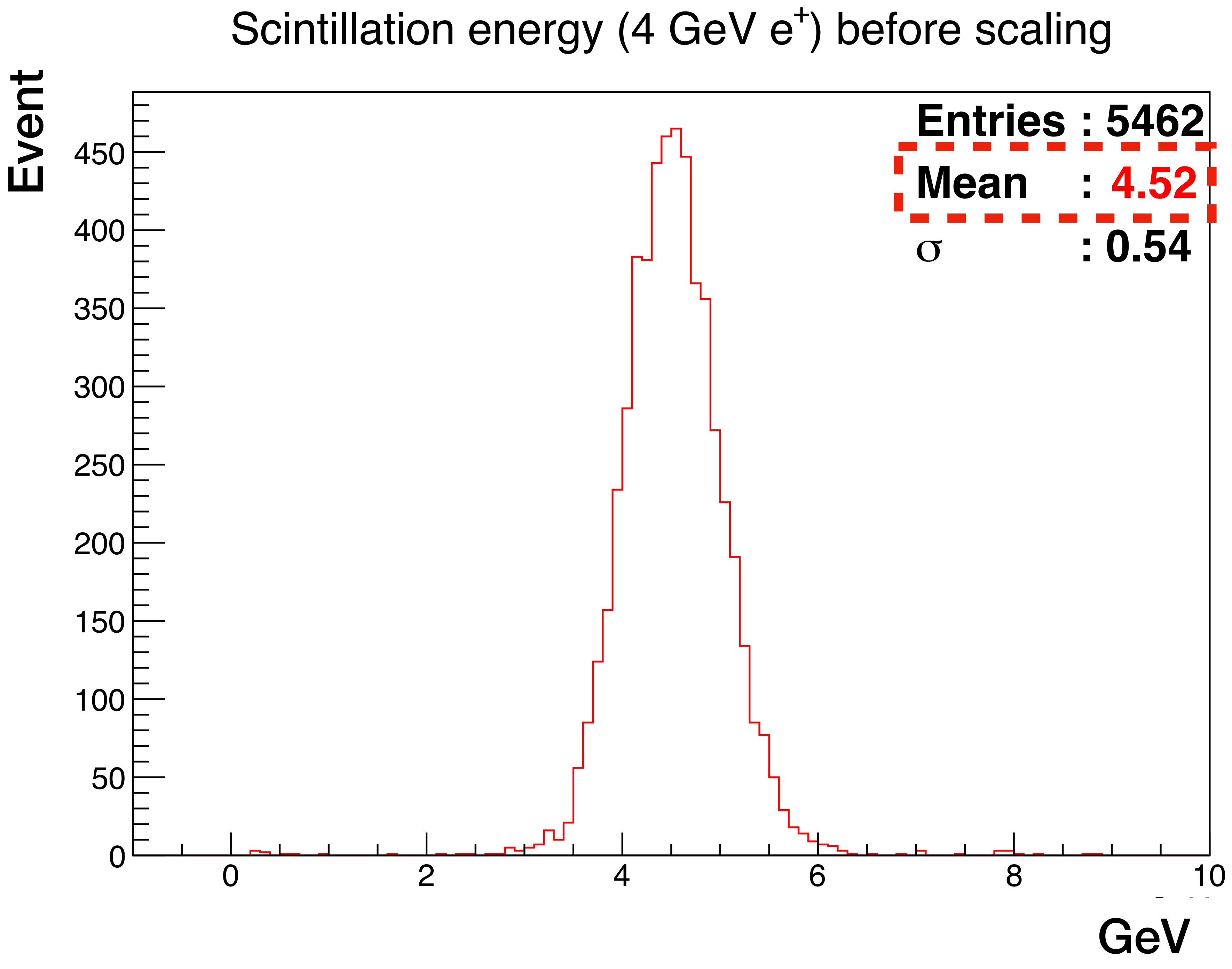


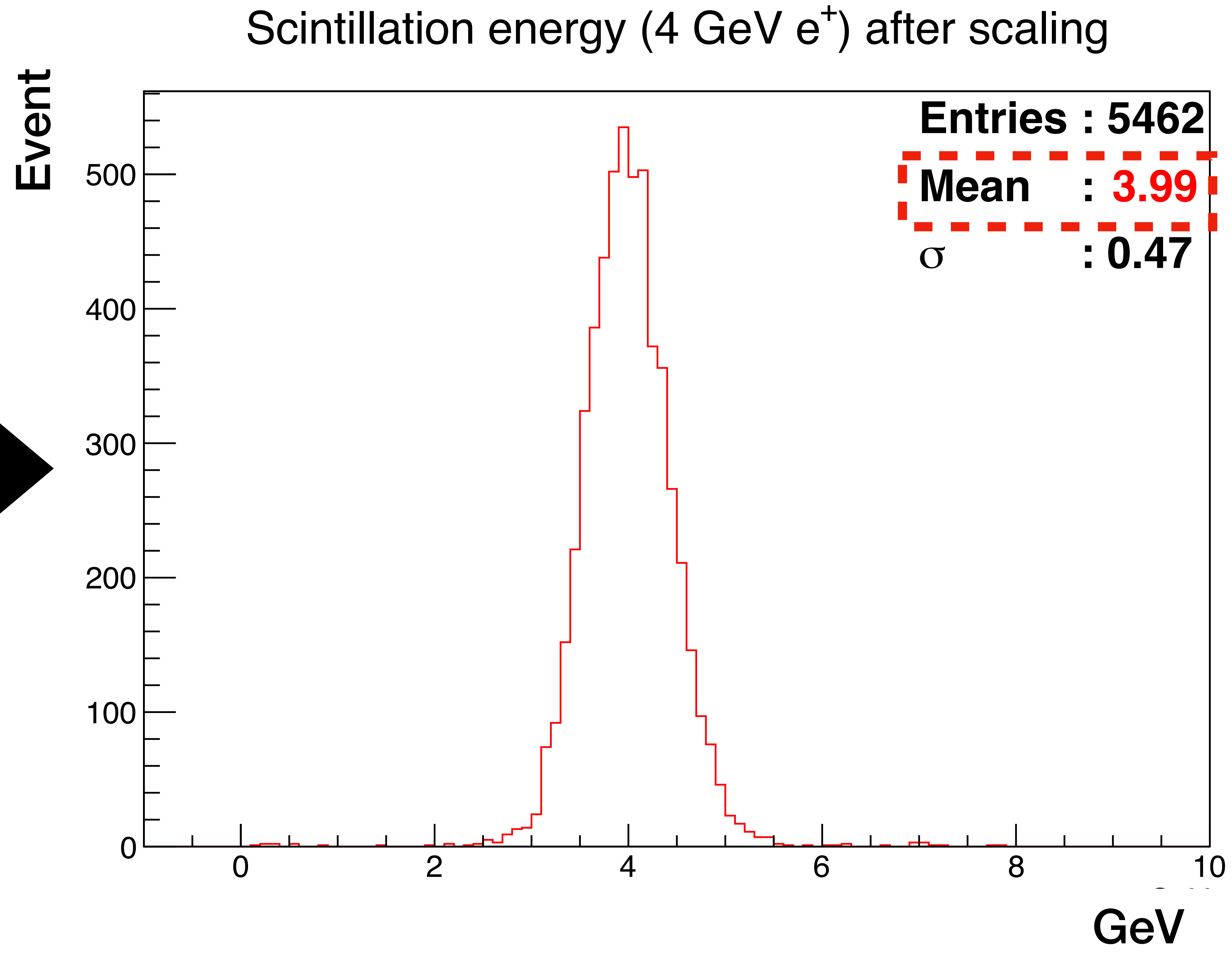
DRC calibration

- **Scale factor** applied to match the measured energy value to incident beam's energy
- Scale factor is calculated by dividing the beam energy with the energy measured with calibrated DRC
- $$Scale\ Factor \times \sum_{tower} (ADC\ count \times Calib.Const.) = Beam\ energy\ (4\ GeV)$$



Use 4 GeV e^+ beam entering the center of the 3D



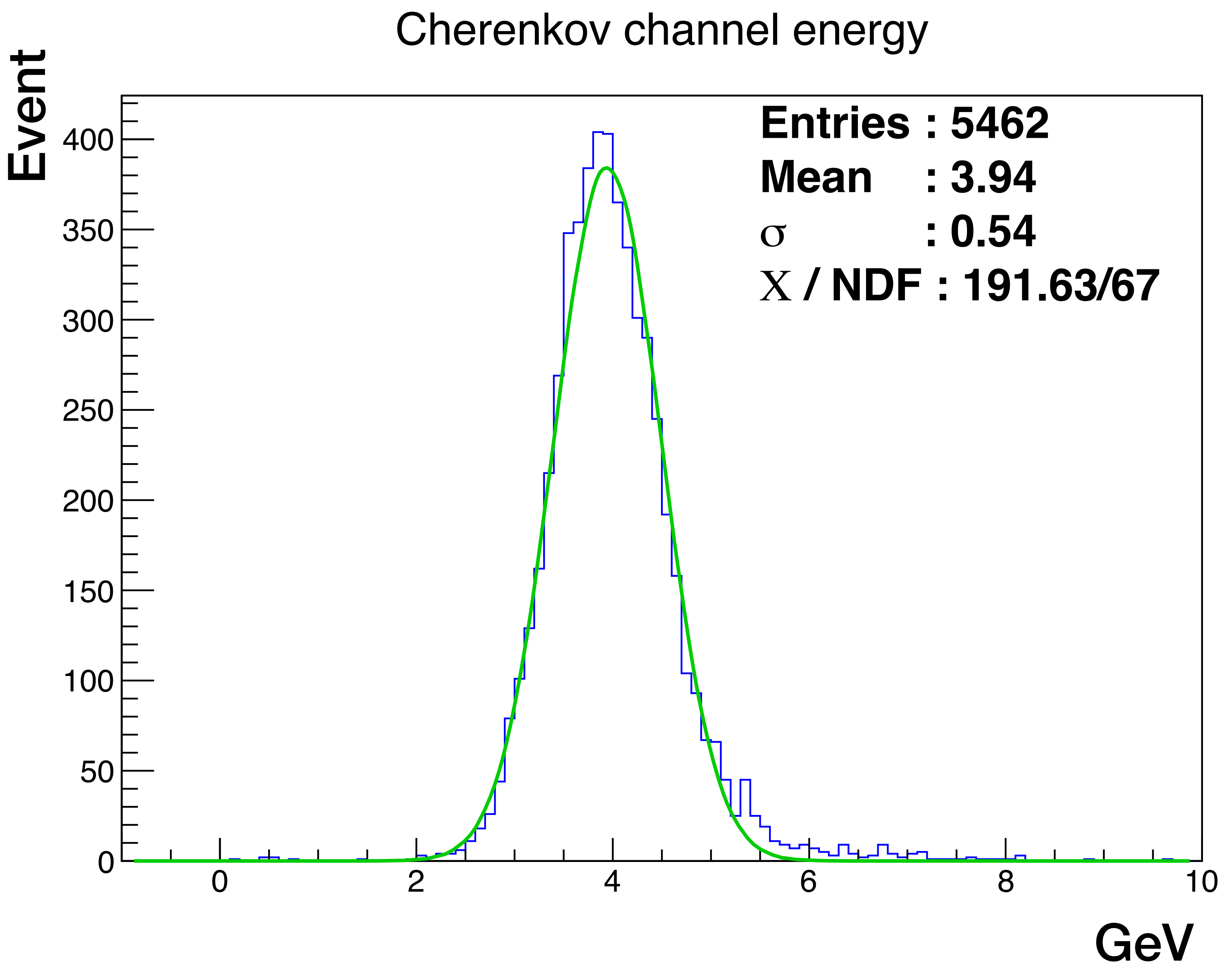


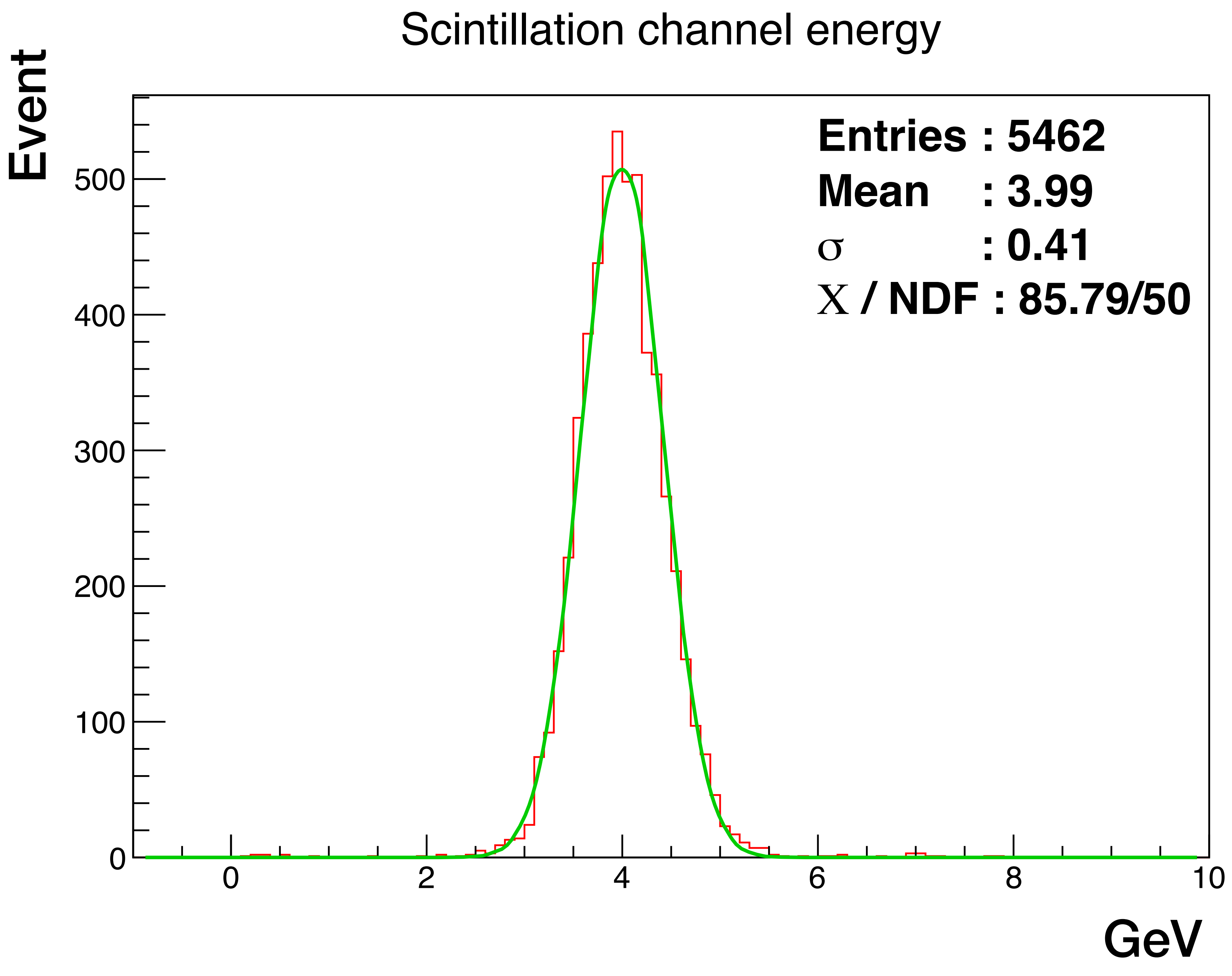
$$Scintillation\ channel\ Scale\ Factor = \frac{4}{4.52}$$

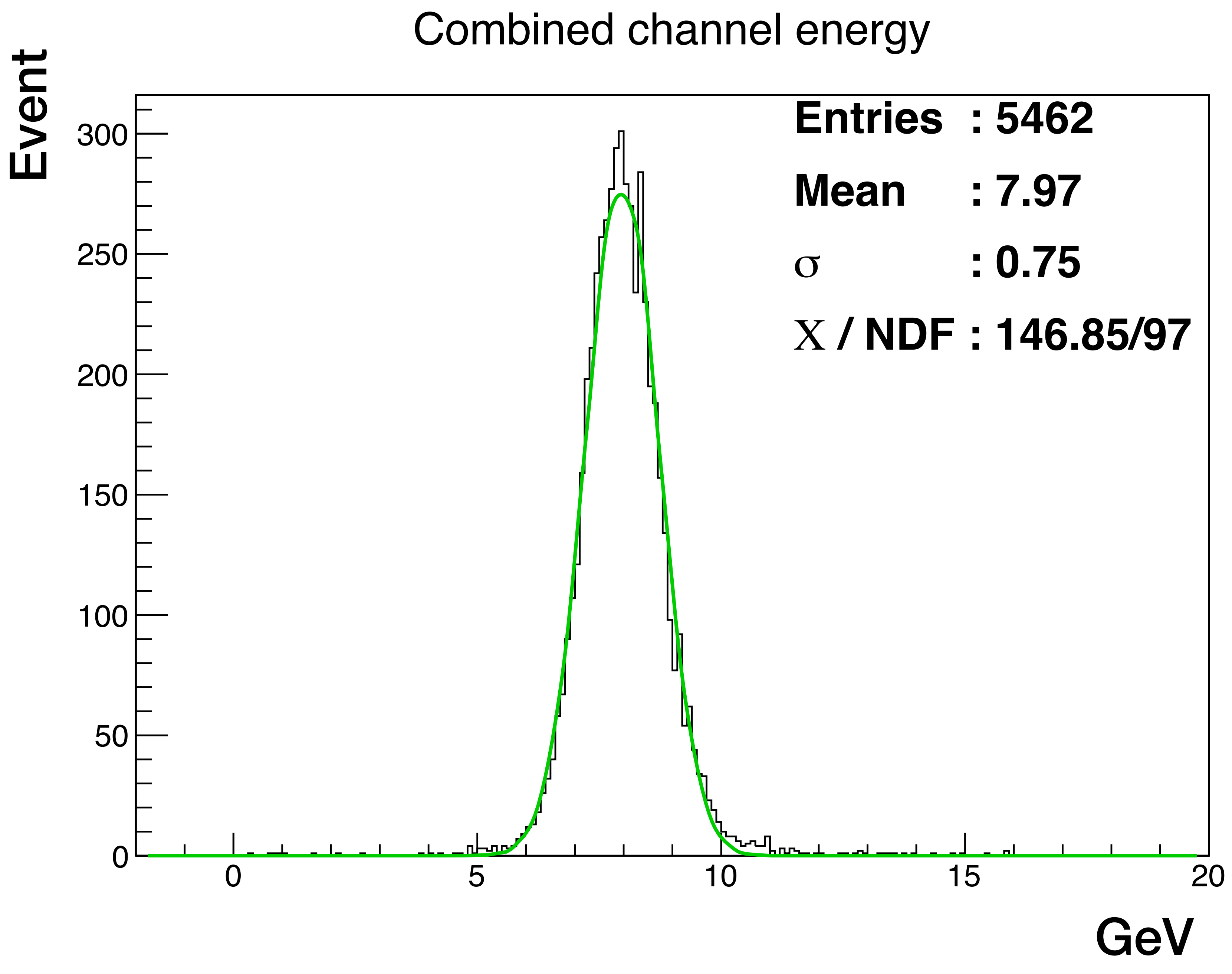
Energy measurement

- Using the calibrated DRC, the **energy** of e^+ beam can be **measured for C., S., Combined channel**
- **Combined channel** : **Sum** C. and S. channel energy **event-by-event**
- Measured e^+ beam with energy **1, 2, 3, 4, 5 GeV**
- Each distribution is fitted with Gaussian function to calculate the energy resolution and linearity

4 GeV e^+ beam energy measurement result with the DRC



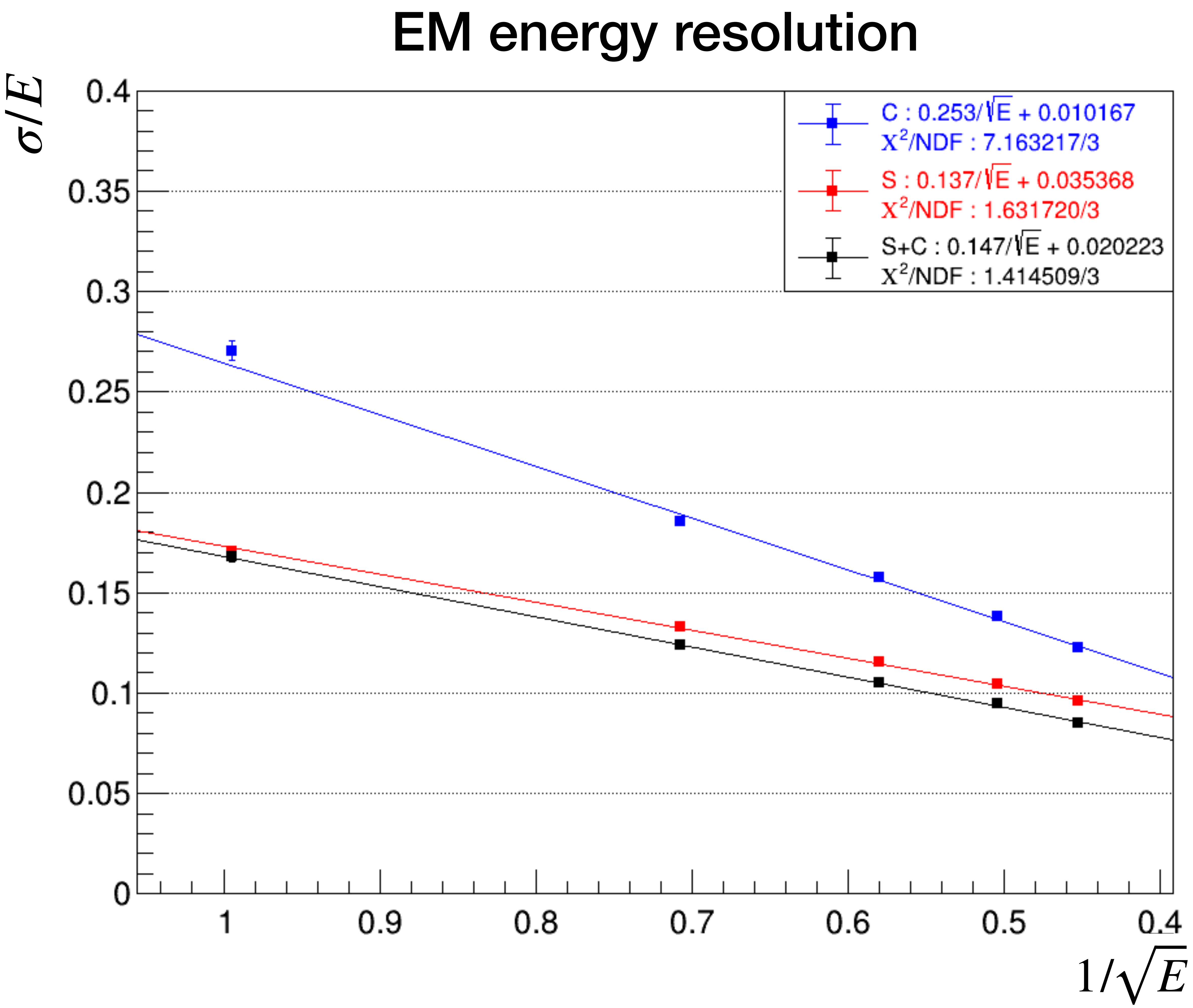


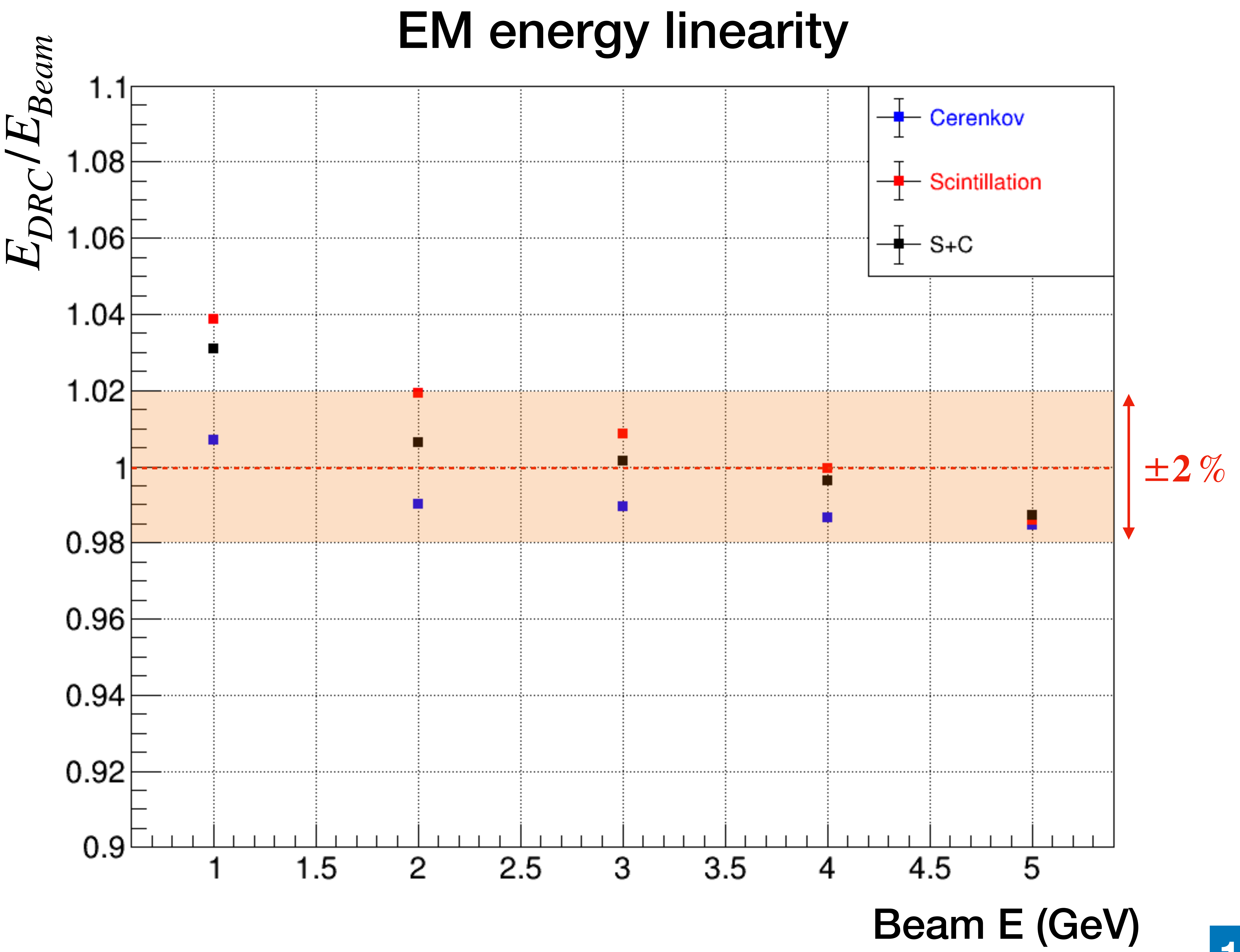


Result : EM energy resolution and linearity

- Result with e^+ beam with **momentum spread ±0.7%**
- **Stochastic** term of **25.3% (C)** , **13.7% (S)**, **14.7% (S+C)**
- **Linearity : ±1.1% (C)**, **±2.6% (S)**, **±2.2% (S+C)**

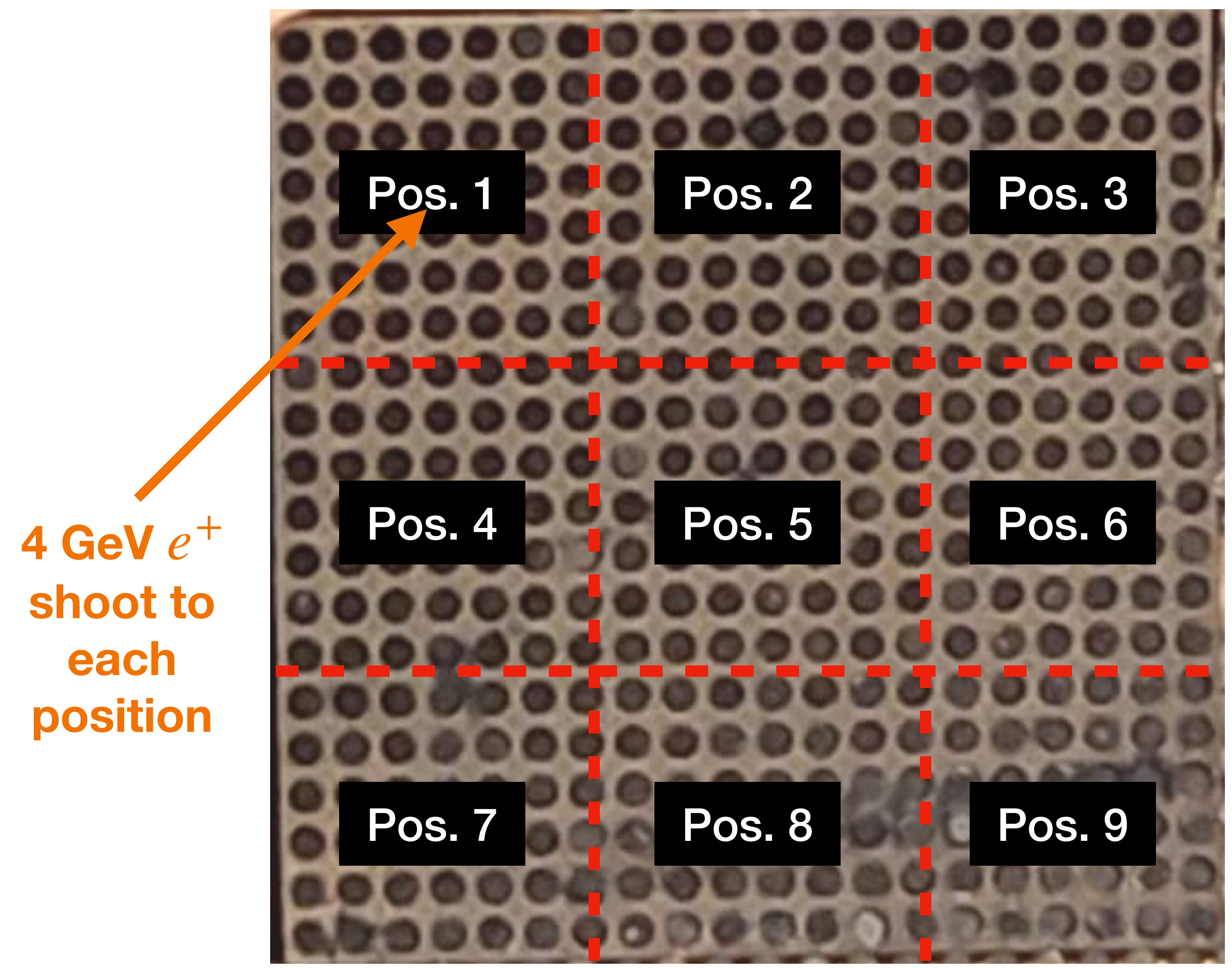
- DRC shows comparable energy resolution result with previous RD52 experiment (14 % stochastic term, ref) **even with ~5 % lateral shower leakage**



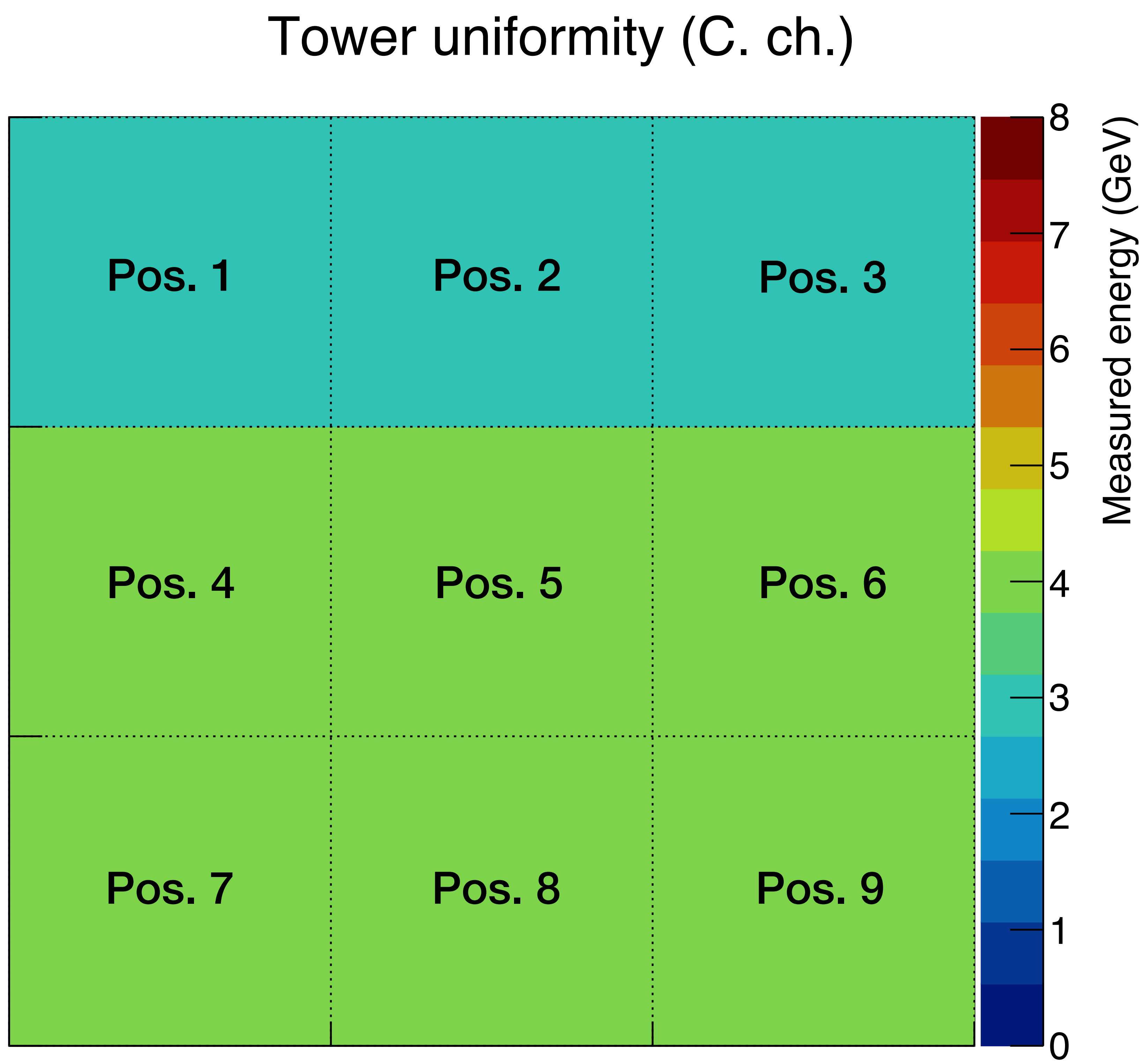


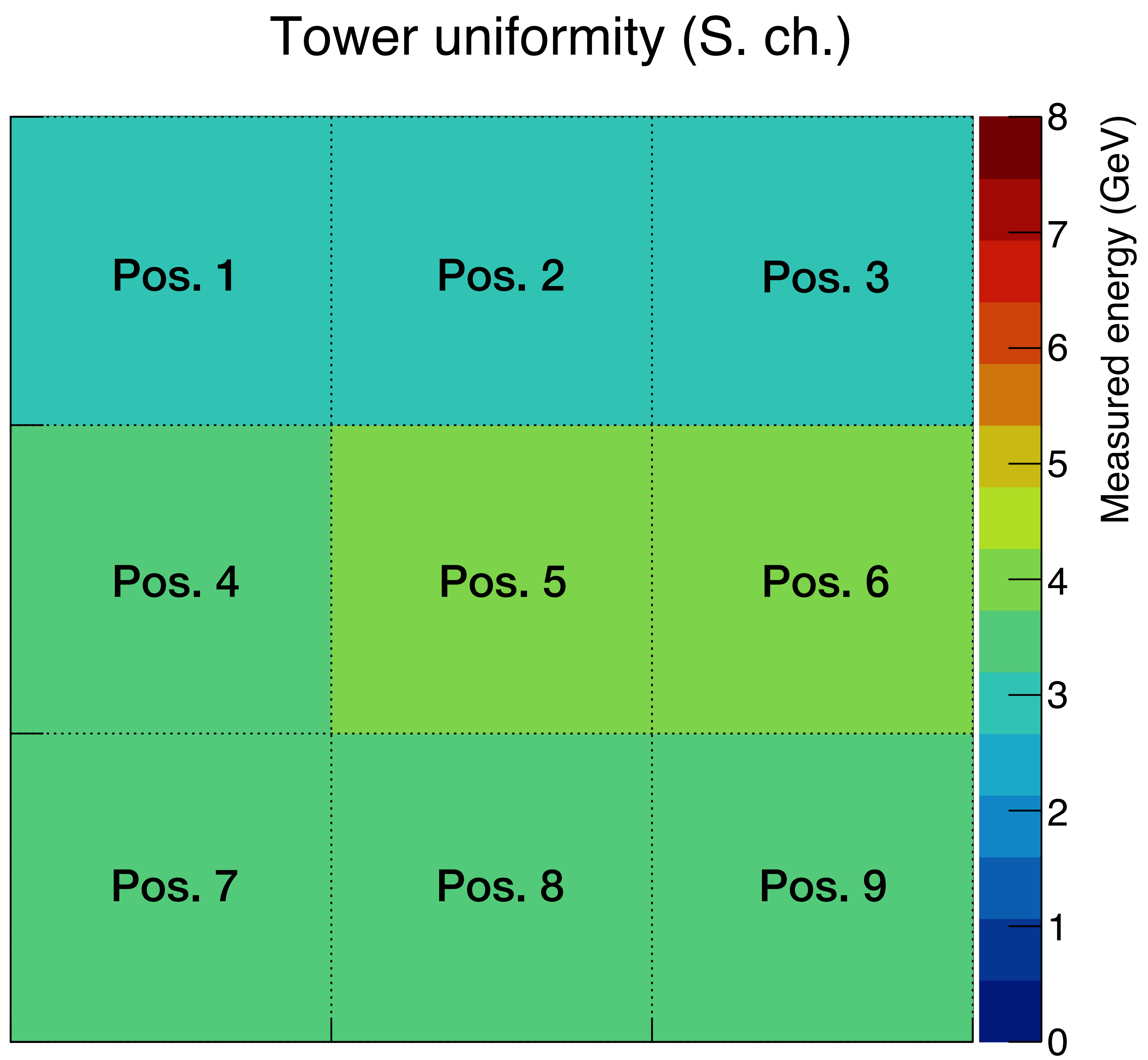
Result : Tower uniformity

- Checked **tower uniformity** for the **towers with projective geometry (3D tower, SFHS (top) tower)**
- 3D tower equally divided into **9 beam spot positions**
- Measured the energy of the 4 GeV e^+ beam shoot to each position of the 3D tower
- The DRC module shows **consistent energy response** regardless of the beam position in 3D tower



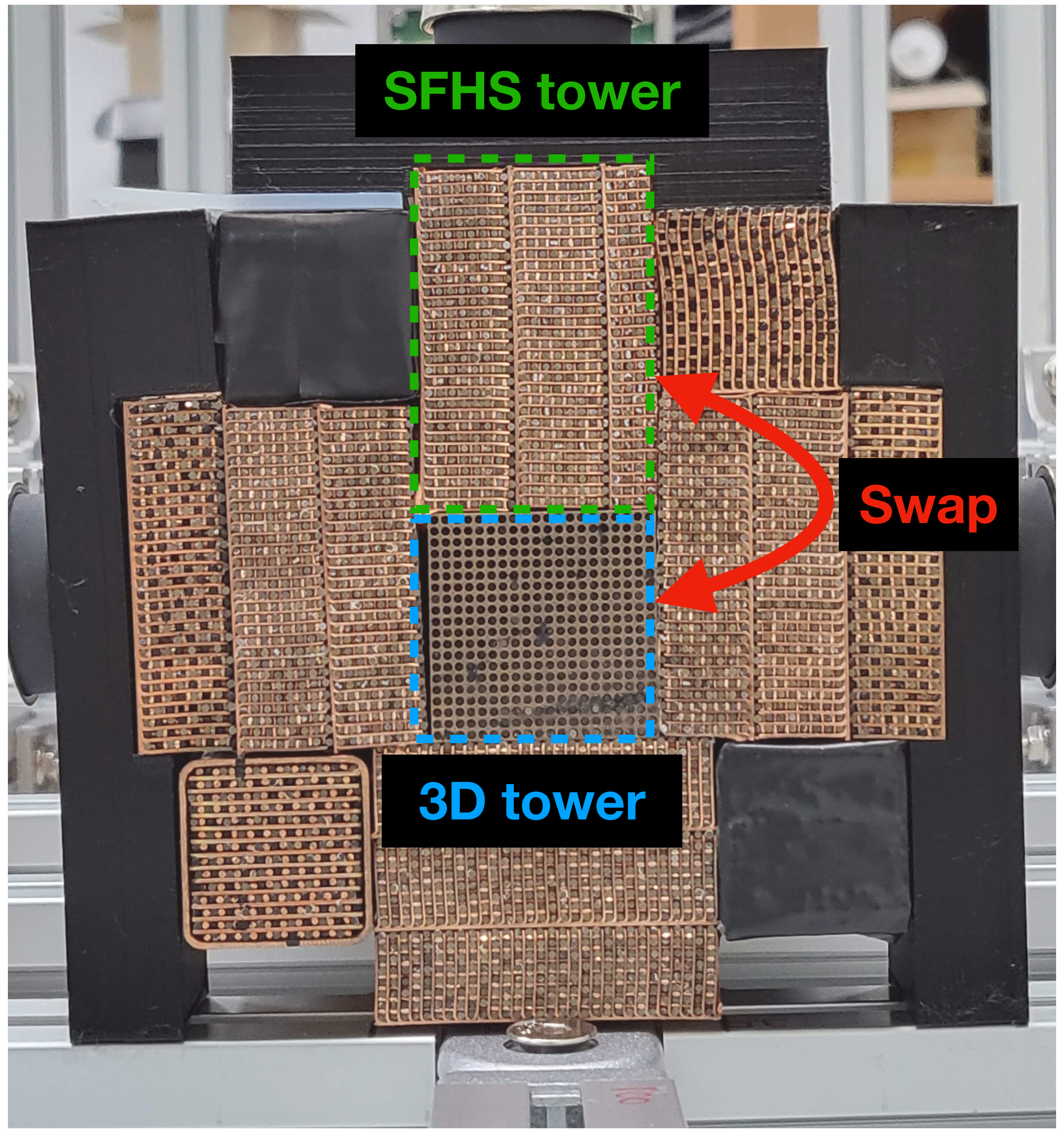
Beam spot positions of 3D tower (upstream view)



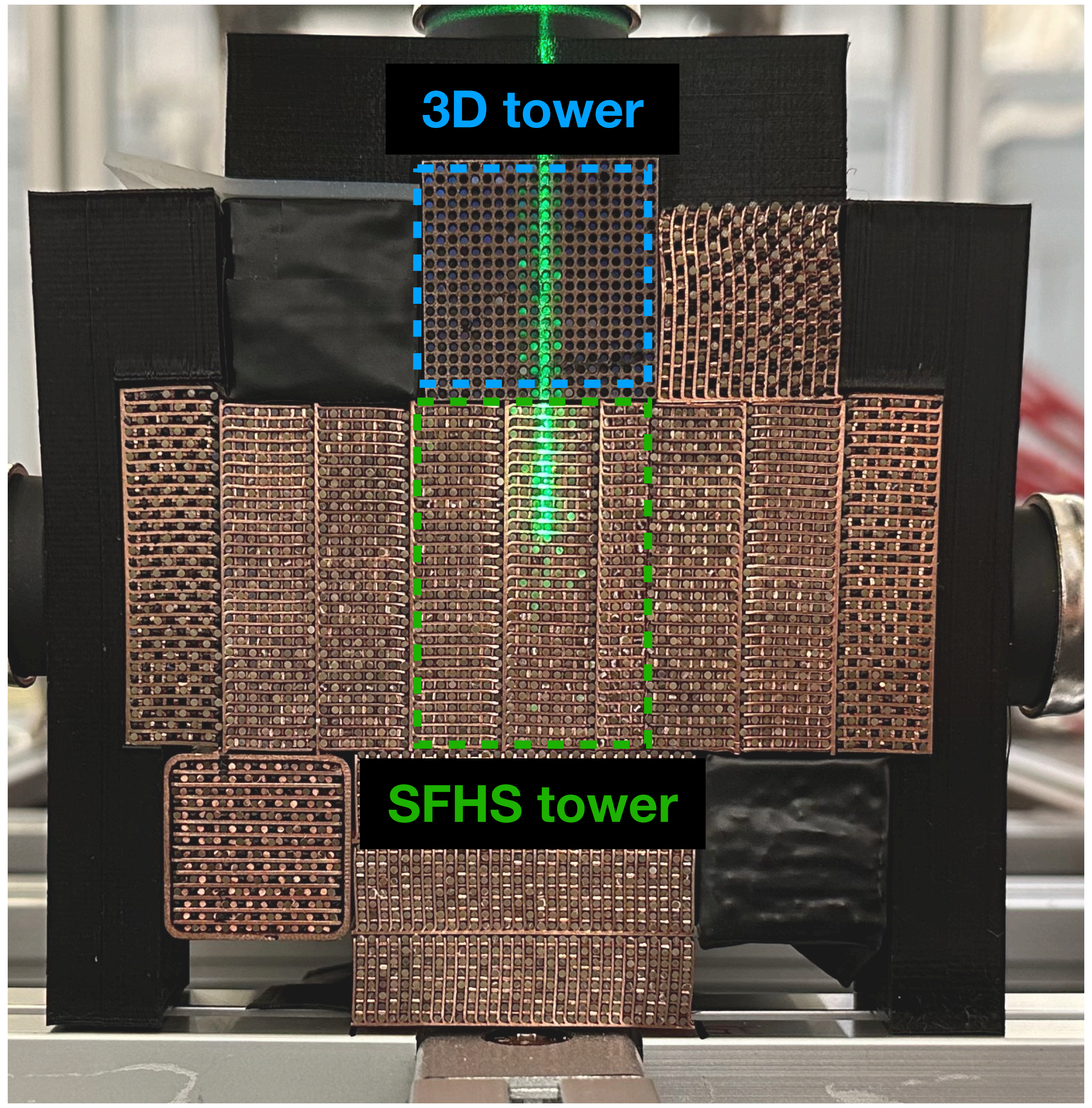


Result : Tower uniformity

- **Swapped 3D tower with SFHS** (top) tower, and checked the uniformity of the SFHS tower
- SFHS tower also divided into **9 beam spot positions**
- Measured the energy of the 4 GeV e^+ beam shoot to each position of the SFHS tower

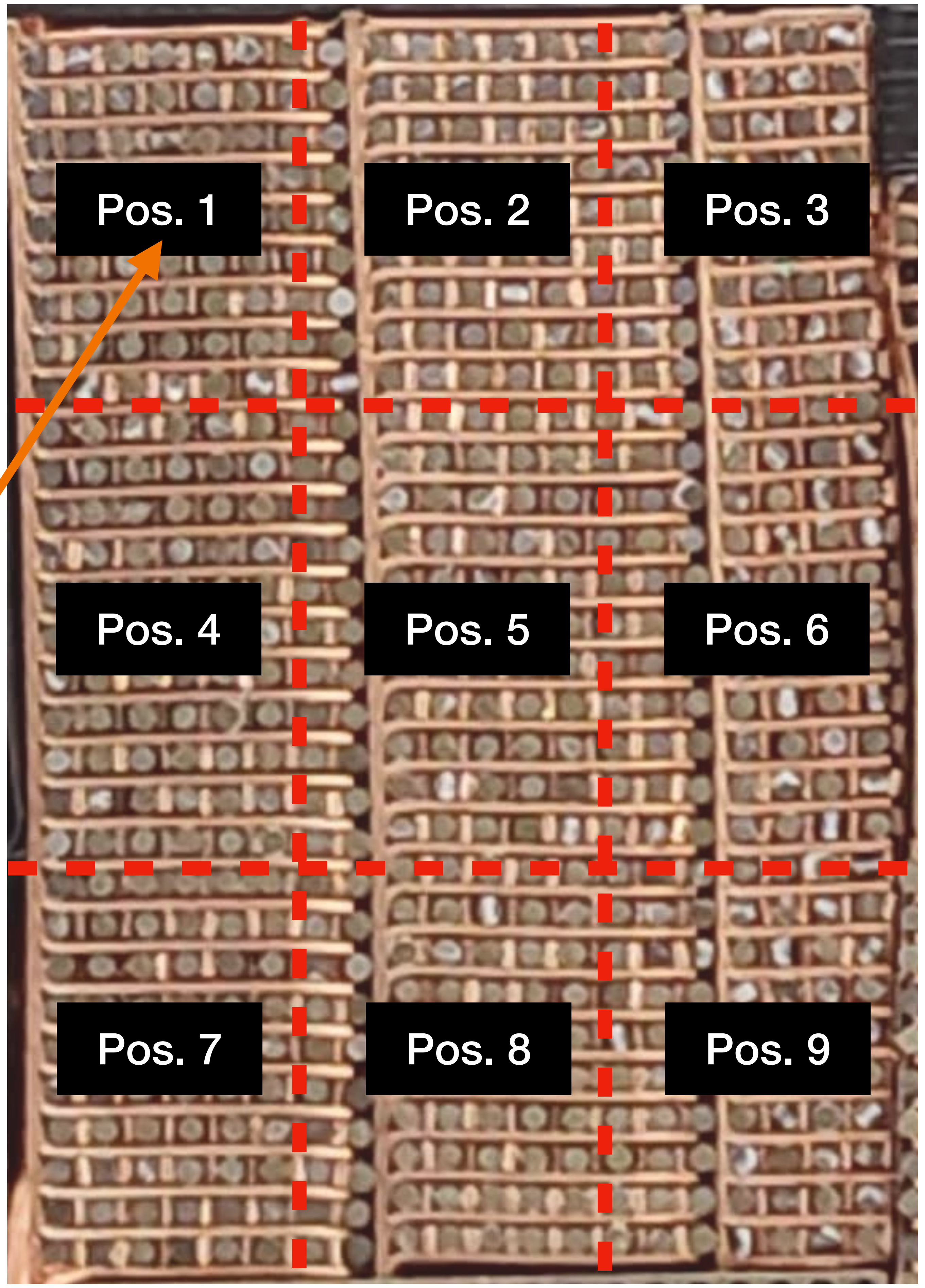


3D centered



SFHS centered

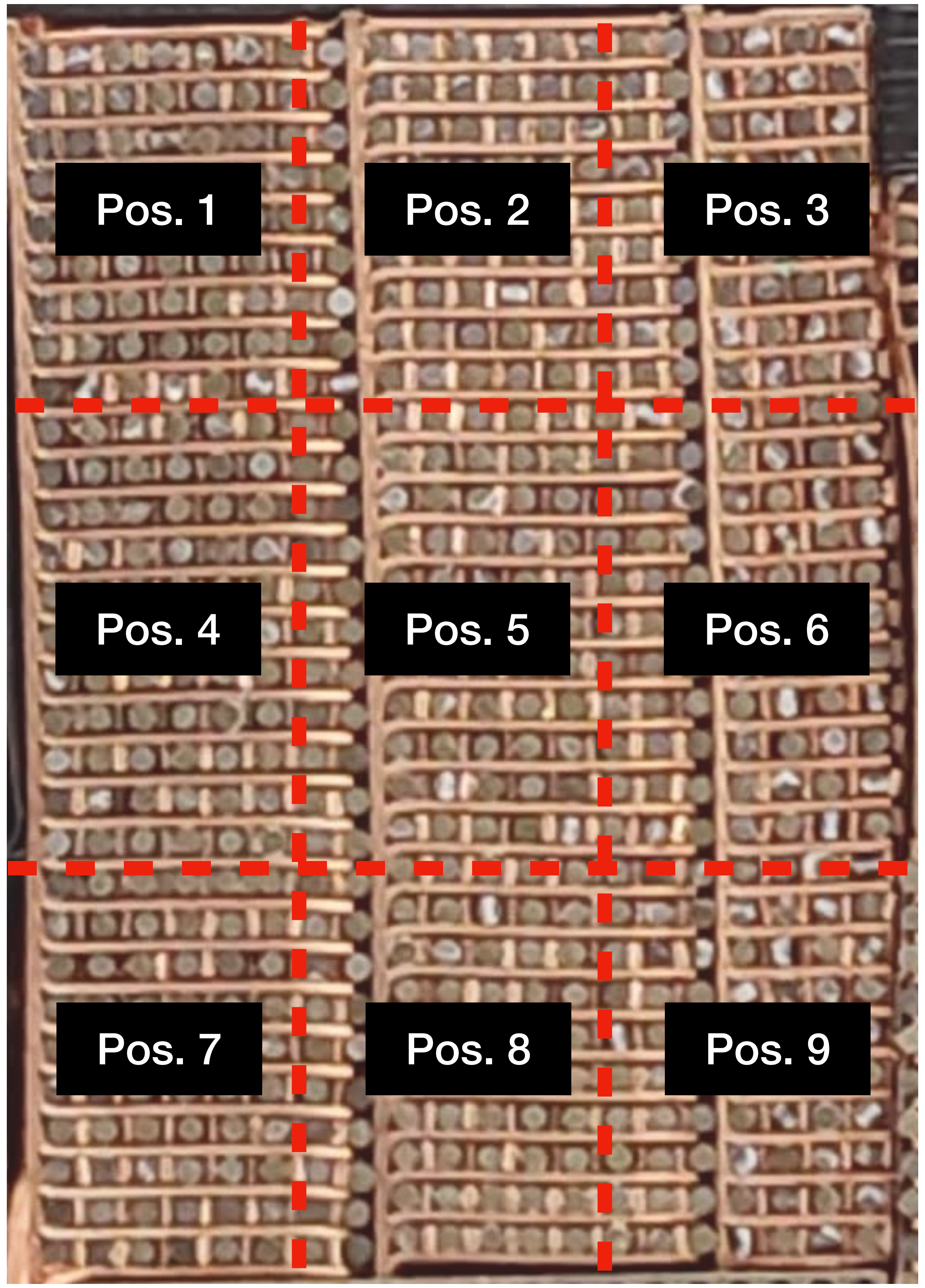
4 GeV e^+ shoot to each position



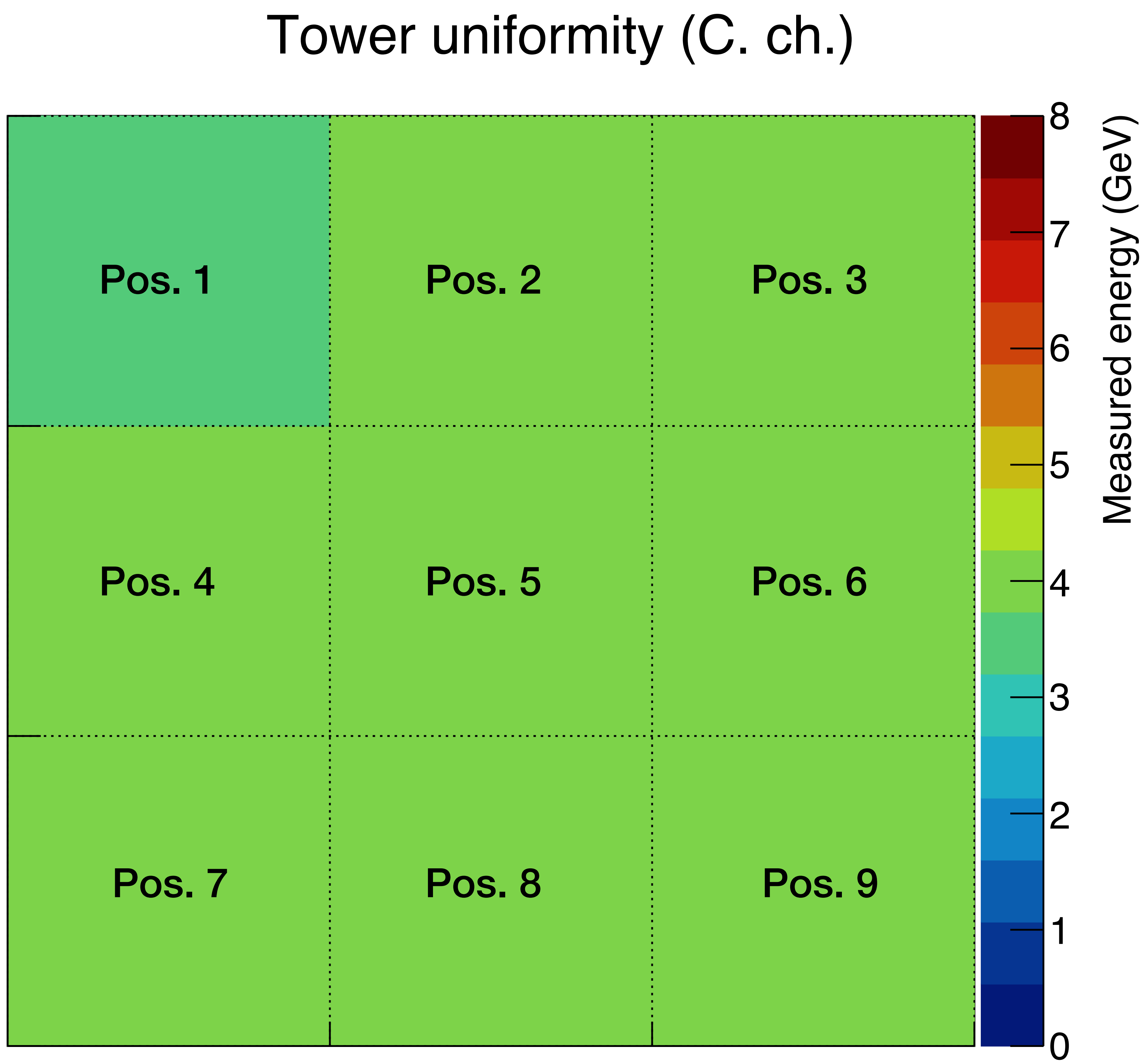
Beam spot positions of SFHS tower (upstream view)

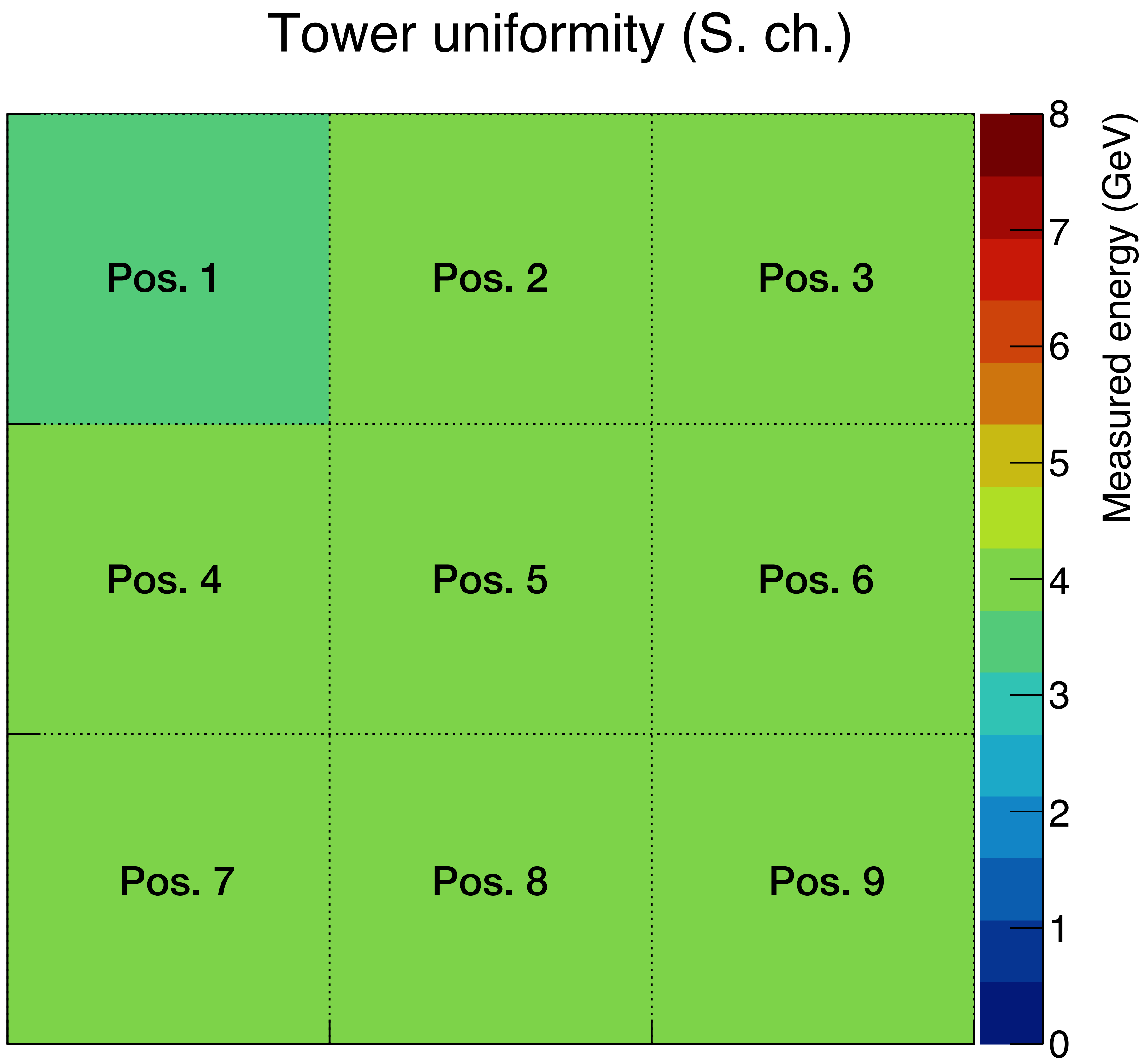
Result : Tower uniformity

- SFHS tower also divided into **9 beam spot positions**
- Measured the energy of the 4 GeV e^+ beam shoot to each position of the SFHS tower
- The DRC module shows **consistent energy response** regardless of the beam position in SFHS tower



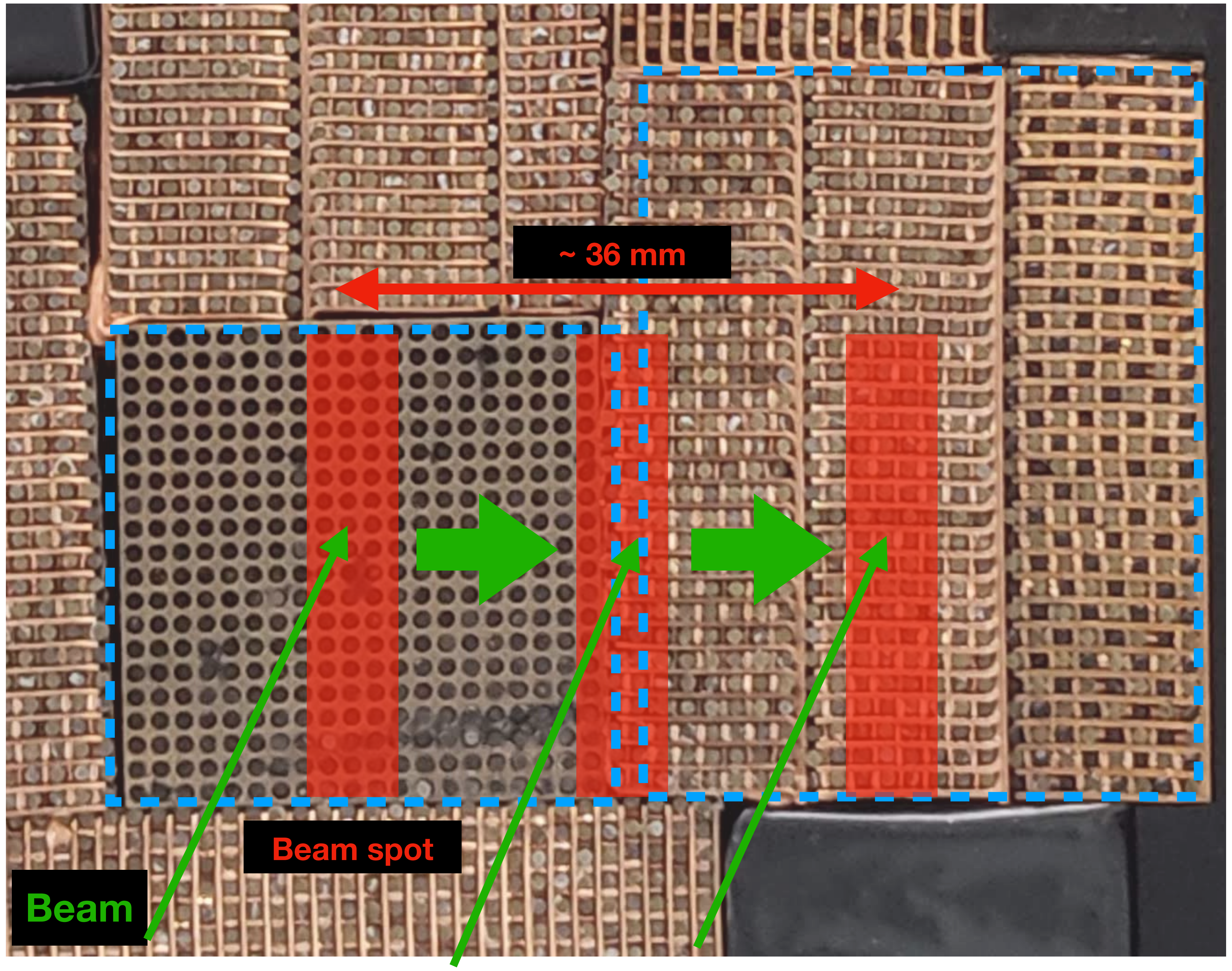
Beam spot positions of SFHS tower (upstream view)





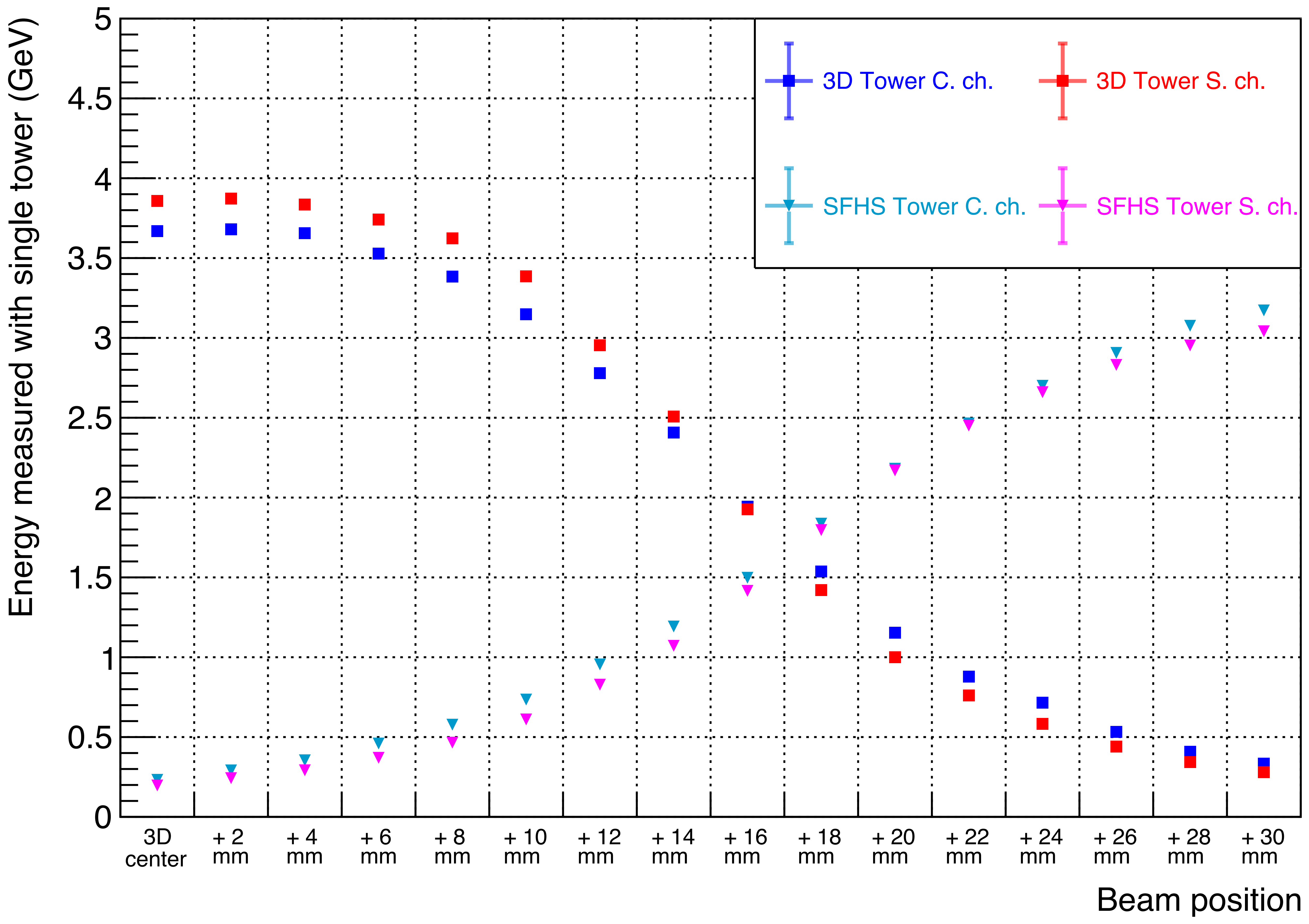
Result : Tower response change

- In 3D center setup, checked the **change in single tower's energy response** as the beam spot moves to its adjacent tower
- From center of the 3D tower, move the beam spot to center of the SFHS tower (right) with **2 mm interval (16 beam spot positions)**
- Check the energy measured with 3D tower and SFHS(right) tower per beam spot
- Even with the **projective geometry of the 3D tower,** tower response showed similar result with previous experiment with non-projective DRC



Moving the beam spot from 3D to SFHS(right) tower with 2 mm interval (upstream view)

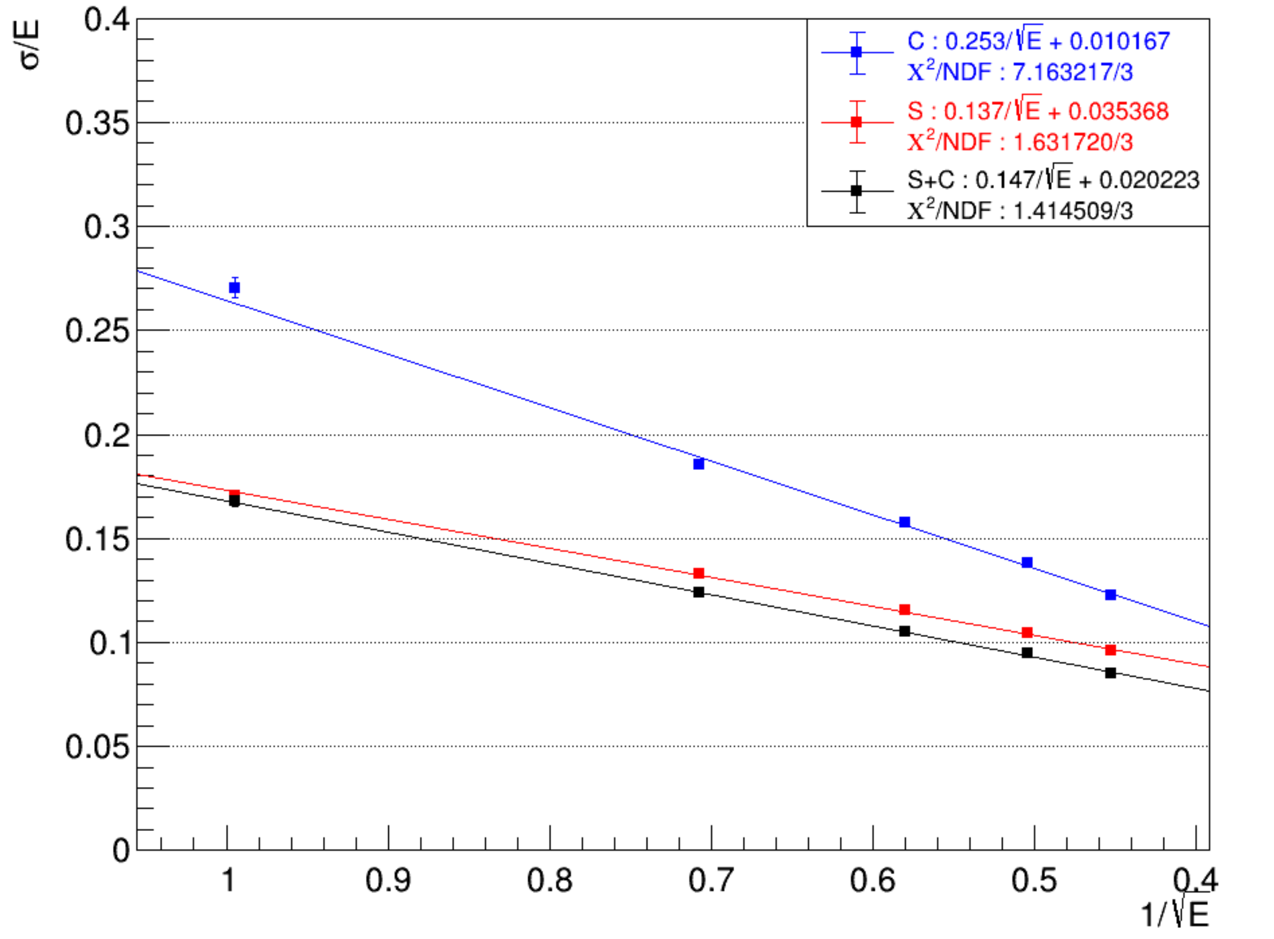
Tower response change



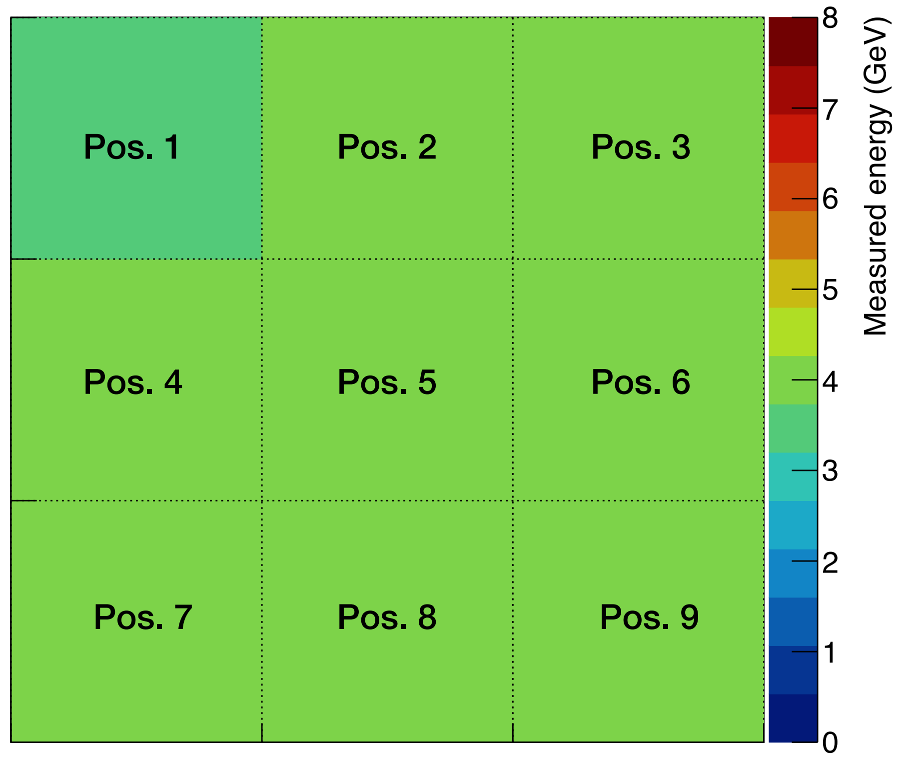
Summary

- Korea DRC collaboration had **test beam** (TB) in **2023** with 50cm **DRC** module at CERN east area **T9**
- **First TB result** using **low energy** (1~5 GeV) EM particles, and with the DRC with **projective geometry**
- The DRC combined channel showed energy resolution of $\frac{14.7\%}{\sqrt{E}} \oplus 2\%$, **which is very promising !**
- The towers with **projective geometry** (3D and top SFHS) showed **uniform structure**
- The construction of the DRC and the data taking at the TB were all conducted by the **graduate students of Korea DRC collaboration**, and we're all **very proud to see these results !**
- Still some analysis items ongoing (MCP-PMT micro channel calibration, timing resolution study etc...), and will be updated

Energy resolution (Set 4, EvtPed)



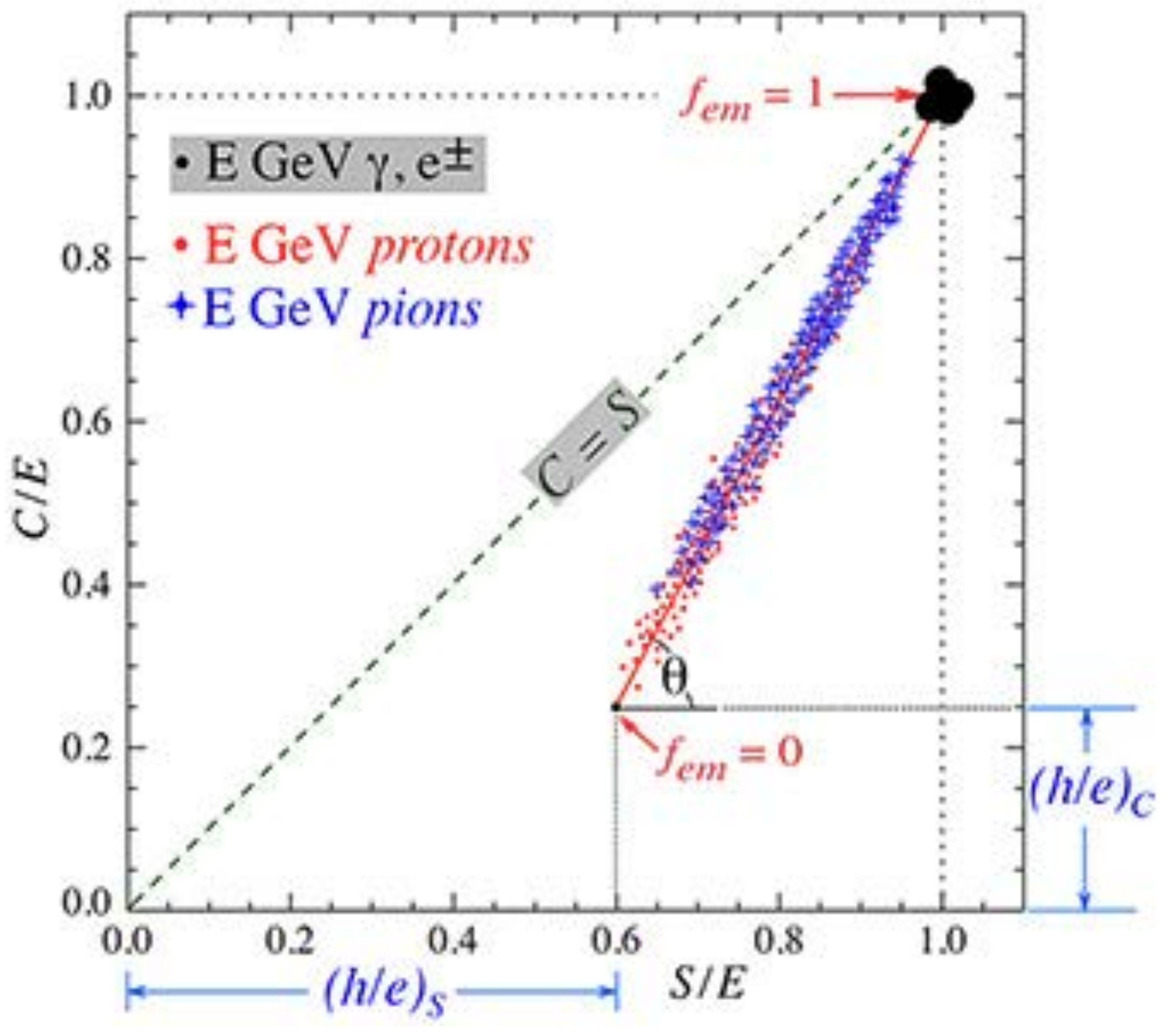
Tower uniformity (S. ch.)

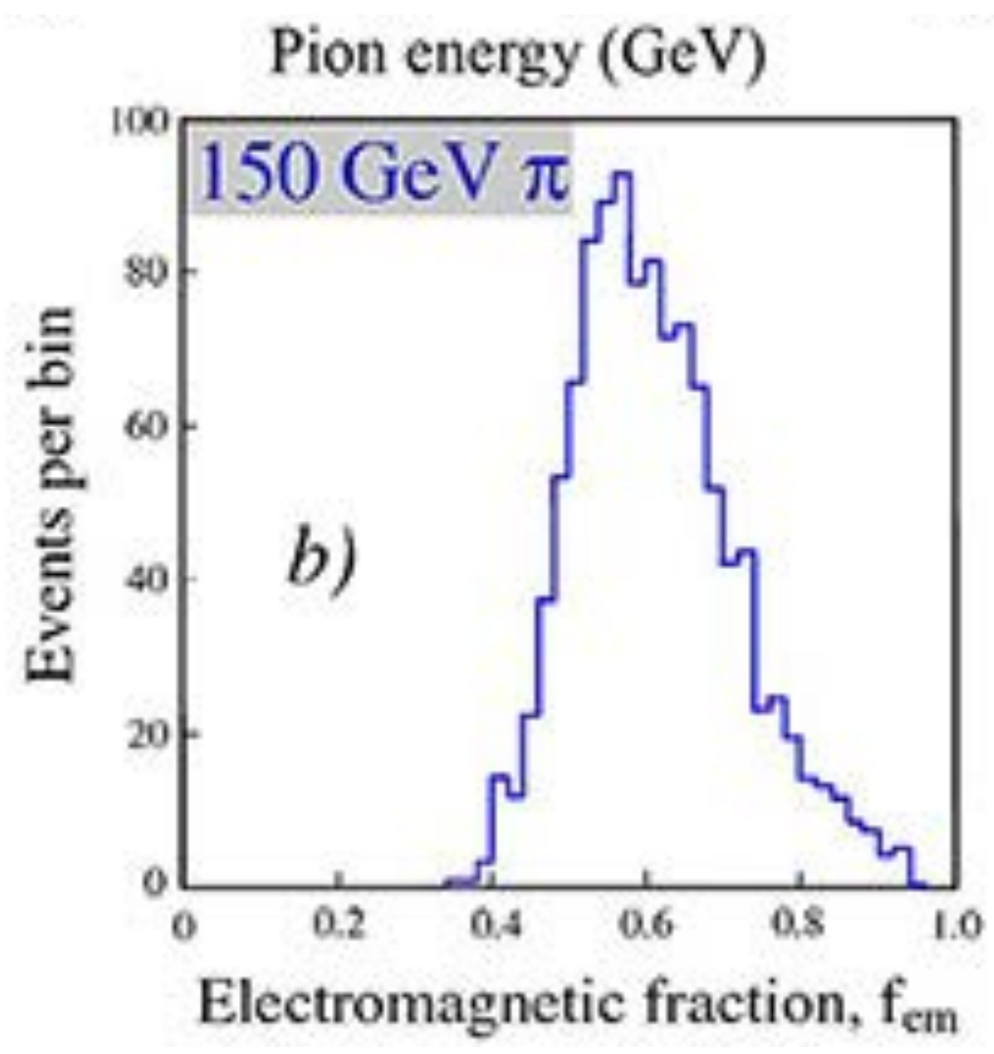


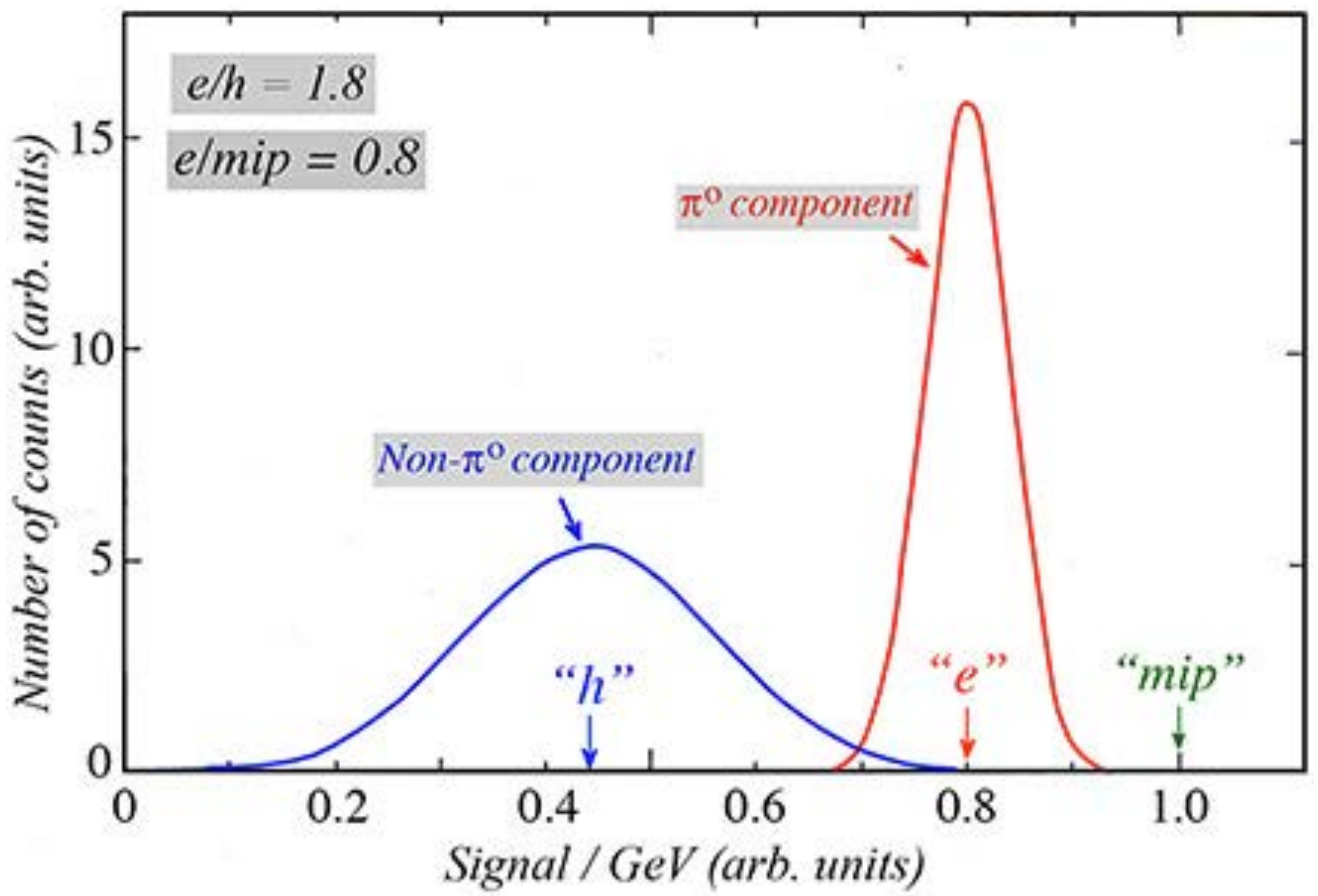
Backup

Dual-readout calorimeter

- **Non-gaussian fluctuation** of fraction of EM shower component (f_{em}) makes it hard to measure E of hadronic showers
- **Cherenkov signal** : Respond only to EM component in practice
  - e^+e^- relativistic down to ~200 KeV
  - Most of non-em energy in hadron showers is deposited by non-relativistic proton
- Can determine f_{em} knowing relative signal strength of C ch
- By knowing f_{em}, can determine both em and non-em energy by using e/h of both S, C channel







$$S = E\left[f_{em} + \frac{1}{(e/h)_S}(1 - f_{em})\right]$$

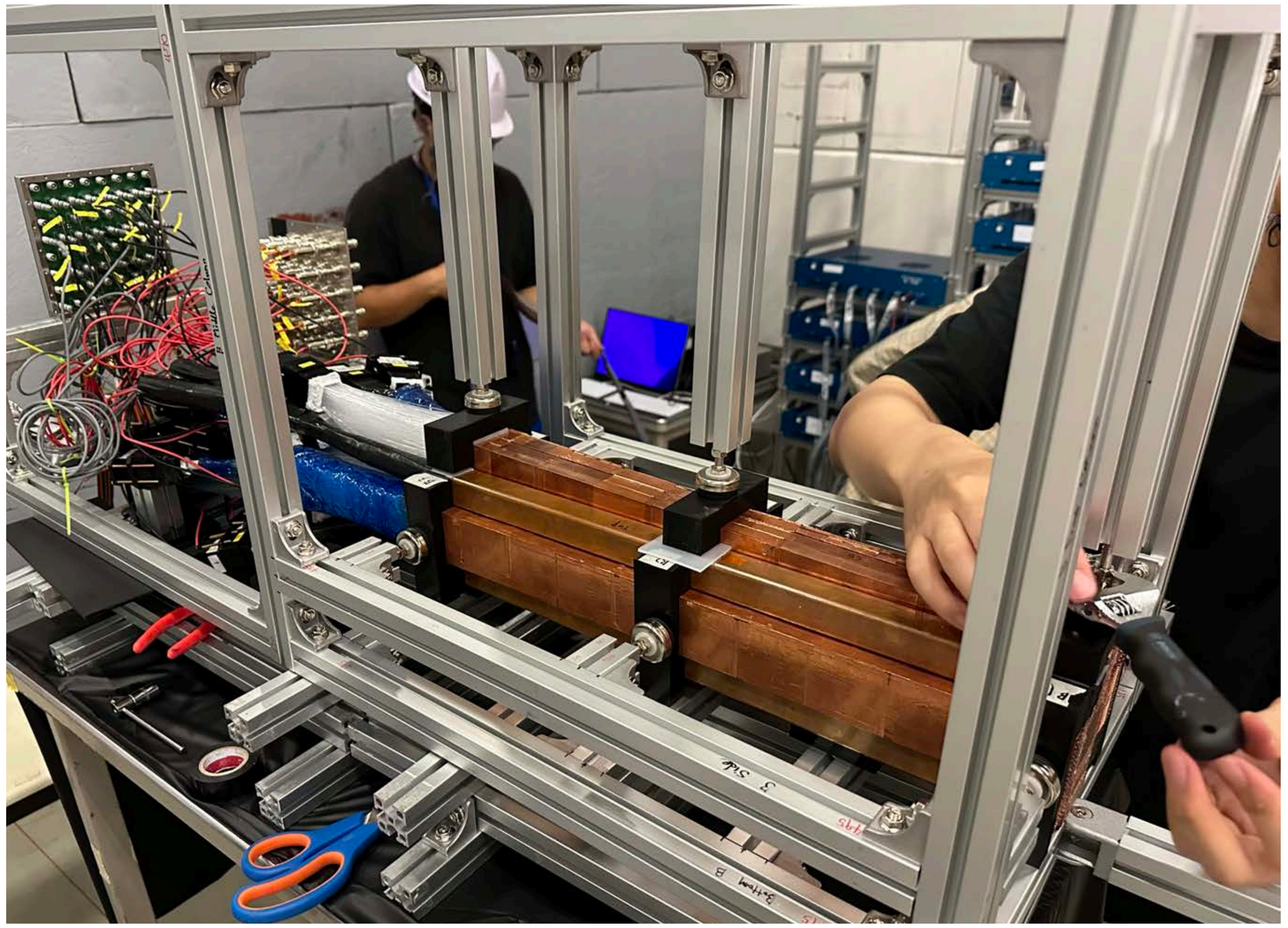
$$C = E\left[f_{em} + \frac{1}{(e/h)_C}(1 - f_{em})\right]$$

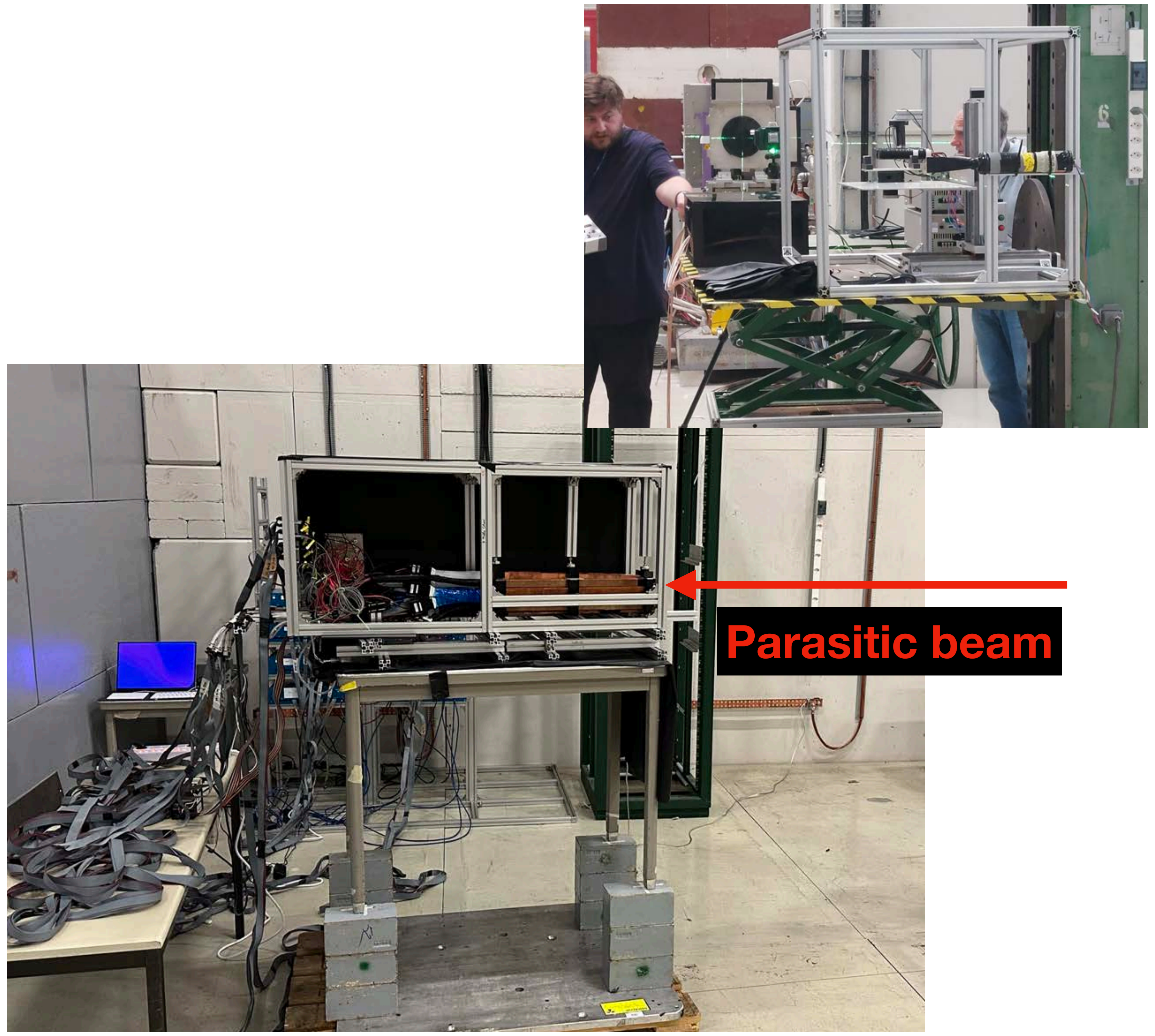
$$S/E = (h/e)_S + f_{em}\left[1 - (h/e)_S\right]$$

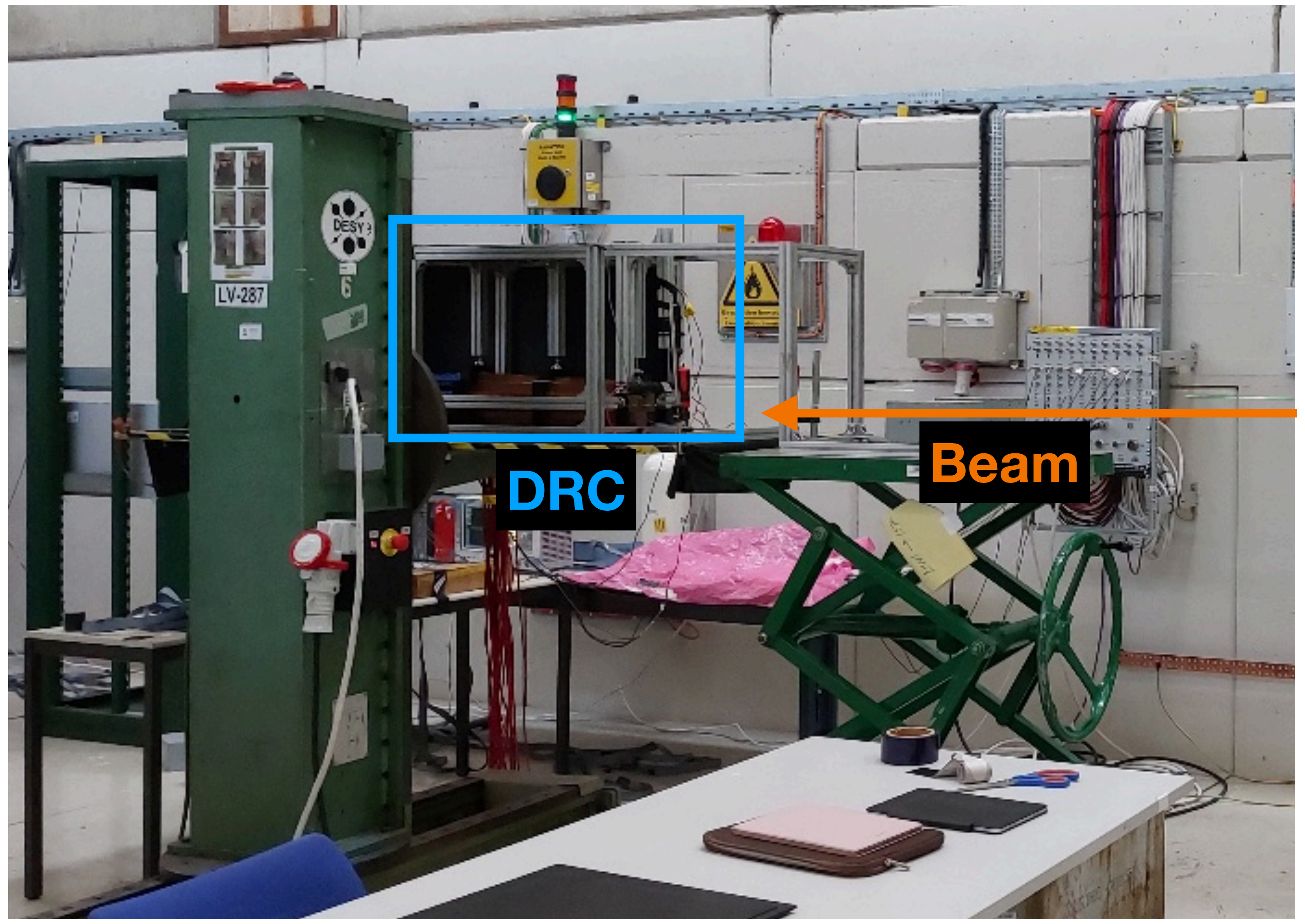
$$C/E = (h/e)_C + f_{em}\left[1 - (h/e)_C\right]$$

Test beam schedule

- Test beam consists of **3 phases**
  - Jun 27th ~ Jun 30th : Detector, DAQ installation and commissioning
  - Jul 1st ~ Jul 4th : Parasitic beam test, shifter training and HW, SW debugging
  - Jul 5th ~ Jul 12th : **TB with 50 cm DRC module**, total 3 setups & 2 additional programs proceeded
- Total **3 different DRC detector setup** was used for the TB
- Beam with various energy & particle type was used for the TB

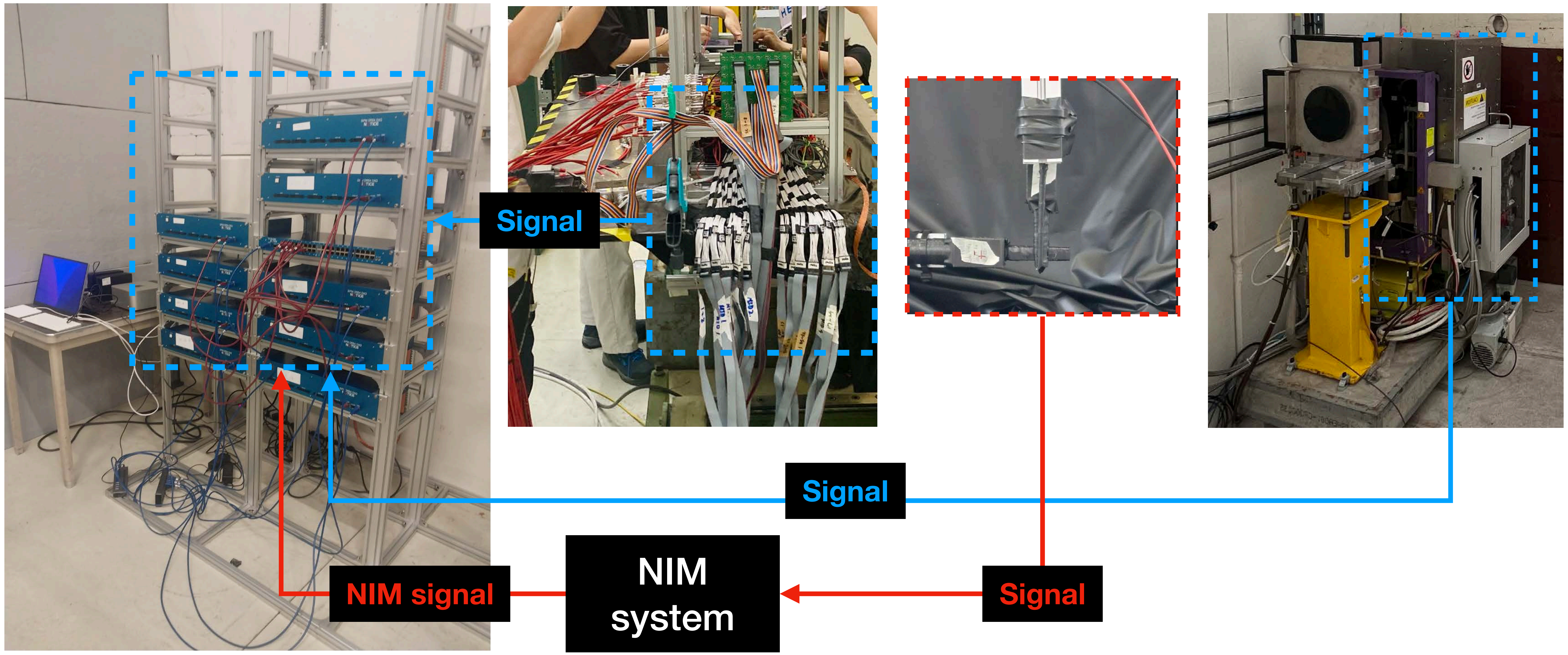


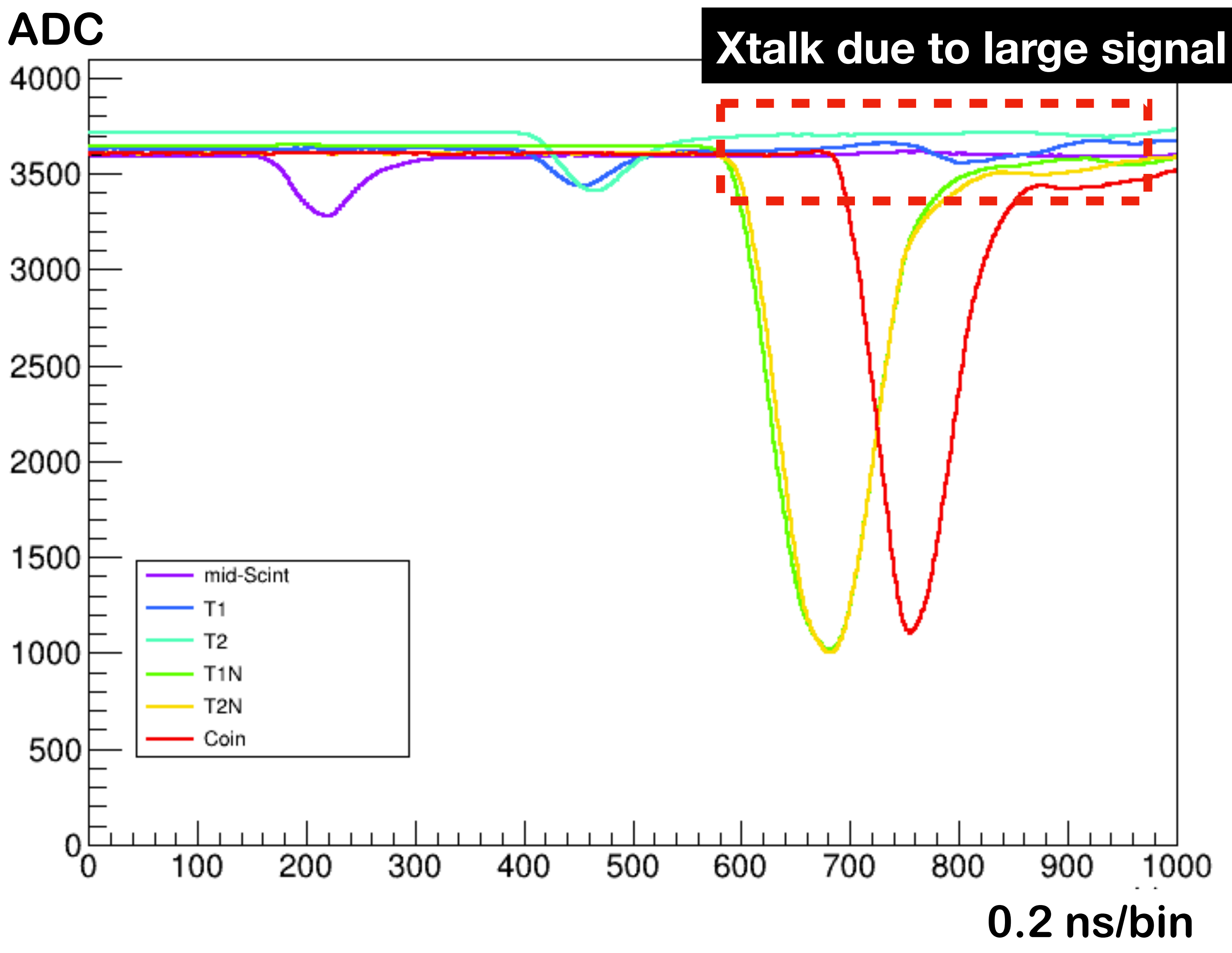


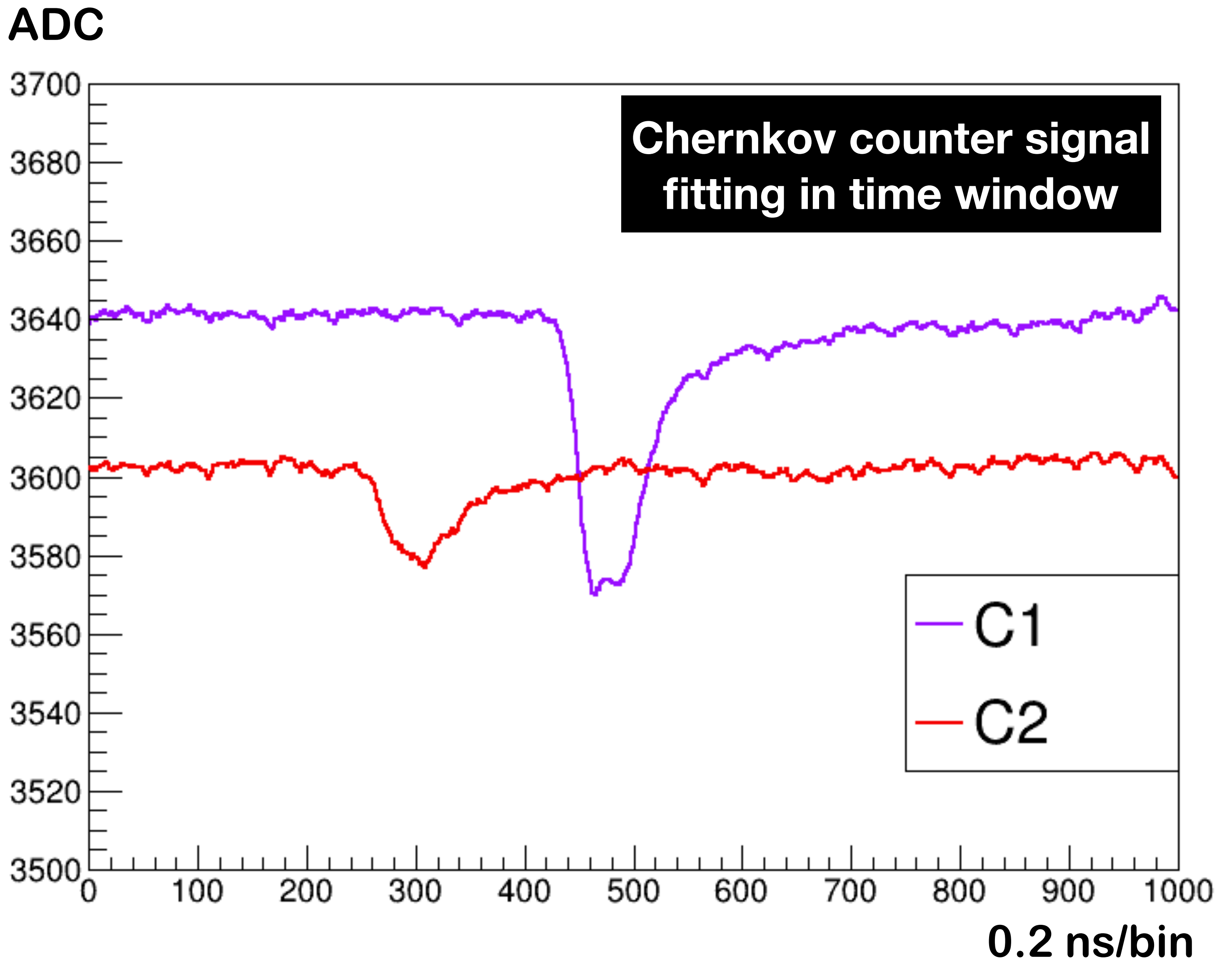


Data Acquisition (DAQ) System

- **DAQ :** When received trigger signal**,** it records detector signals, **digitize** them & **store** it on DAQ PC
- Data flow
  - DRC, C. counter readouts → DAQ system → DAQ PC
  - Trigger readouts → NIM system → DAQ system → DAQ PC
- To **avoid crosstalk** between detector signals, managed signal timing by using different length of cables
- To fit Cherenkov counter signals to our **DAQ time window,** used different time delay for C. counter channels

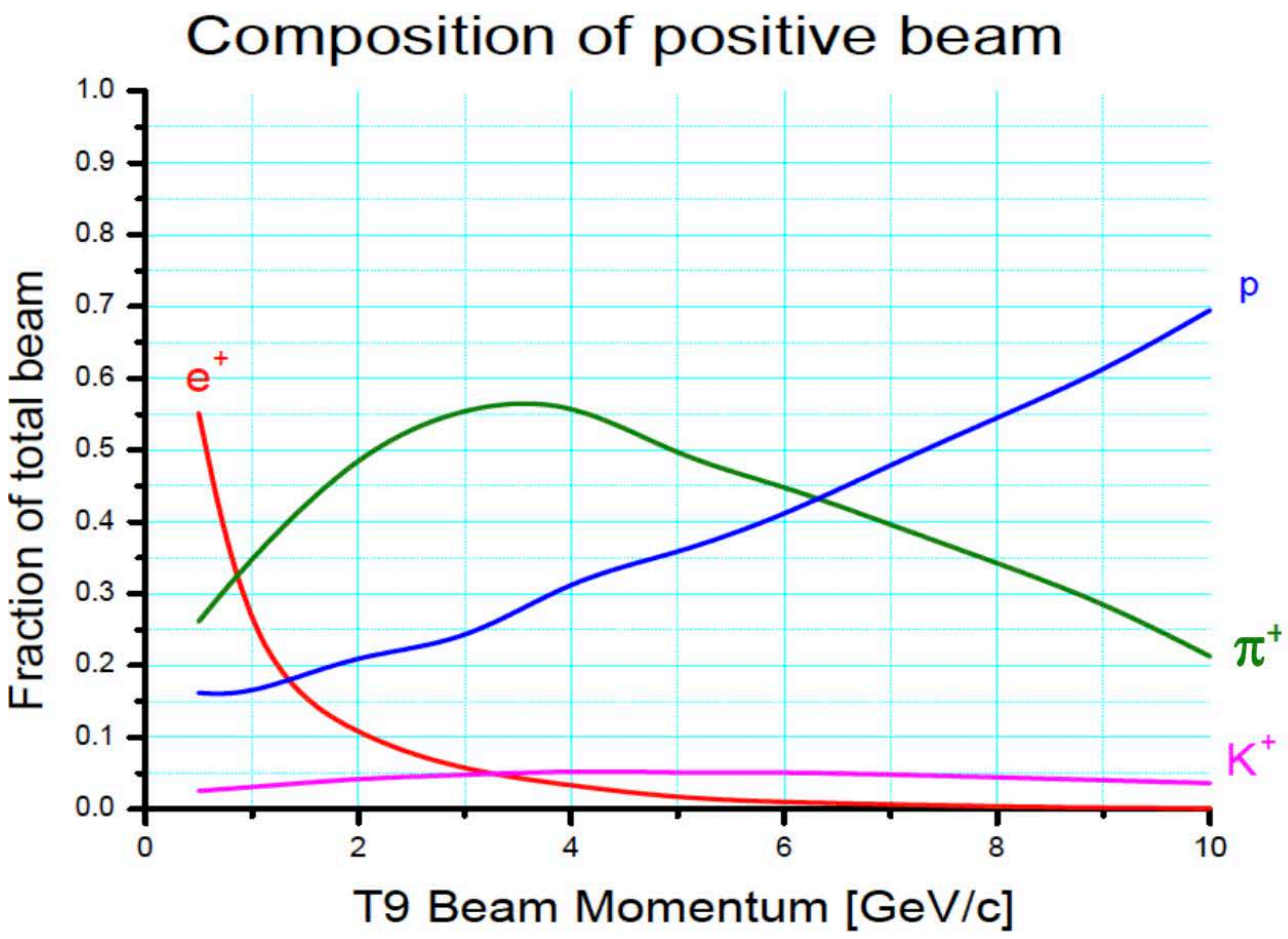


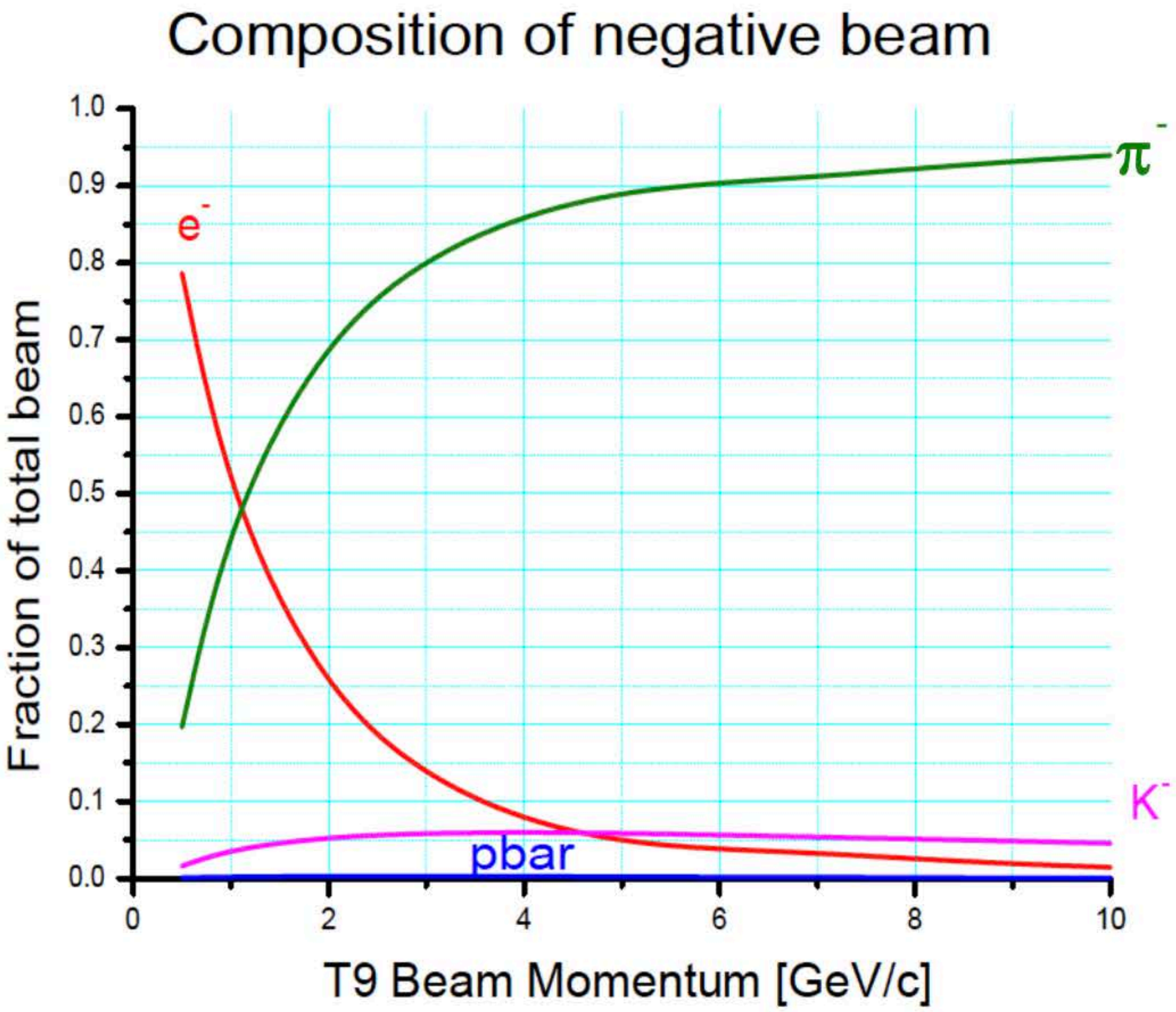




T9 beam spec

Reference Link





Characteristics of the Secondary Beams

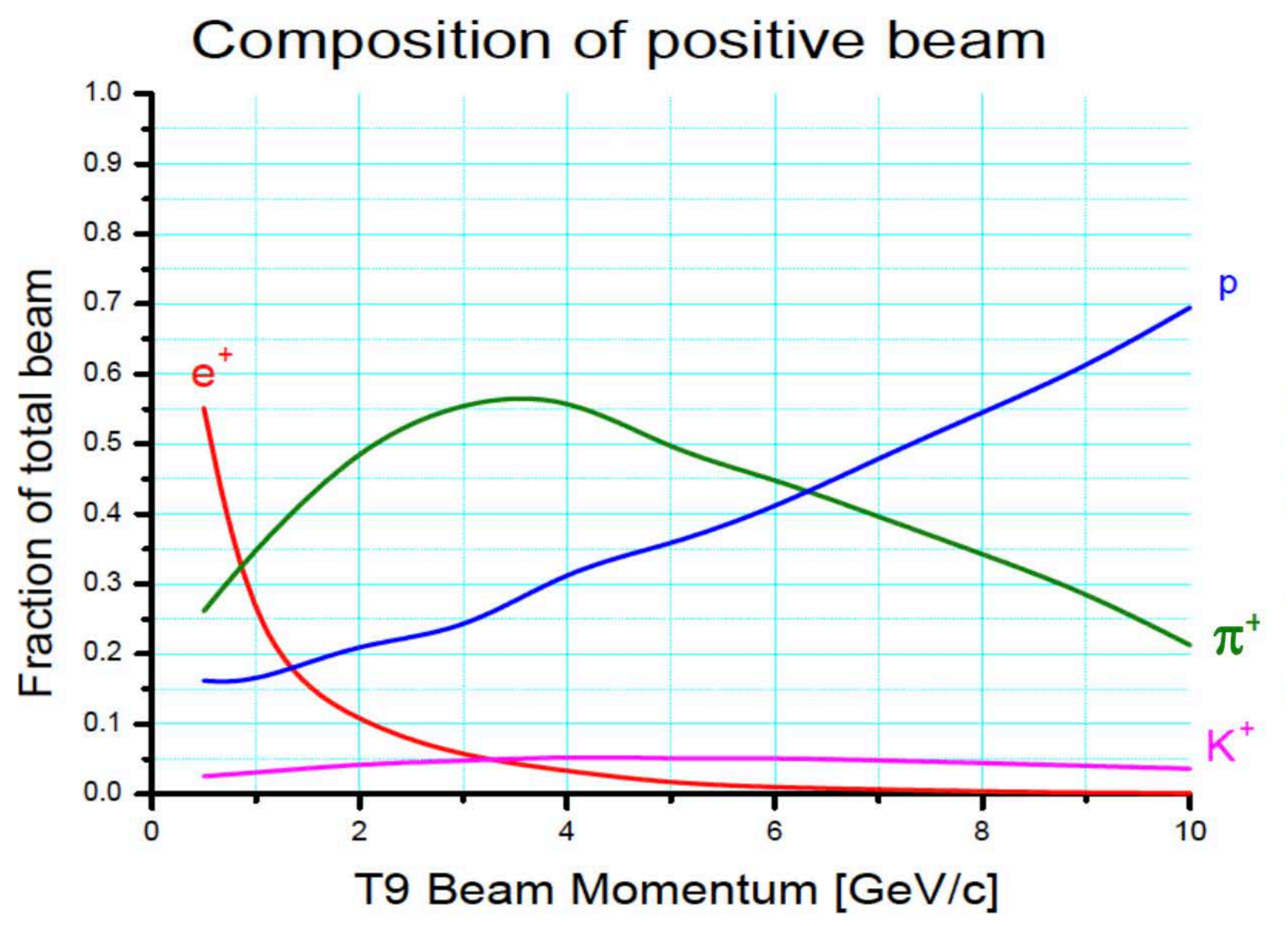
Parameter	T09 Target	T10/T11 Target	
Beam Line	T09	T10	T11
Secondary beam Max Momentum (GeV/c)	15	11.5	3.5
Δp/p (%)	±0.7 to ±15.0	±0.7 to ±15.0	±0.7 to ±15.0
Maximum intensity/spill (hadrons/electrons)	~10^6	~10^6	~10^6
Available particle types	Pure electrons (T09) or mixed/pure hadrons or pure muons		

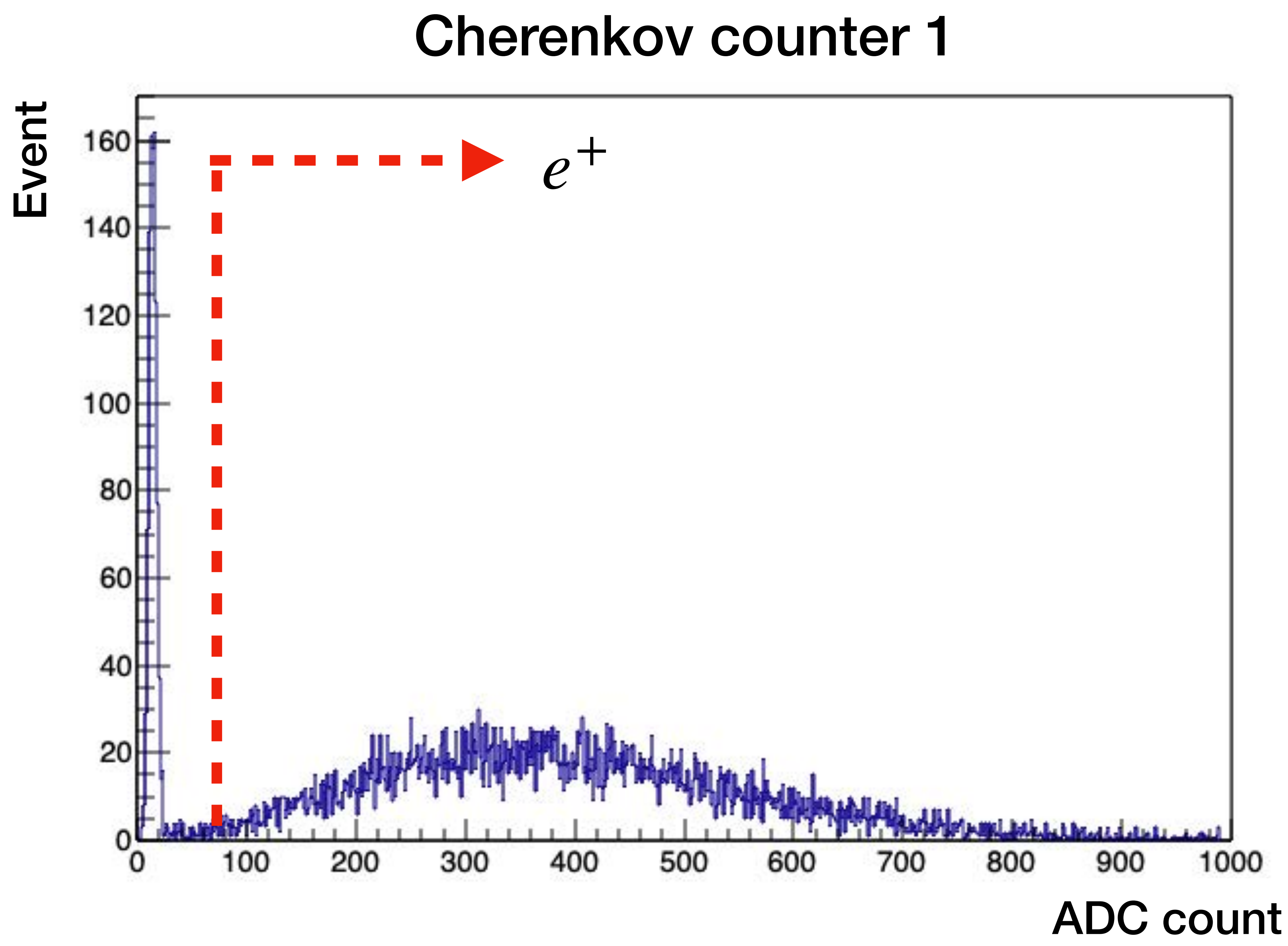
Spill duration: 0.4 second flat top
Usually: **1-2 cycles per minute per East Destination**
Max 6 East cycles (3 each T10/T09) / 40 seconds → RP Limit

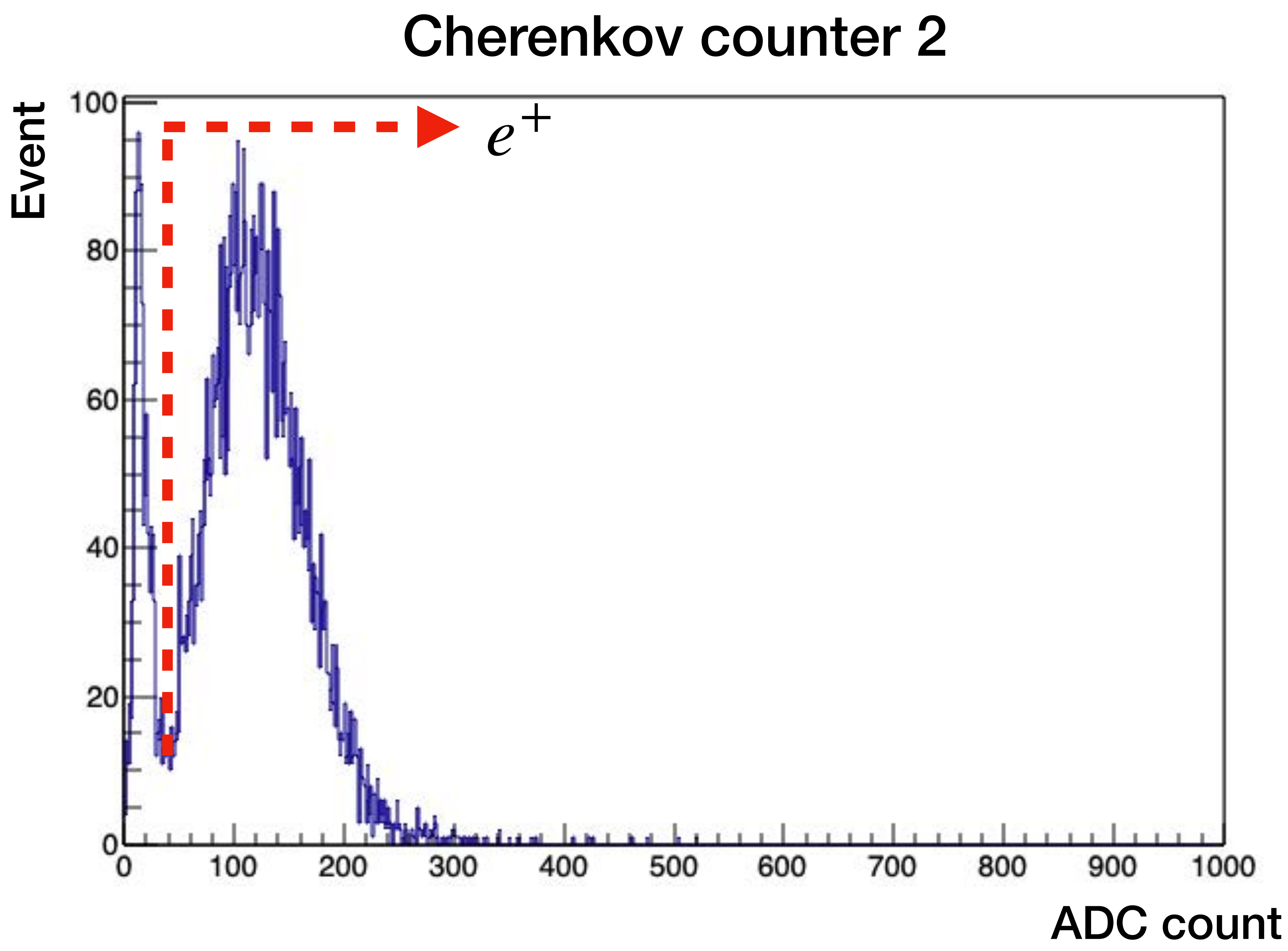
Super-cycle structure dependent on all users (SPS, nTOF ...)

Particle identification

- Since the T9 beam is **secondary beam**, it is composed of mixture of various particles
- **PID** required to select **positron** events for EM energy measurement
- 2 **Cherenkov counters (C.counter)** is used for PID
- By adjusting internal **gas pressure** of C.counter, particle with mass lighter than the target mass creates C. light in the C.counter.
- Desired particles can be selected by applying cuts on C.counter response

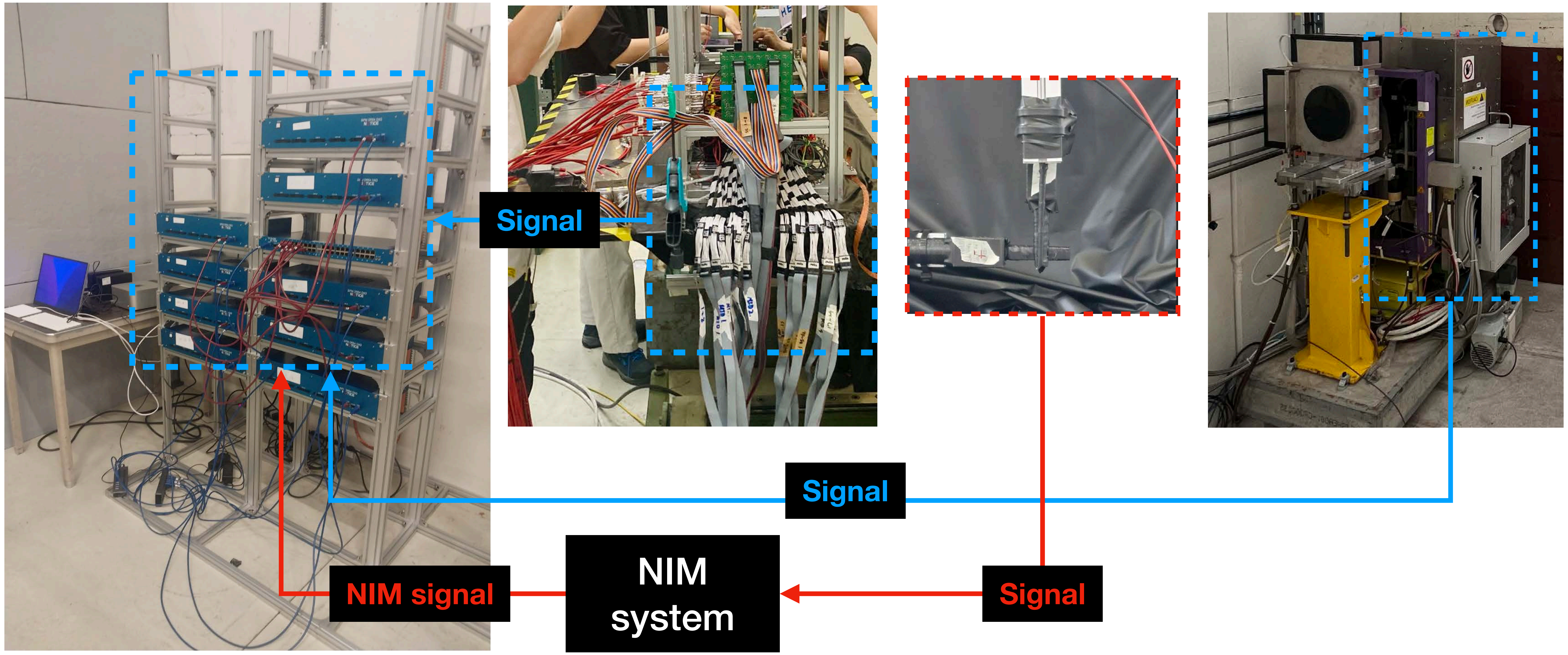


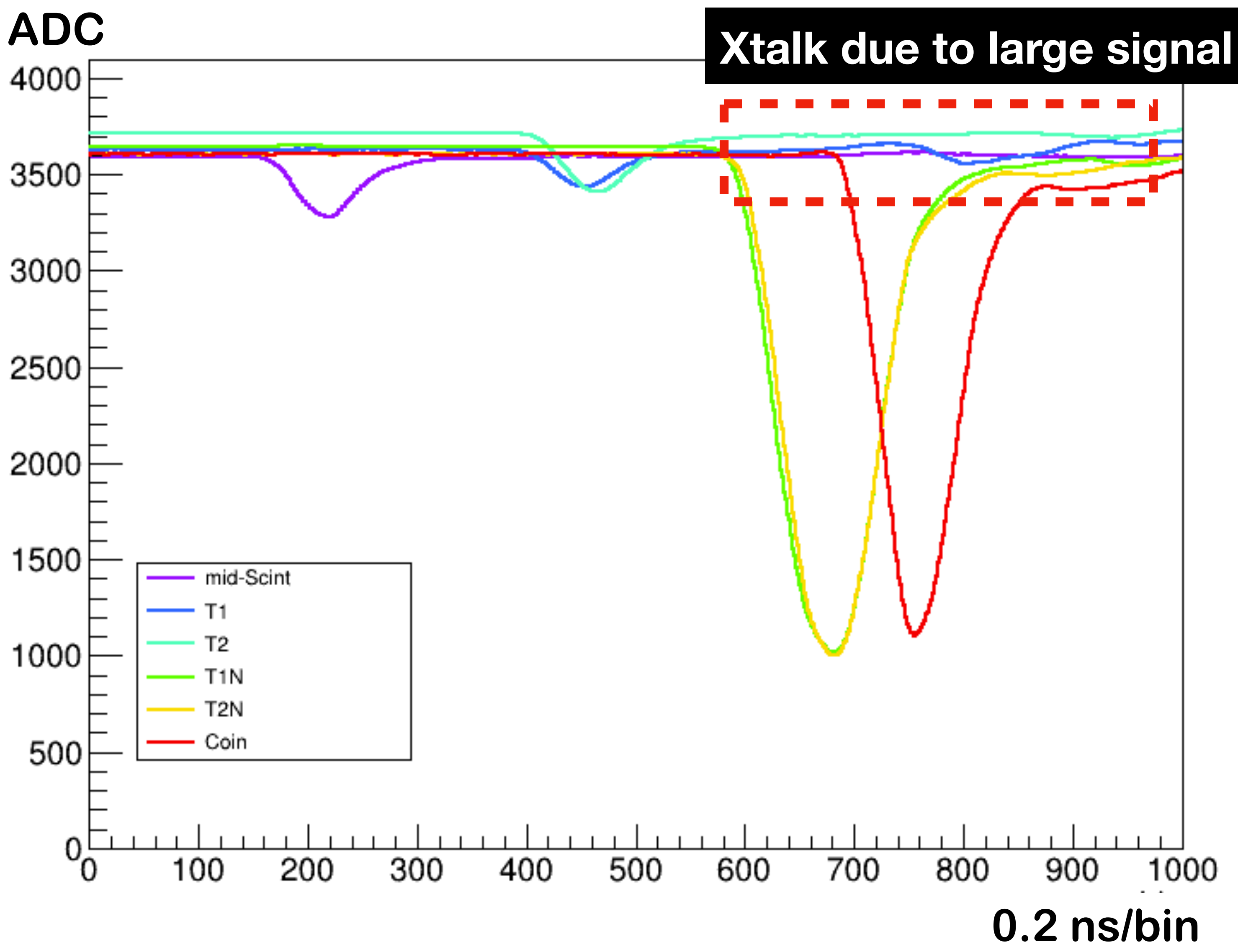


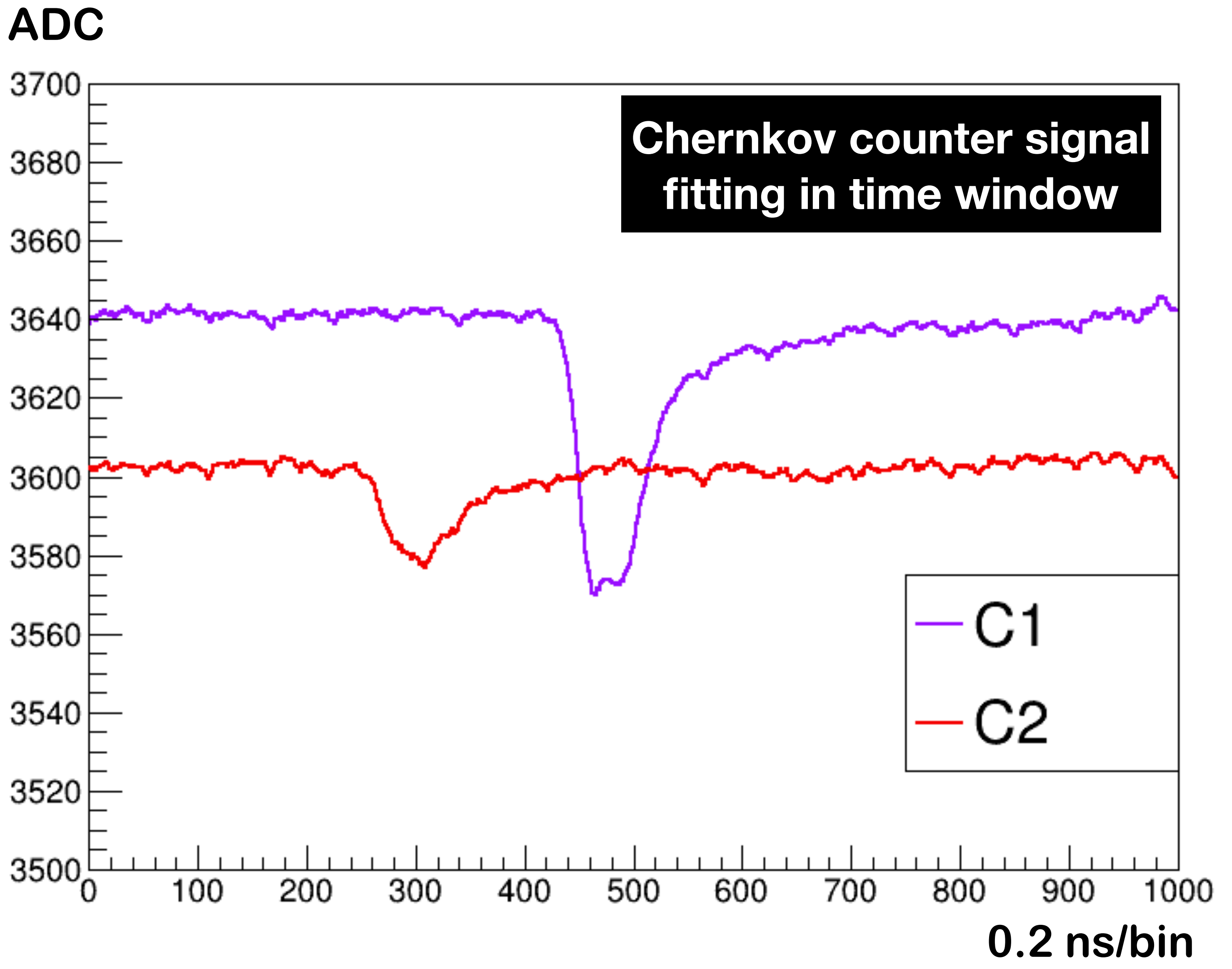


Data Acquisition (DAQ) System

- **DAQ :** When received trigger signal**,** it records detector signals, **digitize** them & **store** it on DAQ PC
- Data flow
  - DRC, C. counter readouts → DAQ system → DAQ PC
  - Trigger readouts → NIM system → DAQ system → DAQ PC
- To **avoid crosstalk** between detector signals, managed signal timing by using different length of cables
- To fit Cherenkov counter signals to our **DAQ time window,** used different time delay for C. counter channels

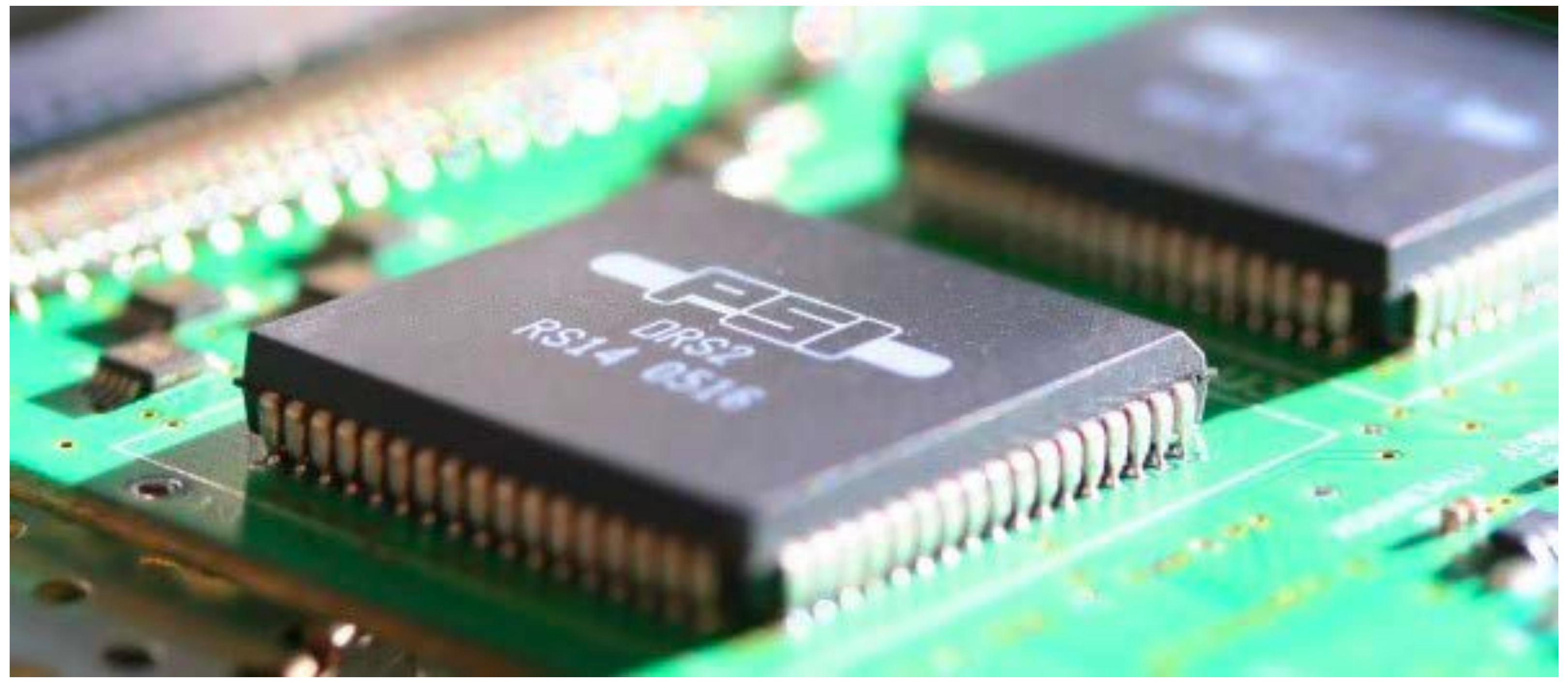






Data Acquisition (DAQ) System

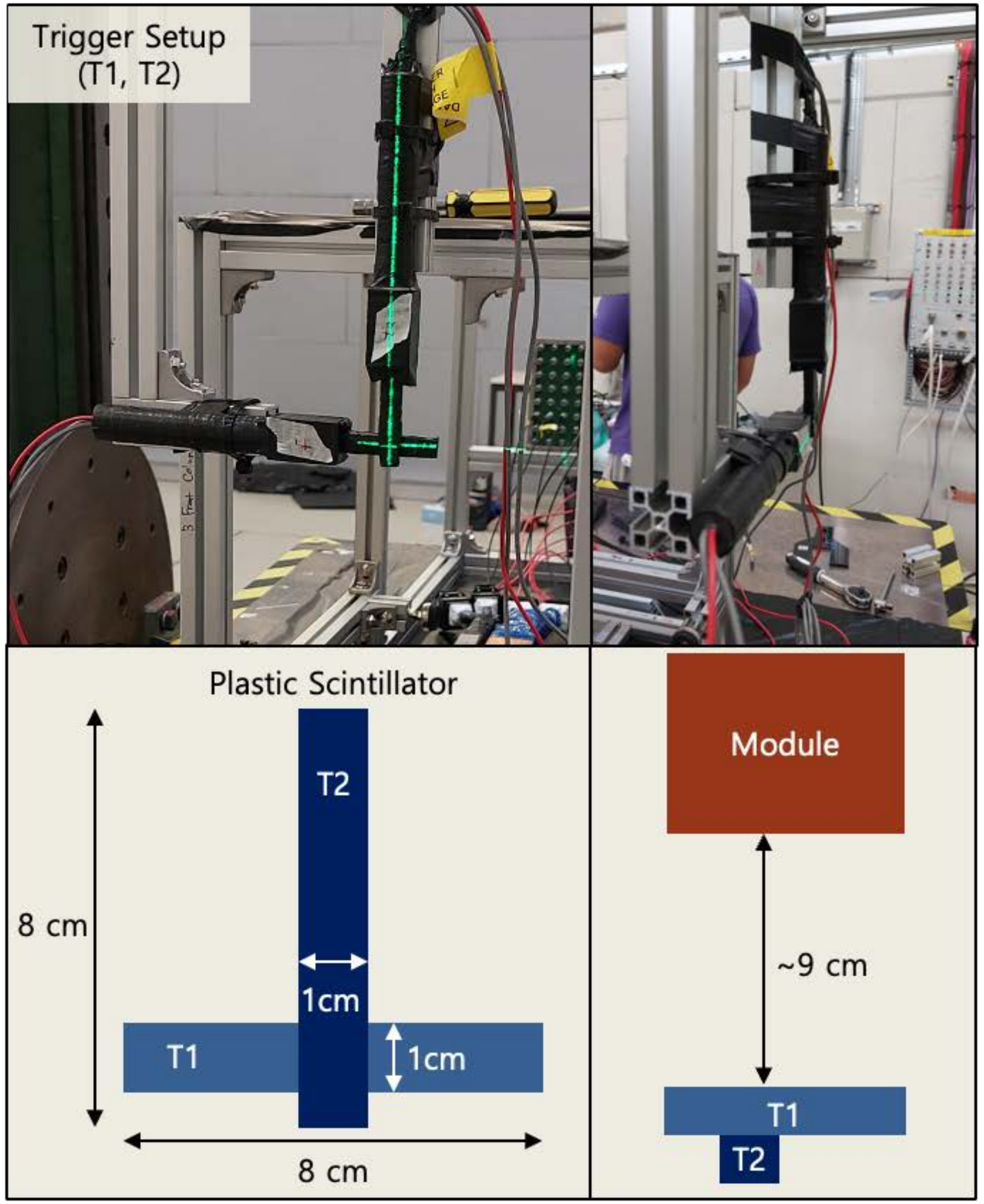
- Use **Domino Ring Sampling (DRS4)** chip
  - Maximum 5 GHz sampling
  - 1024 time bins
  - 1V into 4096 ADC bins
  - Provides 8 channels per chip



- **Data AcQusition (DAQ) board**
  - Use DRS4 chips to digitize the signal
  - 32 channels per board (16 pin ribbon x 4)
  - Supports power supply for SiPM (20 pin ribbon)
  - Two data taking mode
    - Waveform mode : records digitized waveform
    - Fast mode : records integrated ADC count & timing (constant fraction)
  - Connected to DAQ PC using USB3 interface

- **Trigger Clock Board (TCB)**
  - Cover up to 40 DAQ boards
  - Align the clock of the DAQ boards
  - Supports common stop mode trigger

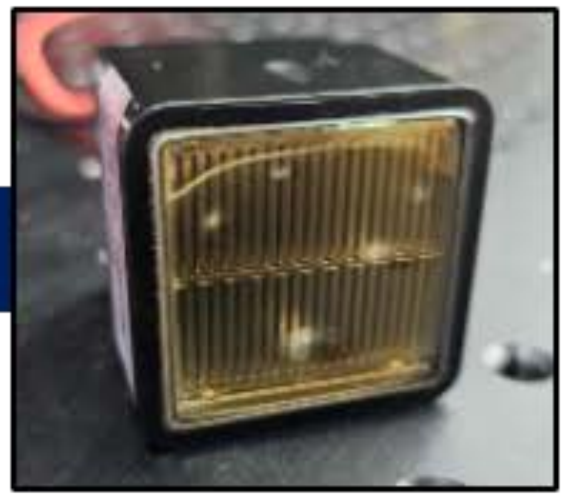
Trigger detectors



T1, T2

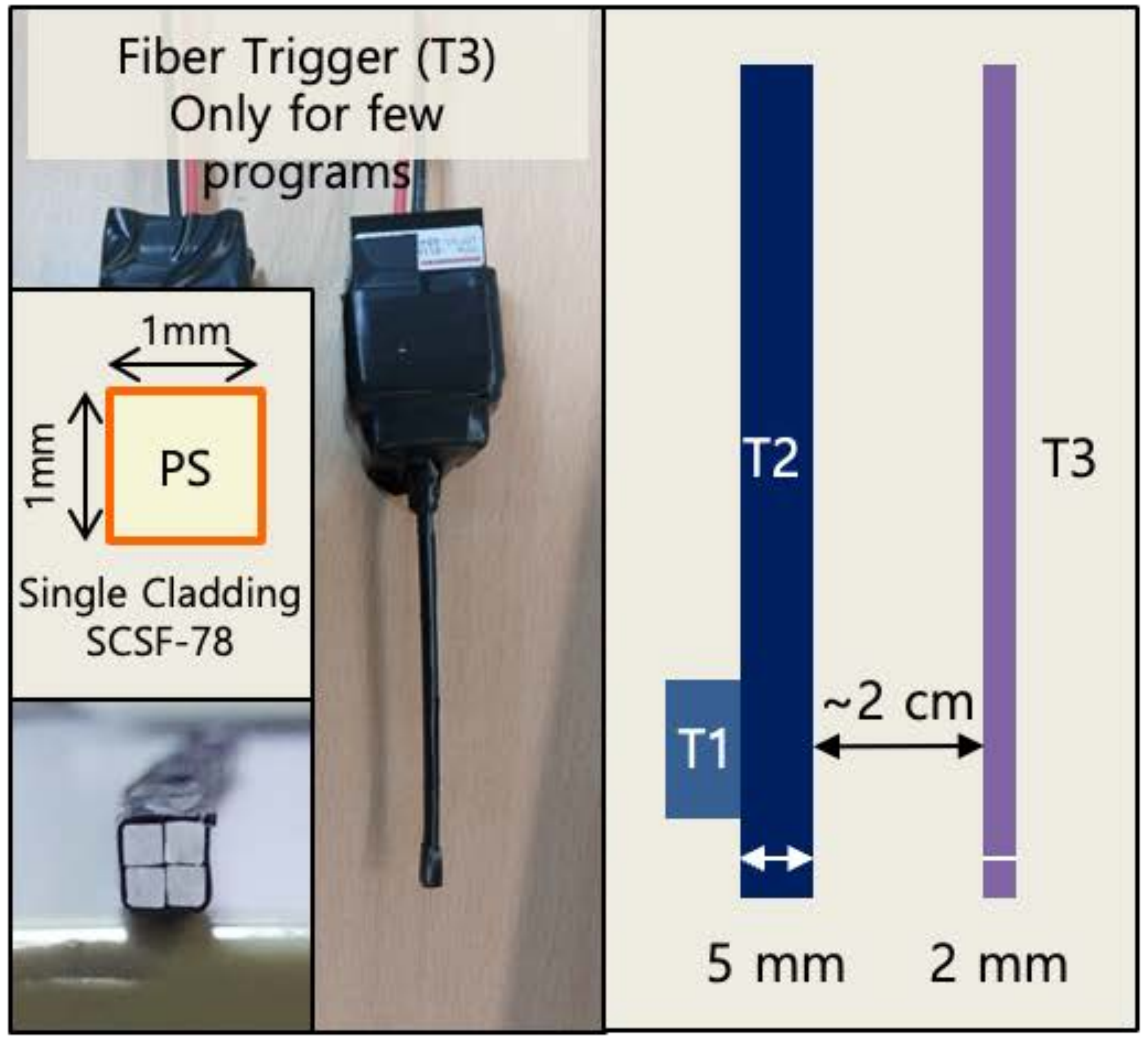
Plastic Scintillator

Polystyrene, 80x10x5 mm



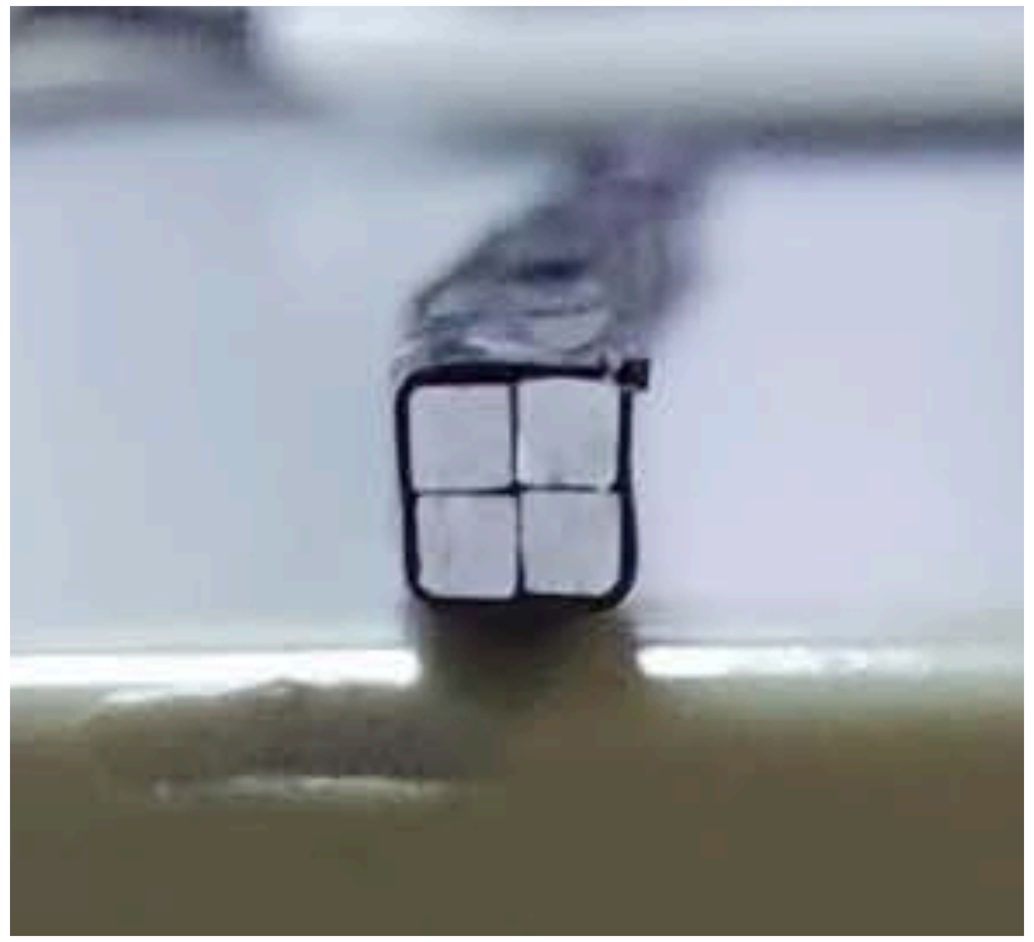
T3

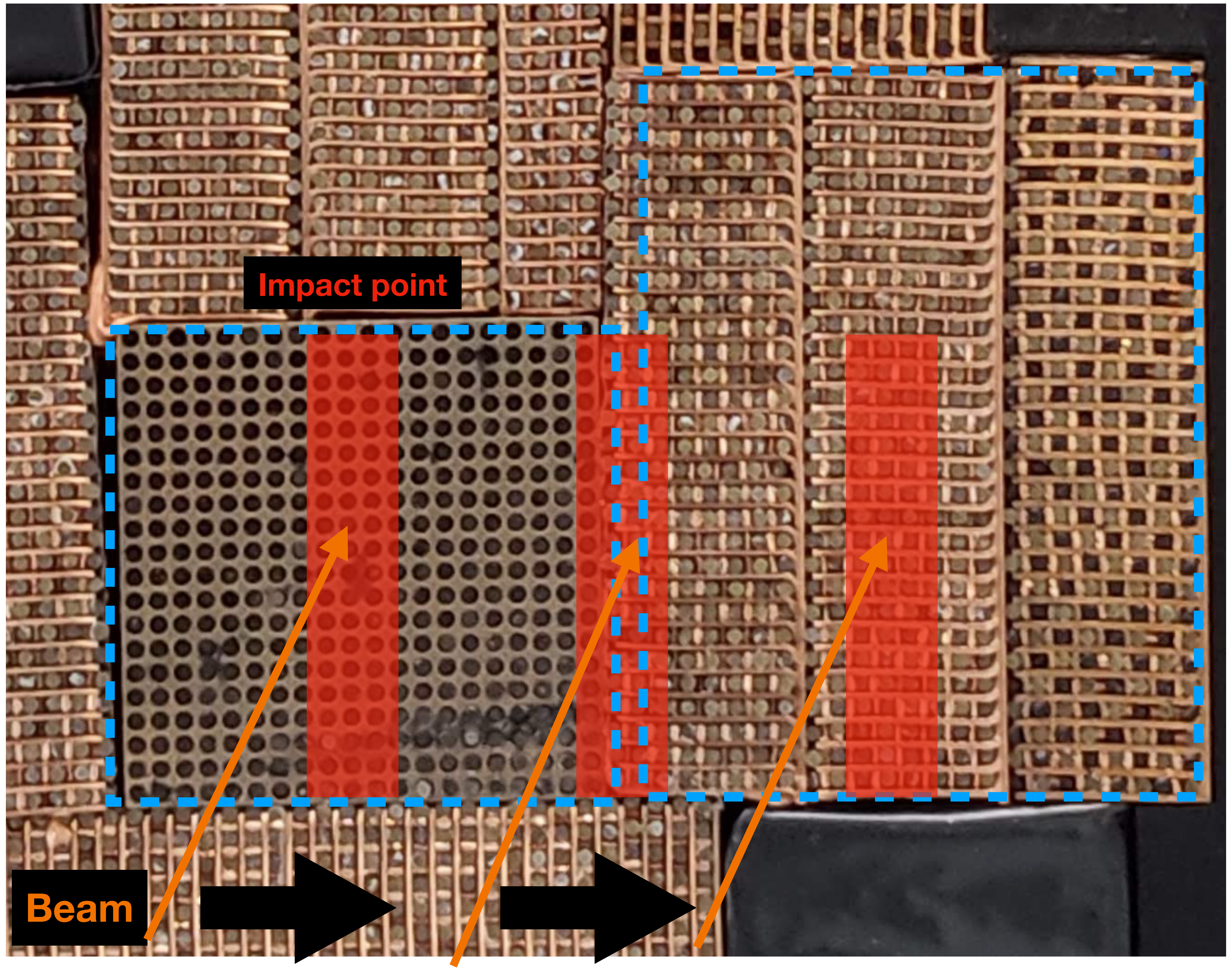
Square type Scintillating fiber,
100x2x2 mm

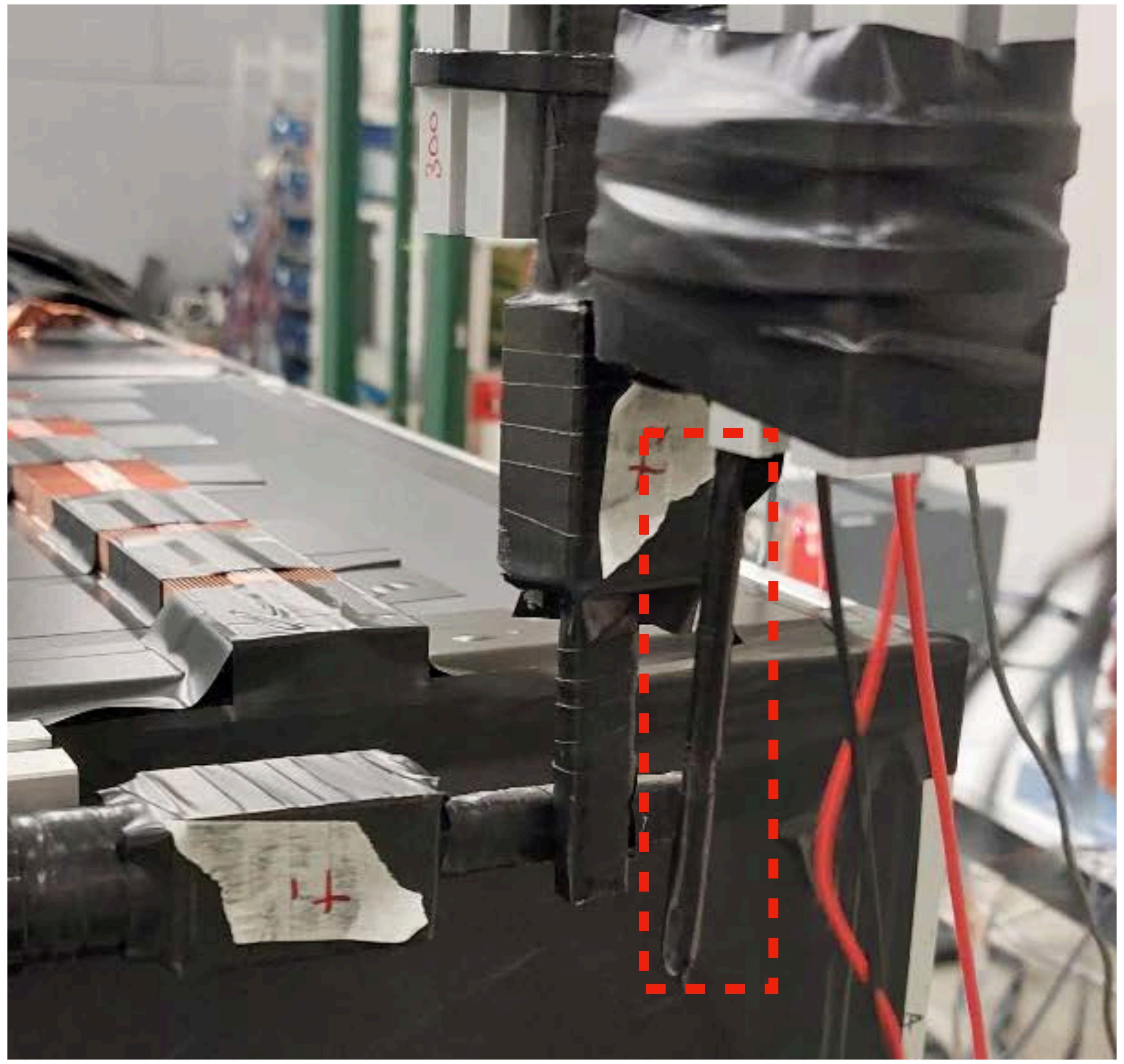


Trigger-3 for fine impact point scan

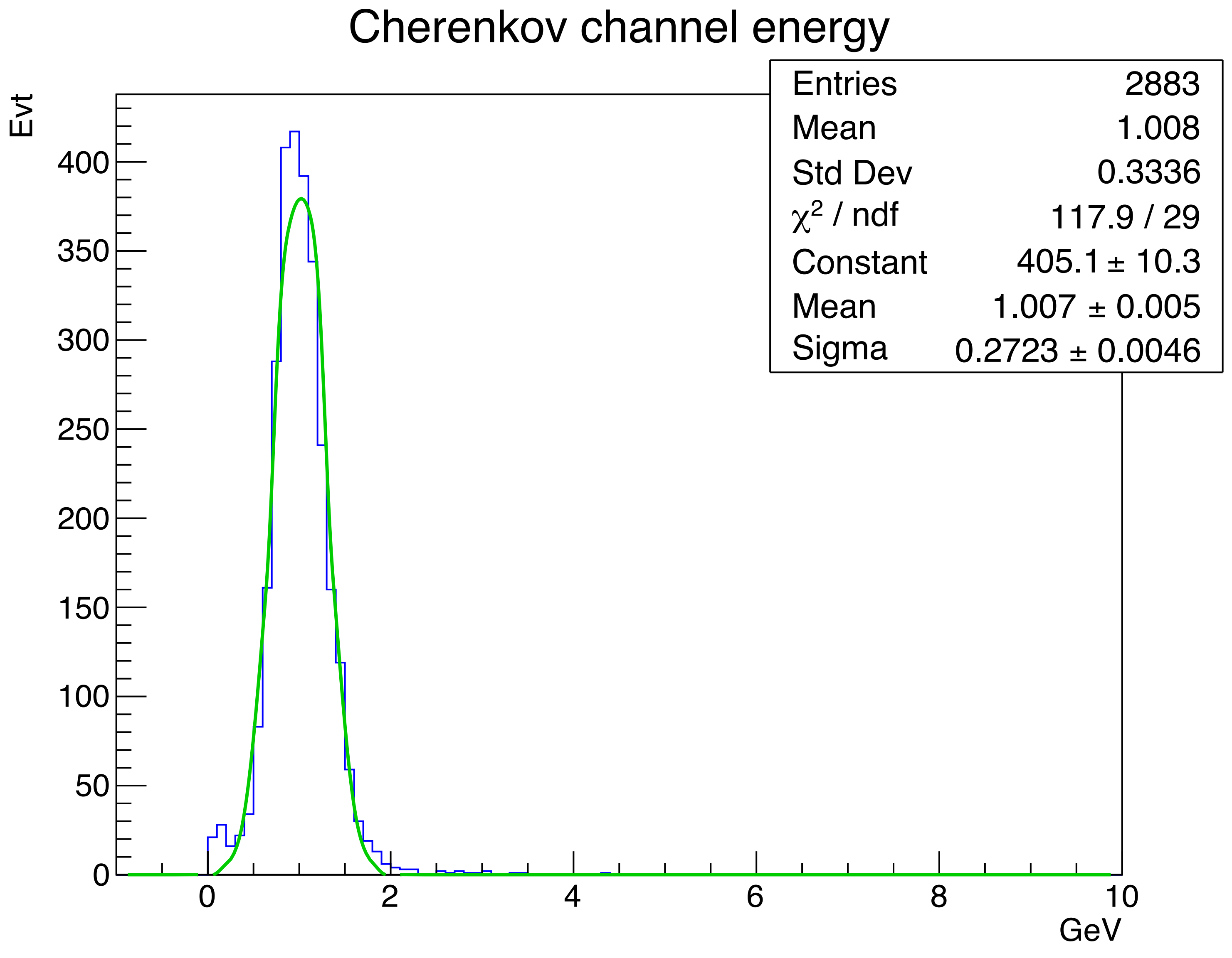
- **Tower response scan** by moving beam from center to neighboring tower
- Need to know beam impact point with ~mm precision for the program
- Built **trigger-3** using square-type scintillation fiber on the spot



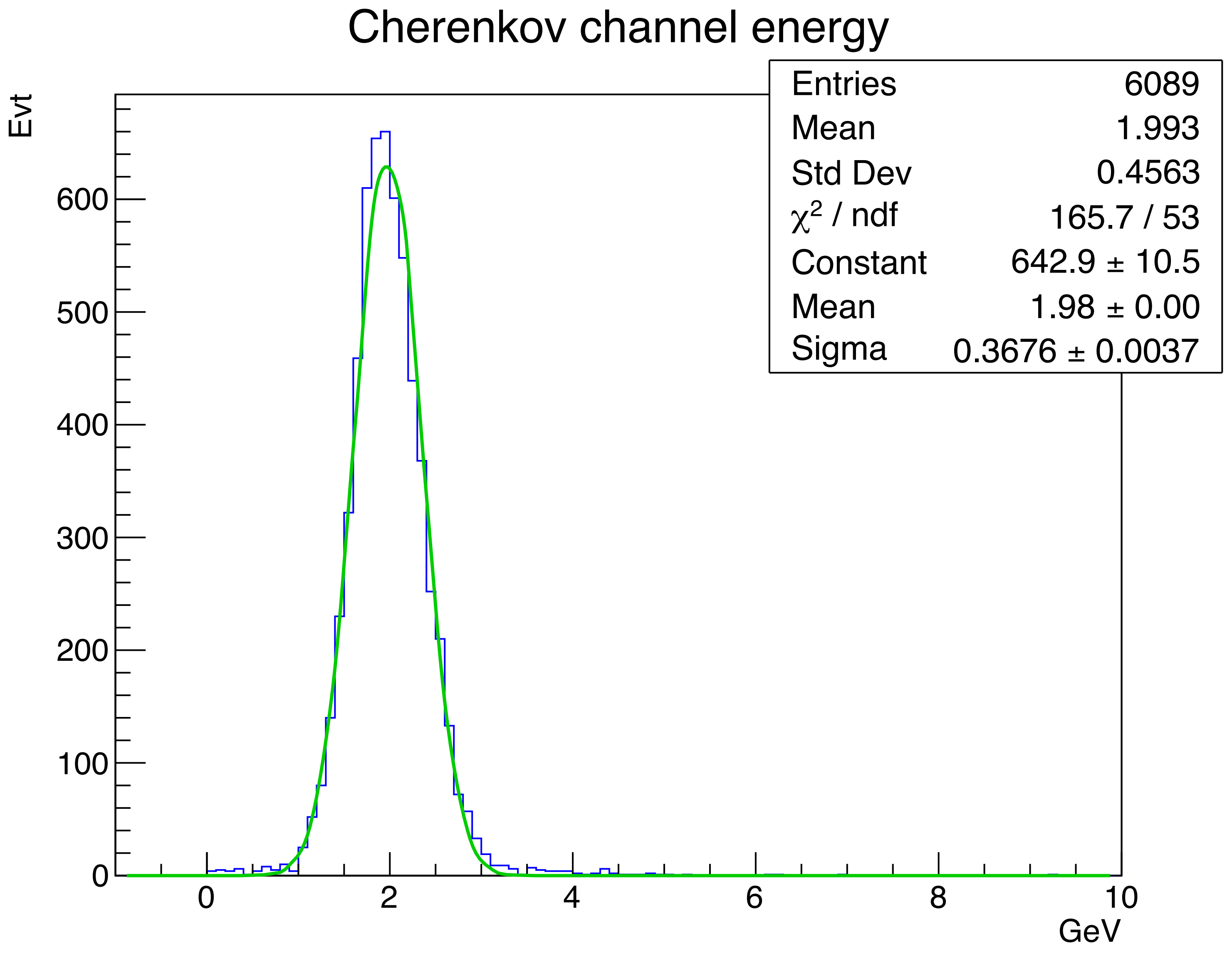




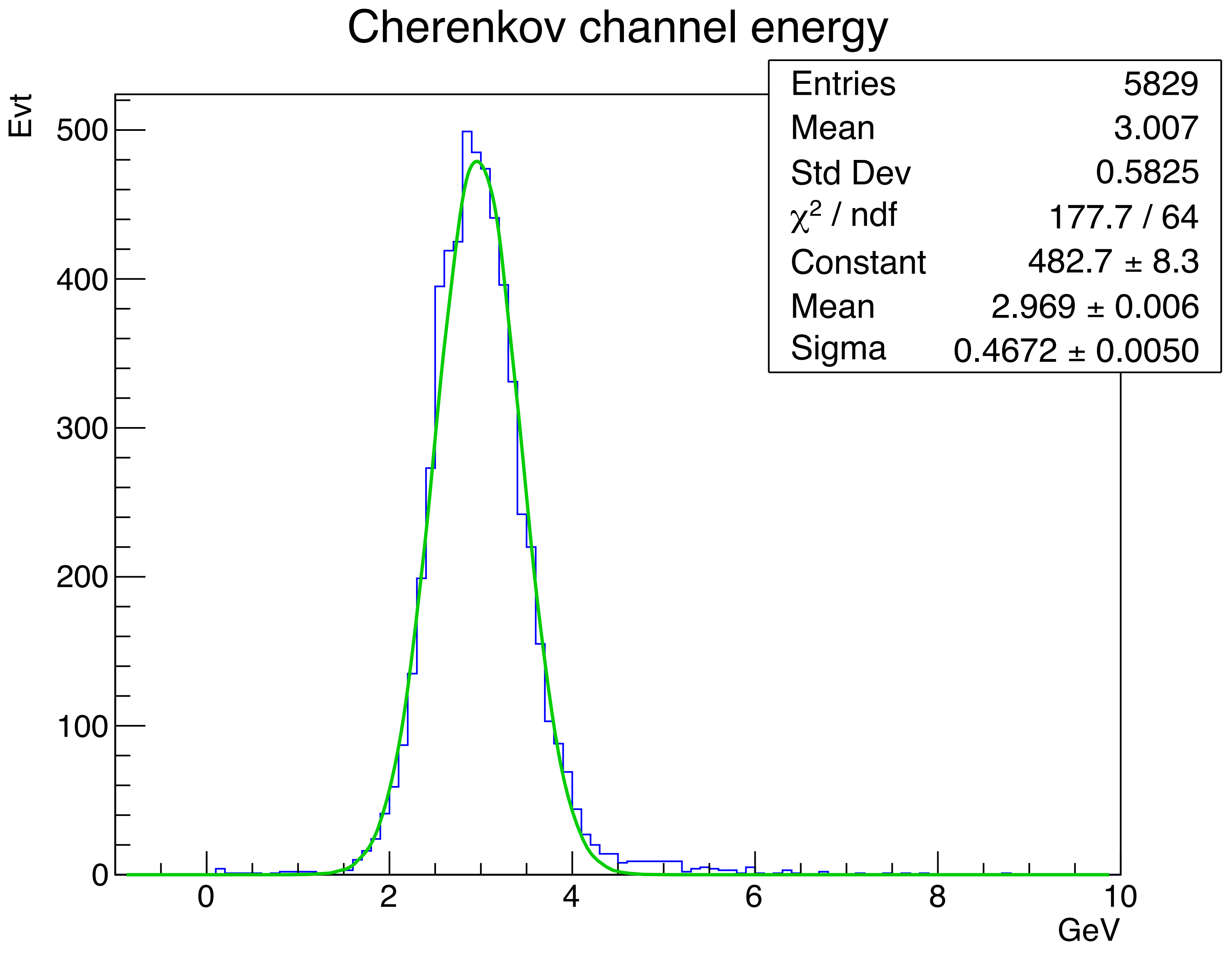
Energy distribution (C. ch.)



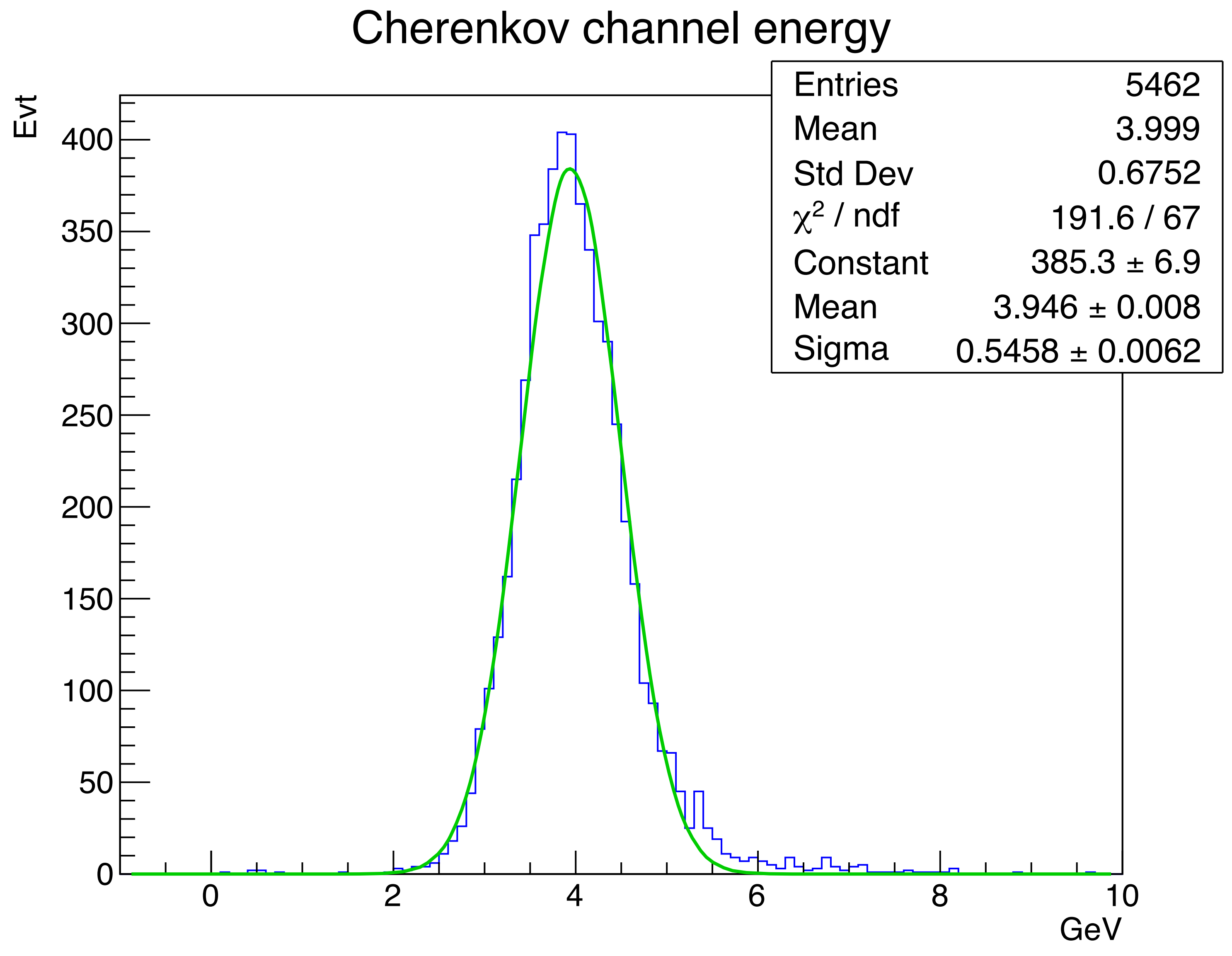
1 GeV



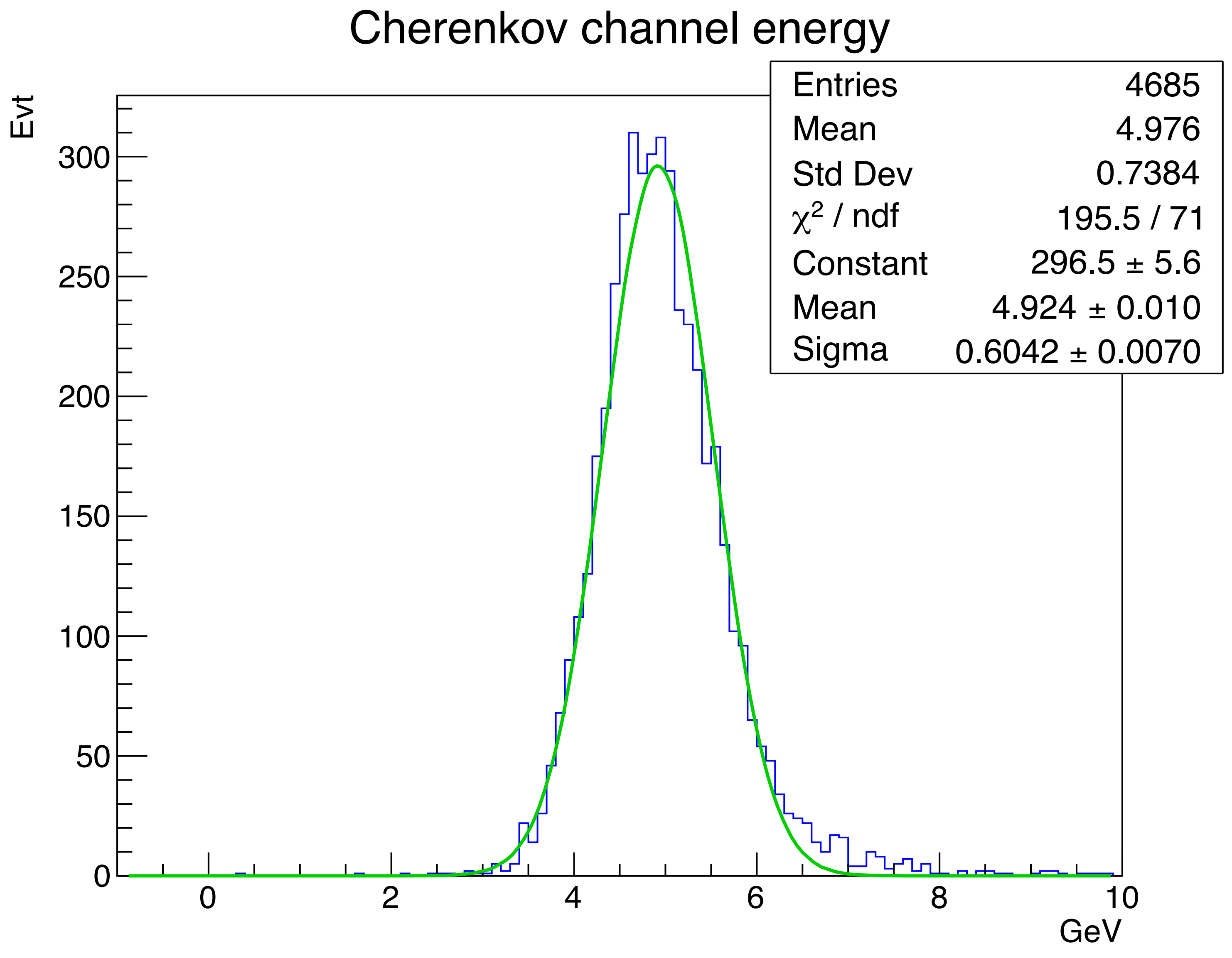
2 GeV



3 GeV

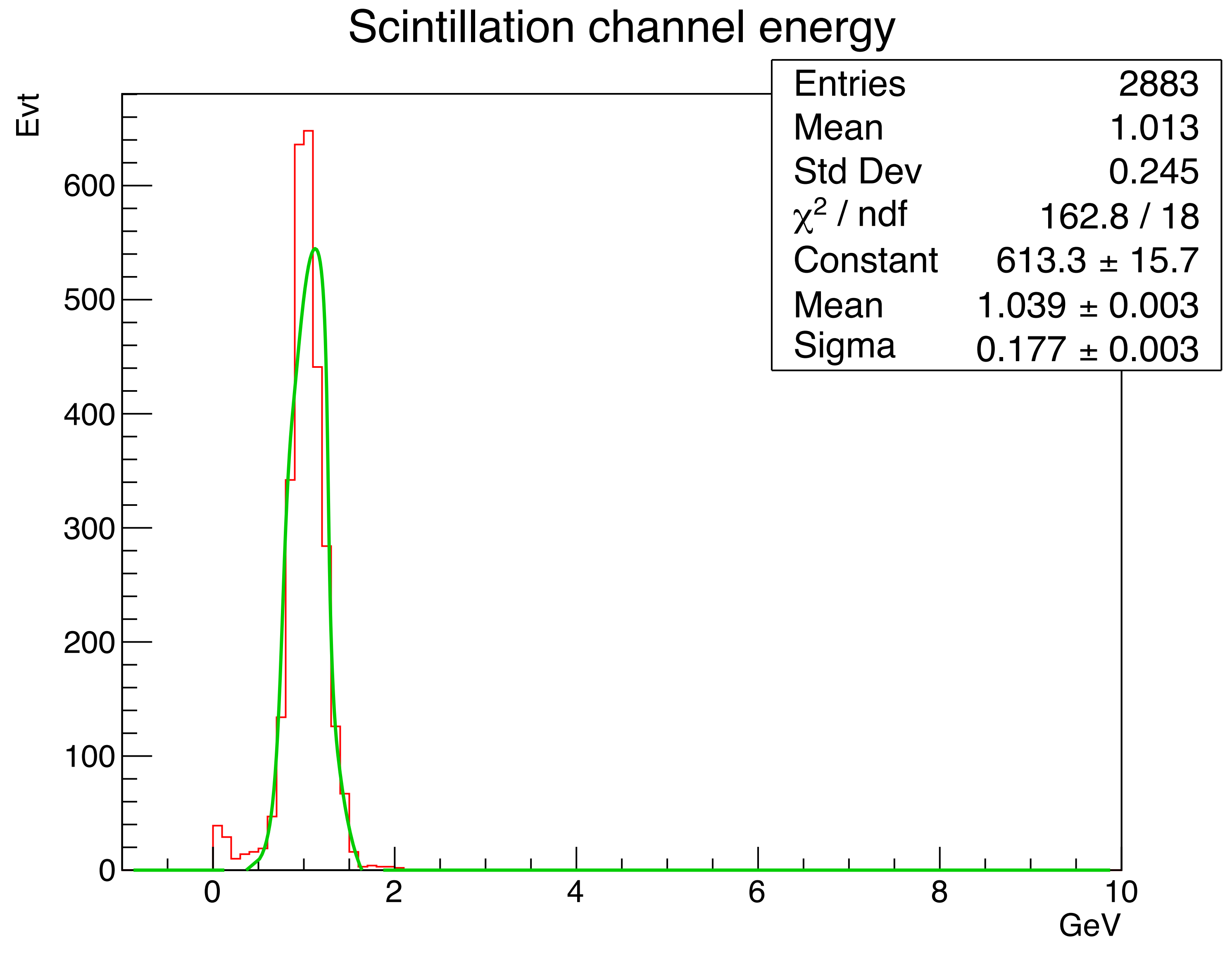


4 GeV

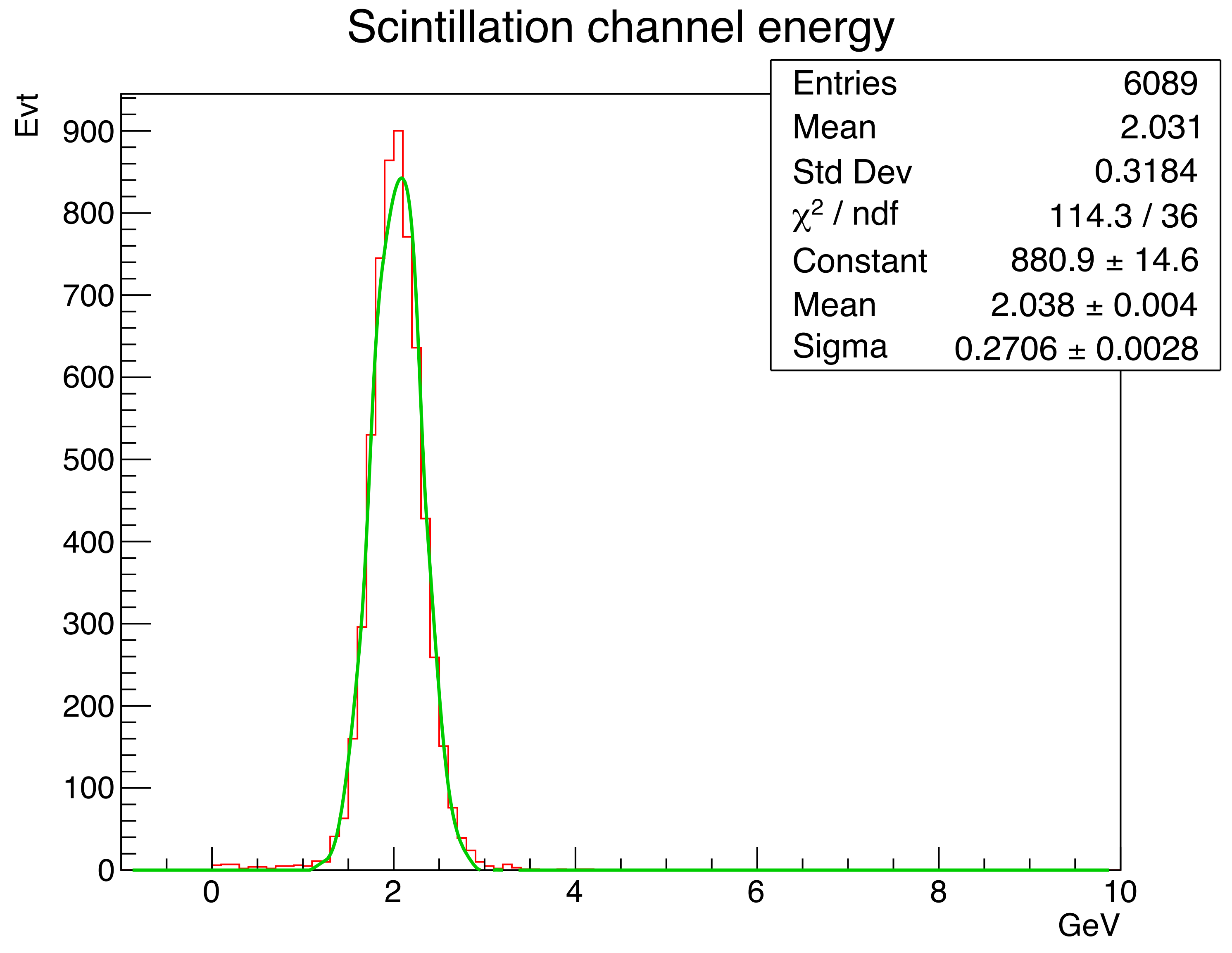


5 GeV

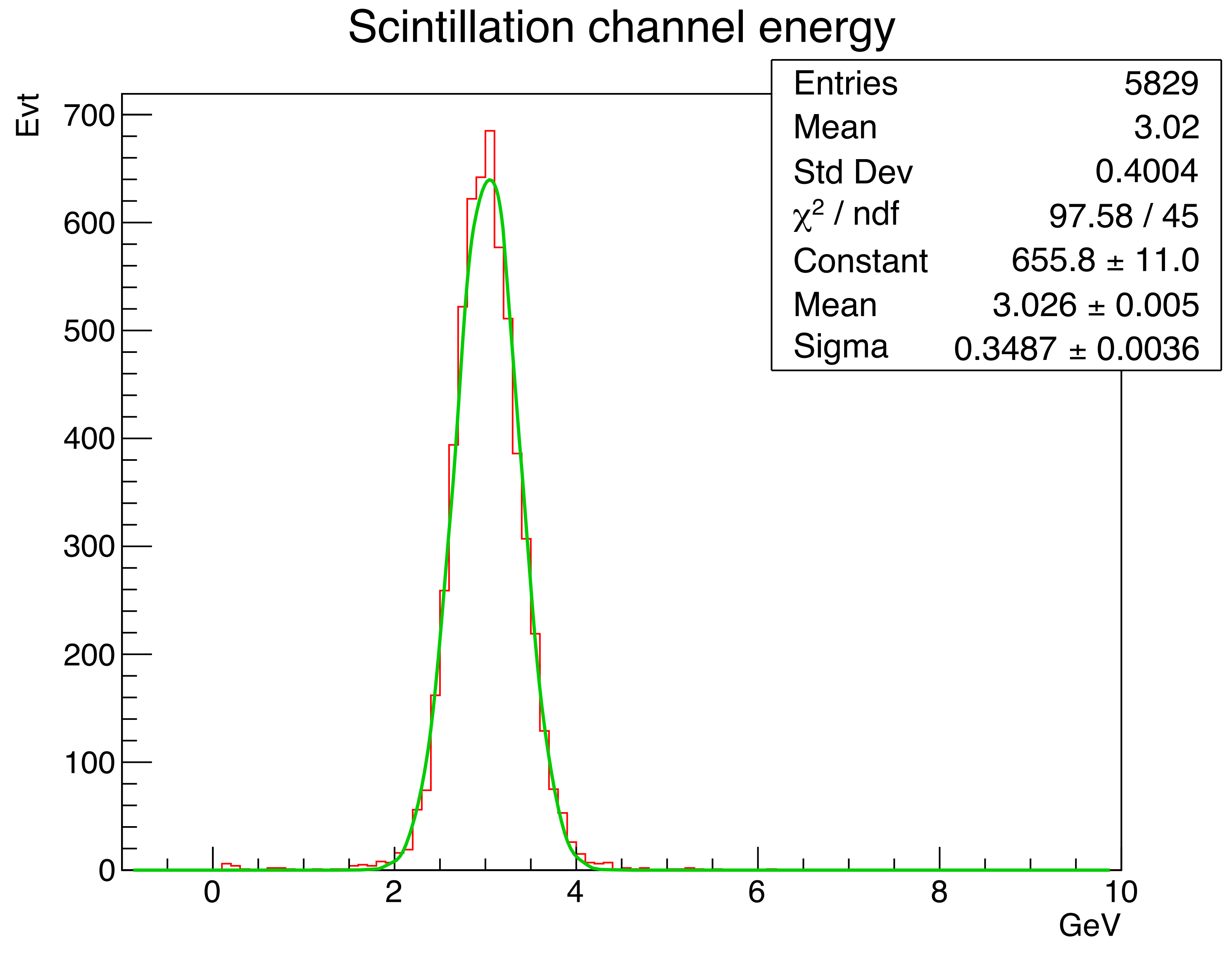
Energy distribution (S. ch.)



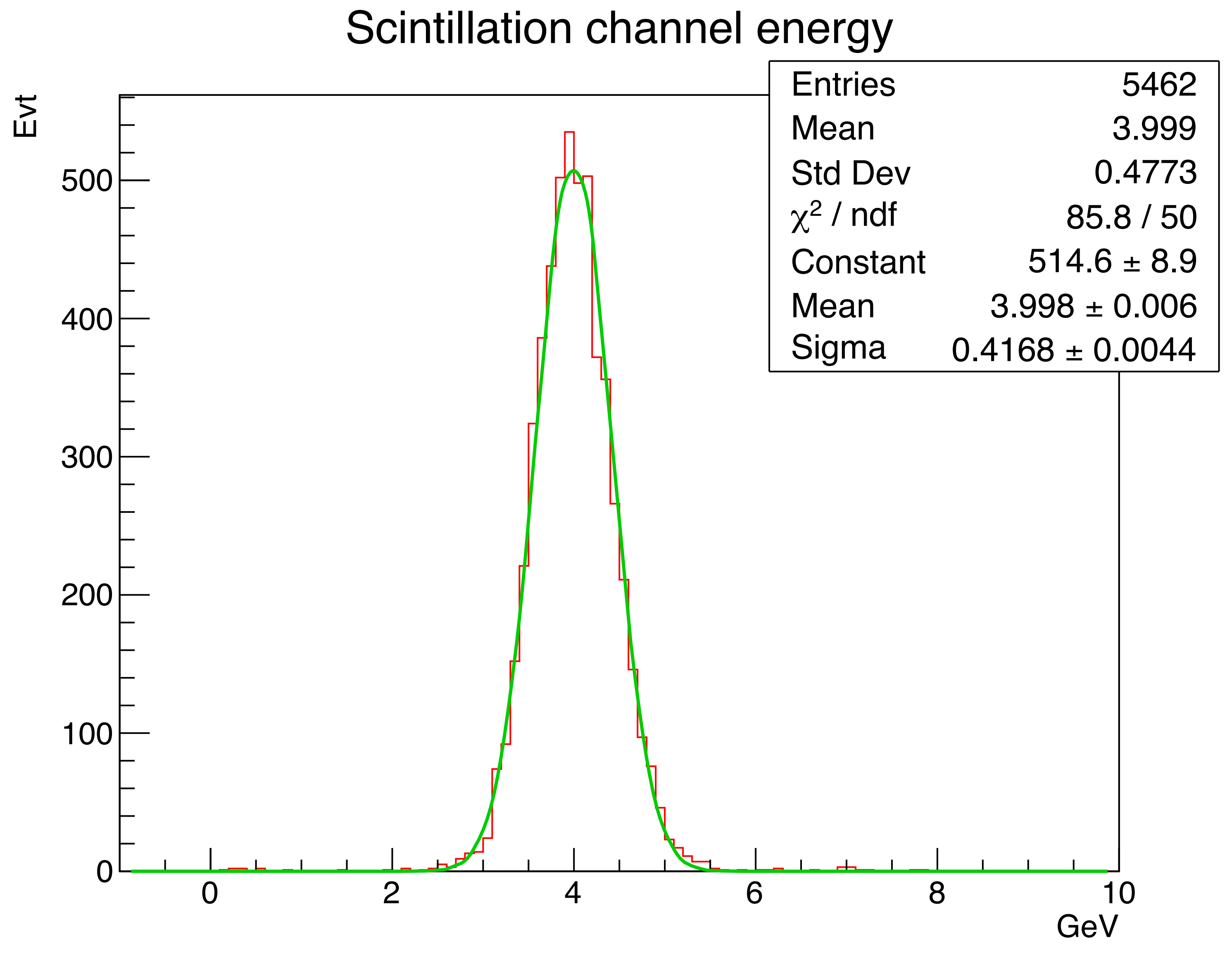
1 GeV



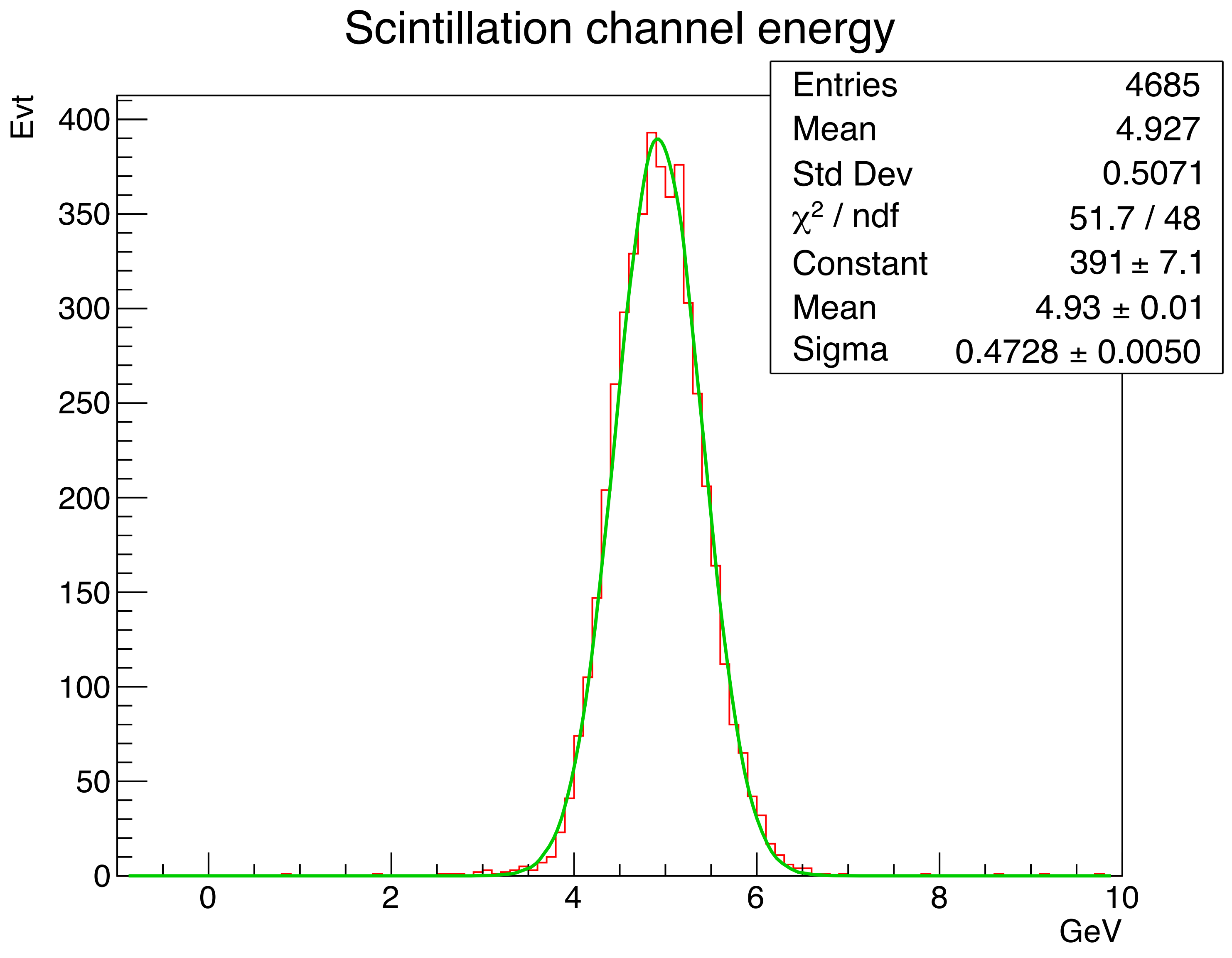
2 GeV



3 GeV

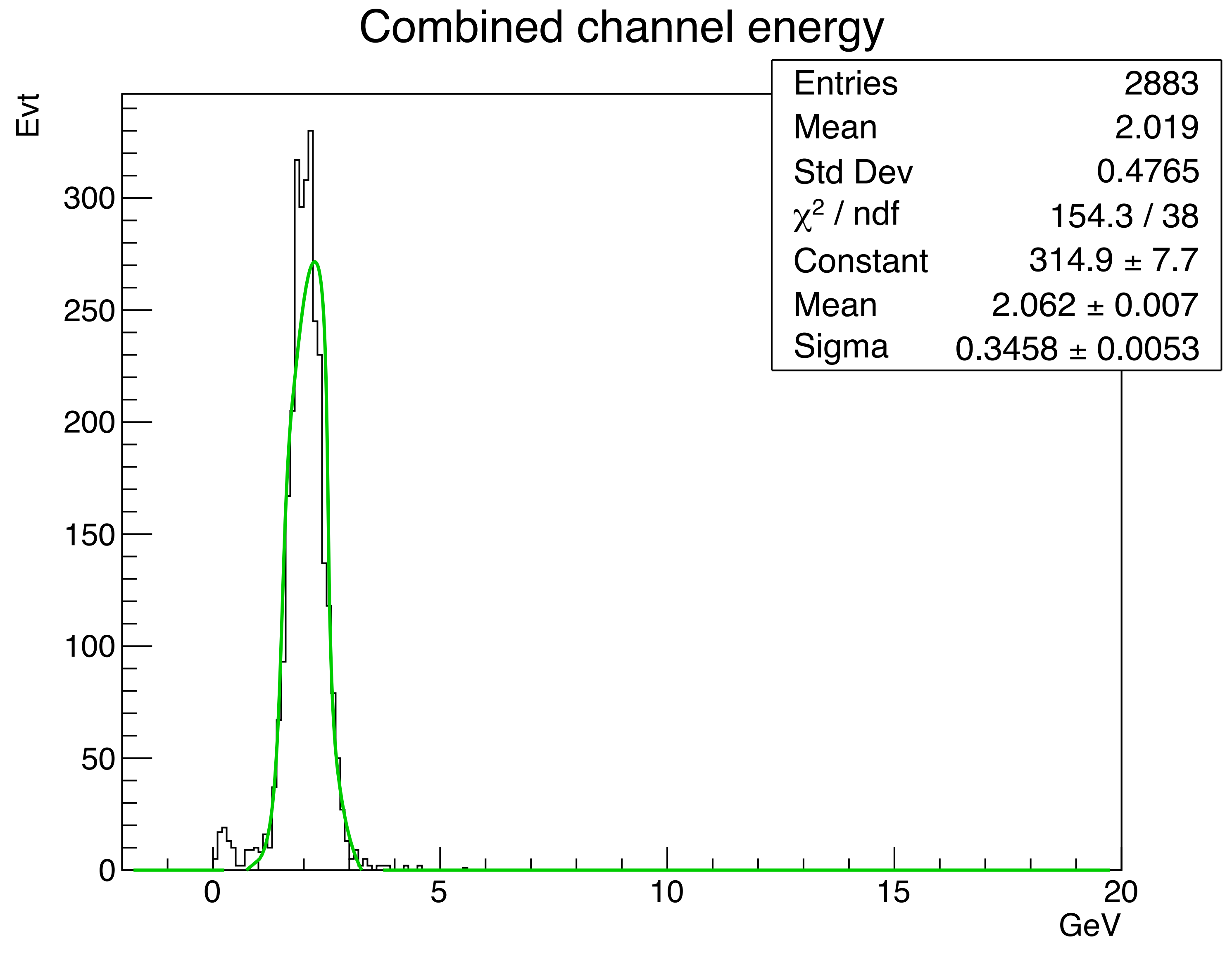


4 GeV

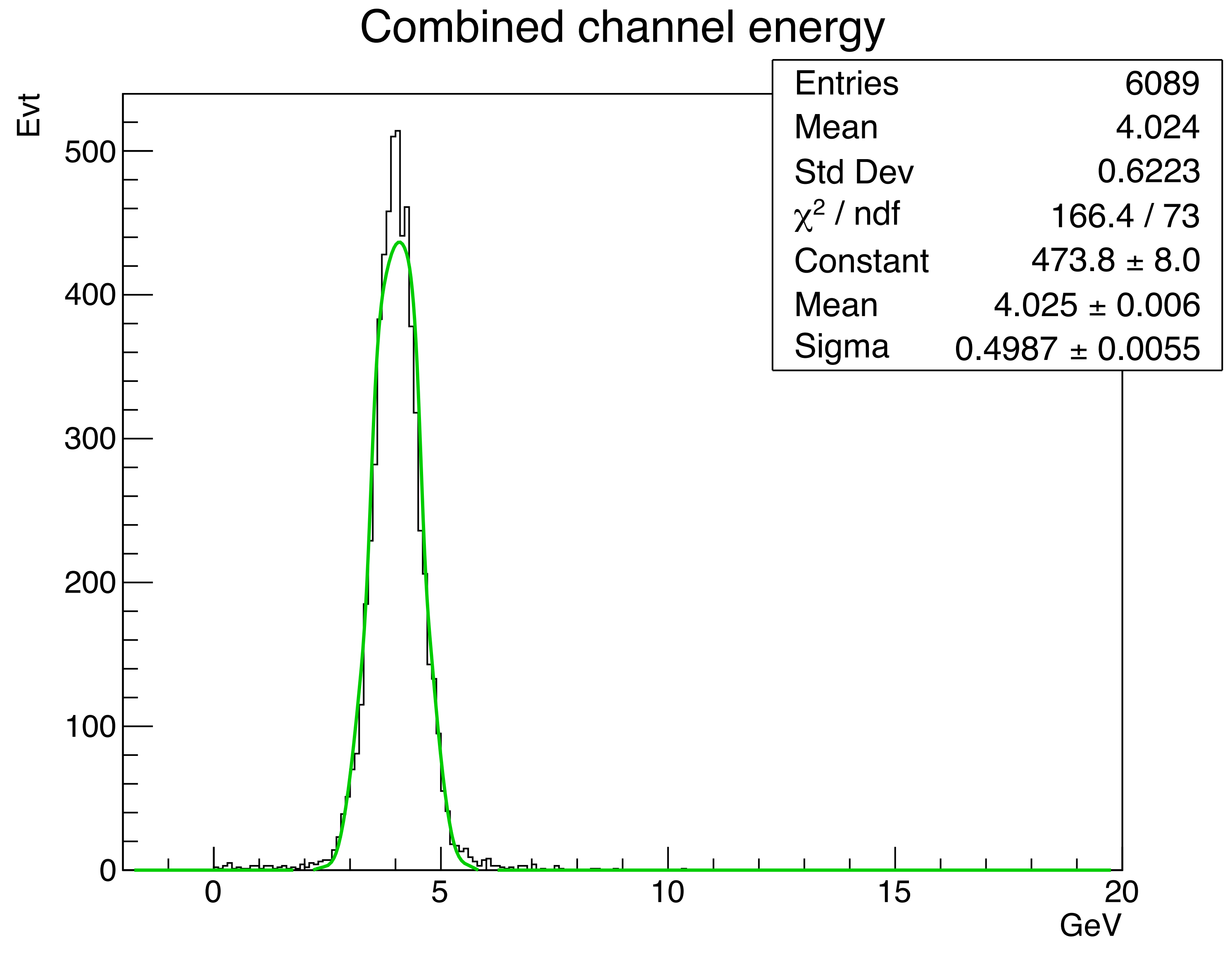


5 GeV

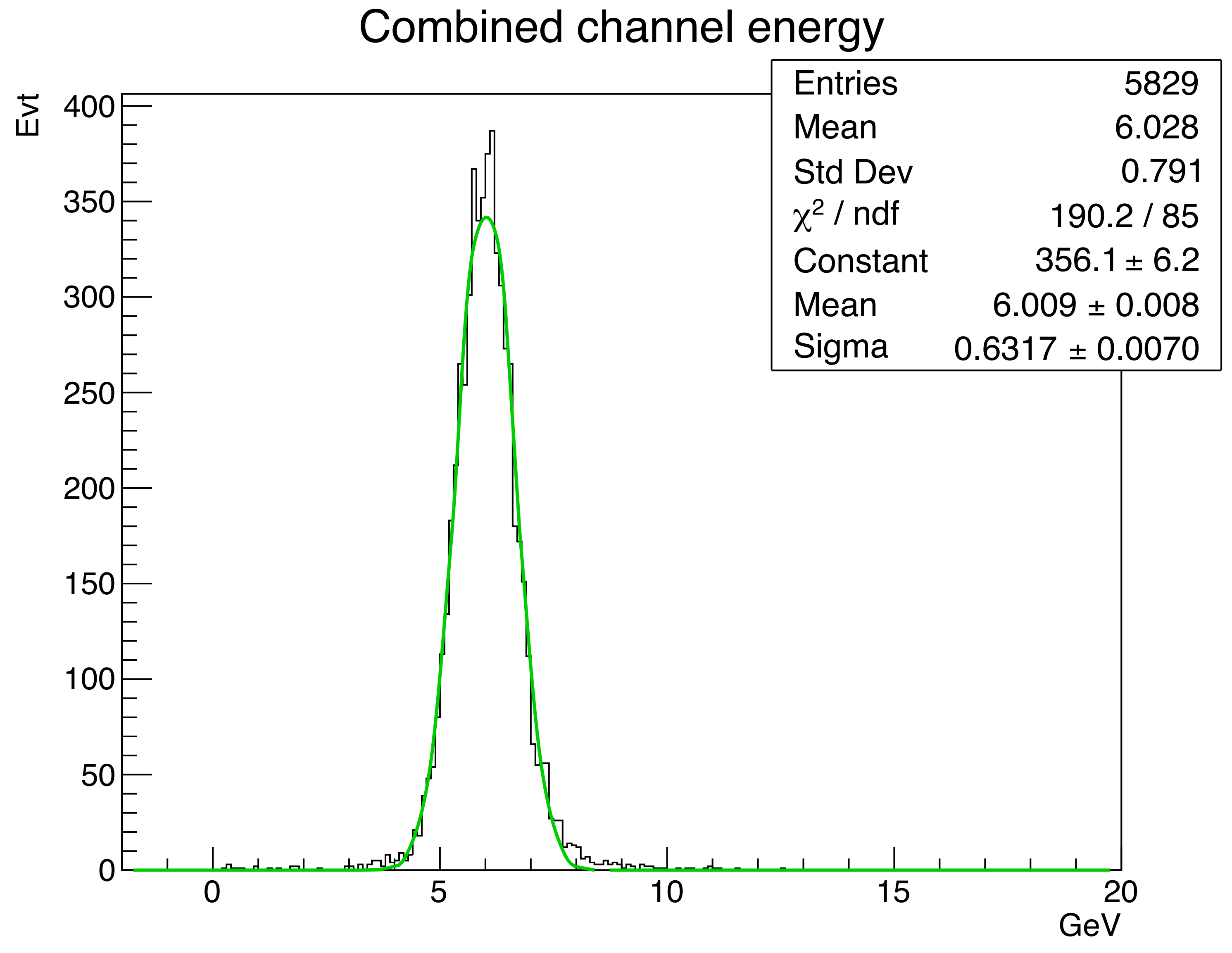
Energy distribution (S+C ch.)



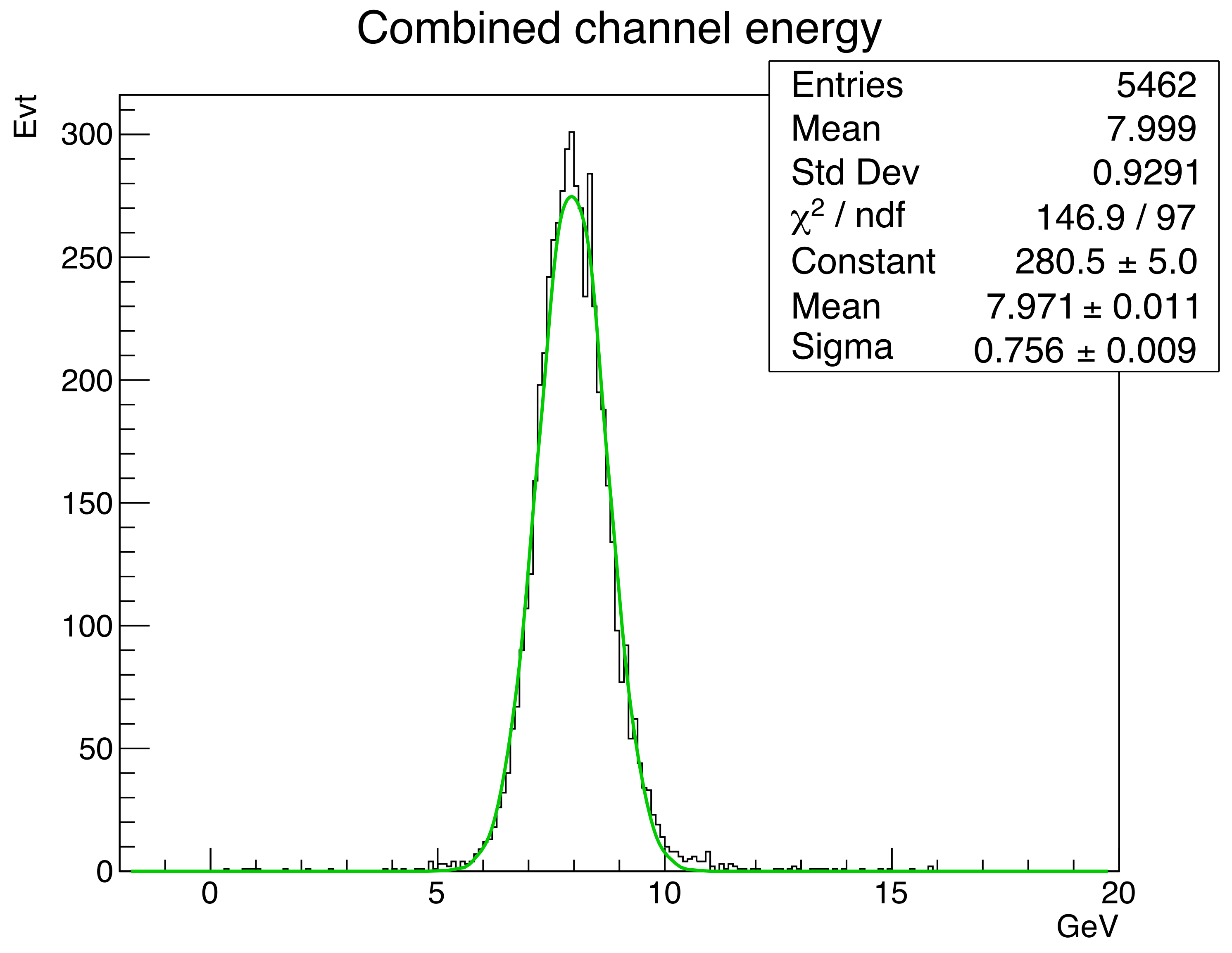
1 GeV



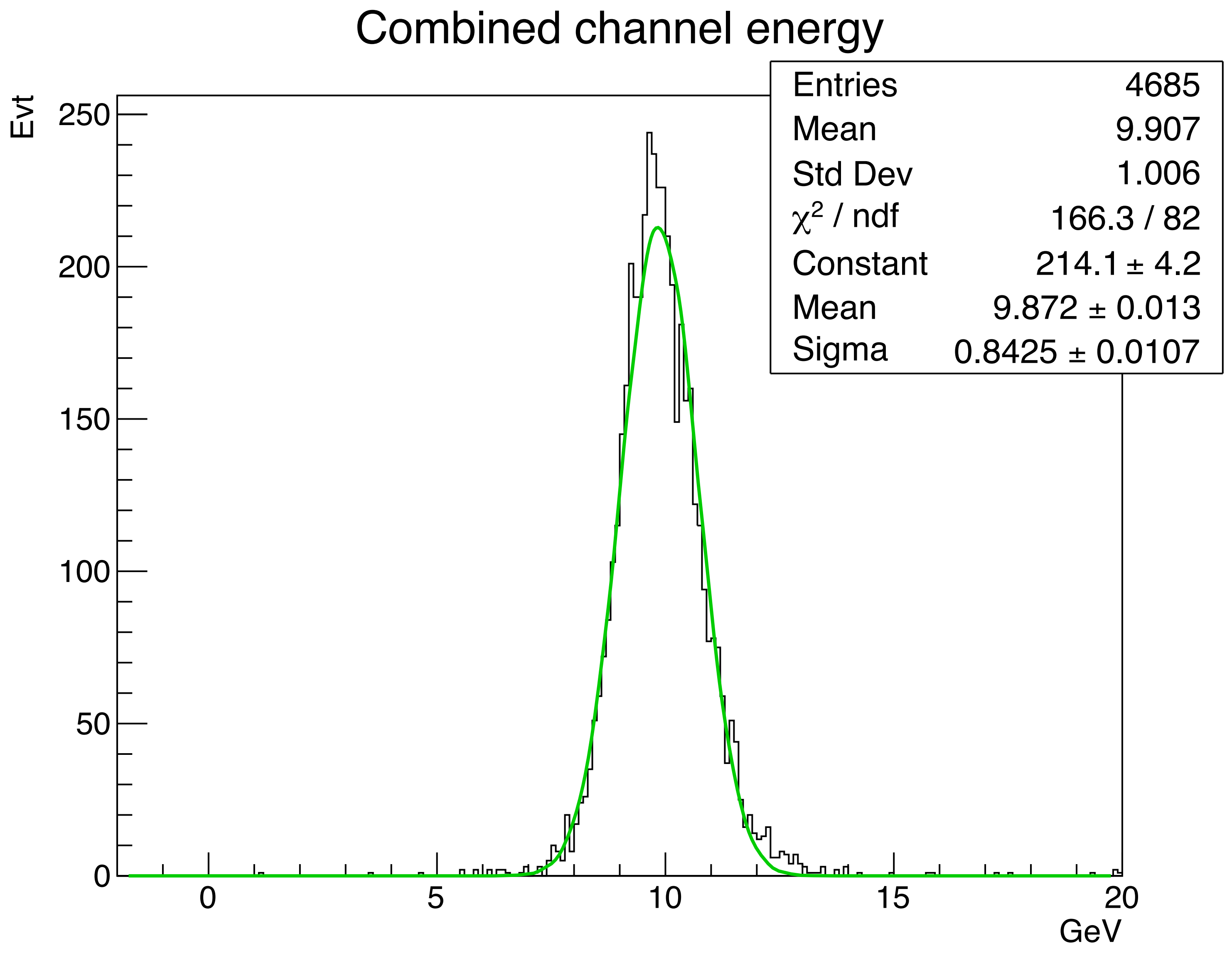
2 GeV



3 GeV

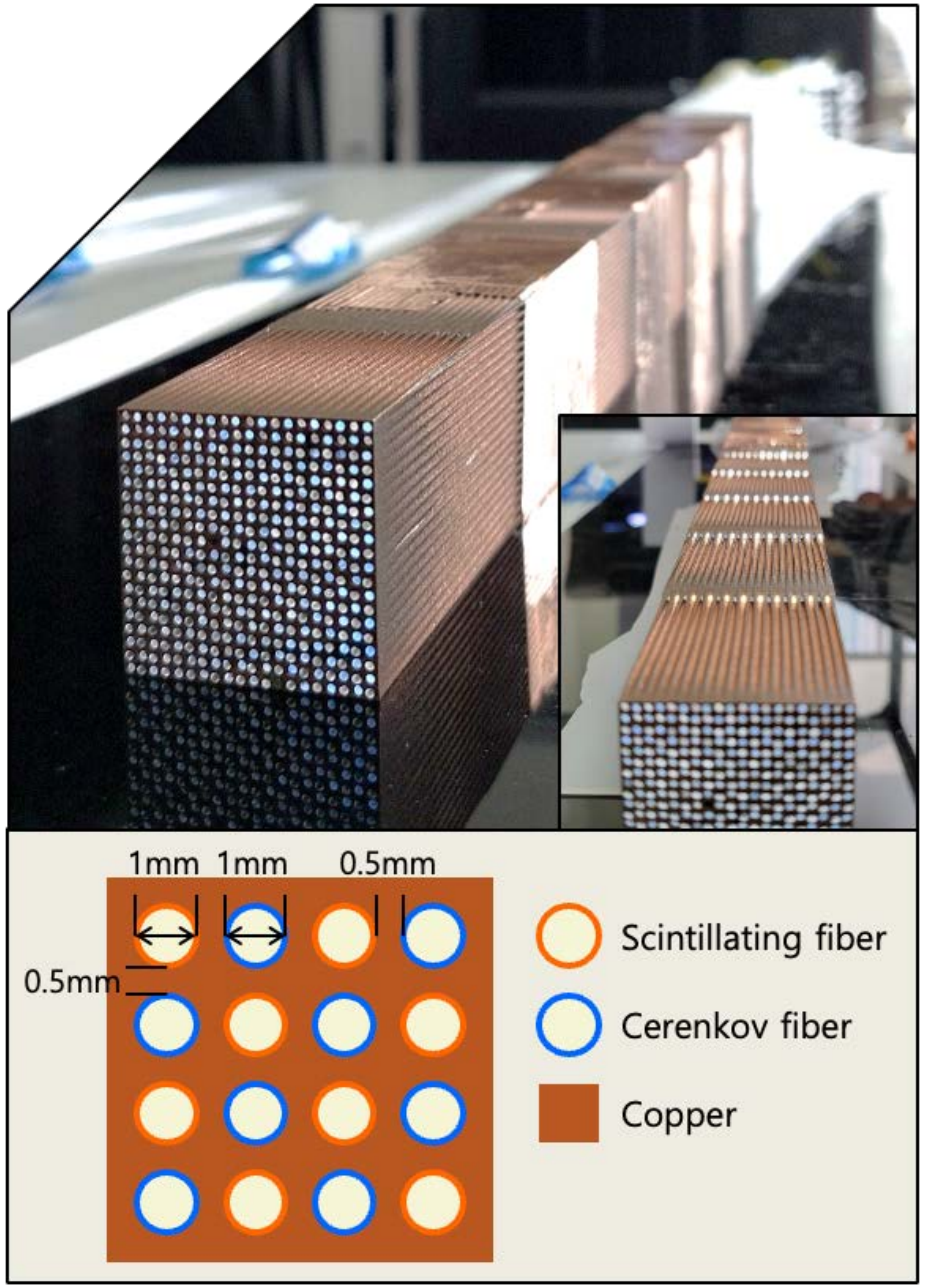


4 GeV

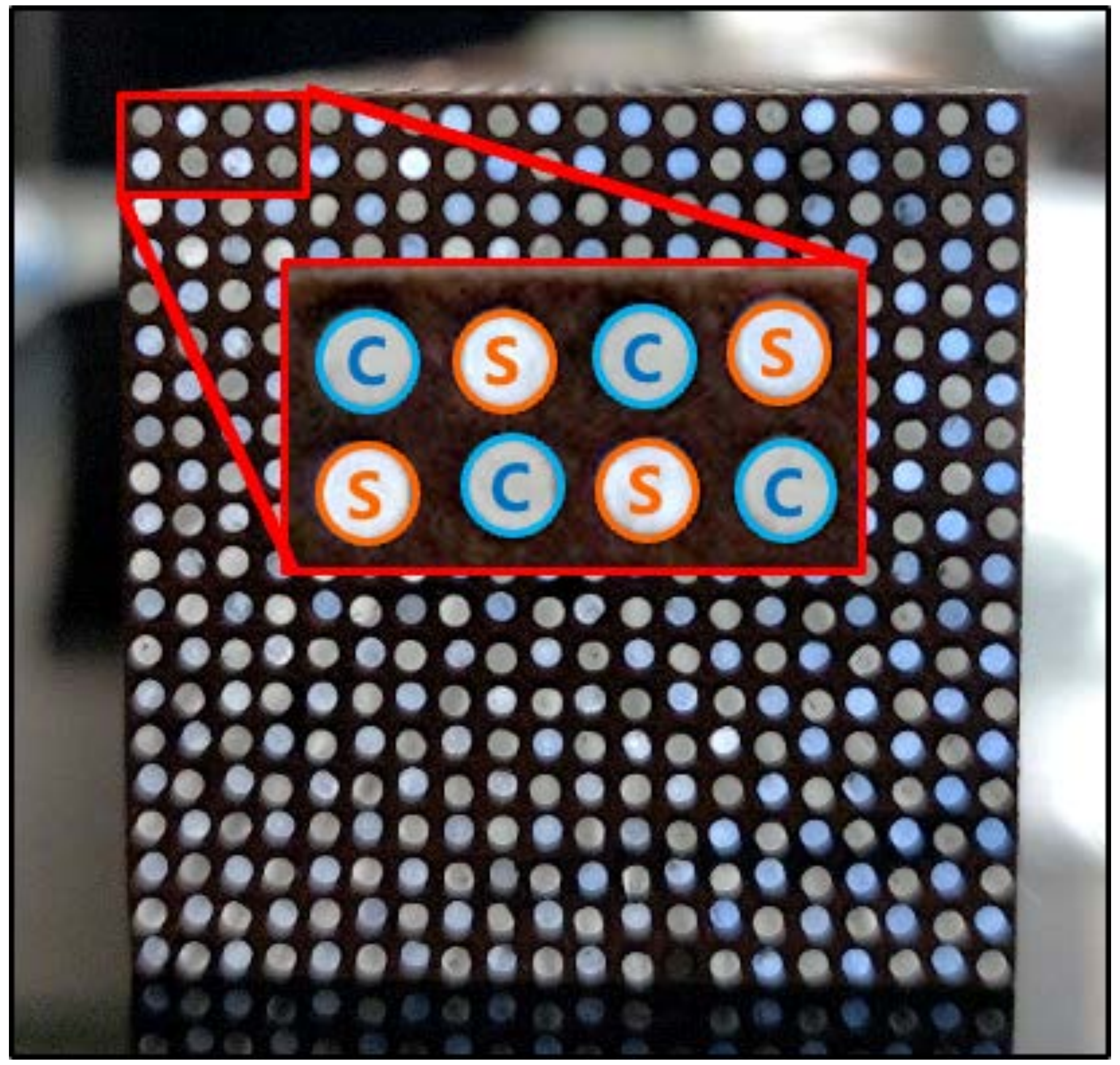


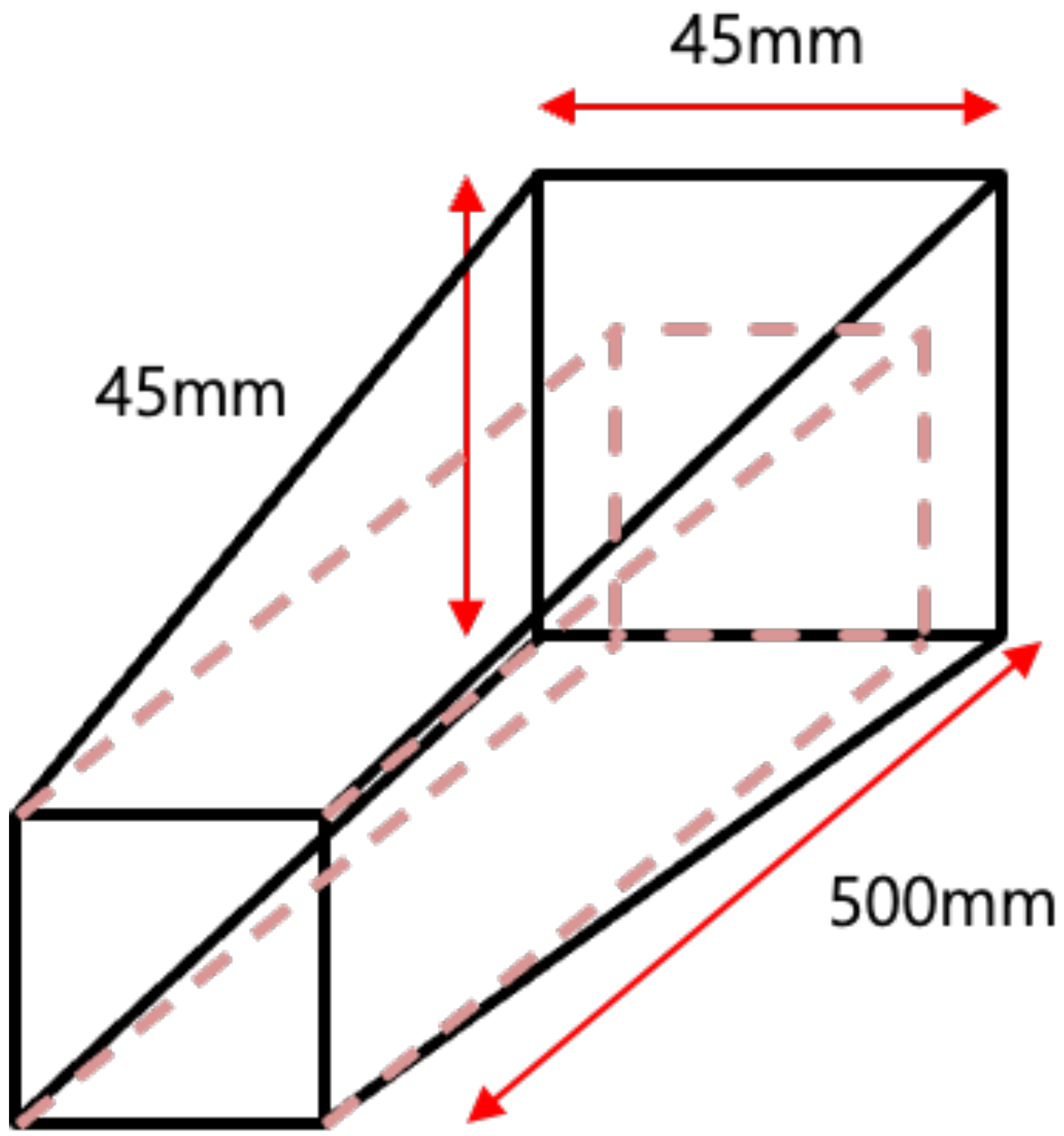
5 GeV

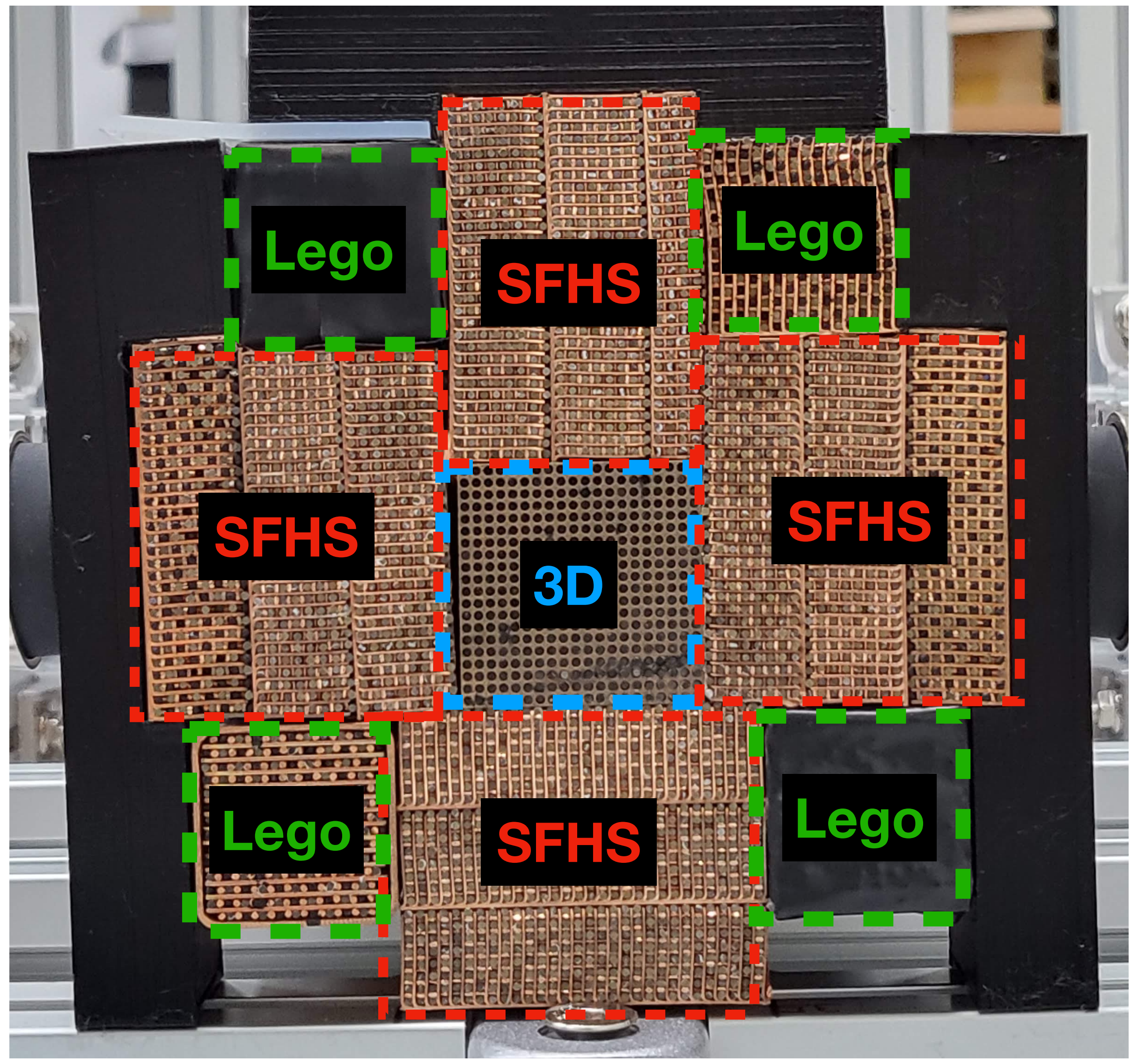
3D tower structure



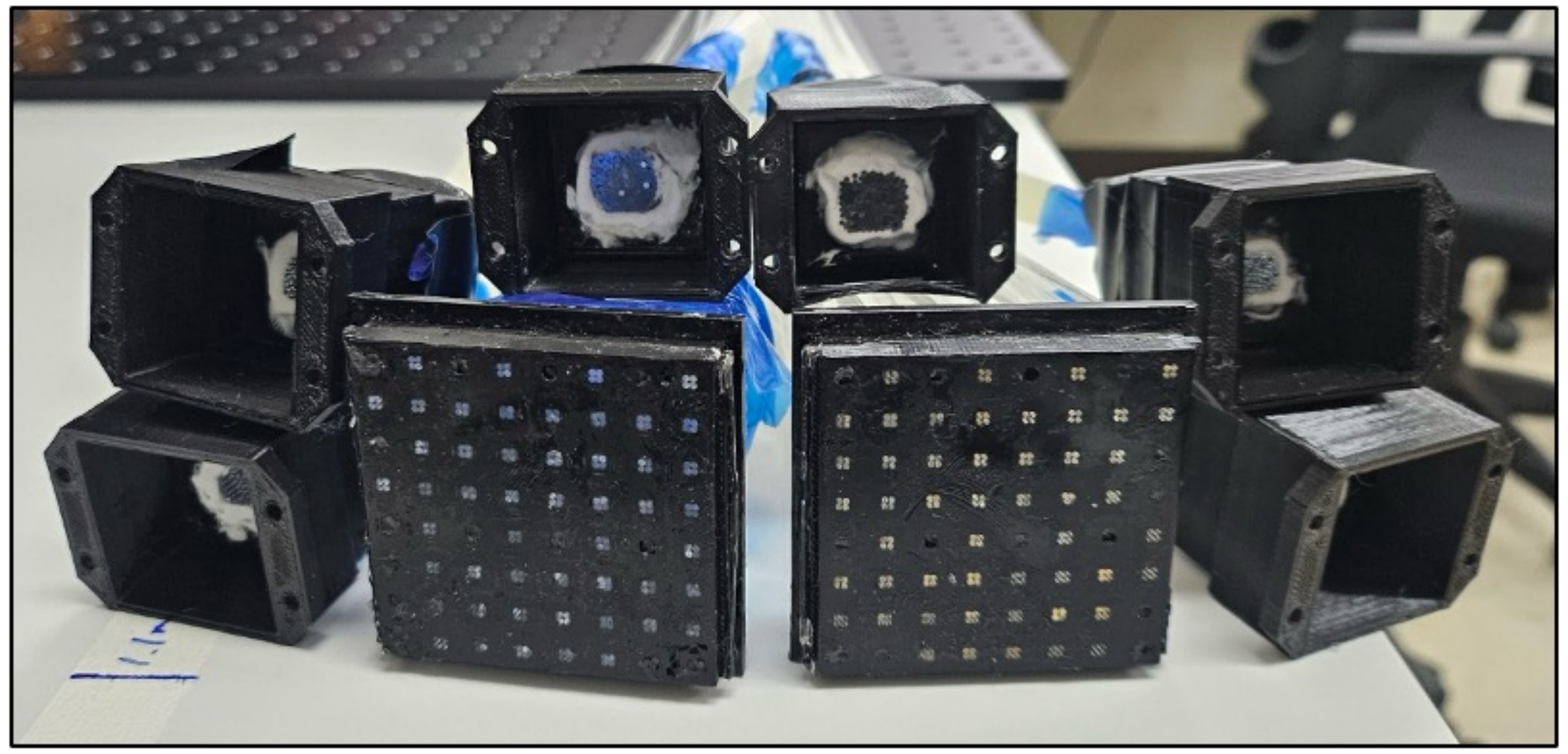
Structure of 3D-Printed Module



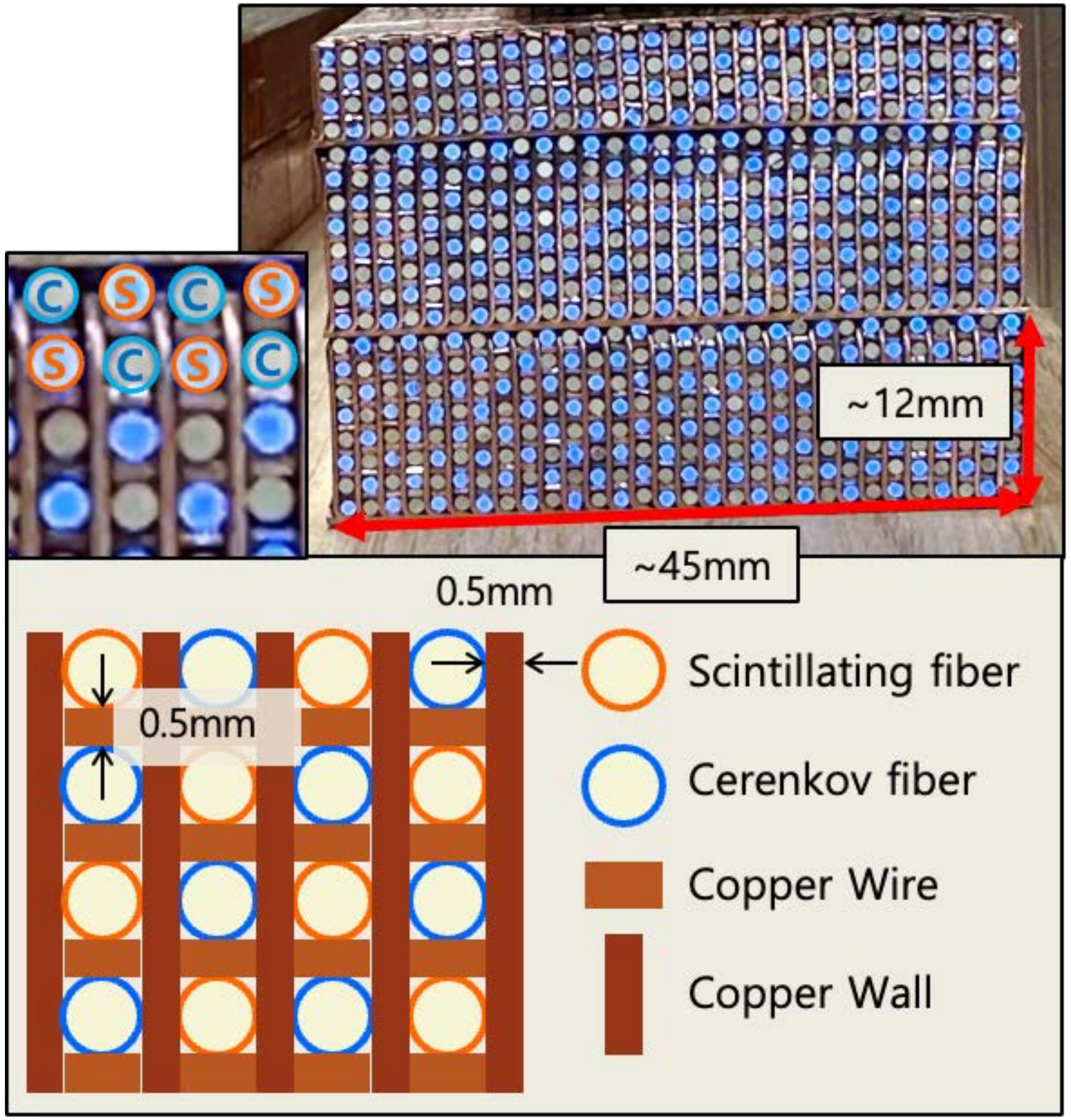


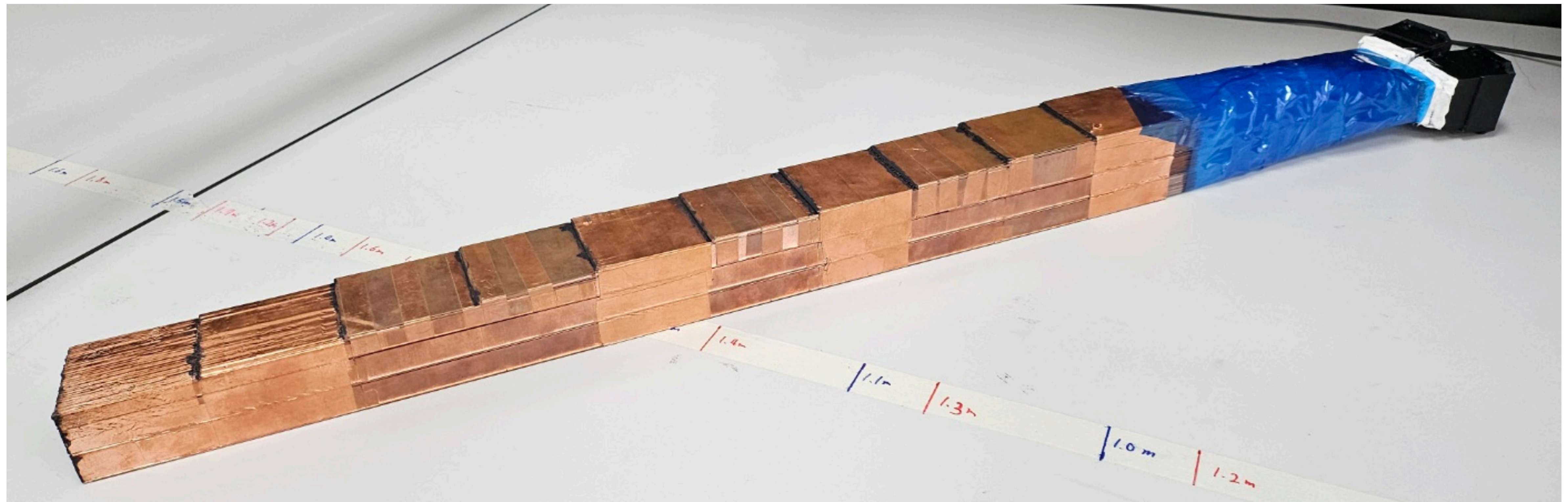


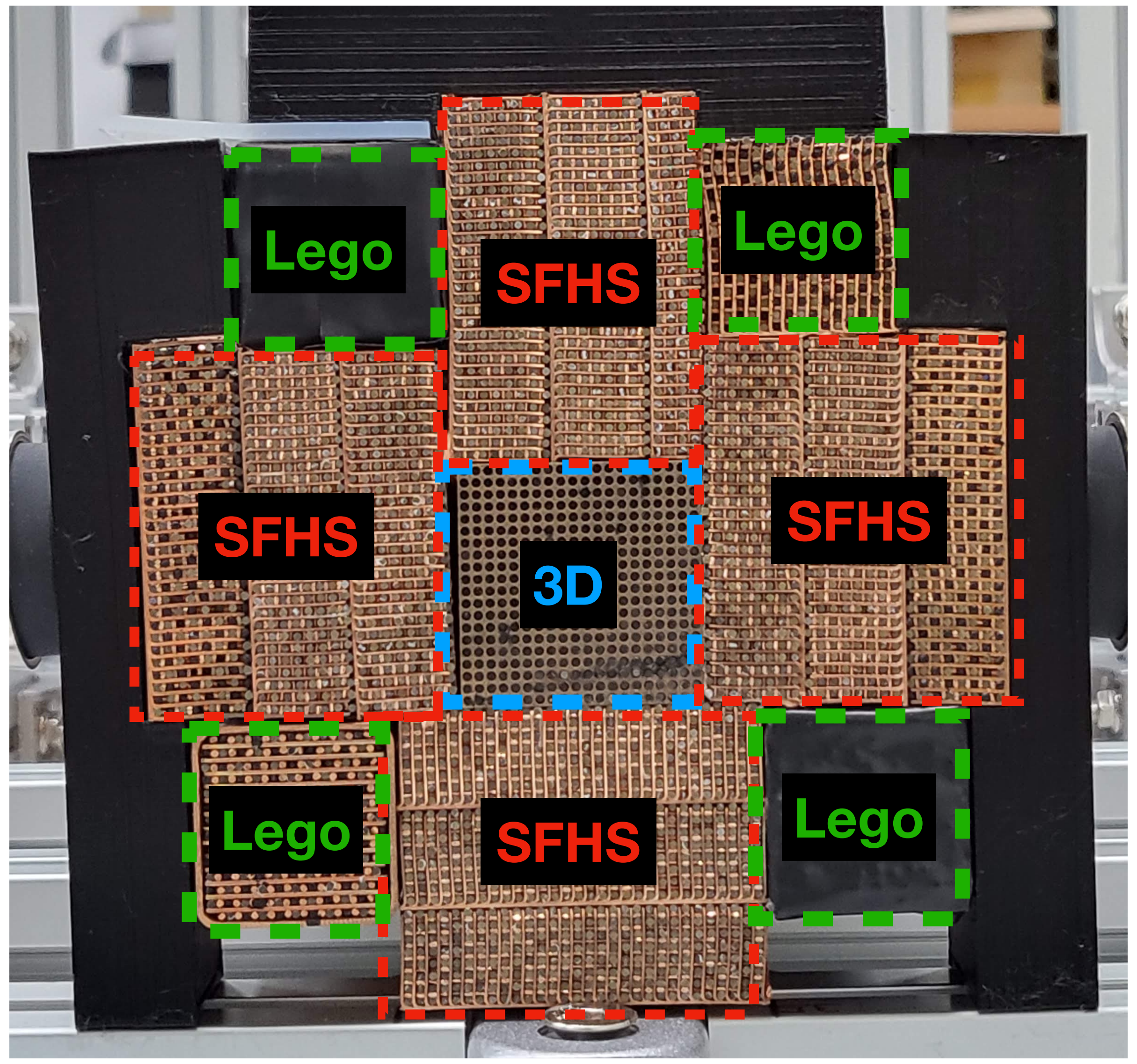
Upstream view of DRC module



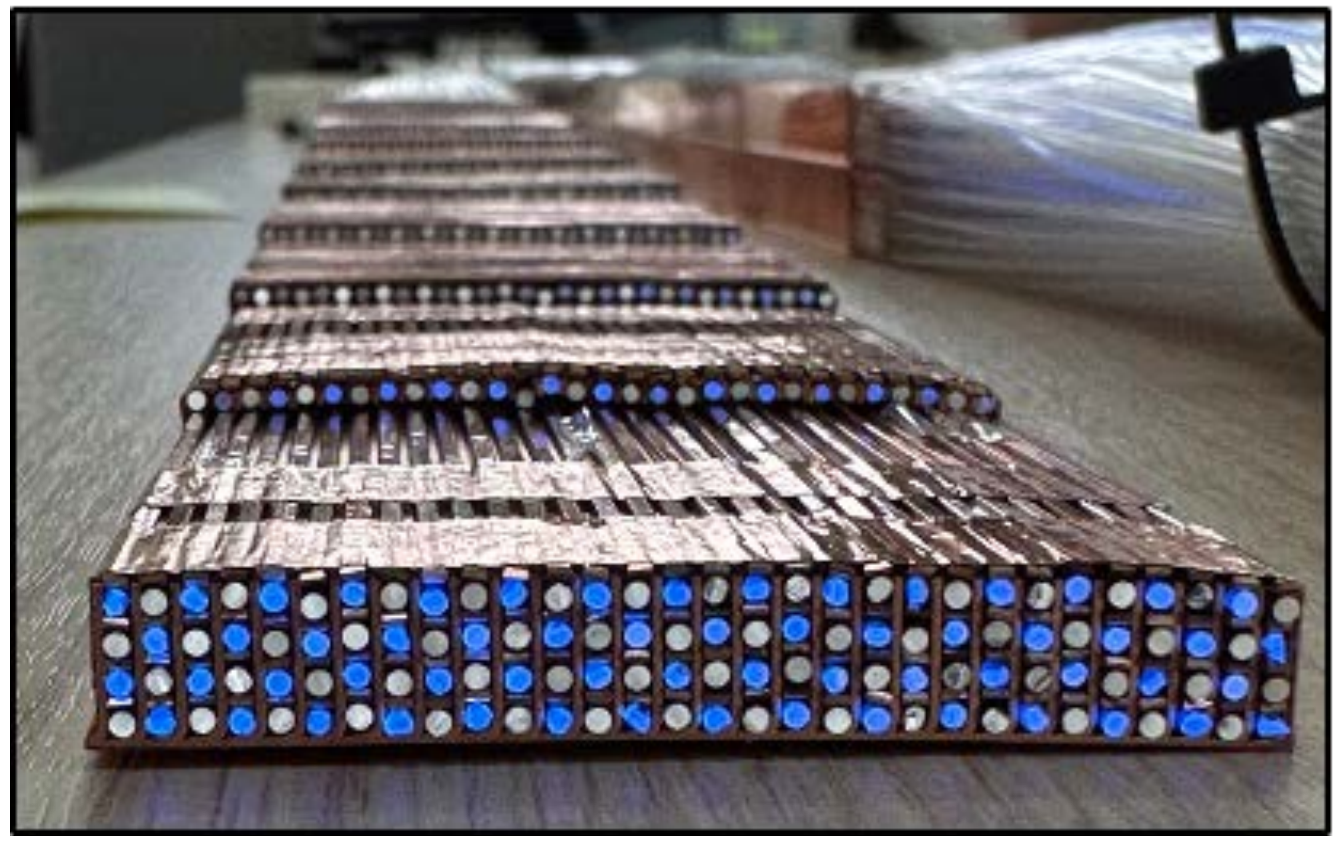
SFHS tower structure

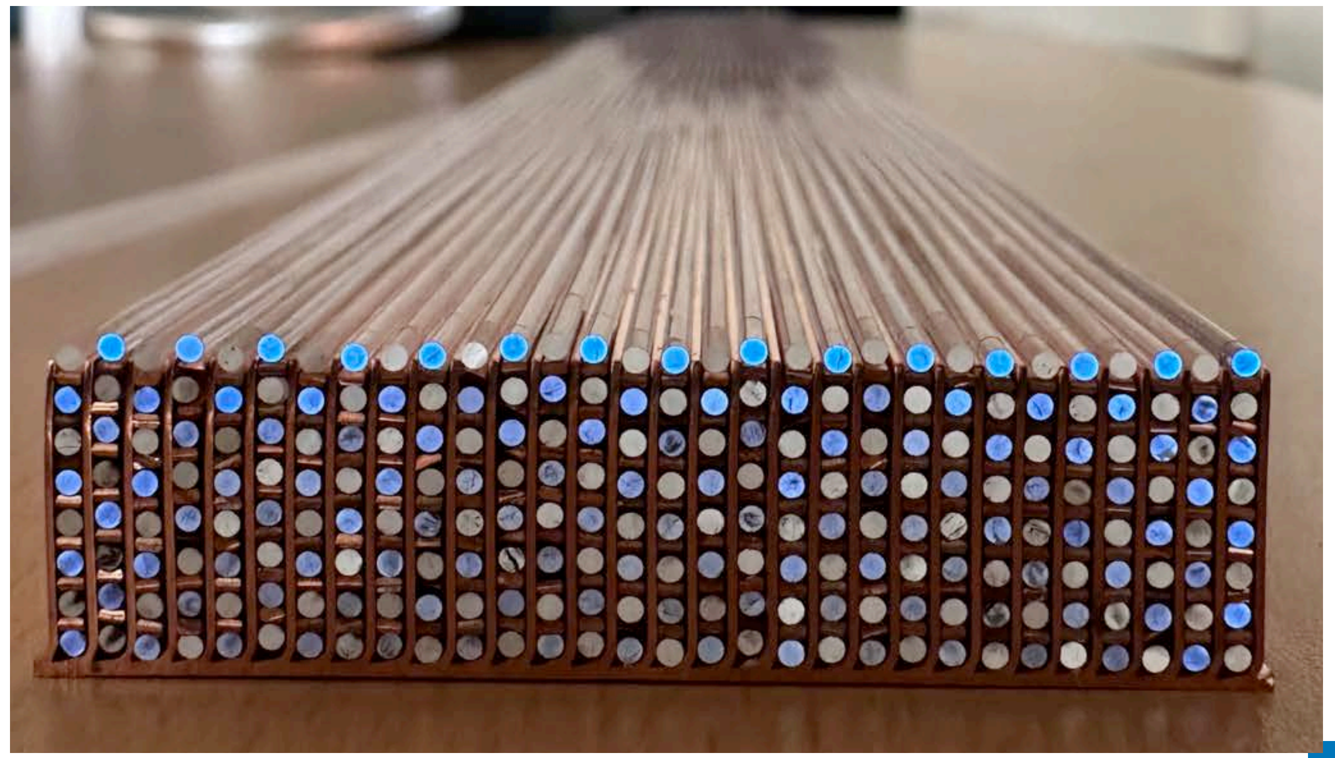




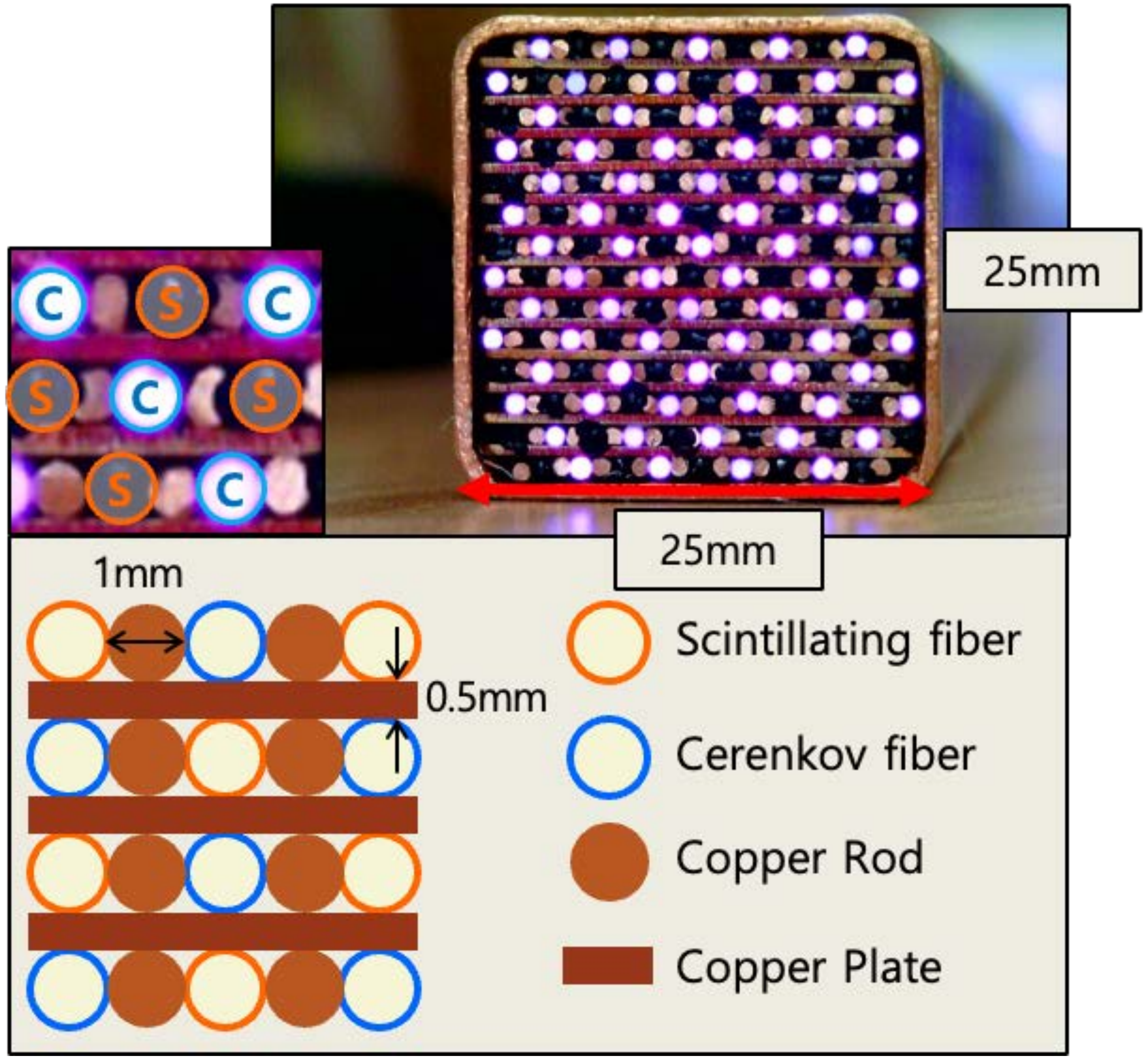


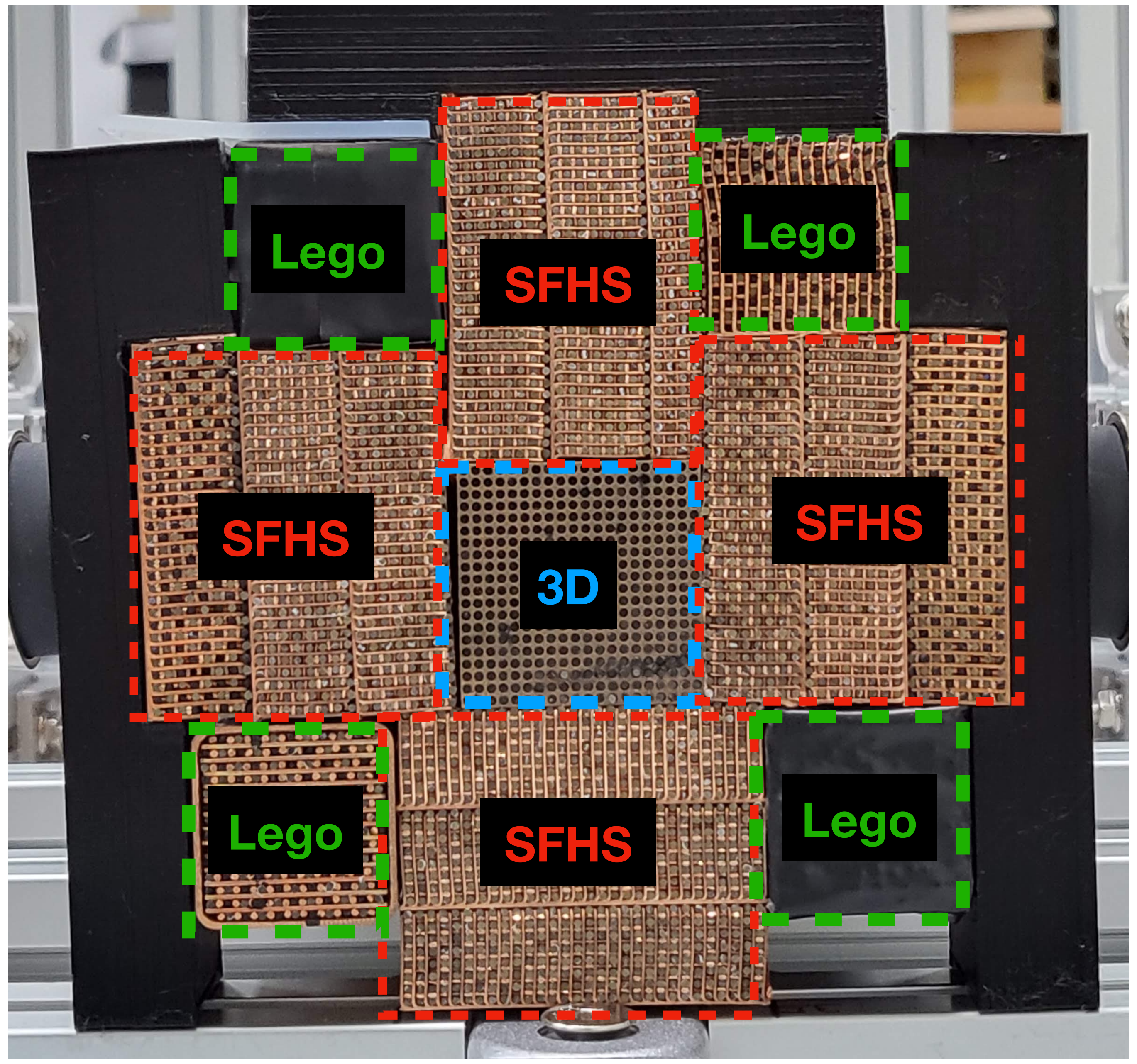
Upstream view of DRC module





Lego-like tower structure





Upstream view of DRC module