CEPC Workshop, 2025.11.08

2025 Test-Beam Experiment of Korea DRC Collaboration

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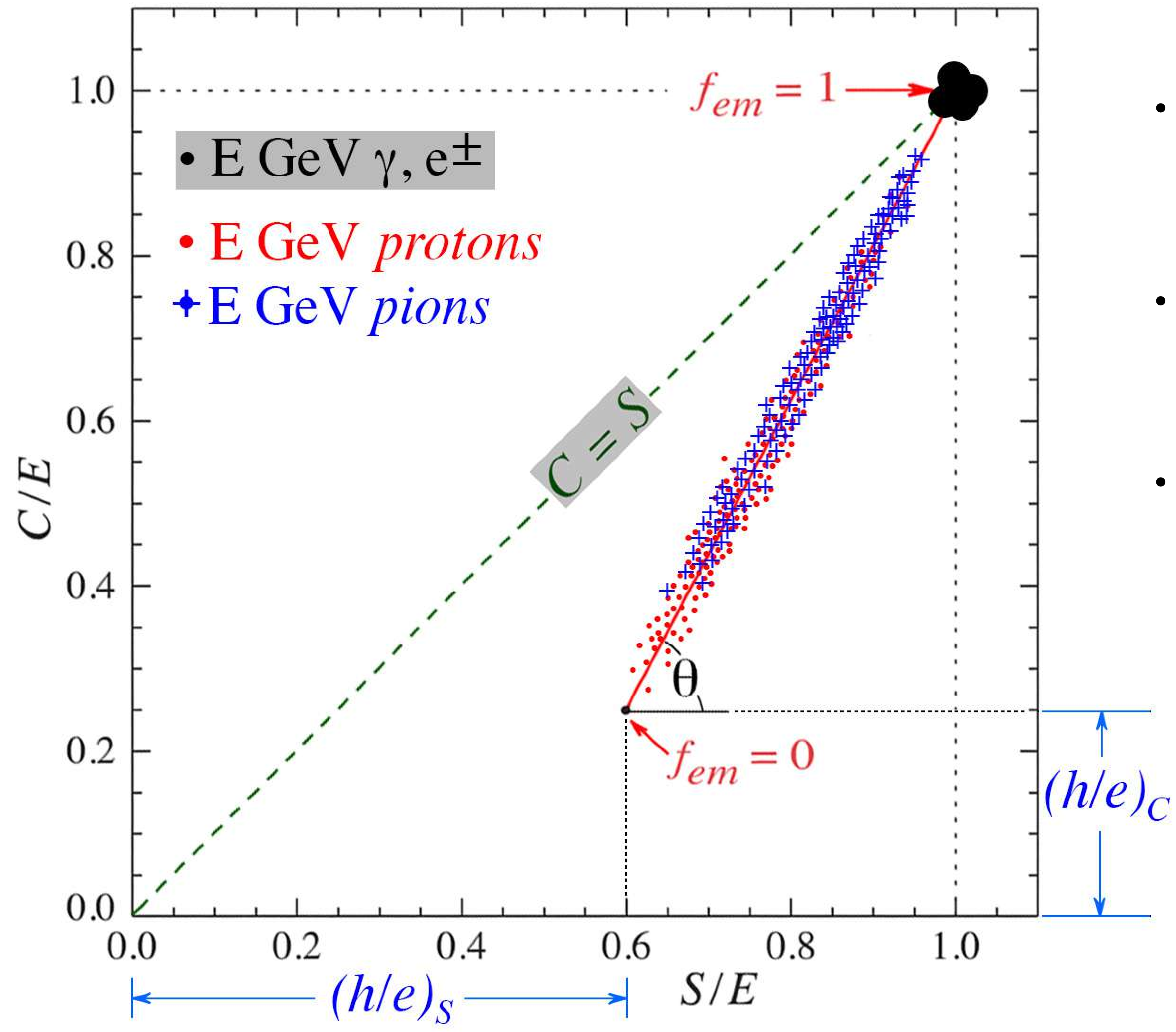
on behalf of Korea DRC Collaboration

Introduction

Dual-Readout Calorimeter

Nucl. Instrum. Meth. A 882 (2018)



Dual-Readout Calorimeter (DRC)

- EM shower component in hadron showers (f_{em}) and nuclear binding energy loss ("invisible") fluctuate **non-Gaussian**, which cause poor hadronic energy resolution
- The DRC consists of two types of optical fibers, which allow to **measure f_{em} event-by-event.**
- This feature provides **excellent hadronic energy resolution**.

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

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

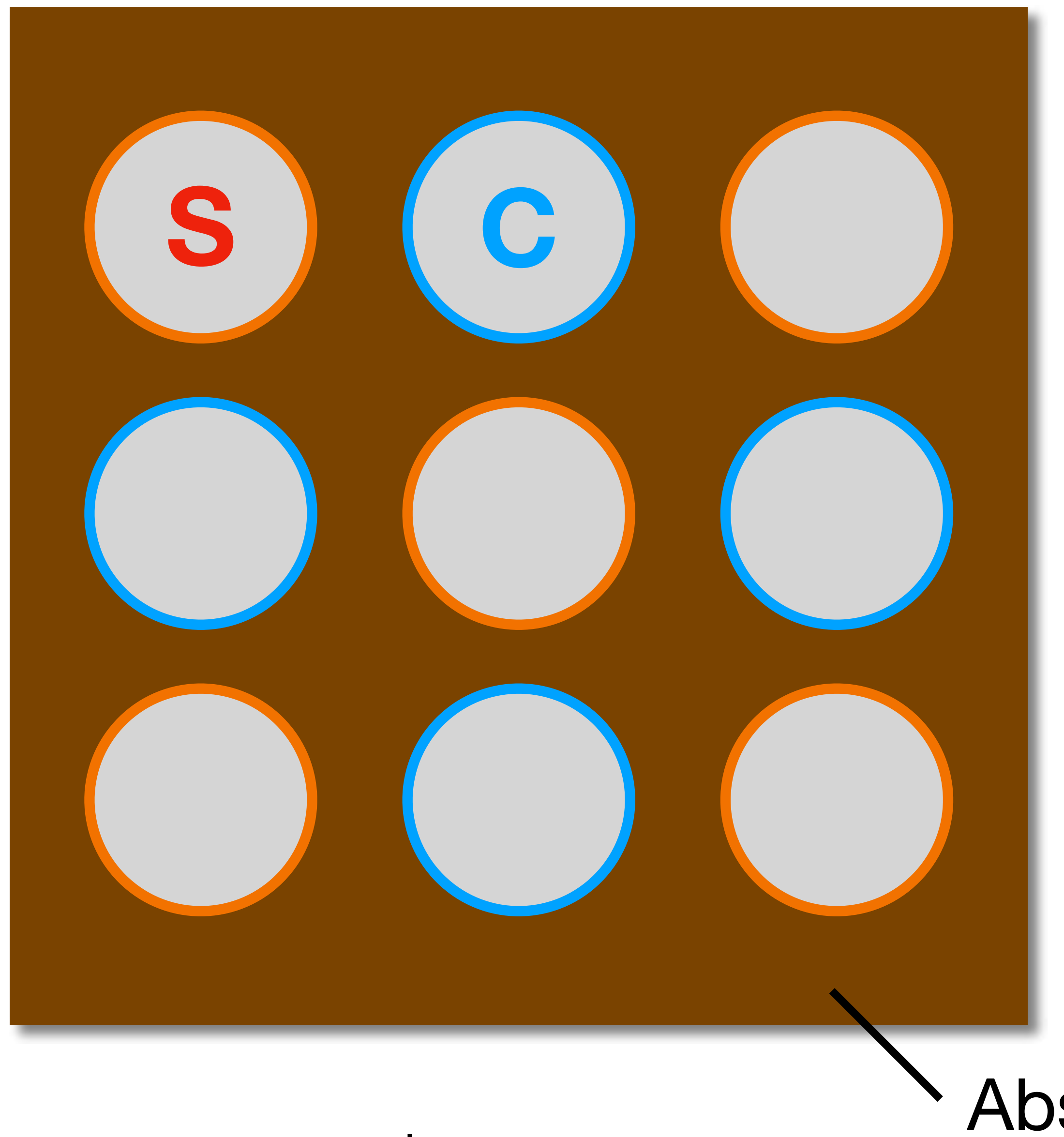
$$\chi = \frac{1 - (h/e)_S}{1 - (h/e)_C} = cot\theta$$

$$f_{em} = \frac{(h/e)_C - (C/S)(h/e)_S}{(C/S)[1 - (h/e)_S] - [1 - (h/e)_C]}$$

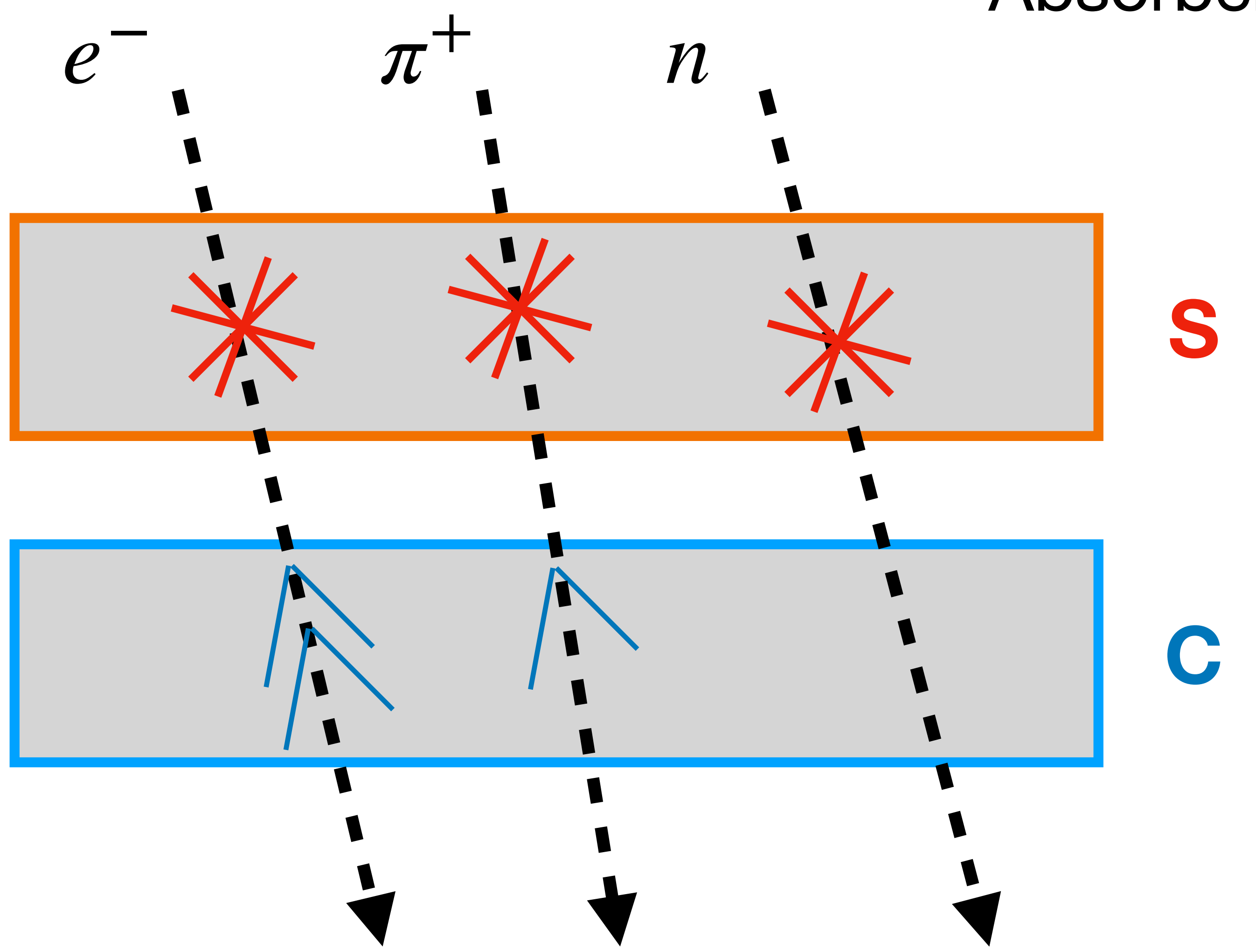
$$\boxed{E = \frac{S - \chi C}{1 - \chi}}$$

Introduction

Dual-Readout Calorimeter

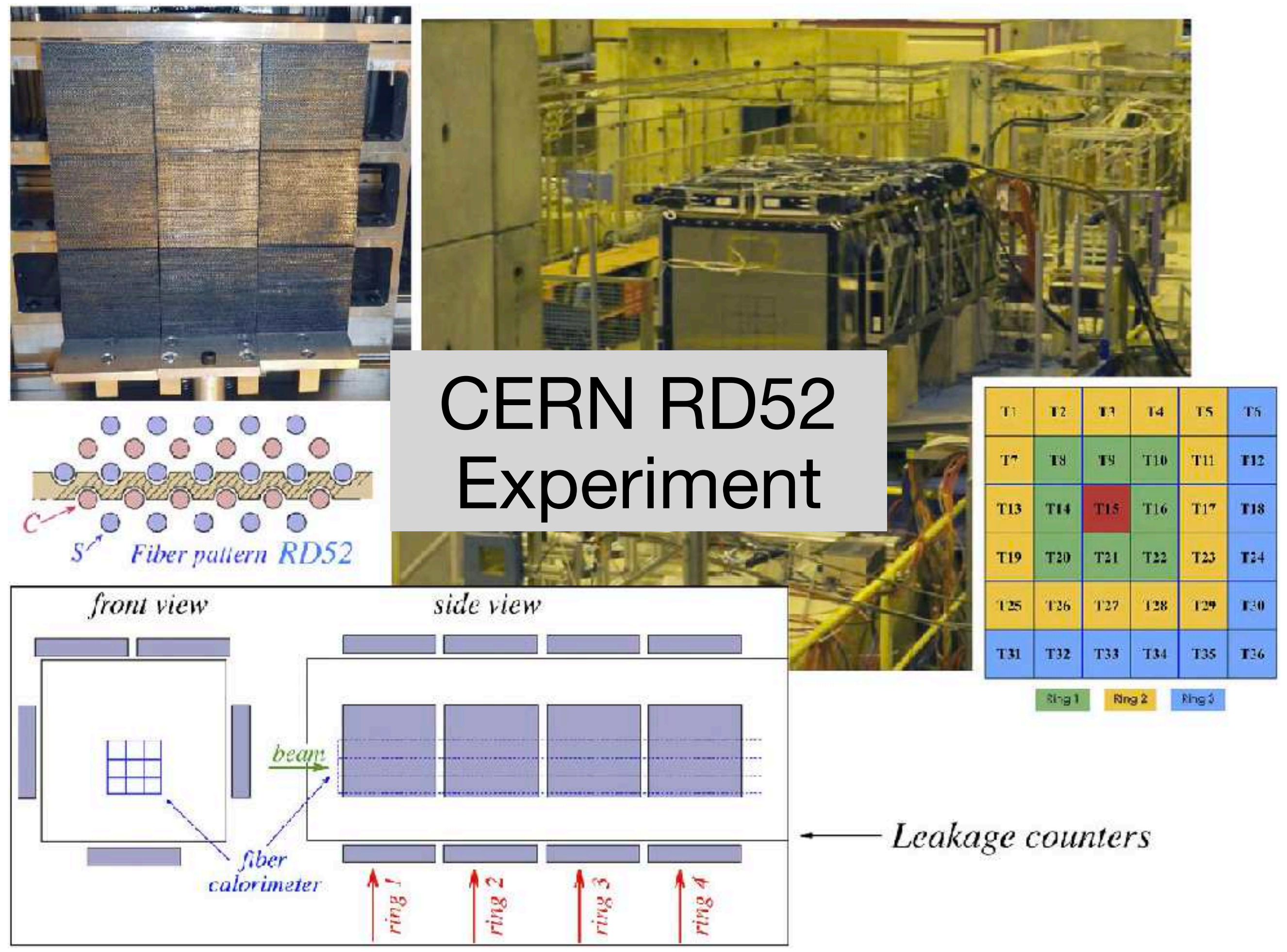


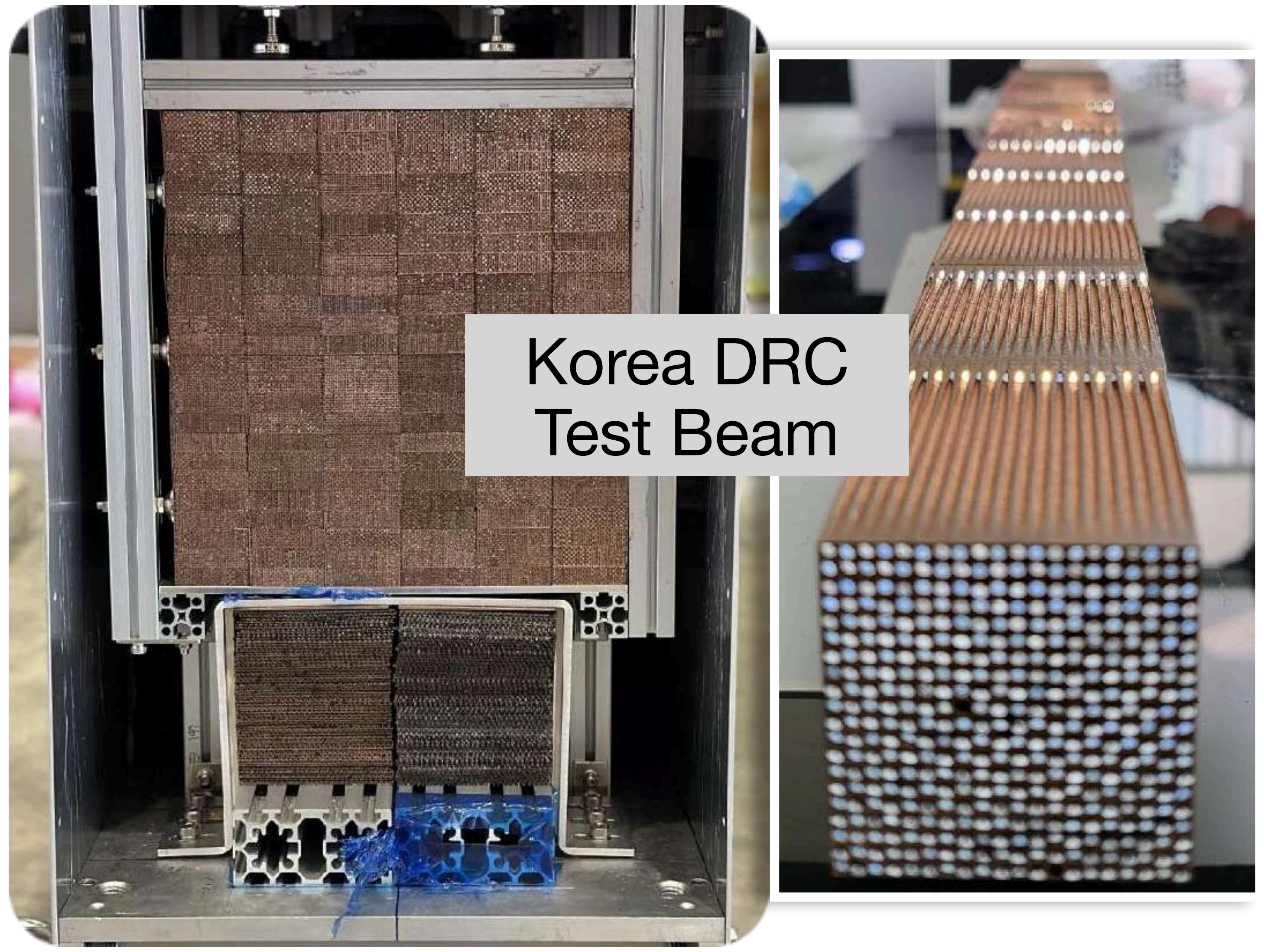
Absorber (Cu)



Optical Fiber Based DRC

- Composed of two types of optical fibers - **scintillating (S) and Cherenkov (C) fibers.**
- The absorber-scintillating fiber and absorber-Cherenkov fiber structures provide different (e/h) ratios.
- The fine absorber-fiber structure allows the achievement of ***high granularity***.
- The optical properties of fibers and the nature of the light produce within them enable ***fast timing performance***.

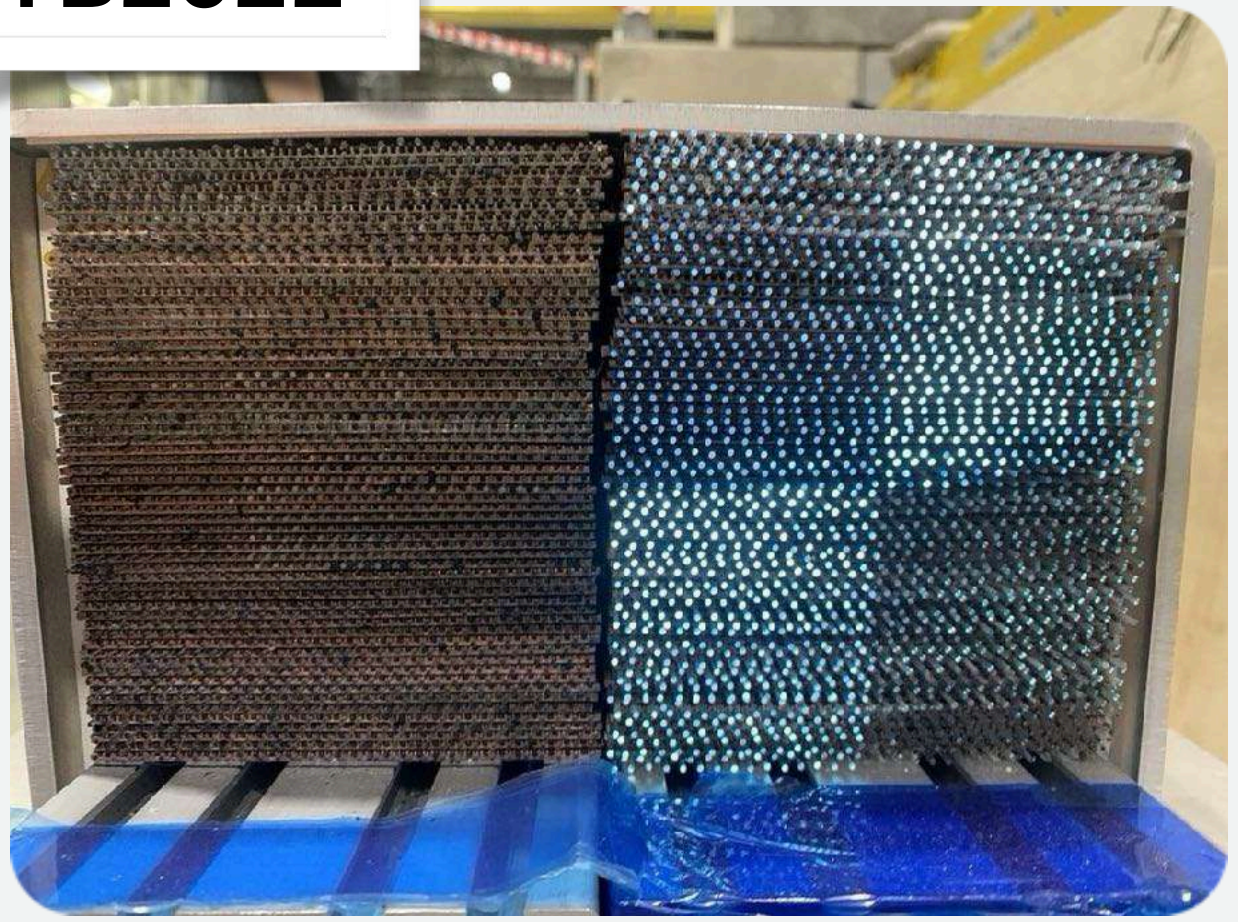


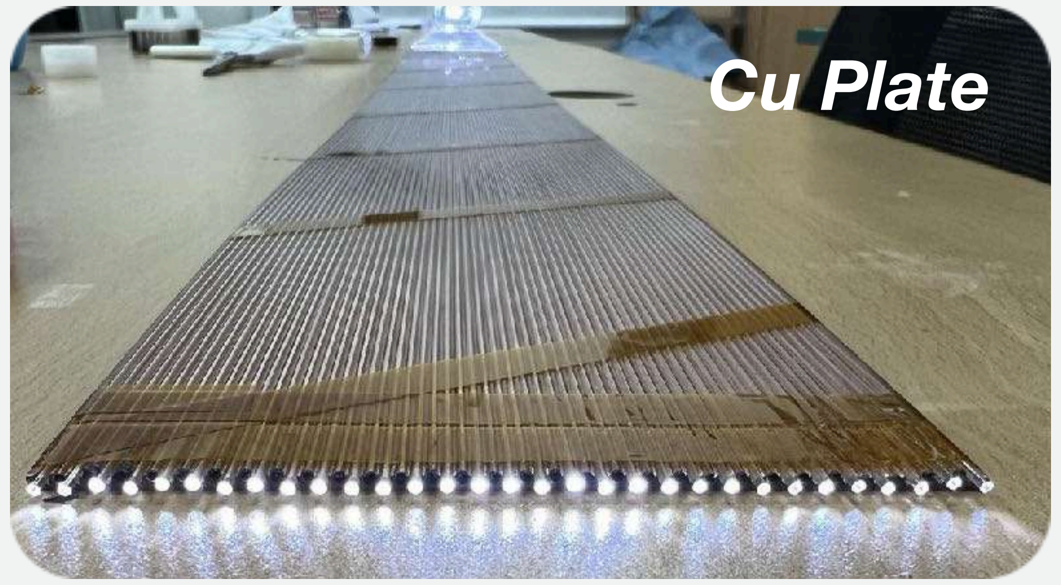


Introduction

Test Beam Experiment History of DREAM

TB2022





EM Performance Study

Cu Plate

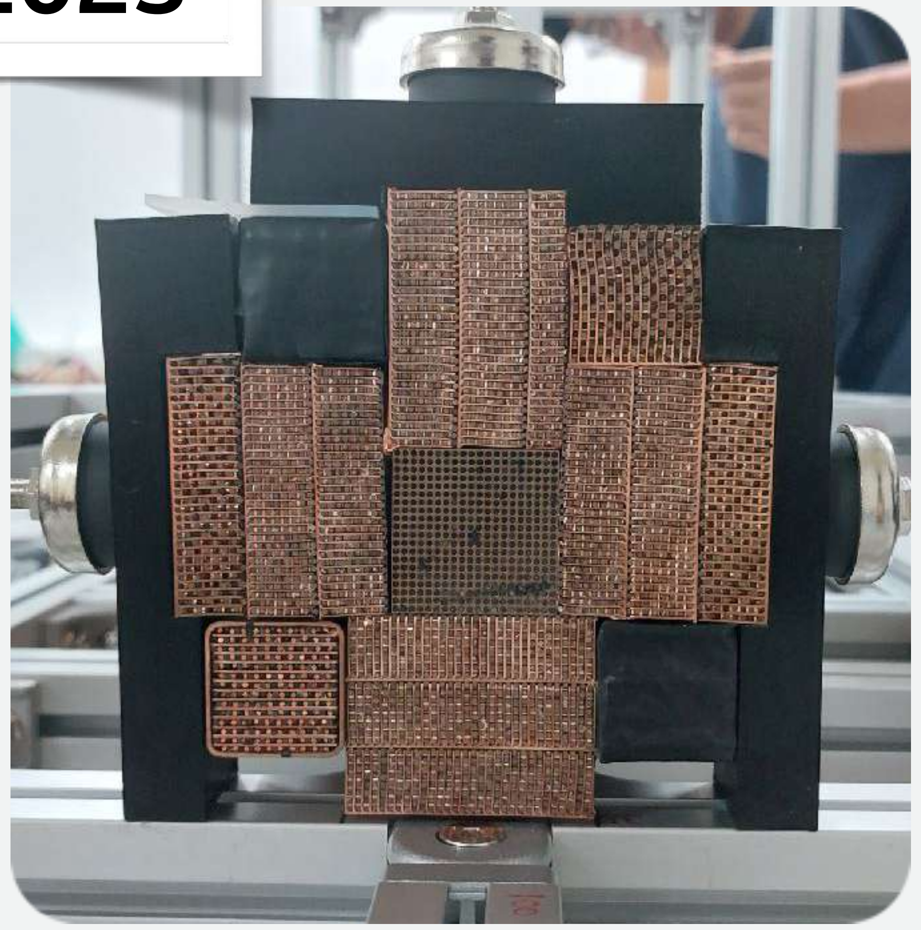
~3.5 ρ_M, > 30 X_0

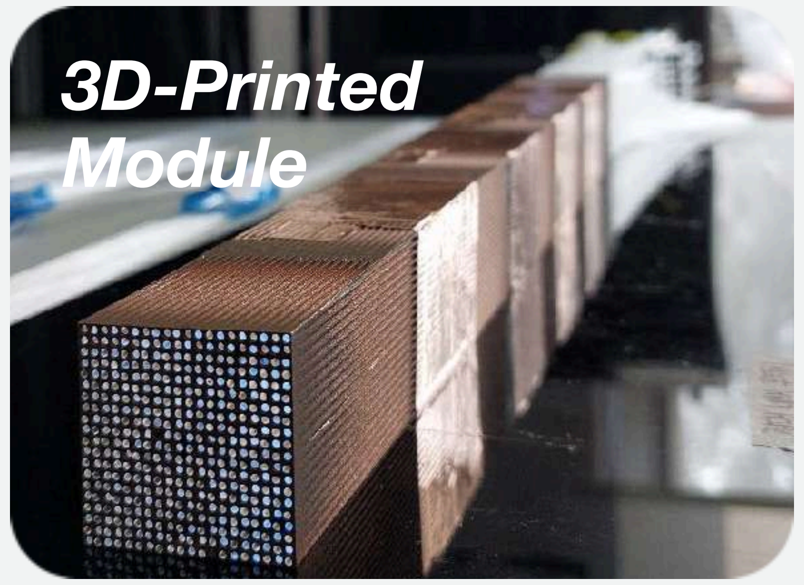
PMT, SiPM

10 ~ 120 GeV e^+

@SPS H8

TB2023





Low Energy EM Performance Study

3D-Printed Module, SFHS, Lego-Like

~3 ρ_M, ~17 X_0

PMT, MCP-PMT

0.5 ~ 5 GeV e^+

@PS T9

TB2024

EM&Hadron Performance Study

SFHS, Cu Plate

~90% lateral hadron deposit, ~10 λ_{int}

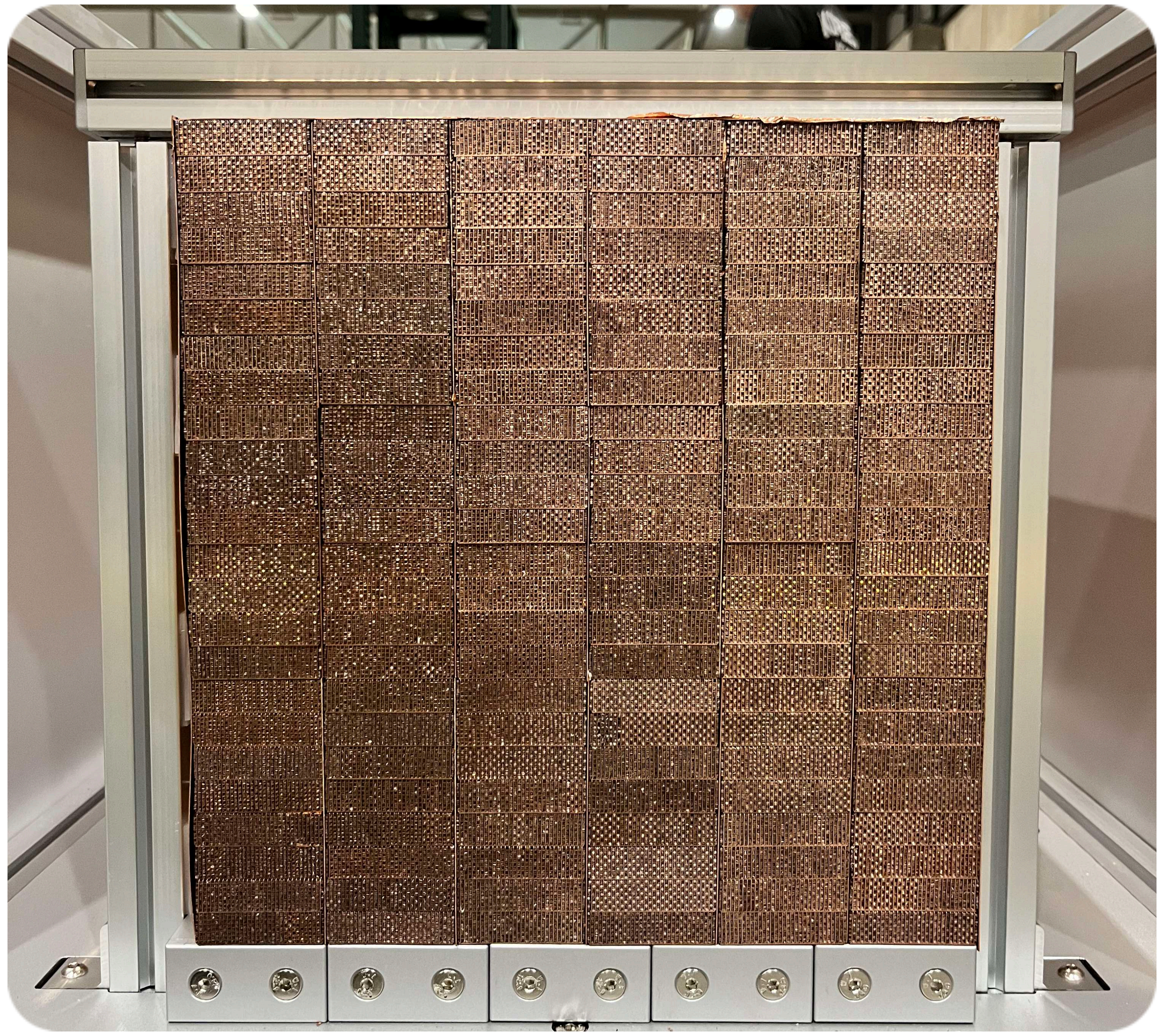
PMT, MCP-PMT, SiPM

10~120 GeV e^+, **20~120 GeV π^+**

@SPS H8

Introduction
Test Beam Experiment History of DREAM

TB2025 *this talk!*



<u>*EM & Hadronic*</u> Performance Study

Skived Fin Heat Sink (SFHS) Module

<u>Depth 2.5 m (~10 λ_{int})</u>

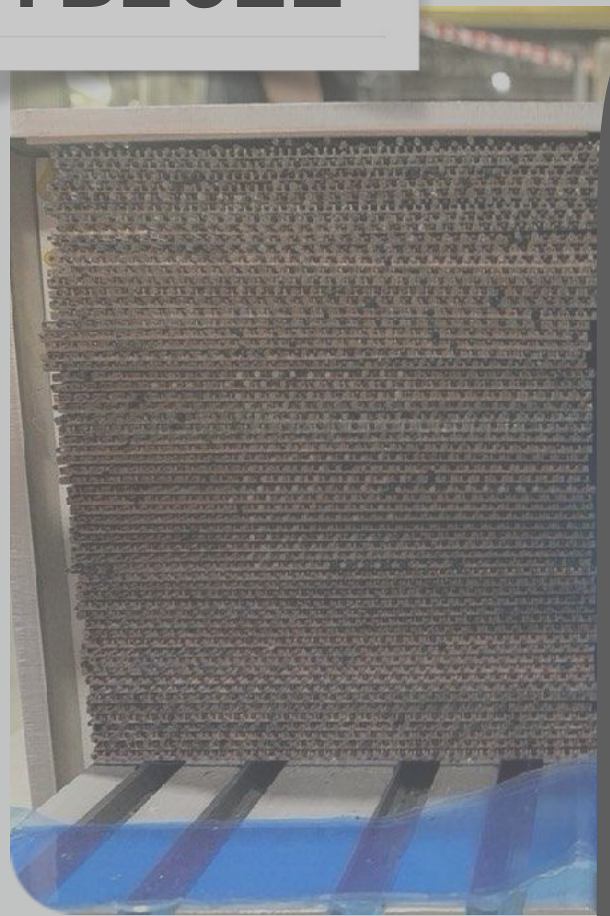
<u>Effective radius 17 cm (~0.8 λ_{int})</u>

PMT, MCP-PMT

10~120 GeV e^+, <u>20~120 GeV hadrons</u>

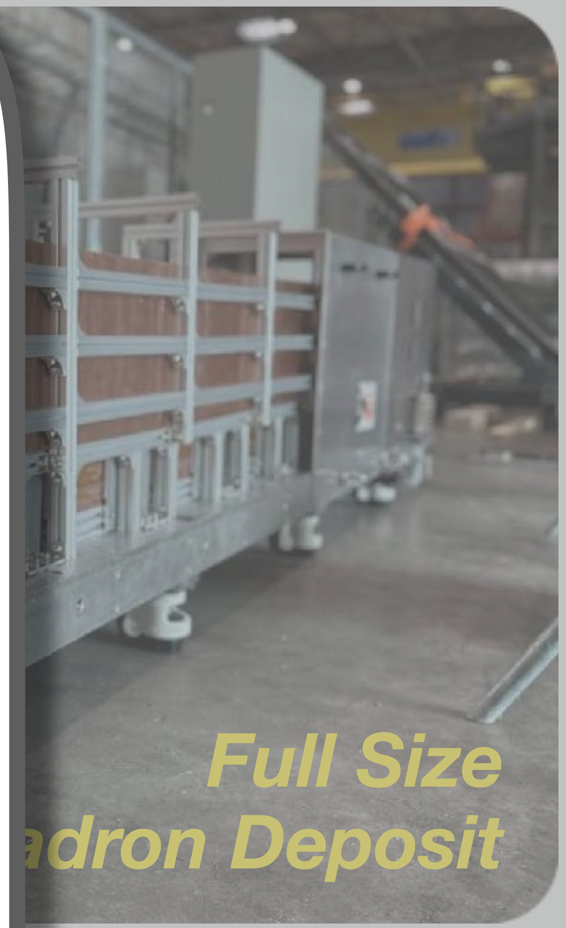
<u>**Many UPGRADES beyond TB2024**</u>

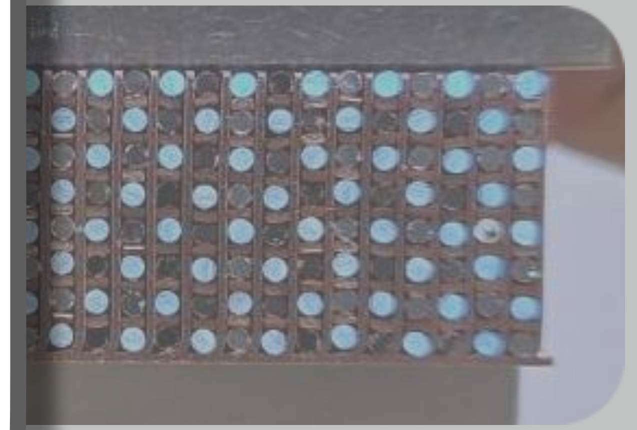
TB2022



<u>**EM Perform**</u>
Cu Pla
~3.5 ρ_M, > 30 X_0
PMT, SiPM
10 ~ 120 GeV e^+
@SPS H8

~3 ρ_M, ~17 X_0
PMT, MCP-PMT
<u>**0.5 ~ 5 GeV e^+**</u>
@PS T9

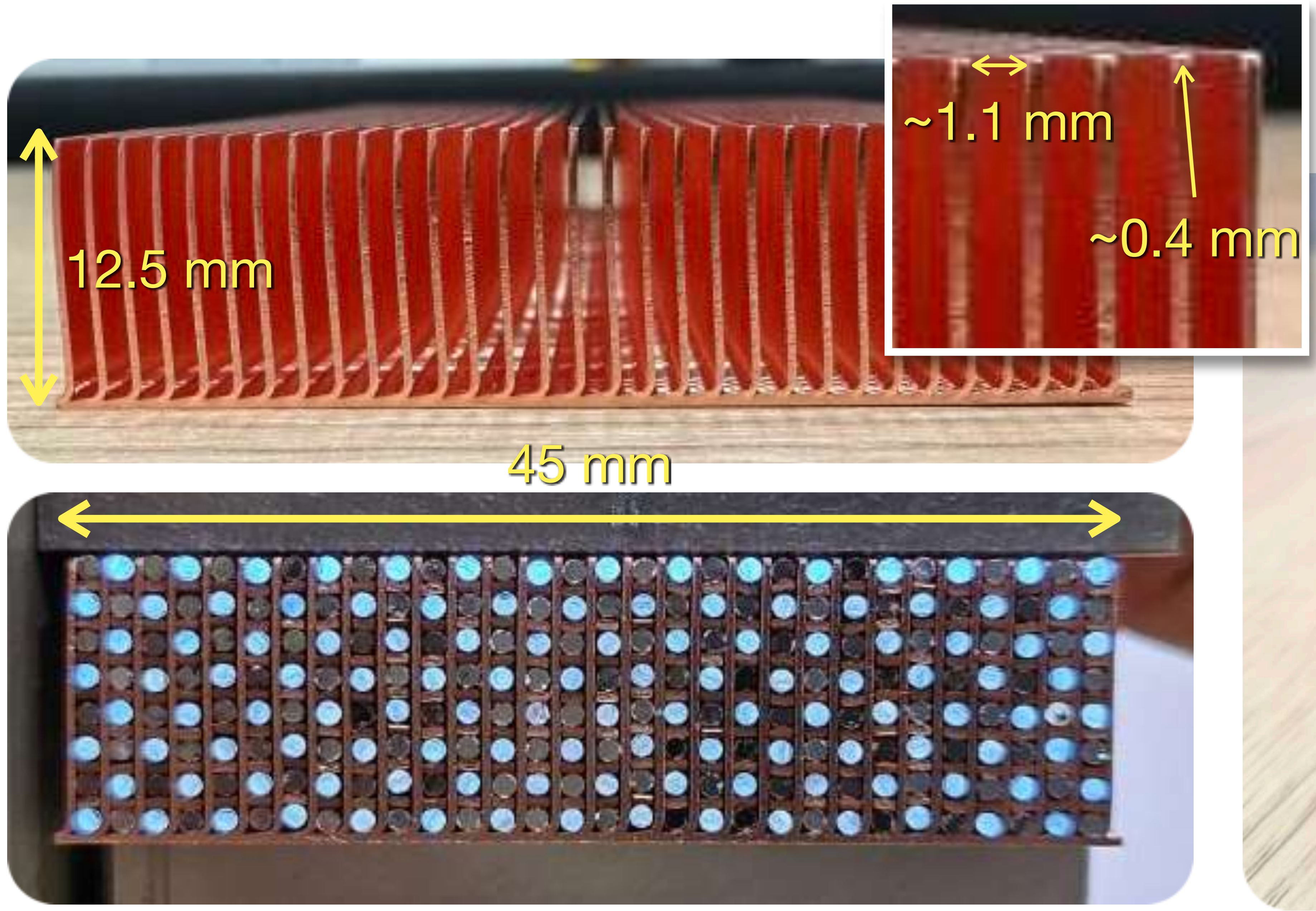




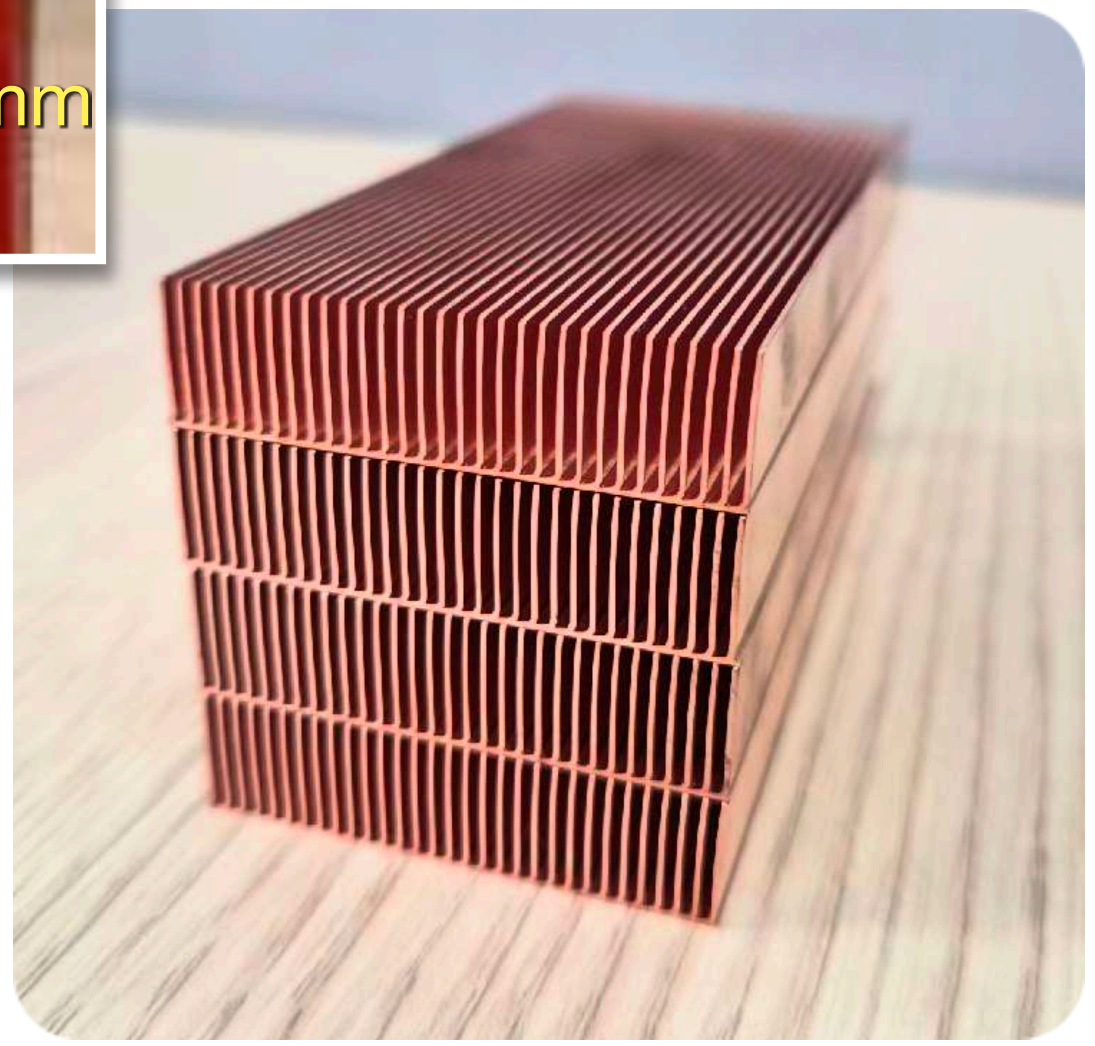
<u>**rformance Study**</u>
, Cu Plate
<u>**~90% lateral hadron deposit, ~10 λ_{int}**</u>
PMT, MCP-PMT, SiPM
10~120 GeV e^+, <u>**20~120 GeV π^+**</u>
@SPS H8

Module for TB2025

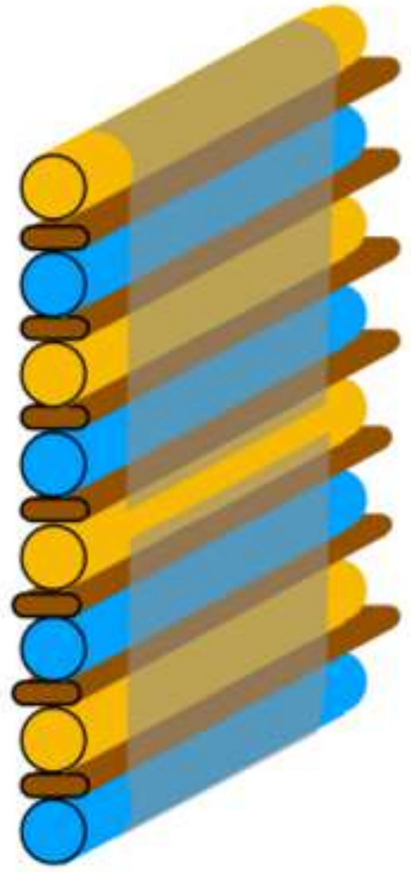
Skived Fin Heat Sink (SFHS) Module

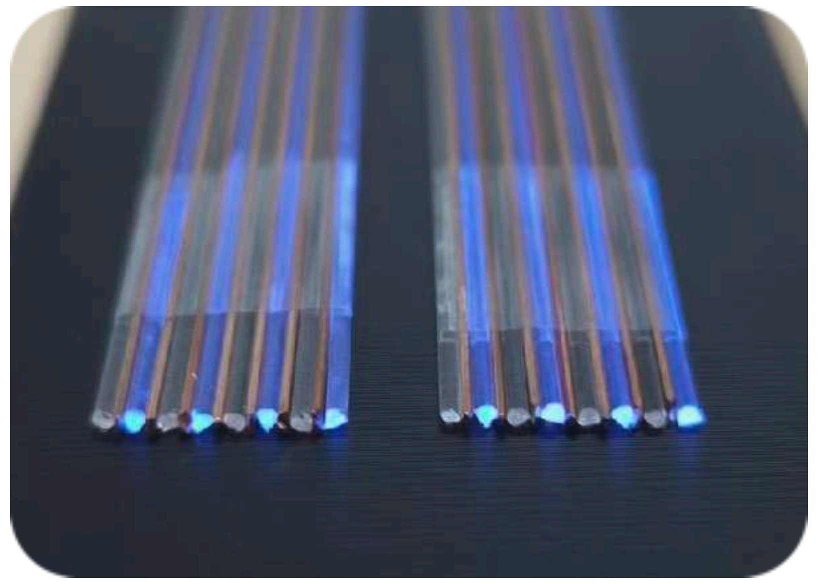


Tower Unit (x 36)

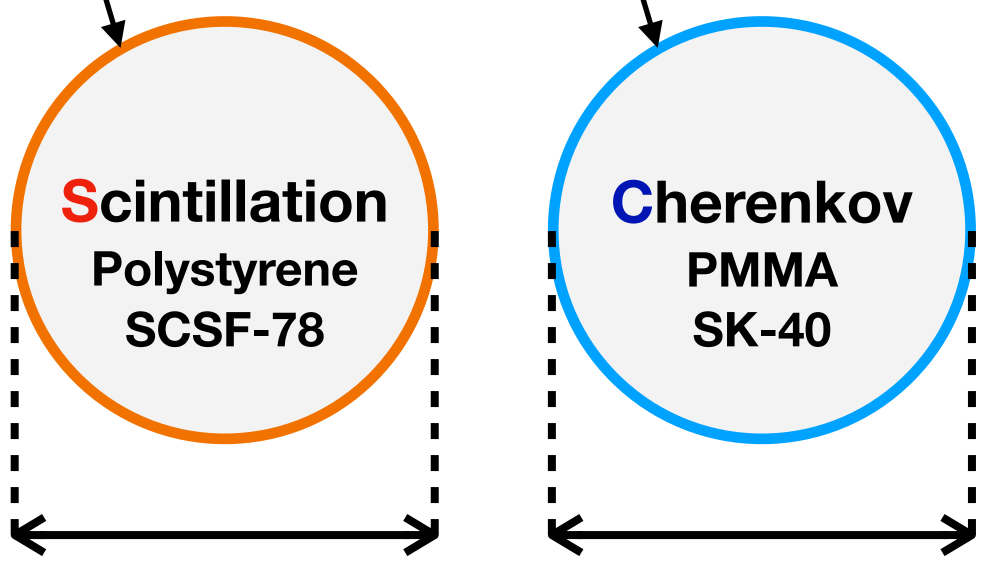


- ***Cu + Optical Fiber*** (SCSF-78 [S], SK-40 [C]) geometry.
  total ~28 km
- 30 cm × 30 cm × 250 cm (~***10*** λ_{int})
- Longitudinally ***unsegmented***





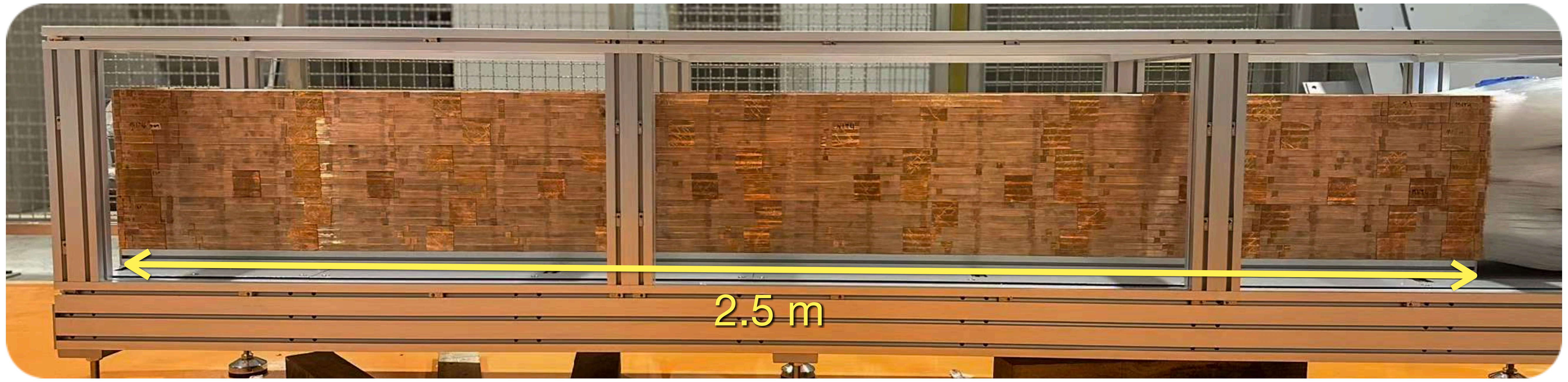
Layer Unit (x 1152)

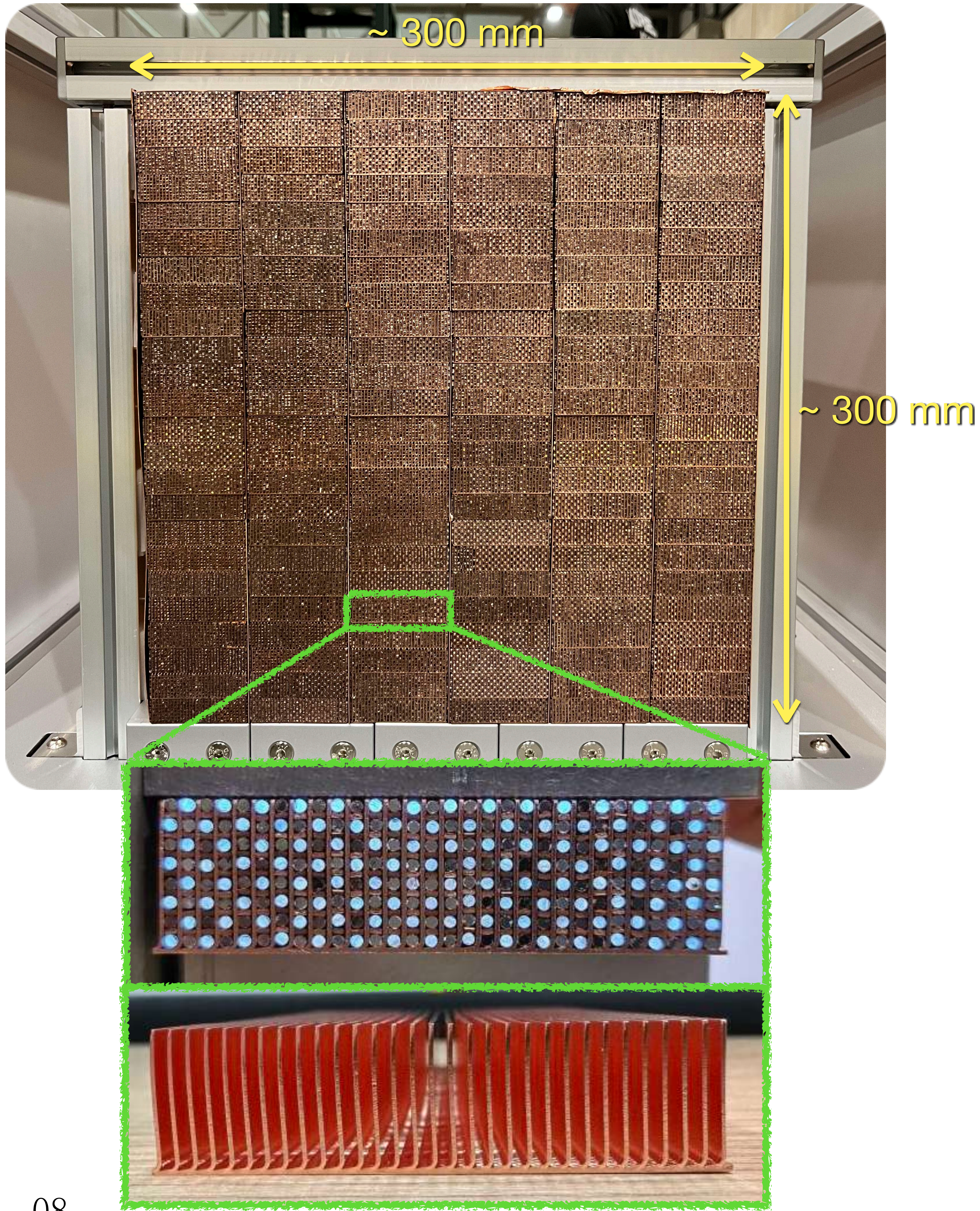


Module for TB2025

Calorimeter Geometry

*TB2025 Update
Same detector of TB2024,
but <u>new mechanical supporter</u>

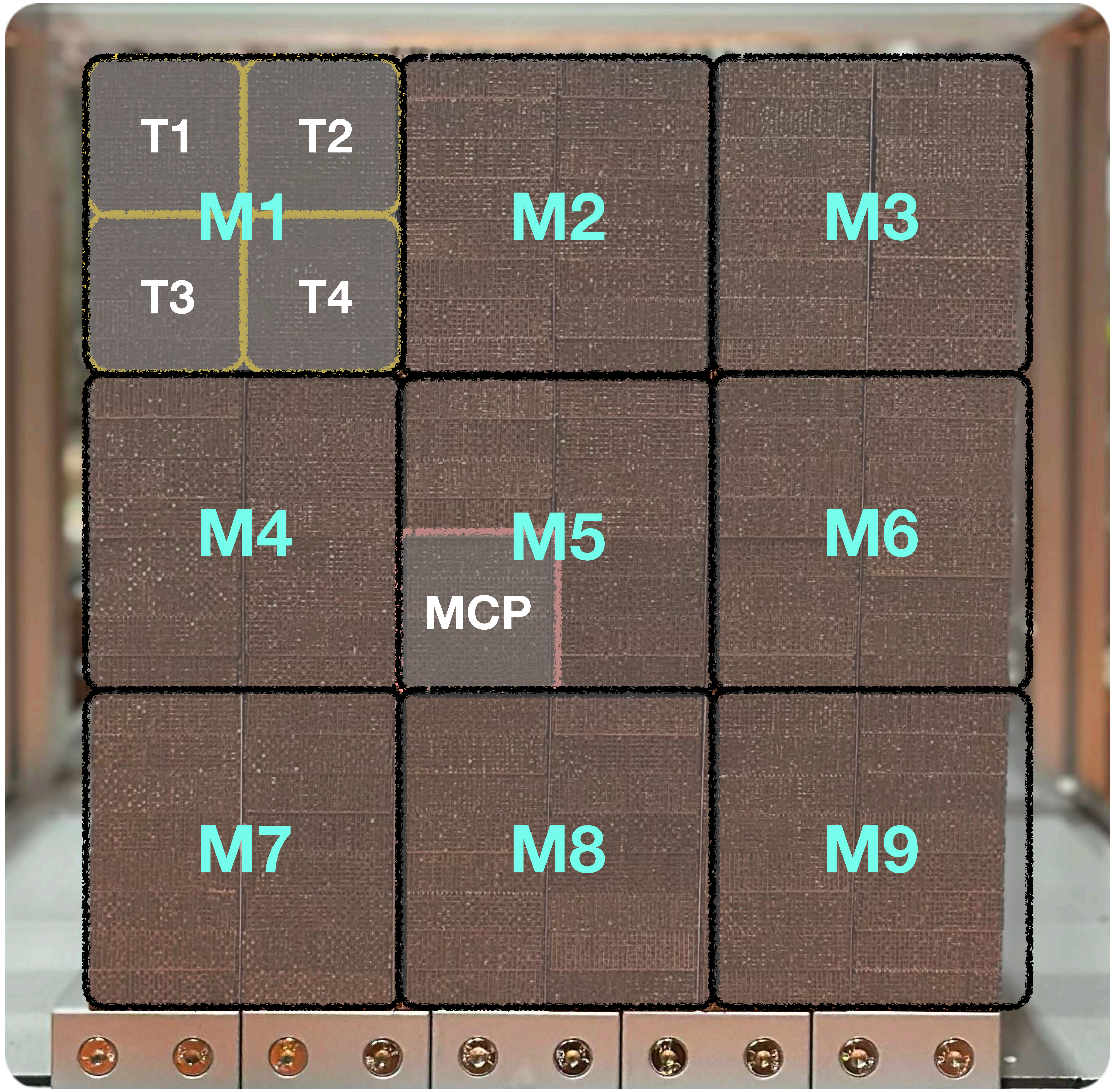


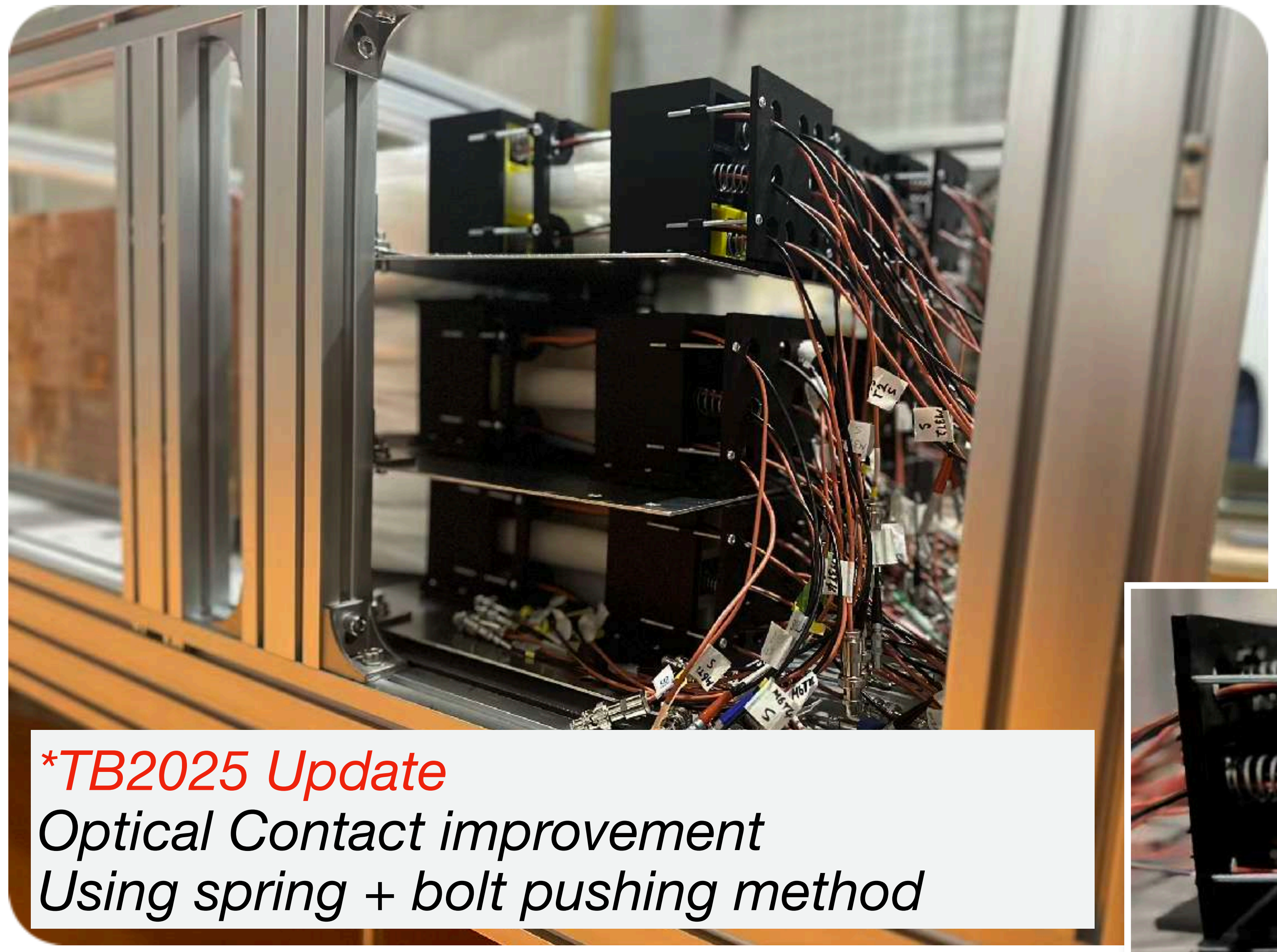


Module for TB2025

Readout Detectors

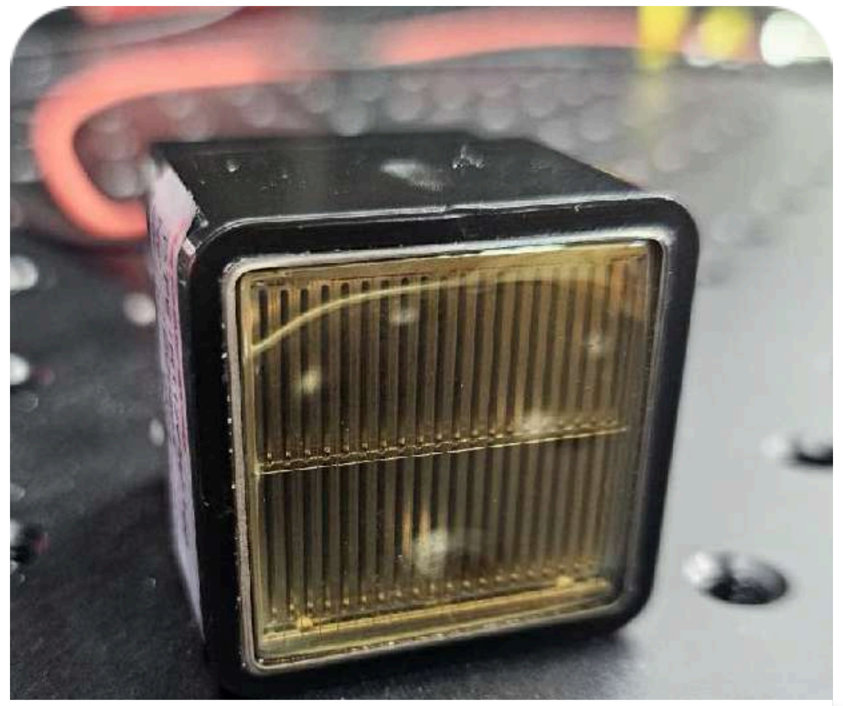
*Total **200** (MCP : **128+2**, PMT : **70**) channels*

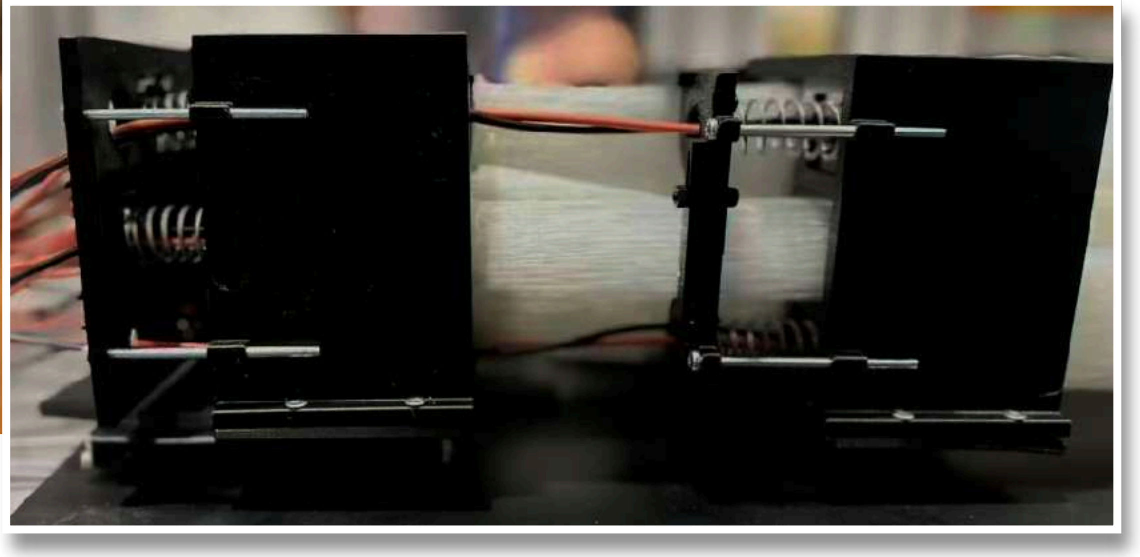




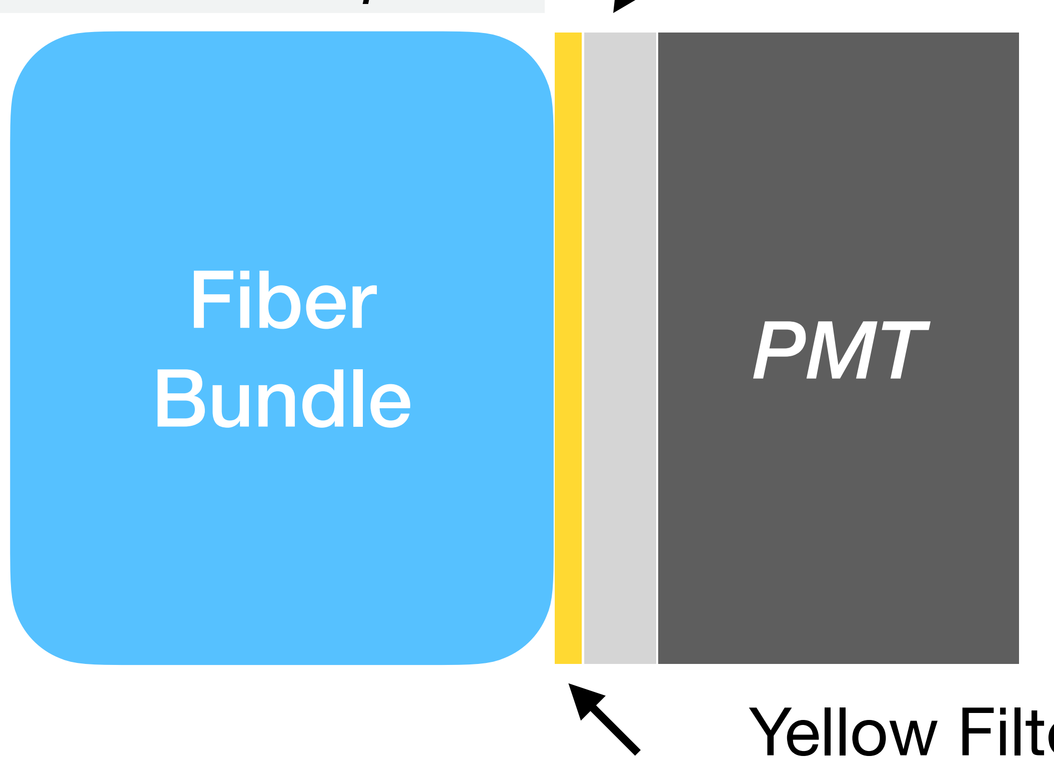
**TB2025 Update*
Optical Contact improvement
Using spring + bolt pushing method

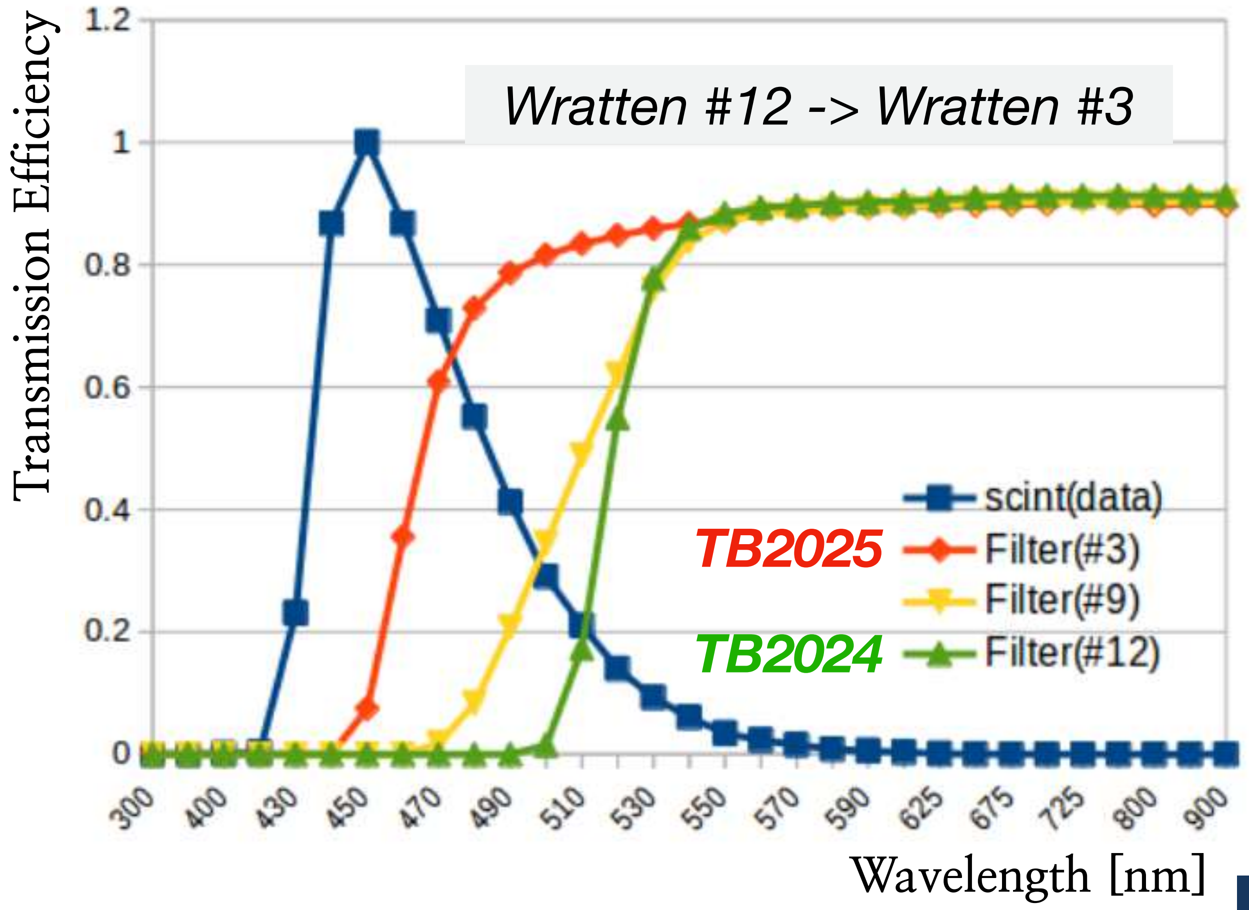
PMT (R11265-100)





**TB2025 Update*
Yellow Filter update

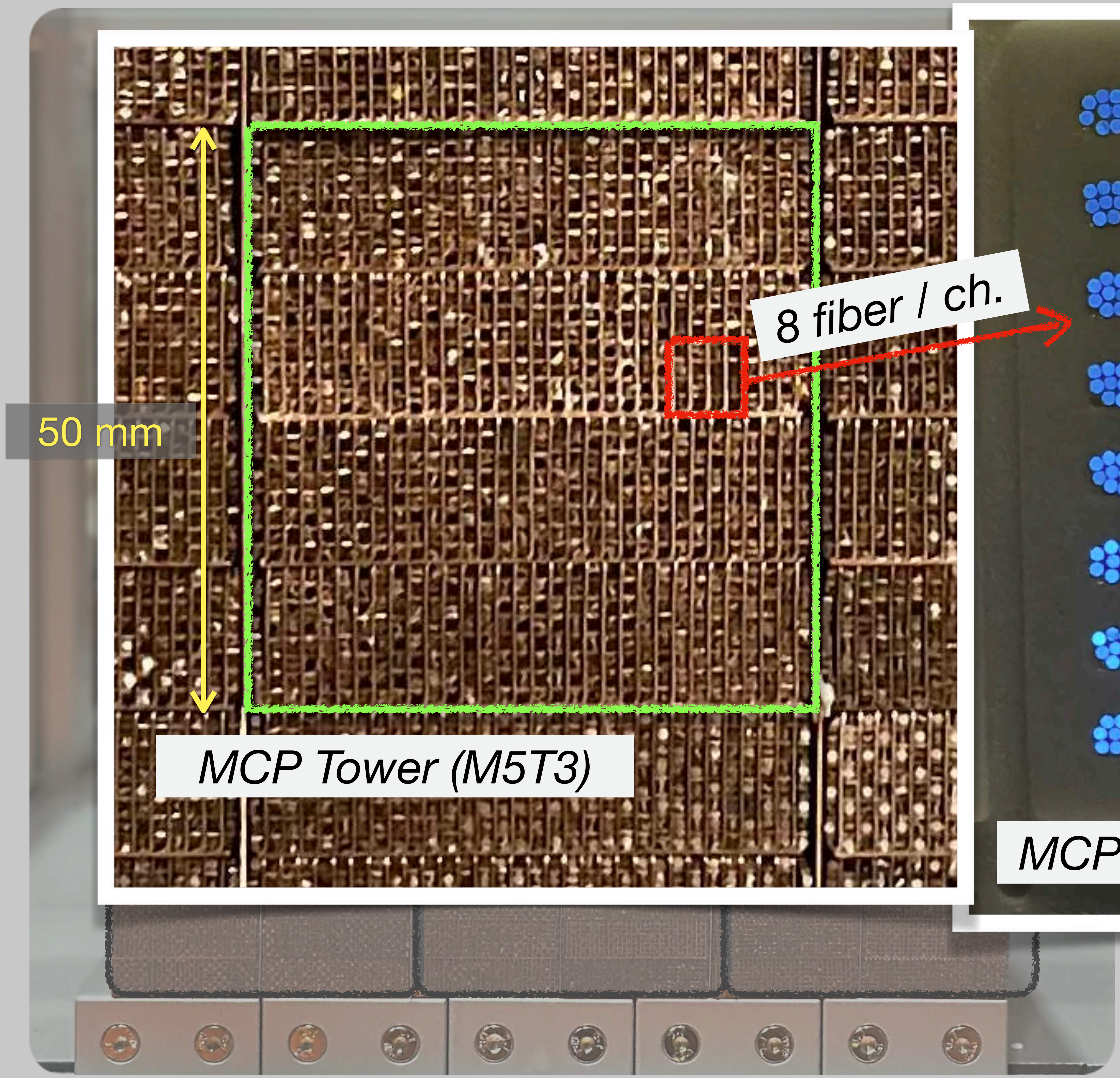


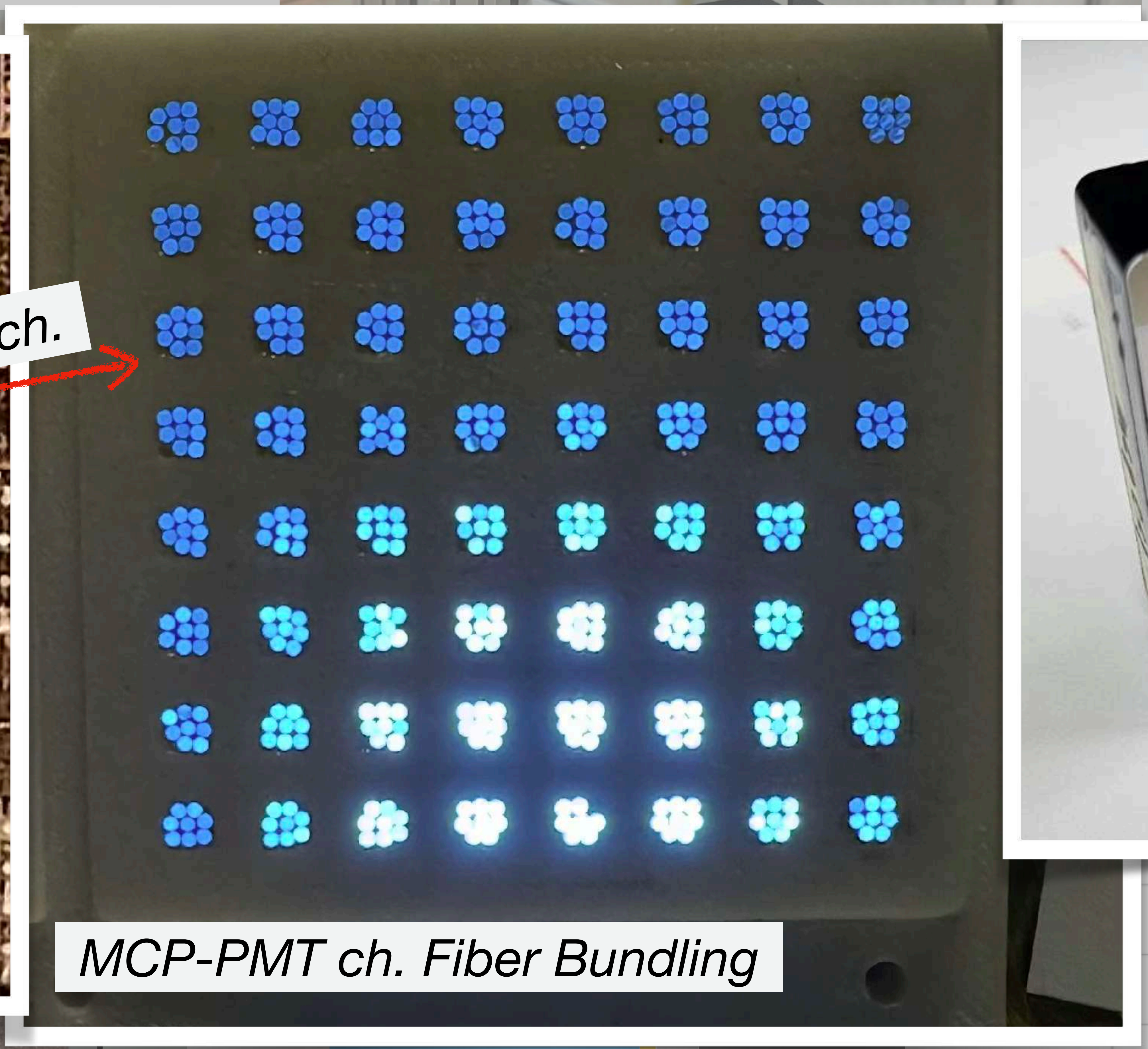


Module for TB2025

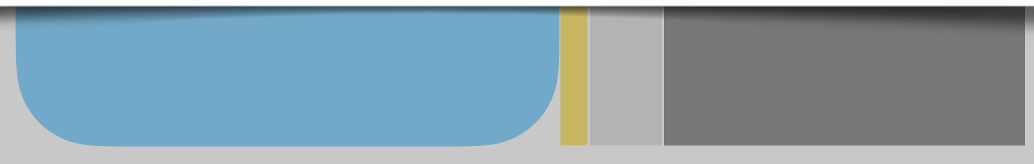
Readout Detectors

*Total **200** (MCP : **128+2**, PMT : **70**) channels*

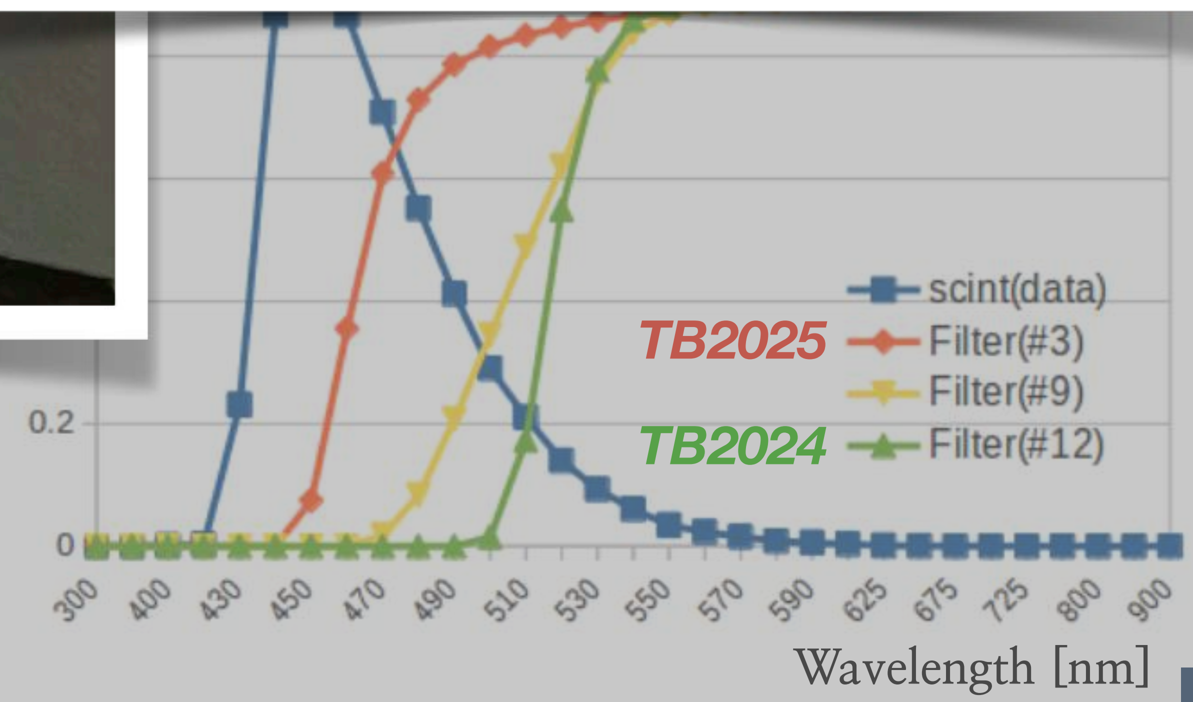




PMT (R11265-100)

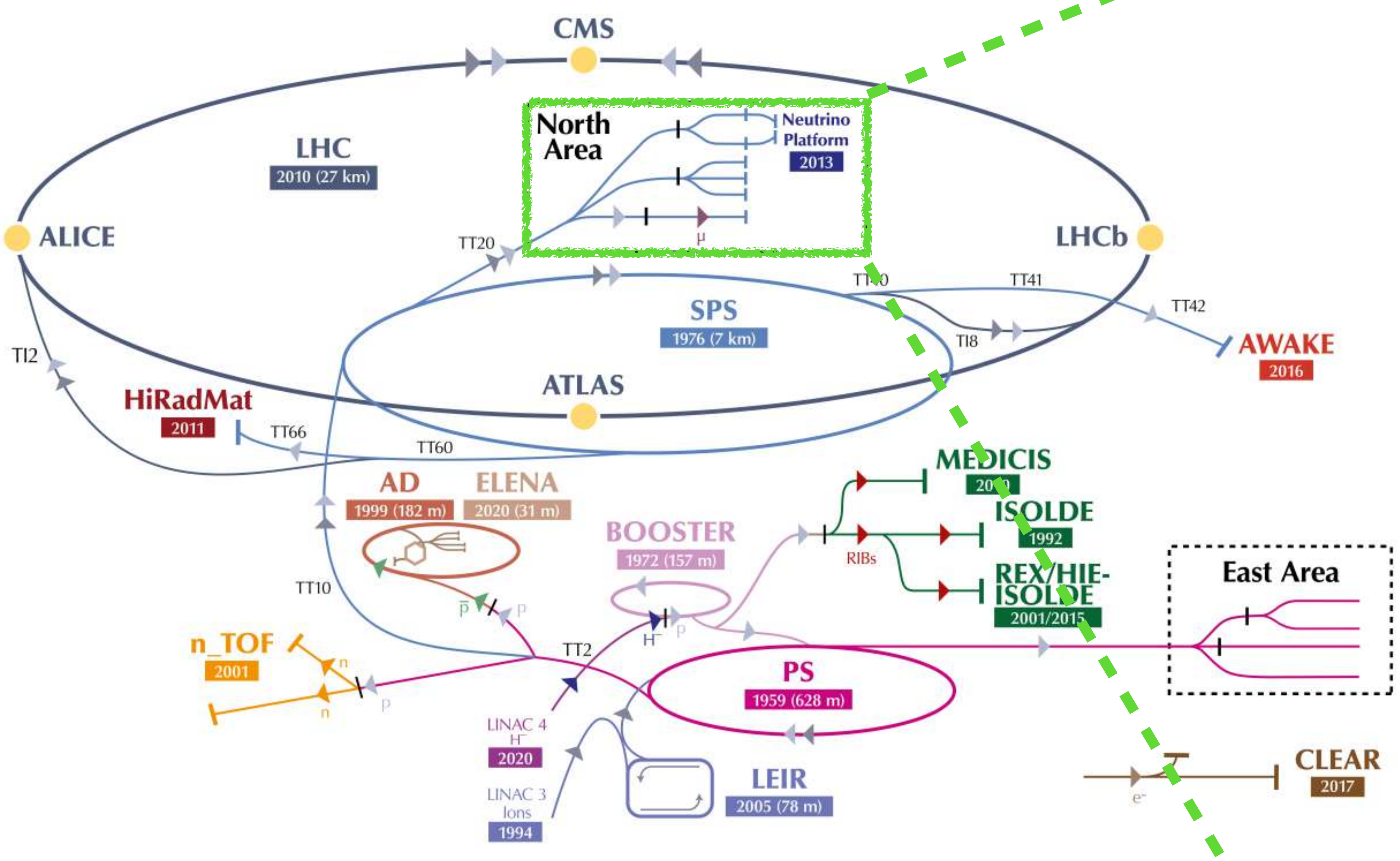


Yellow Filter
(Kodak Wratten #3)
(***Only for S ch.***)



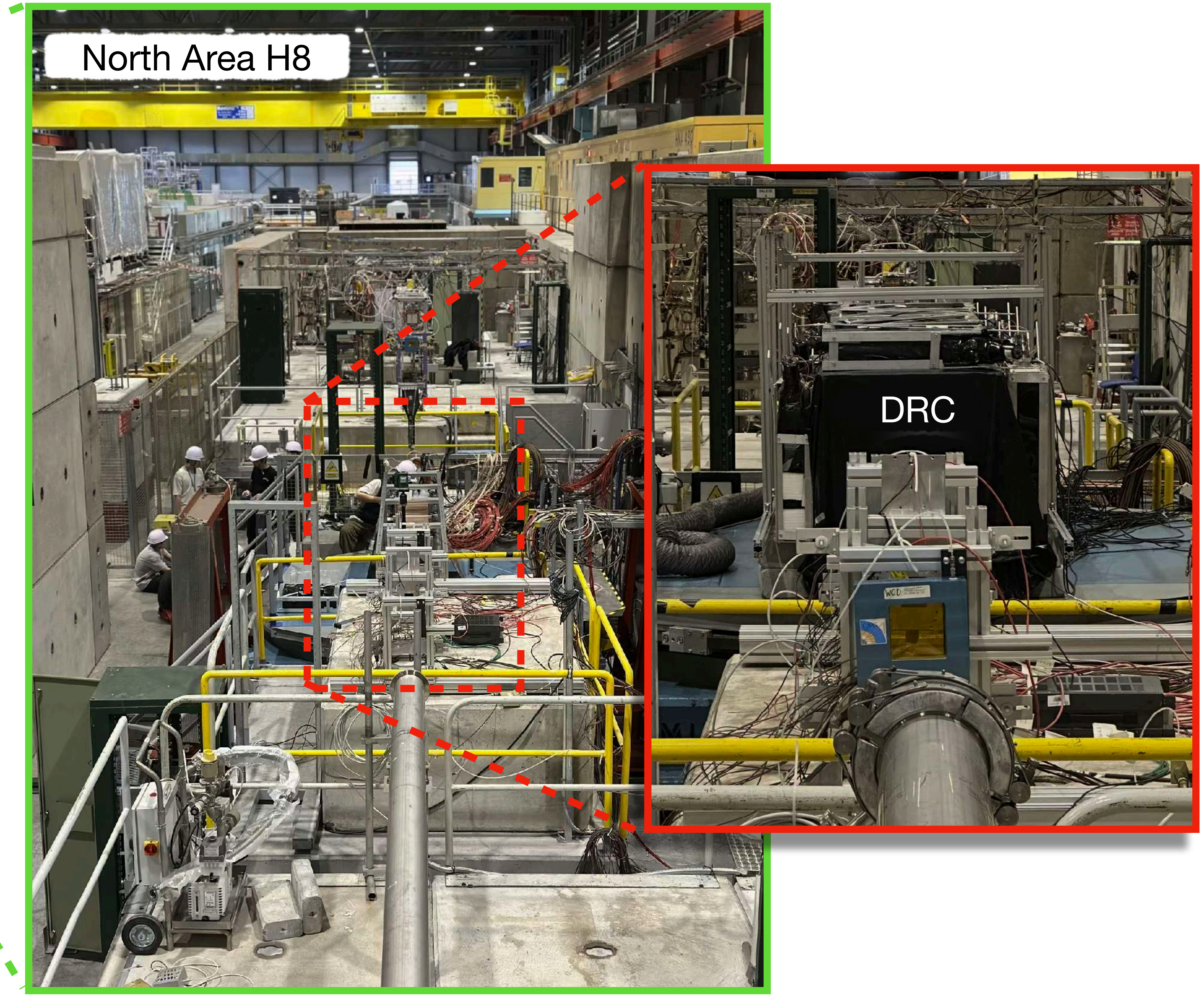
Experimental Setup

Experimental Hall : CERN SPS H8



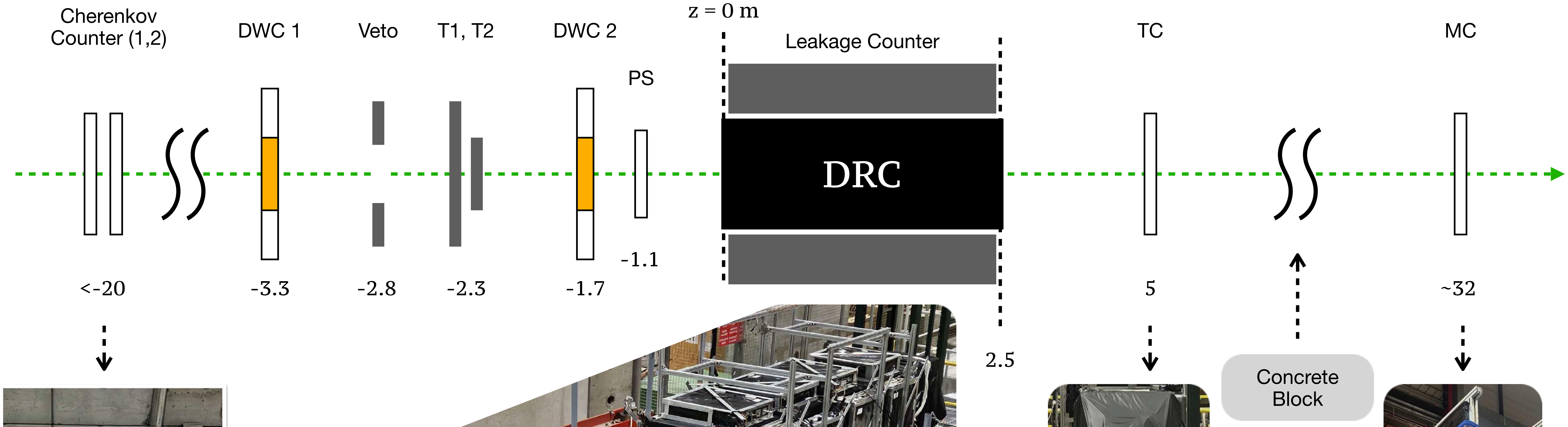
EM : 10 ~ 120 GeV

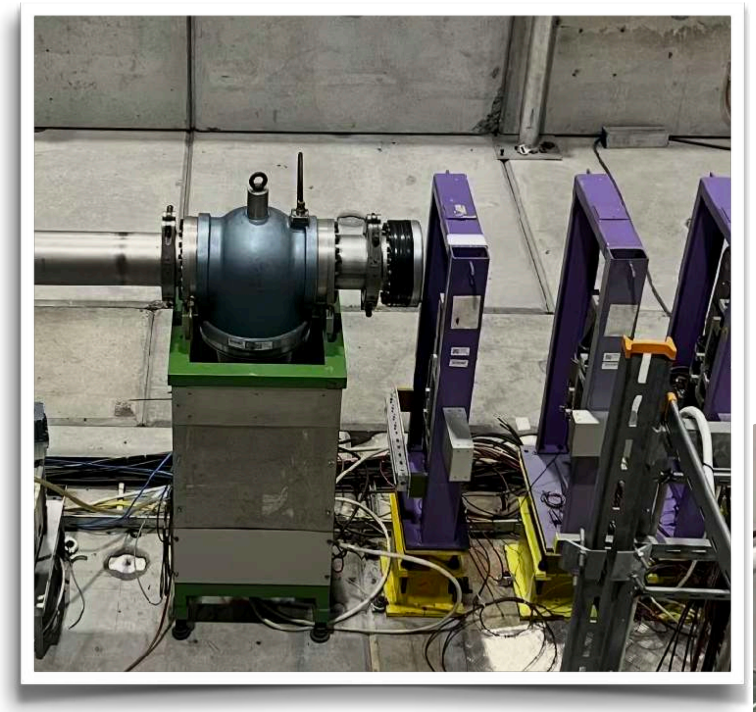
Hadron : 20 ~ 120 GeV

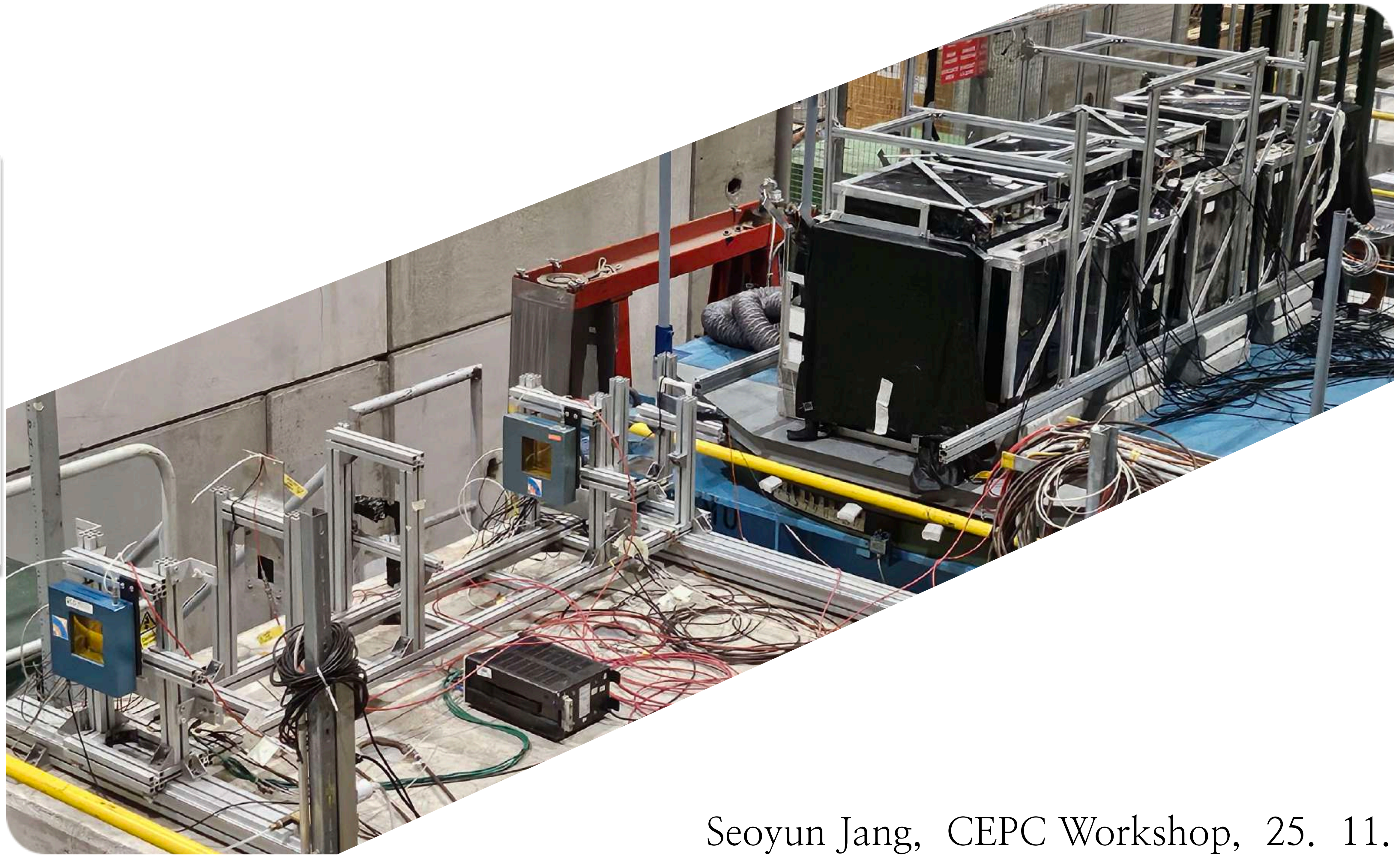


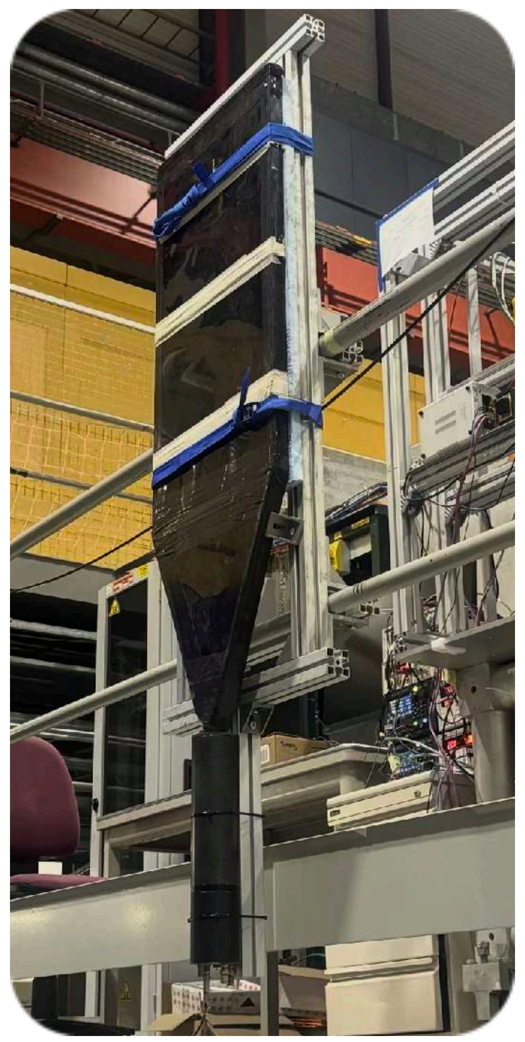
Experimental Setup

Overall Setup



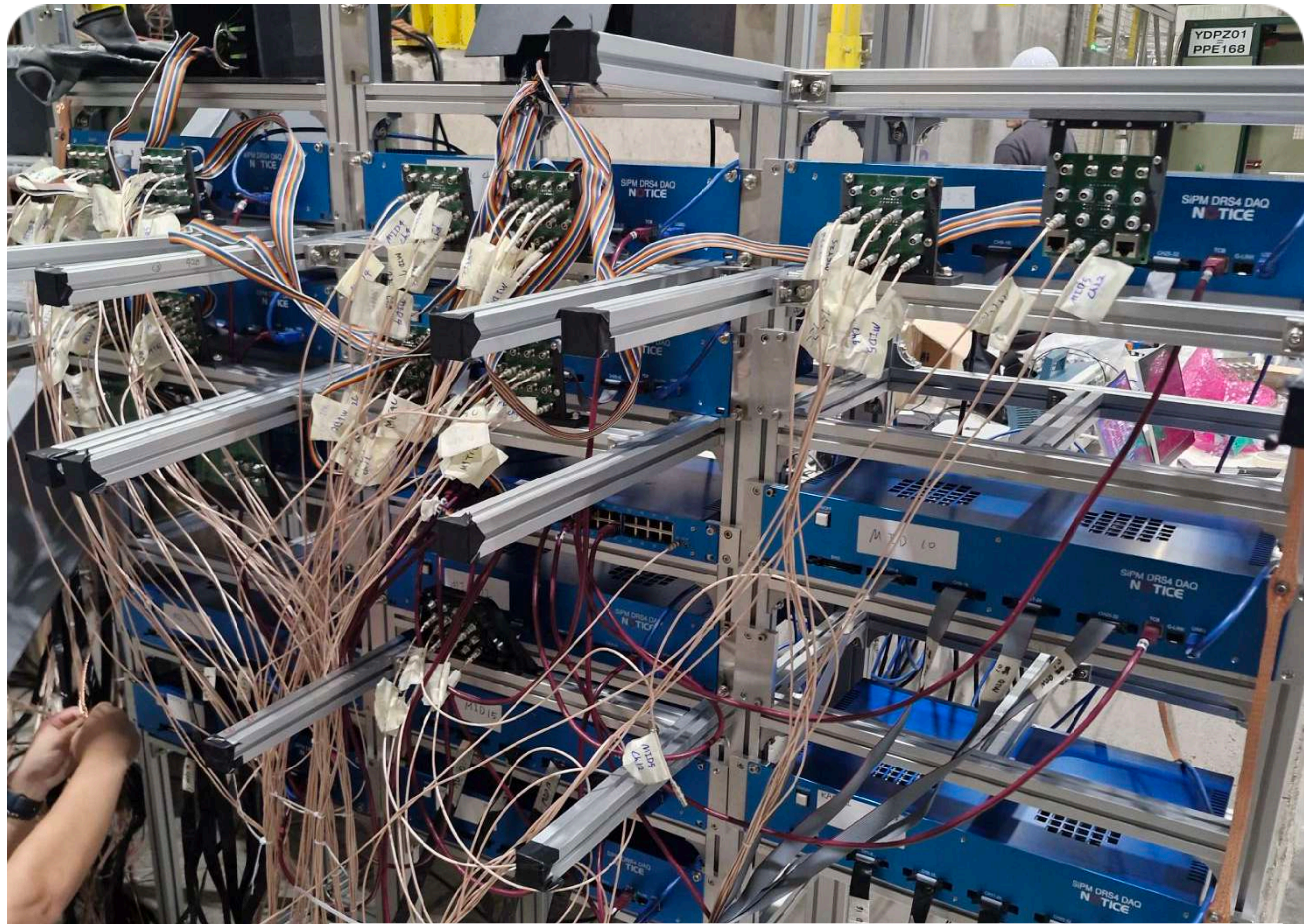


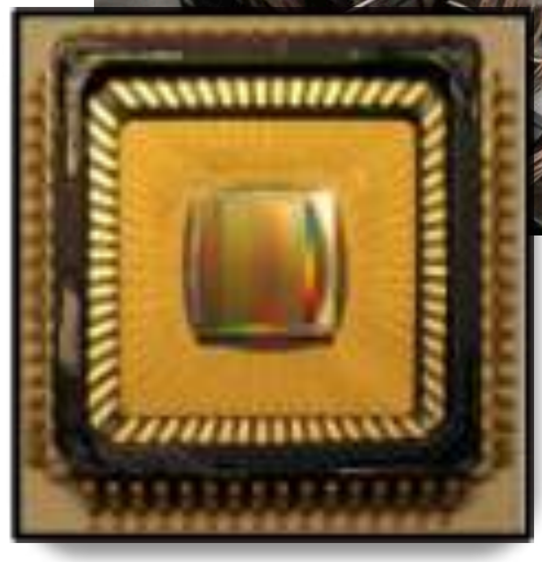




Experimental Setup

DAQ Setup





DRS4 Chip

DAQ Board (32 ch.)

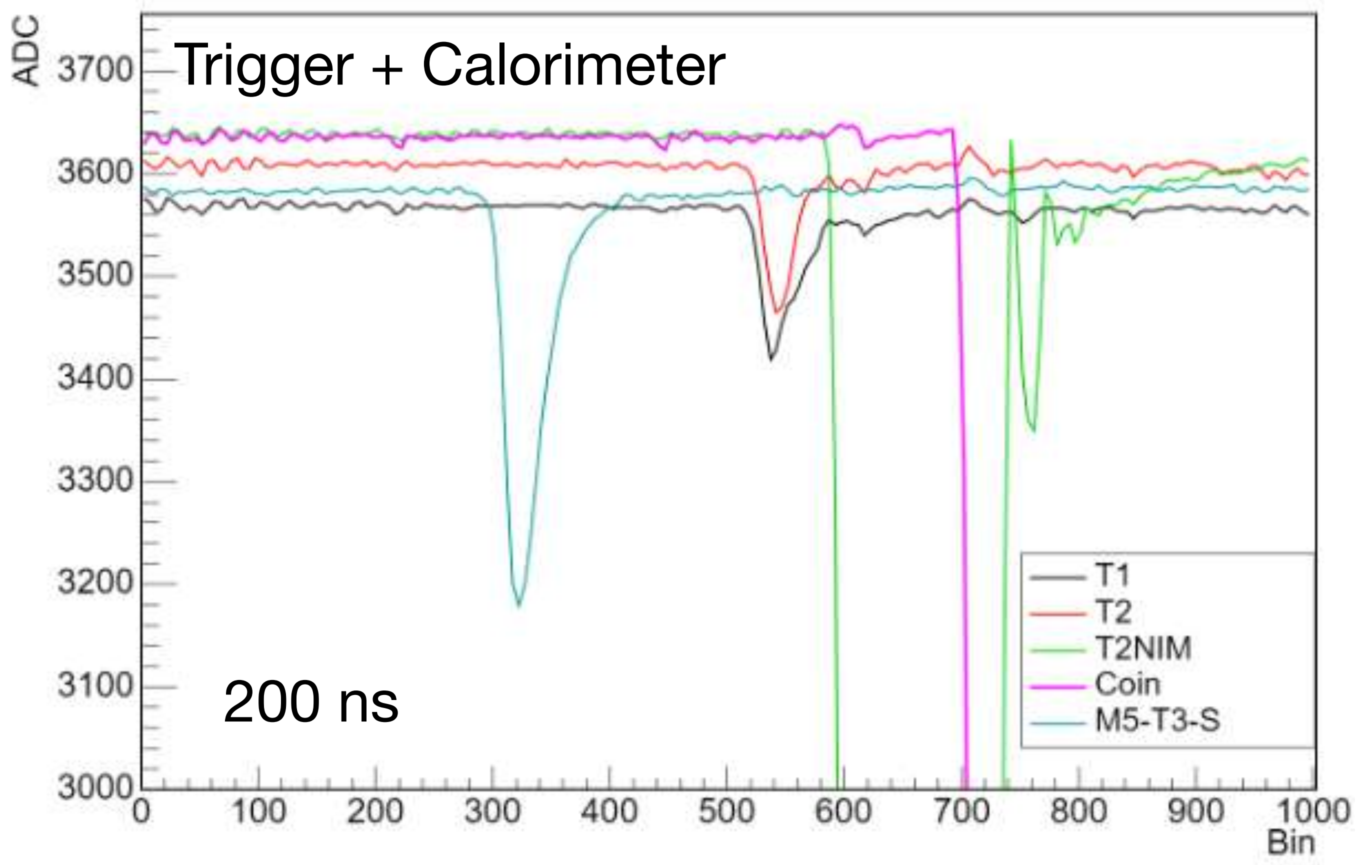
TCB Board

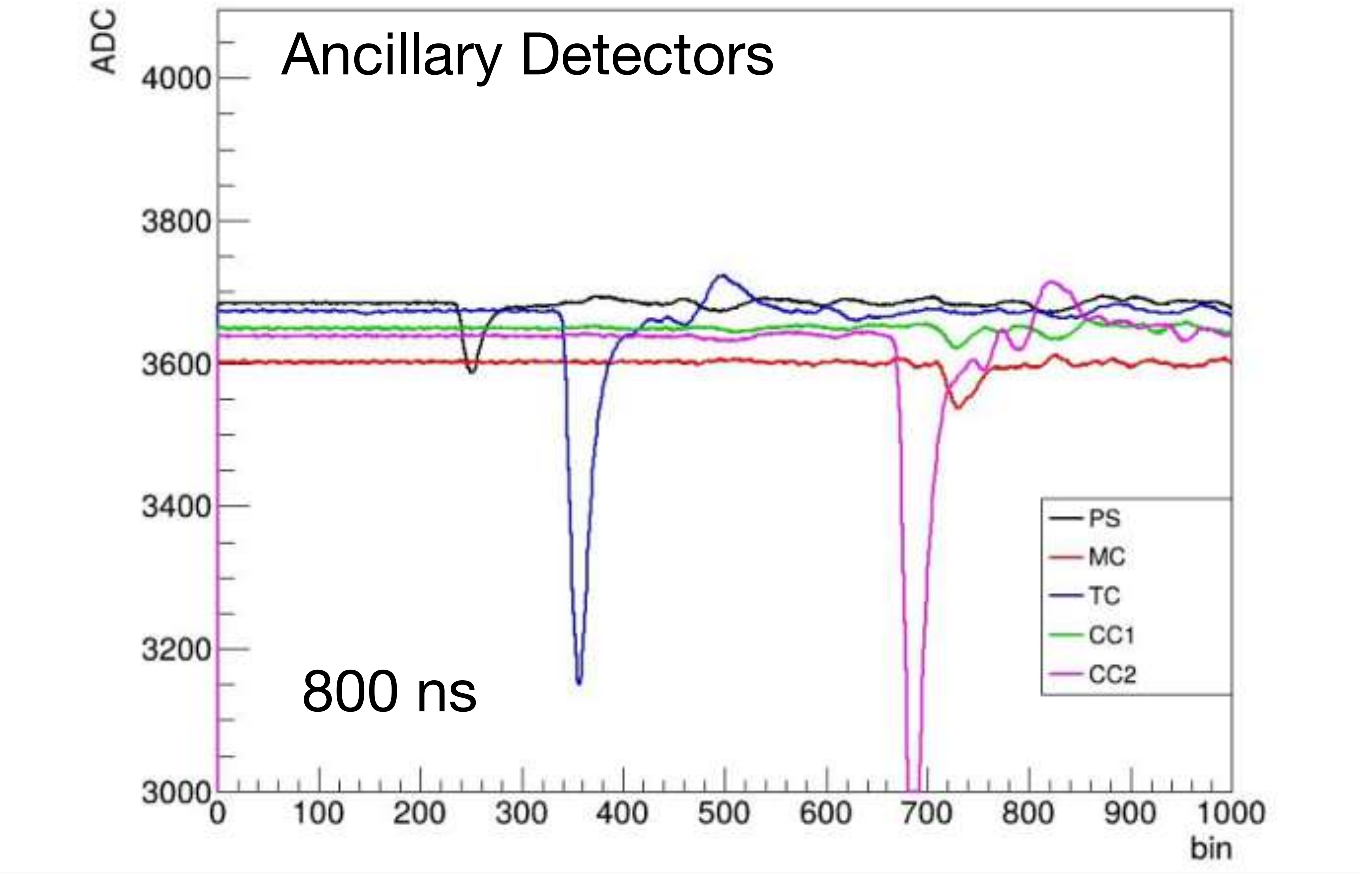
DAQ System

for calorimeter signal

Customized DAQ system based on DRS4 chip, **5 GS/s** sampling rate

Time Window of Ancillary + Calorimeter Signals

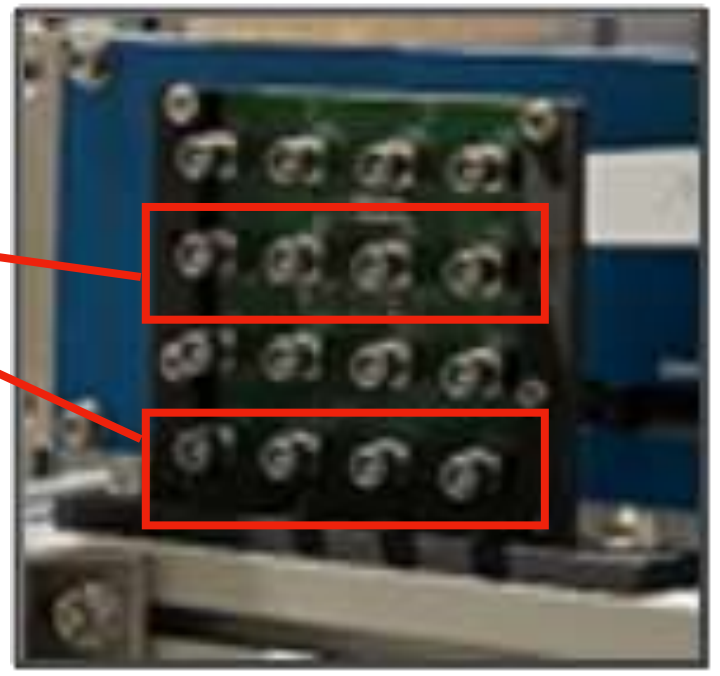




Trigger & Clock Board (TCB) x1
DAQ Board x13

only even channels were used to avoid cross-talk

**TB2025 Update*



Experimental Setup

DAQ Upgrades beyond TB2024

Parameter	R647 (Old)	R2076 (New)
Rise time	~2.2 ns	**~1.0 ns (≈ 2× faster)**
Anode pulse width	~6 ns	**~3 ns (narrower pulse)**
Max anode voltage	1250 V	**1800 V**
Window material	Borosilicate glass	**Quartz (better UV response)**

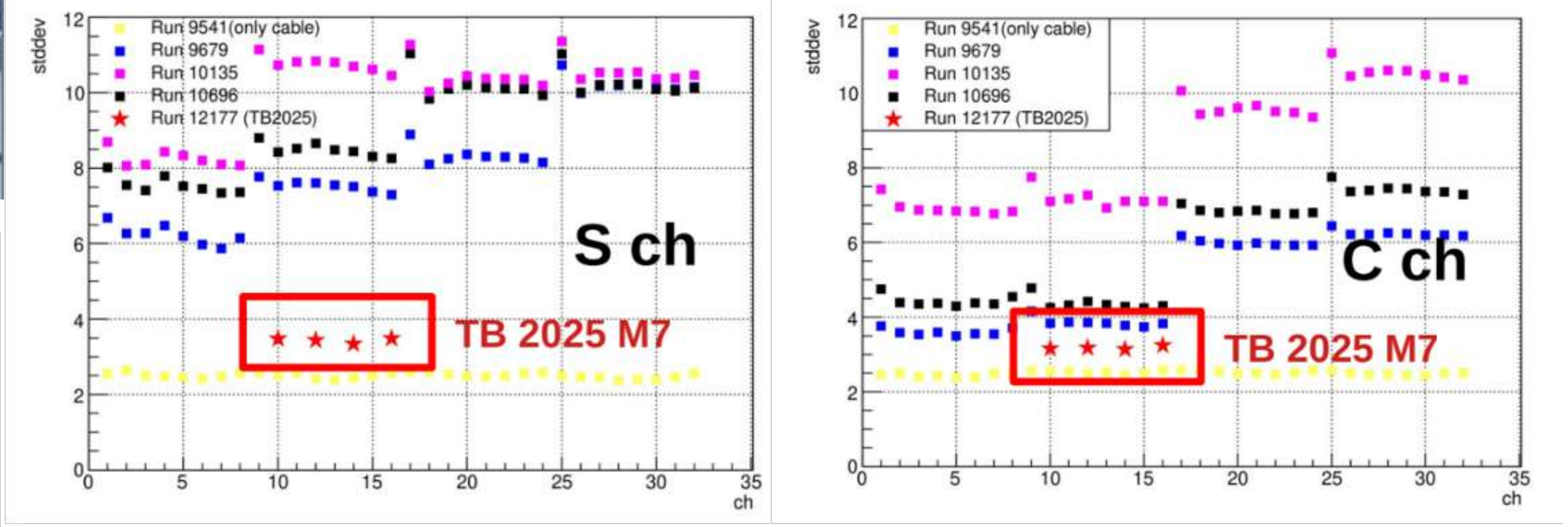
Updated PMT for Trigger Detectors

including beam effect

Event rate (Trigger Rate) increased ***~350 %***

Noise level decreased

Noise Level of TB2024 vs 2025



Physics Programs

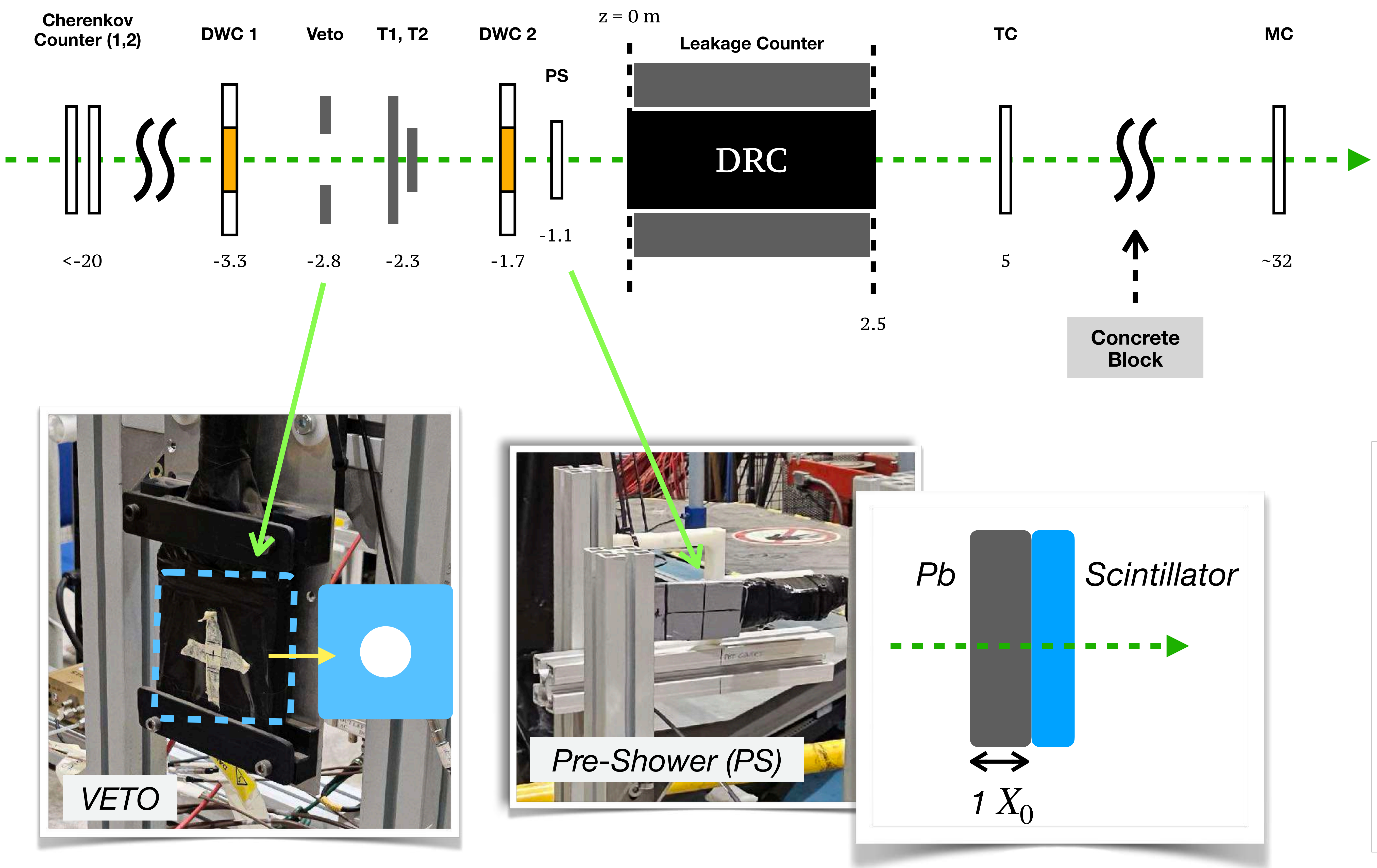
Physics Programs

- ***EM Performance :*** EM Response - Linearity & Resolution
- Uniformity Scan (EM)
- ***Hadron Performance*** : Hadron Response - Linearity, Resolution and Features ($\pi^+, p, jet - like$)
- ***Time Performance*** : Time Resolution
- ***High Granularity Test*** : Position Resolution

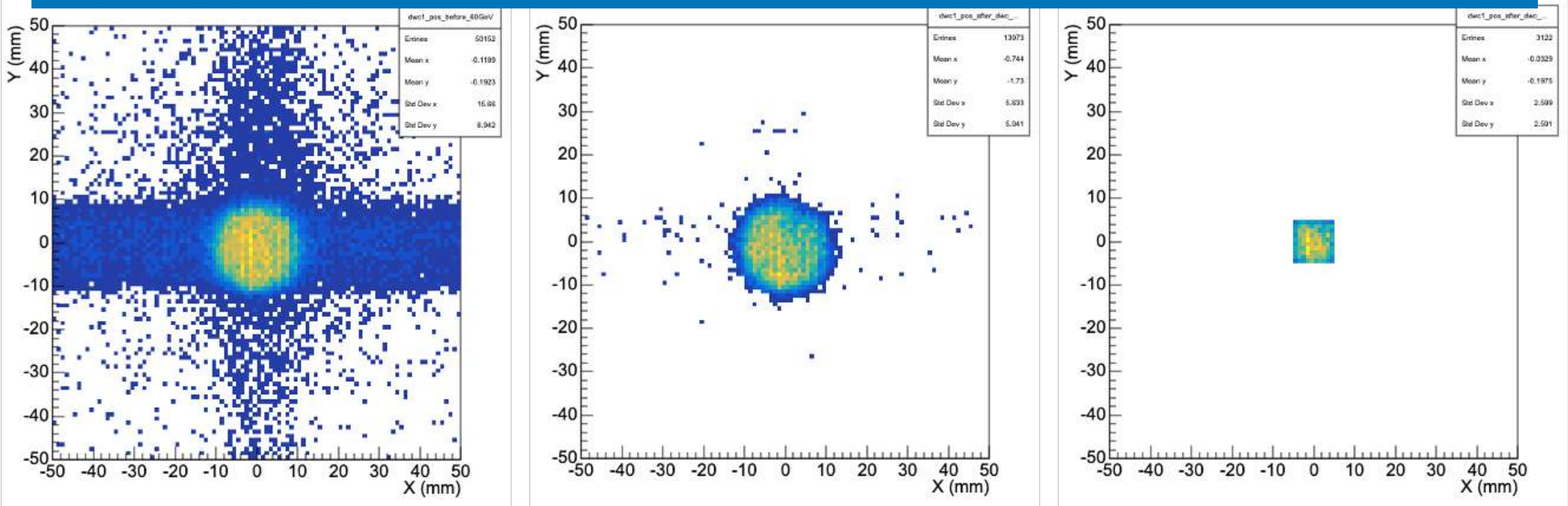
EM Performance

Particle Identification & Cuts

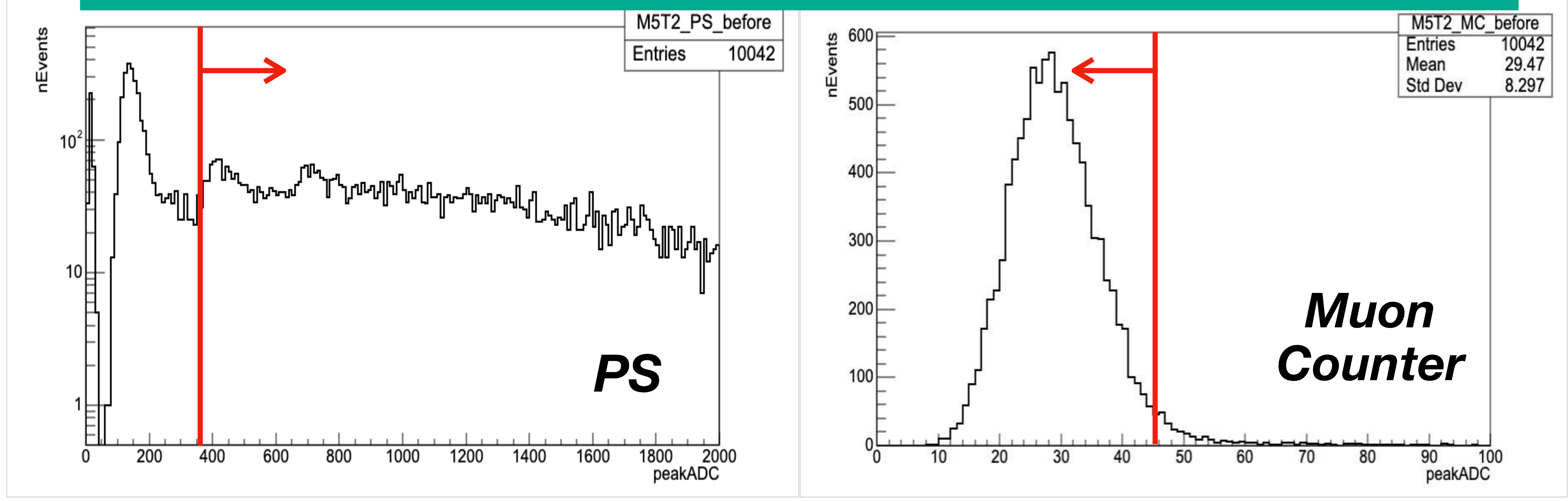
***Ancillary detectors** were exploited to select pure positron and hadron beams*



Beam Geometry Cuts (Delayed Wire Chambers)



Particle Identification Cuts



Hadron Reject

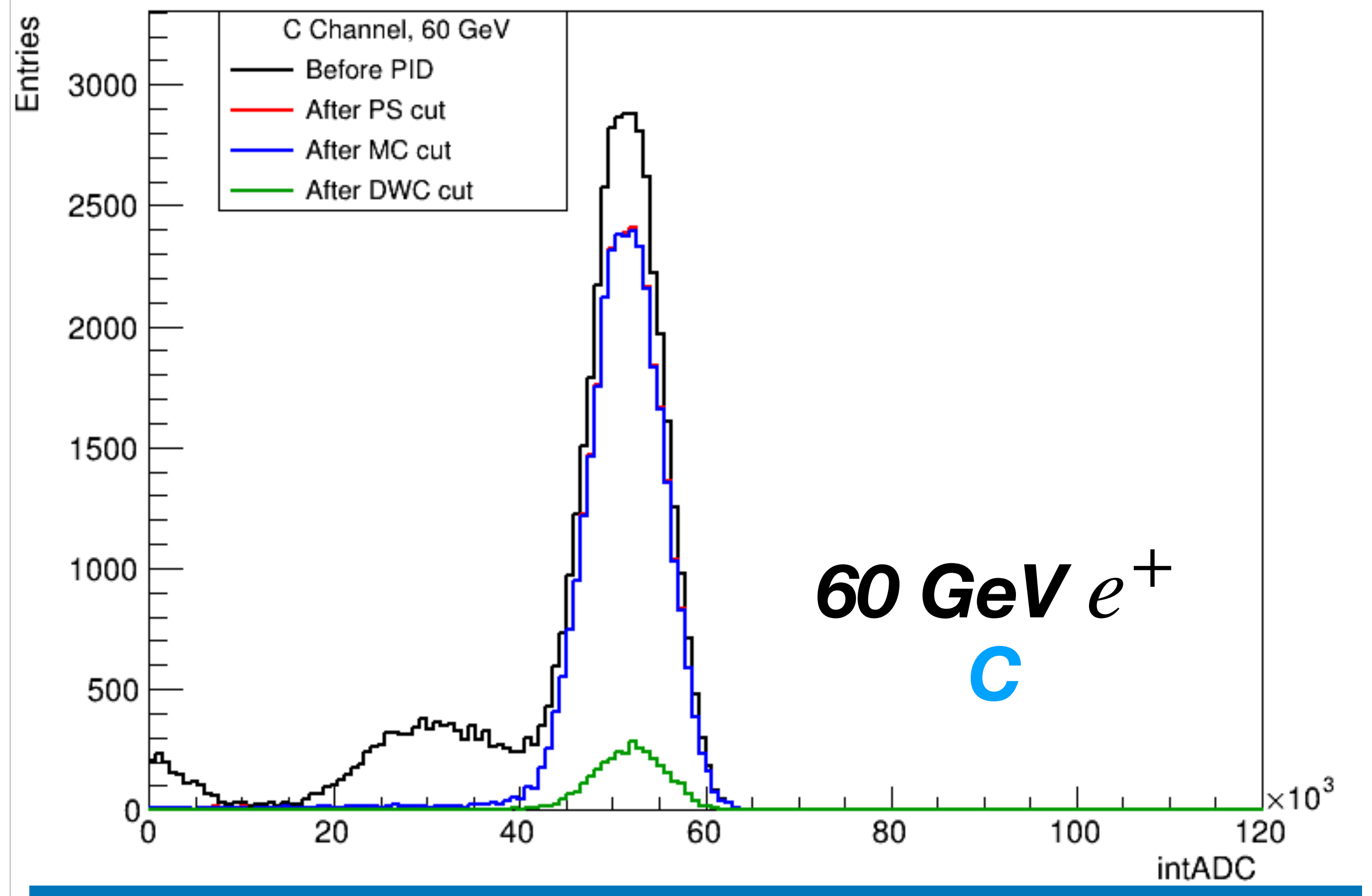
Muon Reject

+ CC cuts on selecting hadrons

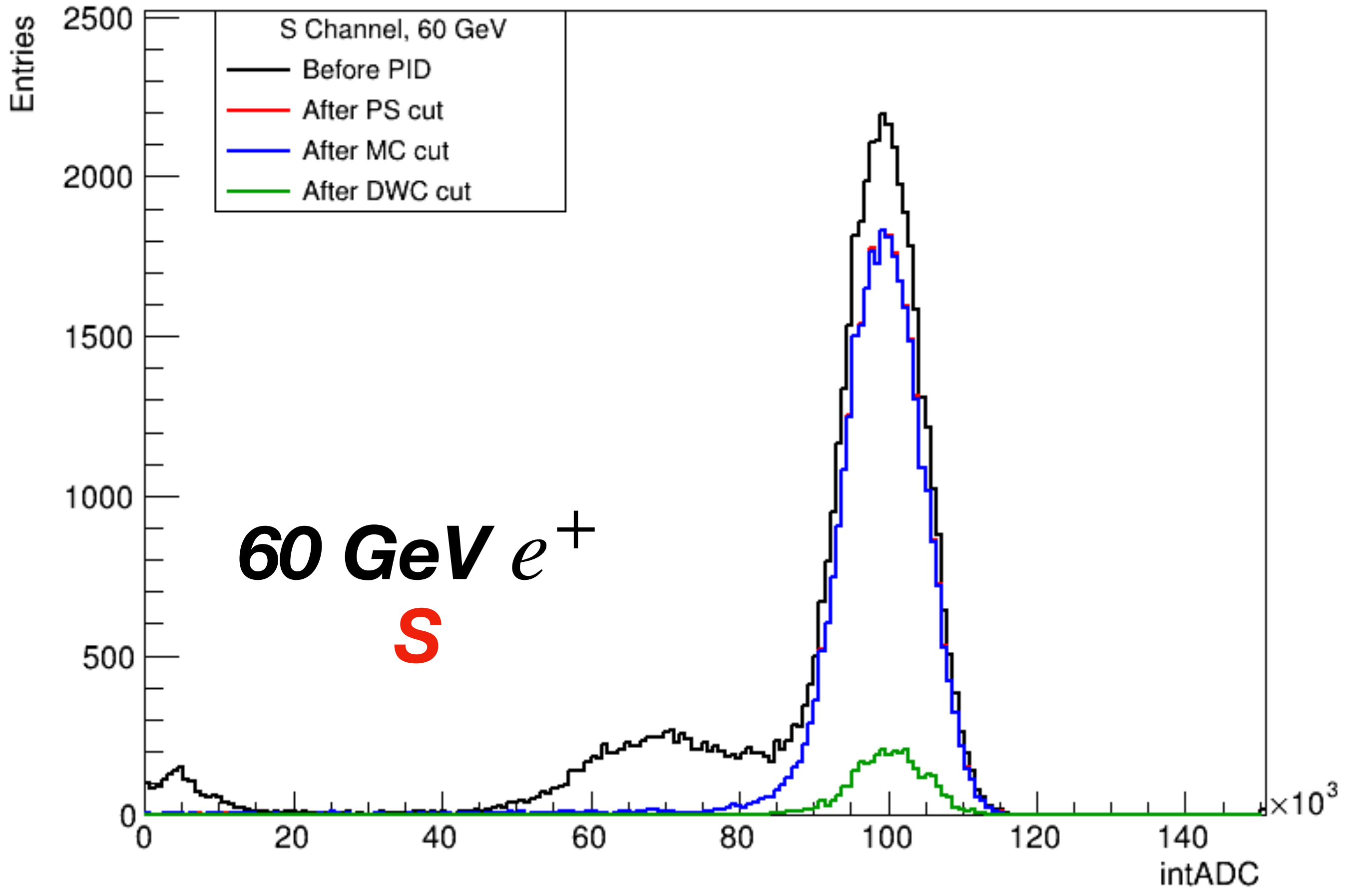
EM Performance

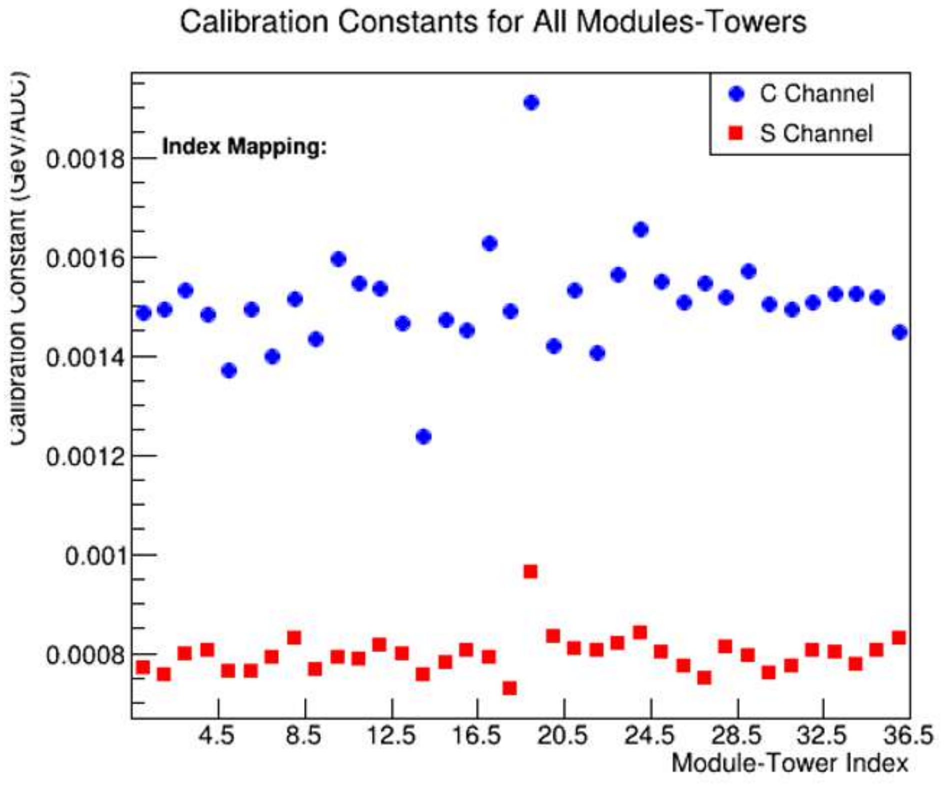
Particle Identification & Cuts

Distribution after Cuts - C

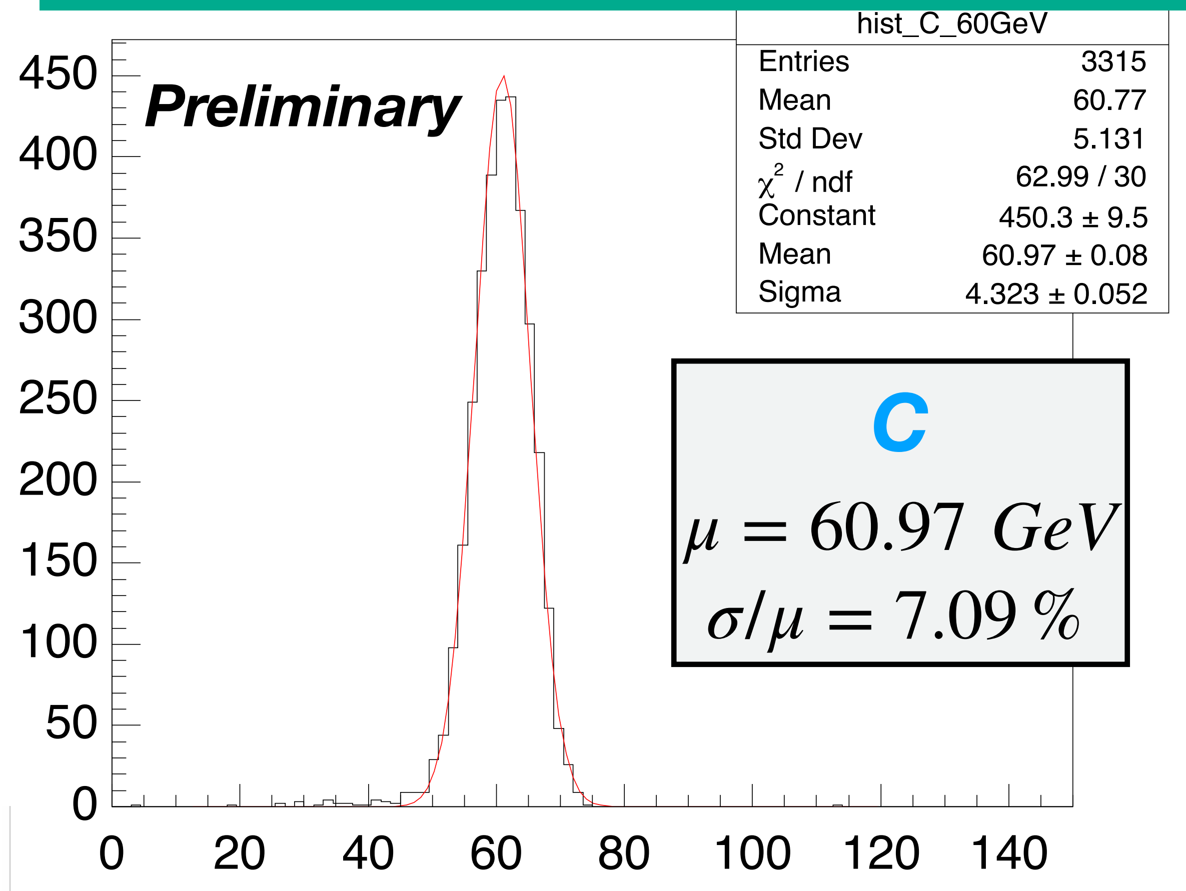


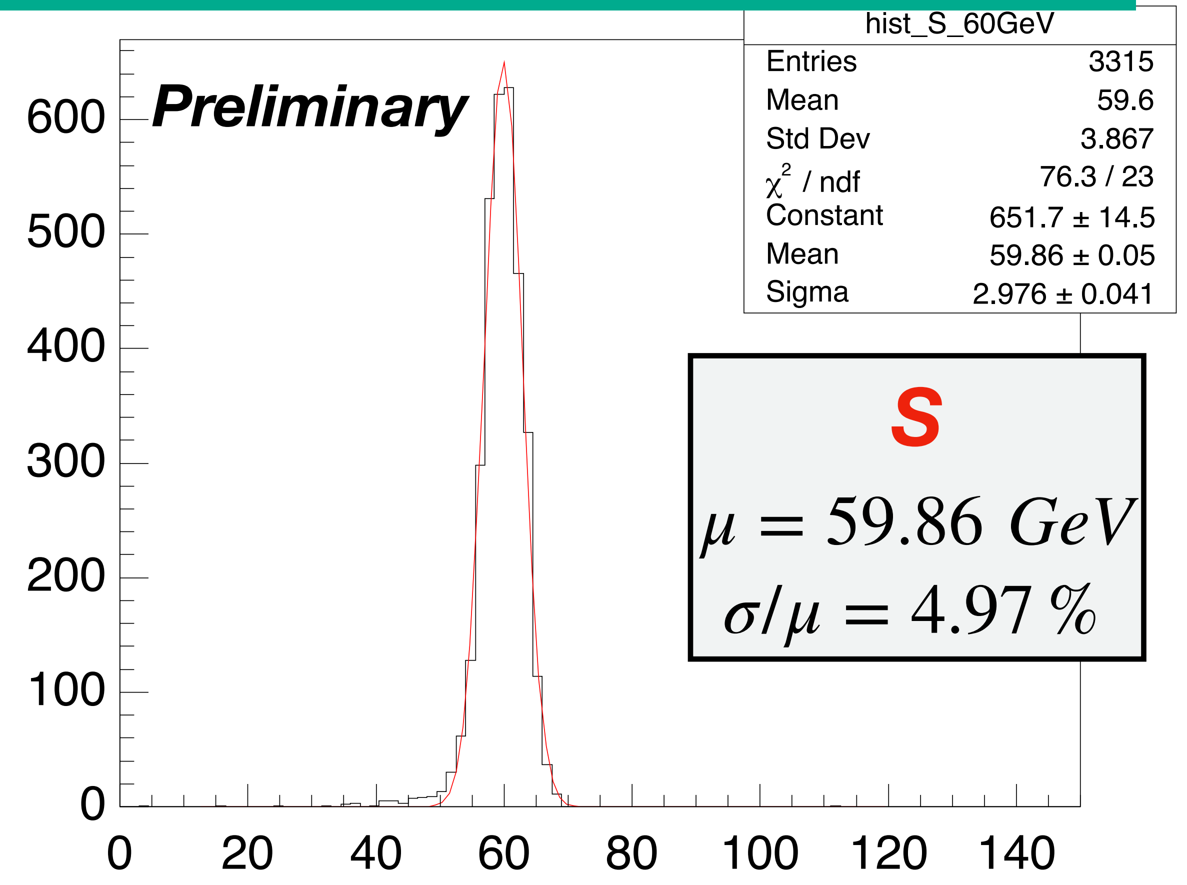
Distribution after Cuts - S

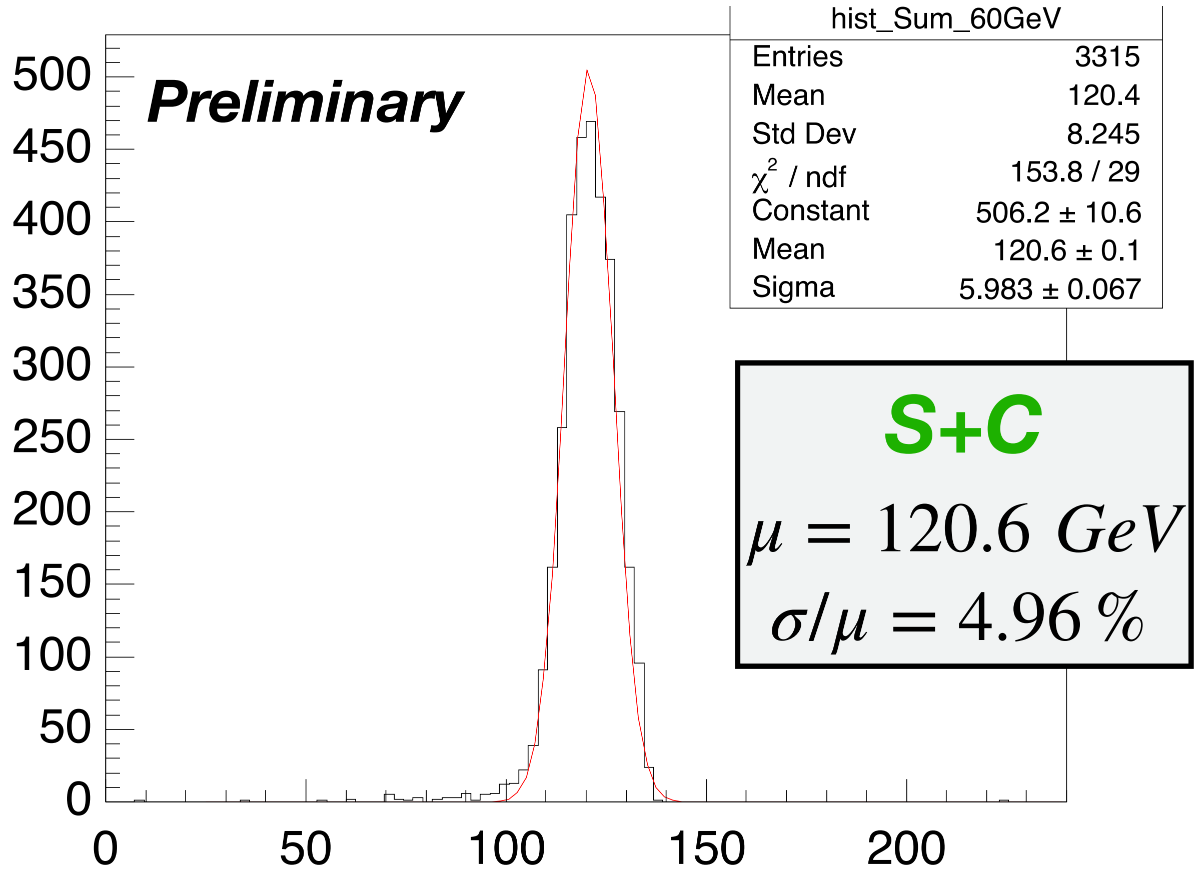




Calibrated Signal of 60 GeV e^+ events (Full Module)







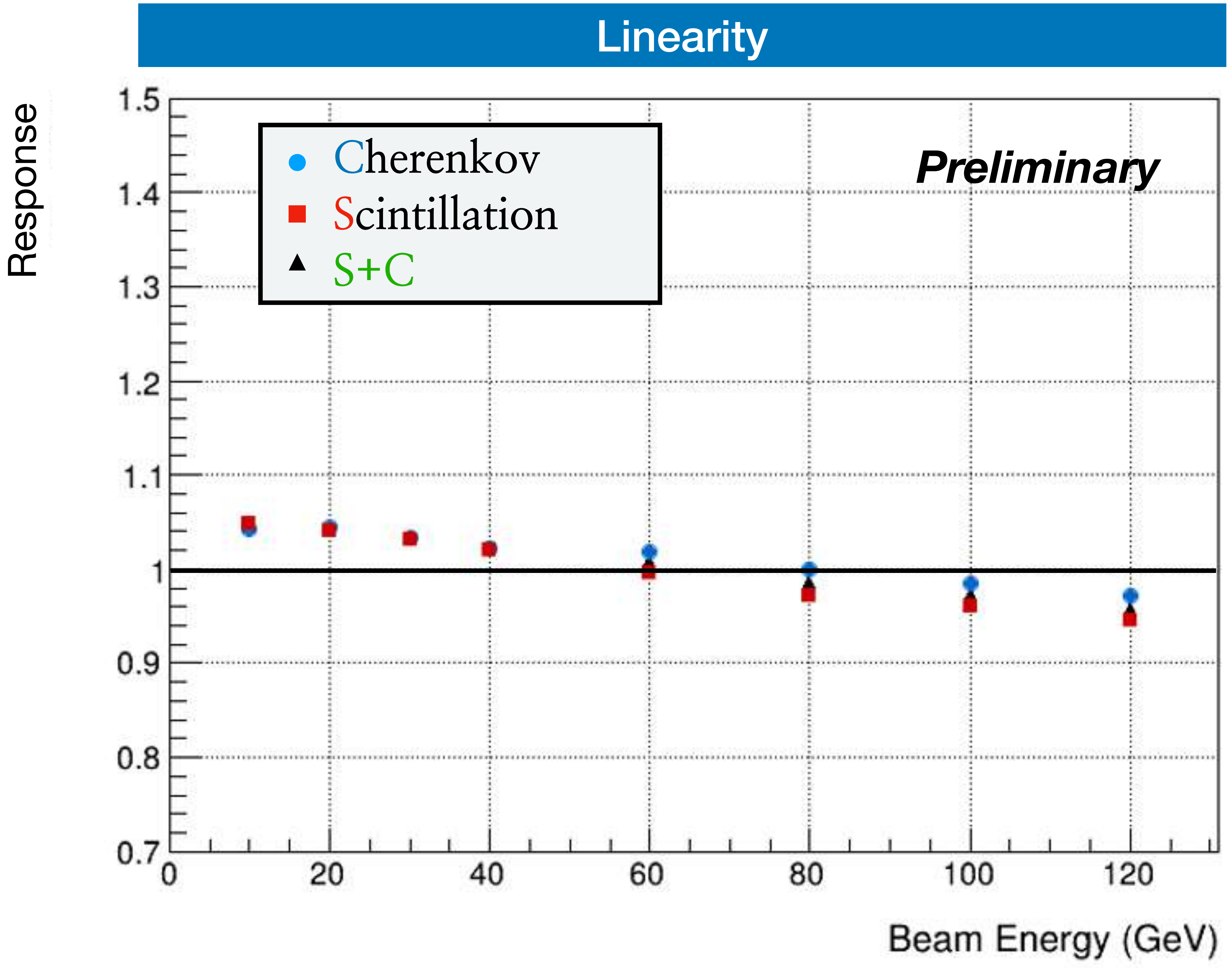
Well calibrated, clear *Gaussian distribution*

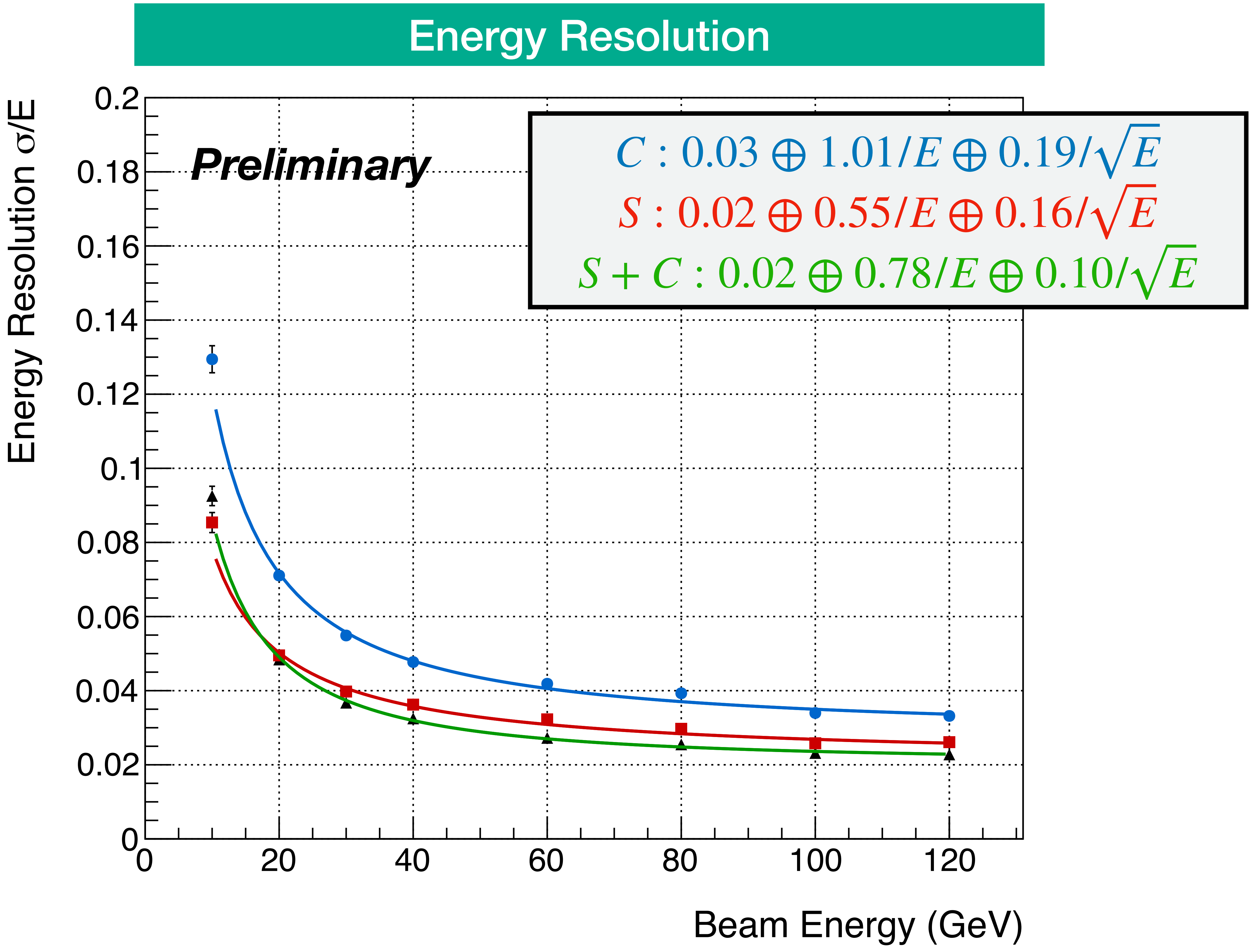
EM Performance

EM Linearity & Resolution

~96 % EM deposit

3 x 3 Matrix Response





10, 20, 30, 40, 60, 80, 100, 120 GeV e^+

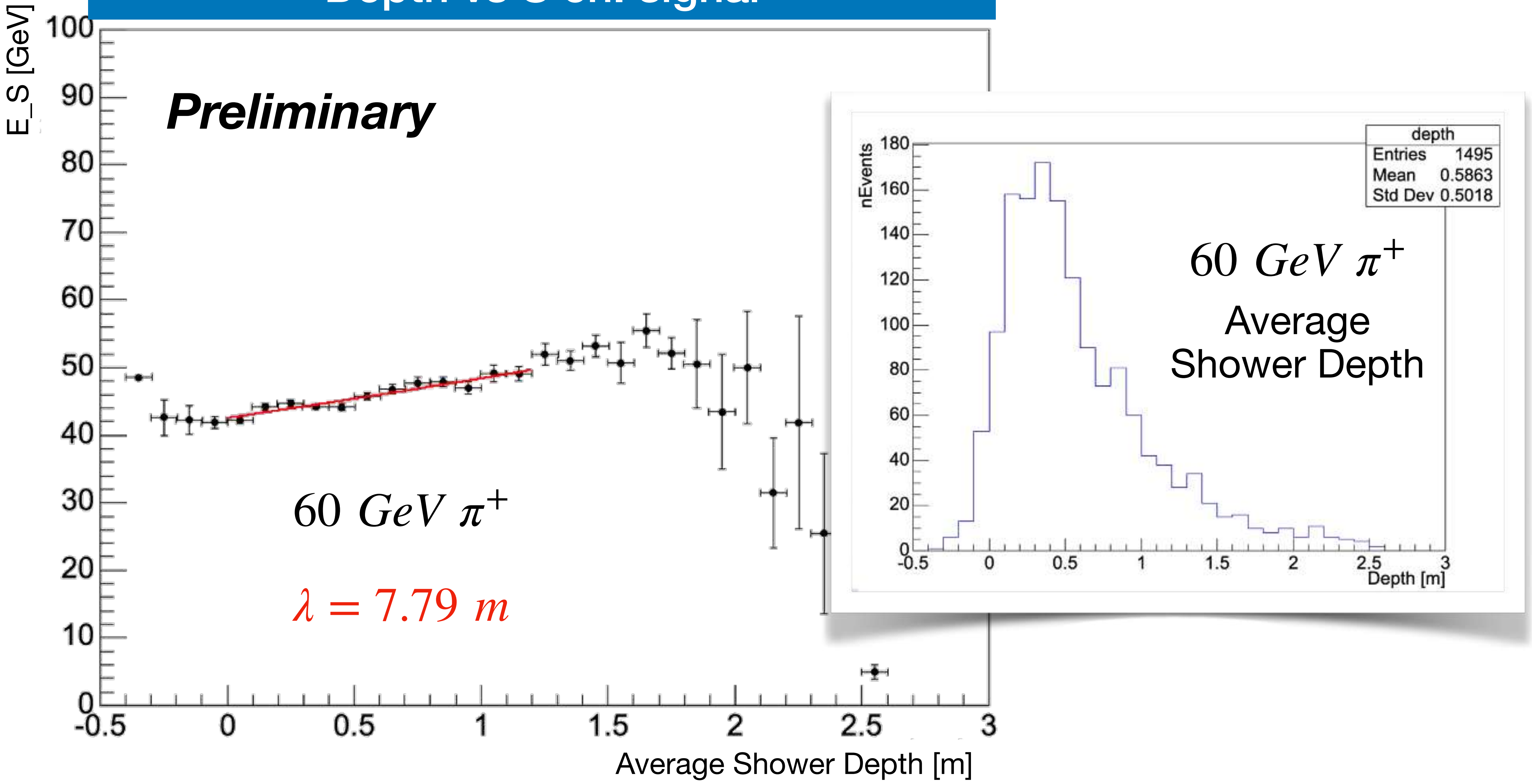
Hadron Performance
Corrections Applied

For Hadron signal, additional corrections are applied on Scintillation channel signal

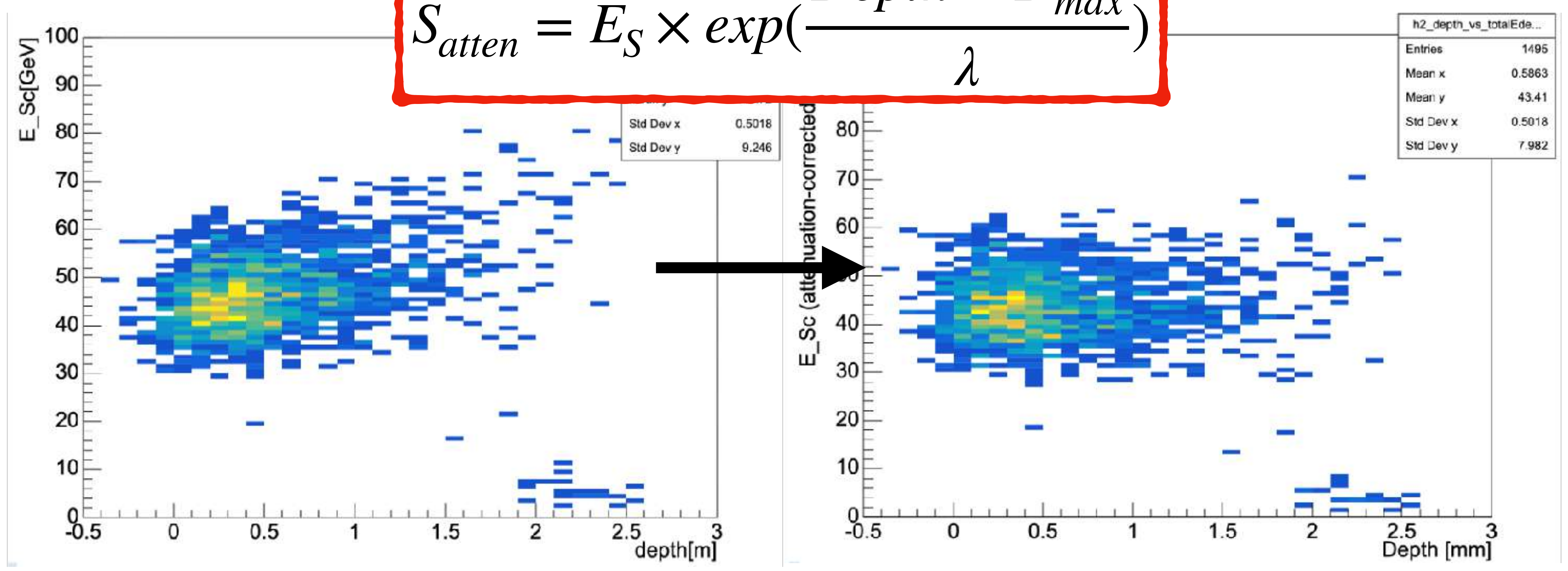
Light Attenuation Correction

- The light attenuation length of scintillating fibers are not negligible compared to our calorimeter geometry.
- By calculating average depth of showers, **measured attenuation length** with π^+ events and **applied attenuation correction on S channel**.

Depth vs S ch. signal



$$S_{atten} = E_S \times exp(\frac{Depth - D_{max}}{\lambda})$$



Before Correction

After Correction

Hadron Performance
Corrections Applied

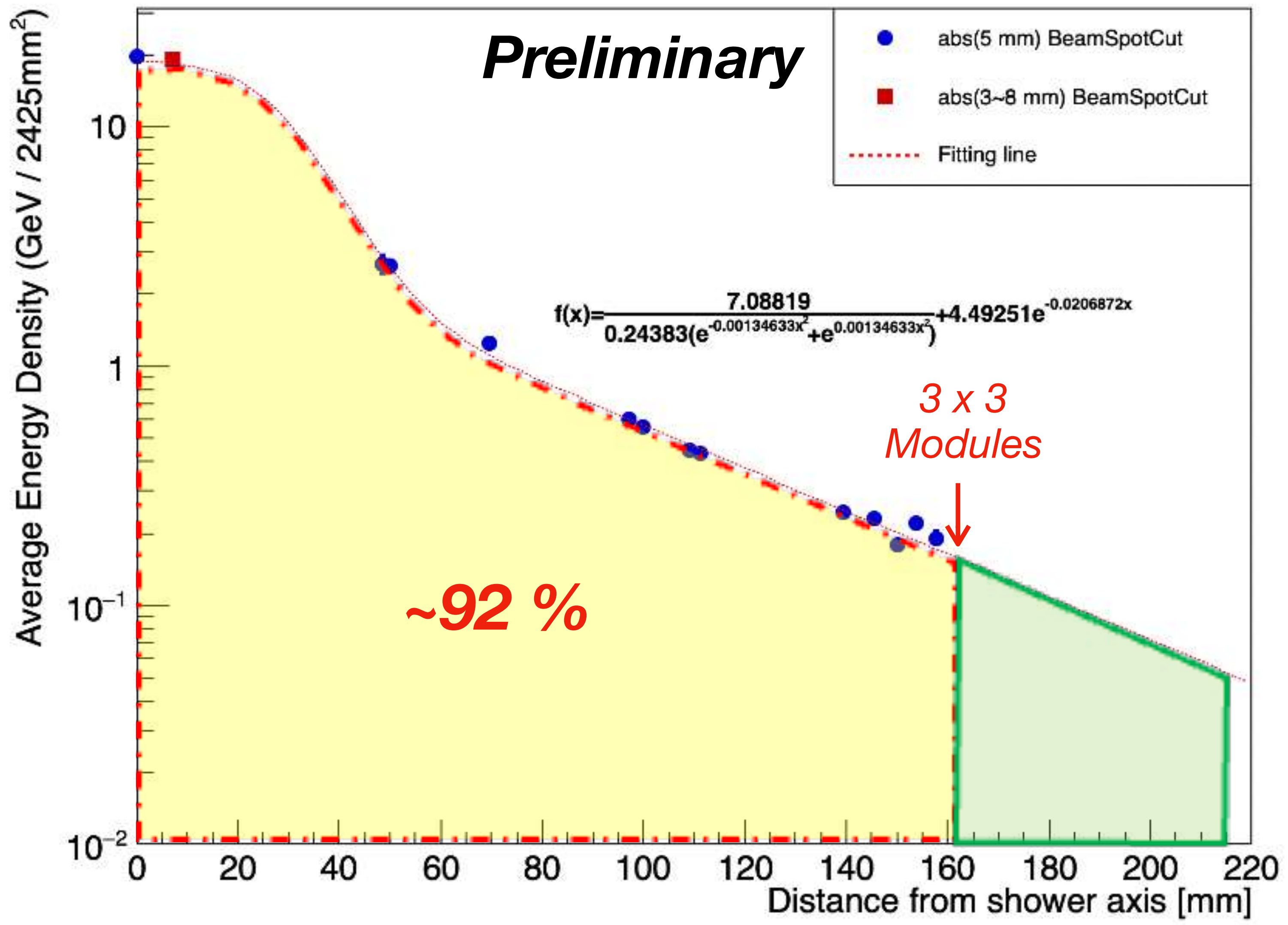
*For Hadron signal, additional corrections are applied on **S**cintillation channel signal*

Lateral Leakage Counter Correction

- The calorimeter geometry is not large enough to contain full hadron shower on lateral direction.
- Placed leakage counters (plastic scintillator) around the calorimeter, measured and **corrected lateral leakage on S channel**.

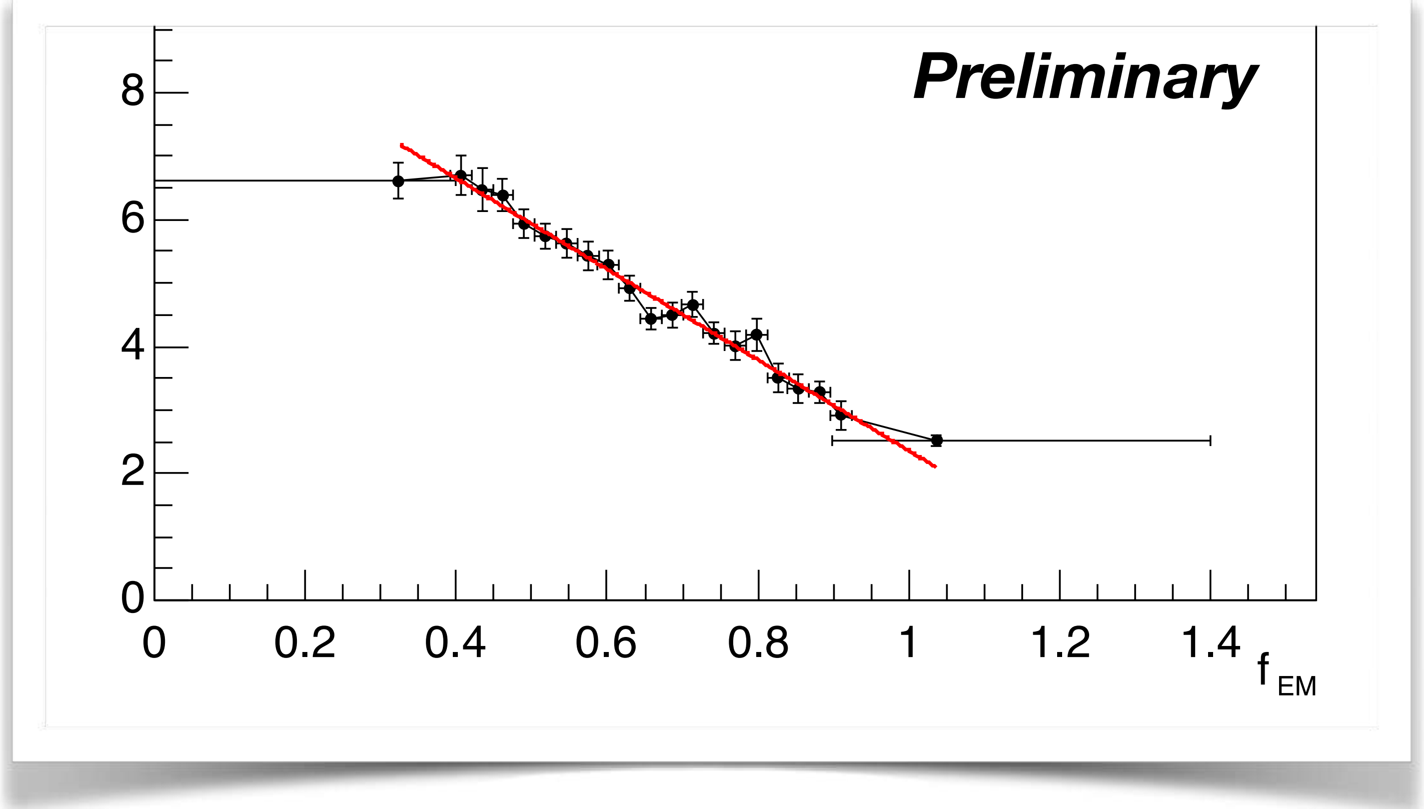
Leakage Counters x 16
$50 \times 50 \times 12\ cm^3$
Plastic Scintillator

Lateral Shower profile (60 GeV π^+)



$$S_{LCcorr} = E_S + E_{LC}$$

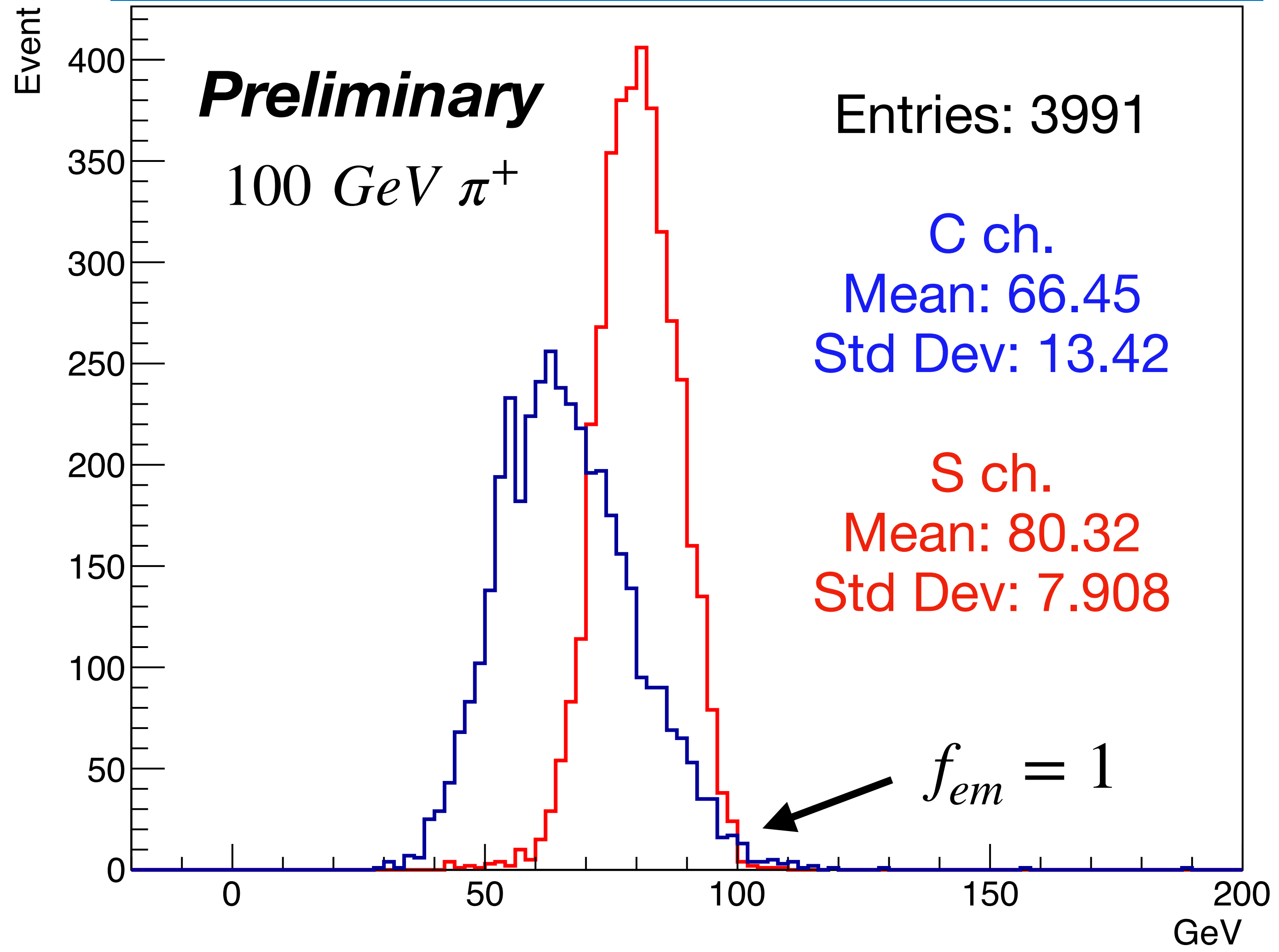
f_{EM} vs LC signal



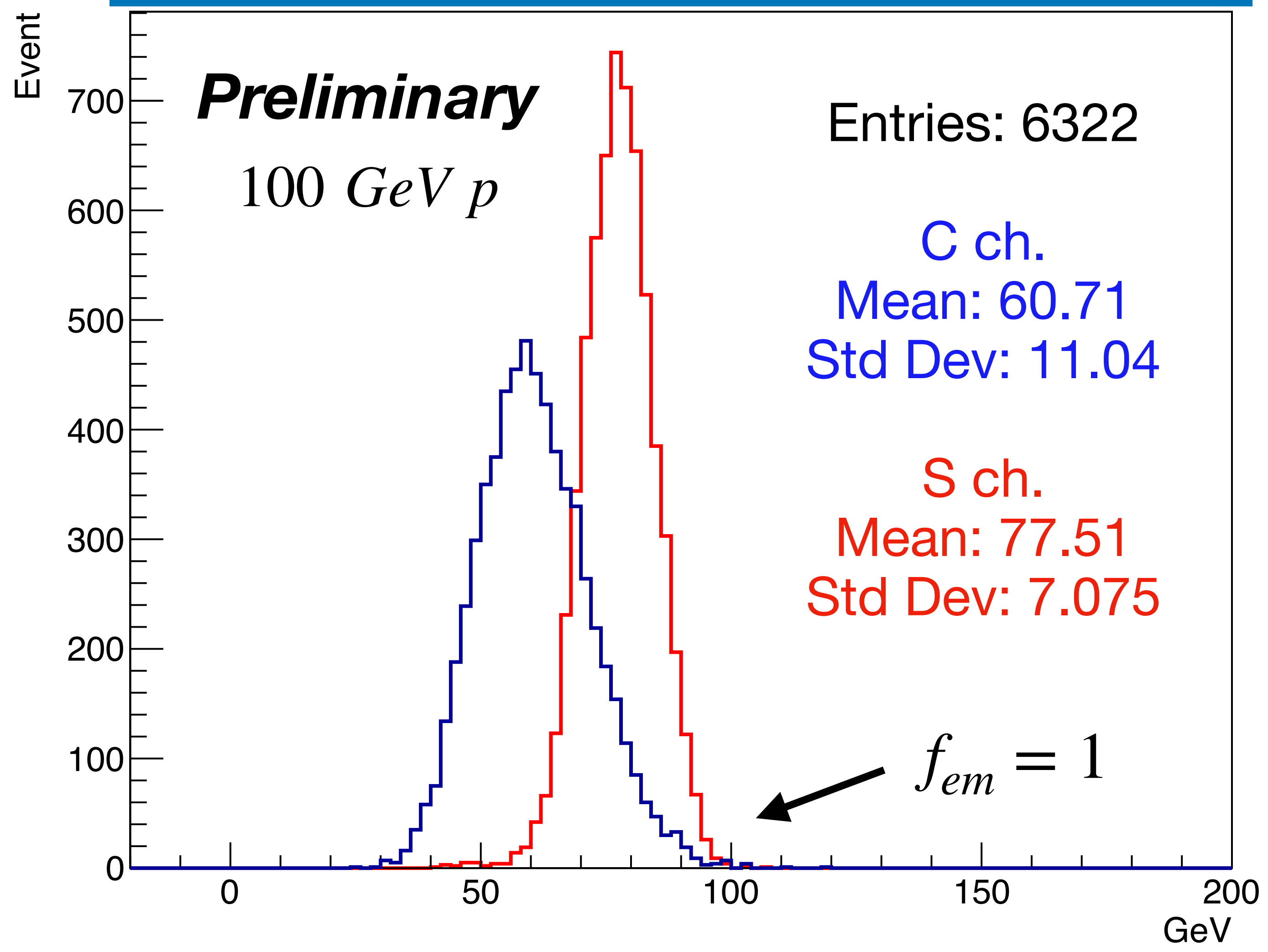
Hadron Performance

Energy Distributions

Energy Distribution - Pion



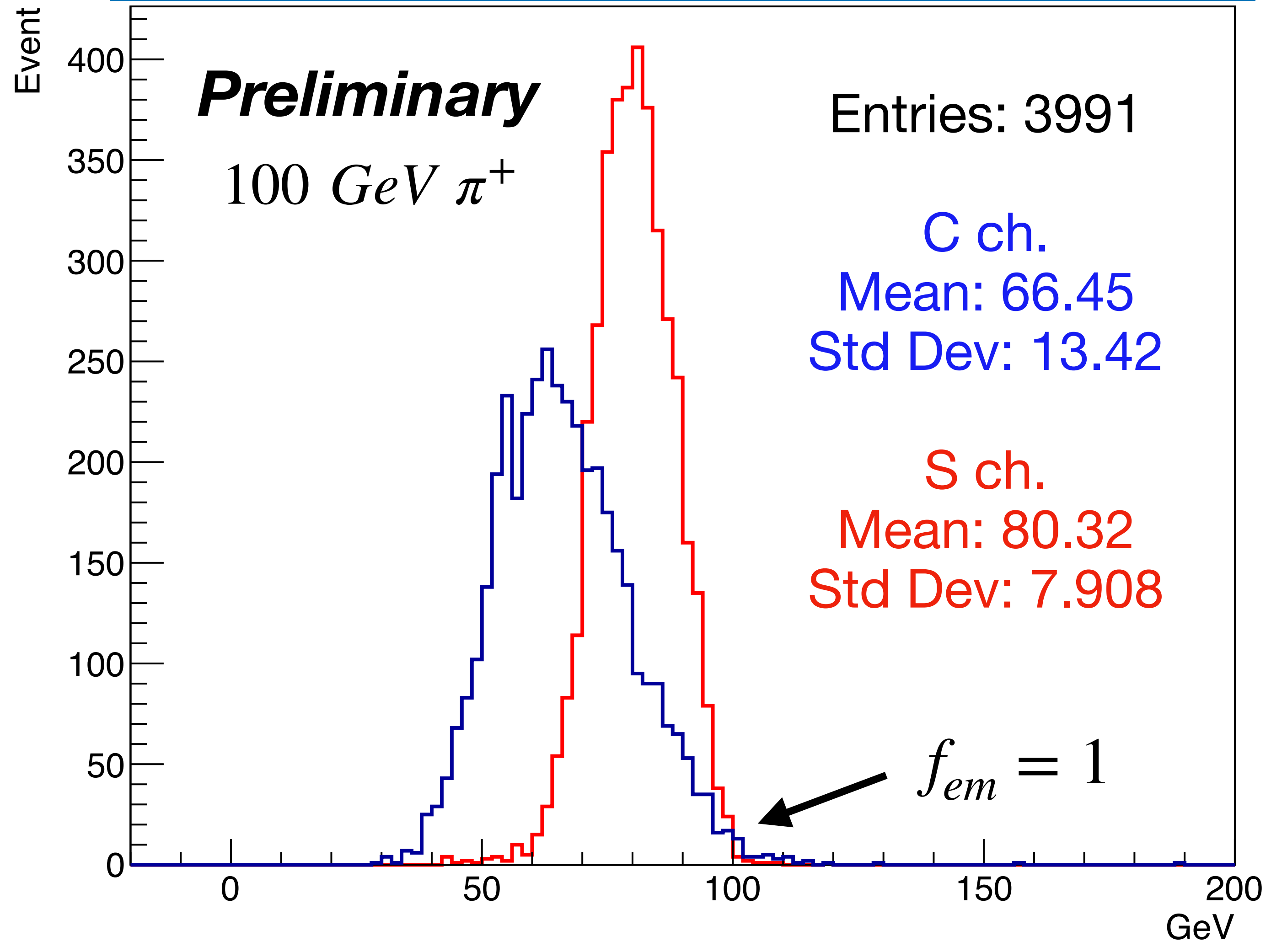
Energy Distribution - Proton



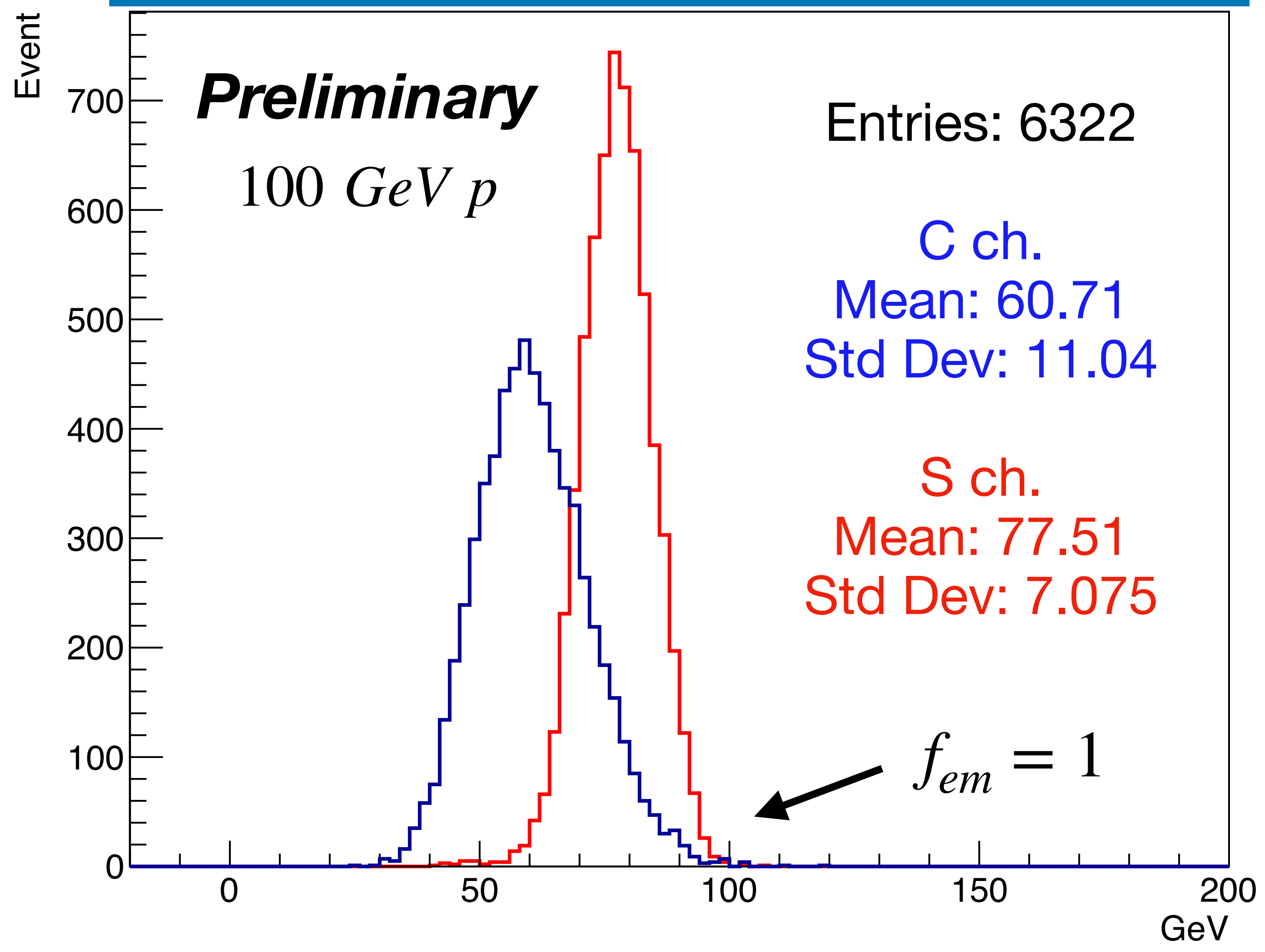
Hadron Performance

Energy Distributions

Energy Distribution - Pion

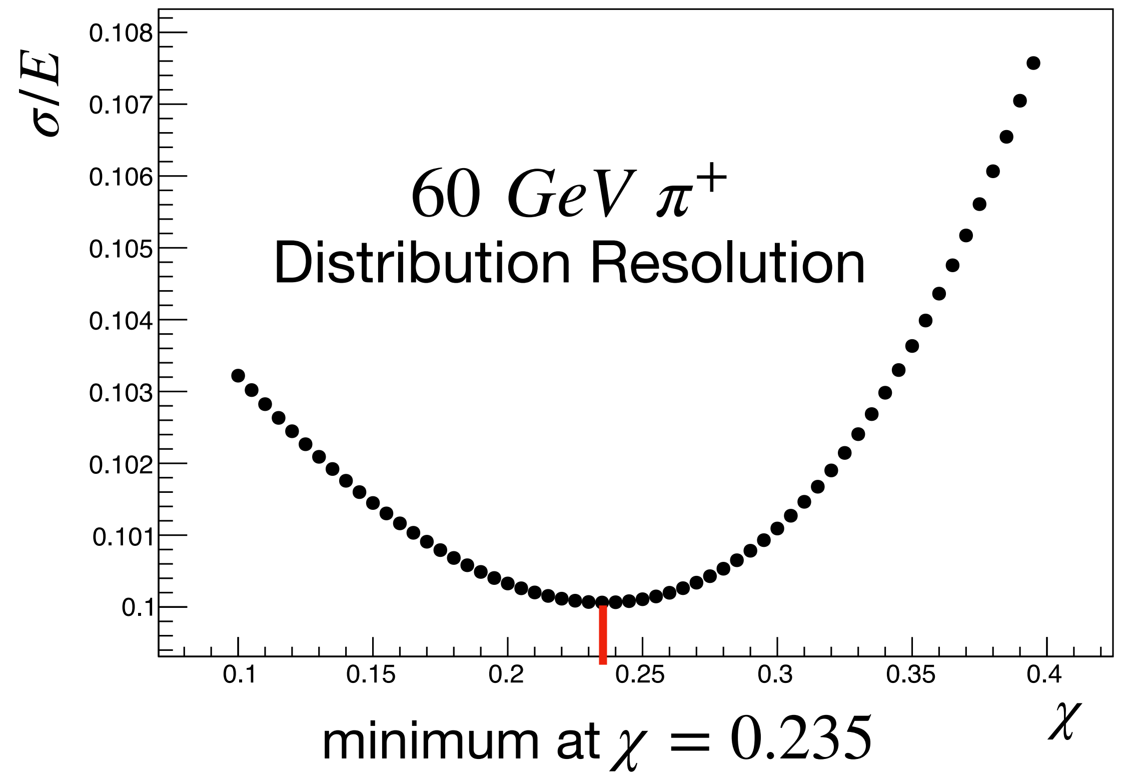


Energy Distribution - Proton



Selected $\chi = 0.235$ to apply DR method, which gives best resolution on scanning χ value

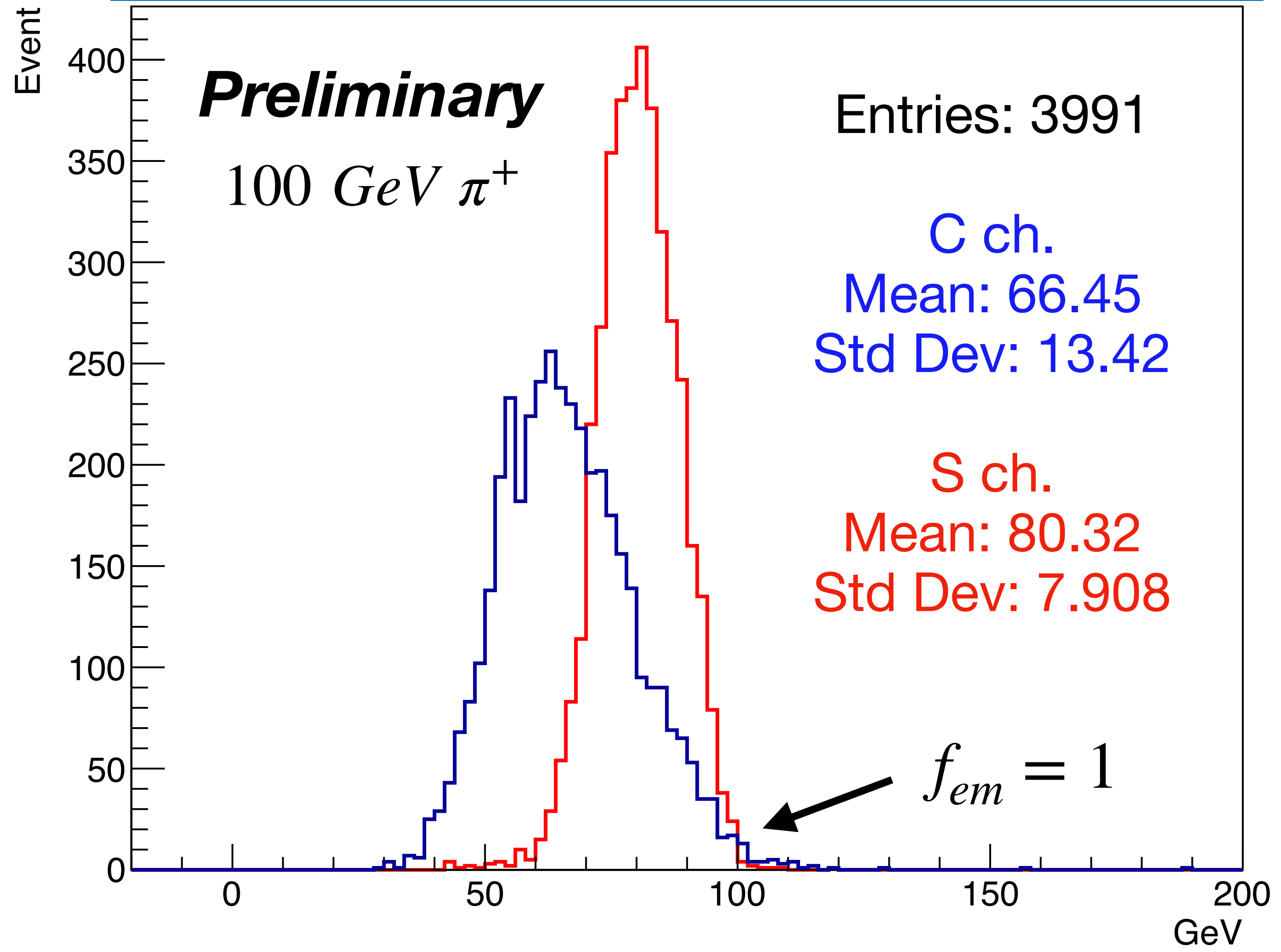
$$E_{DR} = \frac{S - \chi C}{1 - \chi}$$



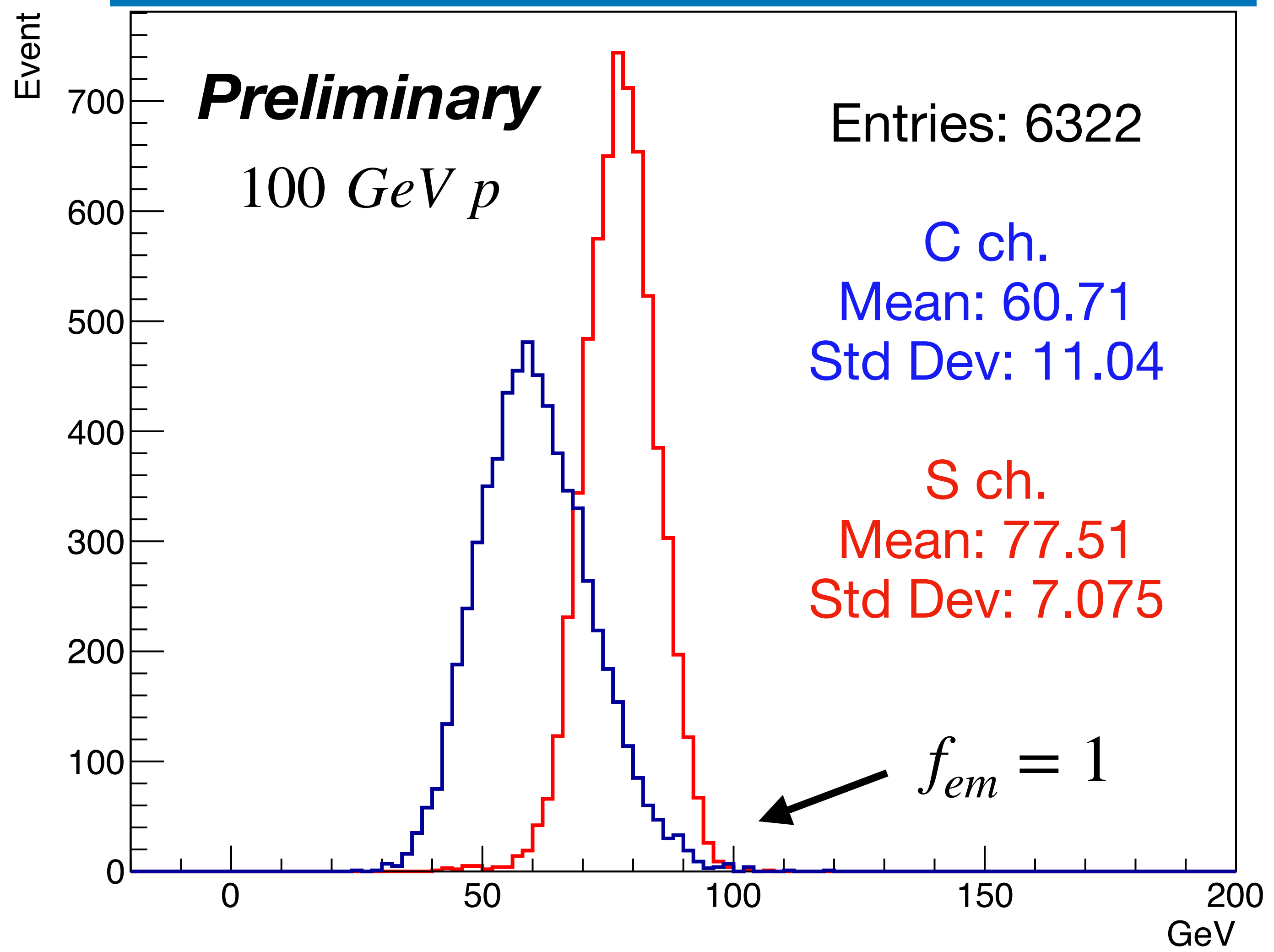
minimum at $\chi = 0.235$

Hadron Performance
Energy Distributions

Energy Distribution - Pion

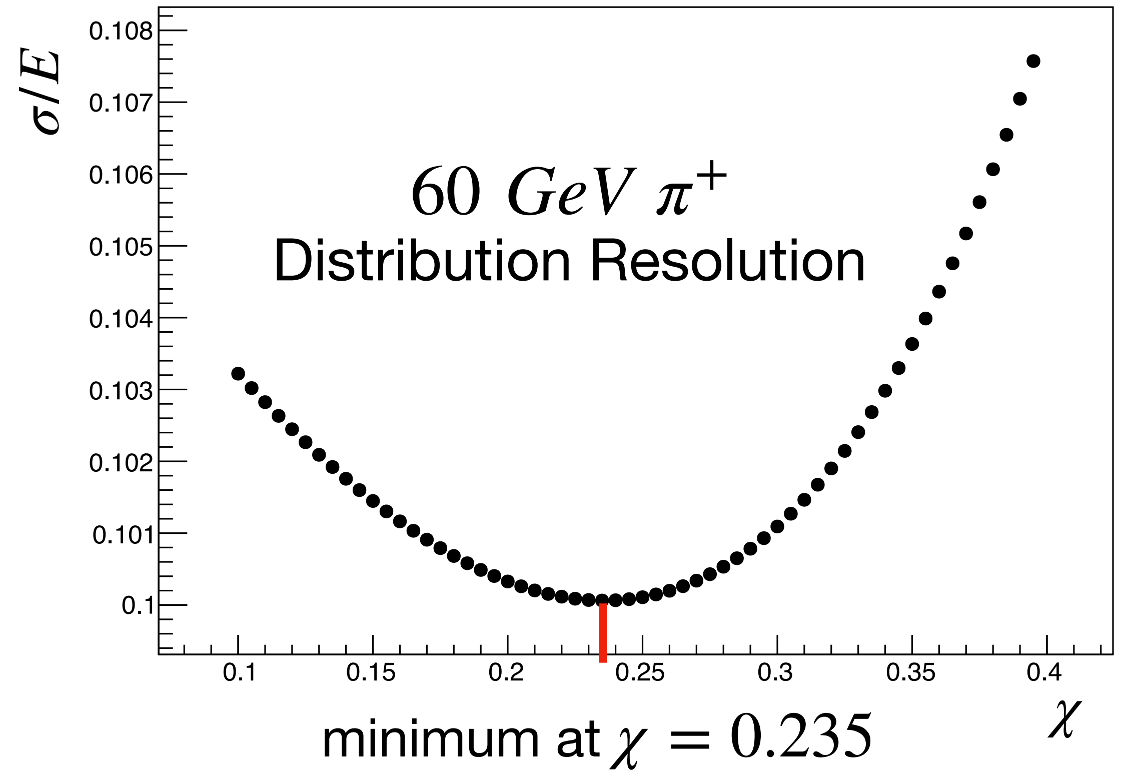


Energy Distribution - Proton



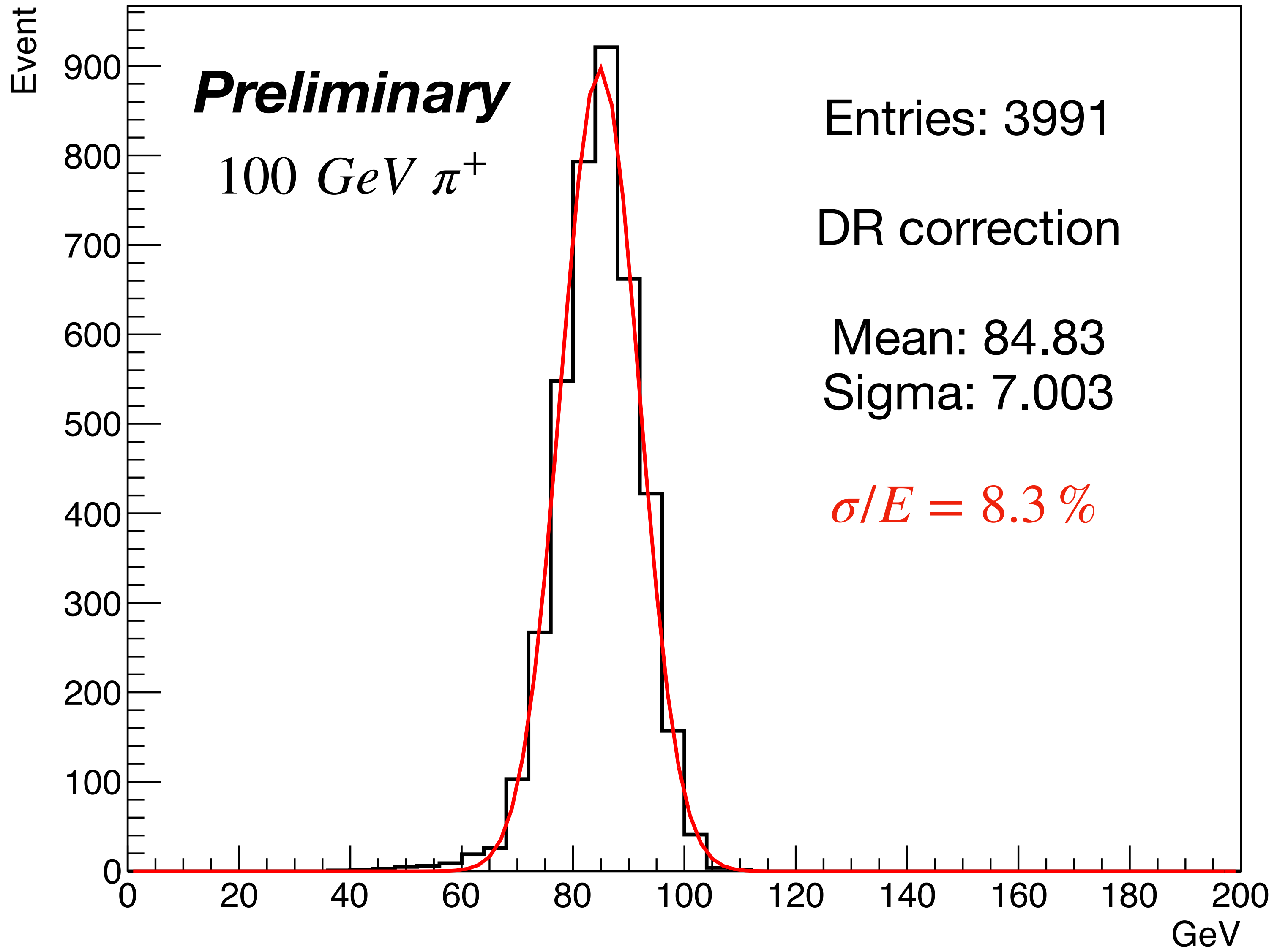
Selected $\chi = 0.235$ to apply DR method, which gives best resolution on scanning χ value

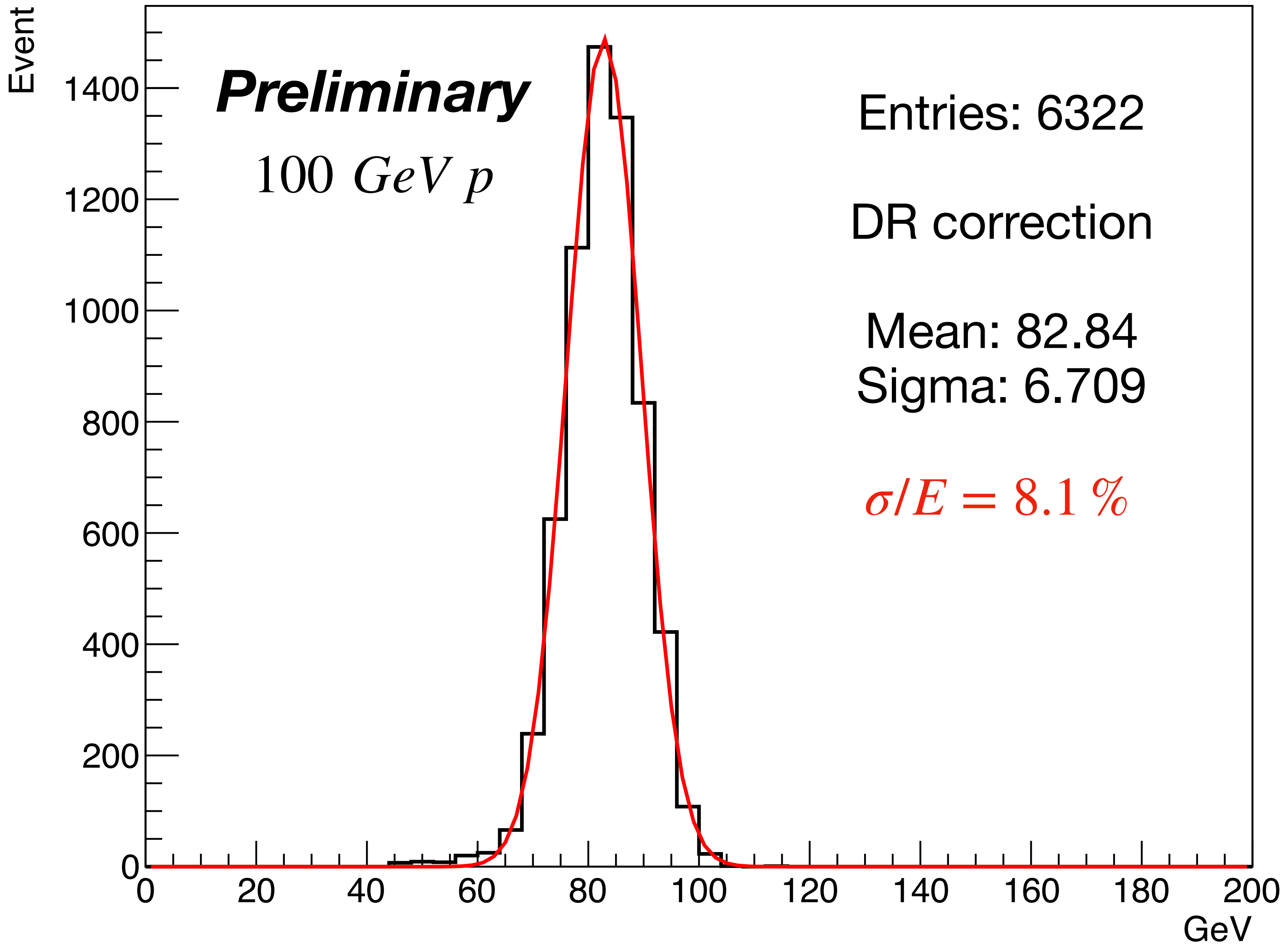
$$E_{DR} = \frac{S - \chi C}{1 - \chi}$$



minimum at $\chi = 0.235$

Dual-Readout Corrected Energy Distribution





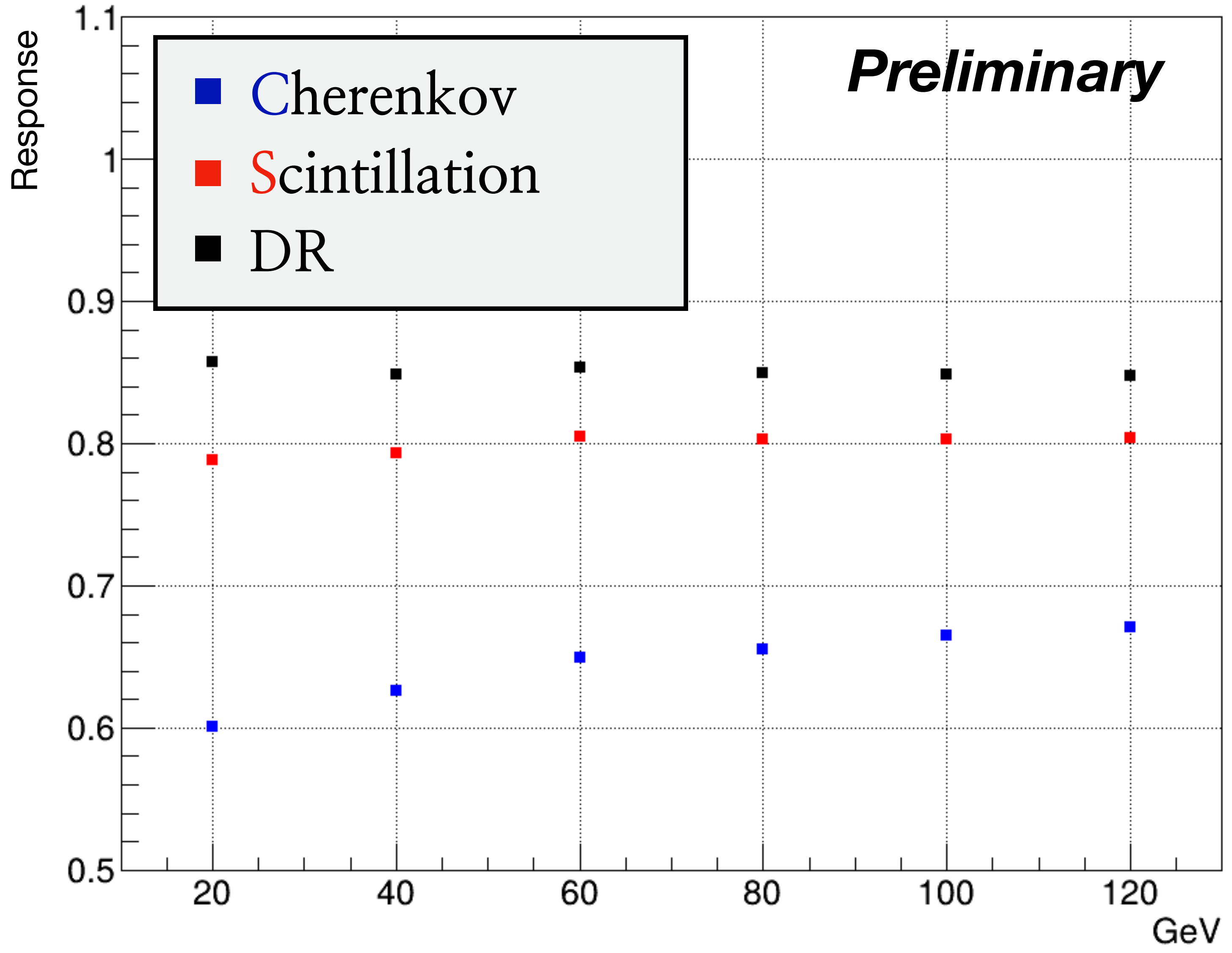
Shows clear Gaussian distribution regardless of particle type

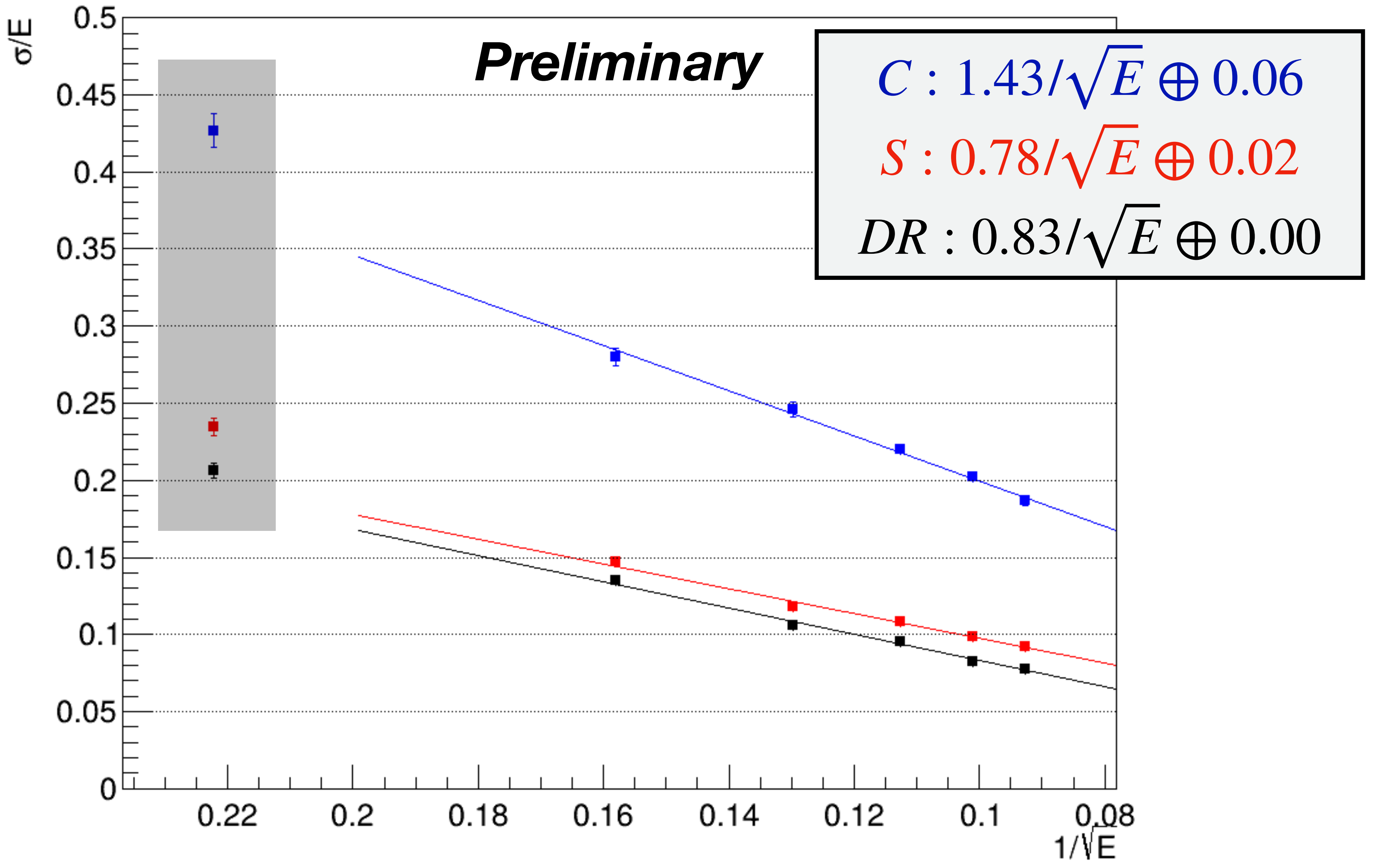
Hadron Performance

Hadron Energy Linearity & Resolution

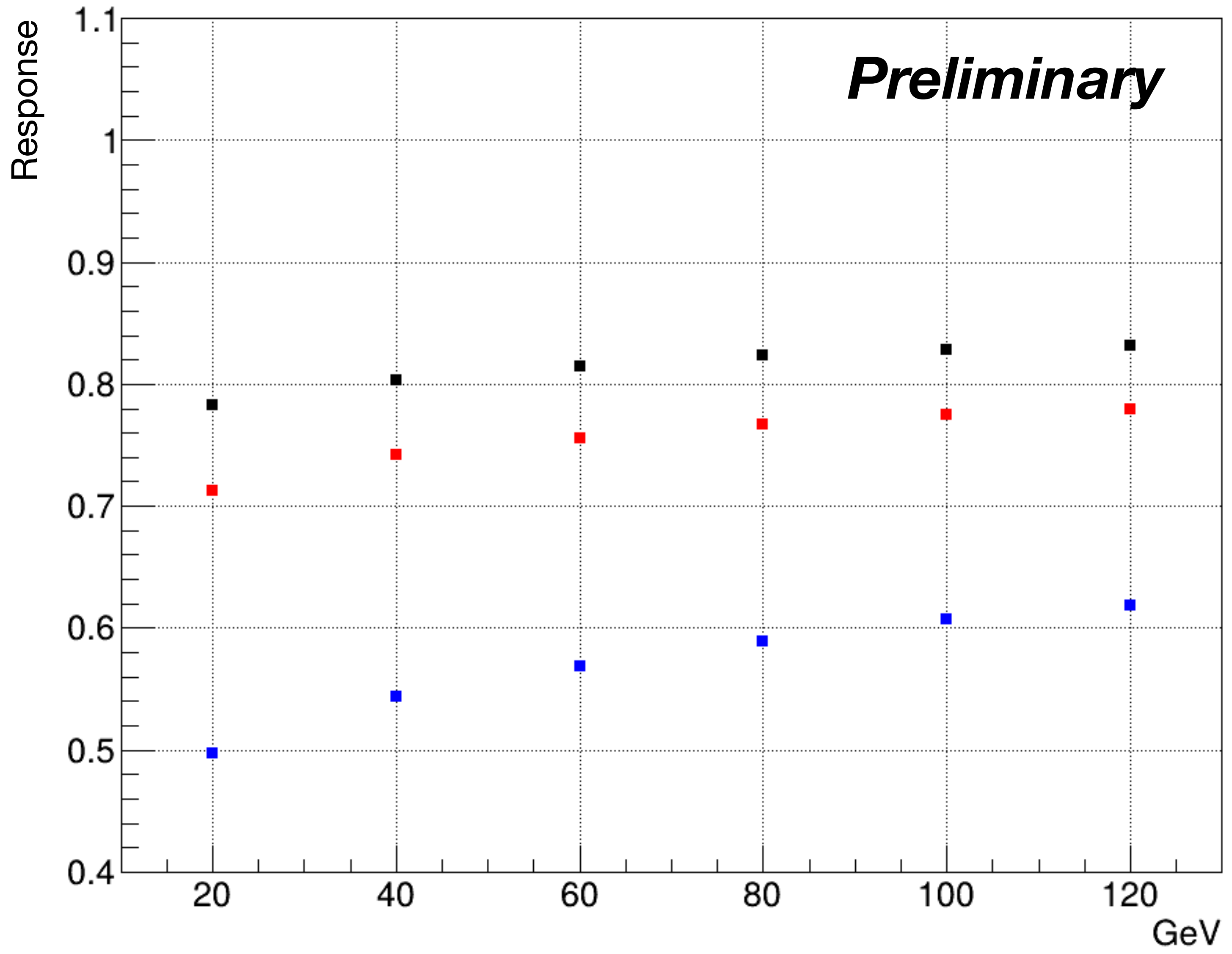
Linearity | **Energy Resolution**

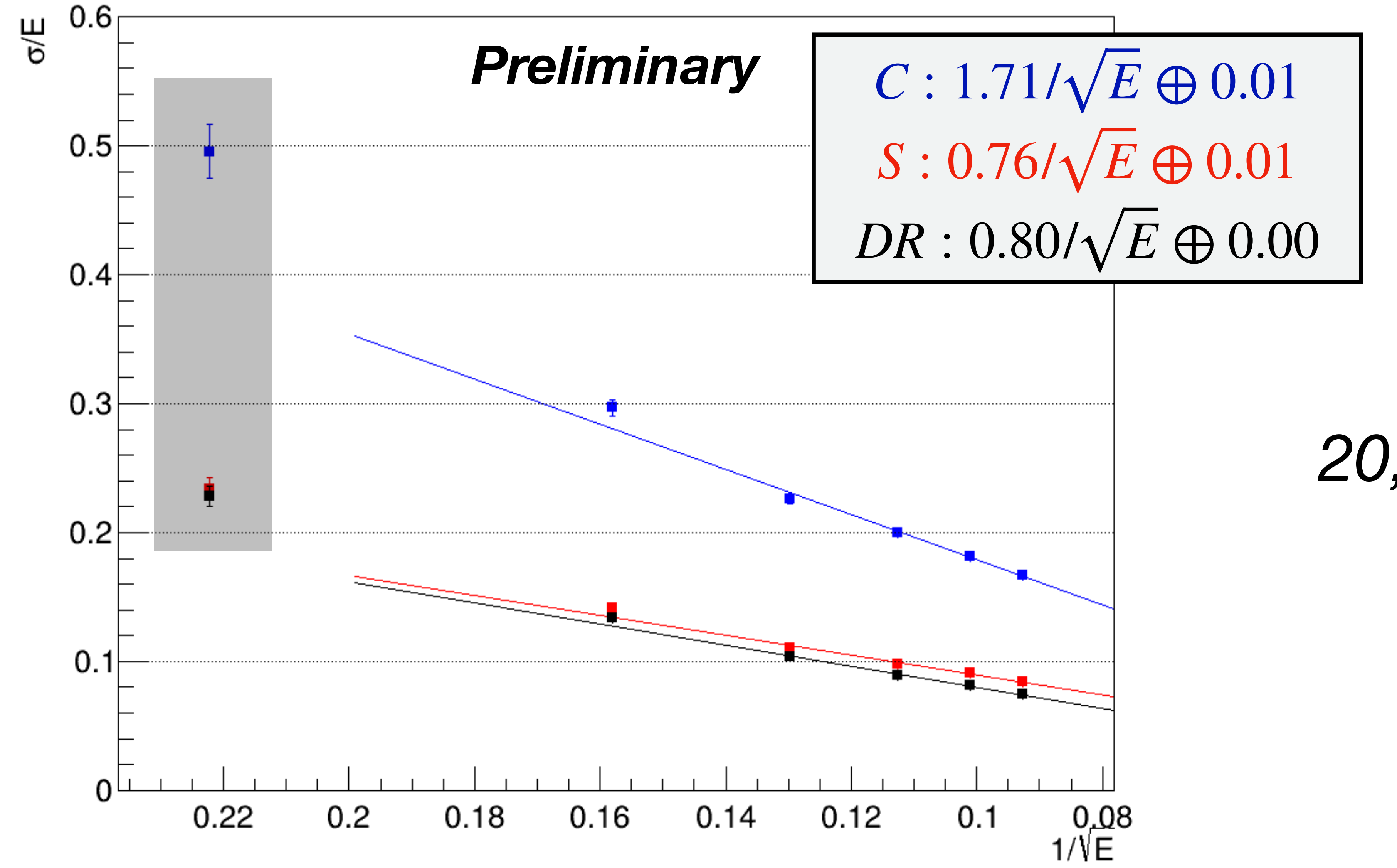
π^+





p





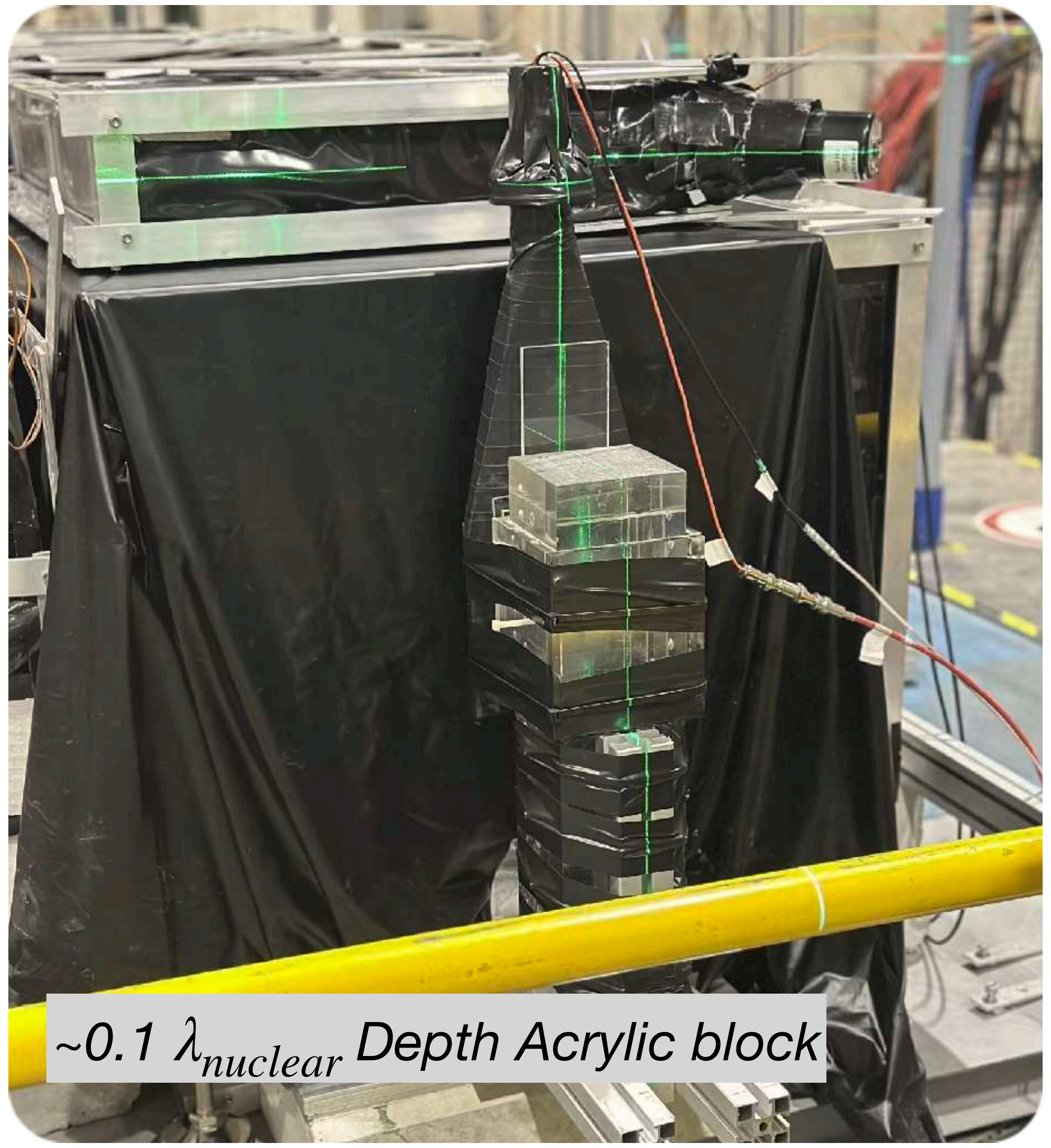
Full Module Response

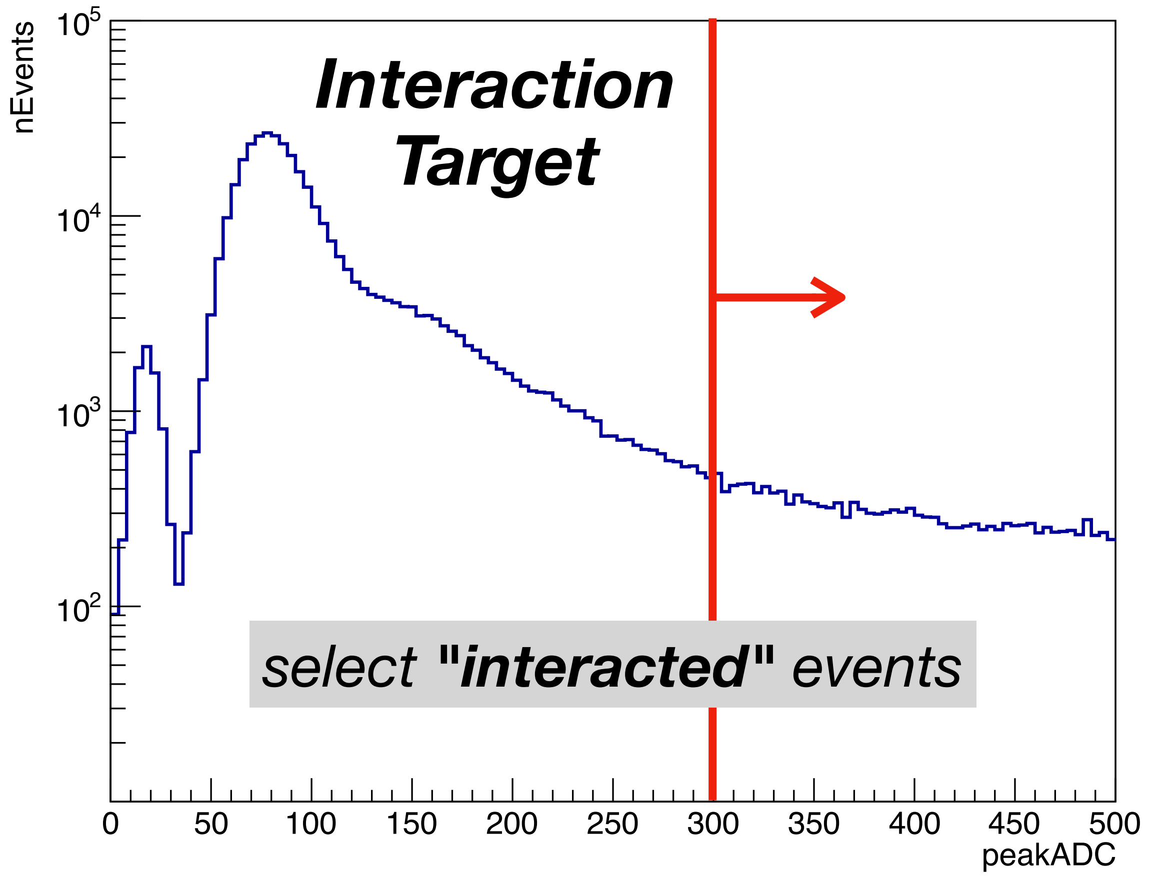
20, 40, 60, 80, 100 and 120 GeV

π^+, p

Hadron Performance

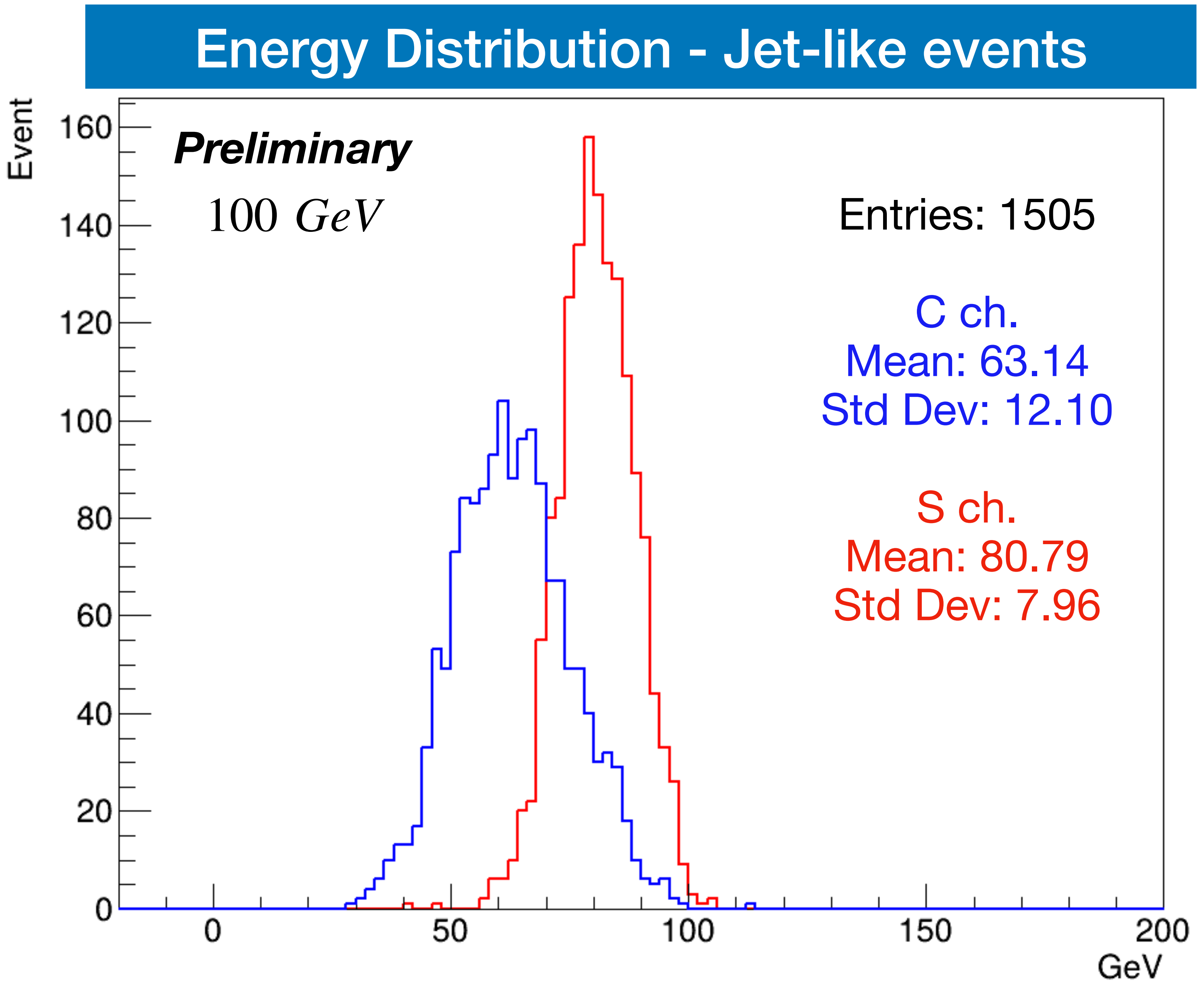
Jet Mimic Events

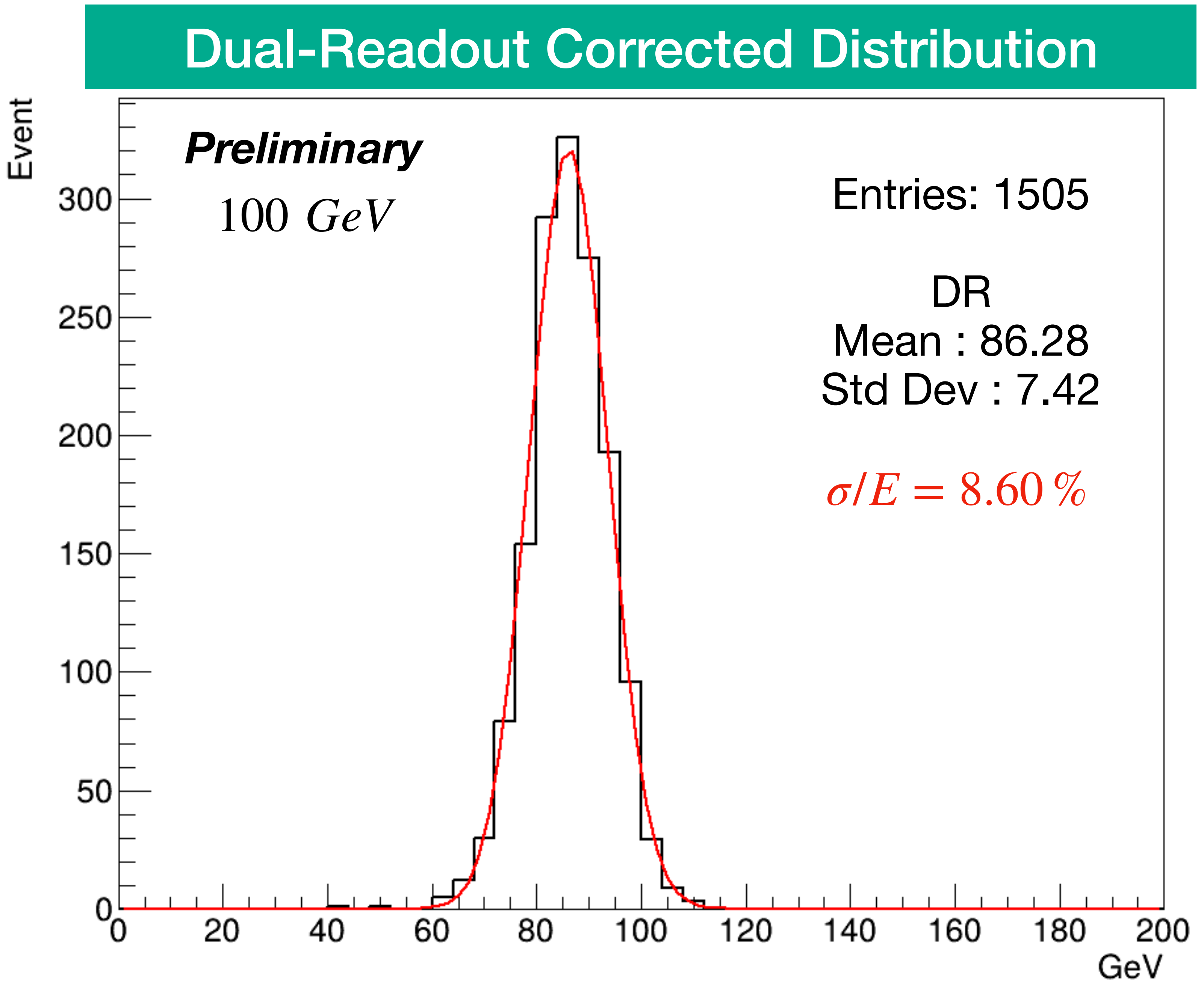




Acrylic block (~0.1 λ_{int}) right front of the calorimeter,

jet-like events were selected by requiring that hadrons interact with the acrylic block (10%)





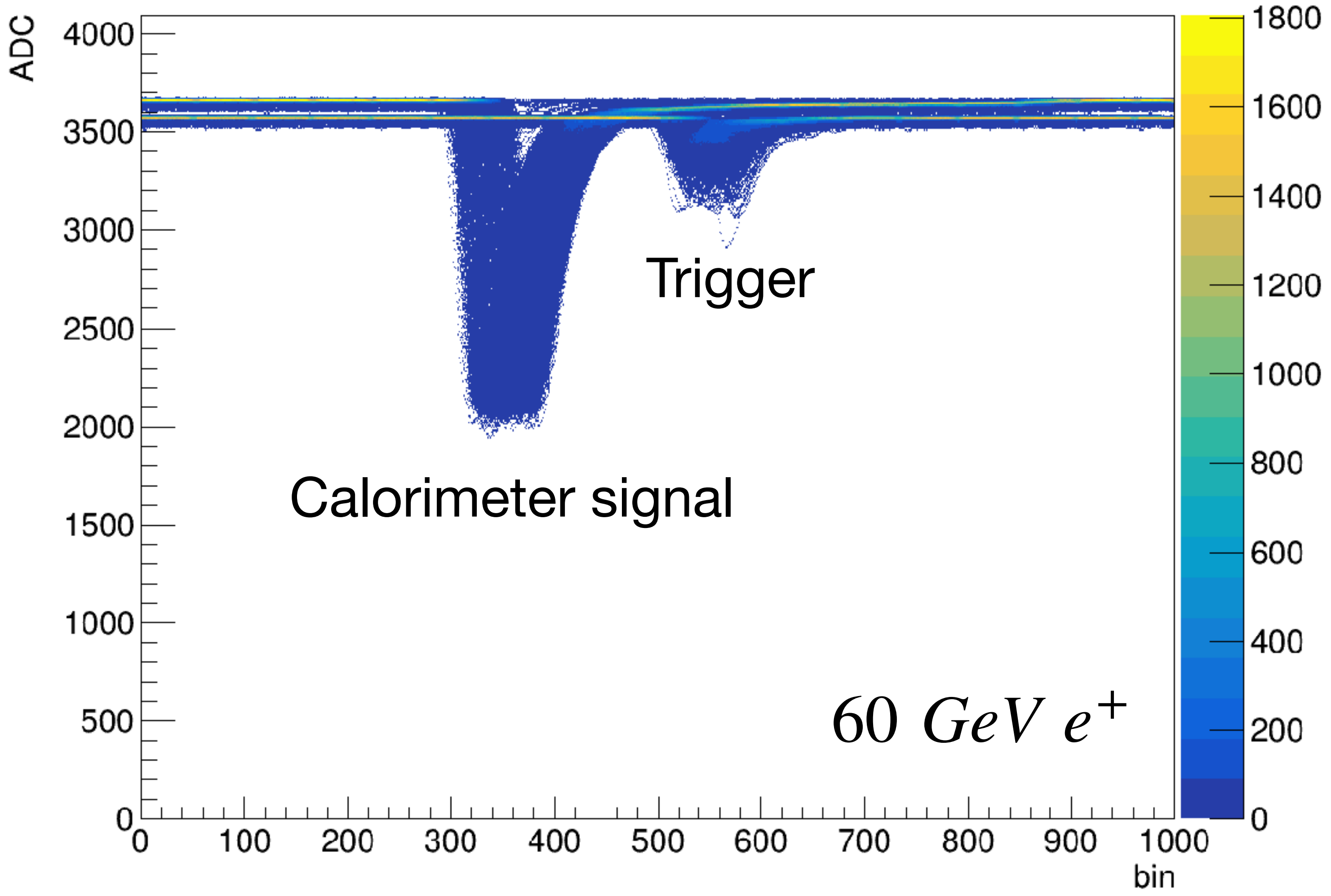
Apply DR method with $\chi = 0.235$

Time Resolution
Calorimeter Time Resolution

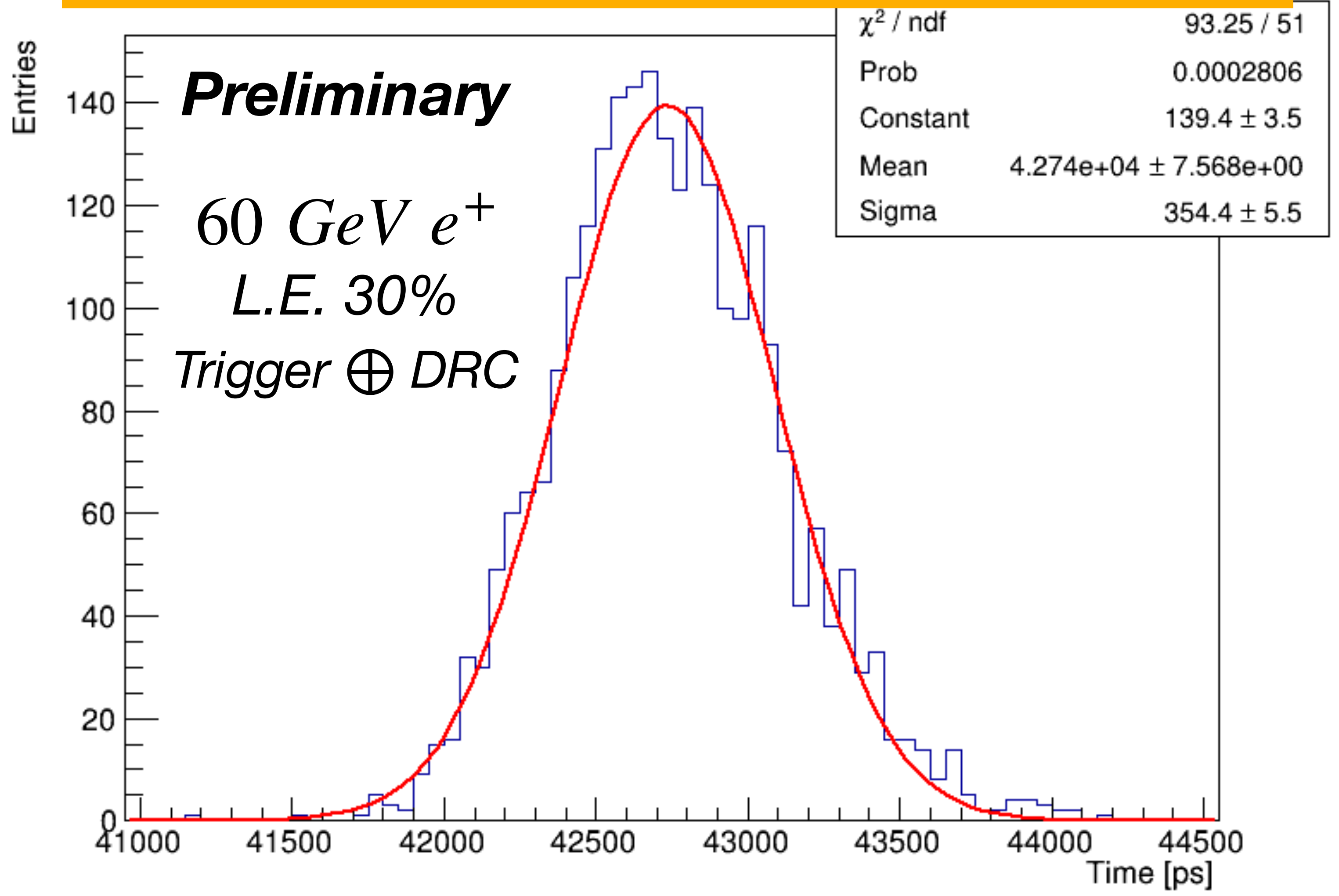
Time Resolution

- Optical properties of fibers and the light produced enable fast time performance.
- With e^+, measured time difference between calorimeter signal and trigger signal, sigma of the distribution giving *time resolution*.
- Subtracting trigger time resolution, measured **average of DRC time resolution** - ***C : 214 ps, S : 251 ps***

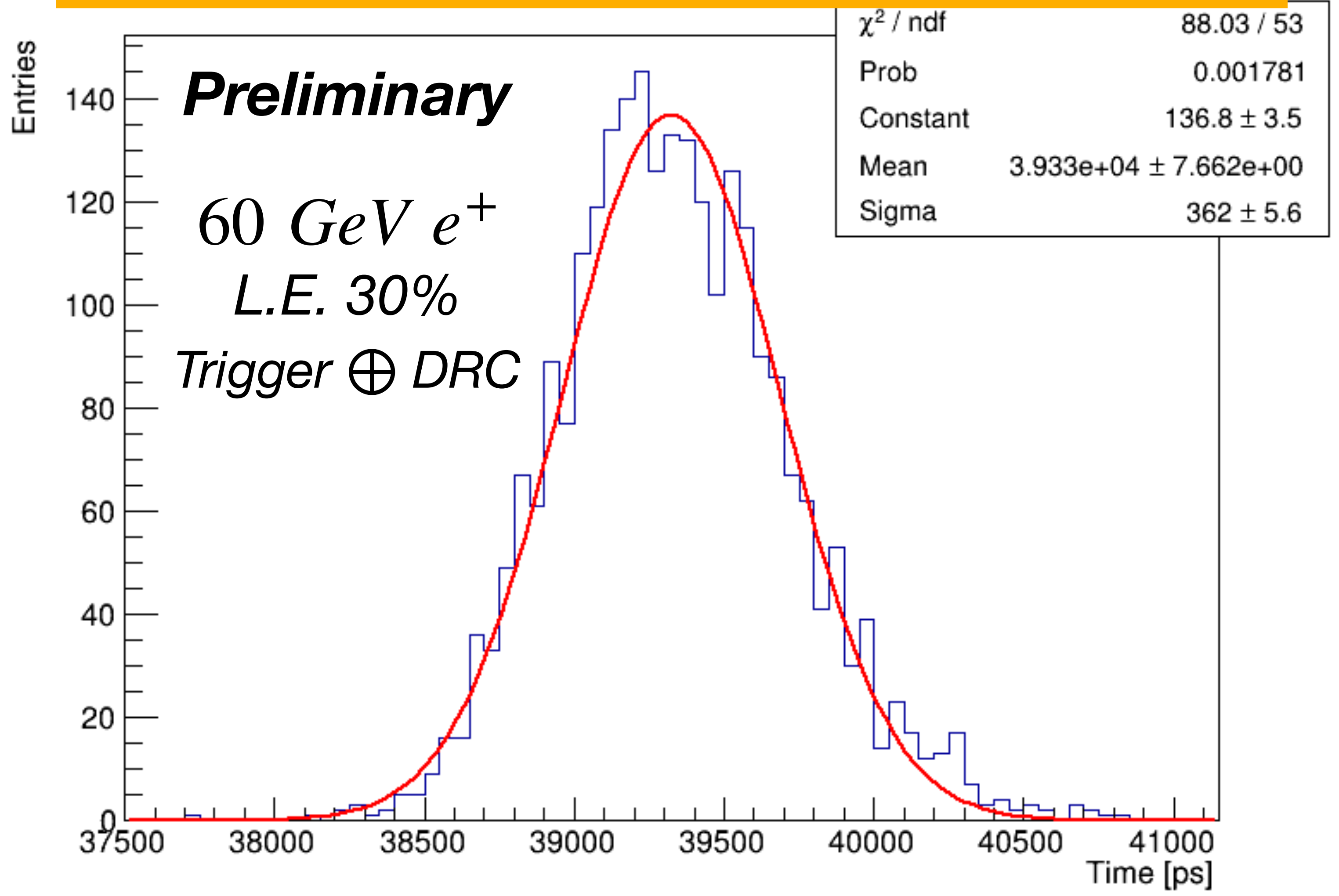
Waveform of Calorimeter & Trigger



C ch. Time Resolution M4T3

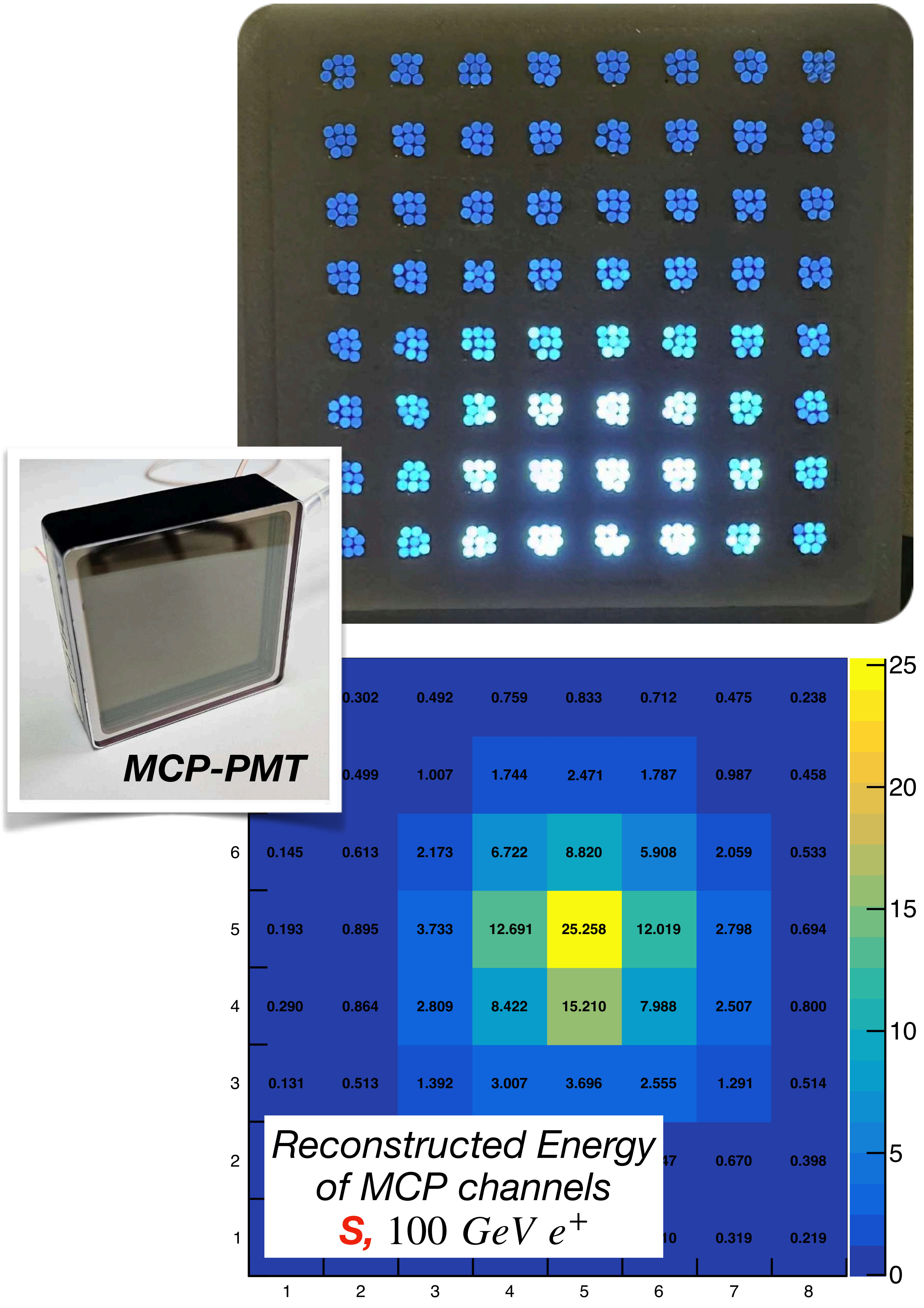


S ch. Time Resolution M4T3



High Granularity
Position Reconstruction

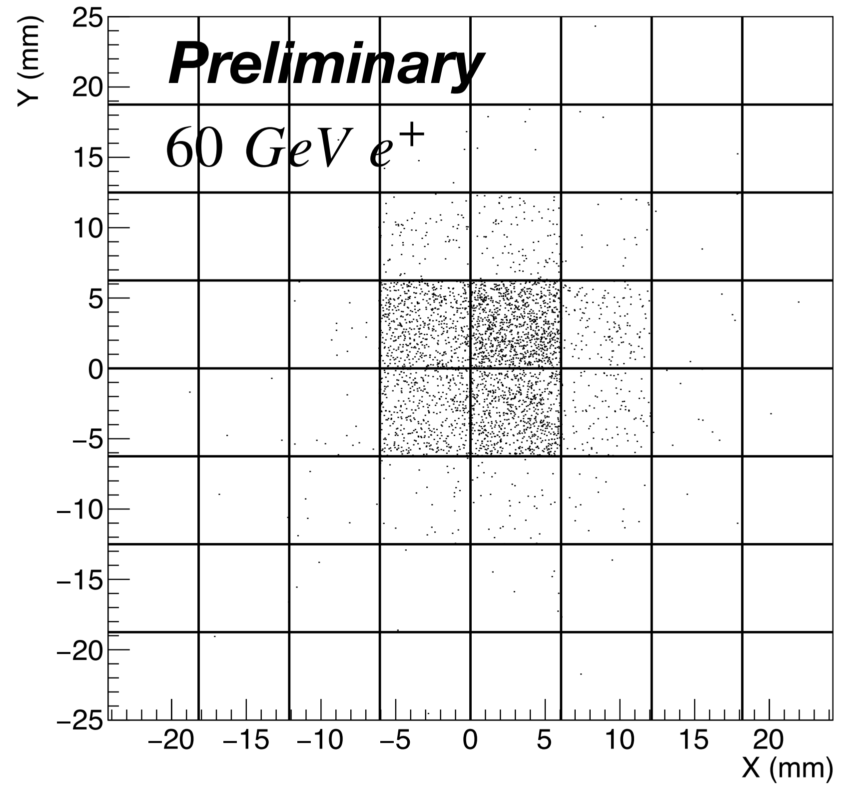
8x8x2, 128 ch.



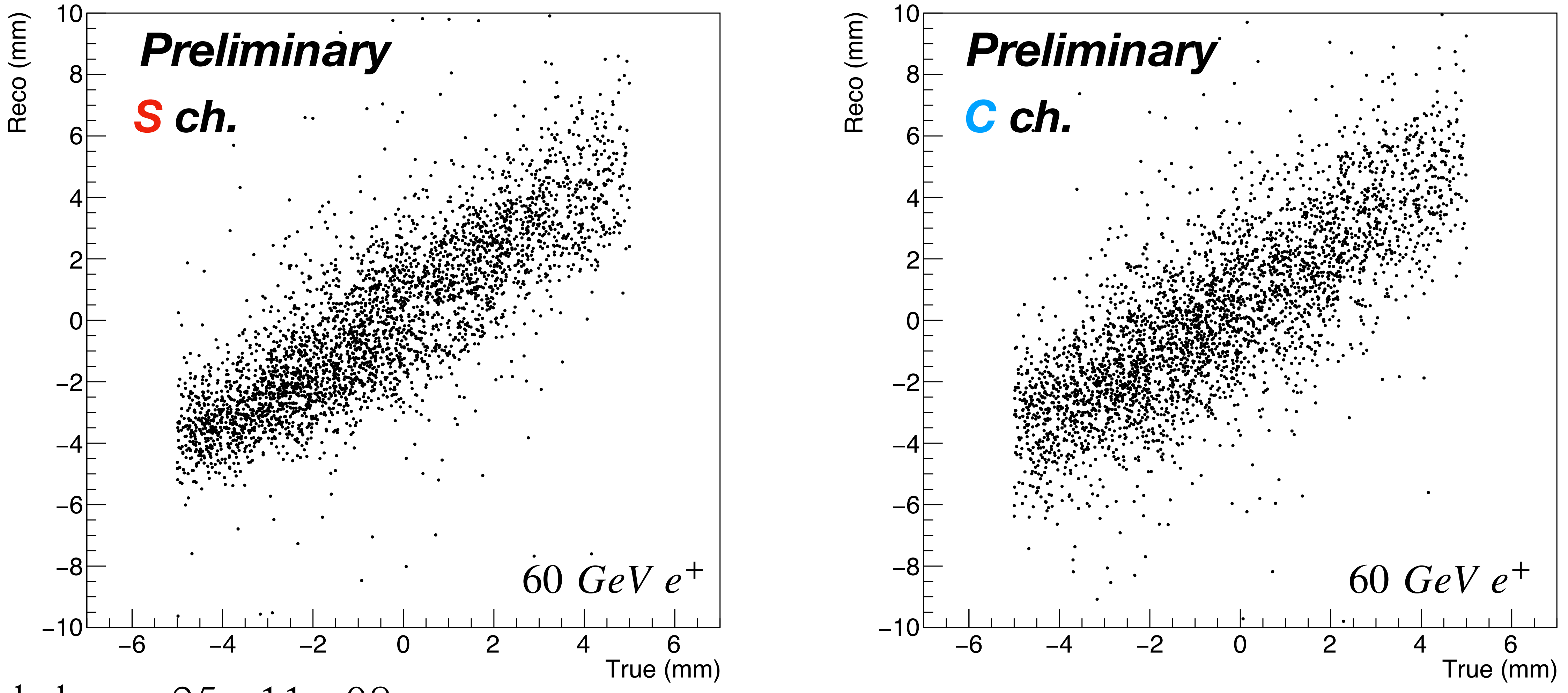
High Granularity

- Tested High Granularity with MCP-PMT placed at center tower of calorimeter.
- With e^{+}, using **center-of-gravity method** weighted by energy, reconstructed initial **beam position**.
- Assuming the position measured with DWC is "true" position, measured difference between the DWC and reconstructed position - *sigma as position resolution*

Reconstructed Beam Position

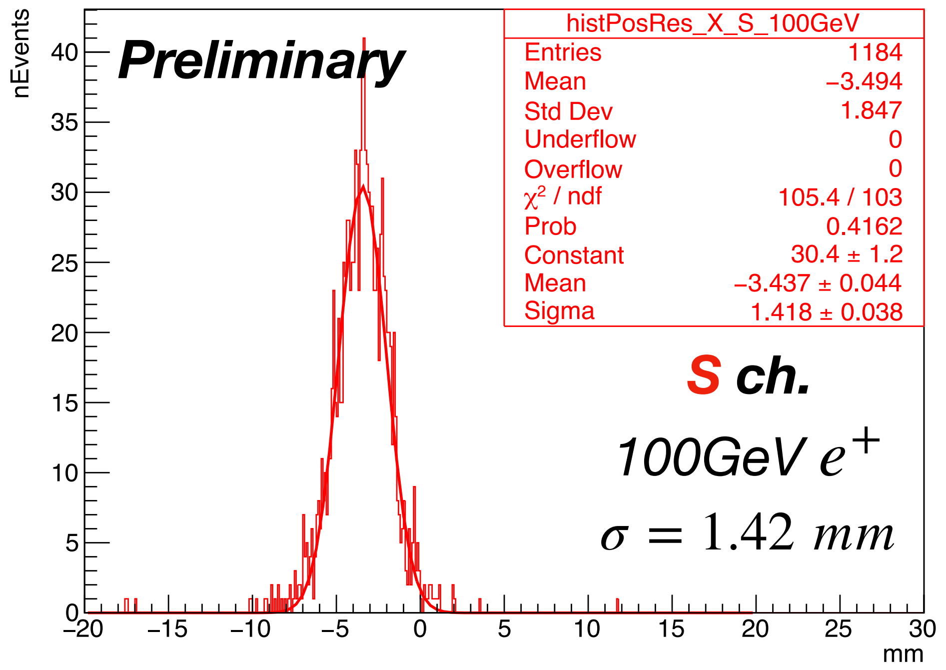


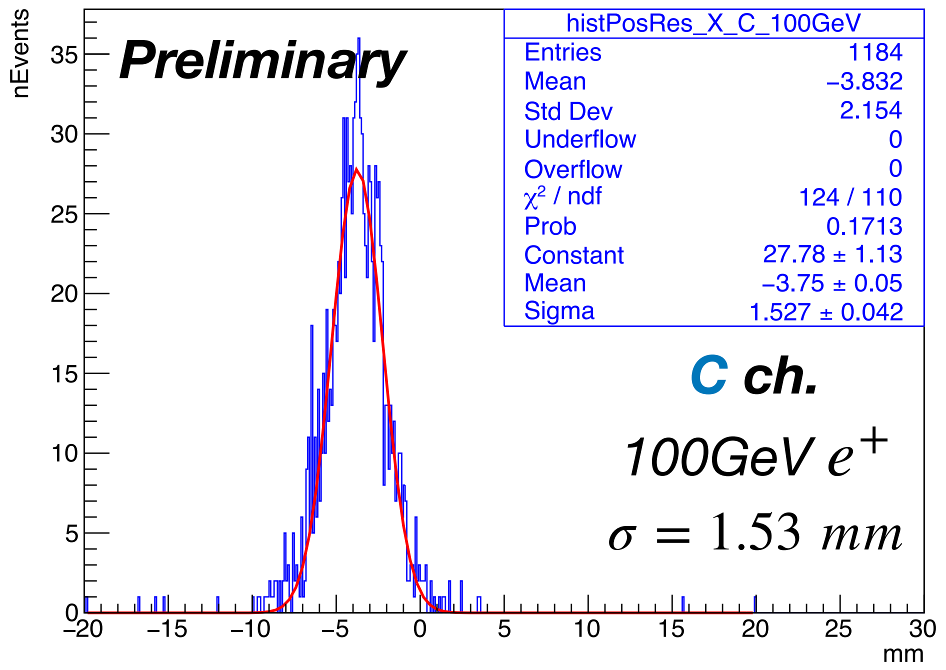
DWC (True) Position vs Reco. Position (Y-axis)



High Granularity
Position Resolution

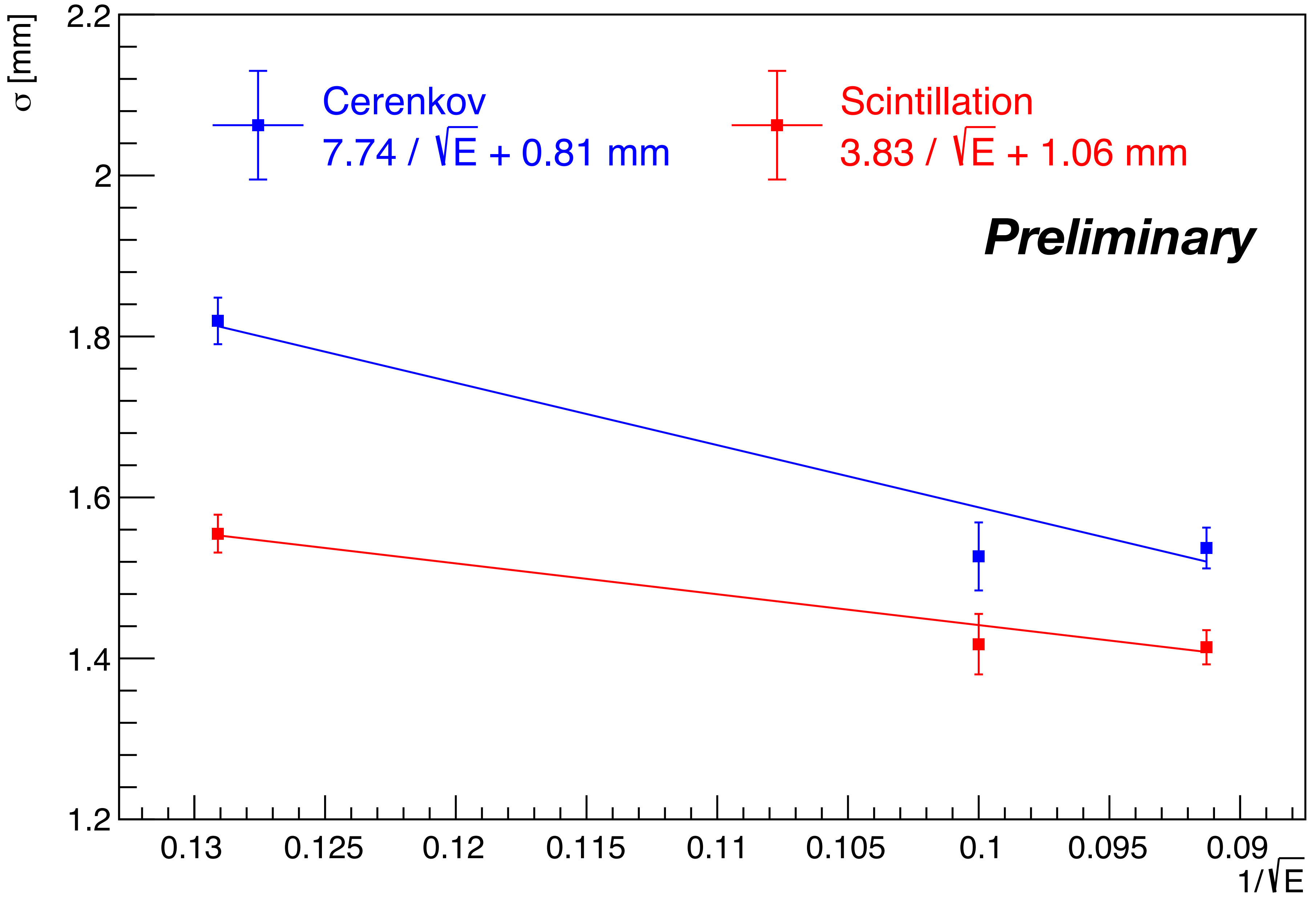
Reconstructed Position Distribution



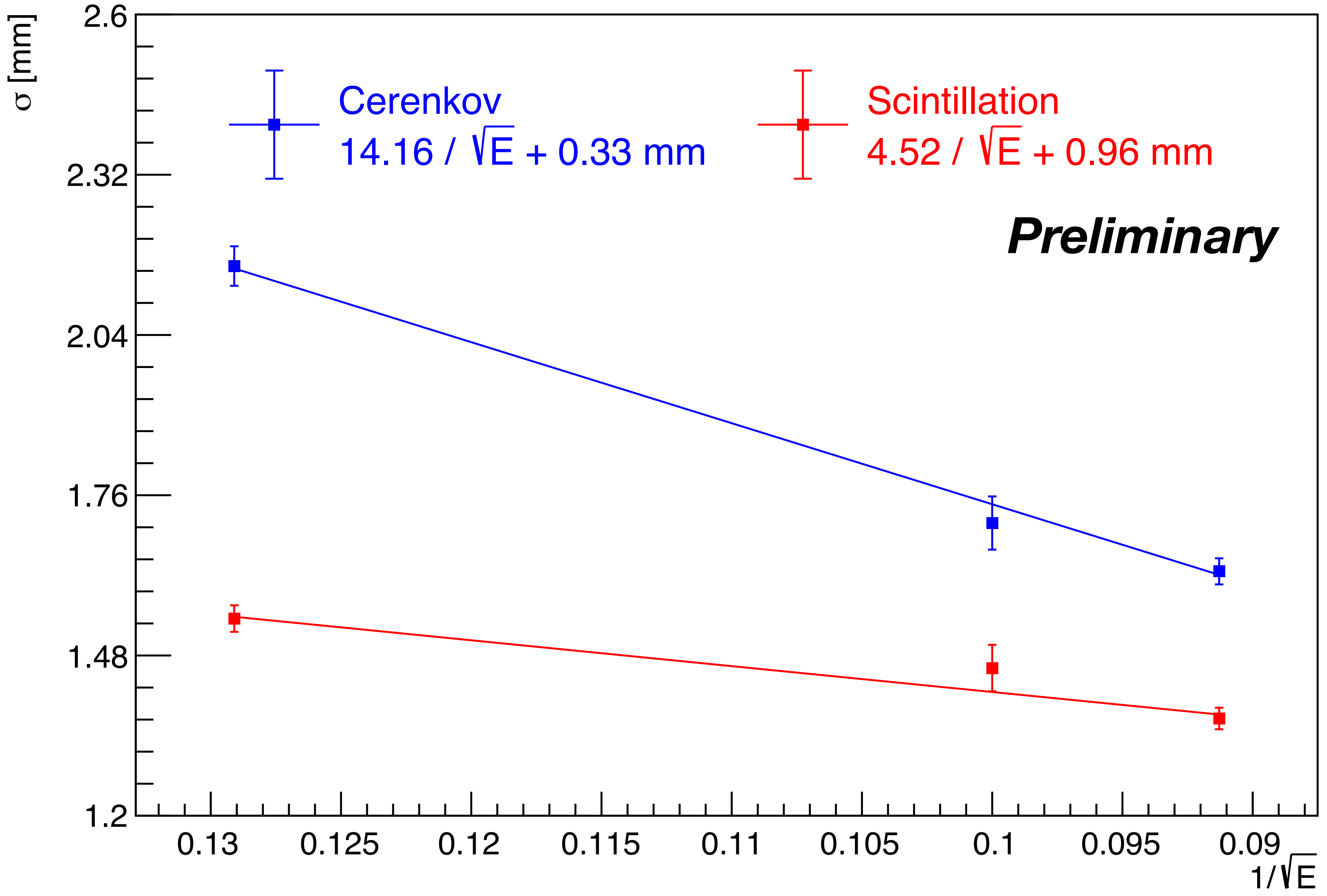


- Measured position resolution for 60, 100, and 120 GeV e^+
- Achieved a resolution of ***~1.5 mm at 100 GeV*** e^+
- Position resolution shows **energy dependence** - improves at high energy

X-axis Position Resolution



Y-axis Position Resolution



Future Plans
R&D and Test Beam Experiments

Super Module

- Compact size (~50 cm) module to test **various module building options**.
- *Absorber type, copper forming method, optical fiber, and high granularity*.
- Planning to conduct test beam at KEK with low energy EM particles.

Readout R&D

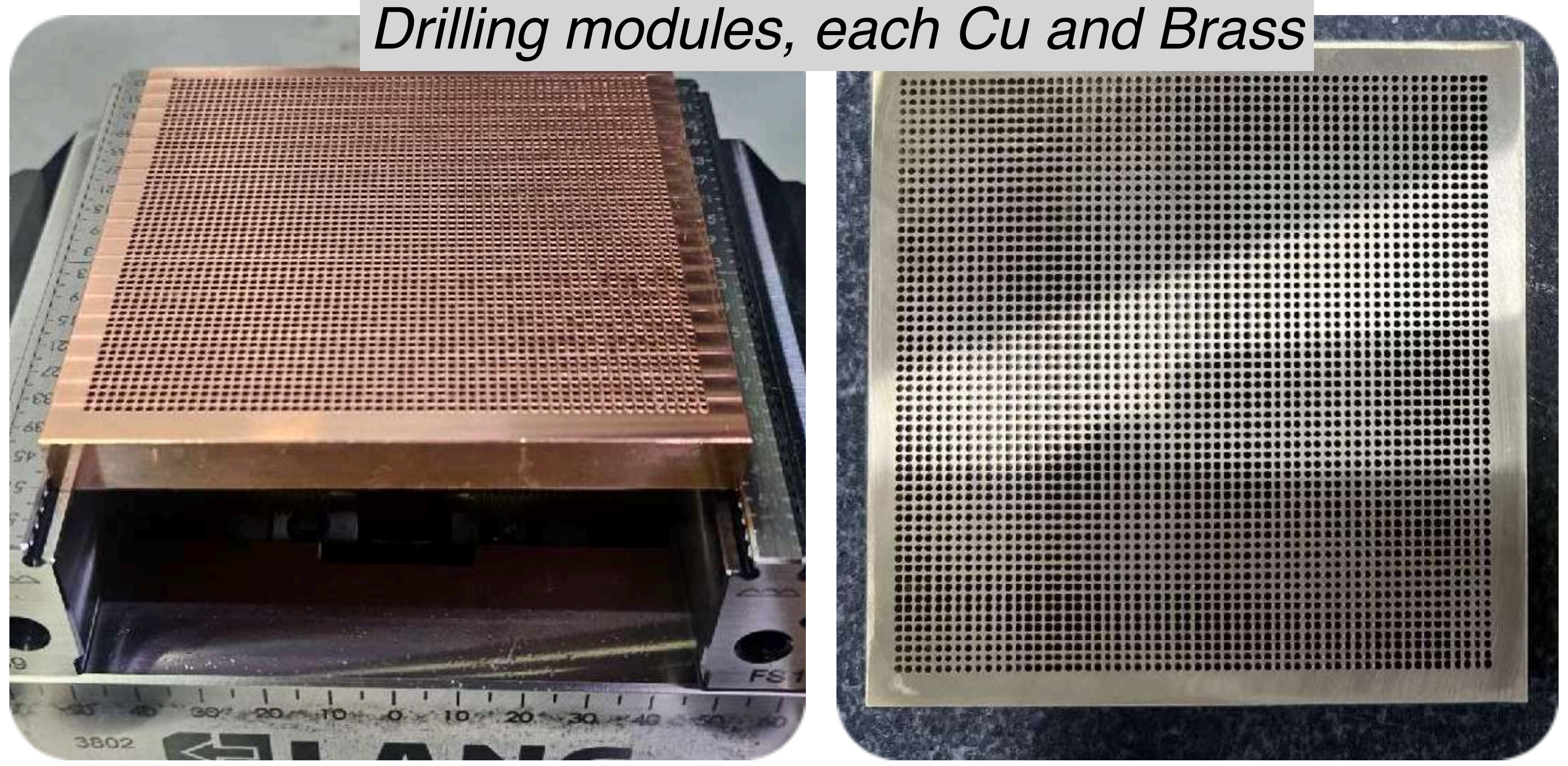
- Developing customized MCP-PMT aiming toward **1-fiber-per-channel readout**.
- Development currently in progress in collaboration with Argonne National Laboratory (ANL).

DAQ Upgrade

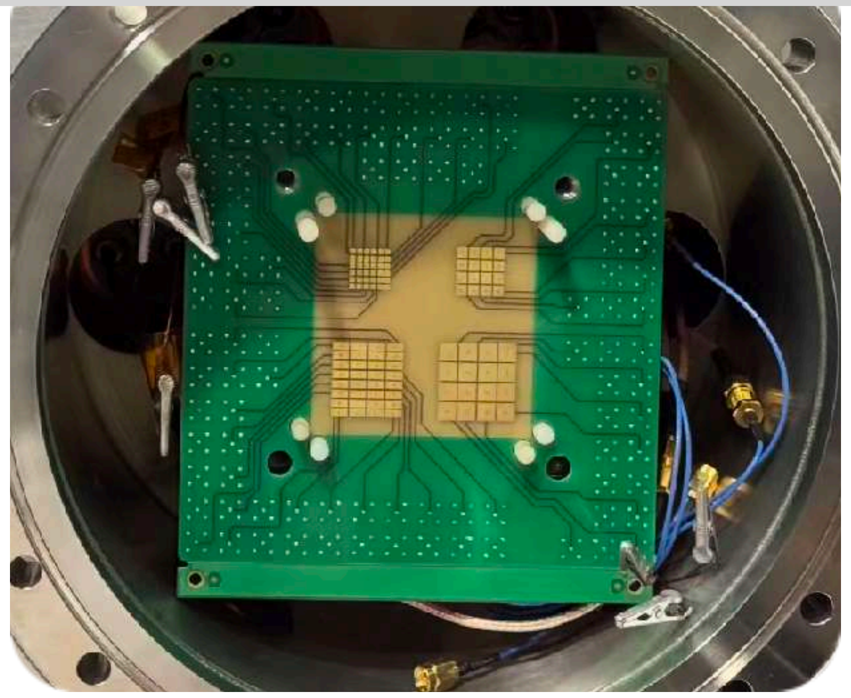
- To improve time resolution, study on **optimization of our DAQ system** is ongoing.
- Through calibration process, time resolution for multi-DRS4 reached ~36 ps.

AND TB2026!

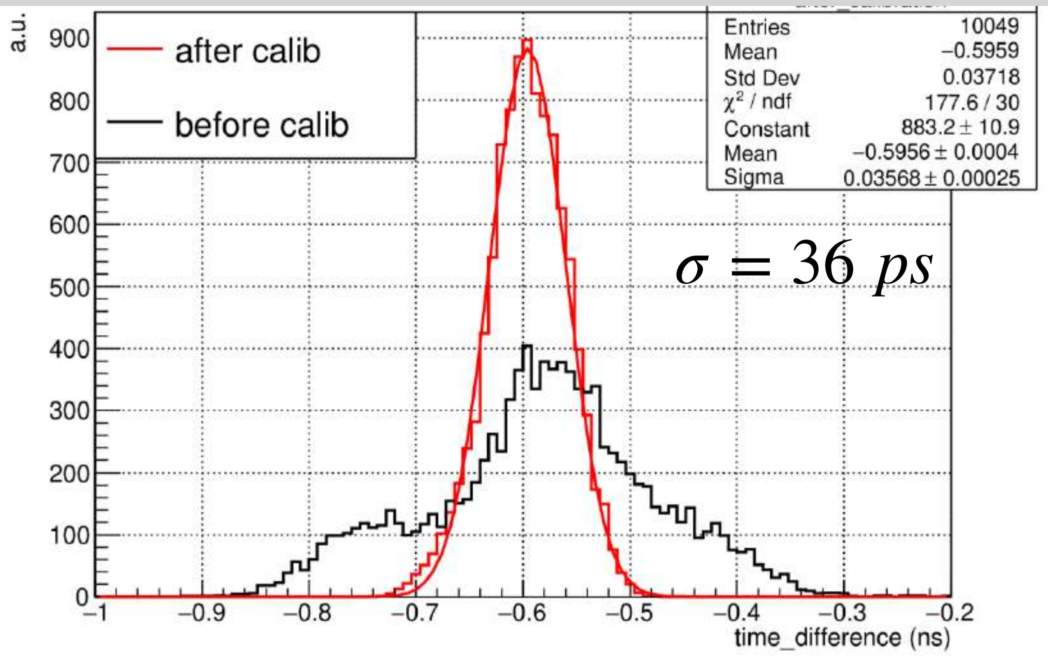
Drilling modules, each Cu and Brass



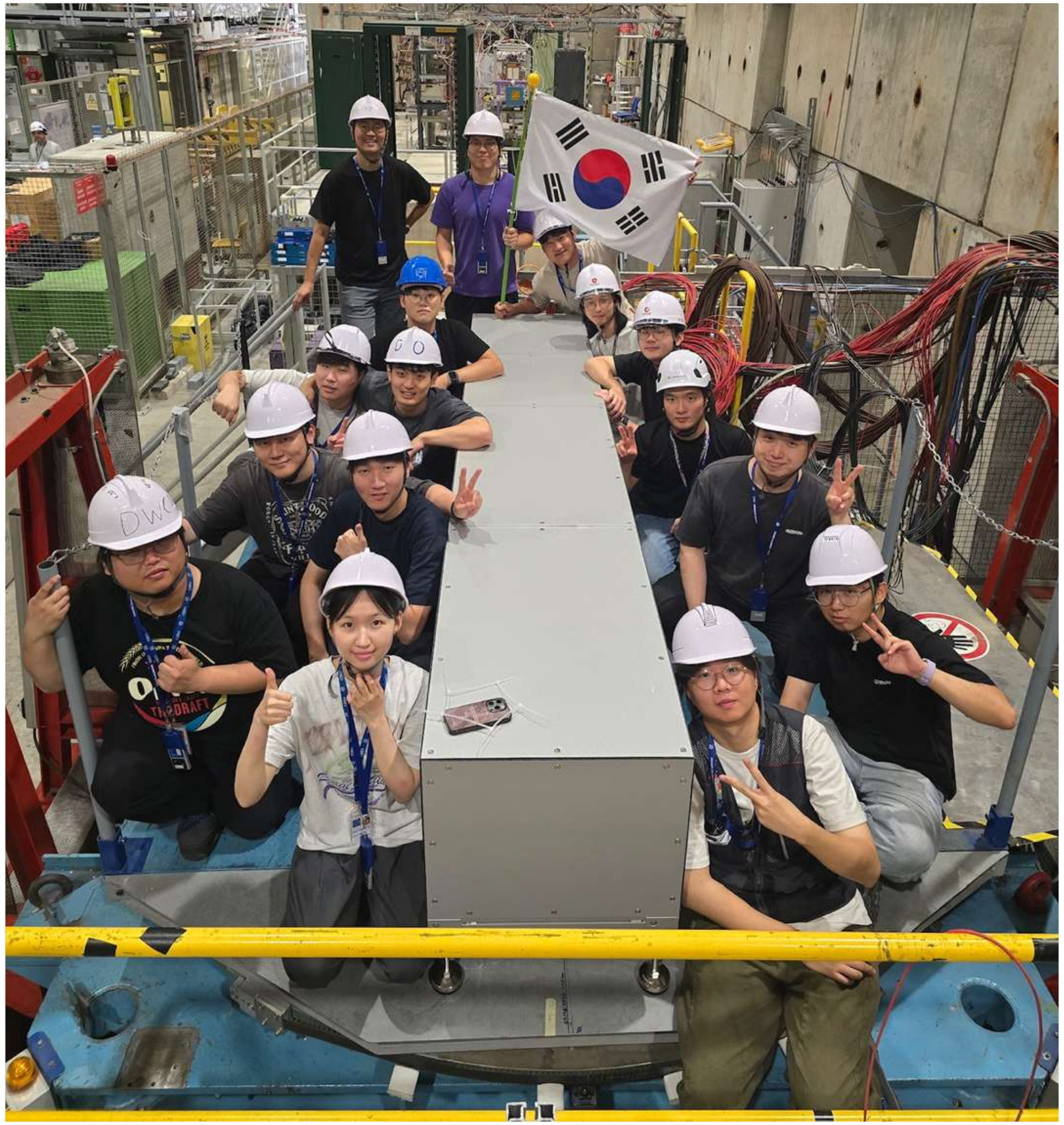
Test setup for MCP-PMT of various pixel size



Time Resolution of multi-DRS4 (w/o module)



Summary



DRC TB2025 @CERN SPS

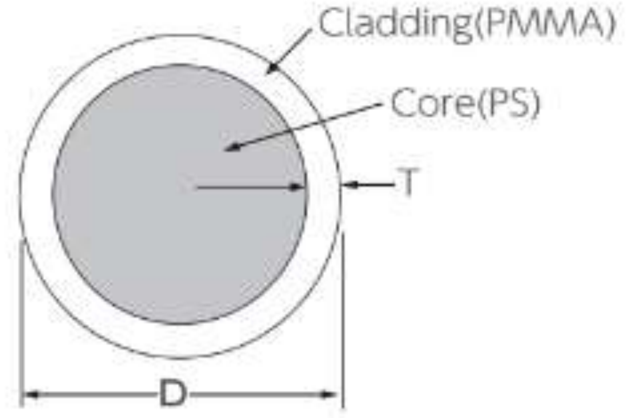
- *Korea DRC collaboration has successfully conducted TB2025*.
- With improvements on mechanical supporter and DAQ system, we took data without any crucial issues.
- Data analysis is now on going, ***we expect wonderful results!***
- And, all aspects of the DRC detector R&D is ongoing for future.

Backup

Optical Fiber Specification

Scintillating Fiber : SCSF-78

Single Cladding



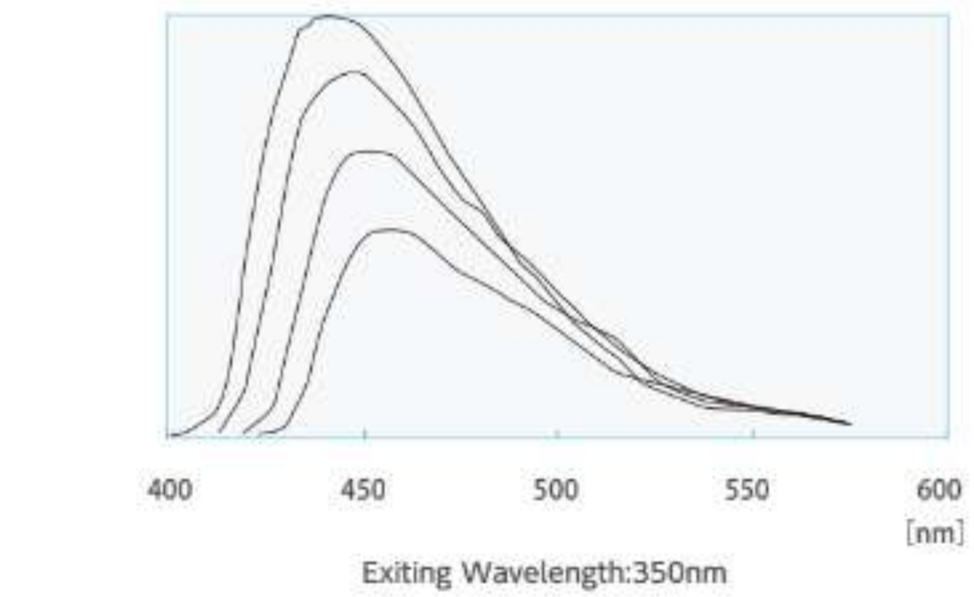
Cladding Thickness[1]: T=2% of D
Numerical Aperture: NA=0.55
Trapping Efficiency : 3.1%

Description	Emission Color	Emission Spectra	Emission Peak[nm]	Decay Time [ns]	Att.Leng.[2] [m]
SCSF-78	blue	See the	450	2.8	>4.0

Core		Polystylene(PS)	n_D=1.59	1.05	C: 4.9x10[22] H: 4.9x10[22]
Cladding	for single cladding inner for multi-cladding	Polymethylmethacrylate (PMMA)	n_D=1.49	1.19	C: 3.6x10[22] H: 5.7x10[22] O: 1.4x10[22]

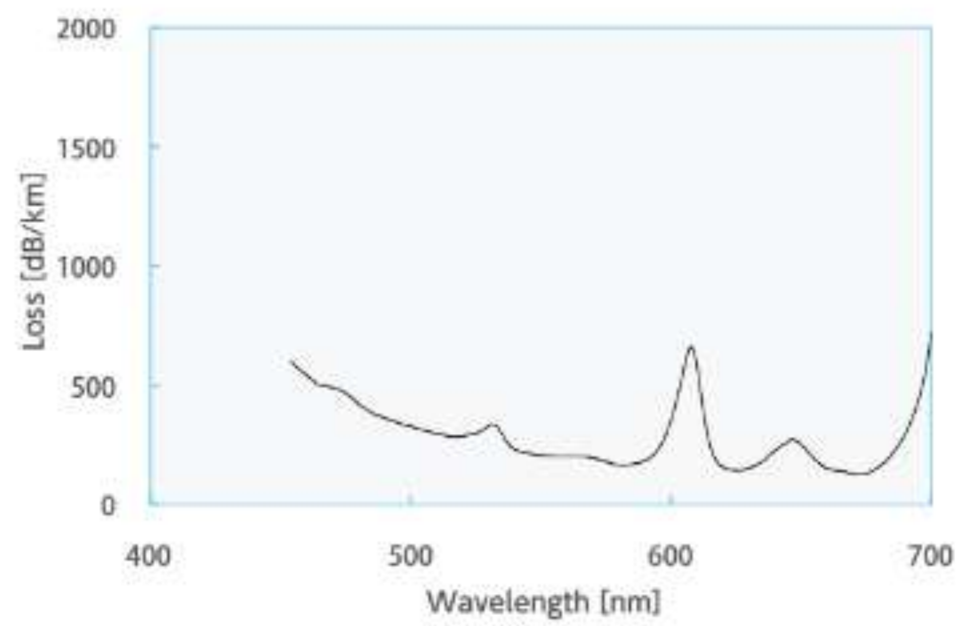
Emission Spectra

SCSF-78



Transmission Loss

SCSF-78

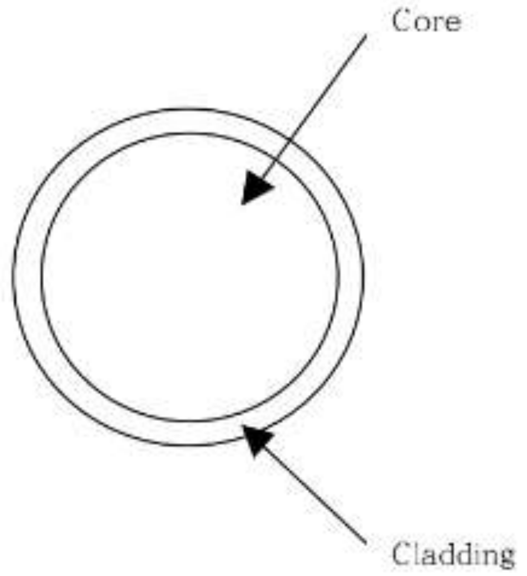


Cherenkov (Clear) Fiber : SK-40

Table 1

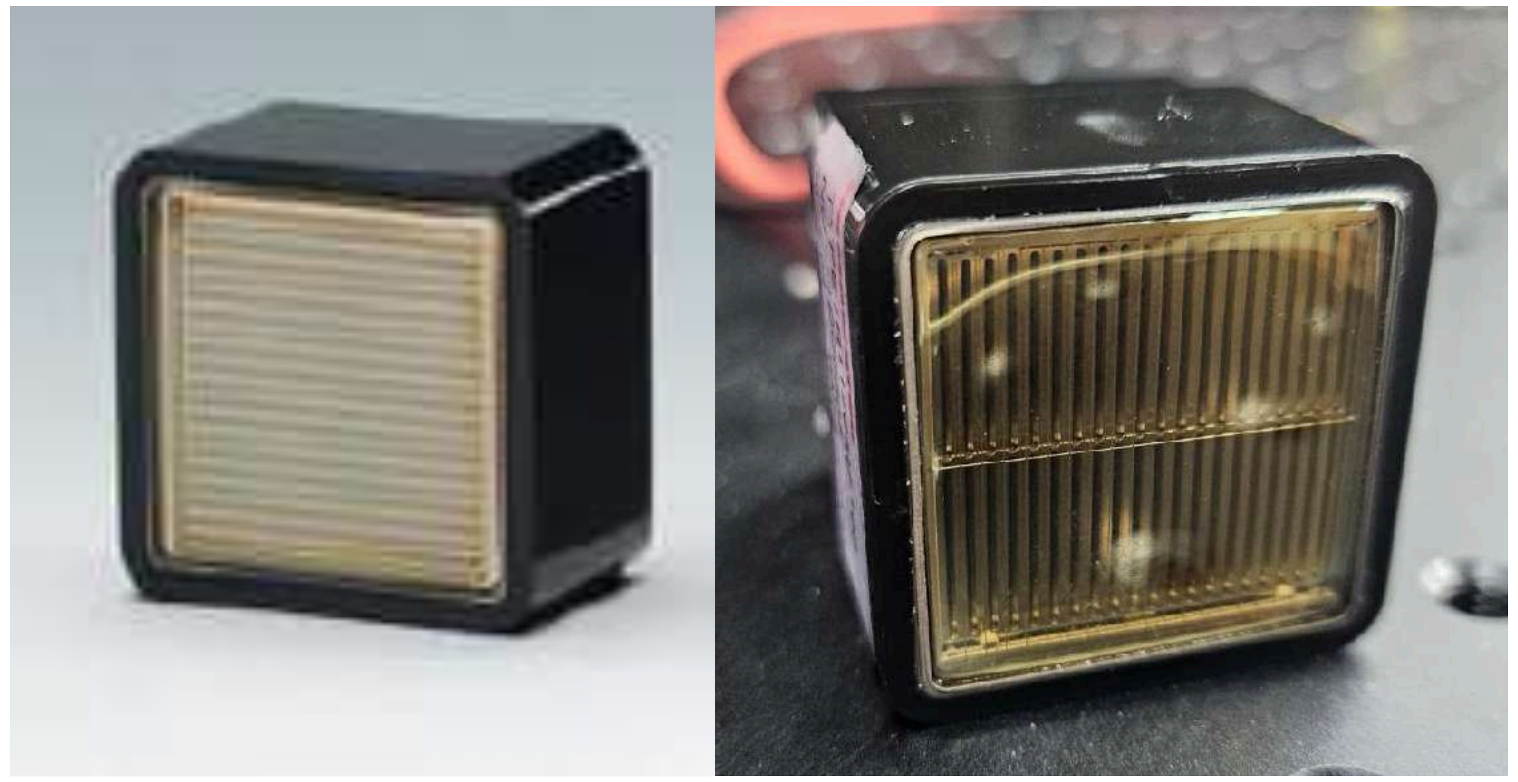
Item		SK-40 Specification Unit	Min.	Typ.	Max.
Optical Fiber 1	Core Material	–	Polymethyl-Methacrylate Resin		
	Cladding Material	–	Fluorinated Polymer		
	Core Refractive Index	–	1.49		
	Refractive Index Profile	–	Step Index		
	Numerical Aperture	–	0.5		
	Core Diameter	µm	920	980	1,040
	Cladding Diameter	µm	940	1,000	1,060
Approximate Weight		g/m	1		

Sectional View



Readout Detector Specification

Hamamatsu R11265-100



PMT	Window Size	Max HV	Rise time
R11265-100	23x23 mm^2	1000 V	1.3 ns

Figure 1: Typical spectral response

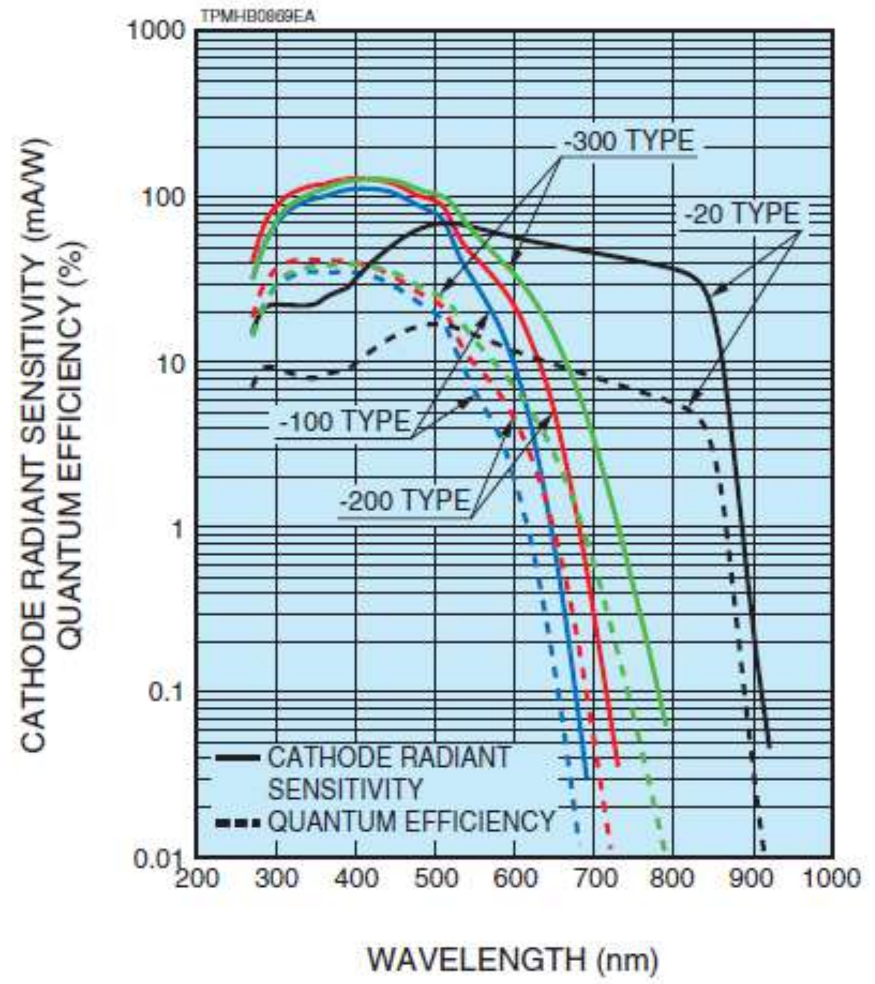
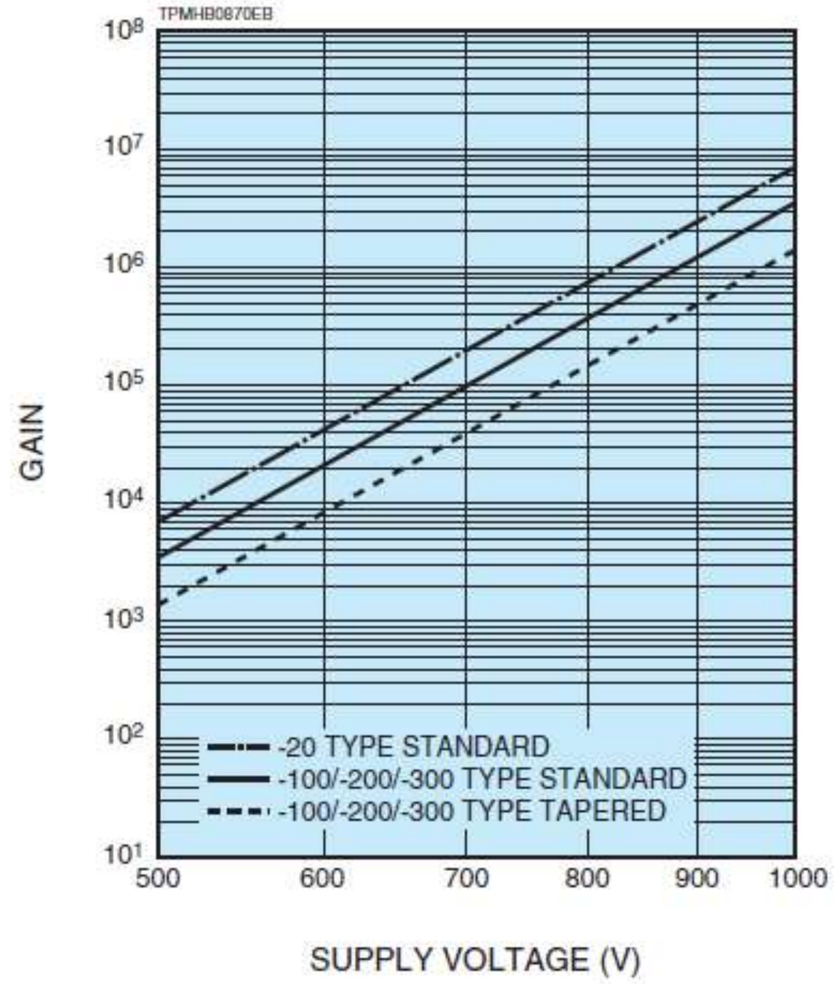


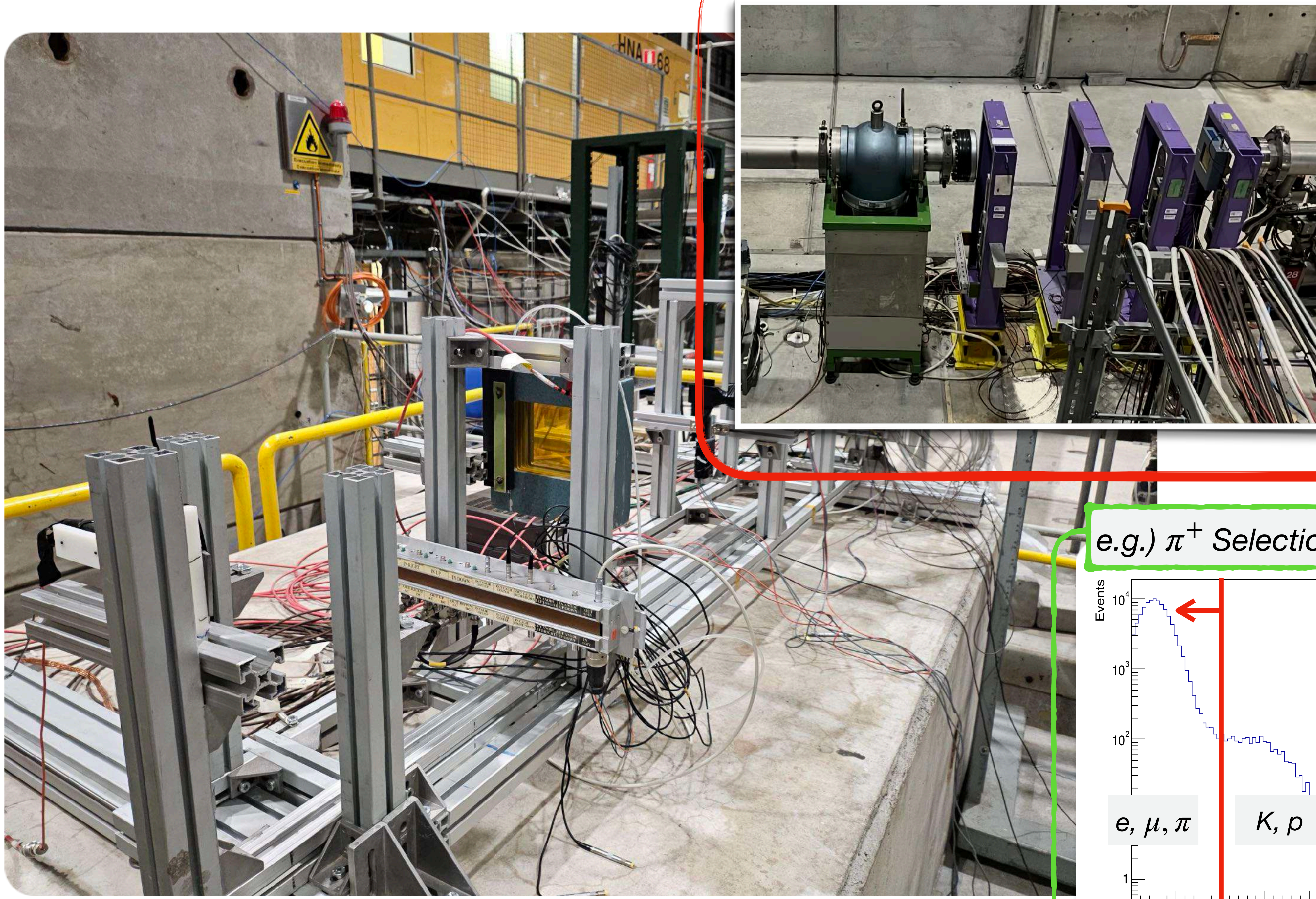
Figure 2: Typical gain



PLANACON XP85012, XP85112

PMT	Window Size	Max HV	Q.E (%)	Rise time
XP85012 (S)	53x53 mm^2	2400 V	~7% at 550nm	0.6 ns
XP85112 (C)		2800 V	~21% at 400nm	0.5 ns

Experimental Setup
Ancillary Detectors - Upstream

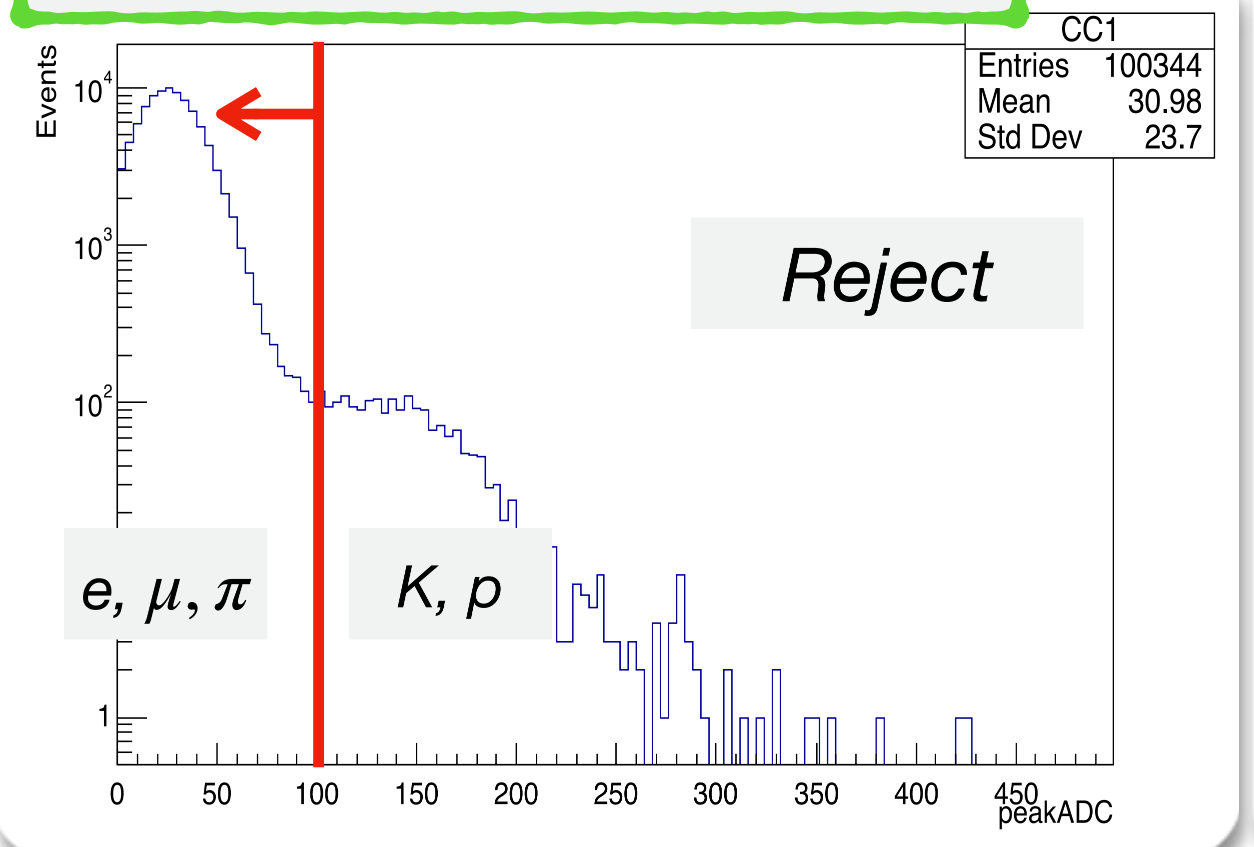


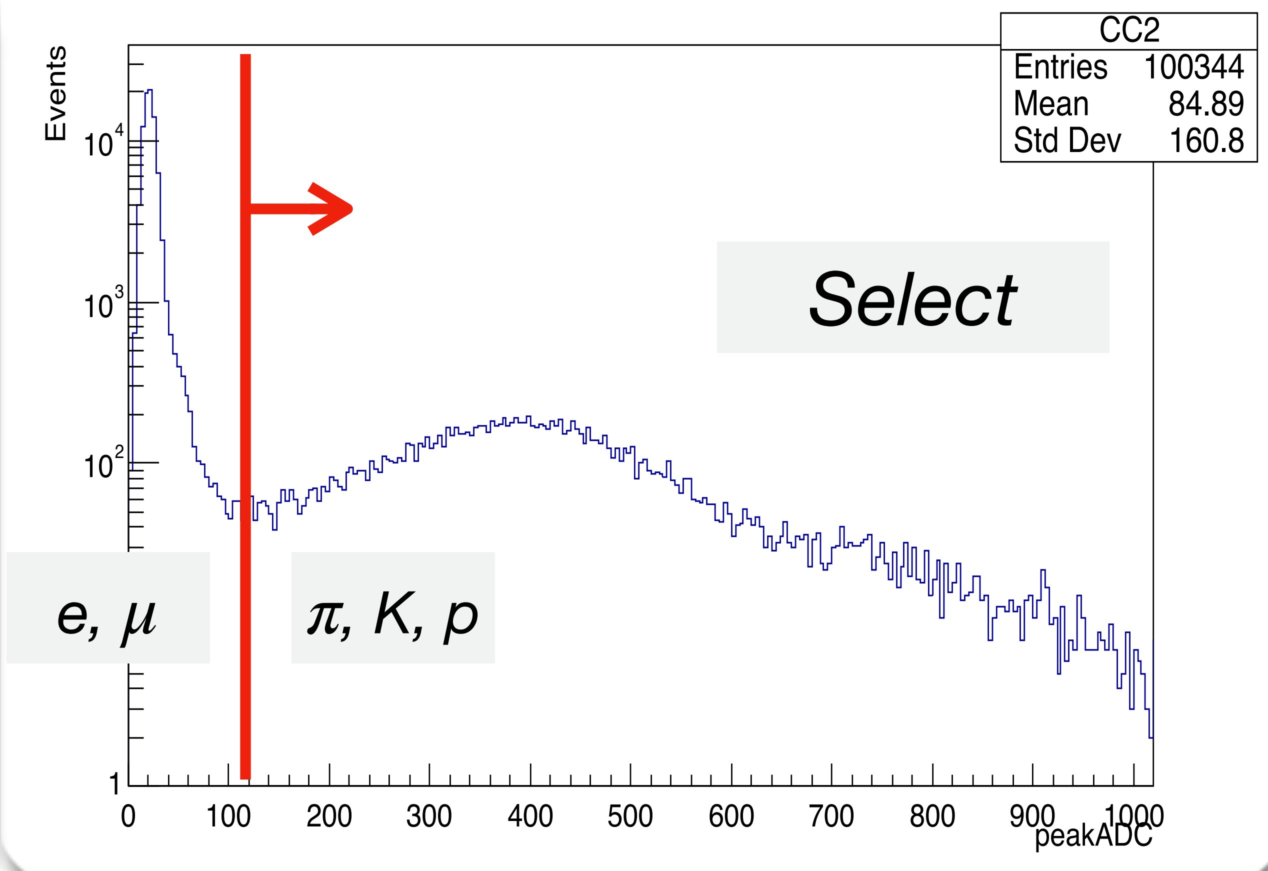
Cherenkov Counter (CC1, CC2) :
Particle identification hadrons, muon

By adjusting *gas pressure*, one can change the type of particle emitting Cherenkov light

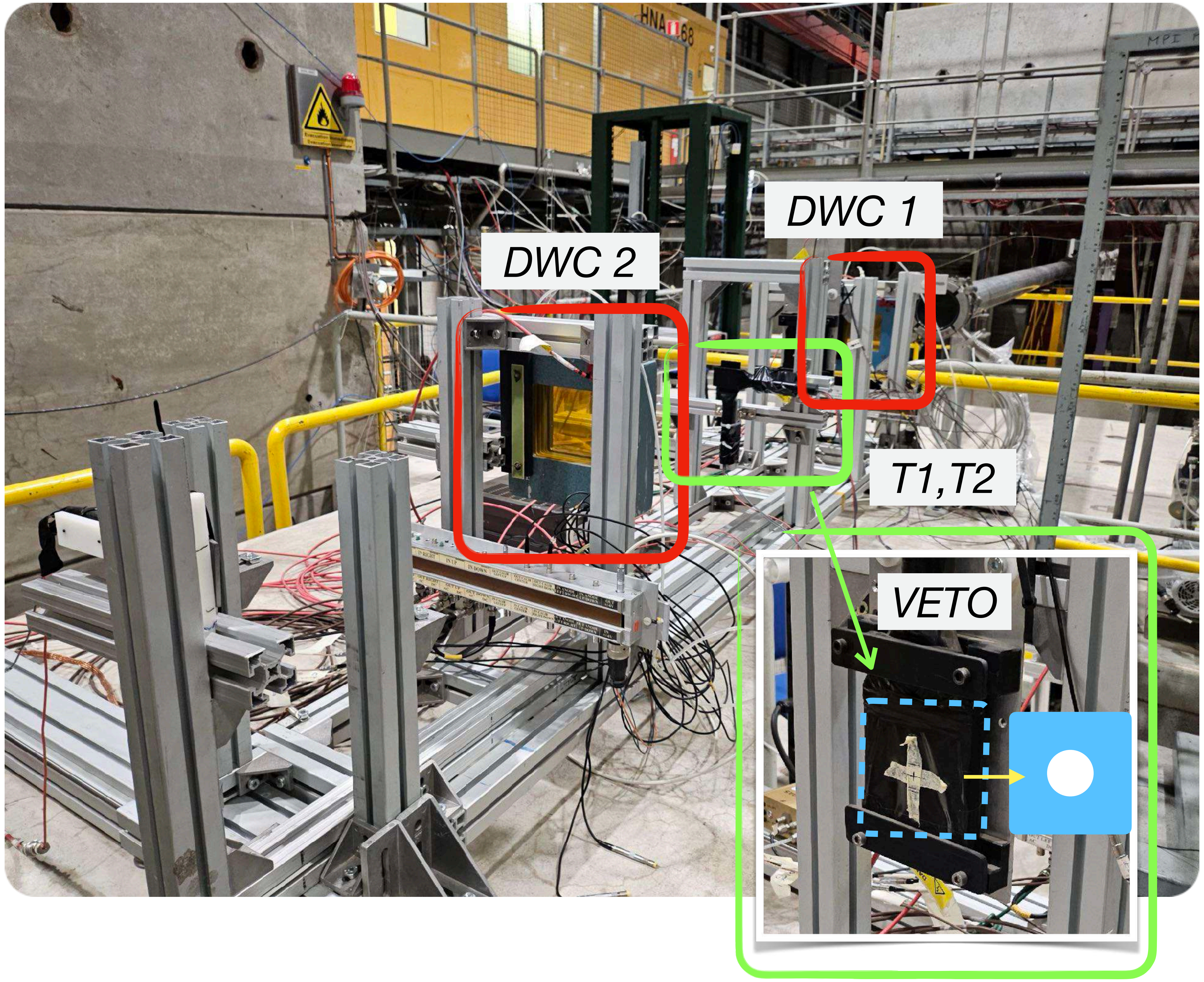
$$v_p > c/n$$
$$(n = Refractive\ Index)$$

e.g.) π^+ *Selection* $(n_{CC1} < n_{CC2})$

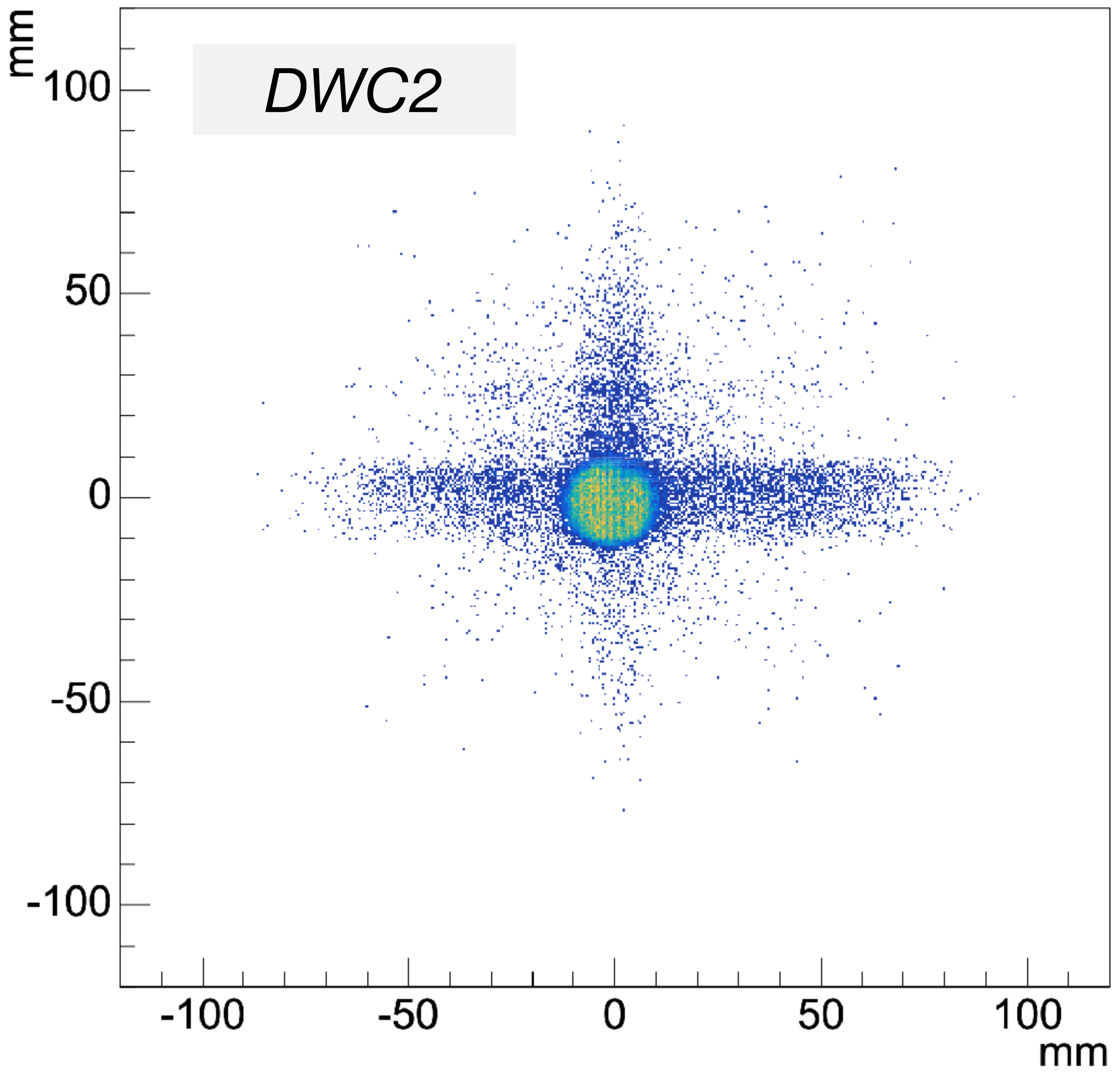




Experimental Setup
Ancillary Detectors - Upstream



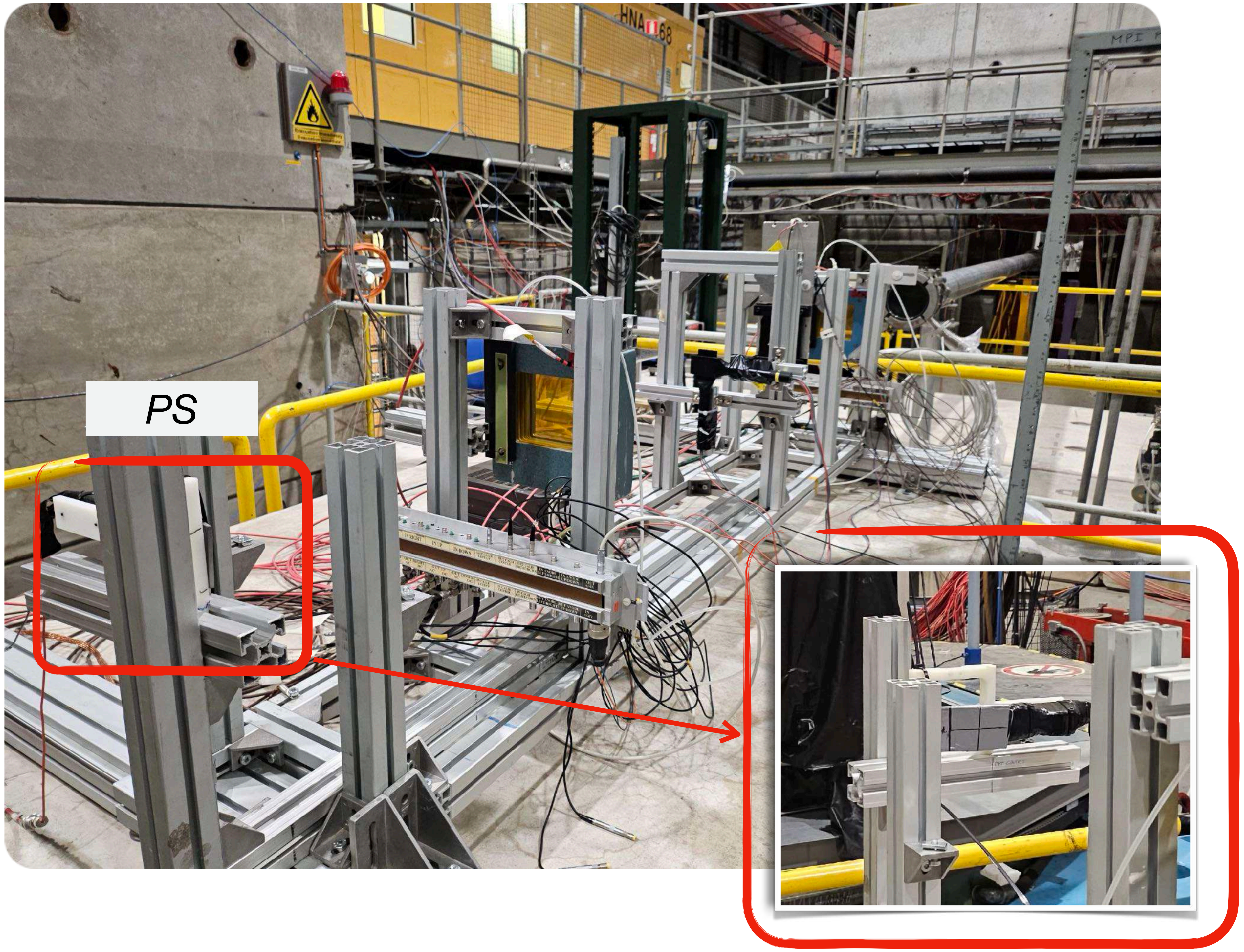
Delayed Wire Chamber (DWC1, DWC2) :
Beam position identification, geometry cuts



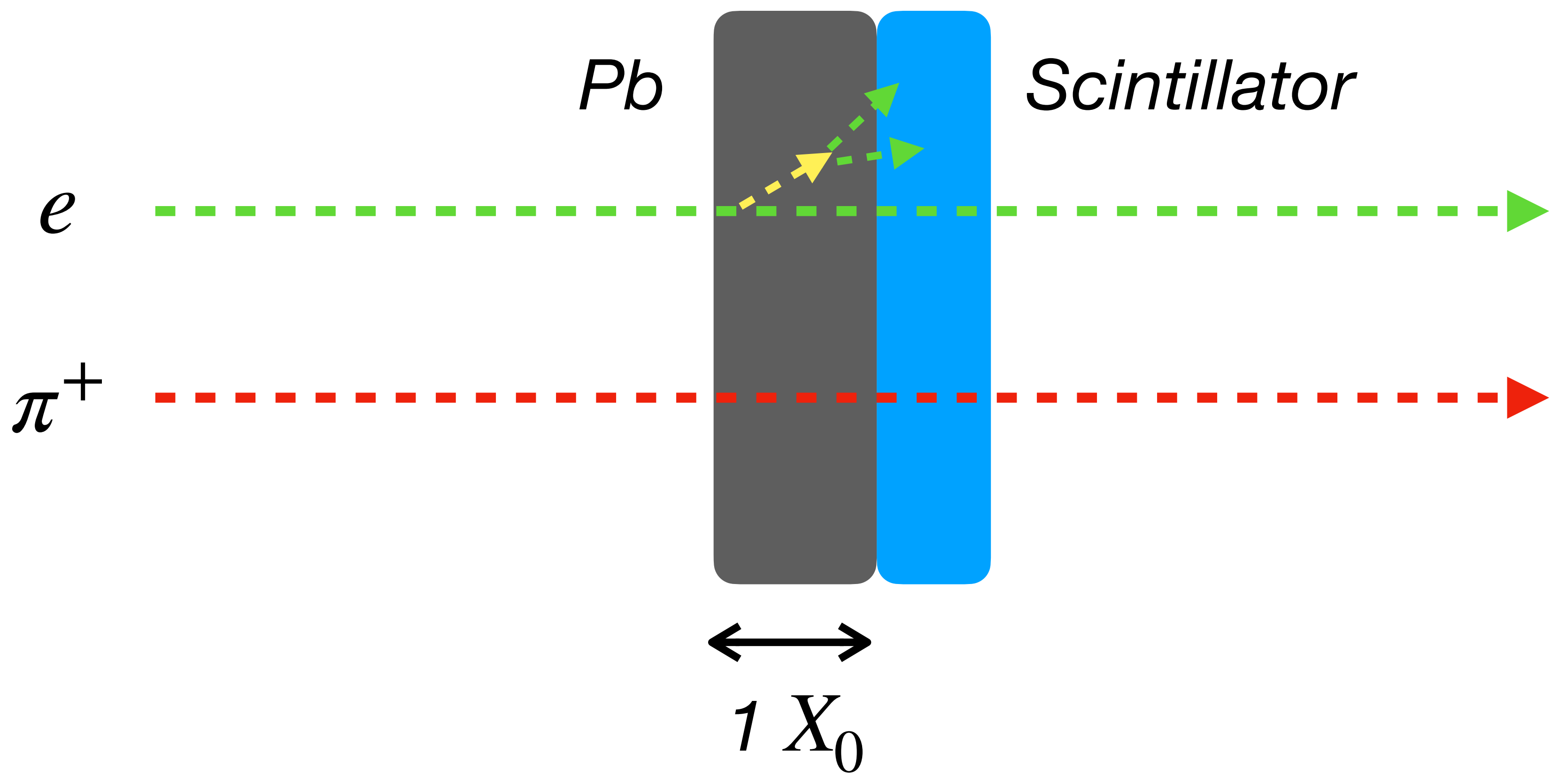
VETO, Trigger (VETO, T1, T2) :
Plastic scintillator, Trigger(veto)-ing events

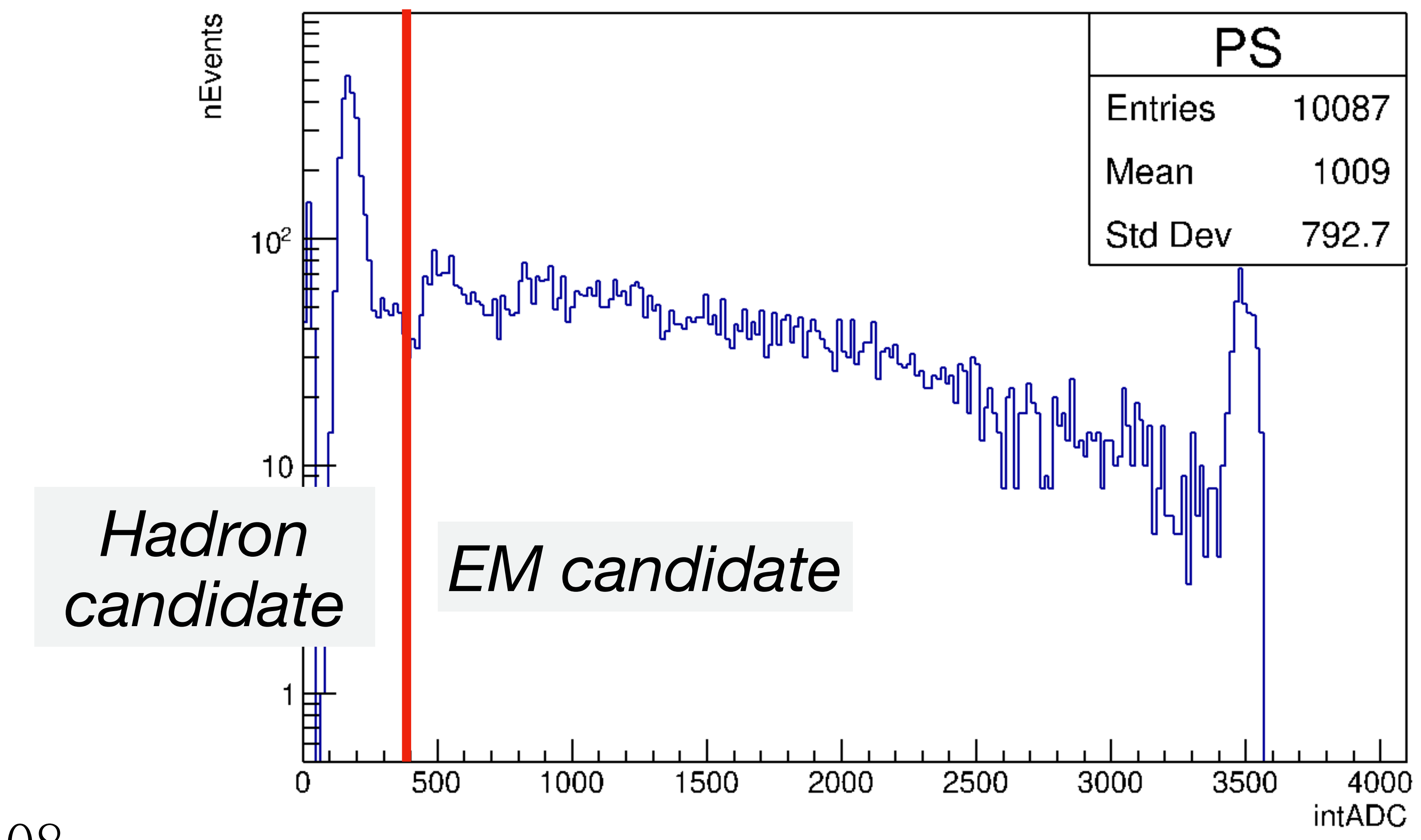
∟ *Upgraded PMTs for better time resolution*

Experimental Setup
Ancillary Detectors - Upstream

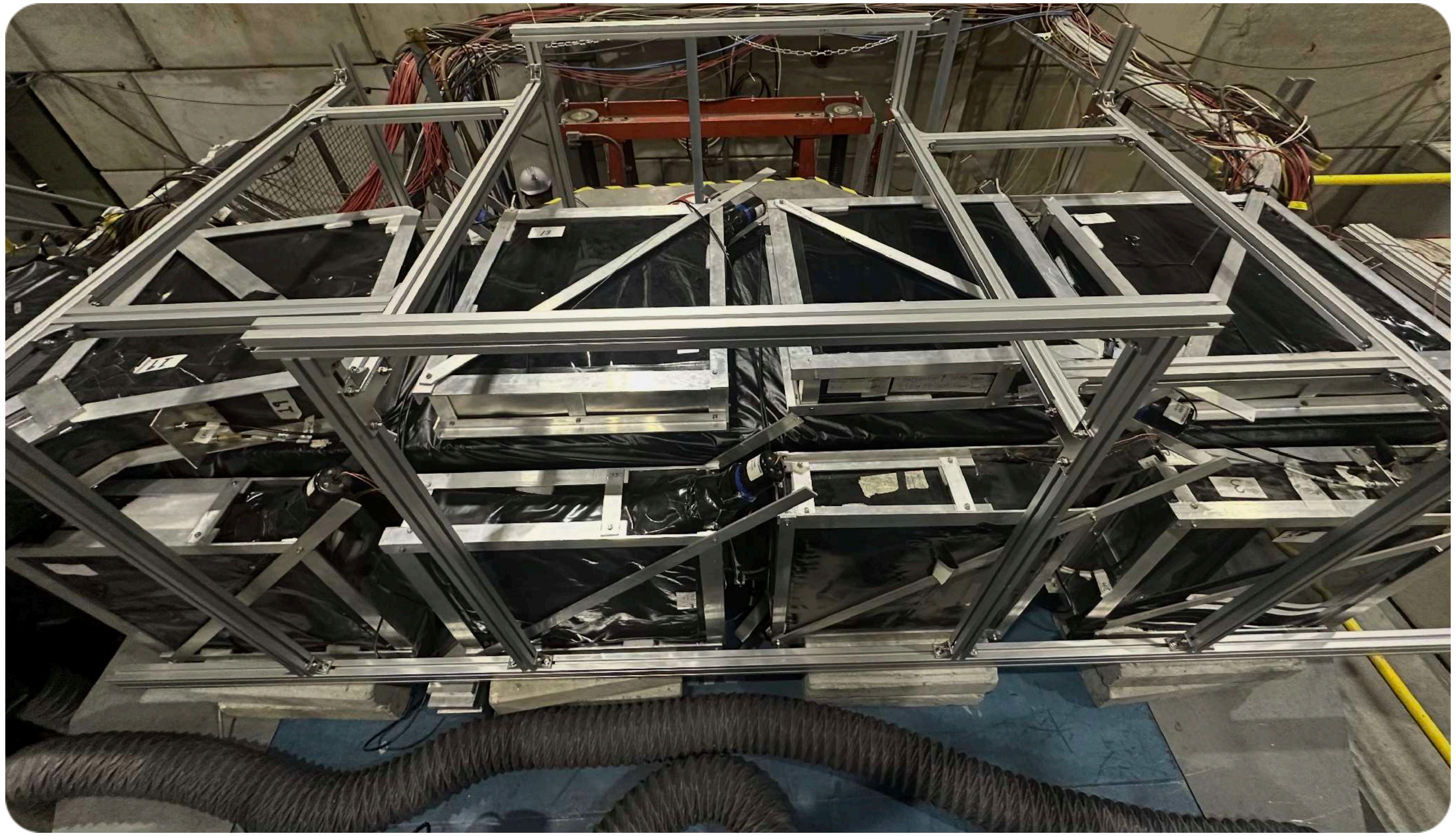


Pre-Shower Detector (PS) :
Particle identification electron, hadrons



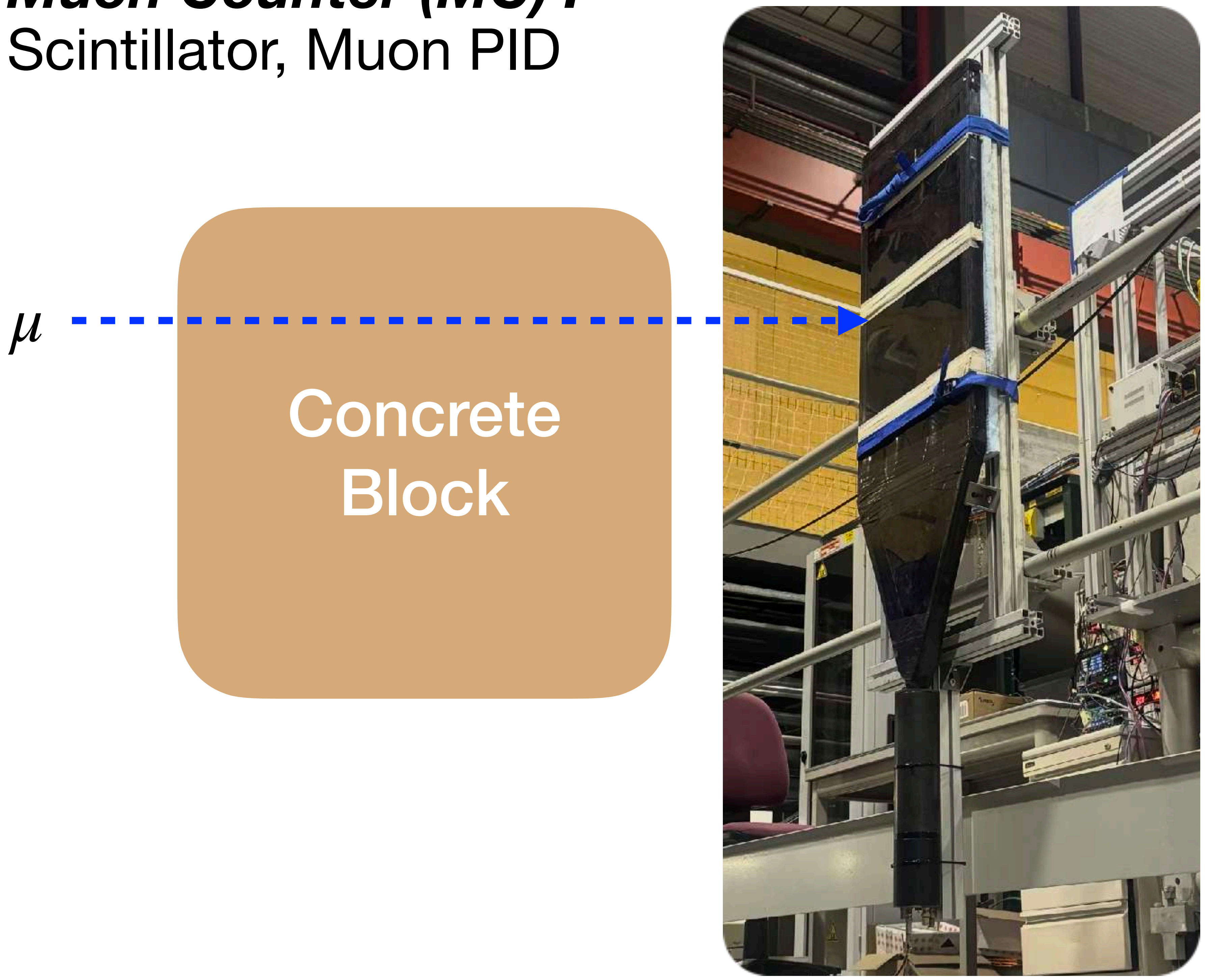


Experimental Setup
Ancillary Detectors - Downstream



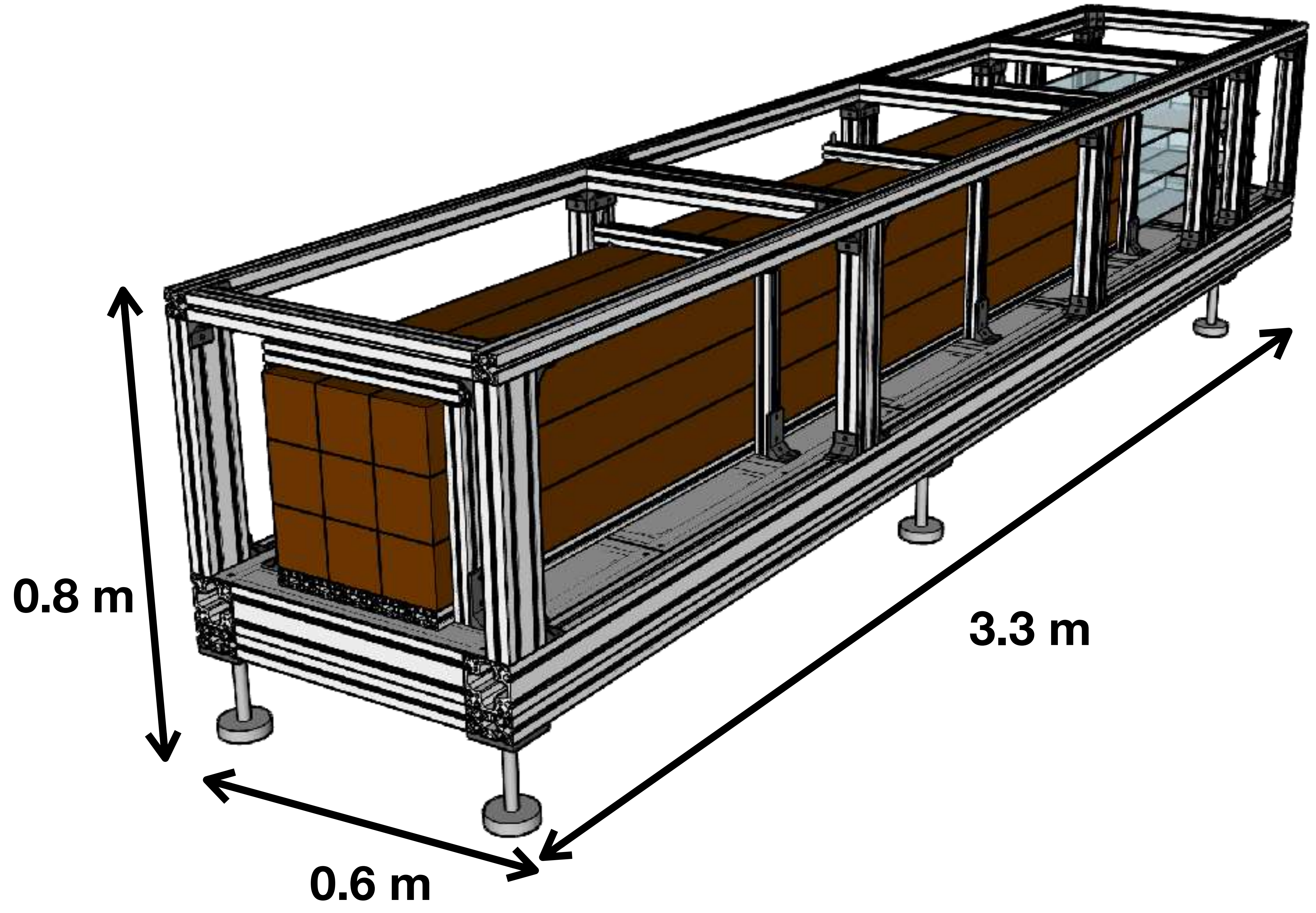
Tail Catcher (TC) :
Scintillator, Longitudinal leakage measurement

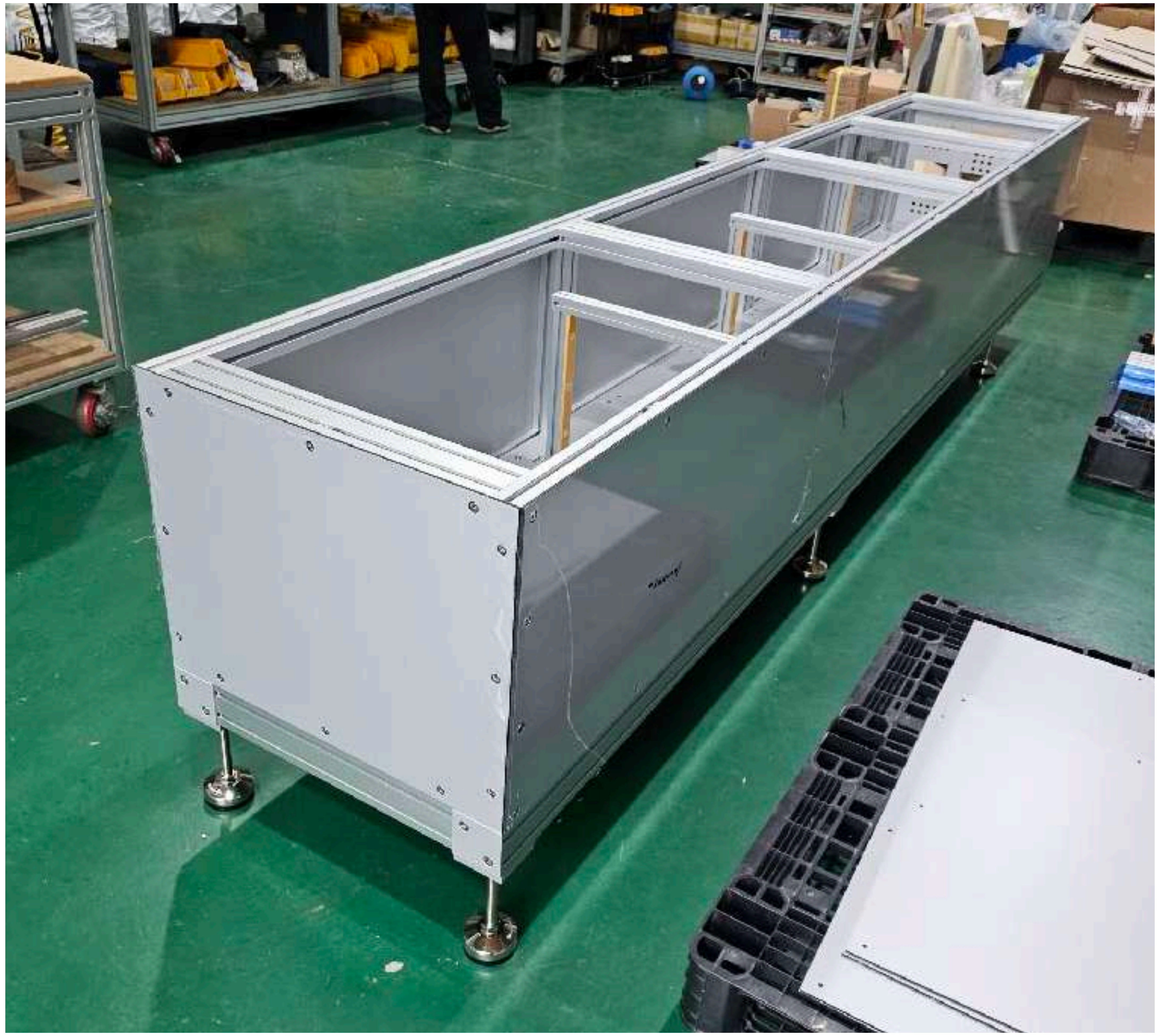
Muon Counter (MC) :
Scintillator, Muon PID



Leakage Counter (LC 1~16) :
50 cm × 50 cm × 12 cm plastic scintillator
Lateral leakage measurement, partial PID

Mechanical Supporter



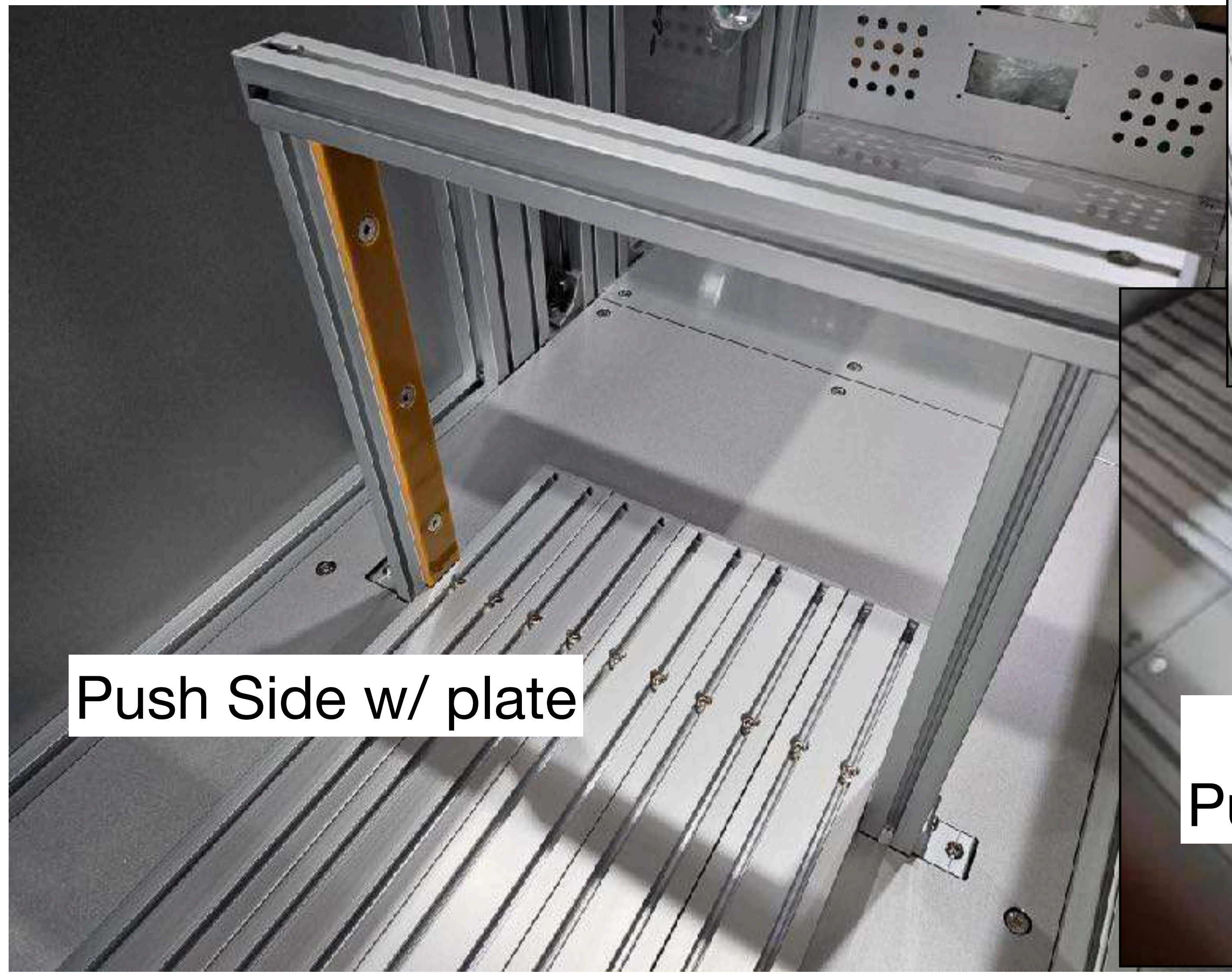


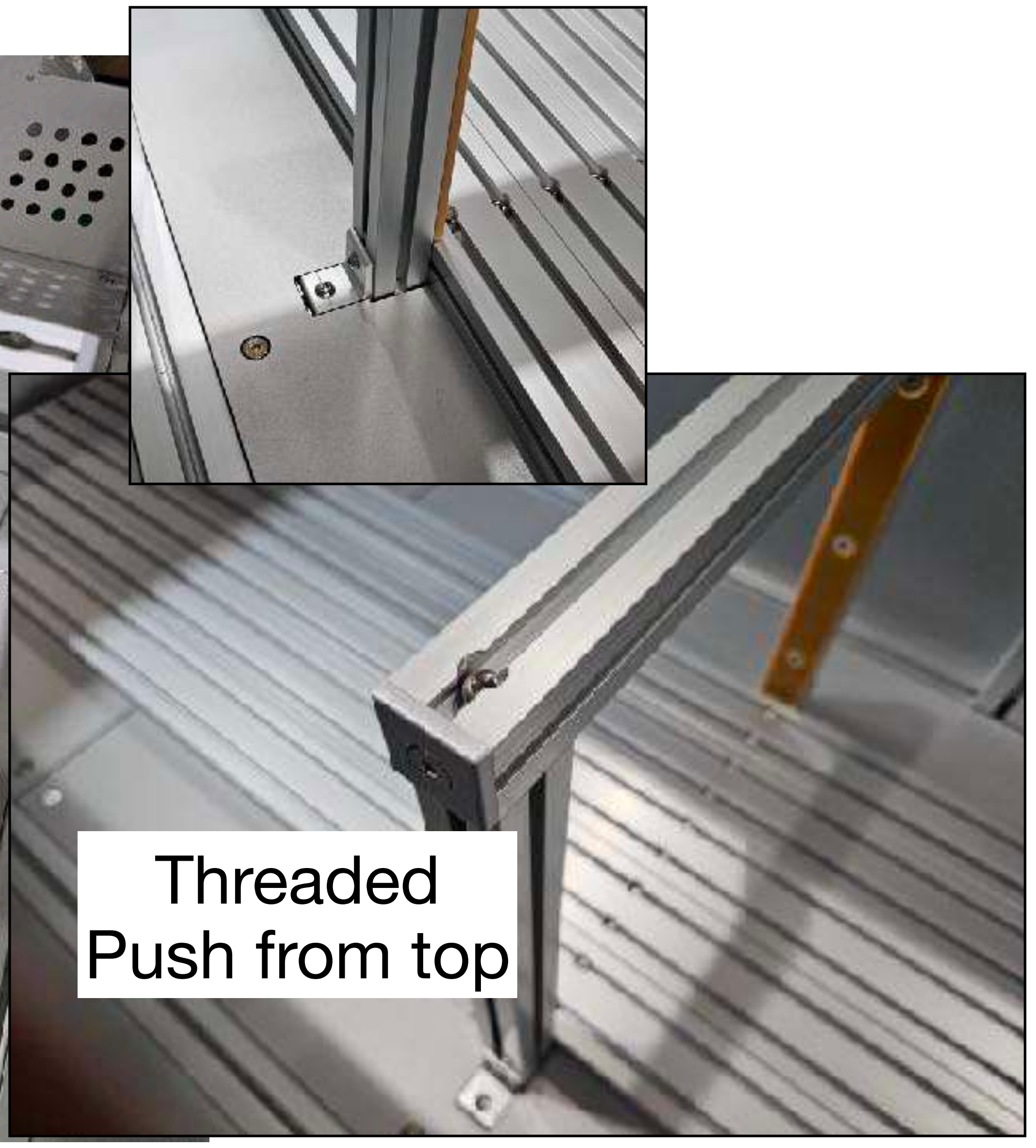
Mechanical Supporter

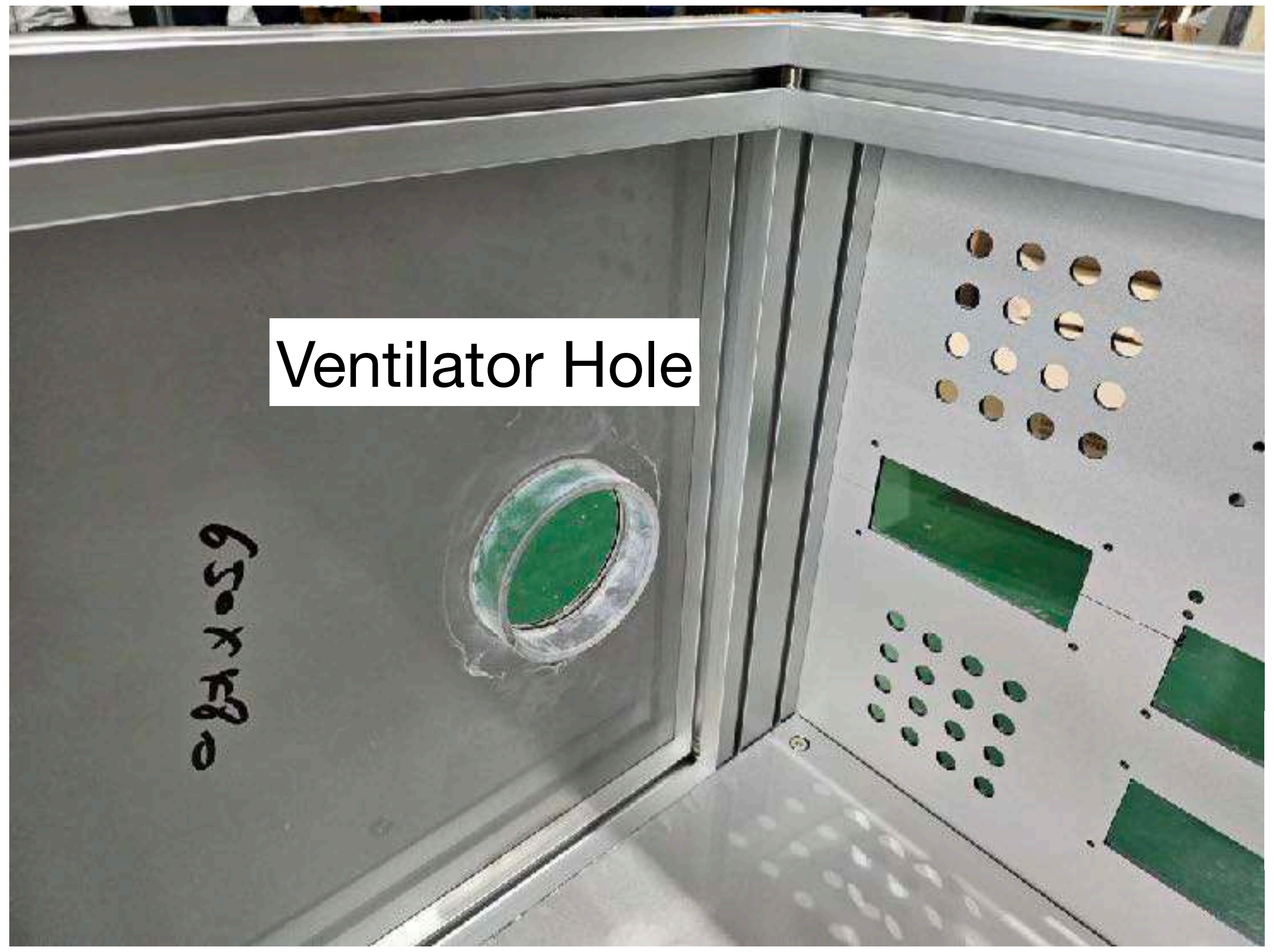

No bracket, Hole connection


Rear Readout Plate


Leveling Foot
At least 16cm from botom

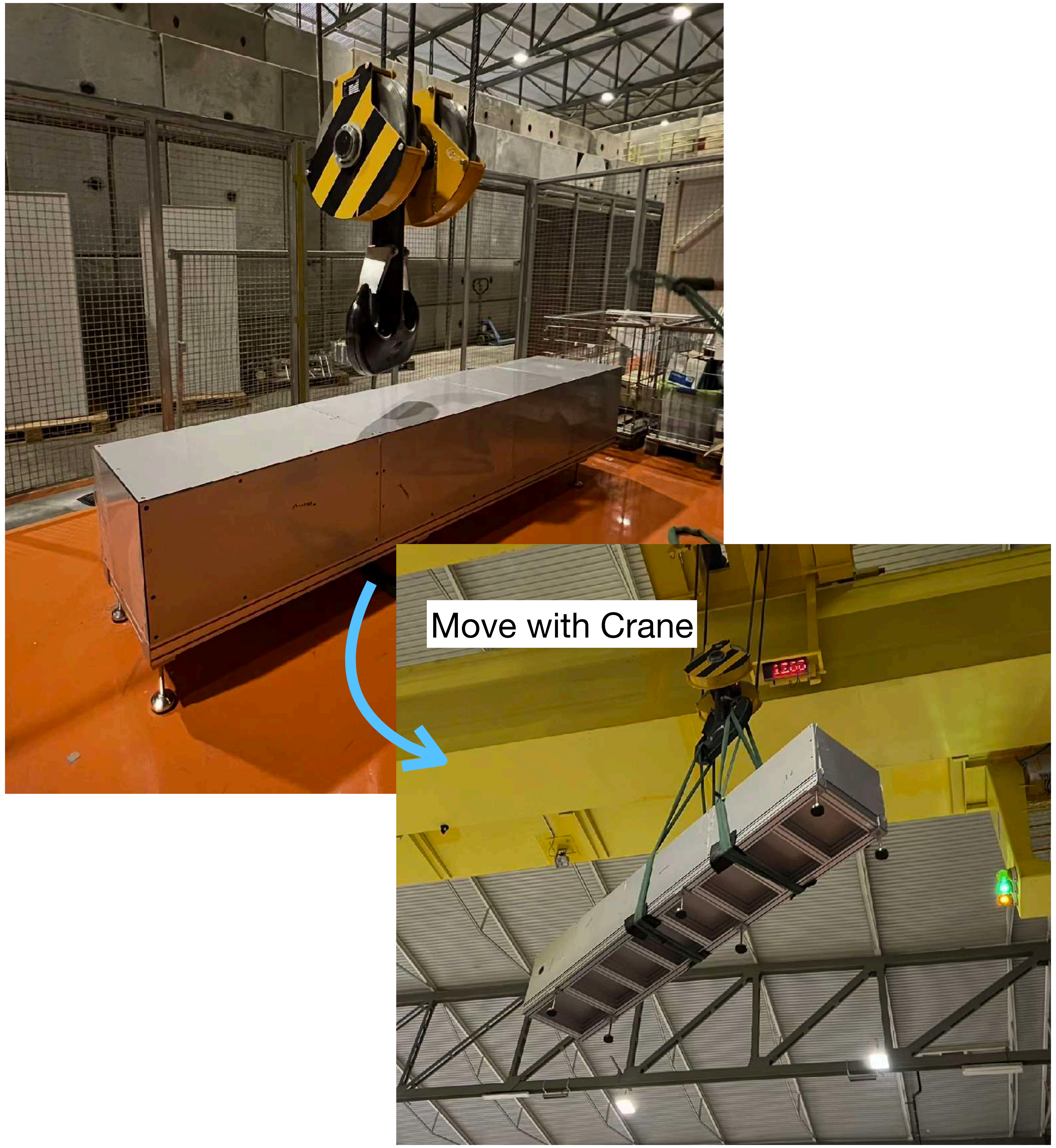

Push Side w/ plate

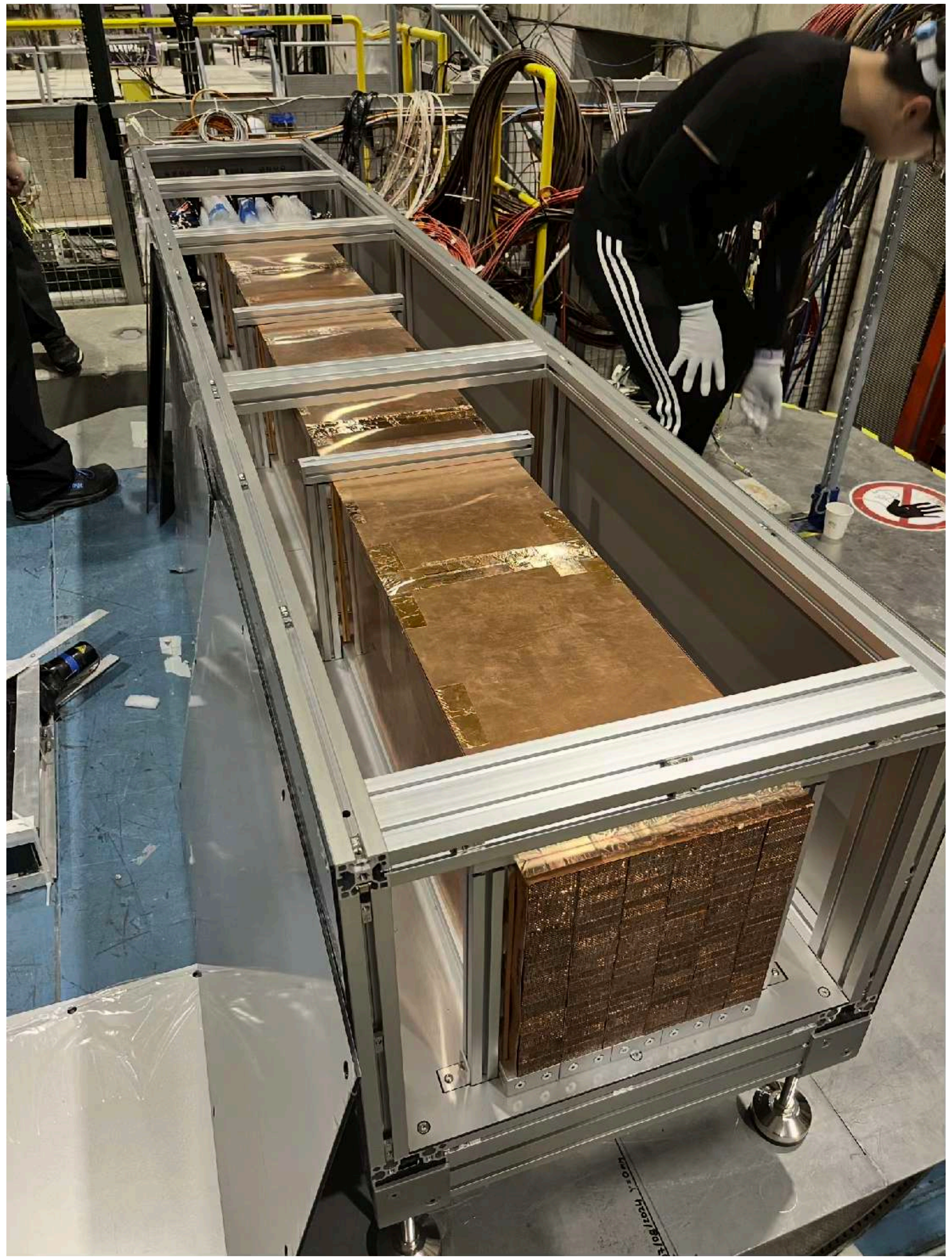

Threaded
Push from top

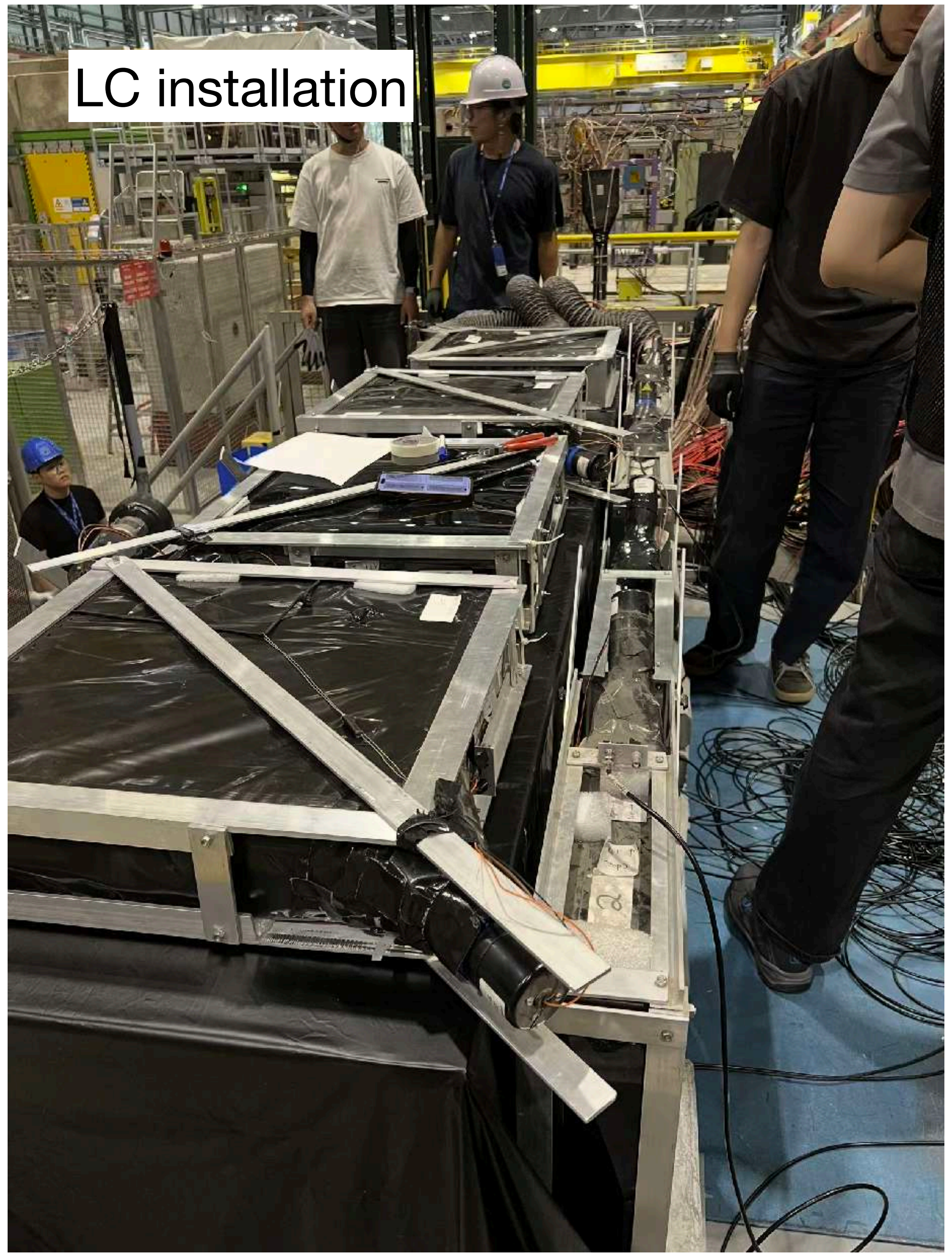

Ventilator Hole


Readout Plate
Attachment

Module Installation



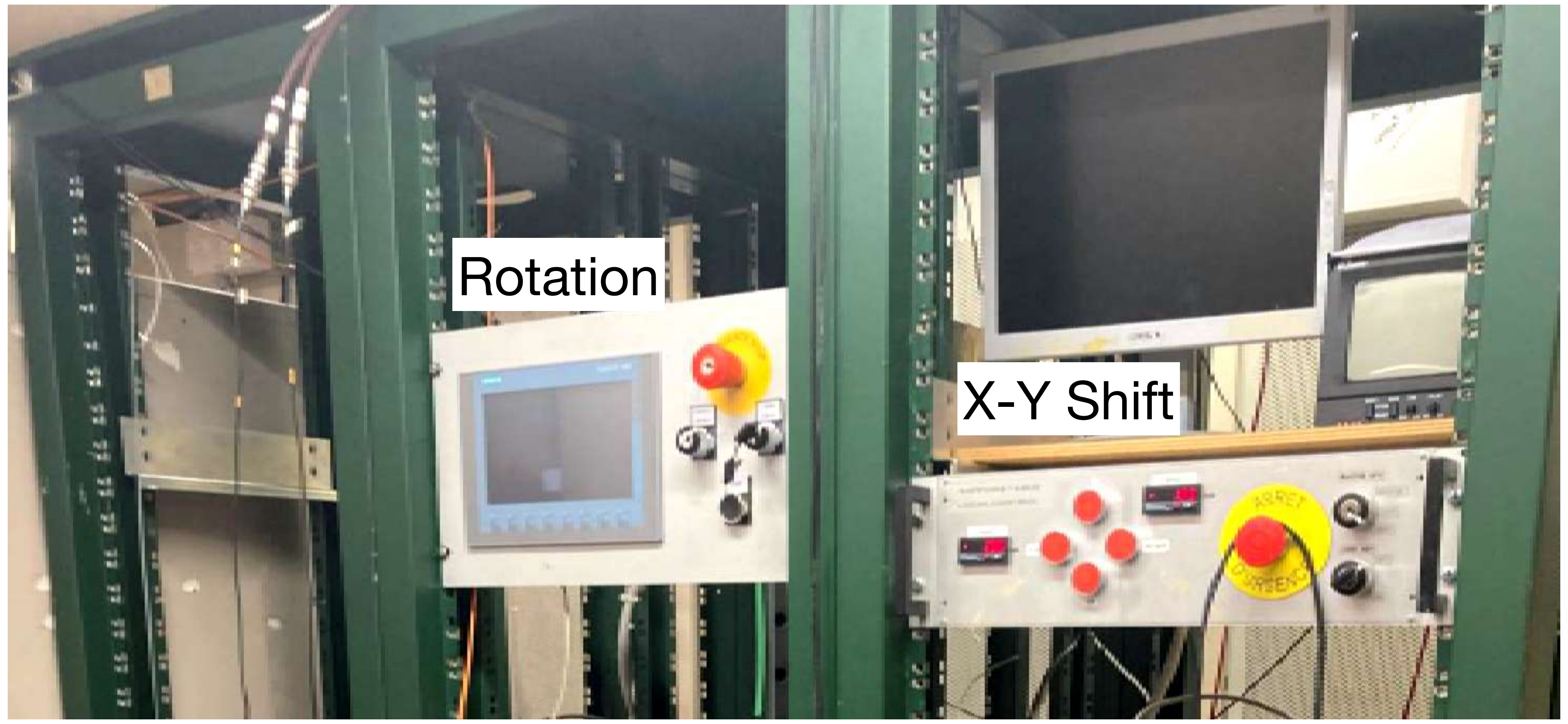


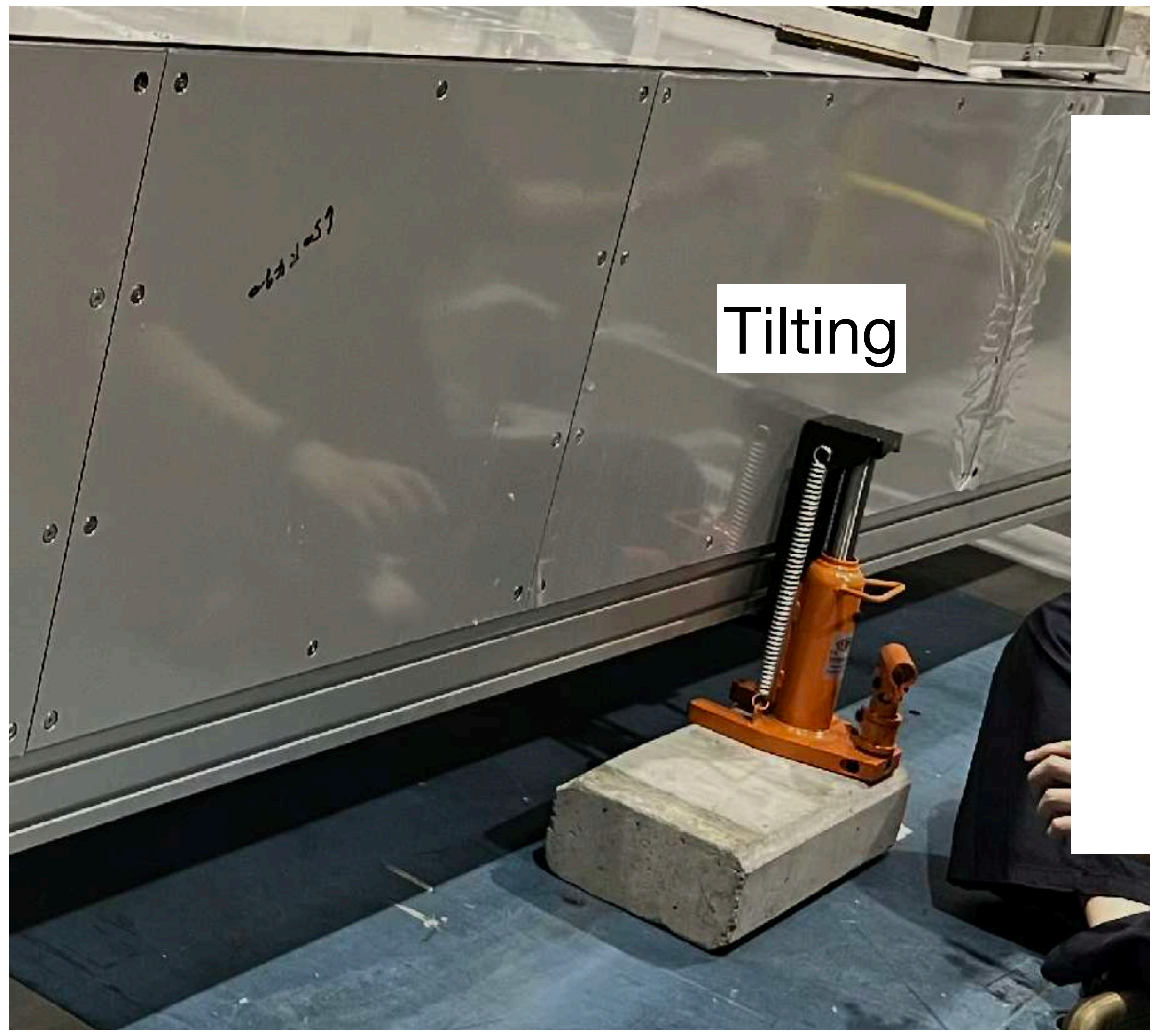


HV Module

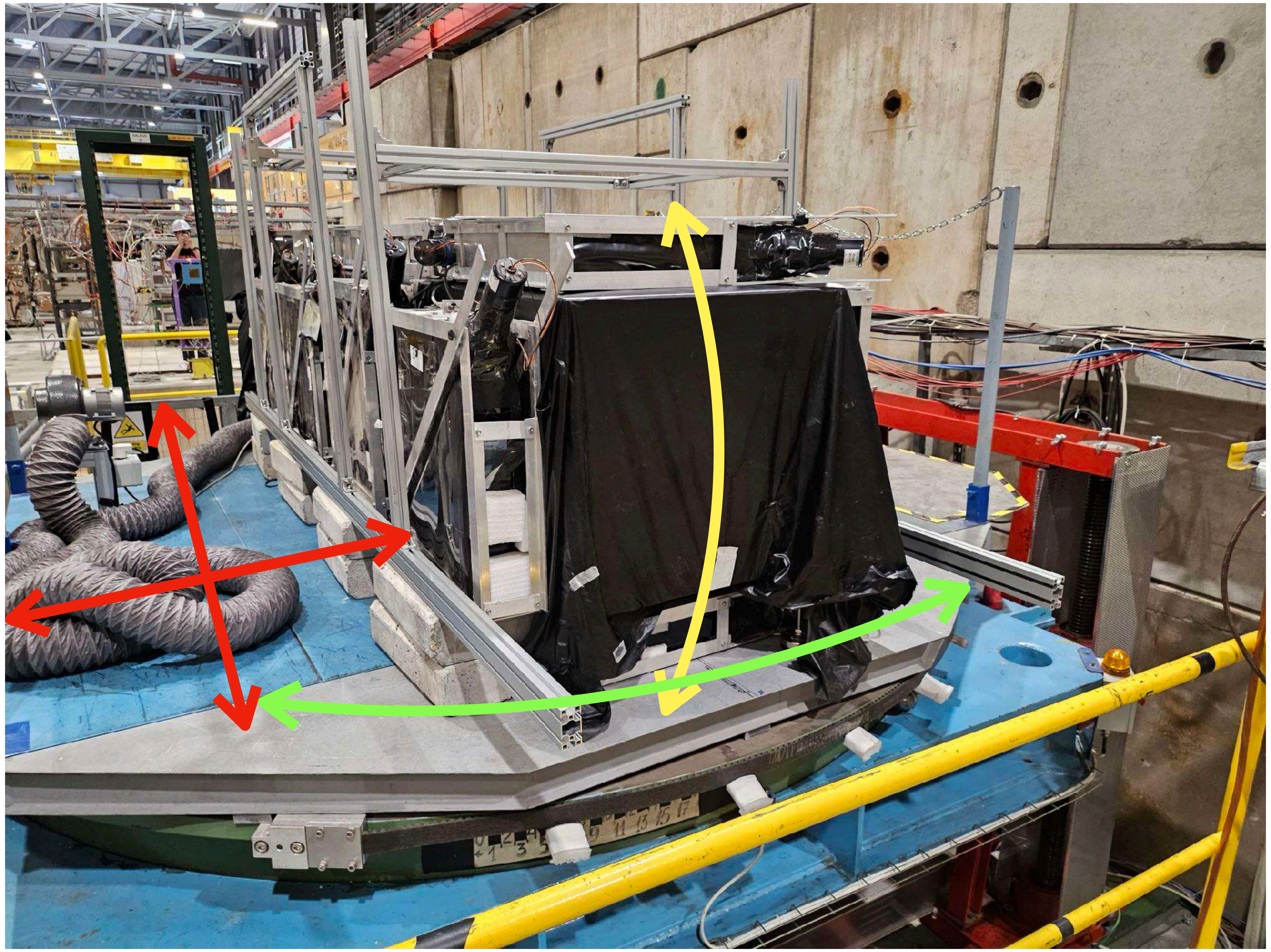
CAEN SY1527LC

Sapphire Table



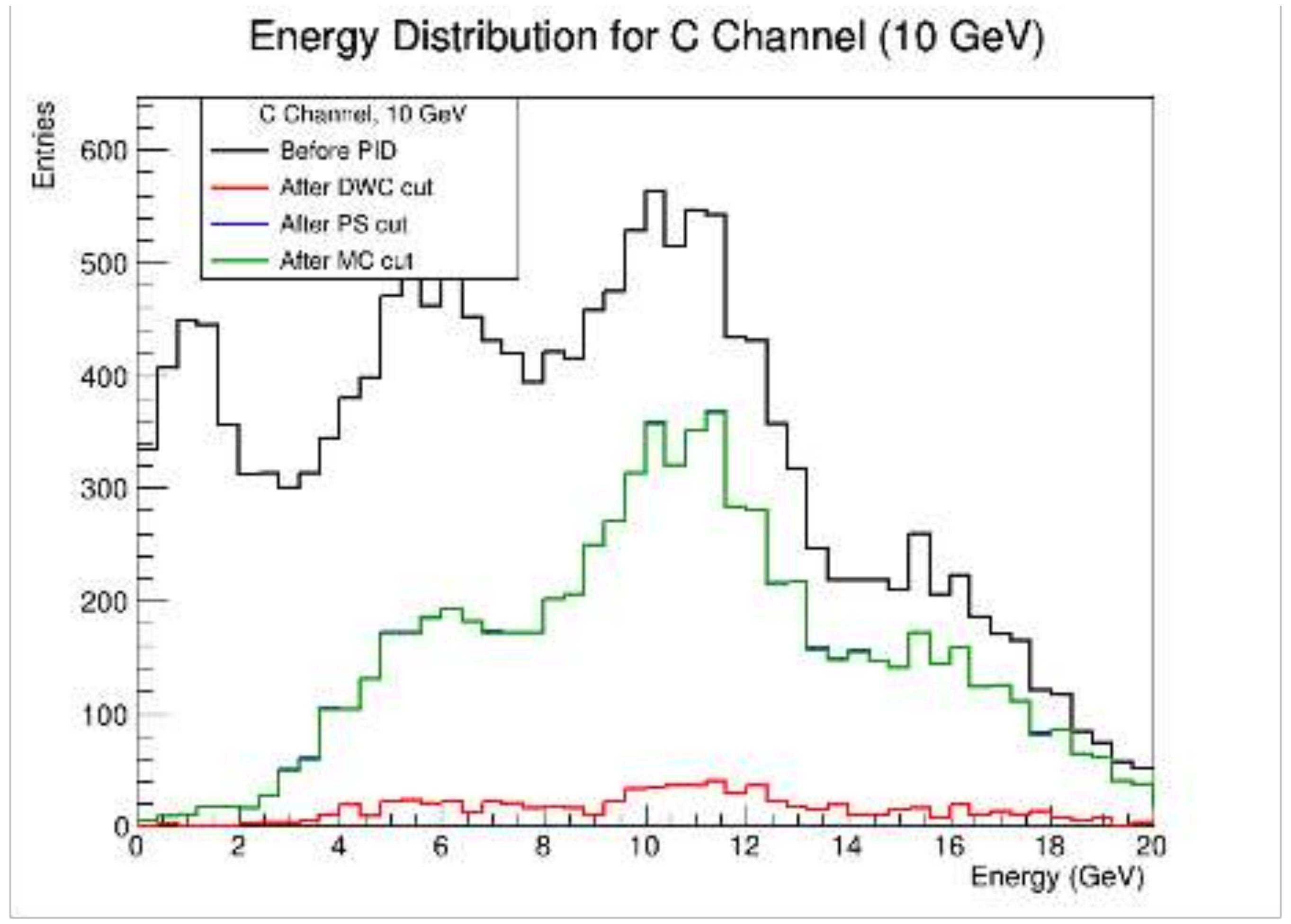


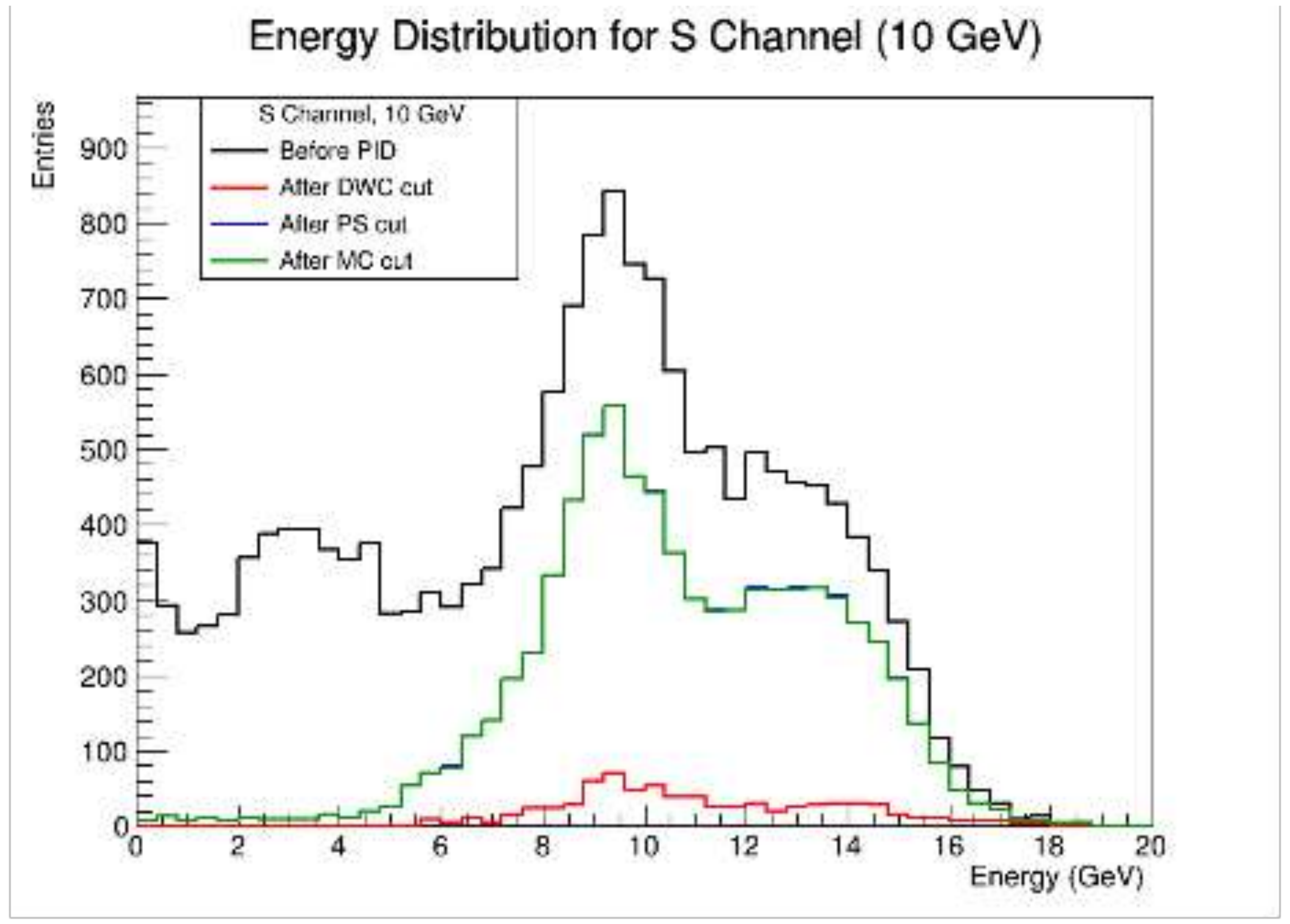
Hydraulic Pump
2.5 t / EA

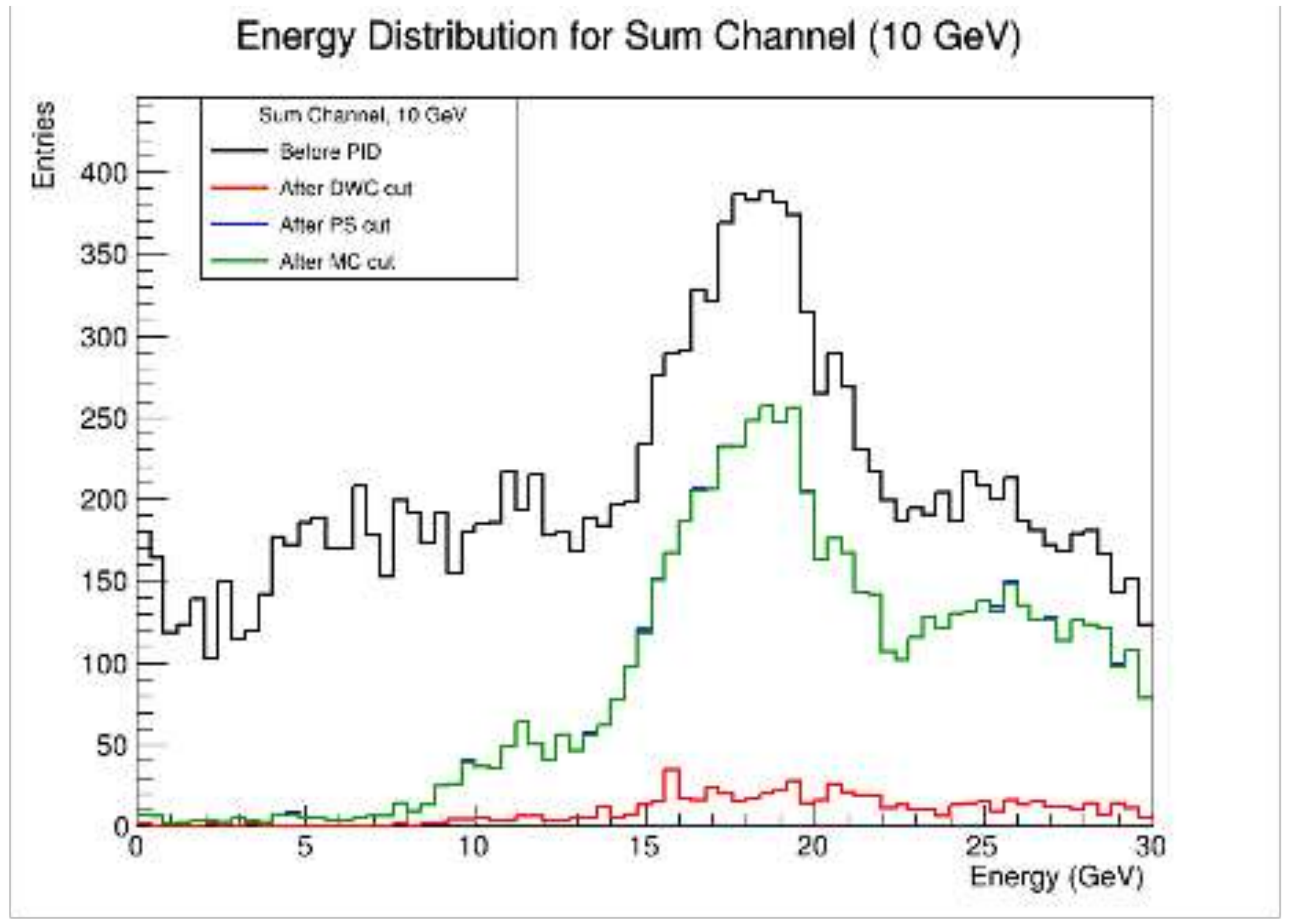


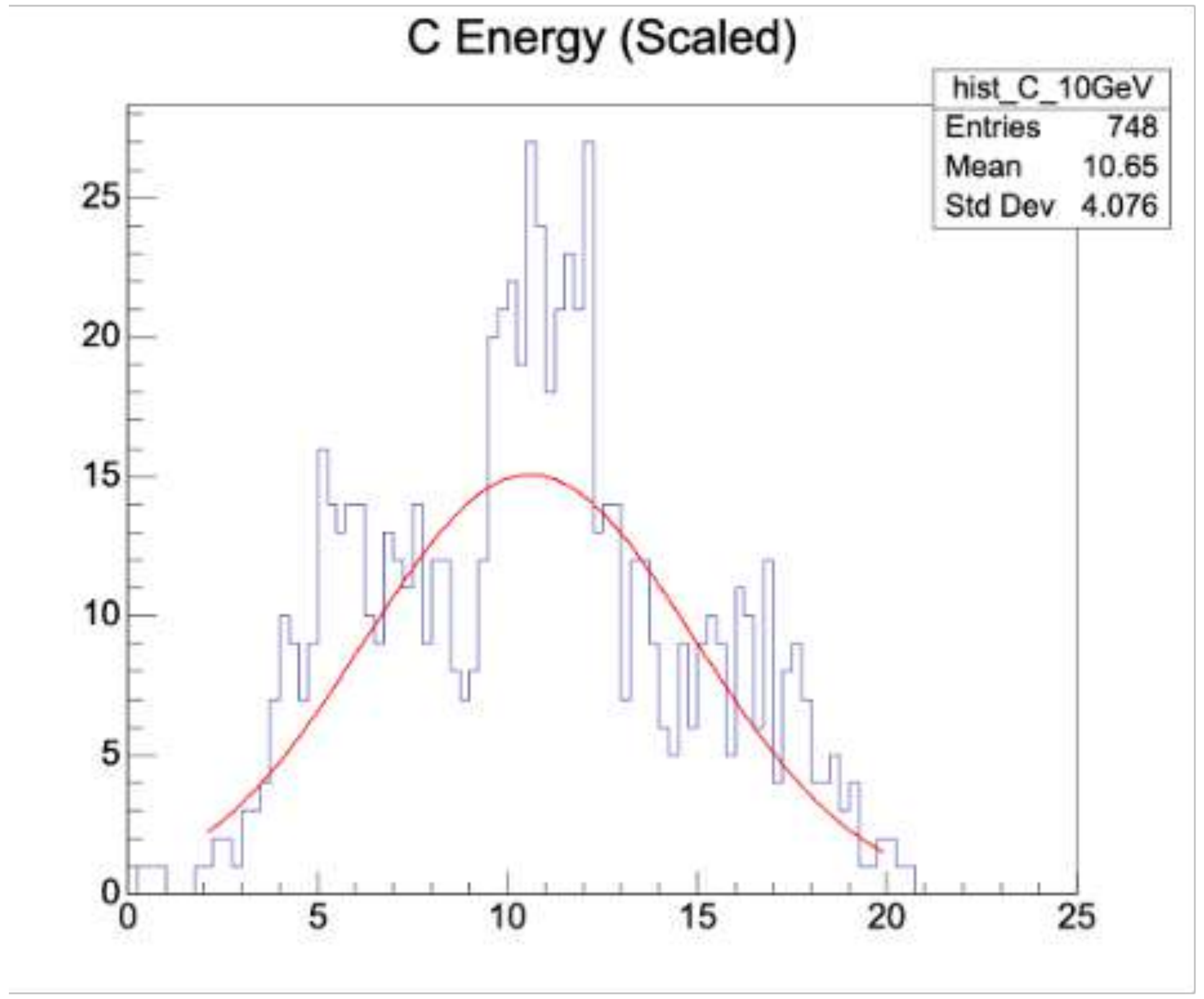
EM Performance

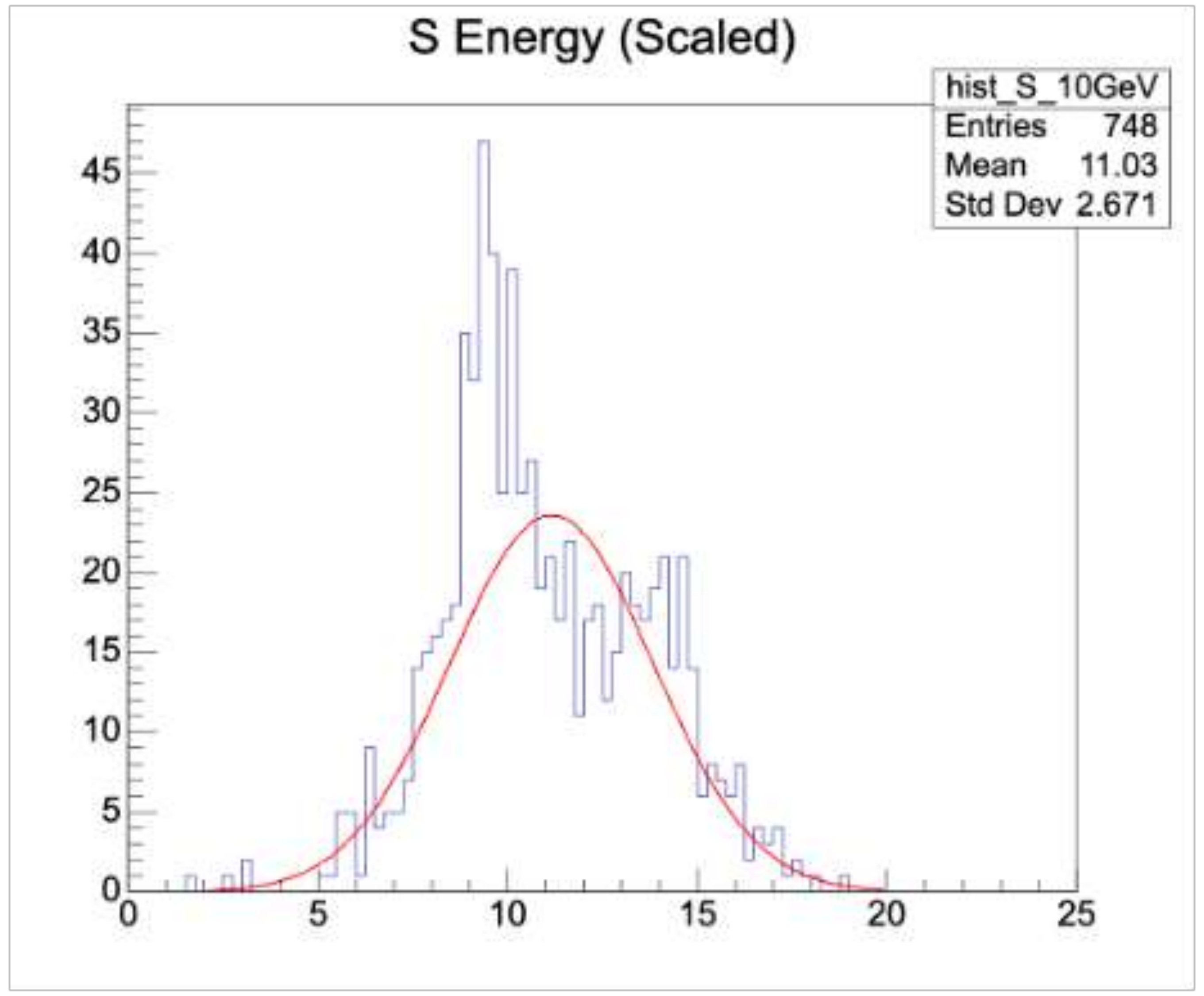
Energy Distribution : 10 GeV

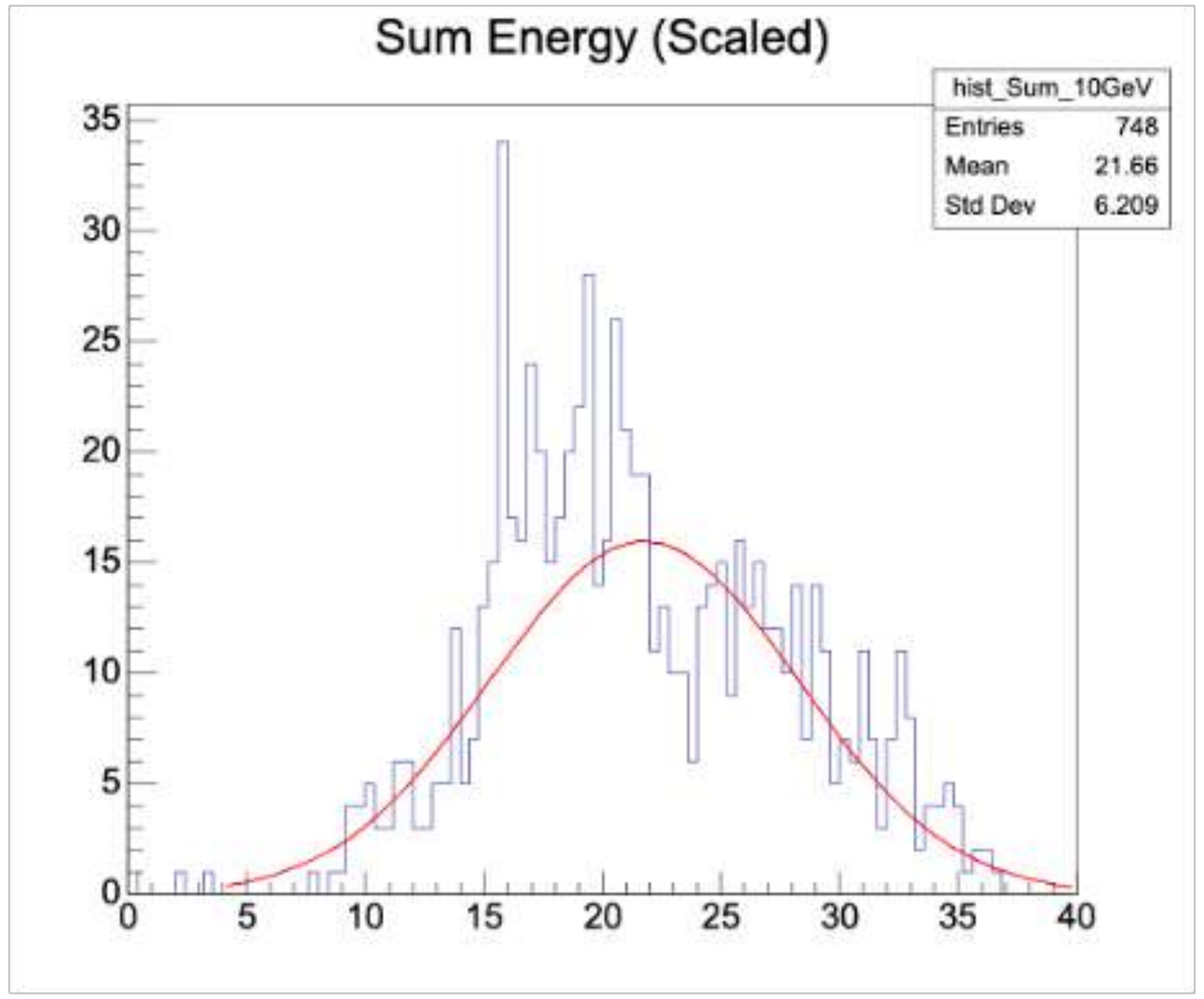




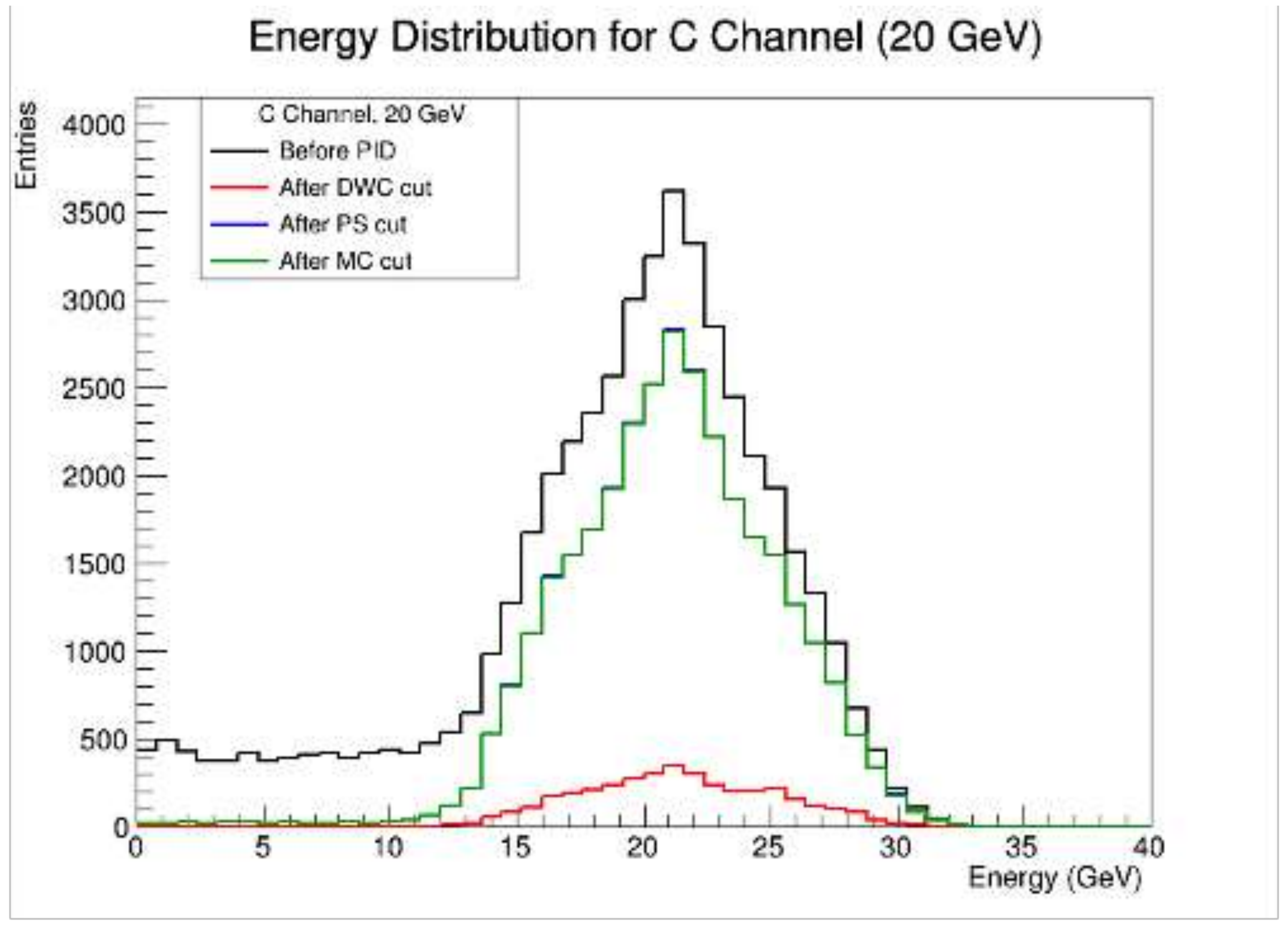


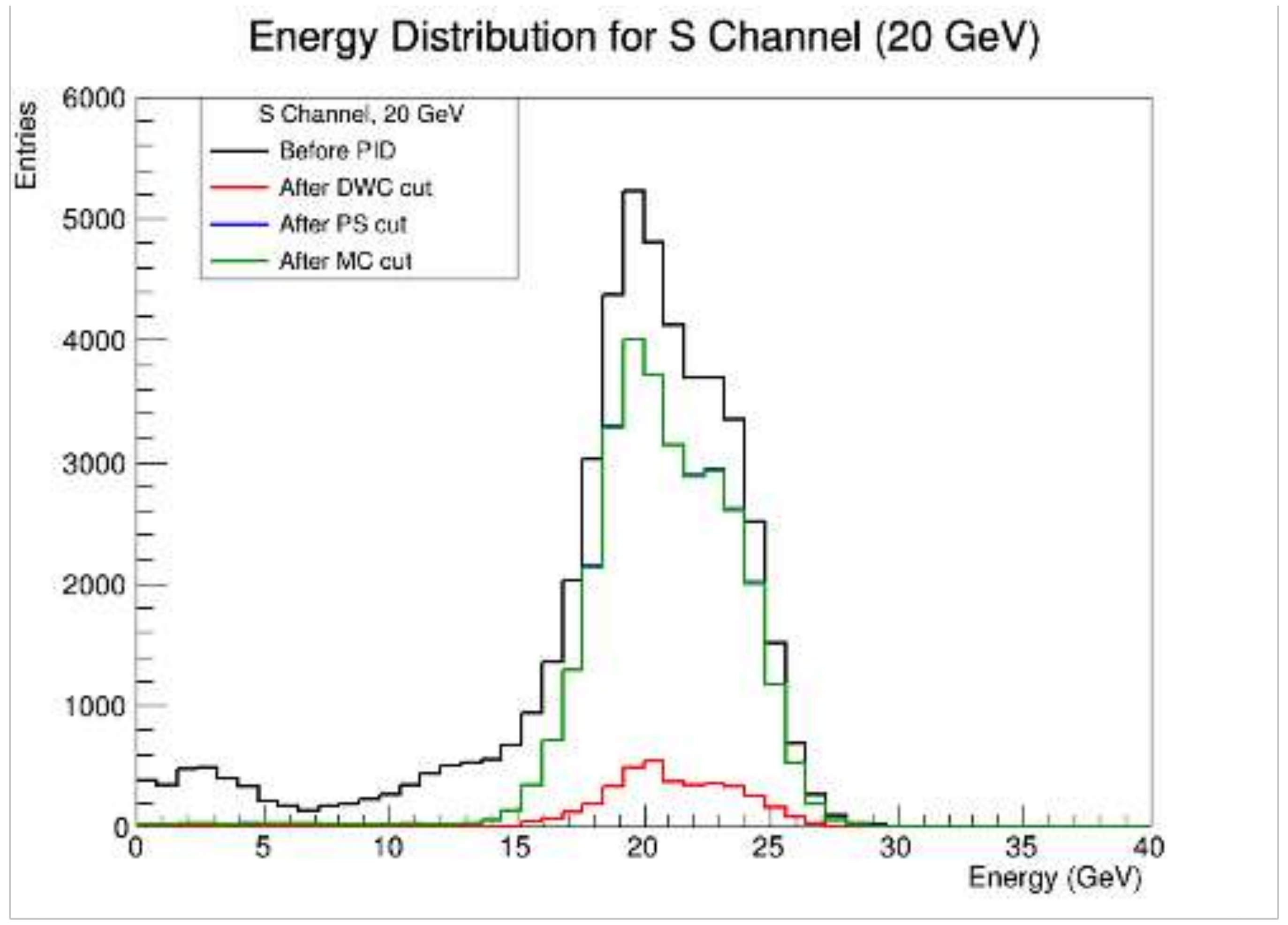


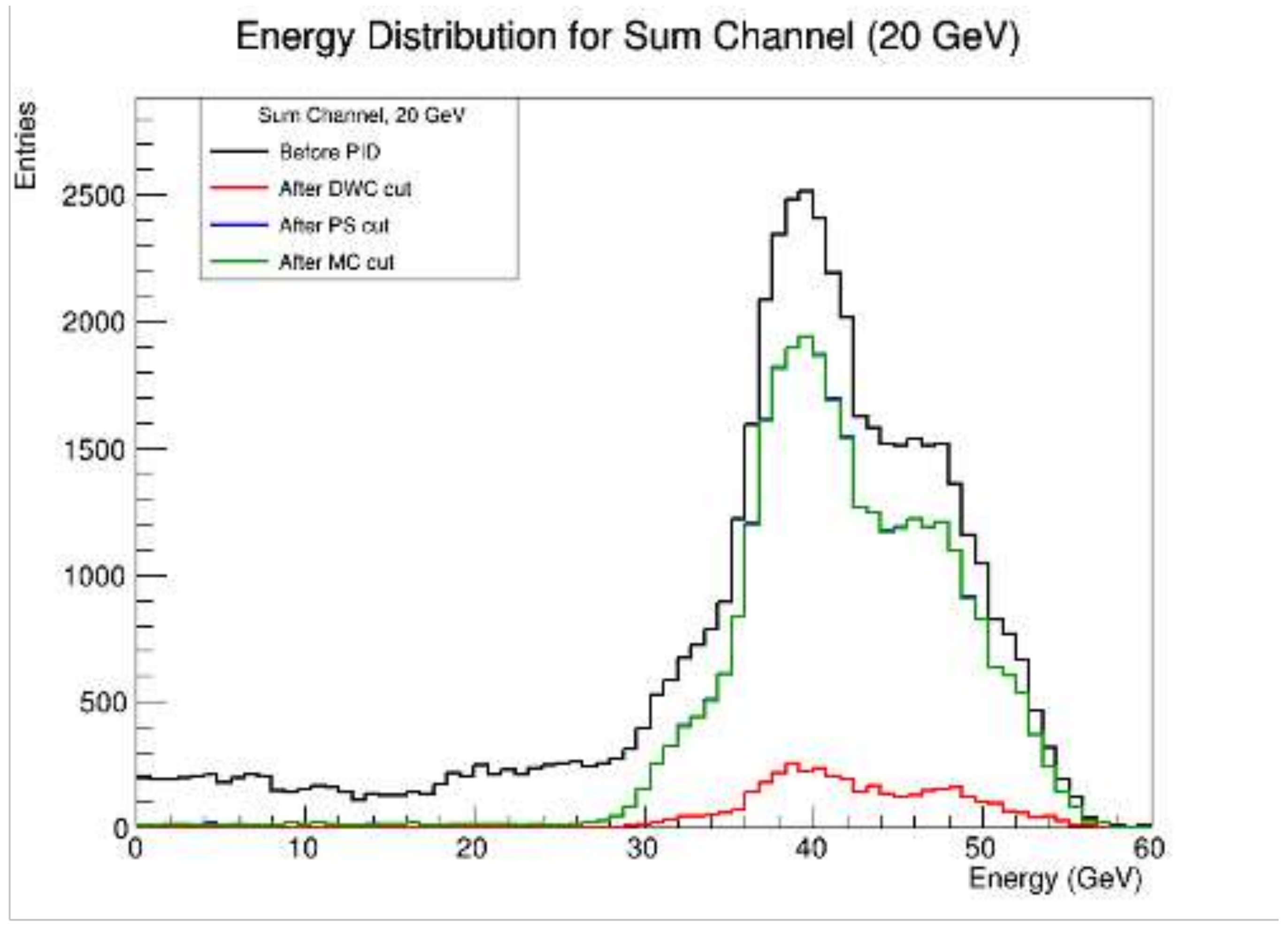


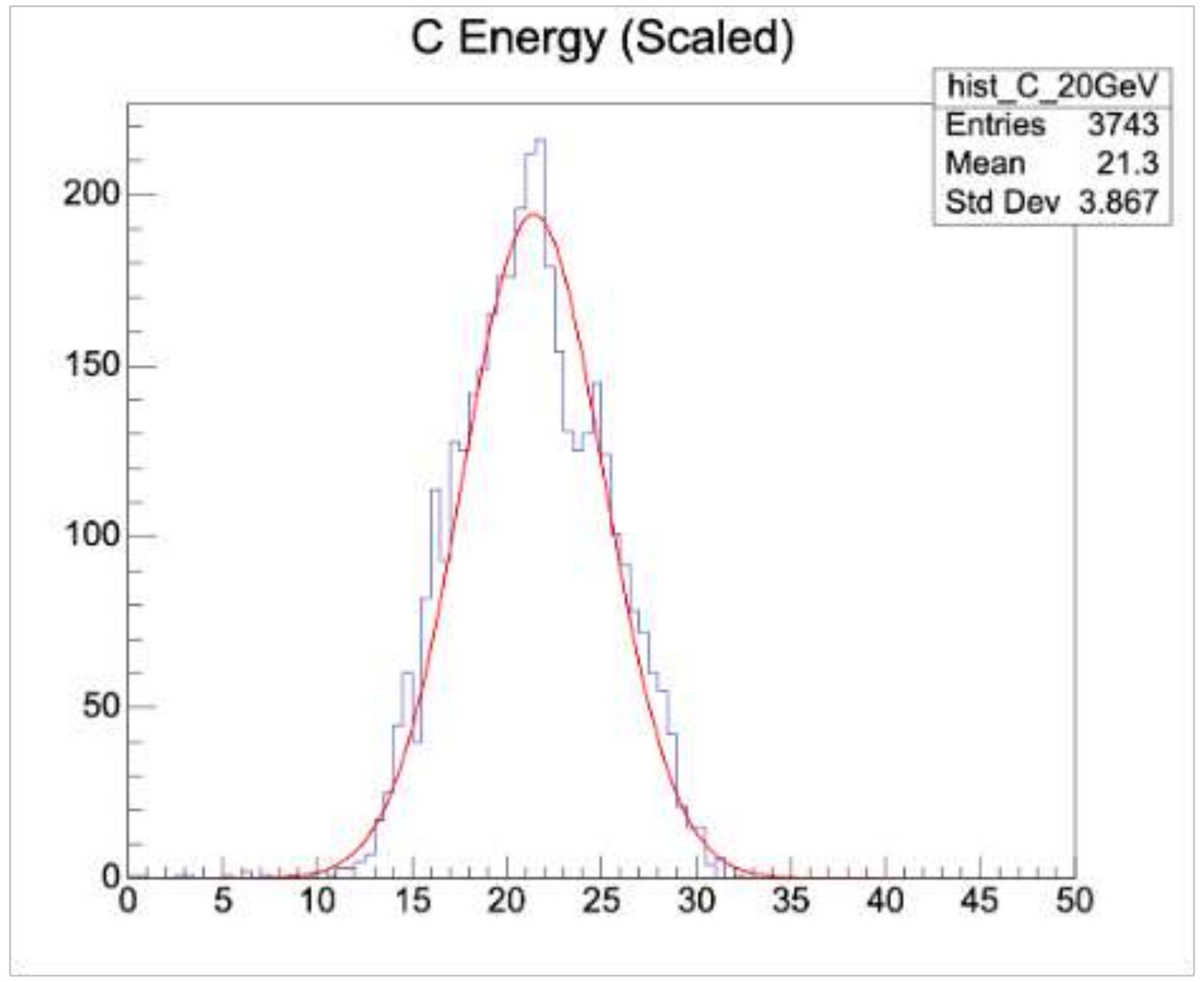


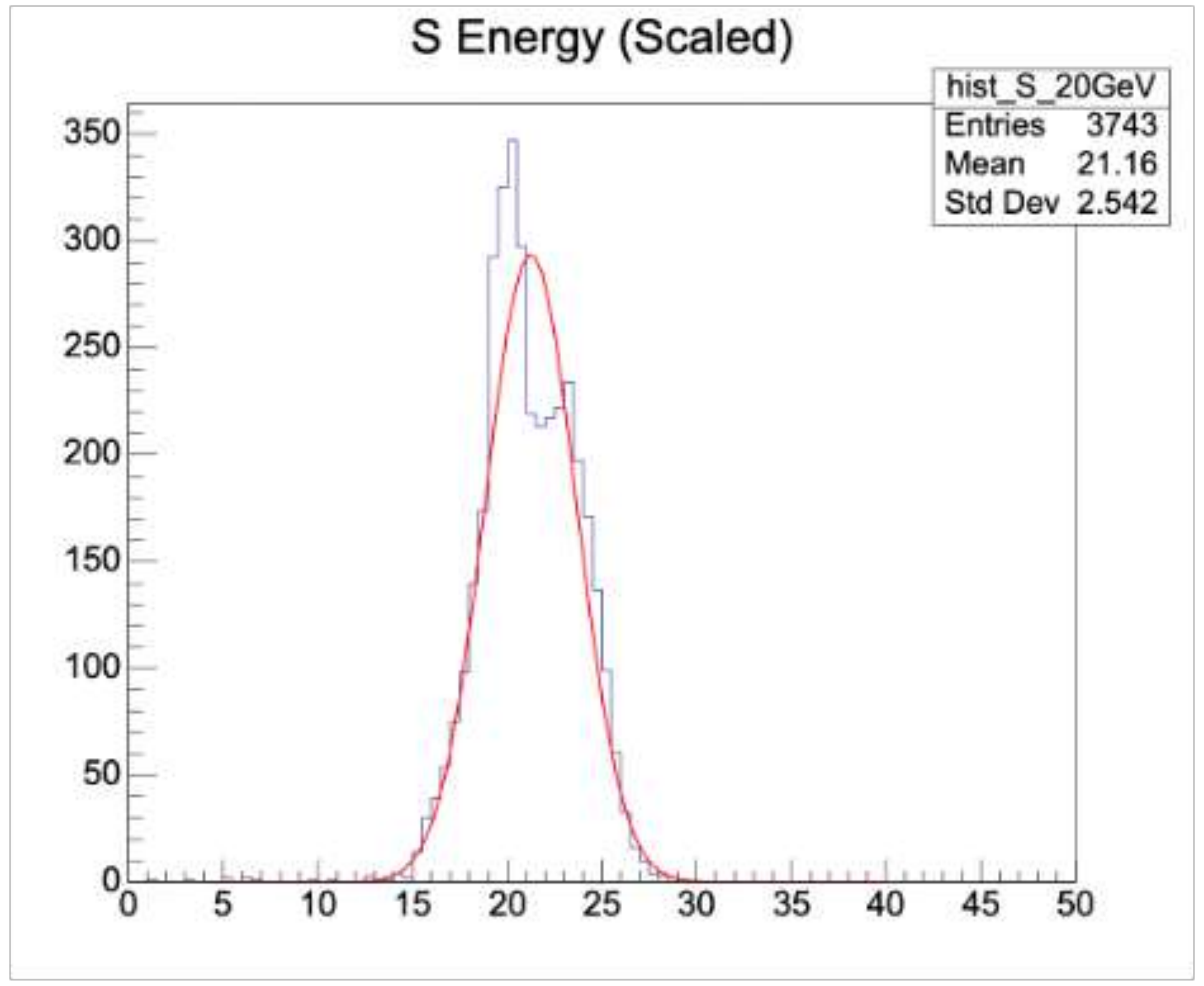
EM Performance
Energy Distribution : 20 GeV

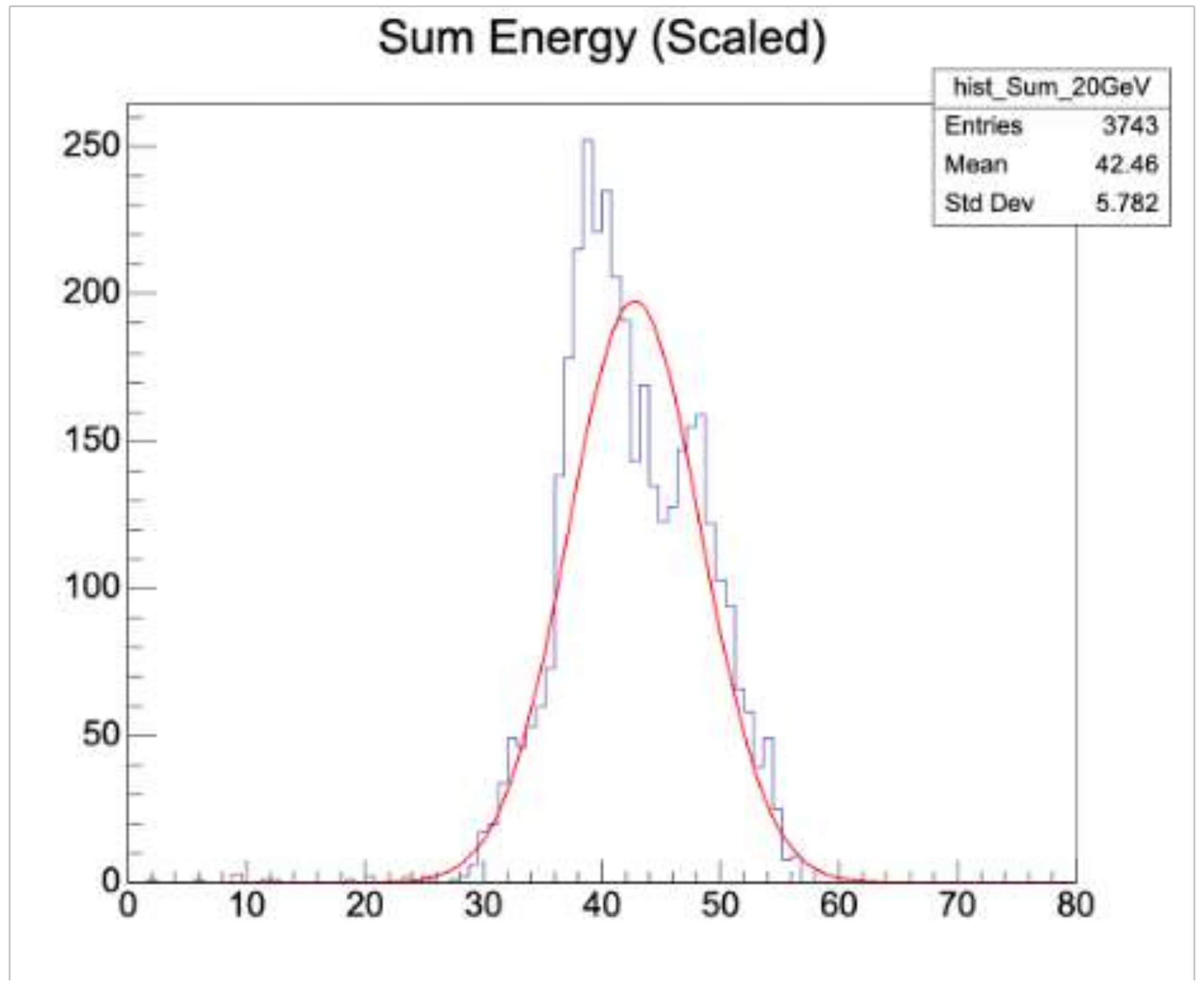




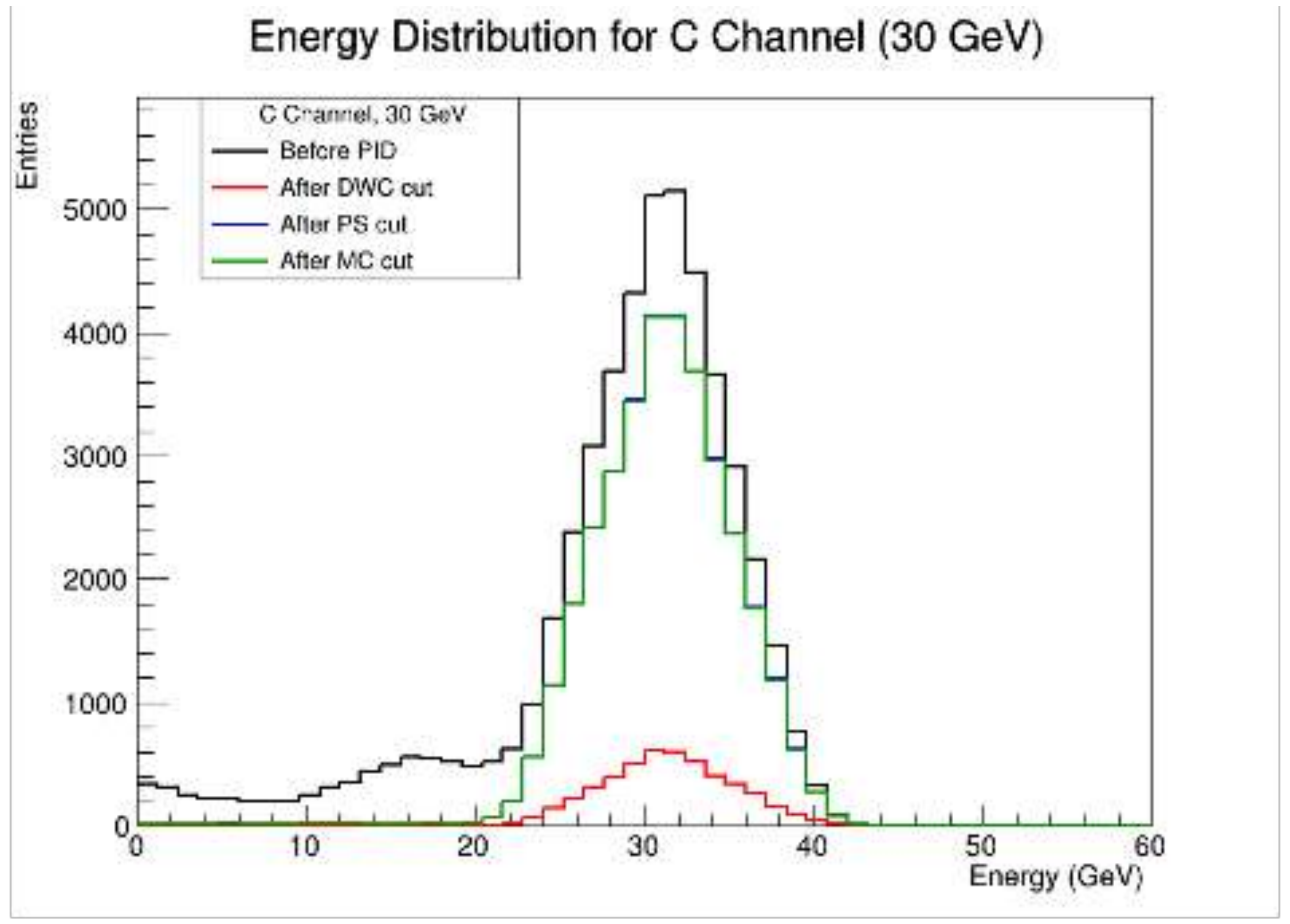


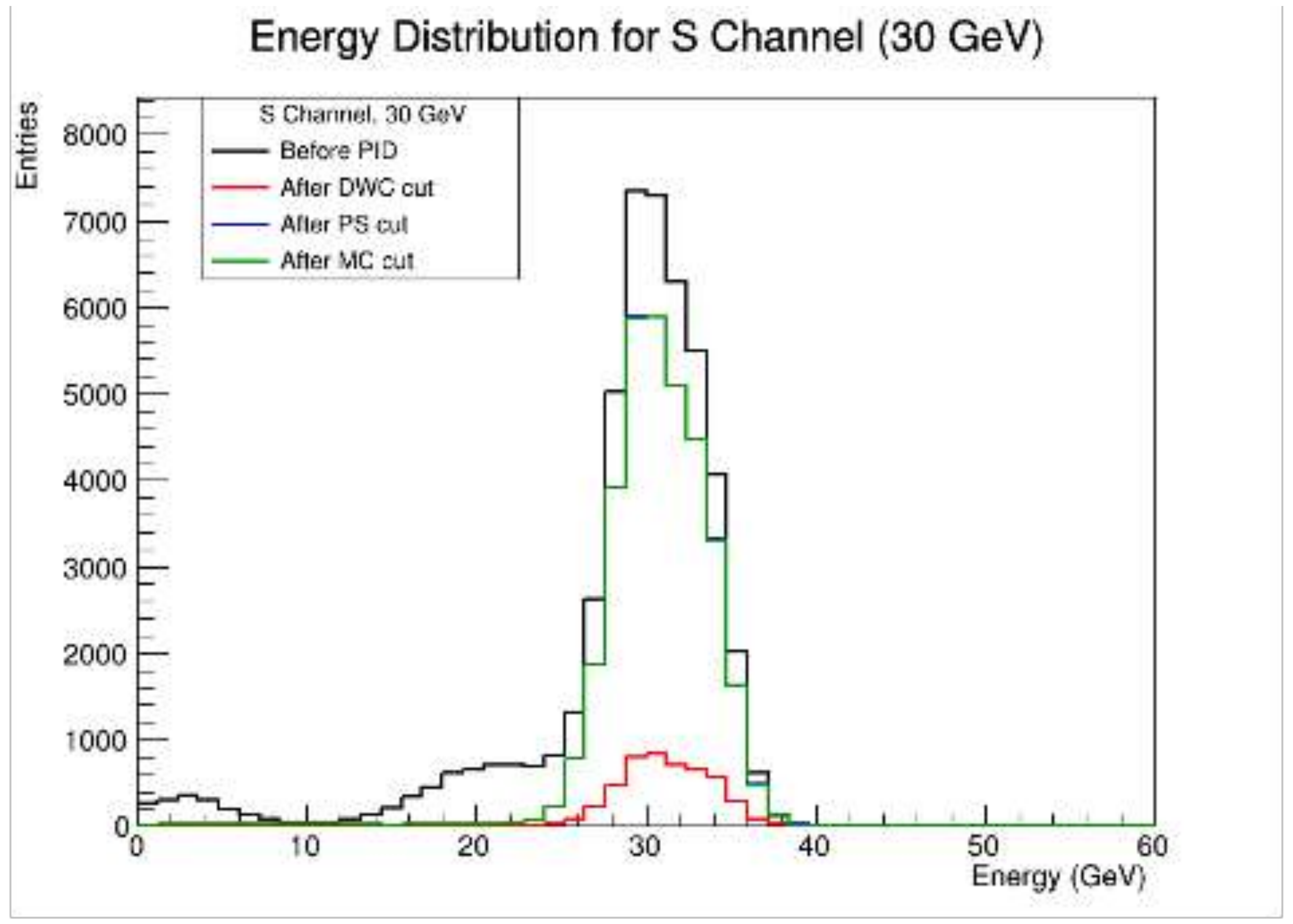


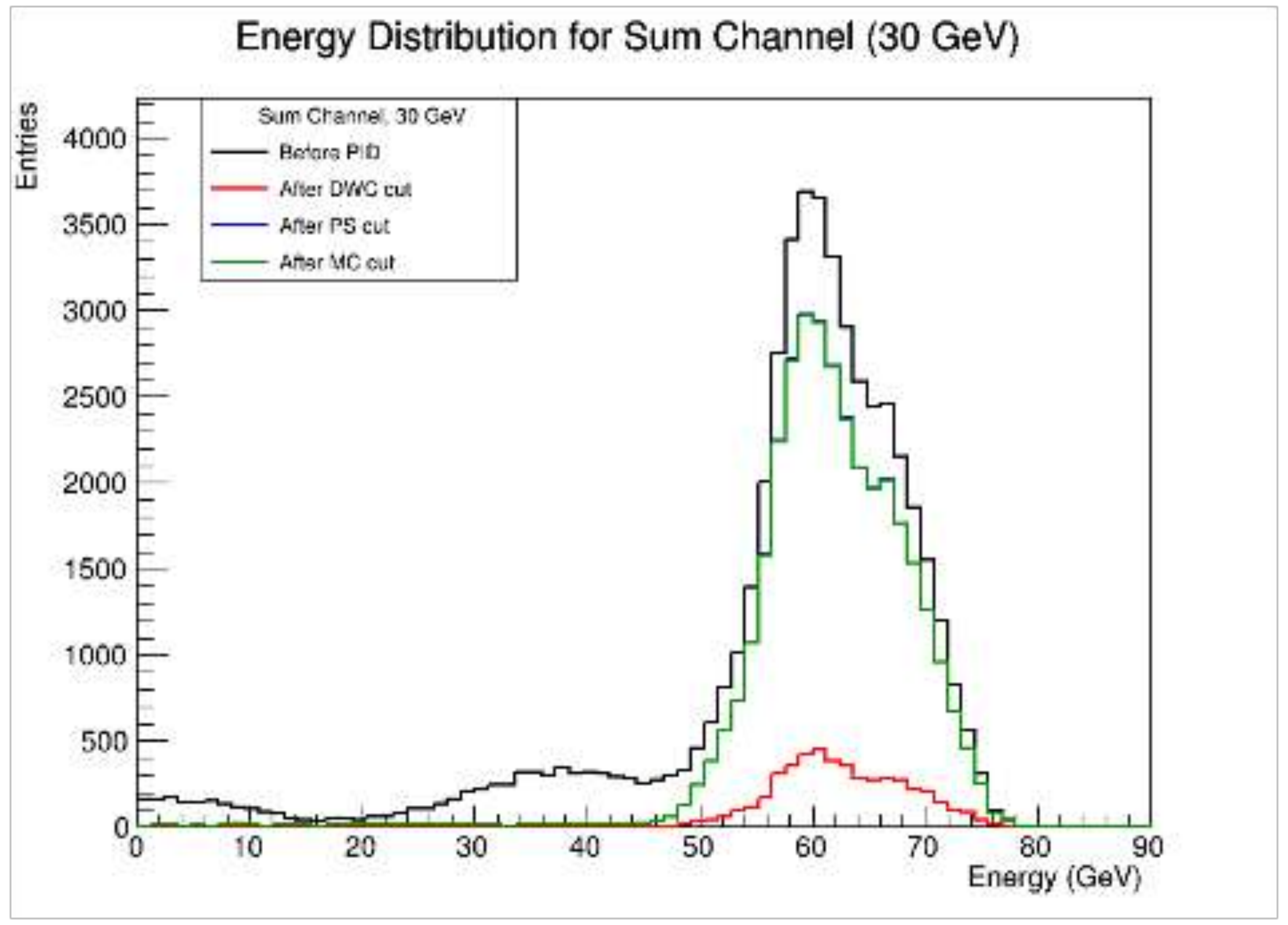


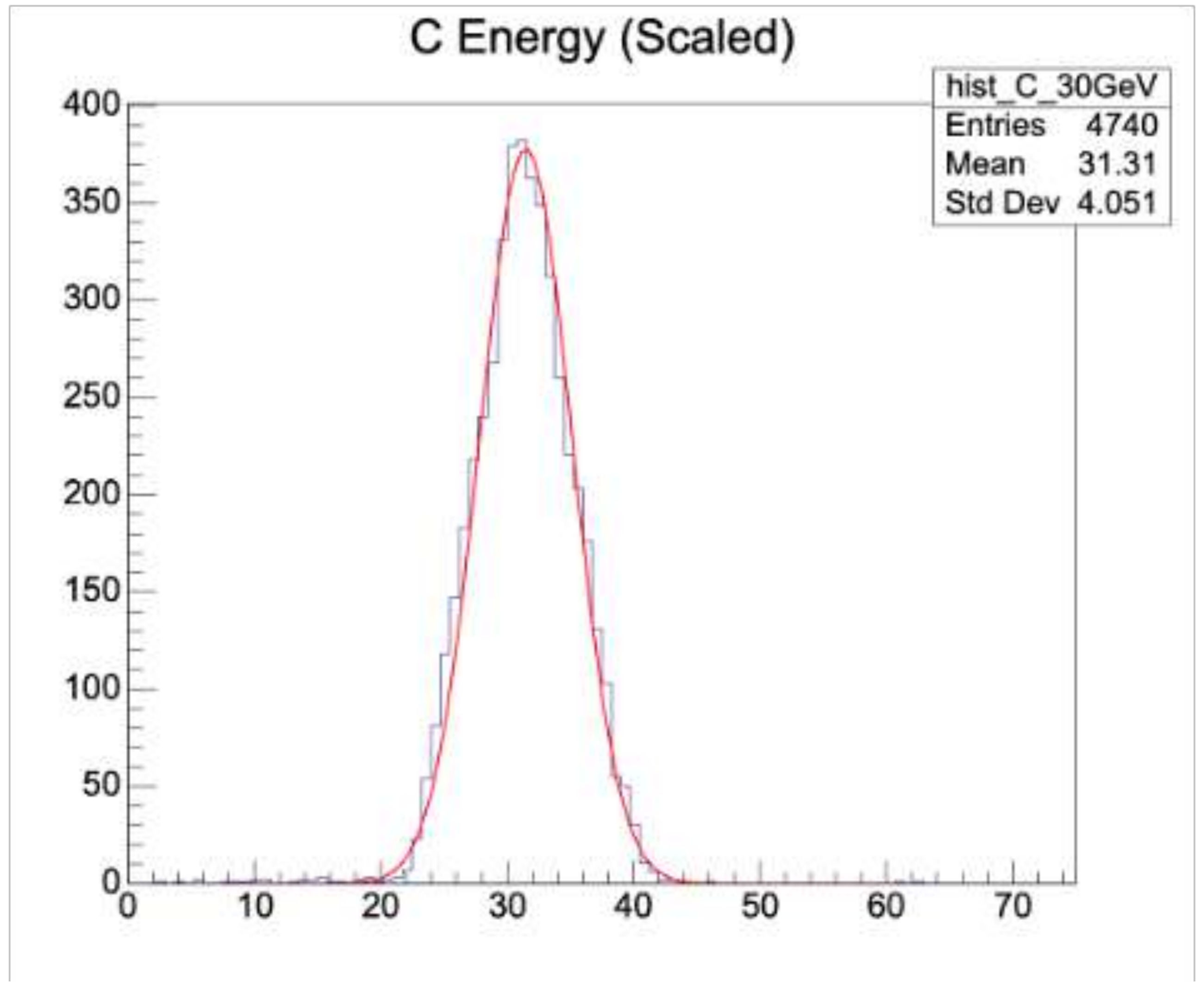


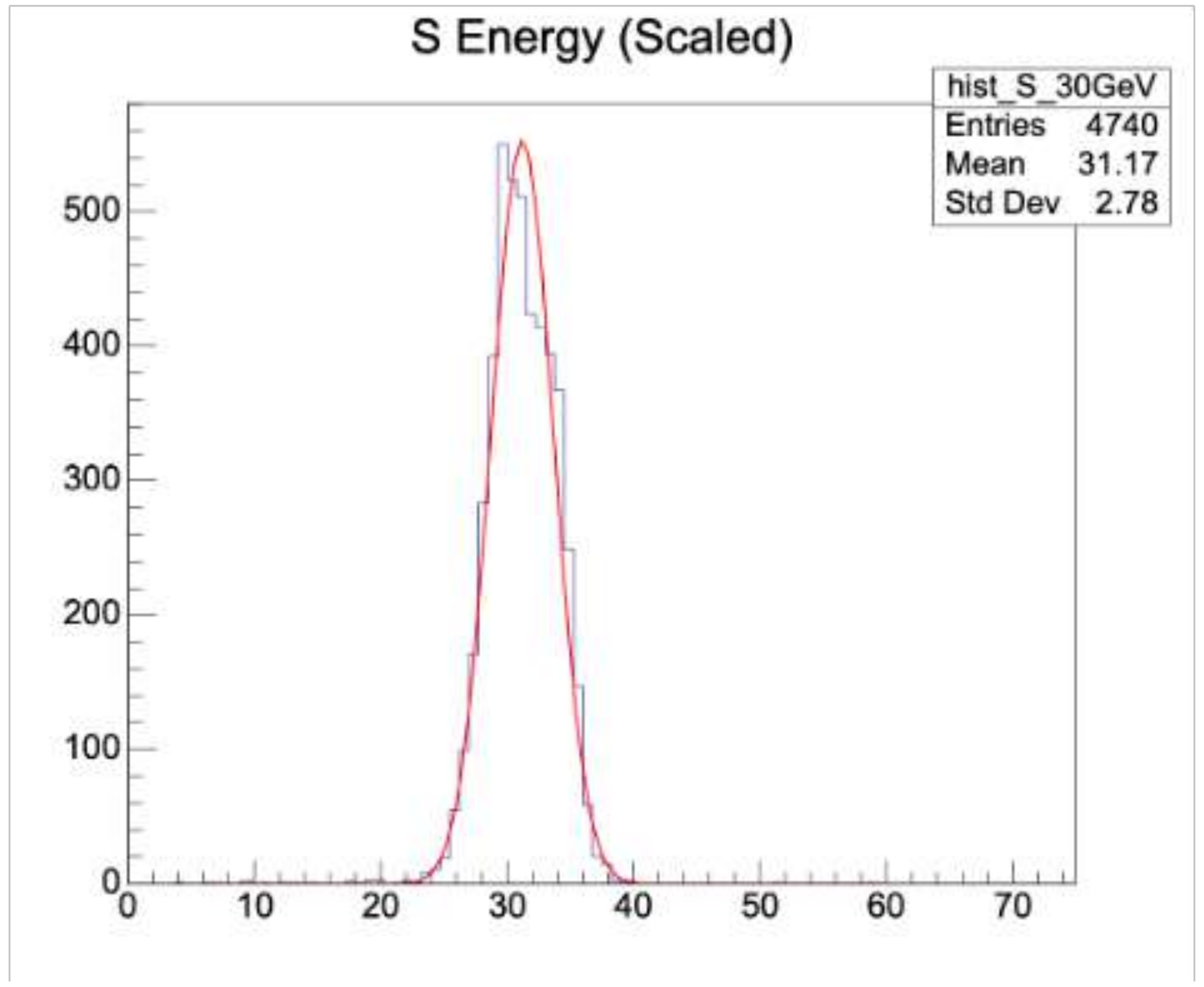
EM Performance
Energy Distribution : 30 GeV

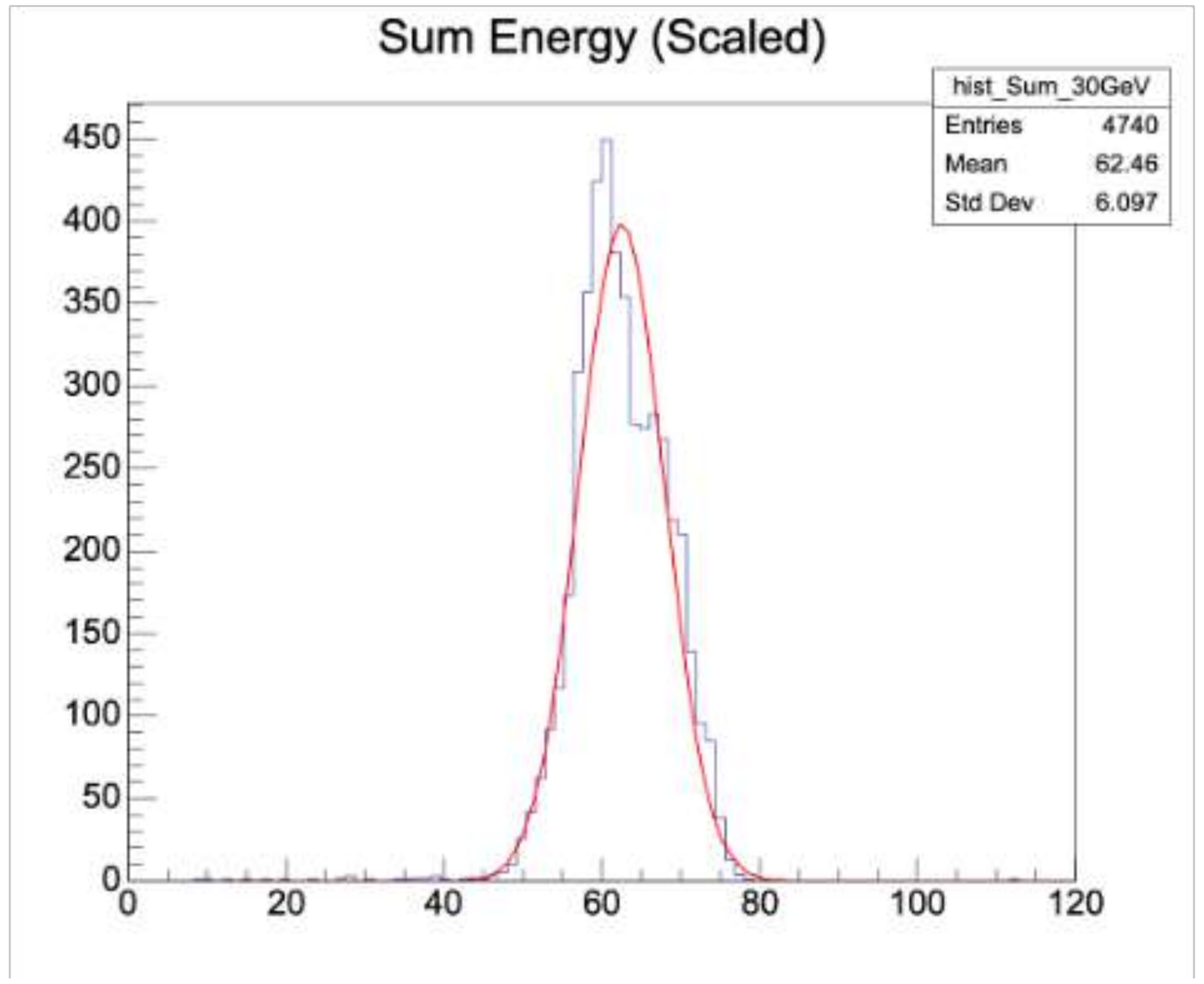




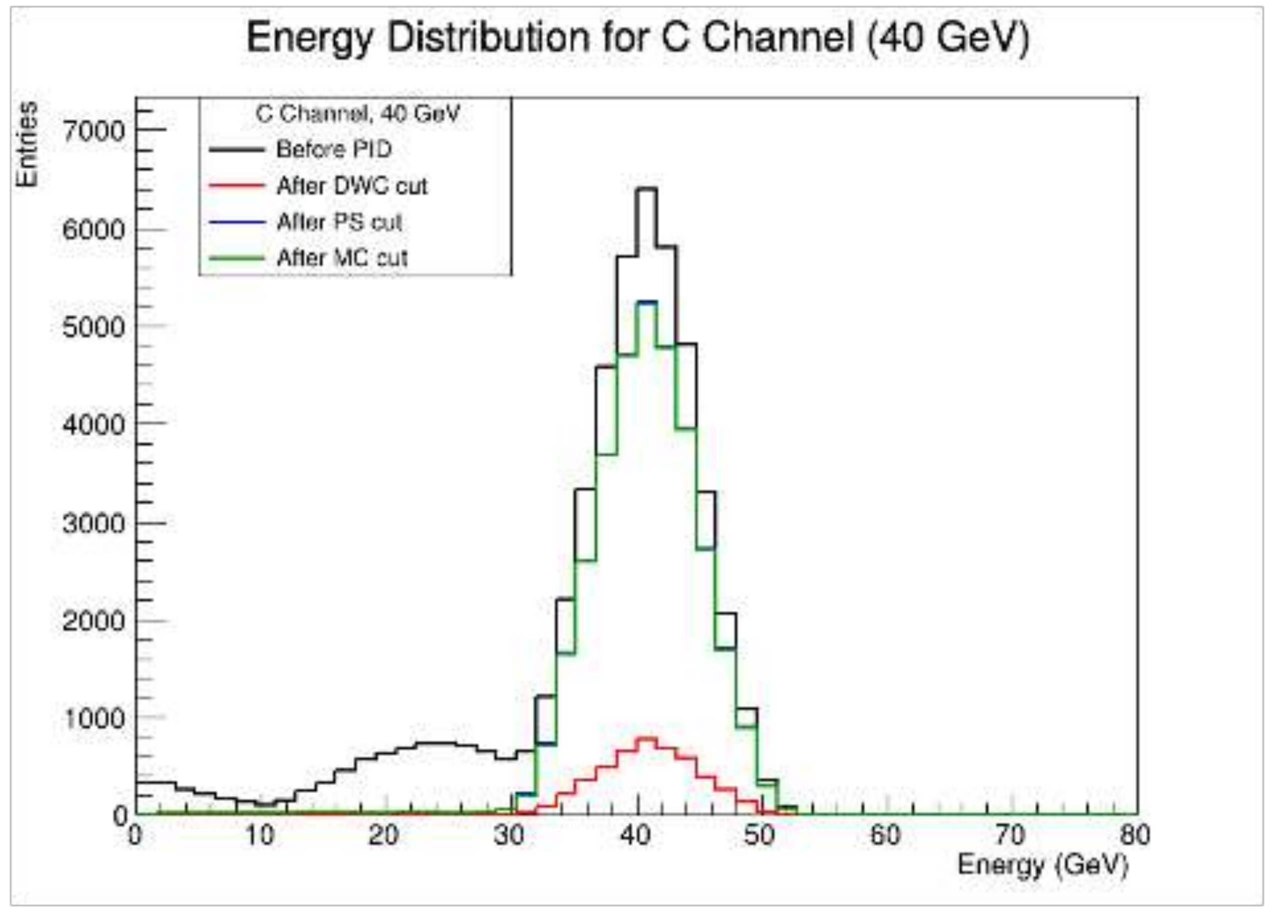


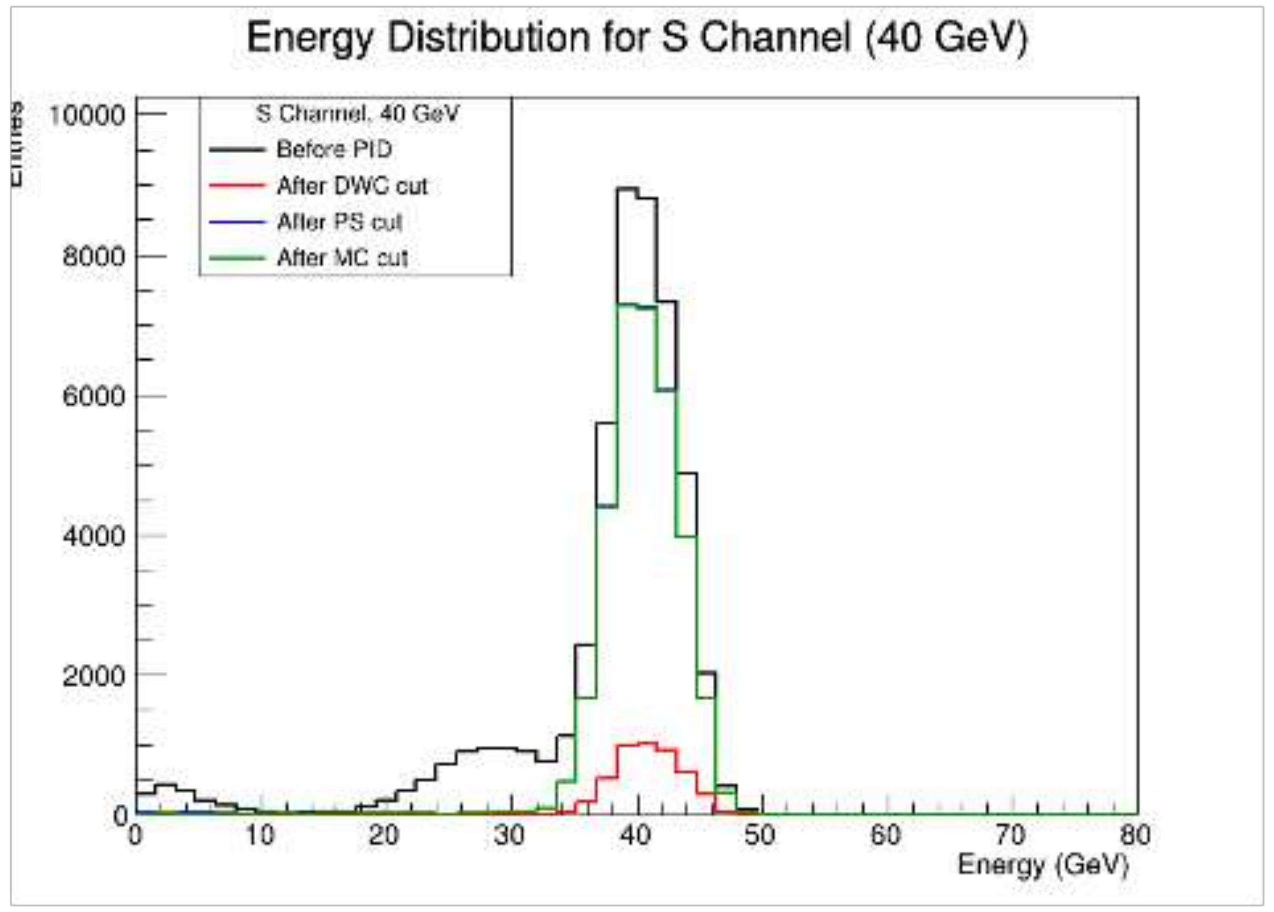


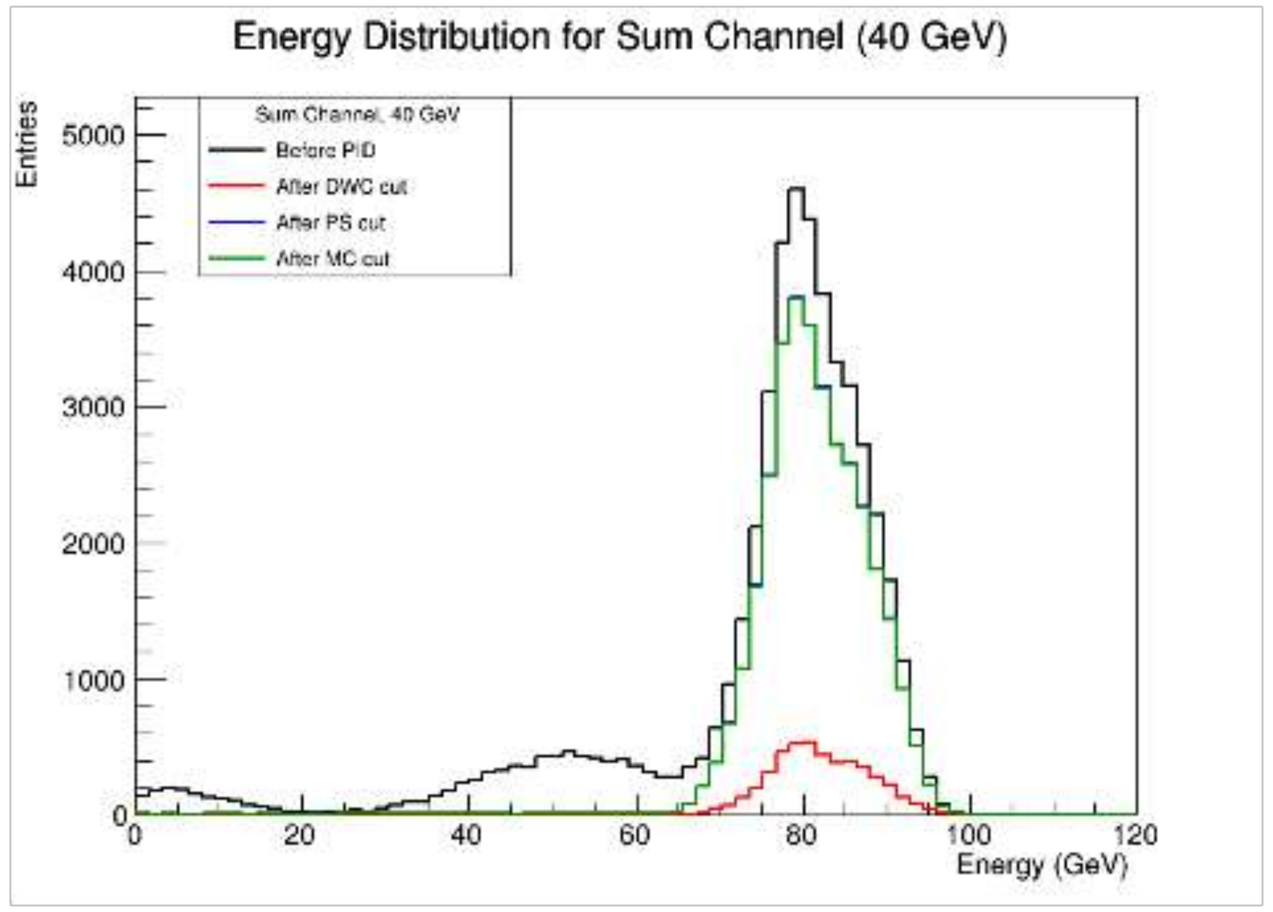


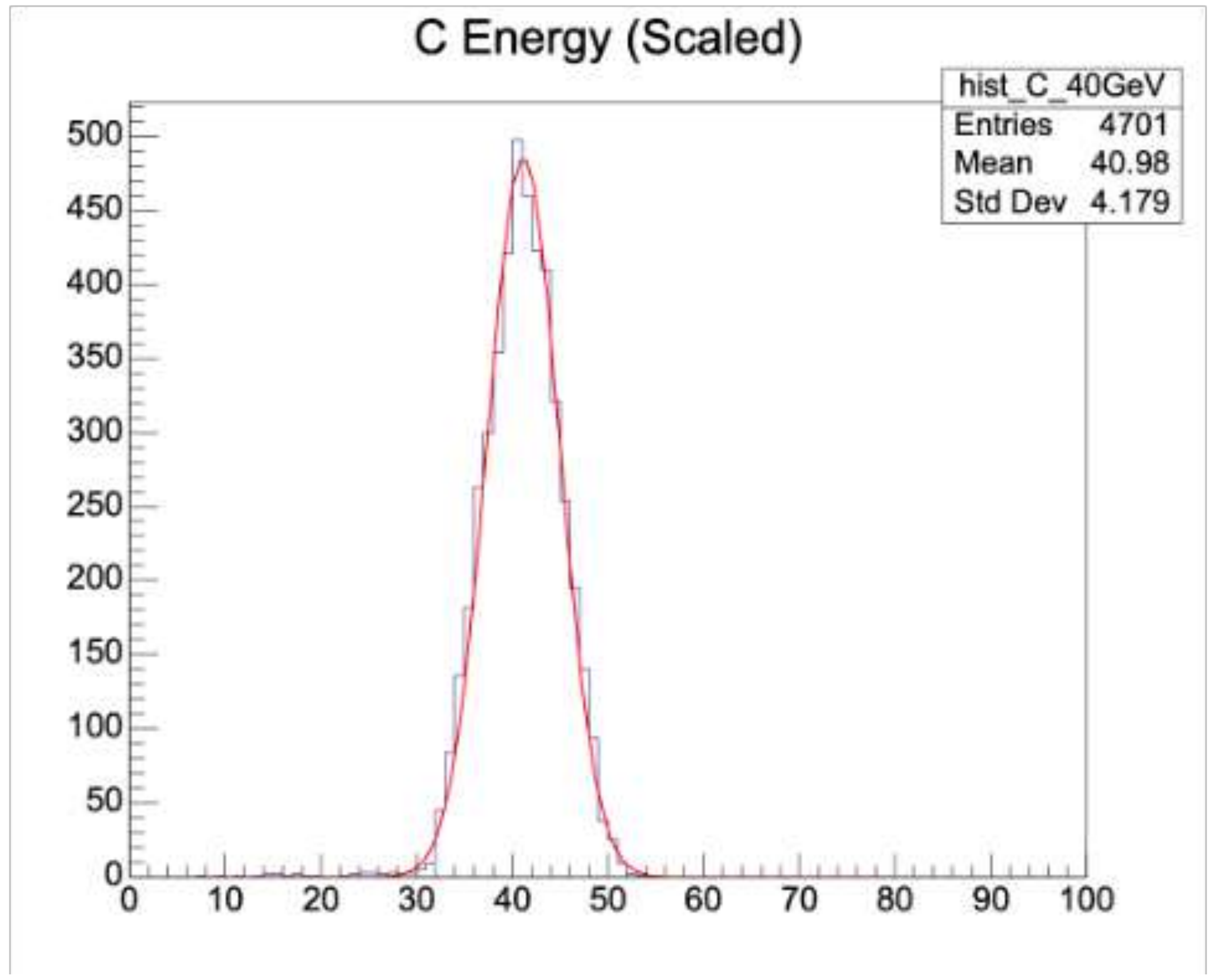


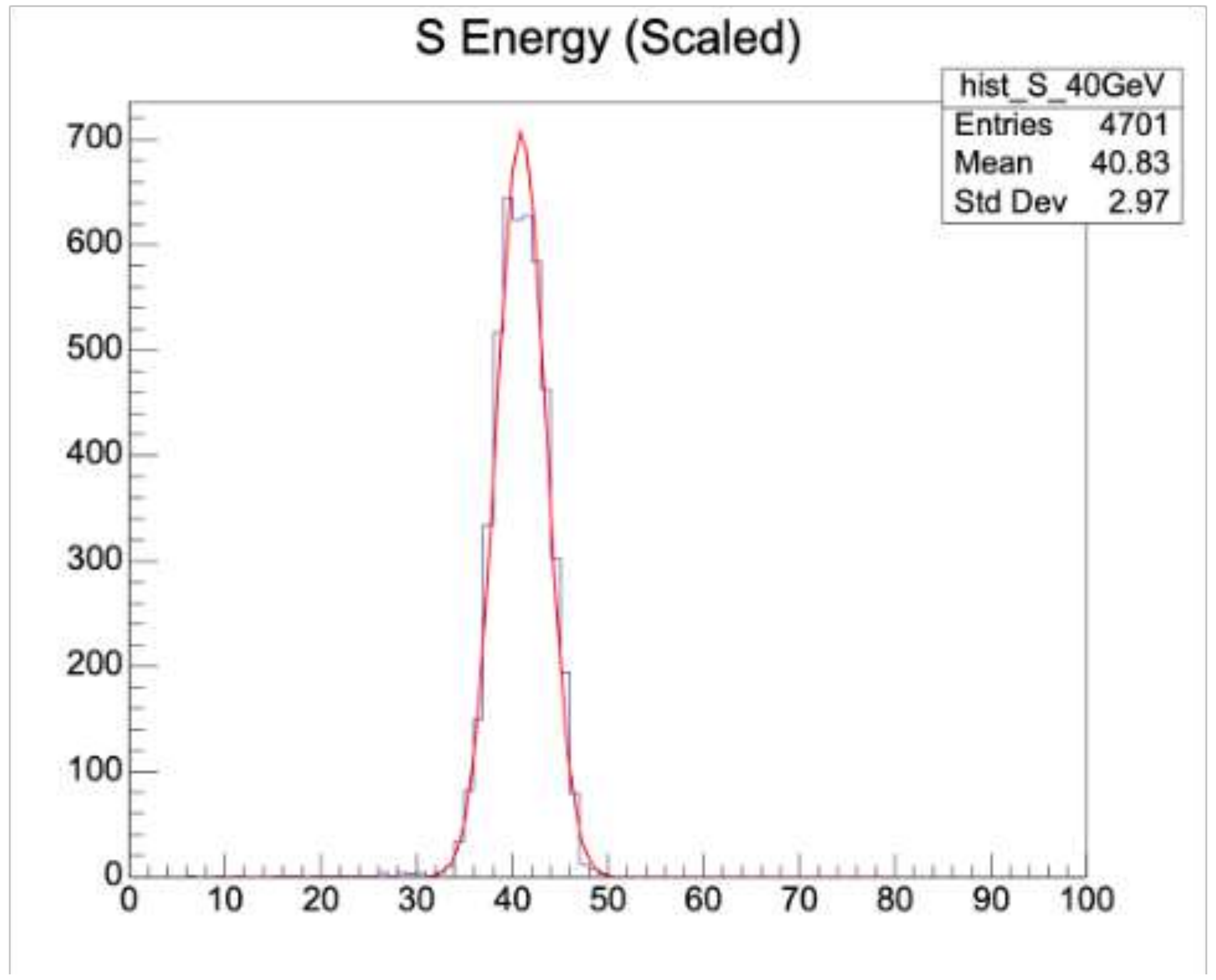
EM Performance
Energy Distribution : 40 GeV

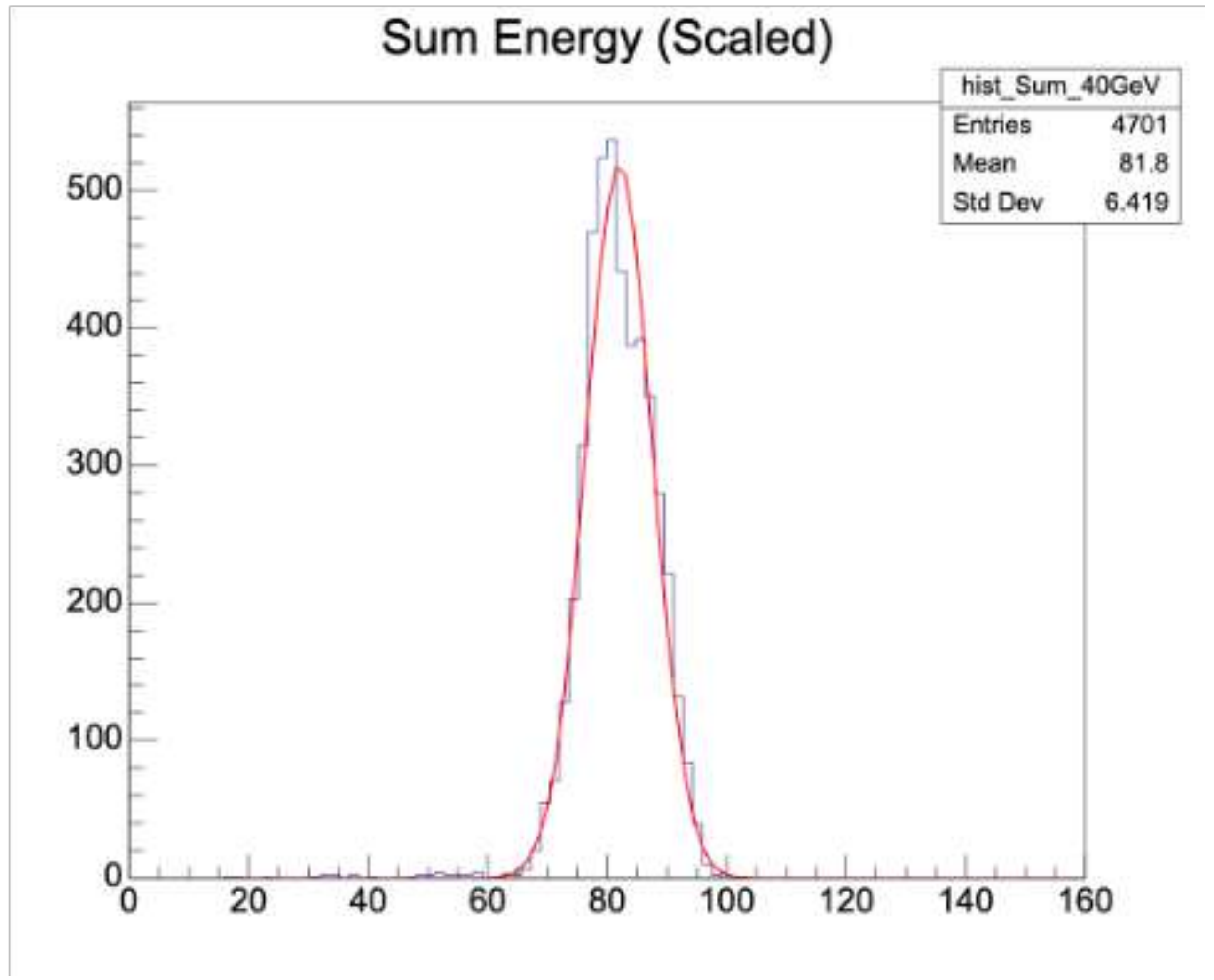




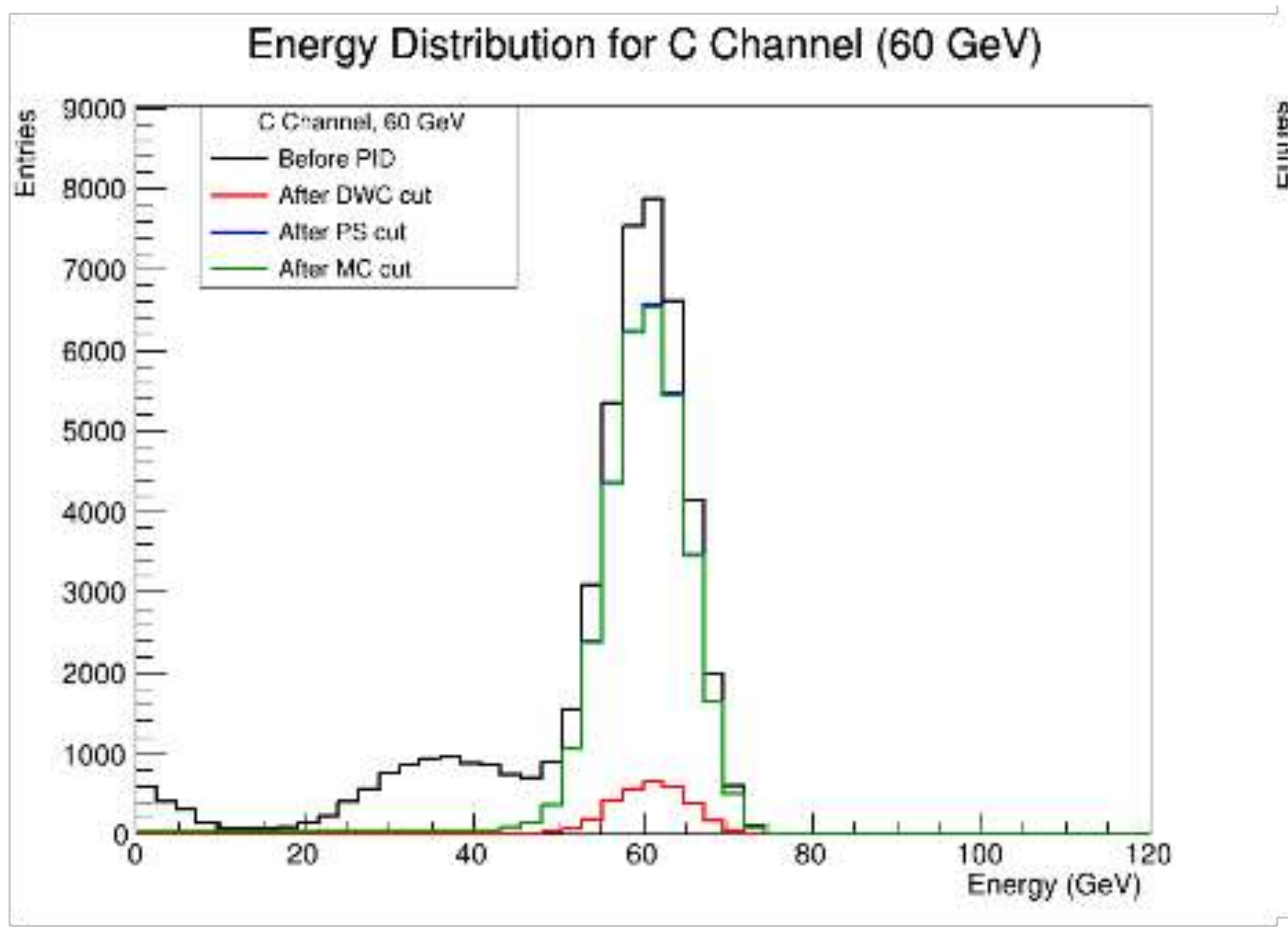


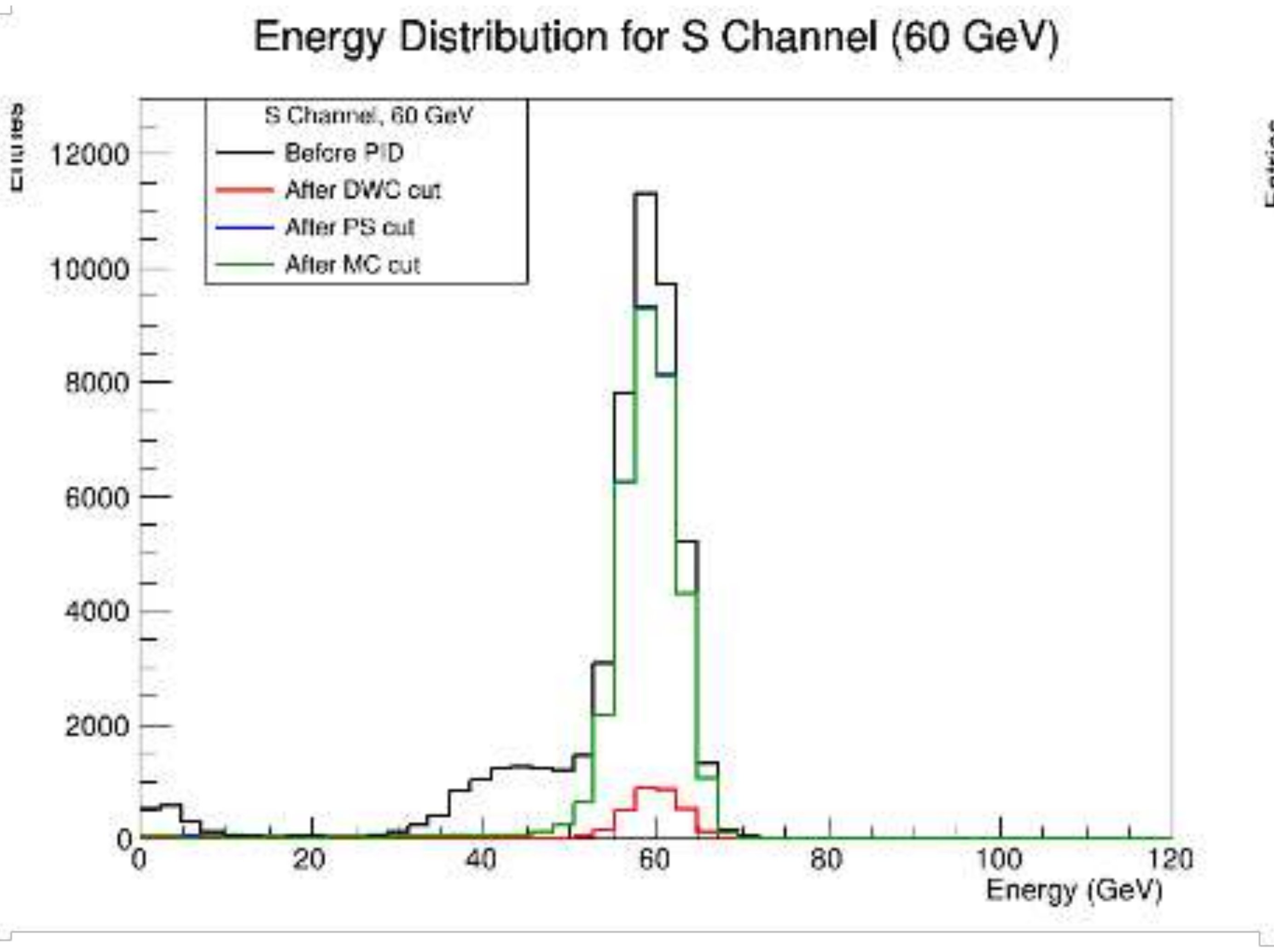


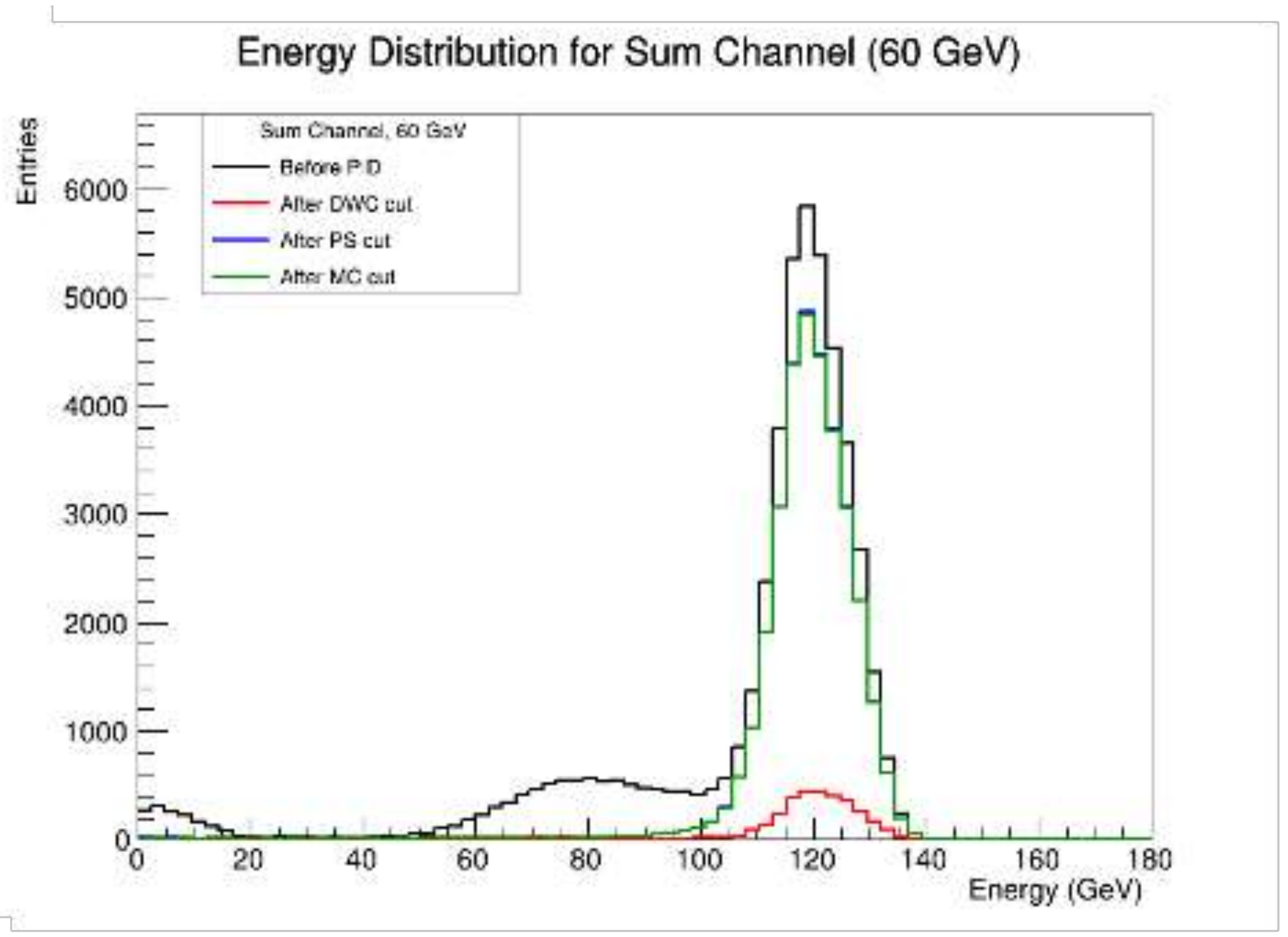


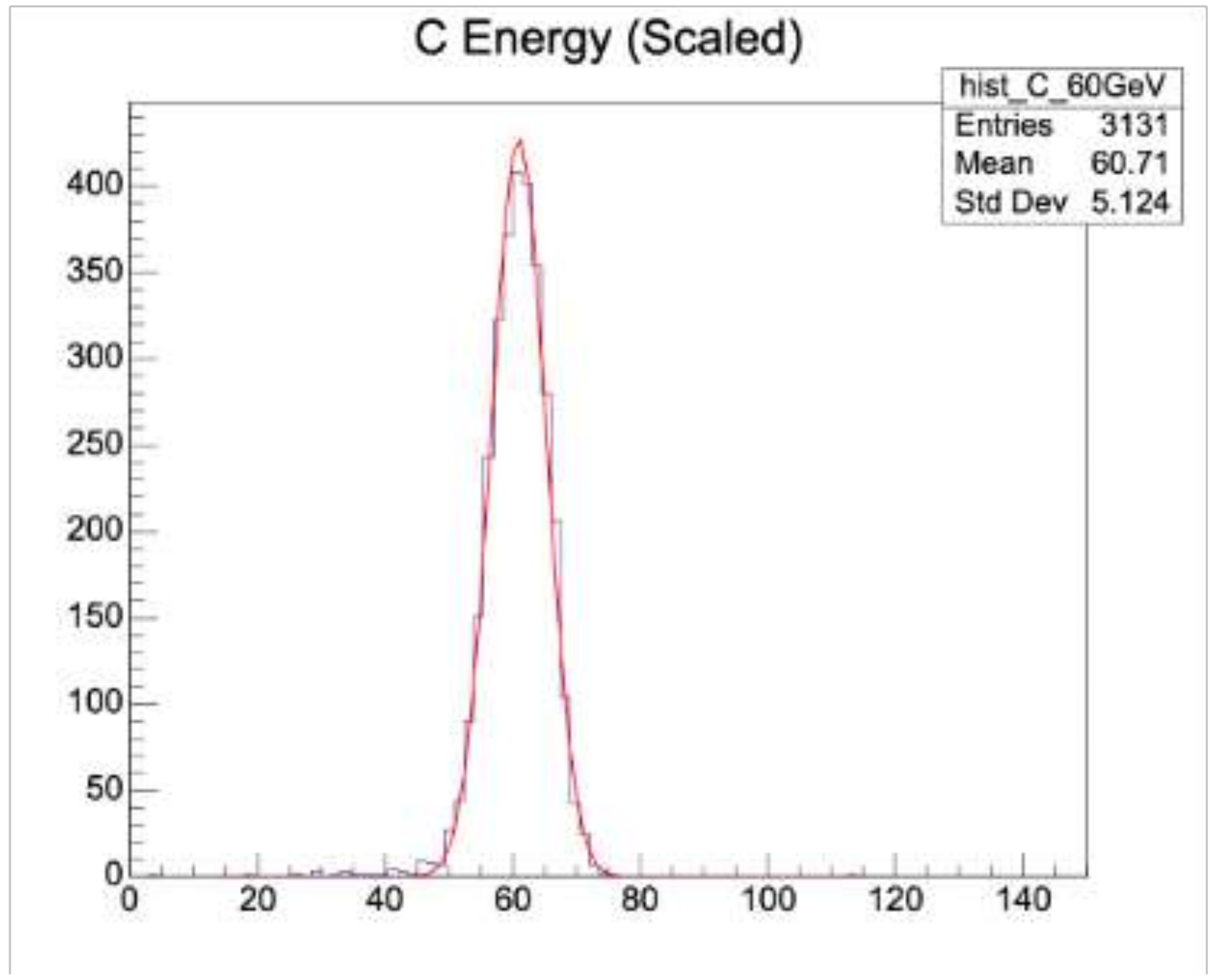


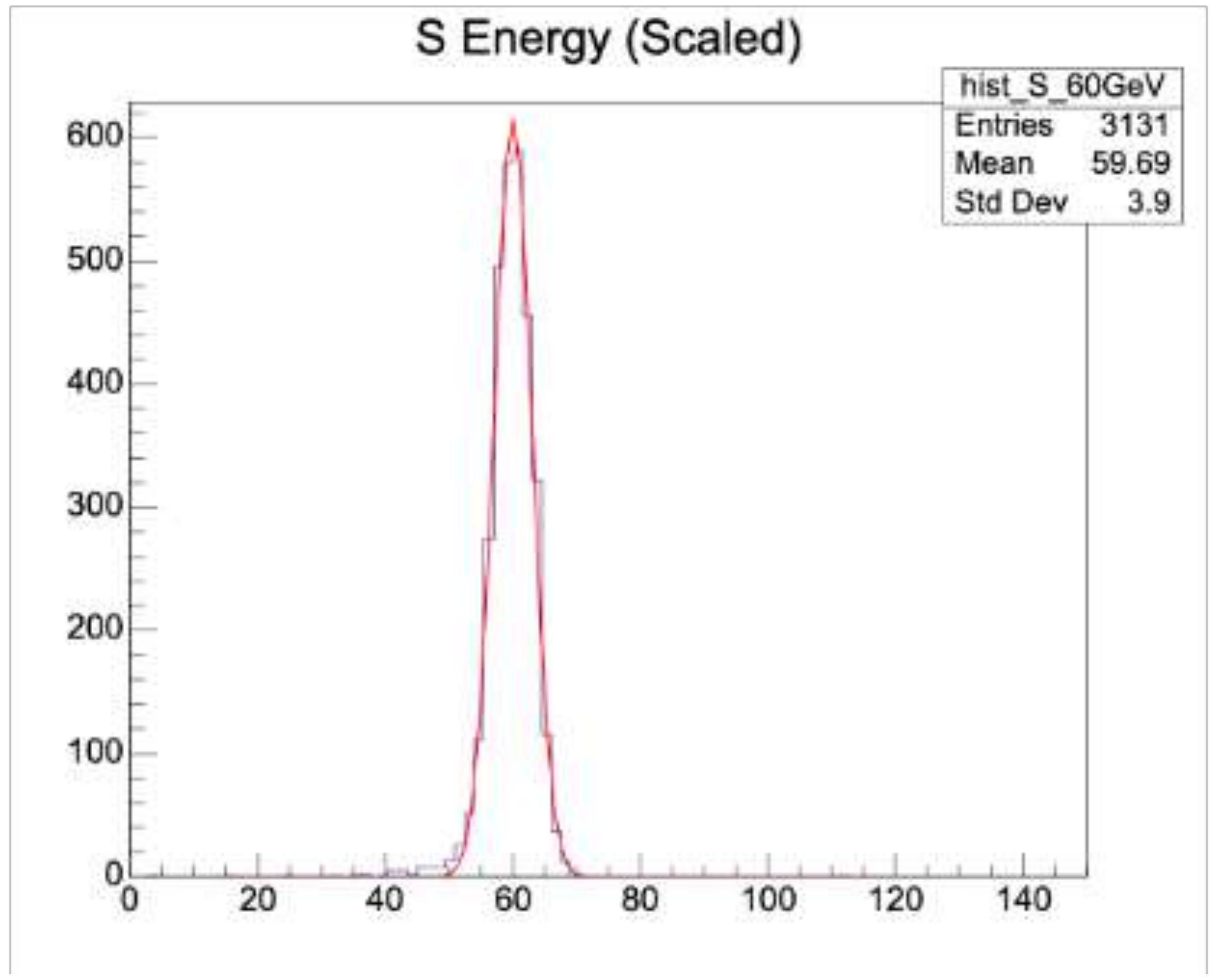
EM Performance
Energy Distribution : 60 GeV

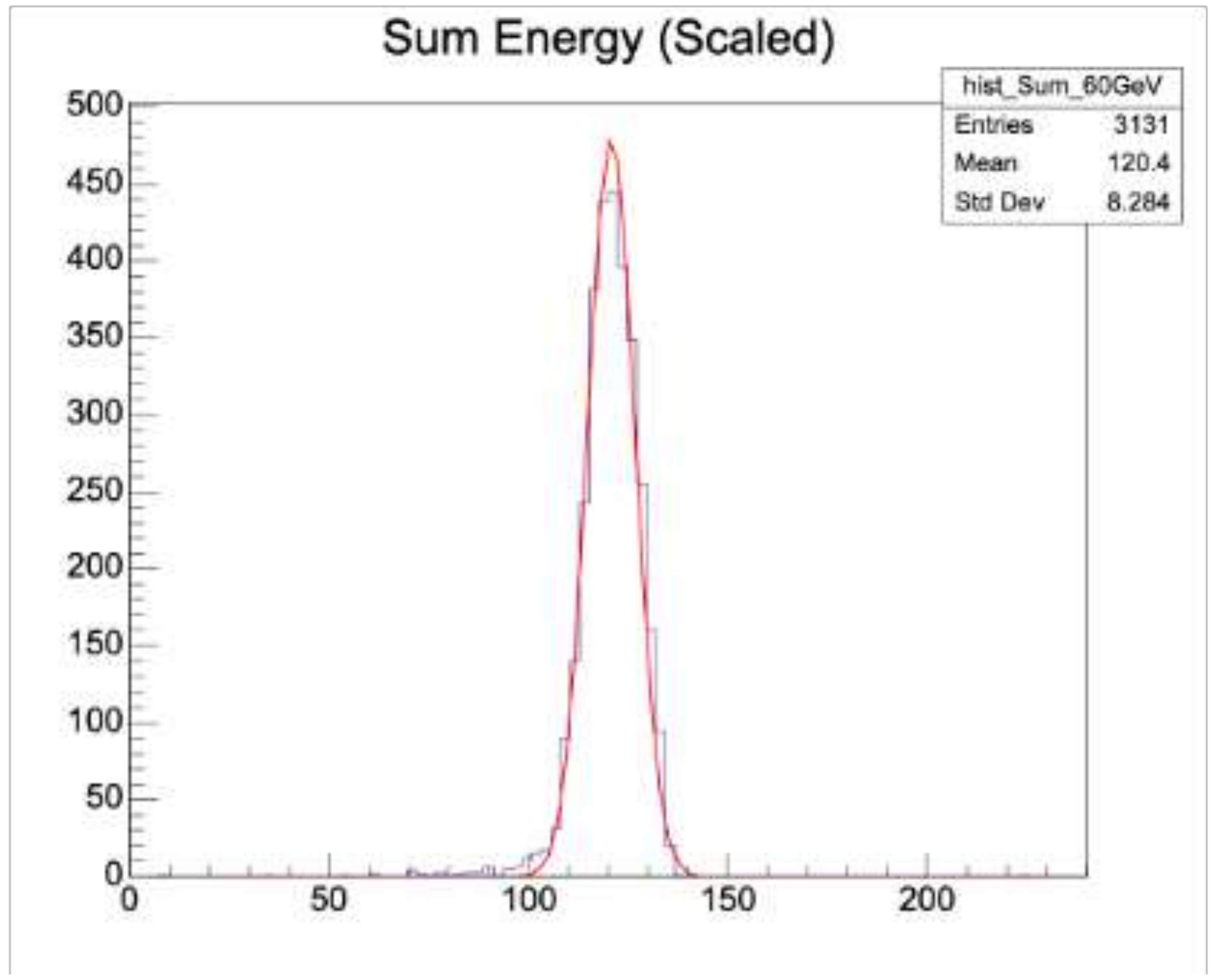






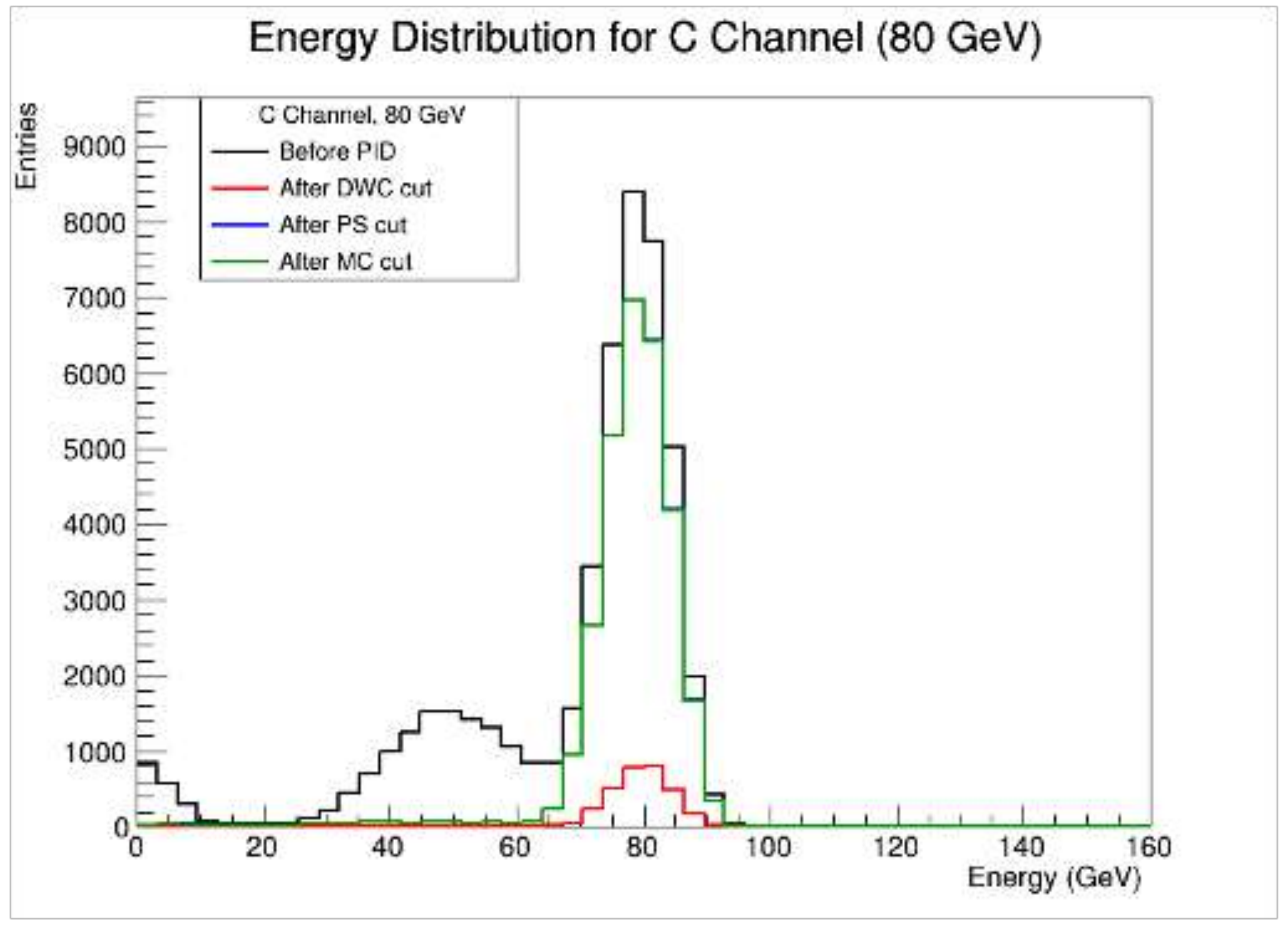


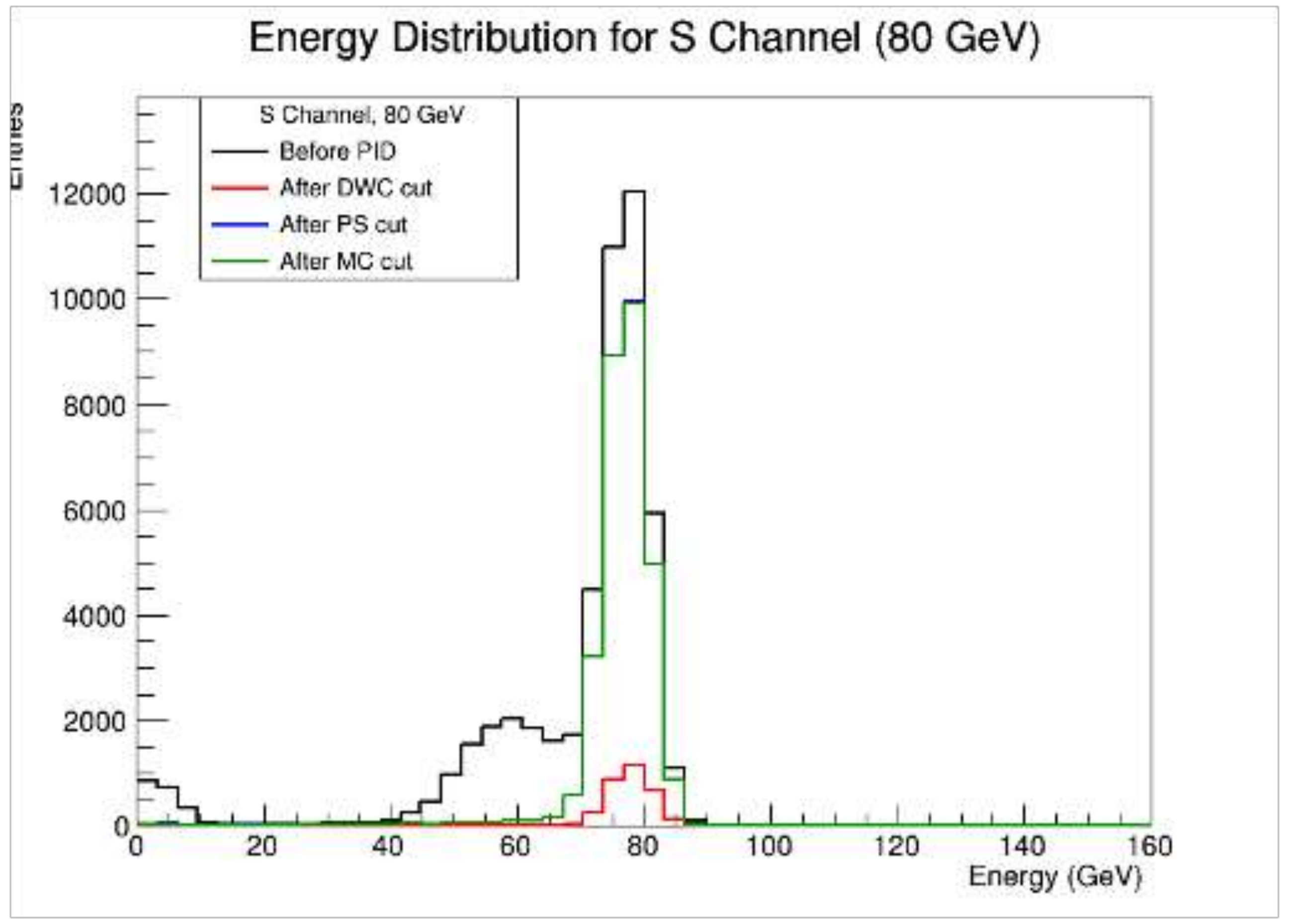


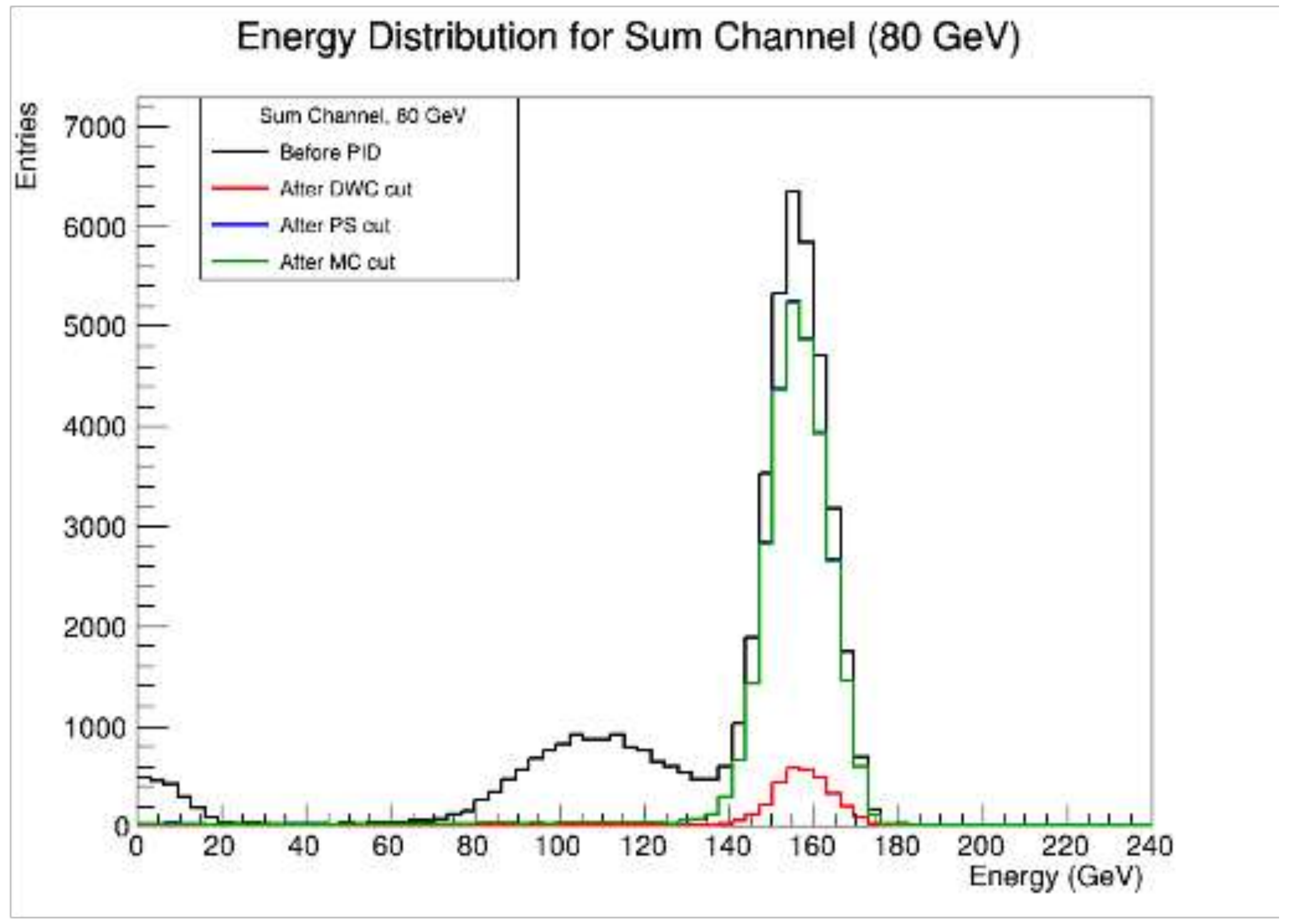


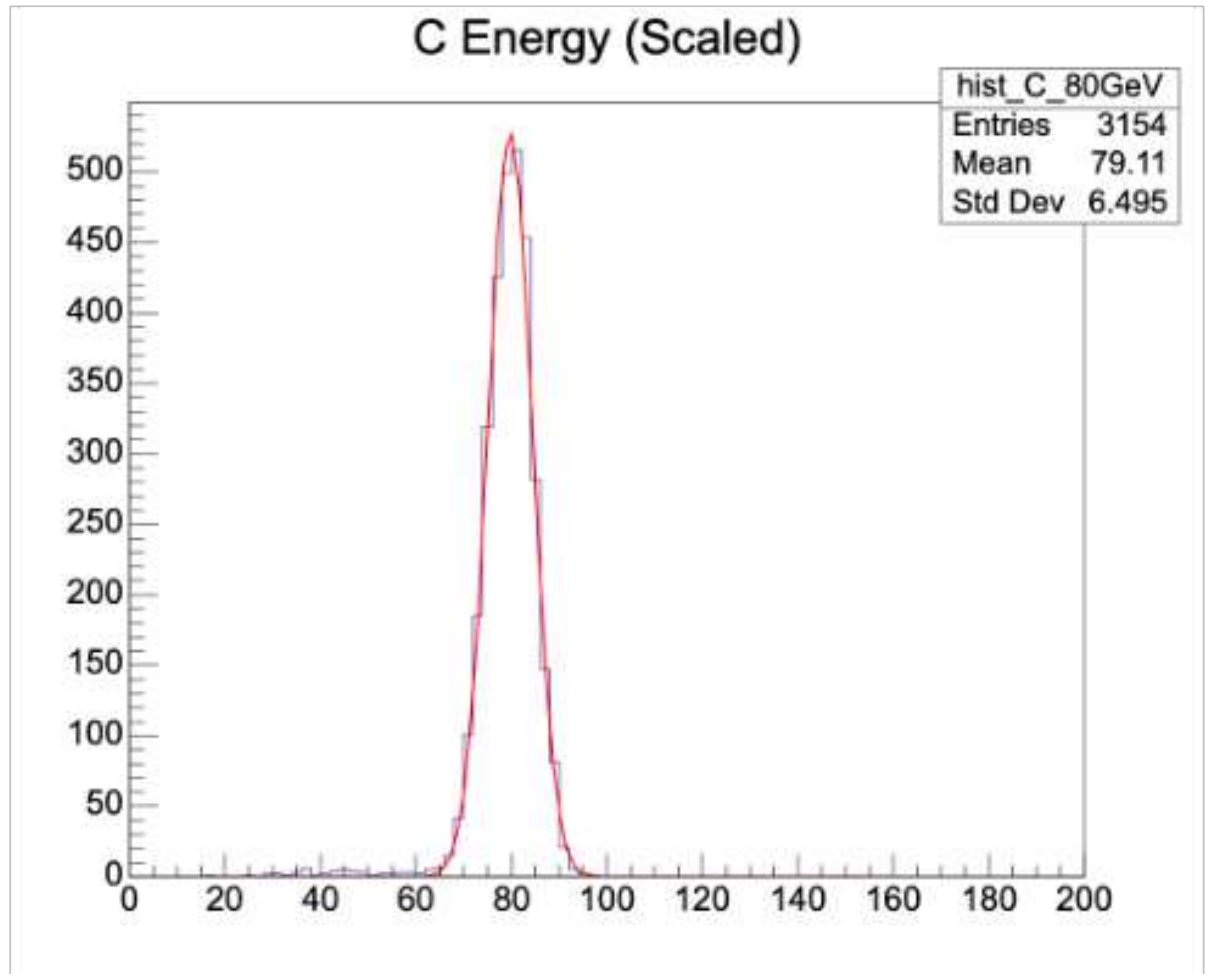
EM Performance

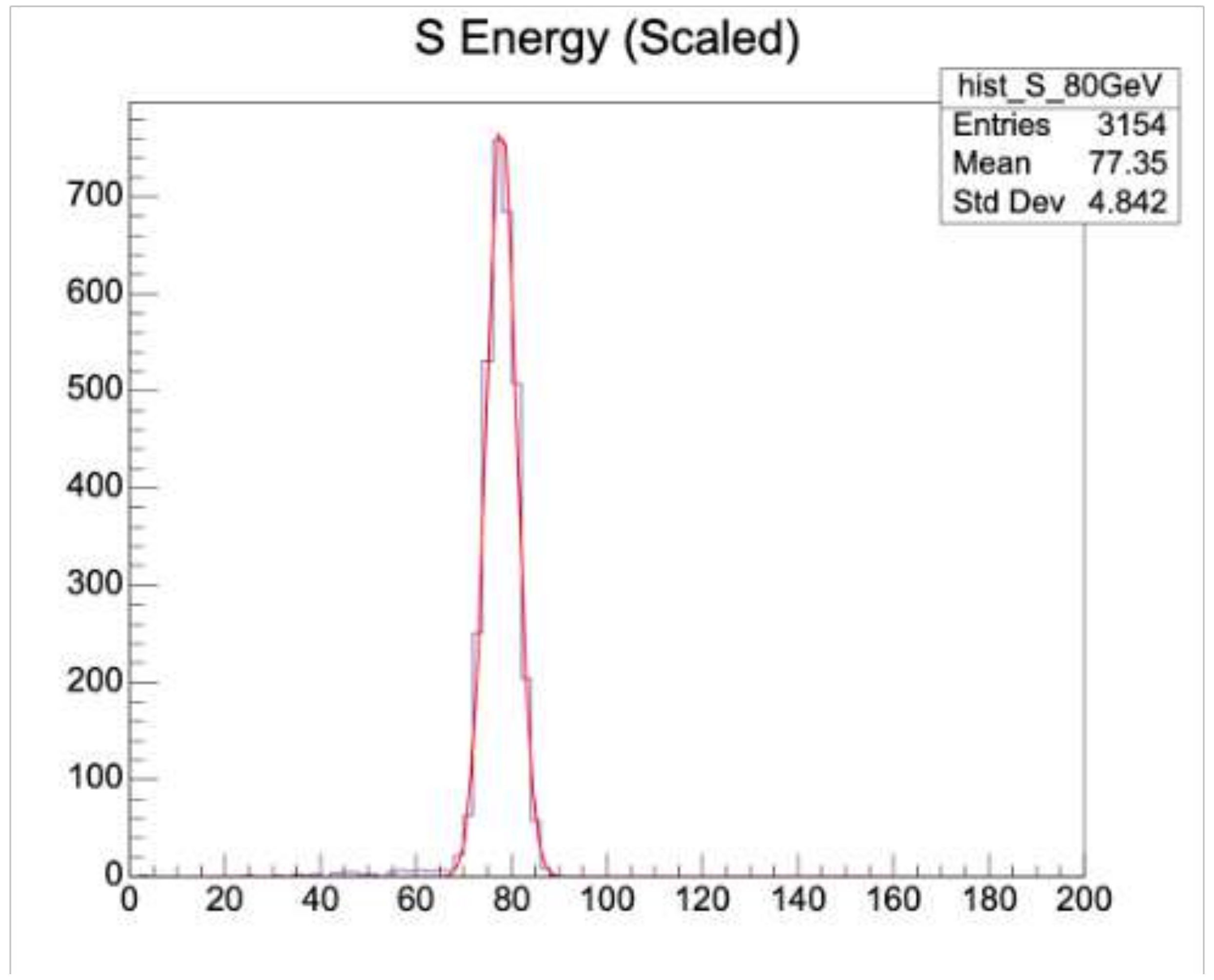
Energy Distribution : 80 GeV

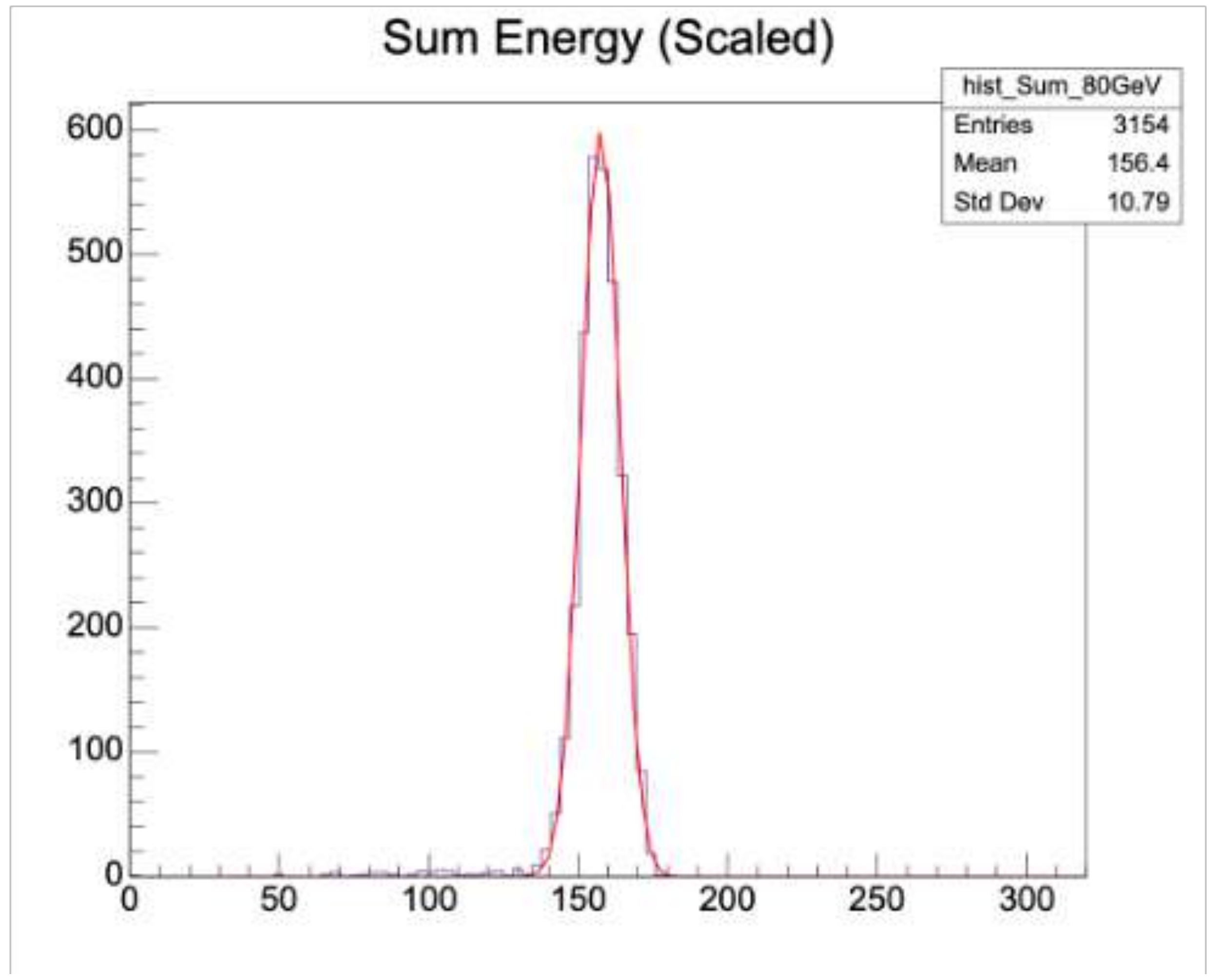






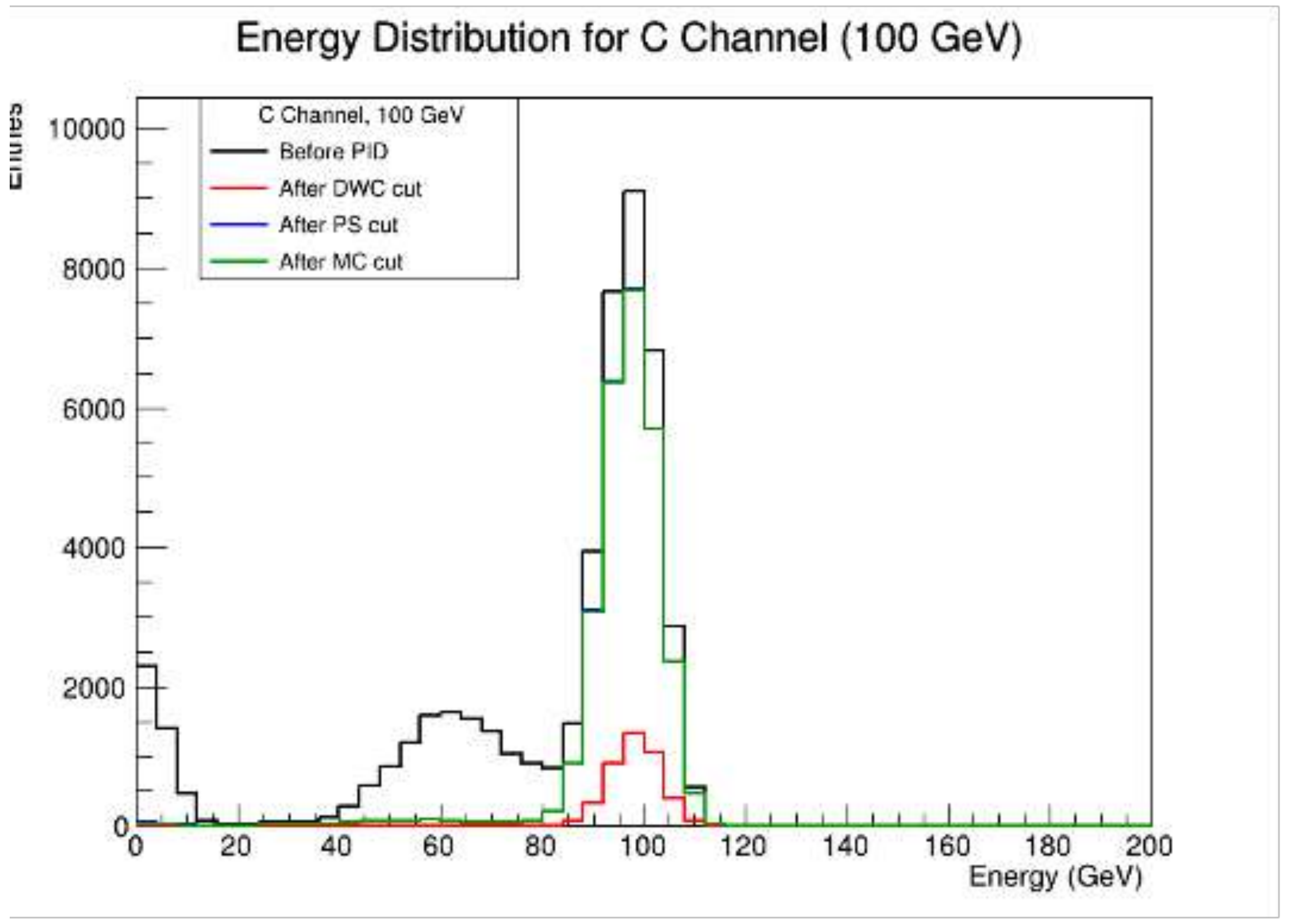


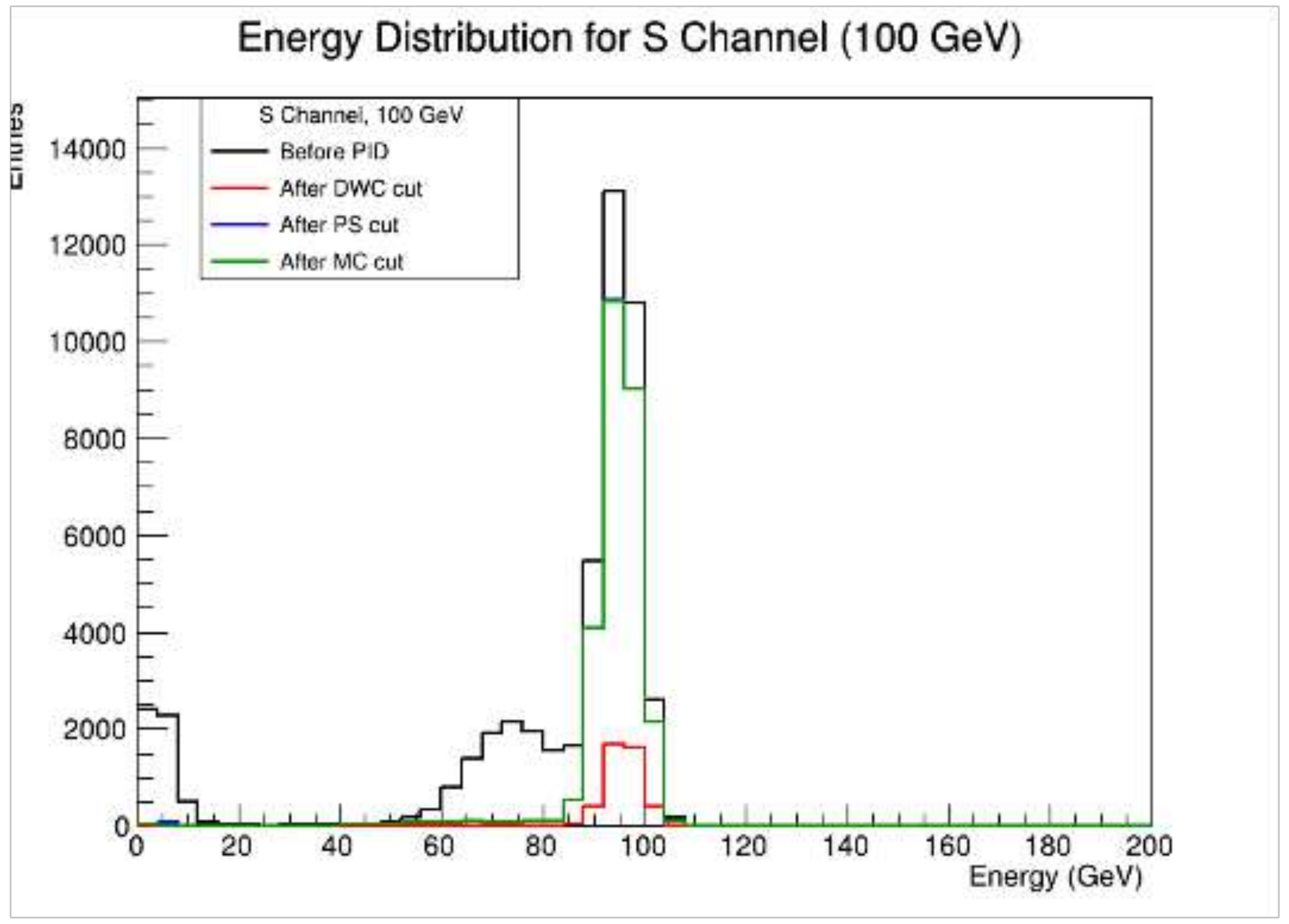


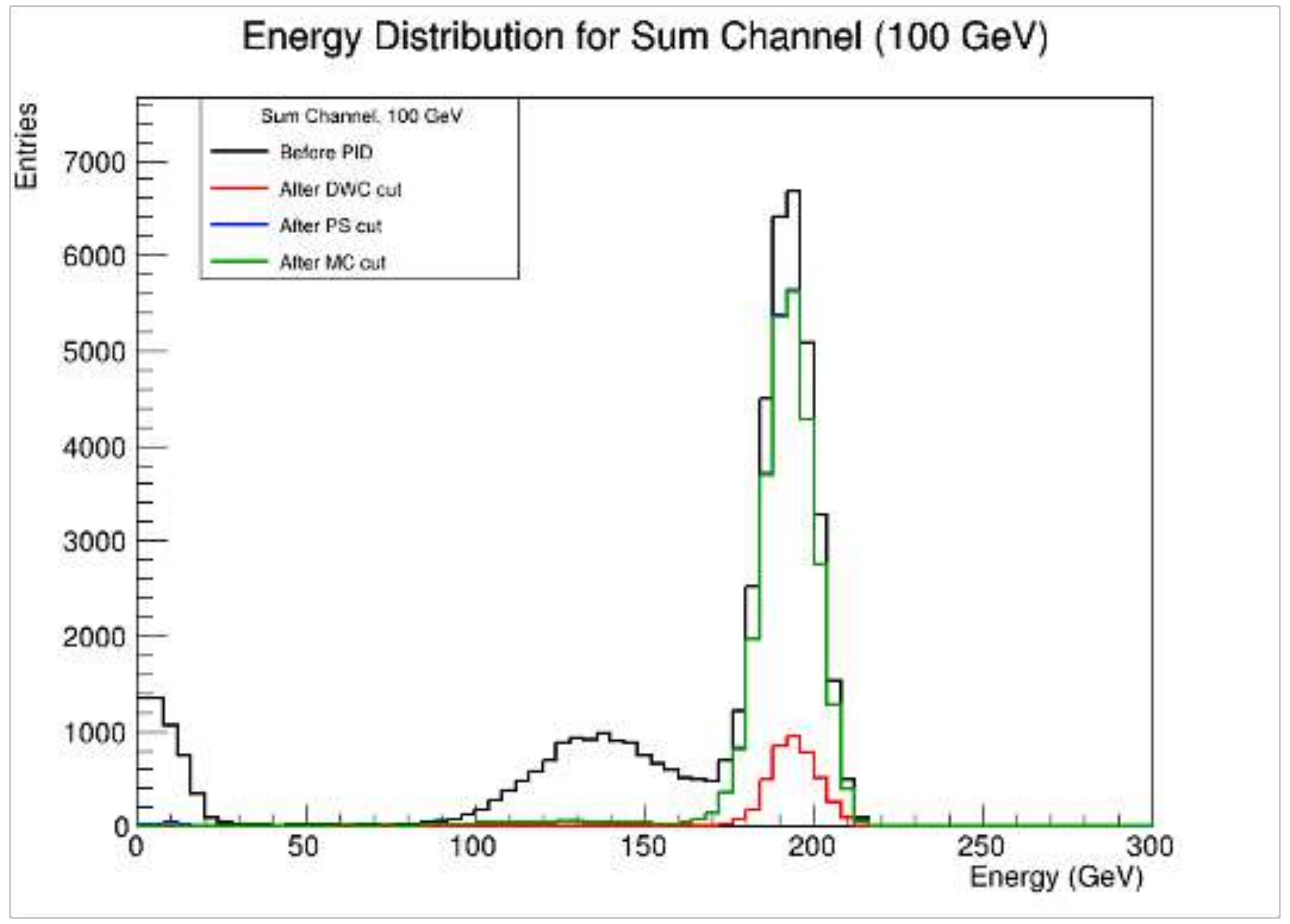


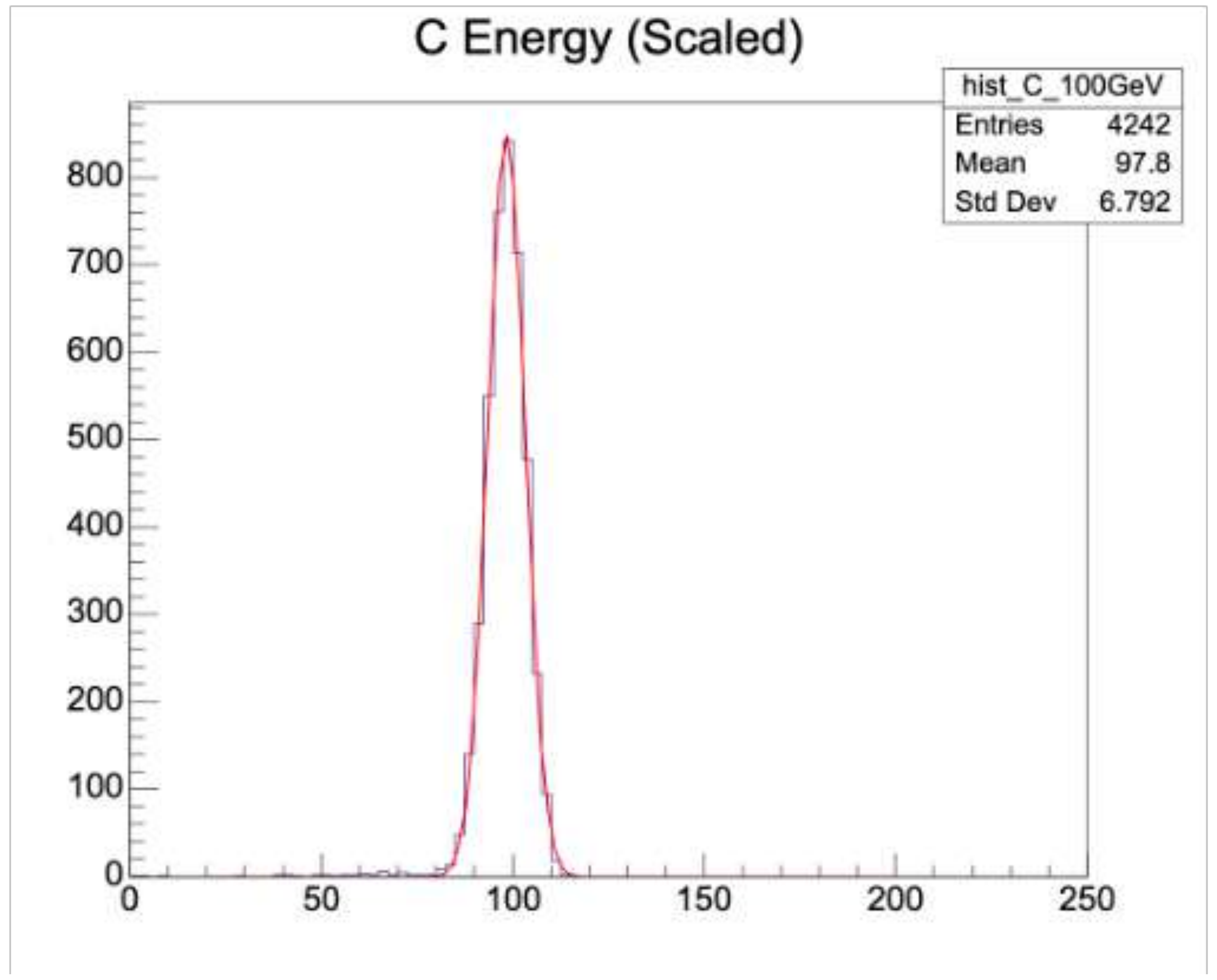
EM Performance

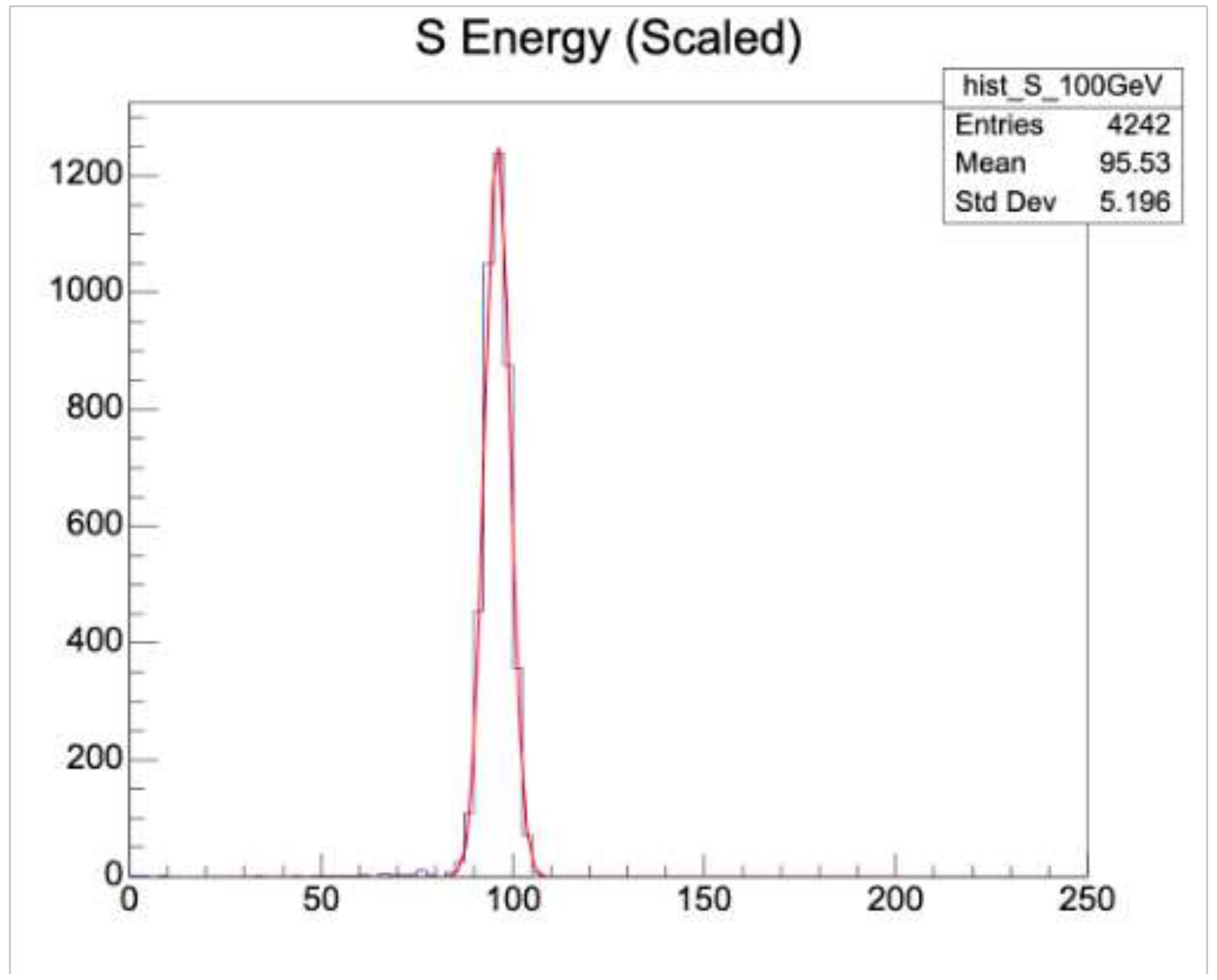
Energy Distribution : 100 GeV

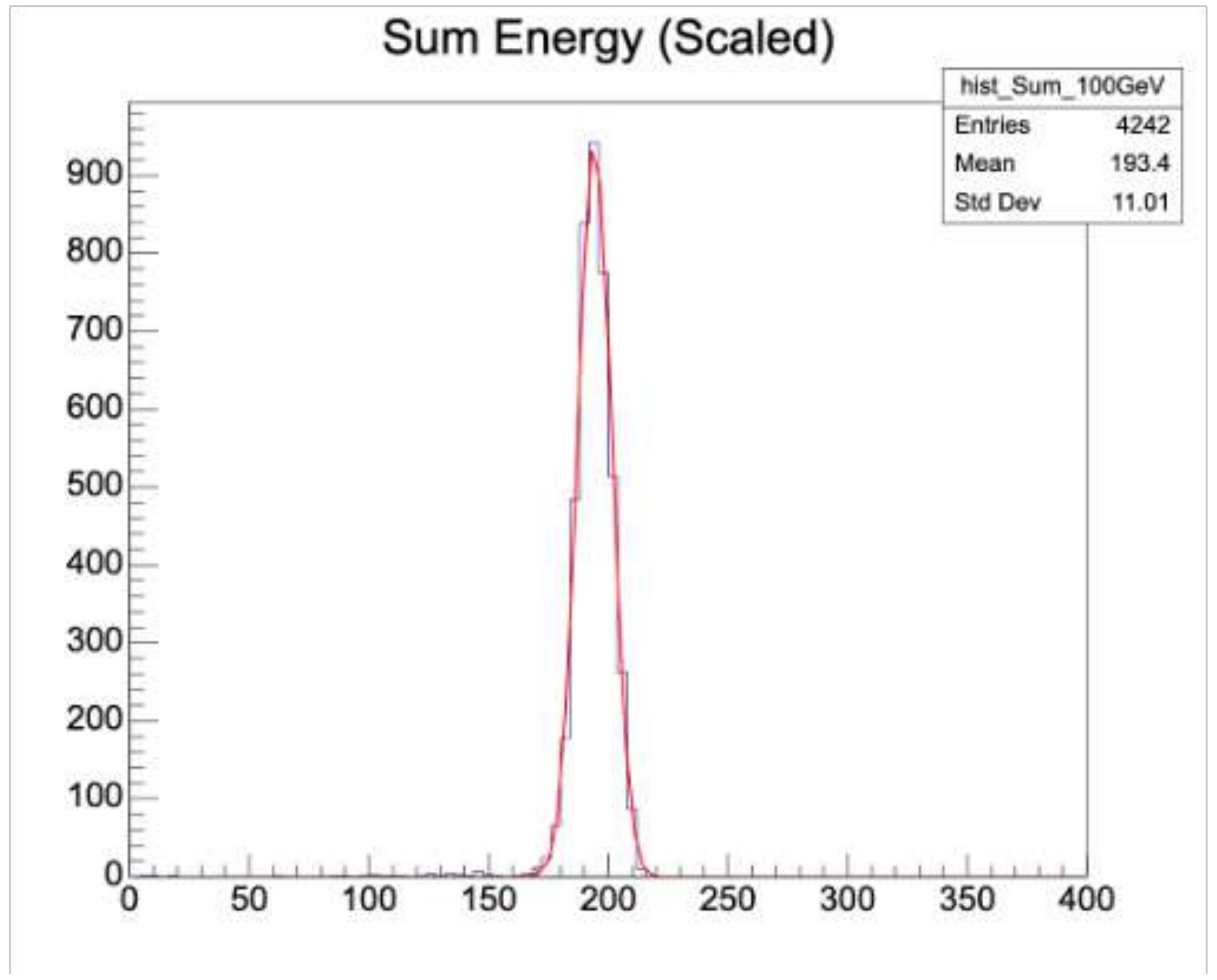




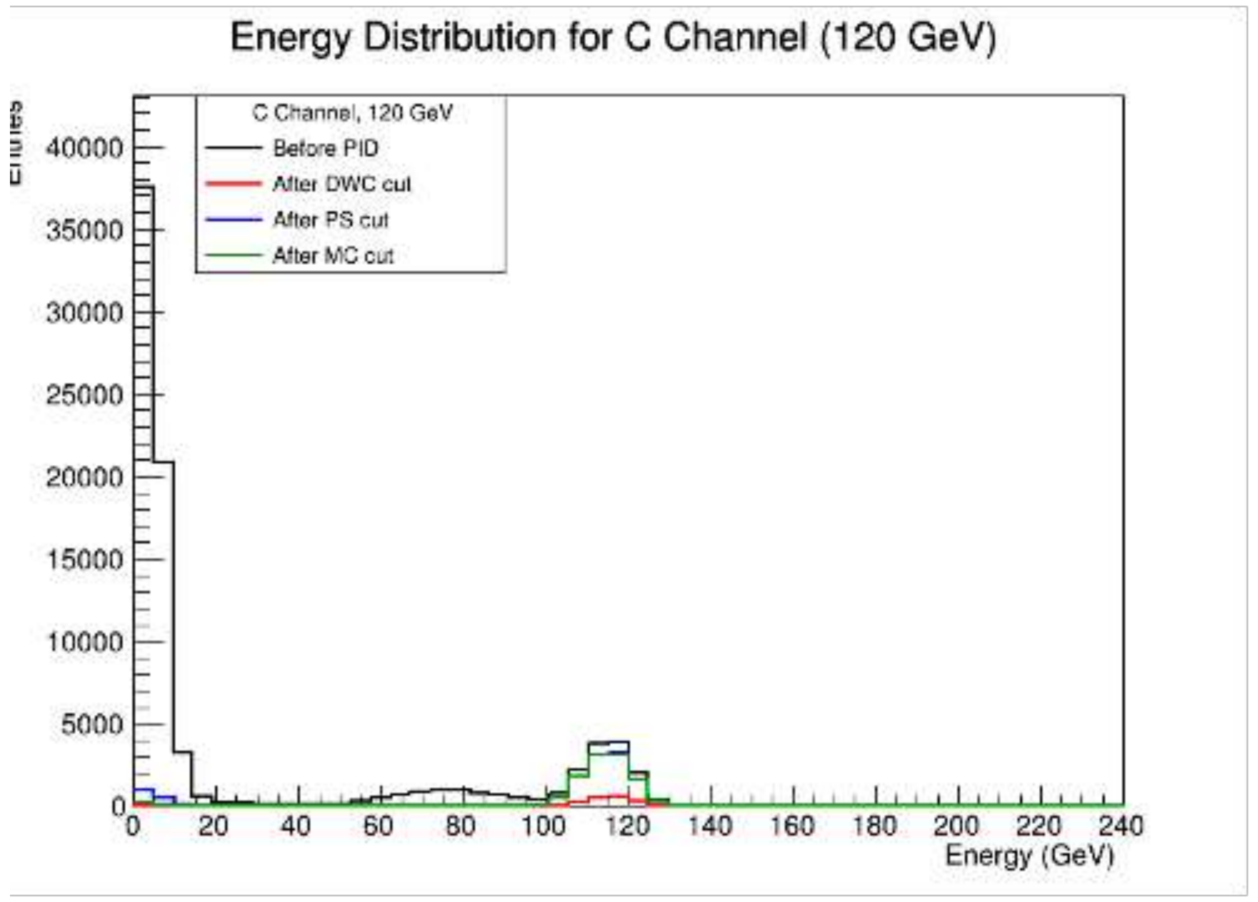


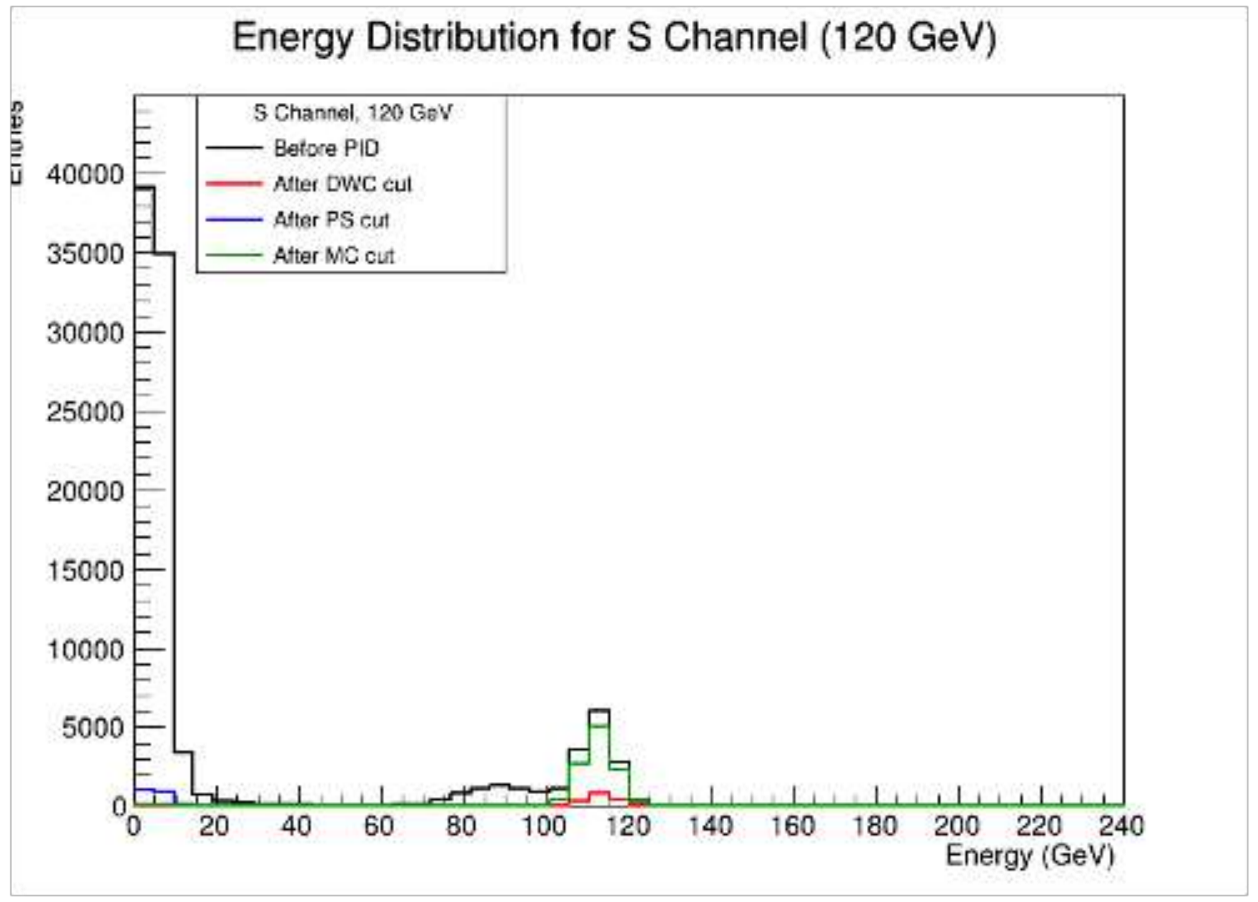


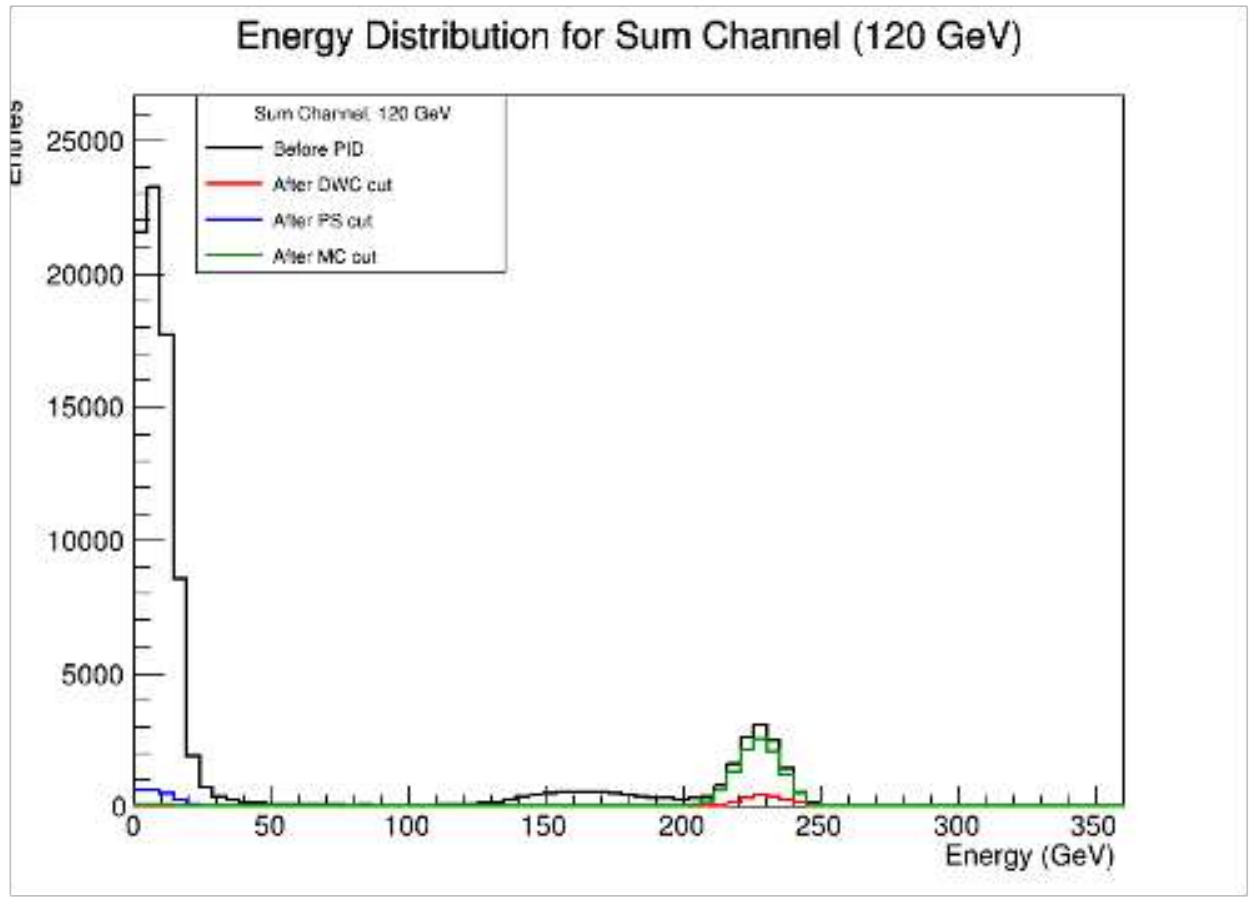


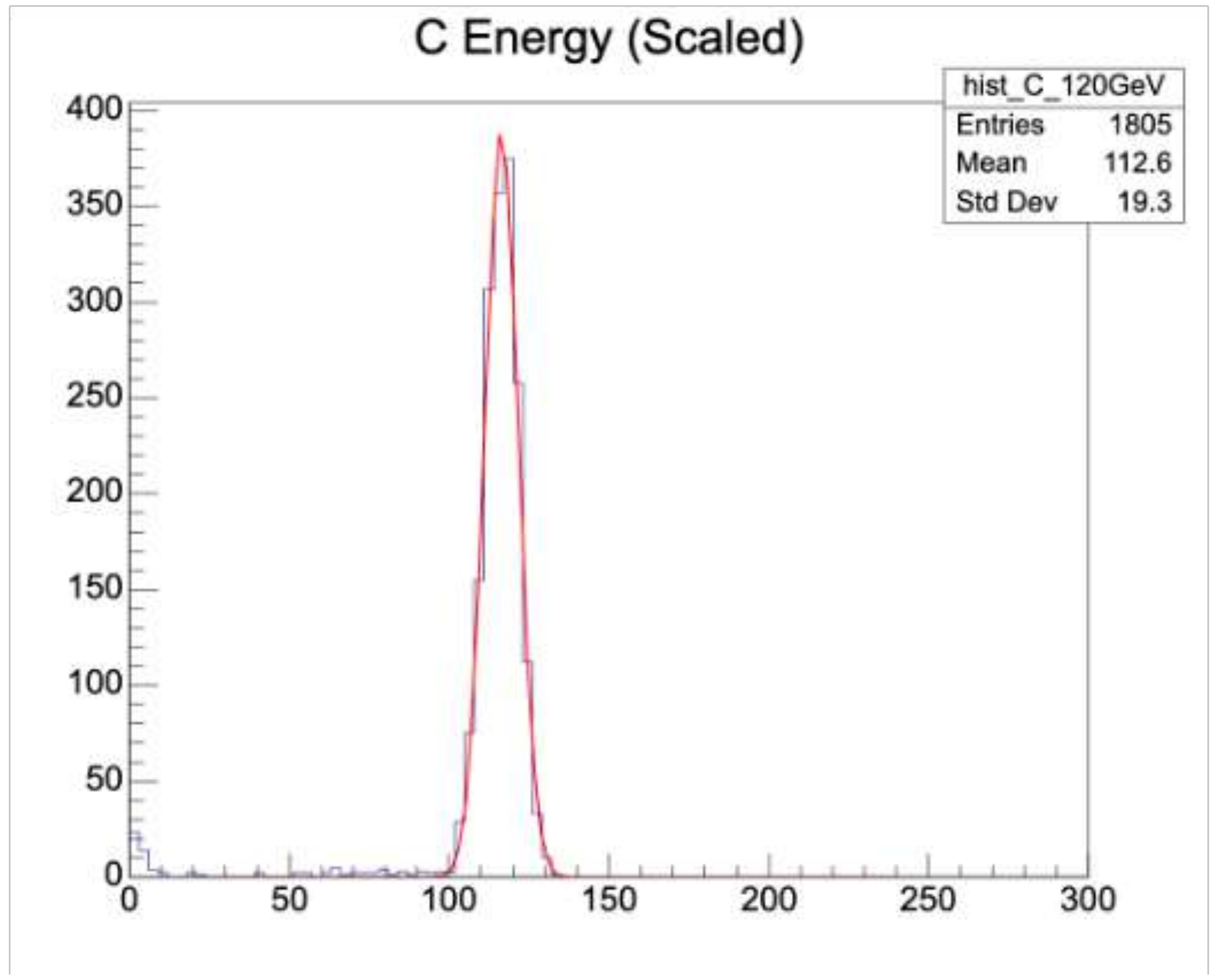


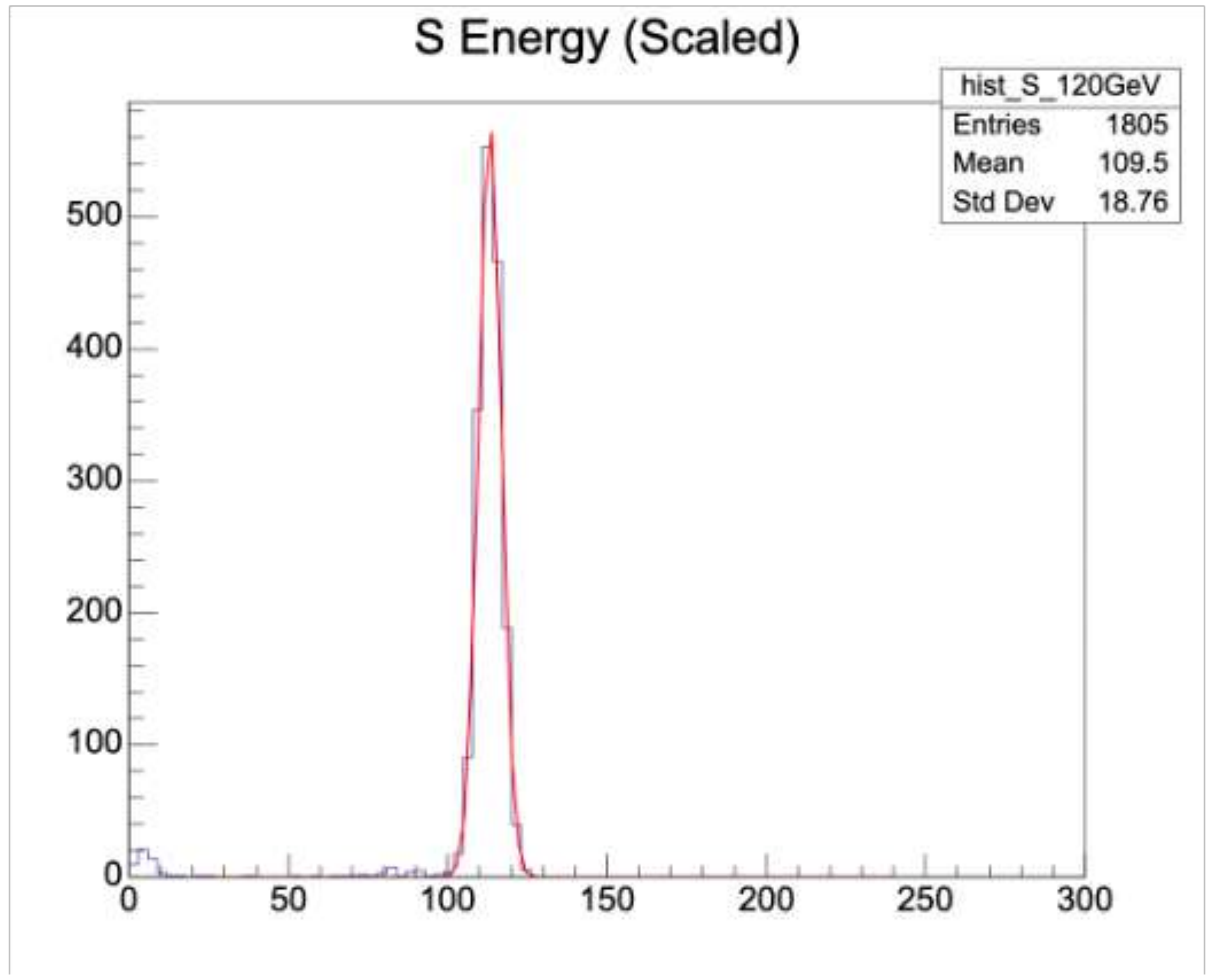
EM Performance
Energy Distribution : 120 GeV

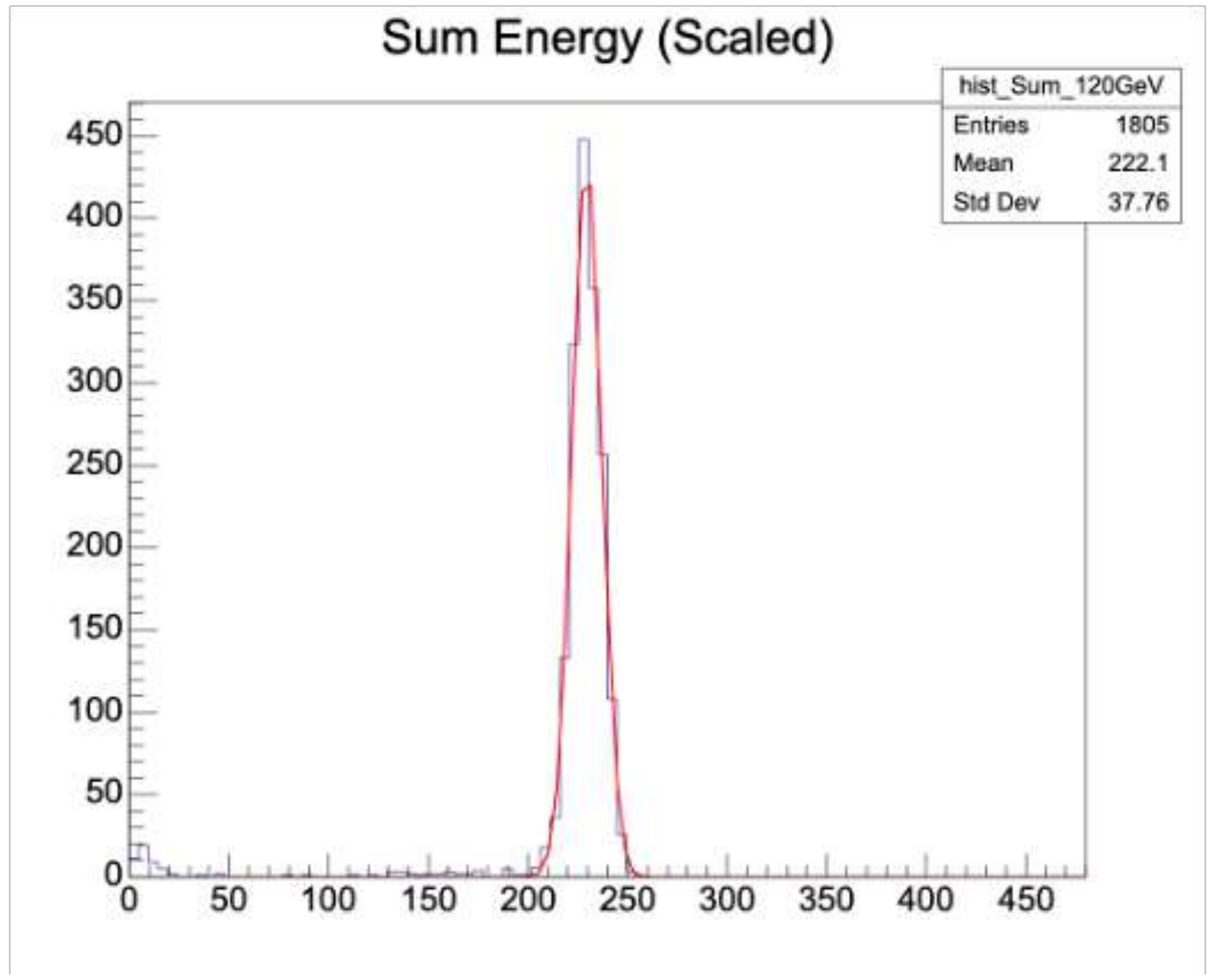








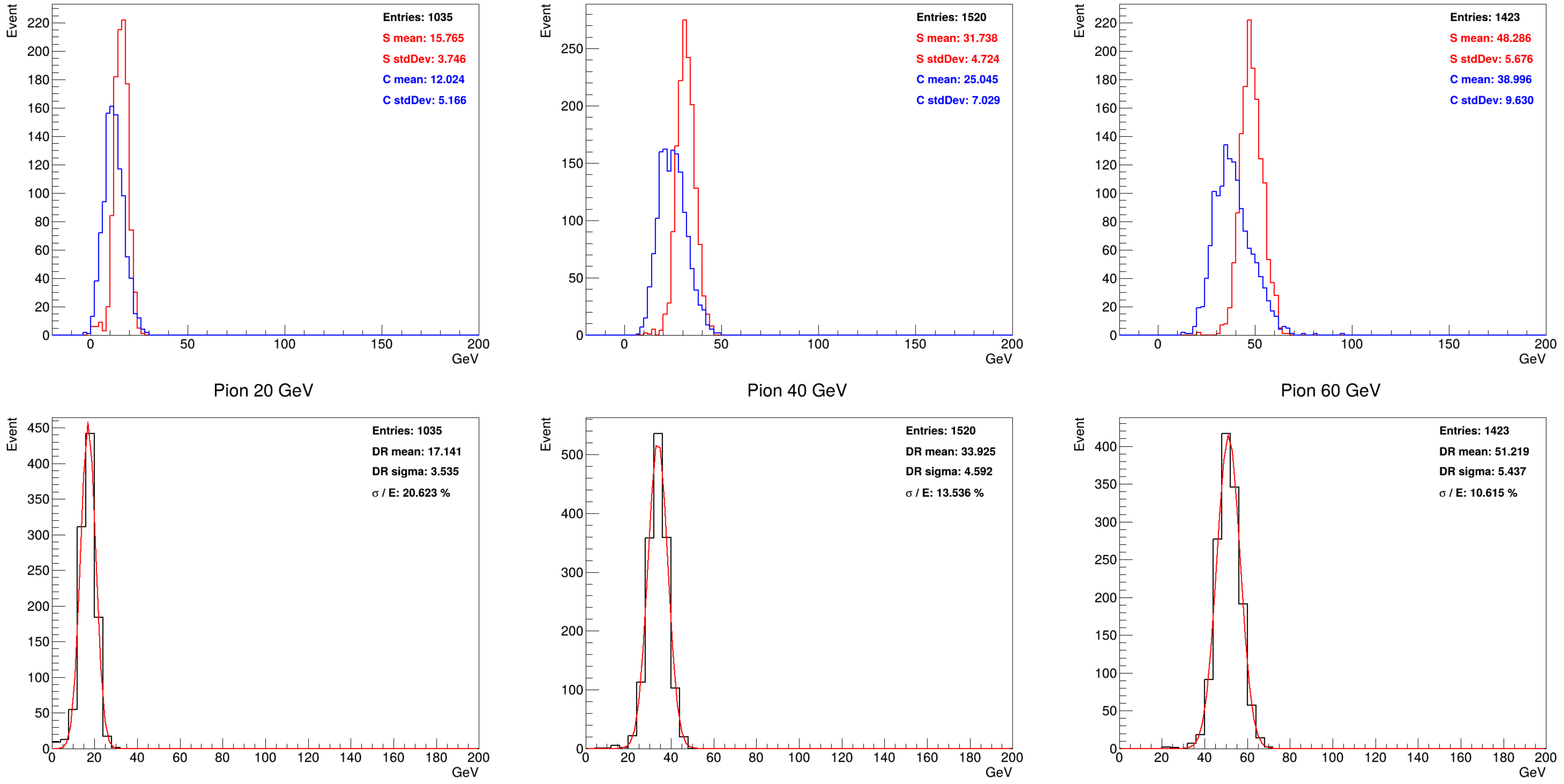




Hadronic Performance

Energy Distribution : Pion 20, 40, 60 GeV

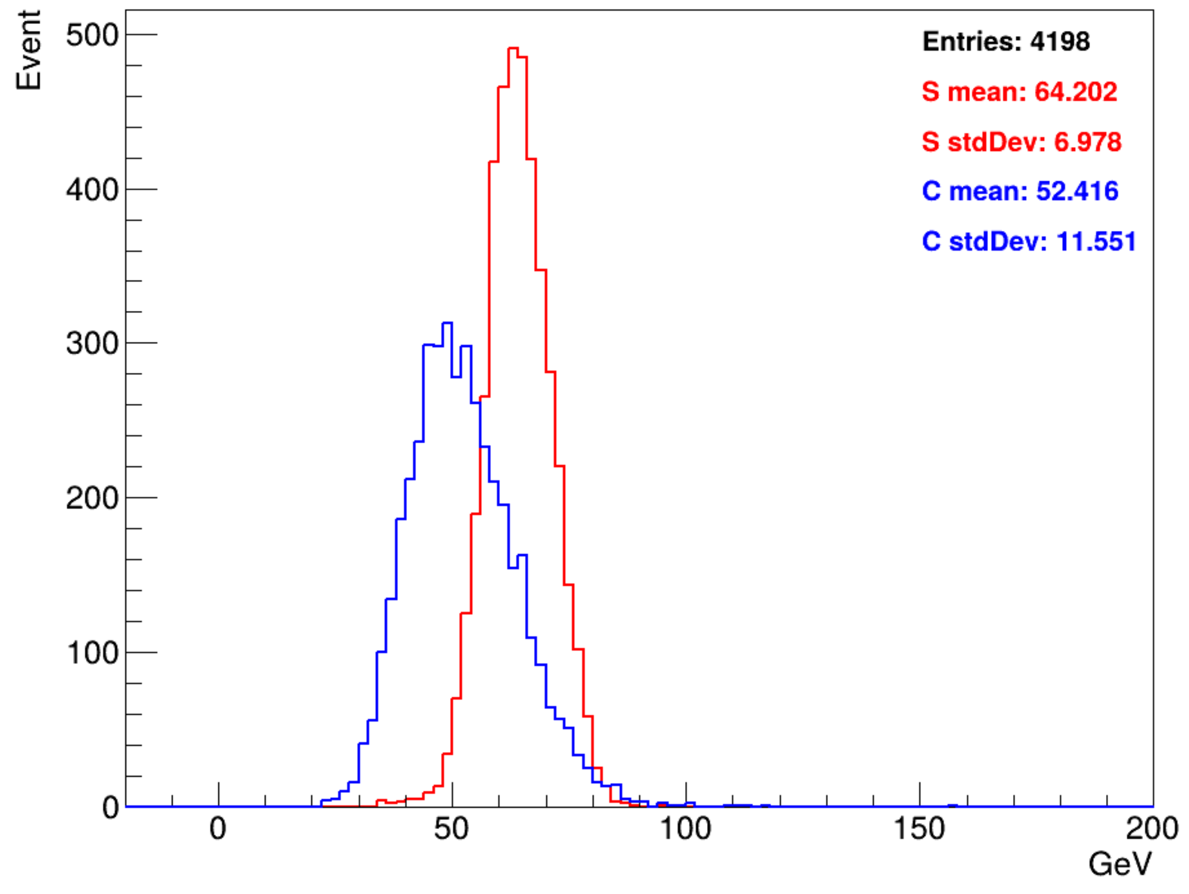
20 GeV	40 GeV	60 GeV

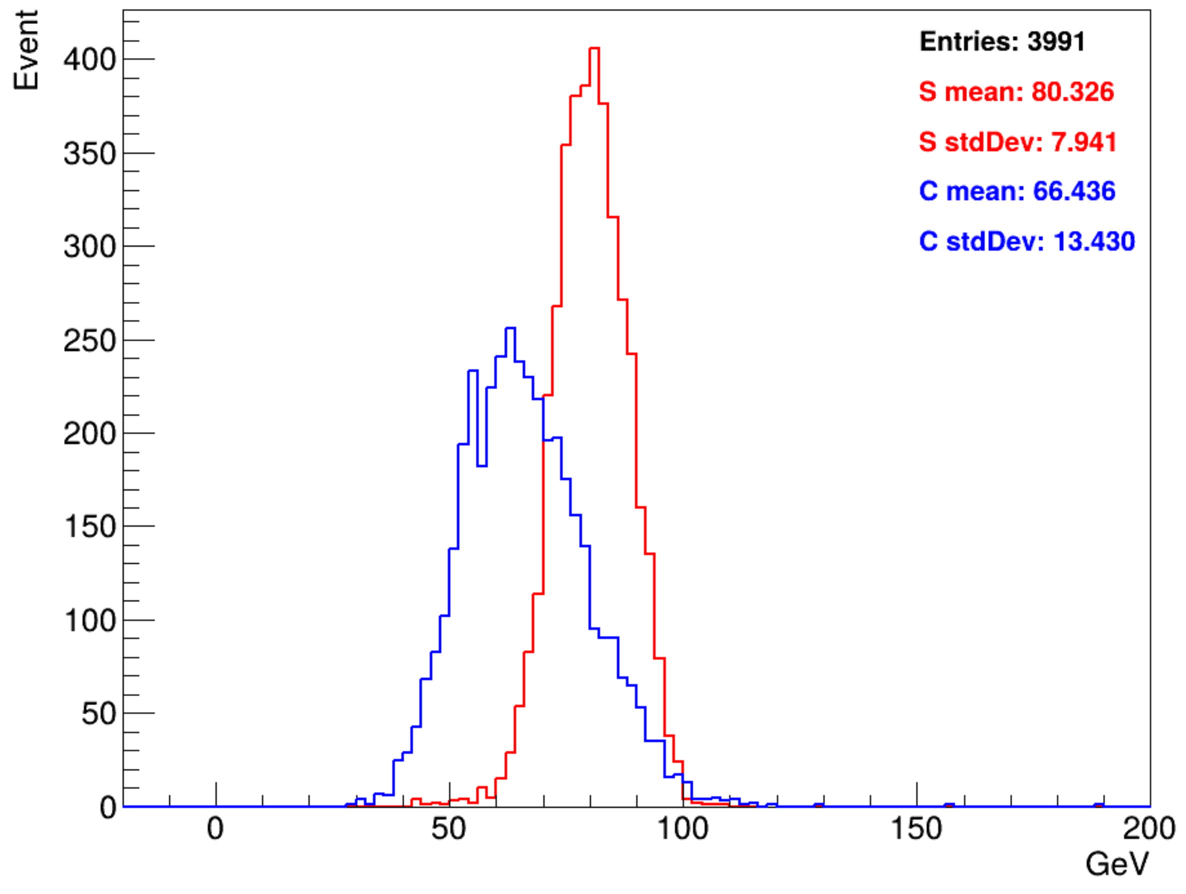


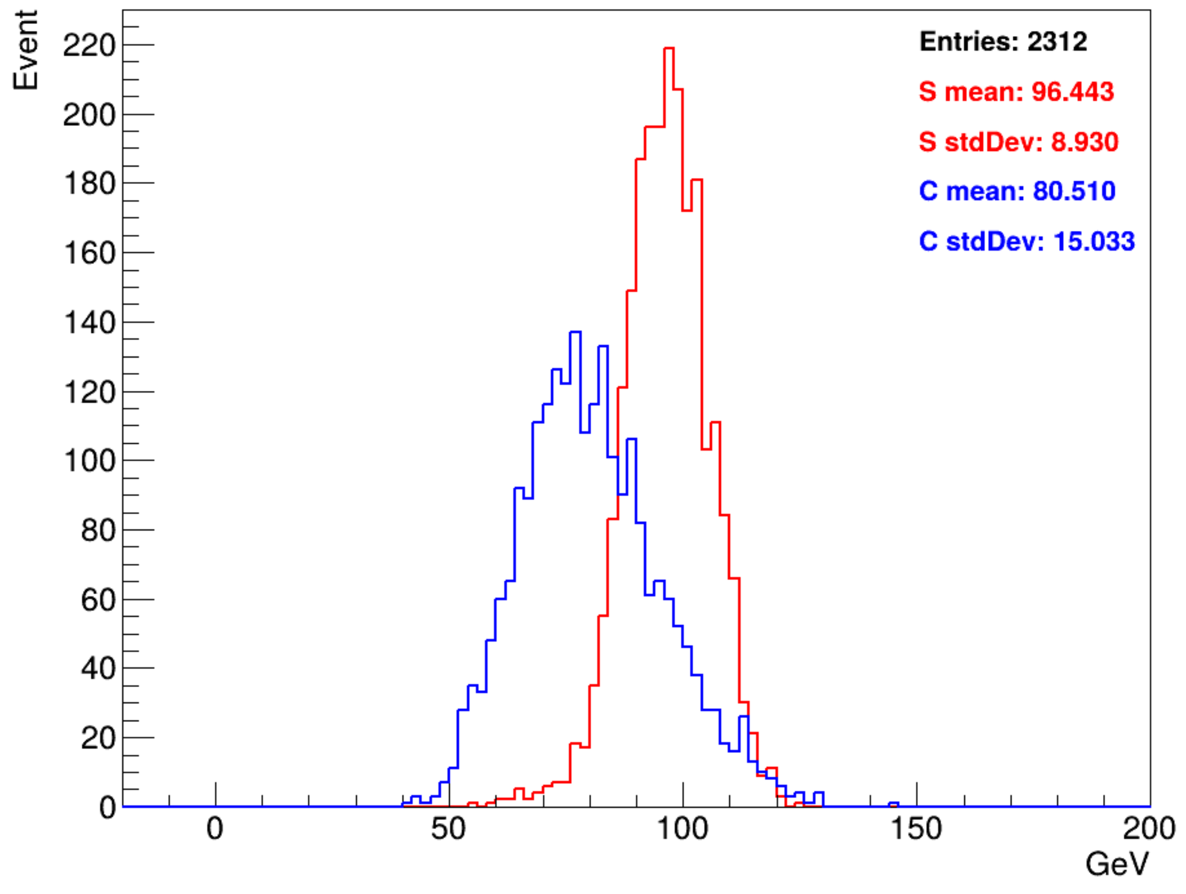
Hadronic Performance

Energy Distribution : Pion 80, 100, 120 GeV

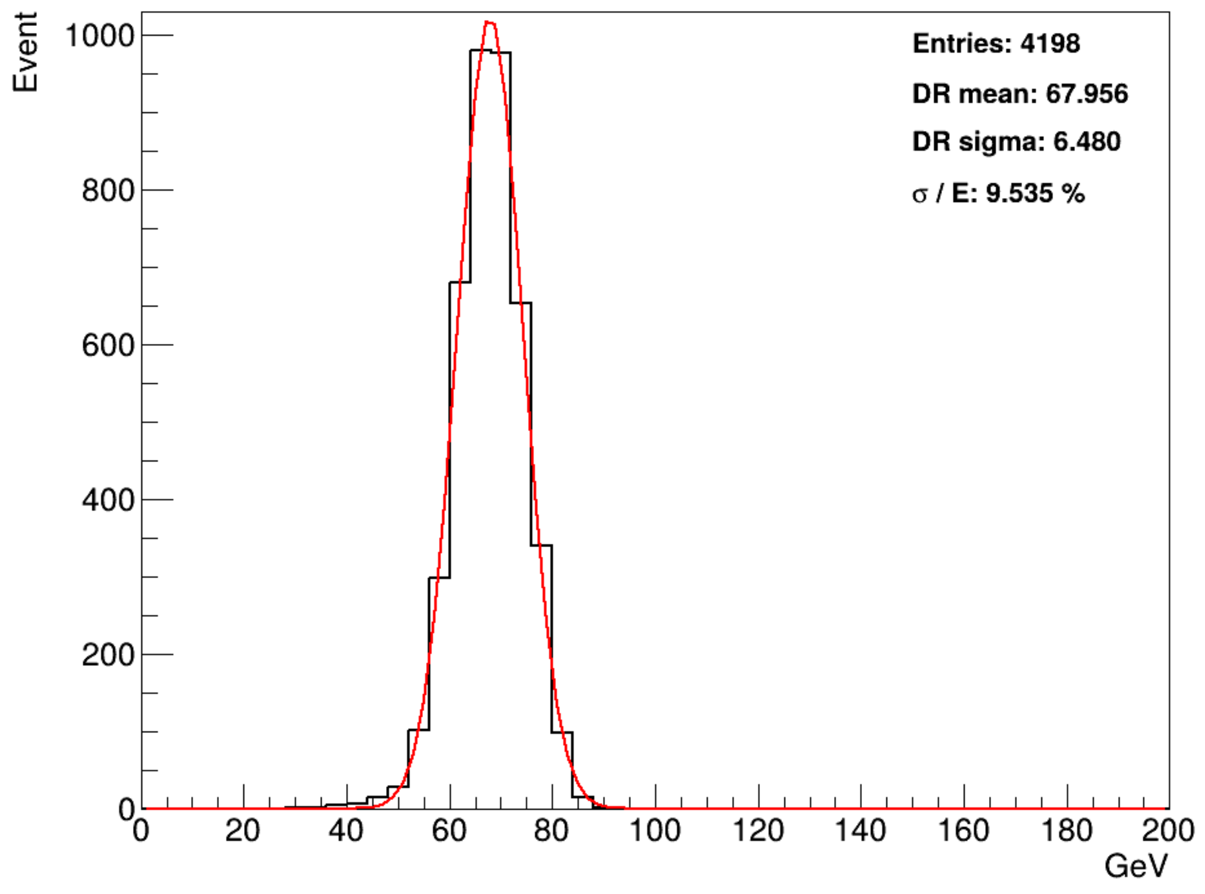
80 GeV	100 GeV	120 GeV



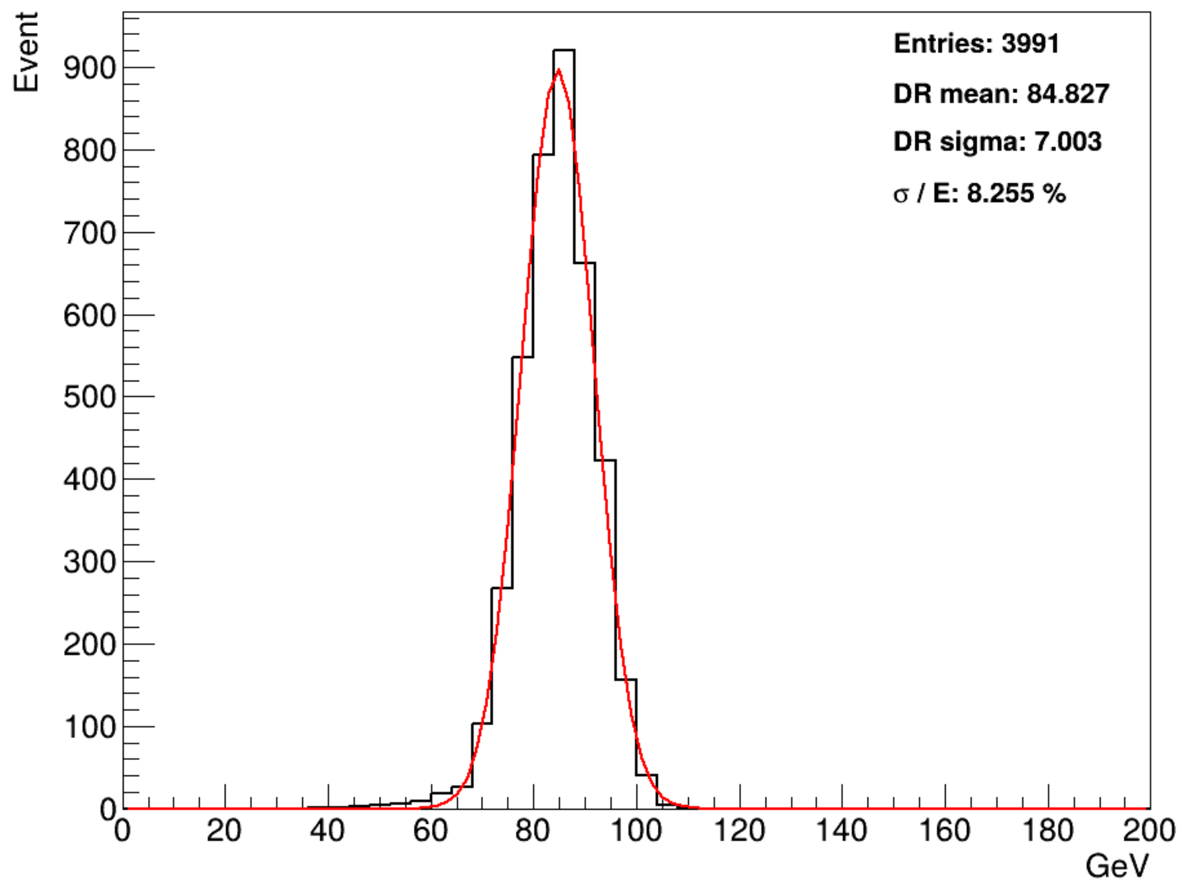




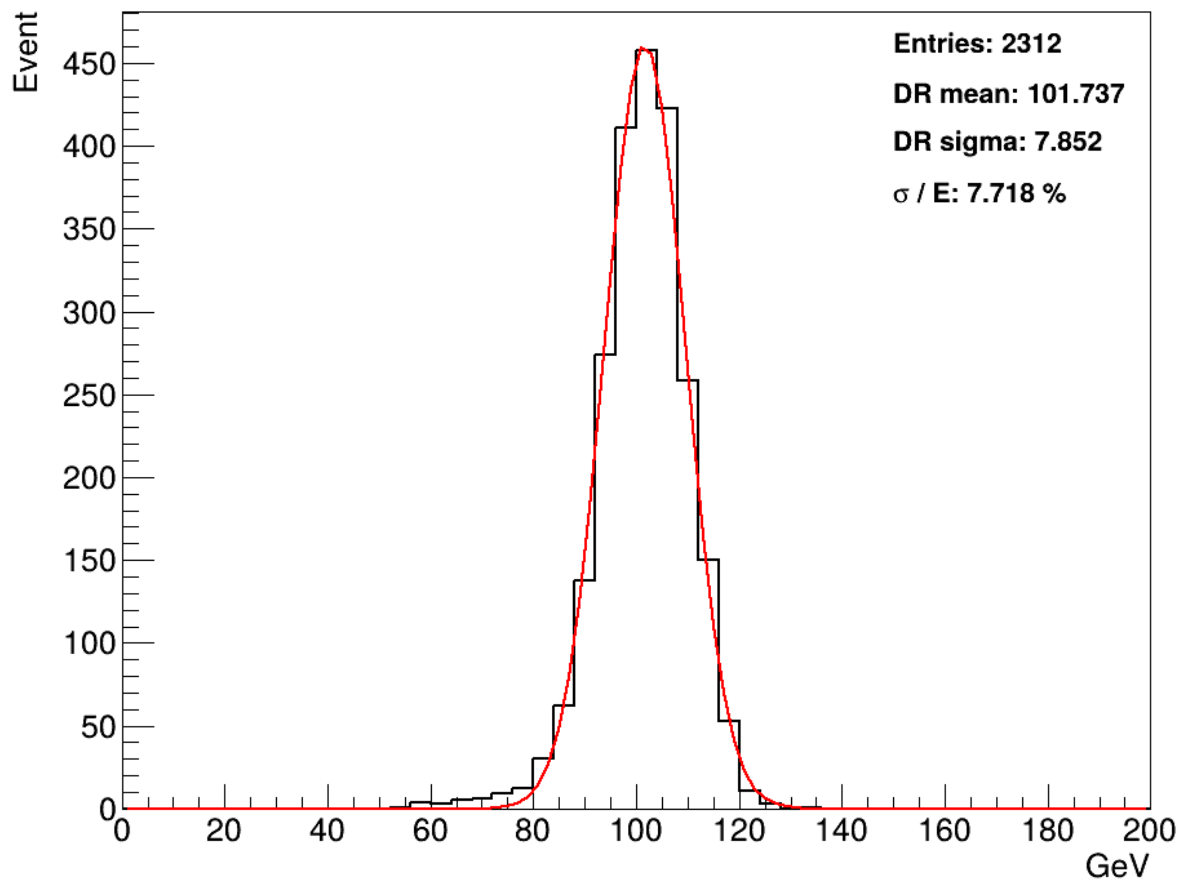
Pion 80 GeV



Pion 100 GeV



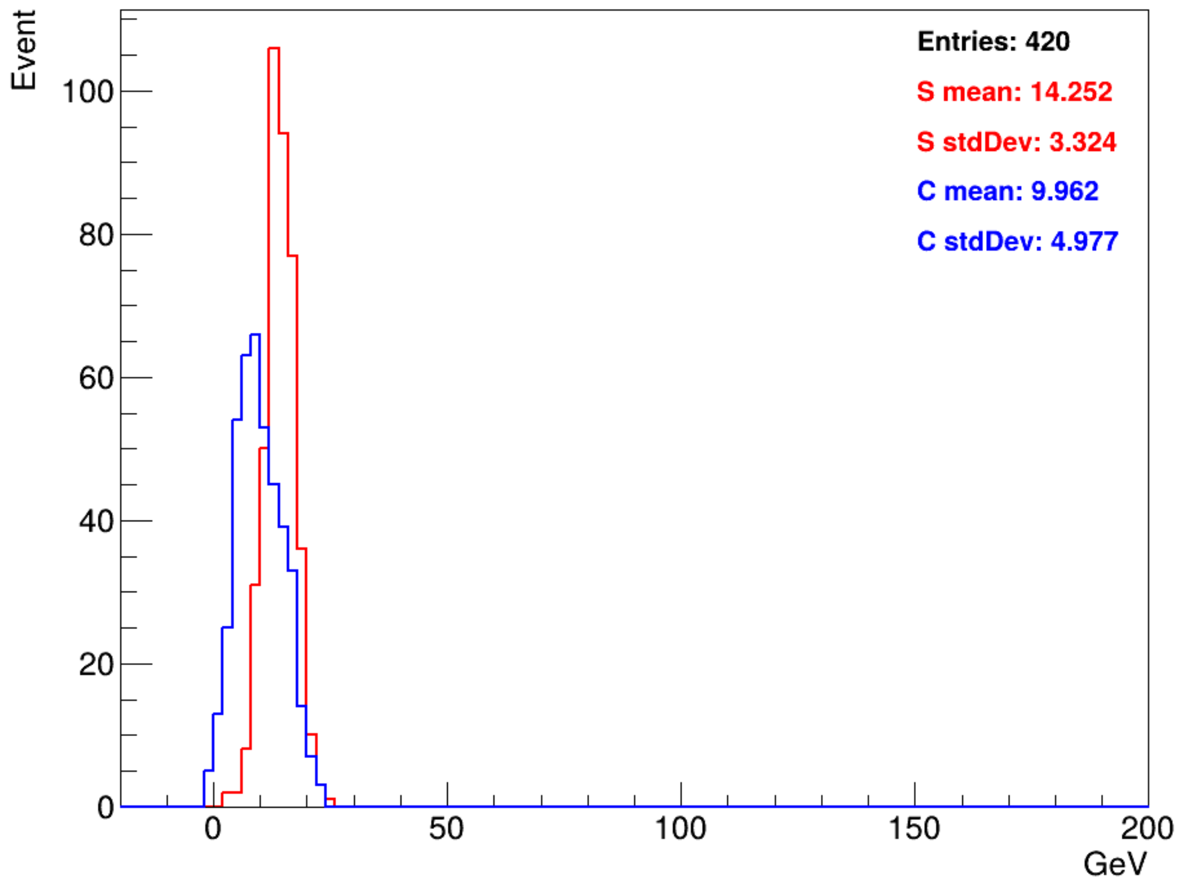
Pion 120 GeV

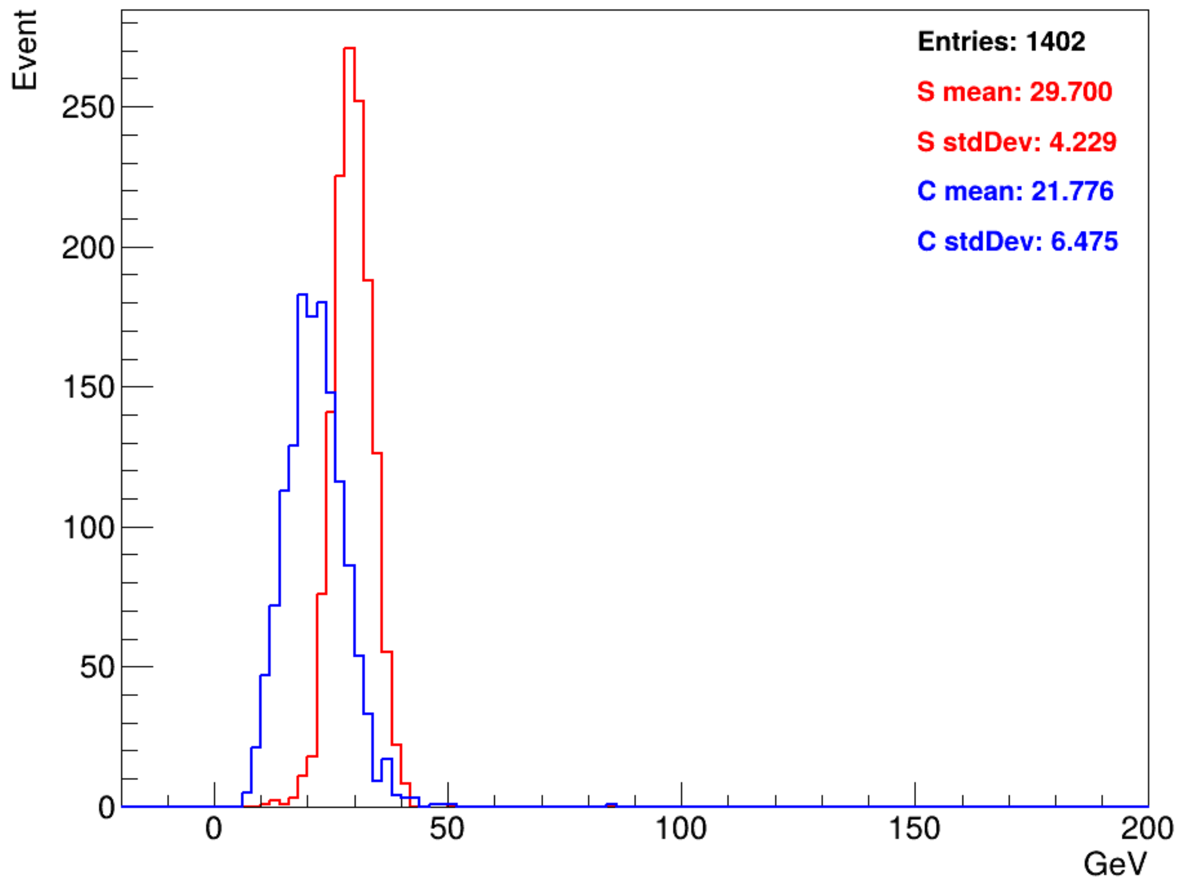


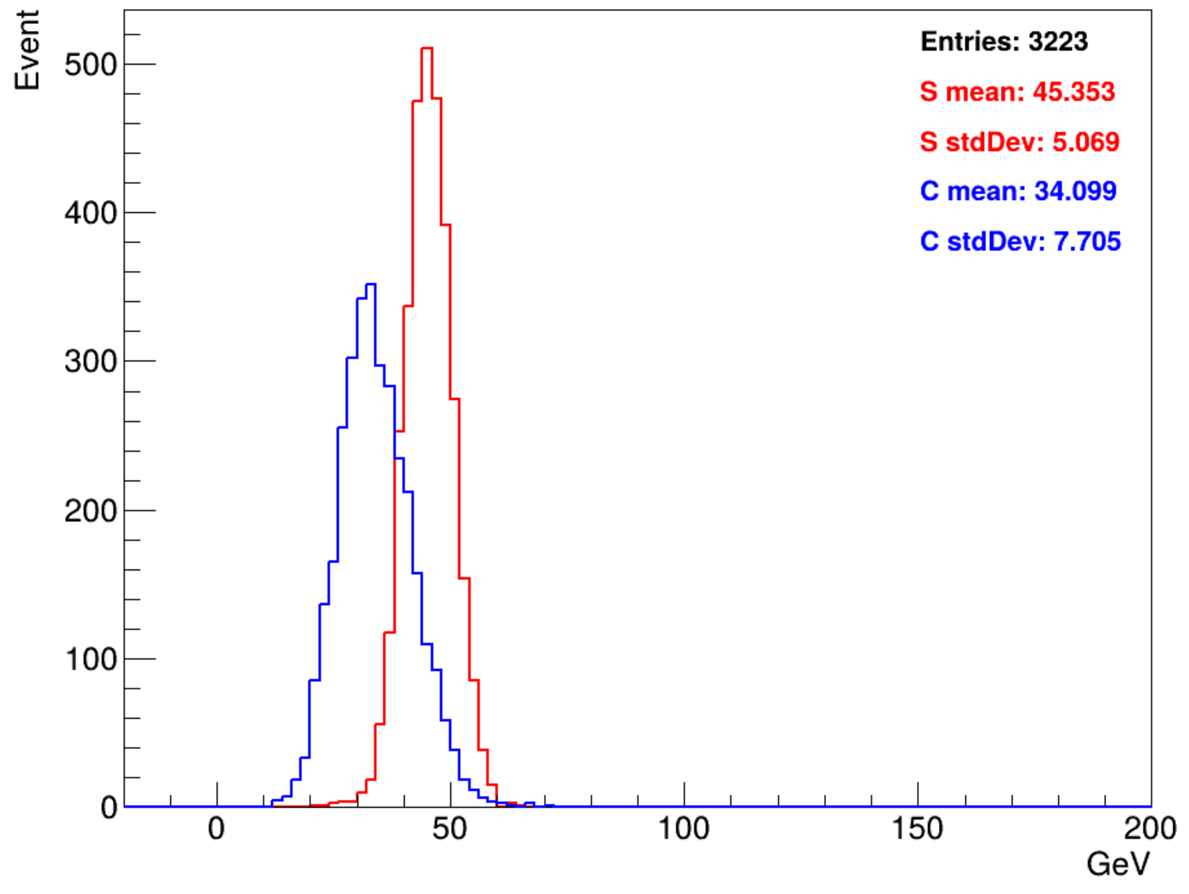
Hadronic Performance

Energy Distribution : Proton 20, 40, 60 GeV

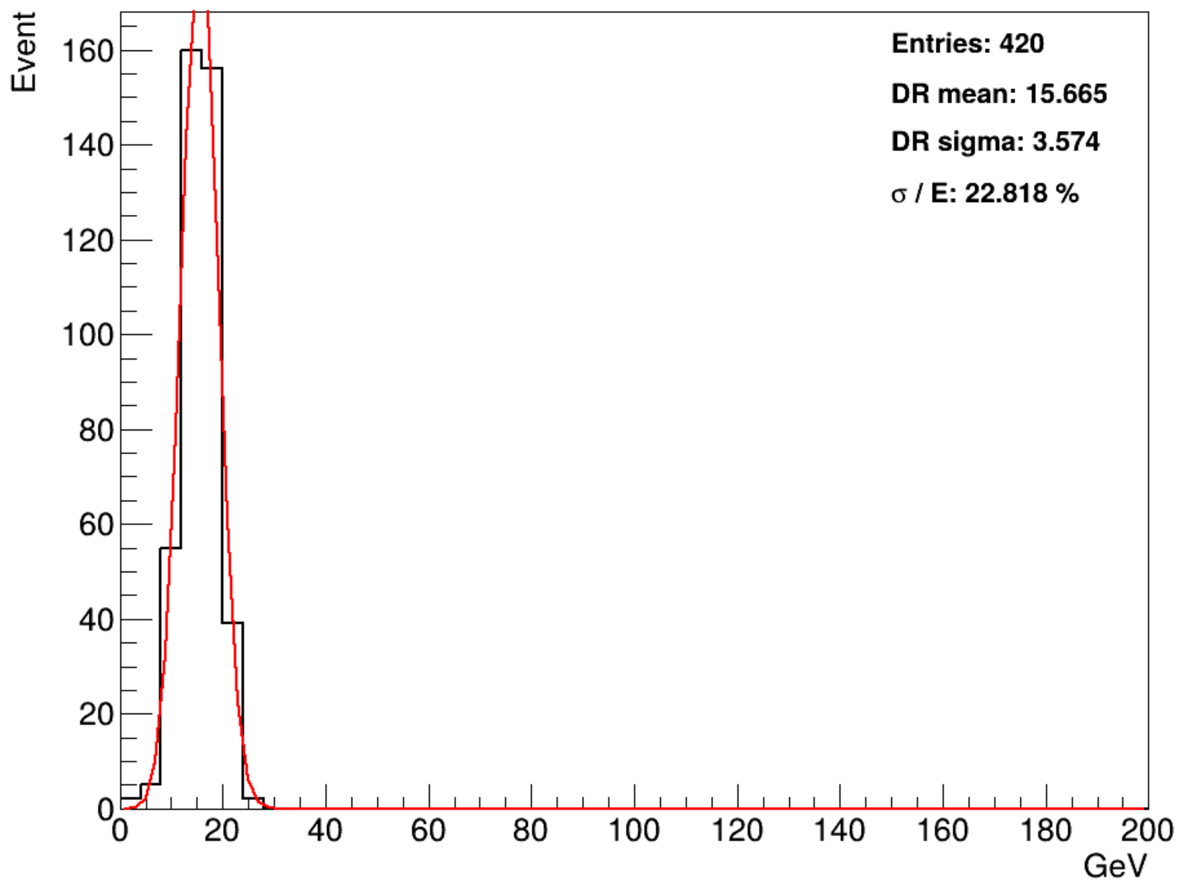
20 GeV	40 GeV	60 GeV



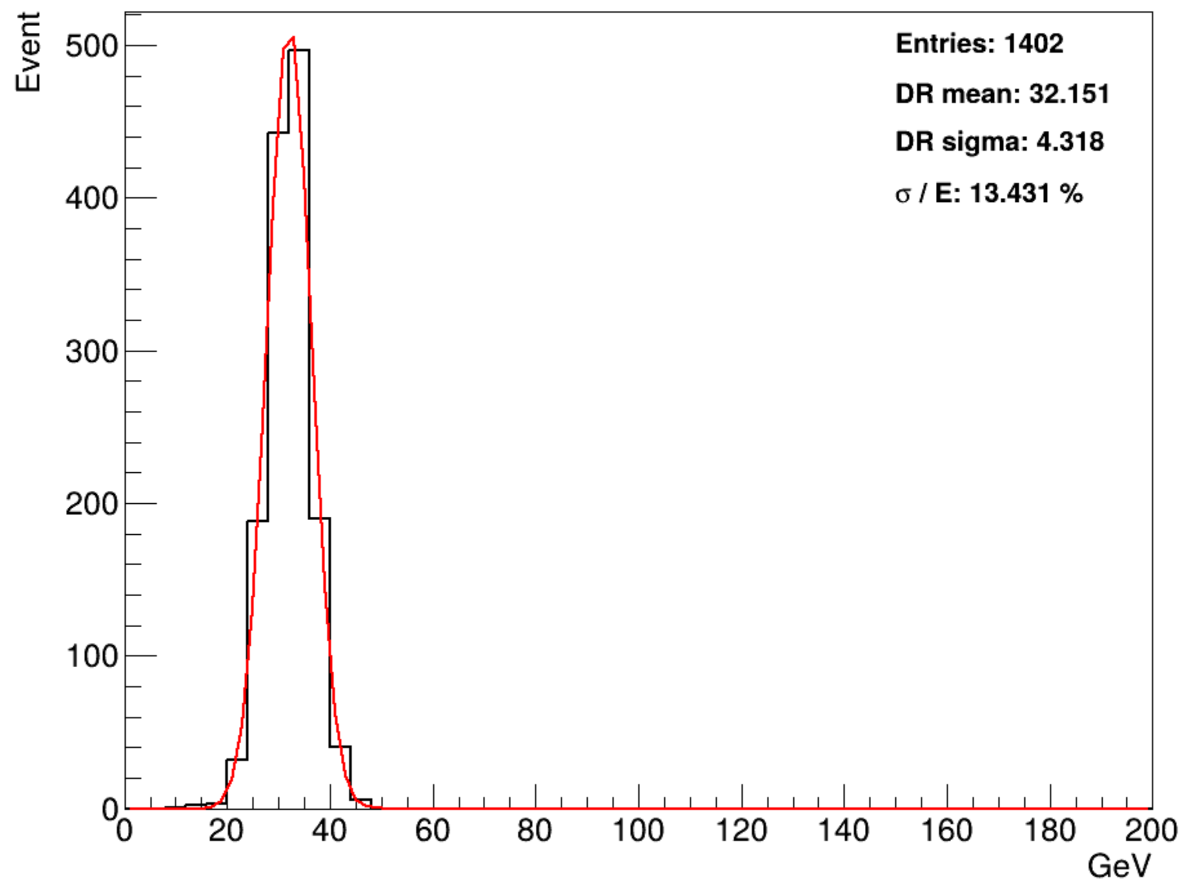




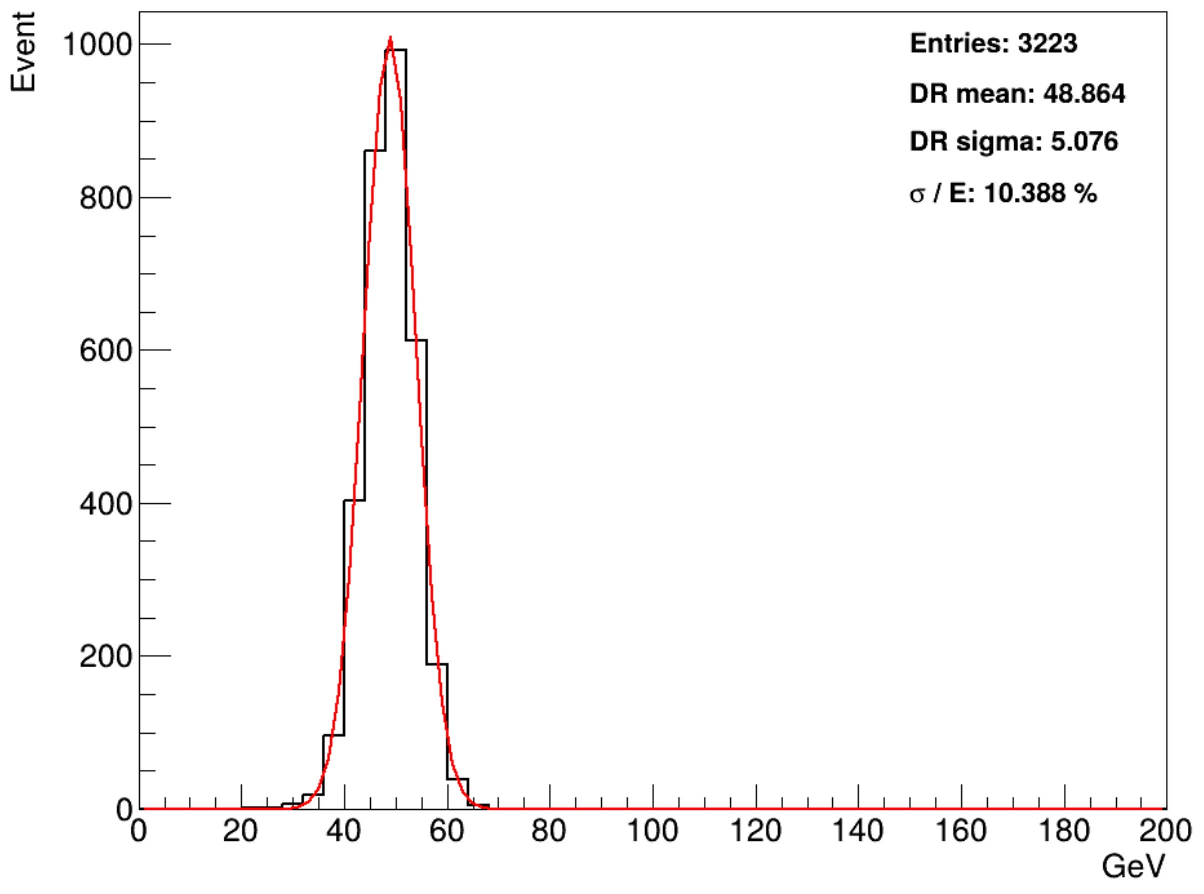
Proton 20 GeV



Proton 40 GeV

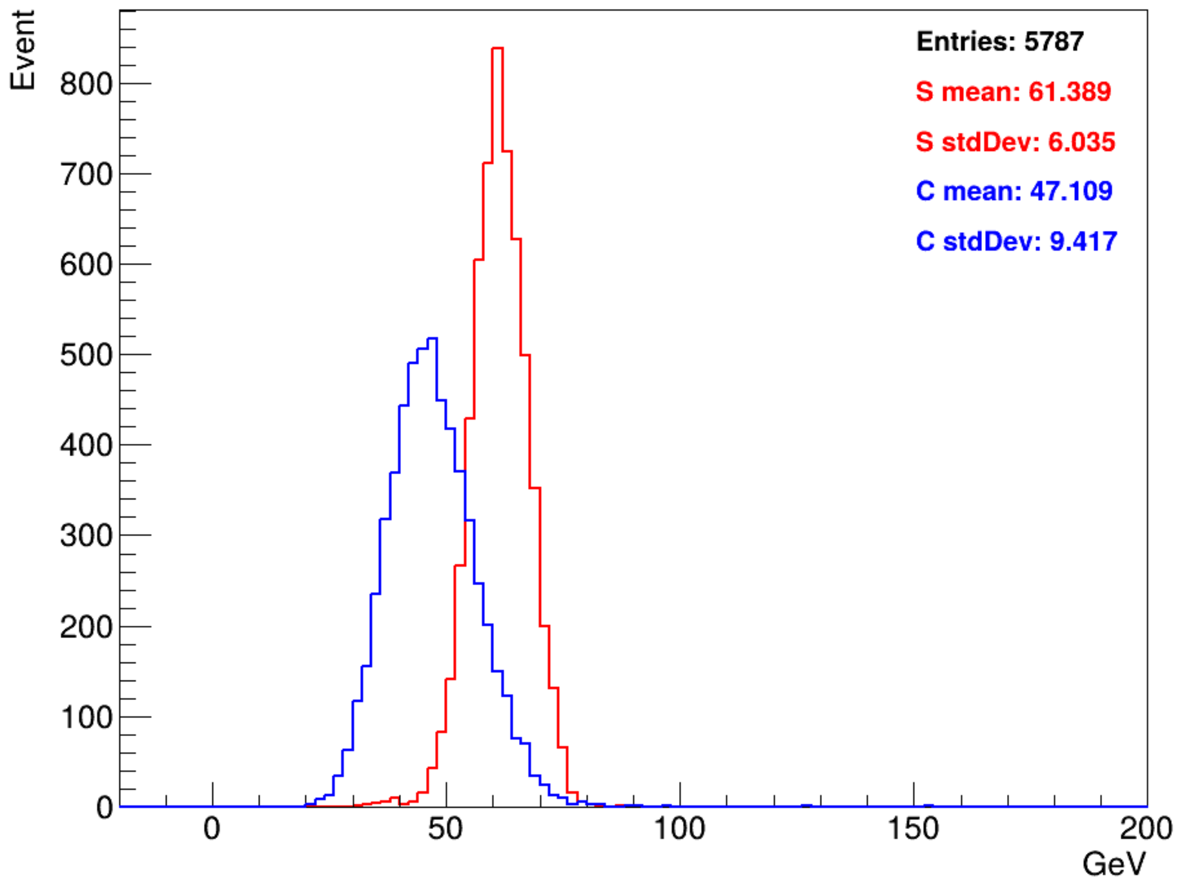


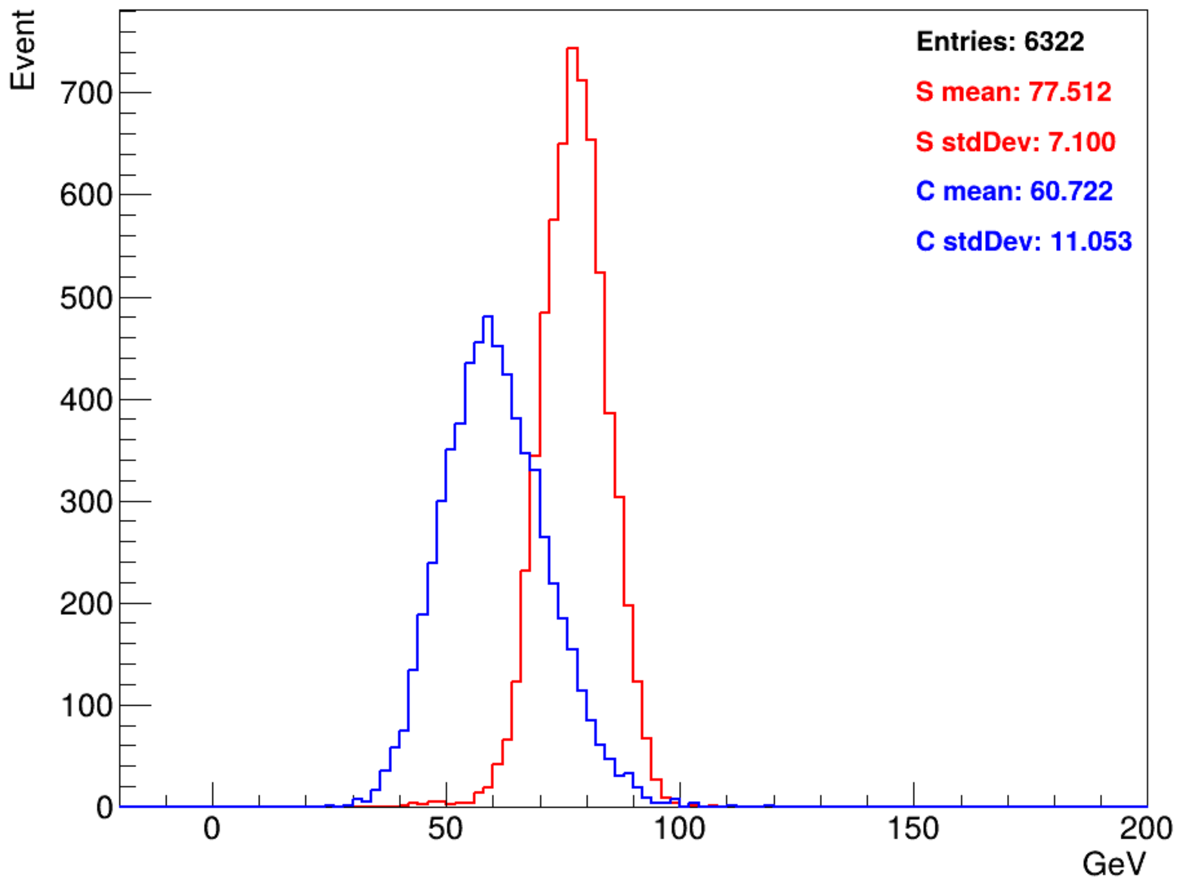
Proton 60 GeV

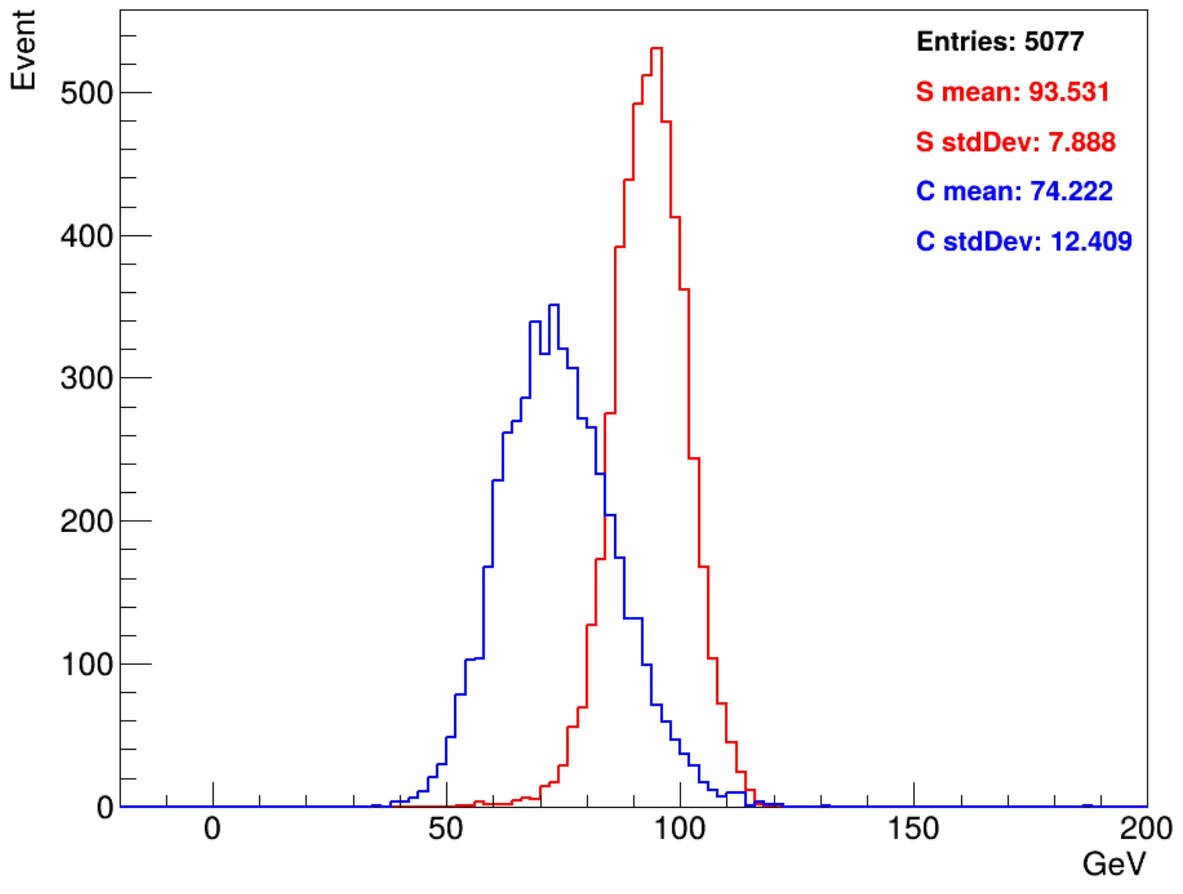


Hadronic Performance
Energy Distribution : Proton 80, 100, 120 GeV

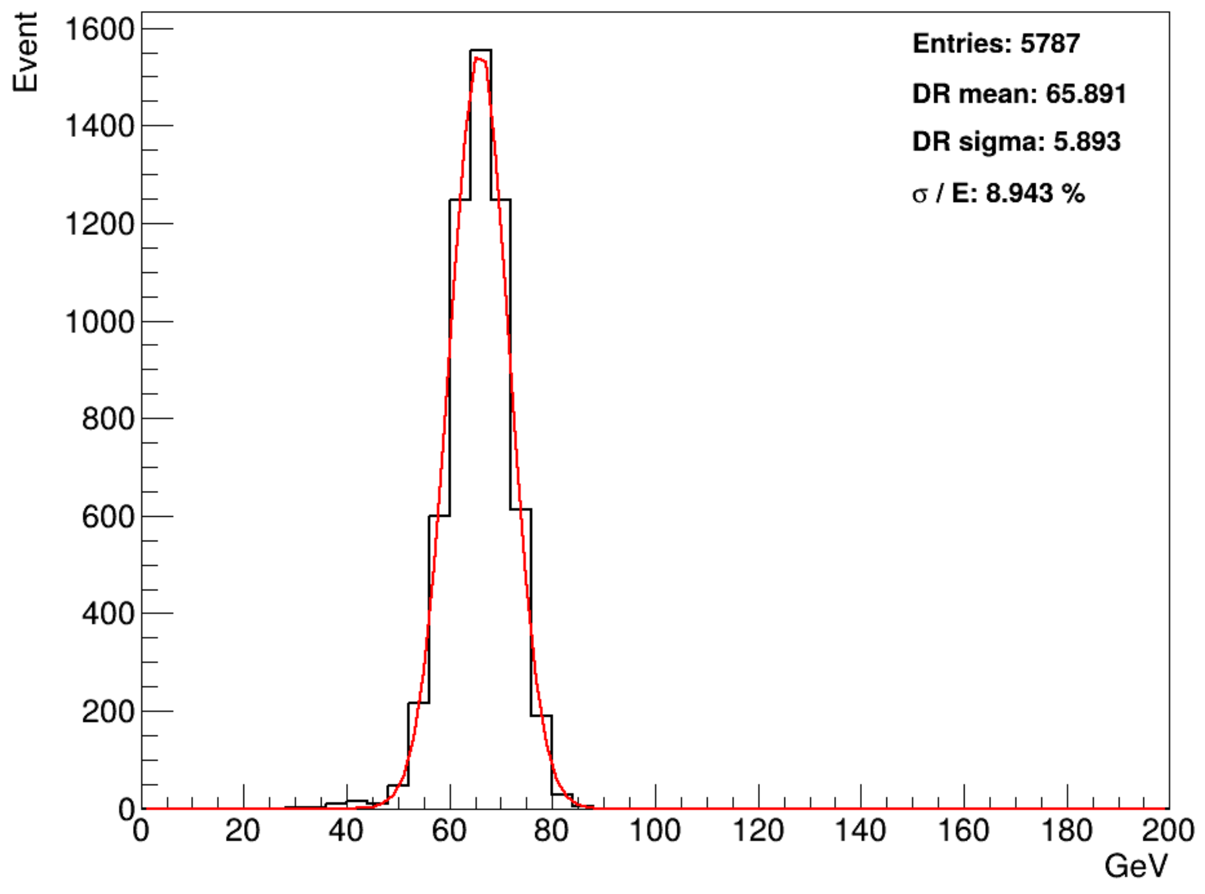
80 GeV	100 GeV	120 GeV



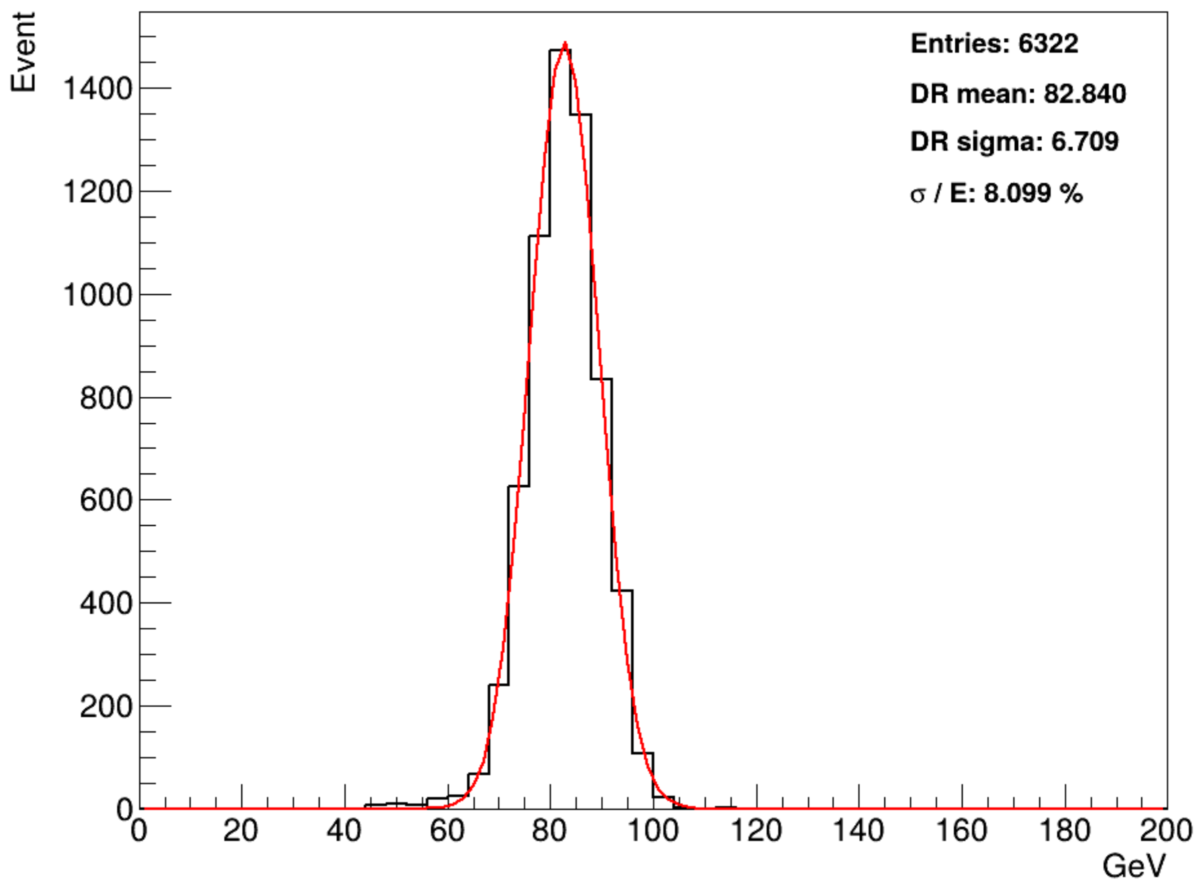




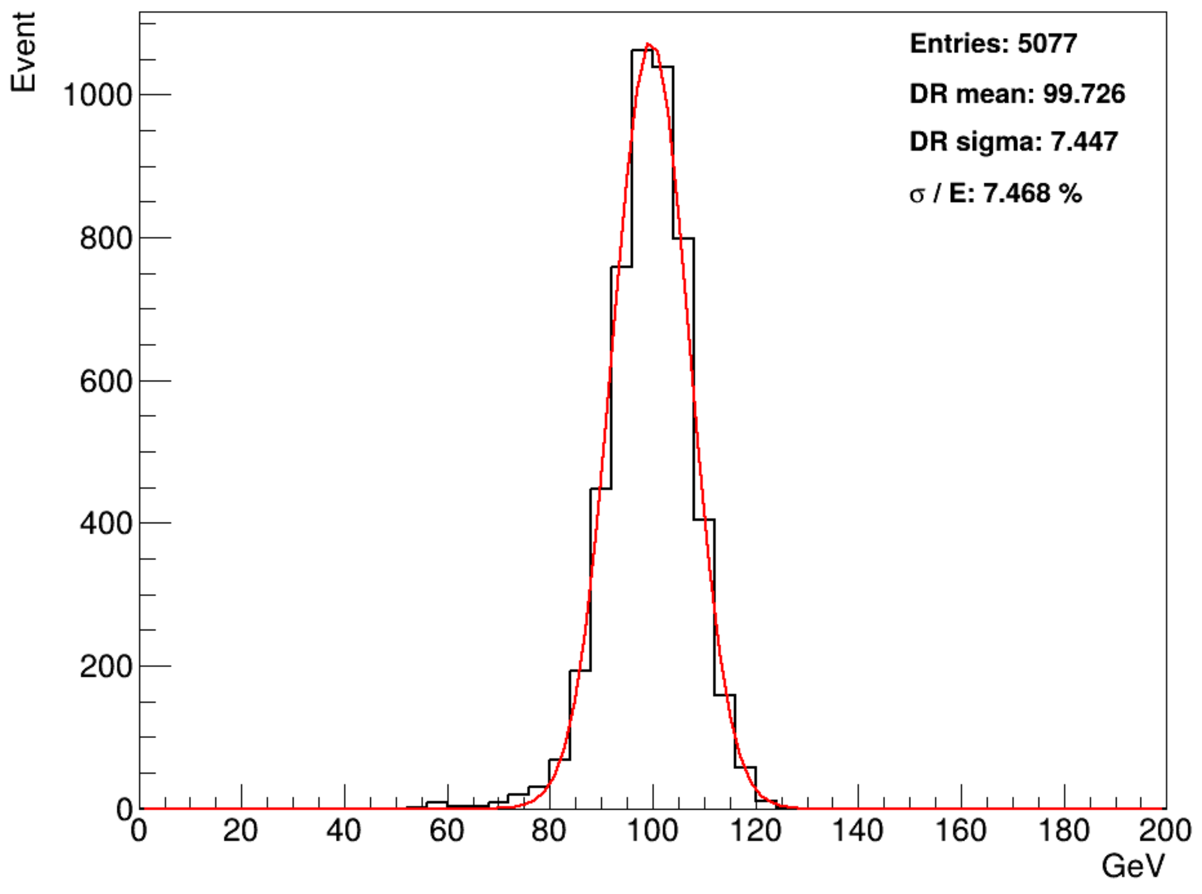
Proton 80 GeV



Proton 100 GeV



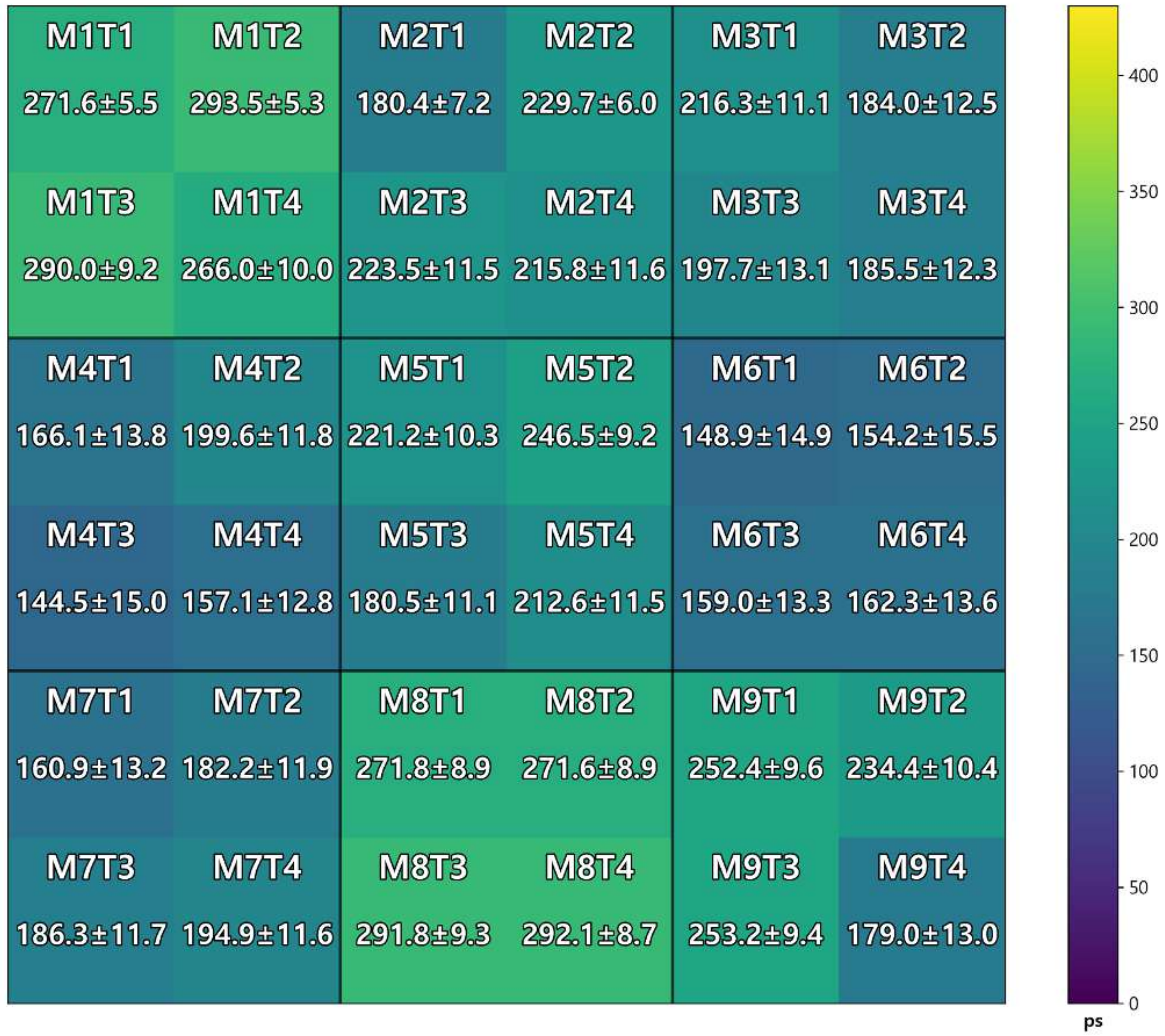
Proton 120 GeV



Time Resolution

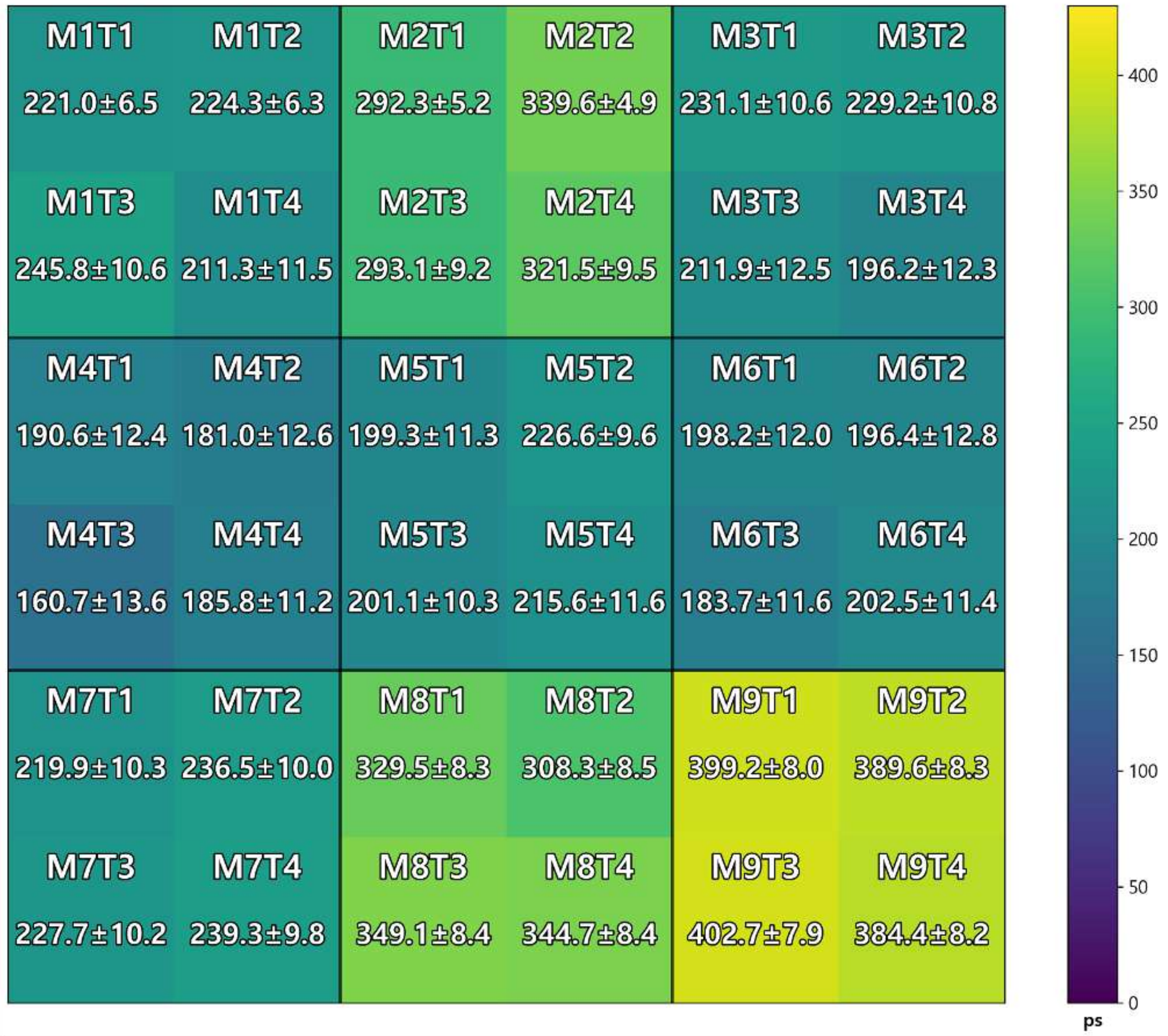
Calorimeter Time Resolution

C ch. Time Resolution



Preliminary

S ch. Time Resolution

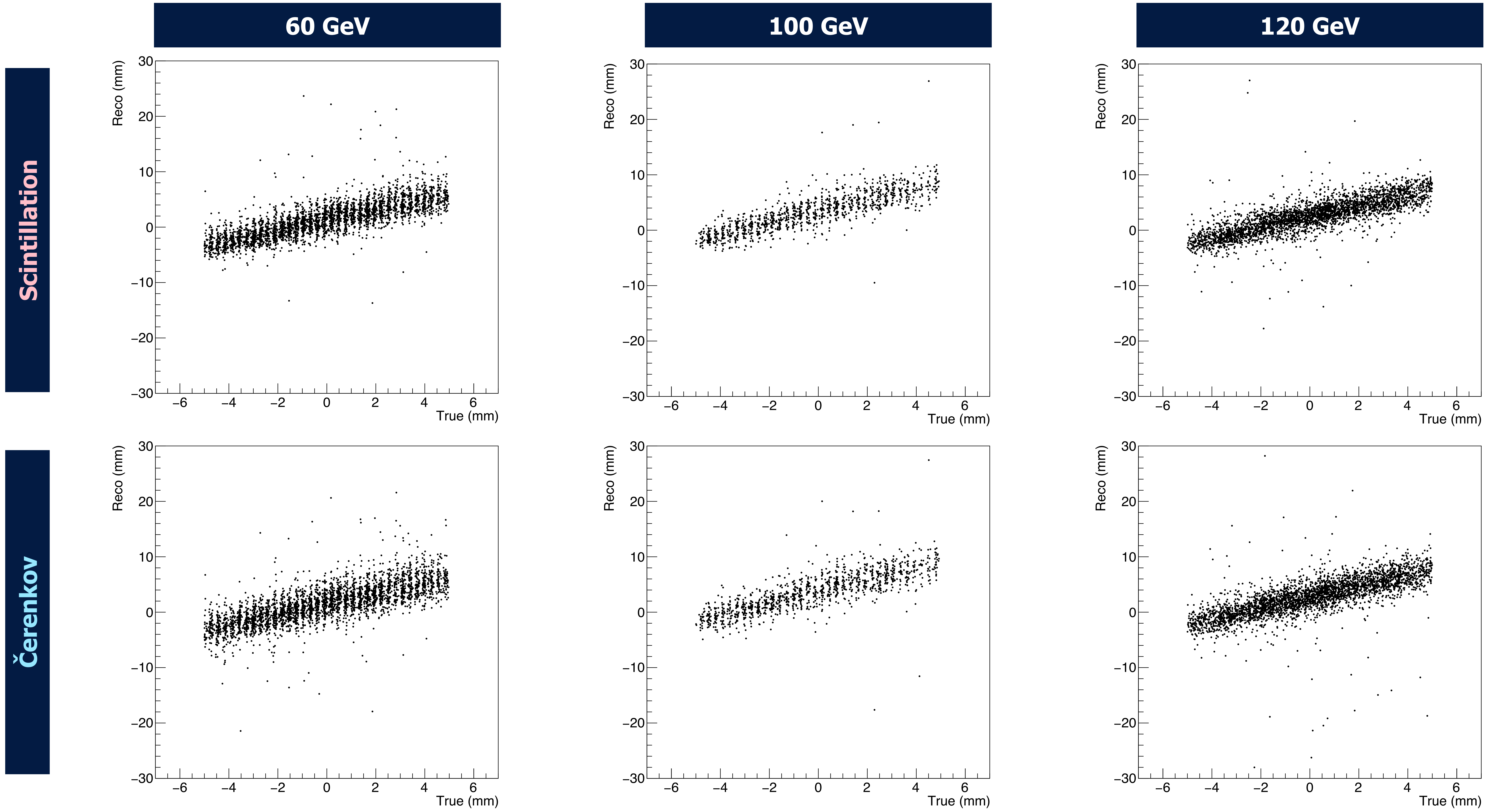


Preliminary

Time Resolution of calorimeter modules, ***trigger time resolution is subtracted***

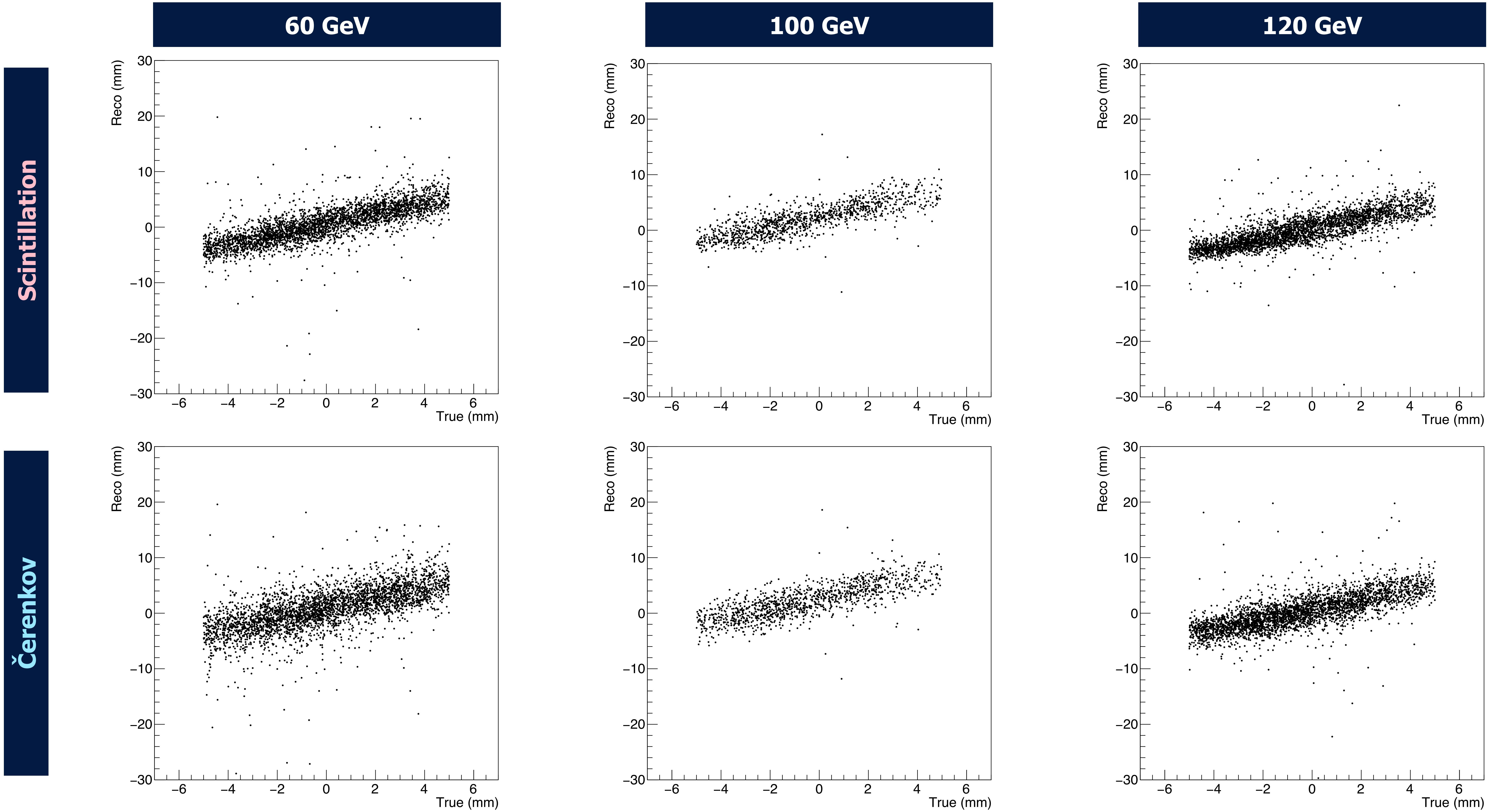
High Granularity

True vs Reconstructed Beam Position - X direciton



High Granularity

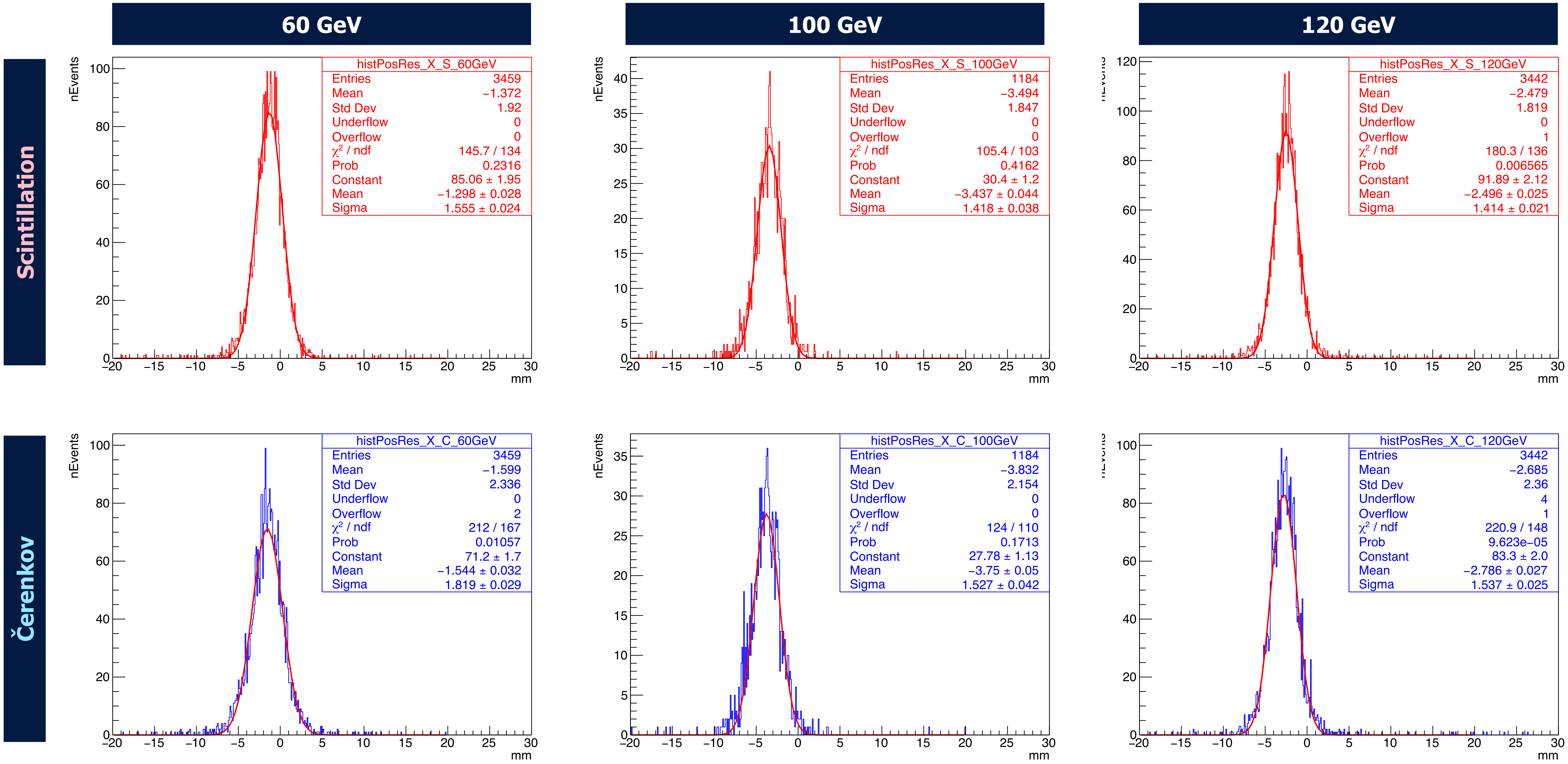
True vs Reconstructed Beam Position - Y direciton



2025, Oct 23rd

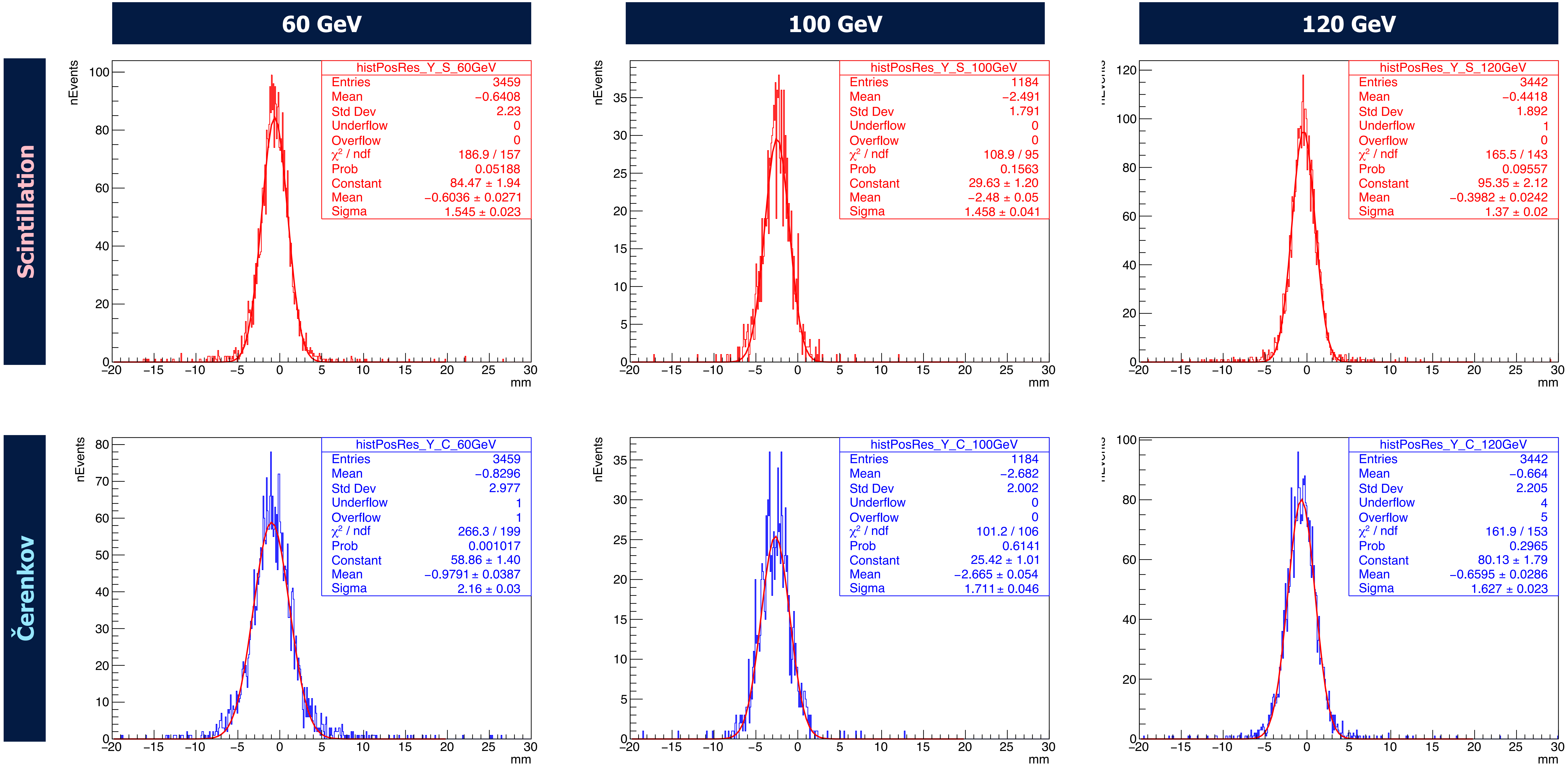
High Granularity

Position Resolution - X direction



High Granularity

Position Resolution - Y direction



2025, Oct 23rd