Test Beam Performance of a Dual-Readout Fiber Calorimeter Prototype

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On behalf of the Korea Dual-Readout Calorimeter Collaboration

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Supported by KiSTi www.kisti.re.kr

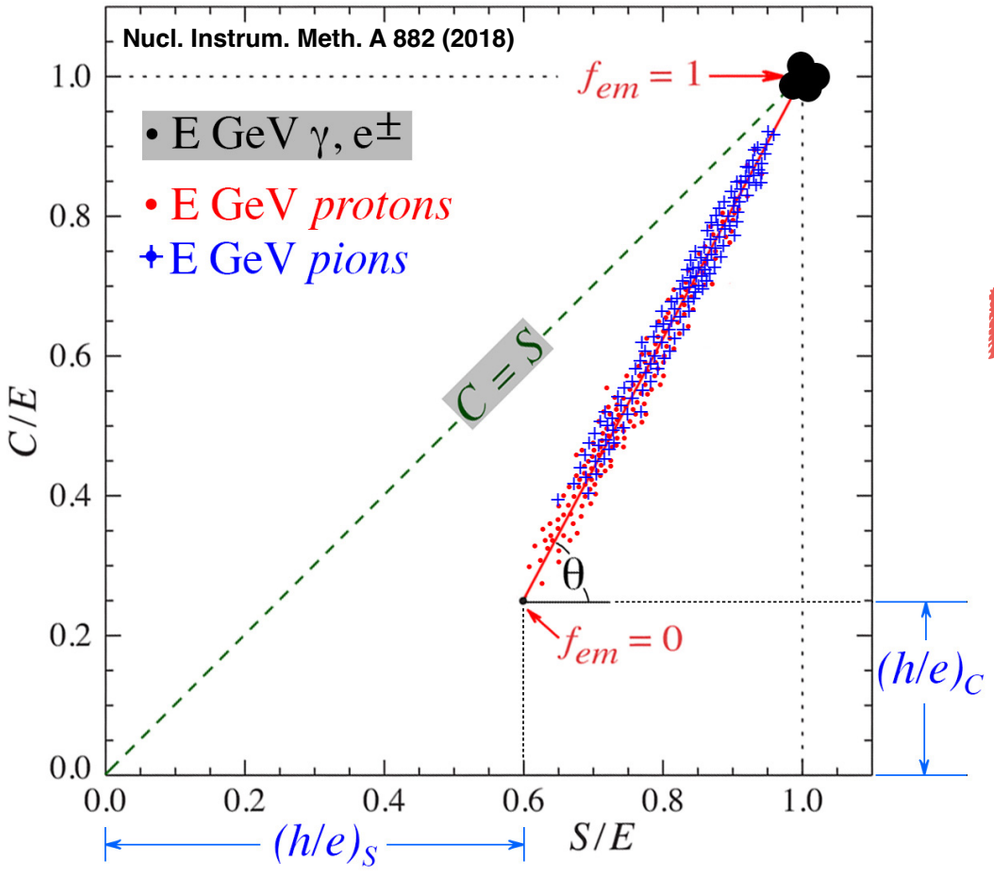
Outline

- Introduction
- TB2026 Setup
- Preliminary results
  - EM Performance
  - Hadronic Performance
- DRC with Low Energy Beam
- Summary

Introduction: Dual-Readout Calorimetry

- The main obstacle for the hadronic energy measurement
  - Non-gaussian fluctuation of the EM components (f_{em}) and nuclear binding energy loss
- One implementation of dual-readout calorimetry uses two types of optical fibers: **Scintillating (S) and Cherenkov (C) fibers**
  - Measure f_{em} event-by-event: provide precise measurement of hadronic energy

S vs C energy fraction



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

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

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

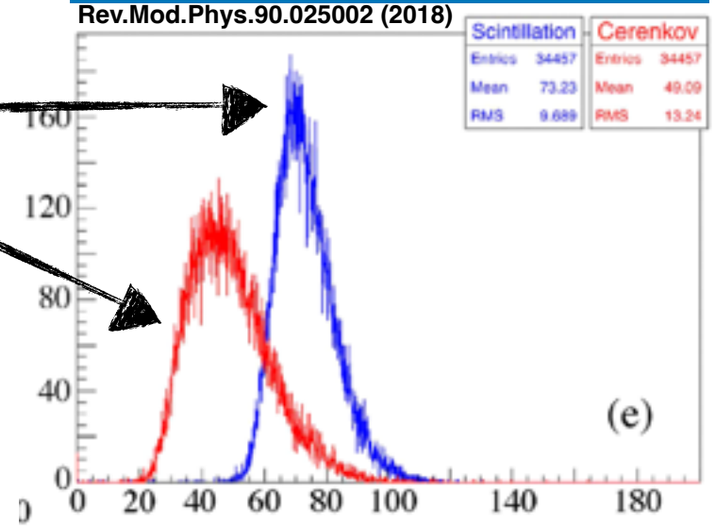
$$\chi = \frac{1 - (h/e)_S}{1 - (h/e)_C} = cot\theta$$

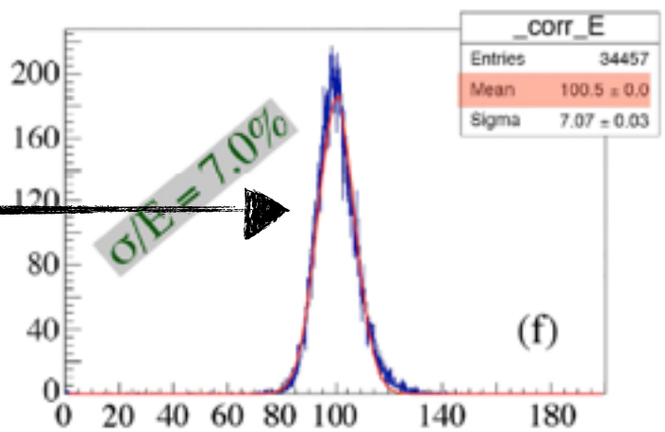
$$E = \frac{S - \chi C}{1 - \chi}$$

"Dual-readout (DR) corrected energy"

S, C and DR-corrected energy (100 GeV π^- beam) by RD52 experiment

Rev.Mod.Phys.90.025002 (2018)

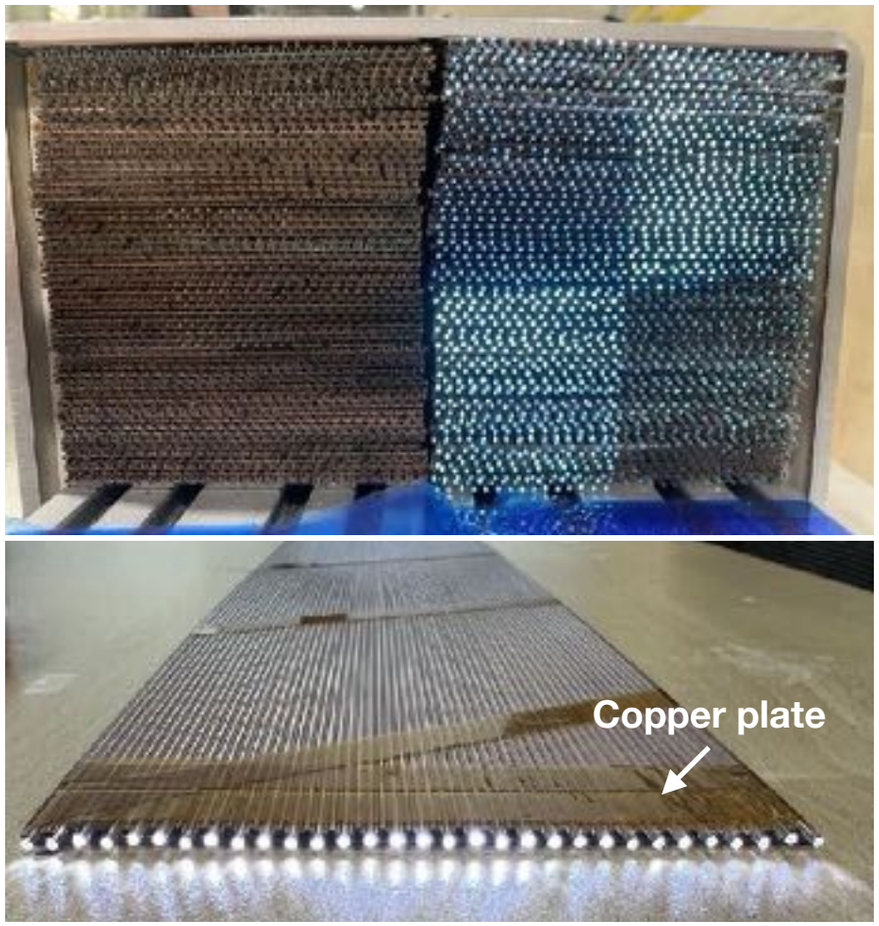




DRC by Korea Collaboration

- Built various types and length of prototype
- Performed test beam experiment at CERN SPS/PS since 2022

TB2022



EM Performance Study

Cu Plate

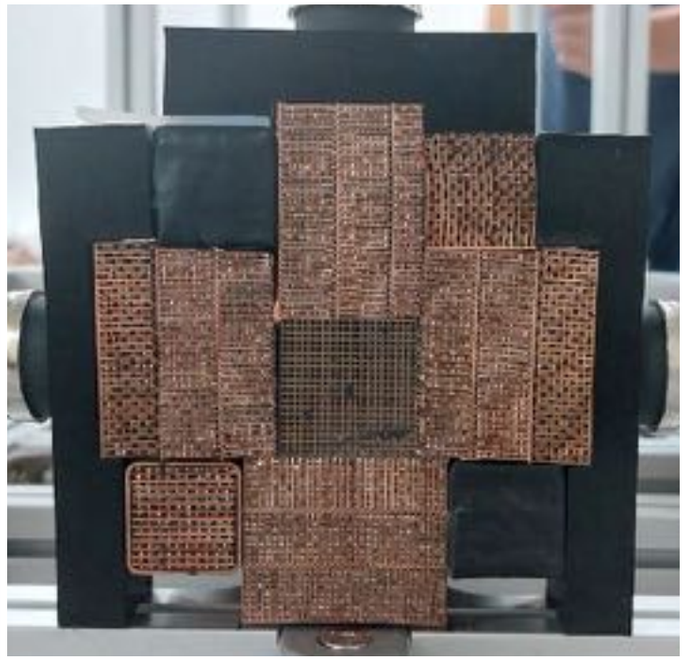
~3.5 ρ_M, > 30 X_0

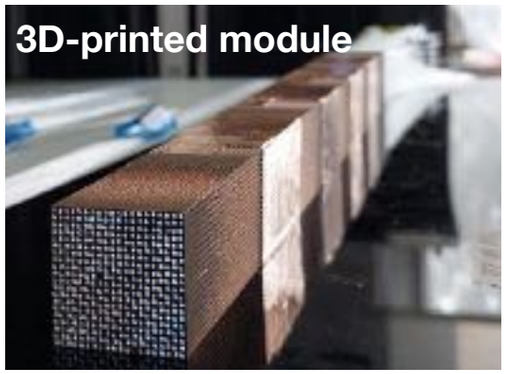
PMT, SiPM

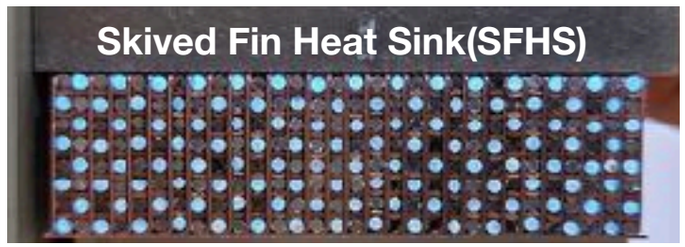
10 ~ 120 GeV e^+

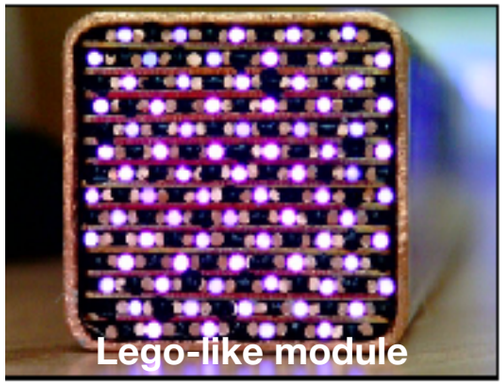
@SPS H8

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

DRC by Korea Collaboration

- Built various types and length of prototype
- Performed test beam experiment at CERN SPS/PS since 2022

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

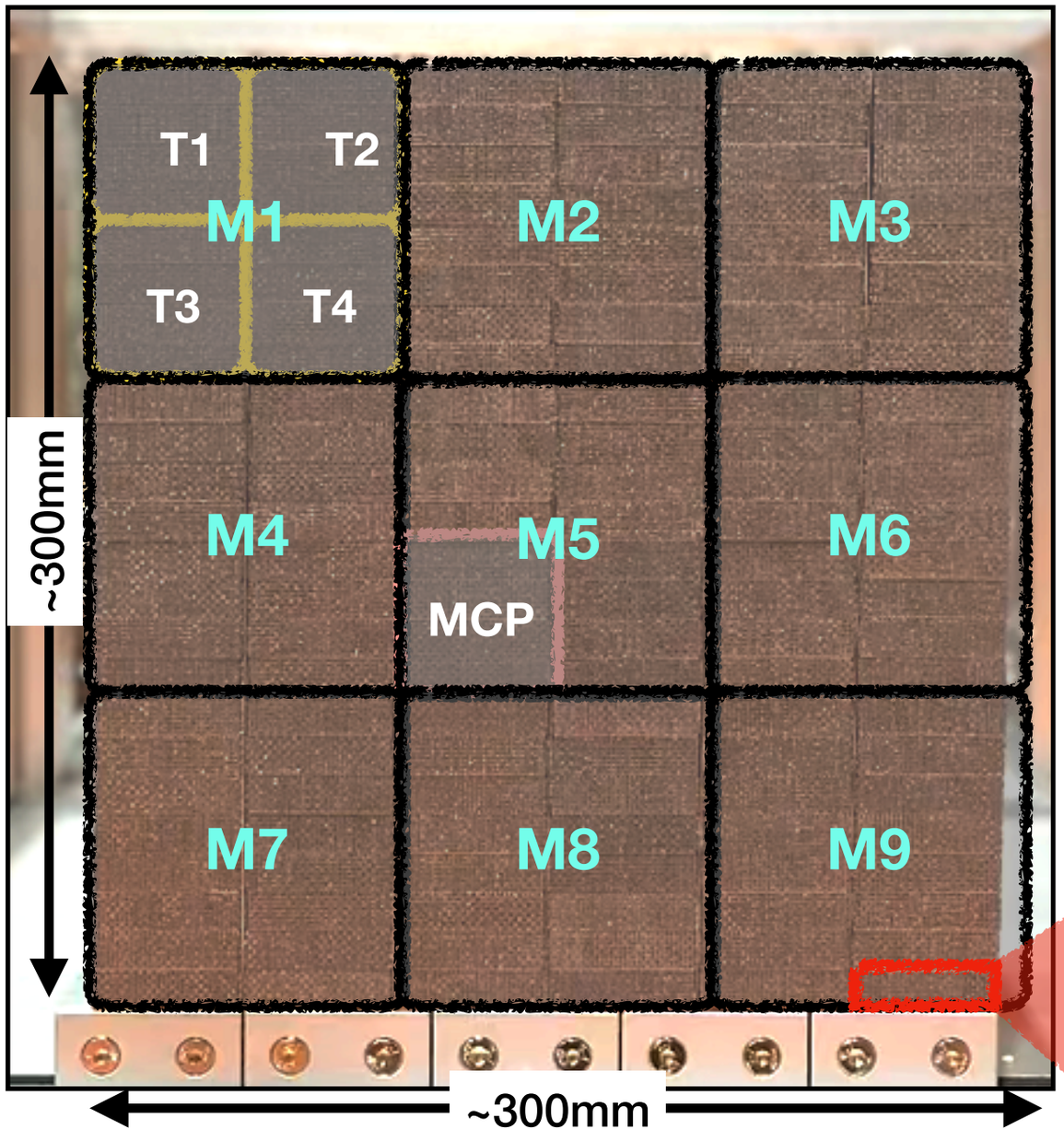
TB2025



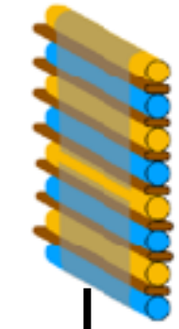
EM&Hadron Performance Study
SFHS
~90% lateral hadron deposit, ~10 λ_{int}
Effective radius 17cm (~0.8 λ_{int})
PMT, MCP-PMT
10~120 GeV e^+, **20~120 GeV Hadrons**
@SPS H8

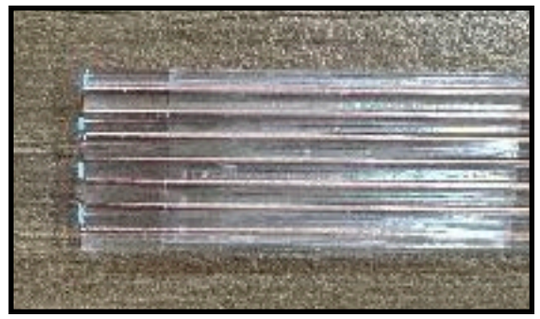
TB2026: Module Structure

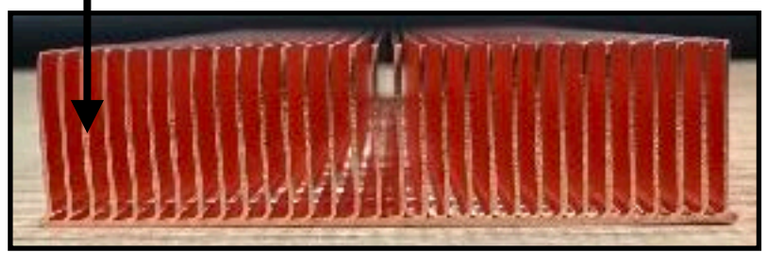
- Same detector of TB2024 and TB2025
  - Skived Fin Heat Sink shape as a copper absorber
  - Alternatively accumulated optical fibers

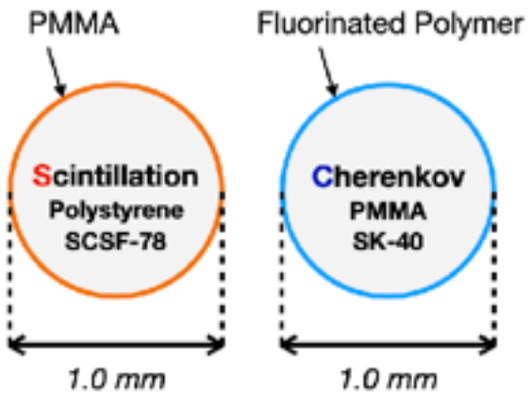


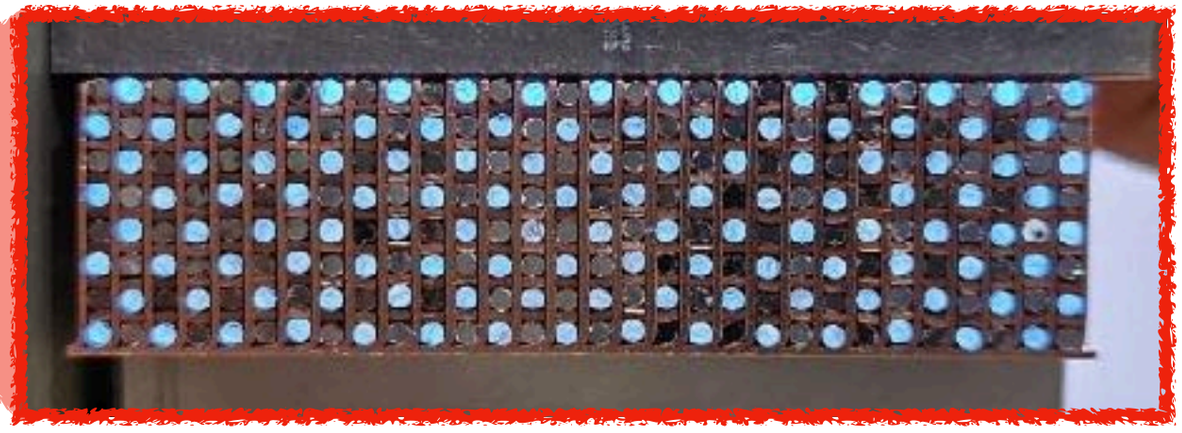
- Dimension: 300 mm x 300 mm x 2.5m
- Longitudinally unsegmented
- Depth: ~$10\lambda_{int}$
- A lateral hadronic shower containment: ~90% ($\pi^{\pm}$, 60GeV)







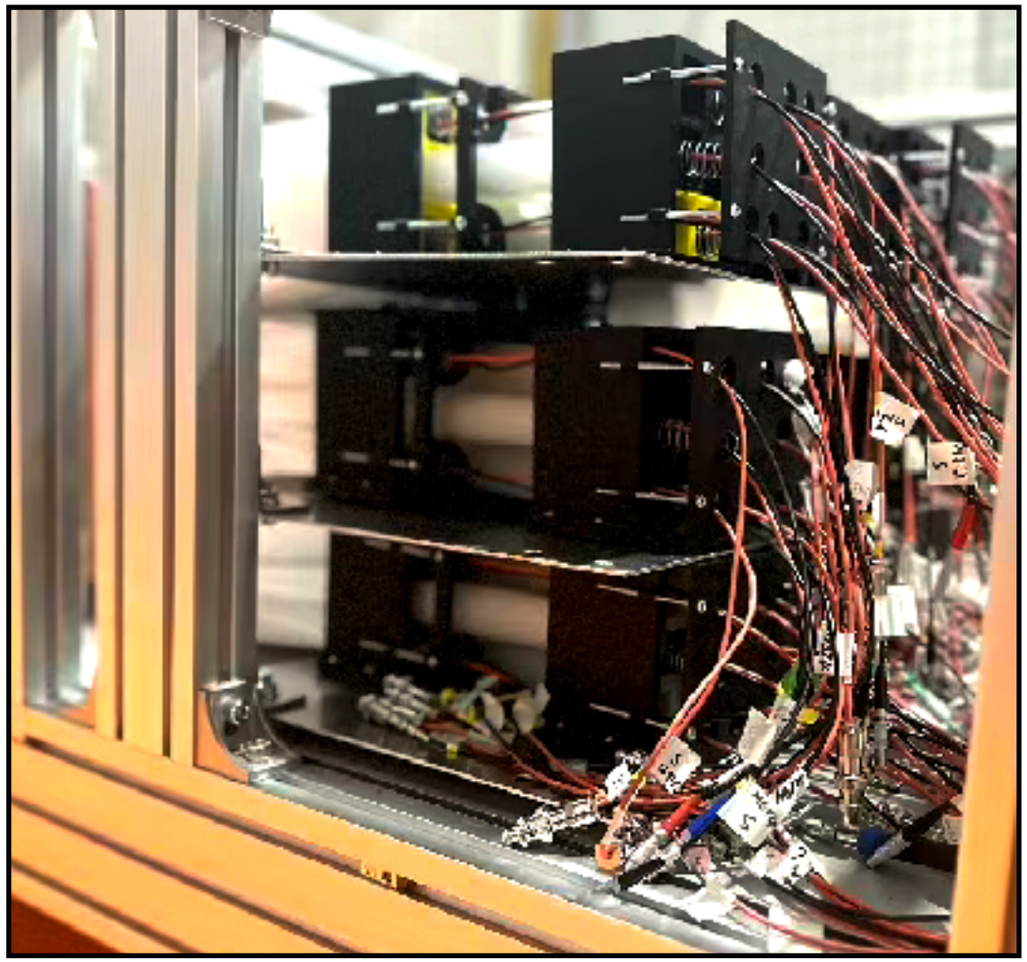




TB2026: Readout Part

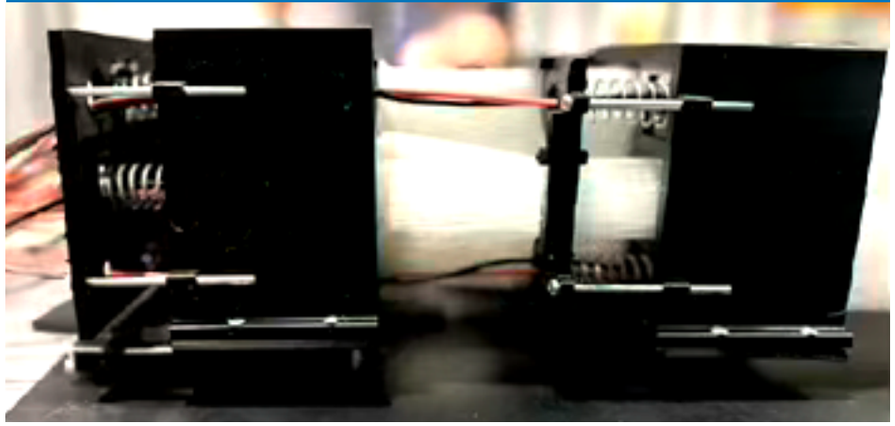
- Usual towers: PMT(R11265-100) for each S and C fiber type
  - 35 towers x 2 fiber type = 70 channels
- Module 5 Tower 3(M5T3): high-granularity MCP-PMT
  - 8 fibers / channel → 64 channels / fiber type
  - 1 summation channel / fiber type

  ➡ 130 channels
- Total 200 (PMT: 70, MCP-PMT: 128+2) channels



Usual tower

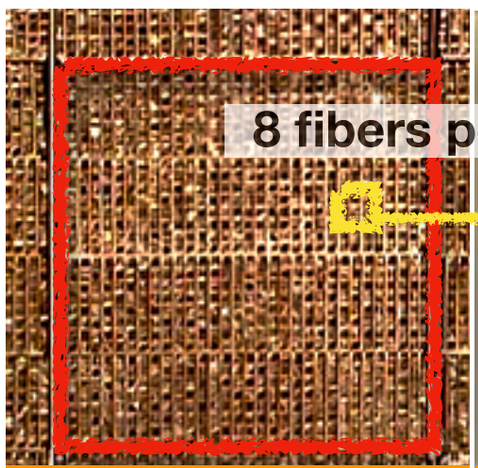
Spring + screw push for stable optical contact



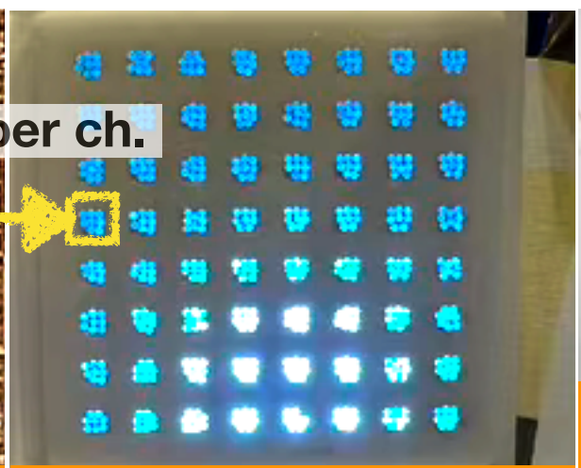
PMT (R11265-100)



MCP-PMT tower



MCP Tower (M5T3)



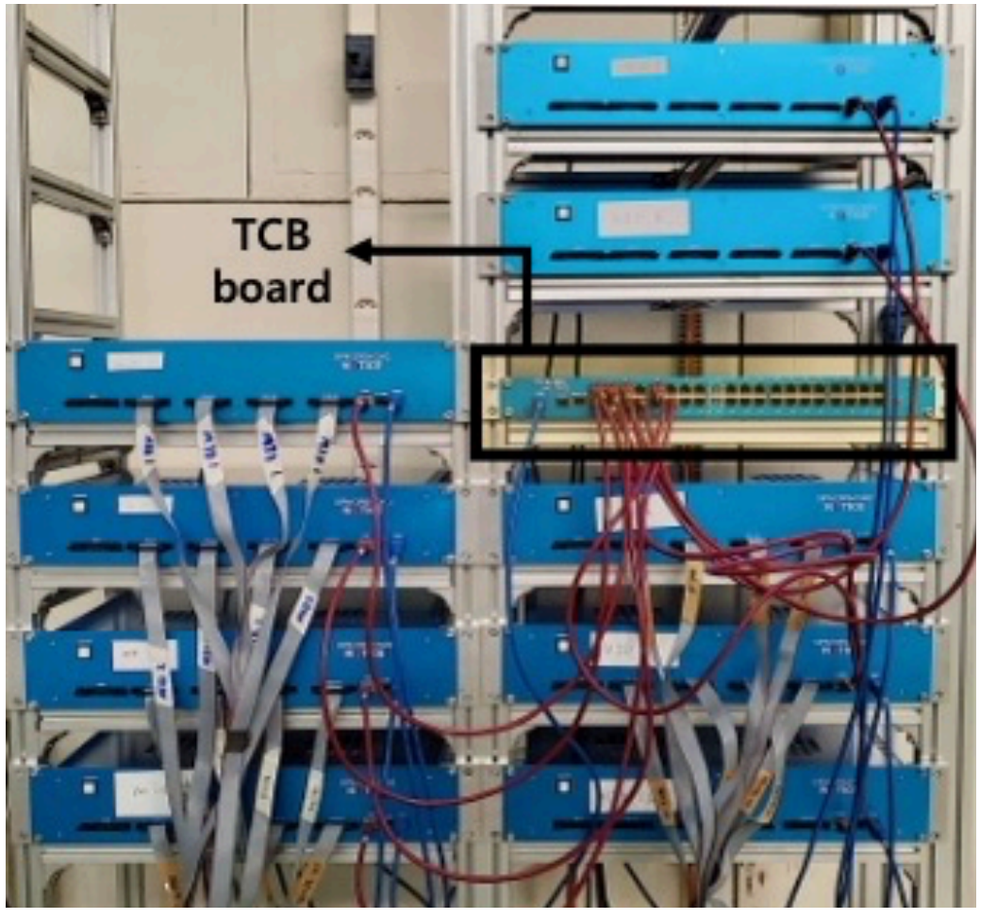
MCP-PMT ch. Fiber Bundling



MCP-PMT
XP85012 (S)
XP85112 (C)

TB2026: DAQ System

- Customized DAQ system based on DRS4 chip (NOTICE Korea)







DRS4 Chip



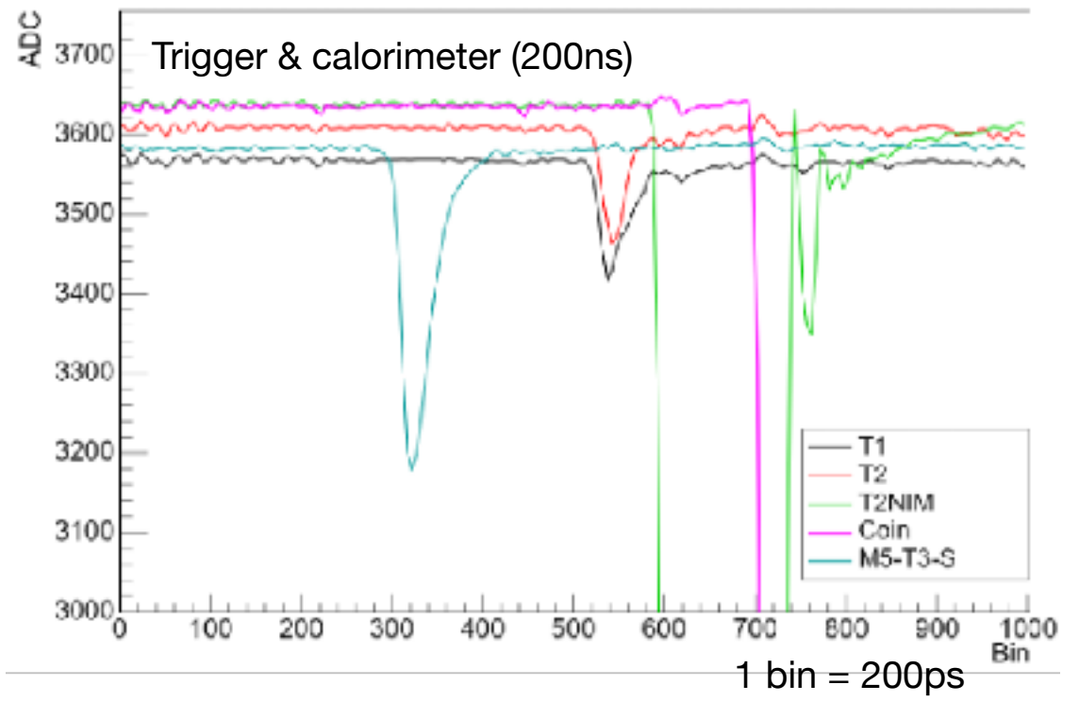
TCB Board

- Trigger and Clock module
- 1 board handles all DAQ boards
- Support various time window (200ns, 400ns, 800ns)

DAQ Board

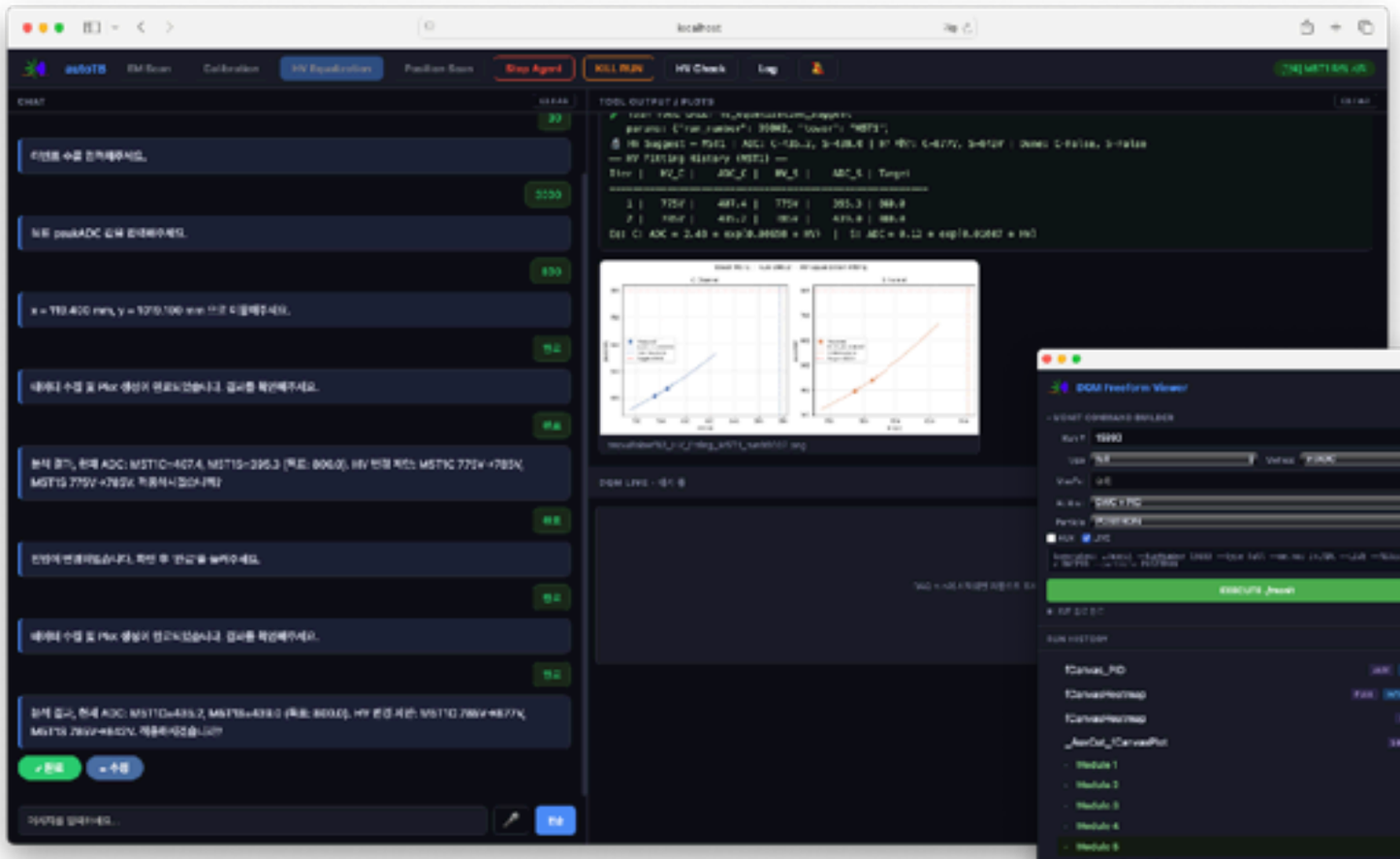
- Data Acquisition board
- 1 board covers 32 channels
- DRS4 chip (involved in time window)

Detector signals from DAQ (ADC vs. time bin)



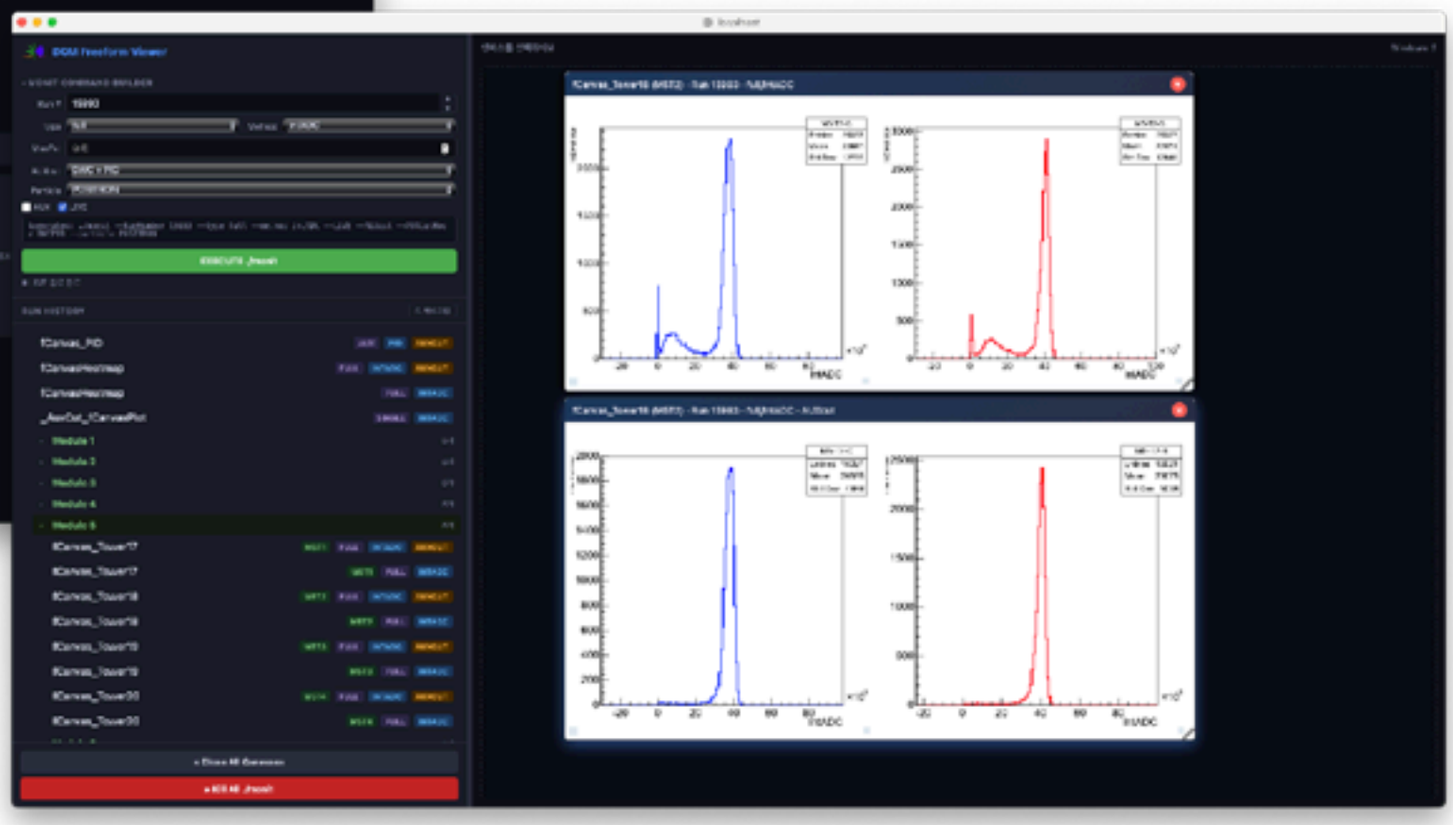
TB2026: DQM System

- Real-time, web-based DQM tool
- Introduced AI-based tool into the experimental workflow
  - Automation of operational procedures: automated logging, HV control, module calibration data taking, etc.
  - Realtime data quality monitoring



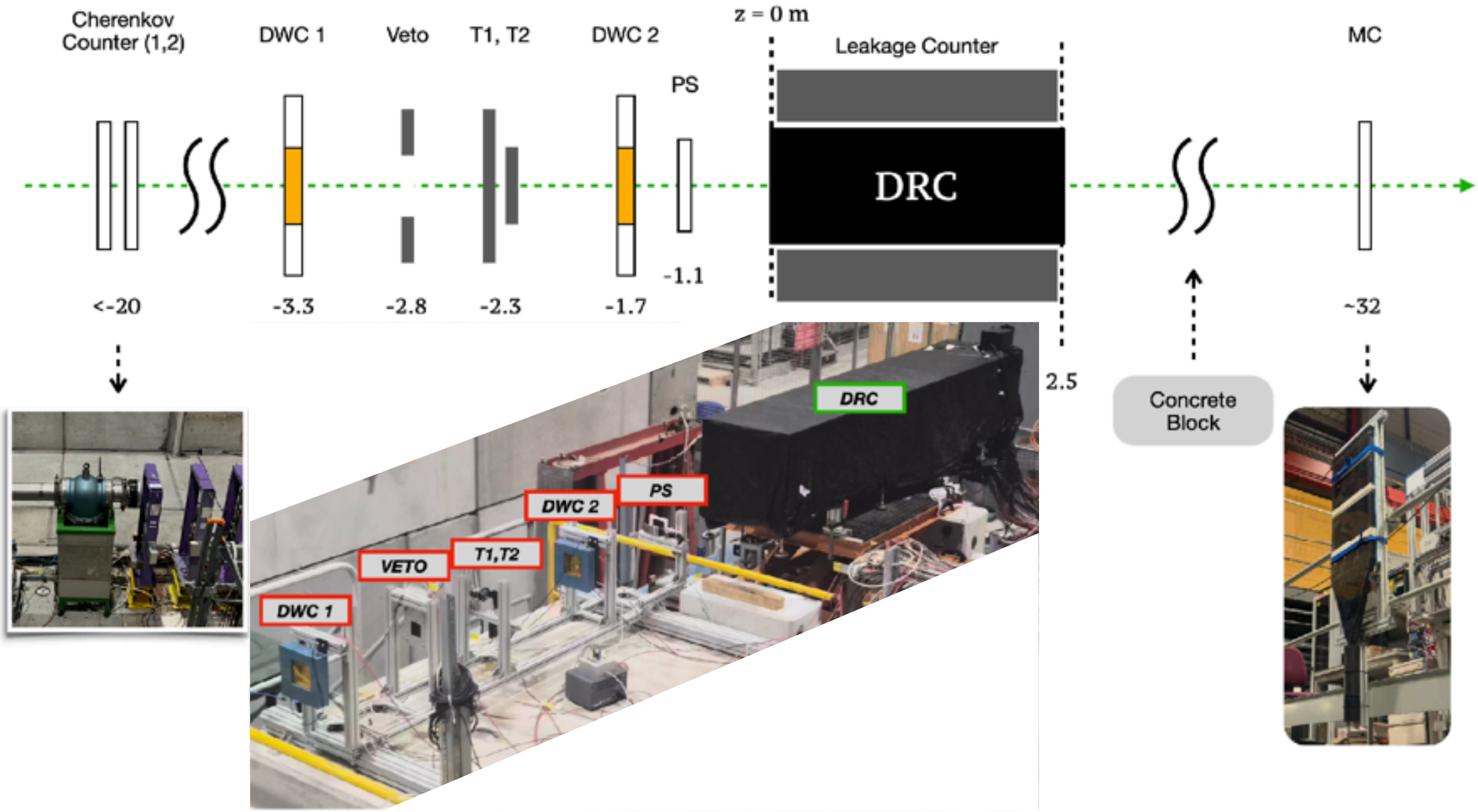
HV calibration with AI tool

Tower signal check



TB2026: Experimental Setup @ CERN SPS H8

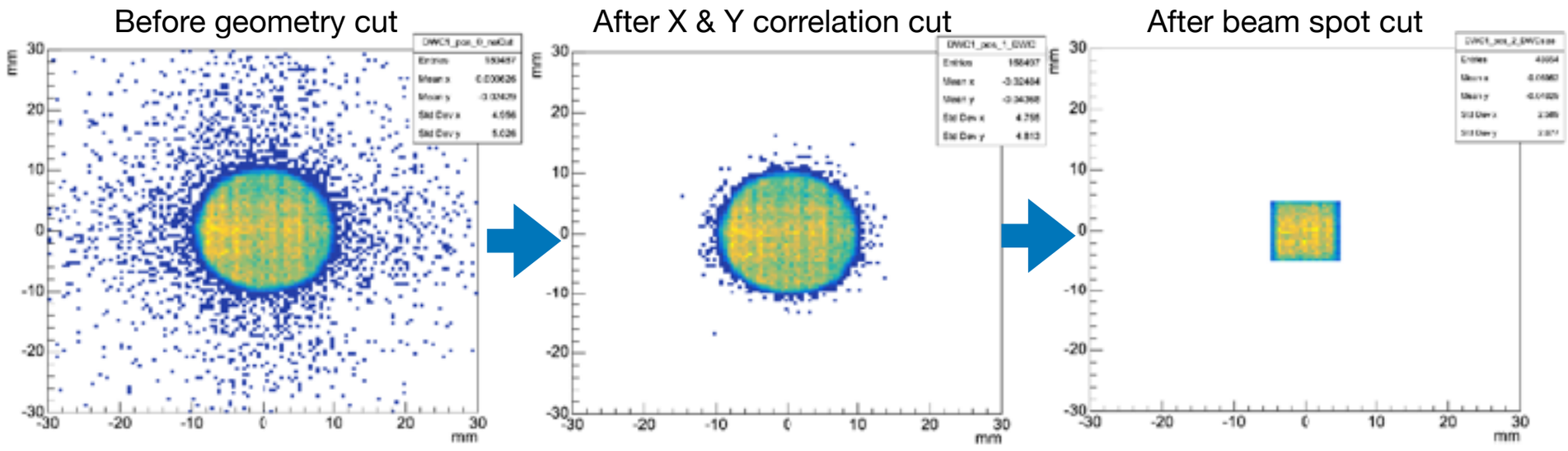
- Auxiliary detectors for particle identification and beam shape monitoring
  - 2 Cherenkov counters (CC1 & CC2), 2 delayed wire chamber (DWC1 & DWC2), pre-shower (PS), muon counter (MC)
- Leakage counters were installed around DRC to capture the hadronic shower leakage
  - 50cm x 50cm 12cm plastic scintillator



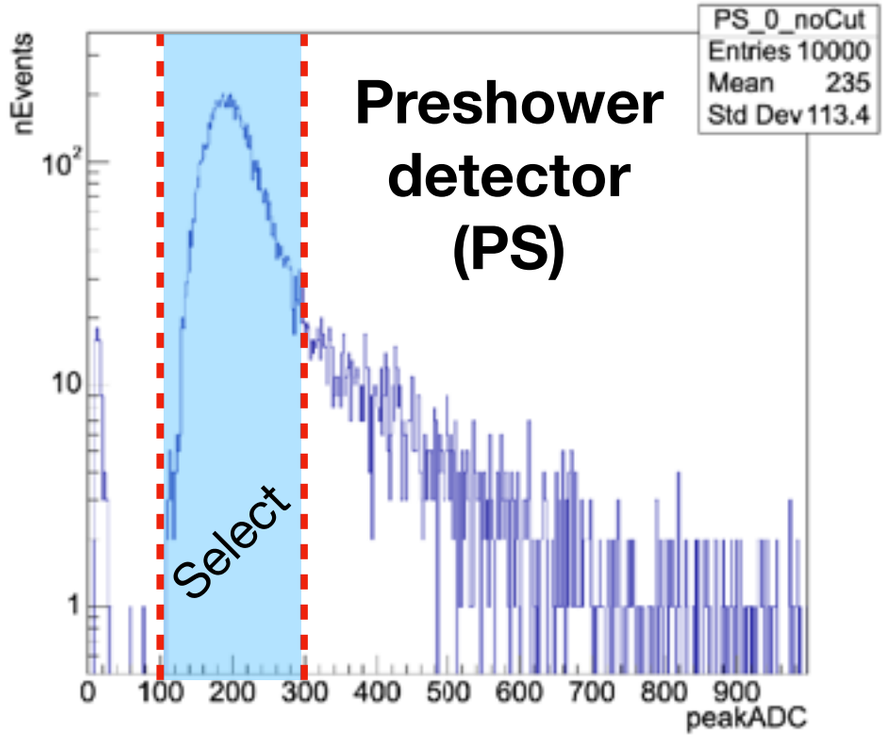
Analysis Procedure

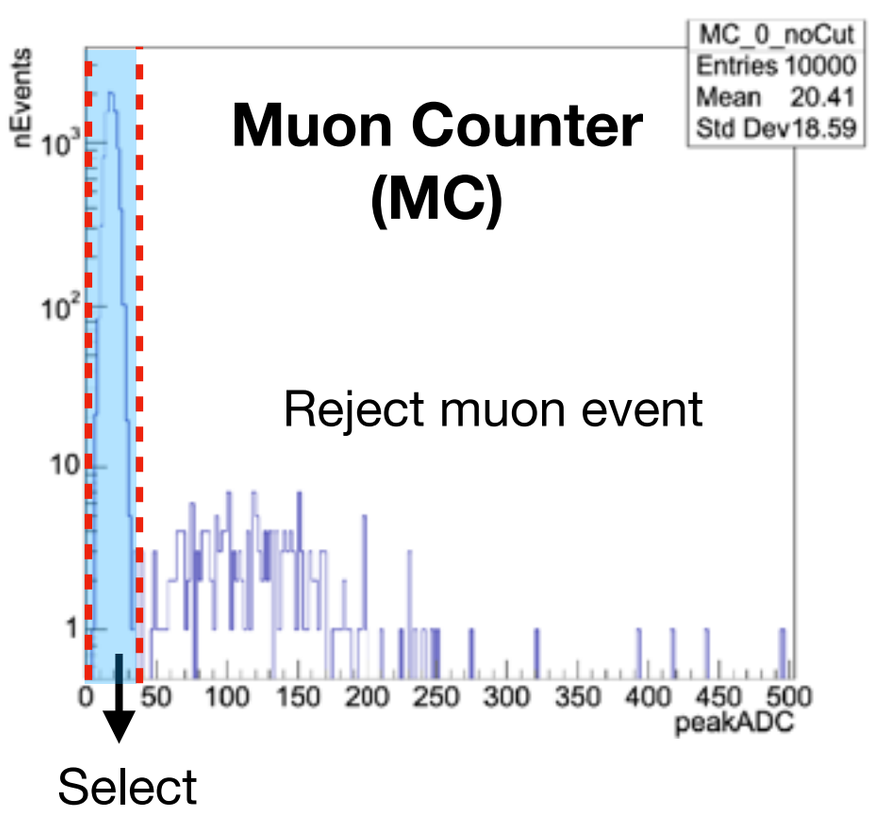
Preliminary

- Beam geometry (DWCs)
  - Select focused beam
  - X & Y-correlation between DWCs to take the straight beams only



- Particle Identification
  - Select/reject electron using preshower and Cherenkov counters (CC1, CC2)
  - Reject muons using moon counter (MC)
  - Select/reject hadrons($\pi^{\pm}$, p) using CC1 and CC2

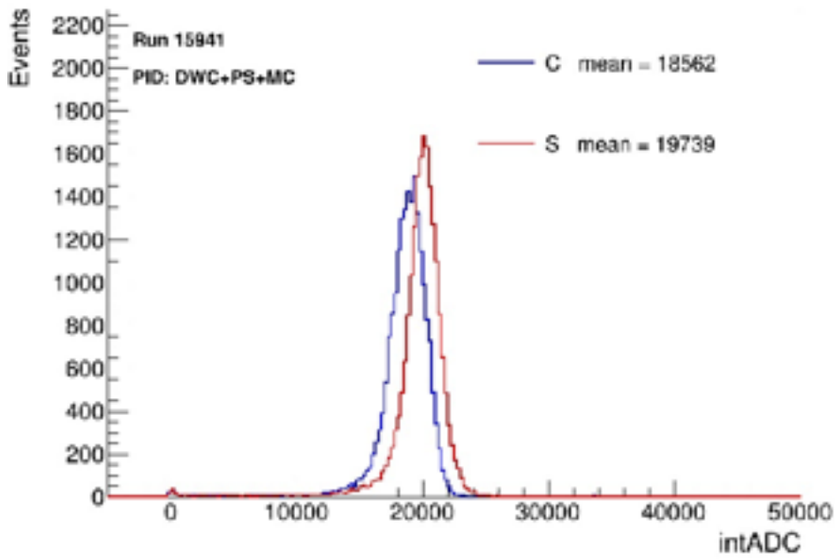




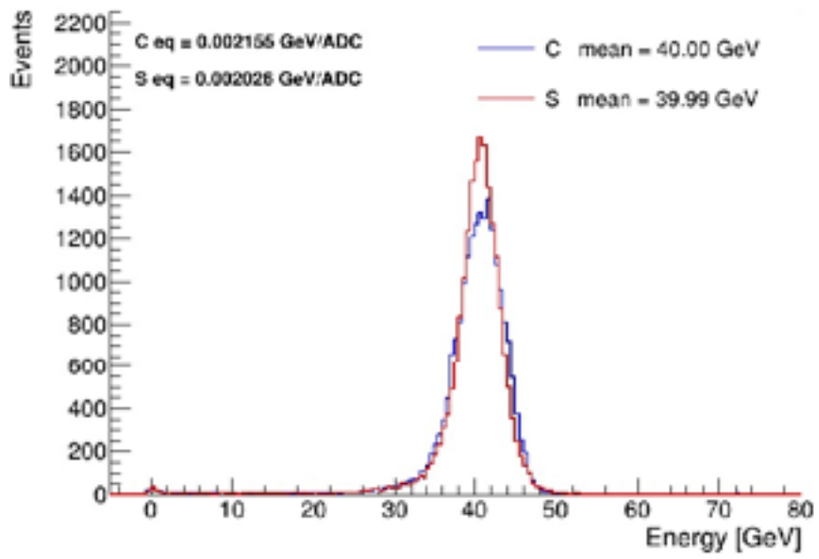
Analysis Procedure

Preliminary

- Calibration
  - Using e+ beam with a fixed energy for each tower
  - Obtain a conversion factor for intADC → energy unit



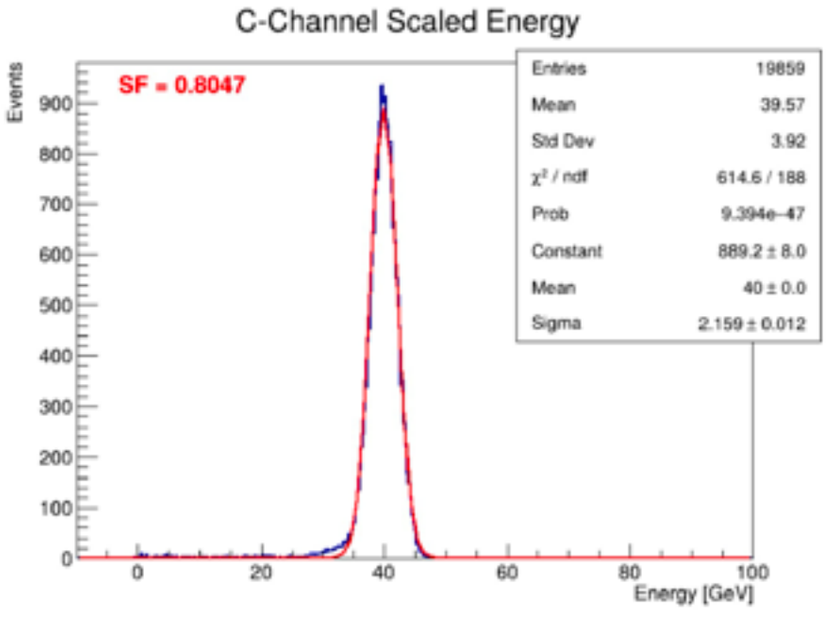
Before calibration (after PID)

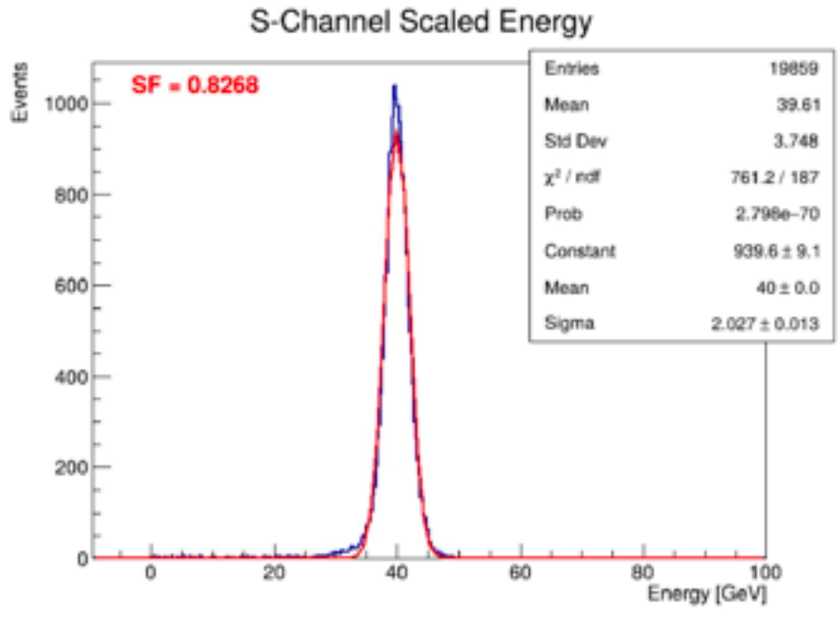


Equalization constant applied

Scale factor applied

- Scale factor: calibrates the measured energy to the beam energy



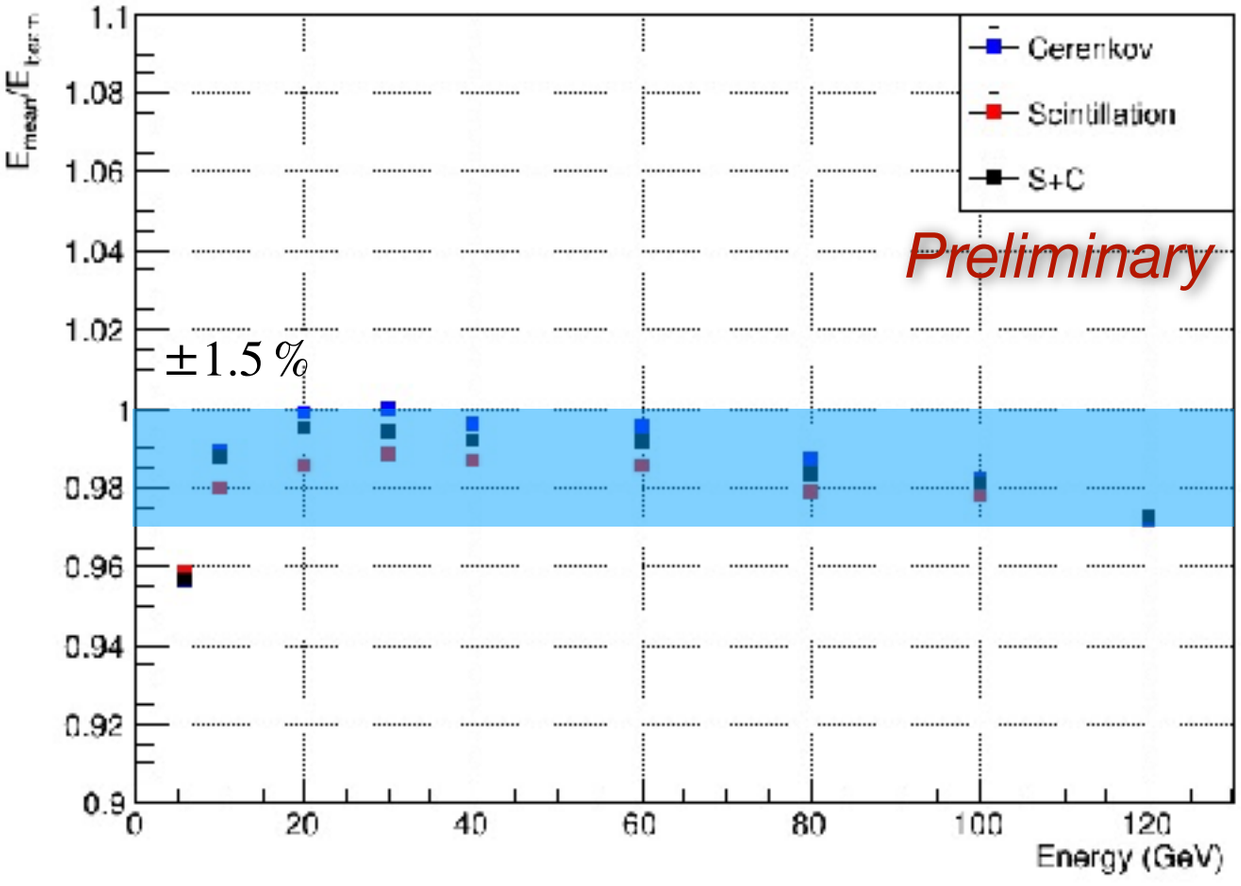


Calibrated signal

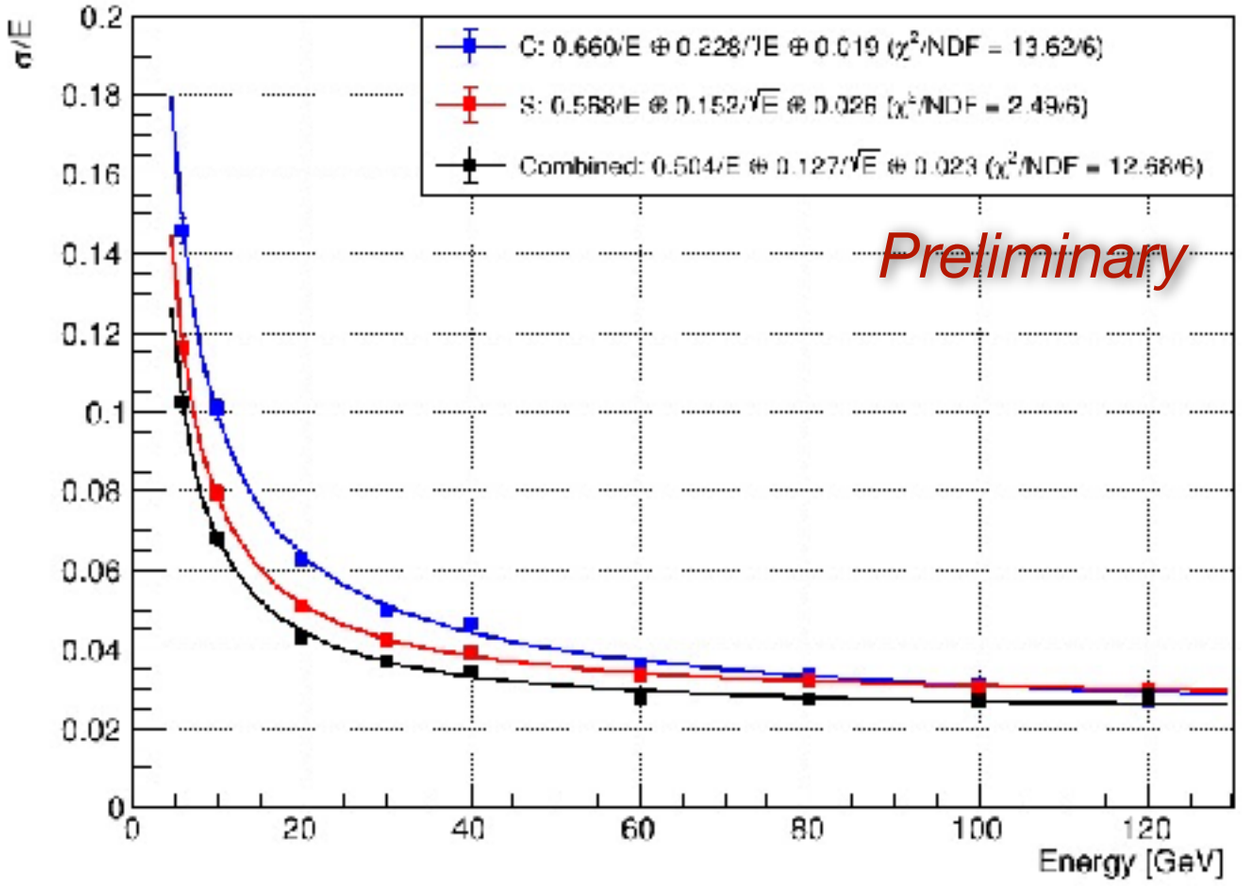
EM Performance

- Energy resolution and linearity using 6, 10, 20, 30, 40, 60, 80, 100, 120 GeV EM event
- Combined (S+C) channel shows linear response for beam energy ($\pm 1.5\,\%$)
- Combined channel presents **~12.7%/$\sqrt{E}$** of energy resolution for EM

Linearity



Energy resolution

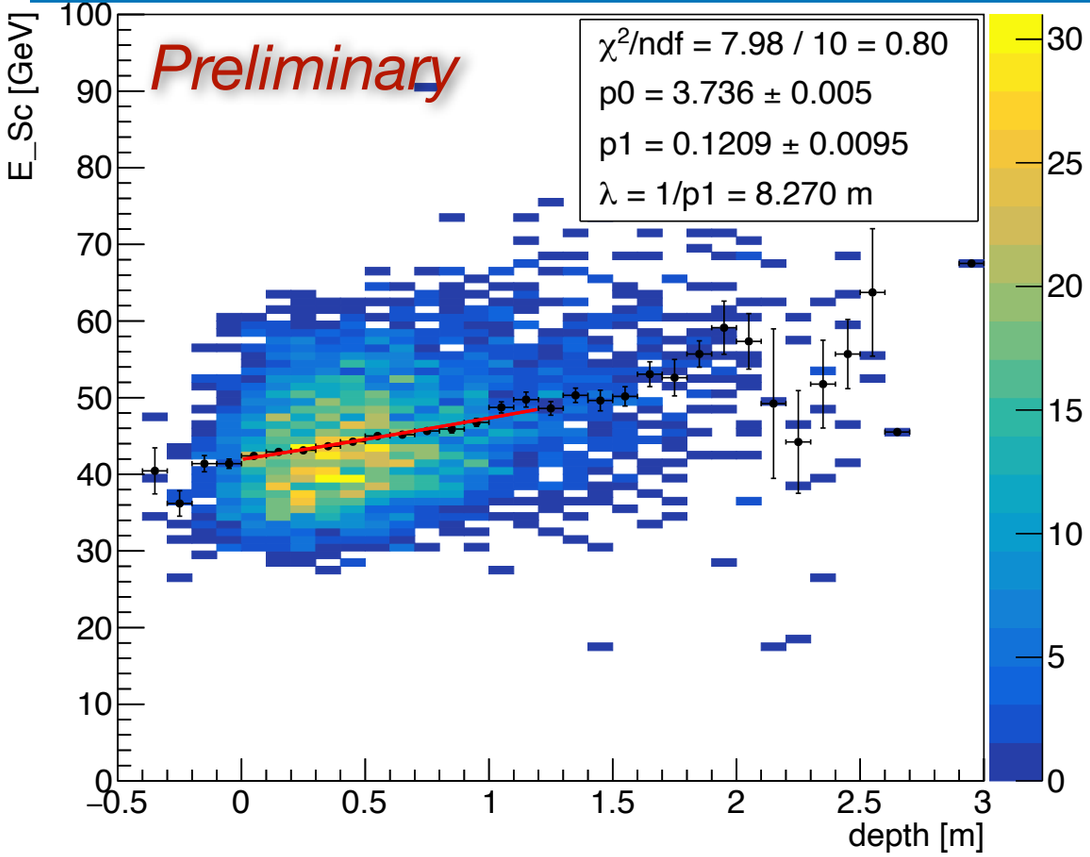


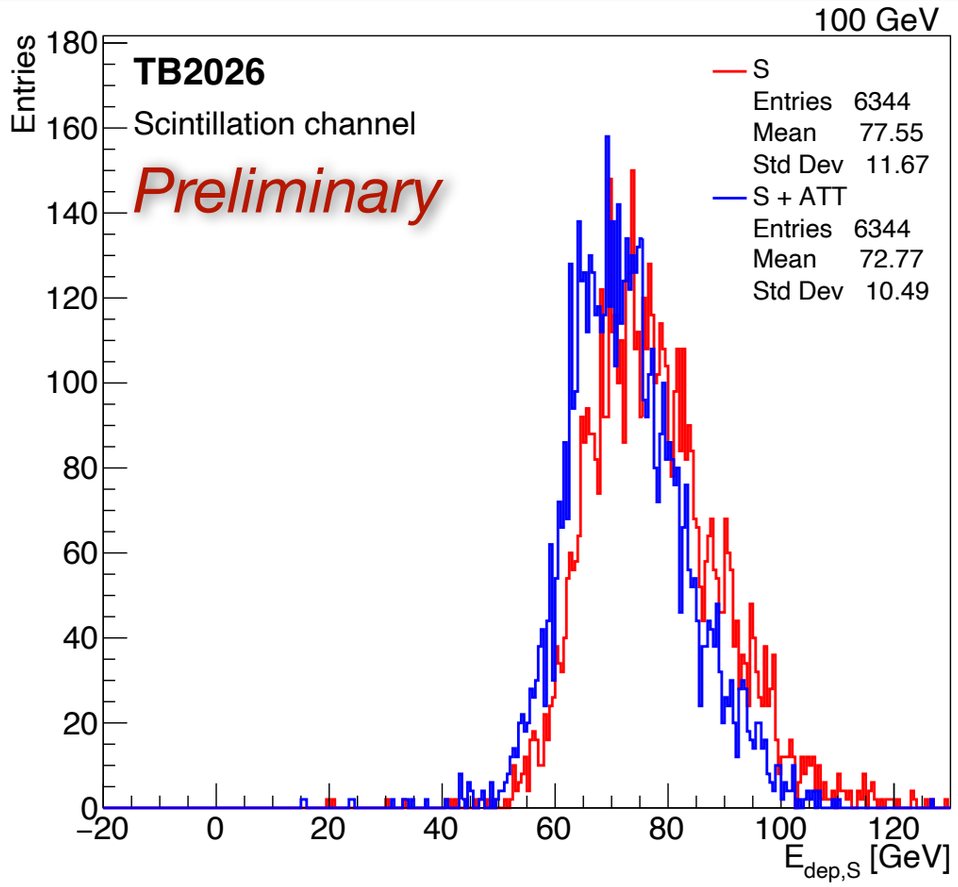
Corrections for Hadronic Events

- **Light attenuation correction**
  - reduces variations in light collection caused by differences in shower depth
  - Depending on the fiber property, light attenuation length $\lambda(I = I_0 e^{-d/\lambda})$
  - By calculating average shower depth, measured attenuation length and applied attenuation correction on **S channel**

$$E_{attenuation\ corrected} = E_{measured} \cdot e^{\frac{actual\ shower\ depth) - D_{max}}{\lambda(=8.270)}}$$

Shower depth vs energy deposit (S channel)

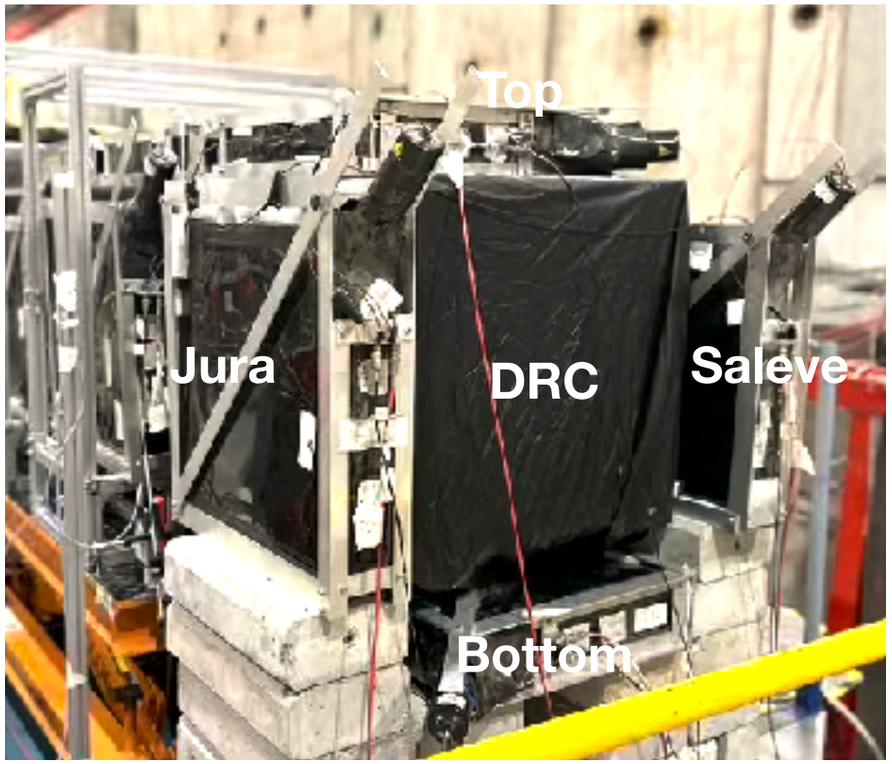




- Light attenuation correction **reduces the shower-depth dependence** of S response, shows **more uniform response**

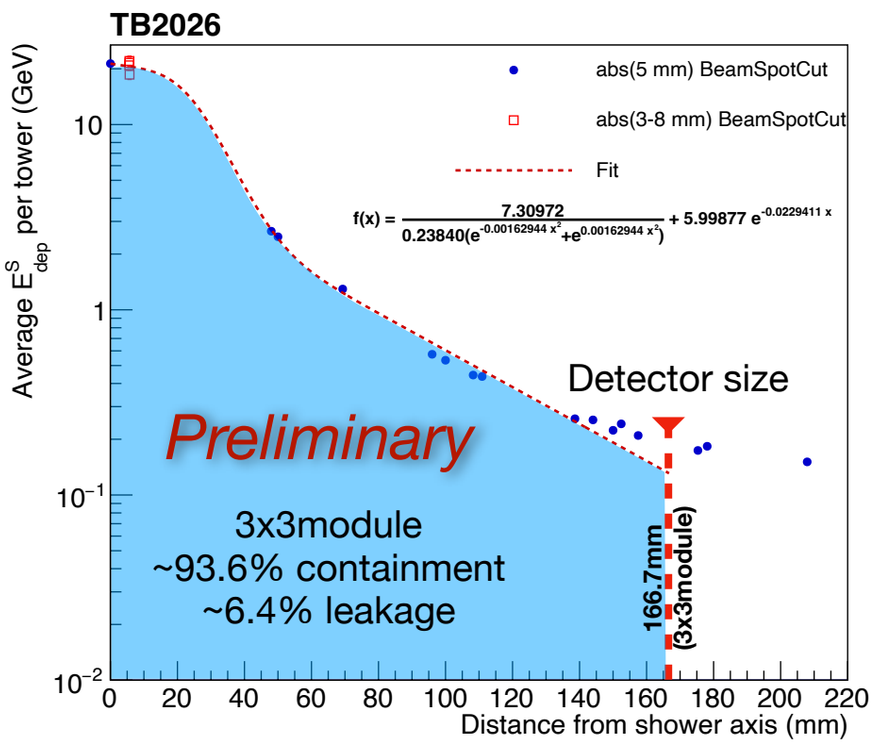
Corrections for Hadronic Events

- **Leakage counter correction**
  - Uses external scintillator signals to account for shower leakage event by event
  - Equalization using 110 GeV muon on each LC
  - Scale the deposited energy using the measured lateral shower profile (60 GeV π^+)
  - Add the LC energy deposit to S channel event-by-event

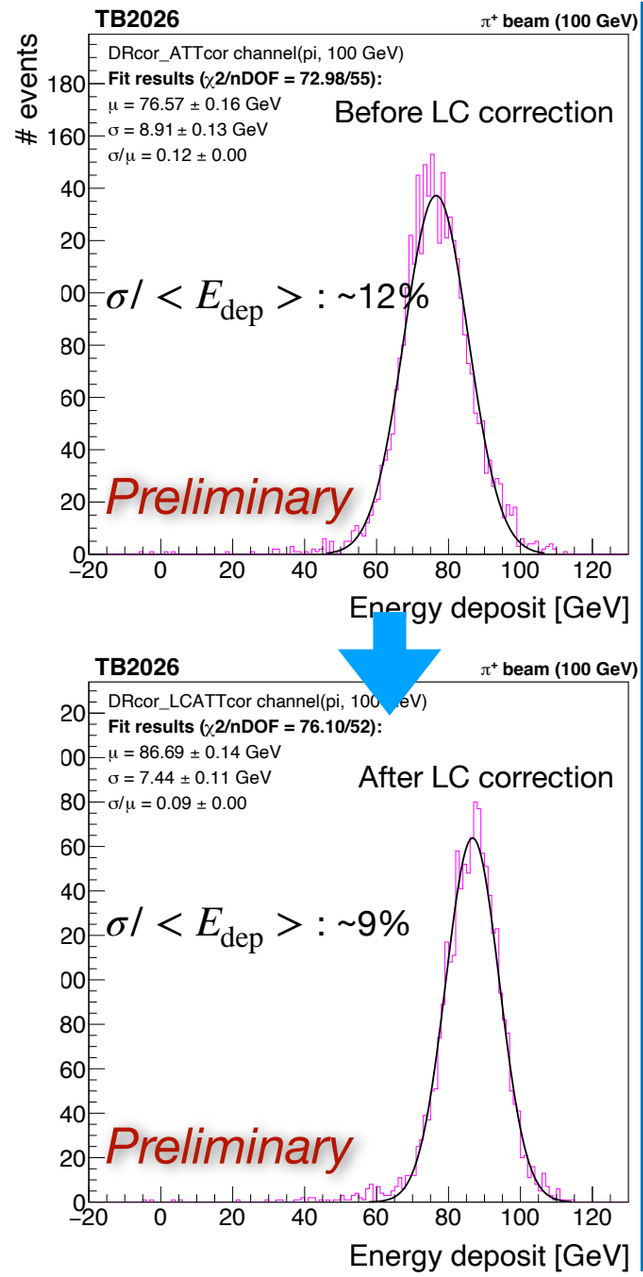


- Total 16 LCs (Plastic scintillator each, 50 x 50 x 12 cm^3) were installed around the DRC

Lateral profile (Data, 60 GeV pion)



- Lateral shower profile was fitted to estimate the average leakage from detector size

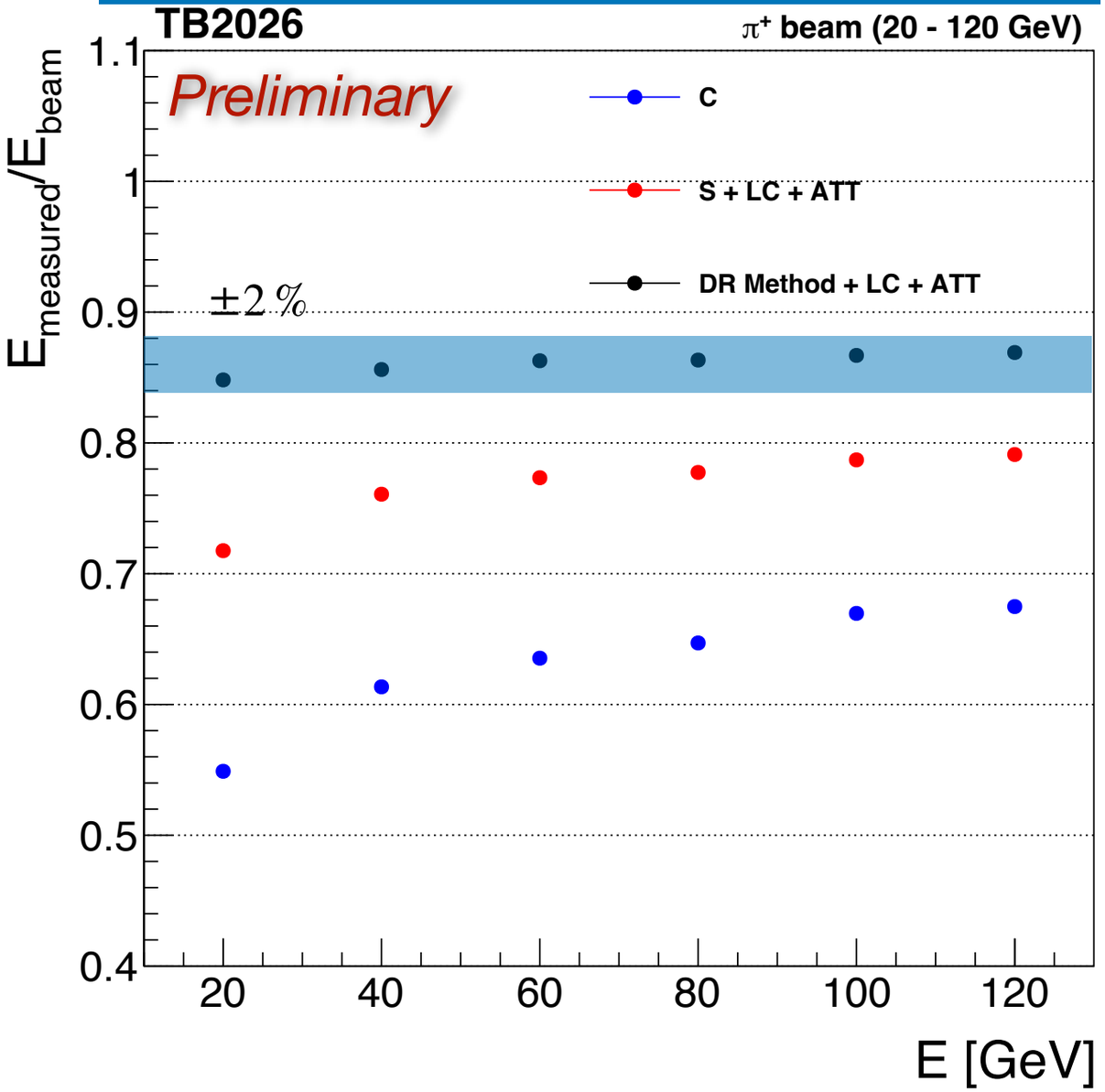


DR corrected energy (100GeV pion)

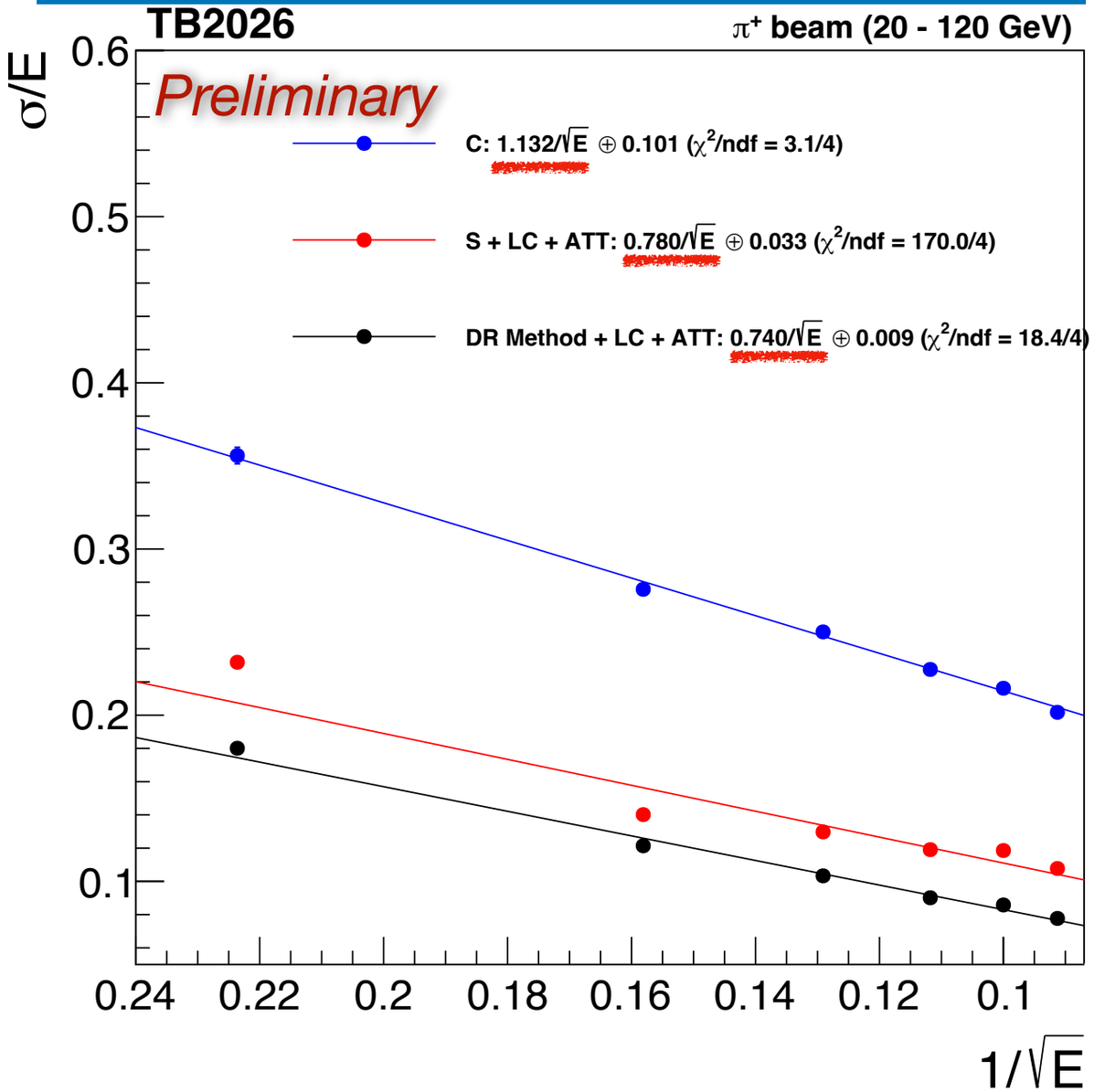
Hadronic Performance (π^+)

- Energy resolution and linearity using 20, 40, 60, 80, 100, 120 GeV π events
- Dual readout(DR)-corrected channel shows linear response for beam energy
- DR-corrected channel presents $\pm 2\,\%$ level linearity **~74%(stoc)** of energy resolution for π

Linearity

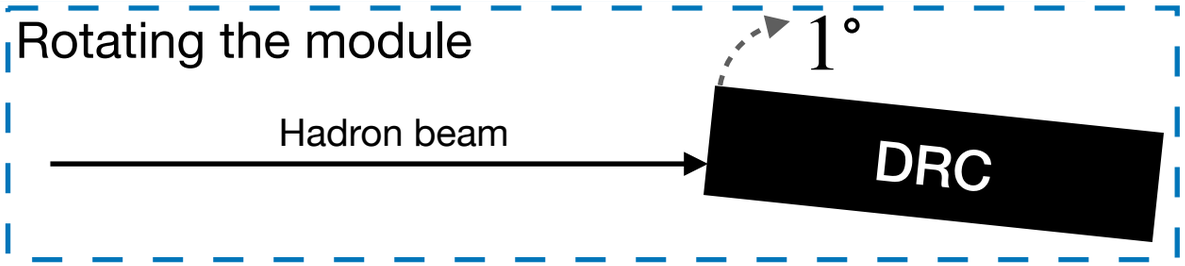


Energy resolution

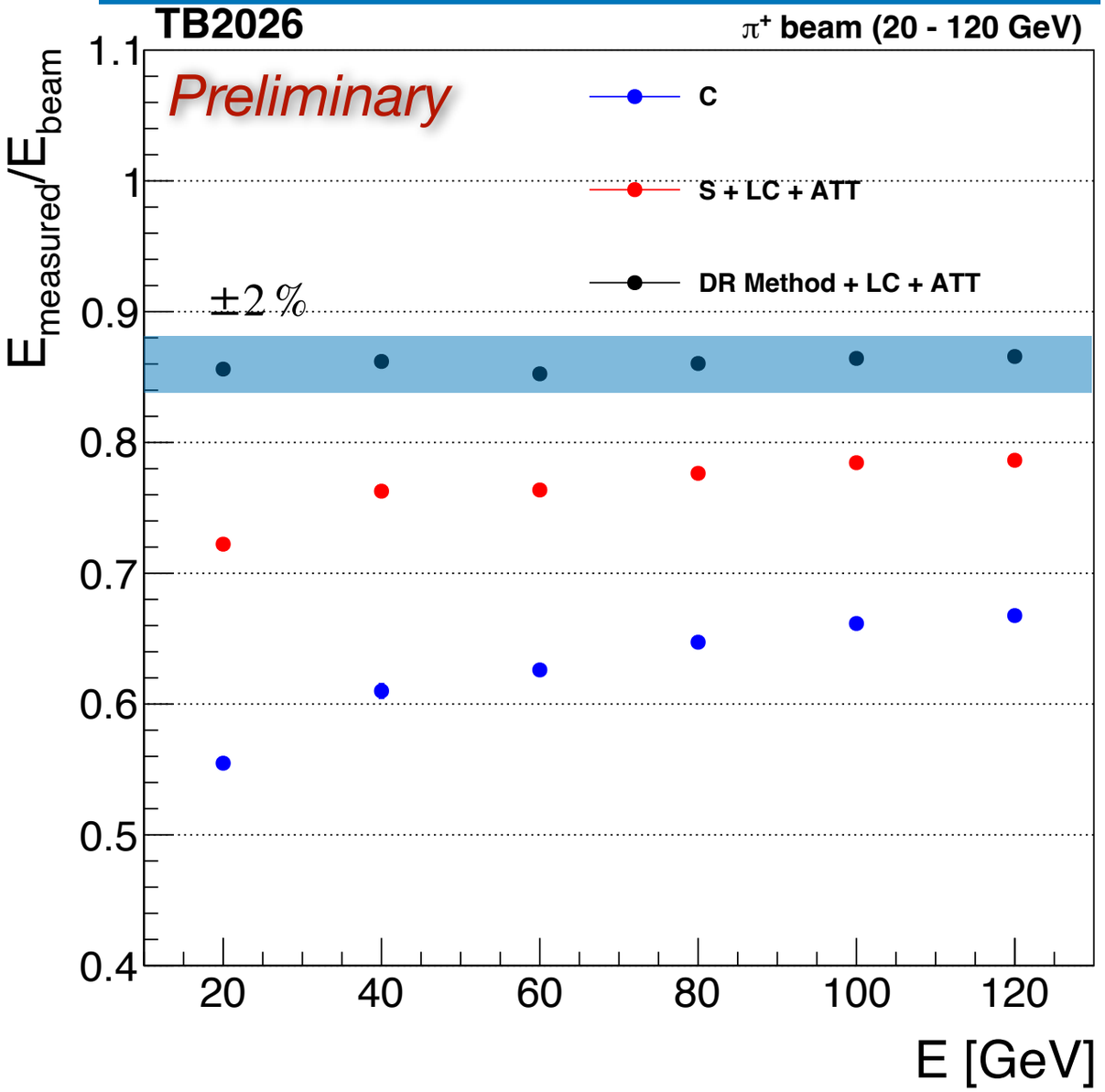


Hadronic Performance (π^+ with rotation)

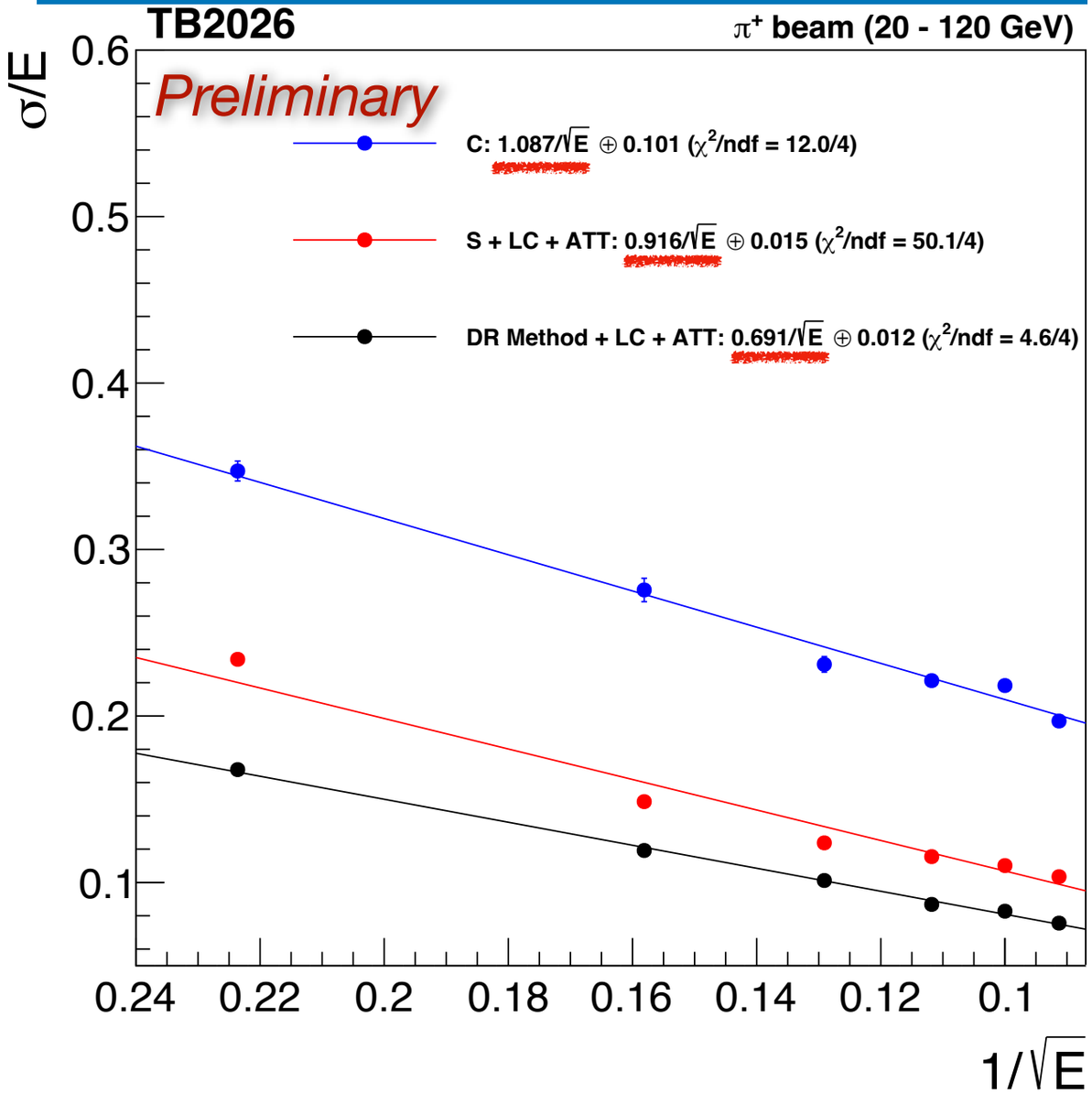
- Same setup, but rotating the module by 1° w.r.t. the beam direction
- DR-corrected channel presents $\pm 2\,\%$ level linearity **~69.1%(stoc)** of energy resolution for π



Linearity



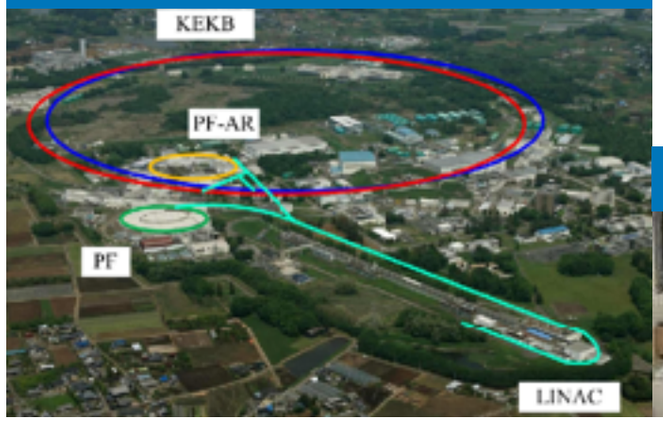
Energy resolution



DRC with Low Energy Beam

- We have also performed other test beam experiment at **KEK**, **PF-AR test beam line**

KEK beam facility



Experimental Hall



- Suitable for low-energy EM performance study
  - Energy range: 0.5 ~ 6.5 GeV
  - Pure electrons with high rate
    - (~10k events per min with DRC setup)
- Will continue DRC test beam studies at KEK and other available facilities

TB2025@KEK

Small prototype module



EM Energy resolution

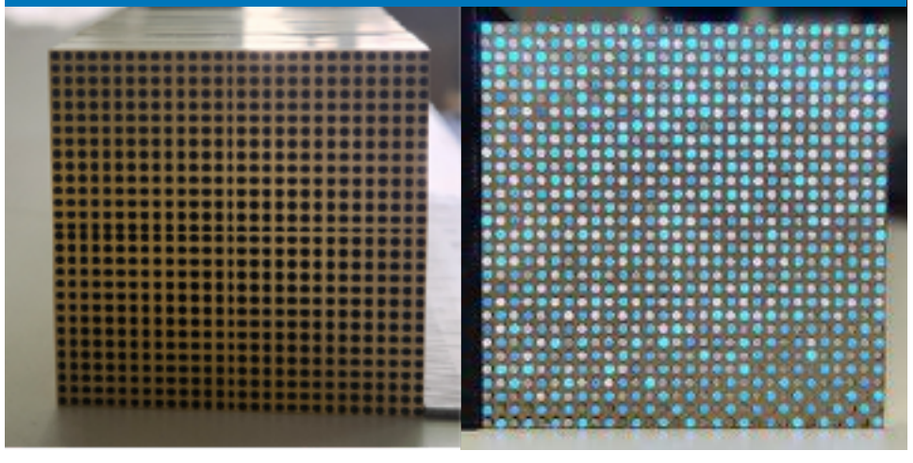
C: $0.000/E + 0.201/\sqrt{E} + 0.001$

S: $0.005/E + 0.145/\sqrt{E} + 0.000$

Sum: $0.007/E + 0.132/\sqrt{E} + 0.000$

TB2026@KEK

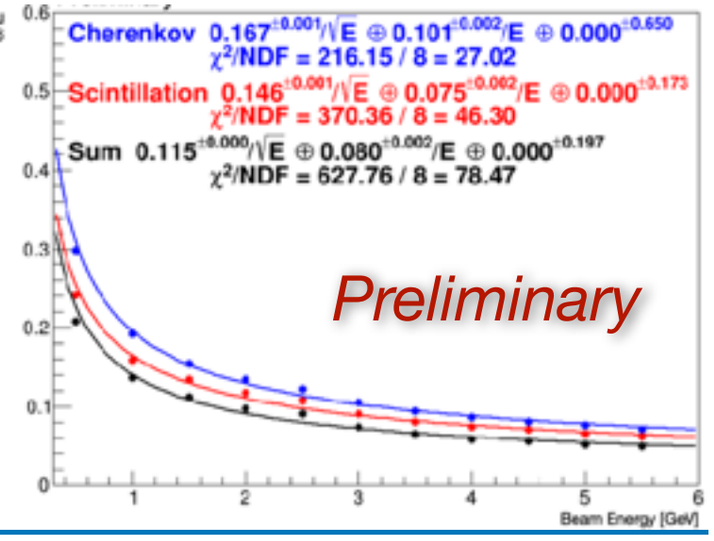
Brass-plate drilling module



C: $0.101/E + 0.167/\sqrt{E} + 0.000$

S: $0.075/E + 0.146/\sqrt{E} + 0.000$

Sum: $0.080/E + 0.115/\sqrt{E} + 0.000$

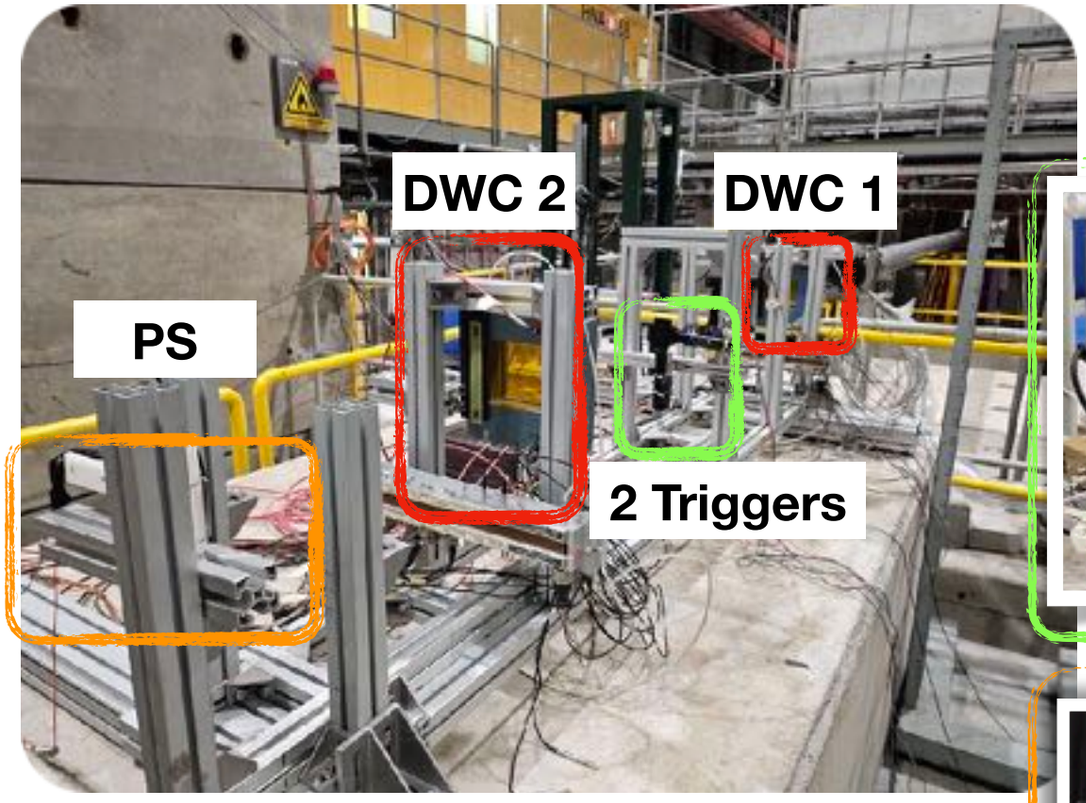


Summary

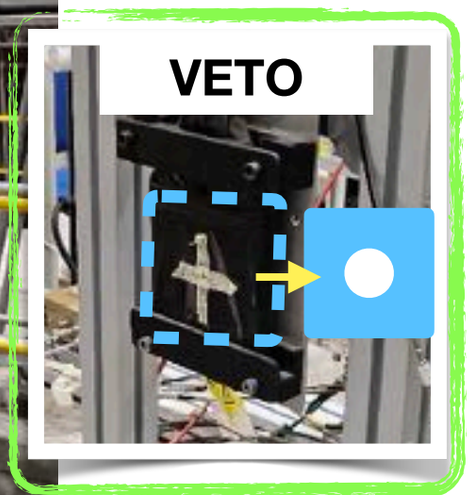
- Dual-Readout Calorimeter is the one of the strong candidate for the future collider
- Korea DRC team has been developing Cu-fiber DRC, performing test beam since 2022
- TB2026 @ CERN SPS
  - Achieved ± 1.5 % linearity and ~12.7%/$\sqrt{E}$ of resolution for EM,
  - ± 2 % linearity and **~74%** (without rotation) and **~69.1%** (with rotation) of resolution for π
- More analyses (position resolution, timing performance, uniformity, etc.) are ongoing

Backup

Auxiliary Detectors



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

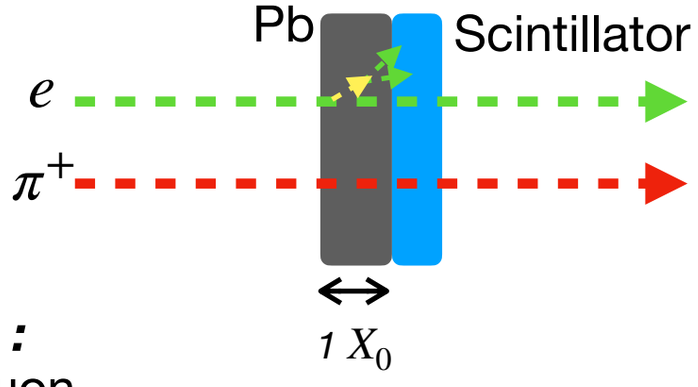


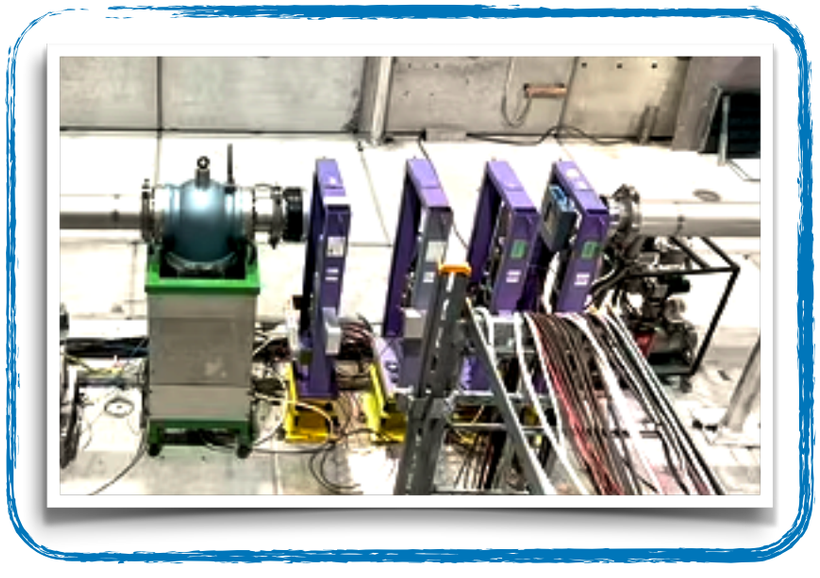
VETO, Trigger (VETO, T1, T2) :
Plastic scintillator, Trigger(veto)-ing events

- Upgraded PMTs for better time resolution



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





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

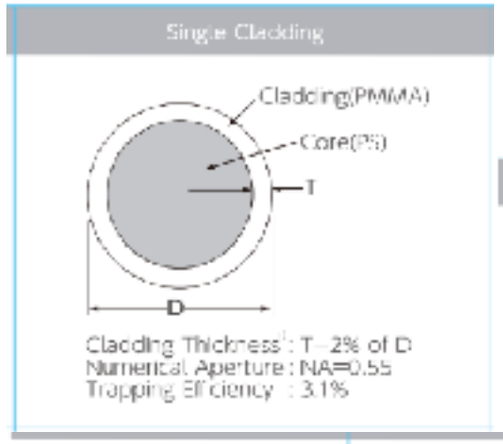
- By adjusting *gas pressure*, one can change the type of particle emitting Cherenkov light

$$v_p > c/n$$

$$(n = Refractive\ Index)$$

Optical fiber specification

Scintillating Fiber : SCSF-78

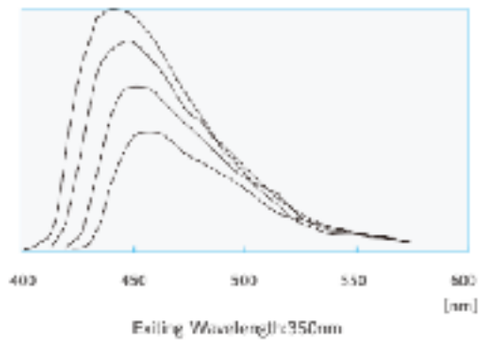


Description	Emission Color	Emission Spectra	Emission Peak[nm]	Decay Time [ns]	Att.Length [m]
SCSF-78	blue	Kuraray	450	2.8	>4.0

Core		Polystyrene(PS)	n=1.59	1.05	C: 4.9x10²⁰ H: 4.9x10²⁰
Cladding	for single cladding inner for multi-cladding	Polymethylmethacrylate (PMMA)	n=1.49	1.19	C: 3.6x10²⁰ H: 5.7x10²⁰ O: 1.4x10²⁰

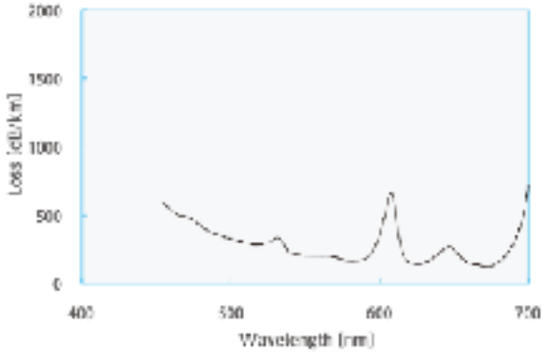
Emission Spectra

SCSF-78



Transmission Loss

SCSF-78

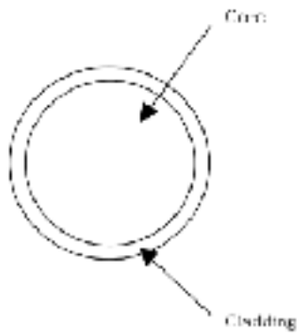


Cherenkov (Clear) Fiber : SK-40

Table 1

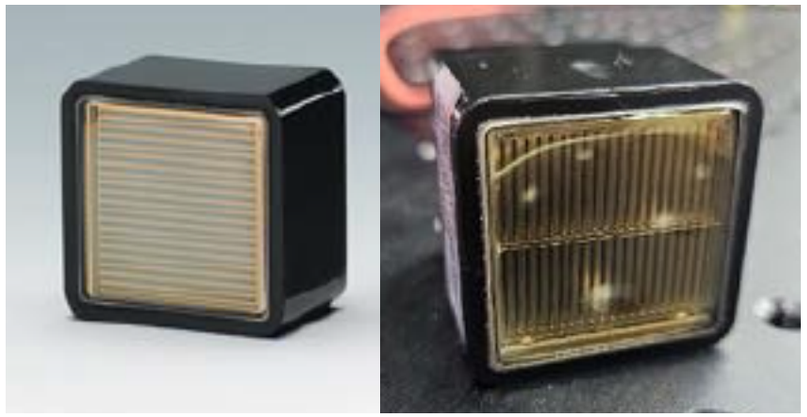
Item			SK-40 Specification		
		Unit	Min.	Typ.	Max.
Optical Fiber 1	Core Material	–	Polymethyl-Methacrylate Resin		
	Cladding Material		Fluorinated Polymer		
	Core Refractive Index	–	1.49		
	Refractive Index Profile	–	Step Index		
	Numerical Aperture	–	0.5		
	Core Diameter	μm	920	980	1,040
	Cladding Diameter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

Sectional View



Photomultiplier specification

Hamamatsu R11265-100



PMT	Window	Max HV	Rise time
R11265-1	23x23	1000 V	1.3 ns

Figure 1: Typical spectral response

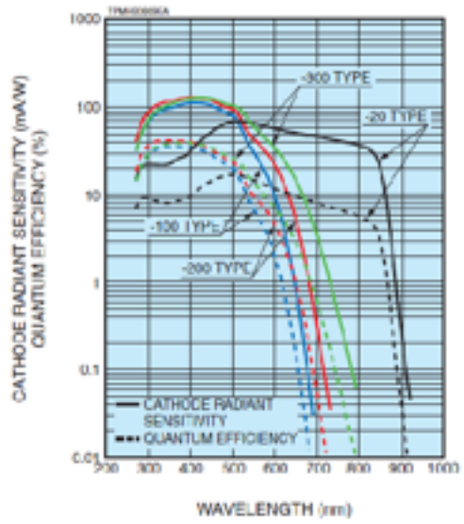
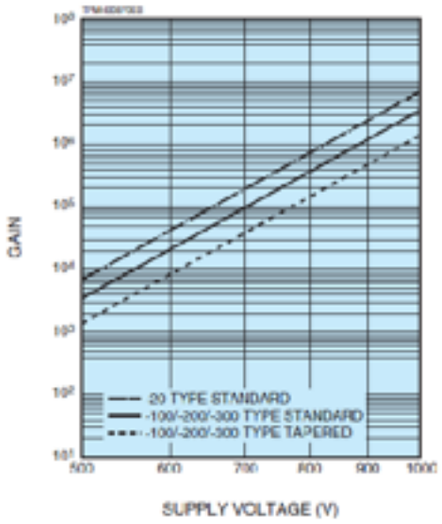
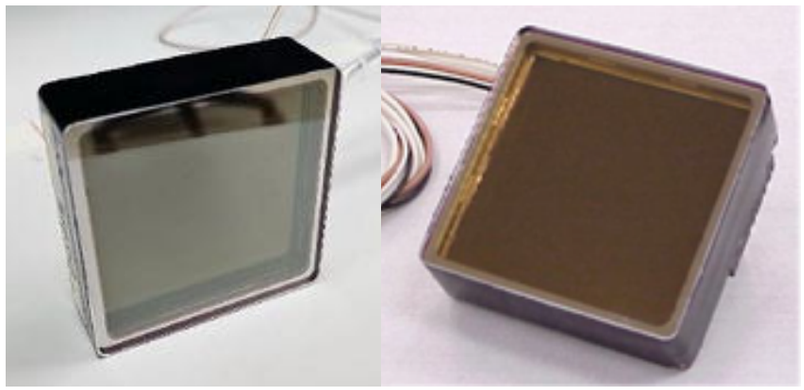


Figure 2: Typical gain

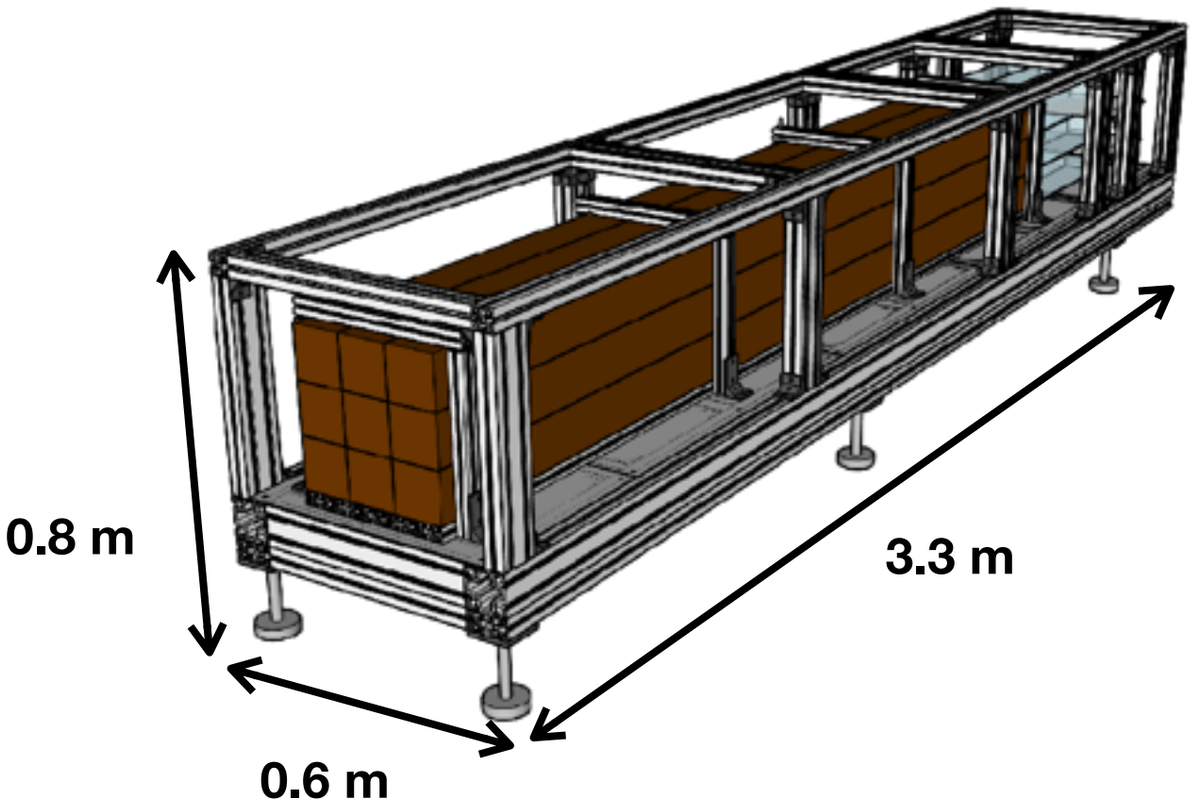


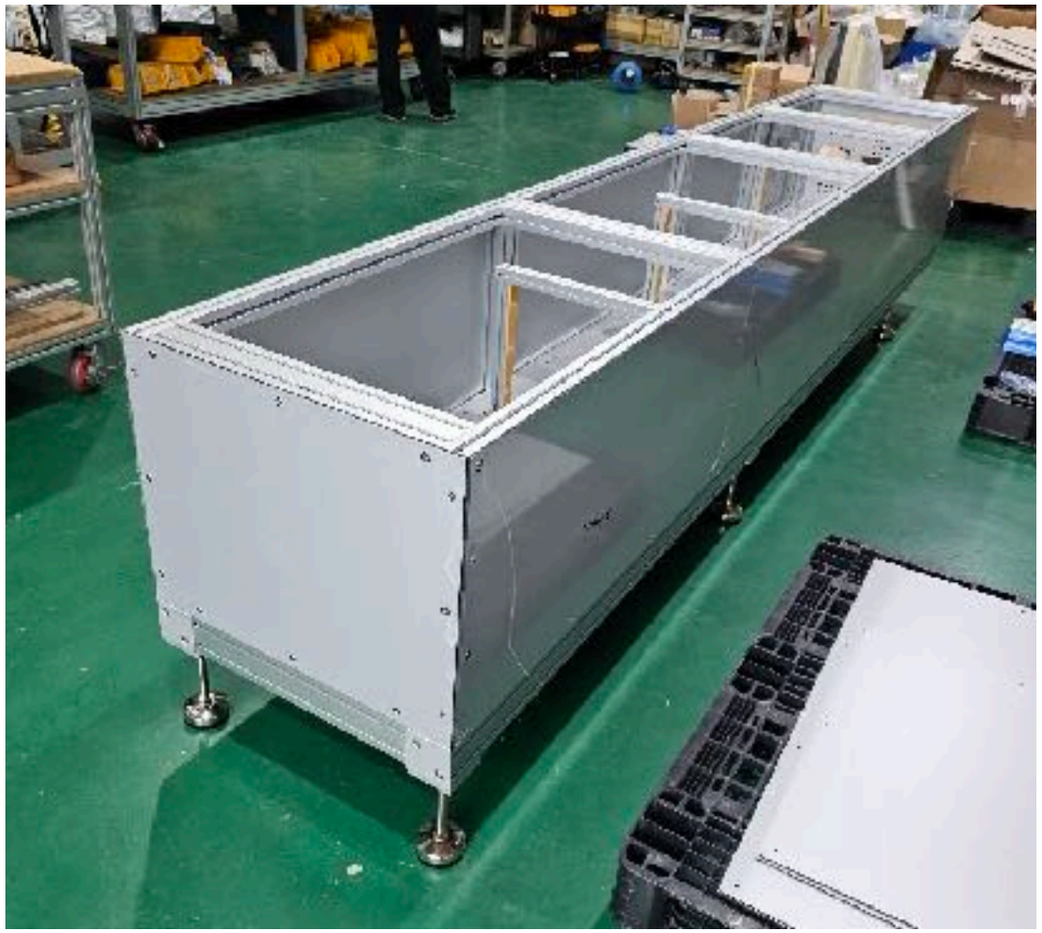
PLANACON XP85012, XP85112



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

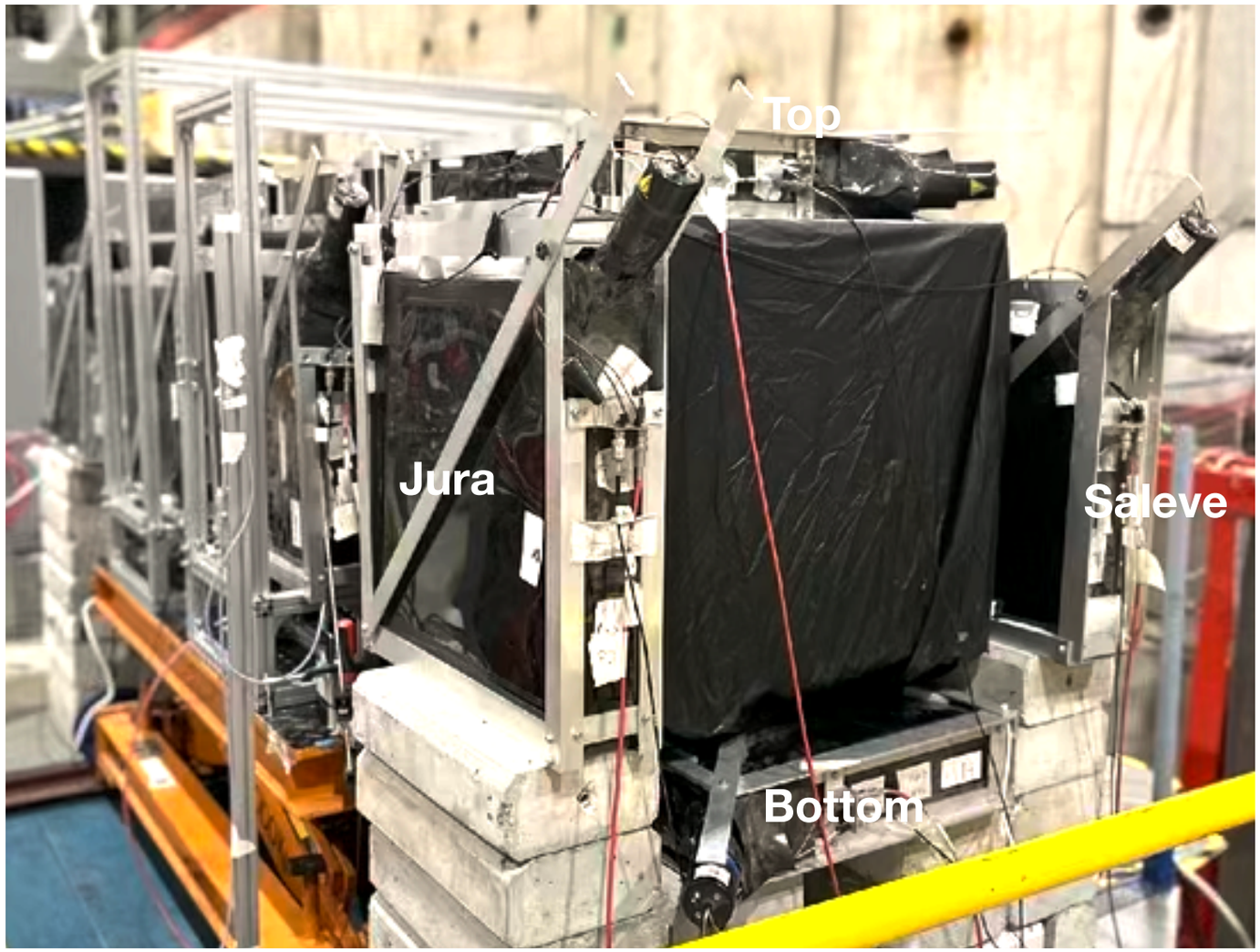
Mechanical Supporter





Corrections: Leakage Counter Correction

- Leakage counter is composed of a large scintillator(50x50x12cm)
- Calibrated at each 4 points (Jura, saleve, top, bottom) using 110GeV muon beam



Muons in polystyrene $[(C_6H_5CHCH_2)_n]$

$\langle Z/A \rangle$	ρ [g/cm^3]	I [eV]	a	$k = m_s$	x_0	x_1	$\overline{C}$	δ_0
0.53768	1.060	68.7	0.16454	3.2224	0.1647	2.5031	3.2999	0.00

T	p [MeV/c]	Ionization	Brems	Pair prod	Photonucl	Total	CSDA range [g/cm^2]
		[MeV cm^2/g]					
10.0 MeV	4.704×10^1	7.803				7.803	7.077×10^{-1}
14.0 MeV	5.616×10^1	6.084				6.084	1.294×10^0
20.0 MeV	6.802×10^1	4.749				4.749	2.424×10^0
30.0 MeV	8.509×10^1	3.683				3.683	4.848×10^0
40.0 MeV	1.003×10^2	3.144				3.144	7.806×10^0
80.0 MeV	1.527×10^2	2.359				2.359	2.296×10^1
100. MeV	1.764×10^2	2.210				2.211	3.174×10^1
140. MeV	2.218×10^2	2.058				2.058	5.059×10^1
200. MeV	2.868×10^2	1.970				1.971	8.049×10^1
300. MeV	3.917×10^2	1.937			0.000	1.937	1.318×10^2
318. MeV	4.105×10^2	1.936			0.000	1.936	*Minimum ionization*
400. MeV	4.945×10^2	1.942			0.000	1.943	1.834×10^2
800. MeV	8.995×10^2	2.015	0.000		0.000	2.015	3.856×10^2
1.00 GeV	1.101×10^3	2.048	0.000		0.000	2.049	4.841×10^2
1.40 GeV	1.502×10^3	2.102	0.000		0.001	2.103	6.767×10^2
2.00 GeV	2.103×10^3	2.161	0.000	0.000	0.001	2.163	9.578×10^2
3.00 GeV	3.104×10^3	2.228	0.001	0.001	0.001	2.231	1.413×10^3
4.00 GeV	4.104×10^3	2.275	0.001	0.001	0.002	2.279	1.856×10^3
8.00 GeV	8.105×10^3	2.382	0.003	0.003	0.004	2.391	3.564×10^3
10.0 GeV	1.011×10^4	2.414	0.004	0.004	0.005	2.427	4.394×10^3
14.0 GeV	1.411×10^4	2.461	0.006	0.006	0.007	2.480	6.023×10^3
20.0 GeV	2.011×10^4	2.509	0.009	0.010	0.009	2.538	8.413×10^3
30.0 GeV	3.011×10^4	2.560	0.015	0.018	0.014	2.607	1.230×10^4
40.0 GeV	4.011×10^4	2.596	0.021	0.027	0.018	2.662	1.609×10^4
80.0 GeV	8.011×10^4	2.677	0.049	0.065	0.035	2.825	3.065×10^4
100. GeV	1.001×10^5	2.702	0.063	0.086	0.043	2.895	3.764×10^4
140. GeV	1.401×10^5	2.740	0.093	0.130	0.059	3.022	5.116×10^4
200. GeV	2.001×10^5	2.779	0.141	0.199	0.084	3.203	7.044×10^4

- Interpolate 110GeV value
- 2.93 $MeVcm^2/g$ * 1.060 g/cm^3 -> 3.103 MeV/cm
- 3.103 * 50 = 155.15 MeV
- Equalization constant = $\frac{155.15}{intADC}$

Corrections: χ Value Determination

- Iterative method
- Initial value
  - $(h/e)_S = 0.8, (h/e)_C = 0.2$

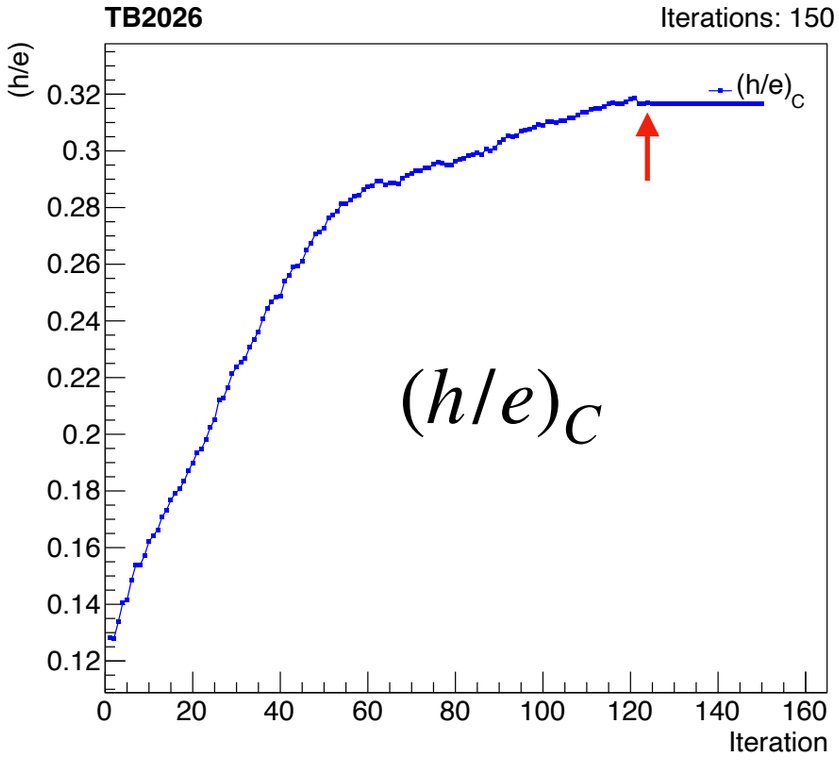
(1) Calculate f_{em} using the current $(h/e)_S$, $(h/e)_C$ values

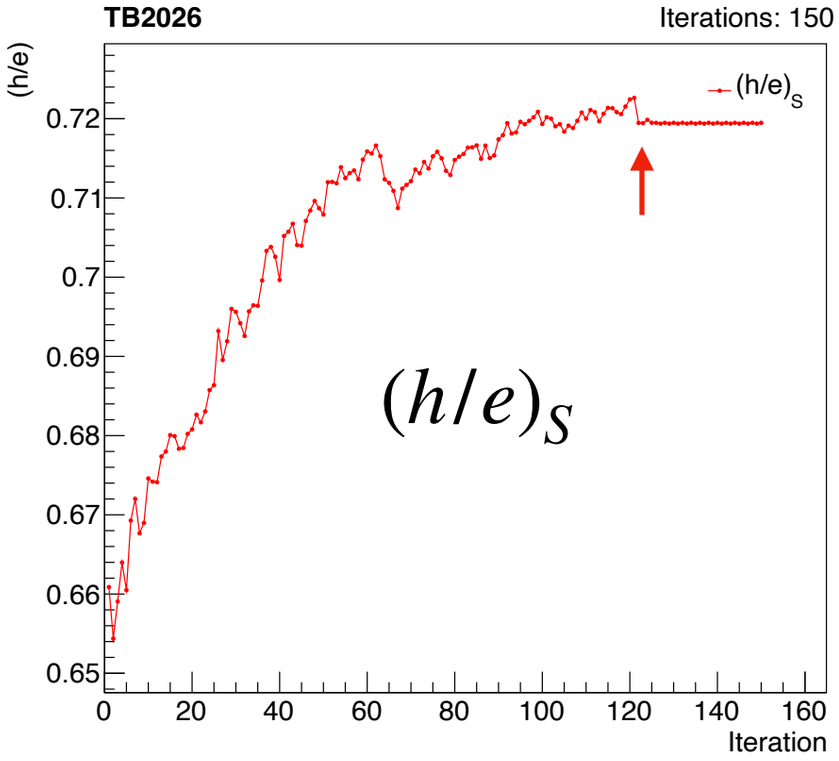
(2) Fill 2D histogram of S vs f_{em} and C vs f_{em}, then extract the mean S and C in each f_{em} bin

(3) Fit each profile with a linear function

- Since $p_0 = E(h/e)$, $p_1 = E(1-(h/e)$, obtain $h/e = \dfrac{p_0}{(p_0 + P_1)}$
- Calculate χ and use the update $(h/e)_S$, $(h/e)_C$

(4) Repeat until convergence

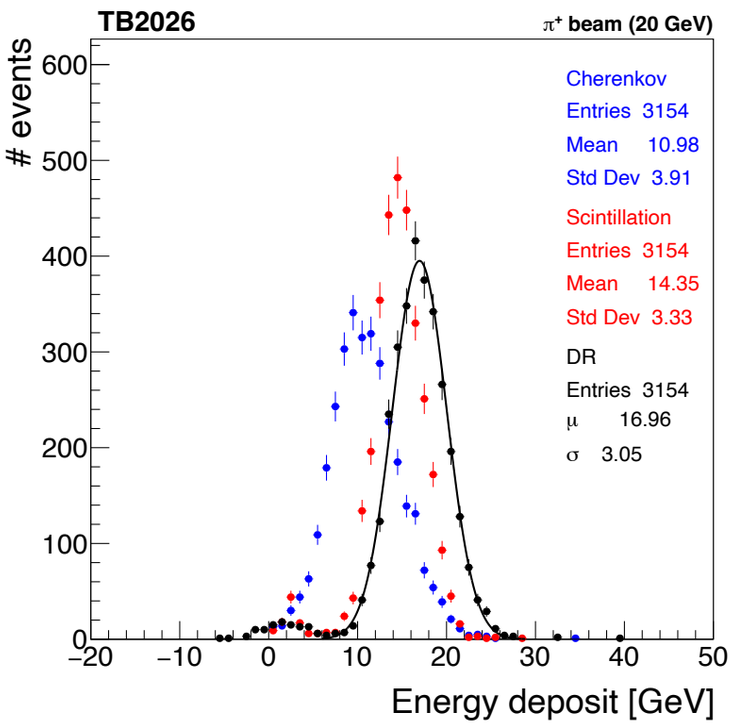




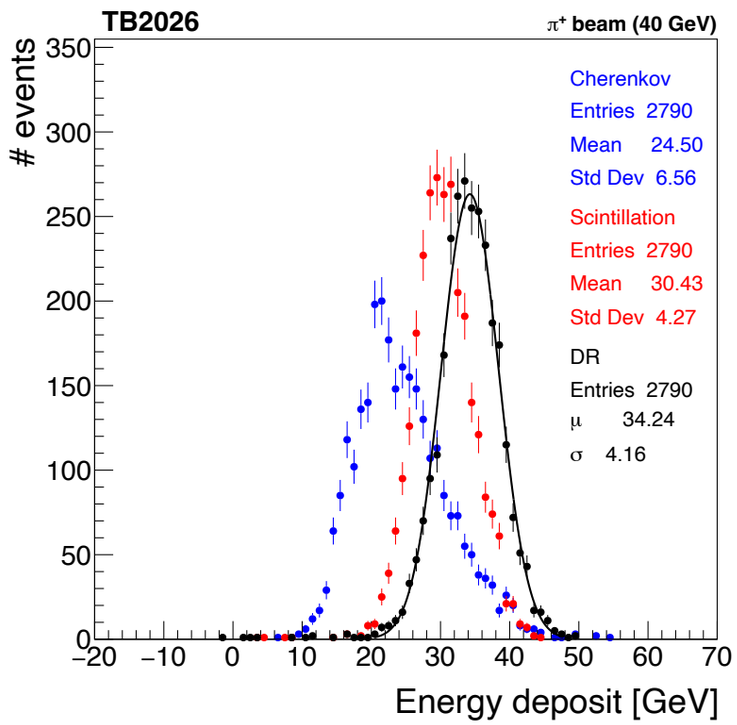
- From 127th iteration, (h/e) is converged
- $(h/e)_S = 0.7195$
- $(h/e)_C = 0.3167$
- $\chi = 0.411$ (used for DR method)

Pion: Energy Deposit Distribution

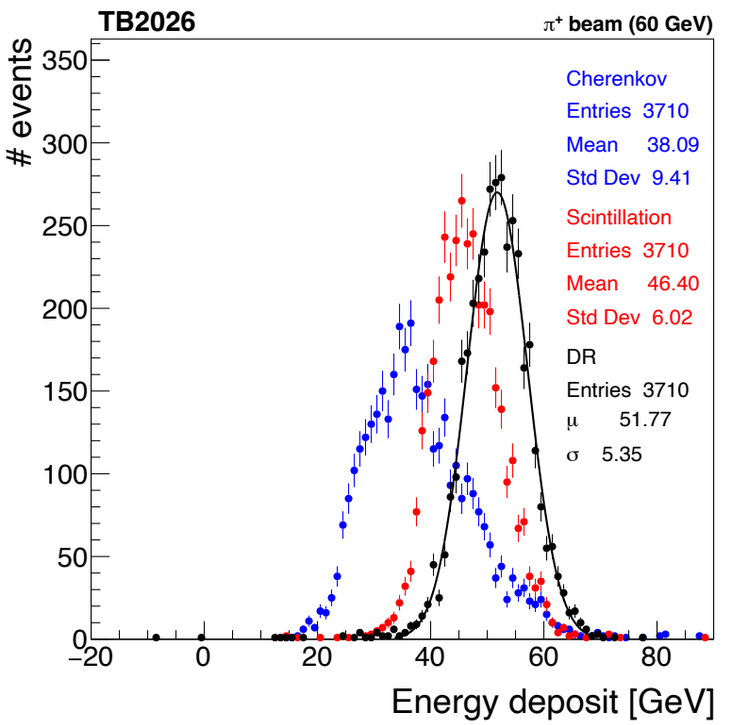
20 GeV



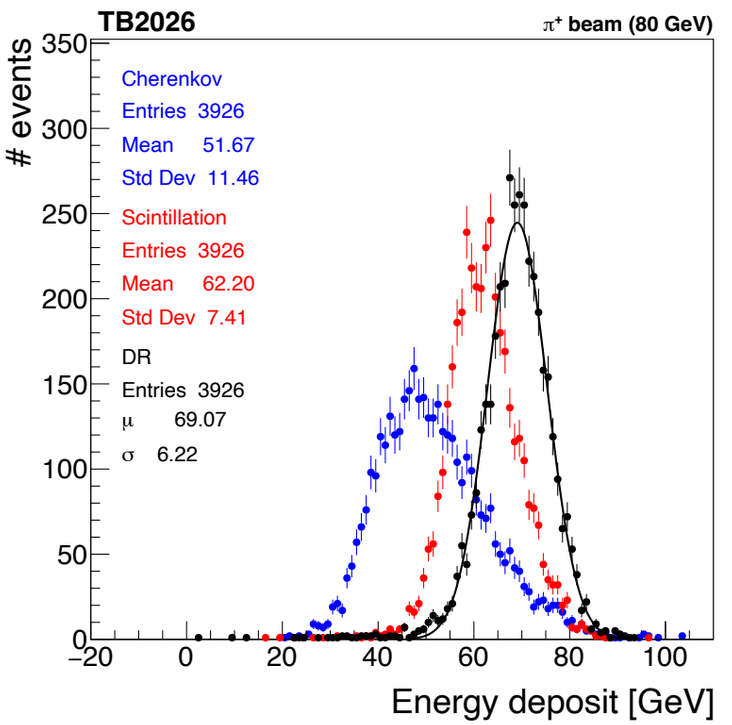
40 GeV



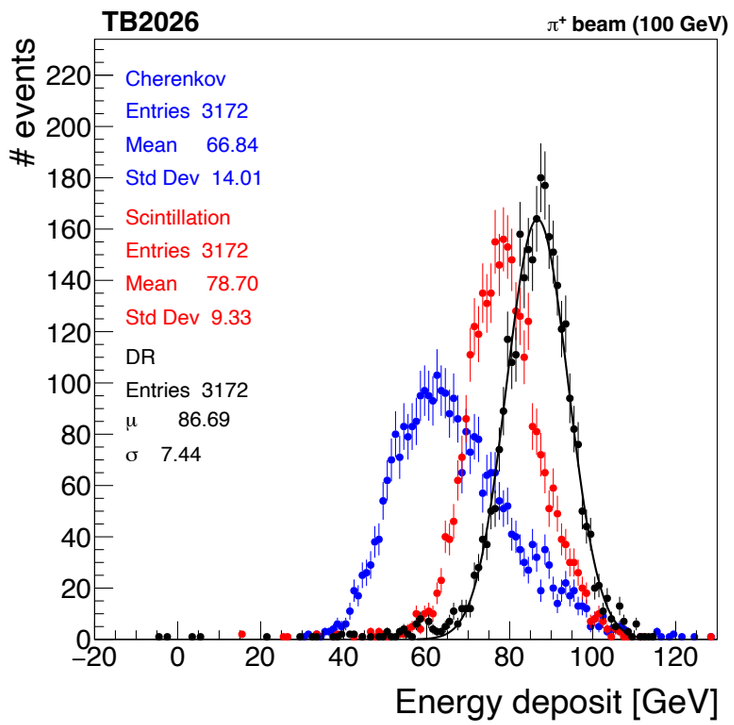
60 GeV



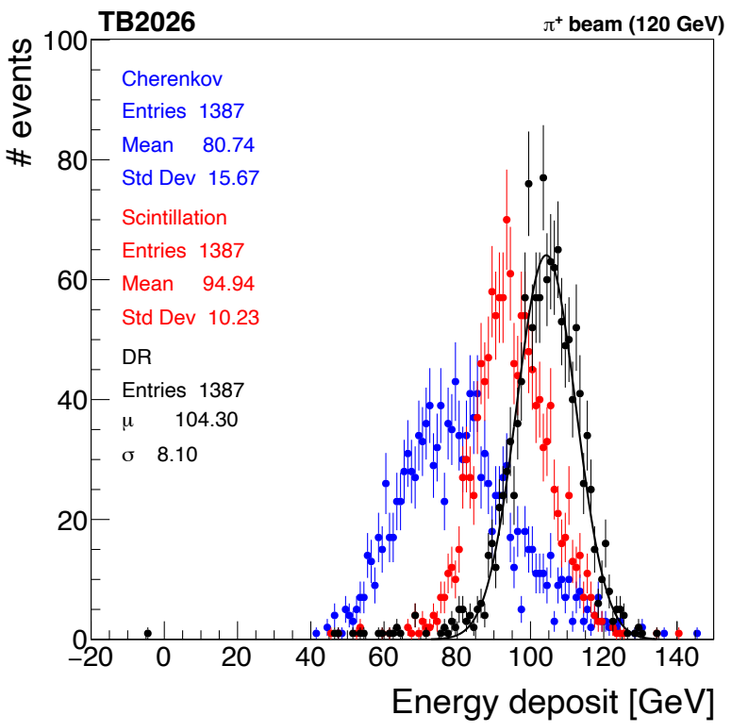
80 GeV



100 GeV

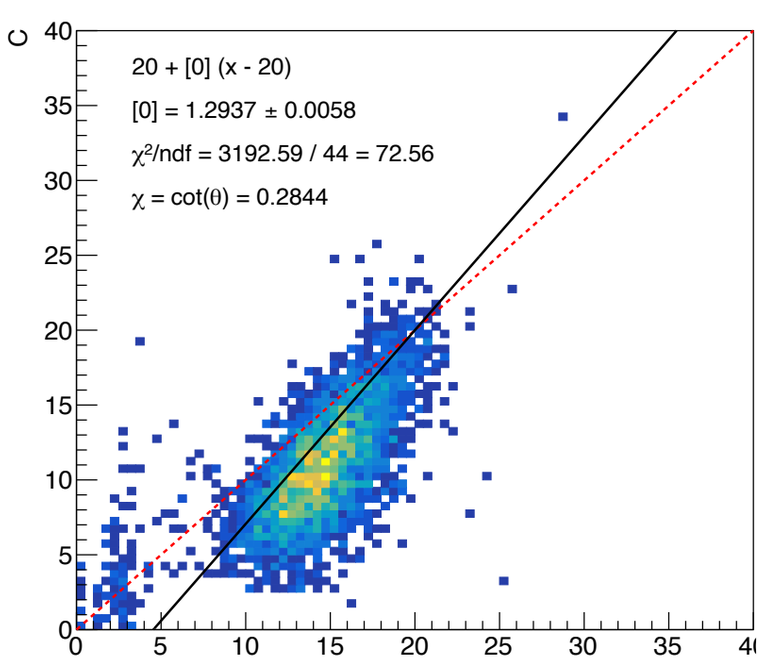


120 GeV

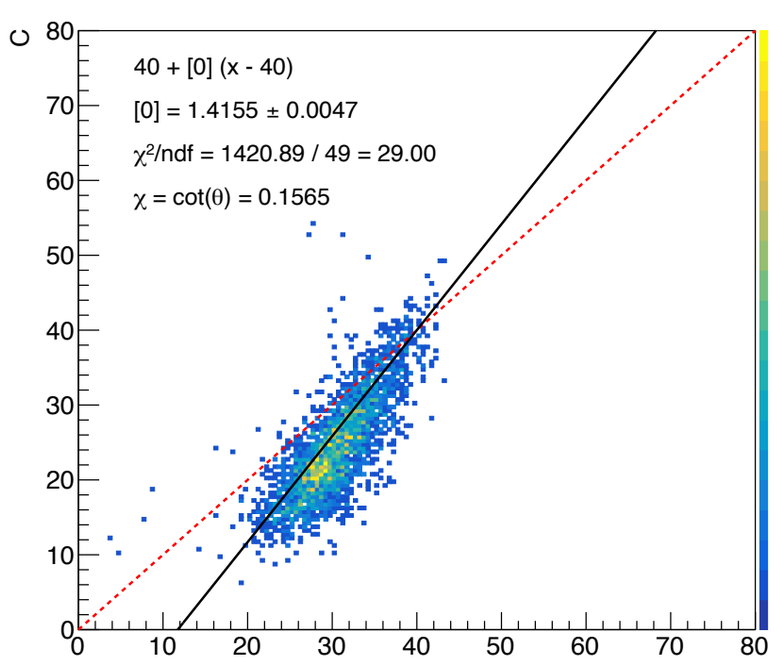


Pion: S vs C

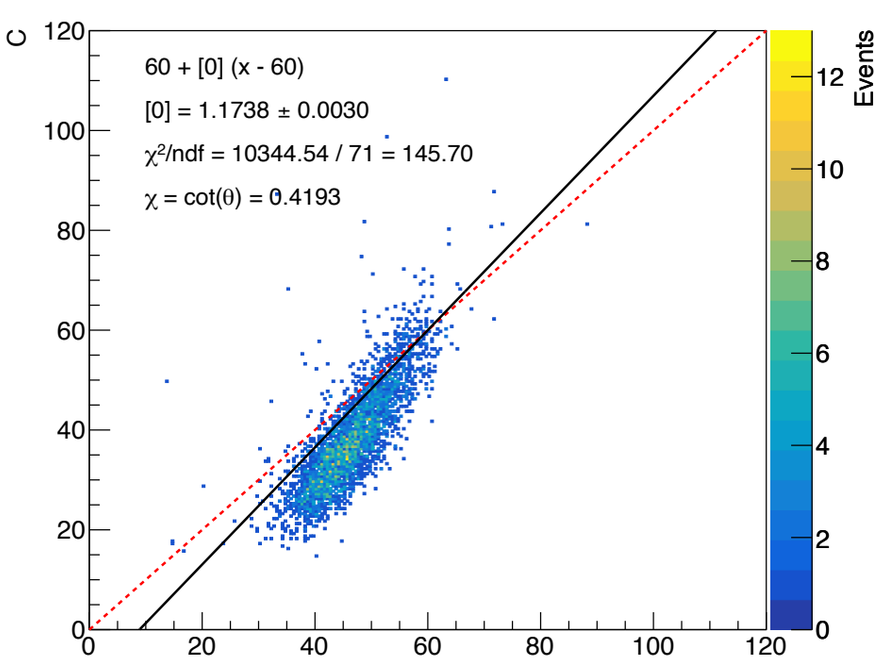
20 GeV



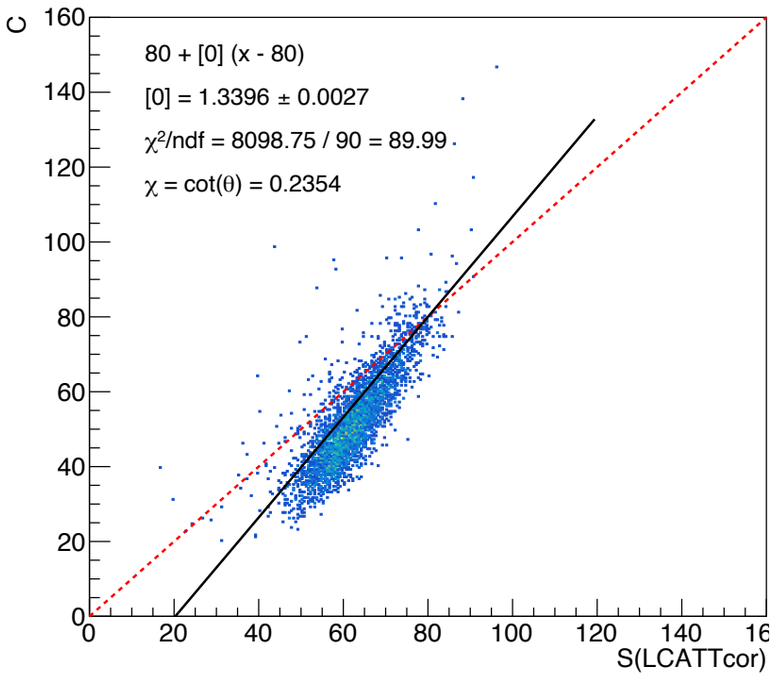
40 GeV



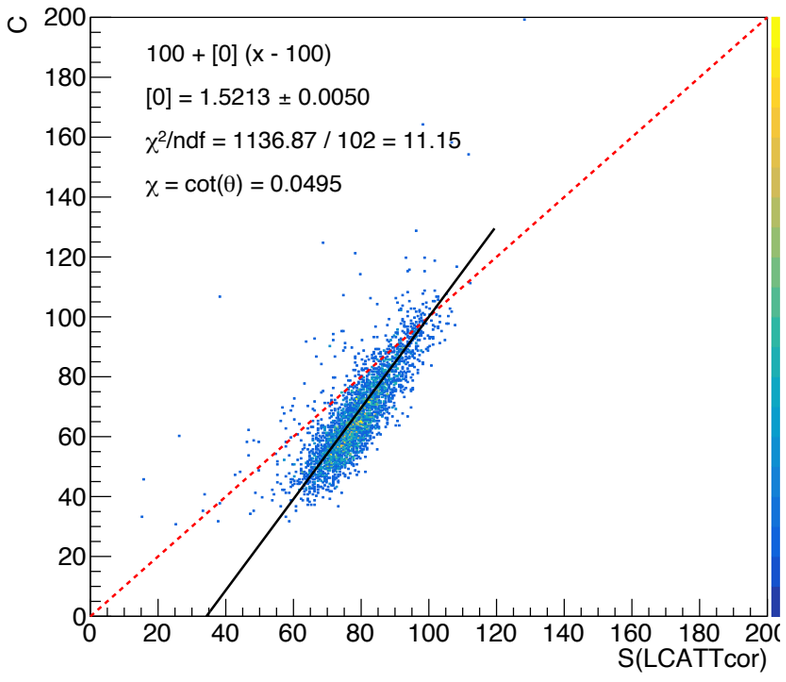
60 GeV



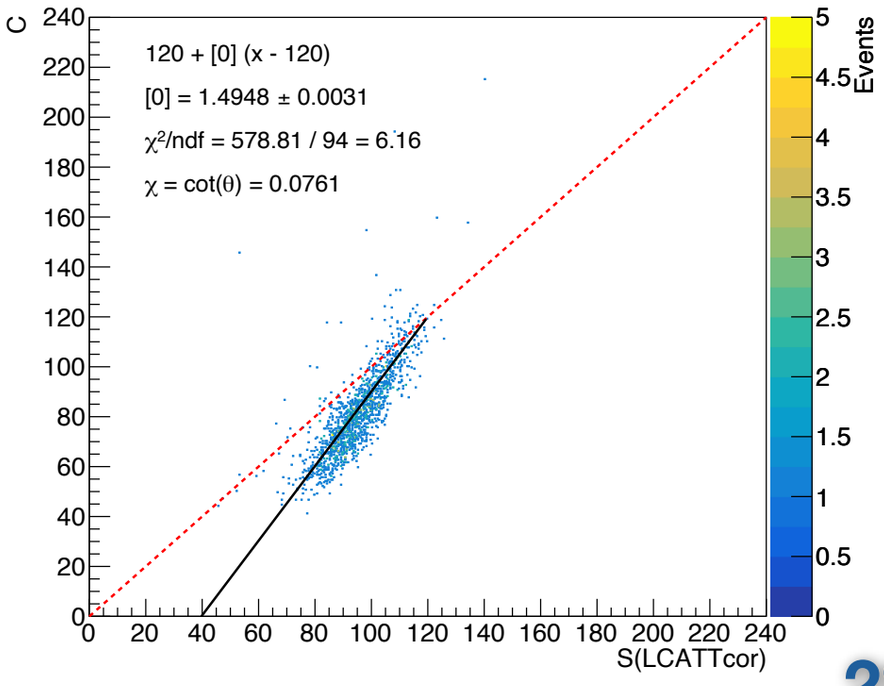
80 GeV



100 GeV

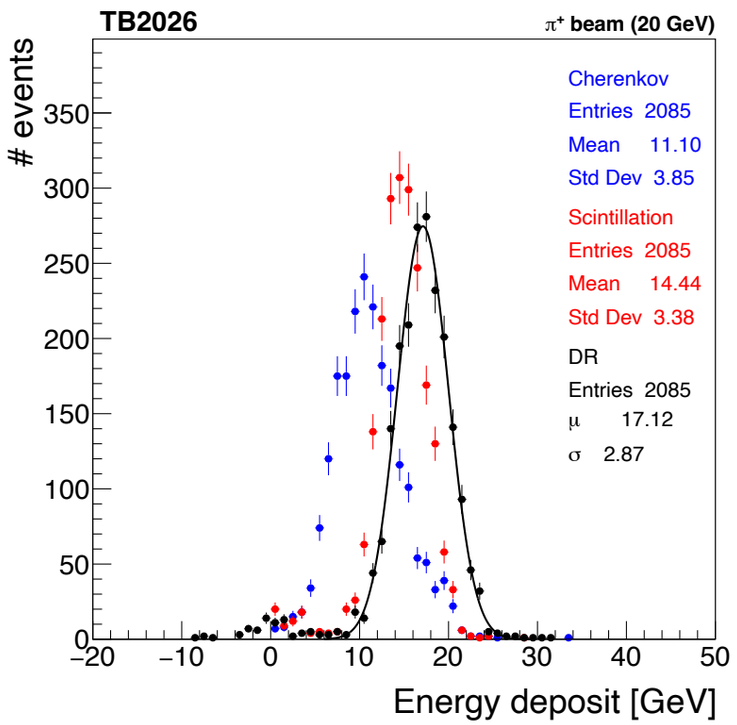


120 GeV

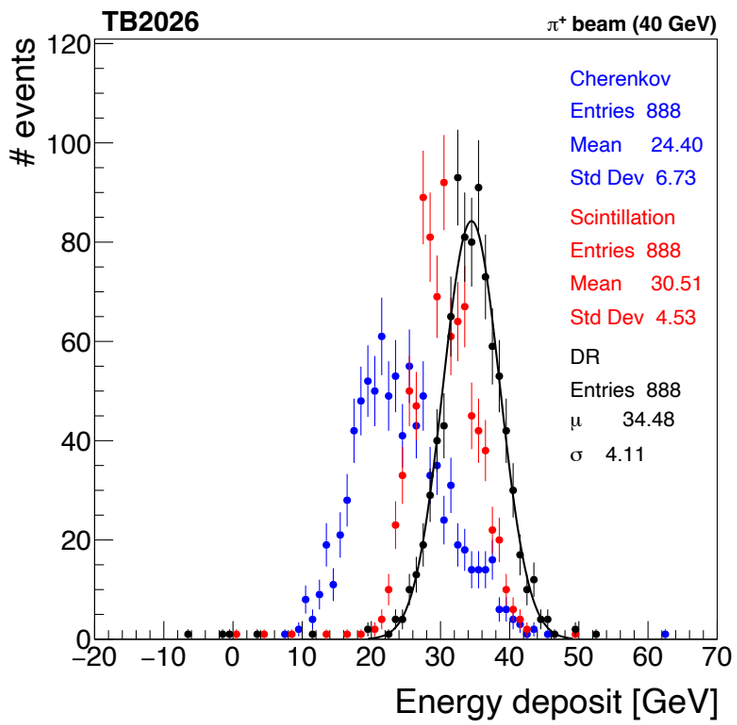


Pion: Energy Deposit Distribution (w/ rotation)

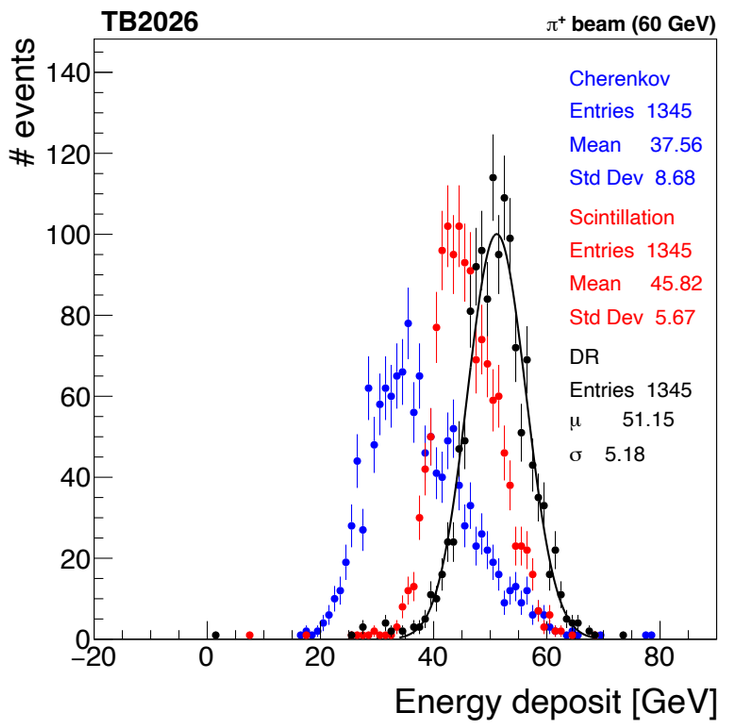
20 GeV



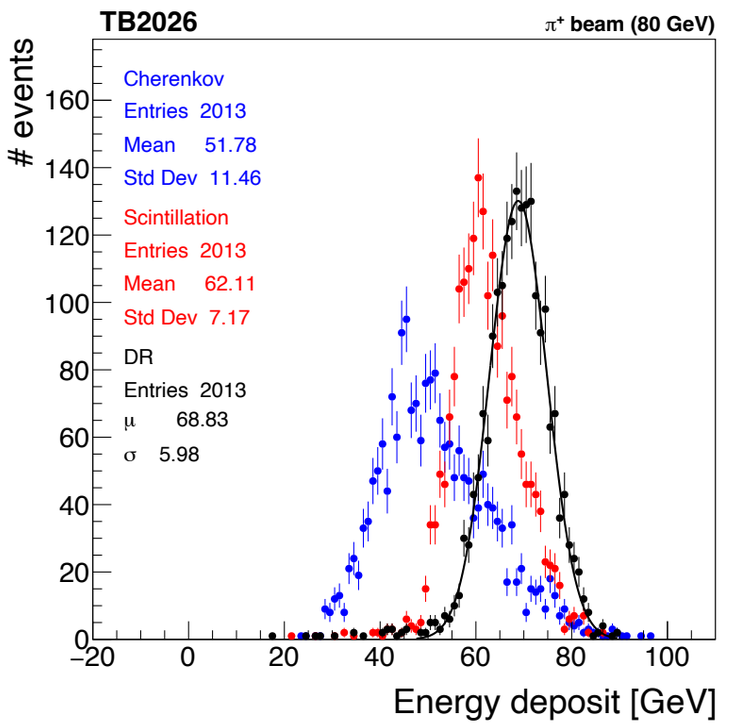
40 GeV



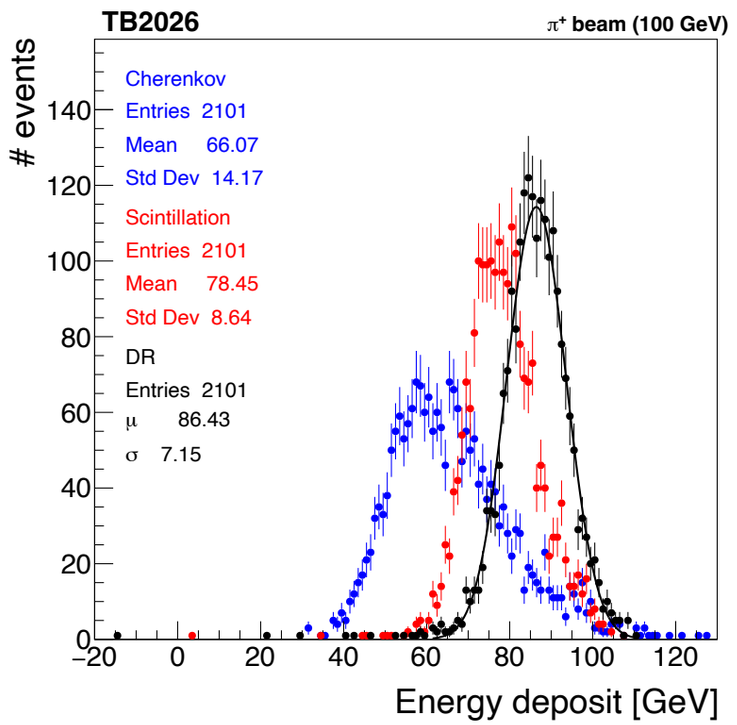
60 GeV



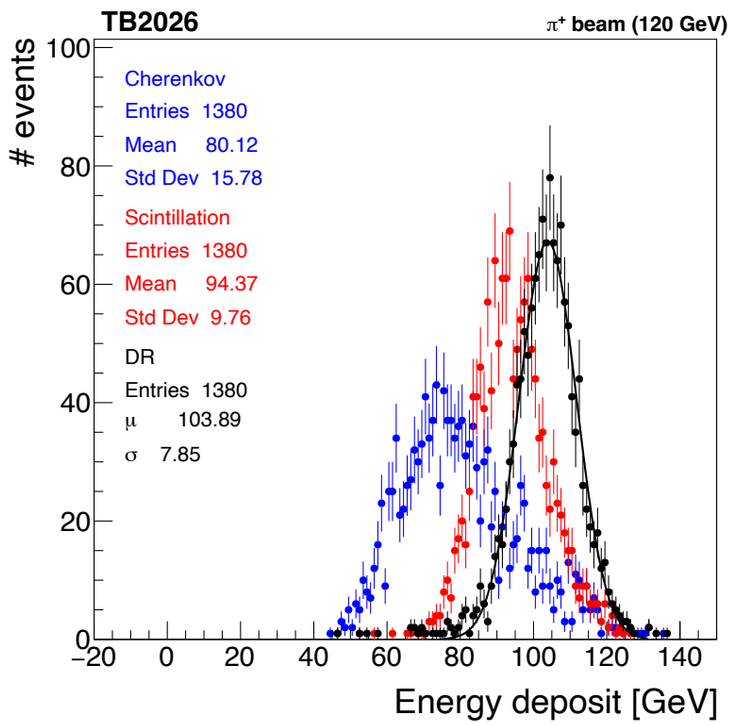
80 GeV



100 GeV

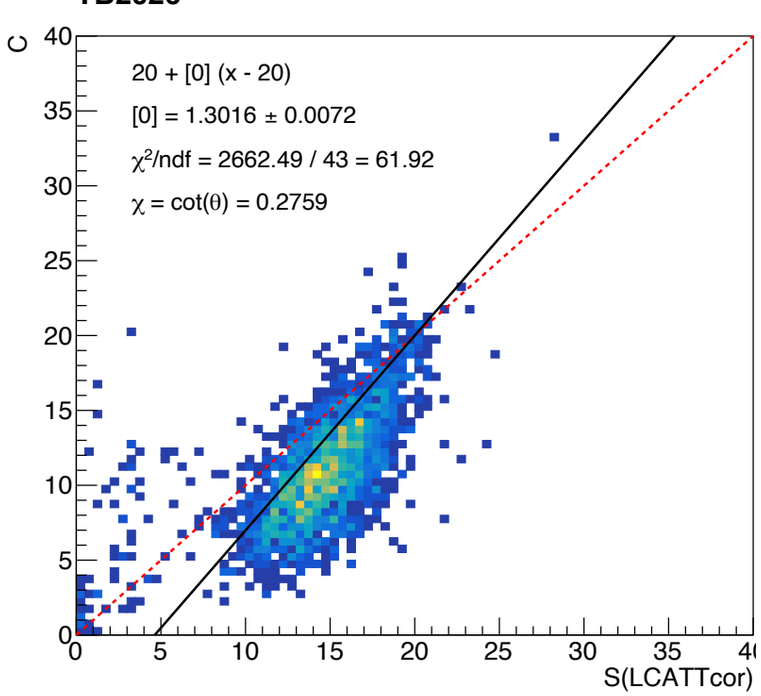


120 GeV

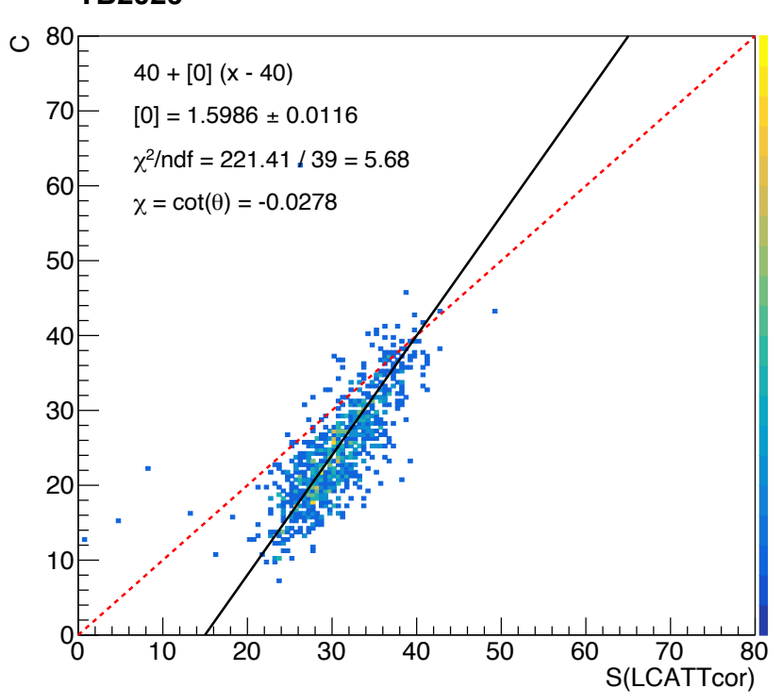


Pion: S vs C (w/ rotation)

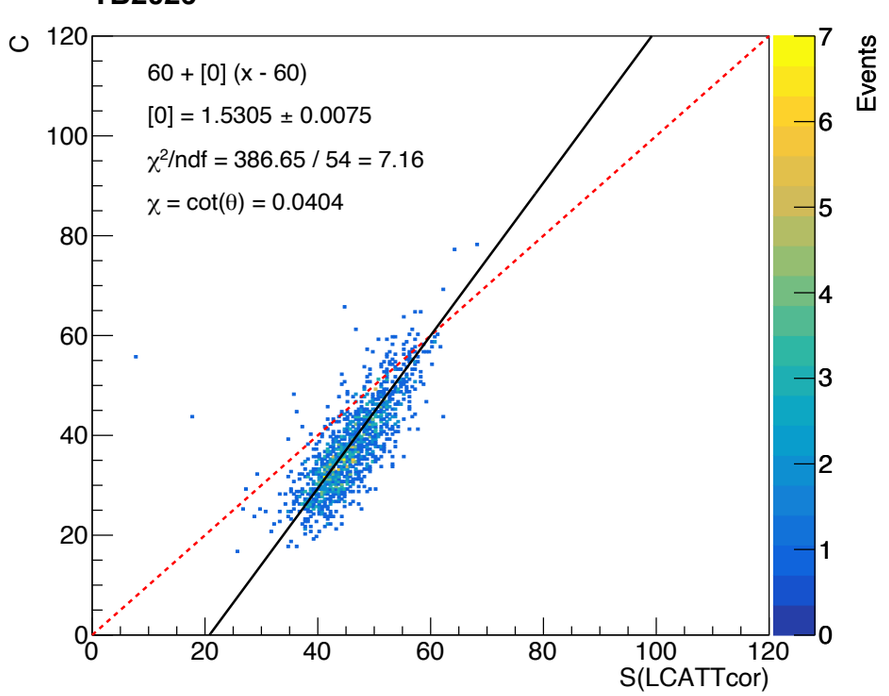
20 GeV



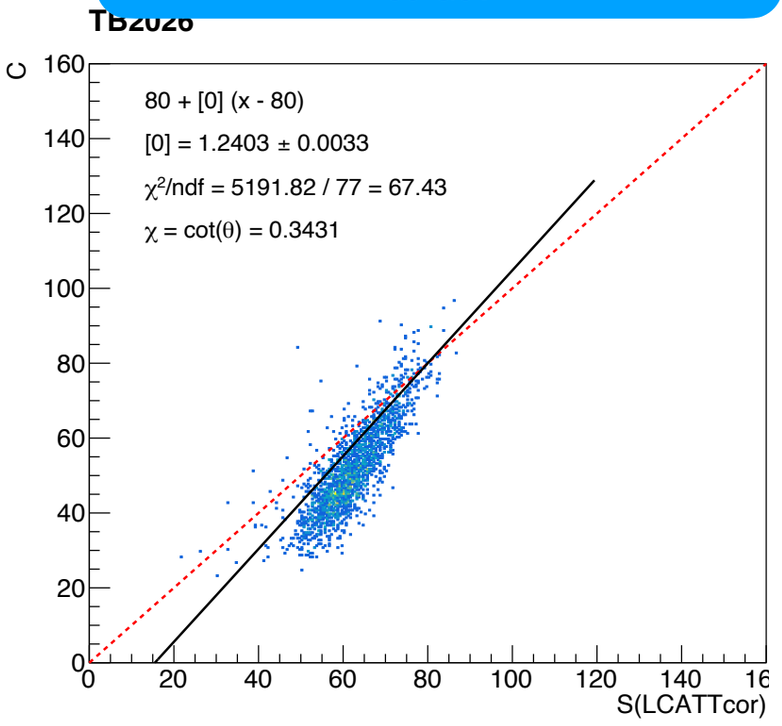
40 GeV



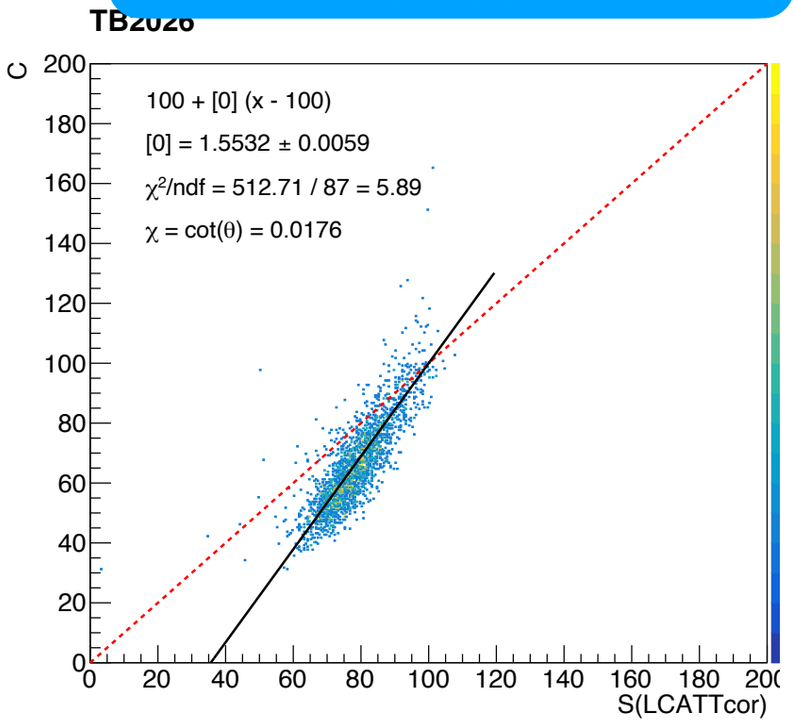
60 GeV



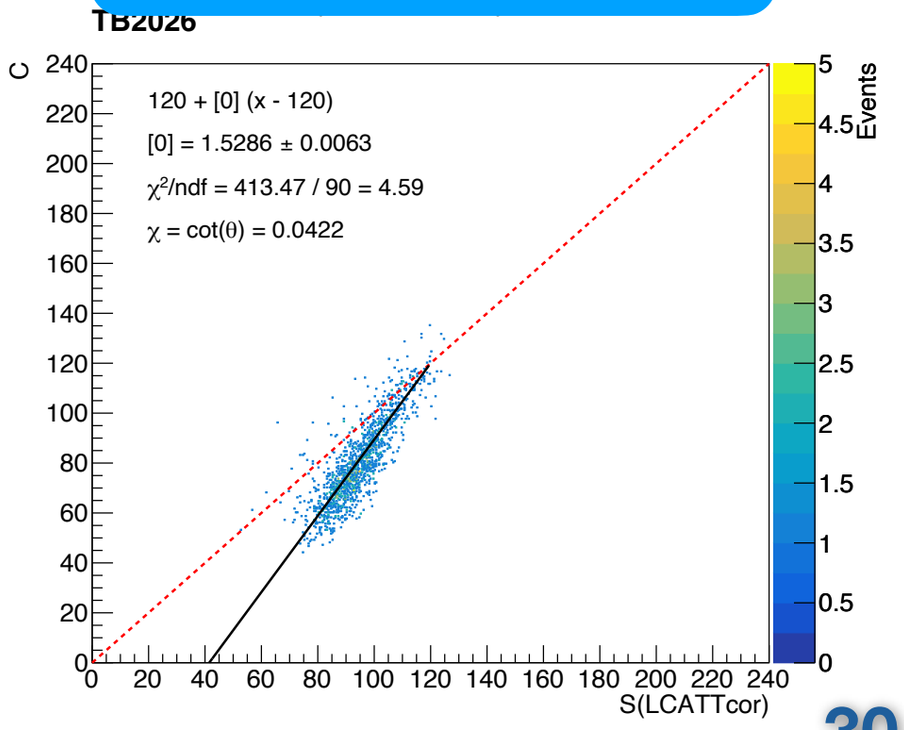
80 GeV



100 GeV

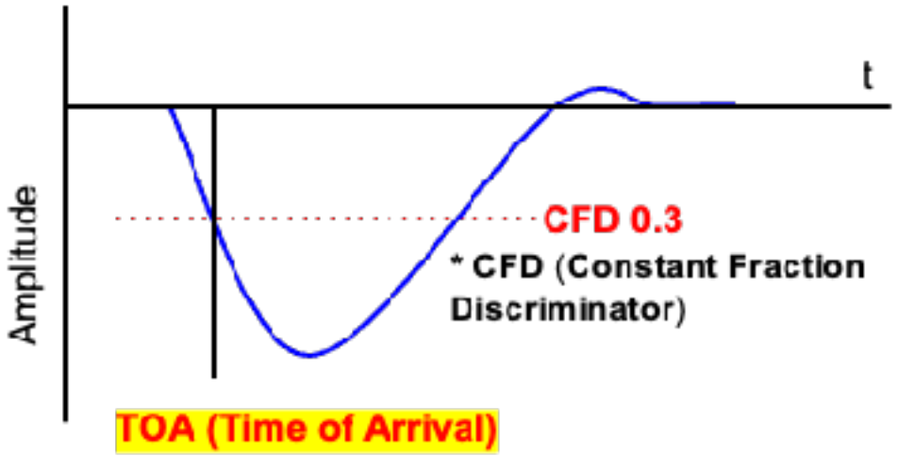


120 GeV



Ongoing Studies (i)

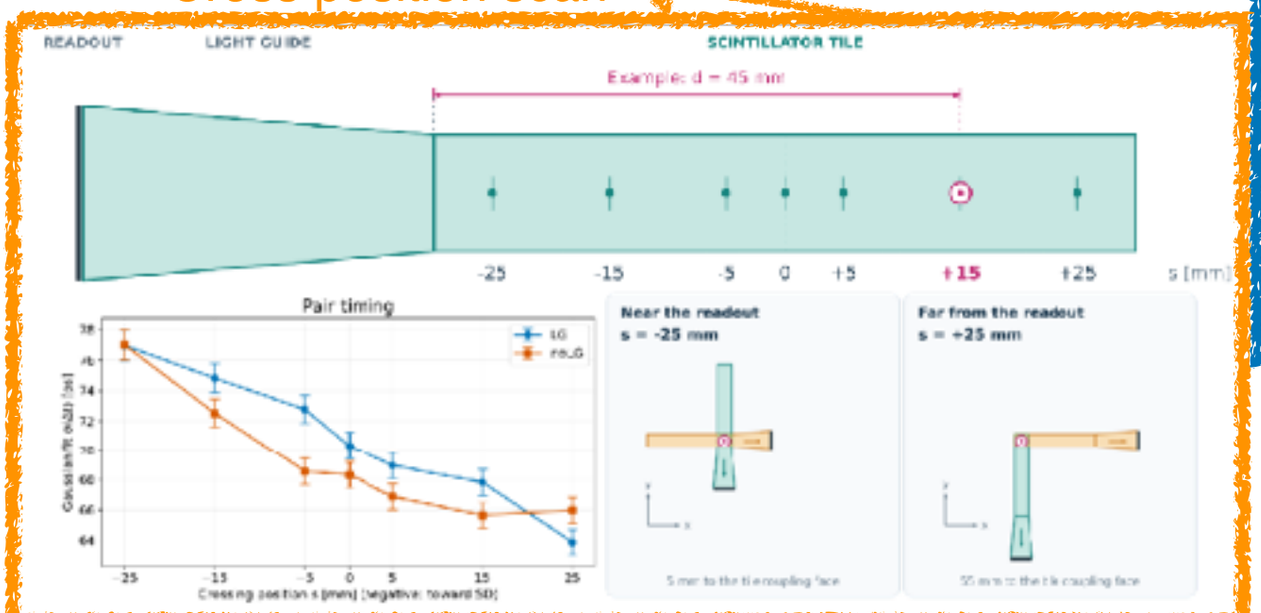
- **Trigger timing performance with simulation**
  - Timing resolution represents the precision of a detector in measuring the time of a particle's arrival

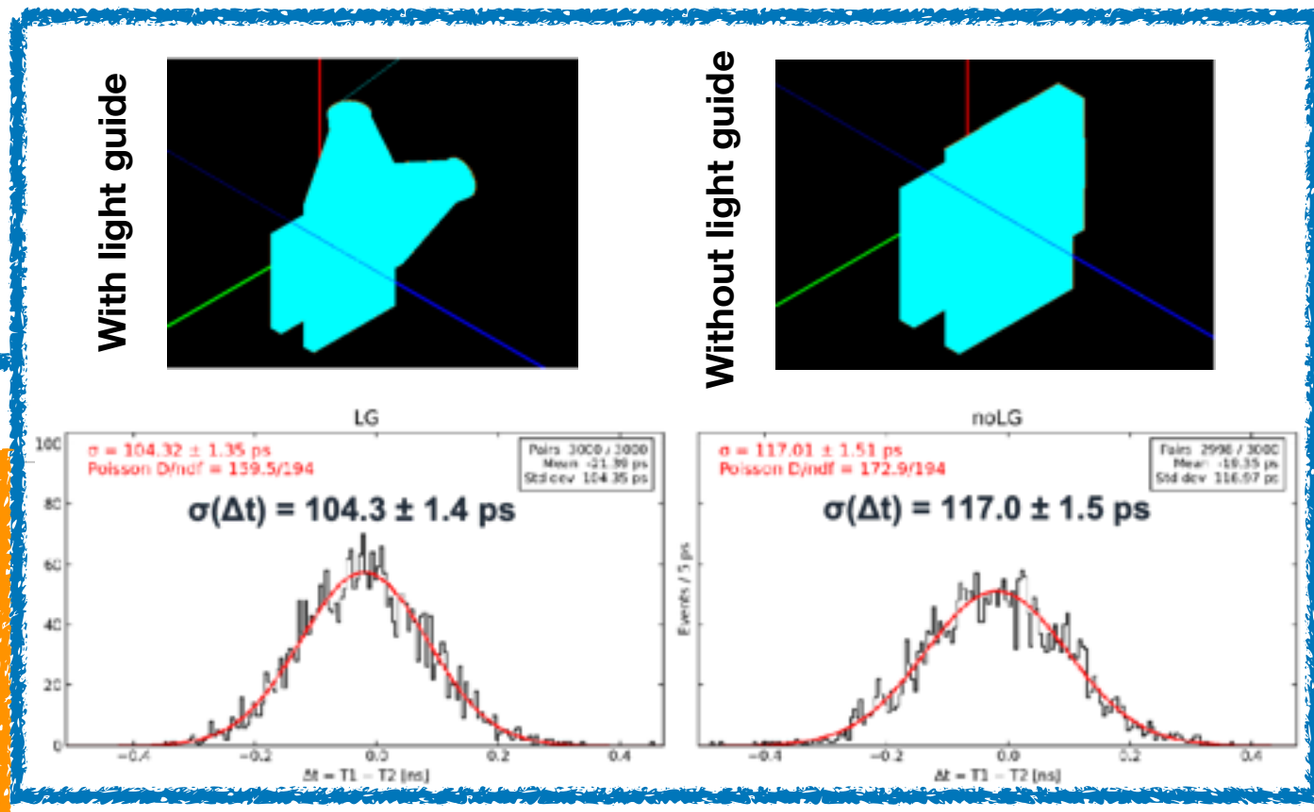


- Three measured time-difference width (D = C or S)

$$\sigma^2_{D-T_1} = \sigma^2_D + \sigma^2_{T_1}$$
$$\sigma^2_{D-T_2} = \sigma^2_D + \sigma^2_{T_2}$$
$$\sigma^2_{T_1-T_2} = \sigma^2_{T_1} + \sigma^2_{T_2}$$

- We are studying trigger timing with GEANT4
  - 60GeV positron beam
  - Modeled PMT waveform
  - CFD 30% timing extraction
- Performance with or without light guide
- Cross position scan

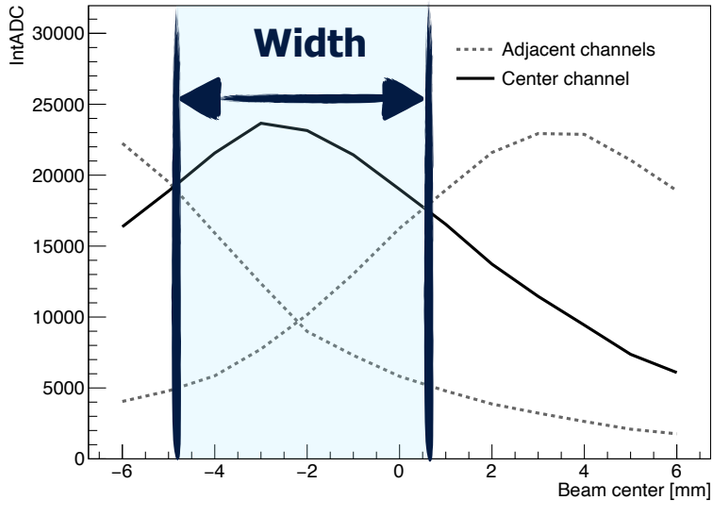




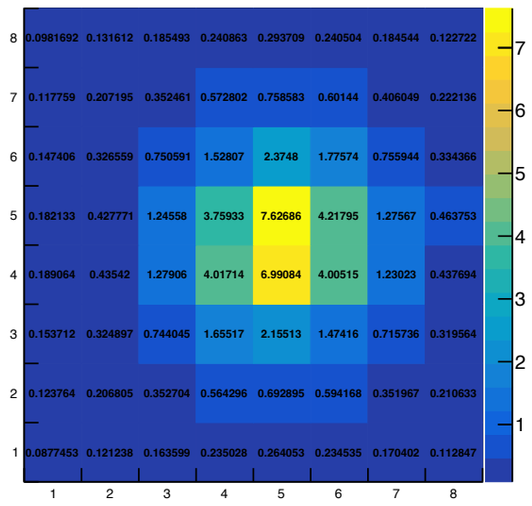
Ongoing Studies (ii)

- **Position resolution with high granularity MCP-PMT**
  - Position is reconstructed by energy, it requires energy calibration
  - Reconstruct the beam position using the center-of-gravity method from weighted channel response

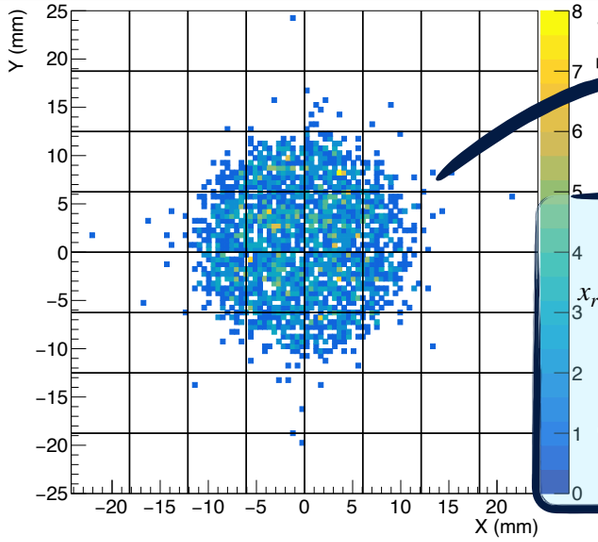
Position scan (horizontal direction)



After Equalization [GeV]



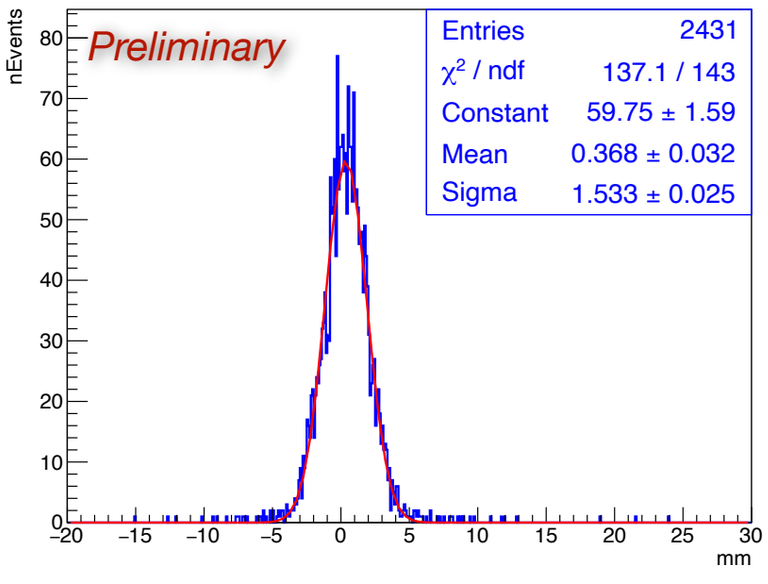
Reconstructed Beam Position



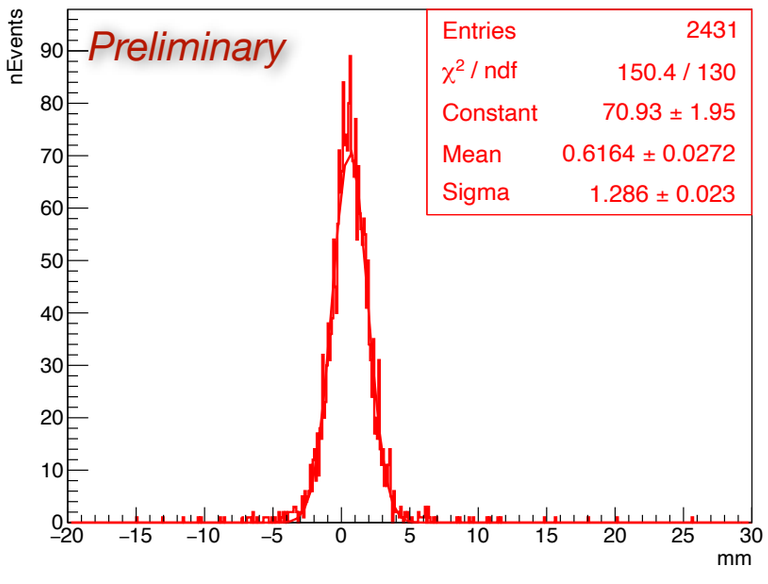
$$x_{reco} = \frac{\sum_i E_i x_i}{\sum_i E_i}, \qquad y_{reco} = \frac{\sum_i E_i y_i}{\sum_i E_i}$$

$$\sigma_{pos} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(x_{reco,i} - x_{true,i}\right)^2}$$

Čerenkov



Scintillation



Combined

