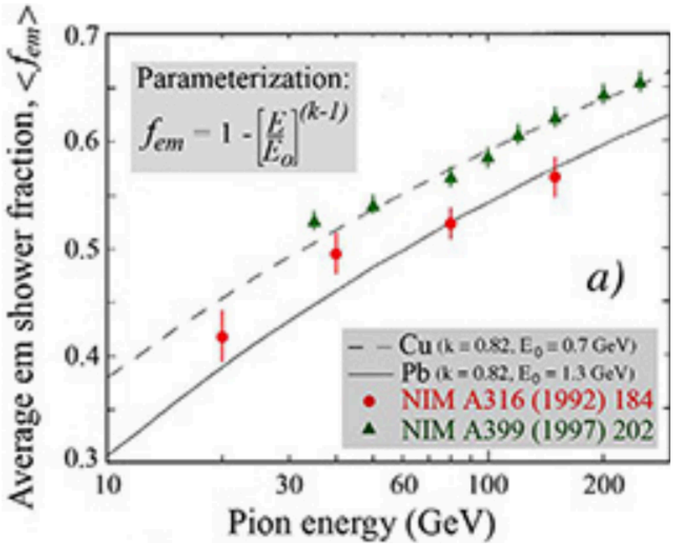
Performance Studies of High-Granularity Dual-REAdout Module from beam tests

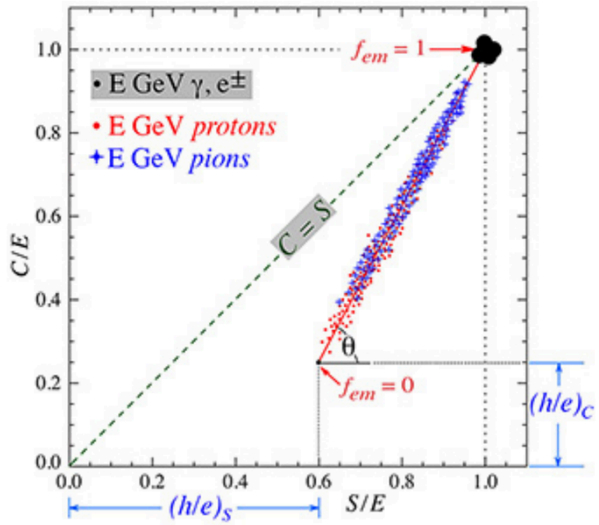
N. Akchurin, H. Brittan, J. Damgov, X. Delashaw, **Y. Feng**, M. Harris, W. Jin, M. Kelley, S. Kunori, Z. Leon-Guerrero, C. Madrid, C. Nunn, A. Shrivastava (Texas Tech University)

CPAD 2026, Seattle, Washington

October 20, 2026

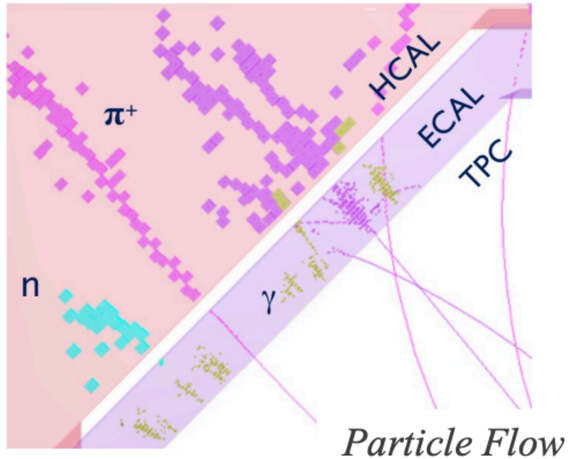
Dual Readout & High-Granularity

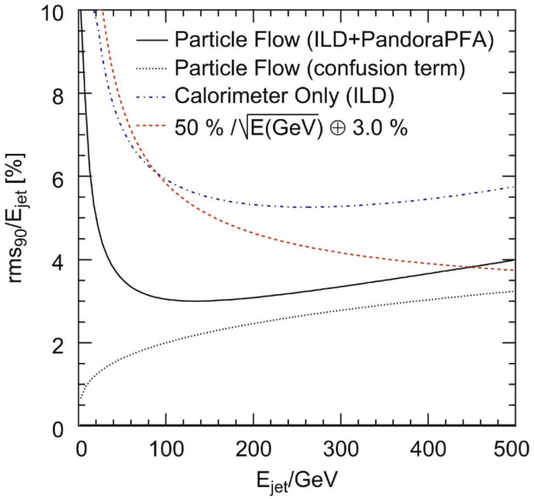




- Hadronic shower includes the electromagnetic (e) component and the hadronic (h) component
  - The EM fraction, f_{EM}, varies from event to event, driving the hadronic energy resolution
- h/e is roughly energy-independent, and differs between C and S
- **Measuring C vs S simultaneously can therefore resolve f_{EM} event-by-event**, improving hadronic energy resolution

- **High-granularity** to help study fine shower structure and resolve the confusion matrix when reconstructing individual particles. **"Imaging" calorimeter**
- Combined with the excellent resolution from other detectors (tracker+ECAL+others), achieve optimal performance on **particle-flow jets**
  - Individual particle reconstruction can also help jet flavor tagging and event classification, etc





Dual Readout + High-Granularity + Timing

- Advancing hadron calorimeter:

Start with “Traditional” Dual Readout

“Spaghetti” dual-readout calorimeter:

- Excellent hadron energy resolution achieved by measuring electromagnetic fraction event by event

Increase **granularity** in the XY plane

in the XY plane:

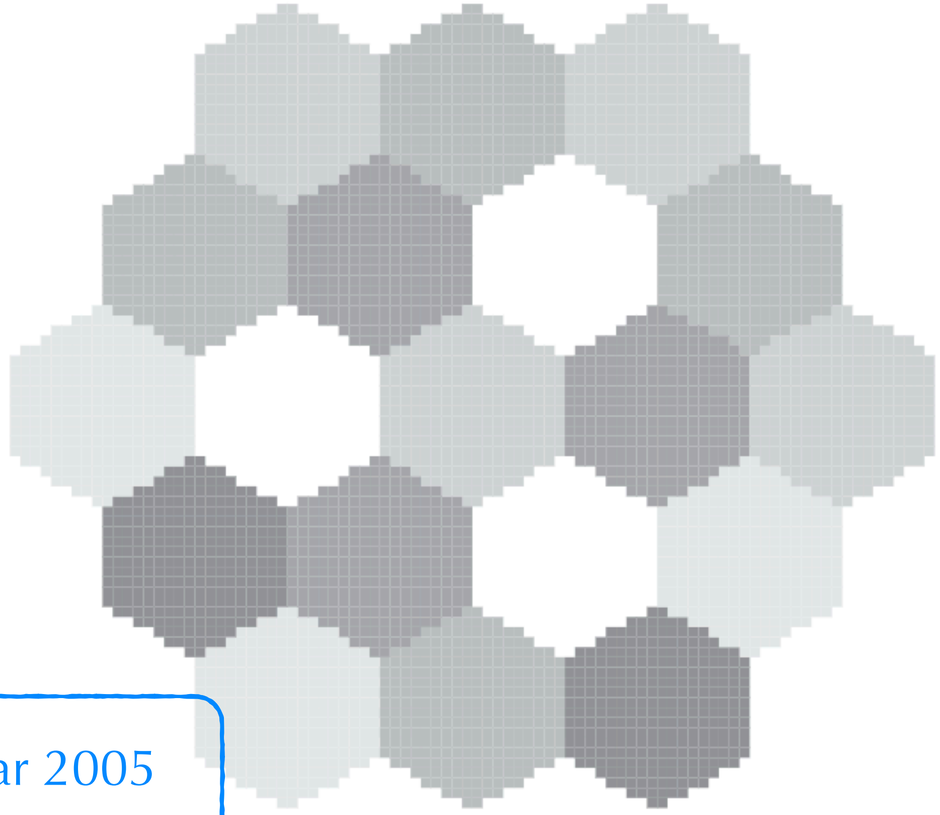
- Fine shower shape structure in the XY plane;
- resolve overlapping showers for particle-flow reconstruction

Enable precise **timing**, which encodes longitudinal segmentation

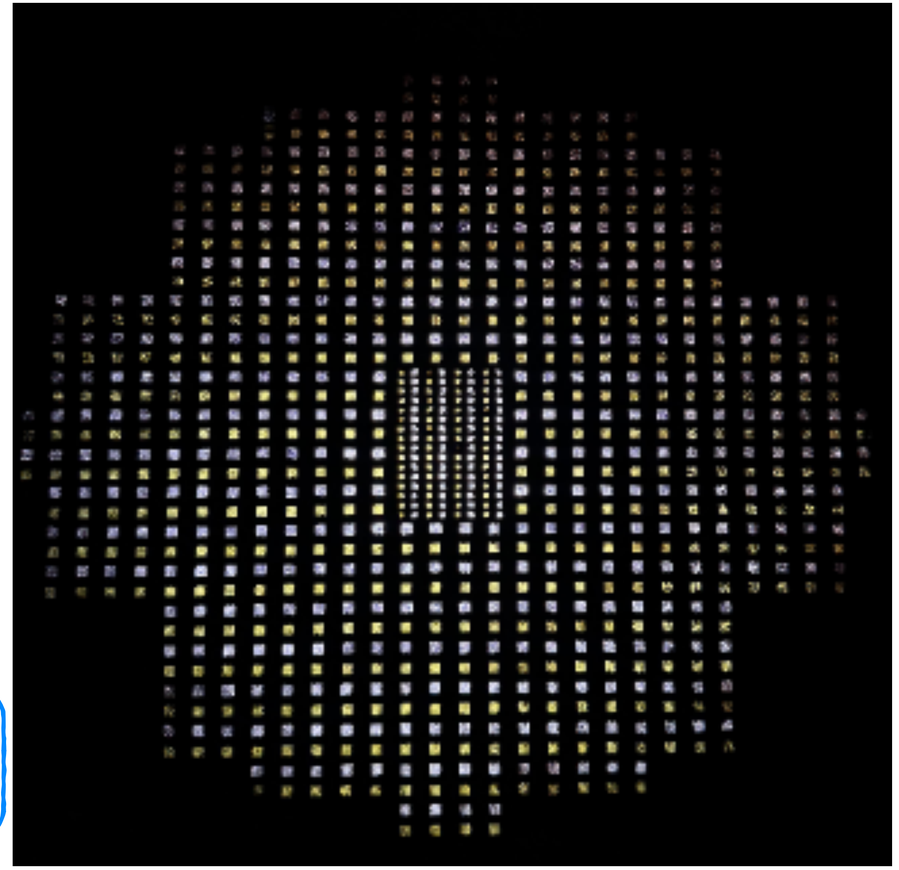
in the Z axis:

- Thanks to developments on photosensors, electronics, and AI/ML algorithms, we can recover the lost **timing (longitudinal) information**, which was not extensively explored previously

XY: High Granularity



Year 2005

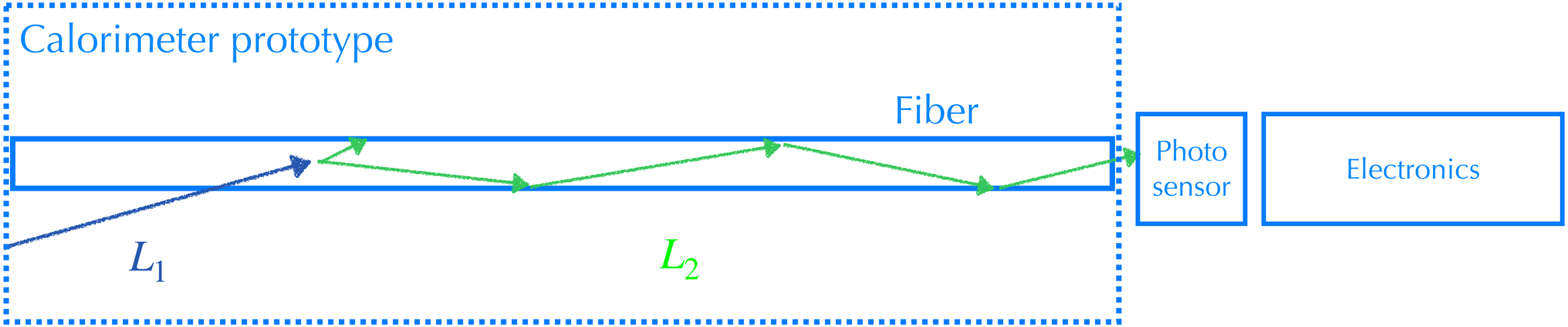


Year
2025/2026

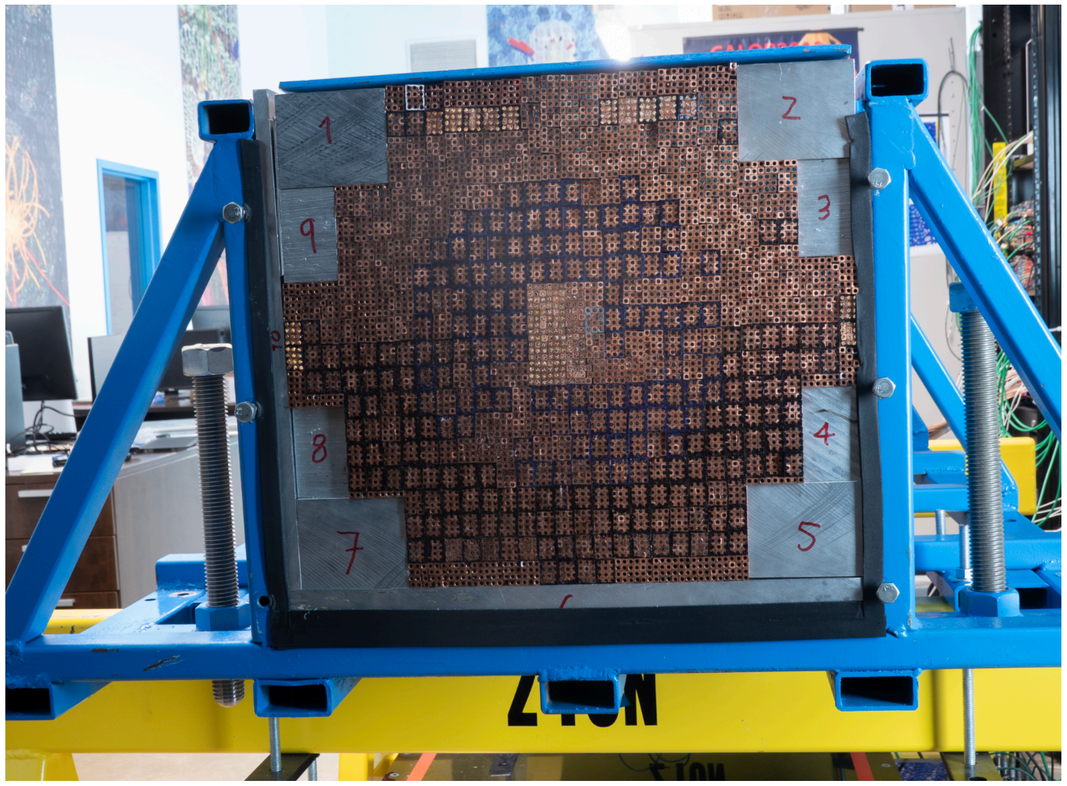
Original “DREAM” in ~2005, **19 towers**, with Cherenkov and scintillation signals read out separately by PMTs -> **38 channels in total**

High-Granularity DREAM in ~2025, **448 towers**, read out by 3mm and 6mm SiPMs, -> **896 channels in total**

Timing -> Longitudinal Segmentation



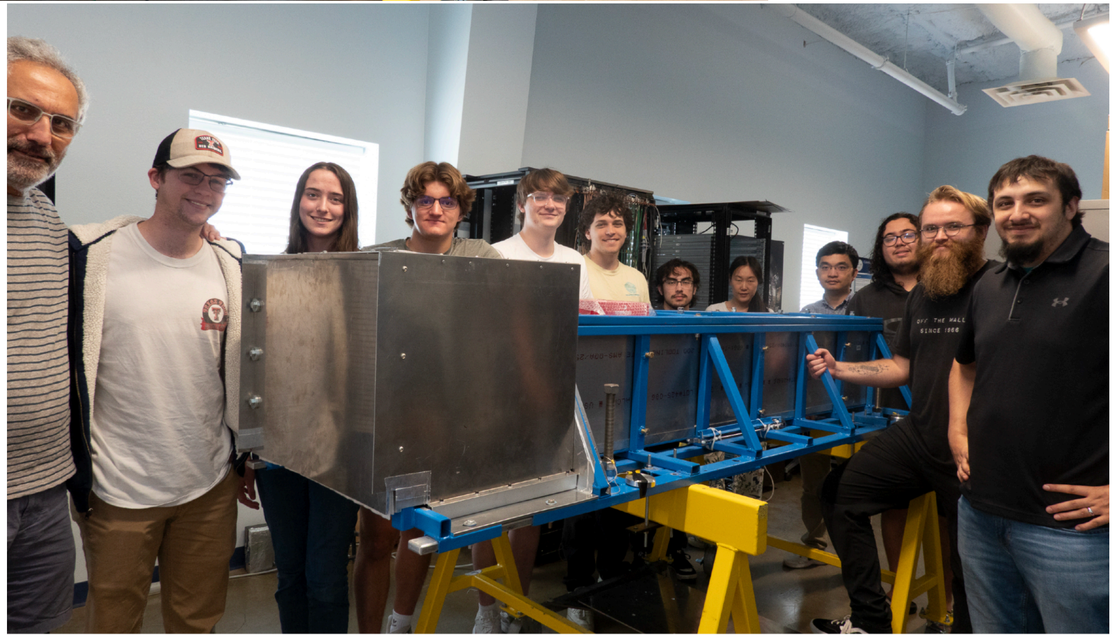
- Photon arrival time $t = L_1/c + L_2/c \cdot n$, where $L_1 + L_2 \approx L$
- Can use photon arriving time to backtrack the energy deposit position, i.e., longitudinal shower information
- **Treat fibers as drift chambers! Use O(n^2) channels to reconstruct O(n^3) information** to improve particle-flow, while preserving excellent hadron energy resolution
- Timing information can also help clustering and reconstruction in (X, Y, E, t) space, attenuation corrections, particle identification, and pileup mitigation, etc



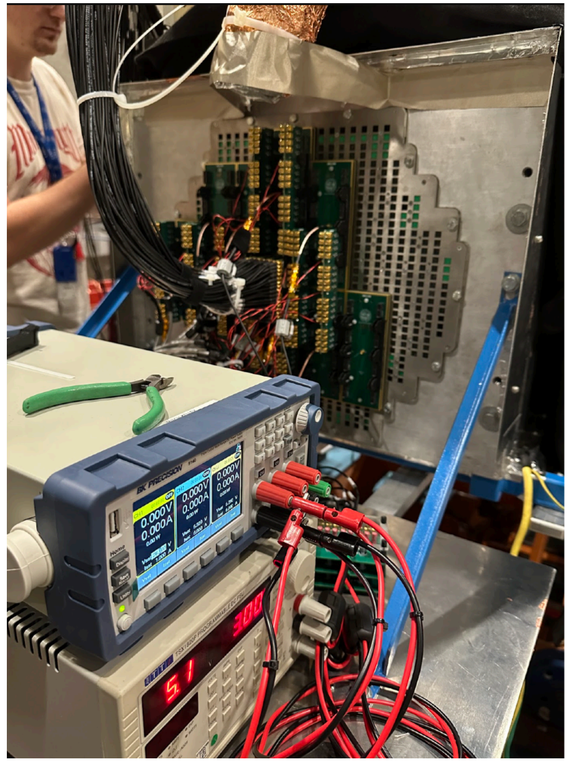


Assembly @ Texas

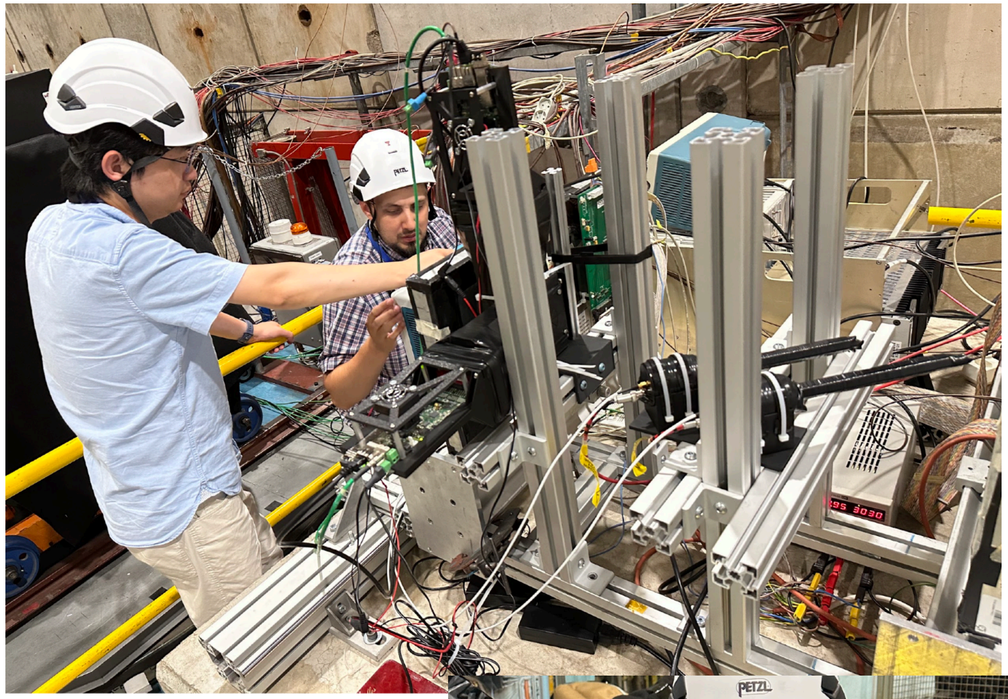




Installation @ CERN H8 TB

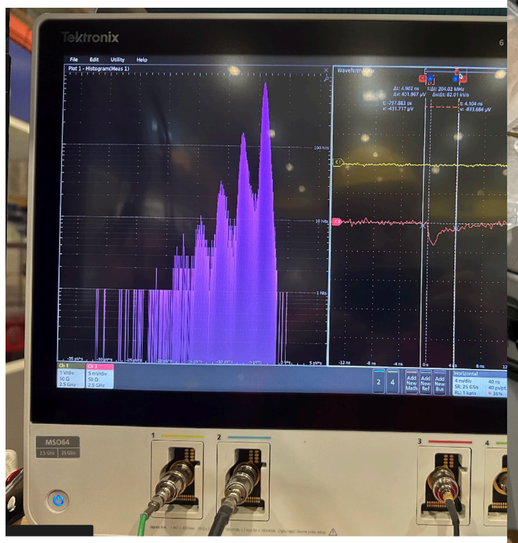


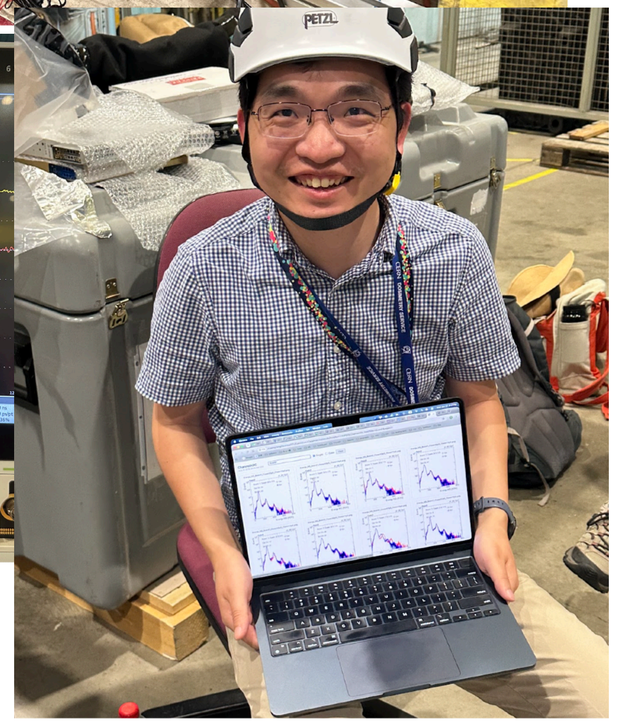


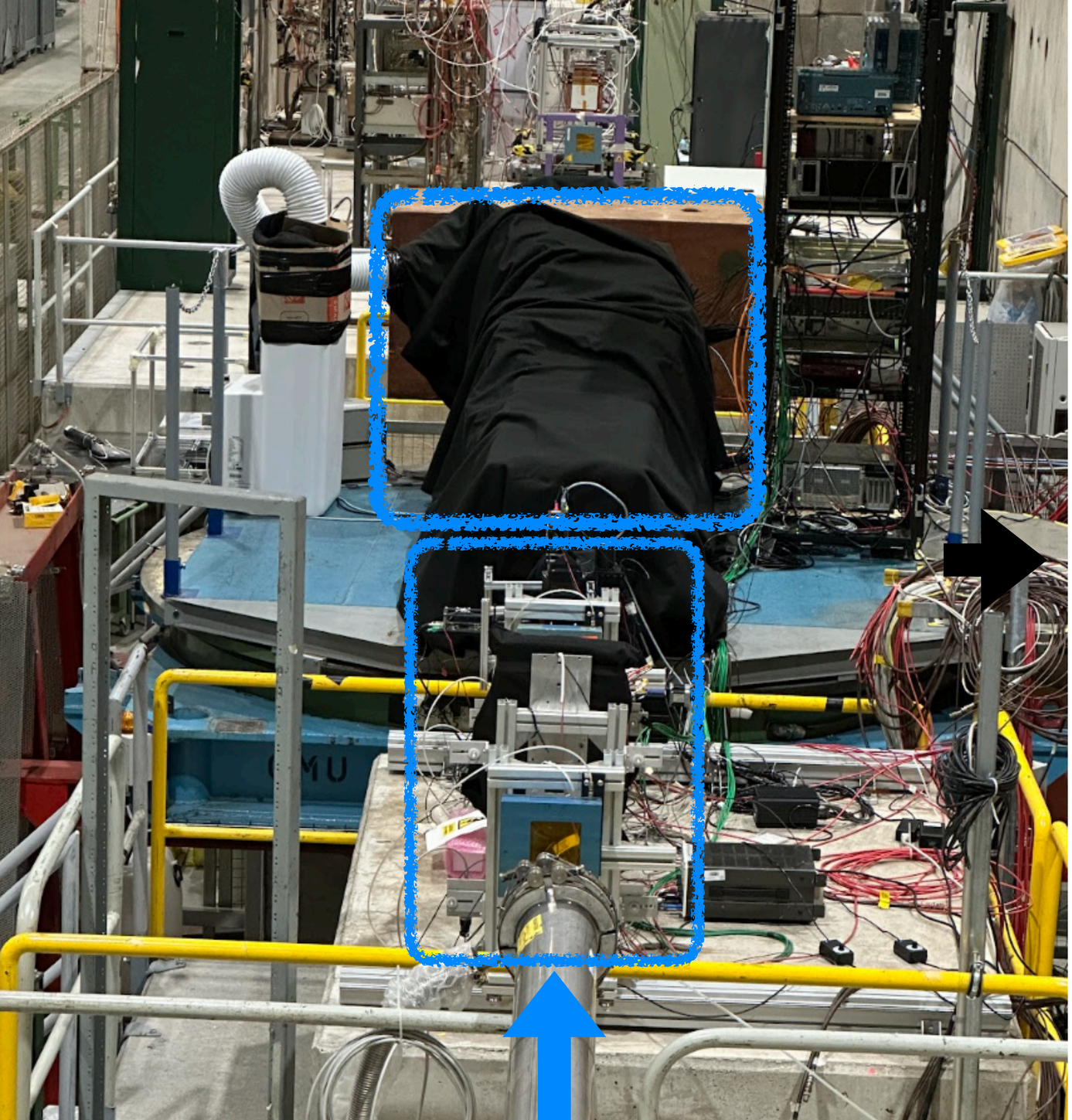


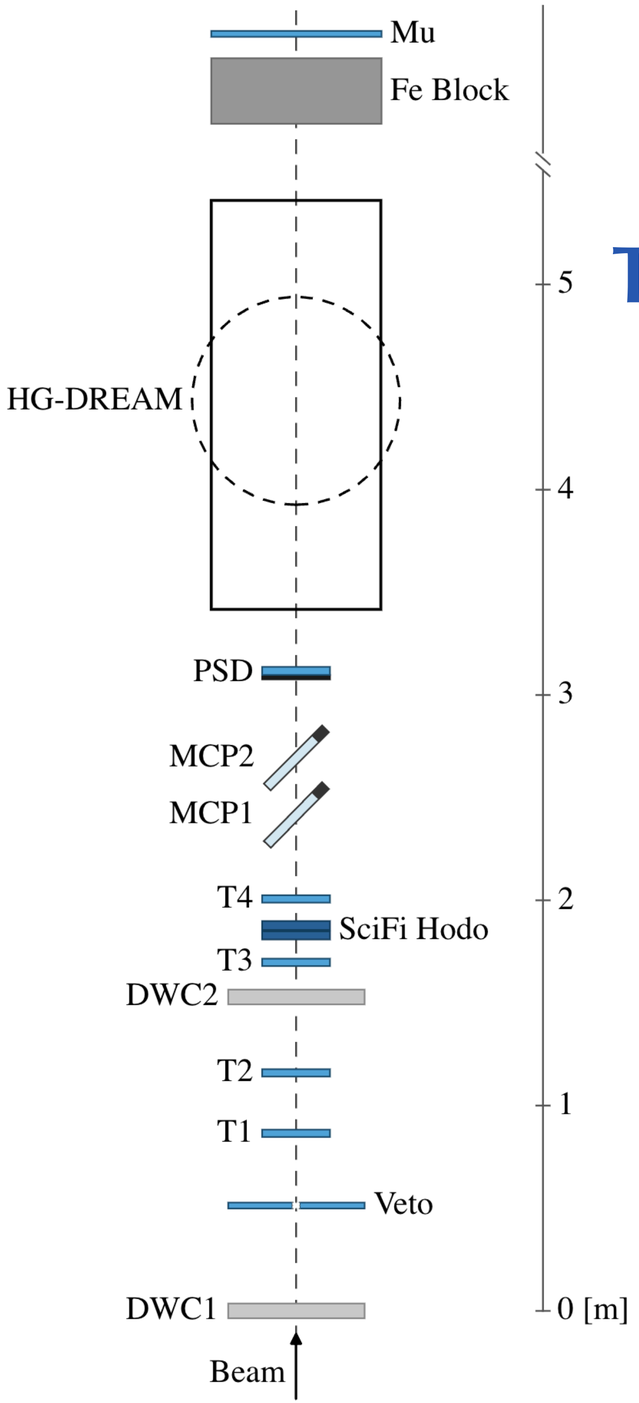










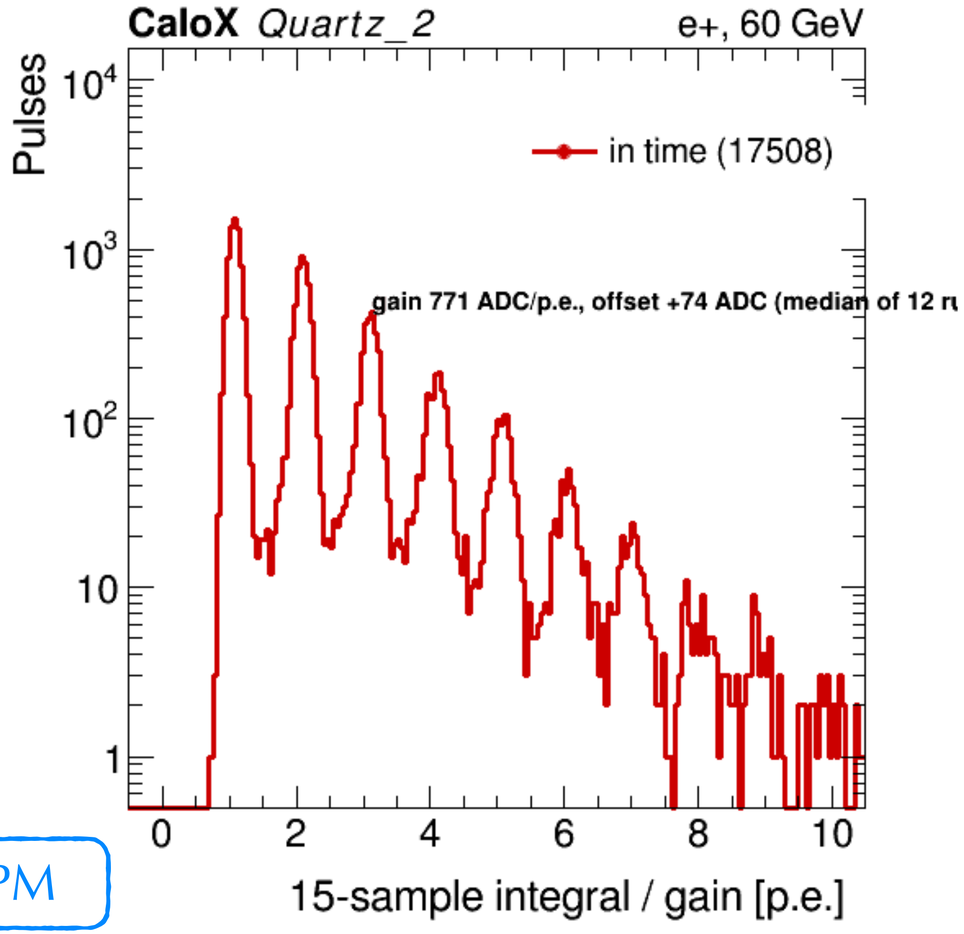


Test beam setup

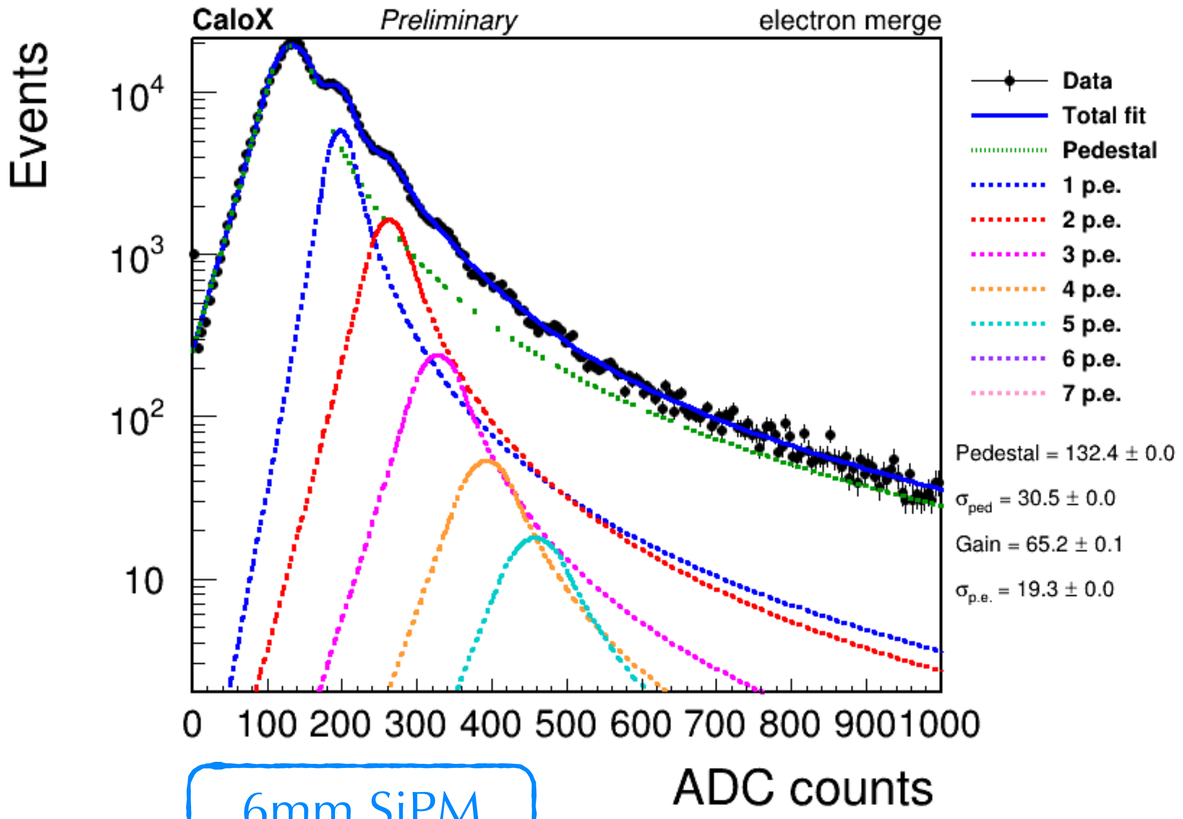
Activities & Study Items

- Managed to perform two beam-test campaigns at CERN H8, in 2025 and 2026, under the coordination of DRDCalo
  - Positron/pion/muon runs at different energies and different positions
- Studies focus on two main thrusts:
  - An effective way to **calibrate** the detector for energy measurements?
  - Can we observe **timing distributions from shower depth** in fibers? What is the resolution?

ADC to N p.e.



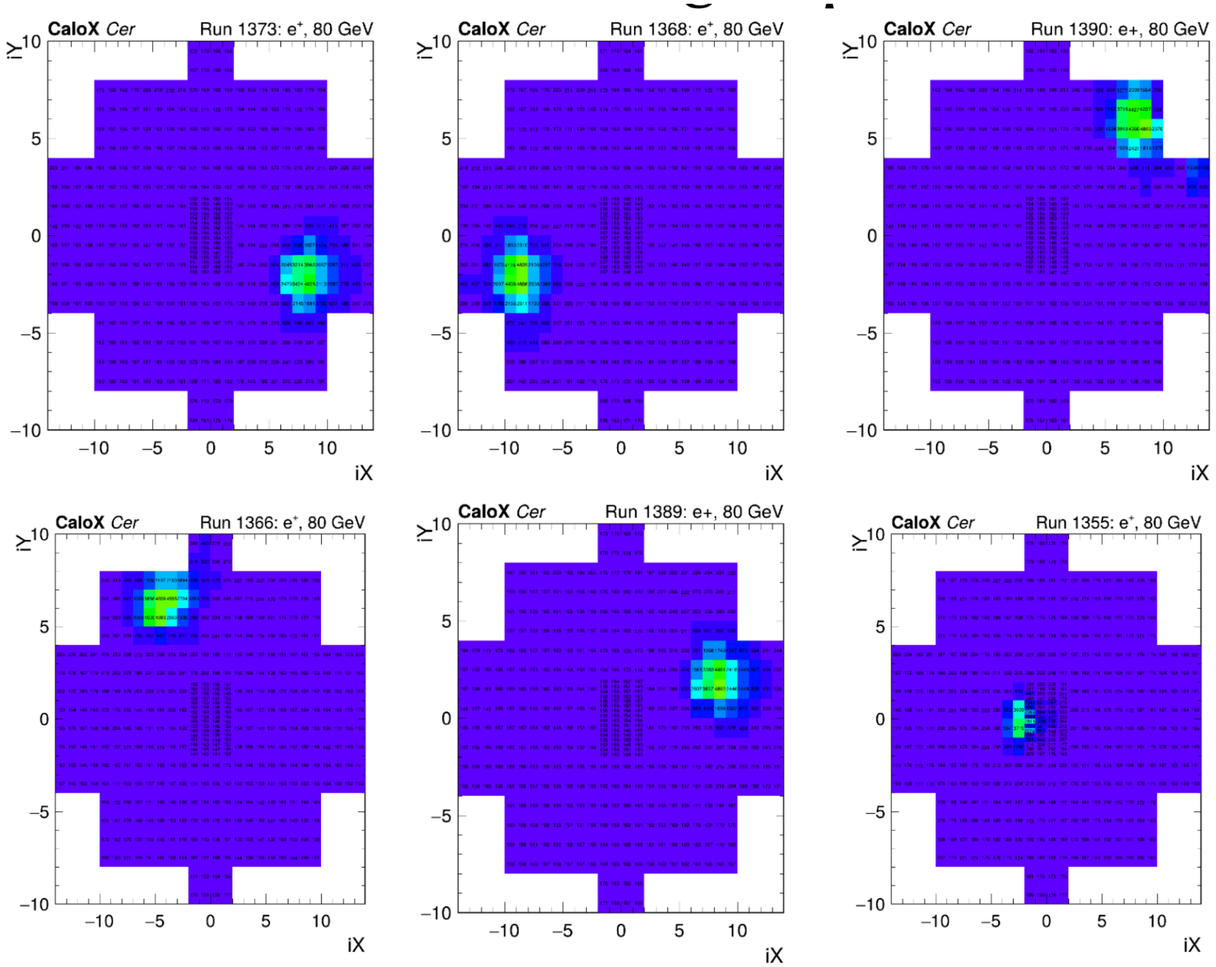
3mm SiPM



6mm SiPM

- Around 60 p.e. per GeV in the scintillation channels
- In the process of understanding number of photoelectrons per GeV in the Cherenkov channels

Linear Regression and Calibration Runs

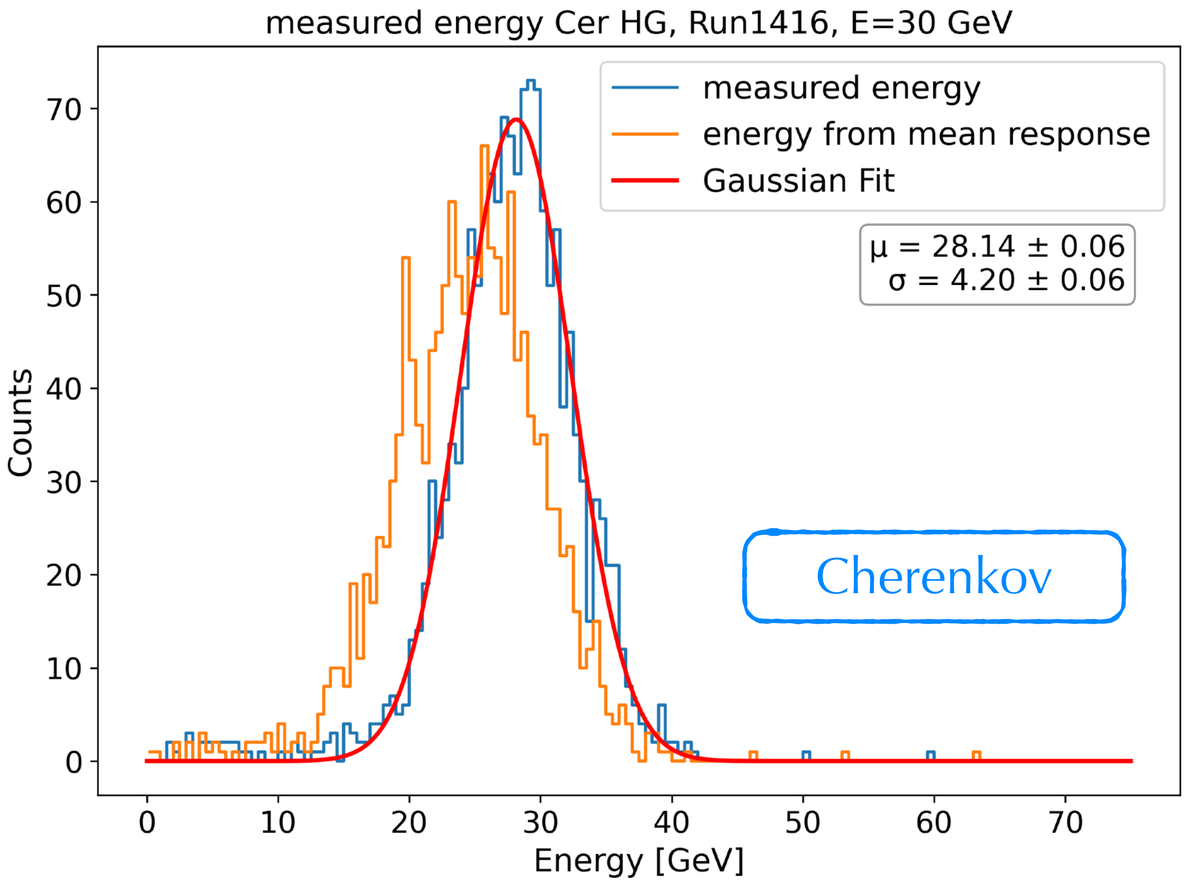


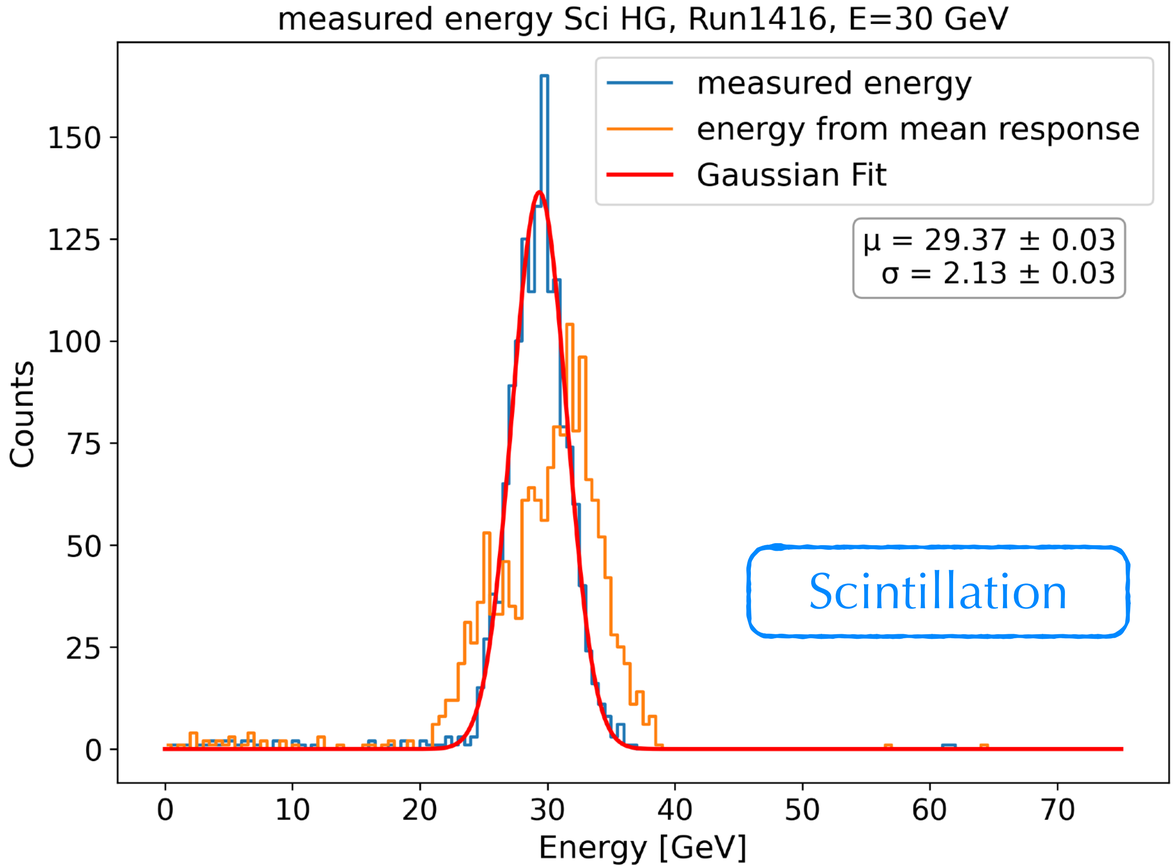
- Carried out "calibration runs", where we moved the detector in XY positions such that the energy deposits are different from channel to channel

- Perform linear regression to optimize $E = \sum_i \mathrm{ADC}_i \times w_i$

  - where w_i are calibration constants, which is optimized during the linear regression process

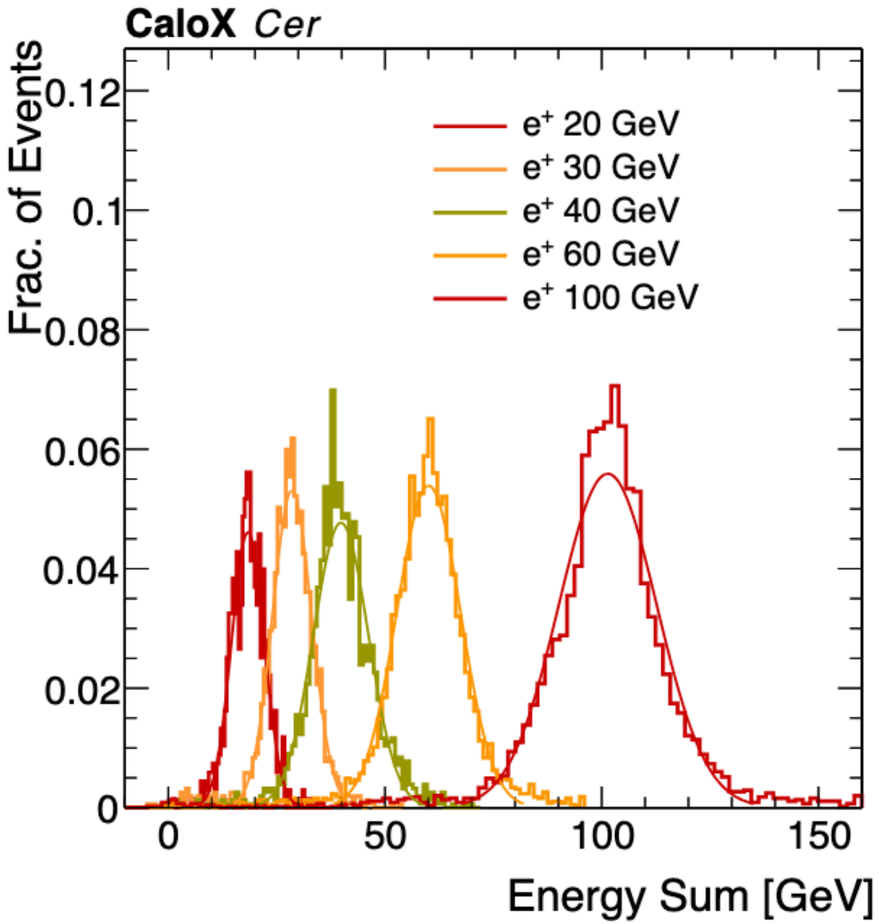
Energy Distribution Before/After Calibration

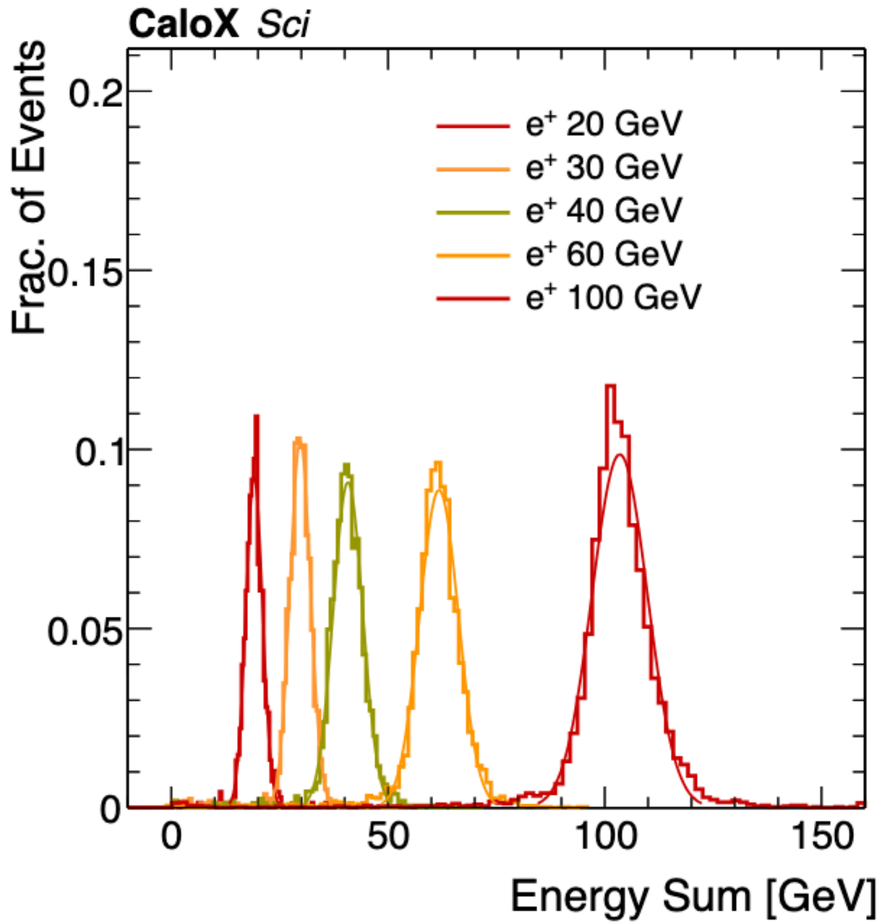




- Comparing the energy distributions for positron showers before and after calibrations, for Cherenkov (left) and scintillation (right) channels
- After calibrations, distributions become much more Gaussian like

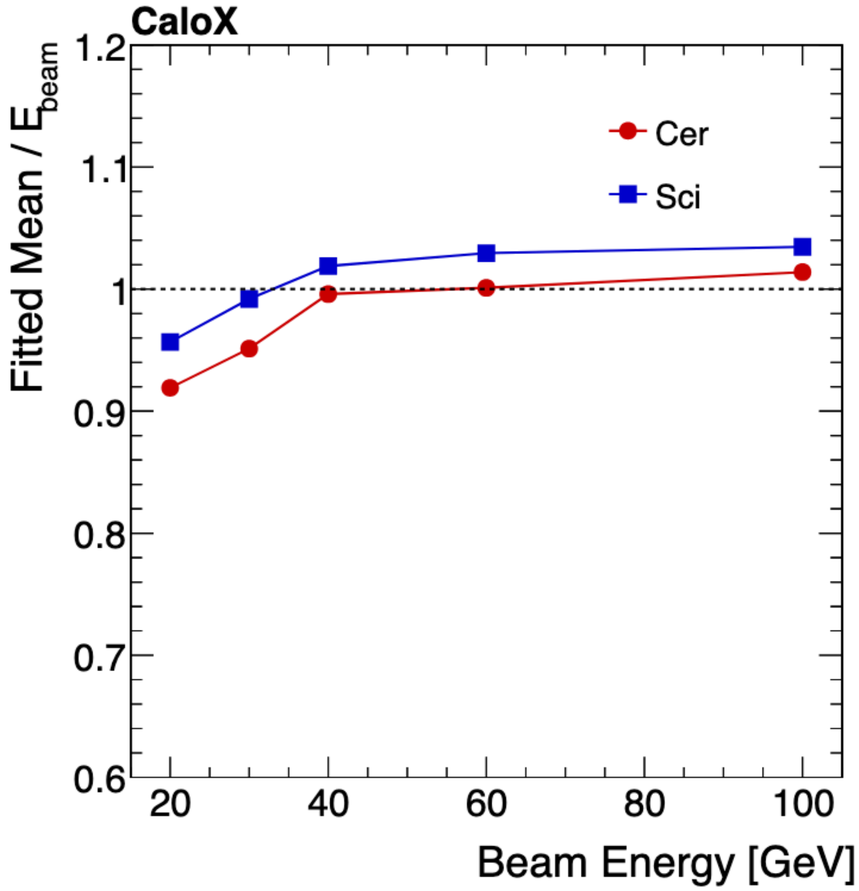
EM Performance

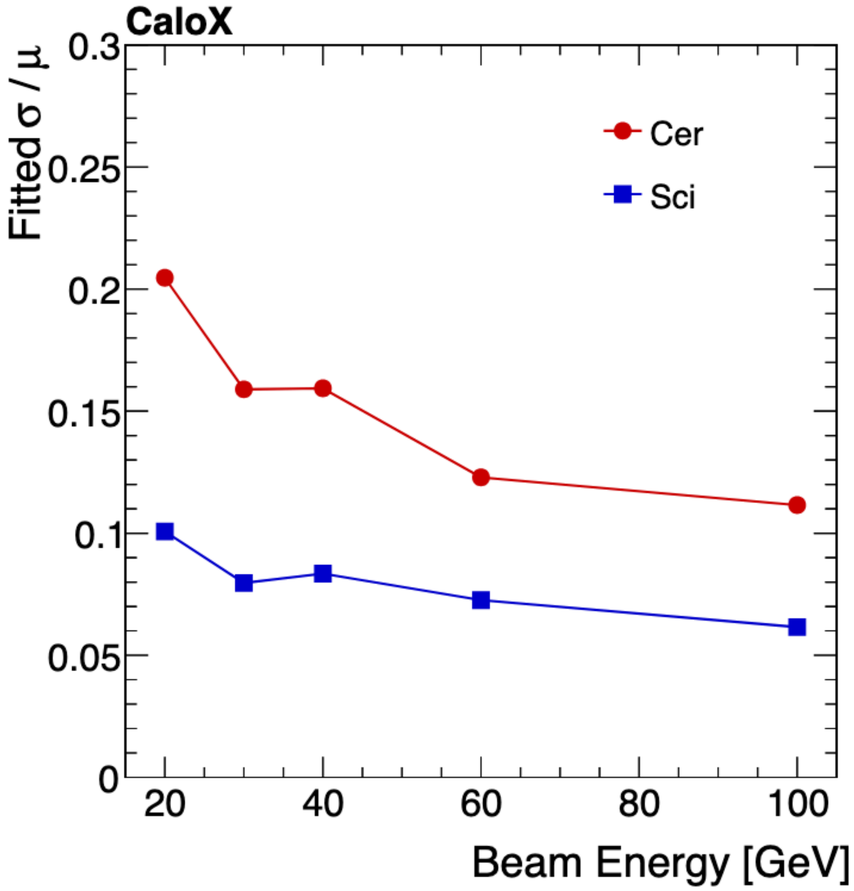




- Measured energy using Cherenkov (left) and scintillation (right) channels after calibration
- Gaussian-like distribution for different energies.
- Worse resolutions of Cherenkov channels compared with scintillation, as expected.

EM Performance

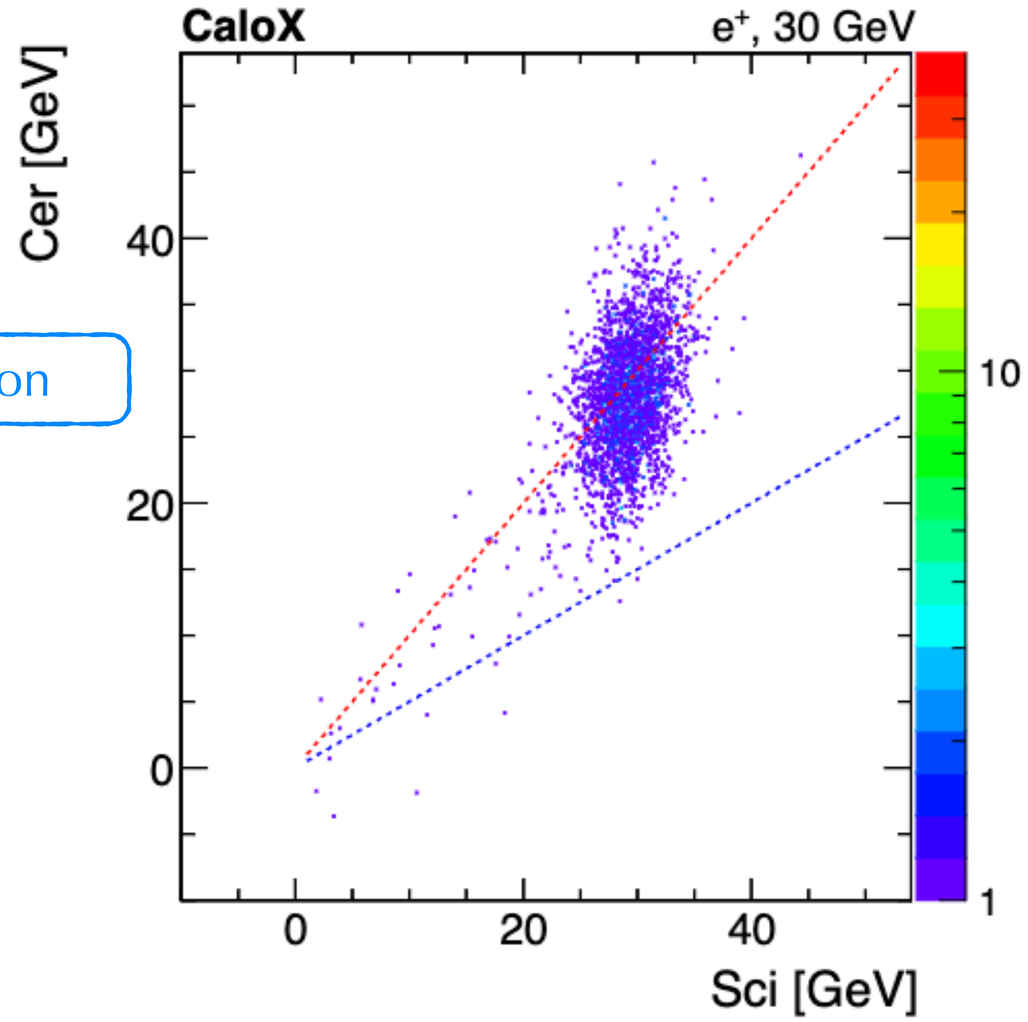




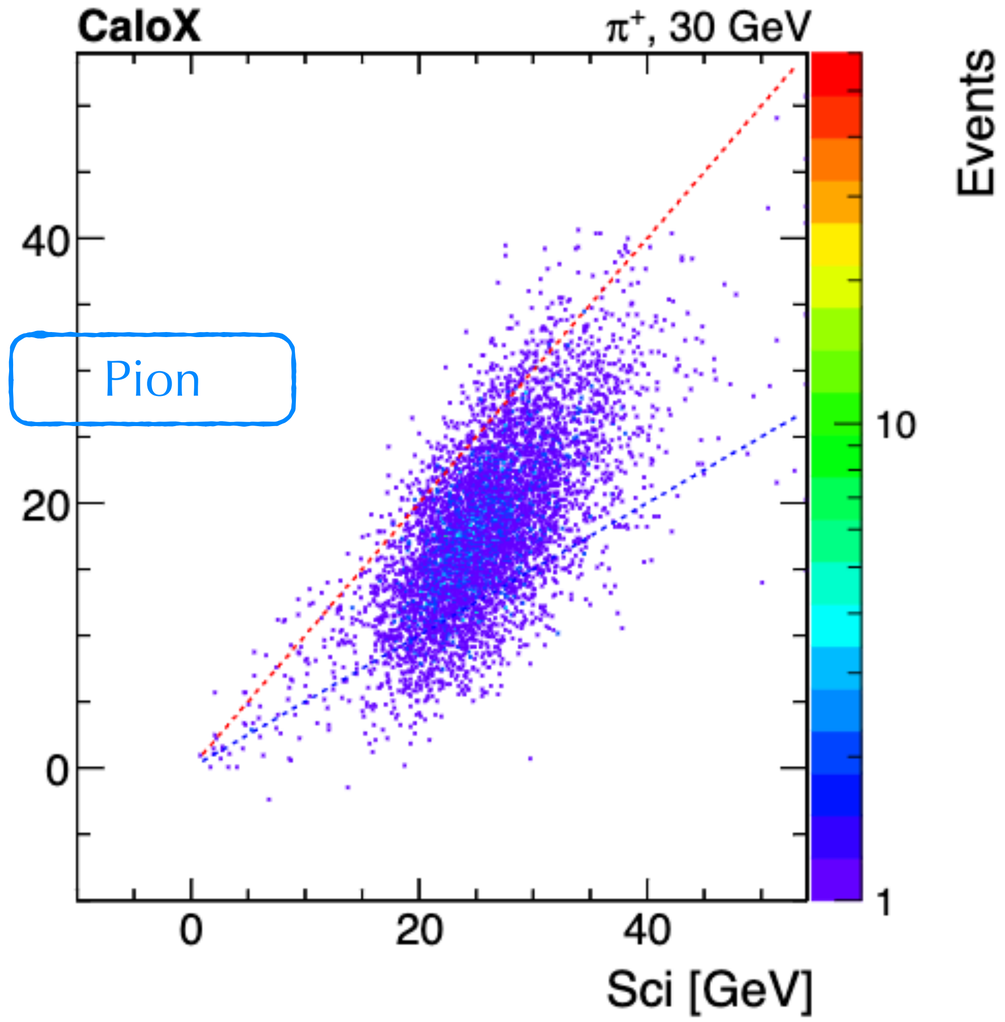
- Responses (left) and resolutions (right) as a function of positron beam energy
- Uniform response (up to ~5% difference) across the energy spectra
- Energy resolutions get better at higher energy: at 100GeV, ~5% for Scintillation; ~10% for Cherenkov

C vs S Energy Deposit

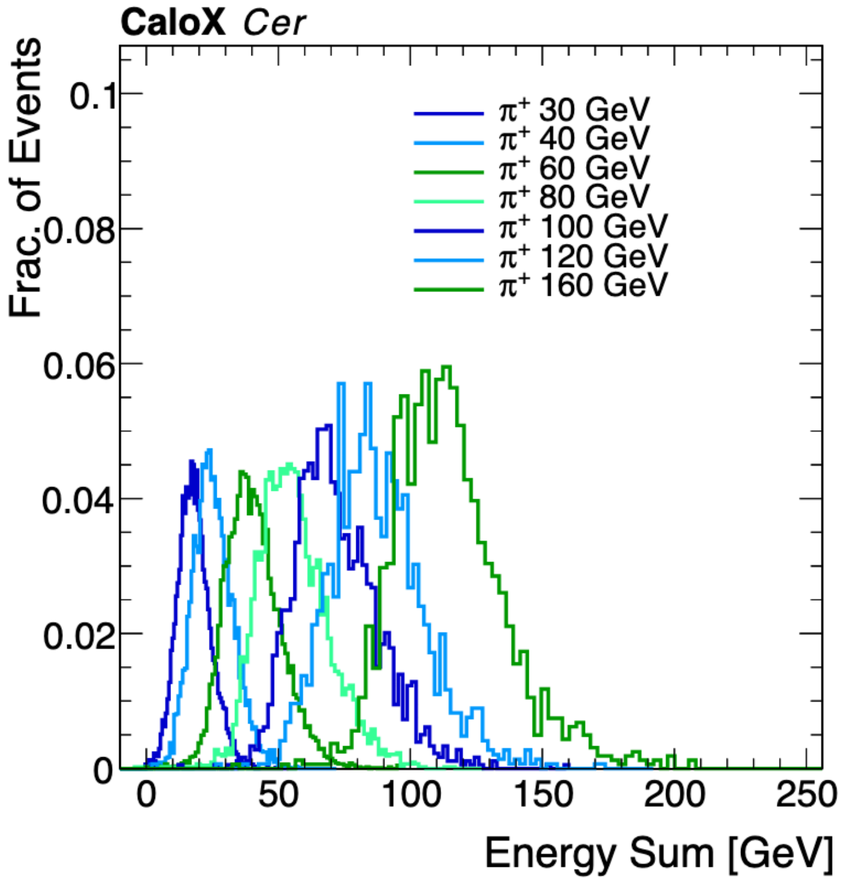
Positron

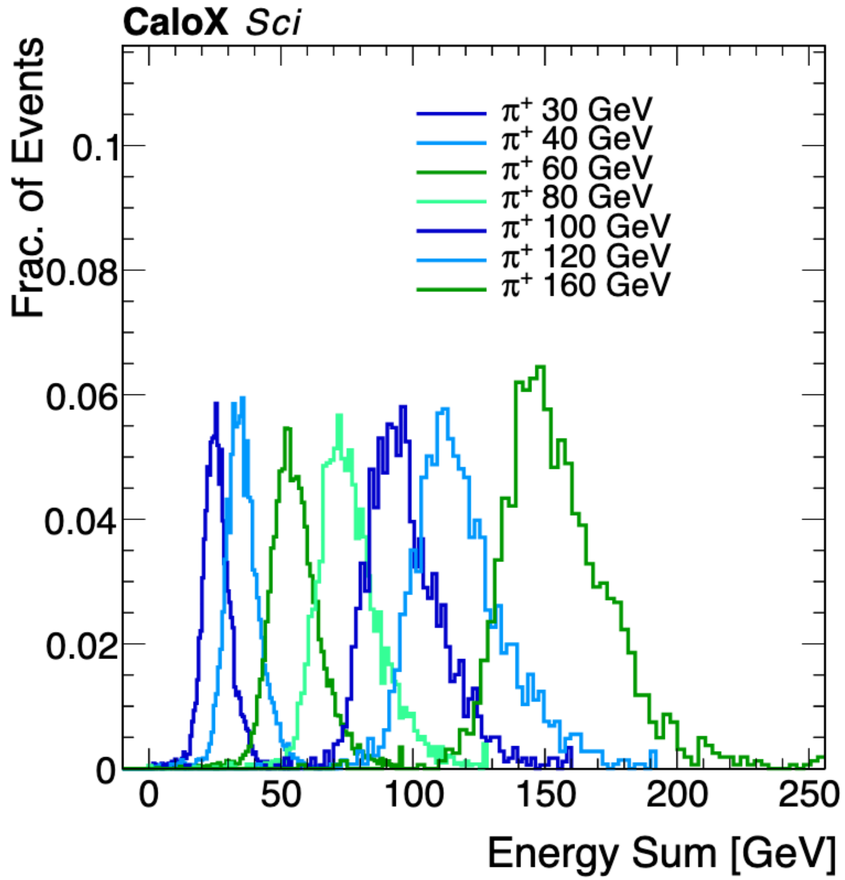


Pion



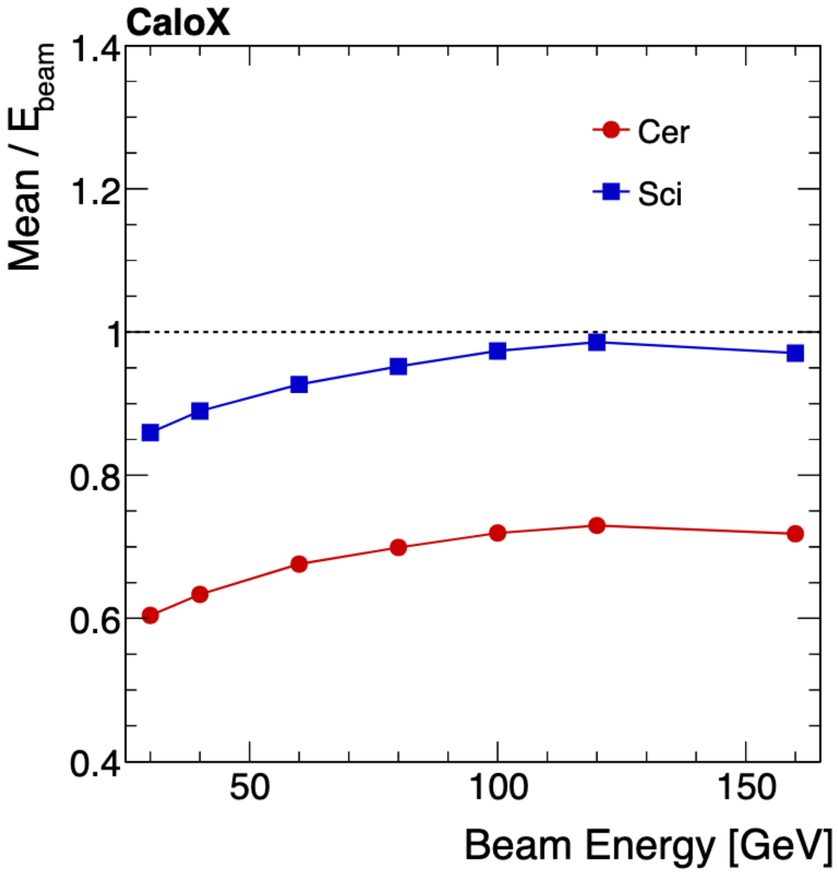
Hadron Shower Performance

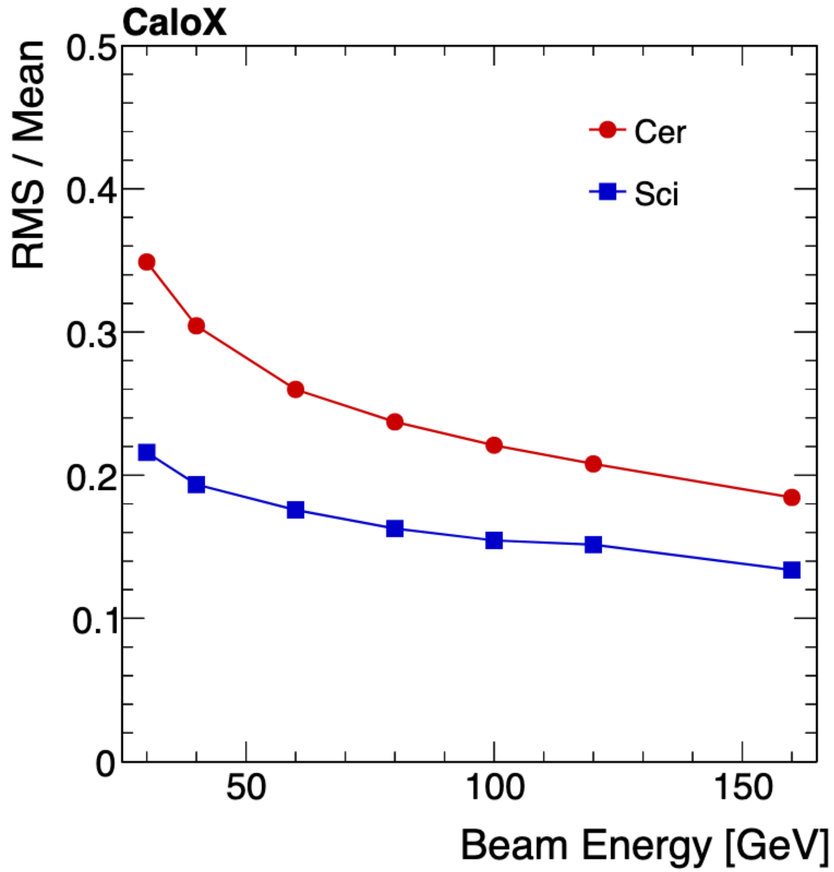




- Measured energy using Cherenkov (left) and scintillation (right) channels after calibration for pion showers

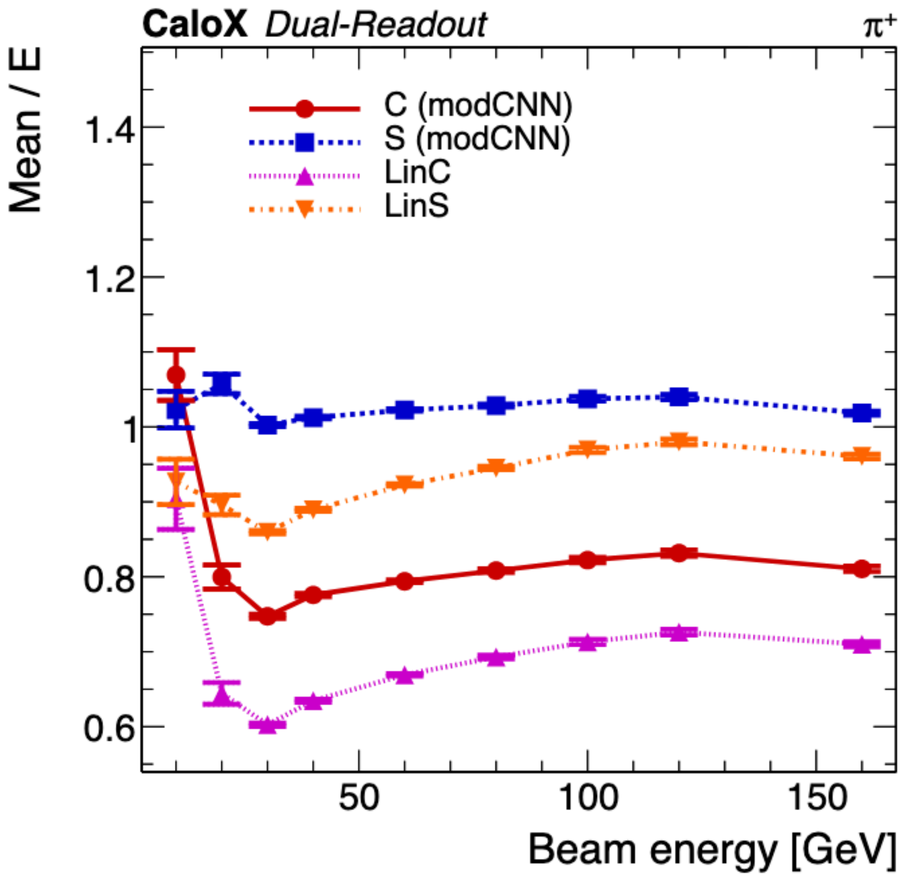
Hadron Shower Performance

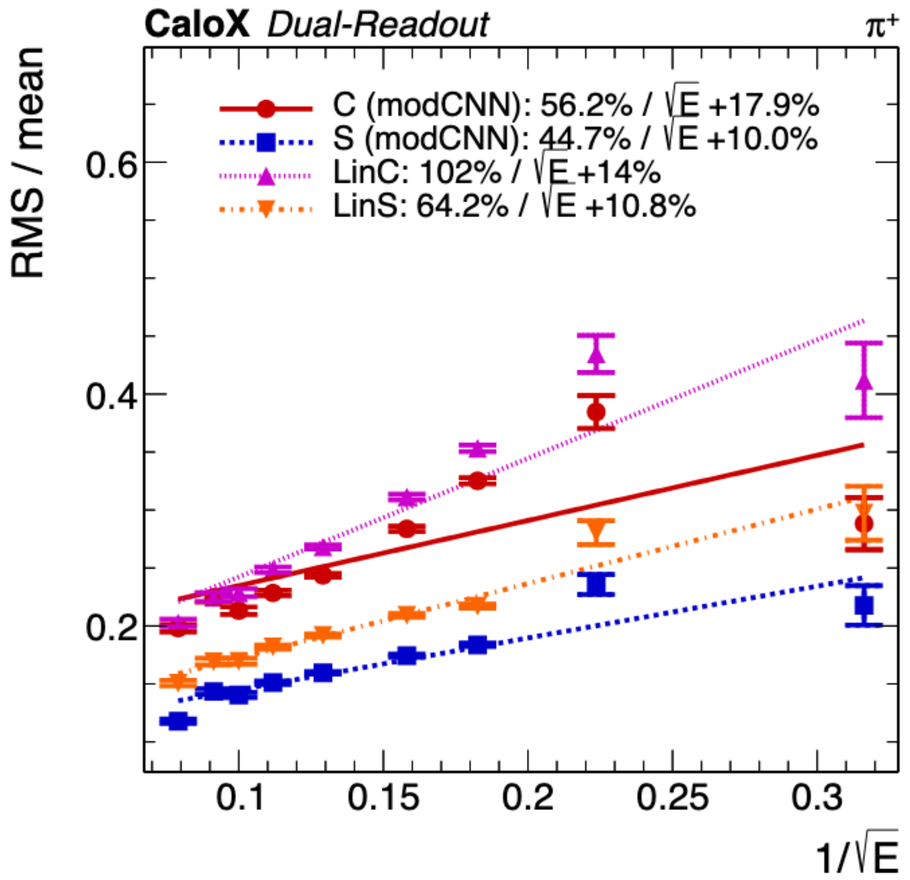




- Measured energy response (left) and resolution (right) using Cherenkov and scintillation channels after calibration for pion showers
- Application of the dual-readout combination is under study.

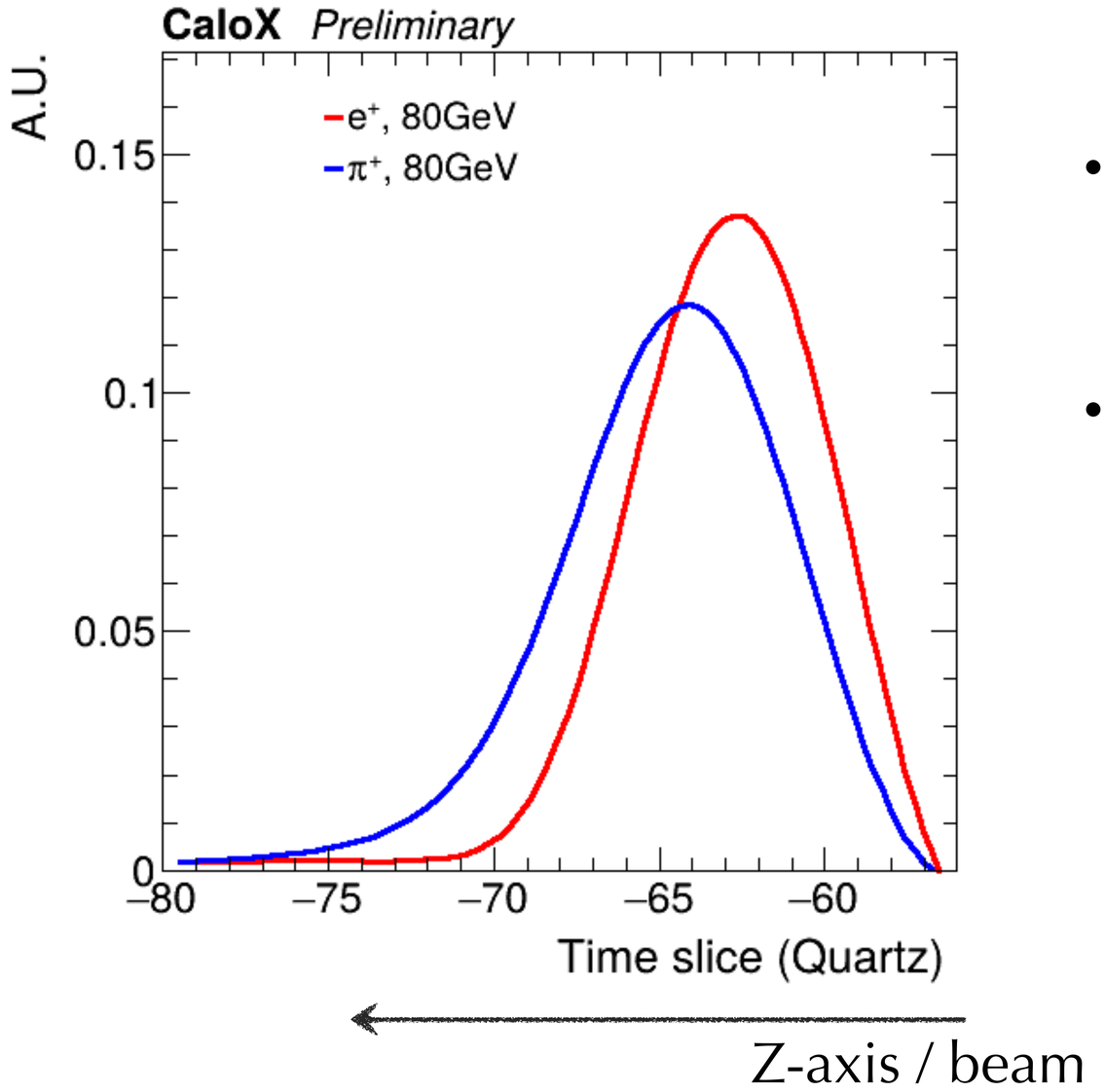
AI/ML "Calibration" Procedure





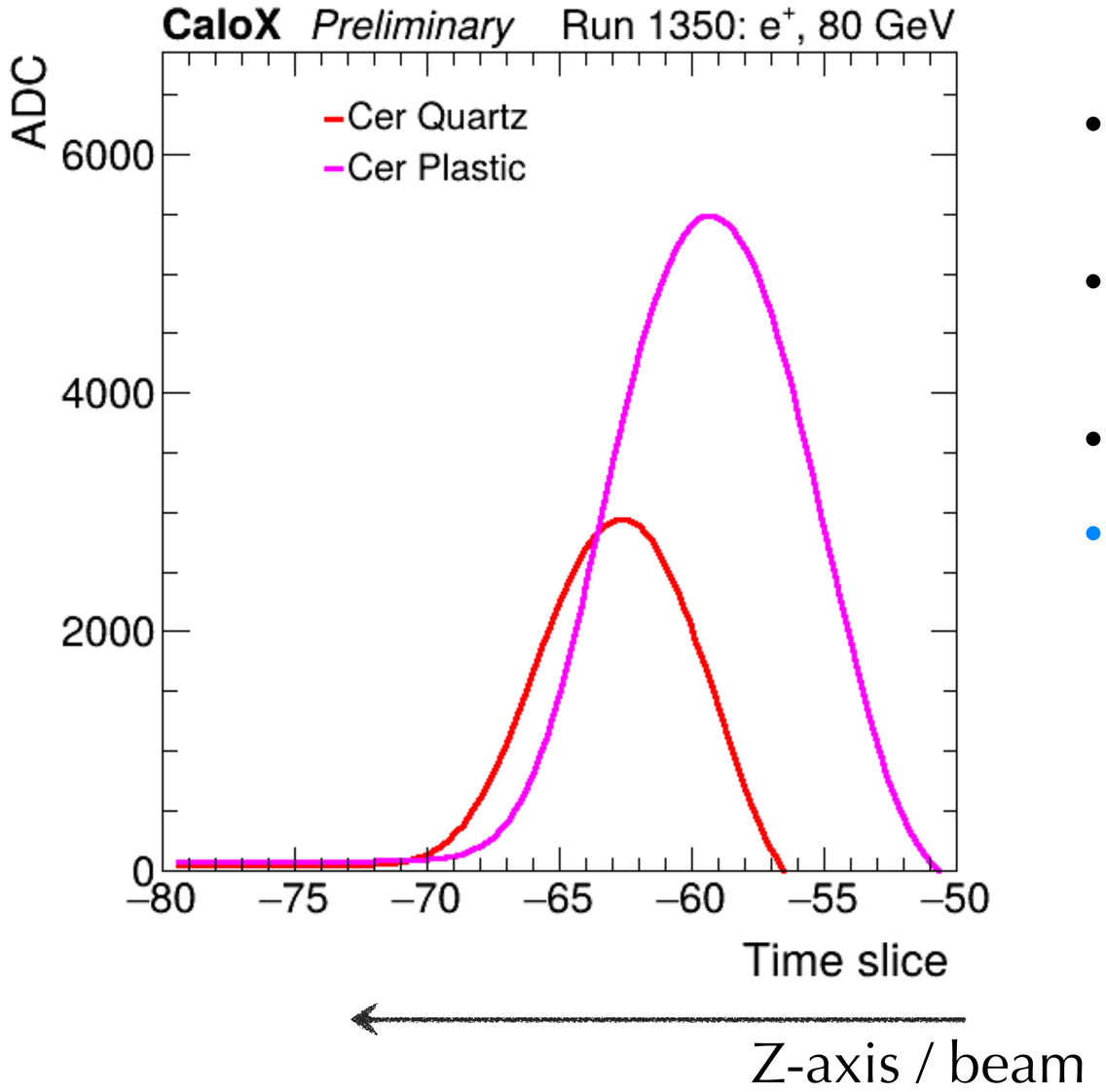
- Trained CNN to regress on w_i to improve the energy performance (inputs are channel-wise position and ADC information, no timing information utilized yet)
- Exploring adding the timing information into the NN to further improve the performance

“Longitudinal” shower profile (e^+ vs π^+)



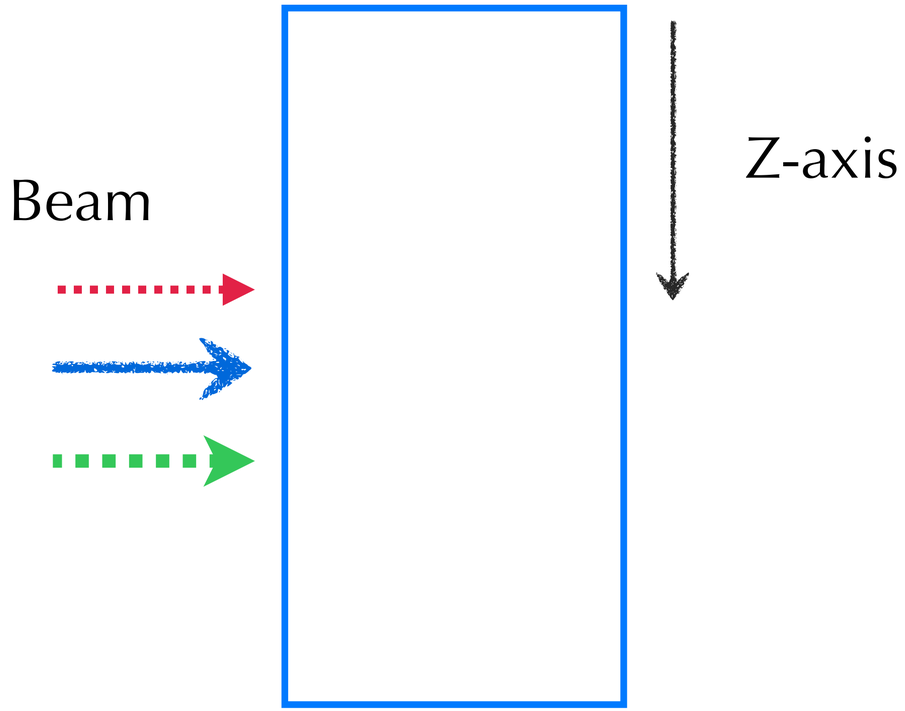
- Compare the hadronic shower profile (pion) with EM shower profile (positrons) at the same beam energy
  - One time slice is 200ps
- **Hadronic shower goes deeper in z-axis into the detector, and has a longer tail at larger z**.
  - Observed results as expected

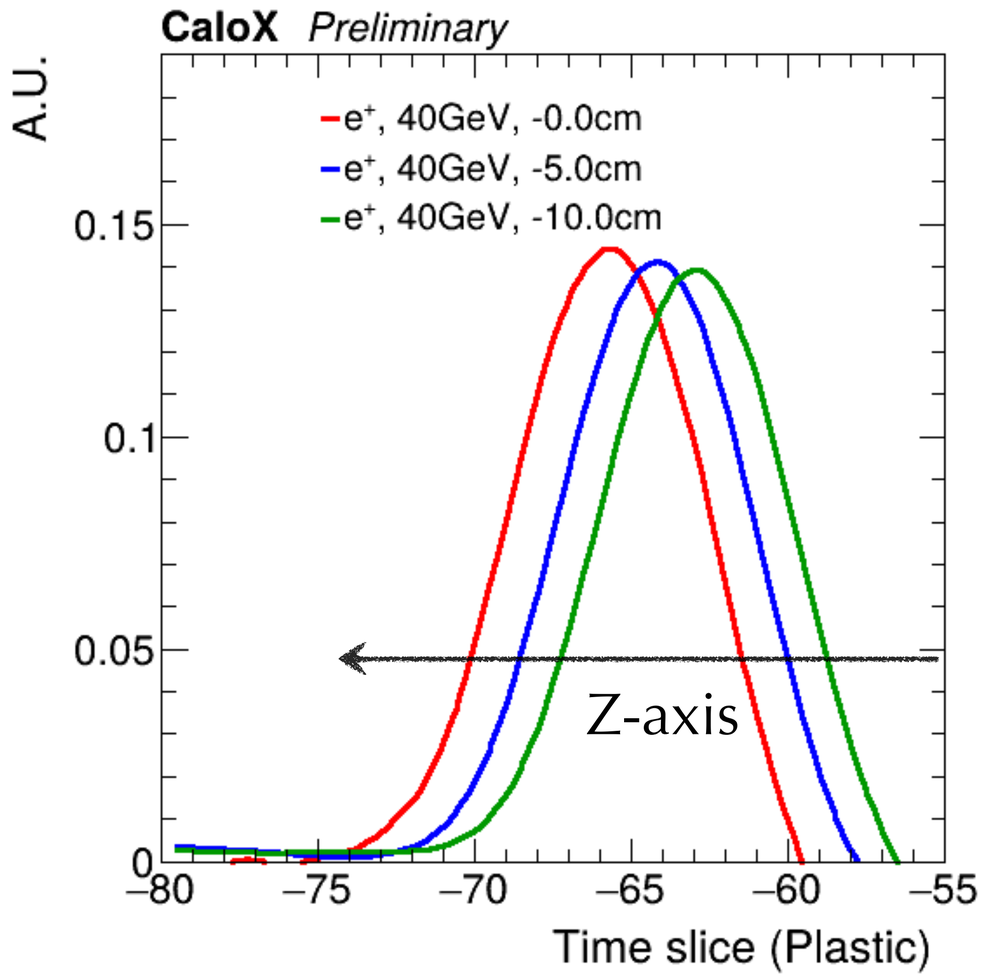
Cherenkov Signals vs Time



- Study the pulses as a function of time, in two different Cherenkov fiber types (refraction indices: 1.48 vs 1.62);
- Rightmost corresponds to the beginning of the shower, where the deltaT between the two fibers are maximal
- DeltaT reduces as shower moves deeper and deeper
- **Successfully observed longitudinal shower shapes from the timing information**

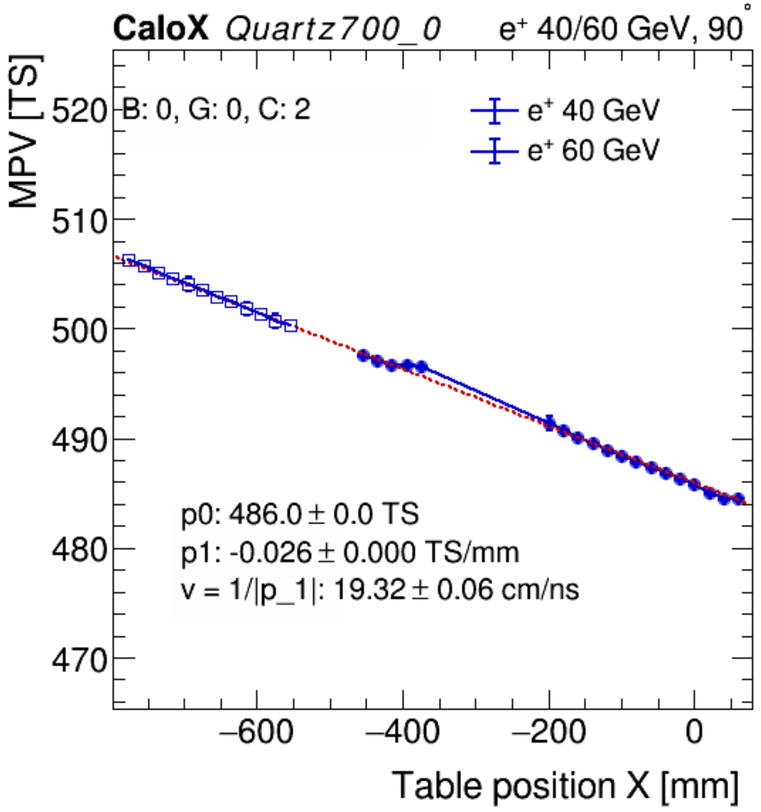
Longitudinal Position Scans

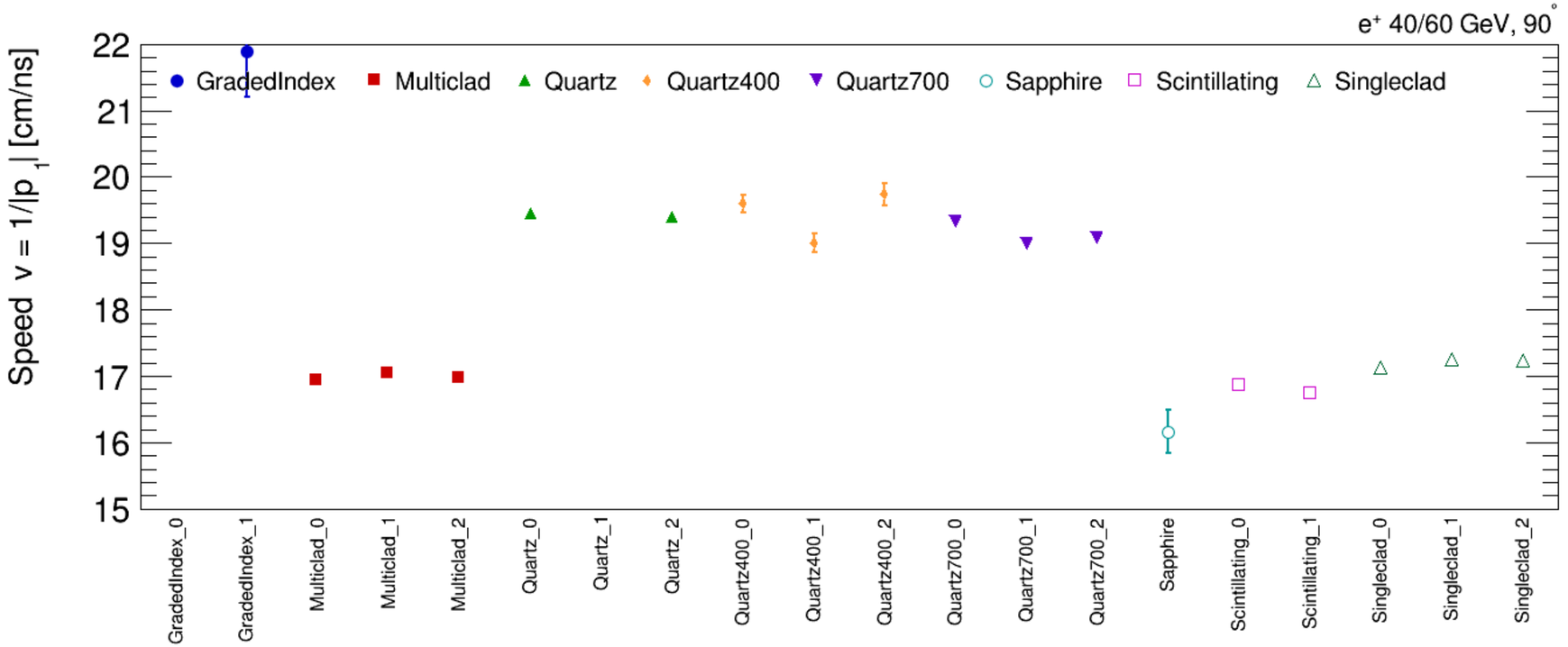




- Rotate the detector by 90 degree; move the detector along the z-axis to check the shower shape change as a function of z
- **Observed the expected shower shape change along the z-axis, using timing information**
- Can measure the light propagation speed in fibers and compare with expectations

Testing fiber results

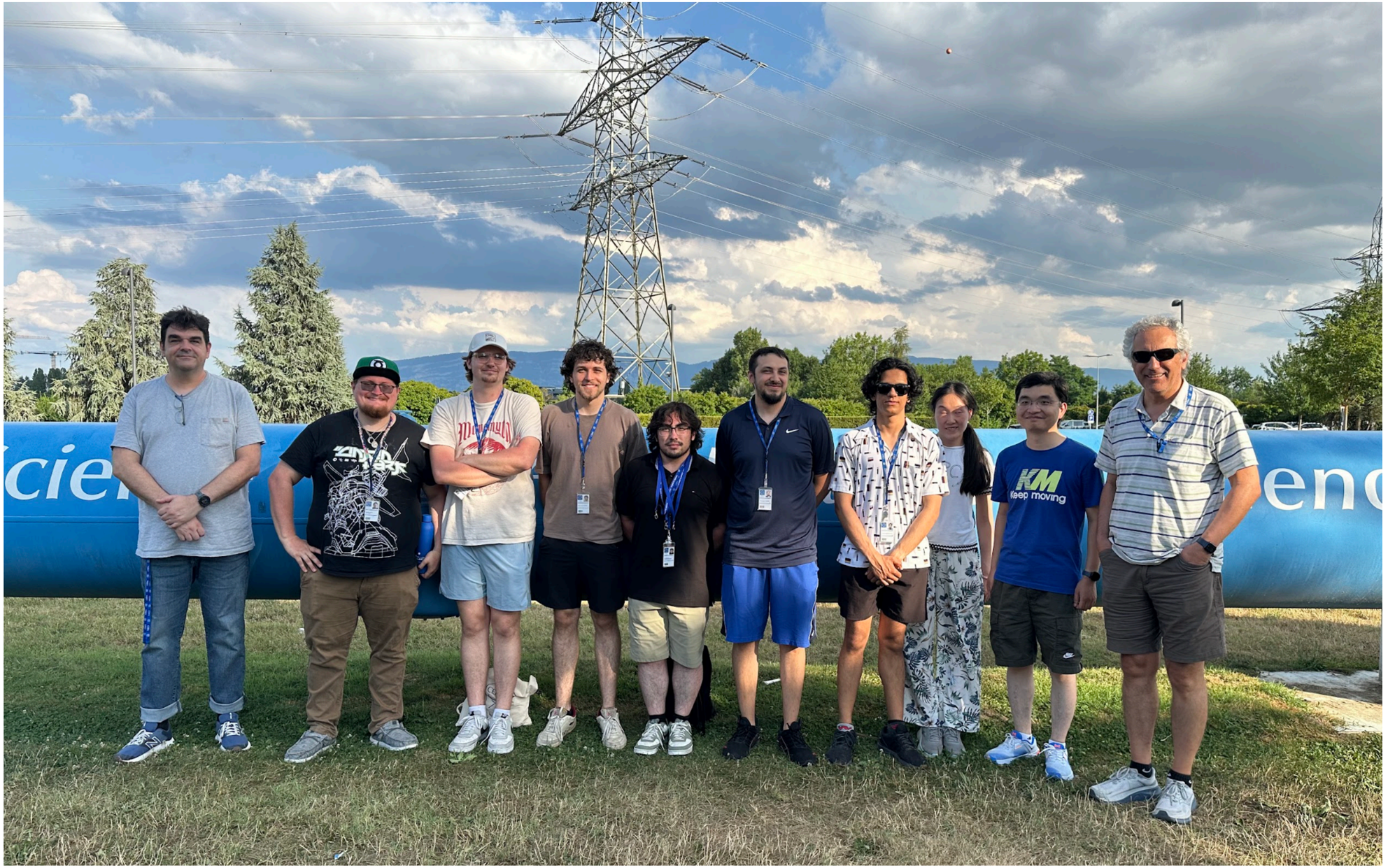




- Tested different types of fibers (quartz, plastic, scintillation, sapphire) with different radius and cladding (single, multiple, graded index)
- Compare the measured speed of light, analog pulse shapes, and number of photons, of different types of fibers

Summary

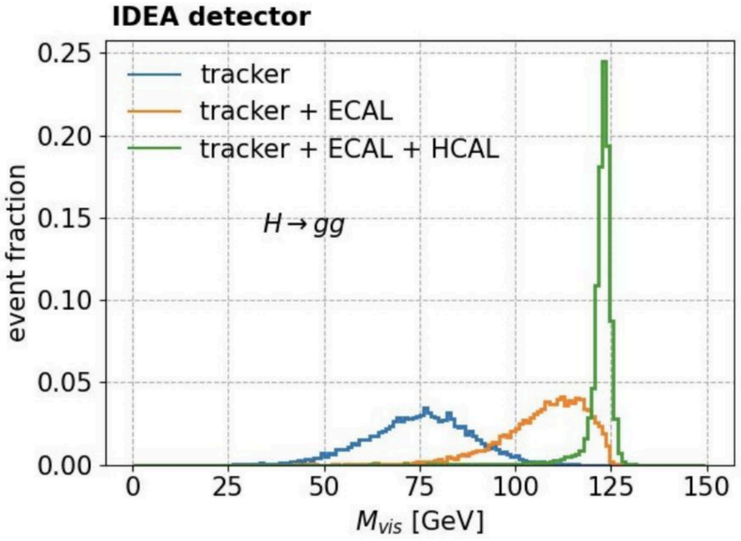
- We built and tested the High-Granularity Dual-REAdout Module (HG-DREAM), equipped with much higher granularity and timing information
- Beam tests performed at CERN H8, where we can study the performance using electrons, pions, muons, and protons
- More detailed data analyses and simulation studies are ongoing, to check how accurate we can understand and model the data, and how much we can push for the energy and timing resolution
- We thank support from DOE Office of Science, High Energy Physics, discussions and comments from DRDCalo Collaboration and CalVision working meetings

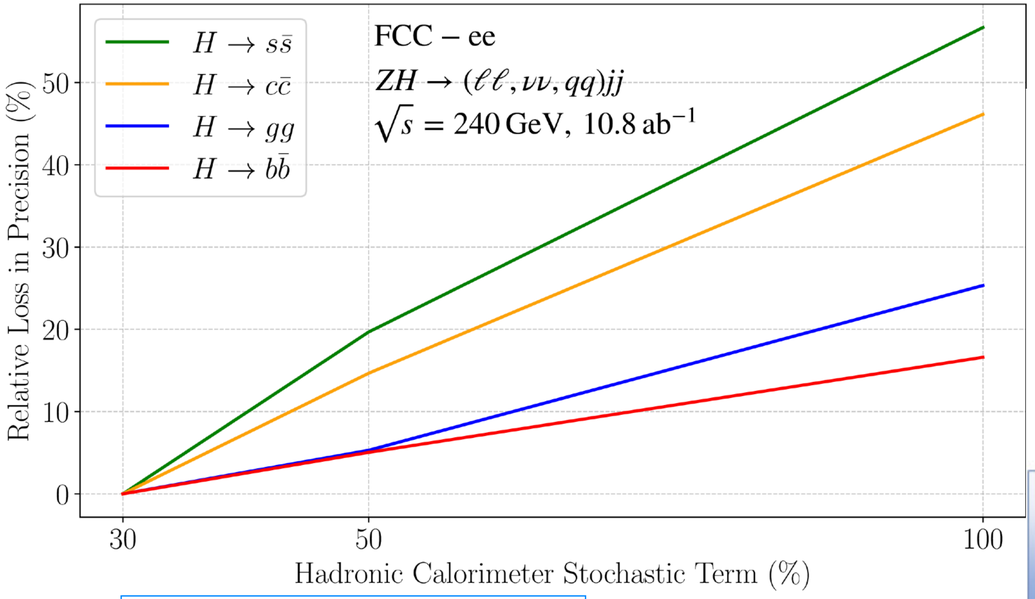

KM
keep moving

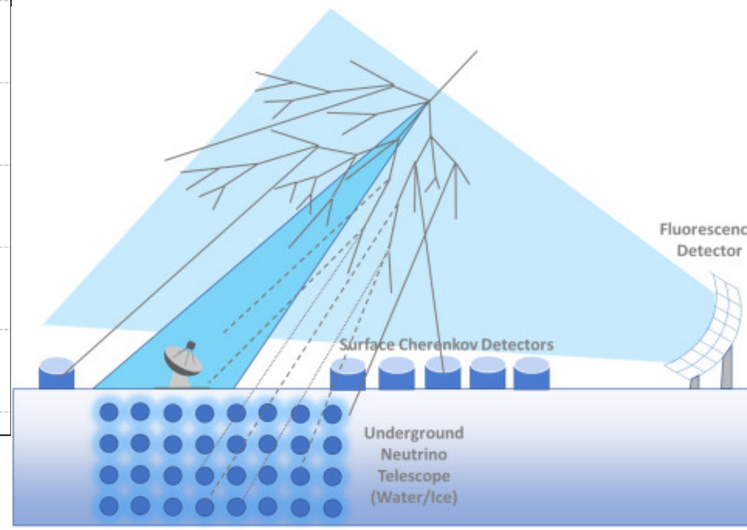
Back Up

(Hadron) Calorimeter

- (Hadron) Calorimeter: Convert the energy information to nPhotons / charges
- To achieve the optimal sensitivity reach of physics goals in future colliders, including FCC-ee/hh, or muon collider, we need an excellent (hadron) calorimeter
- Calorimeter (and the relevant technology) also plays an important role outside of collider physics: neutrinos, dark matter, cosmic, etc

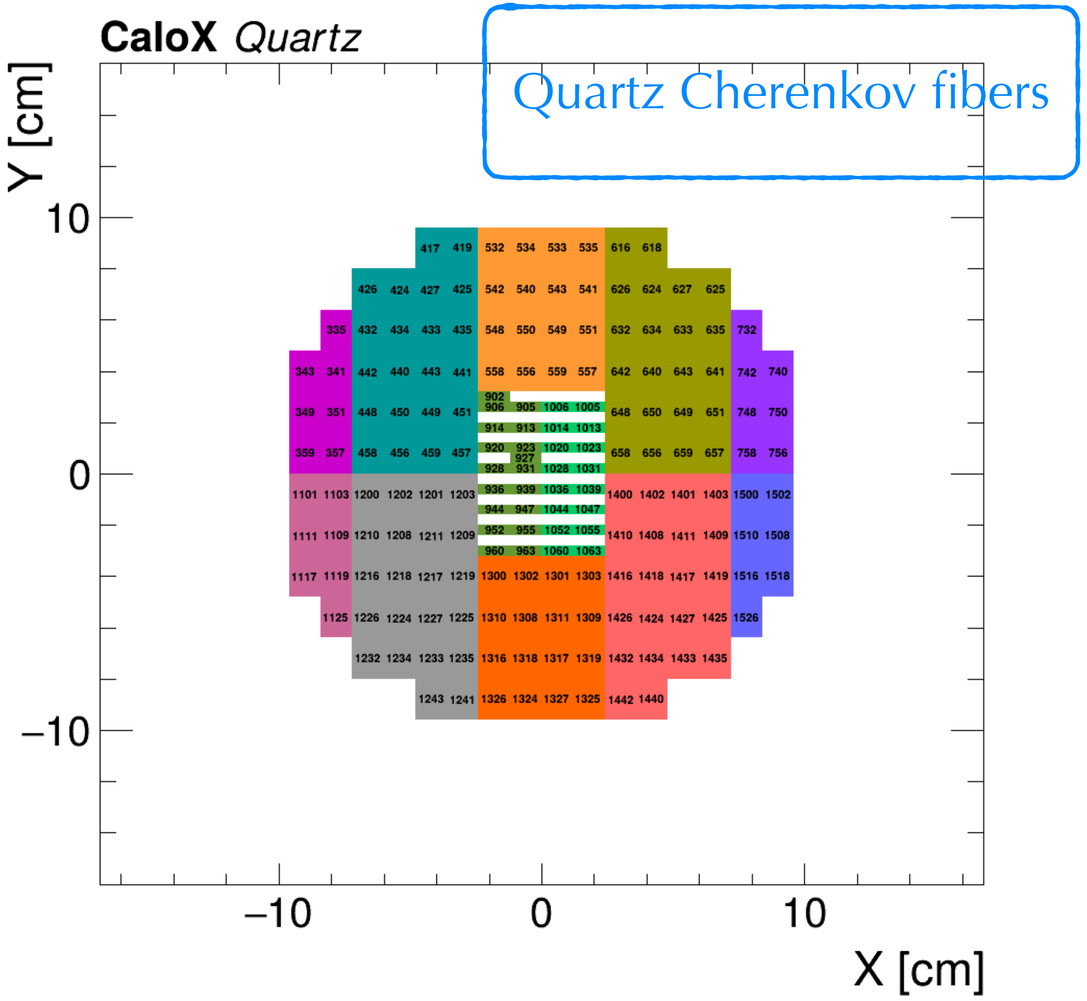


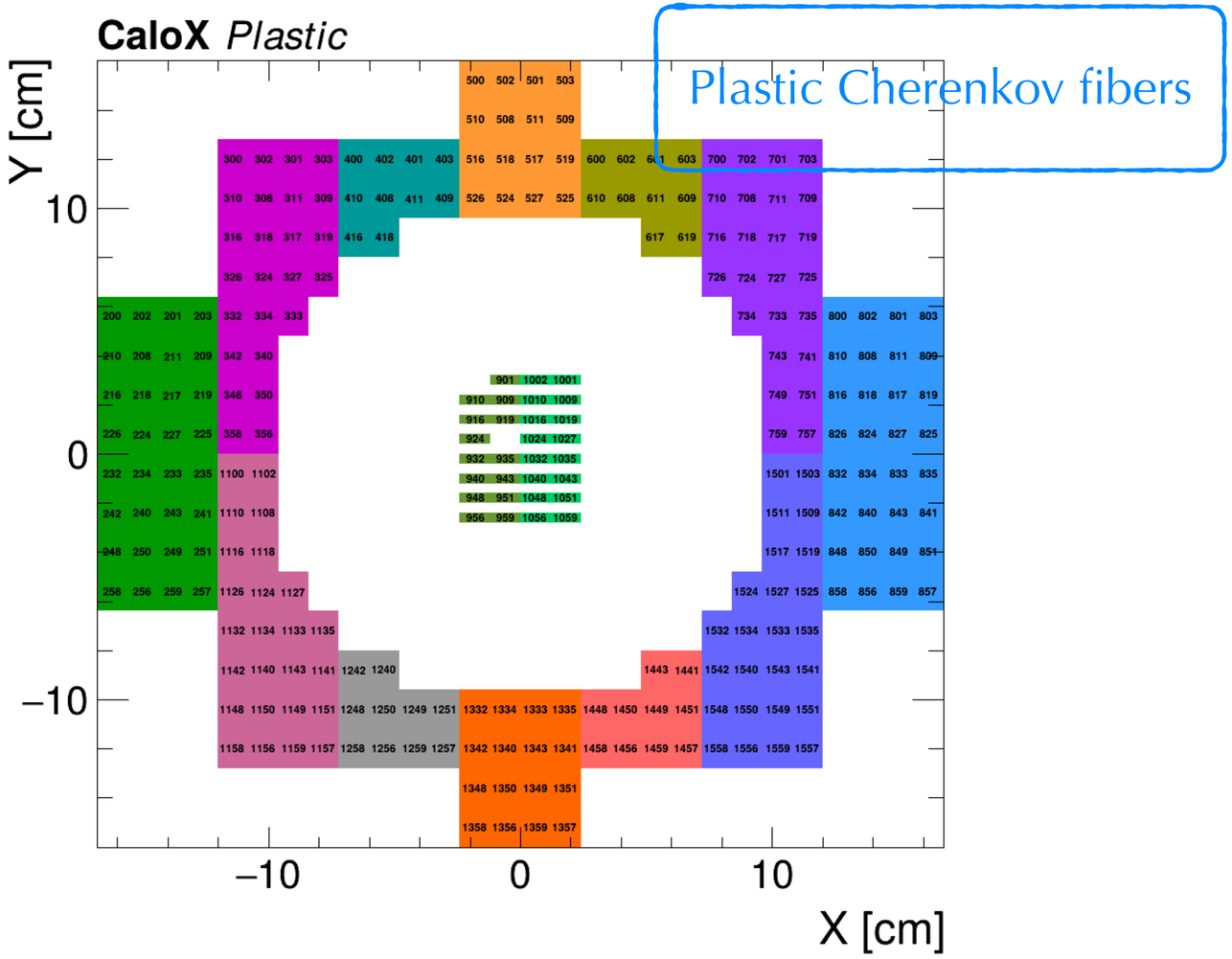




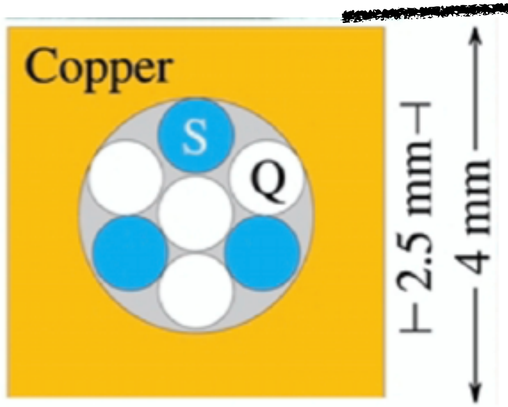
Arxiv:2504.11103v1

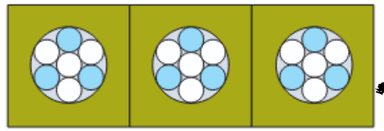
Cherenkov Channels

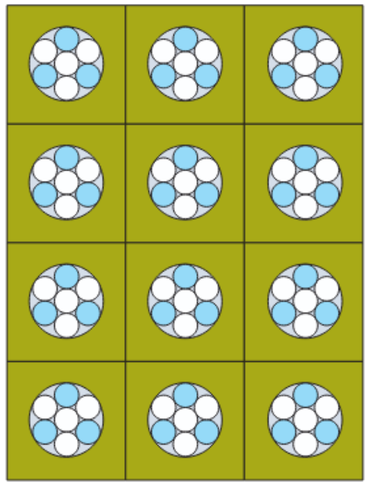


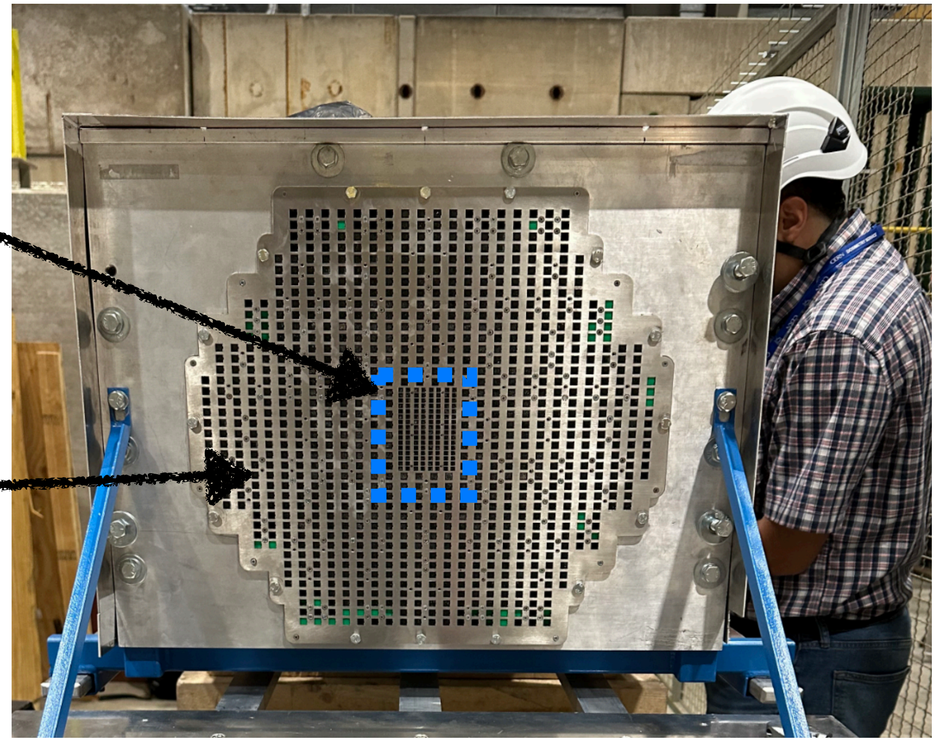


Detector construction





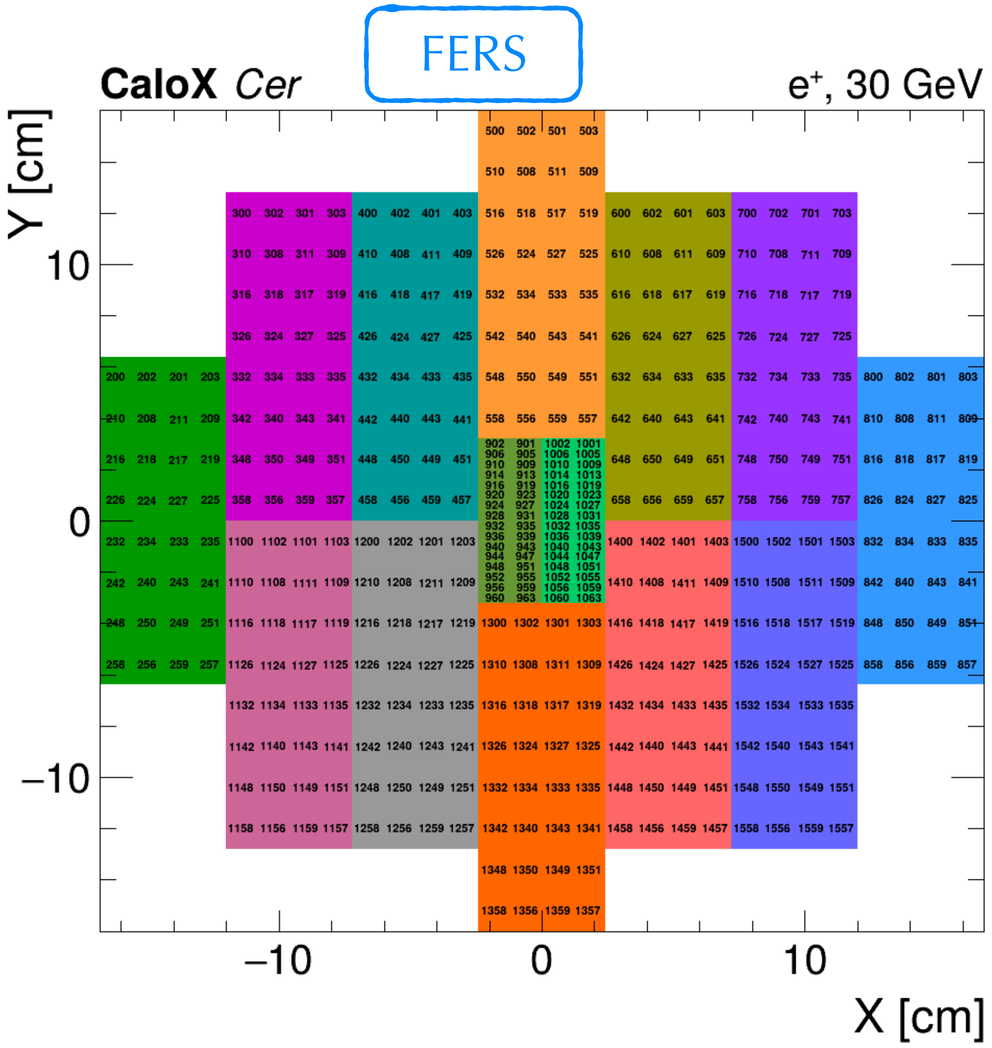


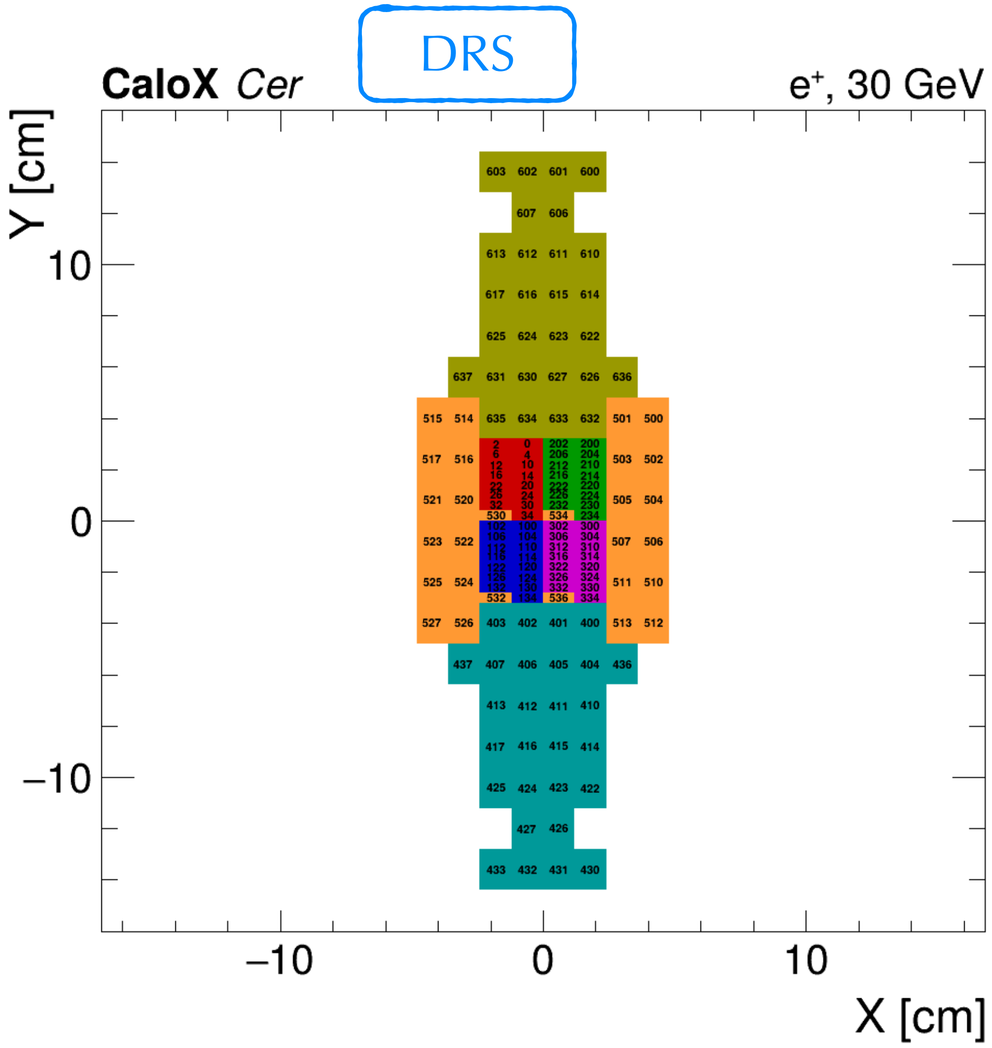


- Copper size 0.4cm x 0.4cm, filled in with 4 Cherenkov fibers and 3 scintillation fibers
  - Use different Cherenkov fibers (quartz and plastic) to study the performance with different refraction index (quartz: ~1.5; plastic: ~1.65)
- Readout tower size is 1.2cm x 0.4cm in the central region; 1.2cm x 1.6cm in the outer region.
  - Effective moliere radius ρ_M ~2cm; radiation length X_0 ~ 2cm; nuclear interaction length λ ~20cm
- Whole detector is 34cm x 32cm x 200cm, with 448 towers (896 channels)
  - whereas traditional high-granularity prototypes typically have O(10K) - O(100K) channels

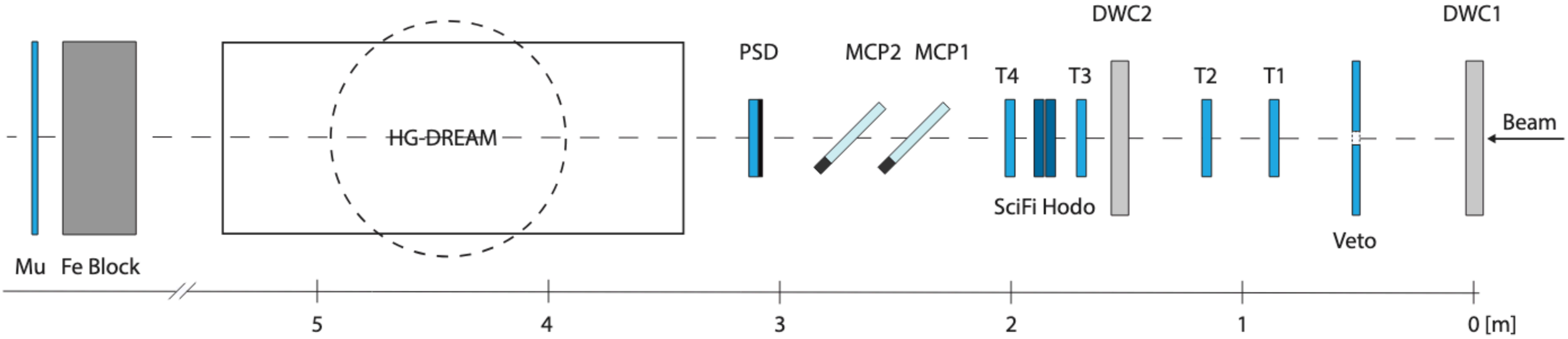
Read-out

- Channels read out simultaneously by CAEN FERS A5202 (for energy) and DRS V1742 (for timing, 5GHz sampling, 12 bits) information



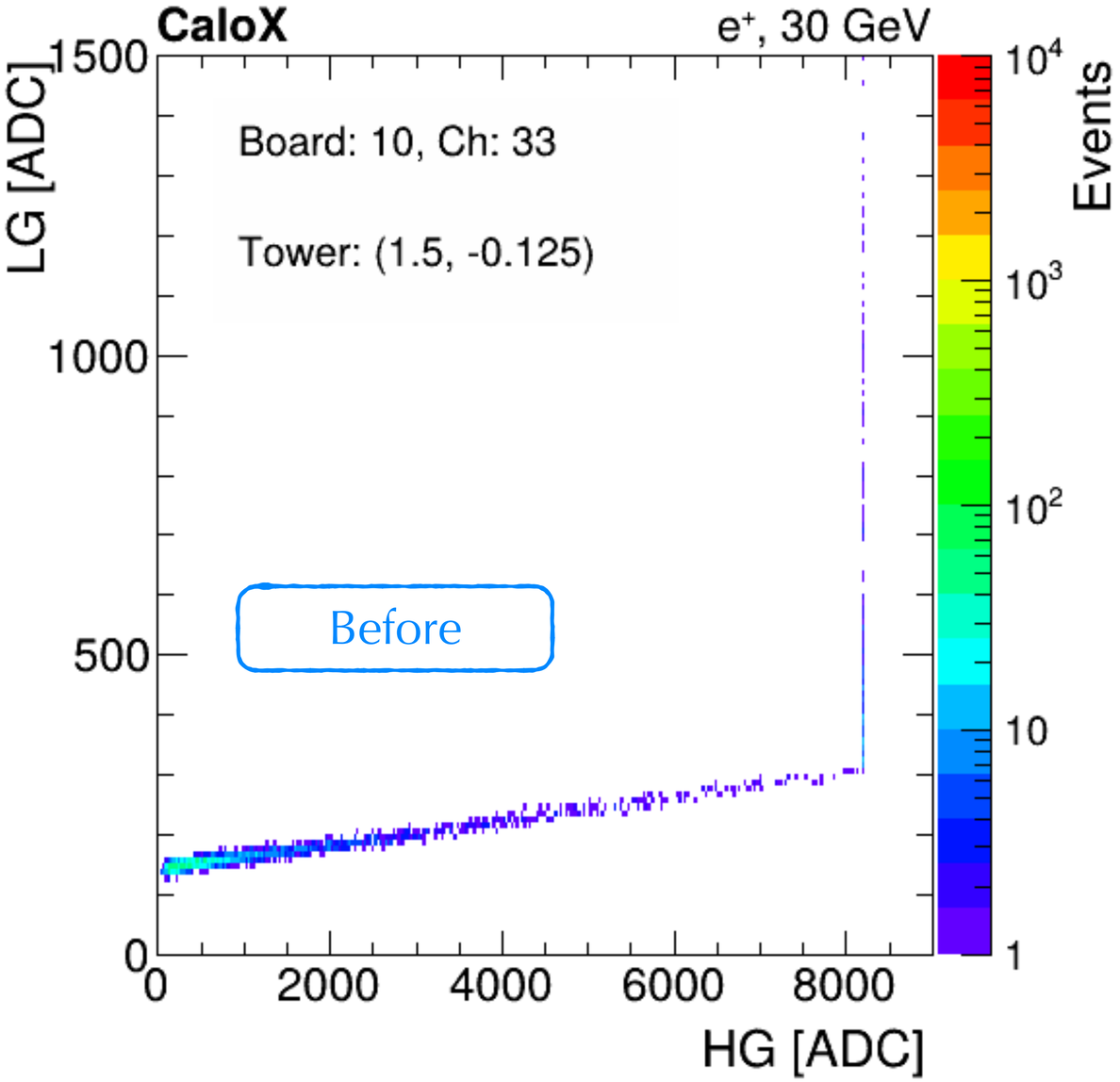


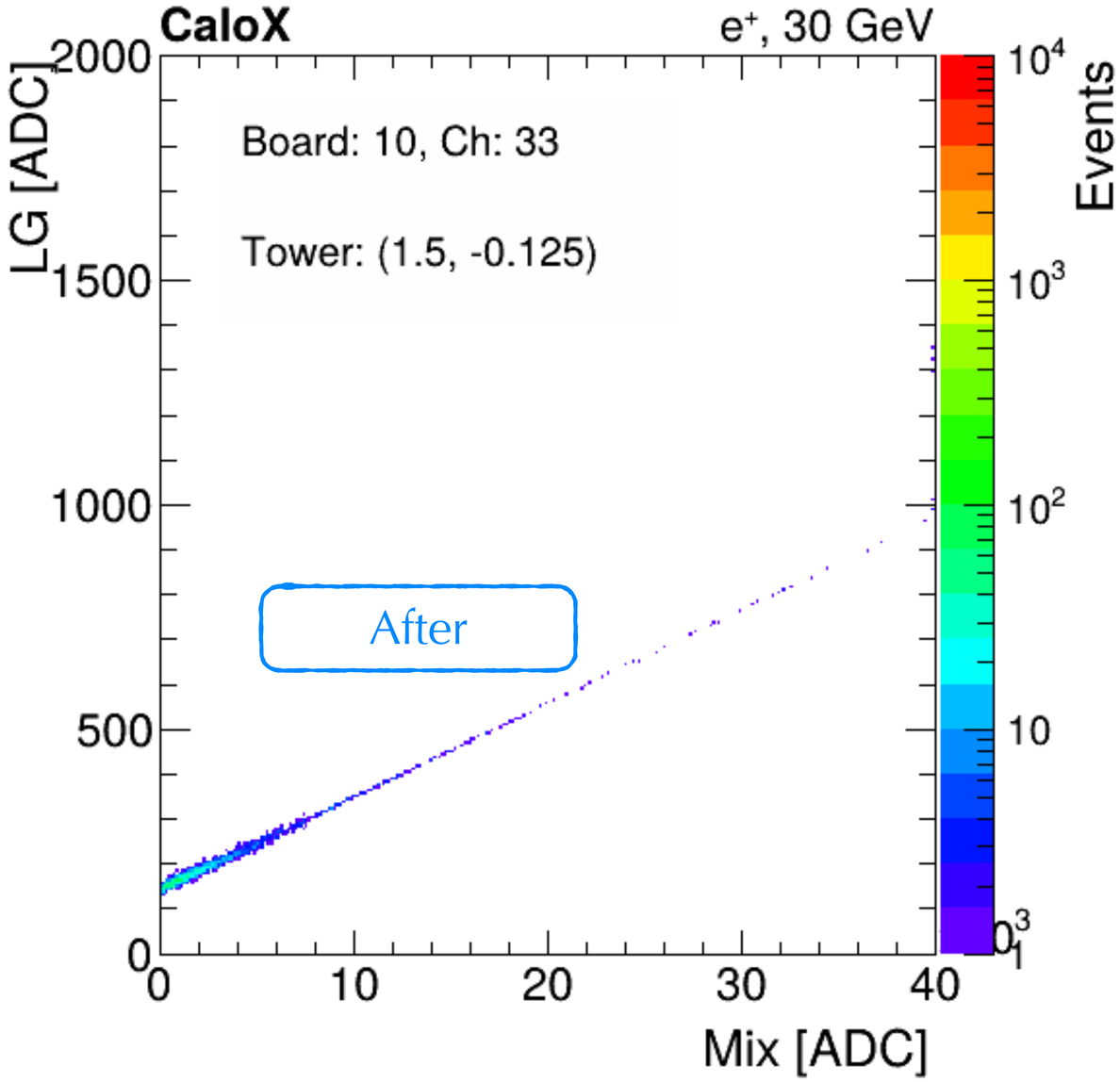
Setup: Beam Tests at H8



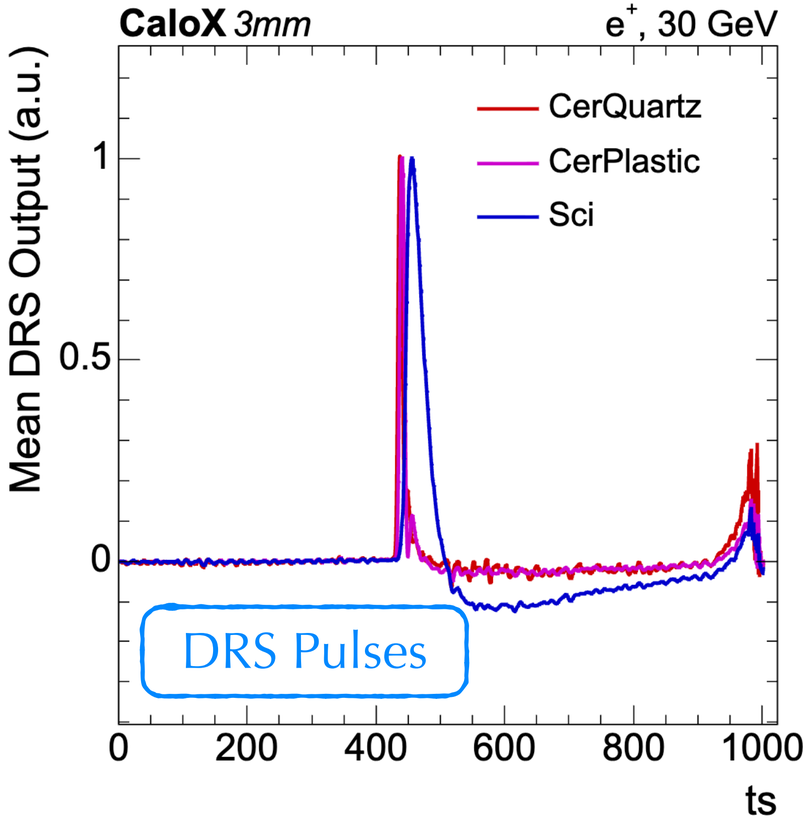
- Drift wire chambers (DWC) and hodoscopes for particle position determination
- HoleVeto to localize the beam
- Preshower detector (PSD), Cherenkov counters, and muon counters for particle identification: e, p, pi, mu
- MCPs for timing alignments

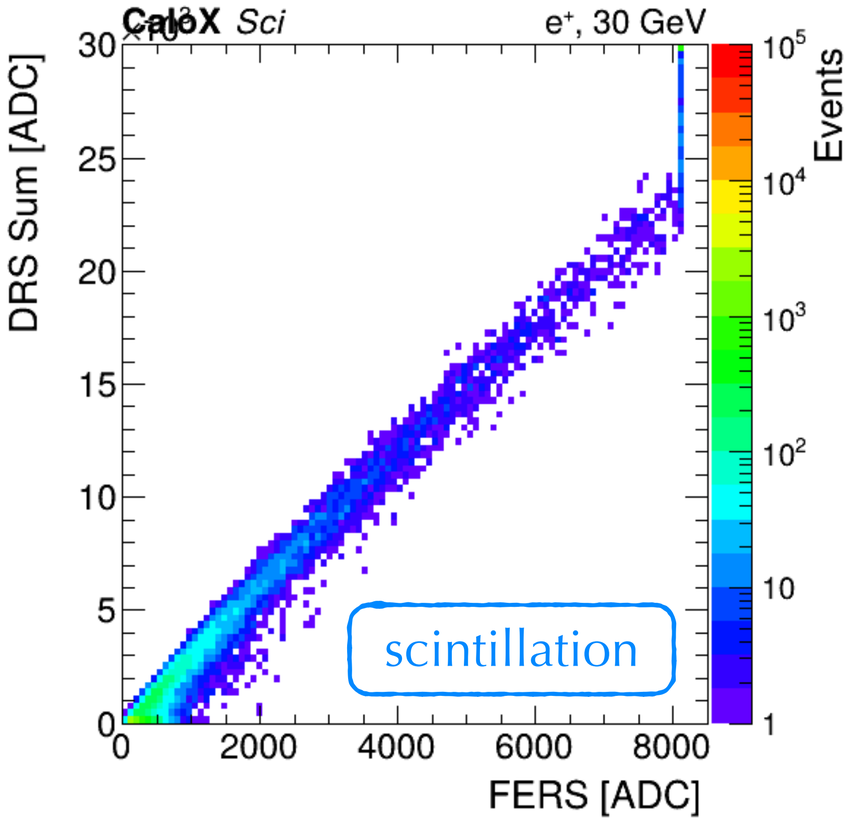
Energy: Linearity: LG vs HG

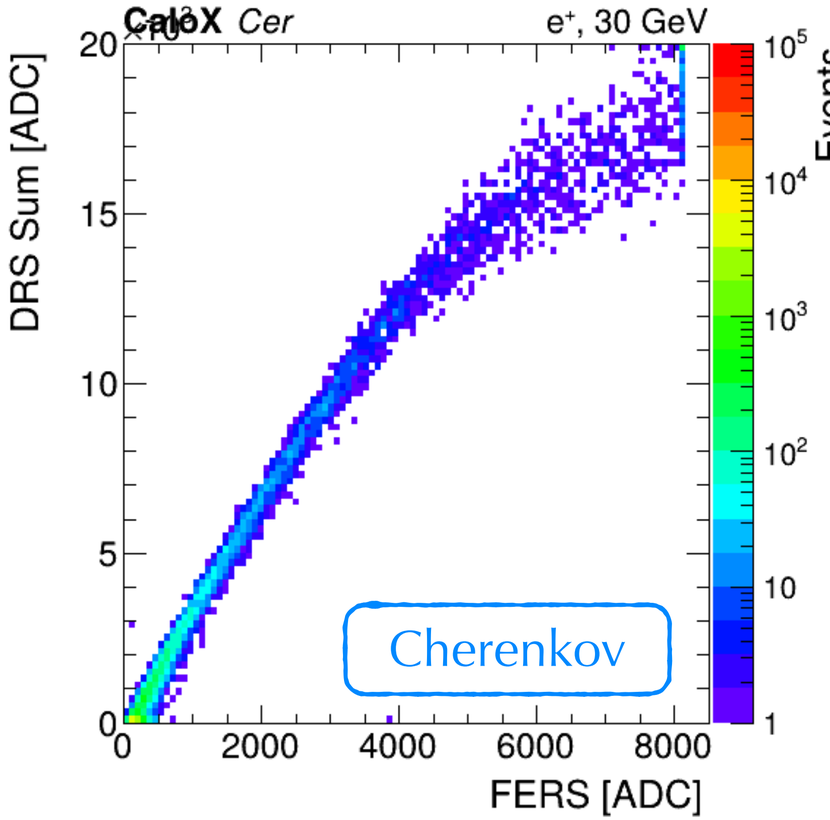




Energy: Linearity: FERS vs DRS integral

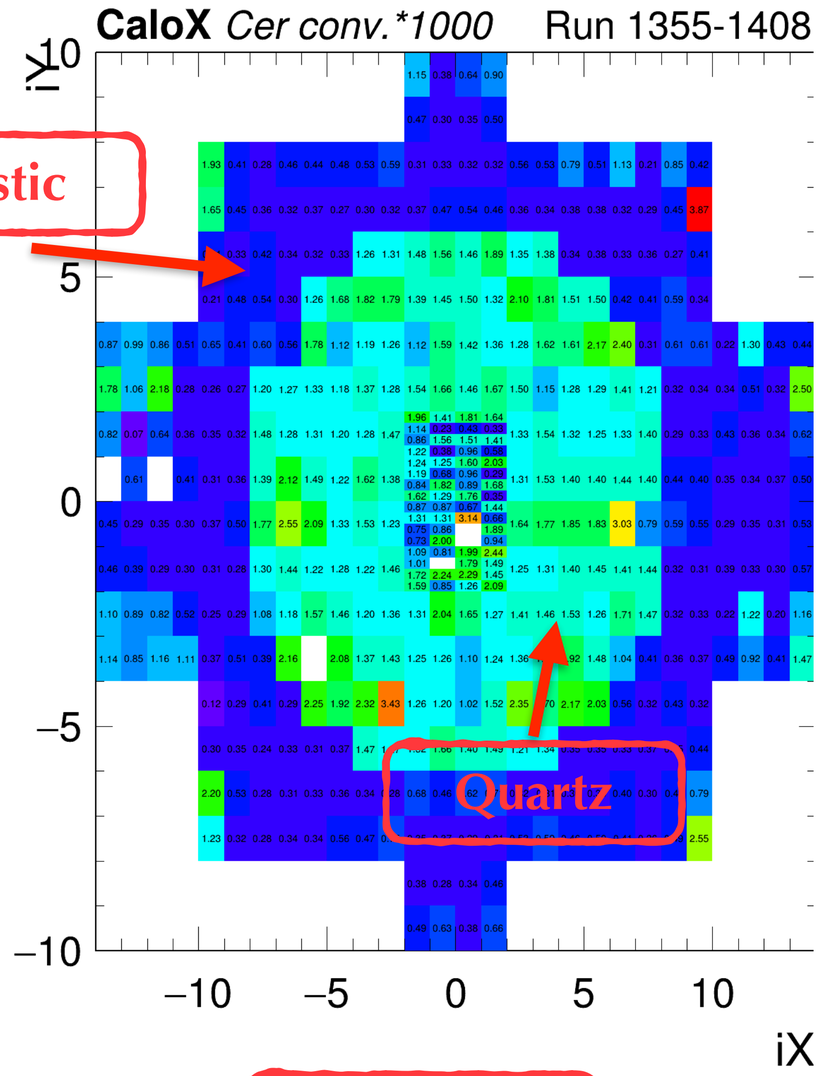


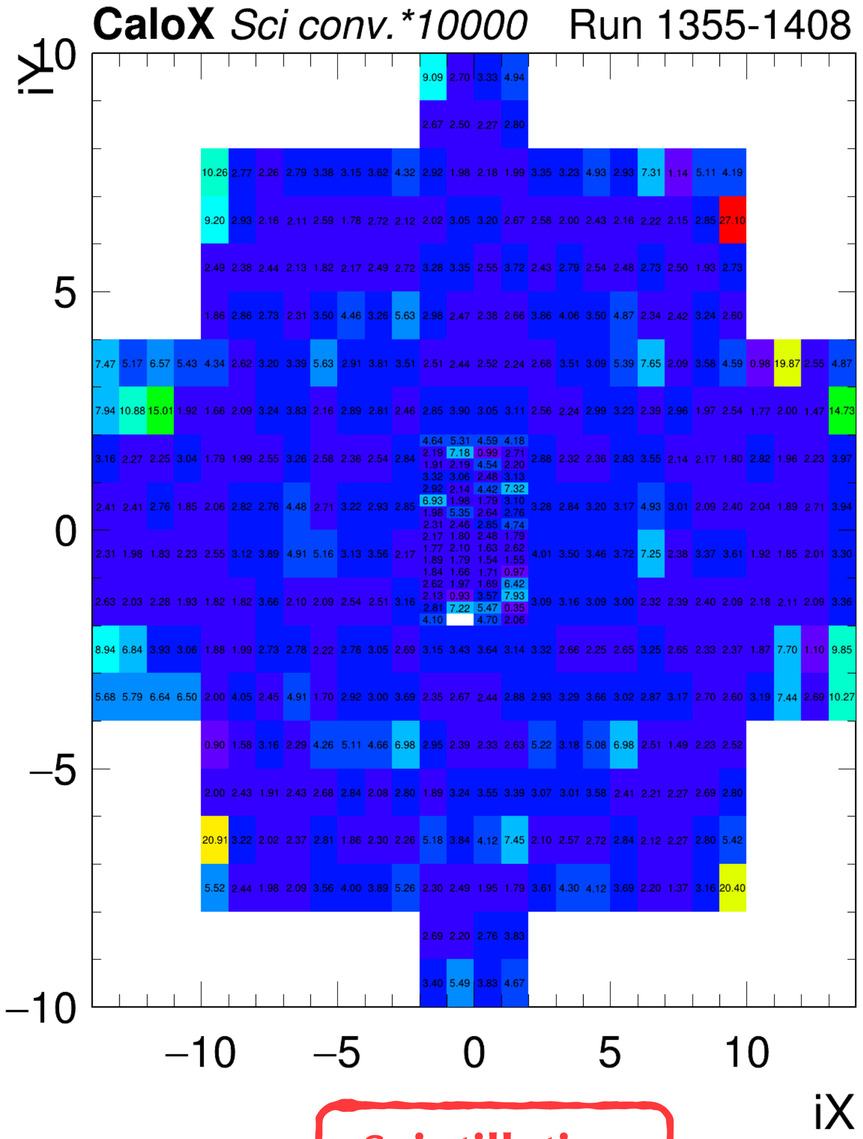




- Good linearity between DRS integral vs FERS for scintillation and Cherenkov channels
- For Cherenkov channels, at larger energy deposit, DRS starts to saturates, which causes the non-linearity between DRS integral vs FERS.

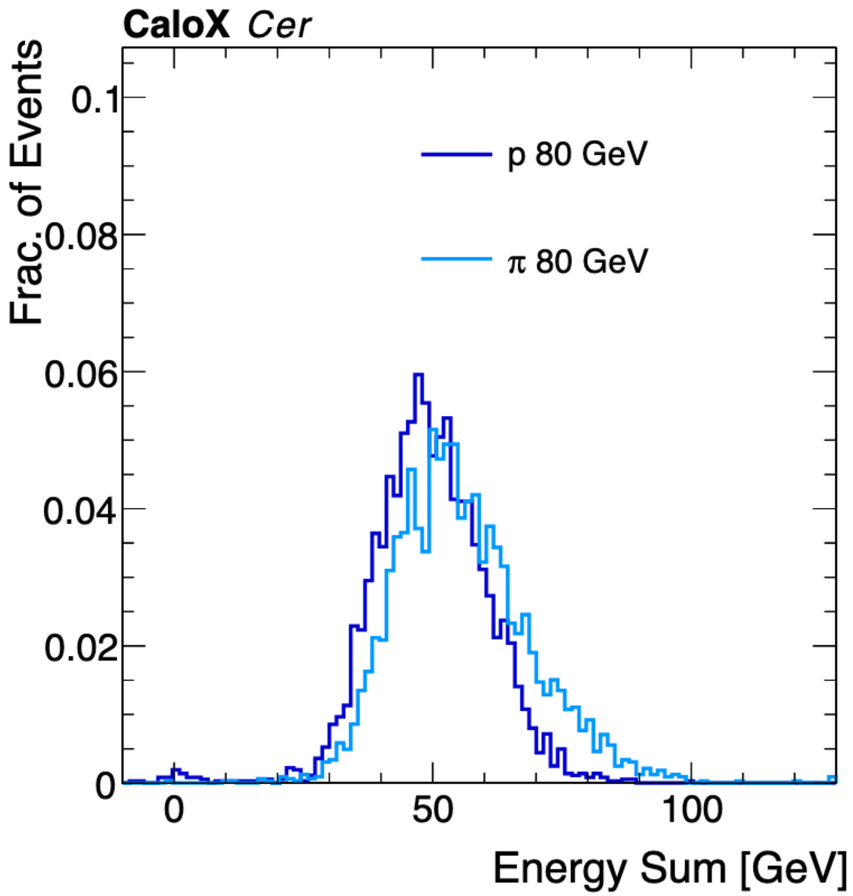
Distribution of Calibration Constants

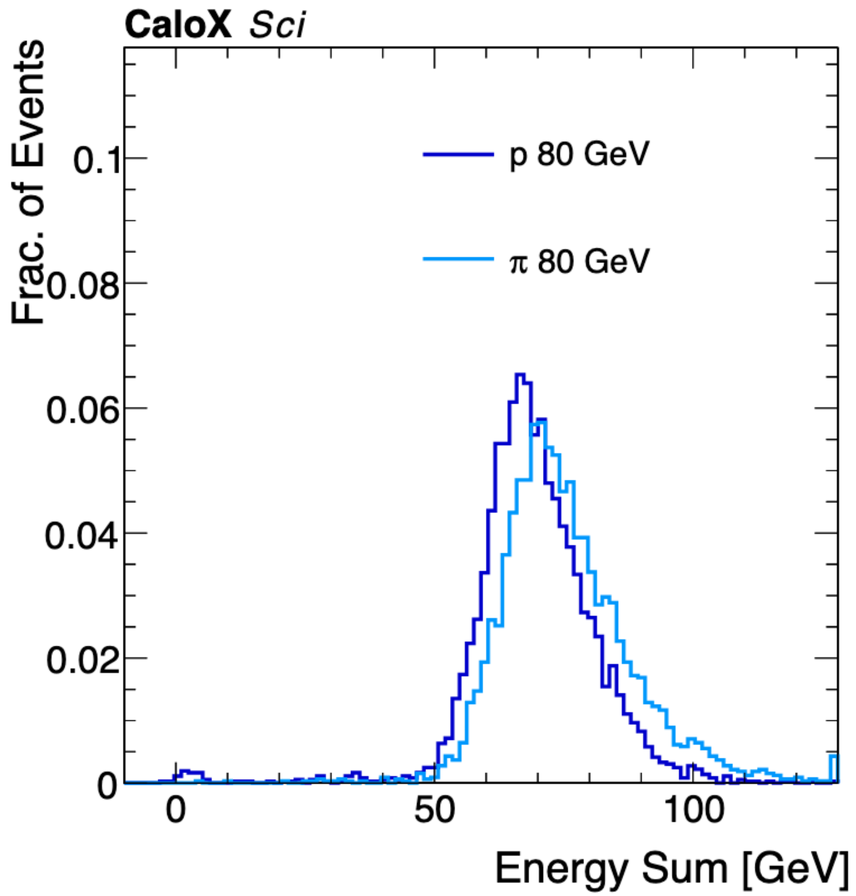




- For Cherenkov channels, managed to separate Quartz fibers from plastic fibers without any prior information
- Among the same types of fibers, calibration constants vary within ~10%

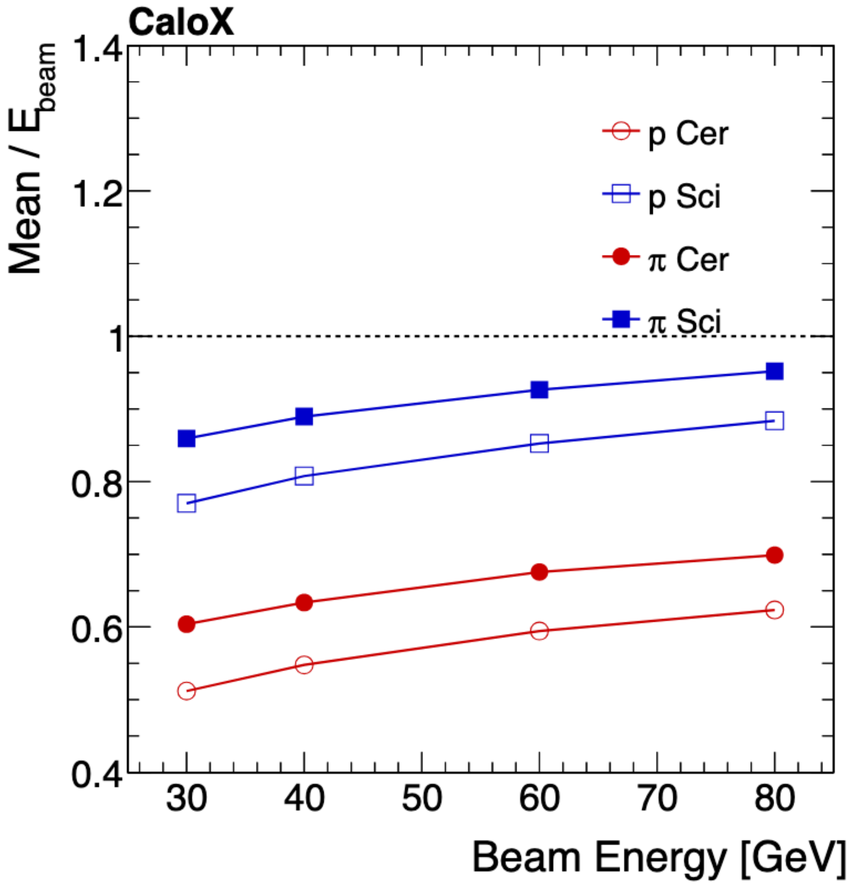
Pion vs Proton

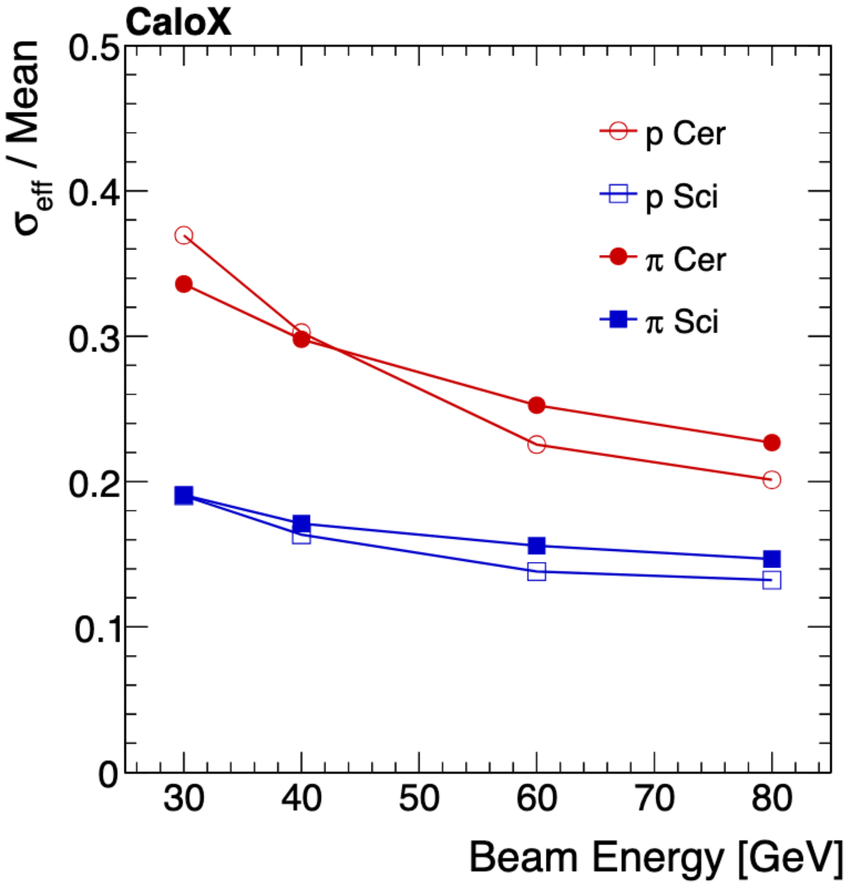




- Lower response for proton showers compared with pion showers, in both C and S channels, as expected:
  - Due to baryon number conservation, proton first interaction produces baryons; whereas pion first interaction can produce pi0 (diphotons). Higher response in pion showers (higher <f_EM>) compared with protons

Pion vs Proton





- Compare with pion showers, proton showers have lower response and better resolutions at high energies

Particle Identification

Table 1. Summary of detector responses used for particle identification.

Particle	PSD	Muon Counter	Cherenkov Counter
e^+	Pass	Fail	–
μ^+	Fail	Pass	–
π^+	Fail	Fail	Pass
p^+	Fail	Fail	Fail