High-granularity Dual-readout Calorimeter: Evolution of a Classic Prototype

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Outline

What do we know already?

1. DREAM prototype performance is well-known and well-documented
2. Dual-readout technique is understood

How do we modify the old DREAM into new HG-DREAM prototype to achieve new objectives?

1. High-granularity with (standard/fast) SiPMs
2. Waveform digitizers (5-10 GHz) in the core of detector

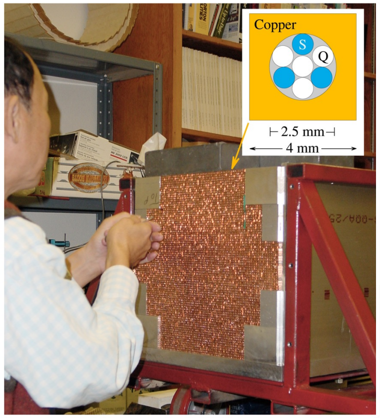
What do we expect?

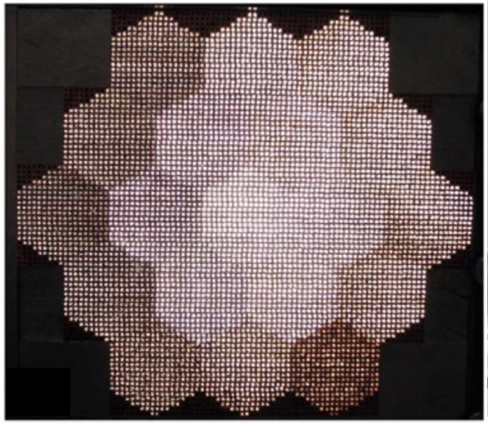
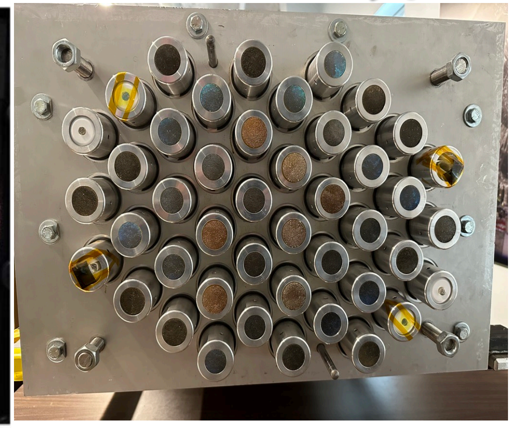
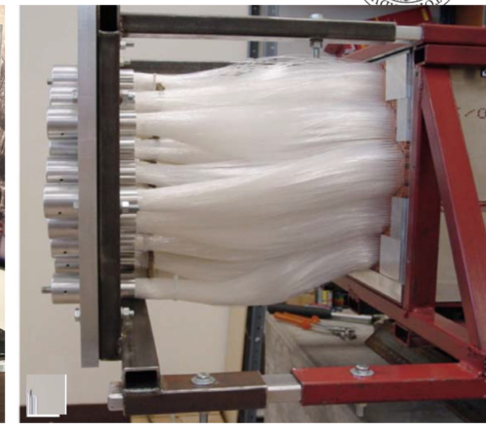
1. Simulations suggest improved performance with NNs compared to traditional approaches for 2D and 3D segmented calorimeters
2. Verify (or not) these expectations in a test beam (CERN H8) this August
3. Sharpen our understanding of
   - Precision and absolute timing,
   - high-granularity, and
   - clear (high *n*), shaped (helical), and scintillating fibers

What are Our Objectives?

1. Longitudinal segmentation by timing of otherwise unsegmented (fiber) calorimeter
   - enables position, energy, and time (5D) reconstruction of showers
   - reduces channel count (n^3 *vs* n^2)
2. Improved calorimeter performance by Cherenkov light alone
   - becomes possible when high-granularity is combined with NNs and fast (short integration times) calorimetry
3. Precision timing coupled with NNs
   - seems to improve energy regression
   - adds a new and independent observable to NN reconstruction algorithms
4. Absolute timing by calorimeter alone
   - introduces a new capability for pileup mitigation, TOF/PID measurements, jet substructure analysis by using different shaped fibers and/or refractive indices
5. Data processing on detector (*e.g.* AI/ML algorithms)

The Original DREAM Prototype



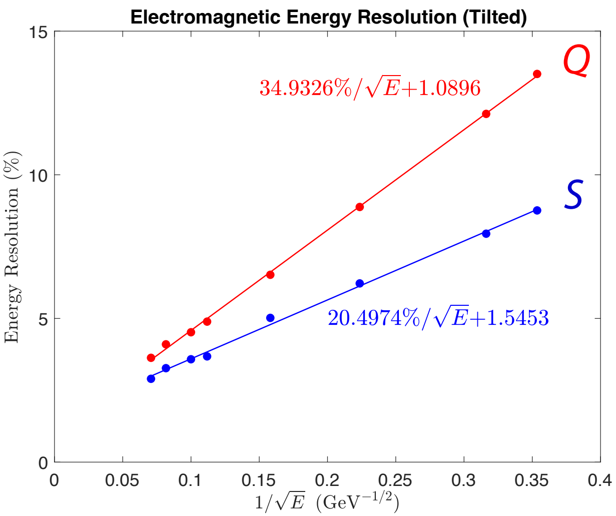




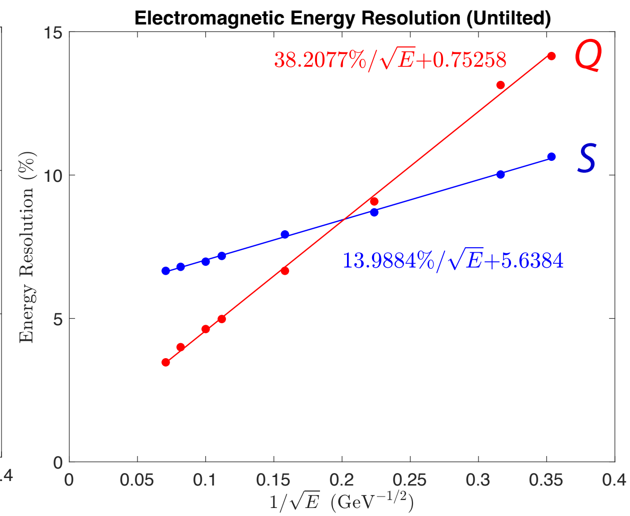
DREAM module was built at TTU and exposed to beams at CERN starting in 2003 in several campaigns

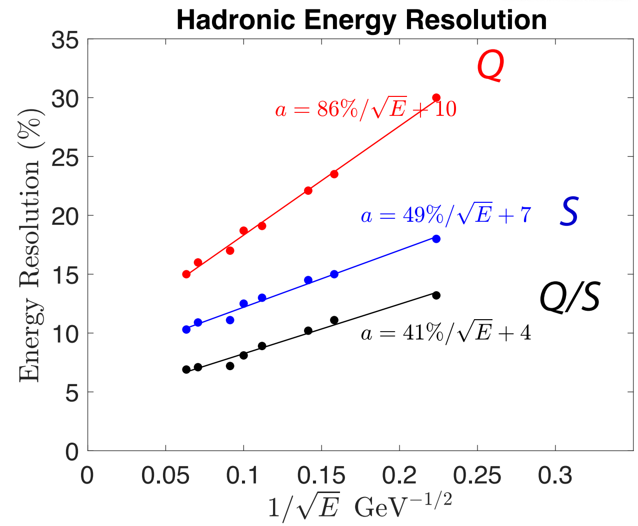
The motivation was to explore the simultaneous measurement of showers using scintillation (*S*) and Cherenkov (*Q*) signals for event-by-event compensation because $Q/S \sim f_{em}$

- X_o ~20.1 mm, ρ_M~ 20.4 mm, λ_I~ 200 mm, and weight ~ 1,030 kg
- Scintillating fiber: SCSF-81J Kuraray
- Clear/Cherenkov fibers: QP Polymicro, Raytela PJR-FB750 Toray
- 69.3% Cu, 9.4% Scintillator, 12.6% Cherenkov, and 8.7% air
- f_{samp} $(Cu/S)_{MIP}$ ~ 2.1%
- 19 Scintillating and 19 Cherenkov towers of *r* ~ 37.1 mm
- PMT R580 10-stage with gain 3.7E5 at -1250 V

DREAM Performance in a Nutshell

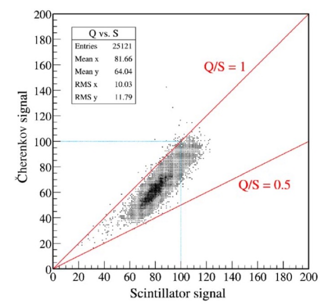


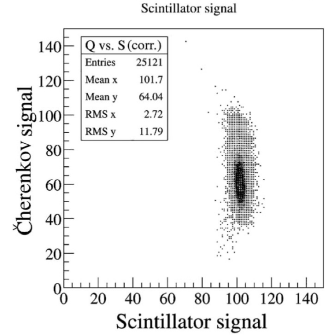


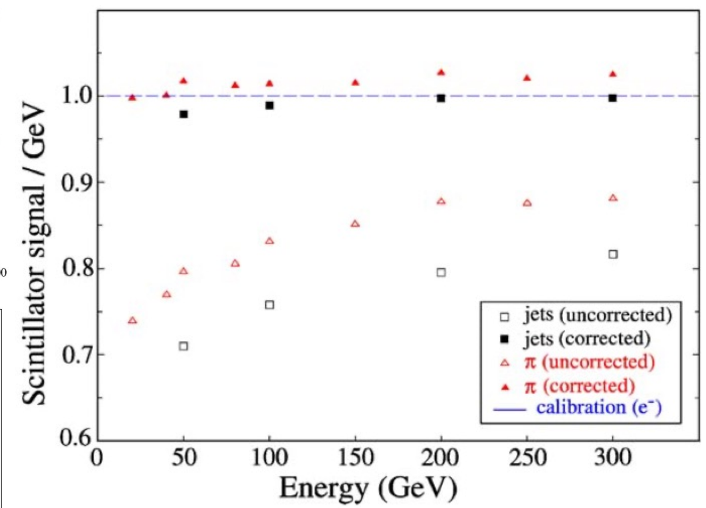


The photoelectron yield was 8 pe/GeV for Cherenkov with fused-silica (Polymicro), 18 pe/GeV for clear plastic (Toray), and 33 pe/GeV for scintillator fibers (Kuraray).

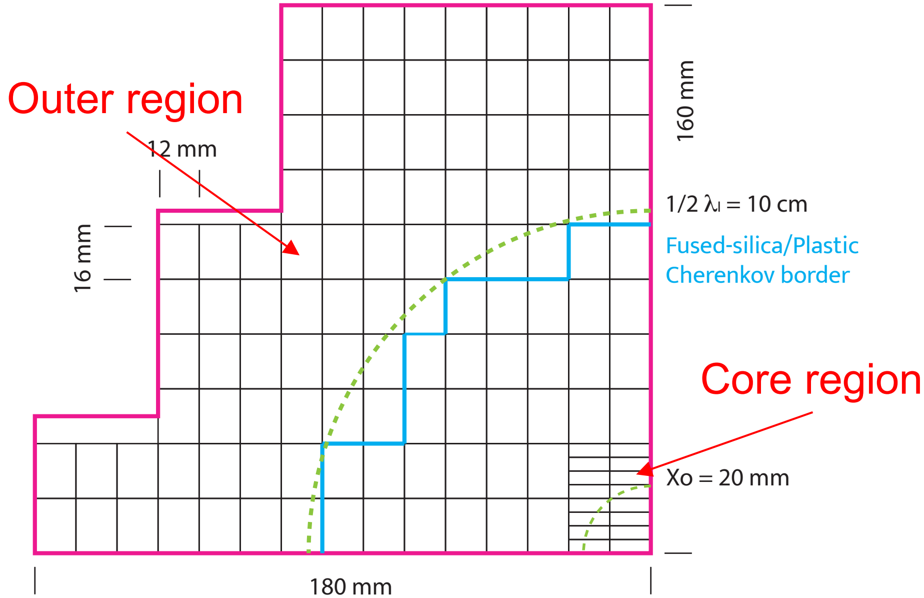
The hadronic energy resolution improves with *Q/S* correction (essentially a rotation in *Q vs S* plane), and the hadronic response linearity is attained as well

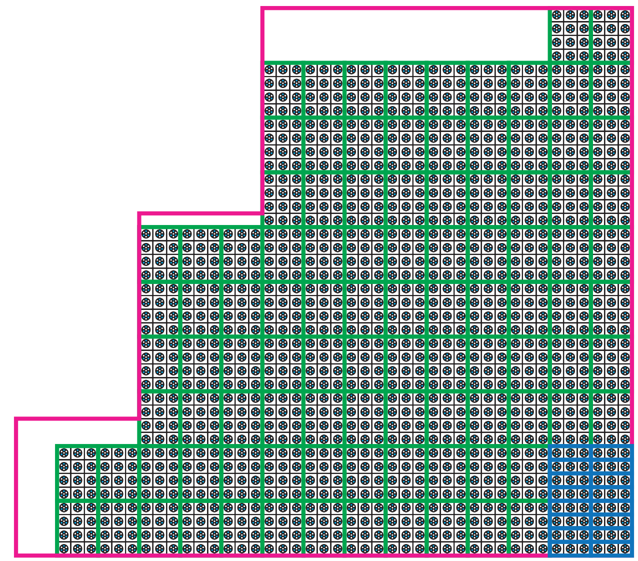




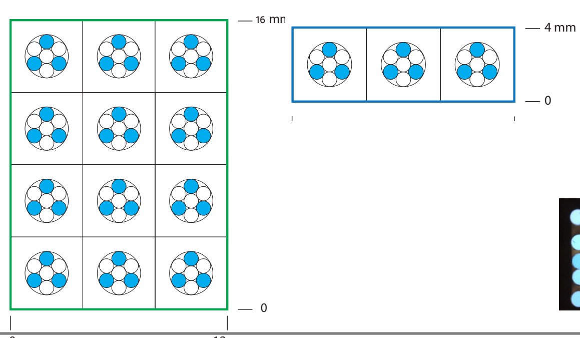


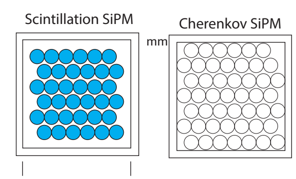
HG-DREAM Segmentation - I

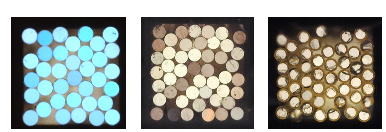


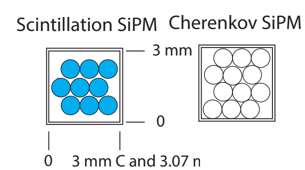


	Tower size (mm²) (No of rods)	No. S/C fibers	SiPM area (mm²)	No. of units
Outer region	12x16 (12)	36 S, 48 C	6x6	440
Core region	12x4 (3)	9 S, 12 C	3x3	64

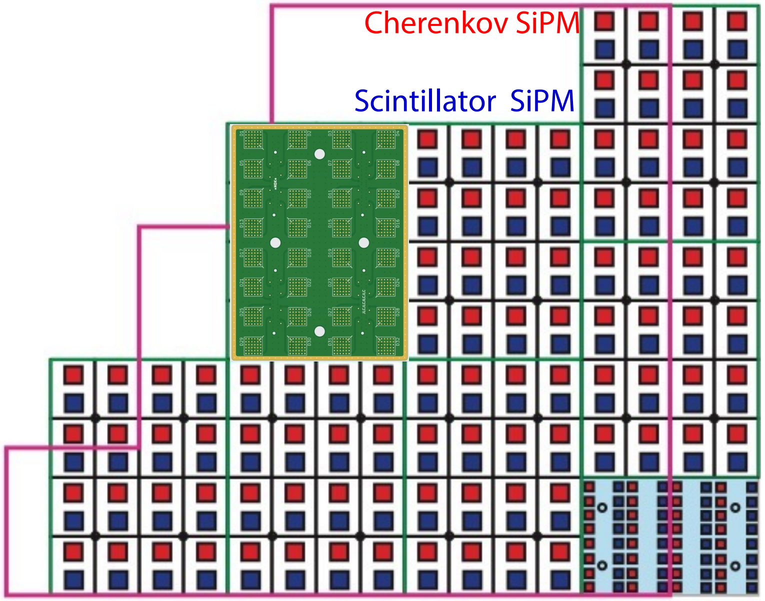


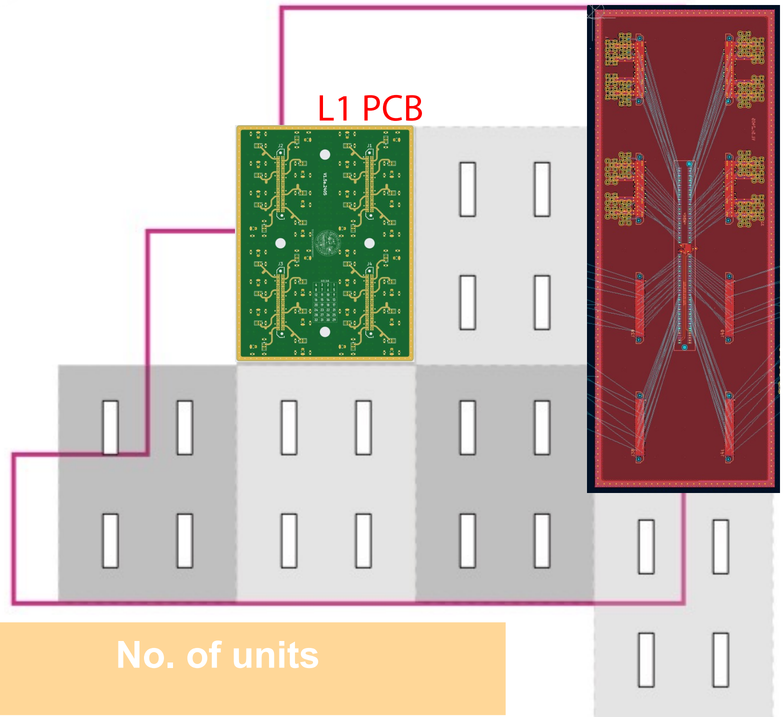






HG-DREAM Segmentation - II

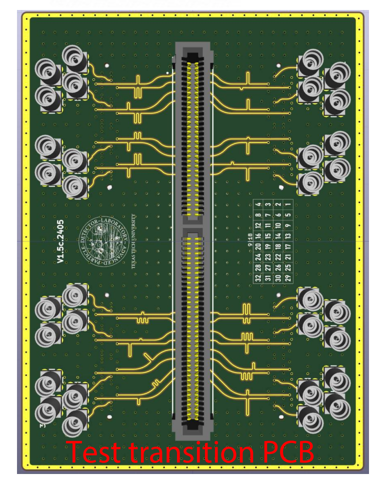




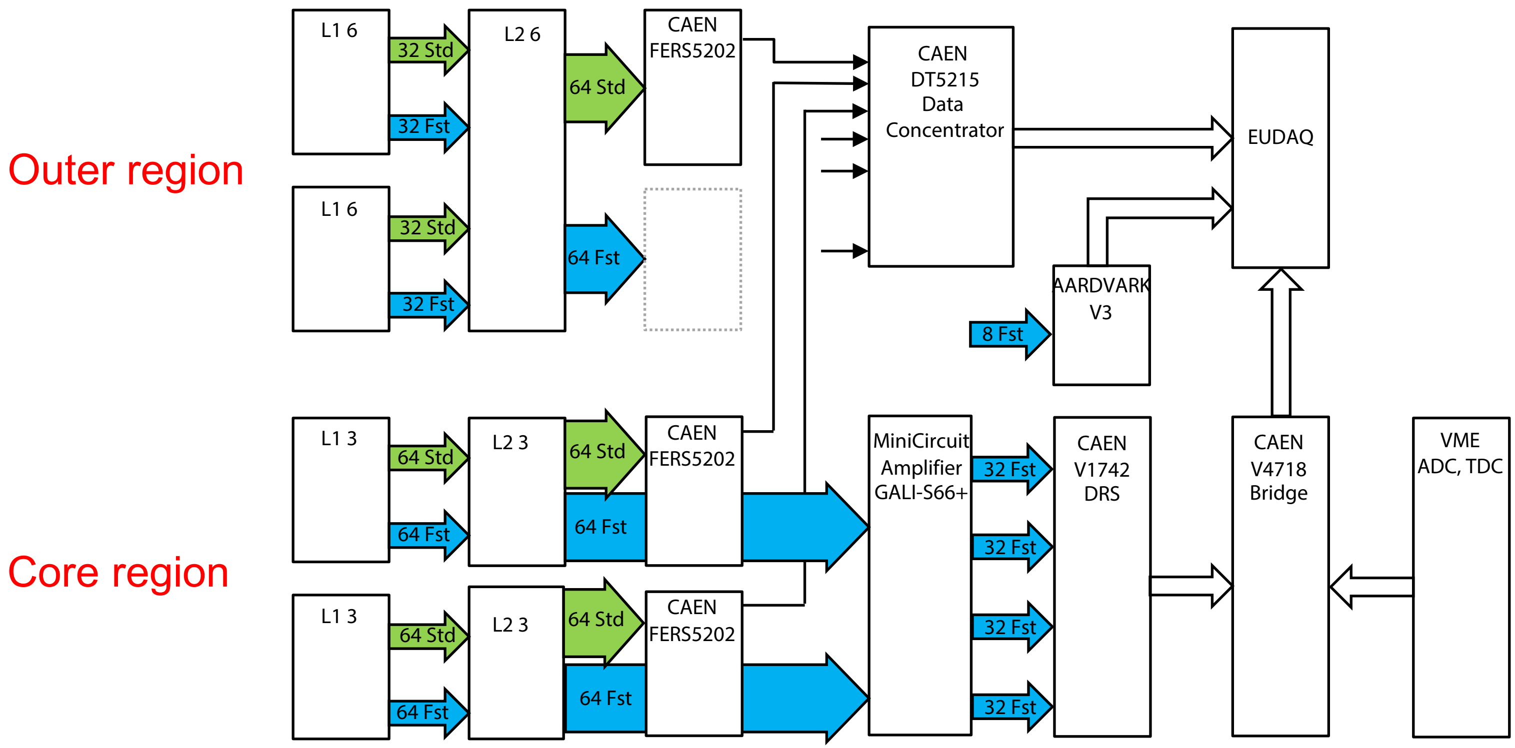
	L1 PCB	No. L1	No. L2	No. of units
Outer region	32 SiPMs	24	12	768 Std (FERS) 768 Fst
Core region	64 SiPMs	2	1/2	128 Std (FERS) 128 Fst (DRS)

L1 and test transition PCBs are designed

1. OnSemi SiPM C- and J-series SiPMs require different designs
2. Trace lengths are kept short: Std 15-18mm and Fst 6-10 mm (tested coplanar waveguide with ground (CPWG) and strip-lines (buried traces) in 6-layer boards)
3. For Std & Bias HSEC8-170-01-S-DV (edge connect to A5202)
4. For Fst MMCX Jack (female direct to amplifier or waveform digitizer)

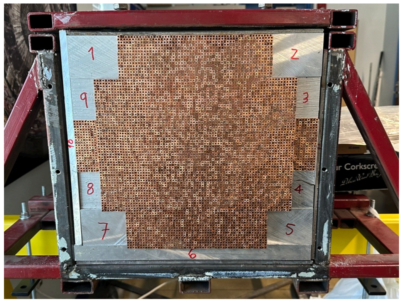
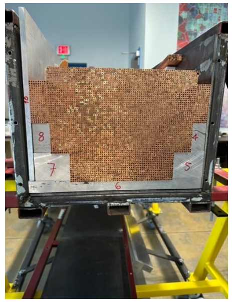


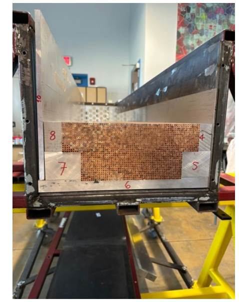
HG-DREAM Readout Configuration



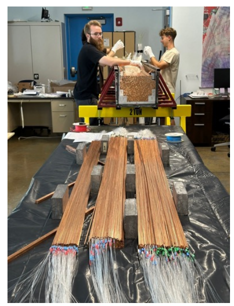
- Different types of information from large number of channels need to be integrated and collected in a unified manner (EUDAQ)
- Expected data size ~220 kB/event for DRS and ~1.7 kB/event for FERS
- The data transfer rate 70-200 MB/s depending on link type
- There is much room for data size optimization but need for on-detector processing becomes evident

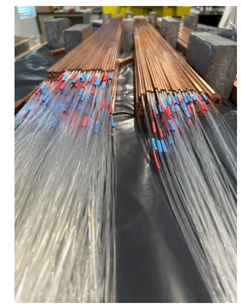
Status of DREAM Disassembly ($S \rightarrow \infty$)



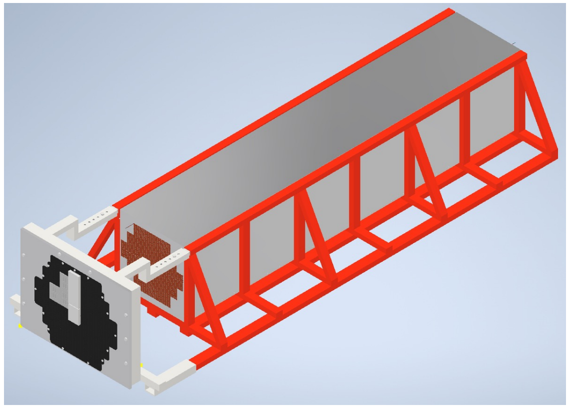
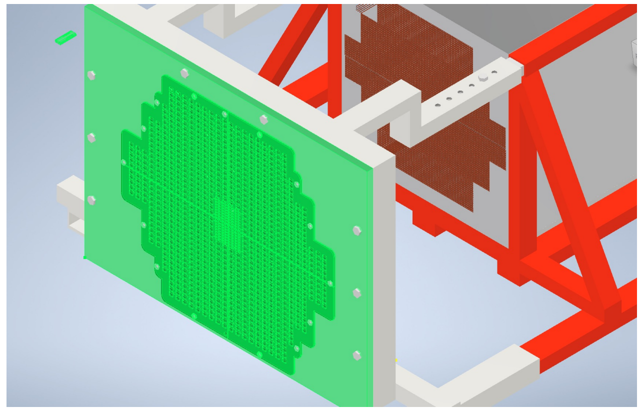
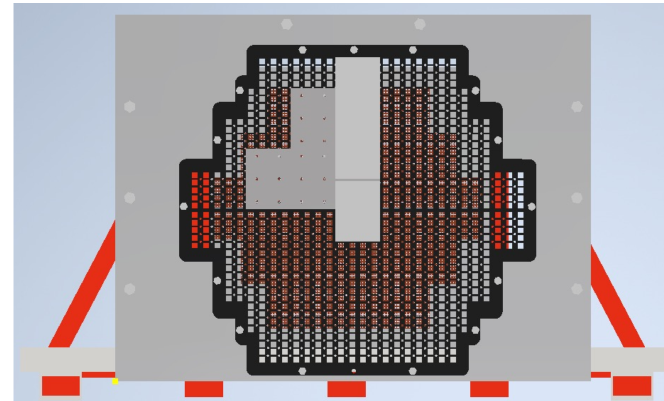



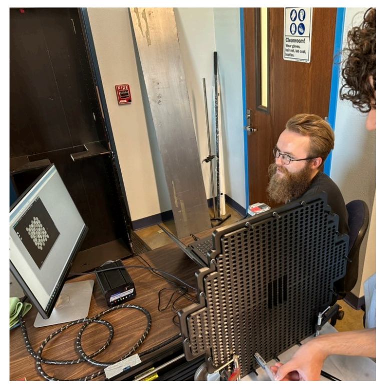
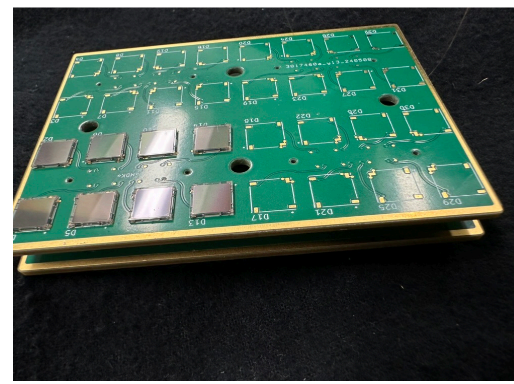

- The disassembly of the old DREAM module is complete. Over 5,580 copper rods with fibers (5,130) are properly sorted and stored for reassembly
- The cage structure is refurbished; moving and tilting mechanisms are reworked

Status of HG-DREAM Assembly ($S \rightarrow 0$)

TEXAS TECH UNIVERSITY

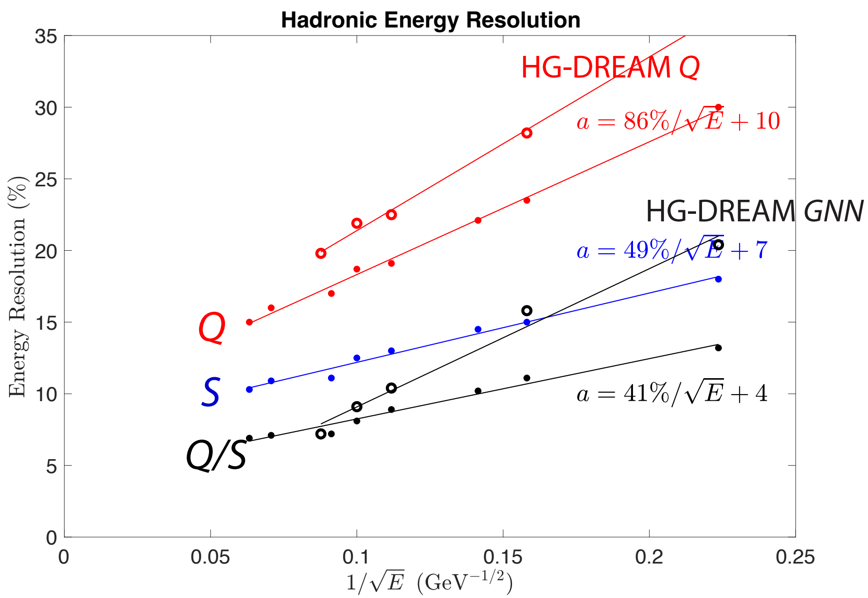




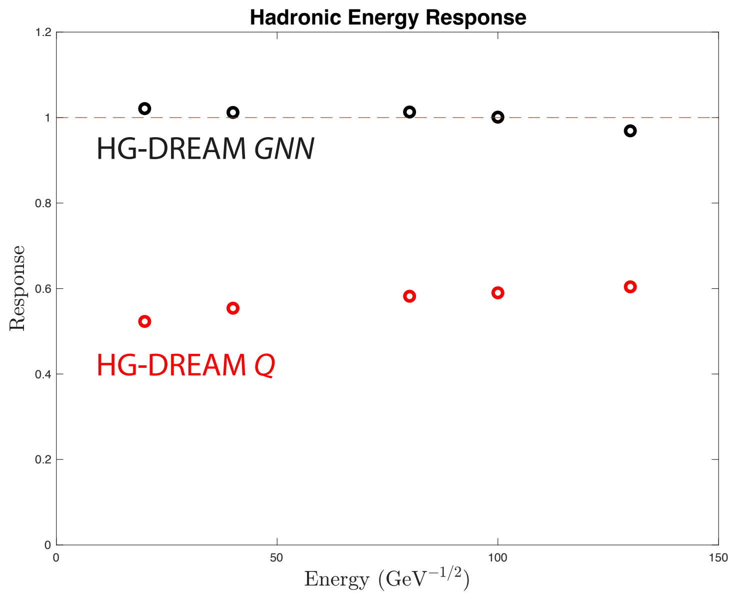


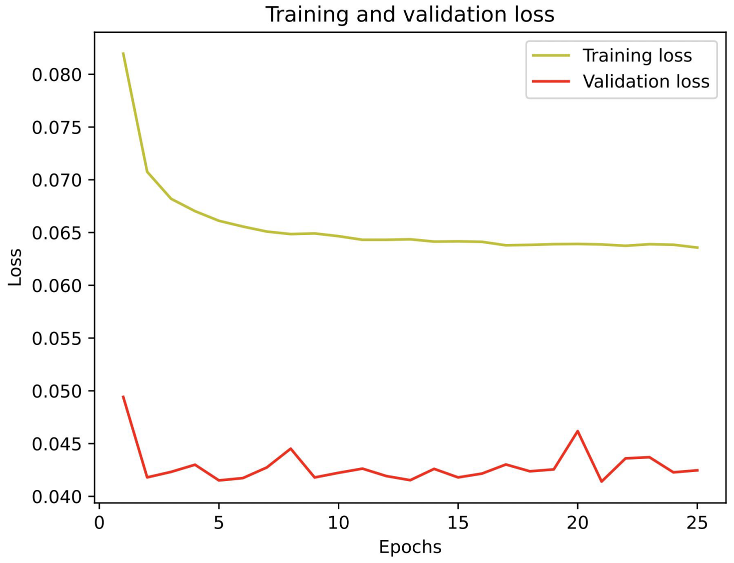
- Individual towers (12x16 mm^2) are constructed using fixtures
- 3D-printed endplate and connectors are developed to bundle scintillator and clear fibers
- Microscope camera aids fiber bundling and quality control (polish, number, placement, …)
- Electronics integration is scheduled for early June
- HG-DREAM module full test will take place in late June and July

HG-DREAM GNN 2D Simulation Example - I

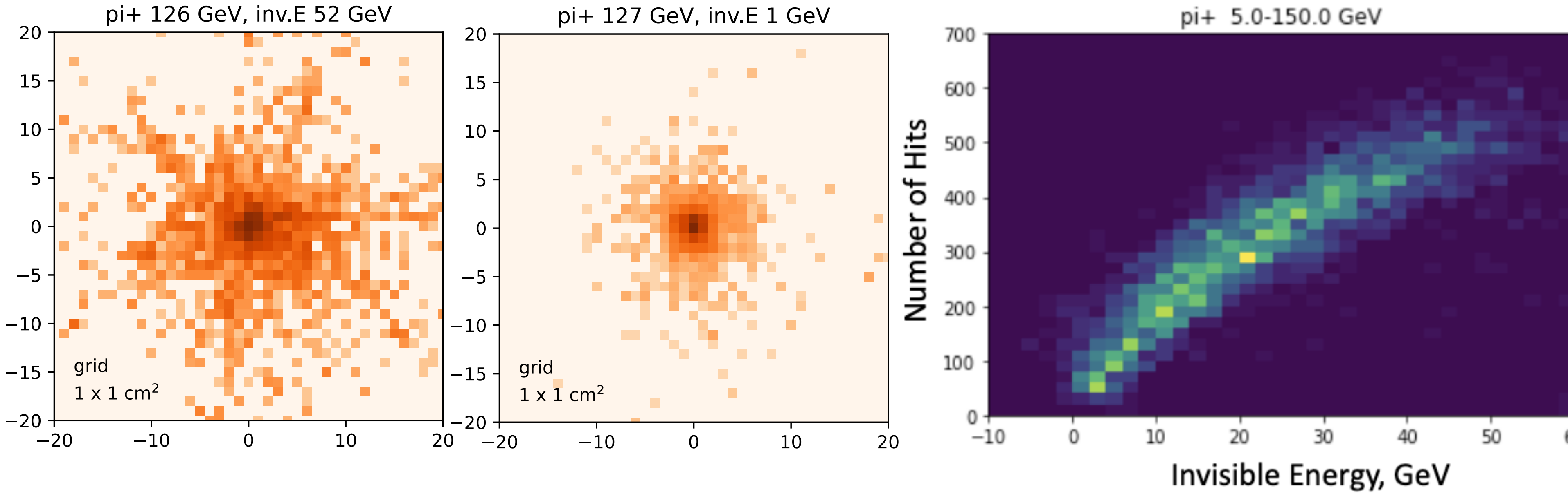




- 1 million pion interactions were generated with GEANT4 in HG-DREAM and GNN (ParticleNet) 70% training, 20% validation, and 10% testing
- Inputs were the (*x*,*y*) hit positions and energy, and the target is the beam energy
- Total number of parameters was 337,861
- Picked the model from epoch 21 *i.e.* with loss value of 0.0414



HG-DREAM GNN 2D Simulation Example -II



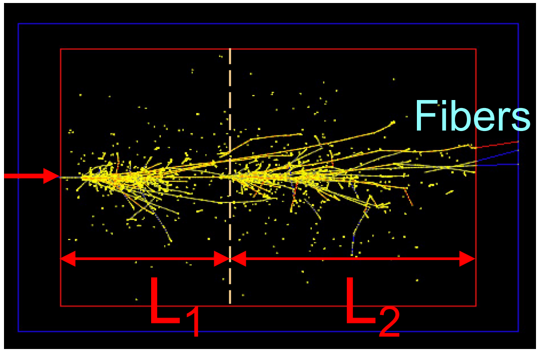
Left: Cherenkov signal with large (52 GeV) of invisible energy in where the color shading is in log(*E*)

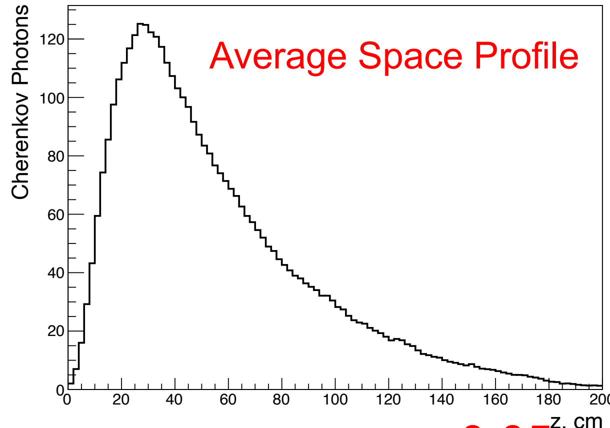
Middle: Cherenkov signal with small (1 GeV) of invisible energy

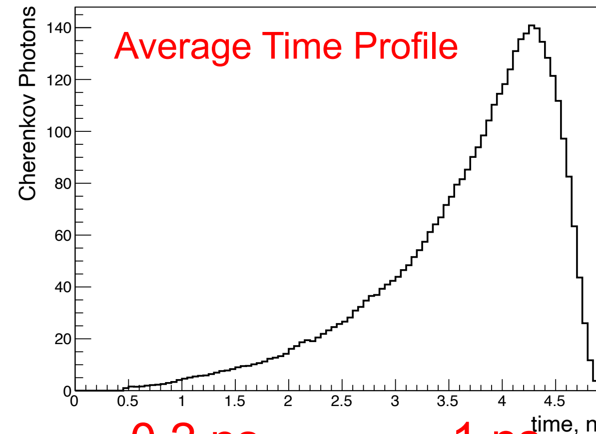
Right: The correlation between the invisible energy and the number of hits is strong and energy-independent. The "image" recognition by the network in this way enables better energy reconstruction and results in improved energy resolution and response linearity compared to more traditional (summing) reconstruction methods

In 3D, we expect better "image" recognition to further improve event reconstruction

Longitudinal Segmentation with Timing





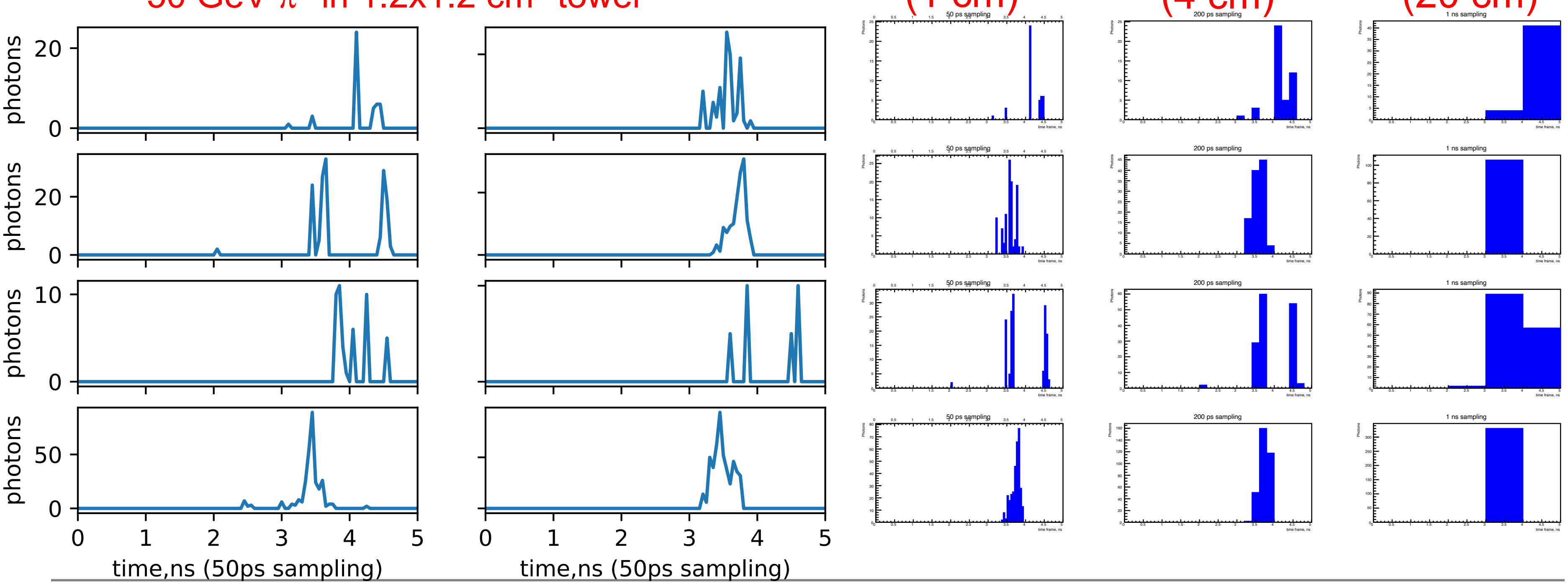


Signal time = $L_1/c + L_2/(c/n)$,

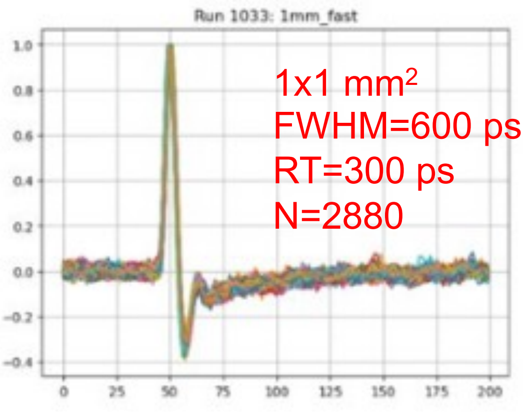
(c/n) ~1 cm/50 ps

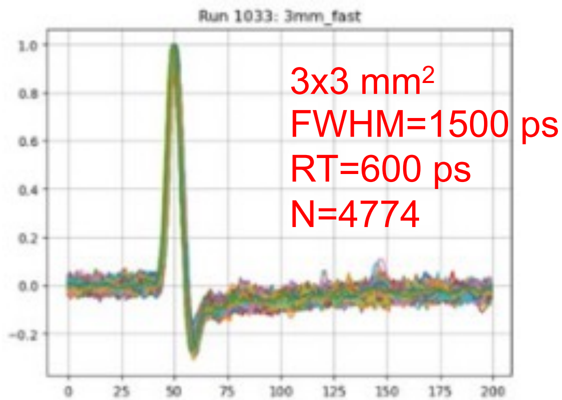
50 GeV π^+ in 1.2x1.2 cm^2 tower

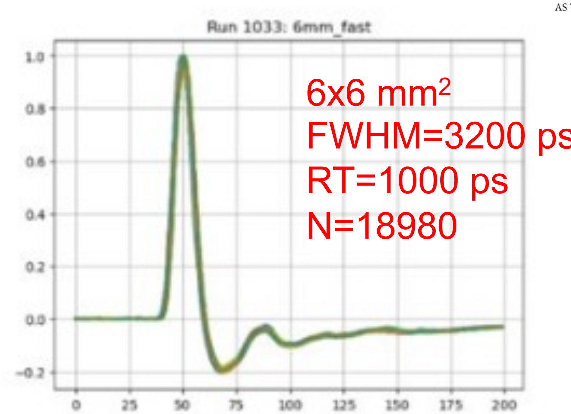
0.05 ns (1 cm) | 0.2 ns (4 cm) | 1 ns (20 cm)

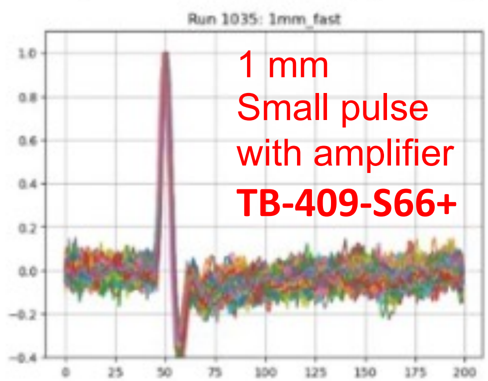


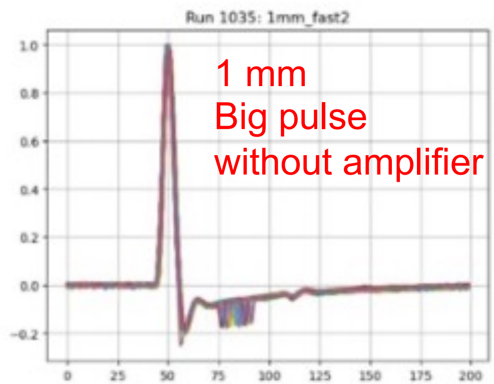
Fast Pulse Shape Studies (OnSemi SiPM C-Series)

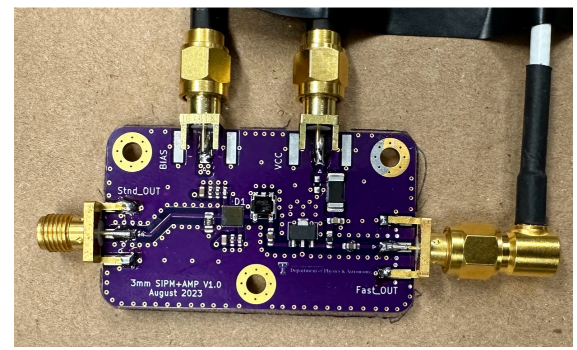


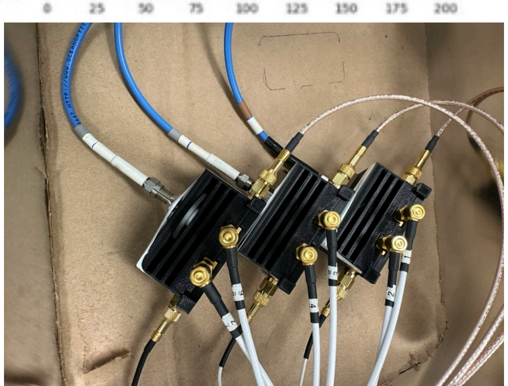








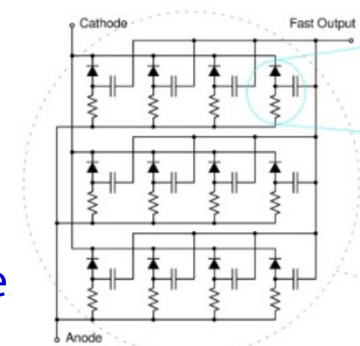




Bench tests using a fast laser (~140 ps pulse)

1,000 pulses in each plot

Stable pulse shapes lend themselve for reliable deconvolution

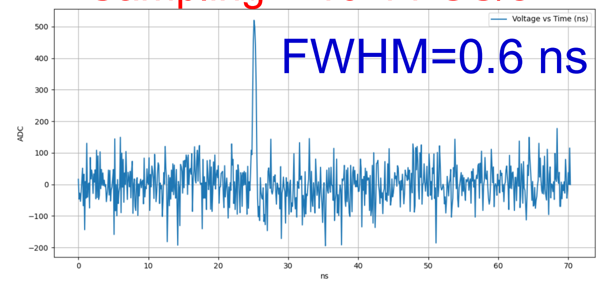


Fast Pulse Shape with DRS and AARDVARCv3

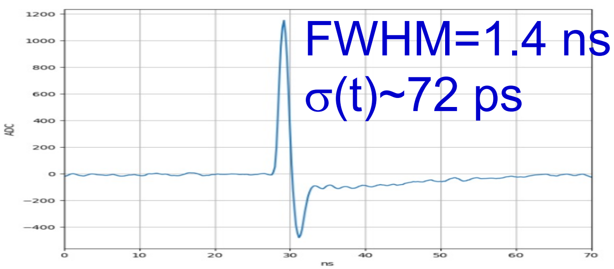
CAEN V1742
(DRS)
Input BW ~ 0.5 GHz
Sampling = 5 GS/s

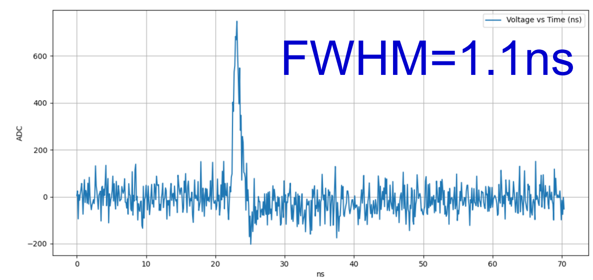
NALU AARDVARC3
(Evaluation Board)
Input BW > 1 GHz
Sampling = 10-14 GS/s

1x1 mm^2 OnSemi
FWHM=0.6 ns



3x3 mm^2 OnSemi
FWHM=1.5 ns

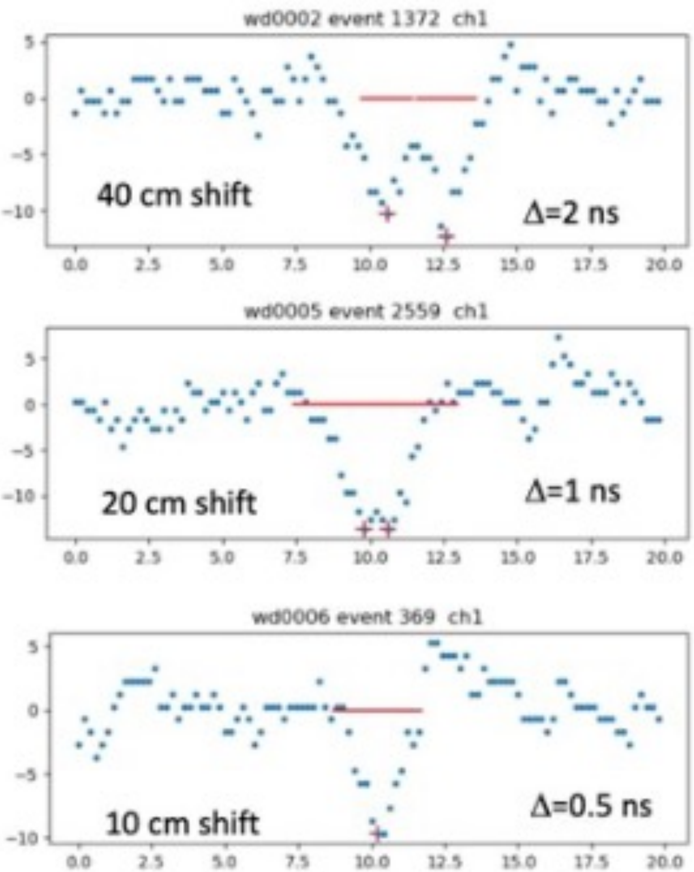




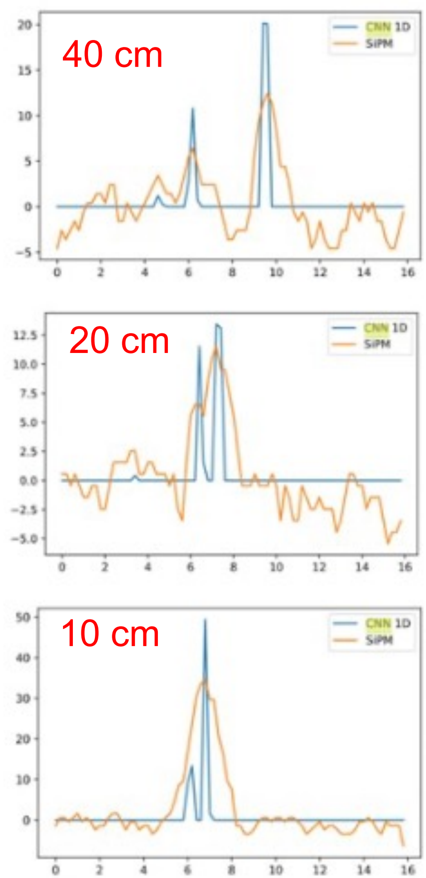
- DRS FWHM for 1 mm^2 is wider than datasheet value, likely due to the limited bandwidth of the DRS
- $\sigma(t)$ is the *rms* of t(SiPM)-t(laser trigger)

Pulse Train Studies - I

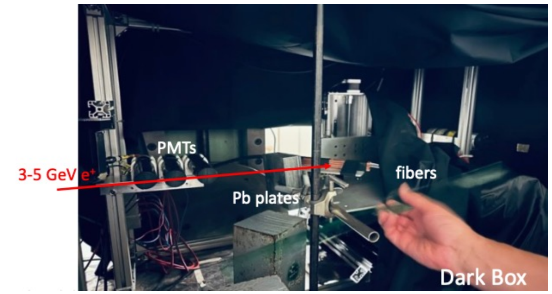
TB23 Data
Cherenkov Signal
(1 photon = 10 ADC counts)
3x3 mm^2 SiPM with a 10x amplifier

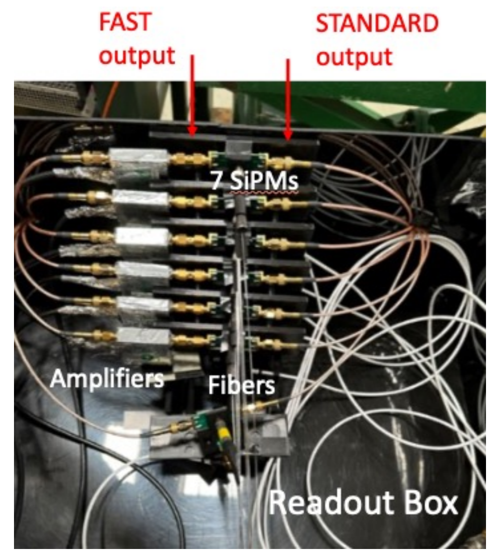


CNN reconstruction
DRS (noisy) data



TB23 Setup





Pulse Train Studies - II

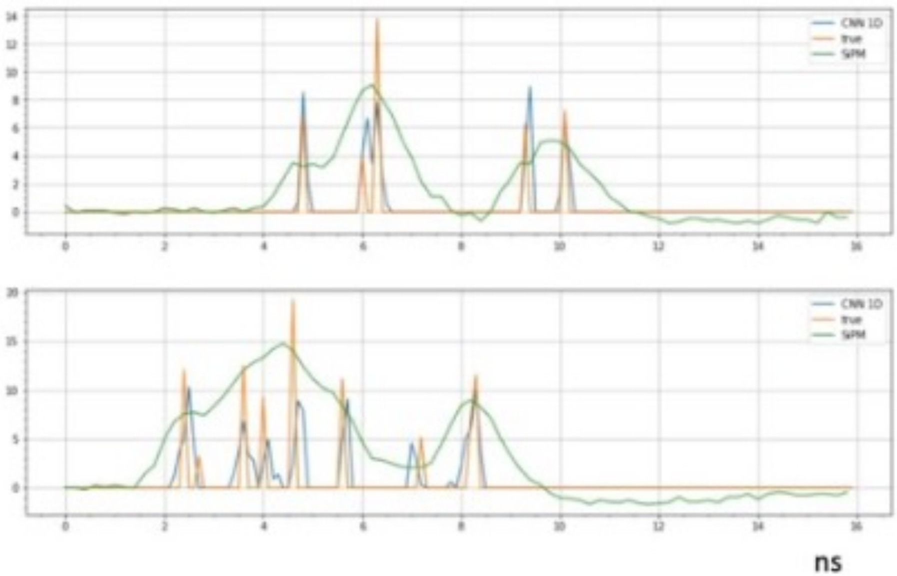
SiPM pulse shape is extracted from data

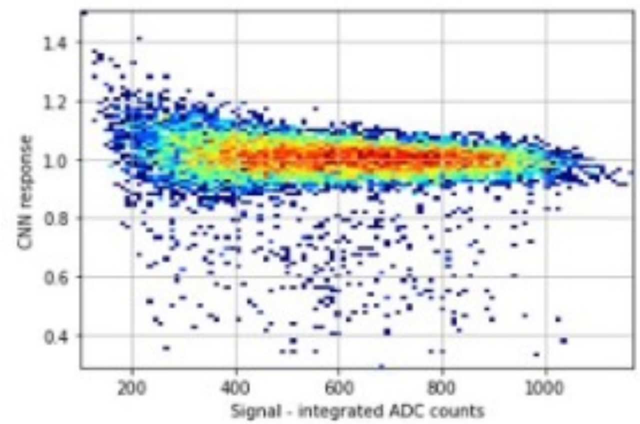
Pseudo-data are produced by overlapping pulses and added Gaussian noise

The amplitude is varied

Time separation between pulses ranged 0-2.6 ns

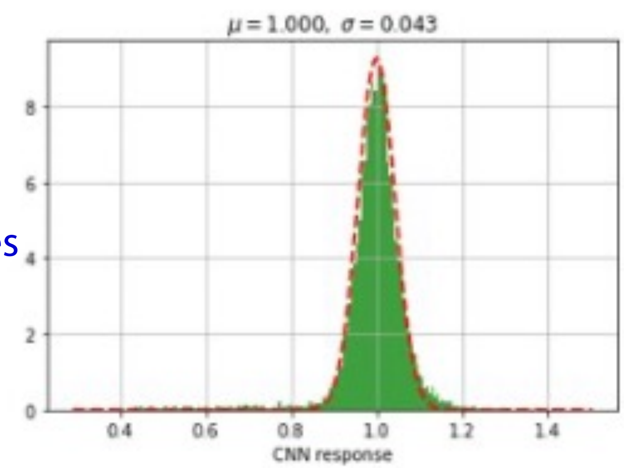
Overall arrival time is varied by ±0.8 ns





It seems possible to deconvolve overlapping SiPM (Cherenkov) pulses to reveal the true distribution of shower components using CNN:

- Green: Convoluted SiPM pulse train
- Blue: Deconvoluted SiPM pulse train
- Orange: True pulse train

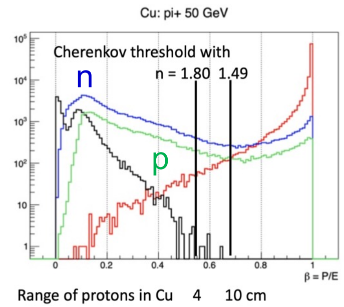


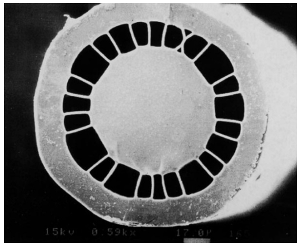
Optical Fibers

Optical fibers offer diverse possibilities beyond what's known/used today both with advantages and disadvantages.

1. Classical structures
2. Shaped (helical) fibers
3. Structured (PCF and capillary) fibers

We will explore their performance with HG-DREAM prototype

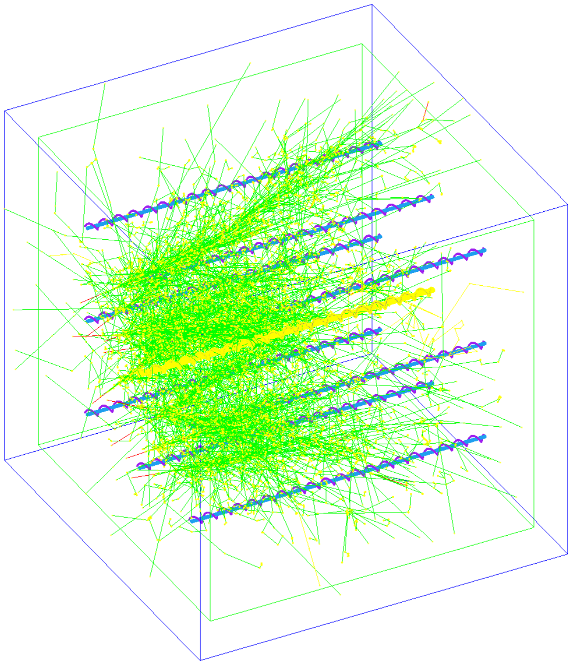


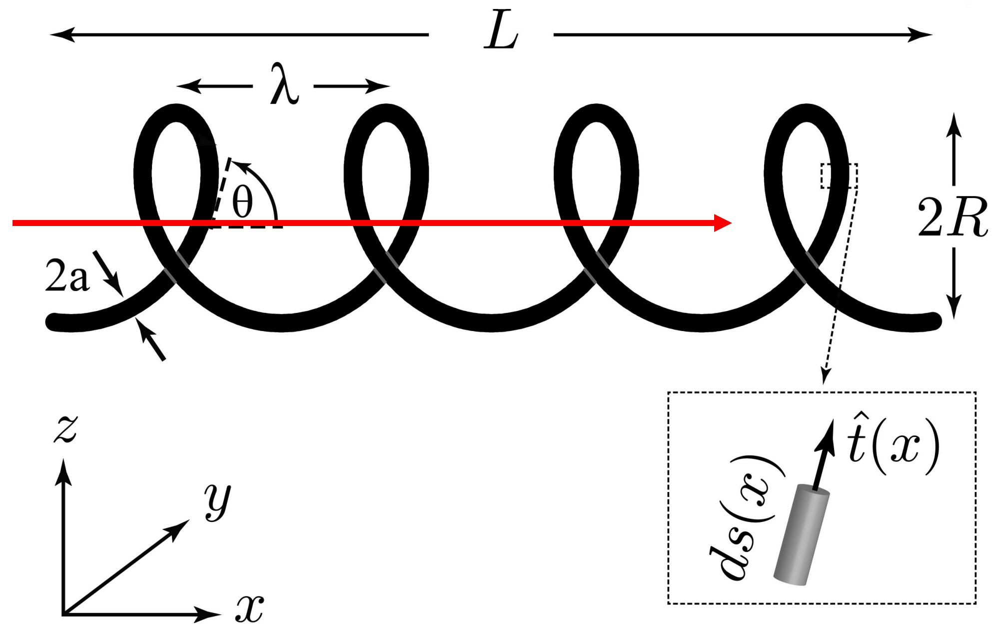


	QQ	QP	Plastic	Sapphire	Air-clad
NA	0.22	0.37	0.55		~0.9
n_{core}	1.46	1.46	1.5	1.77	1.46
f_{trap}	0.57%	1.61%	3.36%		9.5%
$T_{electron}$	190 keV	190 keV	174 keV	108 keV	190 keV
T_{proton}	350 MeV	350 MeV	321 MeV	199 MeV	350 MeV

$$f_{\text{trap}} \approx \left(\frac{\text{NA}}{2n_{\text{core}}}\right)^2 \qquad \text{NA} \approx \sqrt{n_{\text{core}}^2 - n_{\text{clad}}^2}$$

Shaped (Helical) Fibers



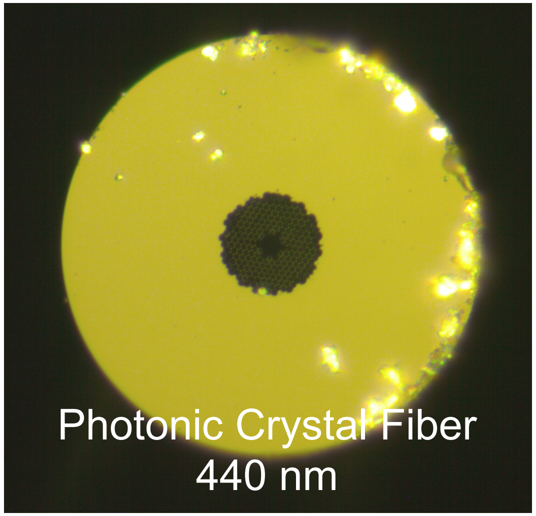


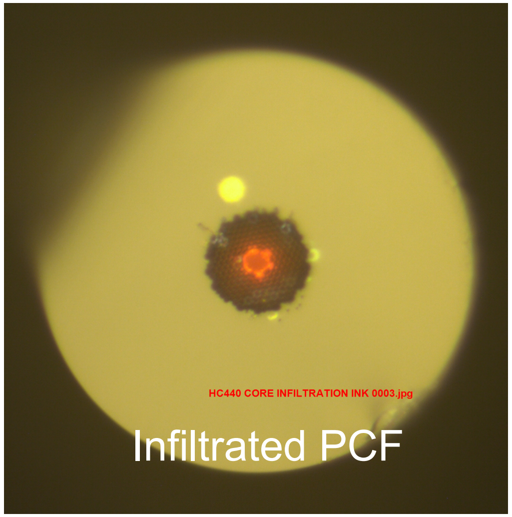
Helical fibers offer unique features for calorimeters:

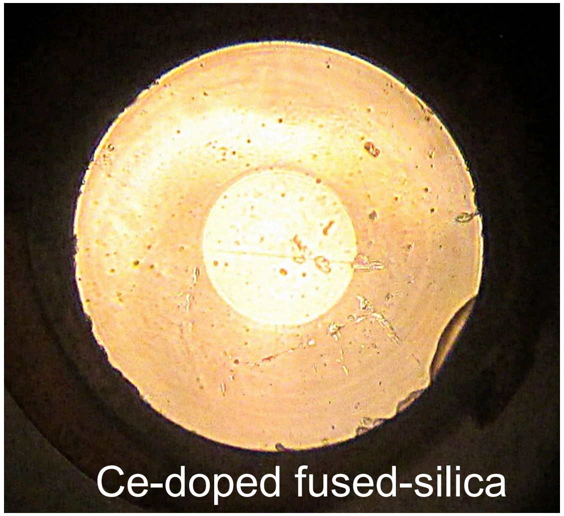
1. More favorable Cherenkov light capture because of geometry but correlated
2. Signal arrival time difference between straight and helical fibers is a measure of where the signal is produced: t'-t ~ 1/(c/n) ($2\pi R - \lambda$) per turn
3. Helical structure can be embedded in a "normal" fiber
   - » e.g. R ~ 0.5 cm, $\theta \sim \theta_c \sim 45^o$, $\lambda \sim$ 1 cm, a ~ 100-300 um

Structured (PCF) Fibers and Capillaries with QDs

- The quantum dots (QDs) embedded in capillaries may offer some advantages in calorimetry. The QDs suffer from self-absorbtion but a similar strategy as in Ce-doped fibers may alleviate this problem to some extent
- The advantage is "tunability" (*e.g.* CdSe/ZnS 2-7 nm particle size)
- Example: PCF 440 nm with embedded dye in the hollow core







Conclusions and Remarks

Evolution in calorimetry

1. Compensation ($e/h=1$) using slow neutrons (~40 years ago)
2. Event-by-event compensation in dual read-out f_{em} ~Q/S (~20 years ago)
3. Particle flow algorithms and high-granularity calorimeter (~20 years ago)
4. High-granularity combined with AI/ML tools (~5 years ago) for position, energy, and time measurements (5D) = (x, y, z, E, t)

HG-DREAM is designed for

1. High-granularity
2. Precision timing with fast SiPMs and electronics
3. Integration of NNs
4. Exploration of new fibers/materials