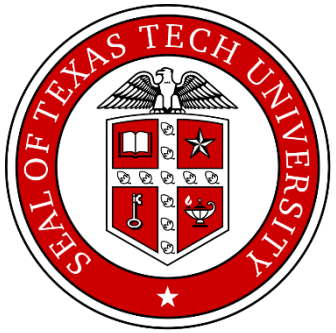


Longitudinal Segmentation of Multi-readout Fiber Calorimeters by Timing for 3D Imaging Calorimetry

Nural Akchurin, Christopher Cowden, Jordan Damgov, Adil Hussain, **Shuichi Kunori**

Texas Tech University

19-Mar-2021

Challenge in Hadron Calorimetry

❖ Invisible energy:

In hadron-nuclei interactions, large fraction of hadron energy goes to nuclear dissociation and becomes invisible. We need to estimate the invisible energy from a visible quantity.

❖ Large volume:

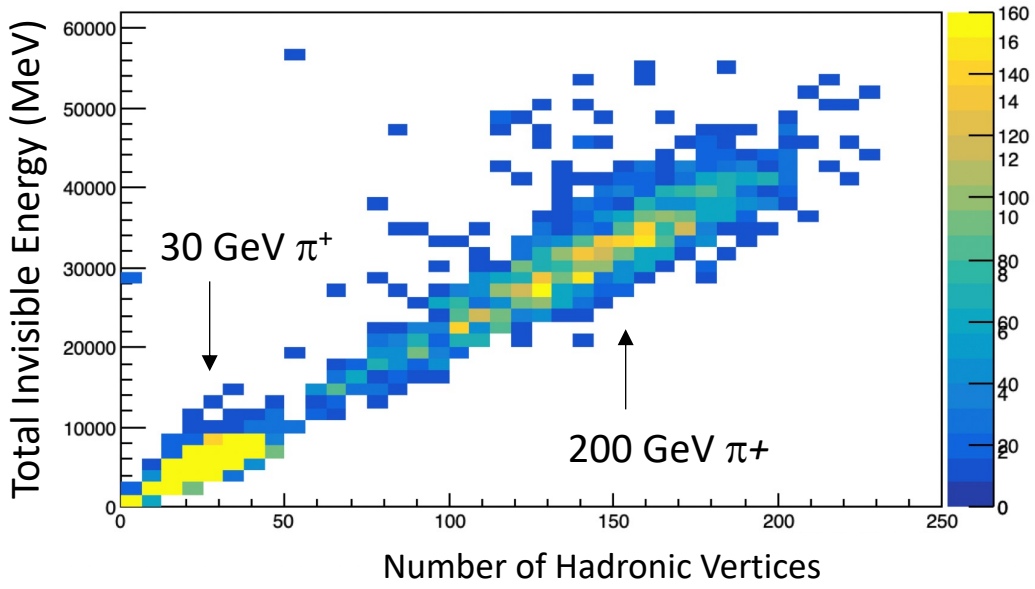
Very high granularity may be a preferable option to deal with the “invisible” energy problem but the cost gets big quickly as the granularity increases.

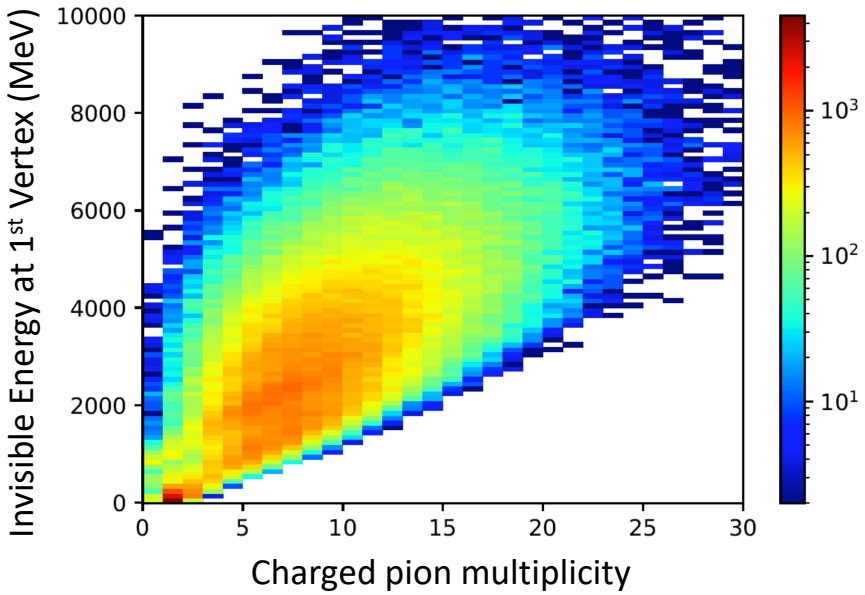
We need a cost-effective way to estimate the invisible energy!

Invisible Energy in Had Shower in Cu Absorber

- ❖ 30 GeV π^+ and 200 GeV π^+ on Cu absorber were simulated with GEANT4.
- ➢ Clear correlation between the total invisible energy *vs* the total number of hadronic vertices (left) and the invisible energy *vs* the number of charged pions in the first interaction (right).

- ❖ How to estimate invisible energy?
- ➢ Simple idea: count the vertices and apply some corrections depending on features at each vertex.
- ➢ Better idea: use 3D imaging capability of ML methods.

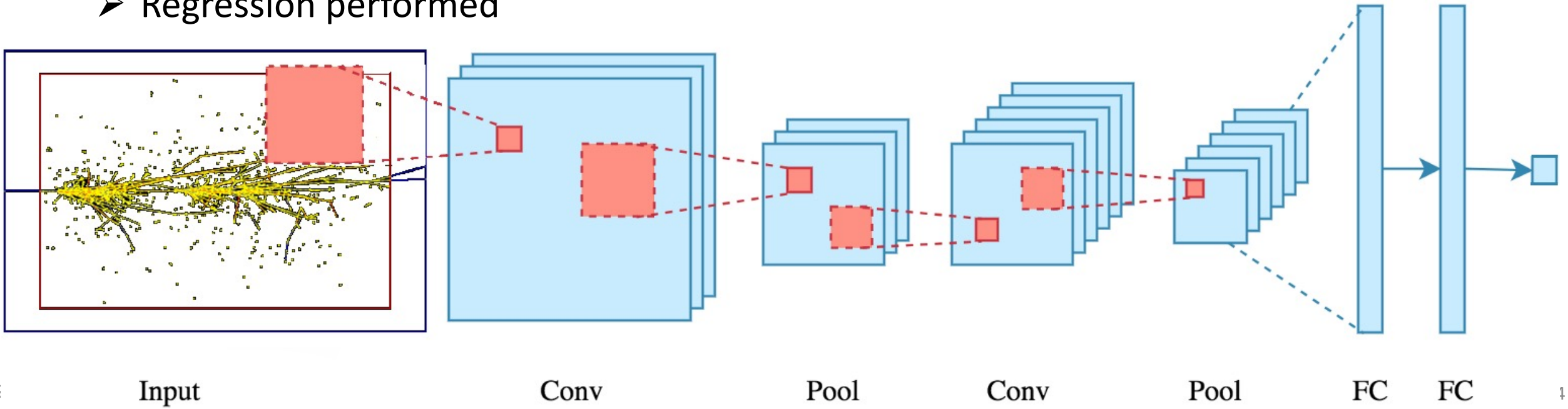




Convolutional Neural Network for Energy Reconstruction

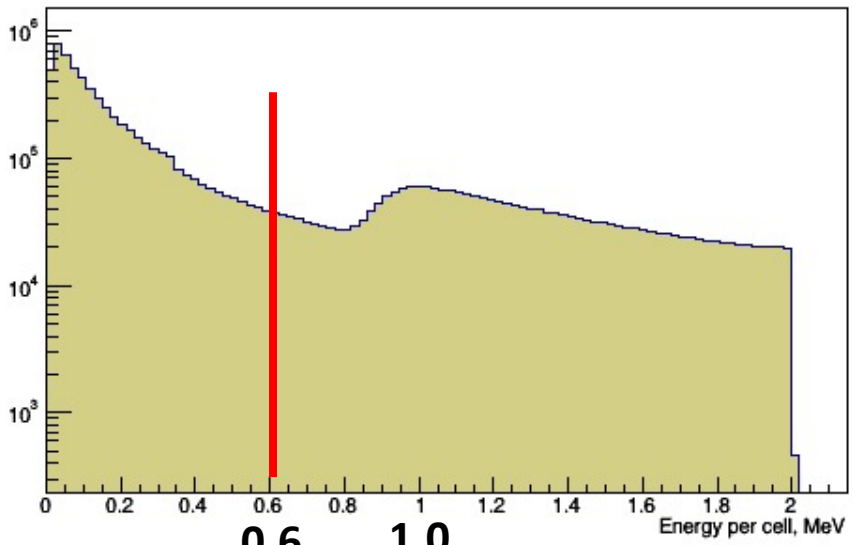
- ❖ Showers in high granularity calorimeters can be viewed as 3D images
  - ➢ Fiber calorimeters with depth segmentation by timing
- ❖ Detailed information on *multiplicity and production angle of the secondaries* can be extracted from the visible signal and used to improve the energy reconstruction

- ❑ Convolutional Neural Networks (CNN) are very good at image classification
  - ➢ Raw images are used
  - ➢ Higher level features extracted using sequential convolutional operations
  - ➢ Regression performed

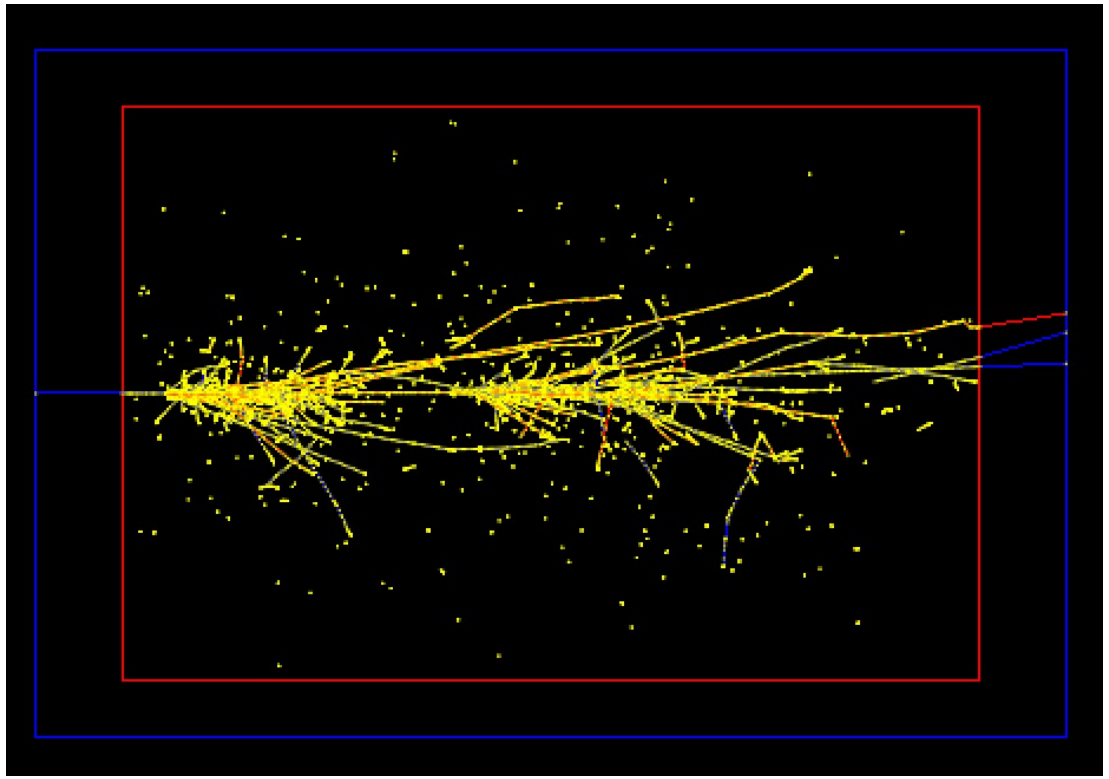


Standalone Calorimeter Setup (simulation)

- Copper / Silicon sampling calorimeter is simulated with GEANT4
  - Alternating Cu 17 mm(absorber), Si 3mm (active) layers, with size of 1.0x1.0x1.5m^3
  - Readout granularity is 2x2x2cm^3
  - Signal is integrated over 5 ns with correction for the longitudinal propagation time
  - Energy threshold of 0.6 MeV per cell is applied, with MIP MPV at about 1.0 MeV
  - No electronics/noise



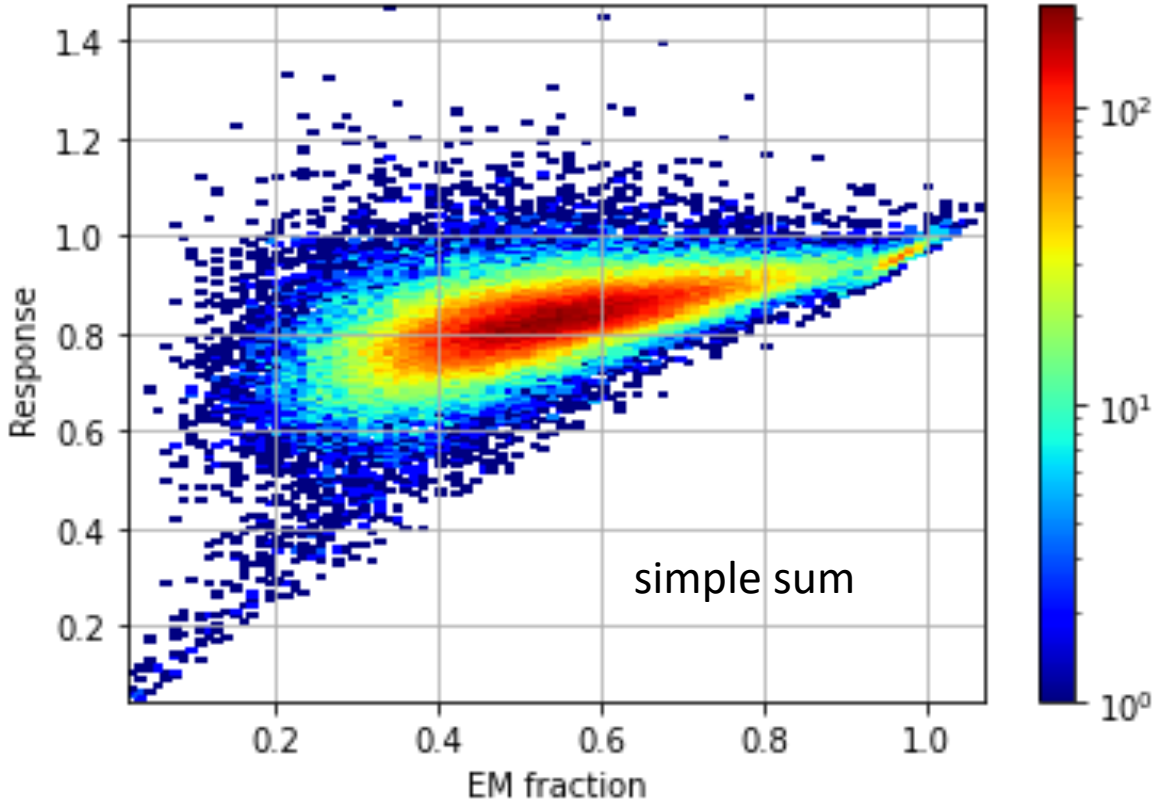
Energy per cell, MeV

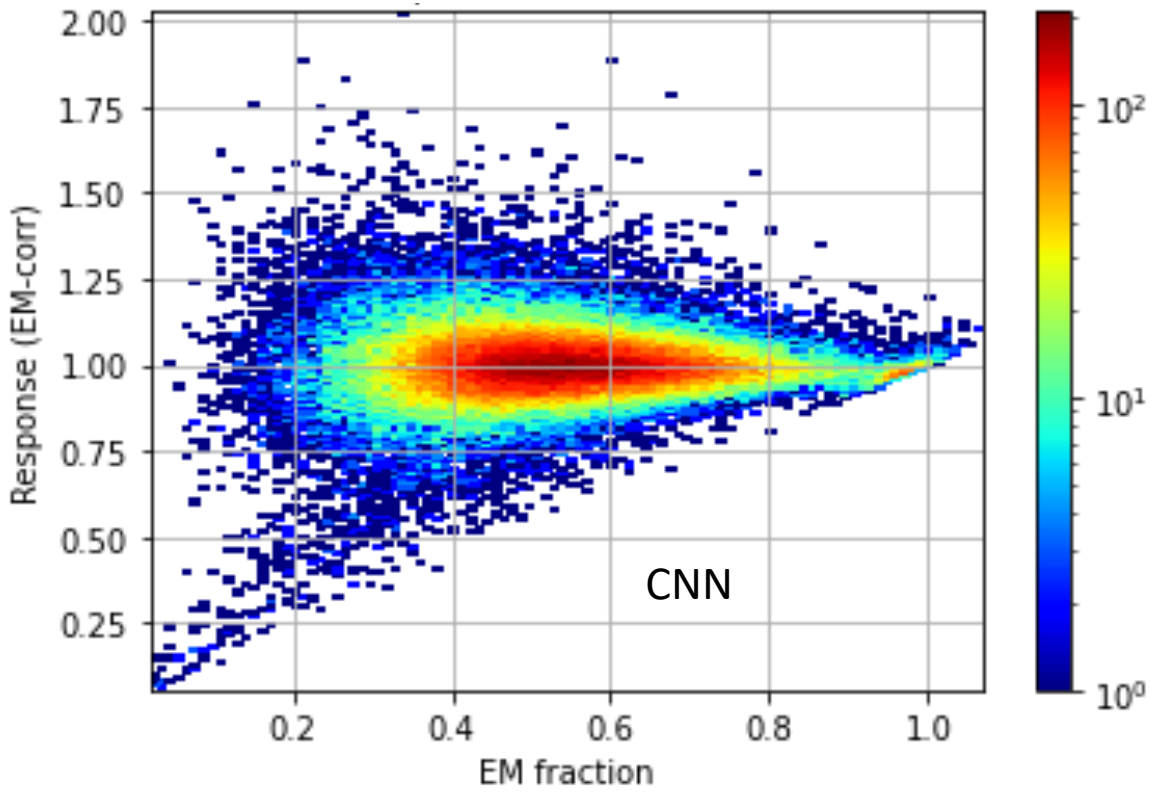


Energy Reconstruction with More Traditional Techniques

The performance of the energy reconstruction with CNN is compared to:

1. Simple energy sum over all channels in the volume
2. Reconstruction with correction for the fluctuations in the EM-fraction

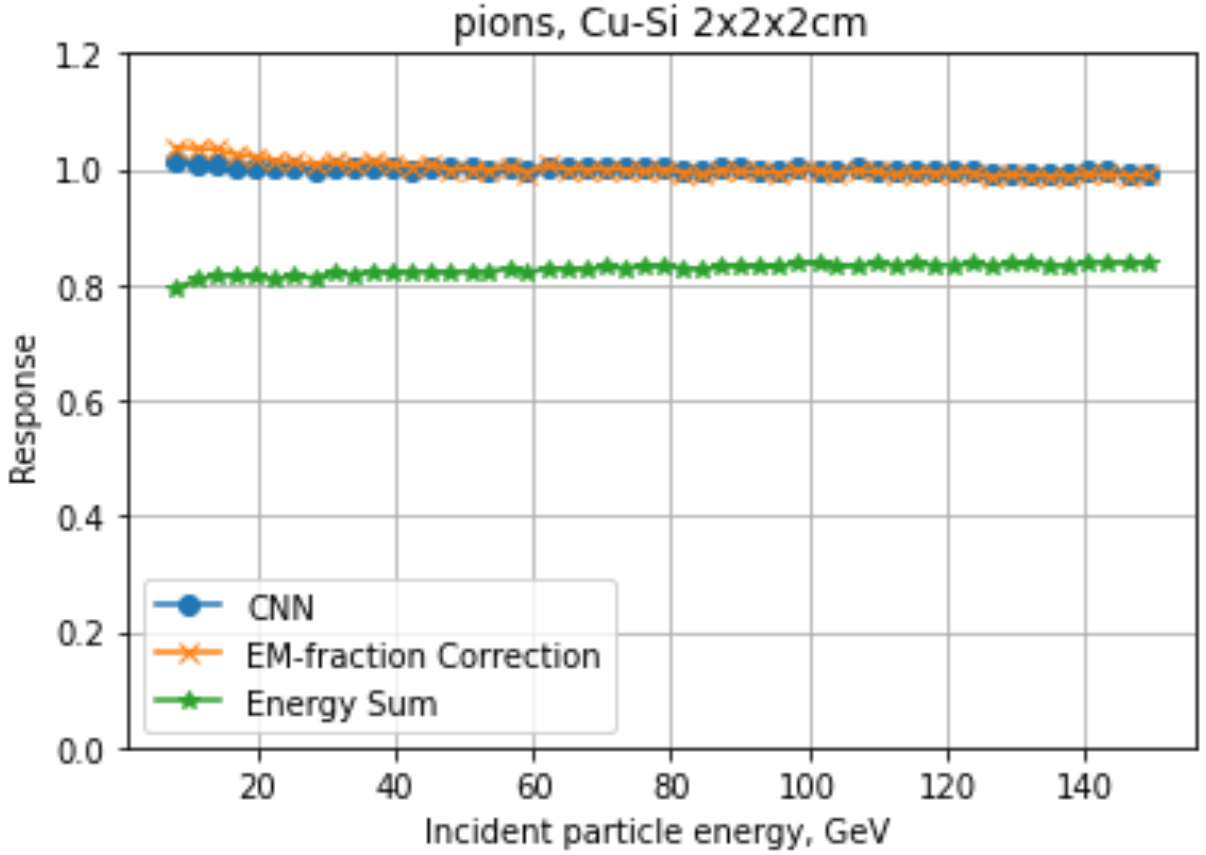


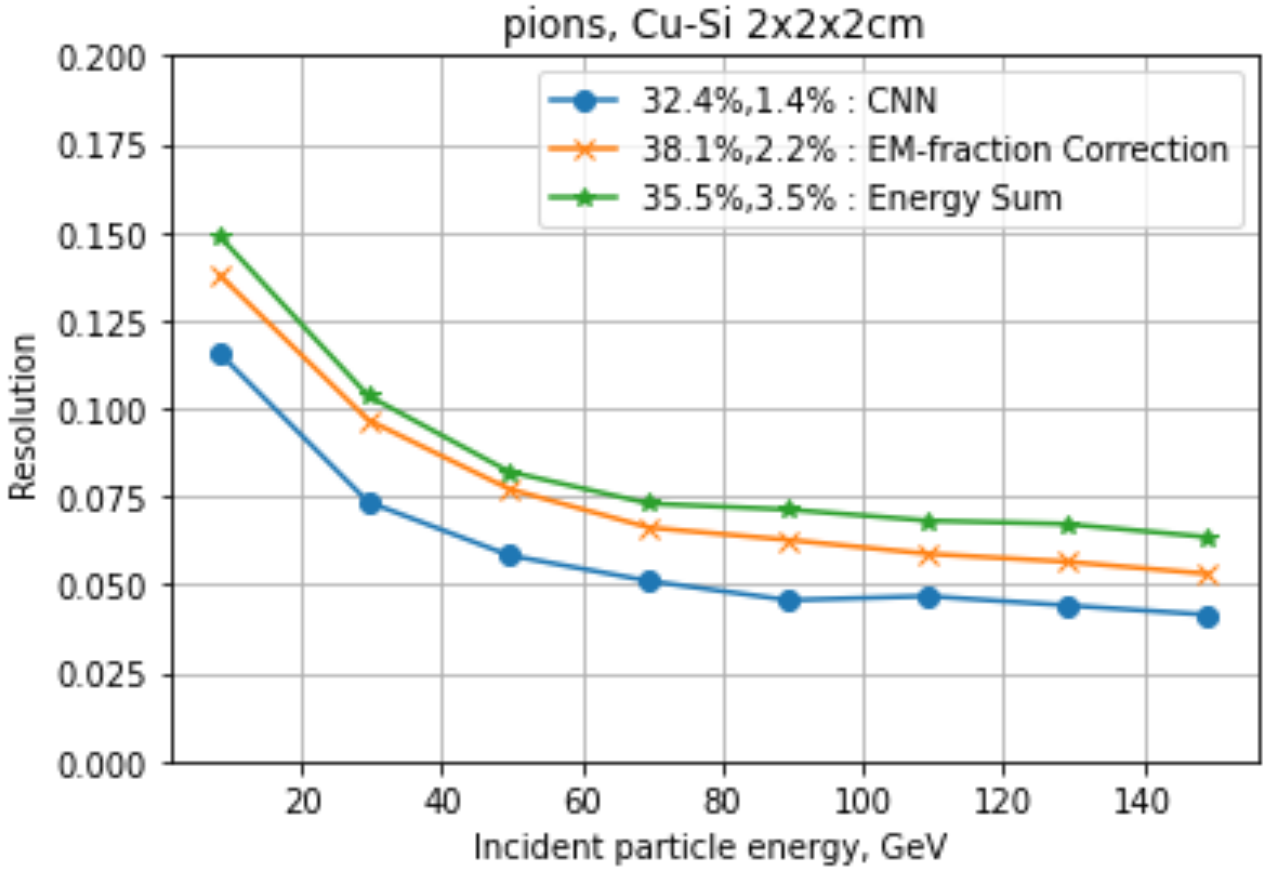


CNN Performance – single hadron Cu/Si

CNN trained with **single pions** outperforms other conventional methods for energy reconstruction.

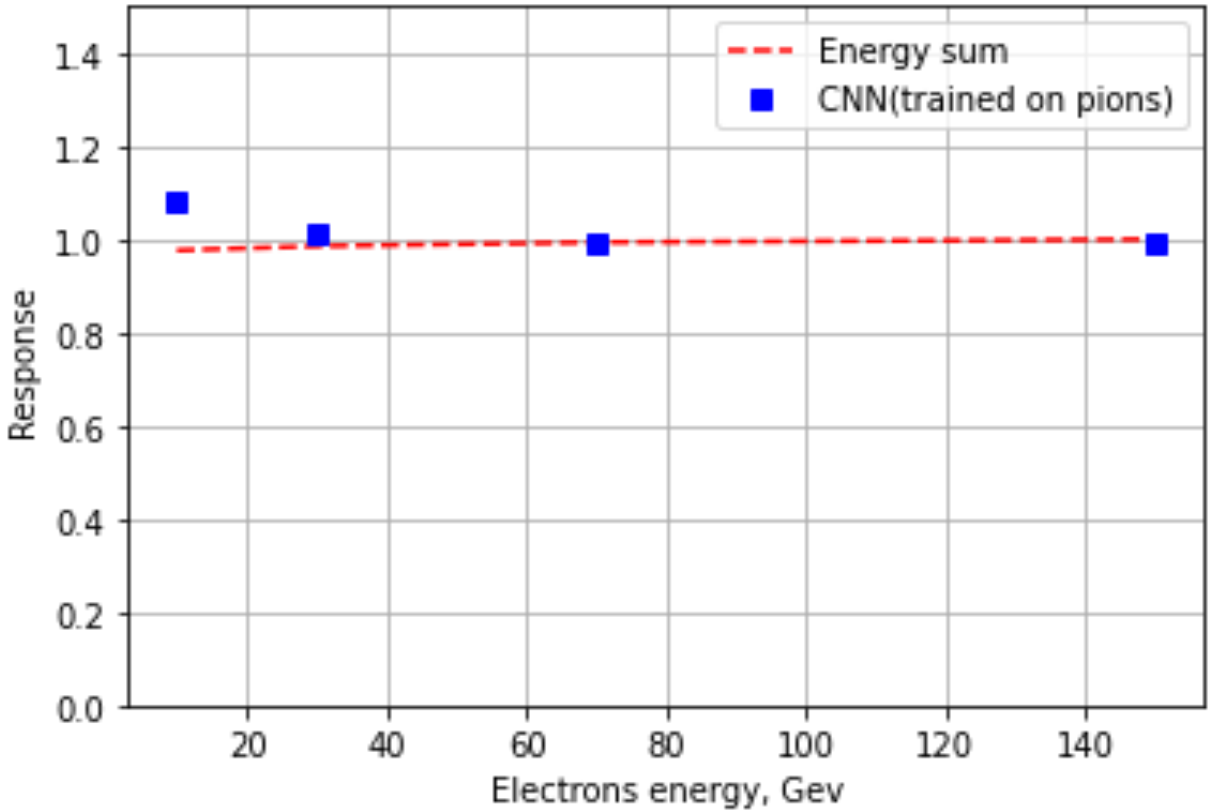
$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus c$$

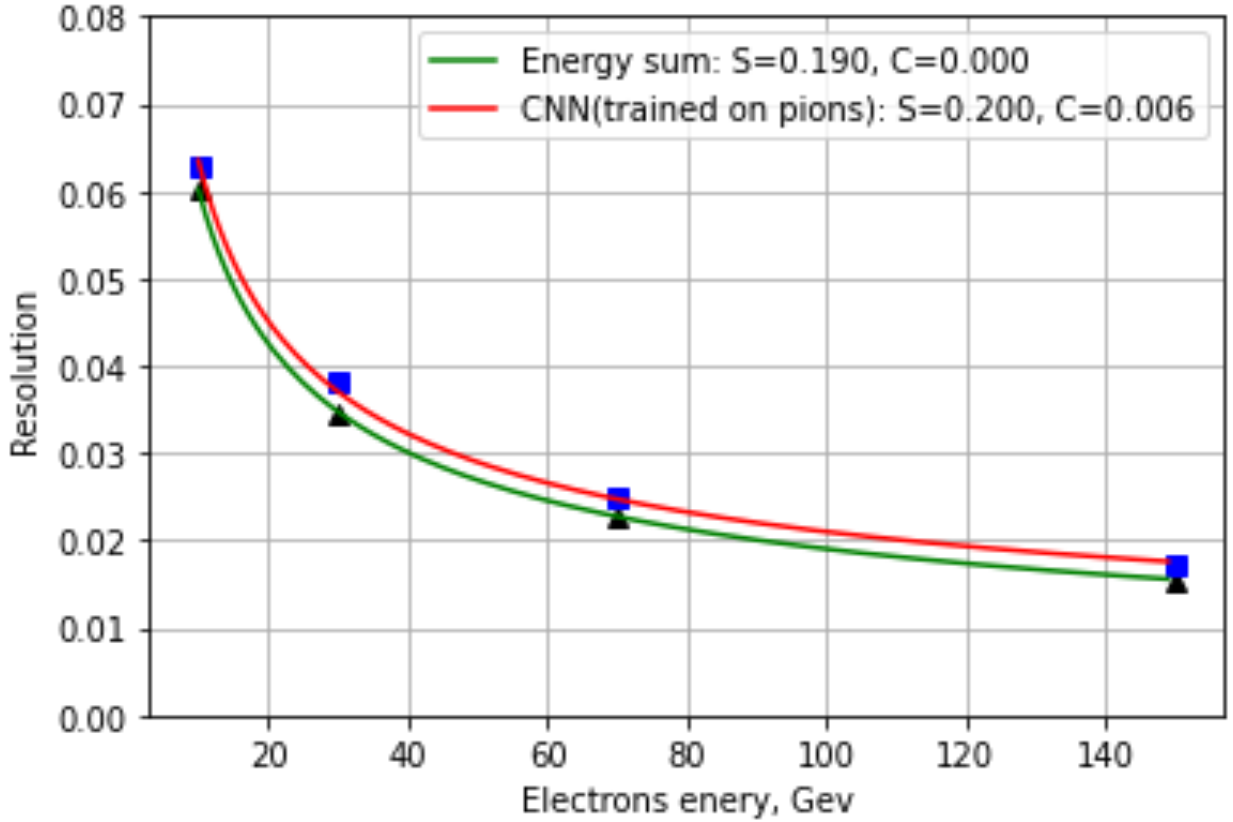




CNN Test with Electron

Electron reconstruction with CNN ***trained on single pions***.

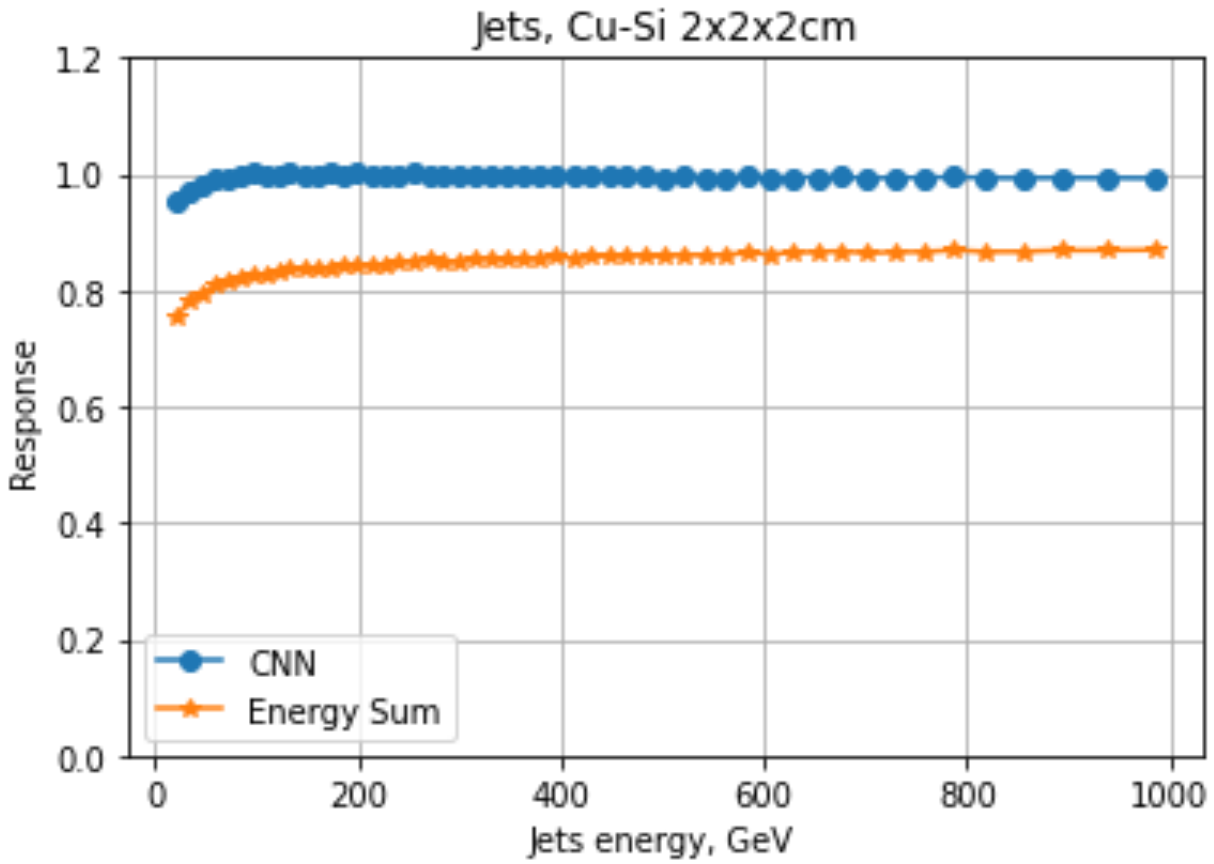


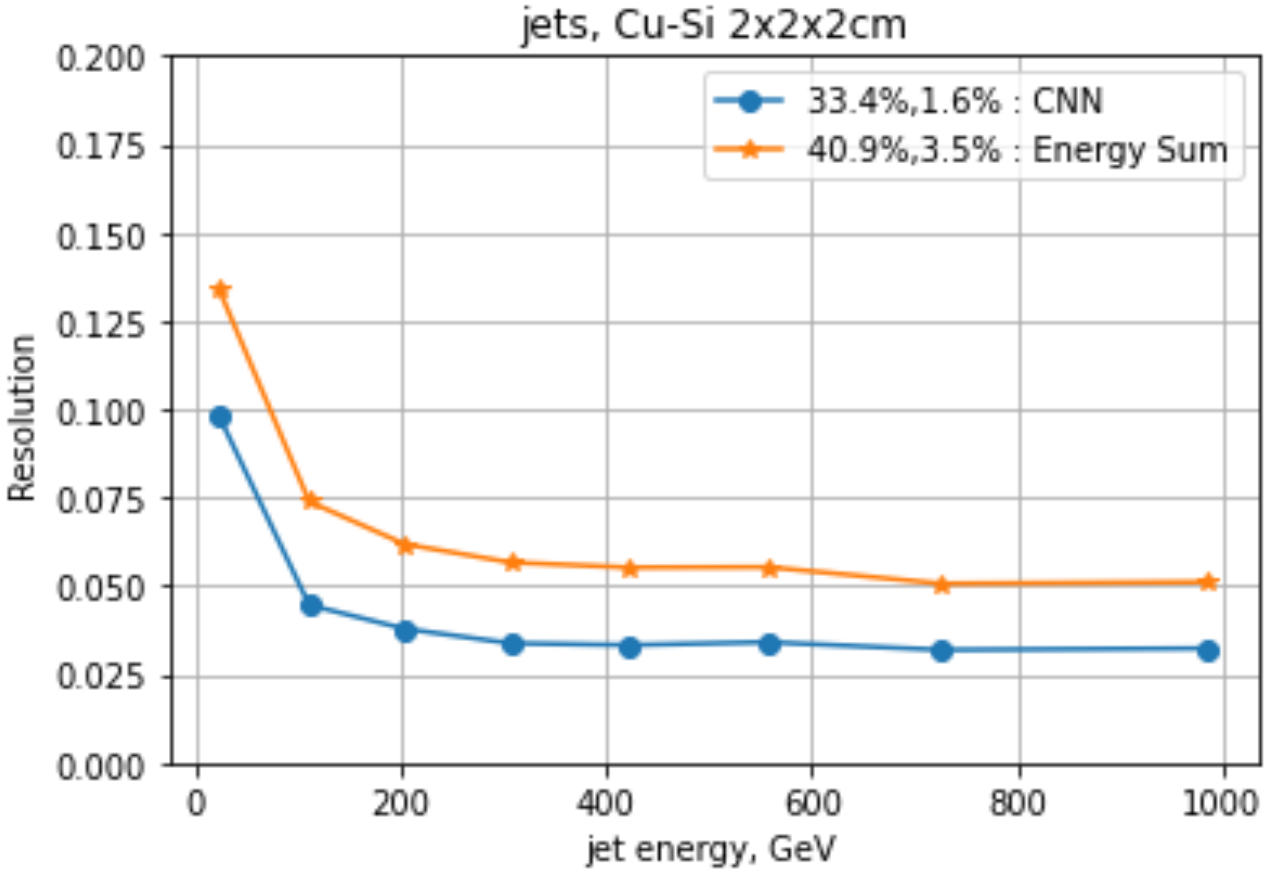


CNN maintains good performance for electron energy reconstruction – comparable to traditional techniques.

CNN Performance – multi-particles: jets

CNN trained on ***single pions*** (0.5-150 GeV) performs very well with **jet reconstruction** in extended energy range – up to 1 TeV

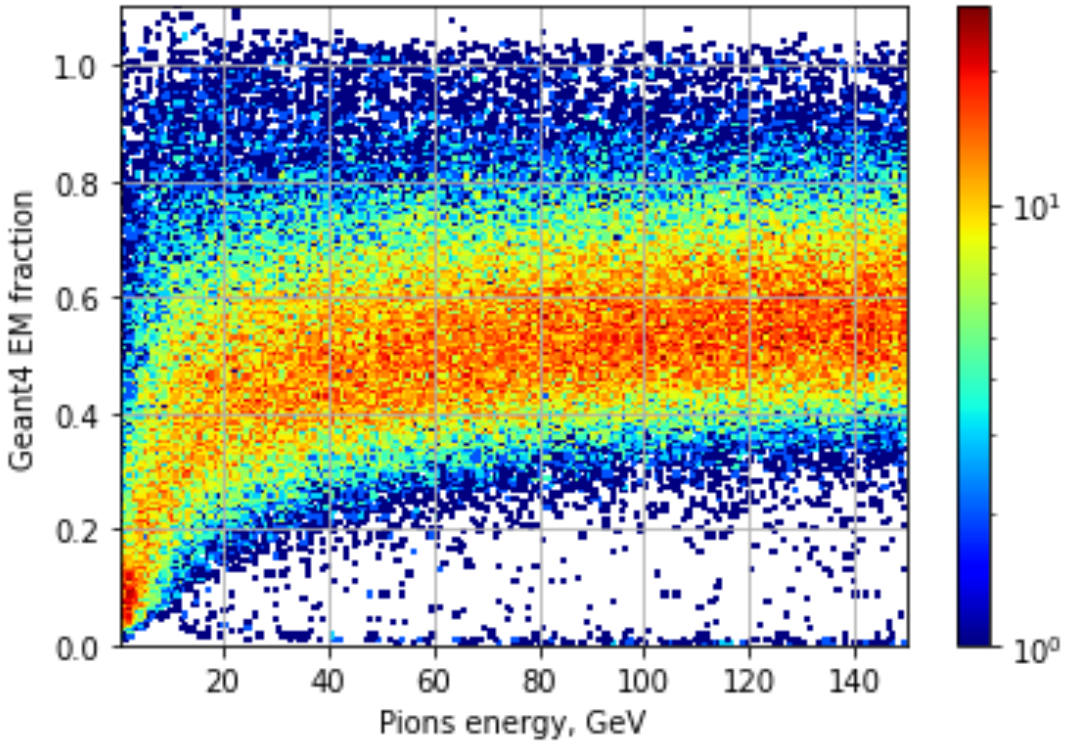




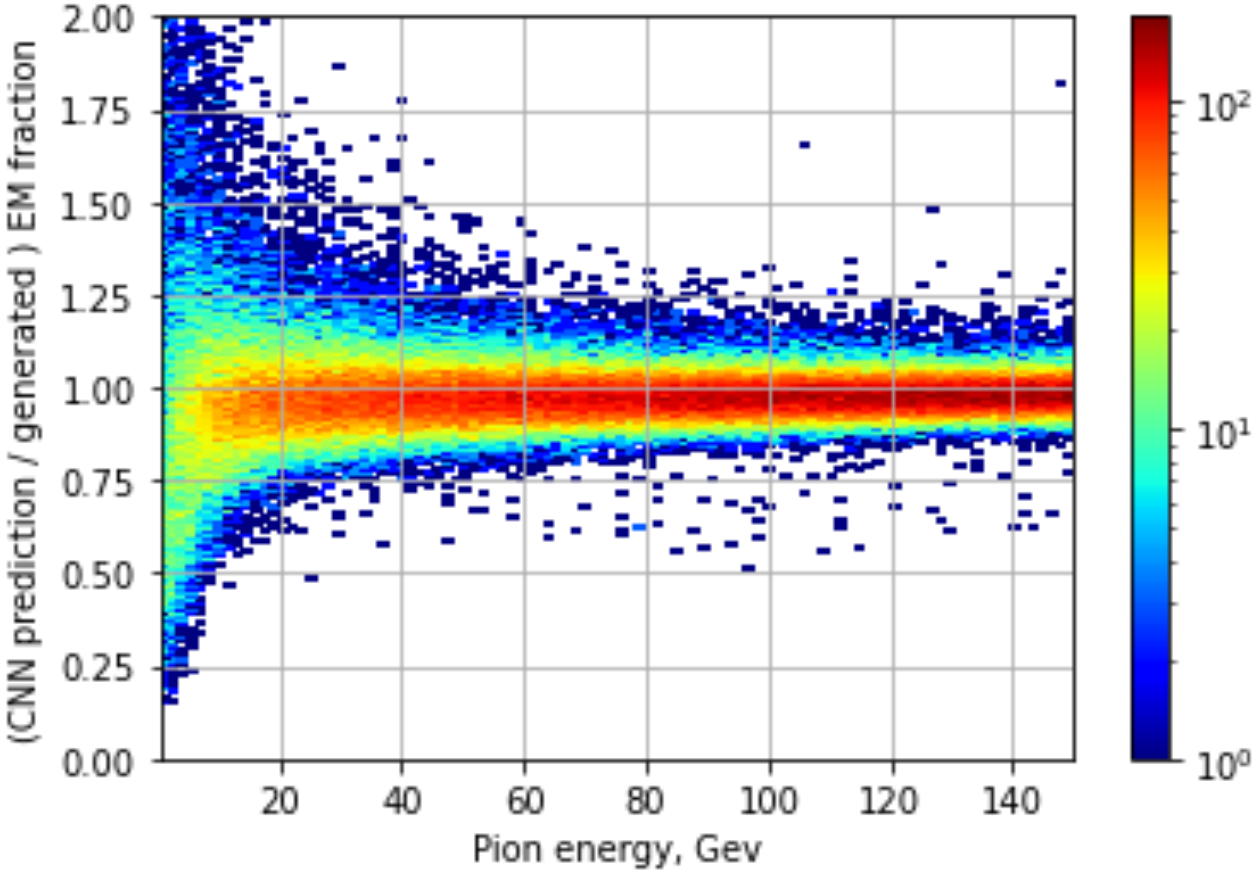
Reconstructing the EM Fraction with CNN

CNN can also be trained to reconstruct the EM-fraction in hadron showers

Geant4 EM Fraction

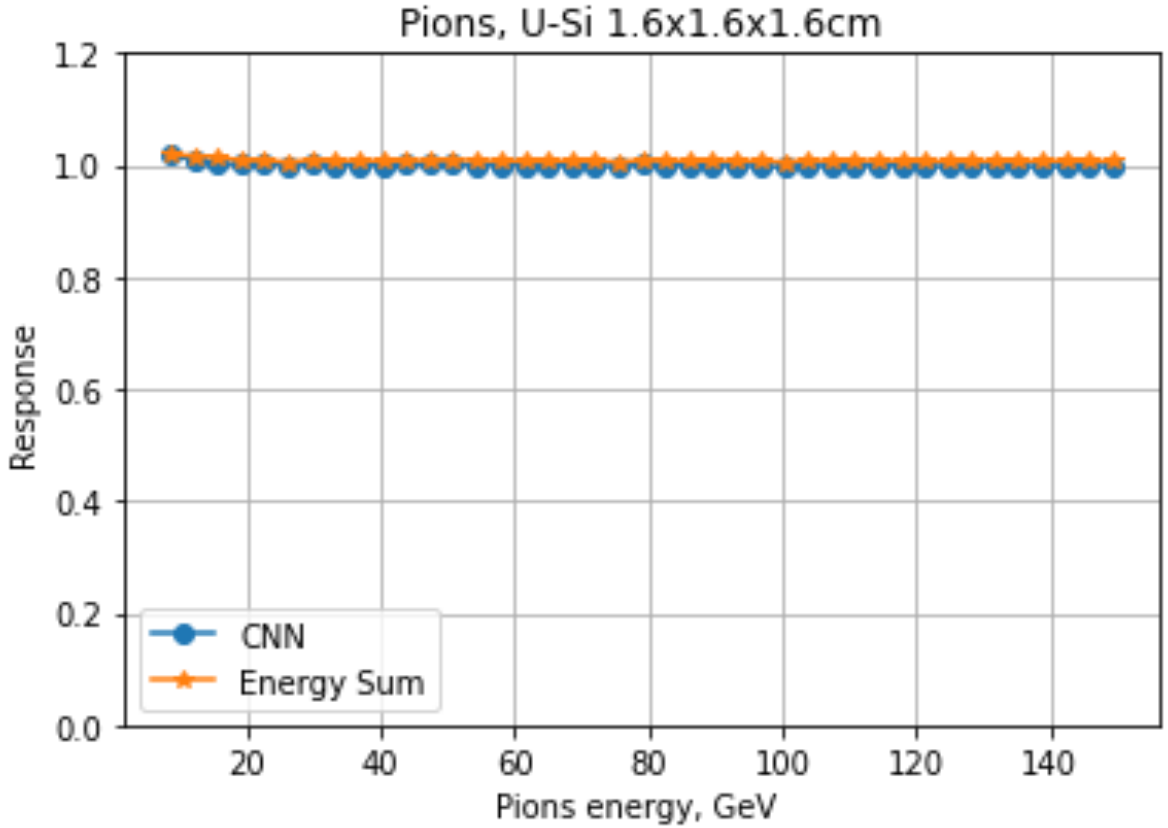


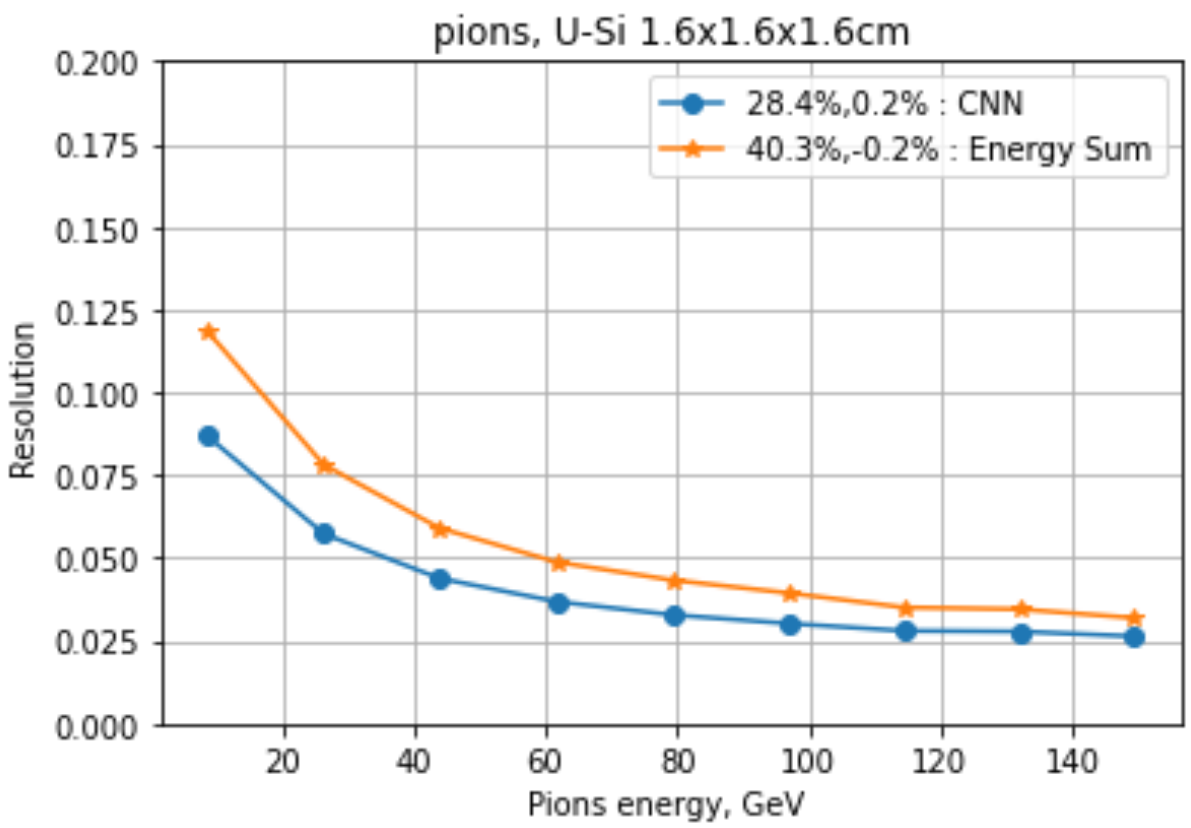
CNN/GEANT4



CNN Performance – Compensating Calorimeter

Uranium – Silicon sampling calorimeter. U-3.3mm, Si-0.7mm
Signal is integrated in 5ns and the cells are combined in 1.6x1.6x1.6cm^3 channels for the CNN reconstruction. CNN is trained on single pions 0.5-150 GeV.



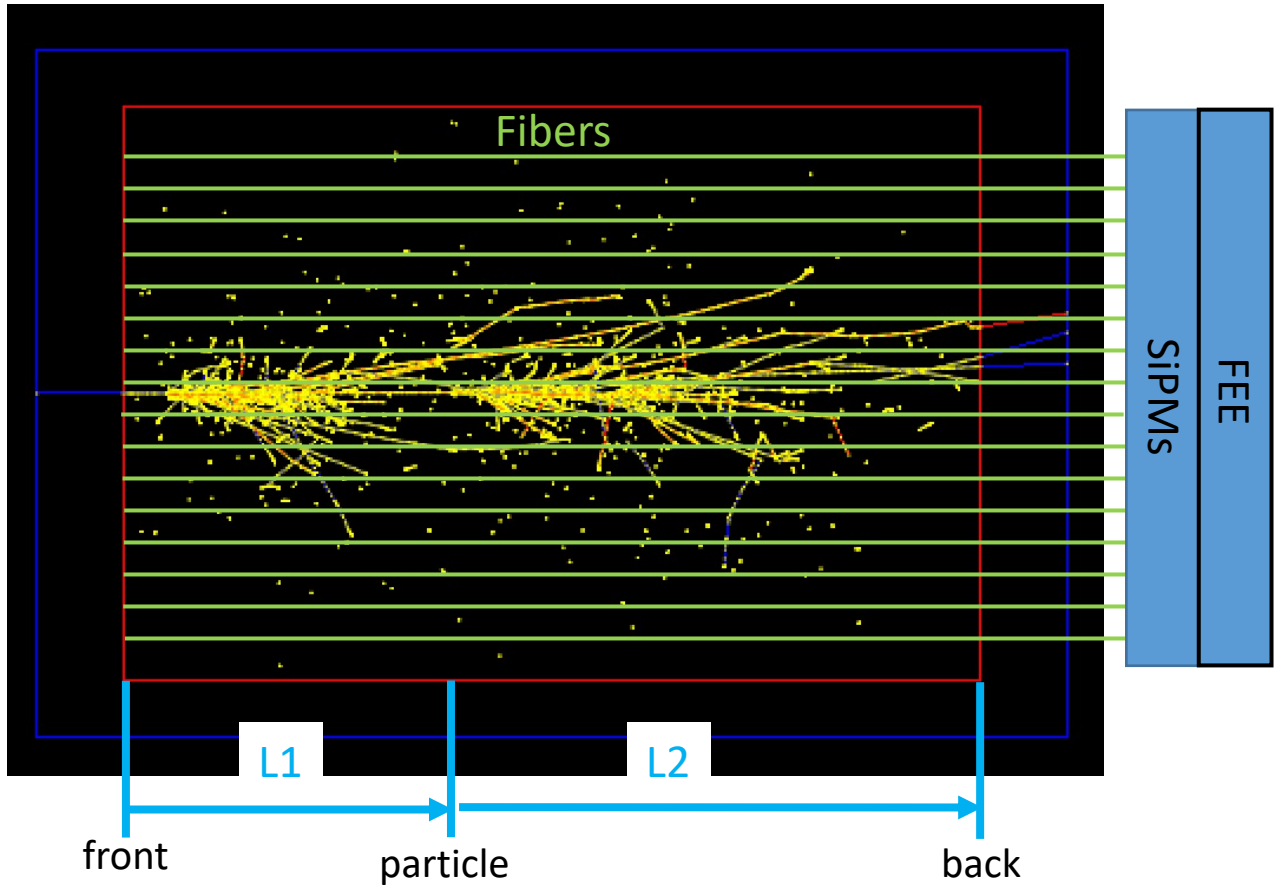


3D Imaging Fiber Calorimeter

- Done
  - Study of a simple calorimeter with CNN.
    - Cu(17mm)/Si(3mm), 2x2x2 cm^3 cube structure.
    - 2x2 cm^2 transverse size matches Cu Moliere radius (1.6 cm).

- Next
  - Design and prototype a 3D imaging calorimeter.
  - First option: Fiber calorimeter with longitudinal segmentation with timing.
    - Evaluate the limitation of current HW (SiPM, FEE, …) and prioritize R&D tasks.
    - Build a prototype to verify the prediction of the CNN study with GEANT simulation.

Fiber Calorimeter with Longitudinal Segmentation with Timing



Signal Time = L1/c + L2/kc,

c = velocity of particle

kc = velocity of light in fiber (k~0.6)

ΔL = 2 cm = 44 ps

❖ Channel counts reduction:

3D Calo: Nx * Ny * Nz

Nz → 1

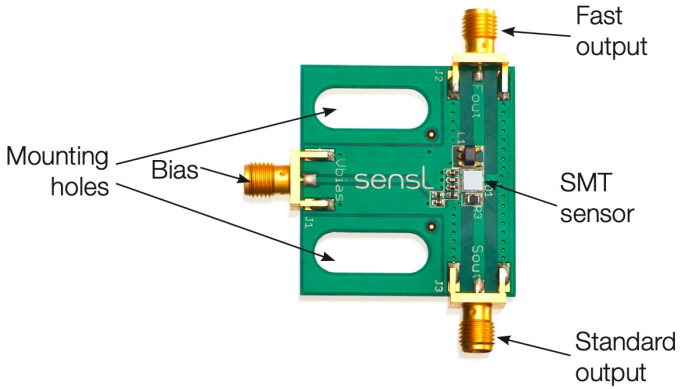
❖ Major Components:

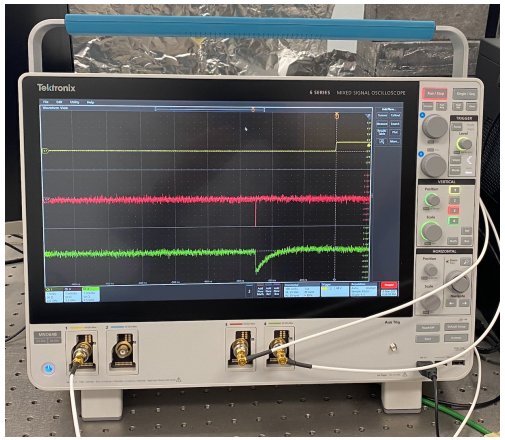
- ❑ Absorber
- ❑ Fibers
- ❑ SiPMs
- ❑ Frontend Electronics
  - Amplifiers
  - Waveform digitizers
- ❑ DAQ

➢ R&D on bench started!

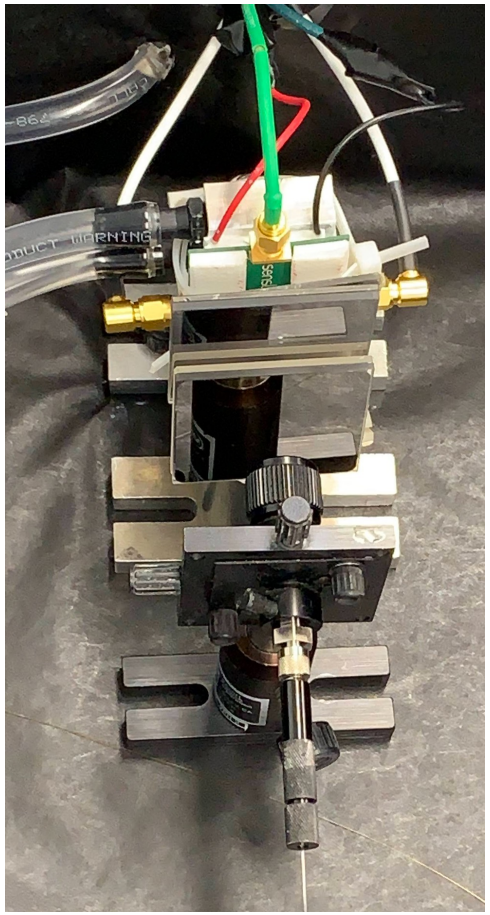
Bench Test Setup

SensL MicroFC-30020-SMT
(evaluation board)

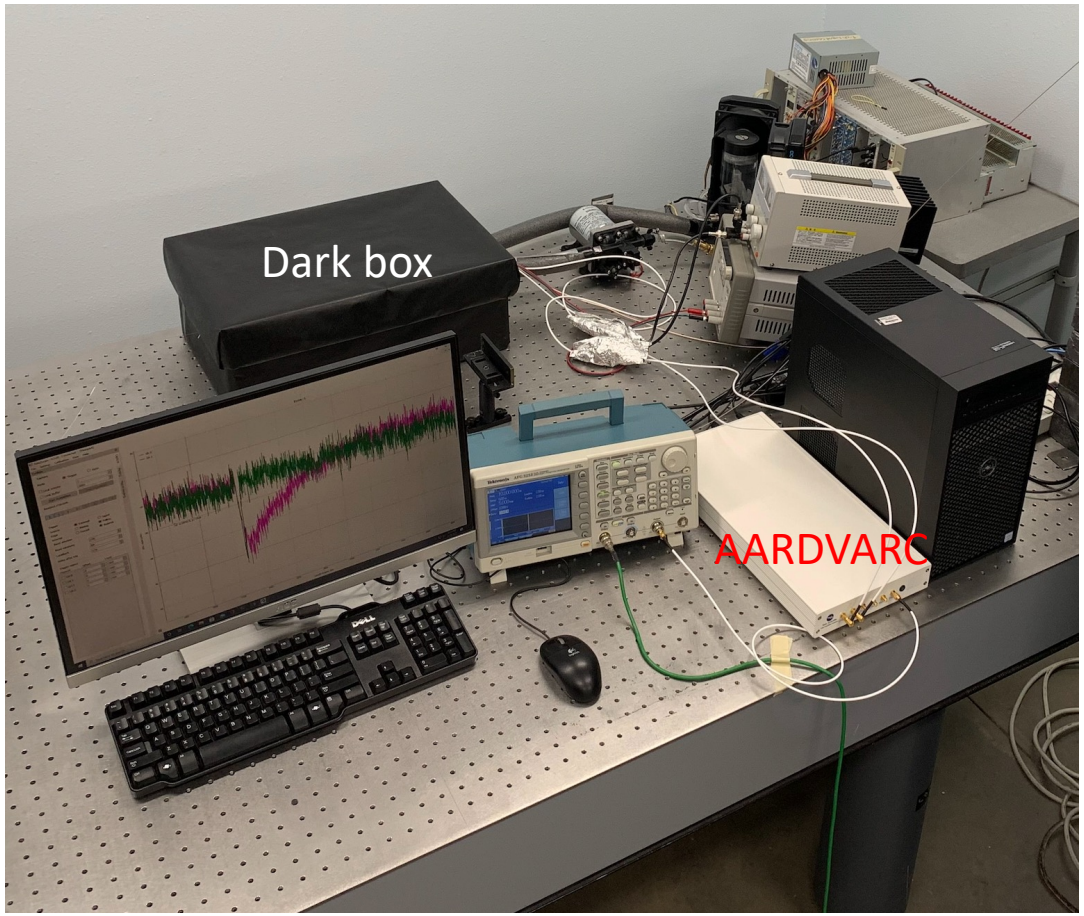




2.5 GHz scope



Fiber-Filter-SiPM-Cooling
(in dark box)

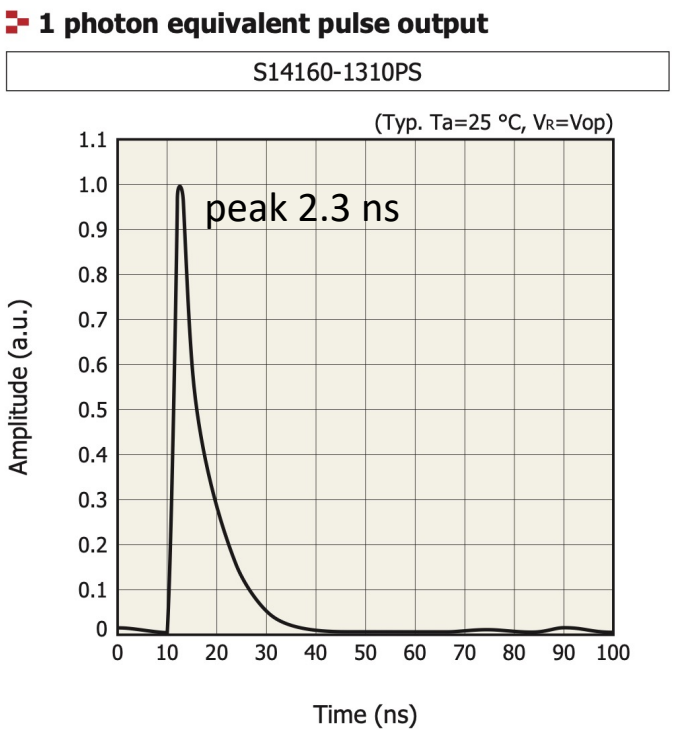


Dark box and NALU Scientific AARDVARC

SiPM- Pulse Shape for Single Photon

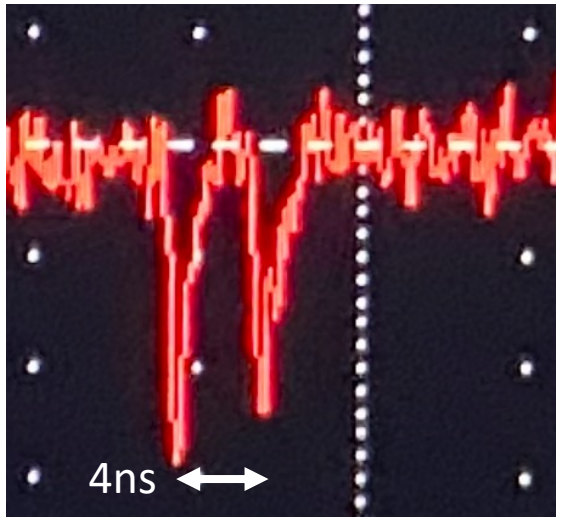
- ❖ Fast photon counting is required for timing measurement.
- ➢ SensL SiPM has two outputs. Fast Output is used for photon counting.

Hamamatsu

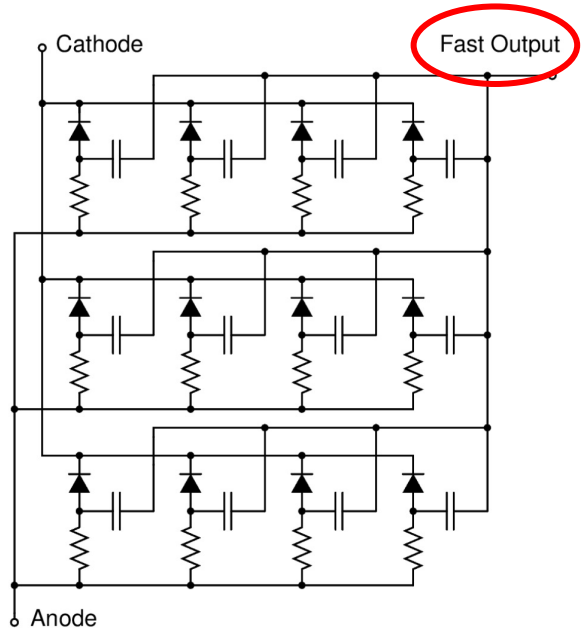


SensL MicroFC-30020SMT (Fast output)

2 photons signal (4 ns apart)



(2.5 Gs/s on scope)



SiPM – Photon Counting with Precision Timing

- SiPMs are excellent photon counting devices and have potential to be excellent timing device to map time structure of showers in calorimeter with high performance waveform digitizer.
  - R&D is required!

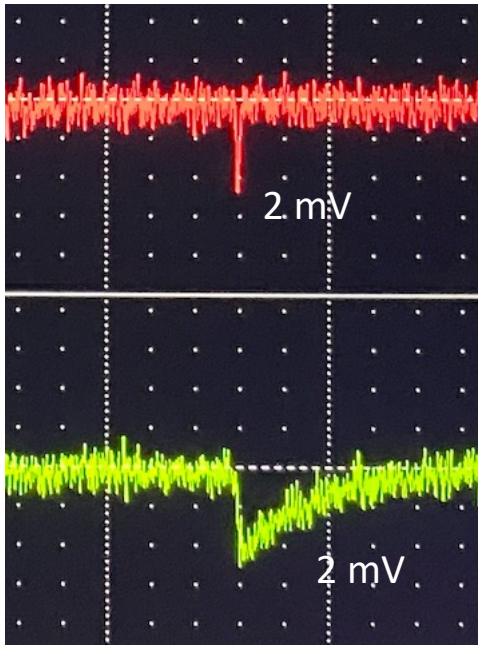
Single photon event

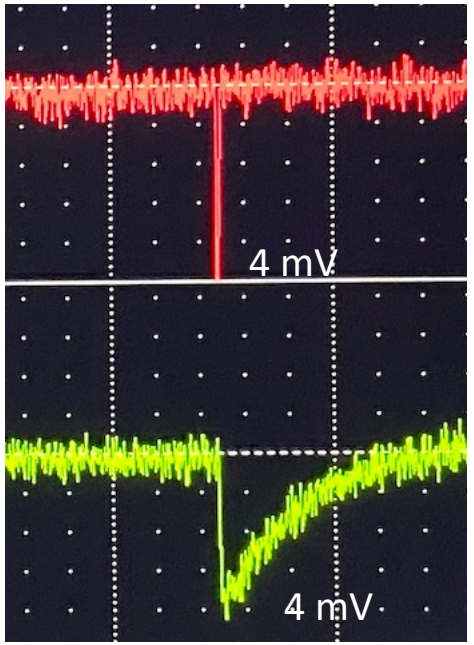
Two photon event (simultaneous)

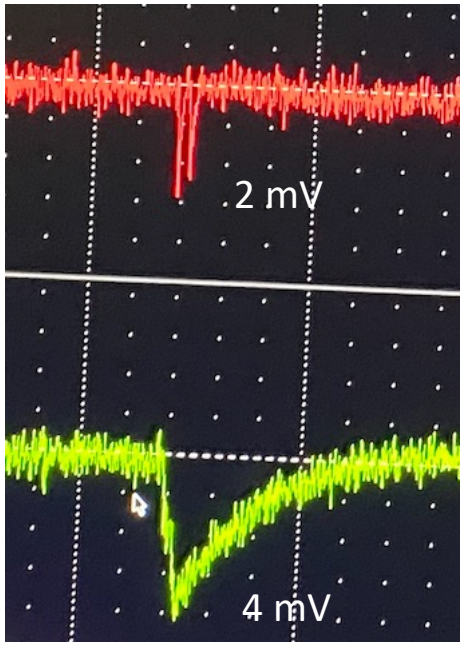
Two photon event (5ns apart)

Fast output
2 mV / photon

Standard output
2 mV / photon





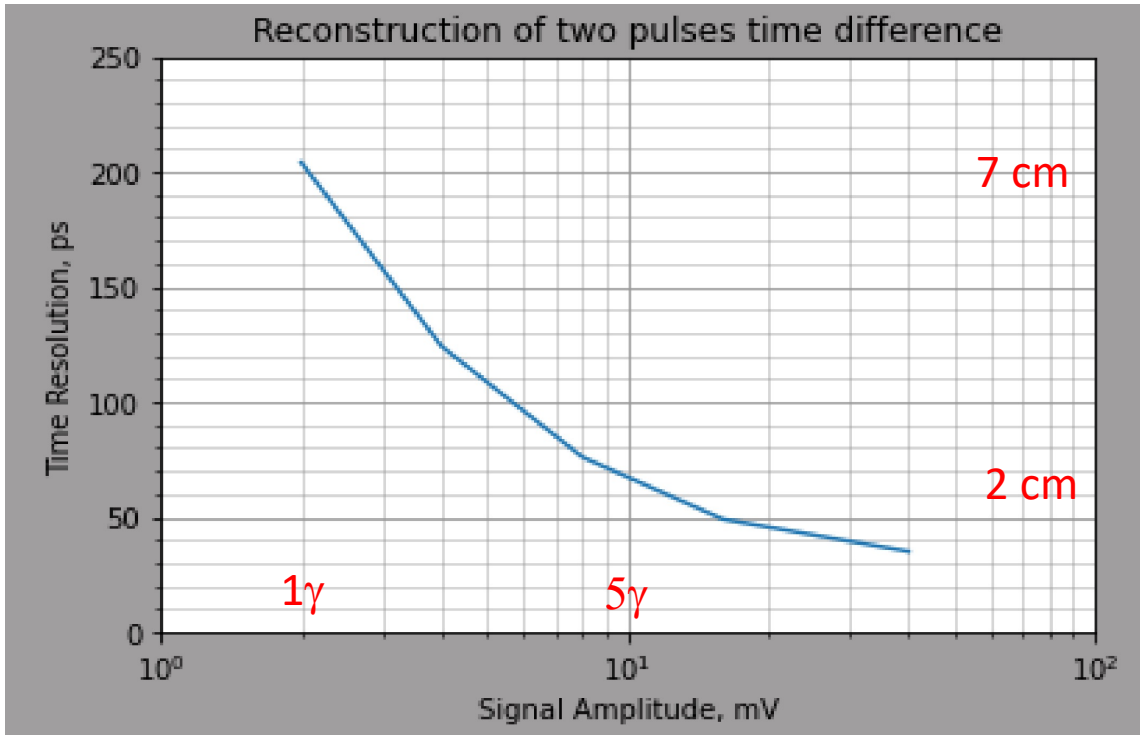


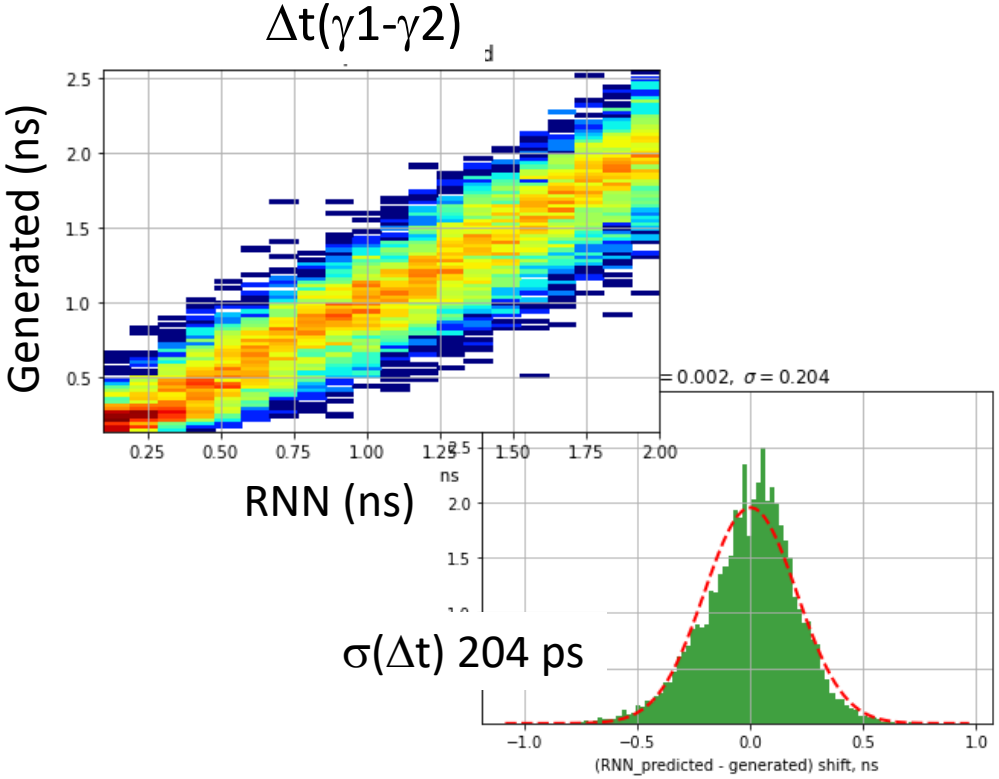
SensL MicroFC-30020SMT

Longitudinal Coordinate Resolution

- ❖ Pulse shape of single photon signal from SensL SiPM was measured with NALU's AARDVAC V3.
  - ➢ The pulse shape was used to simulate waveforms of convoluted pulses of two photon events.

- ❖ Recurrent Neural Network (RNN) was used to reconstruct the timing of two photons.
  - ➢ Resolution of 7 cm (2 cm) will be achieved for 1 (5) photon-equivalent signal.
    - Improvement expected with "better" SiPM and FEE.

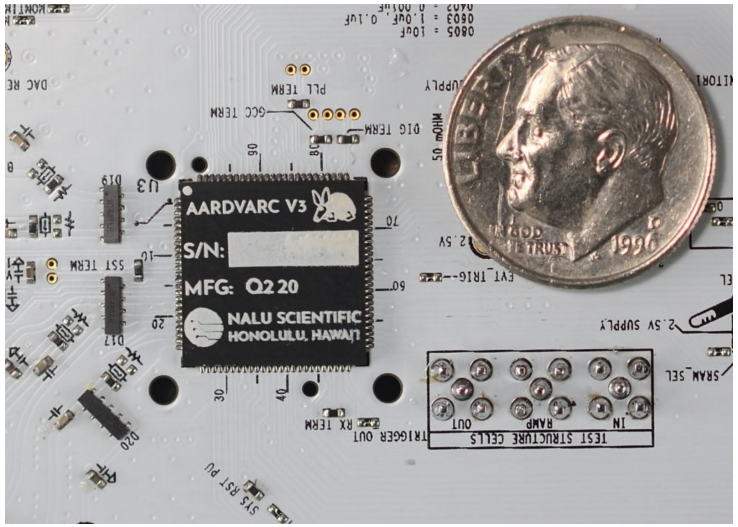


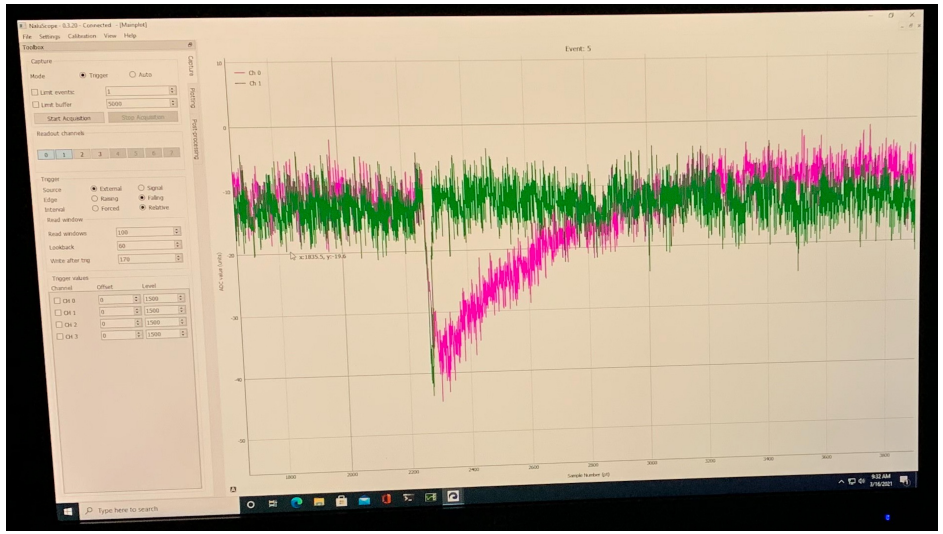


NALU Scientific AARDVARC V3 – System on Chip

- ❖ Compact, high performance waveform sampling and digitizing.
  - ➢ 10-14 Gsa/s, 12 bits ADC, 4-8 ps timing resolution, 32 k sampling buffer, SoC
  - ➢ DOE SBIR project

- ❖ NALU provided TTU an evaluation board (4 ch).
  - ➢ Waveform sampling/digitizing: performed well on our test bench.
  - ➢ System on Chip: not yet tried.
  - ➢ We have regular discussions with the NALU team for improvements and further development





NaluScope – 03.20

SiPM single photon signal
- green: Fast output
- magenta: Standard output

R&D with IDEA Dual-Readout Calorimeter Collaboration

- IDEA protypes include TDC. We evaluate the current design and look for further improvement of timing measurement toward 3D imaging calorimetry. We focus on R&D in the following area.

- Fibers: We have been studying quartz fibers, plastic and rare-earth-doped quartz fibers at TTU. We evaluate fibers for best timing measurement.

- SiPMs: We have been characterizing silicon sensors for the CMS HGCAL using TCAD and testbench measurements. Use of TCAD for SiPM characterization and further development of fast SiPM is under discussion.

- FEE: We have not investigated a potential of SoC technology yet. AARDVARC is under evaluation by IDEA. We evaluate the SoC on AARDVARC and explore further use of the SoC technology.

IDEA: Fiber Layouts:

Capillary-tubes

Capillary-tubes calorimeter

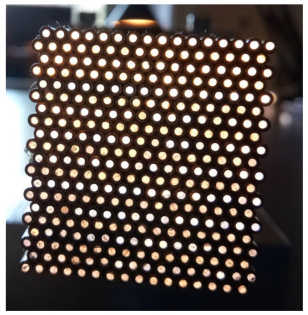


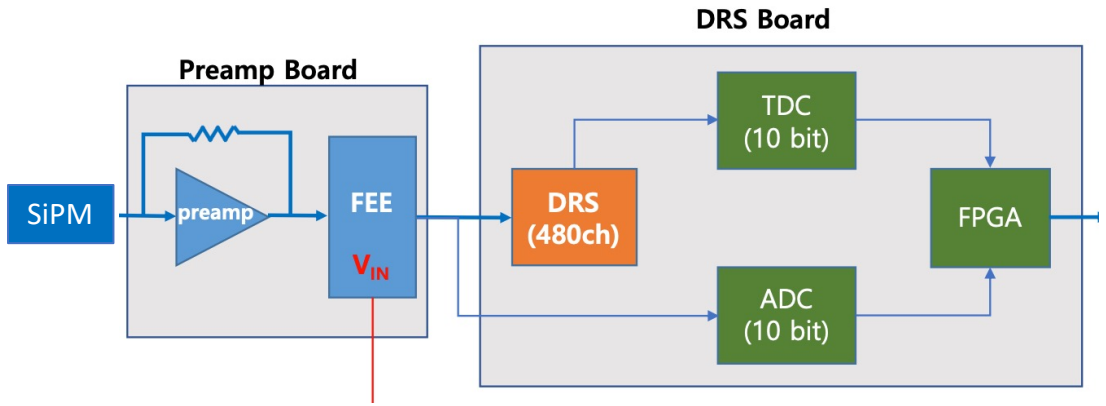
Plate-abosber

Plates-absorber calorimeter

3D-printing matrix

3D-printing matrix calorimeter

IDEA: TDC aiming at < 50ps

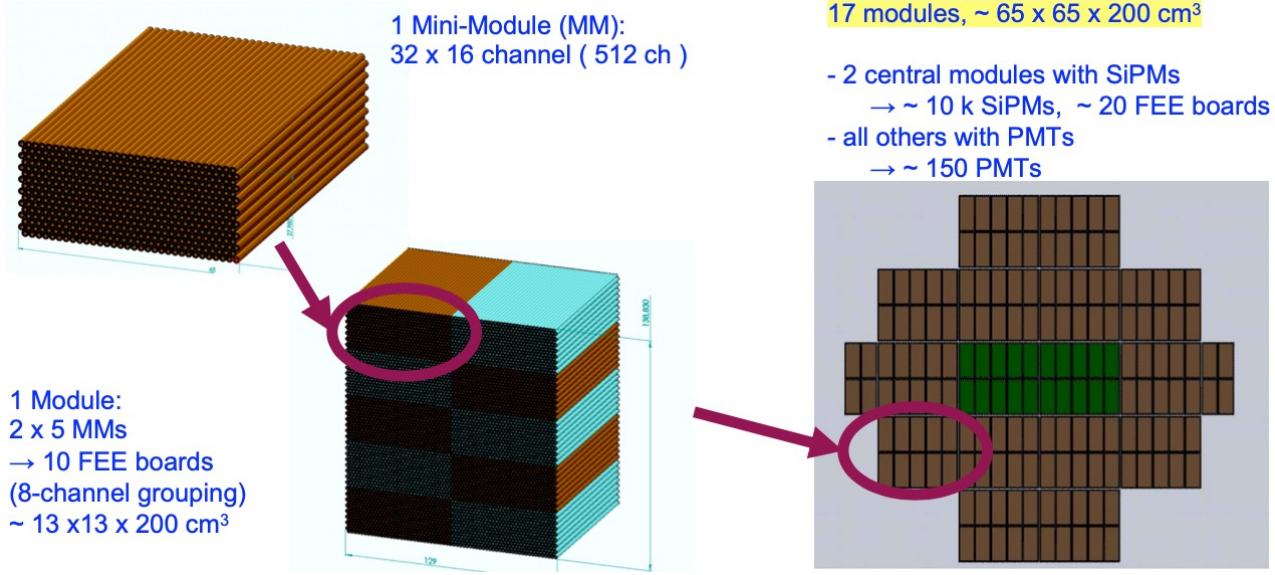


IDEA plans

- Short-term plan: build and test on beam a module with EM shower containment (10x20x100 cm^3) and highly granular core (3.5x3.2x100 cm^3) equipped with SiPMs
  - Testbeam at DESY in early summer (delayed from Nov '20 due to Covid19)
  - Cosmic muon stand under development

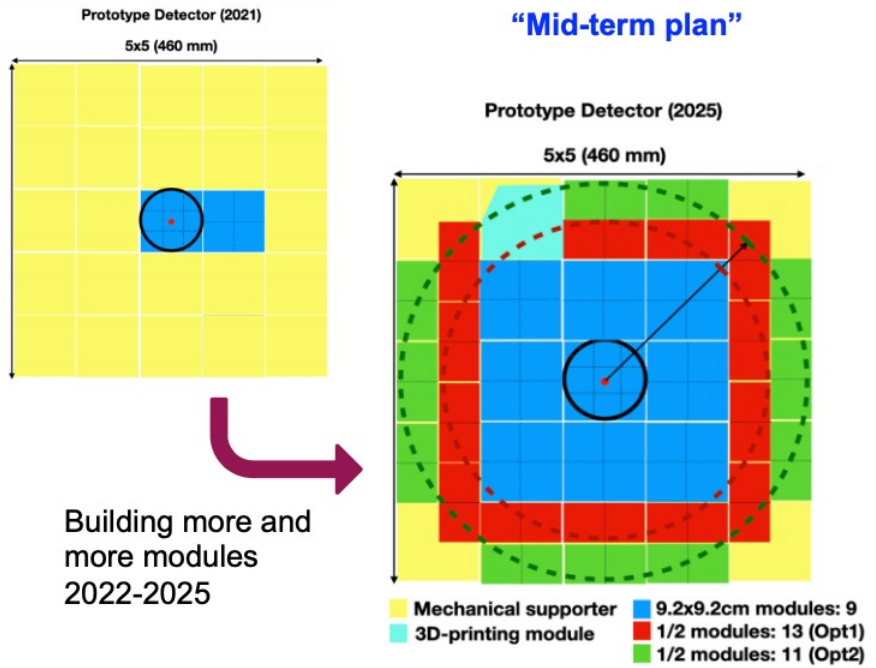
- Mid-term plan: design, build & qualify on beam a scalable system with hadronic containment, partially equipped with SiPM for cost/performance optimization
  - TTU plan under development

Capillary-tube design



3D printing matrix design

"Mid-term plan"



Summary

- ❖ We simulated a simple 3D imaging calorimeter with GEANT4.
  - ➢ Convolutional Neural Network (CNN) reconstructed energy well. It outperforms conventional calorimeters, e.g. EM-fraction corrected one.

- ❖ We started R&D of multi-readout fiber calorimeter with longitudinal segmentation with timing.
  - ➢ Bench tests of HW components (fibers, SiPM, FEE) are in progress.
    - SiPM has good potential for precision timing measurement.
  - ➢ Full Monte Carlo simulation program will be developed with realistic parameters from the bench tests.
  - ➢ The MC program will be used to develop HW design and ML algorithms.

- ❖ We are working with the IDEA collaboration on both HW and SW.
  - ➢ Longitudinal segmentation with timing will be evaluated with the IDEA prototypes.