WG6: TDAQ and AI/ML Summary

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12/02/2022

9 excellent talks

- "Neural network accelerator for quantum control", G. Di Guglielmo et al.
- "Nonlinear On-Chip Waveform Processing for Detector ASICs", S. Mandal et al.
- "Quality control assessment of silicon detector construction using deep learning", K. Lamichhane et al.
- "A Generic Data Acquisition System for Multidisciplinary Detector R&D", S. Watkins et al.
- "The upgrade of the versatile data acquisition system – CaRIBOu", S. Tang et al.
- "The LUX-ZEPLIN Data Acquisition and Real Time Monitoring System", D. Ashish Khaitan et al.
- "Real-Time Object Detection and Identification for DUNE's Data Selection System", J. Clair et al.
- "Usage of Machine Learning in CMS Level-1 Endcap Muon Trigger", E. Yigitbasi et al.
- "Smart pixels with data reduction at source", J. Dickinson et al.

AI/ML talks **TDAQ talks**

AI/ML applications

On-ASIC single channel

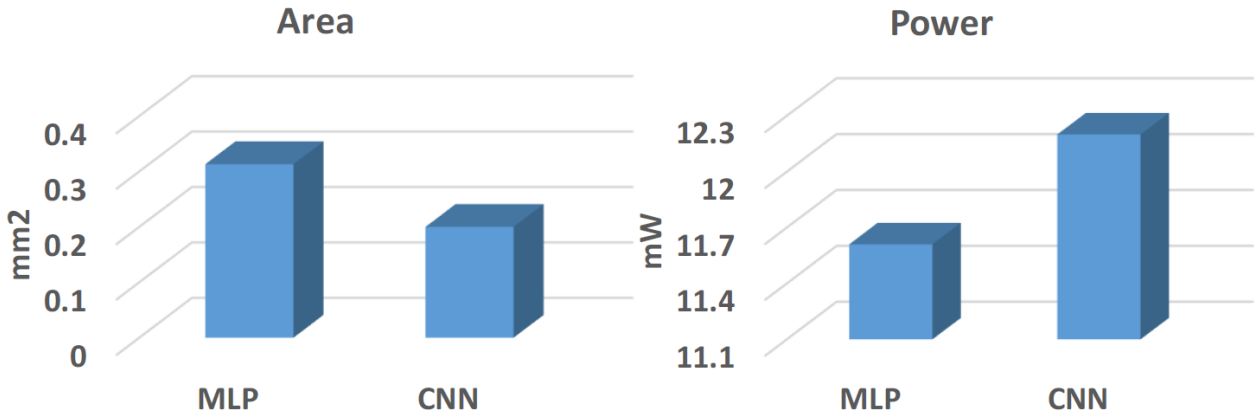
- Nonlinear On-Chip Waveform Processing for Detector ASICs
- Smart pixels with data reduction at source
- Neural network accelerator for quantum control
- Real-Time Object Detection and Identification for DUNE's Data Selection System
- Usage of Machine Learning in CMS Level-1 Endcap Muon Trigger
- Quality control assessment of silicon detector construction using deep learning

Complex off-detector identification of experimental signatures

In the majority of cases the data processing is done with fixed latency (in real time).

On-ASIC AI/ML and processing

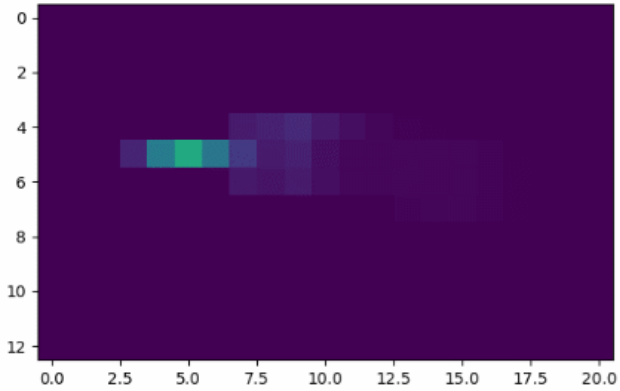
- **ANNs for waveform processing (e.g. for DUNE and ATLAS LAr).**
- "ANNs remain challenging to train and computationally expensive (e.g., in terms of chip area and power consumption) even after optimization."
- "Implementations in beyond-CMOS technologies (e.g., using memristors) may improve area and power. However, such devices are not readily available."

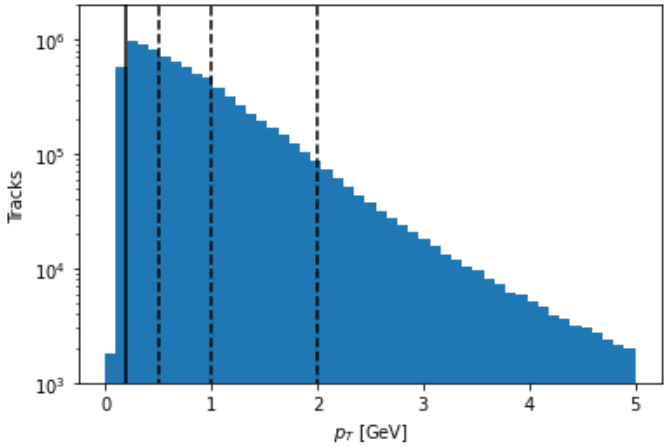


- Non-linear recursive filtering (NRF) is promising for low-complexity waveform processing and on-detector feature extraction.
- Future work will focus on optimized hardware implementations of both single-step (NRF-like) and iterative non-linear filtering / fitting algorithms.

On-ASIC AI/ML and processing

- The majority of hits in the inner-most tracker layer are from low-energy particles. The experimental signatures (pixel cluster) can be used to filter out these hits.
- The rejection rate of the NN classifier is substantial.

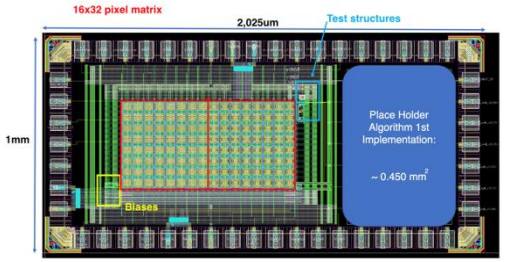




Conservatively reject:

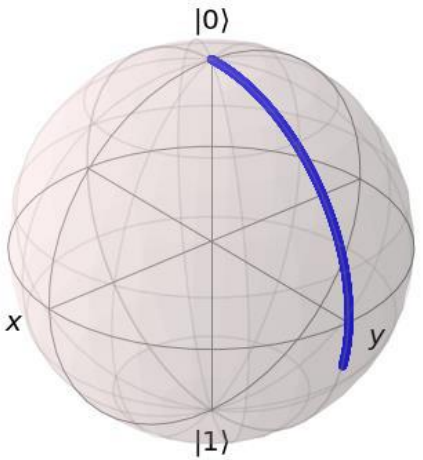
< 0.2 GeV	≥ 6%
< 0.5 GeV	≥ 36%
< 1 GeV	≥ 70%
< 2 GeV	≥ 94%

20x reduction



Test IC is to be submitted in December
More things to explore (e.g. cluster parameter extraction)

AI/ML for Quantum Control

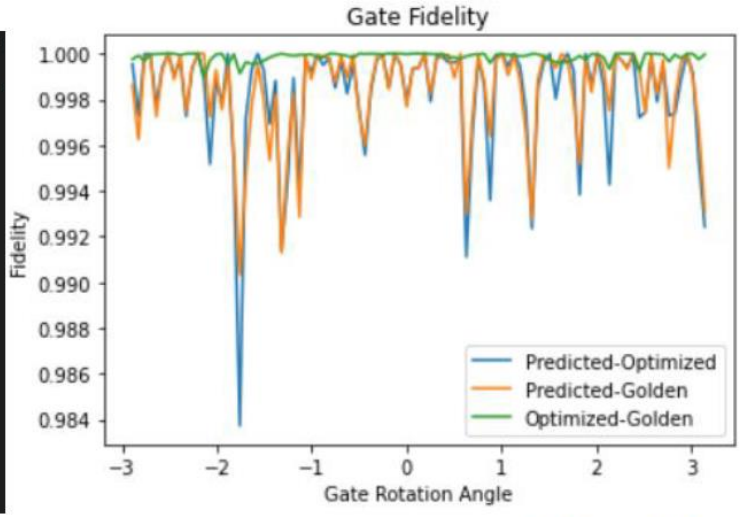


- Required **for fast control** of Q-BITs (few 100 ns)
- Reduction of computational complexity is required to calculate pulse parameters in FPGAs
- Used a Multilayer Perceptron model (MLP) to do the calculations

Great results!

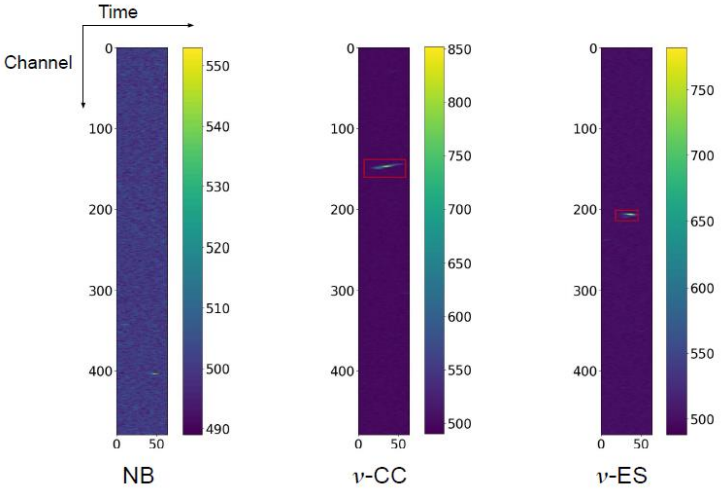
- Fidelity over 0.99 for all angles in (-π, π]
- Same timing maintained

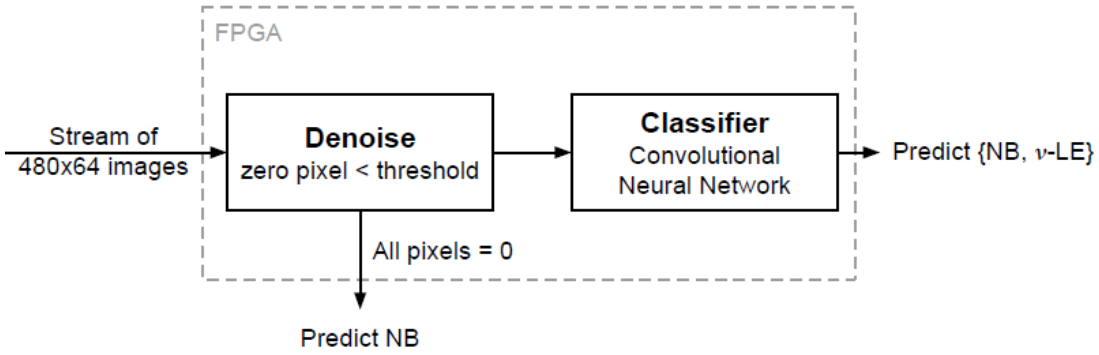
```
================================================================
== Utilization Estimates
================================================================
* Summary:
+-----------------+---------+-------+--------+-------+-----+
|       Name      | BRAM_18K| DSP48E|   FF   |  LUT  | URAM|
+-----------------+---------+-------+--------+-------+-----+
|DSP              |        -|      -|       -|      -|    -|
|Expression       |        -|      -|       0|      6|    -|
|FIFO             |        -|      -|       -|      -|    -|
|Instance         |        -|    238|   14424|  39644|    -|
|Memory           |        -|      -|       -|      -|    -|
|Multiplexer      |        -|      -|       -|     36|    -|
|Register         |        -|      -|    1499|      -|    -|
+-----------------+---------+-------+--------+-------+-----+
|Total            |        0|    238|   15923|  39686|    0|
+-----------------+---------+-------+--------+-------+-----+
|Available        |      270|    240|  126800|  63400|    0|
+-----------------+---------+-------+--------+-------+-----+
|Utilization (%)  |        0|     99|      12|     62|    0|
+-----------------+---------+-------+--------+-------+-----+
```



AI/ML for Dune TDAQ

- Real-time detection is crucial for DUNE off-beam physics program including i) study of supernovae and formation of black holes; ii) search for baryon number violation.
- Demonstration with the collection-plane signal is promising.





Test Set	NB (%)	LE (%)
(Slices) True NB	99.61	0.39
(Images) True LE	8.16	91.84

Train+Val+Test Sets	NB (%)	LE (%)
(Slices) True NB	99.61	0.39
(Images) True LE	7.85	92.15

FPGA implementation of the filter

Resource Utilisation

BRAM	DSP	FF	LUT
306 (5%)	44 (~0%)	48 062 (1%)	104 570 (6%)

Results shown for the Xilinx Alveo U250 board; noting that the Felix board has 76Mb BRAM, 5.5k DSPs, 1.3M FFs, 660k LUTs.

Latency *(clock @ 200 MHz)*

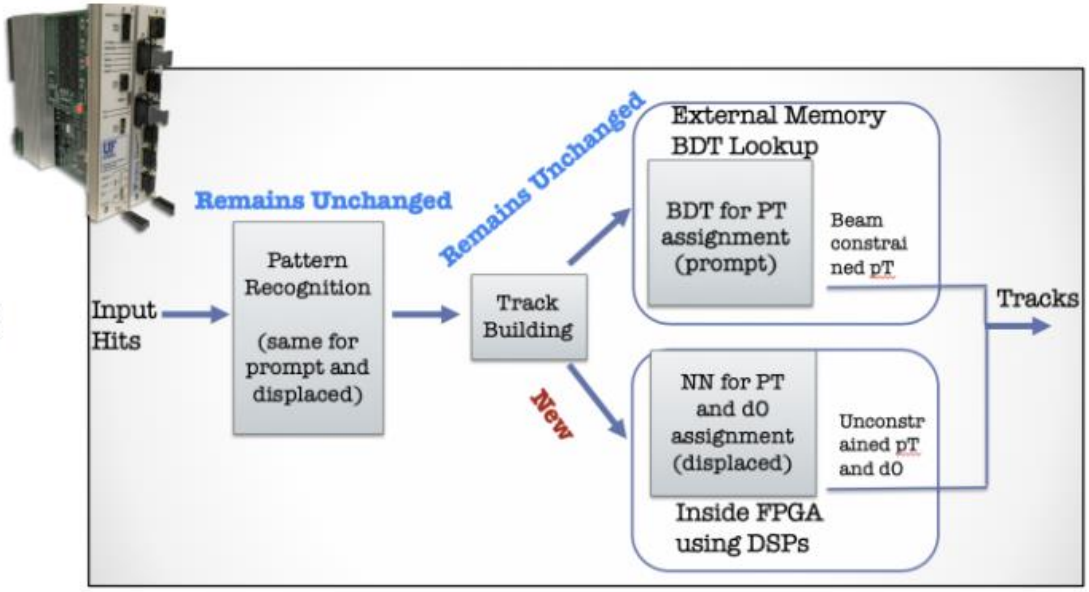
- Fastest unaltered hls4ml implementation: **348 µs** (with 5% LUT utilisation).
- After injecting custom HLS code: **25.18 µs** (with 6% LUT utilisation).
- 25.18 µs ⩽ 32 µs latency target.

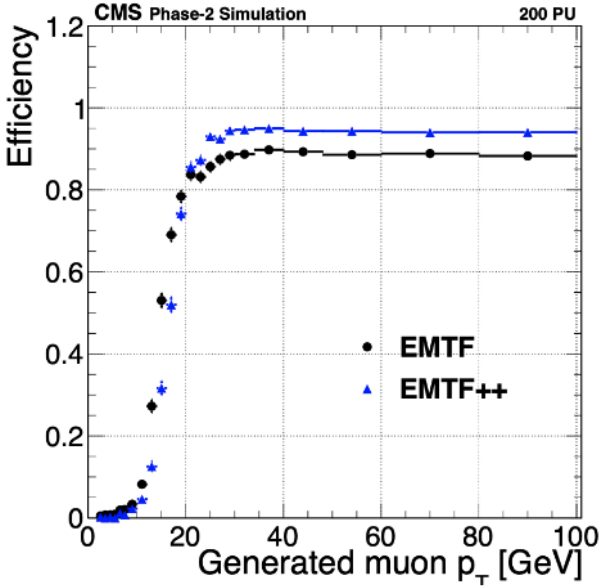
AI/ML for CMS Muon Trigger

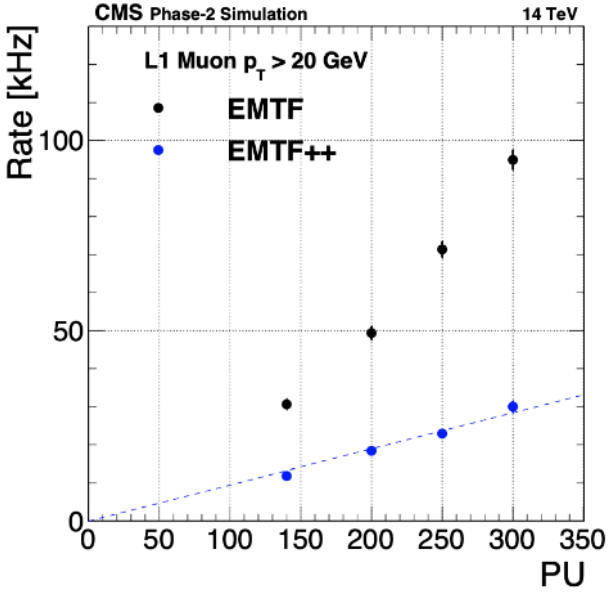
- AI/ML techniques are used to calculate muon track parameters for the trigger

Run 3 EMTF:

- Complexity is driven by non-uniform magnetic field, different detector technologies, backgrounds



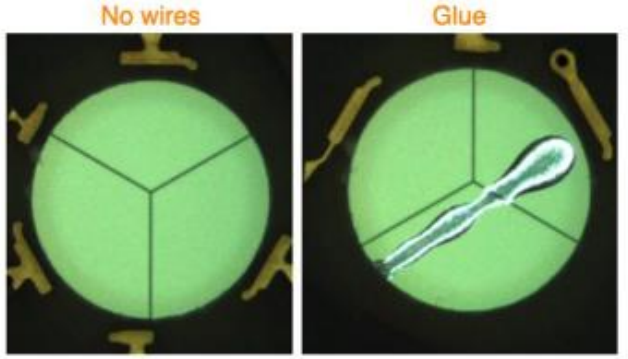


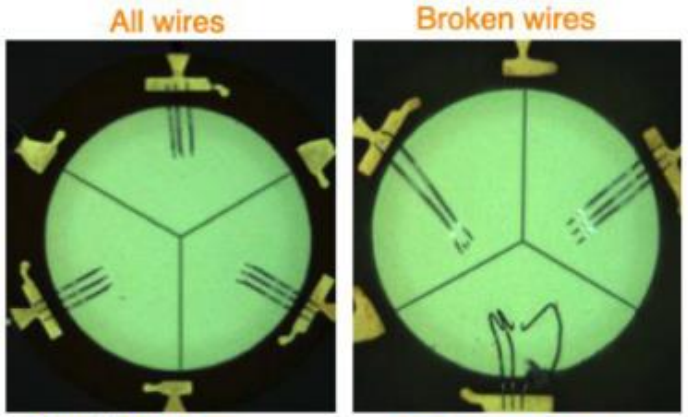


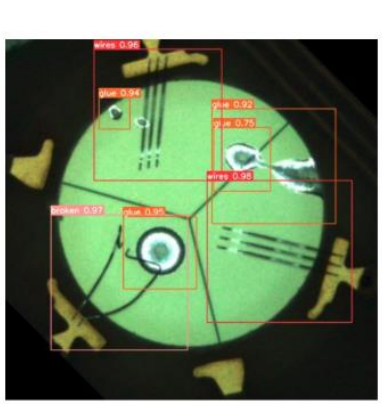
Big improvements in Run-4 (below)

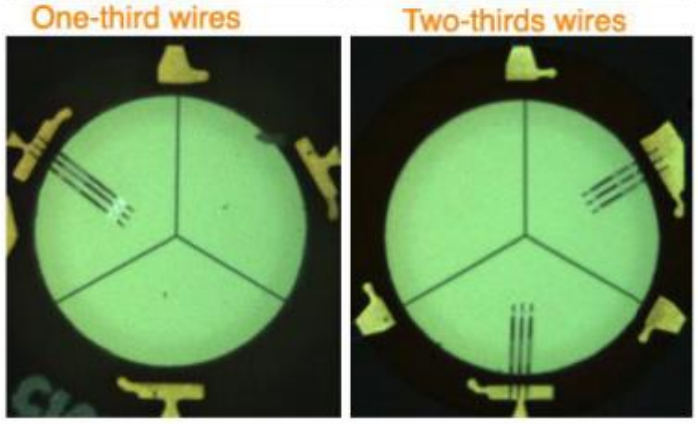
AI/ML for wire-bond QC

- Optical recognition of defective wire bonds for HGCal silicon modules.
- Promising performance
- Web interface









Number of images = 324				
Class	Labels	Precision	Recall	AP
All	764	0.992	0.951	0.962
Wires	420	0.951	0.999	0.984
Broken	96	0.999	0.917	0.934
Glue	192	0.988	0.885	0.935

TDAQ systems

Small & Versatile

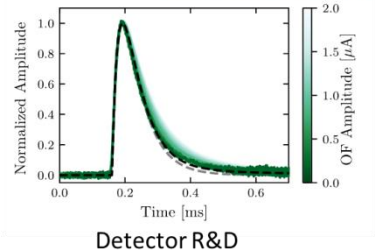
- A Generic Data Acquisition System for Multidisciplinary Detector R&D
- The upgrade of the versatile data acquisition system – CaRIBOu
- The LUX-ZEPLIN Data Acquisition and Real Time Monitoring System

Large & highly customized

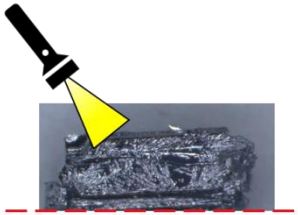
A Generic Data Acquisition System for Multidisciplinary Detector R&D

Applications of a Generic DAQ

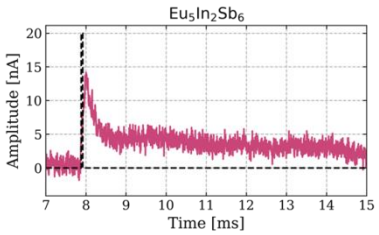
C.W. Fink, S.L Watkins et al., Appl. Phys. Lett. 118, 022601 (2021)



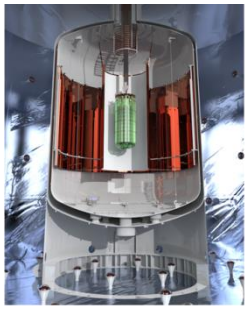
Detector R&D



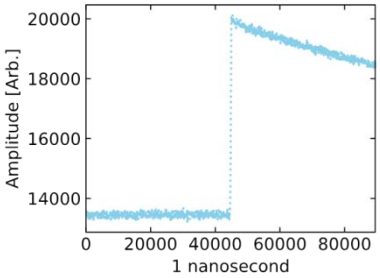
Pulses are ubiquitous!



Materials Characterization



LEGEND-1000 pre-CDR, arXiv:2107.11462

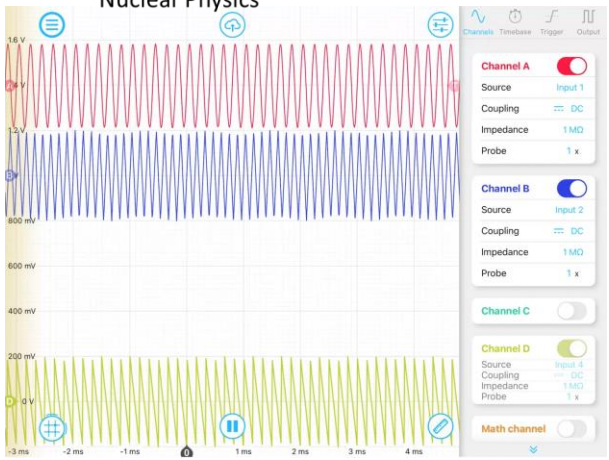


Nuclear Physics

Highly customizable commercial TDAQ platform

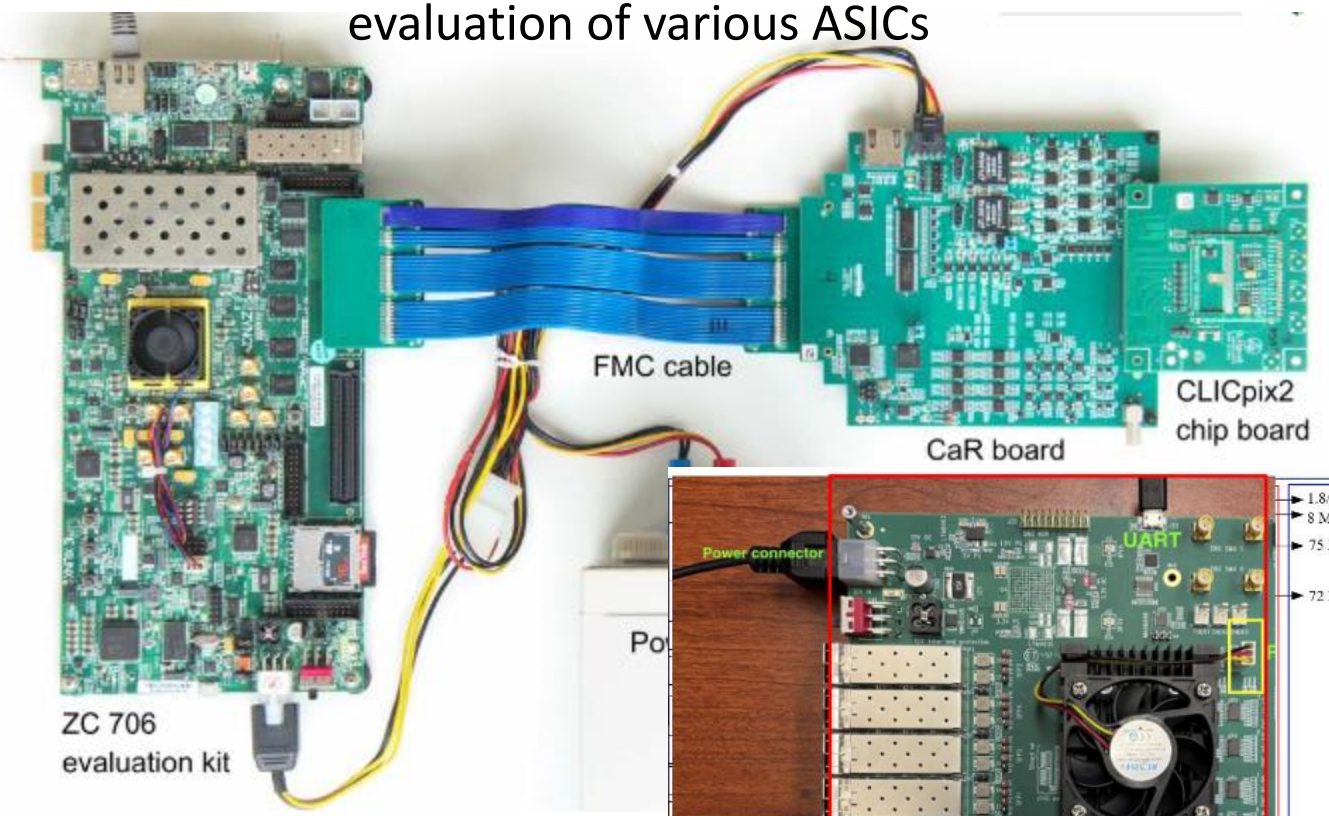
4 Inputs:
- 4 detectors
- High digitization rate
- Low noise

4 Outputs
- Apply DC voltages
- Generate various waveforms

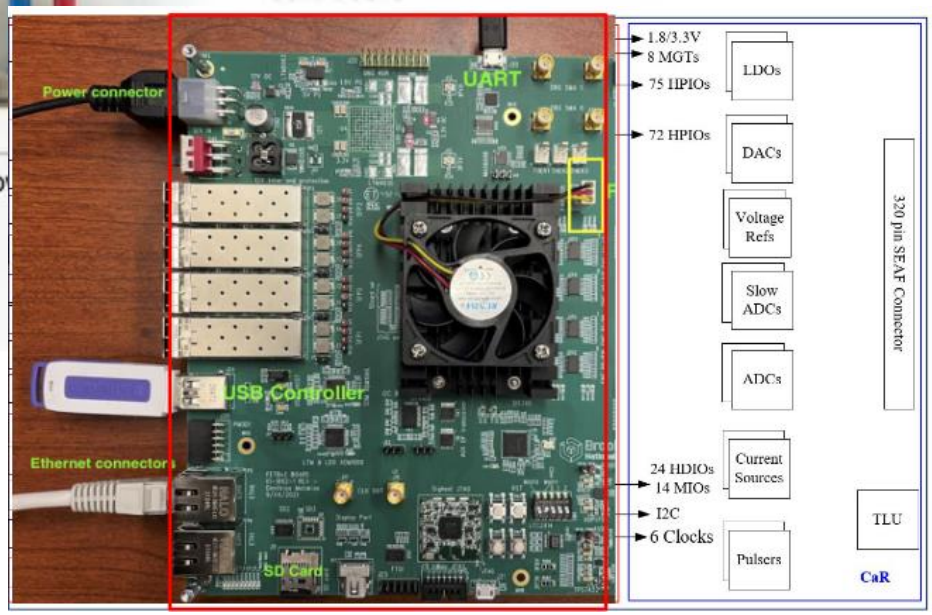


The upgrade of the versatile data acquisition system – CaRIBOu

- Custom highly-flexible TDAQ system. Was used for evaluation of various ASICs

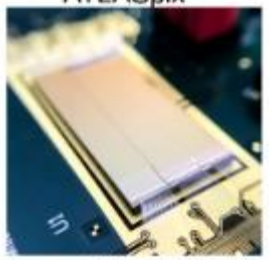


New CaRIBOu →

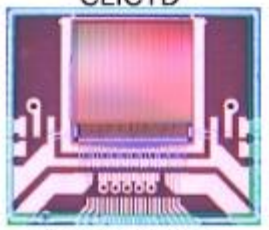


C3PD + CLICpix2

ATLASpix



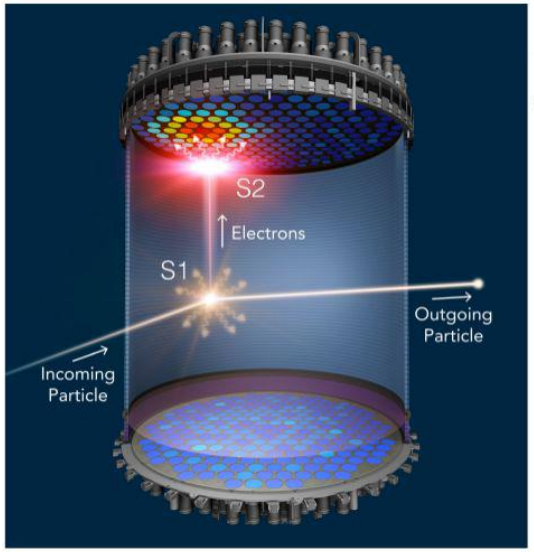
CLICTD



ASTROPIXv1

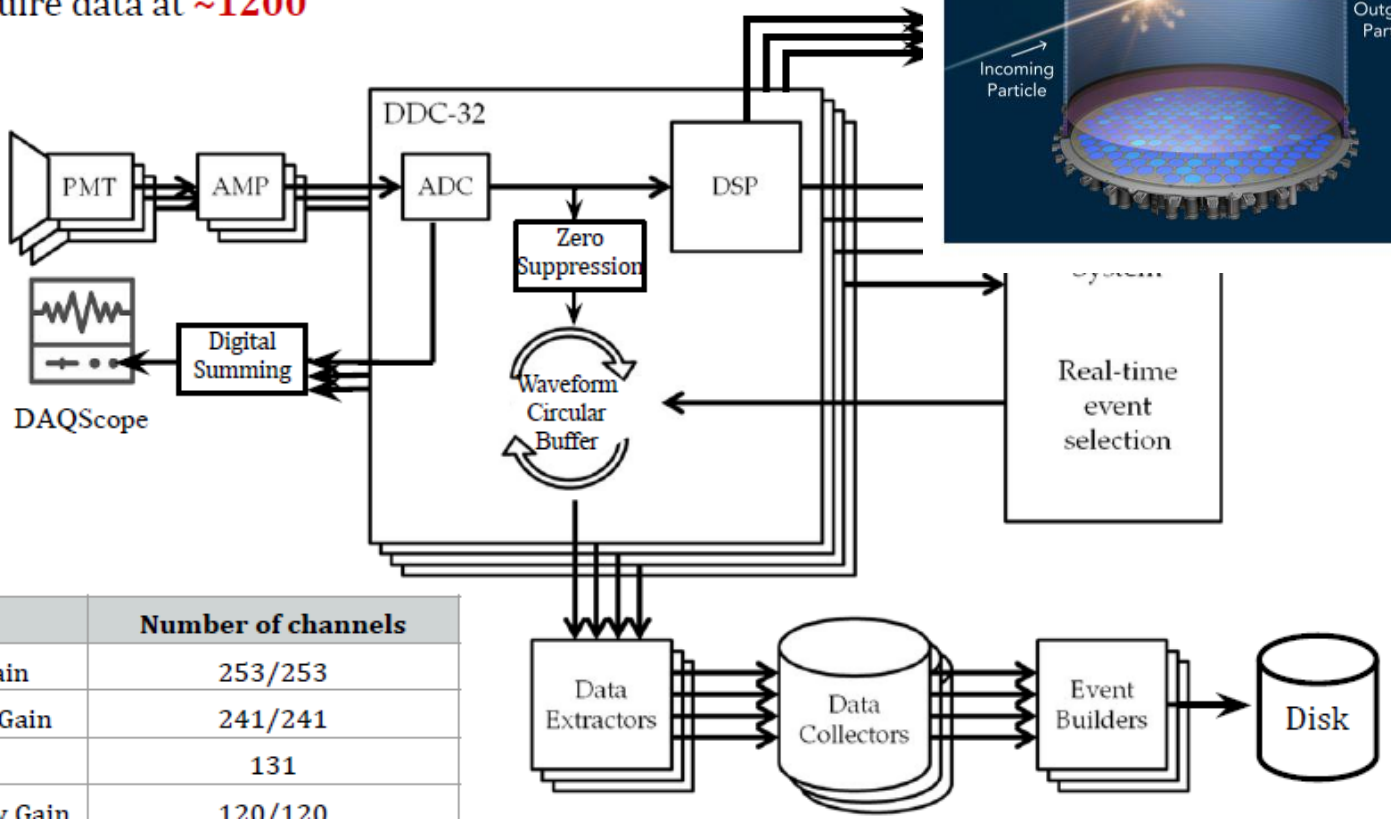
The LUX-ZEPLIN Data Acquisition and Real Time Monitoring System

- Large TDAQ system highly tailored for the experiment.



We can stably acquire data at **~1200 MB/s**.

During LZ's first science campaign, the DAQ had a livetime ~97%.



Group	Number of channels
TPC Top High/Low Gain	253/253
TPC Bottom High/Low Gain	241/241
Skin High Gain	131
Outer Detector High/Low Gain	120/120

Outlook

- This week we enjoyed excellent presentations on the contemporary developments of AI/ML approaches and TDAQ systems.
- However, this is a just small slice of all the ongoing work.
- The AI/ML approaches are benefiting a broad range of applications starting from ASICs to large off-detector systems.
  - AI/ML will be easier to use in ASICs as the CMOS technology improves (smaller area and power consumption)
- The TDAQ systems are also evolving
  - Better digitization
  - Higher channel count
  - Higher link speed
  - More user-friendly

- This work is essential to enabling future experiments and discoveries