HL-LHC **Upgrades** For the ATLAS Liquid Argon Calorimeter

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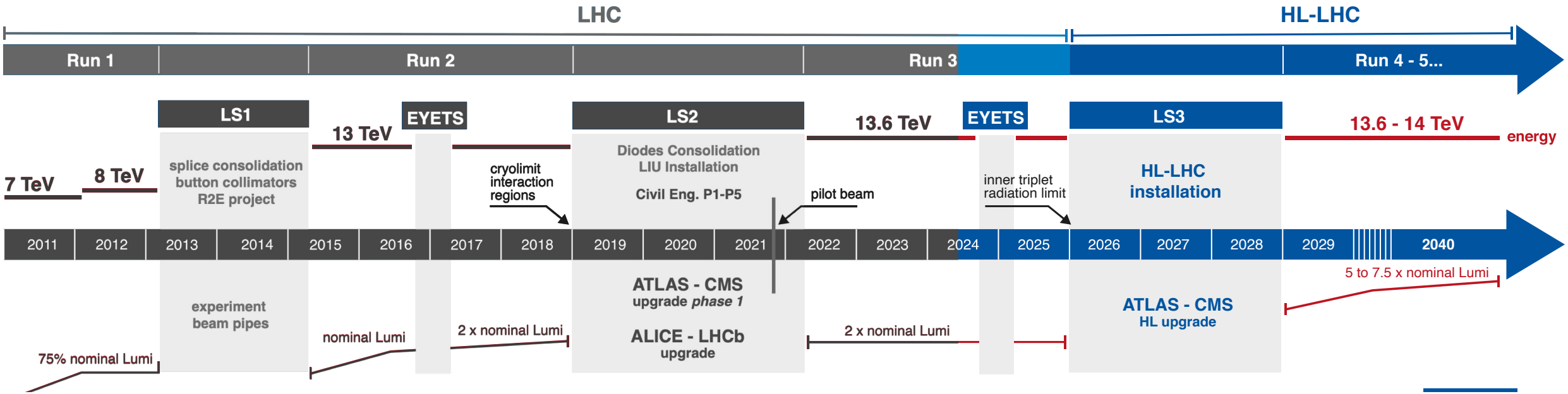
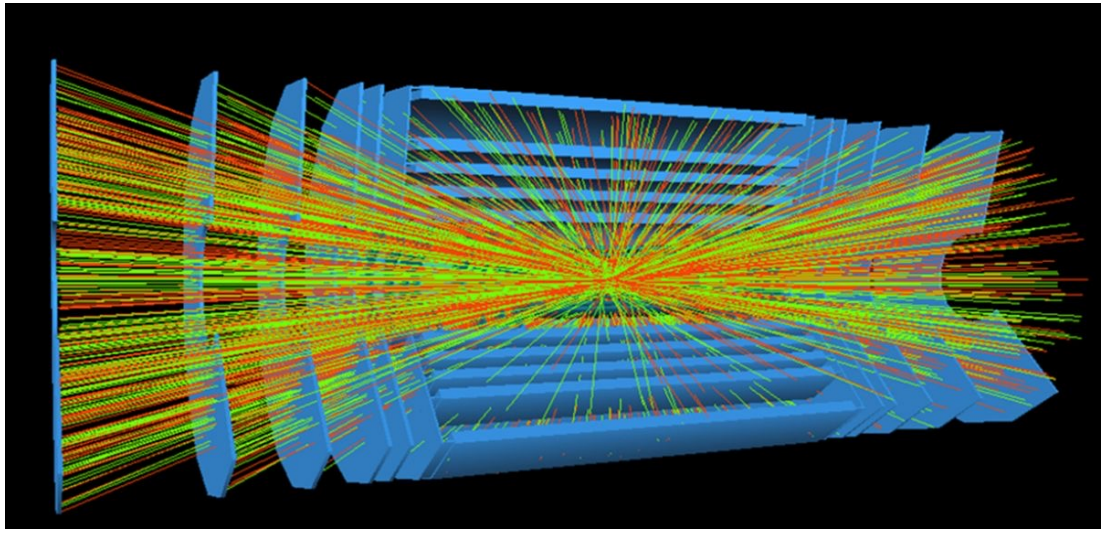
On behalf of the ATLAS LAr Calorimeter project

CALOR 2024 – Tsukuba, Japan

High Luminosity LHC (HL-LHC)

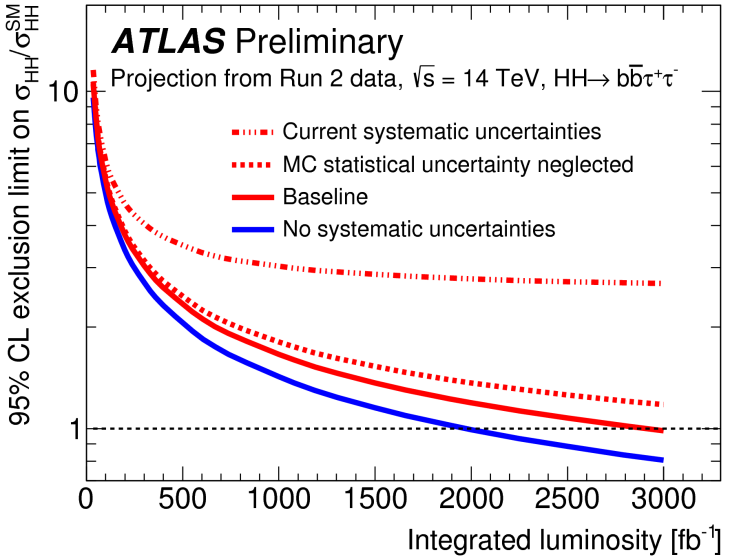


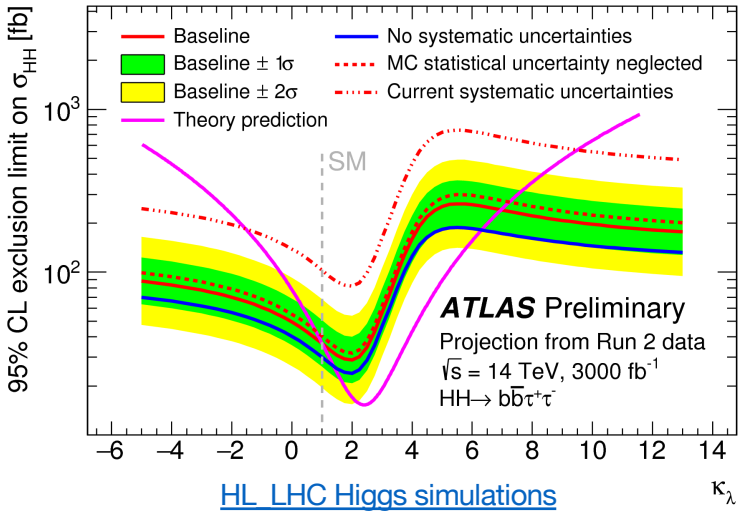
- The HL-LHC with have an integrated luminosity **10 times** greater than the current LHC
- The increased luminosity makes it harder to trigger on signal events
- Larger backgrounds from in-time and out-of-time pileup events



LAr Upgrade Motivation

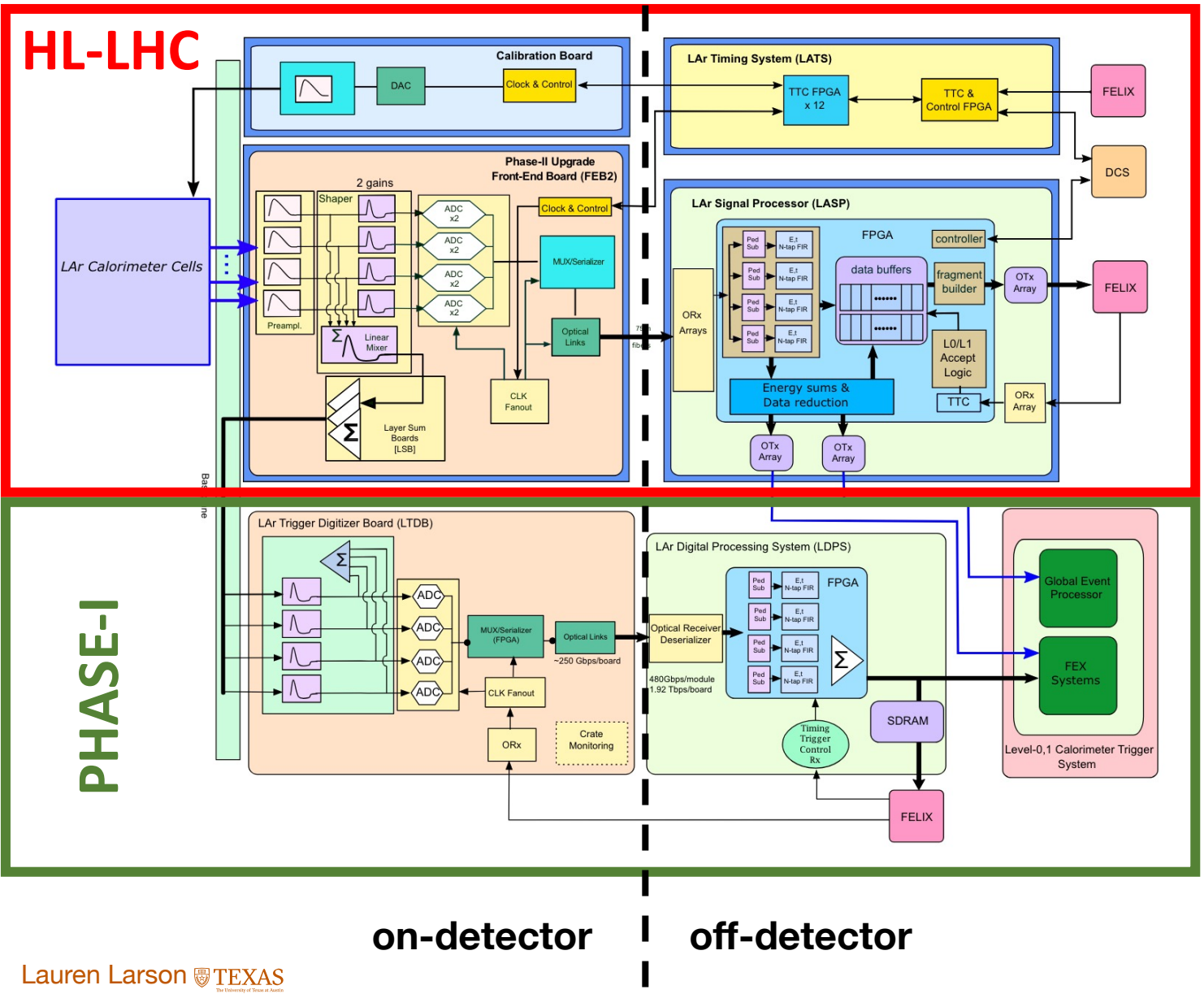
- LAr Calorimeter is a **CRITICAL** sub-detector for most HL-LHC physics signatures
- LAr Calorimeter itself remains unchanged for HL-LHC
  - Liquid argon stability shown in ATLAS and previous experiments
- The calorimeter electronics will be upgraded
  - In order to be compatible with the upgraded trigger and DAQ systems that are being designed for the higher luminosity
- To meet the needs of the HL-LHC LAr will undergo several upgrades
  - Already commissioned, improved Digital Trigger system, providing finer granularity to the trigger system
  - **For the HL-LHC, new radiation hard readout electronics, providing precision readout of all calorimeter cells at 40 MHz**





HL_LHC Higgs simulations

HL-LHC LAr Readout Electronics



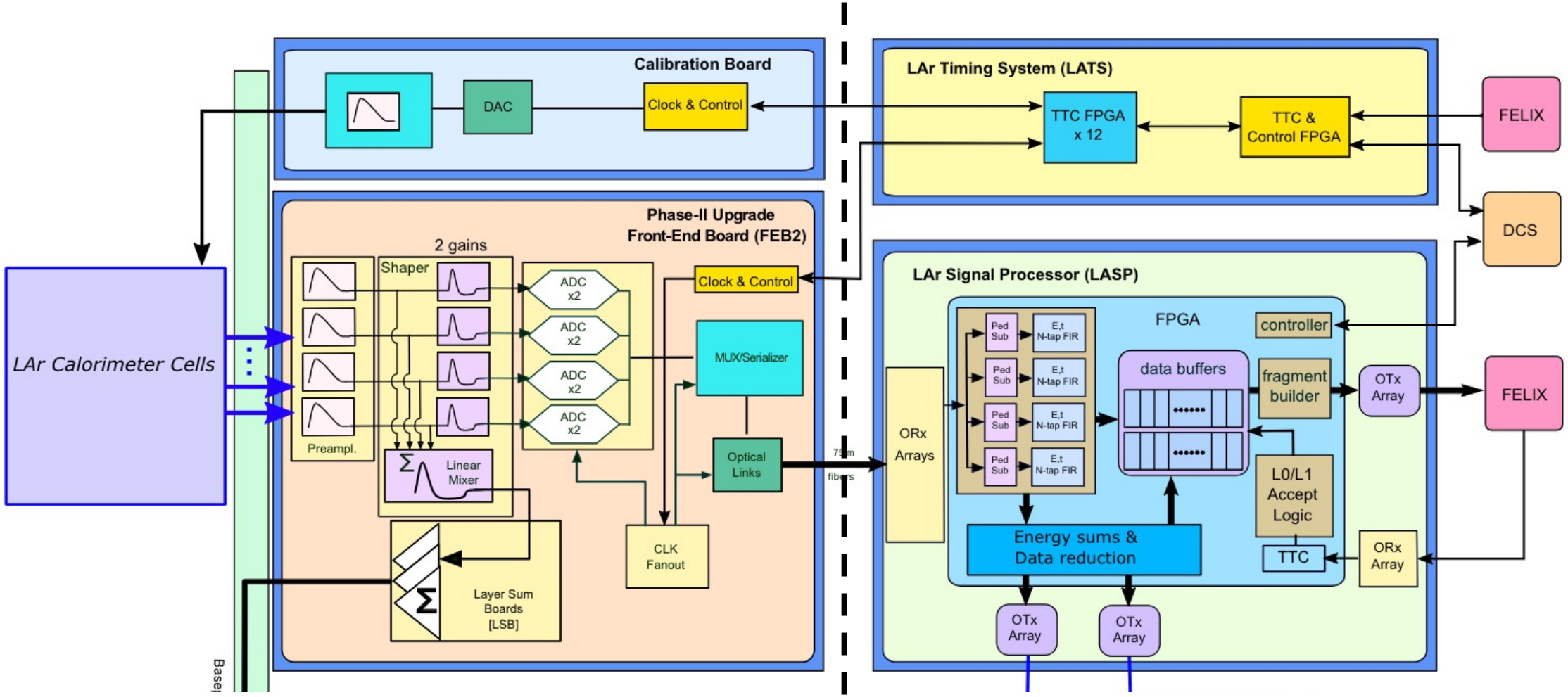
HL-LHC:

- Upgrade electronics currently in preparation, to be installed for use in Run 4
- Cover full range of energy expected in the HL-LHC, from ~ 50 MeV – 3 TeV
- Linearity of 0.1%
- Low electric noise, below intrinsic calorimeter resolution
- 11-bit precision at high energy
- All data sent off detector
  - ~180 Gbps per Front-End-Board
  - ~275 Tbps for the full calorimeter

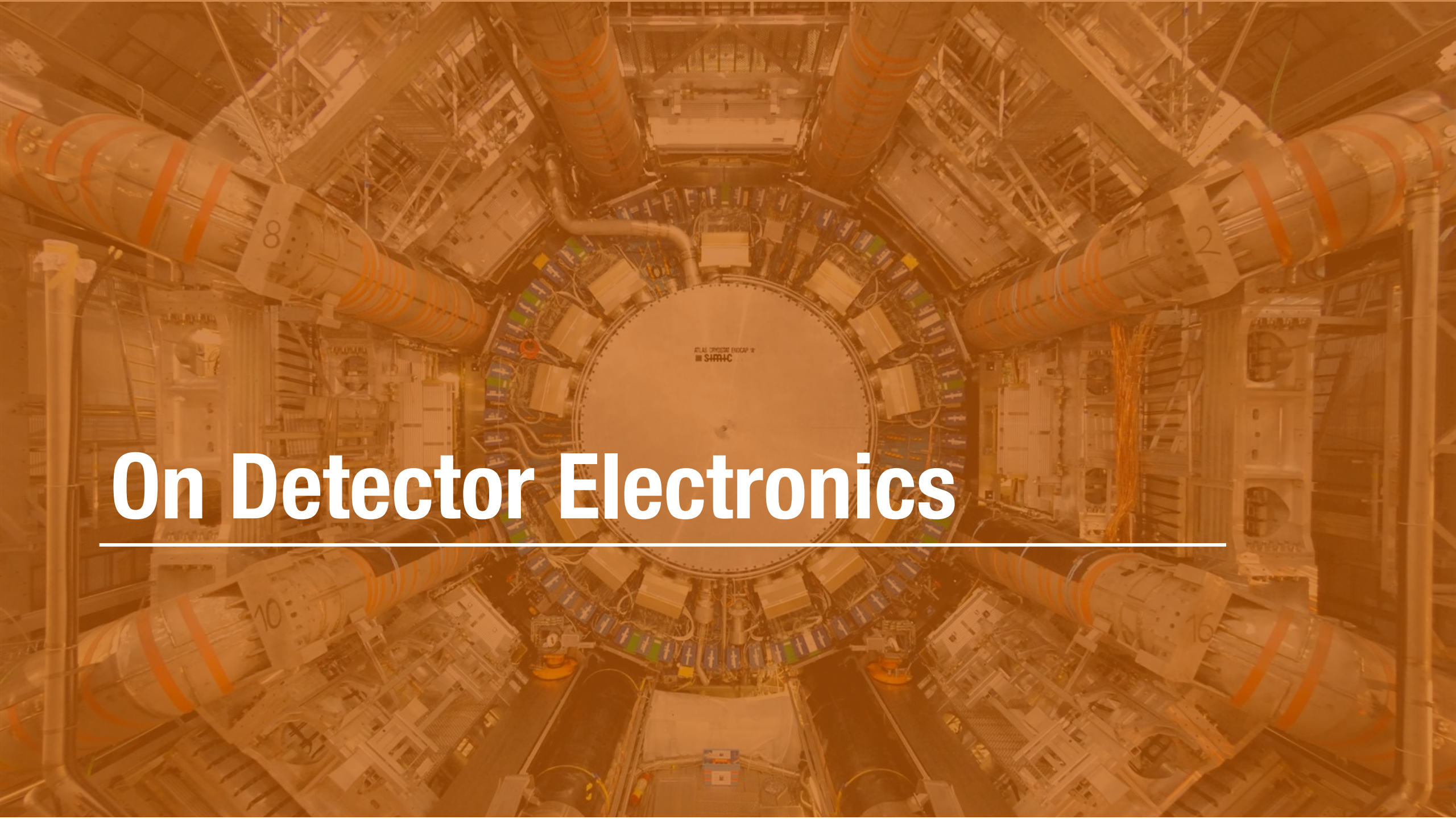
Phase-I:

- Updated L1 Trigger to have finer granularity
- Already Commissioned - used for Run 3

HL-LHC LAr Readout Electronics

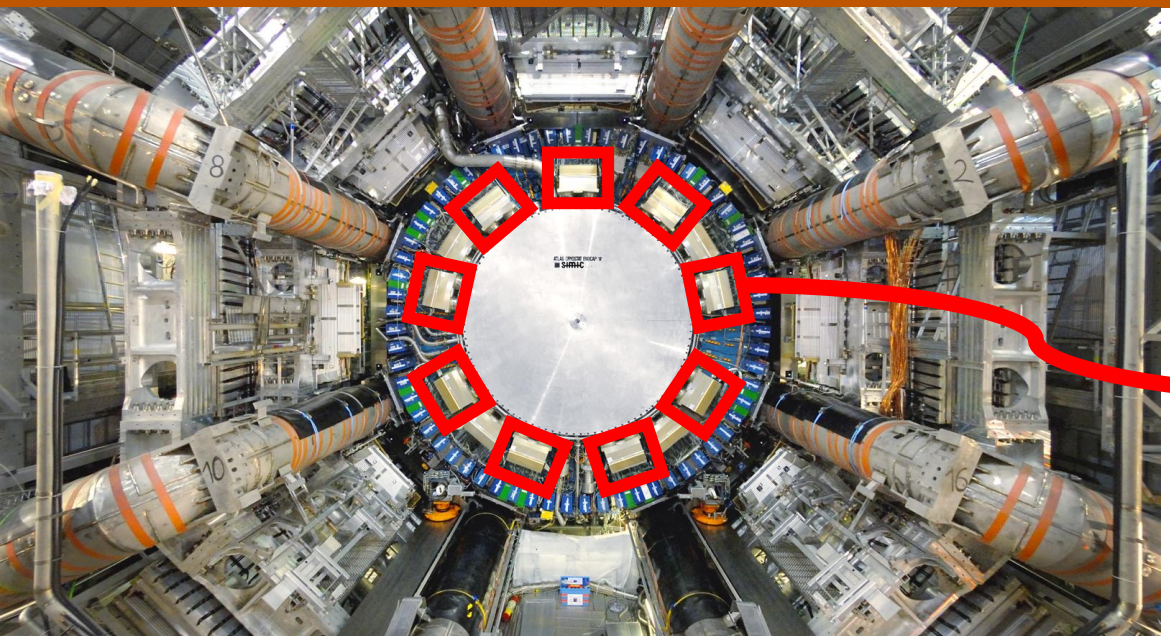


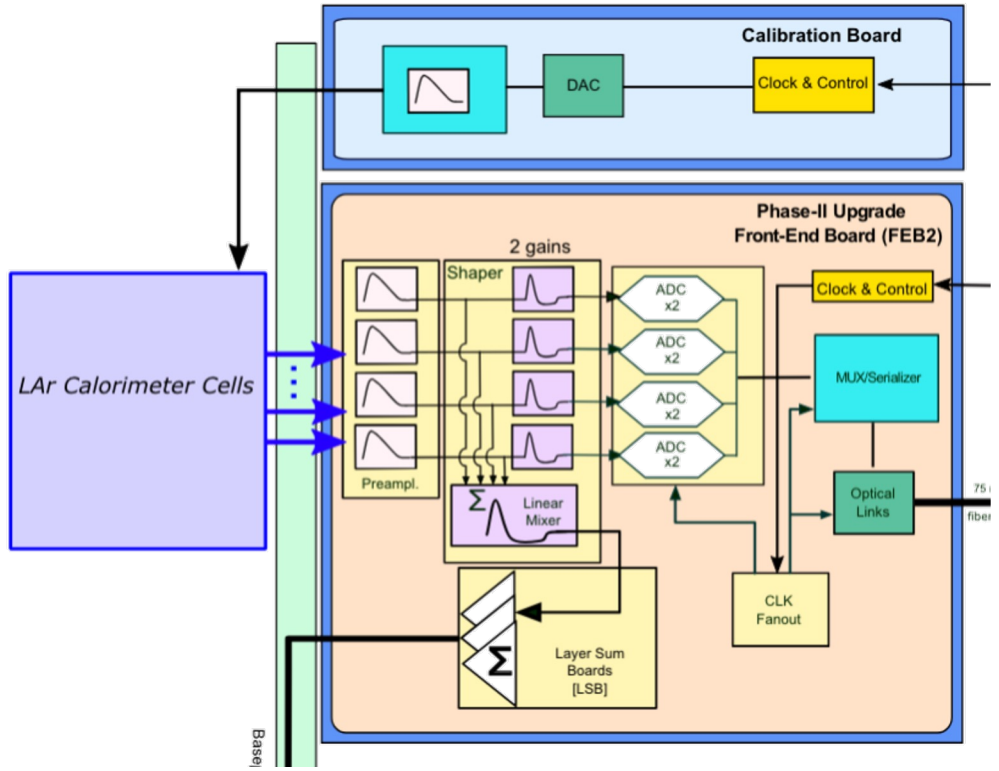
on-detector **off-detector**



On Detector Electronics

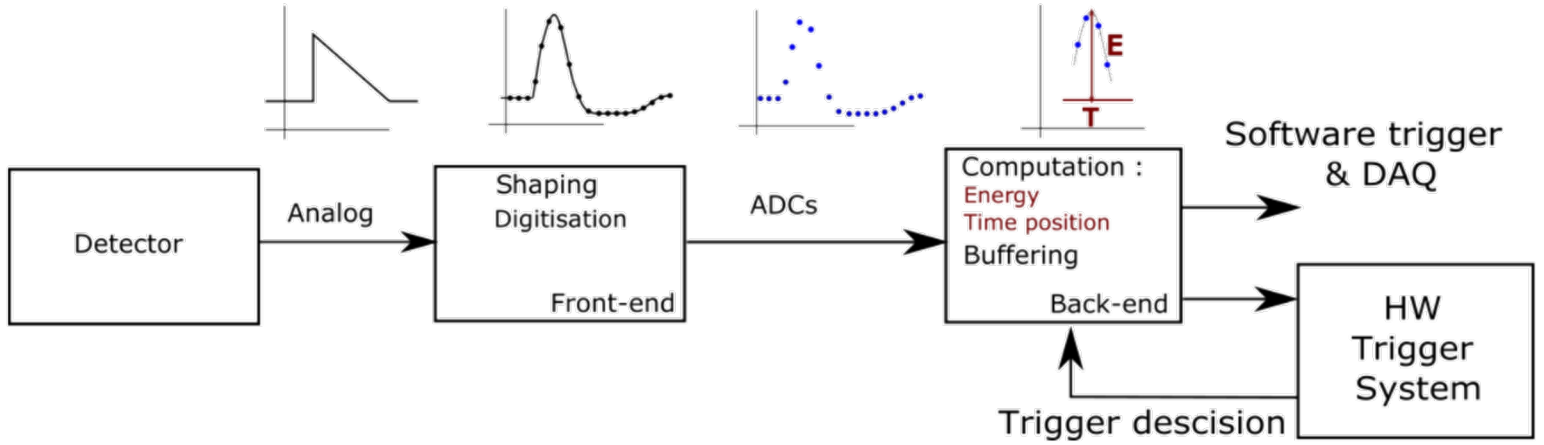
On Detector Electronics





The on detector electronics:

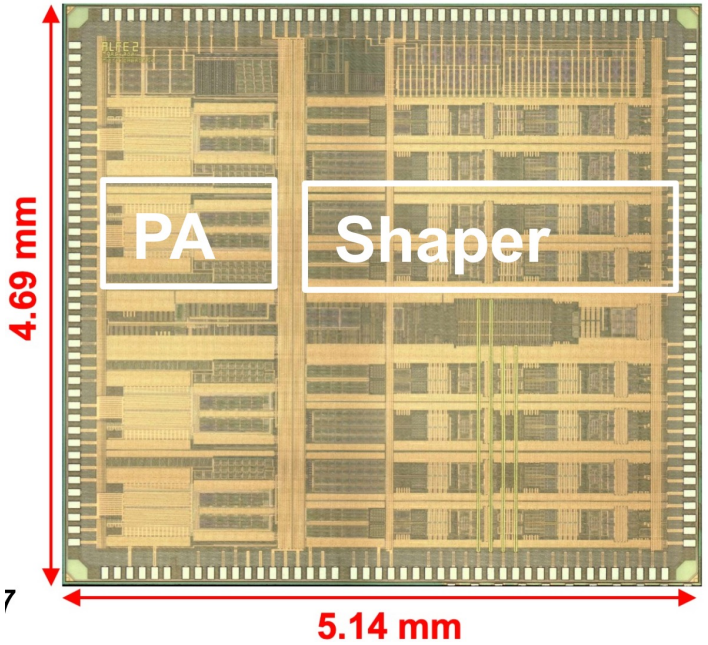
- take a signal from the calorimeter shape and amplify the signal
- sample and digitize the signal
- send the signal off through optical fibers



ALFE2 – Pre-Amplifier and Shaper

Initial analogue processing of the signal

- Custom ASIC designed in 130 nm CMOS
  - Amplification of signal, and bipolar CR-$(RC)^2$ shaping over high and low gain scales
  - 4 input channels and 9 output channels: 4 high gain and 4 low gains + 1 sum over the 4 channels sent to the hardware trigger
  - Input impedance and dynamic range programmability



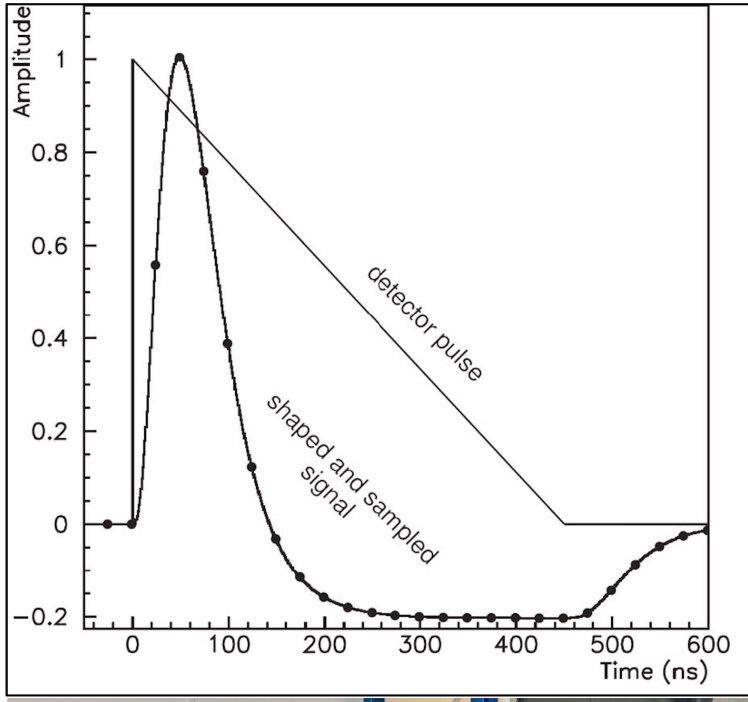
Testing Results:

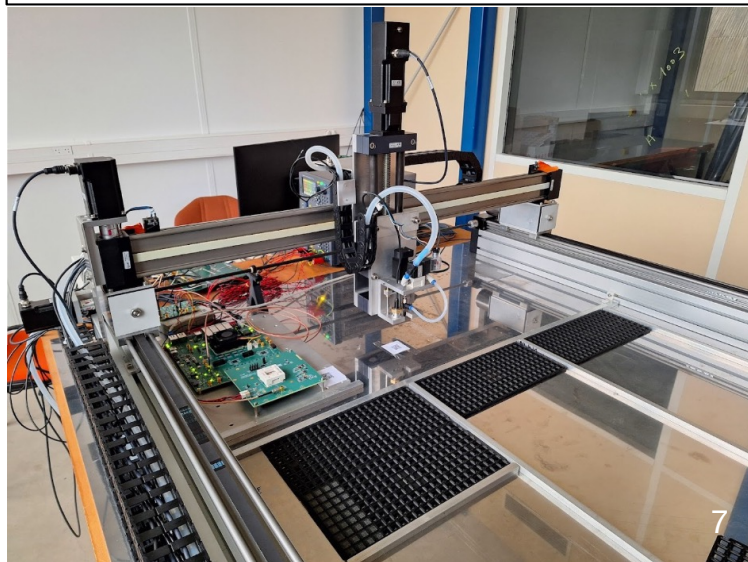
Exceeds specifications

- Non-linearity < 0.1%
- Noise ~150 nA, below specification of 350 nA for 10 mA channels
- Radiation testing showed good performance after 12 kGy dose, this is 8x higher than expected at the HL-LHC

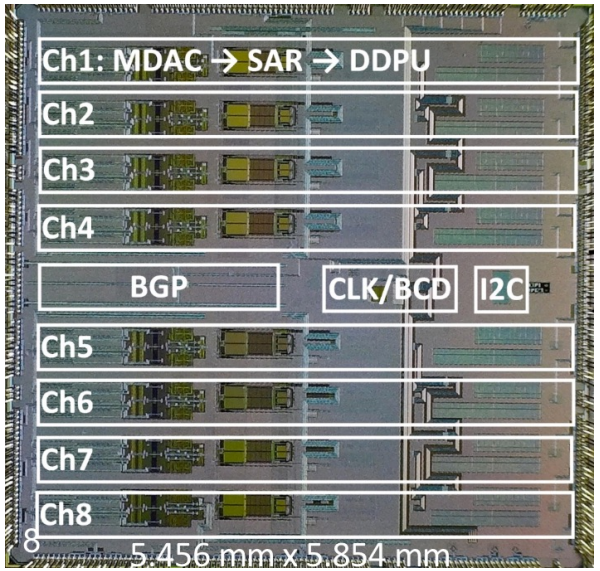
Current Status:

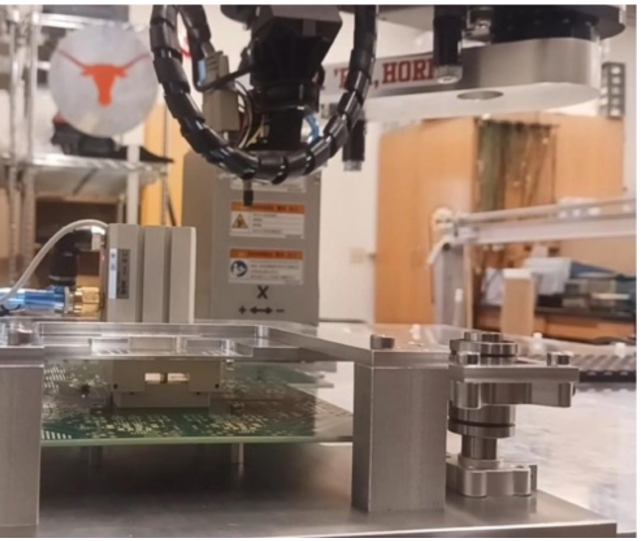
- Production wafers are ready (need ~80k ASICs)
- Begun quality control testing and integration



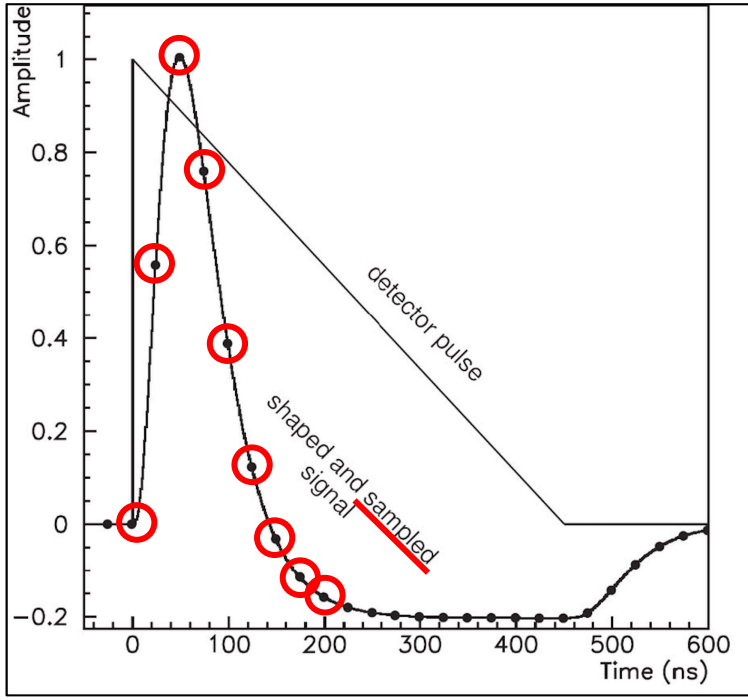


COLUTA- Analogue to Digital Converter





- **Digitizes the PreAmp/Shaper output** at bunch crossing rate of 40 MHz with a 14-bit dynamic range and > 11-bit precision
- 15-bit, 40 MHz ADC
  - Custom ADC ASIC designed in 65 nm CMOS
  - 8 channels – matches ALFE output, 4 channels x 2 gains
  - 3-bit Multiplying DAC (**MDAC**) + 12-bit Successive Approximation Register (**SAR)**
  - Digital Data Processing Unit (**DDPU**) applies calibrations and transmits data (15 bits of ADC + 1 overflow) at 640 Mbps
  - **Fully compatible** with PA/S,
  - eLink interface to lpGBT (optical transmission off-detector)



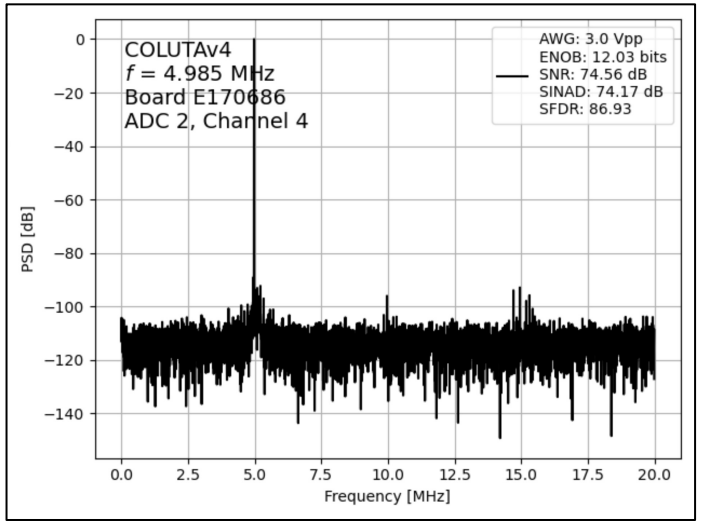
Testing Results:

Exceeds specifications

- ENOB > 12
- Radiation Tested TID up to 1 MRad, SEU performance excellent

Current Status:

- Production wafers are ready (need ~80k ASICs)
- Begun quality control testing and integration

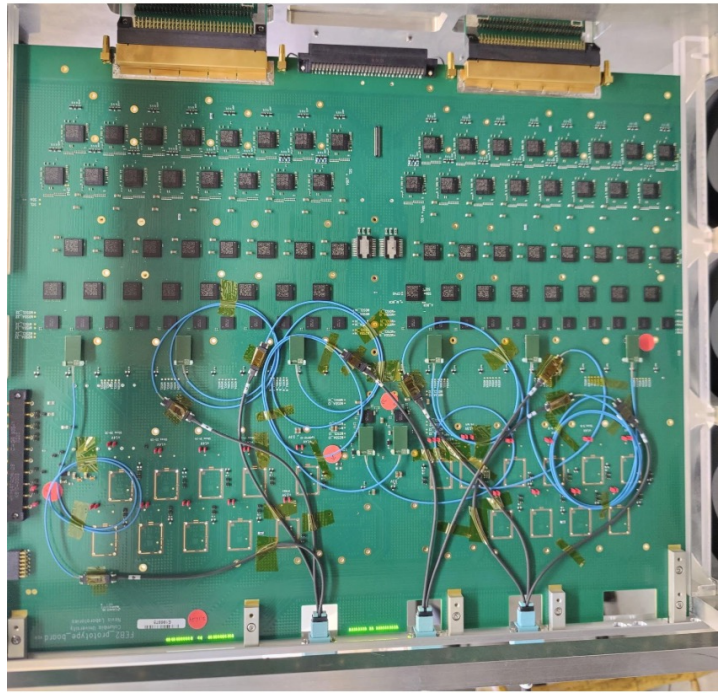


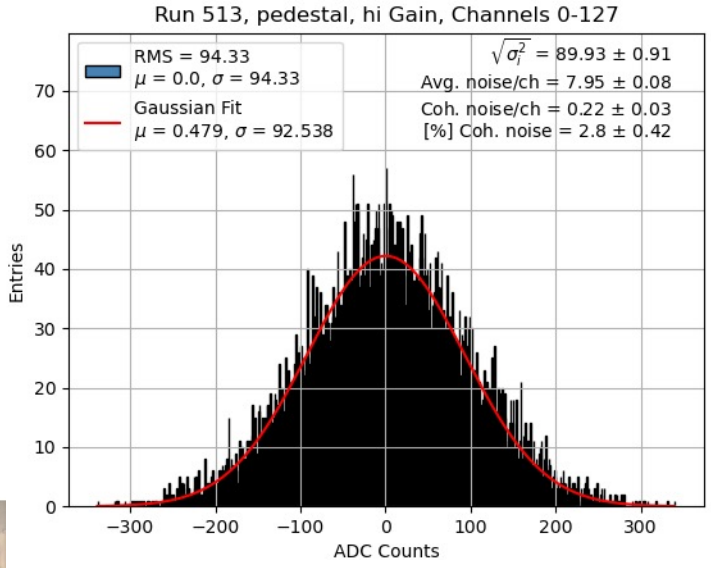
FEB2 Development

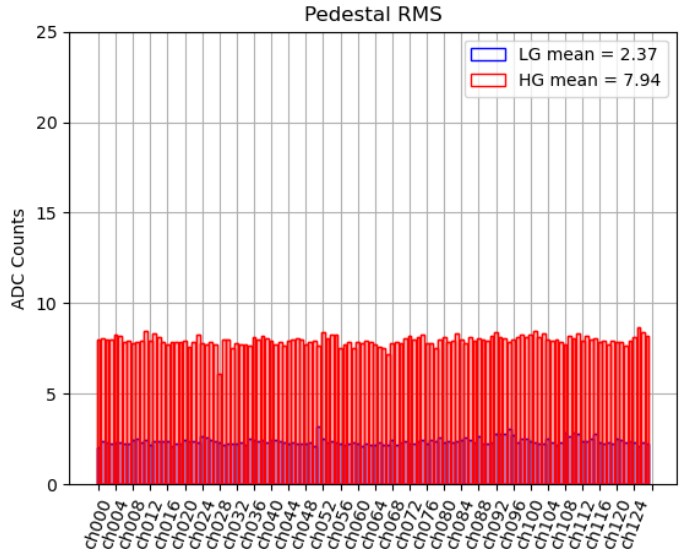
The Front End Boards (FEB2s) receive signals from calorimeter cells and perform analogue processing

- The FEB2 will be on the detector, must be entirely radiation hard, composed of two custom ASICs and optical readouts, all actively cooled
- Signals are digitized, serialized and transmitted off-detector via lpGBT protocol
  - 1524 FEB2s with up to 128 channels each
  - 32 ALFE Preamp/shapers, 32 COLUTA ADCs, and 22 lpGBT serializers

- **First full-size prototype** (with all 128 channels populated) is ready, and is currently being tested
- In particular, tests for radiation-hard powering solutions are in progress
  - Tested various solutions for on-board stepping down 48 V power supply to the voltages needed by the ASICs with the help of mezzanines

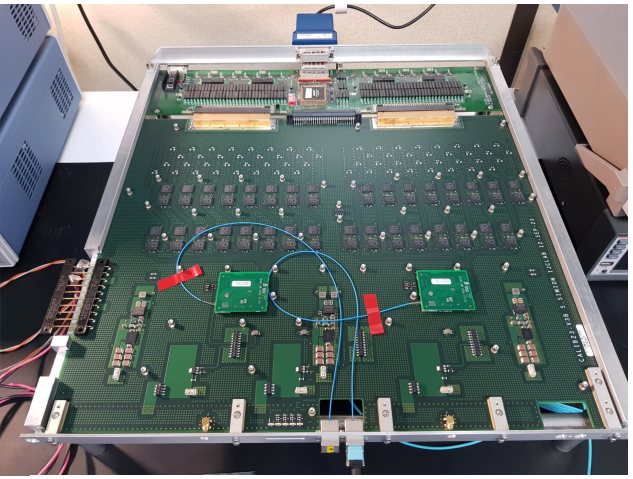


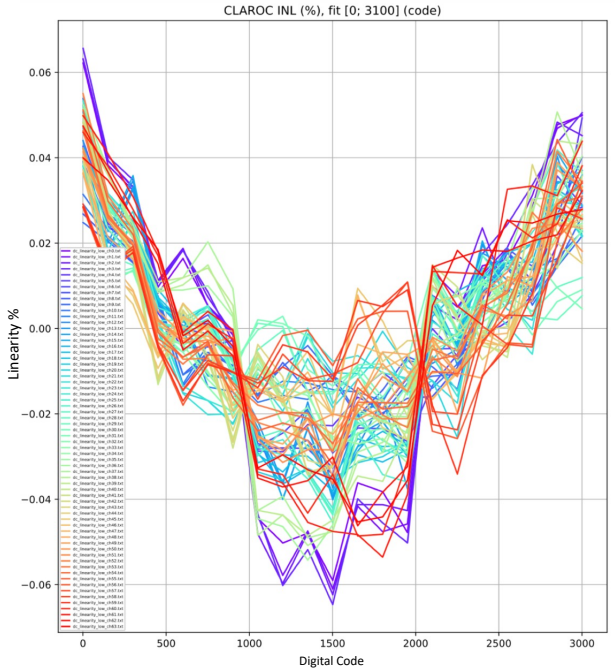




Calibration Board

CABANE Board

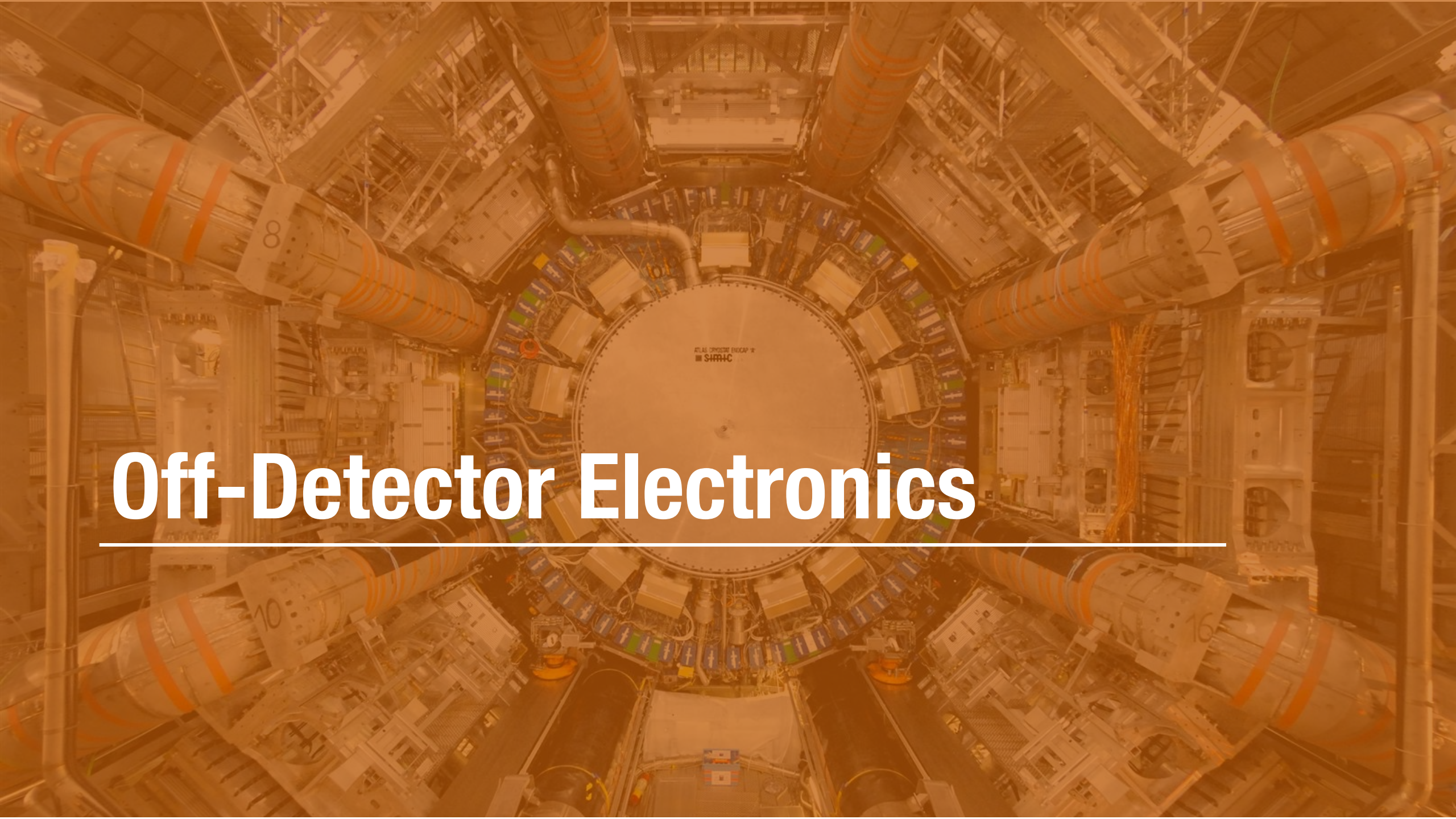




Sends a known LAr-like signal to the electrodes to calibrate the read-out electronics

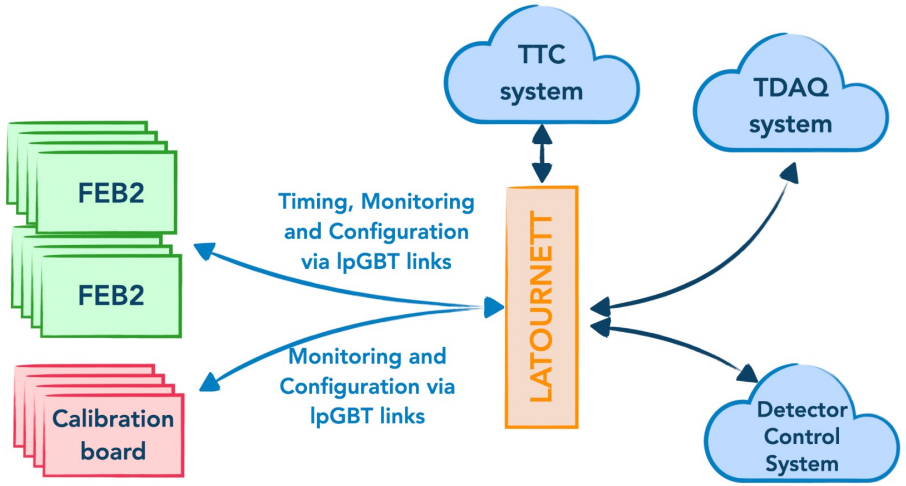
- Full 16-bit dynamic range
- 122 boards installed in the front ends crates, 150 to be fabricated and assembled

- Composed of two custom ASICs
  - CLAROC
    - creates pulse using high frequency (HF) switches, based on 180 nm HV-CMOS
  - LADOC
    - 16-bit DAC, used to send commands to the HF switches, based on 130 nm CMOS
  - Both ASICs are conducting final pre-production tests to validate production routine (QC testing)
- **Both ASICs exceed linearity requirements**
- Construction of the **CABANE**, a full-scale test board, has been completed and will be followed by future iterations



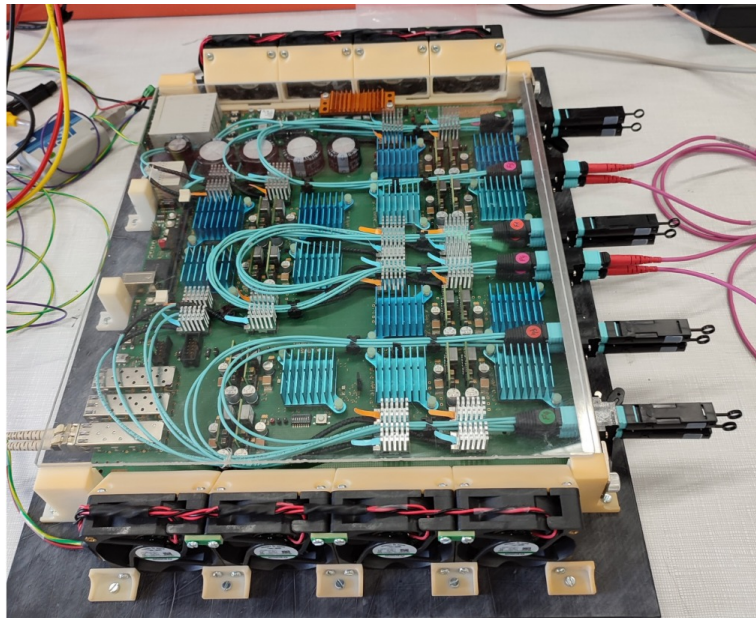
Off-Detector Electronics

LAr Timing System (LATS)



- The LAr timing system (LATS) handles Trigger, Timing and Control (TTC) distribution, configuration, and monitoring of the FEB2 and Calibration boards, relying on lpGBT protocol
- 30 LATOURNETT ATCA Blades
  - Each equipped with 1 central + 12 array Cyclone 10 GX FPGAs
  - Each can control up to 72 on-detector boards

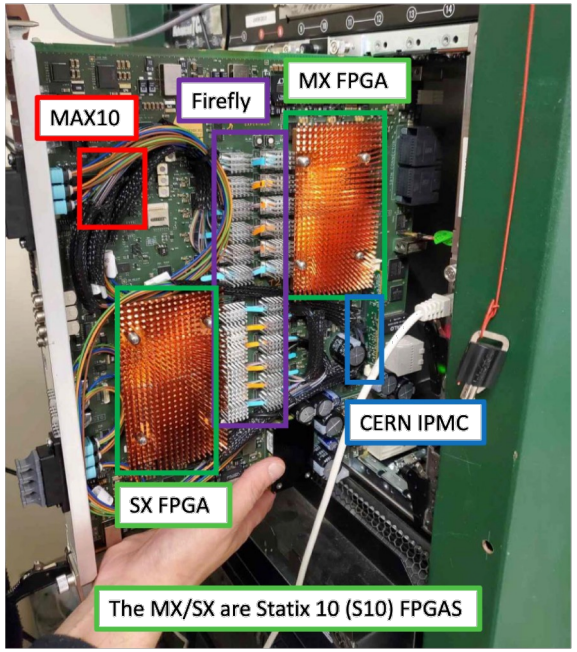
- Completed test board design and prepared test bench
- First full prototype cabled, and passed initial electrical tests
- Proposed architecture for integration with ATLAS TTC and DAQ systems
- First integration tests with FEB2 and Calibration board ongoing
- Software and firmware development ongoing



LATOURNETT

LAr Signal Processor (LASP)

LASP test board

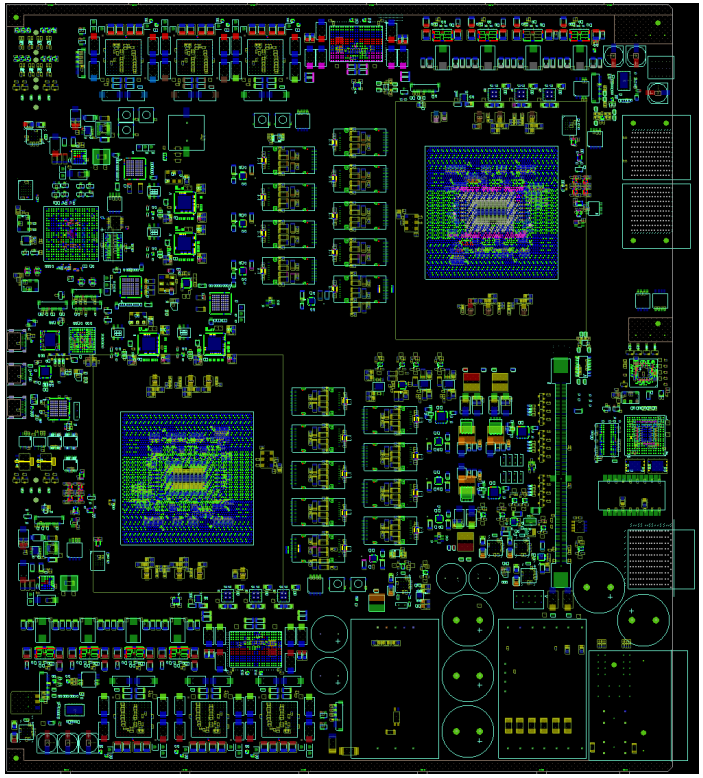


The LAr signal processor (LASP) applies digital filtering to waveforms from the FEB2, calculates energy and time, and transmits to DAQ systems

- Composed of the LASP ATCA board (main blade) and the Smart Rear Transition Module (sRTM)
- Main Blade
  - Receives data from up to 6 FEB2s (768 channels) using lpGBT protocol at 10.24 Gbps
  - Computes energy and time in real time
  - Sends output to the trigger system at 25 Gbps
  - Data is buffered at least 10μs until a trigger decision is reached
  - Implemented using two Intel Agilex FPGAs per blade
- sRTM
  - Used for data transmission with TTC and DCS integration

Development

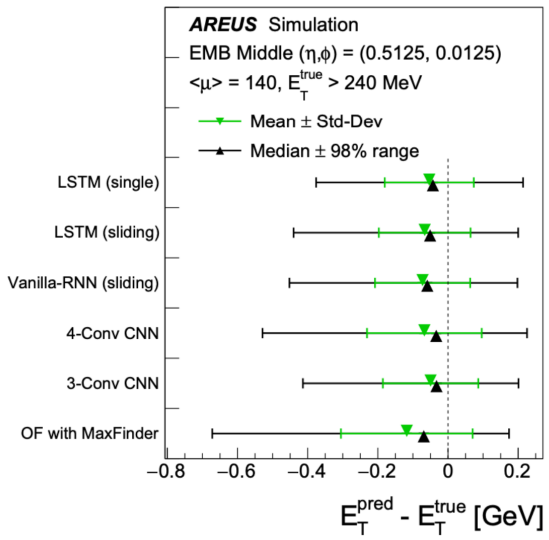
- Prototype LASP + sRTM in development
- A first set of test boards are produced, and are continuously running in test bench
- Regular monitoring of temperature, voltage and current in place
- Validated power, I2C sensors, and FPGA configuration
- Work ongoing on the firmware, including transitioning from the Stratix FPGA to the Agilex FPGAs, and aiming to optimize FPGA resource usage and power consumption
- Long series of tests in stand-alone and within the full system are foreseen

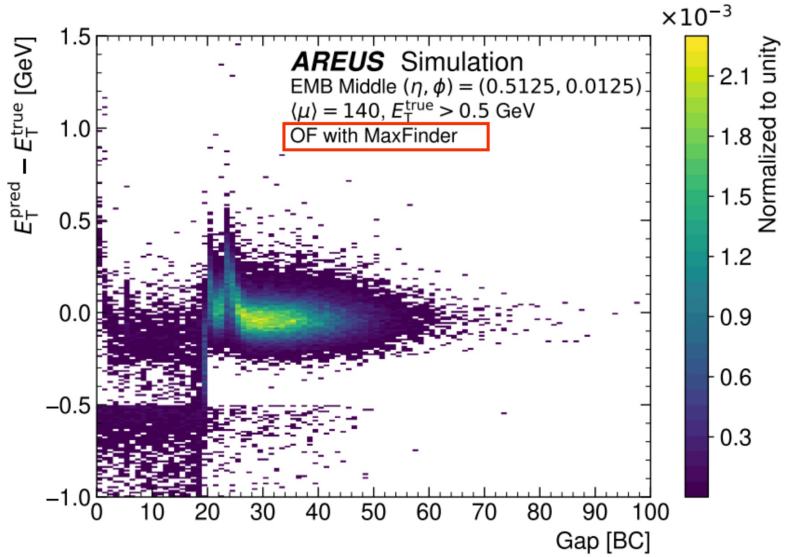


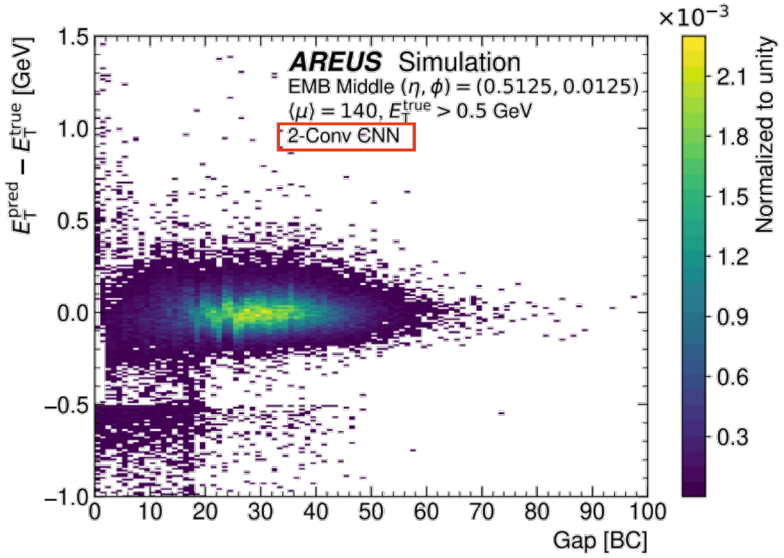
LASP Prototype Design

LASP- FPGA and Machine Learning

- Current signal processing uses Optimal Filtering (OF), modern machine learning techniques may allow us to improve energy and timing calculations in a high pileup environment
- Convolutional and Recurrent Neural Networks (CNN and RNN) are being investigated and show good performance



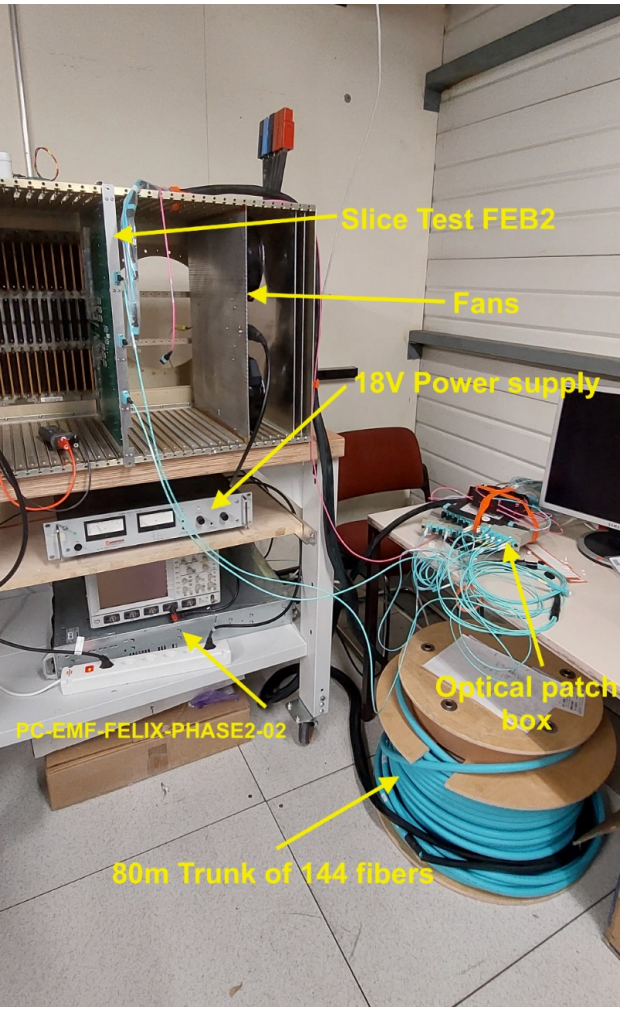




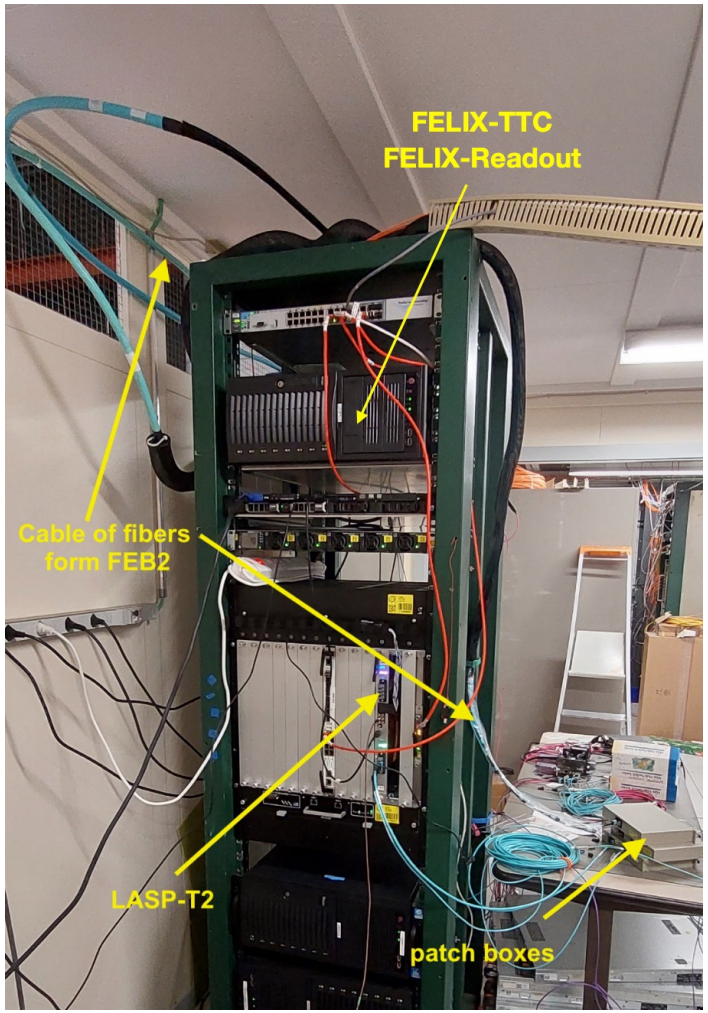
- Understanding trade-off between performance and optimizing FPGA resource usage and power consumption
- Firmware prototype implementations are available for both CNNs and RNNs and fit on one FPGA

Integration at CERN

On-detector



Off-detector

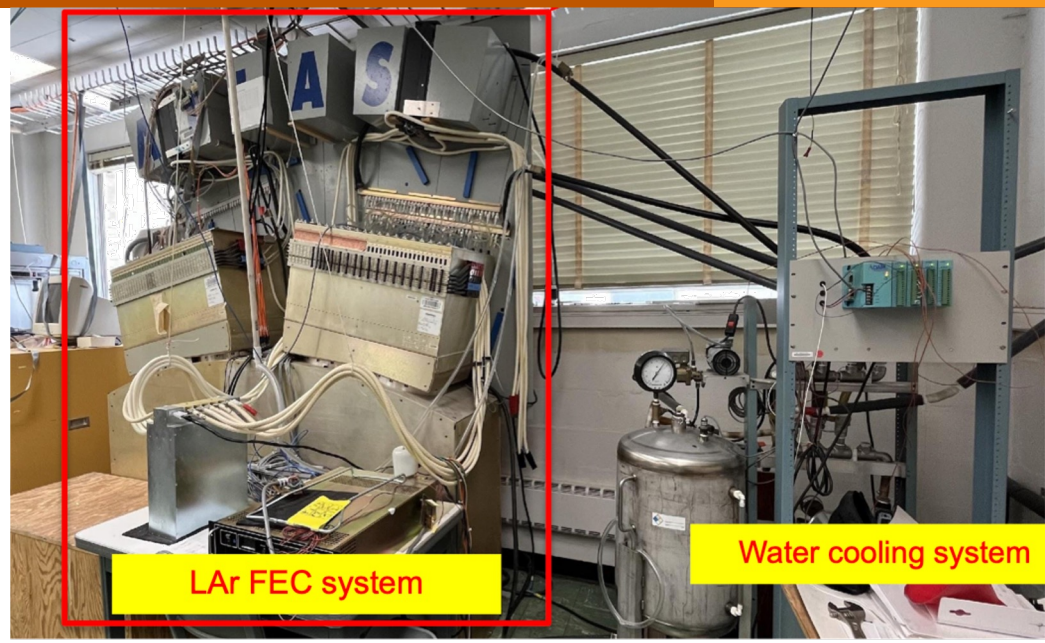


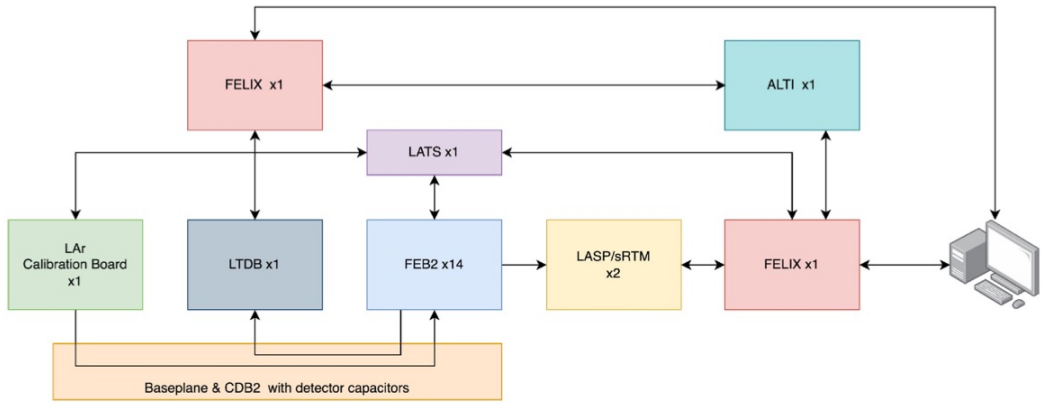
Currently, primary integration tests of FEB2 and LASP + SRTM are underway at CERN

- Constructed a **small scale readout chain** for integration testing
  - 32 channel on and off detector setup with DAQ and TTC from current ATLAS systems
- **Software** effort for online and offline software including reconstruction, monitoring, and analysis is underway

Integration at BNL

- Use BNL's high-fidelity reproduction of the mechanical and electrical properties of the LAr calorimeter
  - Detector cables/feedthrough
  - Power supplies
  - Front-End crates with baseplane
  - Water cooling system
- Measure coherent noise in a realistic setup
- **Half-crate test**: using 14 FEB2 (half a crate), simultaneously readout
  - Integrate FEB2, calibration board and off-detector LASP readout system
  - Testbed for firmware development





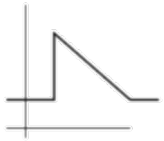
Block diagram of FEB2 FEC test

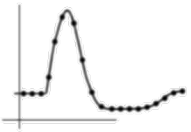
Summary

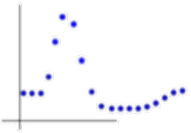
- Upgrading the LAr calorimeter electronics system is **vital** to the success of ATLAS in the HL-LHC
- The **radiation-hard** custom ASICs used on the detector **exceed specification** requirements and are in production
- Final designs for the off-detector boards and firmware are underway
- Integration setups are being constructed for testing the full calibration to readout chain
- **On schedule** for installation into ATLAS cavern beginning in **2027**
  - Designed to run through **2041**

THANK YOU

Front End Board 2 (FEB2)





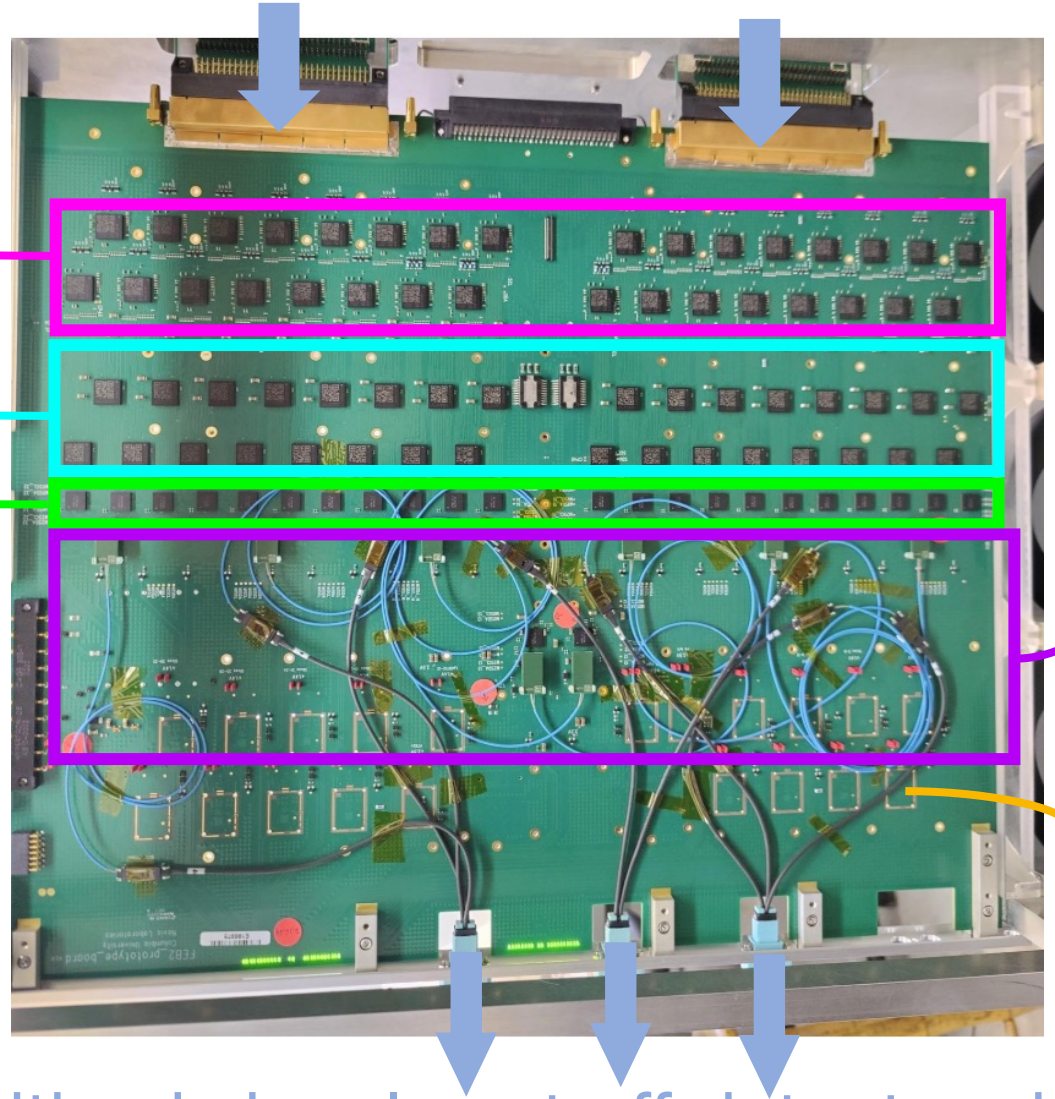


Signal from LAr Calorimeter Cells

ALFE Pre/Amp shaper

COLUTA ADC

lpGBT – used to serialize the data



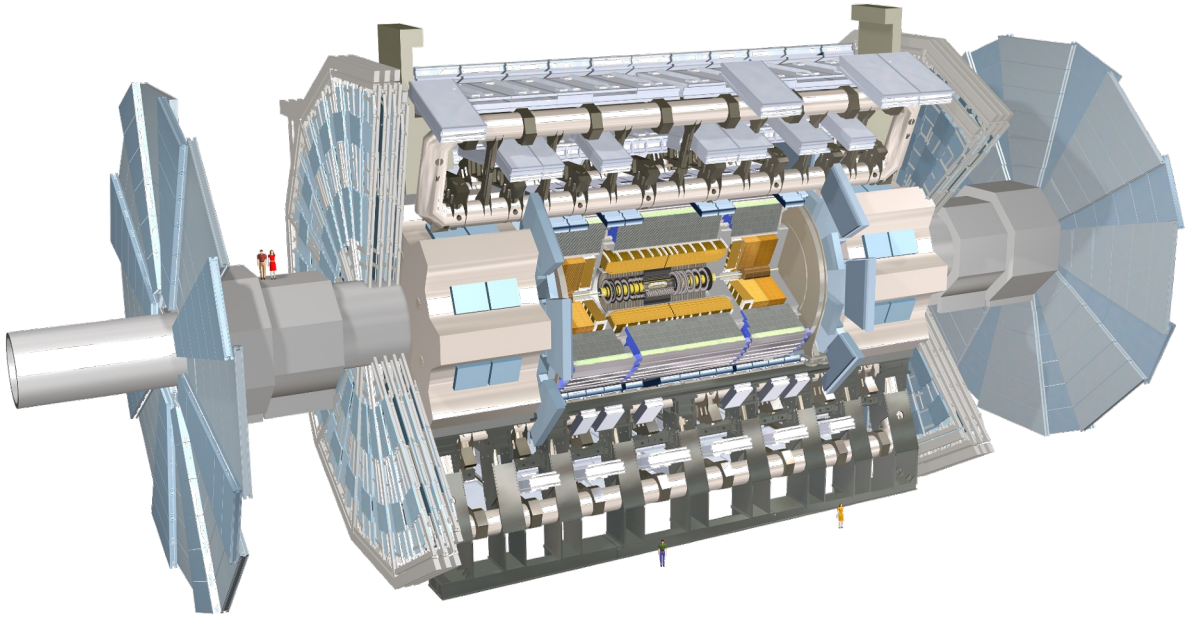
VTRx+ and Fiber optic cables

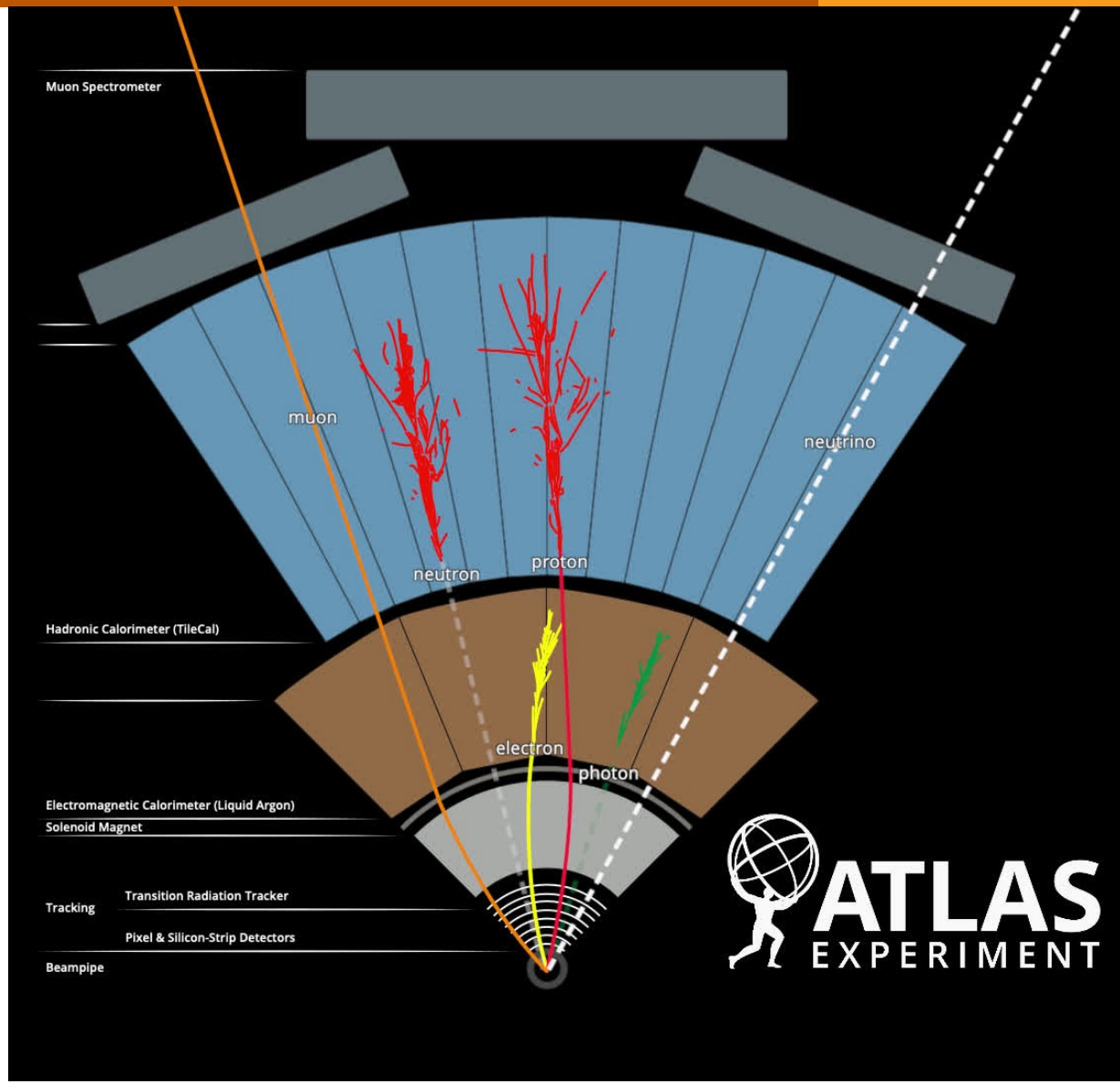
Location for power mezzanines

Digitized signal sent off detector via optical links

ATLAS Experiment

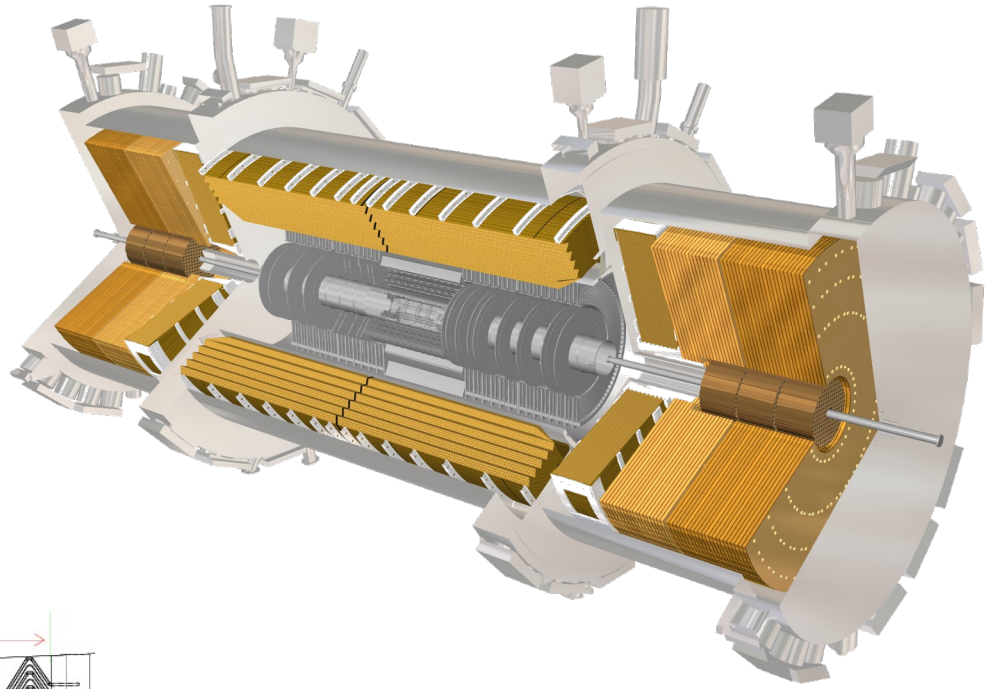
- ATLAS is an mutli-purpose detector
  - Designed to measure a wide range of particles
  - Formed of concentric layers of different subdetectors, each with a unique goal

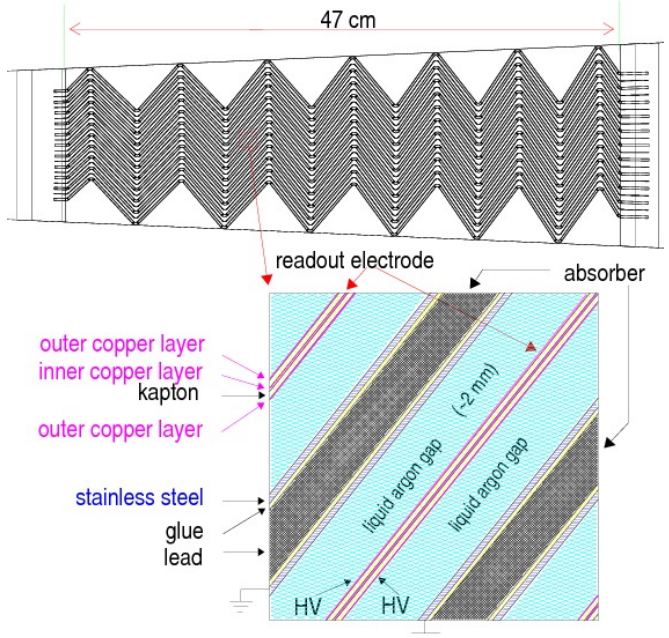




Liquid Argon Calorimeter (LAr)

- Sampling calorimeter with **liquid argon** as the active medium, and lead, copper, and tungsten as the passive material
- Measures energy, position, and timing of **electromatic showers** and hadronic jets
- Accordion geometry allows for full azimuthal coverage
- **182,468 cells** are read off at a rate of **40 MHz** (bunch crossing rate) and sent off the detector or analysis



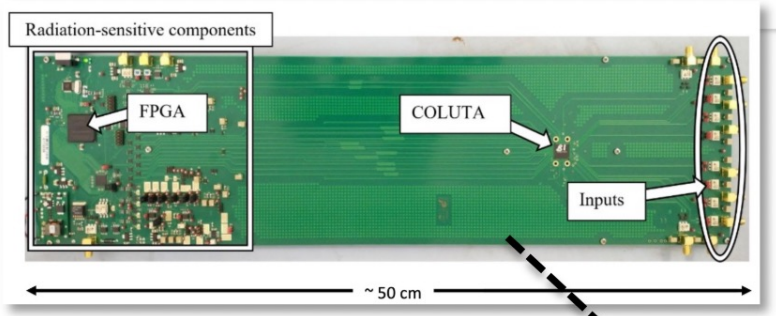


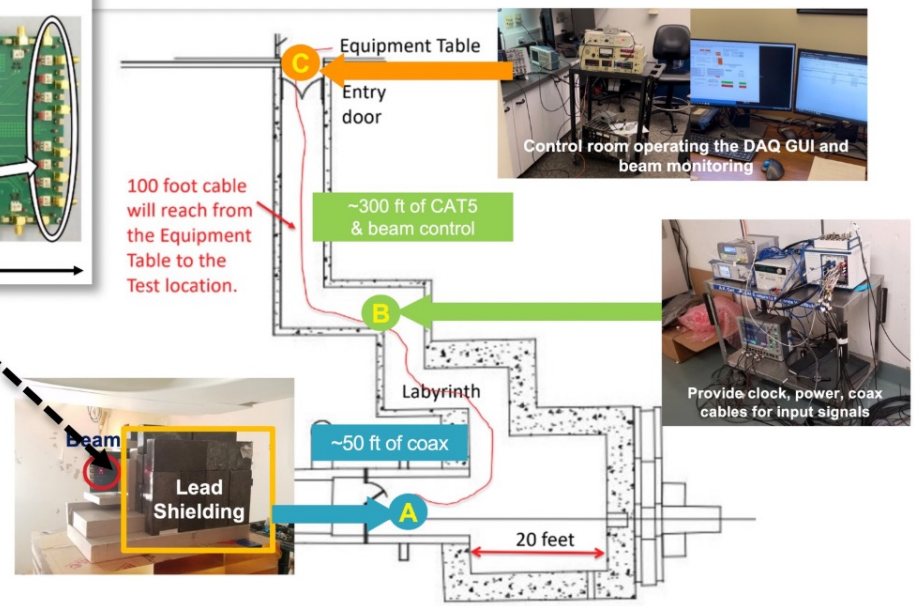
- Calorimeter Electronics will be upgraded, but the calorimeter itself will not
- Cryostat will not be open, performance continues to exceed expectations

Radiation Testing ASICs

FERMILAB Beam Facility


MGH Proton Therapy Beam Facility





	TID [Gy]	NIEL [n_{eq}/cm^2]	SEE [$h_{>20\,MeV}/cm^2$]
FEC (barrel)	1400 (1.5)	4.1×10^{13} (2)	1.0×10^{13} (3)
FEC (endcap)	210 (1.5)	6.0×10^{12} (2)	1.2×10^{12} (3)
LVPS between TileCal fingers (barrel)	430 (1.5)	1.1×10^{13} (2)	2.8×10^{12} (3)
HEC and FEC LVPS (endcap)	81 (1.5)	2.0×10^{12} (2)	4.1×10^{11} (3)
LVPS new position (barrel)	18 (1.5)	5.1×10^{11} (2)	1.1×10^{11} (3)
LVPS new position (endcap)	33 (1.5)	5.2×10^{11} (2)	8.6×10^{10} (3)

- All on-detector ASICs have been tested for radiation hardness
- Custom boards were designed to isolate the ASIC being tested

- COLUTA was tested at Massachusetts General hospital in Boston
  - SEE σ = 3.7 x10-10 cm2/bit
  - Expected 6140 SEE/channel over the lifetime of the HL-LHC
- ALFE was tested at BNL and Fermilab Test Beam Facility Irradiation Testing Area
  - SEE σ < 1.1x10-15 cm2/bit
  - Expected error rate for the full LAr Calorimeter in HL-LHC = 61 SEE bit errors/day.