Readout Electronics Upgrades of the ATLAS Liquid Argon Calorimeter

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on behalf of the ATLAS experiment

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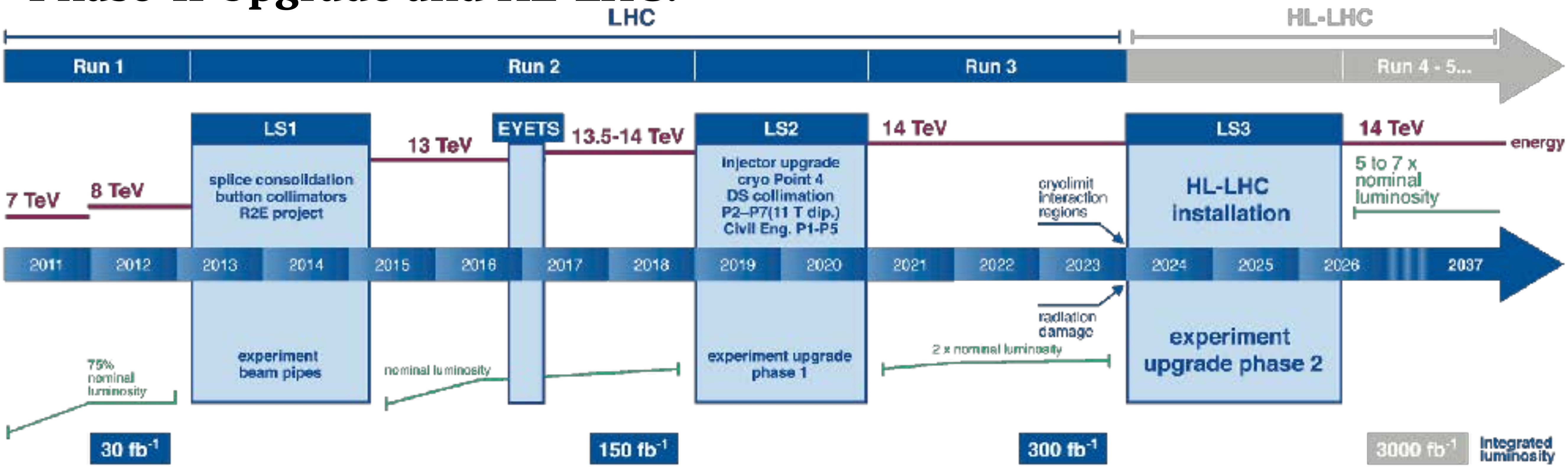
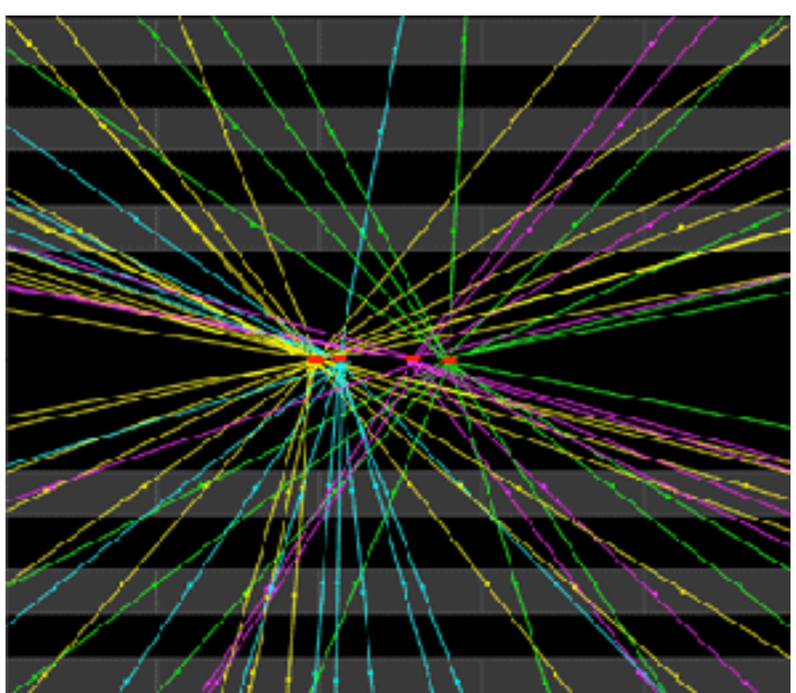
University of Victoria

High Luminosity LHC

Phase-II Upgrade and HL-LHC:



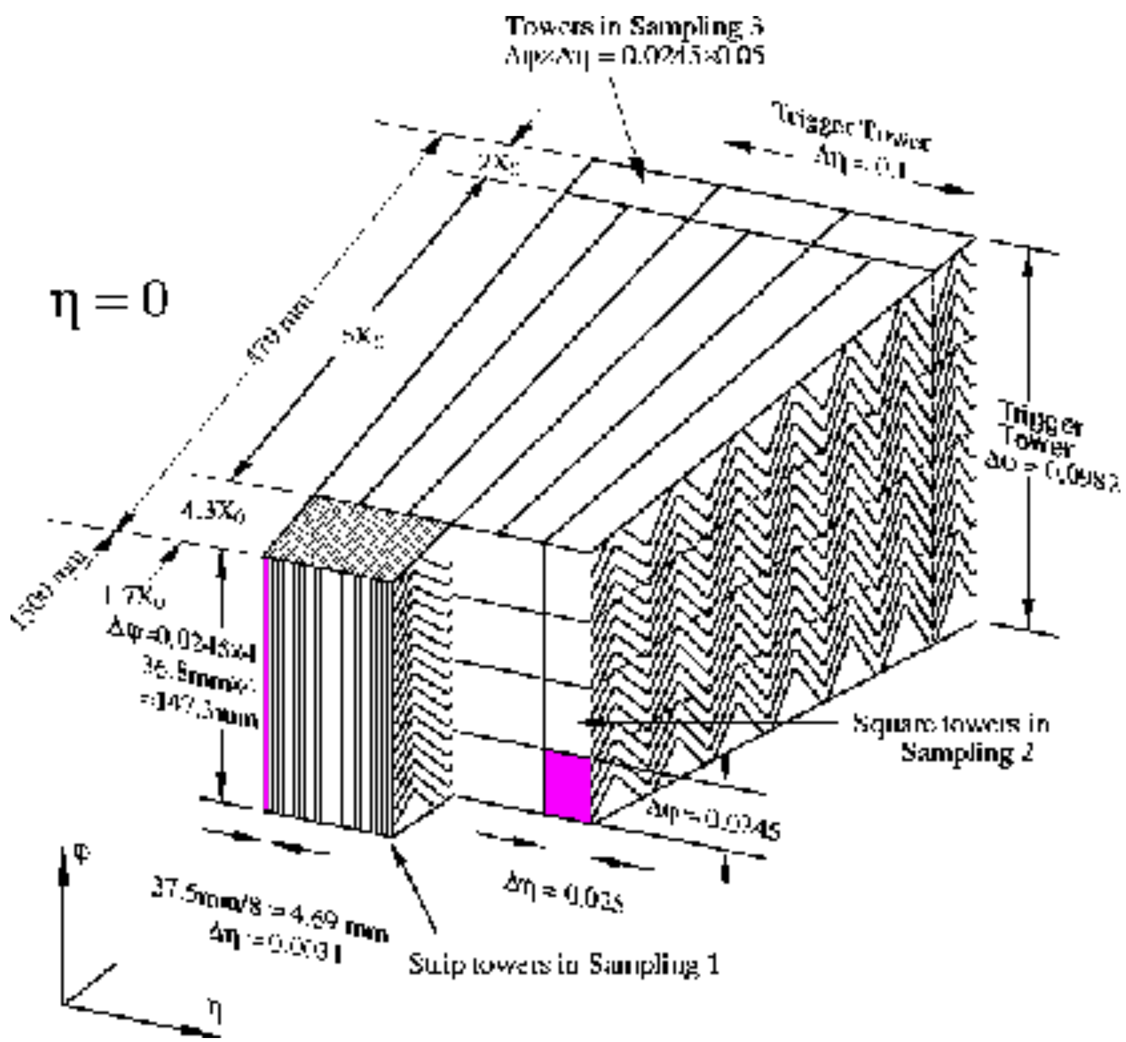


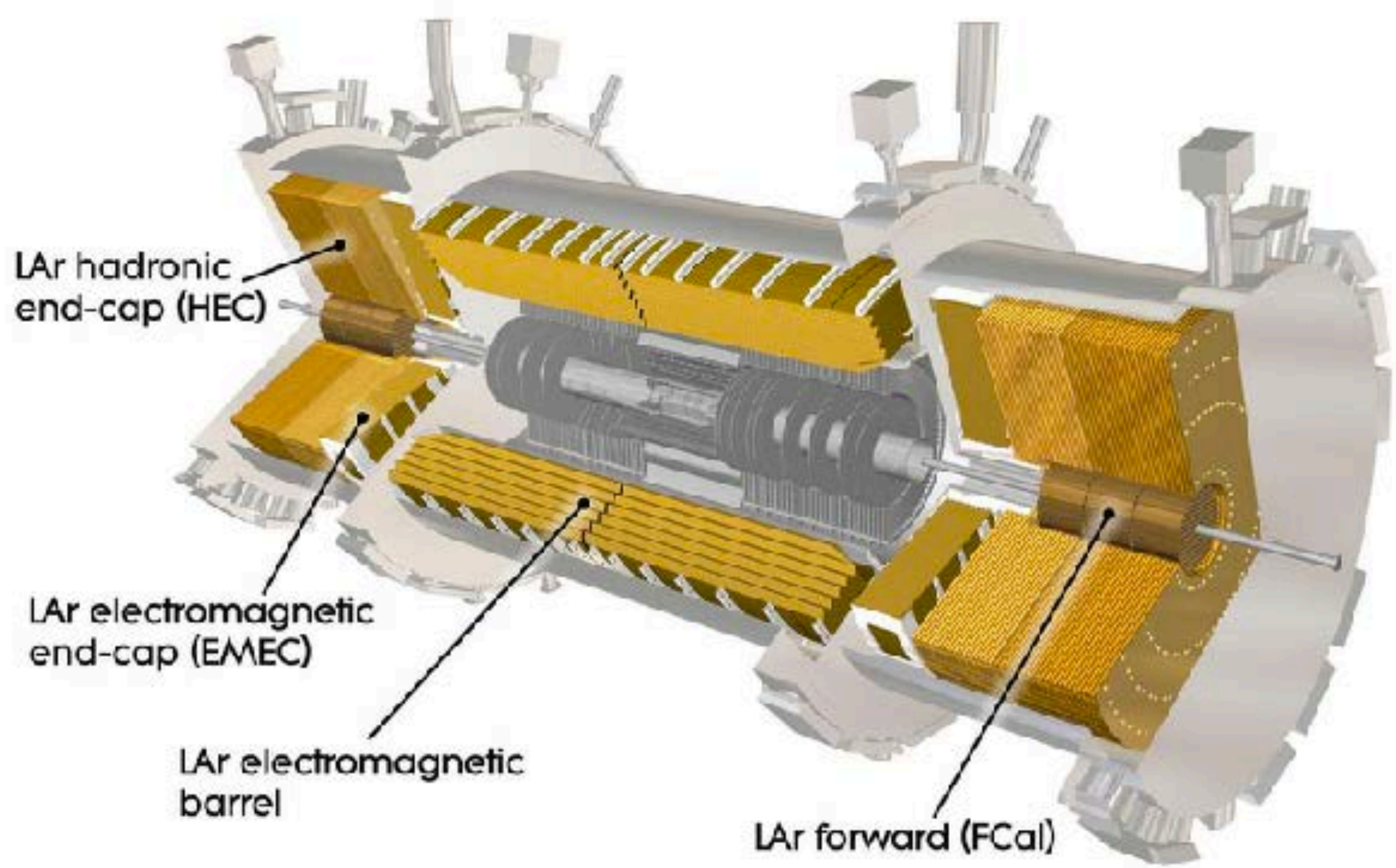
- $7.5 \cdot 10^{-34}$ $cm^{-2}s^{-1}$ peak luminosity.
- 25 ns bunch spacing (40 MHz)
- Expected integrated luminosity of 4000 fb^{-1} (over ~12 years)
- Up to 200 average minimum bias events per bunch crossing
- Increased radiation damage to detector

Liquid Argon Calorimeter

Sampling Calorimeters

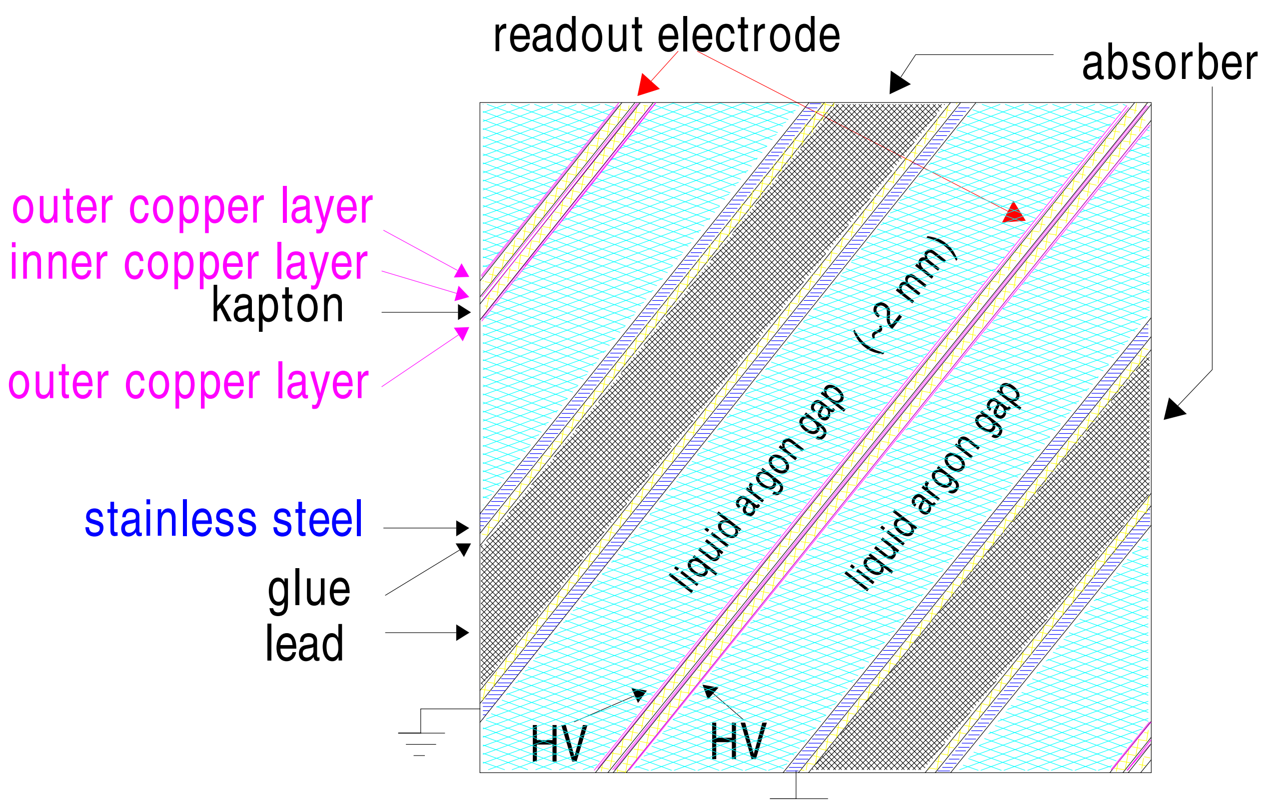
- **EMB**: LAr - Lead, $|\eta| < 1.475$
- **EMEC**: LAr - Lead, $1.375 < |\eta| < 3.2$
- **HEC**: LAr - Copper, $1.5 < |\eta| < 3.2$
- **FCAL**: LAr - Copper, $3.1 < |\eta| < 4.9$
  and LAr - Tungsten





- 182,500 channels.
- The layers of each module have different granularities.
- Largest fraction of energy deposited in middle layer. (EM Calo)
- Fine granularity used to reconstruct incident particle's direction.

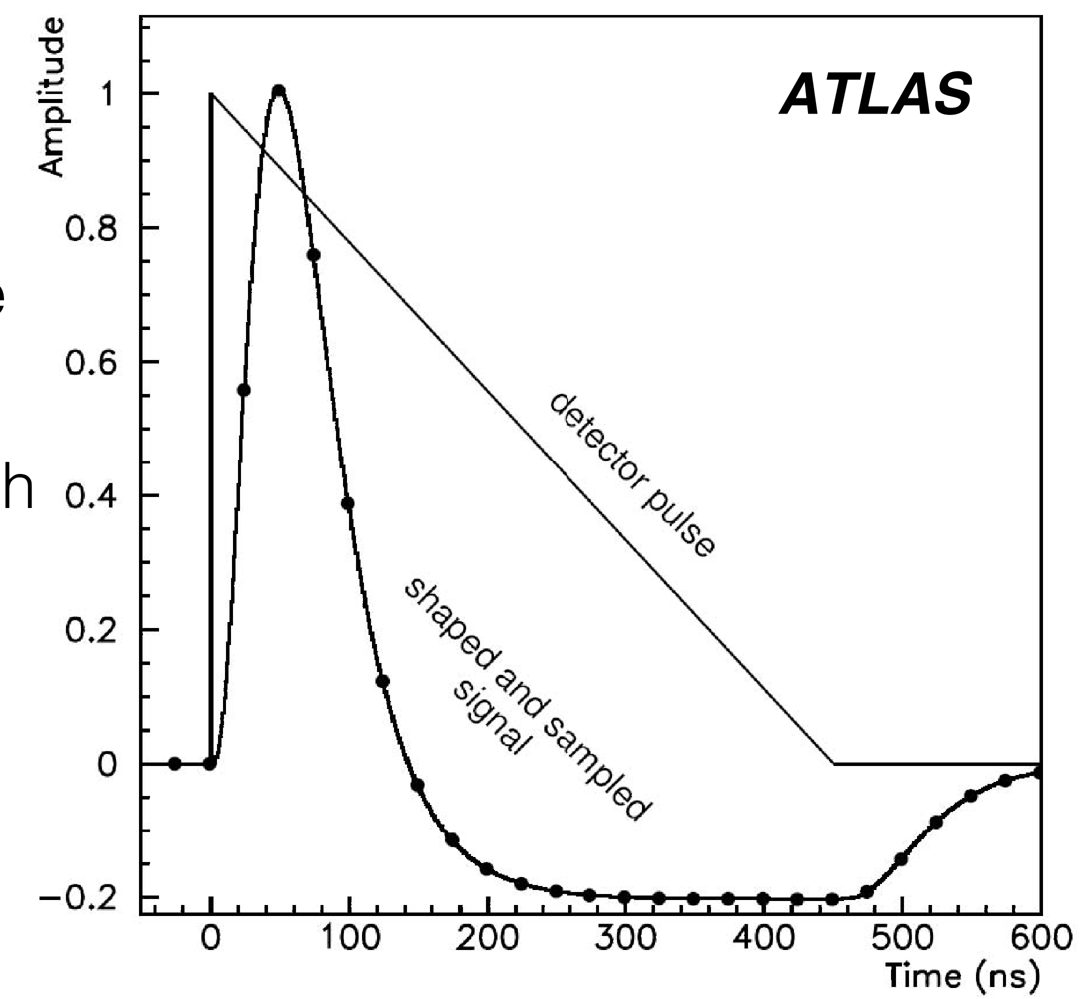
Pulse Shaping



- High energy particles shower in the calorimeter, ionizing the LAr.
- HV readout electrodes placed between grounded absorbers.
- Drift gap of 2.1 mm corresponding to electron drift time of 450 ns (for EM Calo)

- Drift electrons induce triangular pulse, amplitude proportional to deposited energy.
- Pulse passed through Bipolar CR -(RC)^2 filter, with programmable shaping time. (baseline 13 ns)
- 25 nano-second sampling.

For more details checkout the LAr Calorimeter Performance talk by Stefanie Morgenstern



Upgrade Motivation

Technical Motivations:

Preserving physics reach (ie Higgs) for higher data taking rates requires updated triggers:

- Current readout electronics are incompatible with new Trigger System. Upgraded triggers require higher trigger rate (1MHz), longer latency, and higher granularity calorimeter information.
- Existing front-end electronics will reach the limit of their radiation tolerance before the end of the HL-LHC.

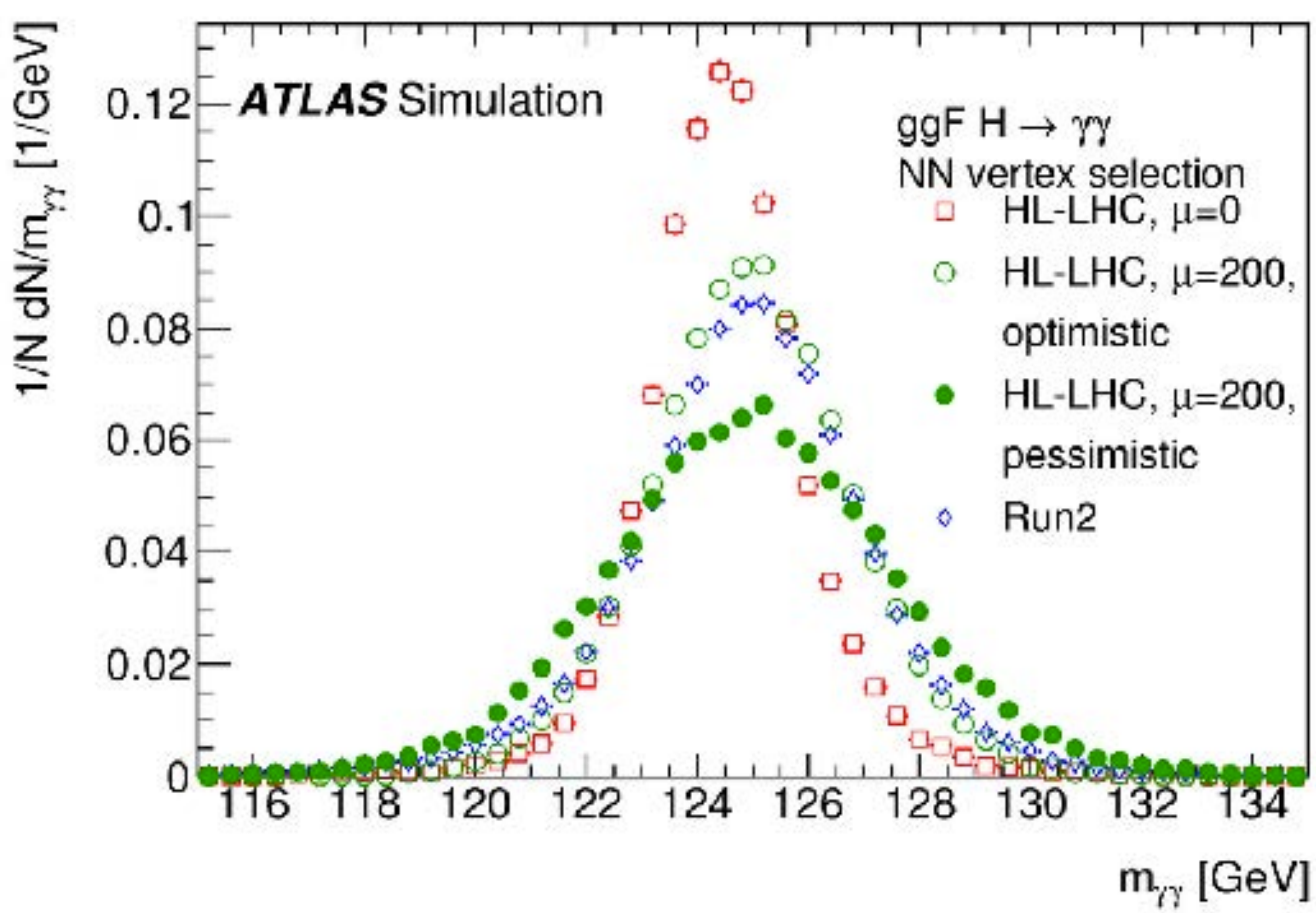
Performance Example:

Simulation shows upgraded ATLAS detector can maintain sensitivity to golden, H-> γγ channel.

Optimistic scenario: increased statistics reduce global constant term to design value, 0.7%.

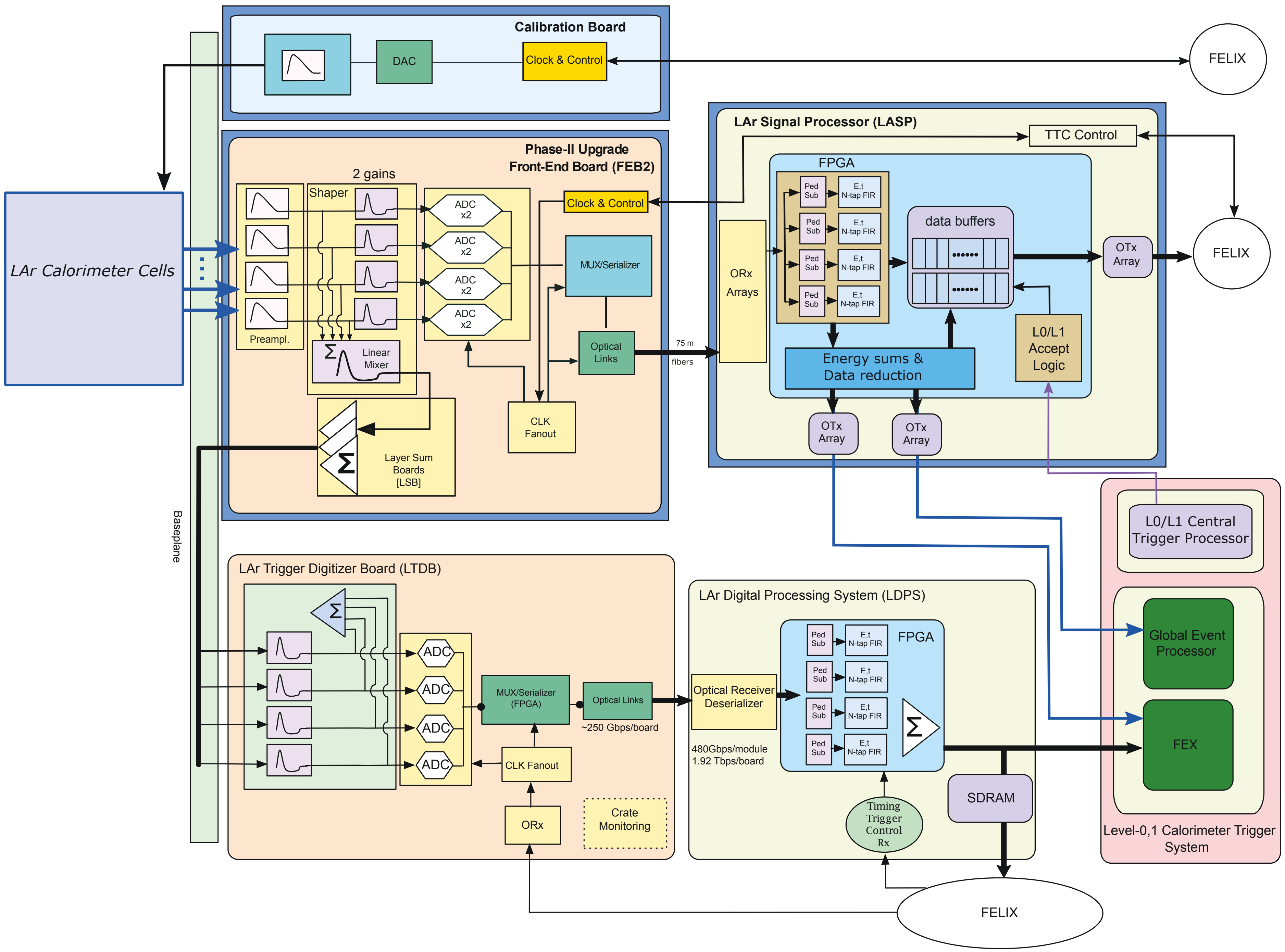
Pessimistic scenario: term remains same as 2015, 1% barrel and 1.4% endcap .

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$



Phase-II Readout Electronics

Existing readout electronics will be completely replaced:



Front-End

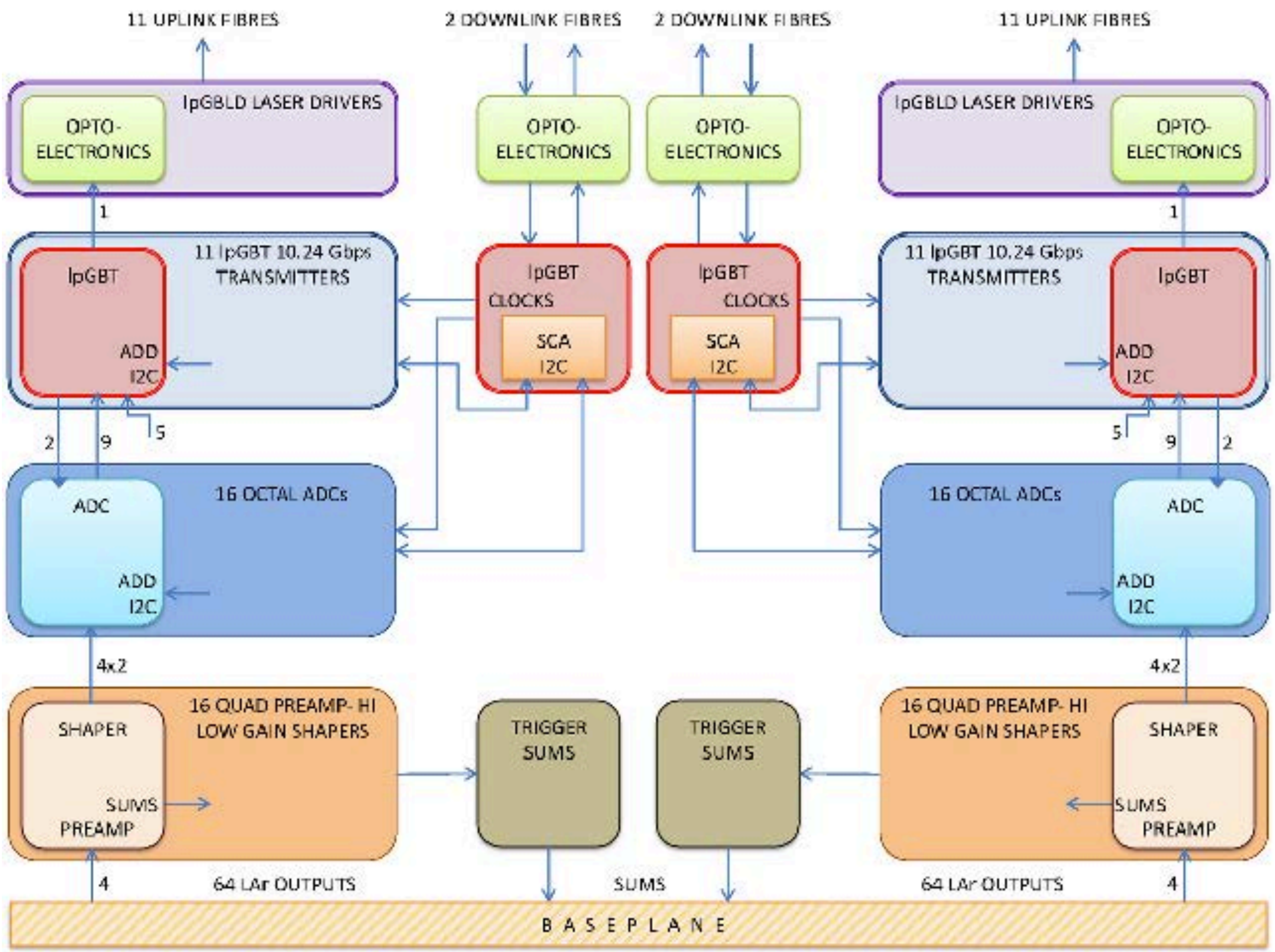
- Pulse shaping optimized to minimize total noise.
- New calibration board.
- Full granularity, each cell is digitized and sent to the backend.

Off Detector

- New, LAr Signal Processor (LASP) board to process digitized inputs and output energy and timing information.
- Information is sent from the LASP to new, L0 Triggers.

Front-End Design

The Front-end board has separate ASICs for the Preamp/Shaper, Digitization, Serialization, and Optical Transmission:



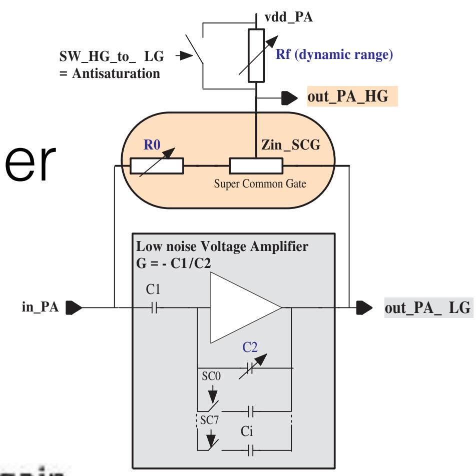
Preamplifier / Shaping ASIC

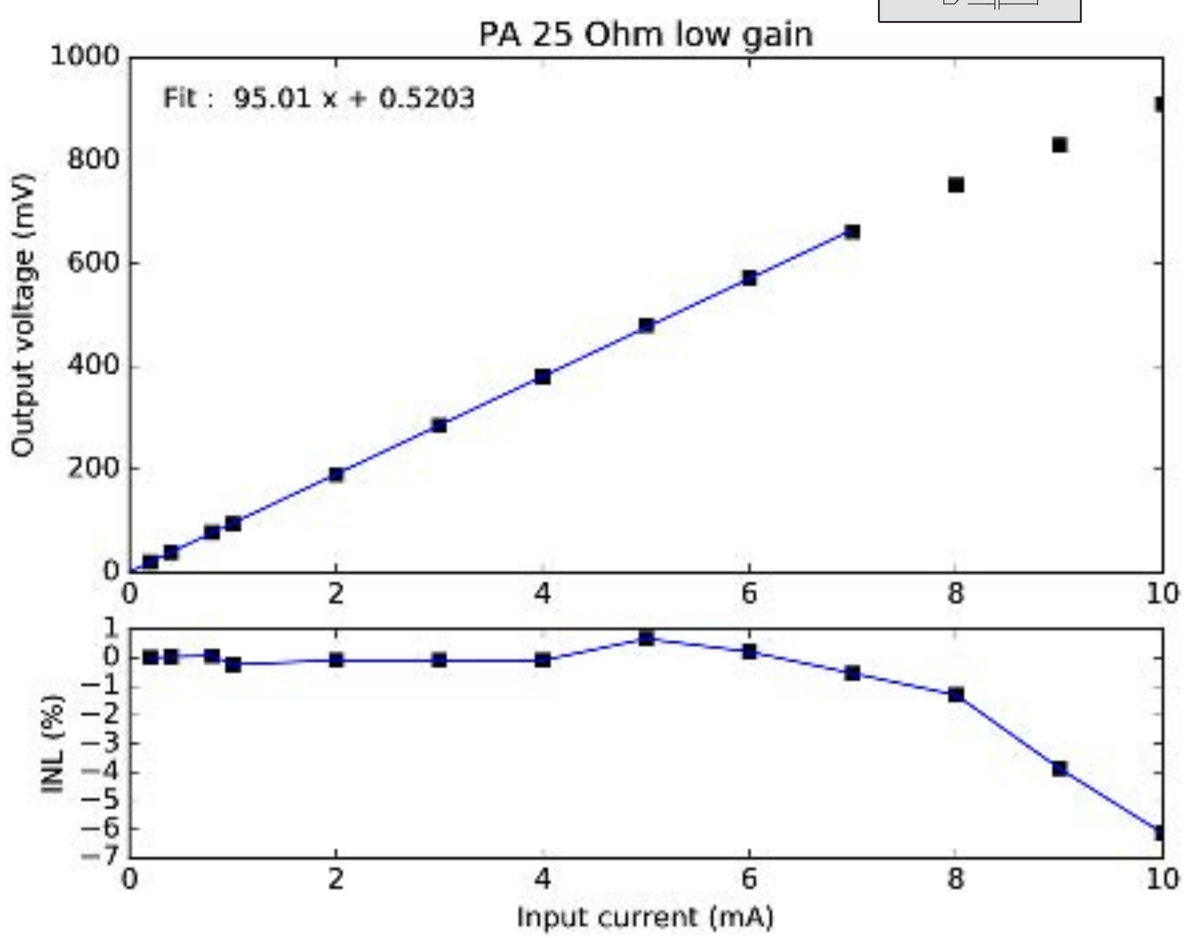
The Preamplifier and Shaping will be implemented on a single ASIC.

- 65 nm and 130 nm CMOS prototypes have both been explored.

130 nm

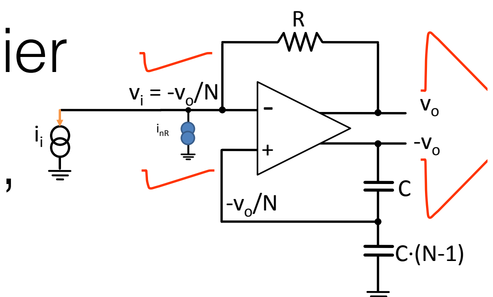
- Line terminating preamplifier
- Linearity better than 0.5%, up to 7 mA.

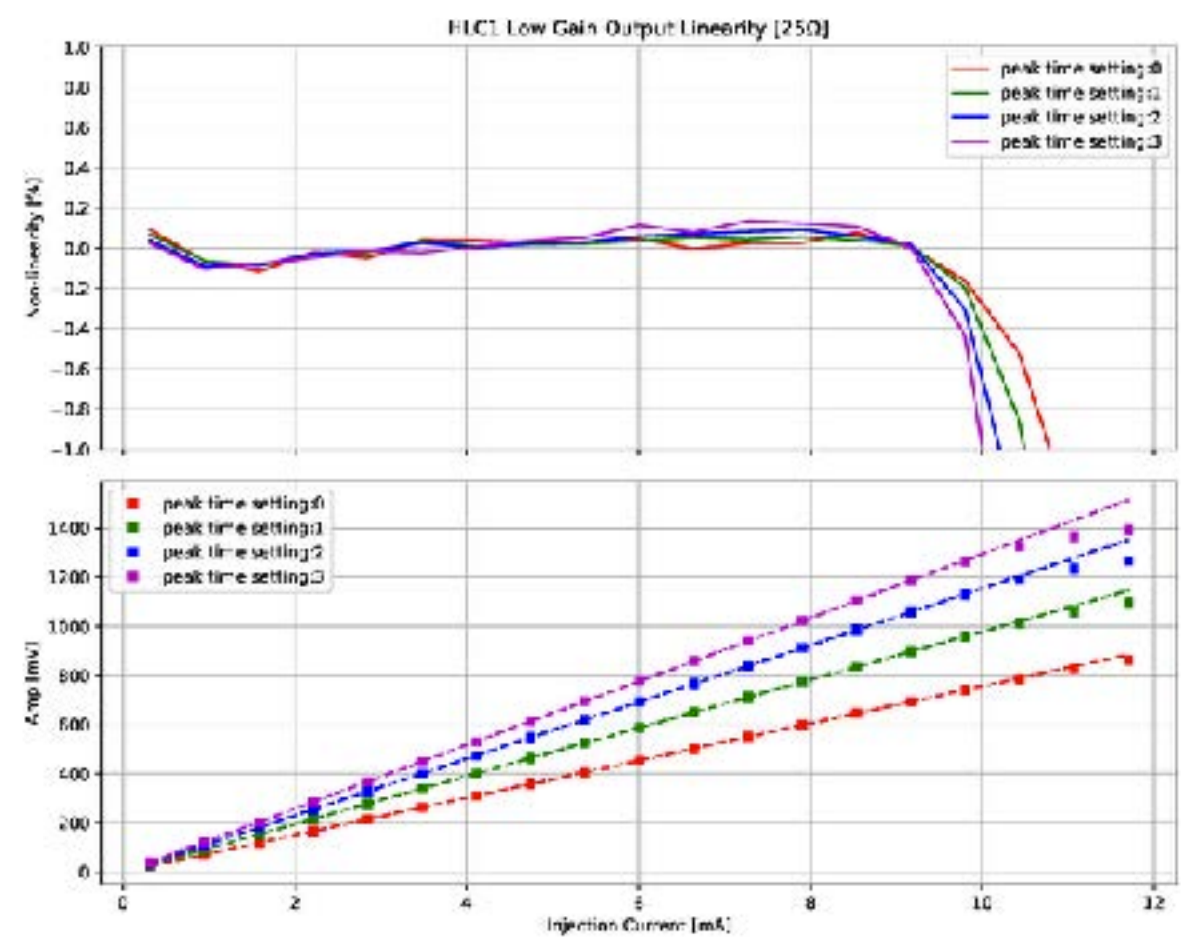




65 nm

- Fully differential preamplifier
- Linearity better than 0.2%, up to 10 mA.



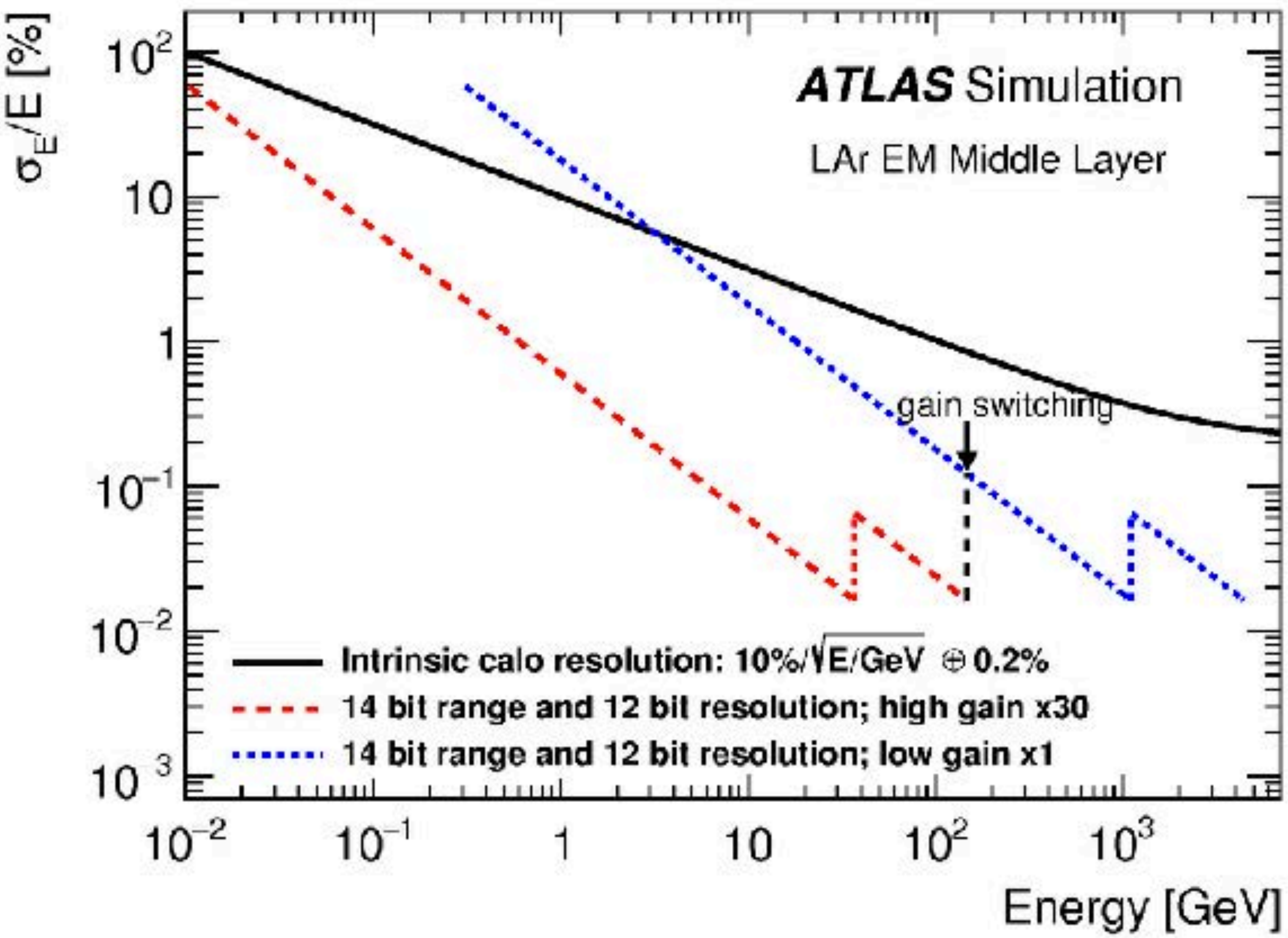


Both designs will be merged into one 130nm chip.

Digitization

The LAr cell's electronic noise must be less than MIP signal. Requiring ADC's least significant bit (LSB) value to be less than electronic noise leads to a dynamic range 16 bits wide.

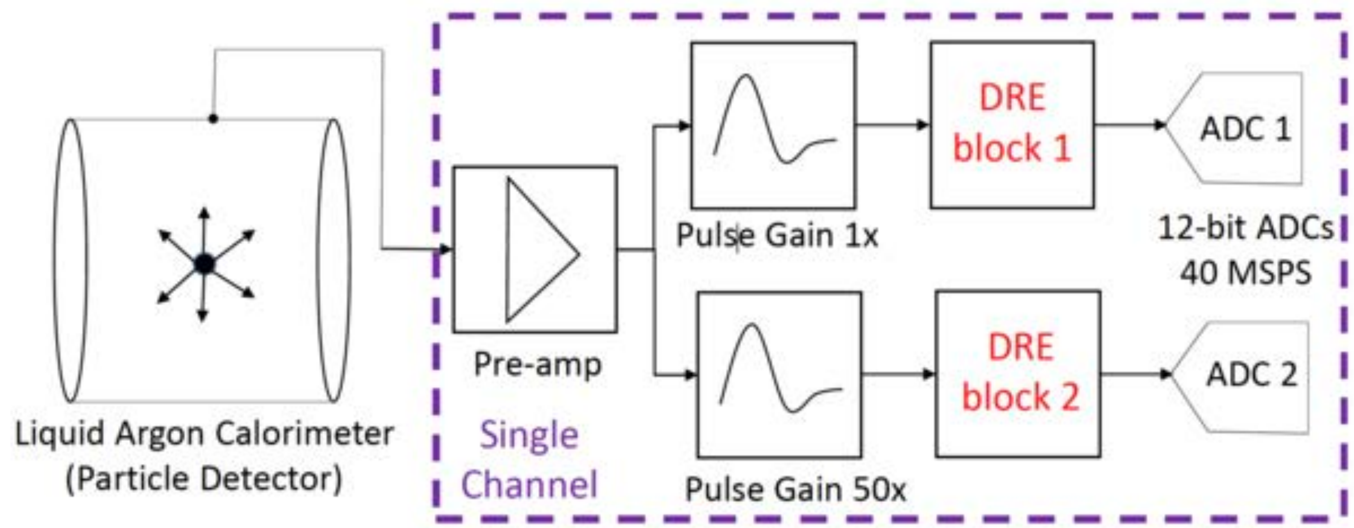
- Readout electronics utilize 14 bit ADCs.
- To cover 16 bit range a two gain system is utilized.
- Energy of gain switching chosen so photons from H→γγ, have the same gain as electrons from Z→ee (used for energy scale calibration.)

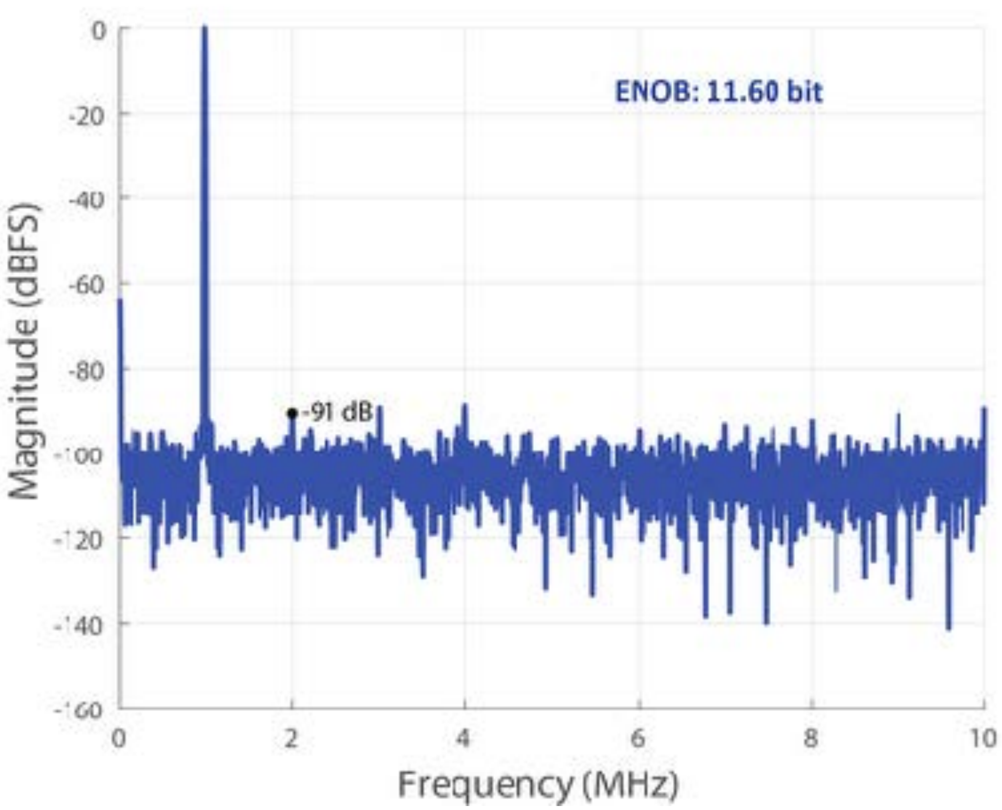


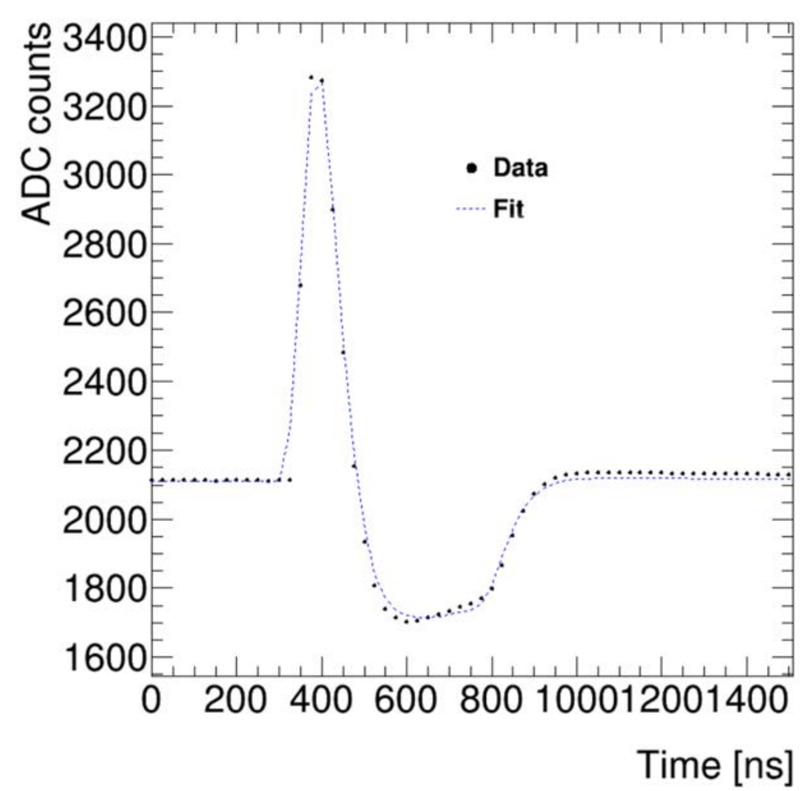
ADC

Digitization handled by 40 MHz,14 bit, radiation hard, ADC. ASIC consists of:

- Dynamic Range Enhancement block (+2 bits), DRE.
- Successive Approximation Register block, SAR.





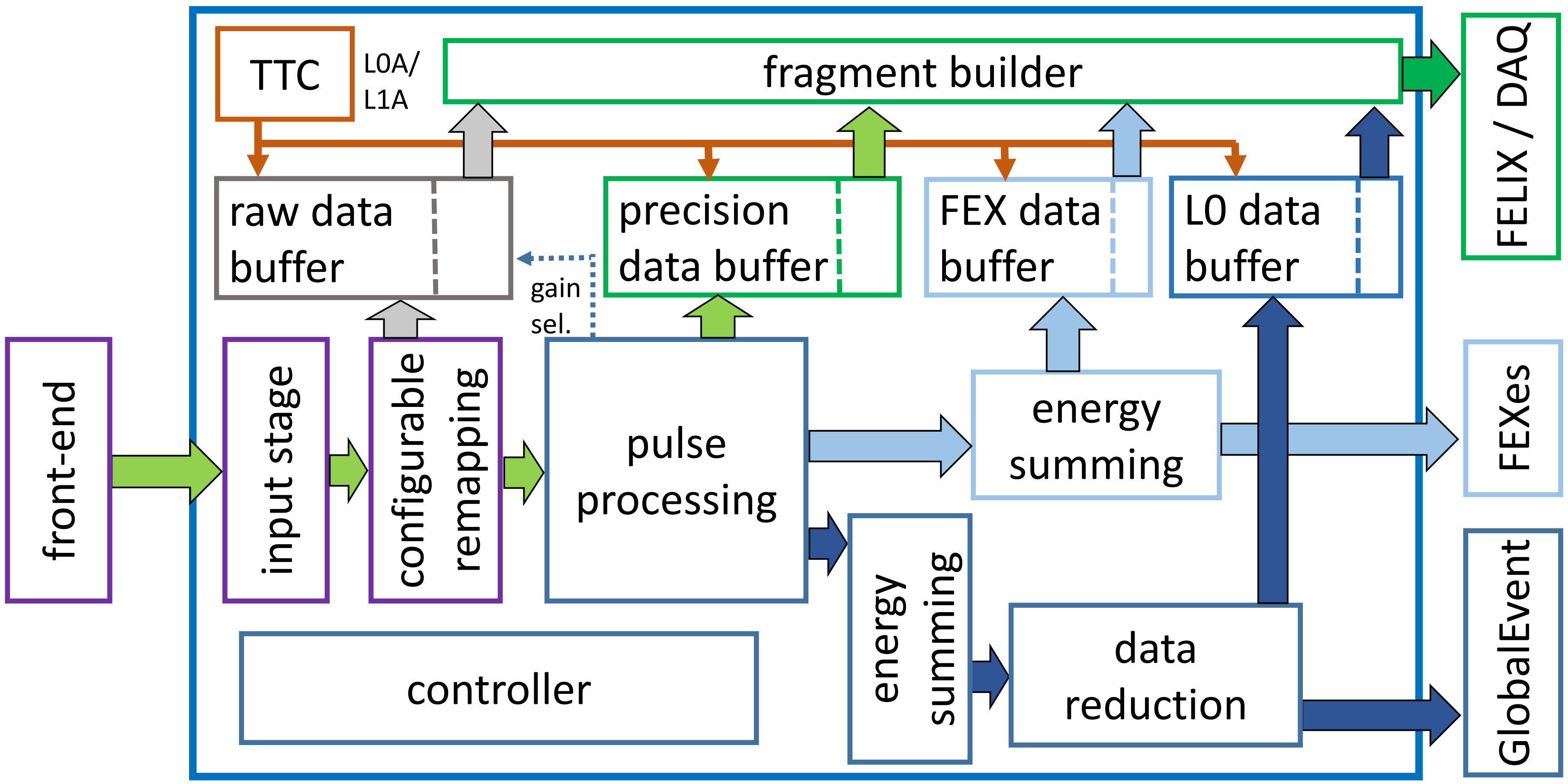


- Have tested ENOB at 20 MSPS.
- Digitization of simulated pulses by the ADC.
- Commercial ADC IP blocks may be available for purchase.

LASP

In the back-end, Phase-II Upgrade introduces new LAr Signal Processor (LASP) based on FPGA technology:

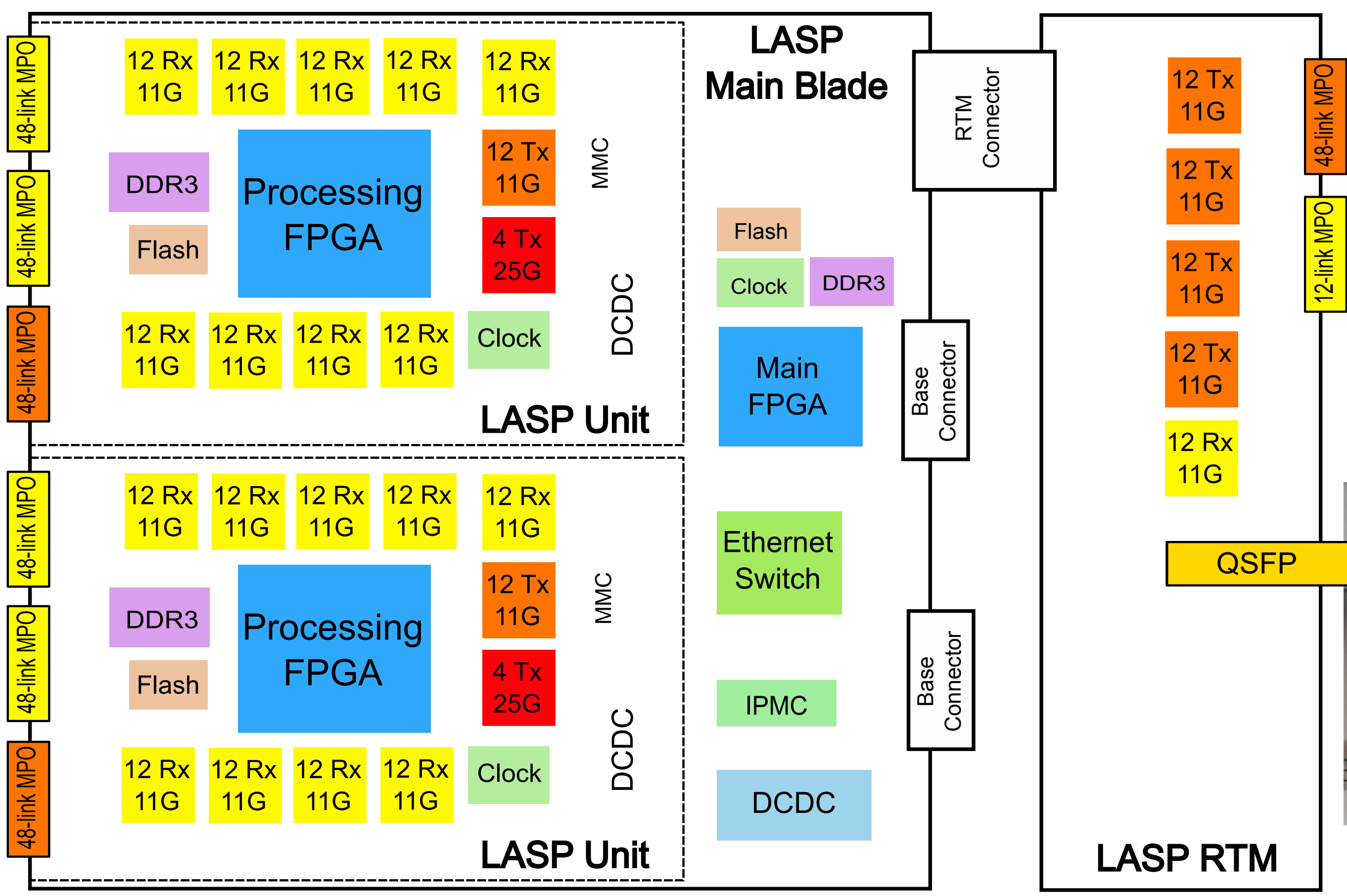
- Processes digitized waveforms from each of the calorimeter cells.
- Digital filtering algorithms to calculate energy and timing of LAr pulse.
- Interfaces to L0, hardware triggers and Data Acquisition (DAQ).
- Buffer data while awaiting trigger decision.



LASP Module

Each LASP module contains two LASP units each with it's own processing FPGA:

- LASP board design is based on Advanced Telecommunication Computing Architecture (ACTA)
- Each unit includes elector-optical receiver and transceiver arrays.
- FPGA takes inputs from up to 4 FEBs, covering 448-512 calorimeter cells.
- A test board is being developed based on the Intel Stratix 10 FPGA.



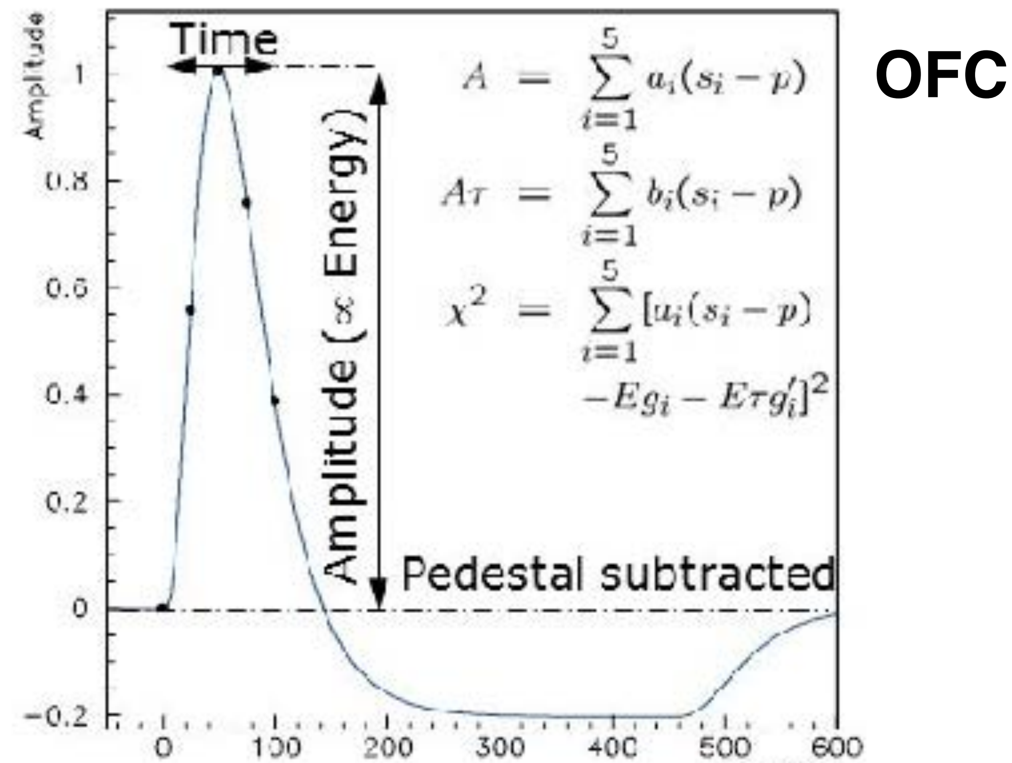
Desire reliability: so LASP processors will not need to be replaced over 10+ years of operation.

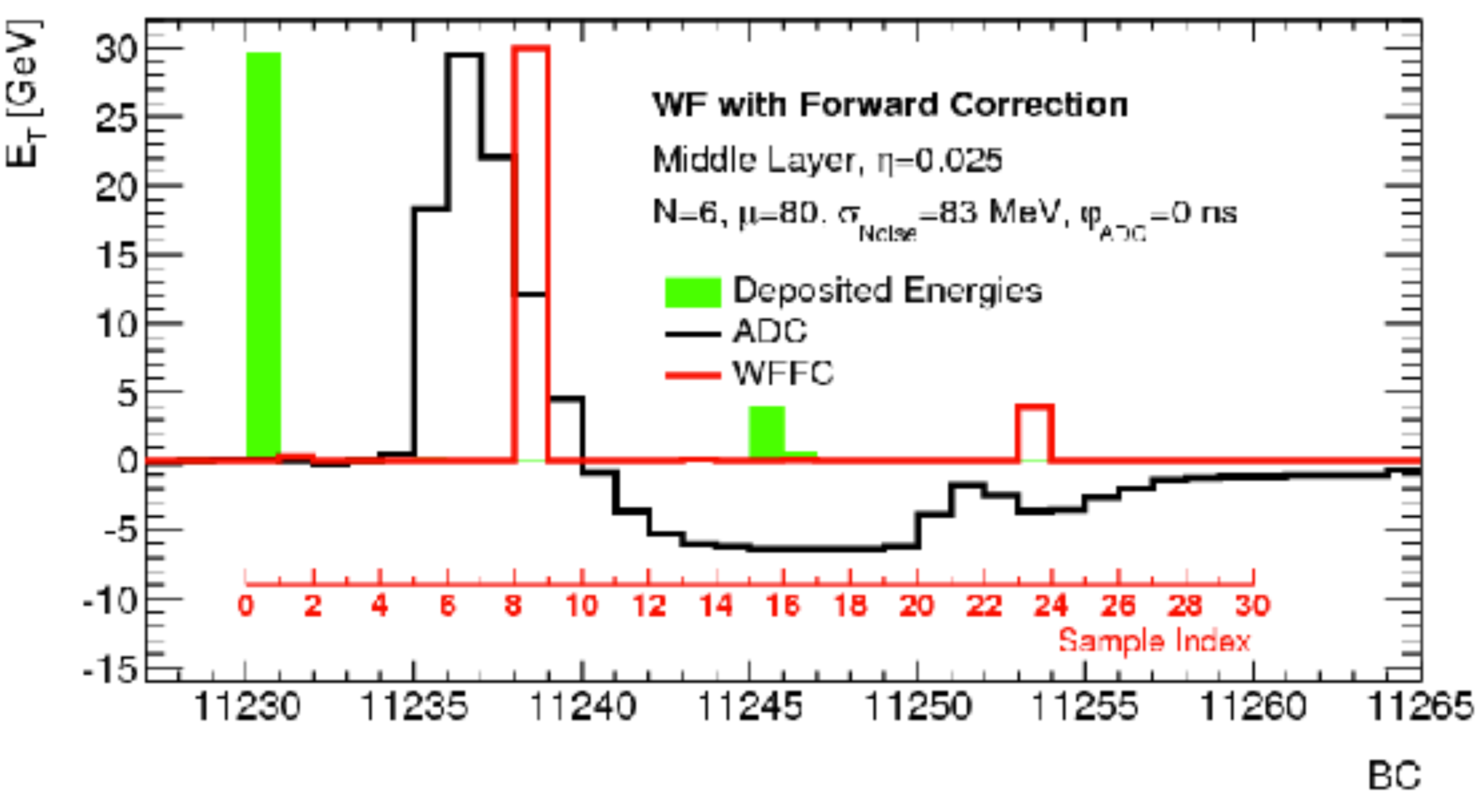
Stratix 10 Development Kit

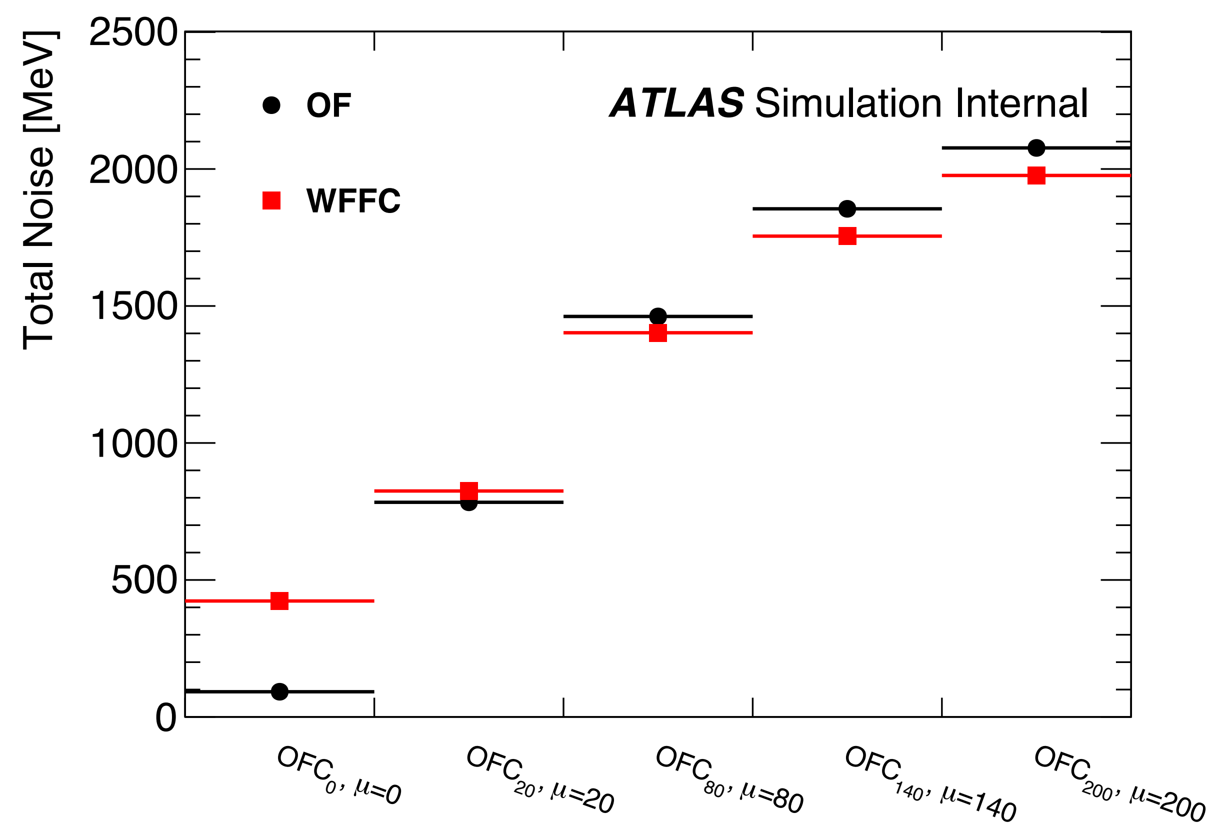
Digital Filtering Algorithms

- Current digital filtering algorithm uses **optimal filtering coefficients (OFC)**, to extract each cell's energy and timing information.
- In some cases, other algorithms such as the **Wiener Filter**, may better suppress the pileup noise. Studies are ongoing.

*Only 4 samples used since Run-2





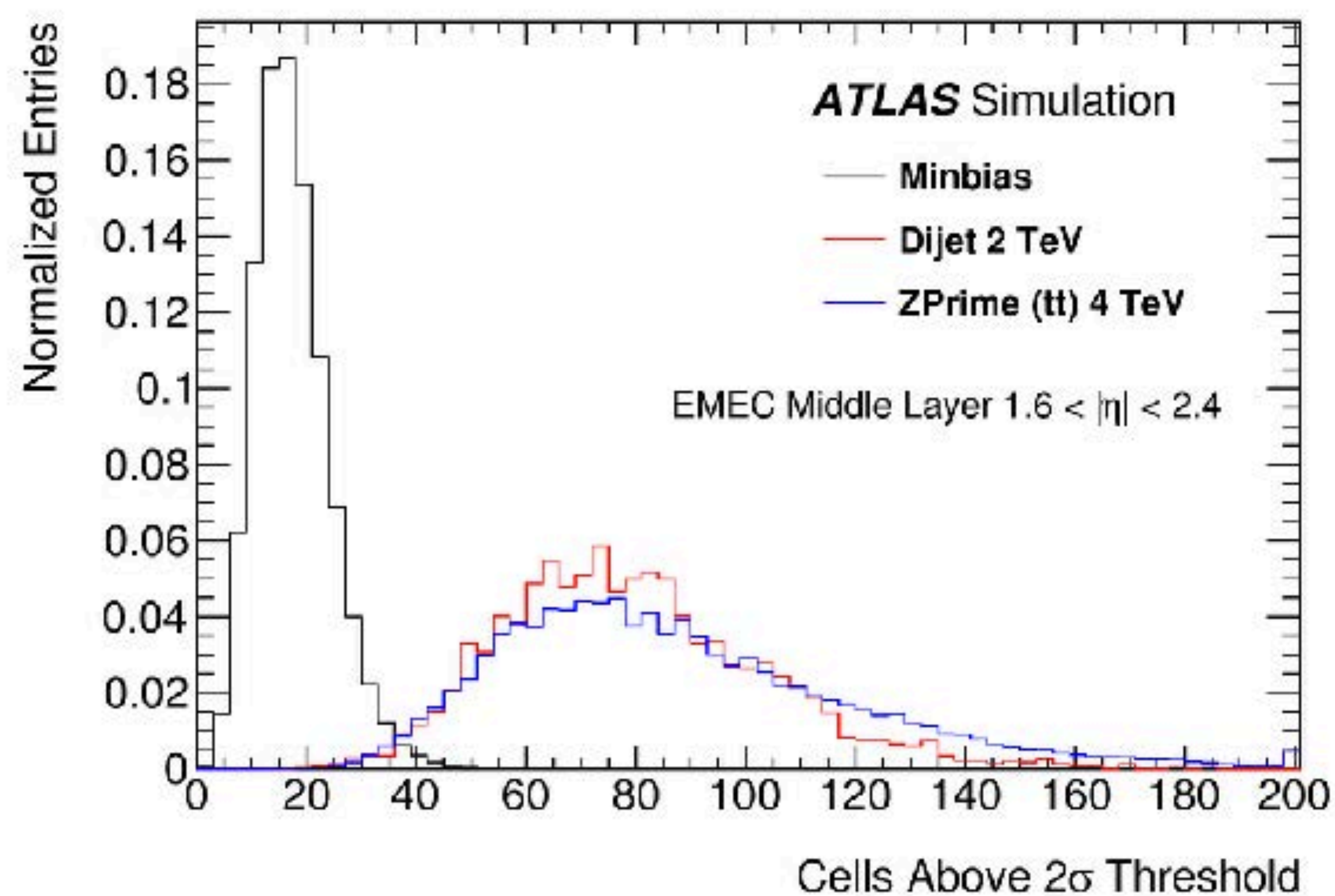


Trigger Bandwidth

LAr Calorimeter interfaces with the L0 (L1) triggers:

- Data bandwidth and links to the FPGA depends on the number of cells transmitted to the trigger.
- For the L0 global trigger, an energy threshold of 2 times the cell noise, 2σ, is applied.

- For 2σ threshold ~5.5% of cells are normally transmitted.
- However, high energy particles or noise bursts can cause individual FPGAs to transmit a significantly greater fraction of cells.
- Planned bandwidth sufficient to transmit 30% of cells, ~153.
- Also requires bit pattern (512 bits) reflecting which cells are above threshold.



- Total per LASP module bandwidth to the L0 Global Trigger is expected to be 102.4 Gbps.

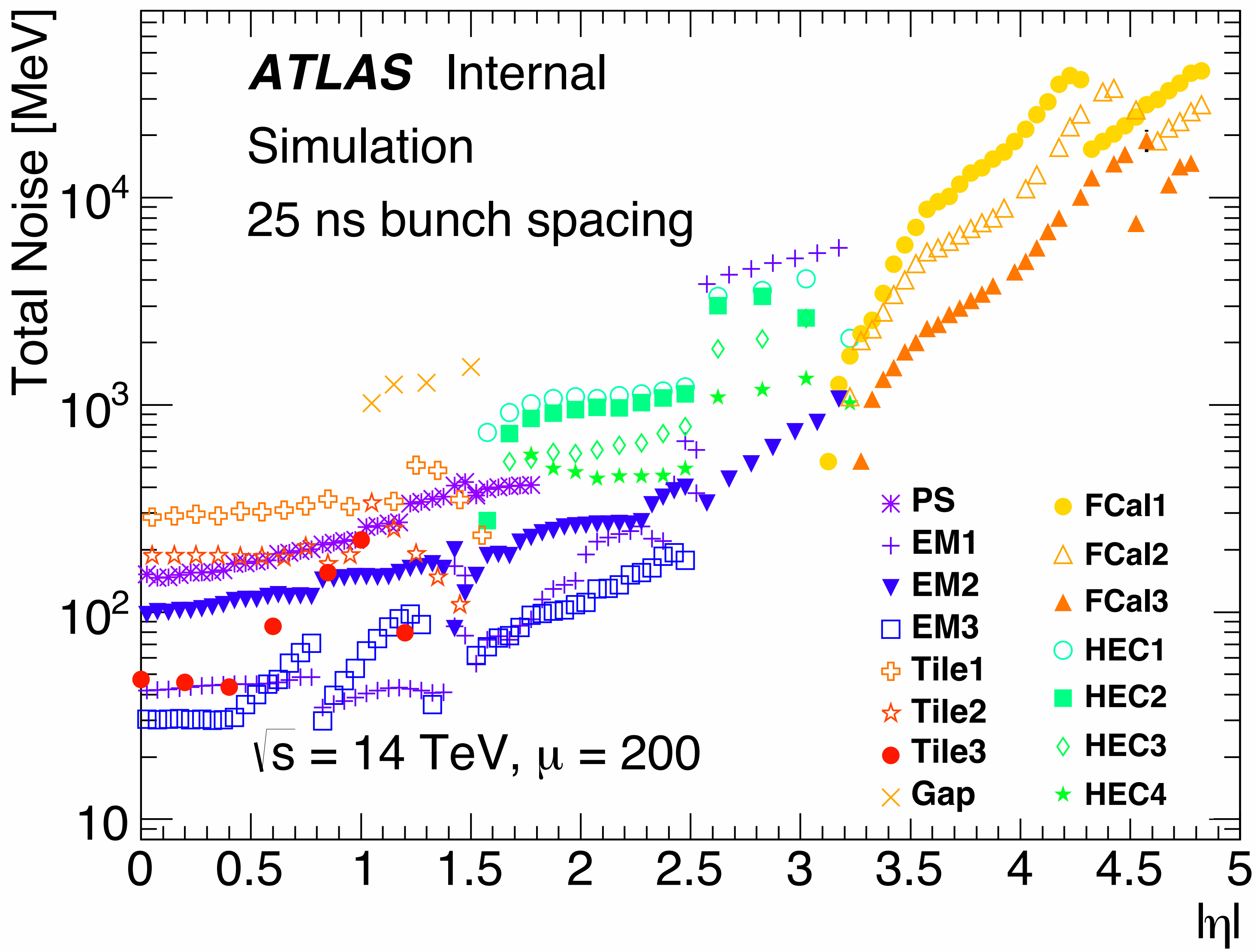
Conclusion

The LAr Calorimeter will remain critical to ATLAS physics during the HL-LHC.
In preparation for the full-replacement of the LAr Readout Electronics:

- A new Technical Design Report of the LAr Phase-II Upgrades has been prepared.
- Tests of first prototype front-end components.
- Simulation of off-detector readout and expected LAr Calorimeter performance.
- Results are guiding new ASIC design and test board construction.
- Target is for system installation during 2024-2025 of LS3.

Backup Slides

LAr CaloCell Noise



Total Noise in the LAr readout electronics combines **electronic** noise and as well **pileup** (in-time and out-of-time) noise**.**

The noise varies by subdetector, |η|, and layer.

For the L0 global trigger, there is proposed energy threshold on the calorimeter cells, of twice the cell's **total noise**, 2σ.

FEB to LASP Mapping

Assuming 25.78 Gbps links, mapping of front-end boards to the LASP:

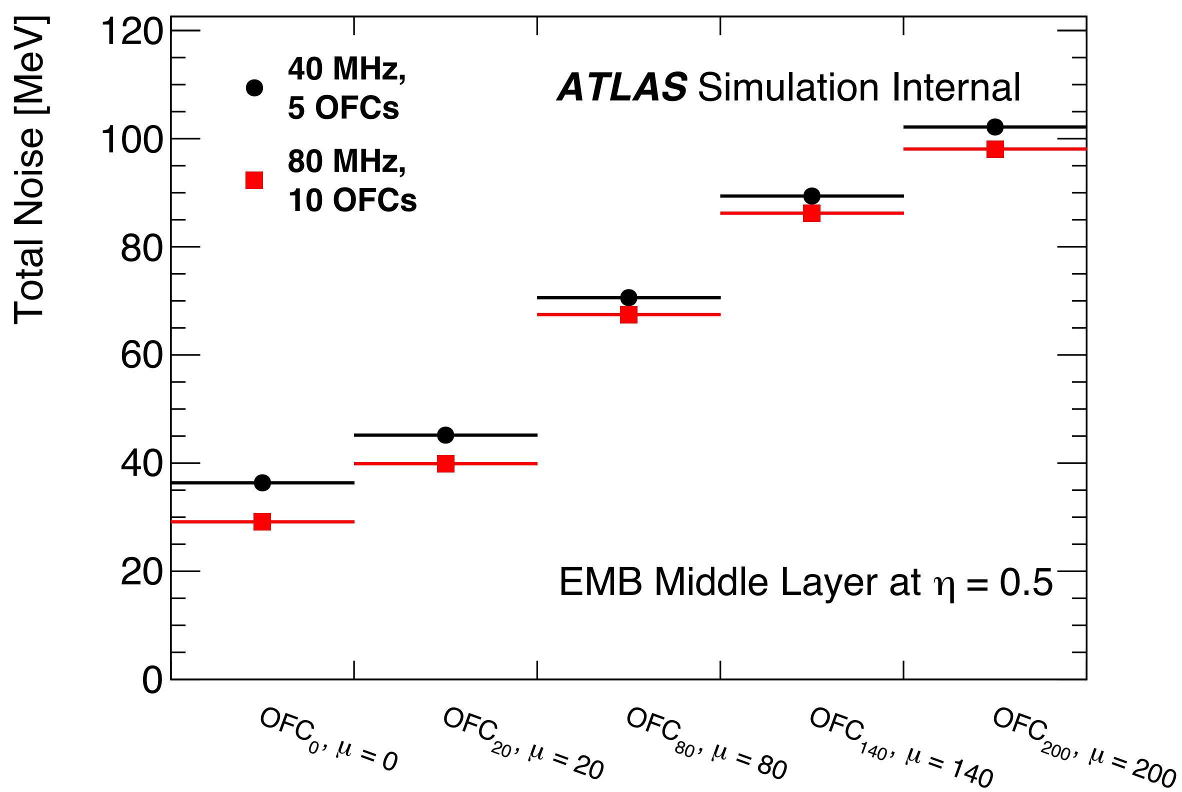
- Each LASP FPGA takes inputs from 4 FEBs, and cover between 448 and 512 calorimeter cells.

LASP ID	**No. of Cells per LASP**	**No. of LASPs**	**Links per LASP**				
			Input	**Output**		**Bidirectional**	
			FEB2	Global Event	FEX	FEB2 TTC	FELIX DAQ/TTC
EMB 1	448	64	80	4	0	8	2
EMB 2	504	64	88	4	0	8	2
EMB 3	512	64	88	4	0	8	2
EMB 4	496	32	88	4	0	8	2
EMEC 1,2	512	64	88	4	0	8	2
EMEC 3	480	32	84	4	0	10	2
EMEC spec 1	448	8	80	4	27	8	2
EMEC spec 2,4	512	12	88	4	0	8	2
EMEC spec 3	512	8	88	4	0	10	2
HEC 2	512	8	88	4	27	8	3
HEC-EMEC 1	480	8	80	4	27	8	3
FCal 1,2	504	4	88	4	23	8	3
FCal 3	500	2	88	4	23	8	3
FCal 4	256	2	48	2	12	4	2
Total		372	31 912	1 484	810	3 048	766

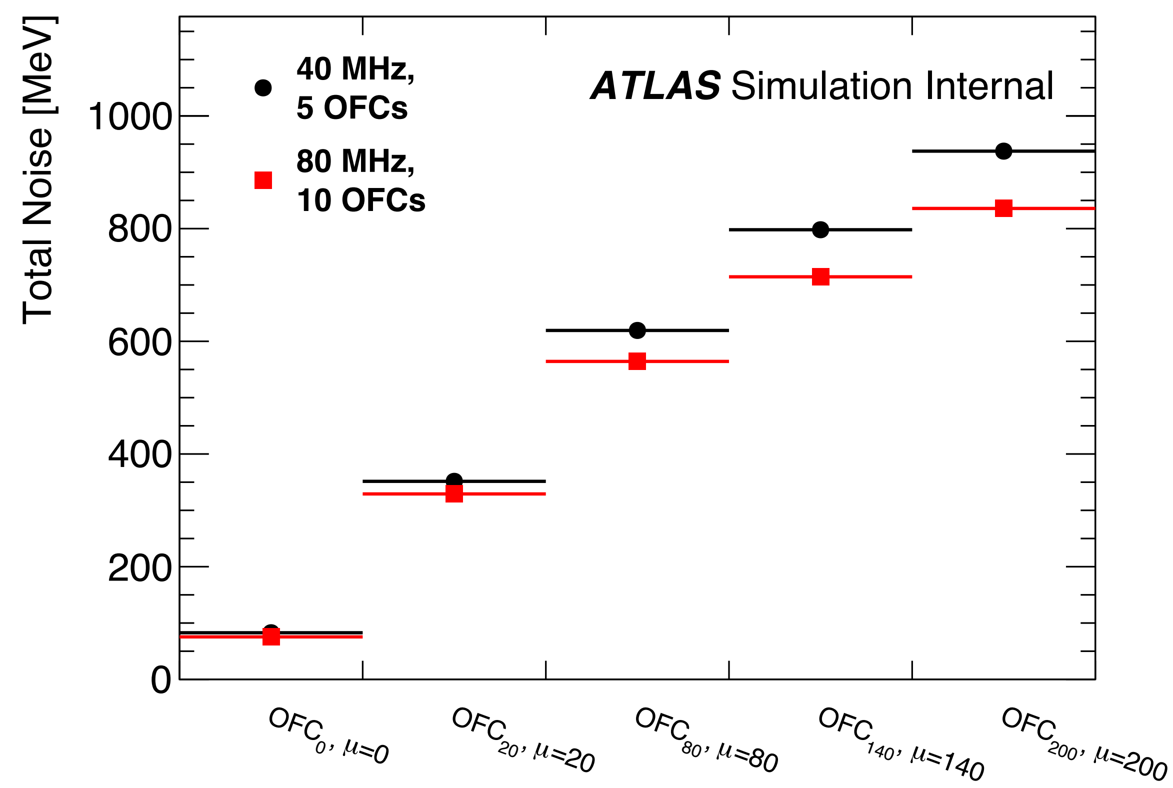
Noise Sampling Dependence

Comparison of total noise as a function of pileup for 40 vs 80 MHz sampling:

EMB



HEC



Increasing the sampling rate results in a 5-10% reduction in noise, but this was deemed insufficient to justify the additional costs.

Optimal Filtering Coefficients

- Review: the amplitude of the LAr readout electronic's pulse shape scales with energy.
- Amplitude is calculated from 5 samples, each weighted by an optimal filtering coefficient, $\mathbf{a_i}$.

$$U = \sum_i a_i S_i$$

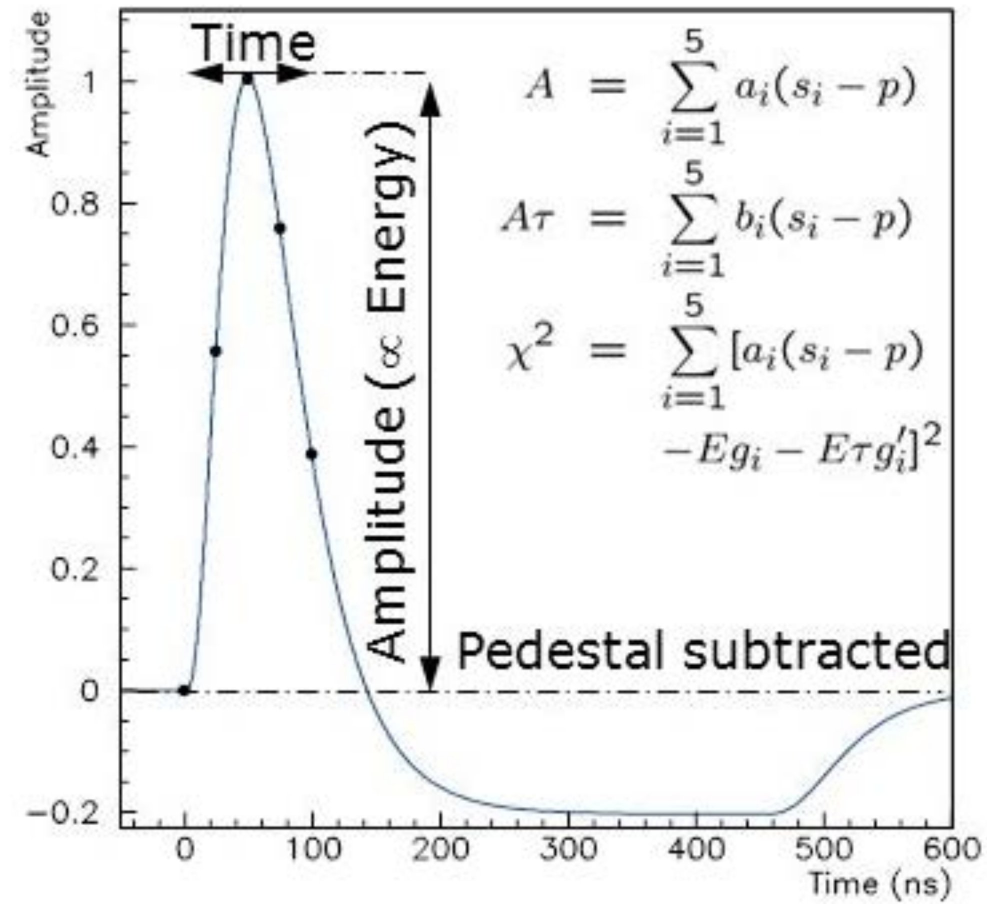
- Knowing the shape of the normalized pulse, the optimal filter sets the coefficients to minimize the uncertainty on U, Var(U).

$$Var[U] = \sum_{ij} a_i a_j R_{ij}$$

- Subject to the constraints:

$$\sum_i a_i g_i = 1 \qquad \sum_i a_i g_i' = 0$$

Becomes a minimization problem with 2 Lagrange multipliers.



R_{ij}
Total Autocorrelation Function
(Combined electronic and pu)

Optimal Filtering Coefficients

- One finds that optimal filtering coefficients are defined as:

$$a_i = \lambda \mathbf{R}^{-1}\vec{g} + \kappa \mathbf{R}^{-1}\vec{g'}$$

- Where the Lagrange multipliers are also functions of the pulse shape and the inverse autocorrelation function.

$$\lambda = \frac{Q_2}{\Delta} \qquad \kappa = \frac{-Q_3}{\Delta}$$

$$Q_1 = \vec{g}^T \mathbf{R}^{-1}\vec{g} \qquad Q_2 = \vec{g'}^T \mathbf{R}^{-1}\vec{g'} \qquad Q_3 = \vec{g'}^T \mathbf{R}^{-1}\vec{g} \qquad \Delta = Q_1 Q_2 - Q_3^2$$

- The autocorrelation function, R_{ij} , is a weighted combination of the electronic and PU autocorrelation functions, that depends on the variance of the pileup energy distribution.

$$R_{ij} = \frac{R^e_{ij} + \mu \frac{(\sigma_{MB})^2 + (\mu_{MB})^2}{f^2_{sampl}(\sigma_e)^2} \sum_k g_{k-i} g_{k-j}}{1 + \frac{(\sigma_{MB})^2 + (\mu_{MB})^2}{f^2_{sampl}(\sigma_e)^2} \sum_k g_k^2}$$

ATLAS Schematic