Machine Learning For Real-Time Processing of ATLAS Liquid Argon Calorimeter signal with FPGAs

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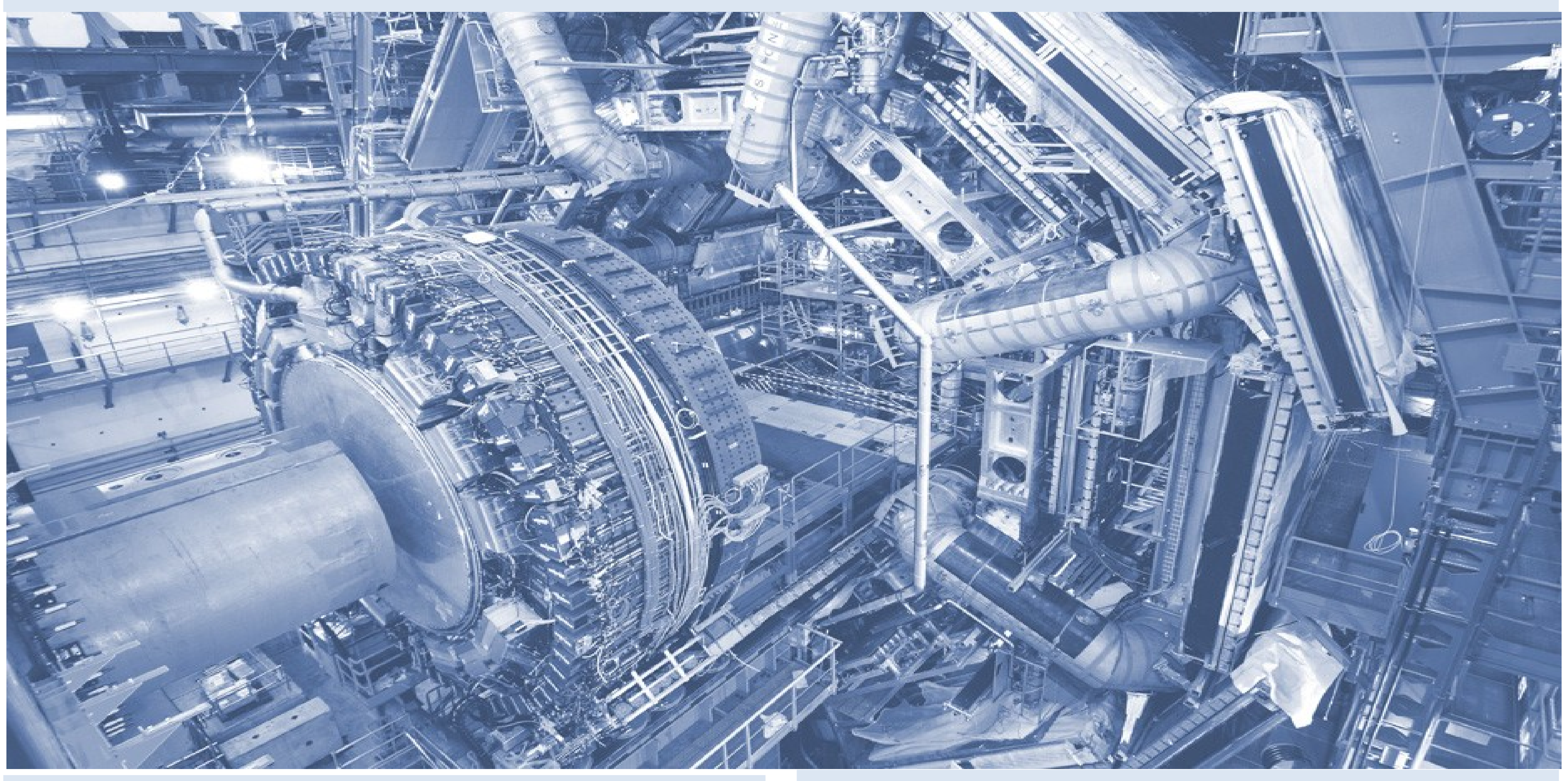
CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM

INTRODUCTION

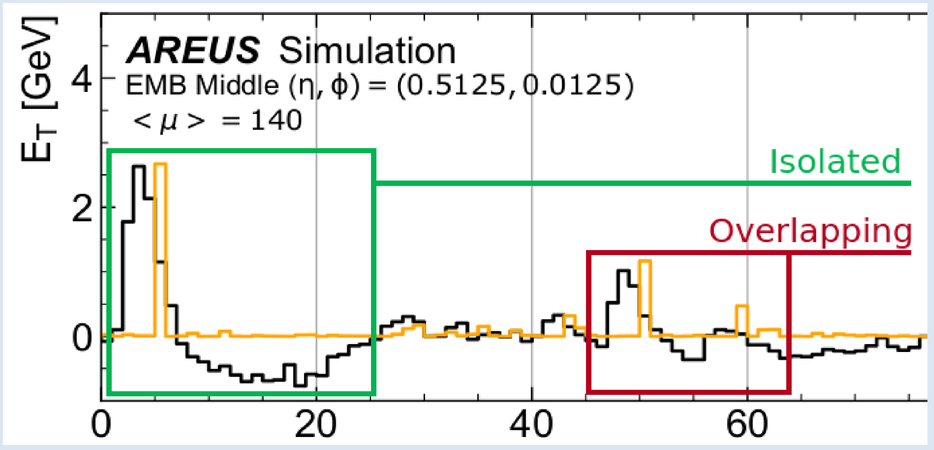
- High-luminosity phase of LHC (HL-LHC) is an important milestone for particles physics
  - Expect to increase instantaneous luminosity by 5-7
  - Trigger frequency : 1MHz
  - Simultaneous proton-proton collisions (pileup) every 25 ns : 140-200 per Bunch crossing (Bc)
- Upgrade of the ATLAS LAr calorimeter off-detector system to meet physics requirement
  - Improvement of computing capacity with Stratix-10 FPGAs
  - Energy reconstruction made by real-time artificial intelligence algorithm
  - Process 256 or 384 LAr calorimeter cells by each FPGA

LHC			HL-LHC
Run 1	Run 2	Run 3	**Run 4**
2011-2013	2015-2018	2022-2026	**2029-2040**
30 fb^{-1}	190 fb^{-1}	350 fb^{-1}	3000 fb^{-1}

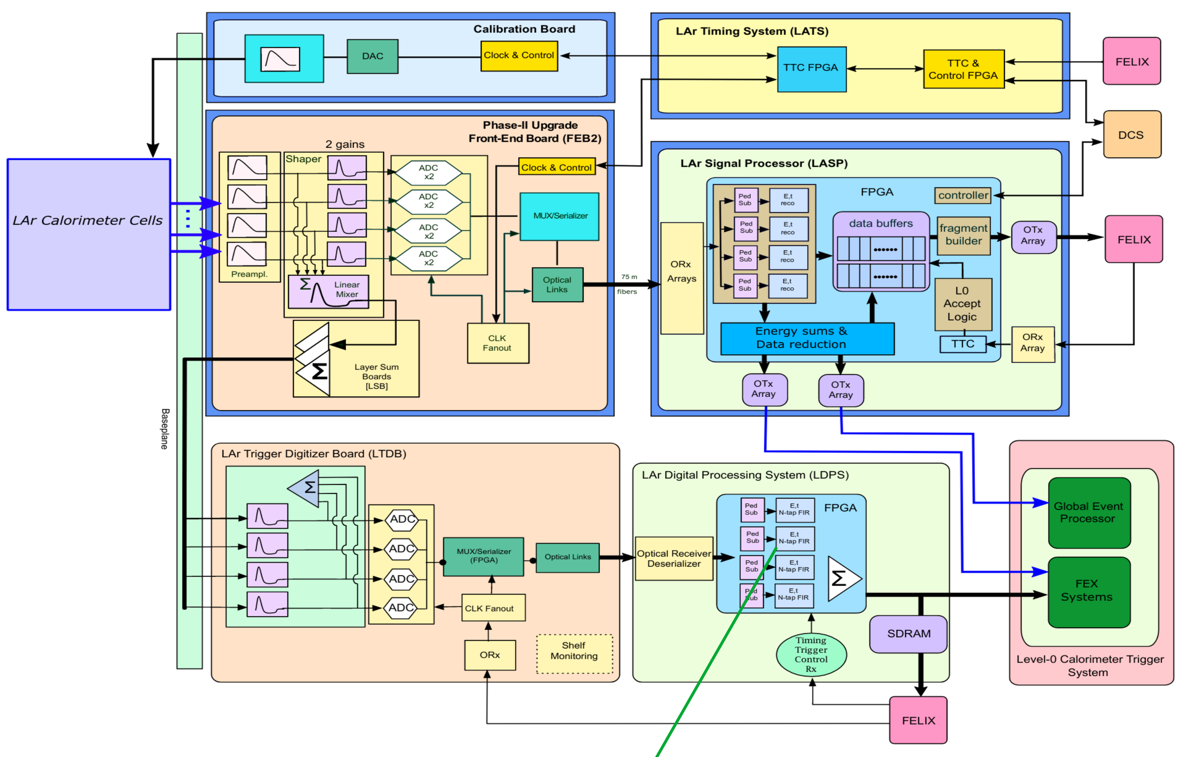


ENERGY RECONSTRUCTION IN LAr CALORIMETER

- Measure the energy of electromagnetic showers of photons/electrons thanks to the ionization signal by the Liquid-Argon (LAr) Calorimeters
  - Calorimeter with ~182.468 cells
- Bipolar pulse shape (total length of up to 600 ns, 25 Bcs).
  - Sampled and digitized at 40 MHz
- ATLAS level-1 calorimeter trigger (L1Calo) data processing uses Optimal Filter (OF) algorithm (readout path) with maximum finder (trigger path)
  - Use four to fives samples around pulse shape peak
  - Assume perfect pulse shape
- High pileup leads to overlapping pulse shapes

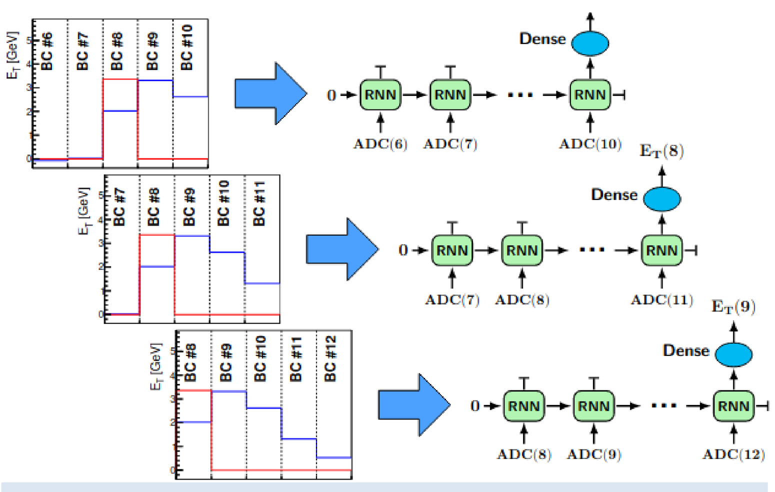


Sample sequence (black) simulated by AREUS, together with the true transverse energy deposits (yellow) shifted by five BC to improve the plot visibility



Recurrent Neural Network (RNN)

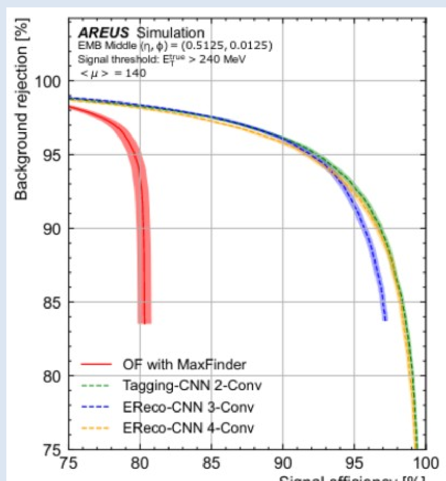
- Process data series input with previous calculated state
- Two format :
  - Sliding window (Vanilla, LSTM)
  - Single cell (LSTM)



RNNs with sliding window

Convolutional Neural Network (CNN)

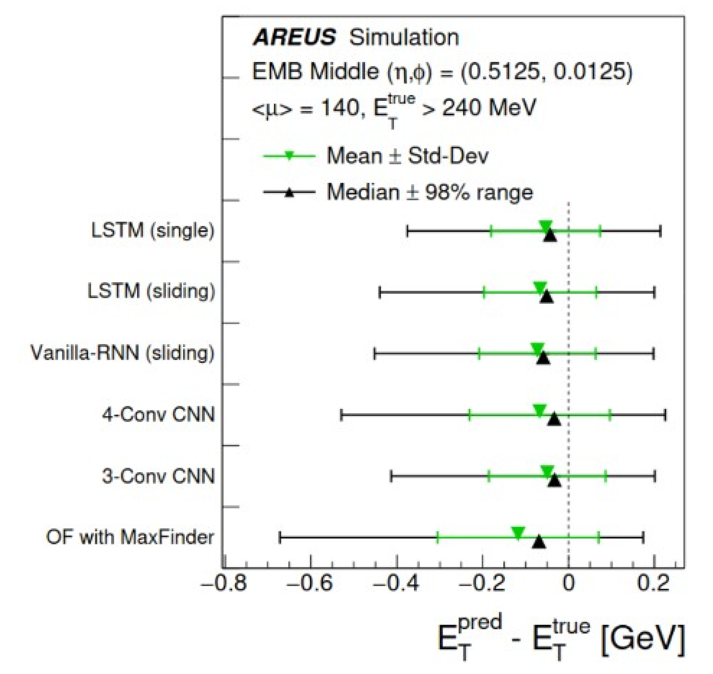
- Process energy through two stages :
  - Pulse tagging with 2 layers (Energy detection above noise and sigmoid activation)
  - Energy reconstruction with 1-2 layers



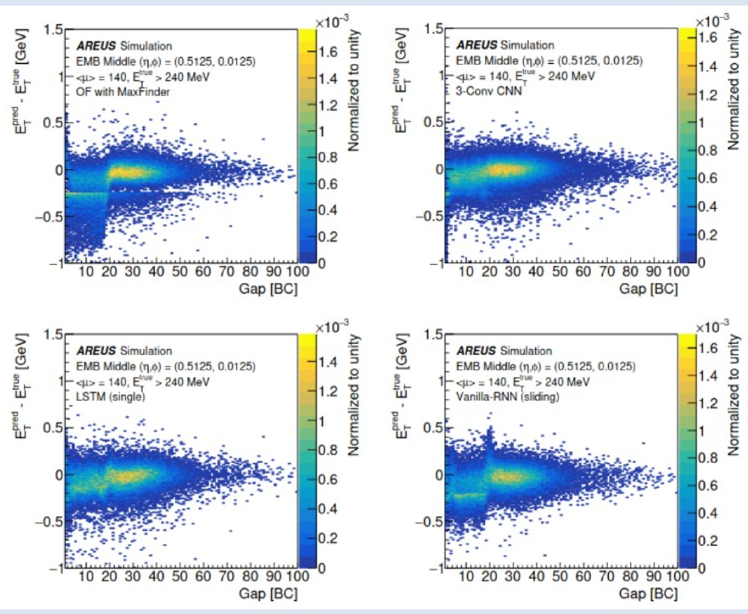
Background rejection and signal efficiency of CNN compared to OF with maximum finder

Network Performance

- Reconstruction of the energy from LAr cells with NNs is better than OF with maximum finder



Energy resolution with different algorithms



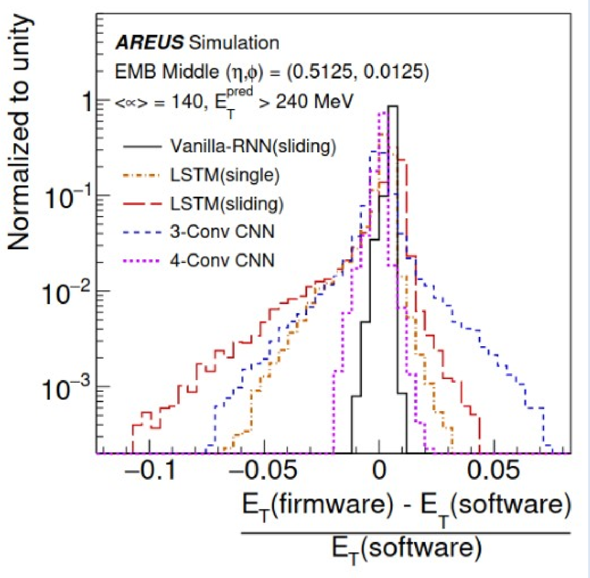
Resolution as function of the distance to previous energy deposit for OF with maximum finder, 3-Conv CNN, LSTM (single), Vanilla RNN (sliding)

FPGA Performance

	Multiplexing	Frequency	Latency	Max Channels	Ressource usage DSP / ALM
3-Conv	6	344	337 ns	390	0,8% / 1,5 %
4-Conv	6	334	258 ns	352	0,7% / 1,7%
Vanilla (HLS)*	15	640	200 ns	576	2,6 % / 0,6%
Vanilla (VHDL) **	11	595	150 ns	465	2,4% / 0,7%

Characteristics of the NN implementation on a Stratix-10 FPGA

- 3-Conv CNN and Vanilla RNN fits for 384 channels but 4-Conv CNN only fits for 256 channels but use a lot of logic
- Vanilla with HLS reports are good but when we add it multiple times with Quartus, the ALM resource usage explode and the frequency decrease a lot
- Placement optimization reduces the randomness of a compilation with better results



Relative deviation of firmware and software results

	Multiplexing	Nb Channels	Frequency	Ressource usage DSP/ALM
Vanilla (HLS)	15	390 (3 FEB)	425	68,6% / 74,5 %
Vanilla (VHDL) No placement	11	385 (3 FEB)	433	82,6 % / 20,6 %
Vanilla (VHDL) With placement	11	385 (3 FEB)	484	82,6 % / 18,7 %

Implementation of RNN on FPGA with Quartus

* : Resource estimated by HLS report

** : Test of a VHDL implementation of a Vanilla NN made after the article

References

[1] W.E Cleland E.G. Stern. Signal processing considerations for liquid ionization calorimeters in a high environment. NIM A Volume 338, 467-497, 1994.

[2] Nico MADYSA. A software framework for atlas readout electronics upgrade simulation (areus). CHEP 2018, 2019.

[3] Aad, G., Berthold, AS., Calvet, T. et al. Artificial Neural Networks on FPGAs for Real-Time Energy Reconstruction of the ATLAS LAr Calorimeters. Comput Softw Big Sci 5, 19 (2021).

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ATLAS EXPERIMENT