Handling large data volumes of CMS High Granularity Calorimeter (HGCAL)

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High luminosity operation of LHC is starting in 2027
Much higher instantaneous luminosity wrt recent Run-II:
  - significant challenges for radiation tolerance on detectors.
  - Average pile up interactions of 140 or 200 (current value ~40).
The HGCAL, a high granularity sampling calorimeter, is an upgrade of CMS current endcap calorimeter for HL-LHC.

Key features:
- Maintained at -30° C.
- $1.5 < |\eta| < 3.0$
- Total Silicon: 600 m$^2$
- Total Scintillator: 500 m$^2$
- ~27k Si modules

CE-H: Si & scintillator + steel absorbers
  22 layers, 8.5$\lambda$

CE-E: Si + Cu & CuW & Pb absorbers
  28 layers, 25 $X_0$ & ~1.3$\lambda$
High data volumes expected at HGCAL

Challenges:
- Total ~6M Si channels.
- At the L1 accept rate of 750 kHz, the data will be read out at an unprecedented rate from the on-detector electronics of up to \( \sim O(10) \) Tb/s
  - For such extreme data rates, need high-speed optical links.
  - Need to have high-bandwidth low-latency specialized computer hardware for off-detector data processing.

- Based on 8-inch sensors, 120, 200 or 300 \( \mu m \) active thickness

- Low density modules (LDM)
  - 192 channels
  - Cell size = 1.18 cm\(^2\)
  - Outer radii

- High Density Modules (HDM)
  - 432 channels
  - Cell size = 0.54 cm\(^2\)
  - Inner radii

Ref: https://cds.cern.ch/record/2293646/files/CMS-TDR-019.pdf
Front-End & Back-End DAQ readout electronics

FE Architecture:
- Charge collected in the silicon/scintillator is sent to HGCROC chips for signal processing.
  - Then goes to Endcap CONcentrator which performs the appropriate zero suppression and transmits the results to the external back-end electronics with the help of elinks (1.44 Gb/s) and lpGBTS (10 Gb/s)
- A maximum of 14 elinks can be connected to an ECON-D.

BE DAQ Architecture:
- Data from the FE using lpGBTs goes into BE-DAQ FPGAs.
  - 28 FPGAs in one 120° HGCAL sector.
- Each FPGA can take inputs from 60 lpGBTs
  - can send output as 12 Slinks to cDAQ.
- Each Slink (16 Gb/s) will behave like an independent Daq system,
  - will take on average 5 lpGBTs as inputs (some can have fewer & more).
- Data rates from FE should be within the limits of available bandwidth in the BE
  - To avoid full buffer saturation and data losses.
Occupancy of modules

- Occupancy - number of cells in a given module which are above certain threshold, and hence will be used for further processing.

- Use MC simulated ttbar events with average pileup of 200 to study the details of occupancy.

- Higher the occupancy, more is instantaneous data transmitted from the given module:
  - Occupancy depends on module type (HDM or LDM)
  - Modules closer to interaction point or beam pipe have higher occupancy than those away from it.
Occupancy of modules

- Studies for physics performance, and DAQ and Trigger considerations are going on in parallel.
- The geometry used for FE & BE architecture implementation studies have to be consistent with the most final design choices to be used for production.
  - Module position is identified by layer (L) and coordinates (u,v)
- There are small differences in the module types at HDM ↔ LDM transition and boundaries (partial modules).

- Starting with the ttbar simulated samples, we correct for these differences by fitting occupancy as a function distance from beampipe (R) for a given layer.
- Predicted and simulated occupancy are matching very well for all the modules to be corrected.
Contribution of noise to the average occupancy

- Predicted HD occupancies are less than the LD after first few layers while we expect opposite.
  - LDM (192 channels/module) higher than HDMs (432 channels/module)
- Occupancy has two components - cells in which there is true energy deposited (signal) and those in which electronics noise fluctuates high (noise). The latter contribution is important for modules far away from interaction point.

- LD modules have higher noise (wider area silicon cells) than the HD modules as observed in neutrino events
- After subtracting the noise, assuming a poisson model, the signal in these modules is similar.
Assignment of lpGBTs to Slinks for BE-DAQ system

Objective: The total data coming into Slinks should not go beyond the available bandwidth to avoid full buffer situation.

- With collision events:
  - neighbouring modules in a layer are expected to be highly correlated (simultaneously recording large occupancy).
  - in presence of an energetic jet, modules in subsequent layers in its direction are expected to be highly correlated.
- Such highly correlated modules should not be linked to the same Slinks
  - tails of occupancy distributions are important
  - need high statistics simulated MC samples
- Not practical to produce a sample of events corresponding to the number of collision events @40MHz with full detailed detector simulation
  - Simulating HGCal requires 10× more geometry volumes → 40–60% increase in simulation time - costing more CPU power & storage
- Instead we can use toy random events with correct modeling of correlations among various modules as well as correct representation of tails.

CMS, work in progress

\[ \rho_{X,Y} = \frac{\text{cov}(X, Y)}{\sigma_X \sigma_Y} \]

-1 ≤ \( \rho \) ≤ +1

Correlation coeff of module(2,3) of Layer 01 with all other modules of the same layer. Neighbour modules are in high correlation.
Generating random samples ($X$) with a multivariate gaussian distribution which captures correlations between different random factors, can be used for gaussian like reference distributions.

- Generate univariates ($r$) with ($\mu = 0$, $\sigma = 1$)
- Then correlate these using $X = Ar + M$
  - Where $A$ is the lower decomposition matrix of correlation matrix $S$ for modules
  - $M$ = vector containing mean for each of the modules,

But not all of occupancy distributions are gaussian,

- Reference distributions for modules situated at outer radii are non-gaussian in shape.
- Need to find a way to morph these into gaussian first.
- Then use the multivariate gaussian distribution.
Generating Toy distributions preserving correlations

- To morph the non-gaussian distribution into a standard normal distributions (μ =0, σ = 1), the quantile transformation is used.
  - This step preserves the original correlations
- Apply inverse quantile transformation on \( X \) to map it to the reference distributions.

- First results look encouraging with predicted distributions matching well with reference distributions
- Further challenges:
  - Limited sample size to train quantile transformation.
  - We are working with discrete variables.
Summary

- Finalizing first version of toy model to correctly account for correlations among different modules as well as faithfully representing the tails
  - Quantile transformation shows some promising results in the bulk region
  - Tails are slightly overpredicted - more conservative

- Improving the model to train (original EDs) accounting for discrete nature of occupancy and get the extended tails,
  - fit a suitable function and get the extended tails by extrapolating that function,
  - But the precision and accuracy of this method has to be checked.

- After successfully getting the toy model correctly, we can then make decision on which ECONs(modules) should go together in a Slinks.