Performance of the CMS HGCAL readout electronics system in a beam test at CERN

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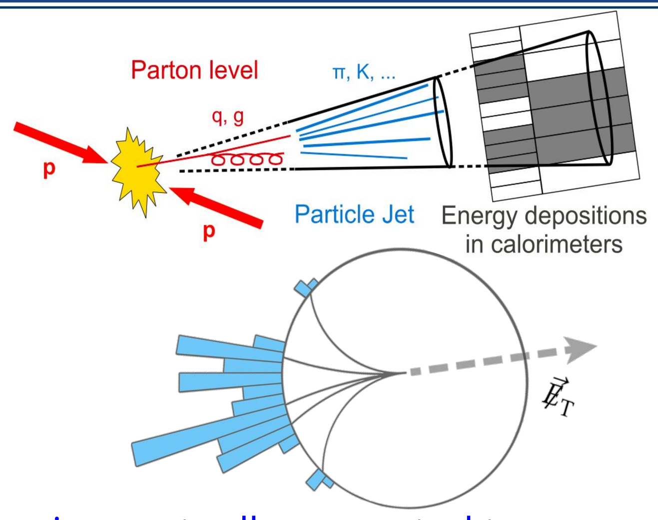
On behalf of CMS collaboration

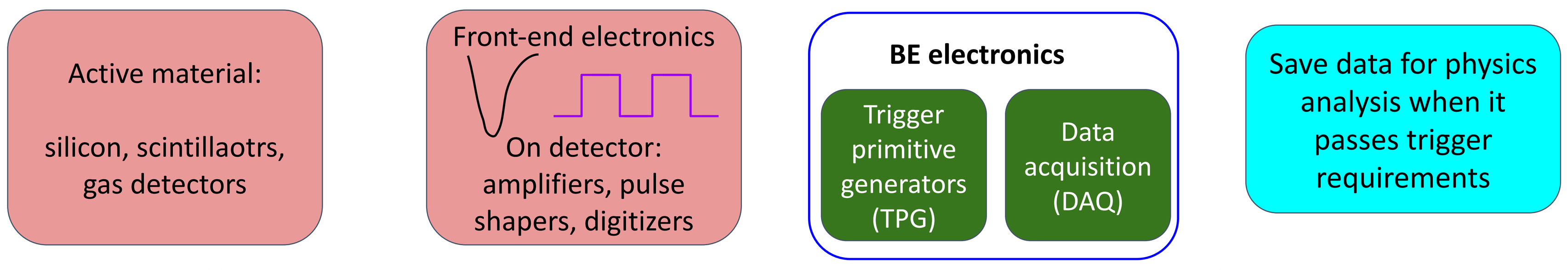
With its unprecedented **longitudinal and transverse granularity, timing information, and large energy dynamic range, the large data volumes** pose an important challenge for the readout of the CMS **High Granularity Calorimeter (HGCAL)**, the endcap calorimeter system to be used during the HL-LHC operation. **Calorimeters are important when measuring missing momentum, electrons and photons, and jets - all of which are tools for exploration and discovery at the LHC.** An important milestone for developing and **testing a full vertical chain of the front-end and back-end readout electronics system** of the HGCAL with real particles was achieved in the Summer of 2023 using the CERN SPS beam test facility. In parallel, offline simulation has been used to **study the amount and impact of deadtime and data truncation by the electronics system**. In this poster, I present challenges involved in operating the readout electronics of the HGCAL, and how that relates to the deadtime and/or data truncation performance expected for the full detector.

From readout electronics to physics inference

- Calorimeters are important to measure the energy, position, and time of charged and neutral hadrons as well as e± and γ.
- These are the building blocks of Jets (quarks & gluons), taus, Missing transverse energy (MET) etc. which are important discovery tools at the LHC.

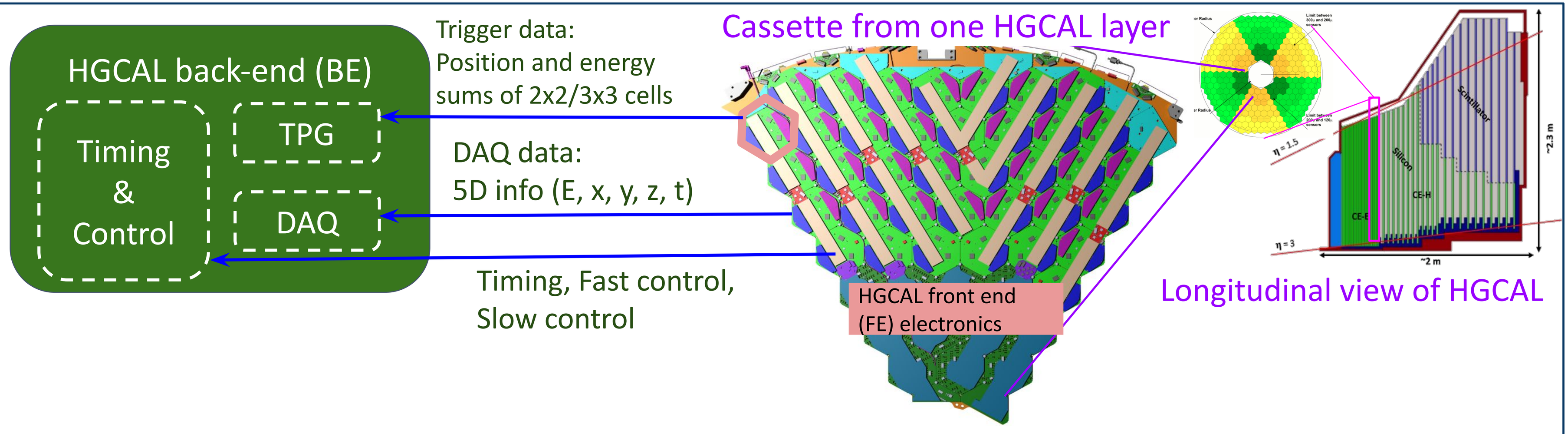


The measurable signal, as the particle traverses the detector, is eventually converted to an electric pulse which is shaped and digitized for further analysis and permanent storage.



Accuracy of offline reconstruction depends on performance & reliability of electronics systems.

HGCAL readout electronics system



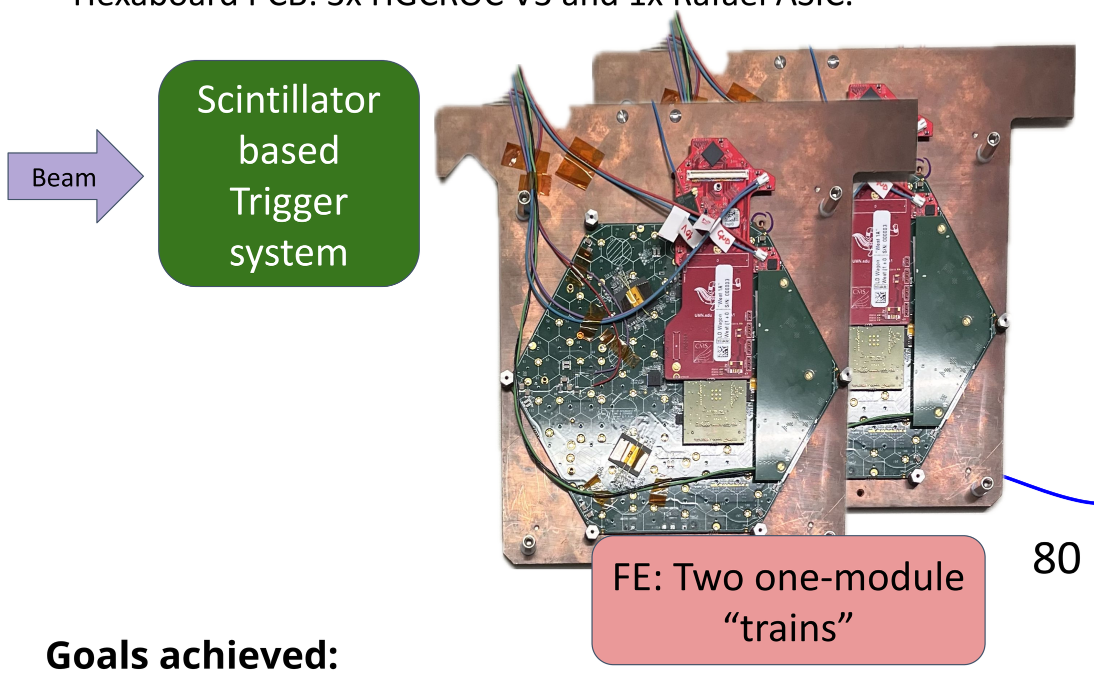
- The CMS High Granularity Calorimeter for HL-LHC comprises around 6 million readout channels.
- Data rates from on-detector electronics are about
  - O(100) Tb/s for Trigger primitives at 40 MHz, and
  - O(20) Tb/s (DAQ) at an L1 accept rate of 750 kHz.
- Complex electronics system: 3 HGCAL-specific ASICs across multiple boards.

Do the ASICs perform as needed?
Beam test measurements with real particles validate the integration of all different ASICs, boards, and their configurations and operation.

Will the system perform as needed?
Simulation-based studies (emulators) to investigate the effect of high trigger and data rates, rare cases of data loss from buffer overflow.

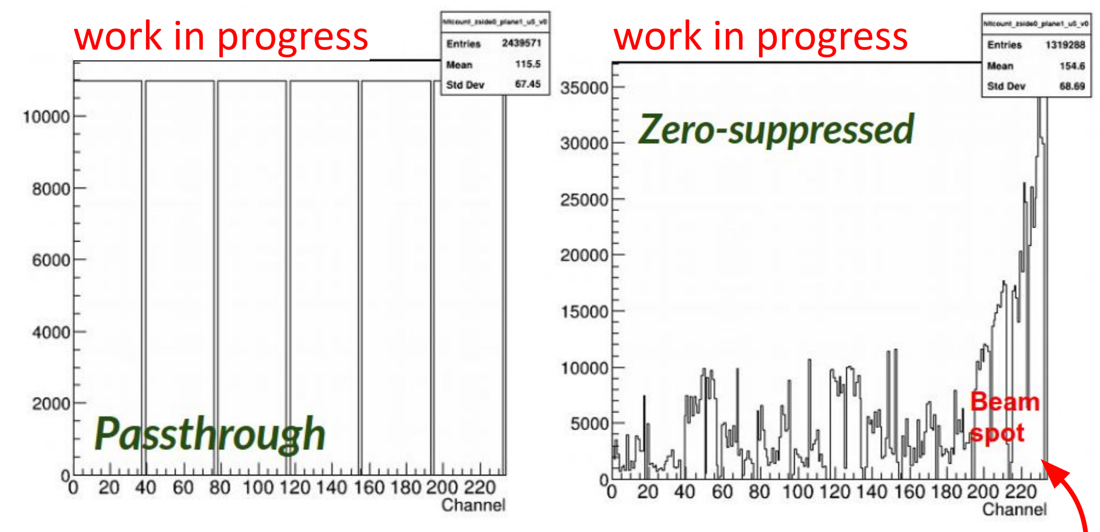
End-to-end validation of the HGCAL readout electronics chain

Two Si Modules (300 μm & 200 μm thick) biased at -270 V.
Hexaboard PCB: 3x HGCROC V3 and 1x Rafael ASIC.



Beam test experiments in Sep. 2023: exposed a full vertical slice of the HGCAL readout chain to particle beams for the first time.

- Two silicon trains with **Engine V3** (3x lpGBT V1 and VTRX+) and **Wagon PCB**,
- One ECON mezzanine per module with one **ECON-T**-P1 and **ECON-D**-P1.
- Silicon signal measured by **HGCROC** (amplitude and timing).
- **E**link **CON**centrators process data, build event packets, and send data to BE via **lpGBT**s.
- BE "**miniDAQ**" validates and saves raw event packets from ECON-D to disk using **Slink**.



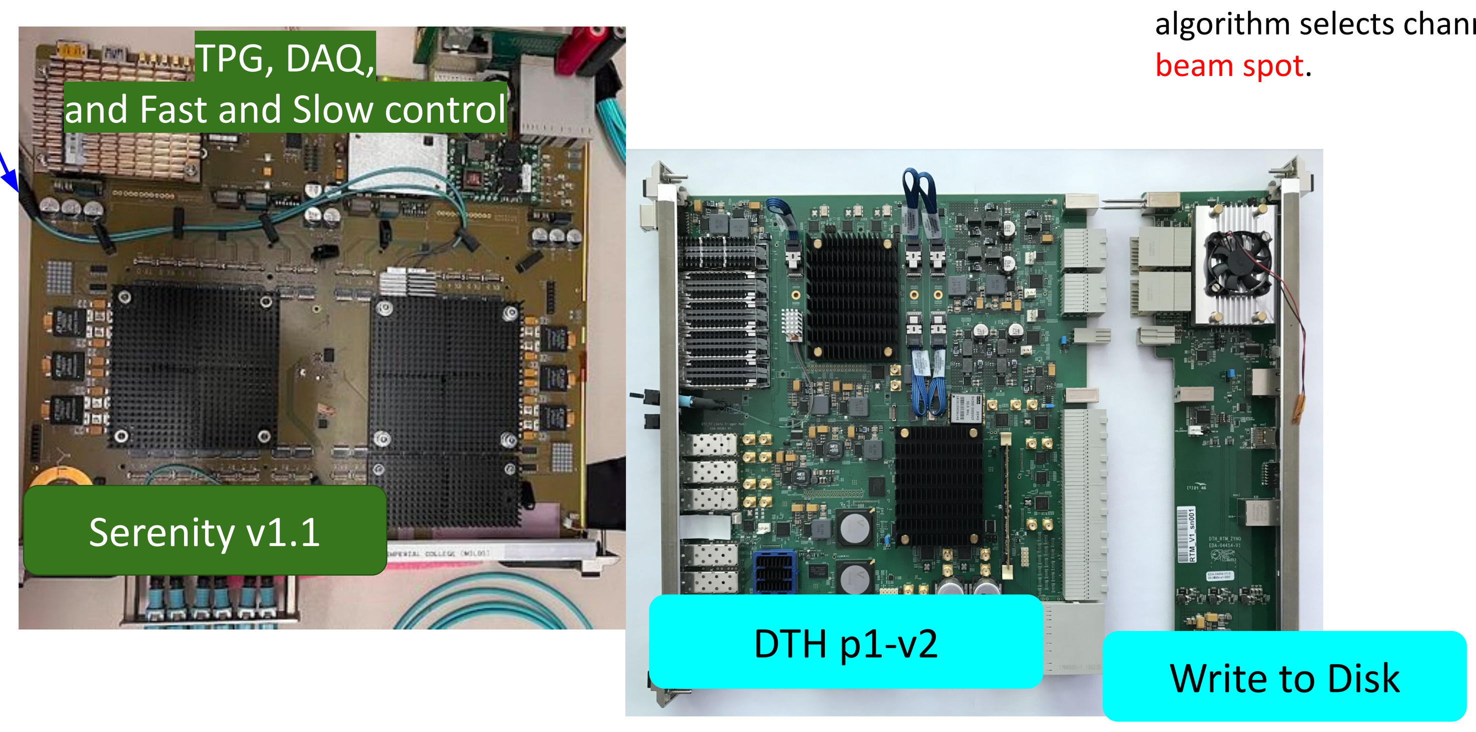
Effect of of zero-suppression: number of hits per channel read out without ZS applied (passthrough) and with ZS applied (right). The ECON-D ZS algorithm selects channels with above threshold, like those close to the beam spot.

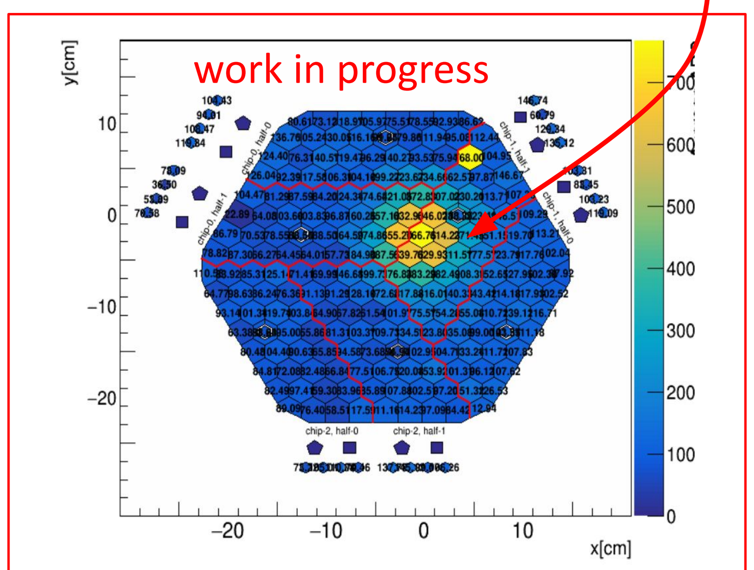
Goals achieved:

- System ran unattended without major data losses, capturing over 1 billion events with varied particle beams, calibration, and pedestal data, at up to 100 kHz rate.
- Tested two **ECON-T** algorithms and self-triggered using TPG data.
- Tested zero-suppression of DAQ data in FE using **ECON-D**.
- Tested **DTH** (non-HGCAL CMS board common to all Phase 2).

Ongoing efforts & next steps:

- Stress test the multiple interfaces: **BE** → **ROC** → **ECON-{T,D}** → **lpGBT** → **VTRX+** → **BE**.
- Verify event synchronization: examine timestamps across all ASICs and BE, and confirm consistency event-by-event.

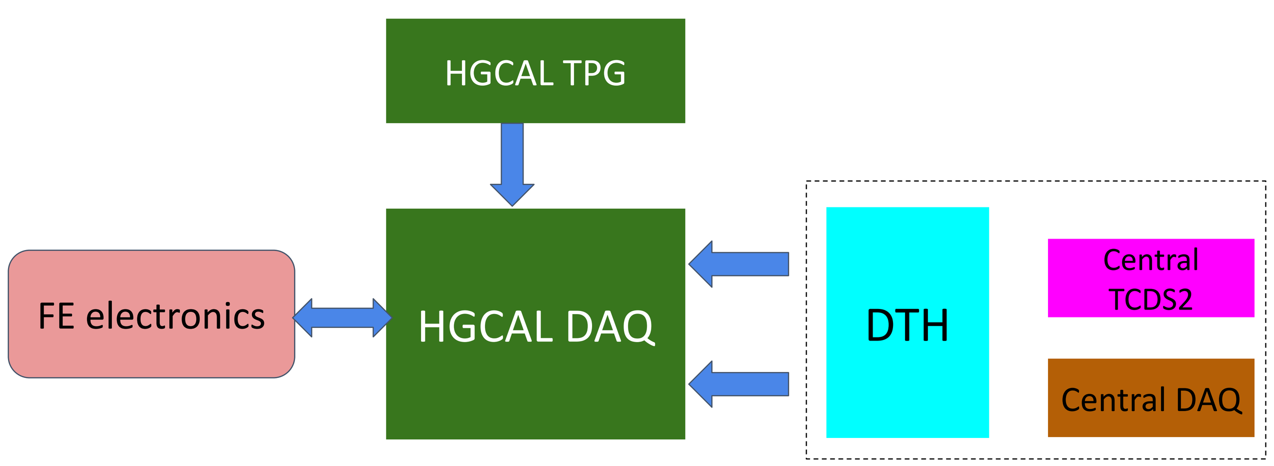




Standard deviation of ADC count distribution in different channels indicating the beam spot

Throttle or truncate? Software optimization of data loss studies for HGCAL DAQ

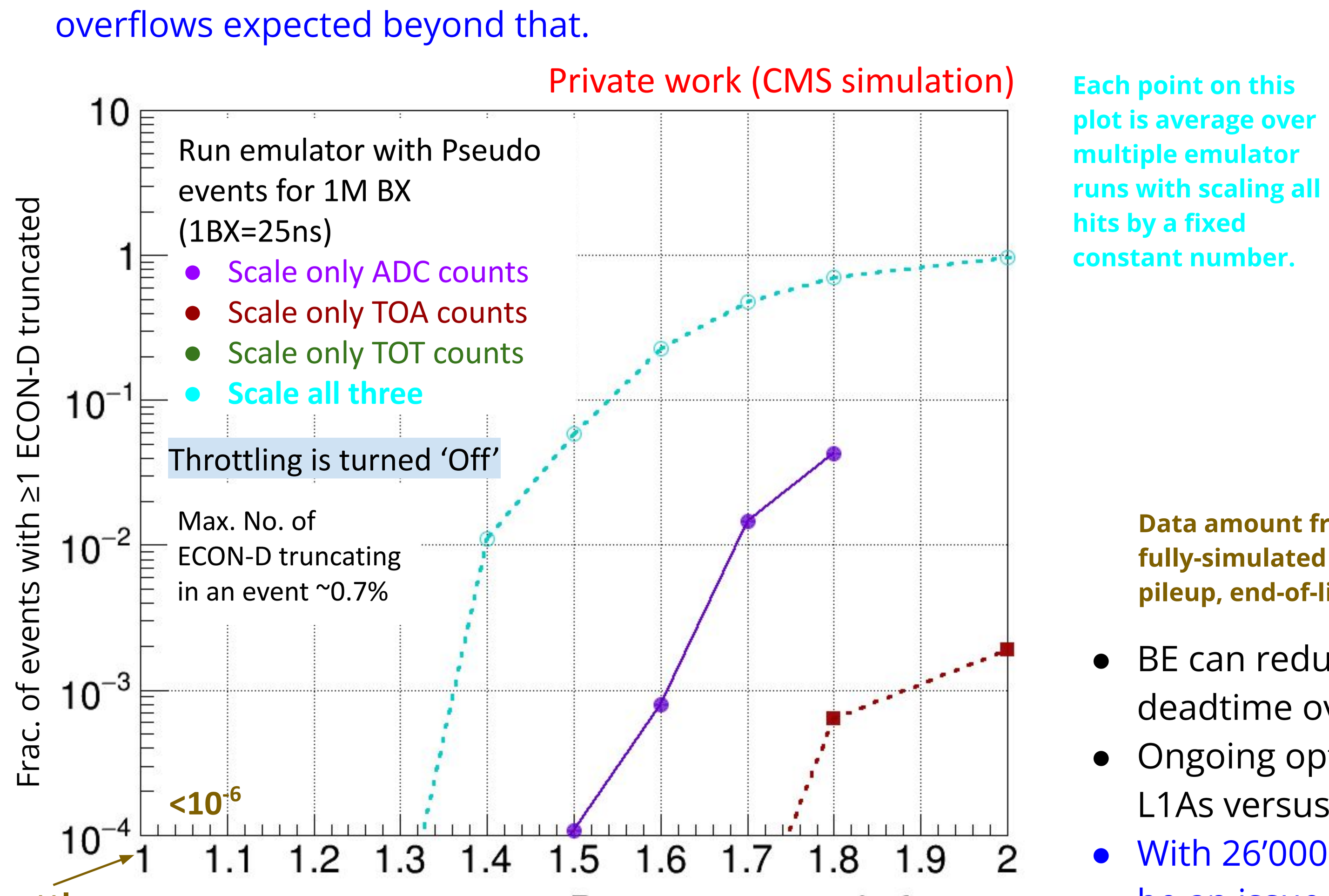
- Study ASIC buffer usage in terms of deadtime (global) vs. truncation (localised).
- C++ code simulates full readout chain (FE and BE Emulator).



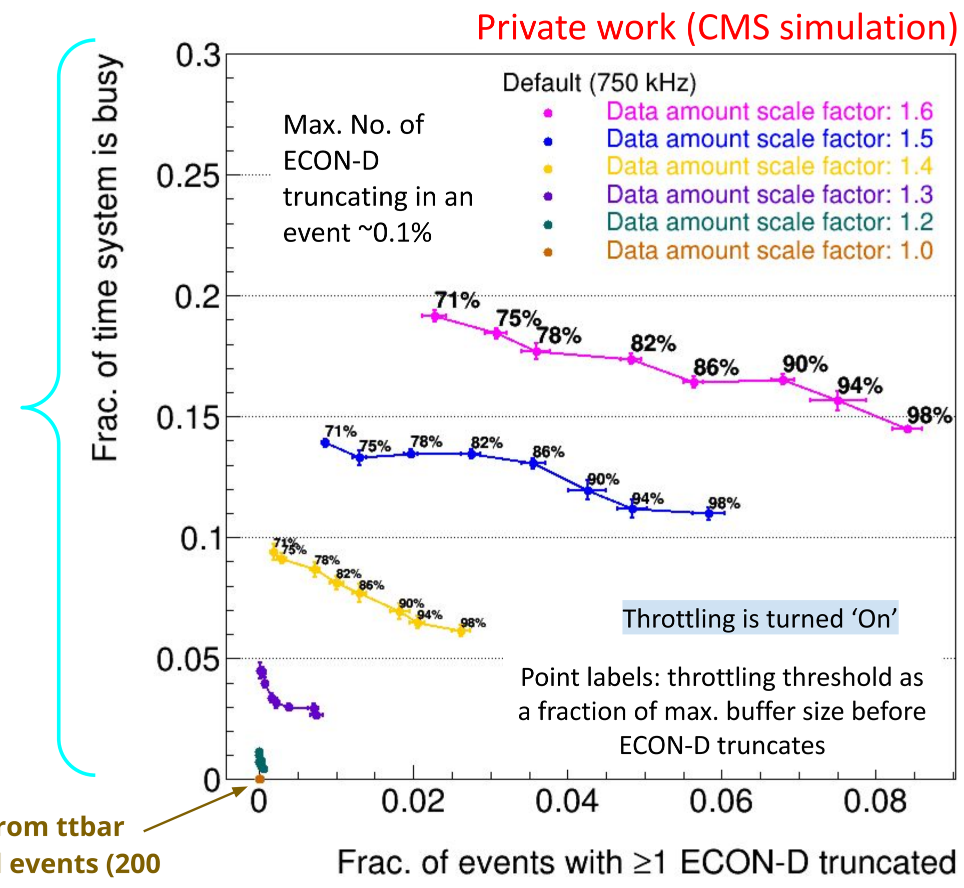
C++ based emulator for HGCAL readout system

- Need high-statistics for rare throttling cases at low dead time (<1%) and 750 kHz L1 rate.
- Create O(10^7) pseudo-events from O(10^5) ttbar fully-simulated events (200 pileup, end-of-life noise) that preserve the module-to-module occupancy correlations in HGCAL.

- The readout electronics system is optimized for average data rates.
- Fluctuations may lead to truncation (some ECON-D data may be lost) because of buffer overflows in different parts of the system.
- No data loss upto <1.3x average rate increase, but ECON-D buffer overflows expected beyond that.



Data amount from ttbar fully-simulated events (200 pileup, end-of-life noise).



Data amount from ttbar fully-simulated events (200 pileup, end-of-life noise).

- BE can reduce truncation by throttling CMS L1As but this raises deadtime overall for the experiment.
- Ongoing optimization to determine the logic to be used to throttle L1As versus when to allow for more extensive truncation.
- With 26'000 ECON-D spread across 47 layers, truncation may not be an issue but it is crucial to avoid projective areas being truncated.

Conclusion

- After running the entire DAQ chain, valuable data was collected, and a thorough follow up of failure modes is taking place.
- Insights gained from this beam test will significantly contribute to the final system's construction.
- Optimizing deadtime versus incomplete events (with truncated data) are crucial for system-level validation.

Acknowledgement

The successful execution of the beam test was only possible through concerted efforts and collaboration involving a substantial number of individuals and this work is part of a collaborative endeavor undertaken by the **CMS-HGCAL collaboration.**
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