IMPERIAL

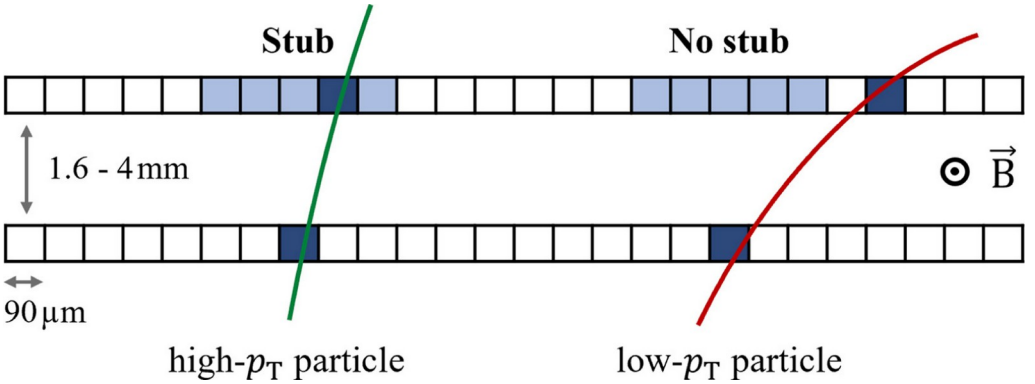
Commissioning of the CMS Phase-2 Tracker Cosmic Test Stand

April 8th 2026

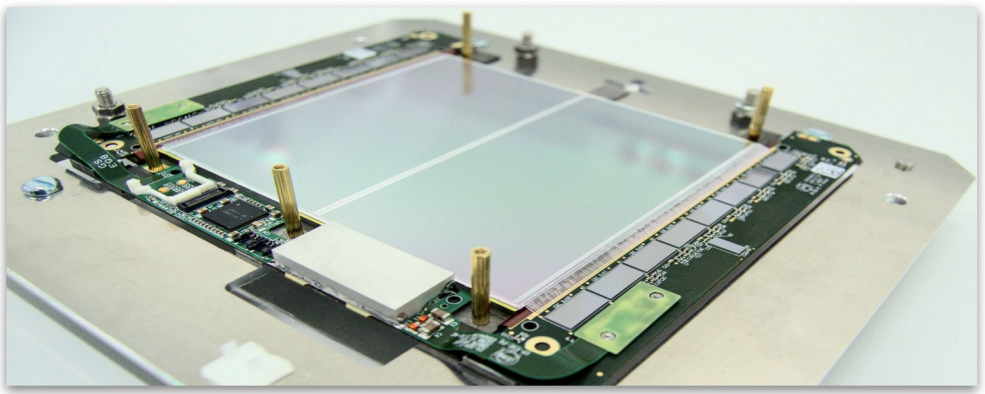
Andrew Mastronikolis

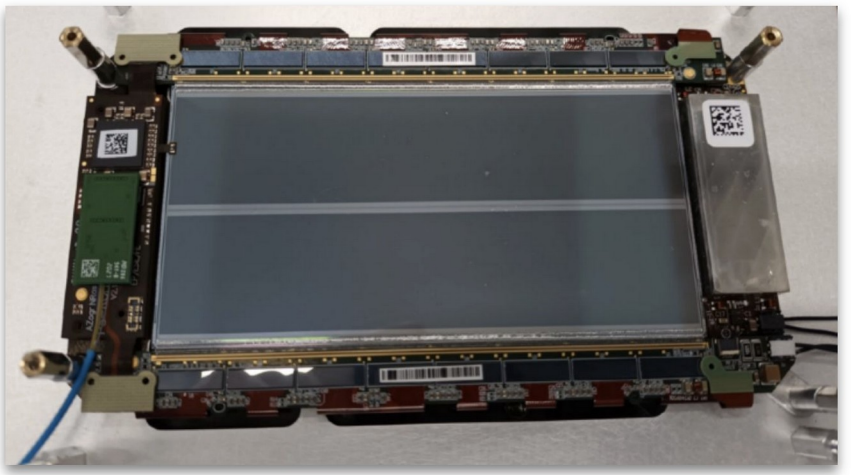
Introduction to CMS Phase 2 Outer Tracker

- The Phase 2 Outer Tracker systems consists:
  - 13,200 Silicon pT Modules.
  - 2S-Modules & PS-Modules
- Transmit two types of objects: Stubs and Clusters.
- A "Stub" is simply a set of 2 clusters within a window
- Modules transmit stubs at 40MHz
- Modules send full cluster data upon L1A
- New Upgrade Feature: Tracks Reconstructed Online!



2S pre-production module



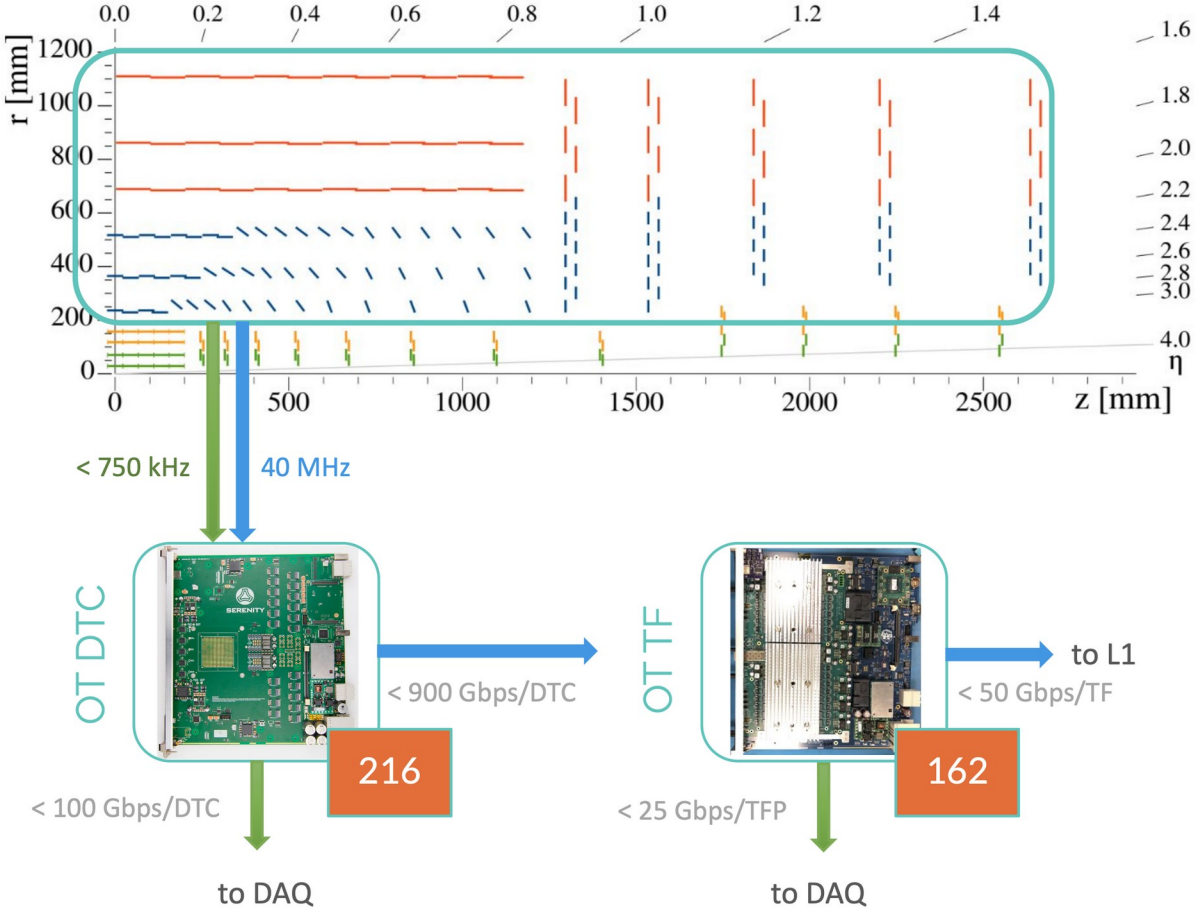


PS pre-production module

Introduction to CMS Phase 2 Outer Tracker Backend Systems (I)

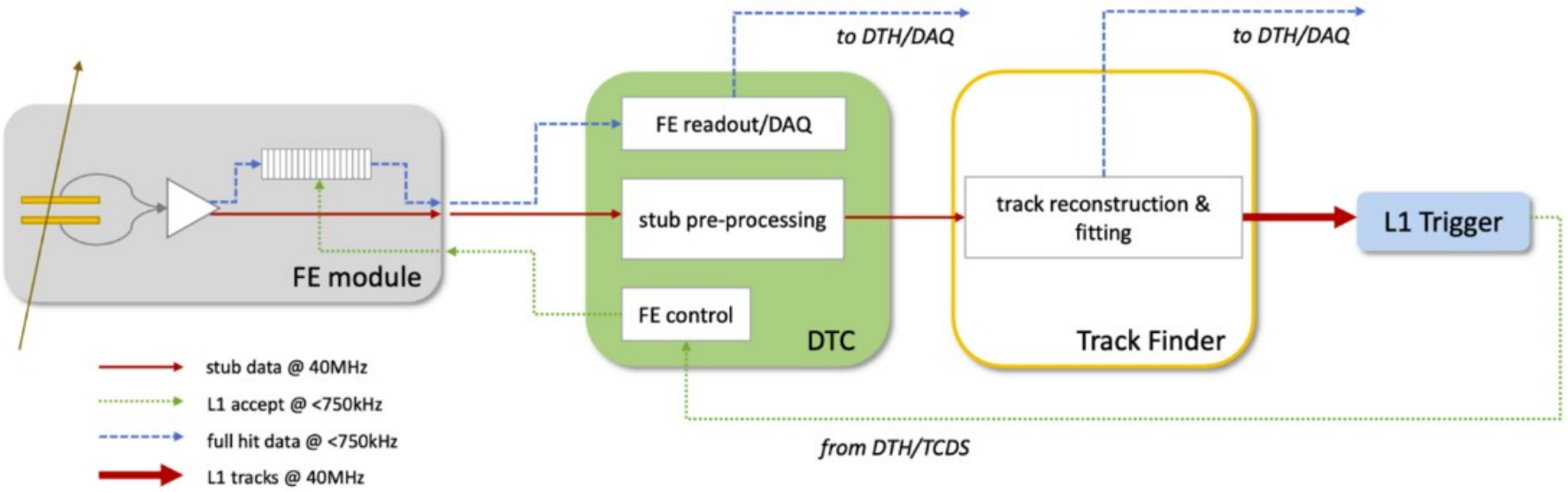
Outer Tracker Backend composed of two stages:

- Data, Trigger and Control (OT DTC) Boards.
  - Uses **Serenity** Platform
  - Employs 128 Channels for Optical I/O
  - Single FPGA on Board.
- Track Finder System (OT TF)
  - Uses **Apollo** Plaftform
  - Employs two FPGAs on Board.
- Total of 378 Blades needed @ P5 in ATCA Crates.
- **A 738 Gb/s event processor (Output to L1) !**



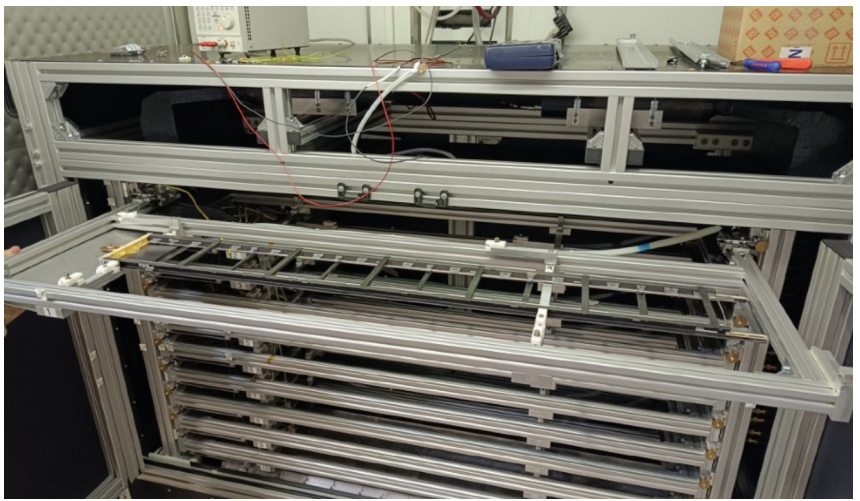
Introduction to CMS Phase 2 Outer Tracker Backend Systems (II)

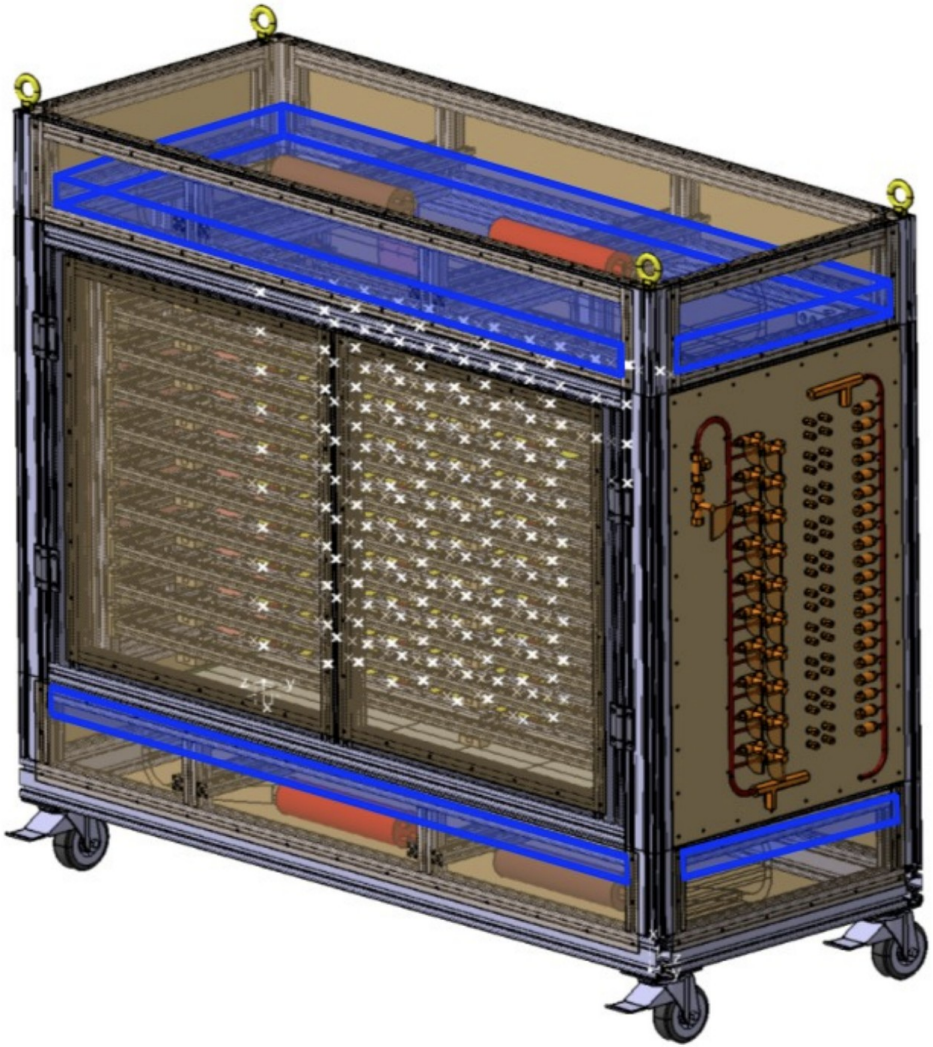
- L1 builds physics objects.
  - e.g. **Vertex Finding** and **Jet Clustering**
- Global Trigger issues an L1A for a specific event.
- L1A arrives at the DTC boards, which forwards the signal to front end modules.
- Front Ends have a SRAM memory that saves 512 BX (25 ns) of information.
- This implies that computing has to happen within 12.5 microseconds from the original event.
- Upon recenption of L1 packets from the front ends, **DTC perfroms event building** and routes everything off to DAQ.
- Full Trigger & DAQ Chain was never exercised before 2026 (with physics).



Introduction to the CMS Phase 2 Cosmic Stand (Front End)

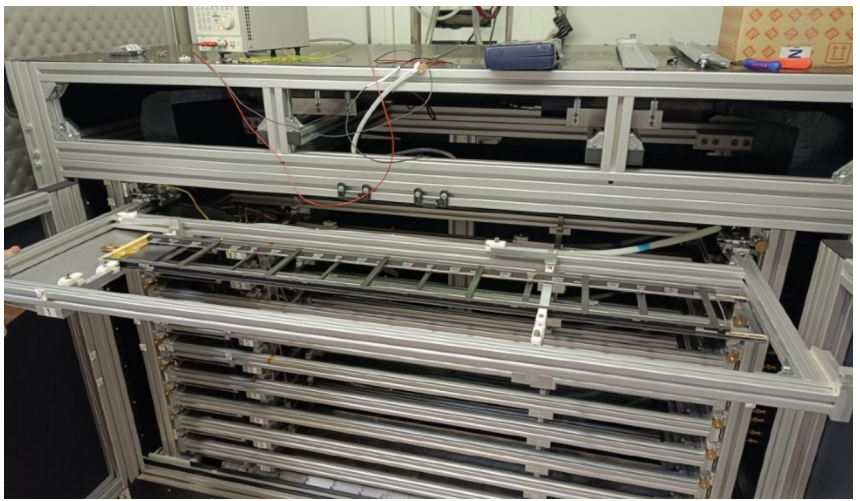
- CMS Cosmic Stand (or Rack) or **CRACK**
  - **Fundamental Goal:** Exercise the Full TDAQ Chain.
  - Use Cosmic Muons to do this.
- Components (Front End)
  - Vertical assembly of **72 2S Modules** (currently 48 only)
  - Two plastic scintillators (blue, top and base)
  - Four PMTs (red, top and base)
  - The top and base scintillators are connected to their two respective PMTs.
  - Electrical signals from PMTs fed to the CRACKs backend system (next slide)





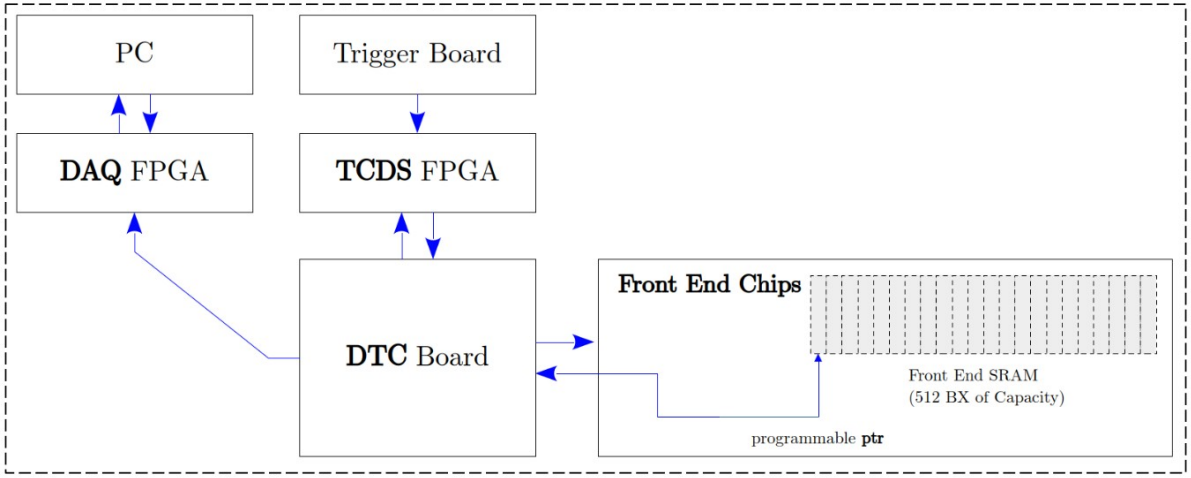
Introduction to the CMS Phase 2 Cosmic Stand (Front End)

- CMS Cosmic Stand (or Rack) or **CRACK**
  - **Fundamental Goal:** Exercise the Full TDAQ Chain.
  - Use Cosmic Muons to do this.
- Components (Front End)
  - Vertical assembly of **72 2S Modules** (currently 48 only)
  - Two plastic scintillators (blue, top and base)
  - Four PMTs (red, top and base)
  - The top and base scintillators are connected to their two respective PMTs.
  - Electrical signals from PMTs fed to the CRACKs backend system (next slide)

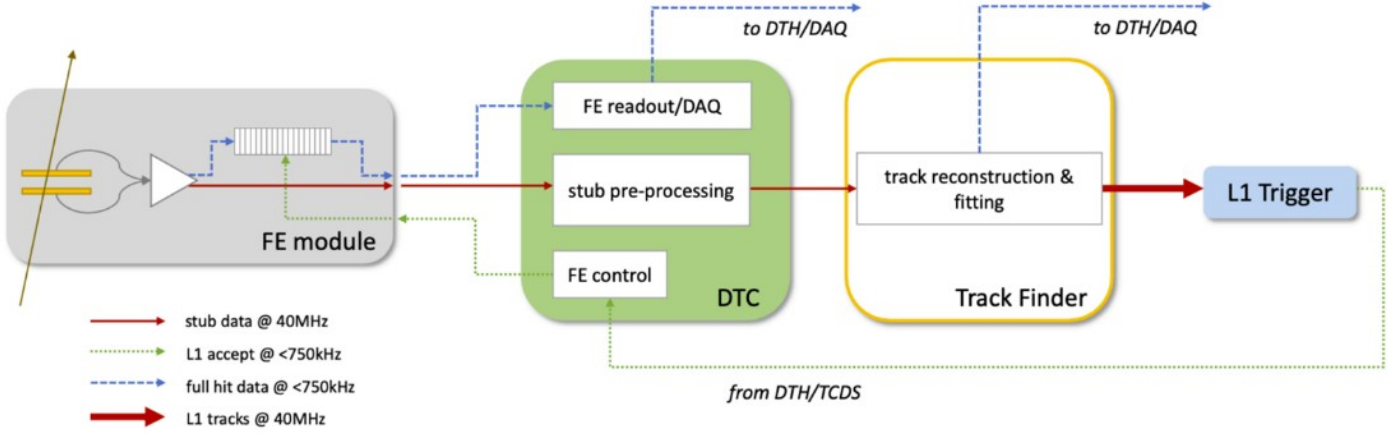


Introduction to the CMS Phase 2 Cosmic Stand (Backend)

- CRACK Backend (Top Picture)
  - Two Types of Boards: Serenity and DTH P2
  - Trigger Board (Input from CRACK PMTs)
  - TCDS FPGA (**DTH Board**, Trigger Handling and Clock Distribution)
  - DTC Board.
  - DAQ FPGA (**DTH Board**, Further Event Aggregation)



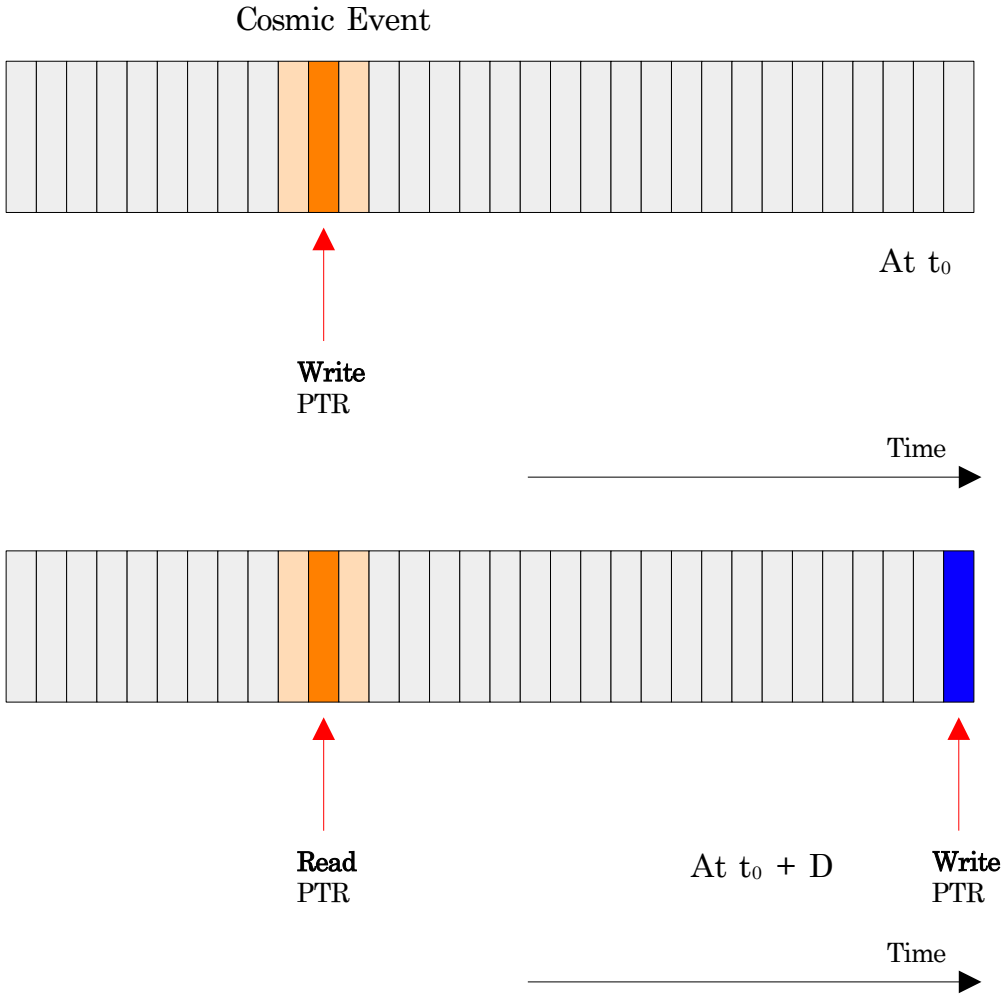
CRACK TDAQ Architecture



CMS TDAQ Architecture

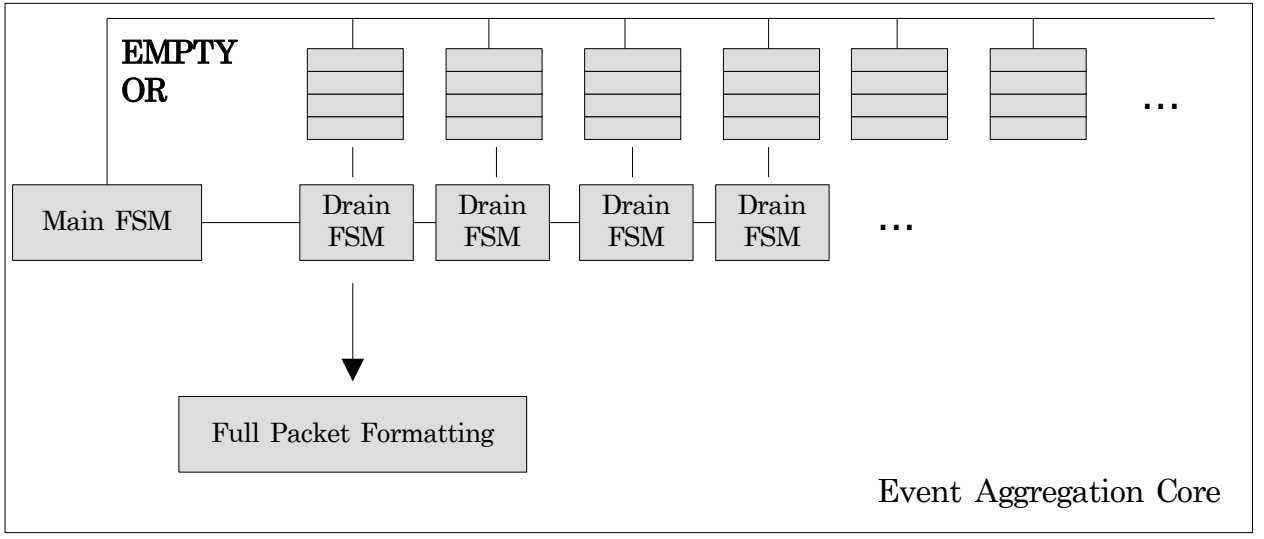
Brief Review of Front End Chip Architecture

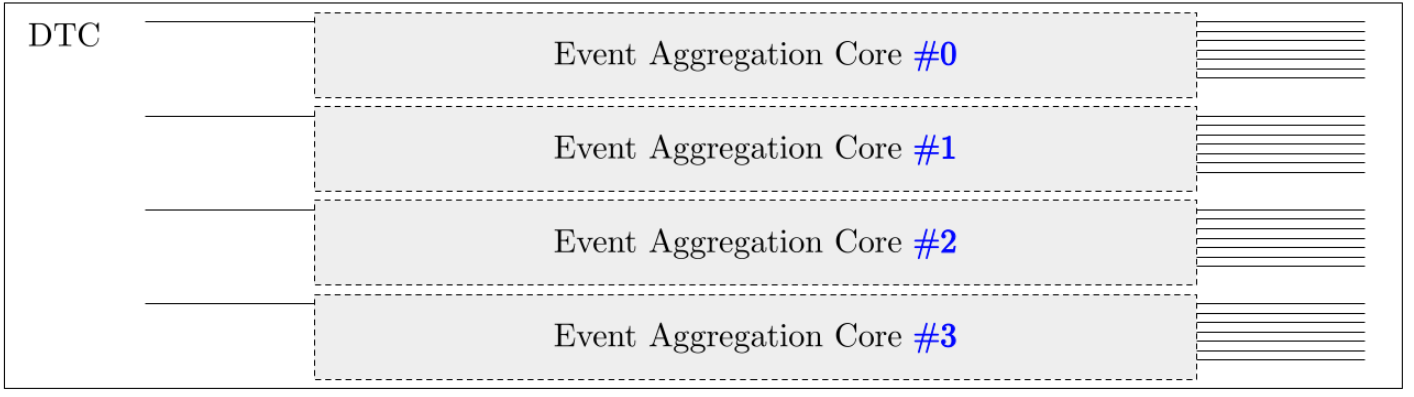
- Each front end chip contains a buffer SRAM that can save up to 512 Events (BX := 25ns) worth of data.
- When a cosmic passes through, it leaves detector hits (orange) and at the same time, triggers the PMTs.
- By the time the L1A reaches the front end, write slot has drifted to the right (**blue**)
- Read PTR is programmable and can be set to be any value in [0, 512] BX.
- A "Latency Scan" should yield a peak, since physics event and the delay are correlated.



Brief Review of DTC DAQ Firmware Architecture

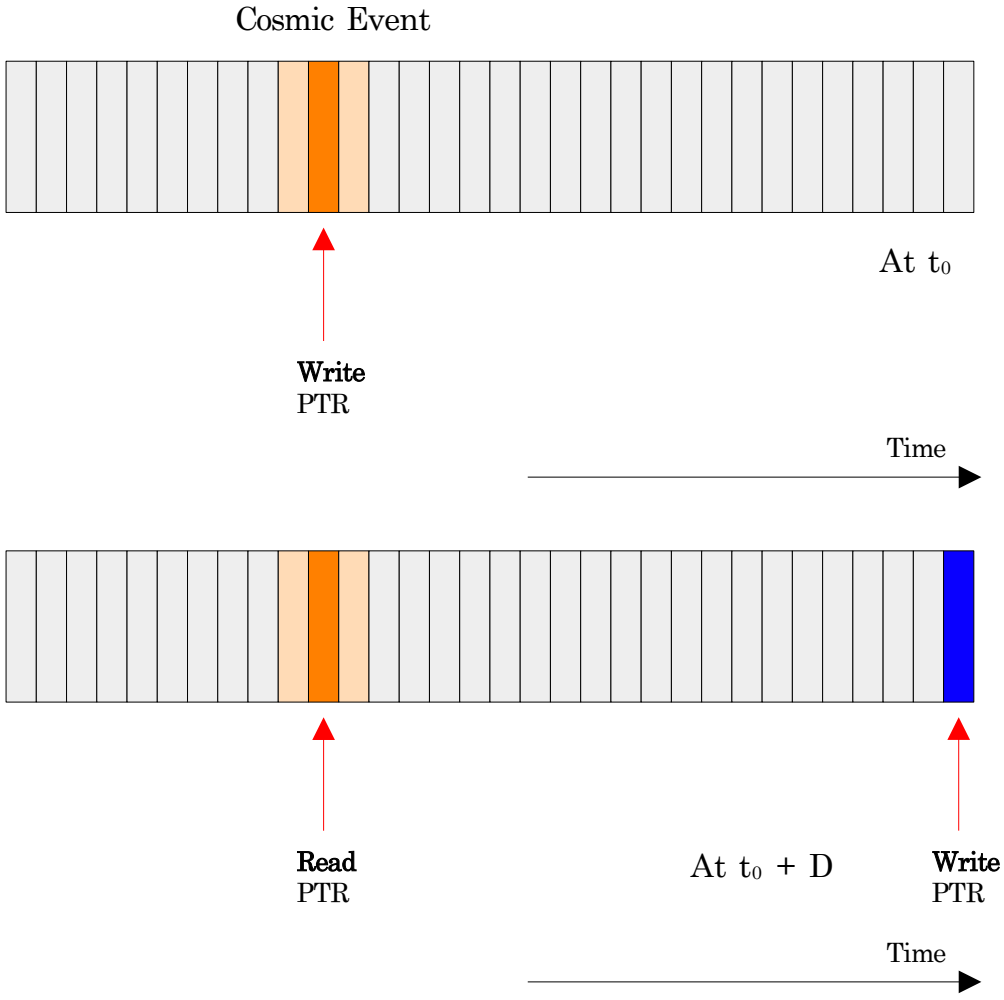
- For event building on the DTC, a **token ring** is implemented.
- Token is passed around each Front End FIFO on the FPGA, collecting data for that event from that link.
- Each firmware unit that performs aggregation over N links is called a **Event Aggregation Core.**
- OTC DAQ is implemented in 4 distinct Cores that aggregate 18 Front-End links each (72 in total)





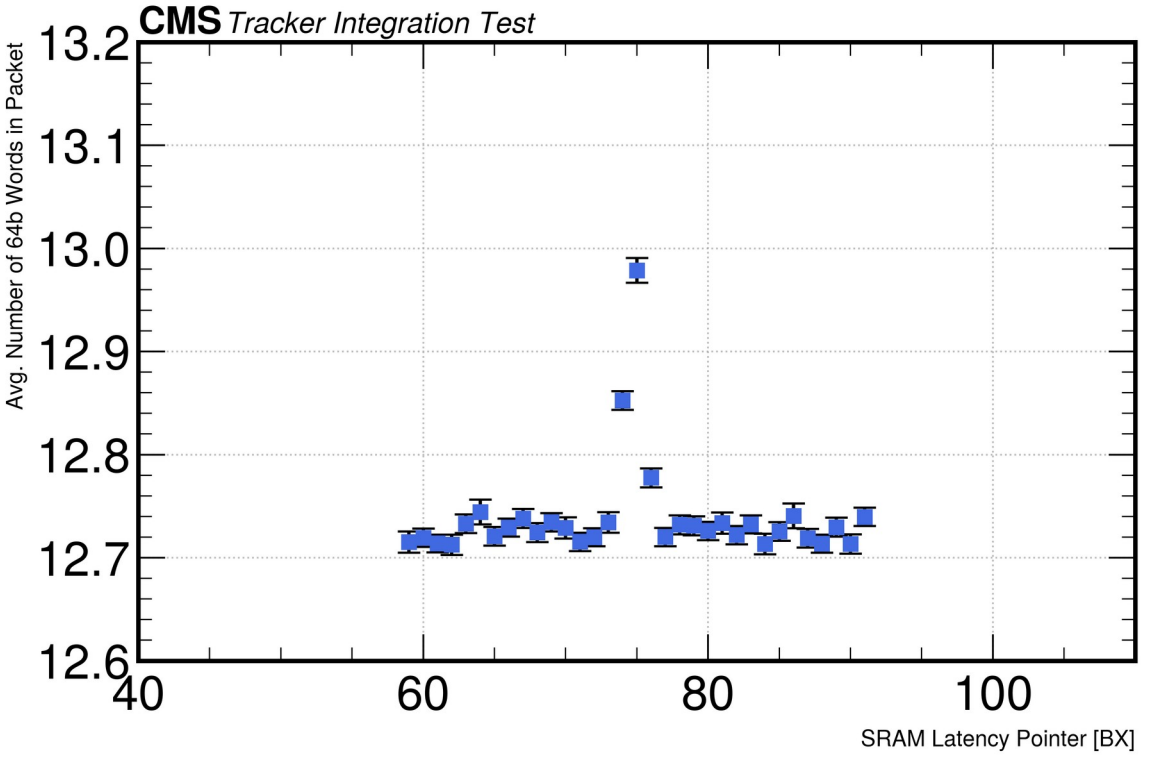
Quick Review of TDAQ

- ✔ We can send triggers to the front ends via PMT trigger signals
- ✔ We can perform event based aggregation on the returned packets from the front end, **in a scalable manner.**
- One thing left to do:
  Directly measure the packets sizes (as a proxy for detector activity) vs. latency read addresses in the SRAM.
- **If things were done right**, we should observe a clean peak at one address, **that corresponds to physics.**



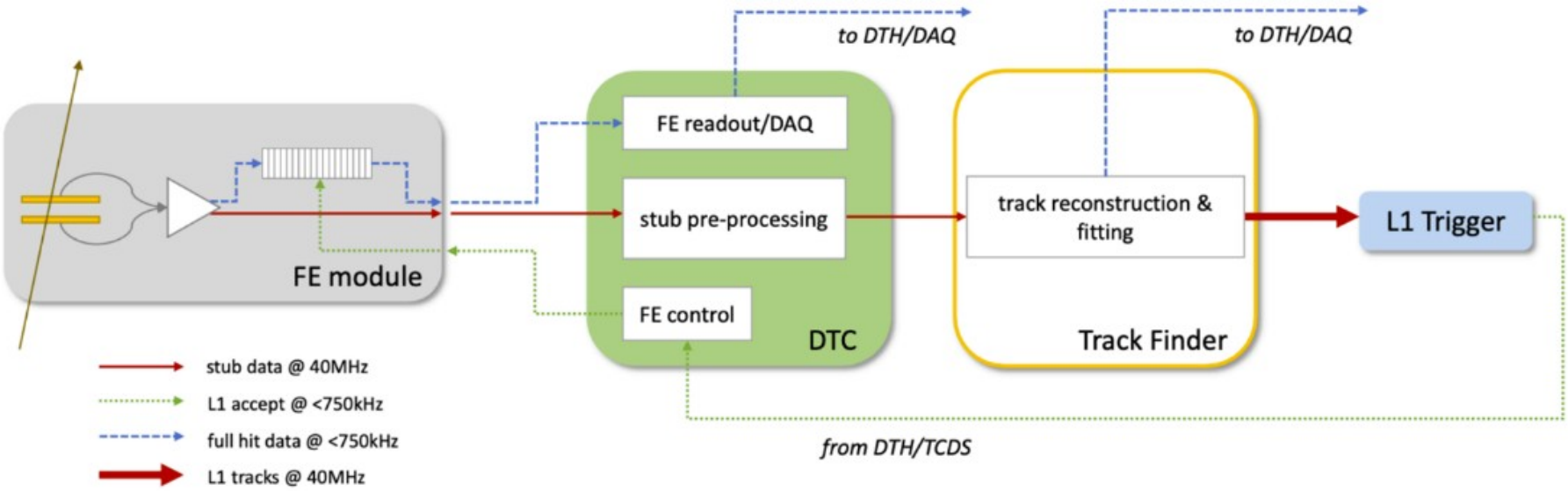
Calibrating the Cosmic Stand with Physics

- Procedure:
  - Look at an average of # of 64b words @ each SRAM address.
  - Plot the entire spectrum.
- Peak observed in latency scan @ 75 BX behind the write pointer.
- Plotting purely average packet size at each point.
- Read out from **3 Event Aggregation Cores**, each one aggregating 12 Links.
- Covers 50% of the DTC.



Conclusion and Next Steps

- We have exericsed, for the first time, a full Trigger & DAQ chain in the CRACK, using a single physics trigger channel.
- Validates the core design principle of CMS Outer Tracker for the Phase 2 Upgrade, although at lower rate (10 Hz)
- Used bleeding edge hardware, firmware and software.
- **Next Steps:**
  - Developing online software for control and performing long physics runs.
  - Perform tracking studies and module performance plots from the DAQ route.



IMPERIAL

Thank you

And many thanks to:
- Giacomo Fedi
- Michelangelo Pari
- Giovanni Zevi Della Porta
- Matteo Magherini
- David Gabiel Monk
- Mark Pesaresi