The Barrel Muon Trigger system of CMS in Phase-2 - Design and Performance

HEP2022 - 39th Conference on Recent Developments in High Energy Physics and Cosmology, Thessaloniki, Greece

15.06.2022

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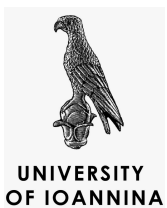

Outline

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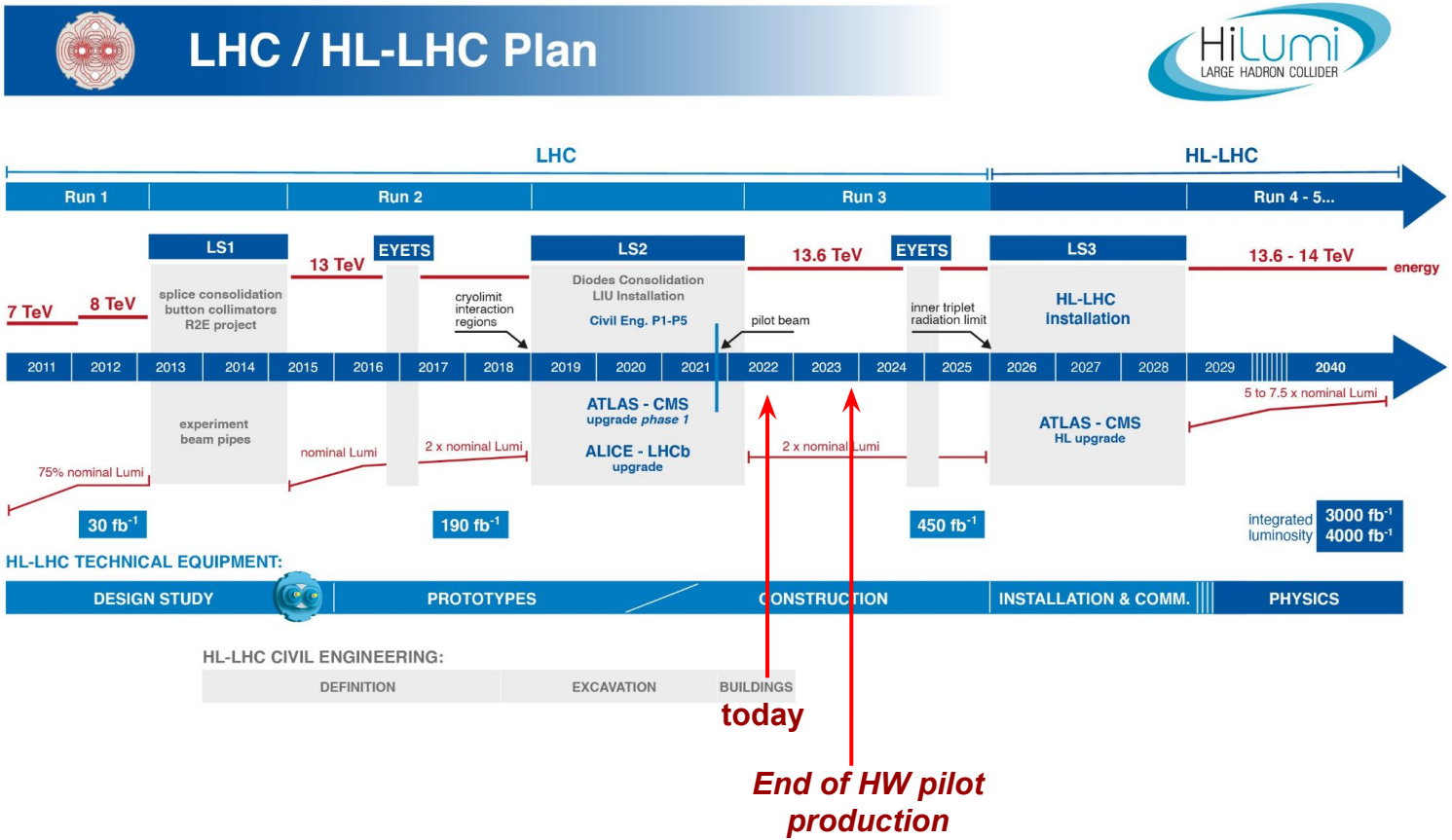
- Phase-2 Level-1 Trigger of CMS Experiment
- Barrel Muon Trigger system in Phase-2
- Hermes and CSP optical protocols
- BMT Layer-1 Hardware and Firmware
- Barrel Muon Trigger slice tests
- Future Plans

Updated LHC/HL-LHC Plan



CMS Phase-2 Trigger System

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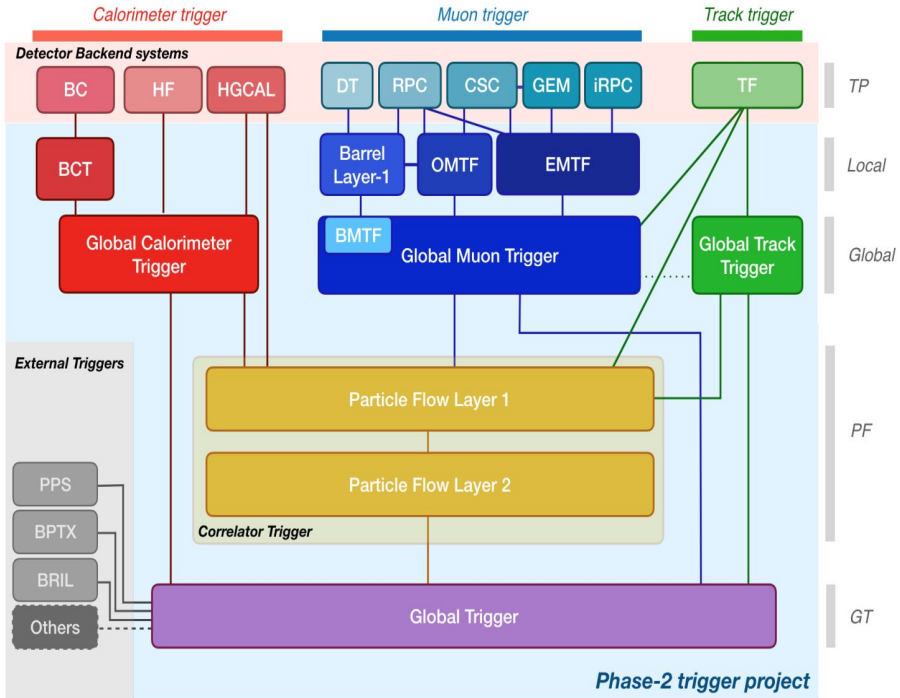
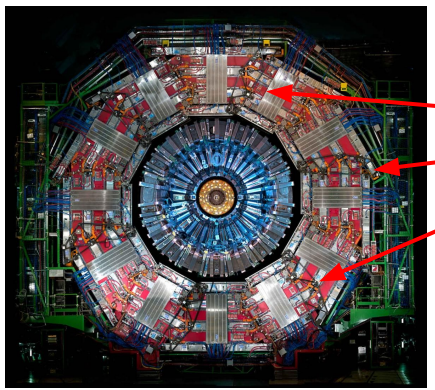
Four independent data processing paths

- Calorimeter Trigger Path
  - **Builds calorimeter-only objects**
  - e/γ, tau leptons, jets and energy sums
- Muon Trigger Path
  - Reconstructs **muon candidates**
- Track Trigger Path *(not present in Phase-1)*
  - **Reconstructs tracks** of charged particles
- Particle-Flow Trigger path *(not present in Phase-1)*
  - Implements sophisticated algorithms to **produce higher-level trigger objects**
  - Provides a sorted list of objects to the Global Trigger
- Global Trigger
  - Receives outputs of the four Trigger paths
  - **Runs physics menu** of algorights
  - Calculates the **trigger decision - accept or ignore** an event

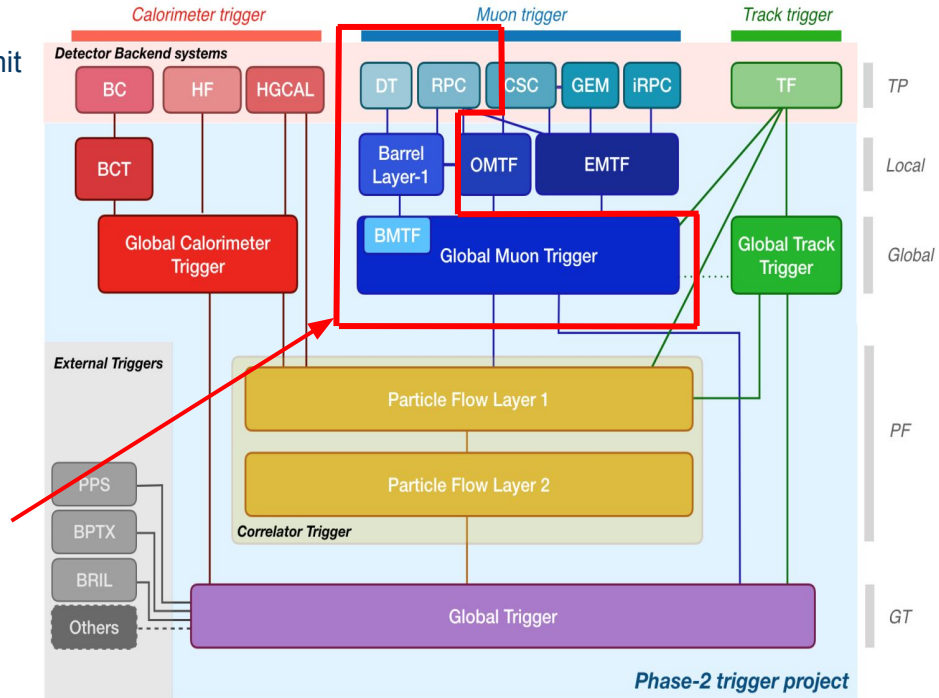


Barrel Muon Trigger Structure - 1

- Barrel Muon Trigger (BMT) **reconstructs Muons** of the CMS Barrel
- **On-Detector**
  - Drift Tubes (DT) and Resistive Plate Chambers (RPC) transmit Muon hits to the BMT Layer-1
- **BMT Layer-1** (BMTL1)
  - Builds DT track segments and clusters RPC hits
  - Merges both sub-system information to the combined "super-primitives"
- **Global Muon Trigger** (GMT)
  - Matches track segments to reconstruct standalone Muon objects

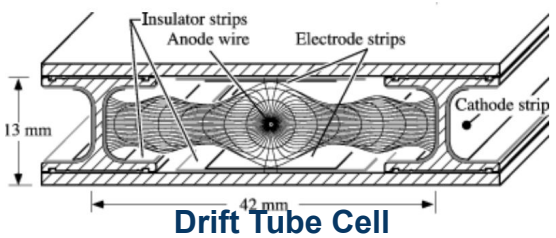


Barrel Muon Trigger



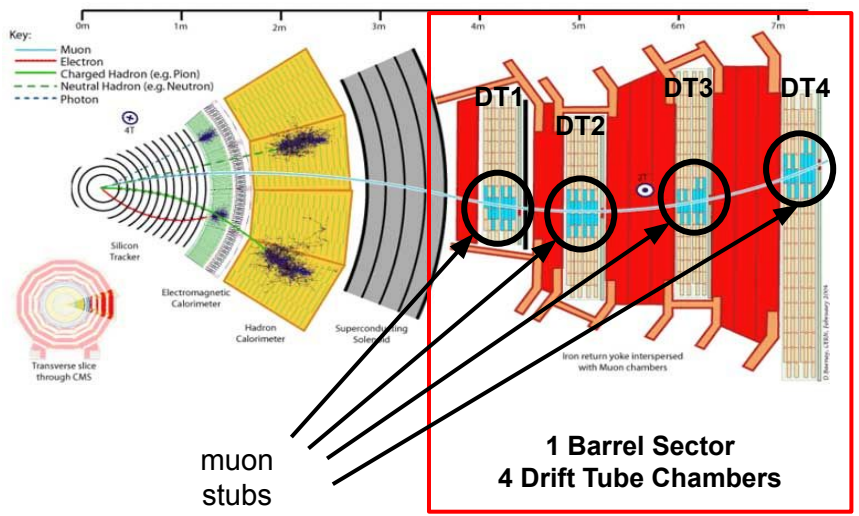
Barrel Muon Trigger Structure - 2

- "On detector Board for Drift Tubes" board (**OBDT**) transmits detector data to BMTL1
  - Responsible of the **time digitization of the DT signals**
- BMTL1 processes hits information per one DT Chamber
  - Analytical Method (AM) algorithm **produces muon stubs (track segments)**
    - Bunch Crossing, Stub Position & Bending Angle
- Stubs of the 4 Chambers are received in the GMT
  - Kalman Muon Track Finder (KMTF) algorithm matches tracks and **reconstructs Muon candidates**
    - Assigns them Position and Momentum



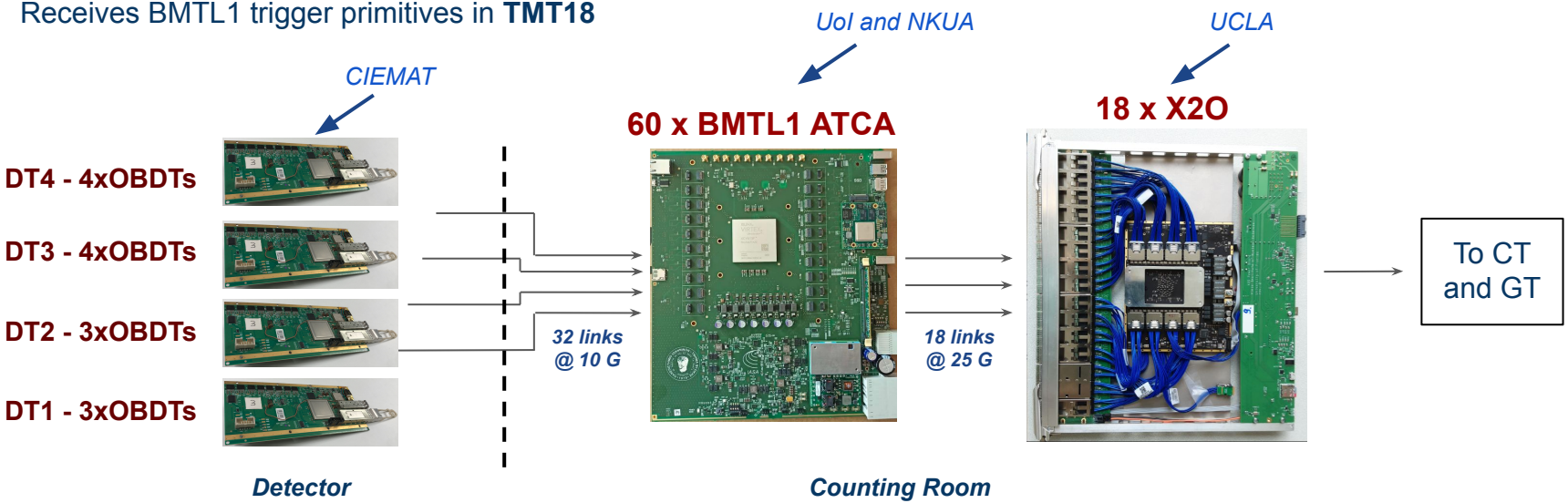
Drift Tube Cell

Detector		BMTL1 AM algorithm	GMT KMTF algorithm
Drift Tube Barrel Sector	Hits on Chamber 4	Stubs of Chamber 4	Reconstructed Muons of Sector
	Hits on Chamber 3	Stubs of Chamber 3	
	Hits on Chamber 2	Stubs of Chamber 2	
	Hits on Chamber 1	Stubs of Chamber 1	



Barrel Muon Trigger Structure - 3

- CMS Barrel Muon system consists of **60 DT Sectors**
  - 4 DT Chambers each
- OBDT board transmit TDC hits to BMTL1
  - About **14 OBDTs per DT Sector**
- Every BMTL1 board process information from 1 Sector
  - **60 BMTL1 boards needed** for the whole Barrel
- GMT consists of **18 X2O boards** in total
  - Receives BMTL1 trigger primitives in **TMT18**



Synchronicity and Data processing in CMS

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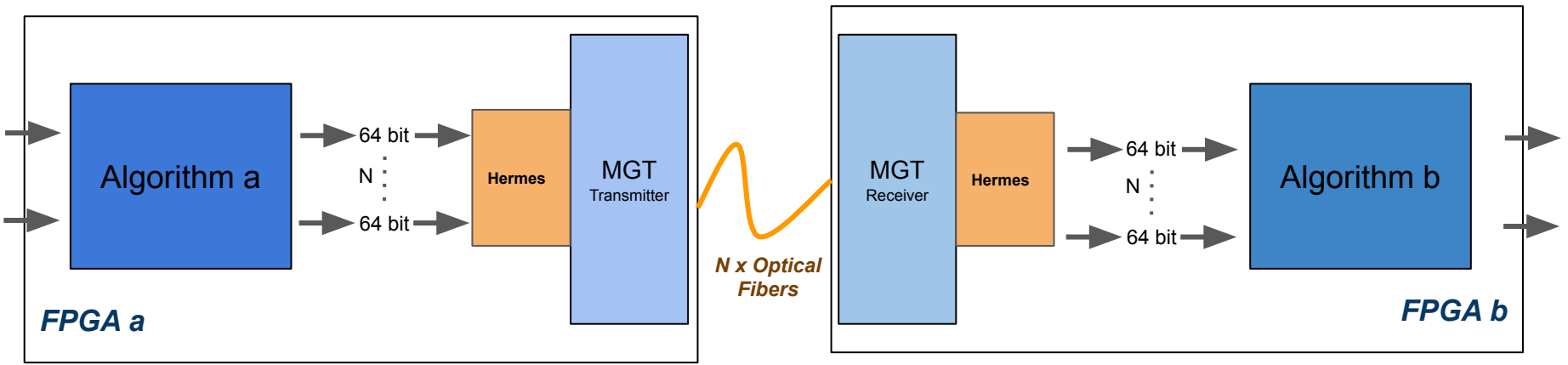
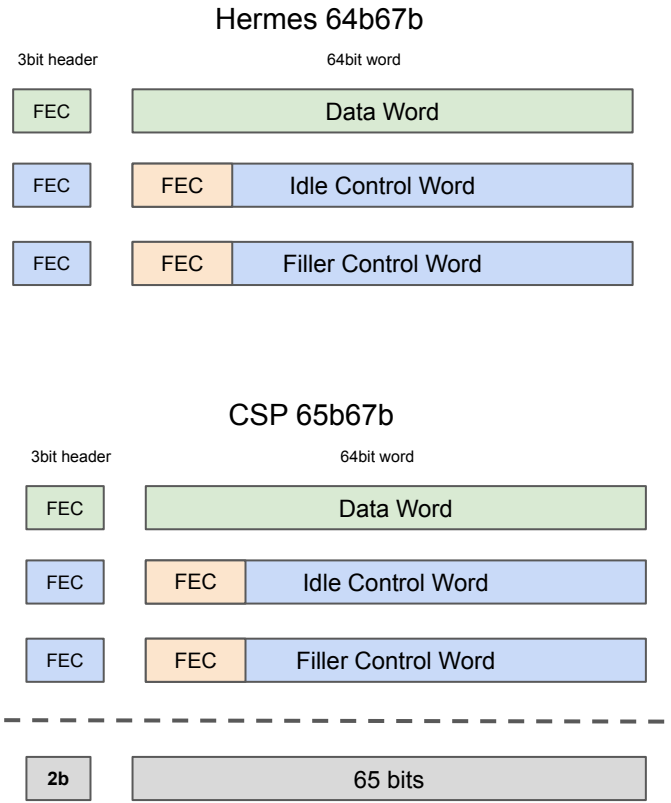
- CMS subsystems must be **synchronous with the LHC 40 MHz clock**
  - Subsystems must **be aware of which Bunch Crossing data they process**
- Trigger Algorithms run on FPGAs and **process 64bit data words**
  - Data are **received from previous processing stage**
  - The algorithm block **runs the necessary processing**
  - Produced data are **transmitted to the next subsystem**
- This operation must be **synchronous with the LHC clock**
- To transfer data two FPGAs must run the **same optical Protocol**
  - Optical Protocols utilize the Xilinx FPGAs **MGT Transceiver devices**



Hermes and CSP

- **Hermes** was a joint project between University of Ioannina and the Imperial College of London
  - **Optical link protocol** running at 16 and 25 Gbps
  - Physical layer runs **asynchronously wrt the processing clock**
  - User data delivered synchronously wrt to the LHC clock
  - **Reliable data transmission protected from synchronization loss**
  - Devotes all payload bandwidth to the transmission of physics data
- Hermes and Iridis (UW) were merged to the **CMS Standard Protocol (CSP)**
  - Common syntax - different VHDL implementations
  - Includes advantages of both protocols
  - Uses two FEC mechanisms and scrambles the 65th bit to achieve DC balancing
- **CSP will be used by all Level-1 Trigger ATCA cards**



BMTL1 Hardware Developments

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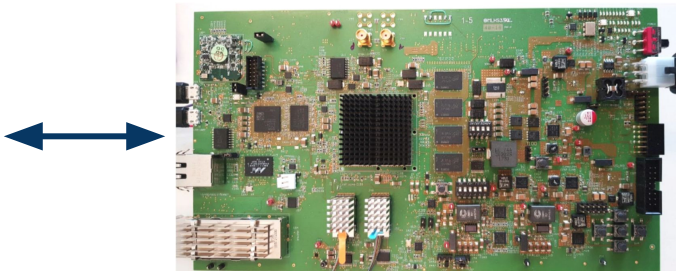
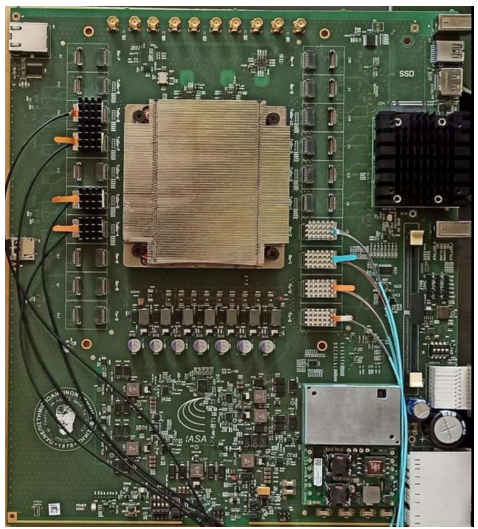
- BMTL1 Demonstrator
  - First hardware platform developed by the group (2019)
  - Kintex Ultrascale **KU040 FPGA**
  - 16 Optical Links @ 16G
    - 12 via Samtec Firefly
    - 4 via QSFP
  - Simple clocking network
  - No form factor



- BMTL1 ATCA card
  - Full functionality ATCA card
  - Virtex Ultrascale Plus **VU13P FPGA**
  - 40 Bidirectional Optical Links @ 25G via Samtec Firefly
  - 80 Rx & 36 Tx Optical Links @ 16G via Samtec Firefly
  - ZYNQ SoC to control FPGA & peripherals
  - Complex multipurpose clocking network
  - And more



BMT Slice Tests

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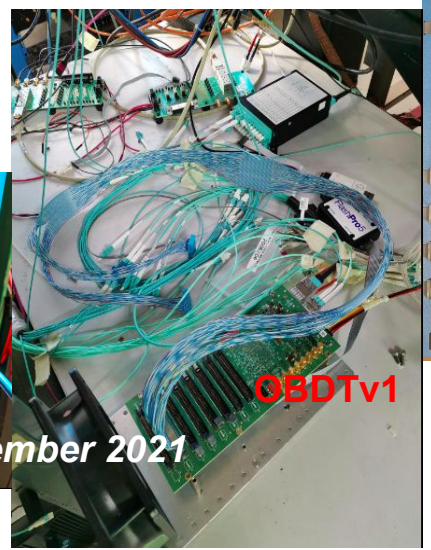
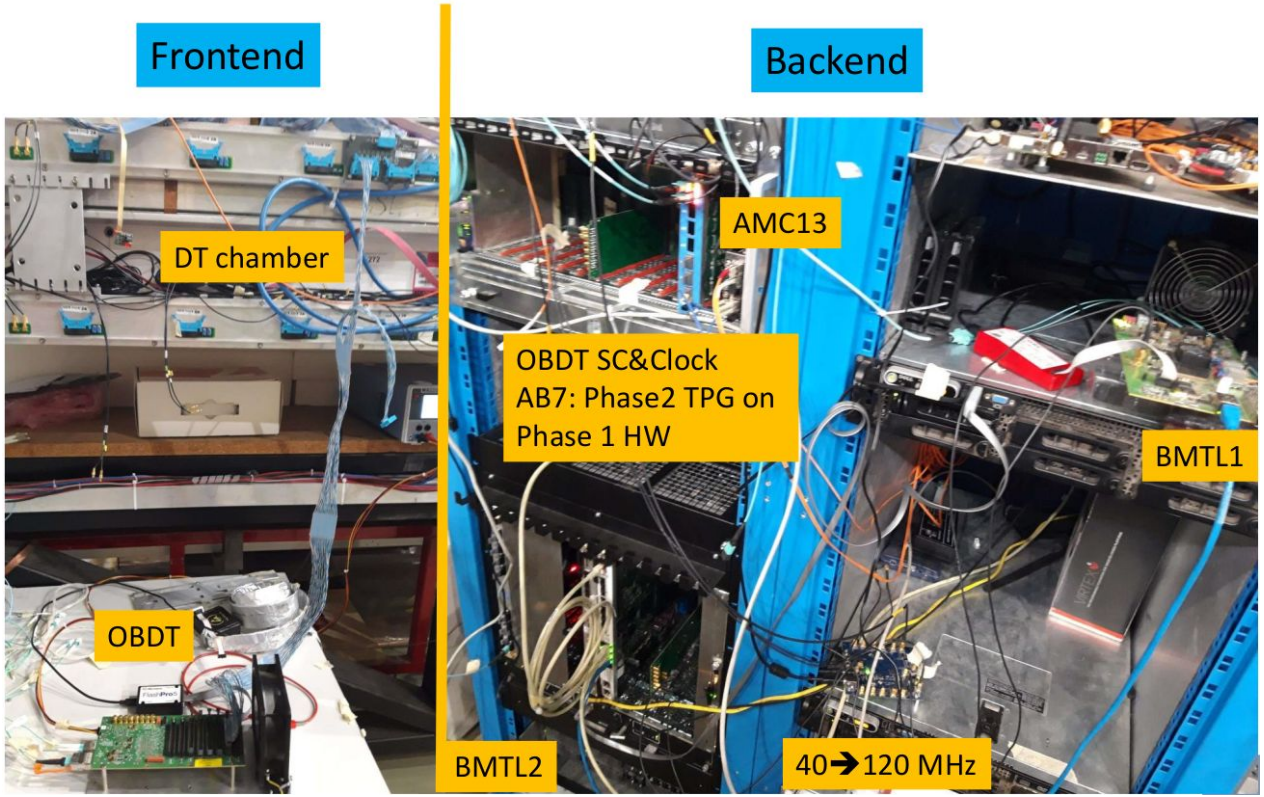
- BMT hardware and firmware have matured enough to start having board to board tests
  - First versions of Phase-2 hardware
- BMT slice tests **started September 2021** at CMS surface and now include
  - **1 DT Chamber** connected to **1 OBDT board**
  - The **BMTL1 Demonstrator** card until production of the ATCA card
  - The **Ocean** card
- **Full Detector to GMT processing chain**



Slice Tests - P5 Setup



Setup at CMS surface area

BMT Slice chain: DT Chamber -> OBDTv1 -> BMTL1 Demo -> Ocean

Slice Tests - P5 Setup

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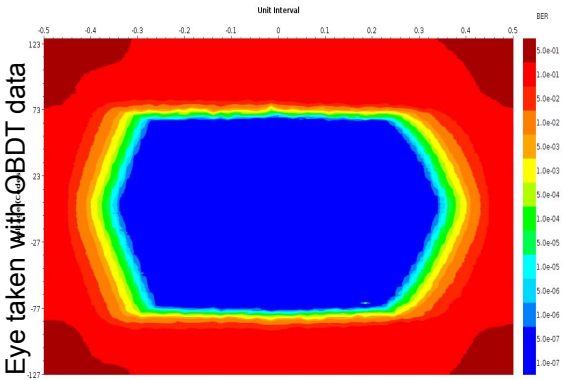
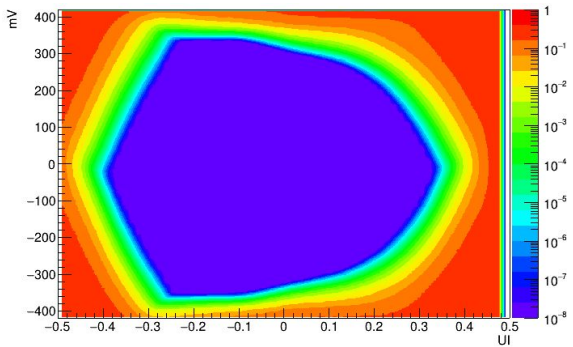
➢ **First action on the setup was to validate data reception between the two individual chains**

- **OBDT -> BMTL1 Demo**
  - 2 Tx GBT Links @ 4.8 Gb/s
  - Counter data running for 7 days
  - No Errors



- **BMTL1 Demo -> Ocean**
  - Using CMS Standard Protocol (CSP)
  - 4Tx & 4Rx Links @ 16 Gb/s
  - Running 2 days - No CRC Errors



➢ **Next action to validate the firmware of BMTL1**

BMTL1 Firmware

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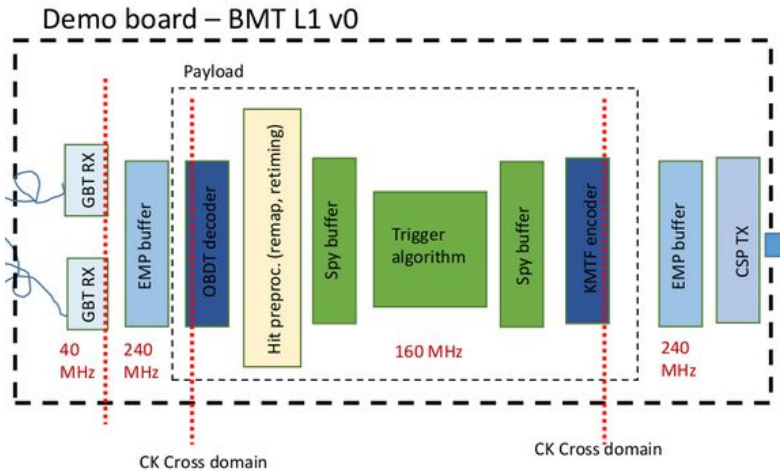
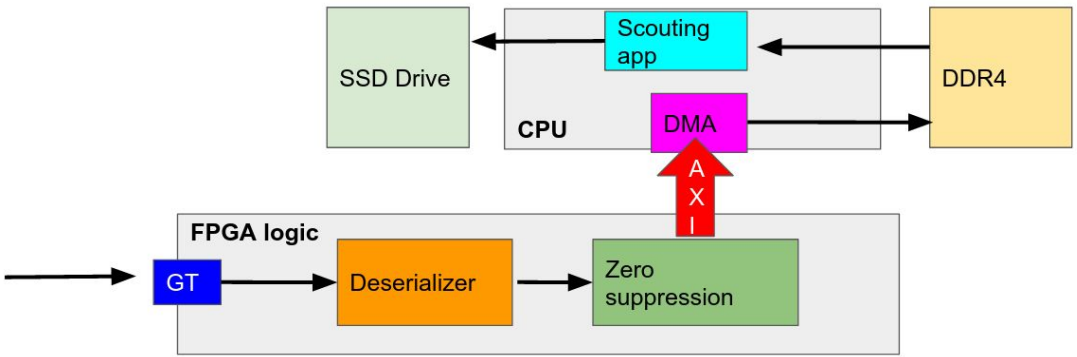
- BMTL1 uses the **EMP framework** - framework of the Serenity boards
  - Modified version to match characteristics of Demonstrator board
- BMTL1v0 framework includes
  - GBT protocol to communicate with OBDT
  - **1 instance of the Analytical Method algorithm** to produce Muon Trigger Primitives (stubs) for 1 Chamber
    - Developed by CIEMAT
  - CSP protocol to transmit data to GMT
  - TTC block to synchronize with the BC0 tag
  - EMP Buffers for testing purposes

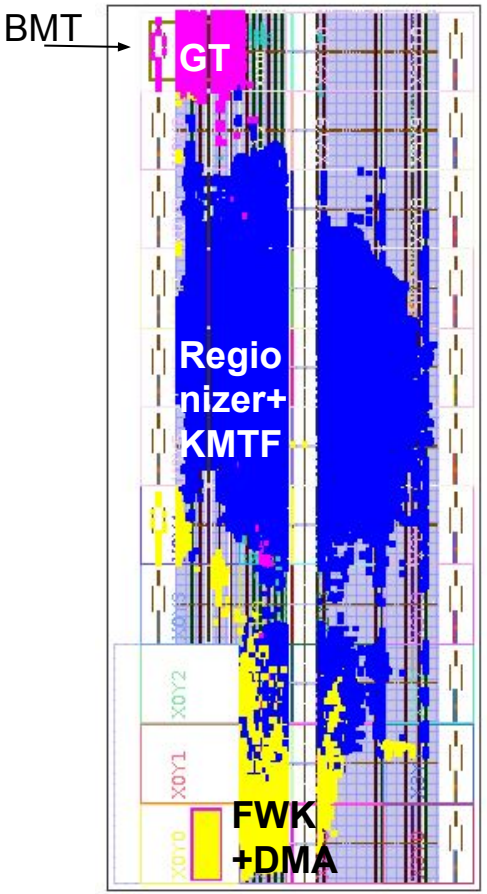


Ocean Firmware - UCLA

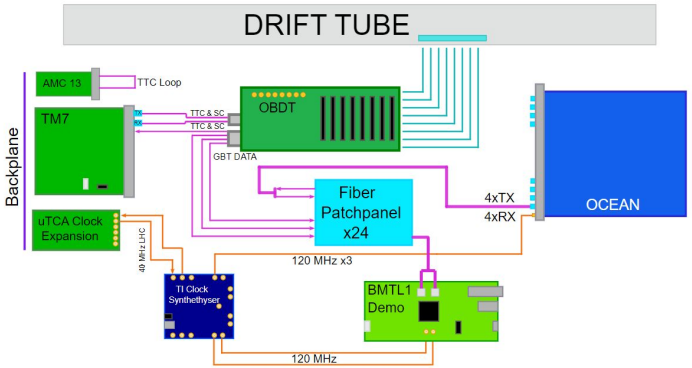
- Ocean firmware runs the **KMTF algorithm** to match tracks and reconstruct Muon candidates

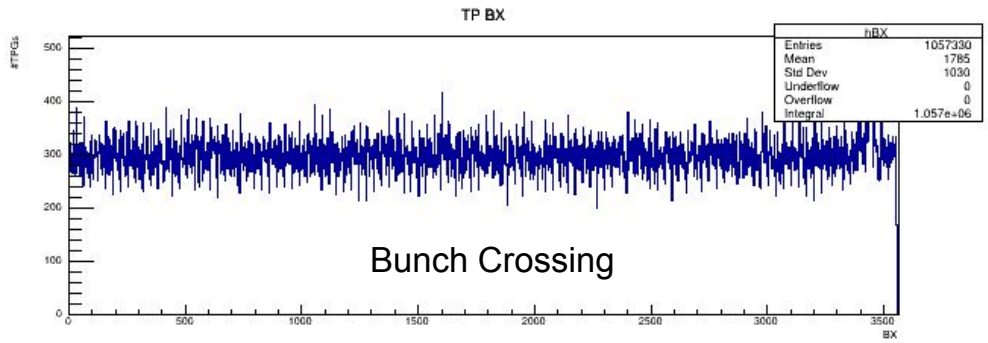
- **Ocean runs scouting system that allows collection of cosmic data over many hours**
  - Features a ZYNQ US+ SoC and **DDR4 memory tightly connected to the FPGA**
  - S**trearna data from the FPGA Logic to the DDR4 memory**
    - Through an AXI interface configured for Direct Memory Access
  - Linux application in the **CPU reads the data from the memory and writes to the SSD drive**



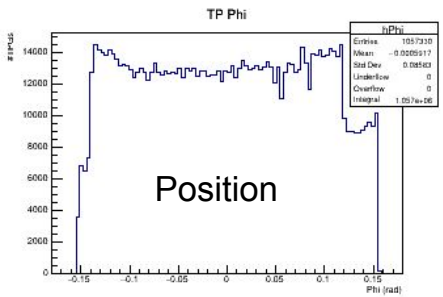


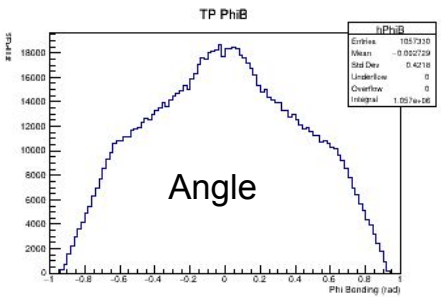
Slice Tests - Results with Cosmic Muons





- Data from **real cosmic Muons** as they pass through the Drift Tube Chamber (4 m^2)
- **Flat distribution of Bunch Crossing**
- **Flat distribution of Position**
- **Symmetric distribution of the Angle**
- Results are what expected for cosmic Muons



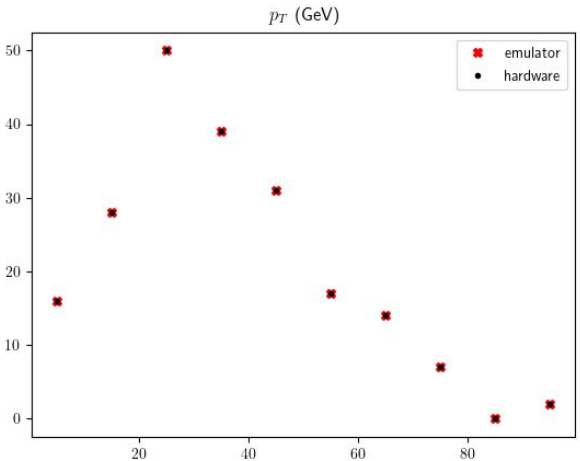


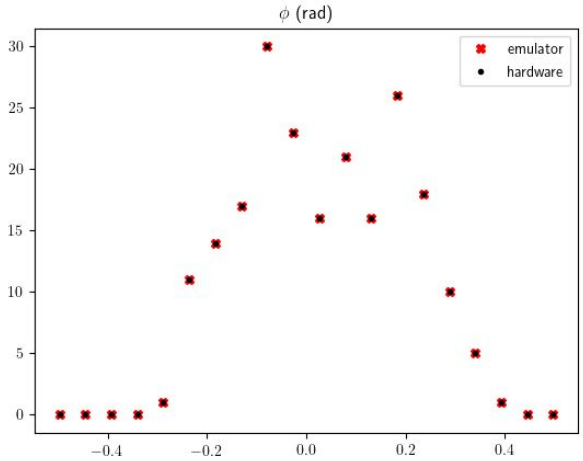
DT TP Format

Data field	Fine t0 (ns)	BX in-orbit	Position (Phi)	Bending angle (PhiB)	Chi2	RPC info	Quality	Spare	SuperLayer	Chamber
Bits	5	12	17	13	4	3	4	2	2	2

BMTL1 to GMT slice test

DY → μμ (200PU)





- KMTF algorithm validated using **patterns passed from BMTL1 Demo to Ocean**
  - Monte Carlo patterns from Z→ μμ events
- Plots compare Algorithm results with CMSSW emulator
  - **100% agreement on Pt and Phi**

Slice Tests with BMTL1-ATCA

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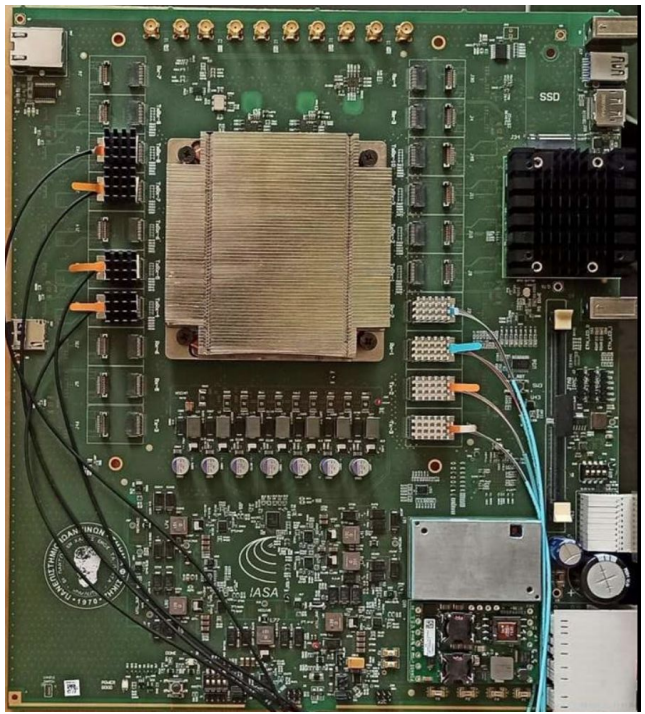
- BMTL1-ATCA board produced on May
  - All tests have shown very good results
- Next plan is to **perform Slice Tests using the actual BMTL1 ATCA card**
  - Slice test closer to the final system
- Many developments still needed to have the card ready to be used
  - Trying to have it ready by the end of summer



Conclusions

- Many developments of last years are now used in realistic tests
- Barrel Muon Trigger slice test setup includes a full chain from the Detector to GMT
- Cosmic Muon results validate the operation of the subsystem
- More remain to be done with the new BMTL1 ATCA card

Funding: is financed from the project DeTAnet – MIS 5029538 – Ministry of development & Investments

Thank you for your attention!

Back Up

BMTL1-v0 Firmware Integration Steps

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1. **Trigger algorithm integration and evaluation** through custom spy buffers with simulation data.
2. **EMP buffer injection and EMP buffer readout**: validates all payload module (including algorithm plus hit decoding and conditioning and clock-domain crossings).
3. **Injection of a golden muon in OBDT** (as a pattern but a pattern that would really generate a correlated trigger primitive). Readout in final EMP buffers.
4. Injection of a golden muon in OBDT and **readout of the TPGs at the Ocean.**
5. **Injection of real cosmic data in the OBDT and readout in the Ocean.**