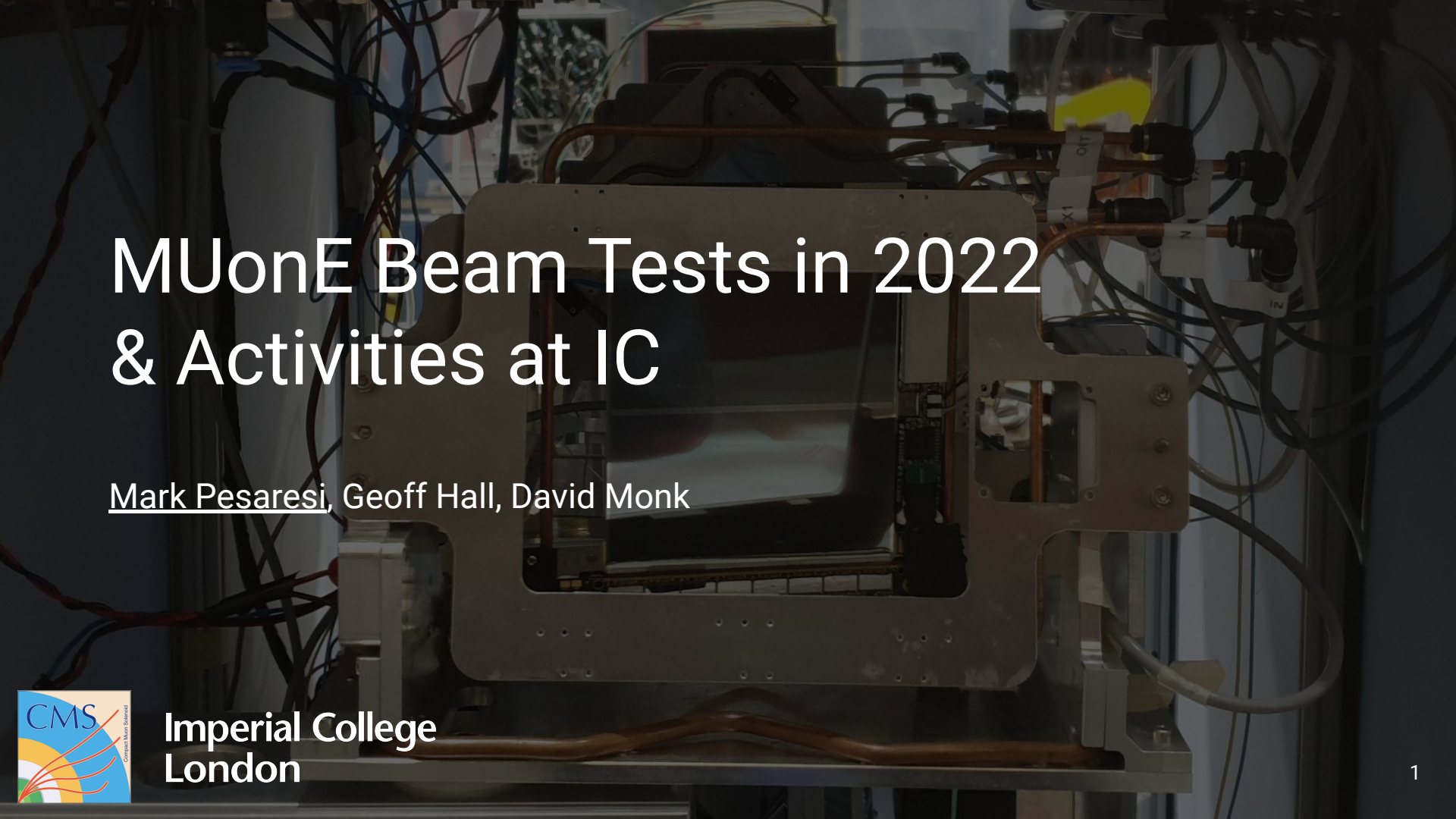

MUonE Beam Tests in 2022 & Activities at IC

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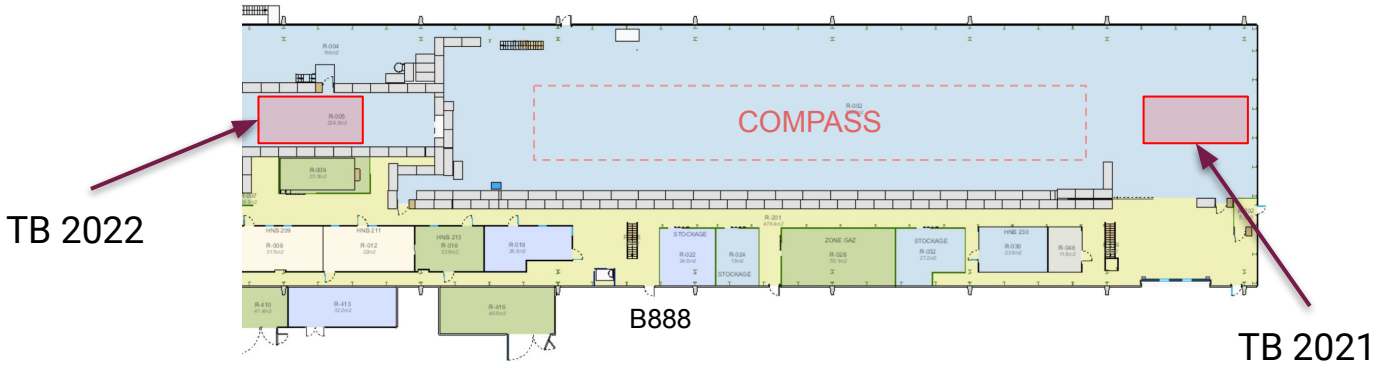
Introduction

- MUonE test beams in 2021-2022
- Experimental setup
- Readout & DAQ
- Data collected & early analysis

Most MUonE activity at IC sits in the overlap between CMS and MUonE, in particular:

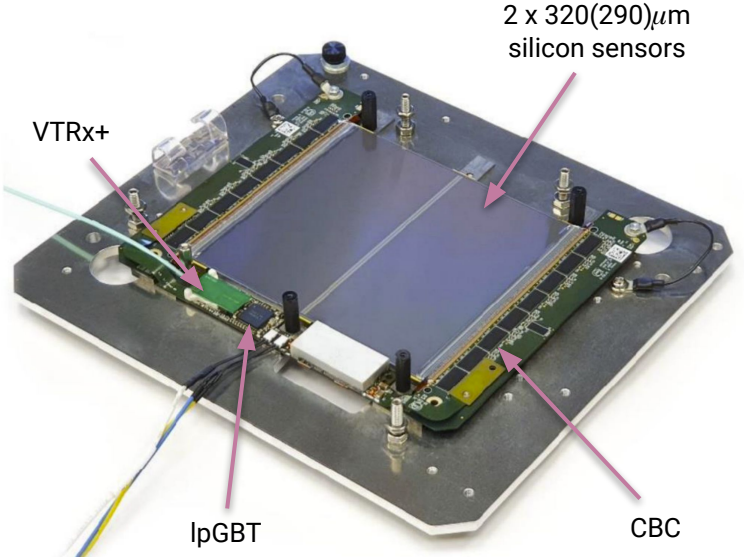
- FE hardware and readout ASICs
- BE hardware and online processing/tracking
- System tests and performance evaluation

Test Beams at M2

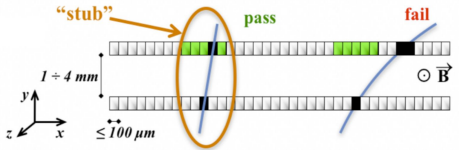


- High intensity, asynchronous beam, up to 2×10^8 muons per spill
- 160 GeV muons or 40 GeV electrons
- MUonE setup located downstream (2021) / upstream (2022) of COMPASS experiment
  - Low intensity halo muons in 2021, ~two weeks
  - High intensity muons in 2022 for 1-2 days every ~14 days (during COMPASS target repolarisation)
  - High intensity muons, end-October for 5 days

Silicon Tracker



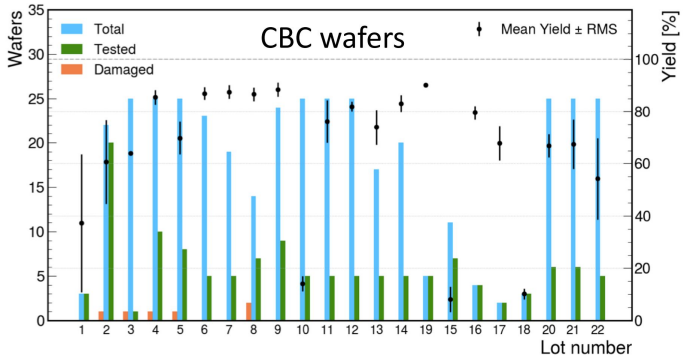
- Based on the CMS 2S module
  - Pair of n-on-p sensors, separated by 1.8/4.0mm
  - 90μm x 5cm strips, 2032 strips per sensor
- Used to identify high pT charged particles in CMS
  - Stacked tracking method
  - Correlation provided by the 130nm CBC ASIC
  - Readout of stubs at 40MHz

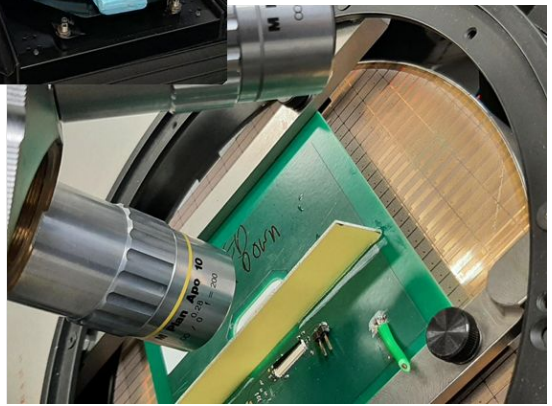


- Moving from prototyping to construction
  - Final ASICs available, sensor production >40% complete
  - Hybrid designs finalised, components for O(200) 2S modules next year
  - ~35 modules produced so far, less than expected (hybrid manufacturing issues)
  - Expect around ~20 more later this year

CBC Wafer Testing at IC

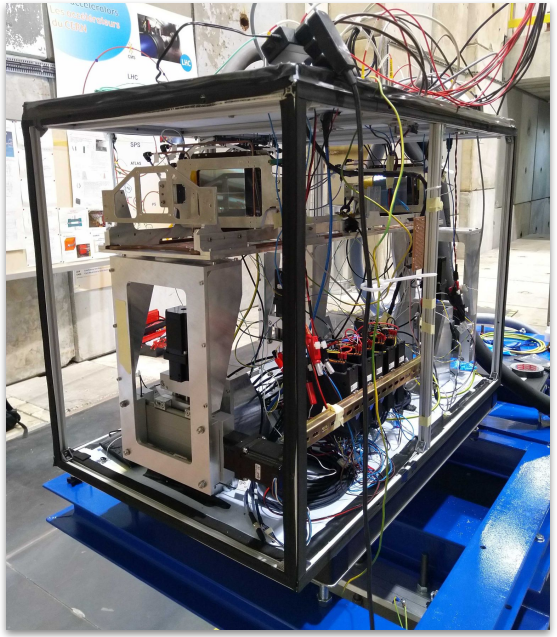
- Production of ~500 CBC wafers ongoing
  - Testing at IC (and now RAL)
  - Yield generally high (~80%)
  - Though detected some lot-to-lot variation



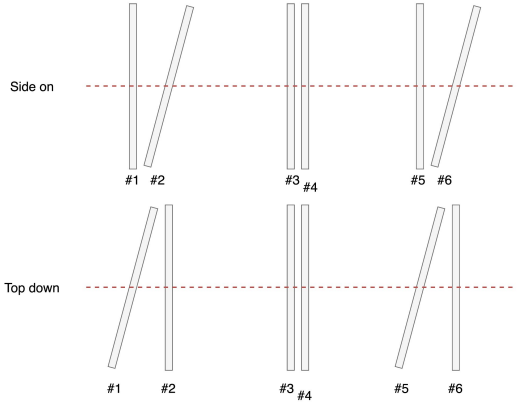


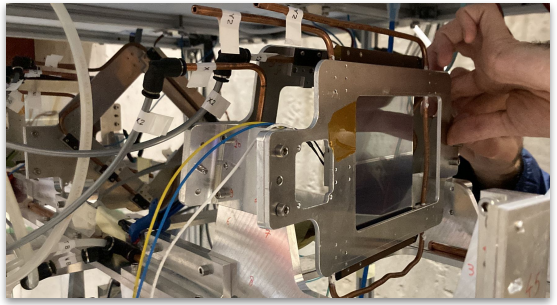
Test Beam Setup

- 2S modules housed within ‘station’ (Pisa)
  - Structural support for for 6 modules and target
  - Alignment stages for fine translation/rotations of system
  - New for 2022 - entire apparatus can be **moved in and out of beam** (sliding rails)



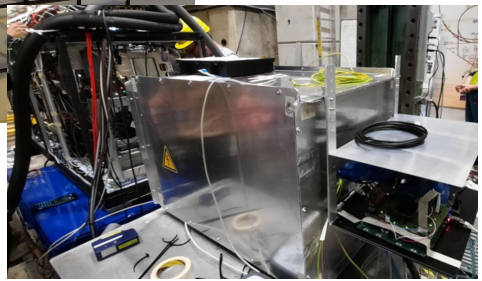
- Various configurations:
  - 2021 - 2 modules in station (x + x)
  - 2022 - 4 modules in station (xy + xy)
  - Oct 2022 - 6 modules (xy + uv + xy)
  - Tilted modules to improve resolution



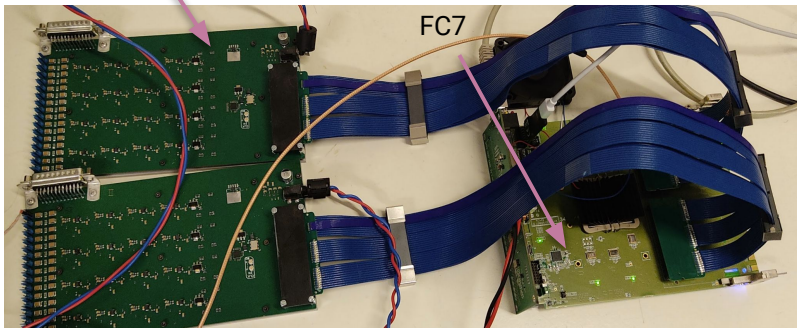


Electromagnetic Calorimeter

- New for 2022
  - ECAL using current CMS barrel ECAL components (PbWO4 crystals, APDs)
  - Also reusing same FE electronics (MGPA - IC/RAL)
  - 5x5 array of crystals, 25 X_0
  - Tested in standalone test in July (EA/T9), and with station in M2 in October



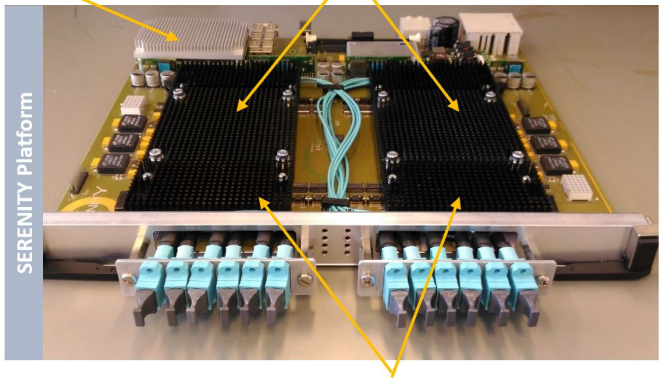
- FE boards hosting MGPAs designed at IC
  - Each providing 16 channels, 16bit ADCs
  - Standalone readout using FC7 (IC) -> up to 32 channels
  - Self-triggered, up to few kHz

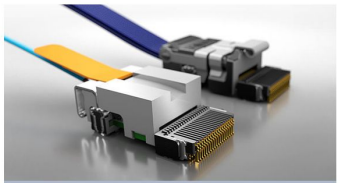


Readout & DAQ

- Module readout via Serenity platform (IC)
  - Also to be used in CMS as Tracker BE
  - ATCA form factor
- Prototype with dual KU15P FPGA
  - Final board with single VU13P FPGA
- Design supports:
  - readout of up to 72 modules (5/10 Gb/s lpGBT links)
  - up to 48 25Gb/s high b/w links
  - Onboard CPU (4-core Intel i5) with IPBus over PCIe, CentOS 7 - in future Zynq Ultrascale+
- Currently using only two high b/w links
  - 2x 10GbE to PCs direct from FPGA

Onboard Intel Computer On Module

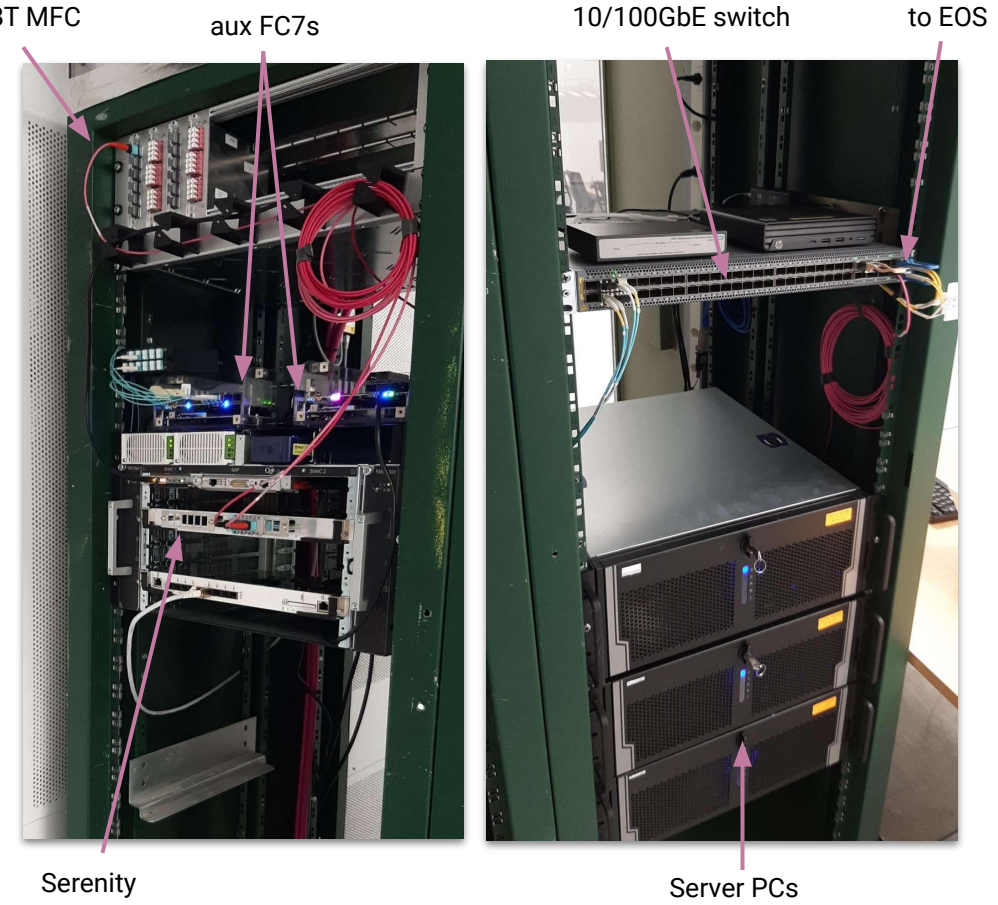




Samtec Firefly optical transceivers up to 25Gb/s

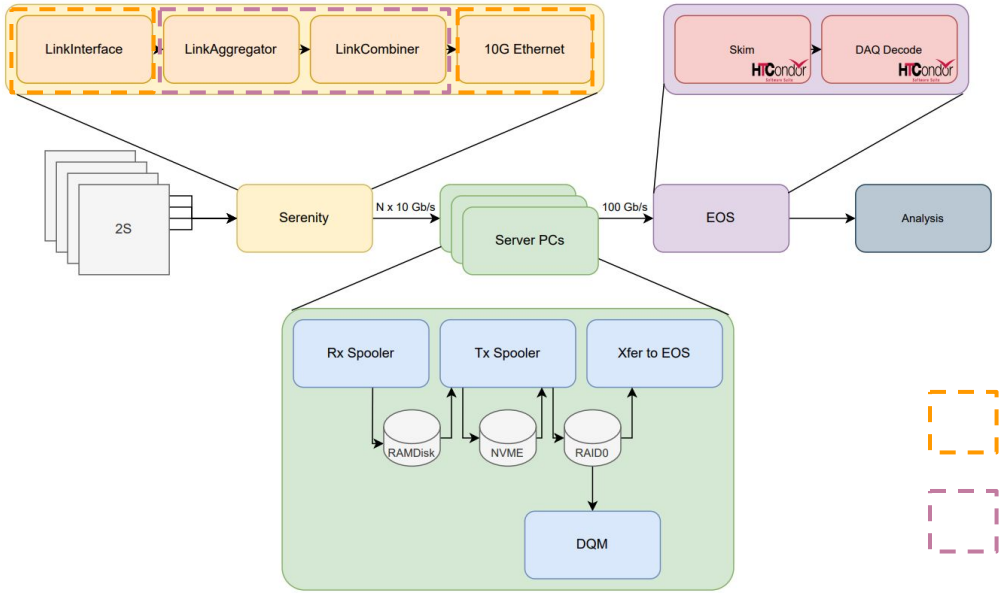
Readout & DAQ

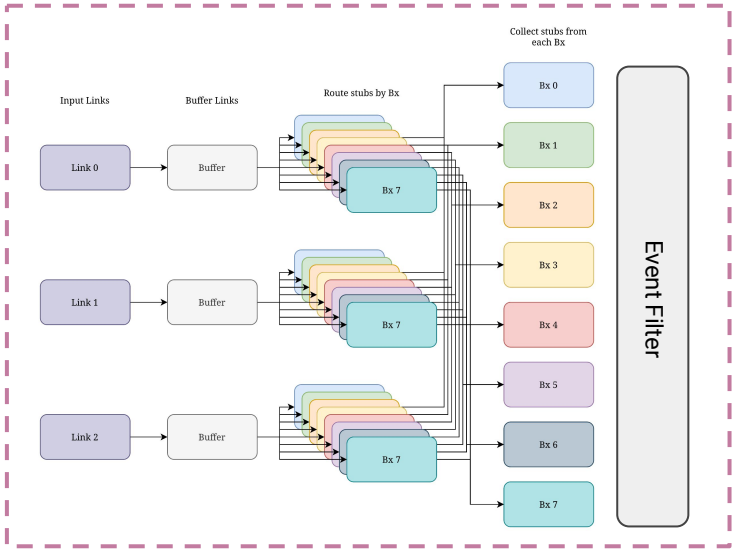
- Station is read out optically (lpGBT)
  - ~60m optical fibre from detector to barracks
  - Serenity implements lpGBT serial link and FE decoding, stub data processing at 40MHz and optionally event filtering
  - Packaged events transmitted over 10GbE links to servers
- Servers receive 10GbE data
  - Ryzen 9 5900X server PCs
  - 128GB RAM, 1TB NVMe SSD, 40TB RAID
  - Buffering, packaging, DQM, ship to EOS
- 10/100GbE switch
  - Direct 100GbE connection to B513/EOS
- FC7s for aux functions



Dataflow

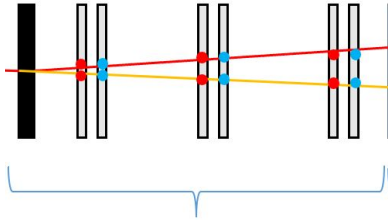
- Firmware and software (IC, and others)





CMS-TK common

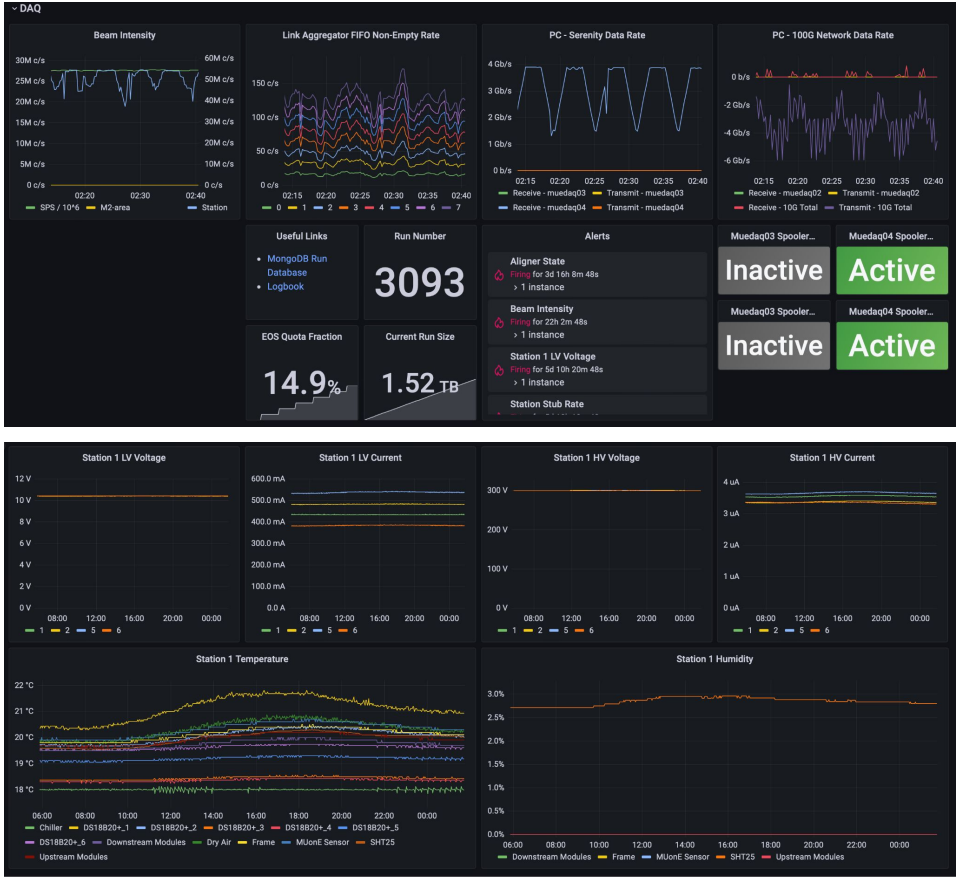
MUonE specific



Control & Monitoring

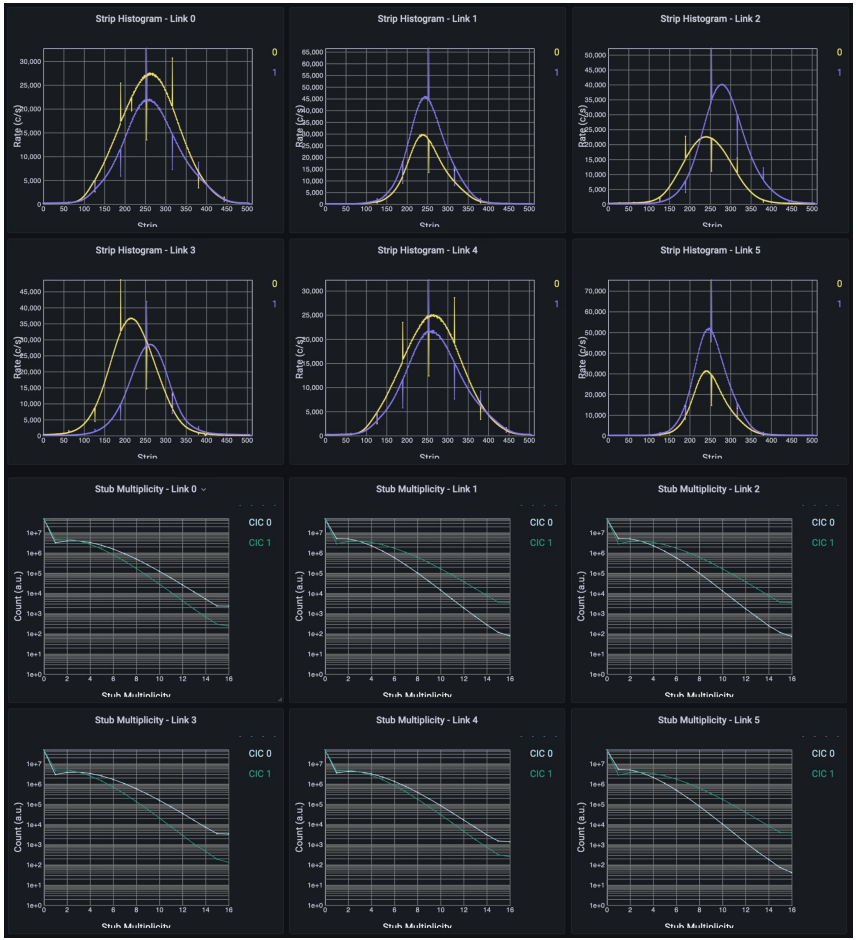
- Prometheus/Grafana stack used to collect and display metrics from system
  - Network rates in and out of PCs
  - CPU/RAM usage
  - Voltage & current from module PSUs
  - Temperature and humidity within station
  - Fast feedback on module/link status

- Records of configurations for runs stored in a database, allowed for full traceability



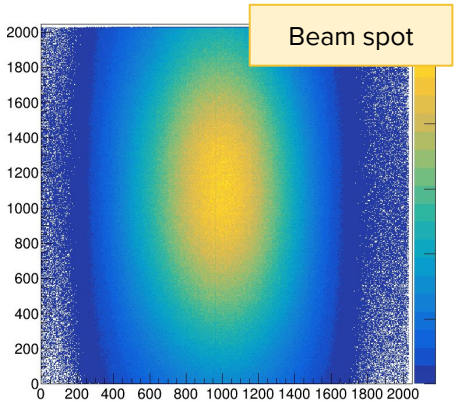
Fast DQM

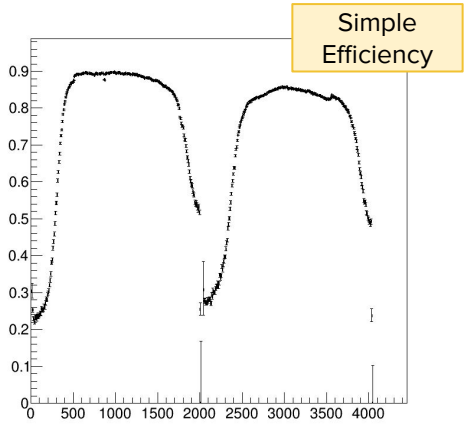
- Some metrics recorded directly on the FPGA
  - Check of system stability before starting data-taking
  - Fast tuning without needing access to data
- Key metrics exported:
  - Beam Profile
  - Stub multiplicity
  - Link status & errors
  - Stub rate

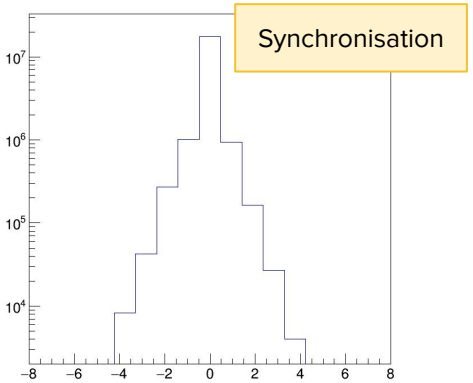


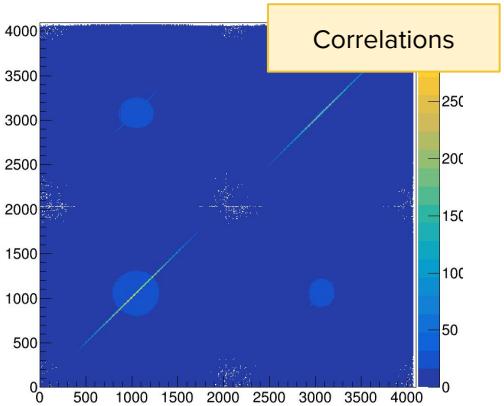
Online DQM

- Data stored on EOS for current data-taking run is sampled
  - Plots displayed on webUI
- Performed more complex calculations on data:
  - Synchronisation between modules
  - System alignment
  - Beam spot
  - Stub efficiency
- Many previous analyses have now become part of the DQM!







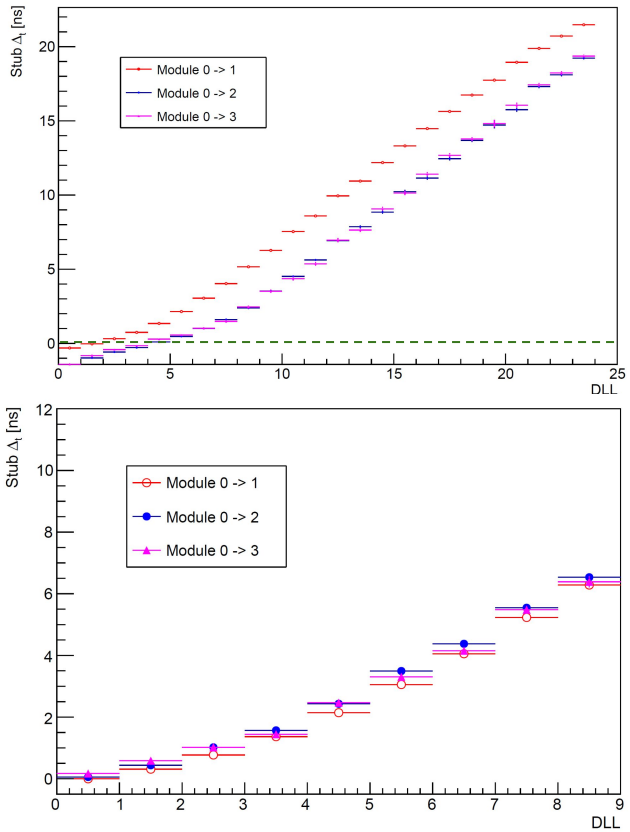


Testbeam Programme

- Nov 2021 : First test of 2S modules in M2 beam + DAQ, and station infrastructure
  - Poor beam, but successful demonstration (pre-empting CMS!)
- Summer 2022 : Commissioning tests in M2 with 4 modules with high-rate beam
  - Prove synchronisation across modules, and long-term stability
  - Quantify 2S module performance, operating points, use of bend-information
  - Scale up firmware and DAQ for >4 modules, implement scans
  - Significantly augment online DQM and monitoring tools, prep for main TB
  - 19 days of ‘beam time’ -> 51 TB stub data, ~2.5 trillion stubs
- October 2022: Full station (6 module) test with target, + standalone ECAL
  - 6.5 days total; ~5 days with ‘beam’ - mix of muon (~1E8) and electron (v. low intensity) runs
  - Tracker system always on, DAQ reliable throughout
  - Some 100TB of stub data collected
  - Only a few minutes of 2E8 muons (beam not in our control)

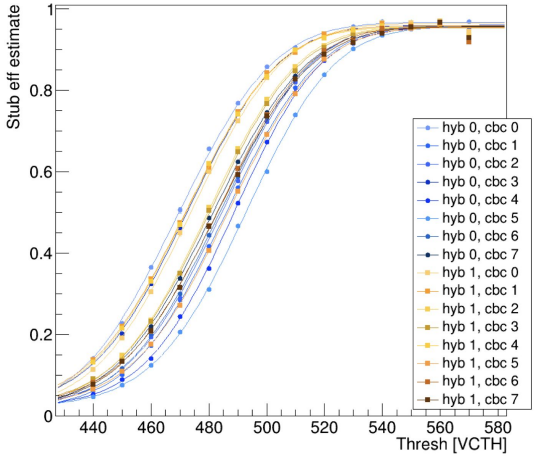
Analysis - Synchronisation

- Summer commissioning showed we could synchronise multiple modules wrt each other
  - Maintained over many months of running for 4 modules
- From the most recent tests, this has now been increased to 6 modules
  - Not a trivial scaling
  - Requires multiple quads/clocks to be used in the Serenity for optical links
- Sub-Bx synchronisation possible through tuning of FEs
  - Synchronisation < 0.5 ns achieved

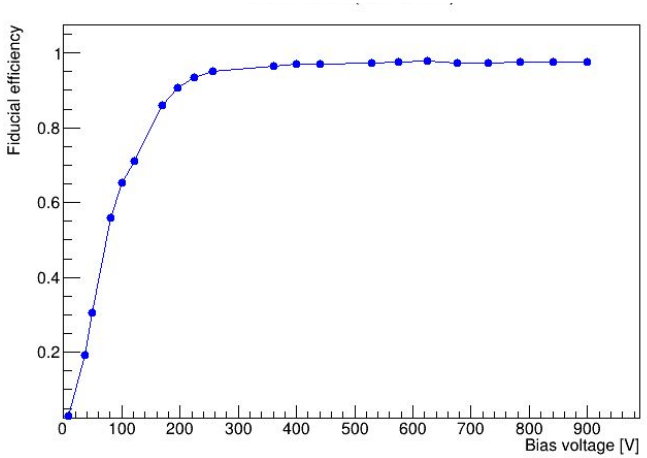


Analysis - Efficiency

- FE scans developed during summer commissioning, e.g. threshold & bias
  - Threshold scans are most interesting - interplay with asynchronous beam
  - Important to maximise efficiency (and resolution) -> ongoing analysis from Oct TB
  - Threshold set to ~5x noise, full depletion at ~300V -> Vbias set to 400V



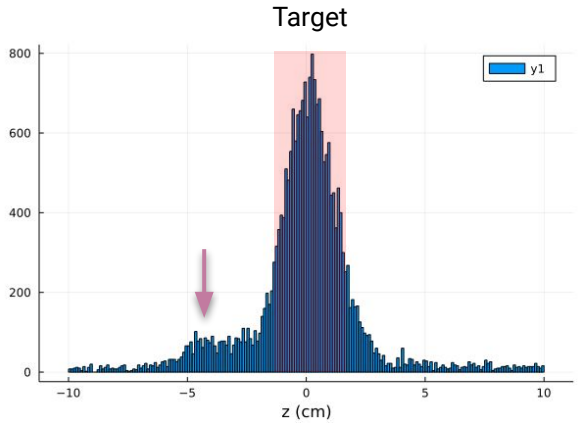
Stub efficiency as a function of CBC threshold voltage

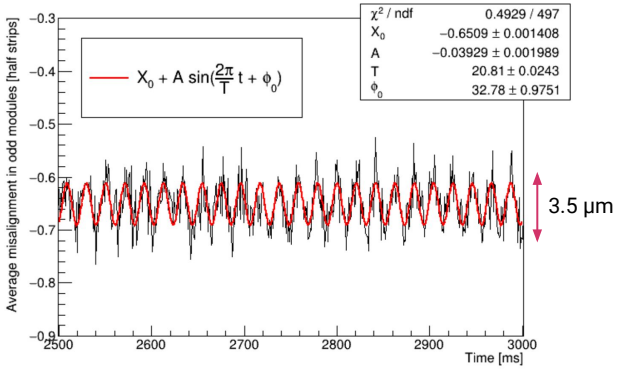


Efficiency as a function of module HV bias

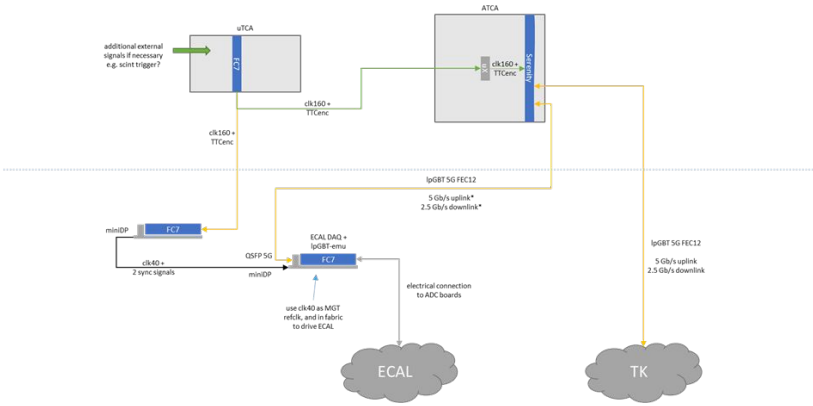
Analysis - Tracking & Vertexing

- October TB was first possibility for MUonE to perform track reconstruction with 2S modules
- Need u-v plane to reject “ghost” hits, produced when 2+ hits occur in the same BX
  - As well as to improve tracking, and remove fakes
- Events with 2 tracks can be used to perform vertex finding
  - Peak correlates with position of target when mounted
  - Some background material present -> needs further investigation
  - Transitioning analysis to full reco s/w (Marcin)
- Some interesting beam features discovered
  - O(um) time-dependent variations measured (50Hz)

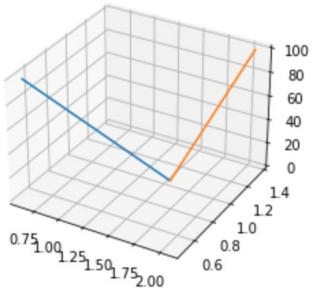




Look ahead to 2023



- Increased number of stations (-> 2/3)
  - 2S modules available towards end-year
  - Some DAQ tests to be completed in advance
- Integration of the ECAL readout with the full DAQ
  - Most elements already in place, but testing required
- Implementation of online (in-FPGA) event-selection
  - Could already flag events of interest in Oct TB (e.g. two track compatible events)
  - [un-sparsified readout for now - avoid bias in data collected]
  - Implementing simple track/vertex reconstruction in firmware
    - Most complexity lies in buffering/combinatorial requirements
    - Though still a lot simpler than in CMS (i.e. find 200 tracks from 20k stubs every BX within 5us!)



Summary

- 2022 was a busy but successful year for the MUonE detector and integration
  - Full station demonstration with 6 2S modules
  - Leading CMS in many respects
  - High bandwidth DAQ - trillions of stubs on tape
  - First tests with the ECAL
- Excellent overall stability of the system
  - Demonstrated operation under very high intensity
  - DQM tools and early prompt analysis indicate good quality data collected
- Analysis just beginning...!