Electronics System of the CMS GE1/1 Muon Upgrade and Performance of the Slice Test During the 2017-18 LHC Run

Elizabeth Rose Starling

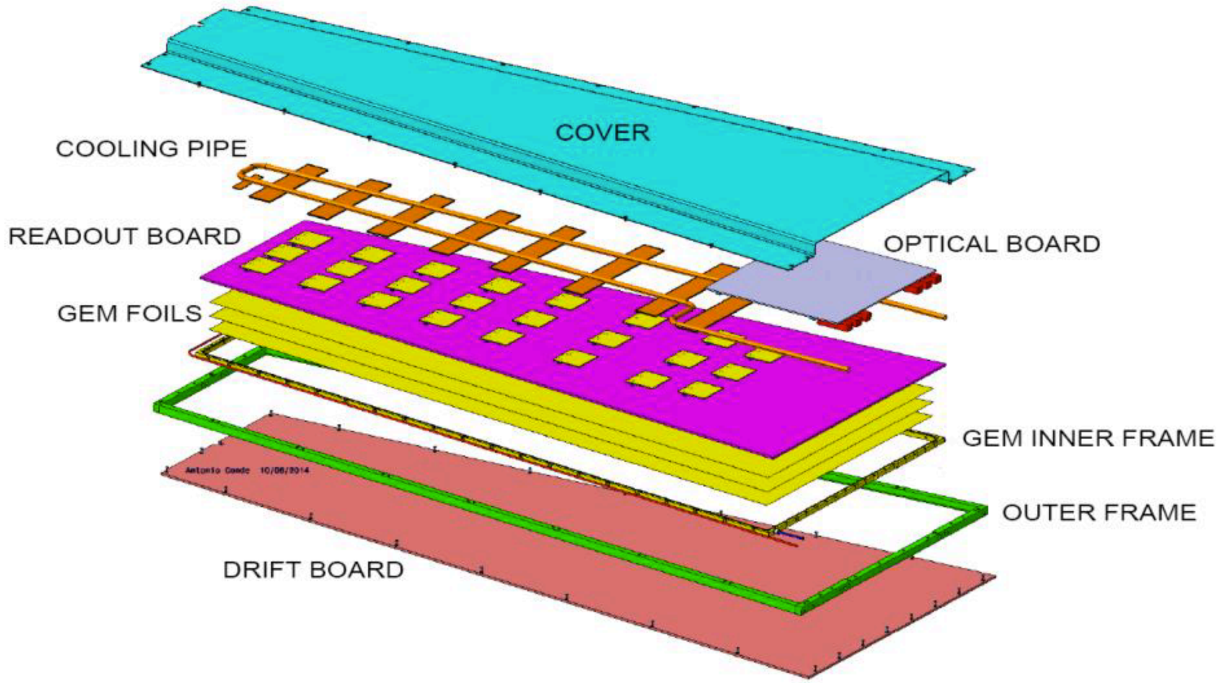
on behalf of the CMS muon group

September 3rd, 2019

FREEDOM TO RESEARCH

Triple-GEM Detectors

- Triple gas electron multiplier (GEM) detectors are composed of six main layers:



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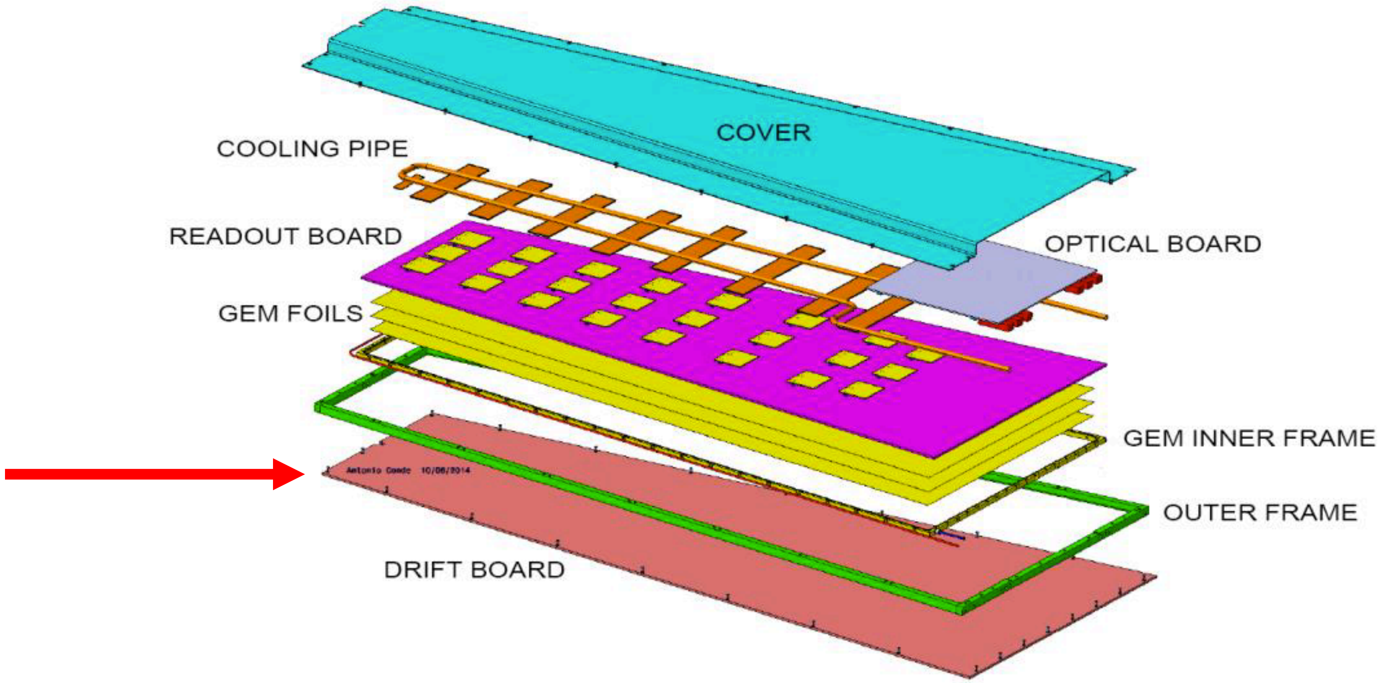
  - A drift cathode



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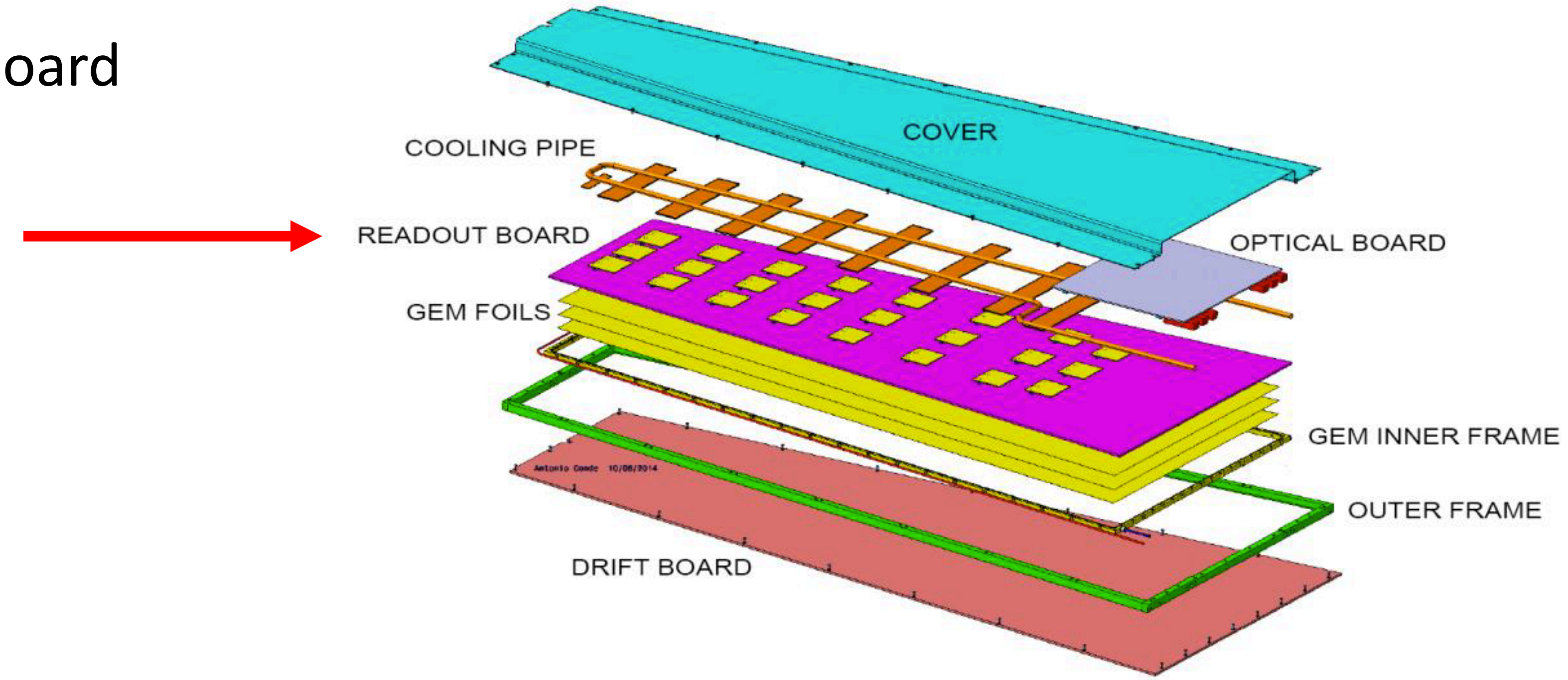

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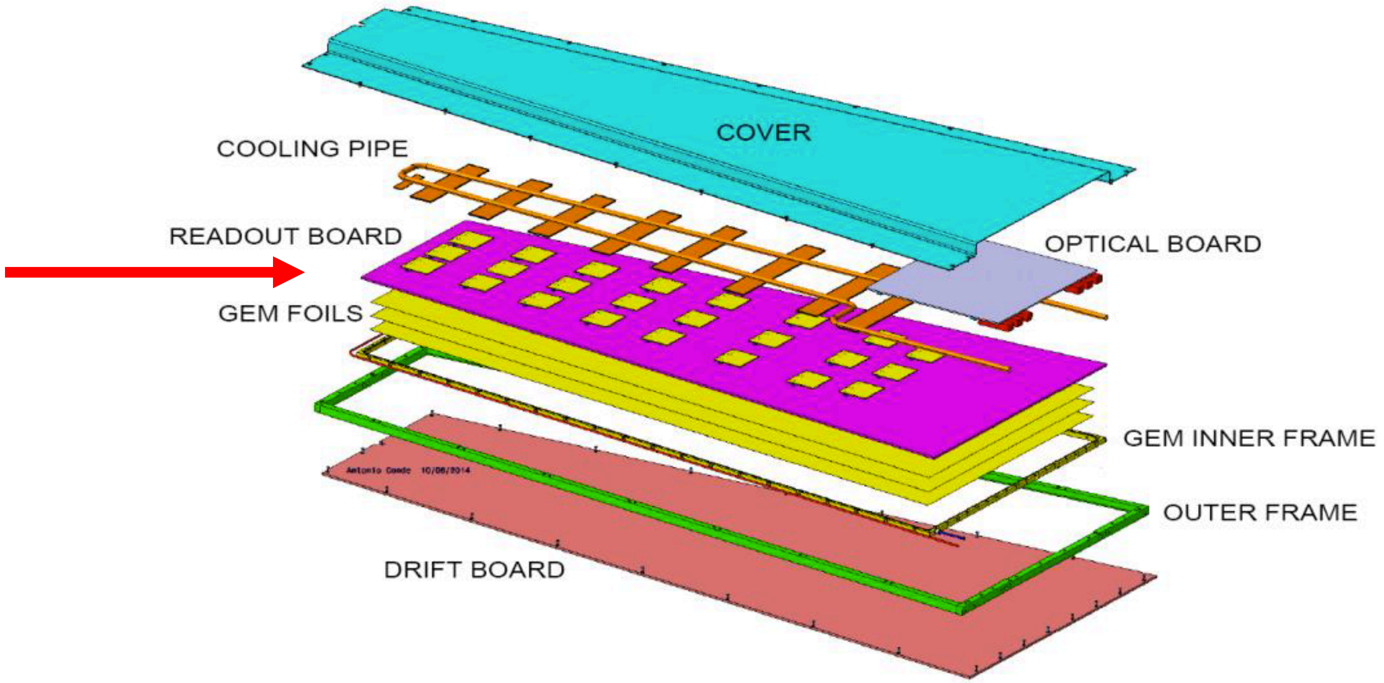
  - A gem electronics board (GEB)



Triple-GEM Detectors

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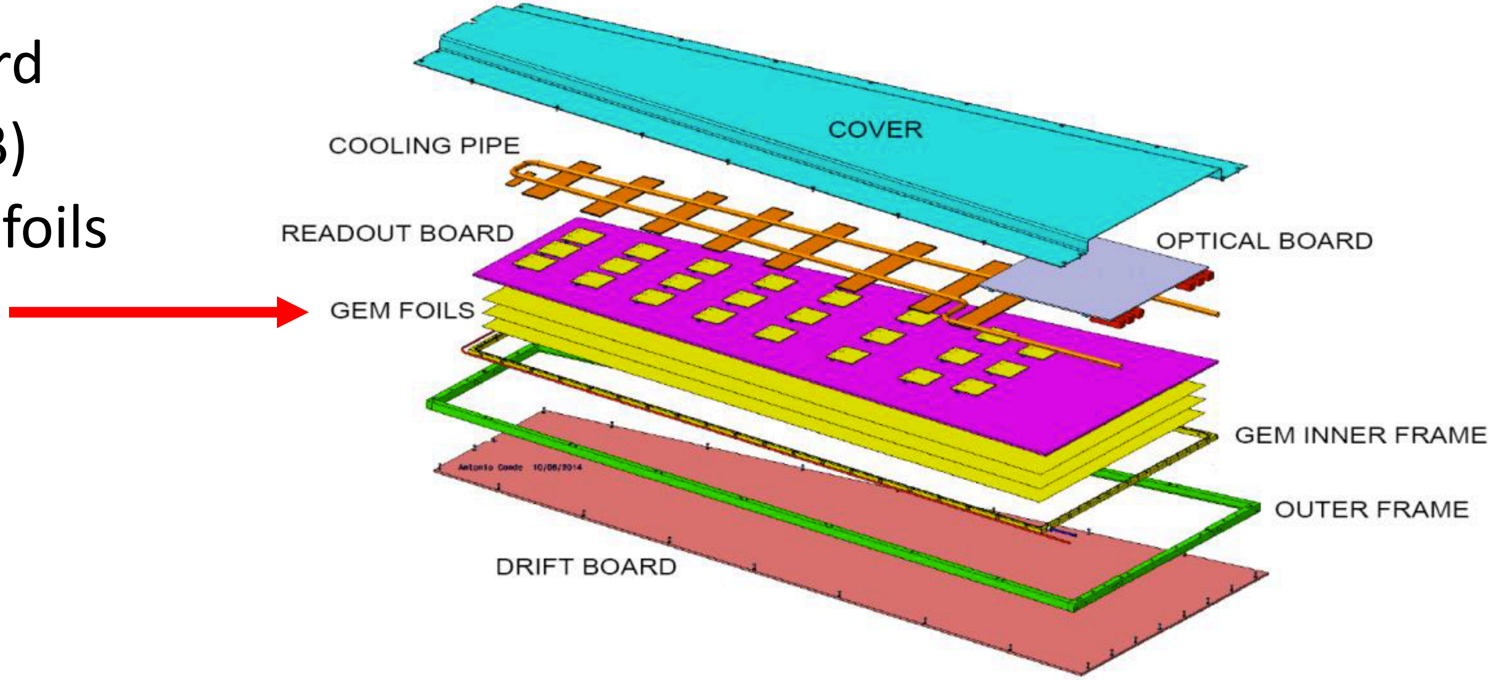
  - A drift cathode
  - A printed circuit readout board
  - A gem electronics board (GEB)
  - Three 50 µm-thick polyimide foils



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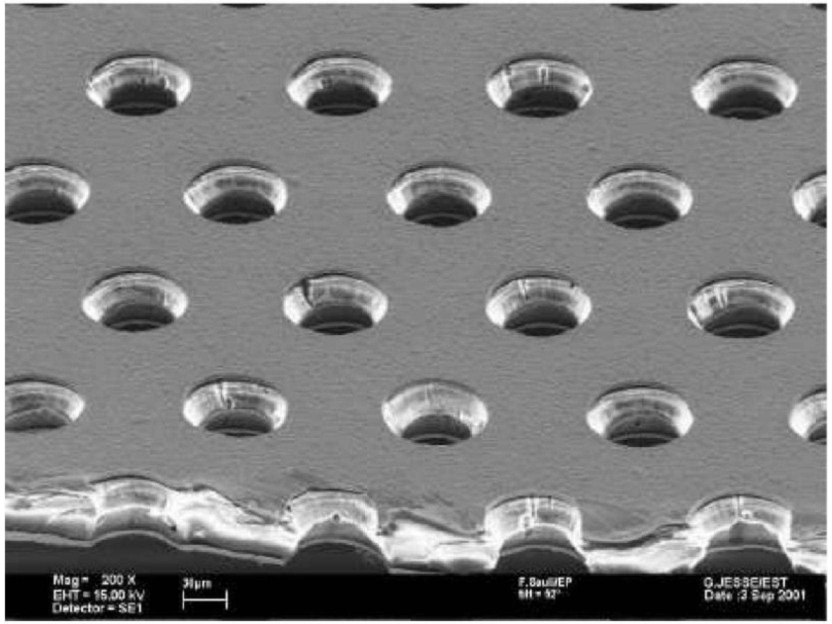
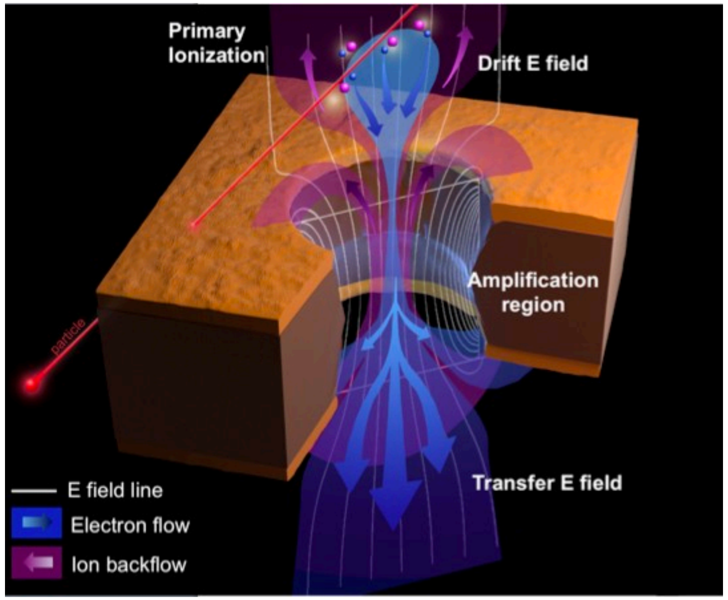


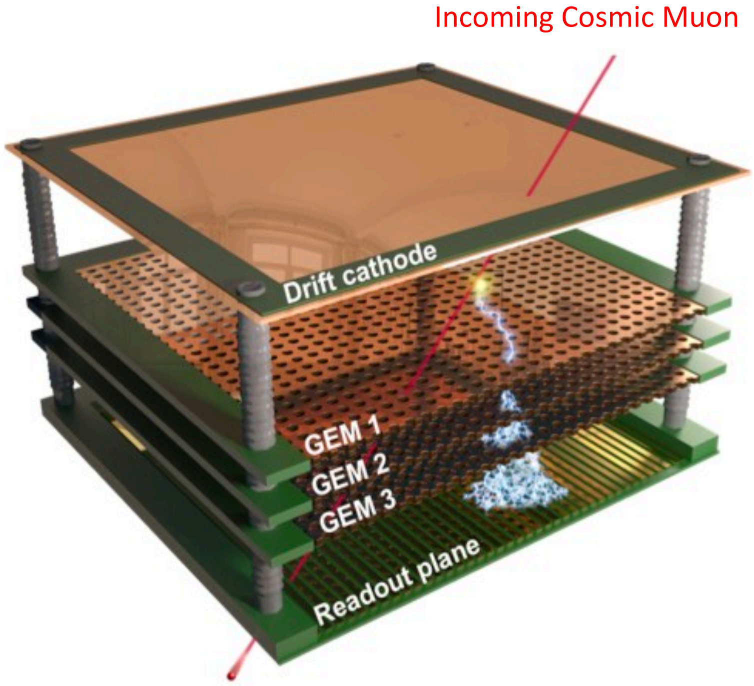
- The foils are coated on both sides with 5 µm of copper and chemically etched with 50-70 µm holes at a pitch of ~140 µm.

Triple-GEM Detectors

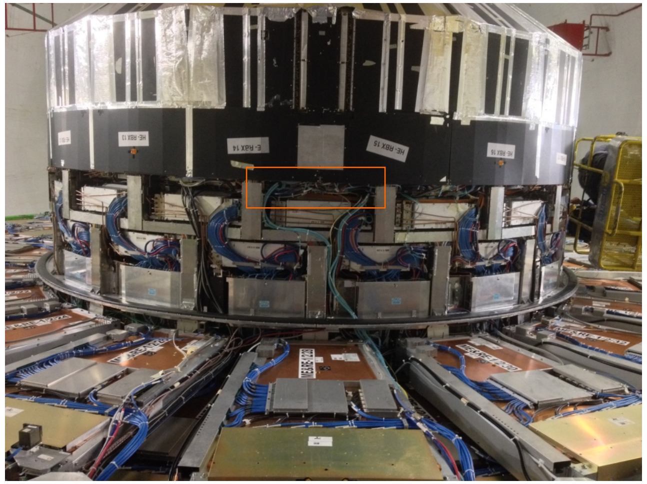
- The layers are sealed within a gas-tight volume and flooded with a gas mixture of 70% Argon and 30% CO_2.
- The foils are then put to a high voltage, which creates an electric field around the holes in the foils.



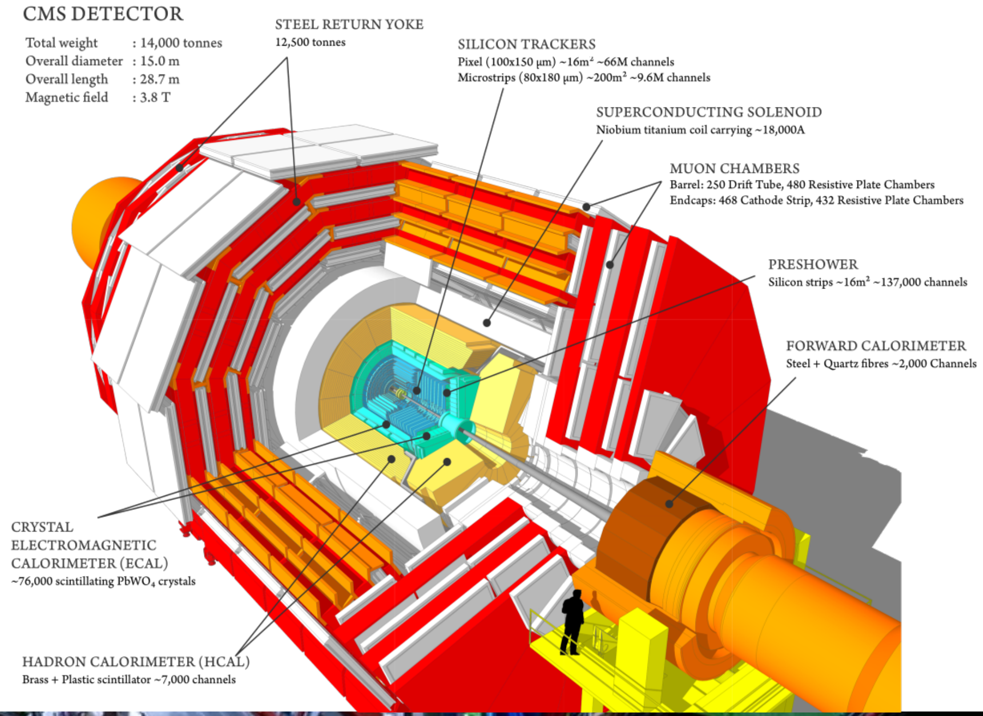
- A muon that enters the detector ionizes the gas, and as those electrons encounter these electric fields, they multiply in an electron avalanche and are read out at the PCB layer at a gain of ~10^4.



- The GE1/1 project takes place in the context of CMS’ endcap muon system, adding GEMs for the first (but not last) time to CMS.

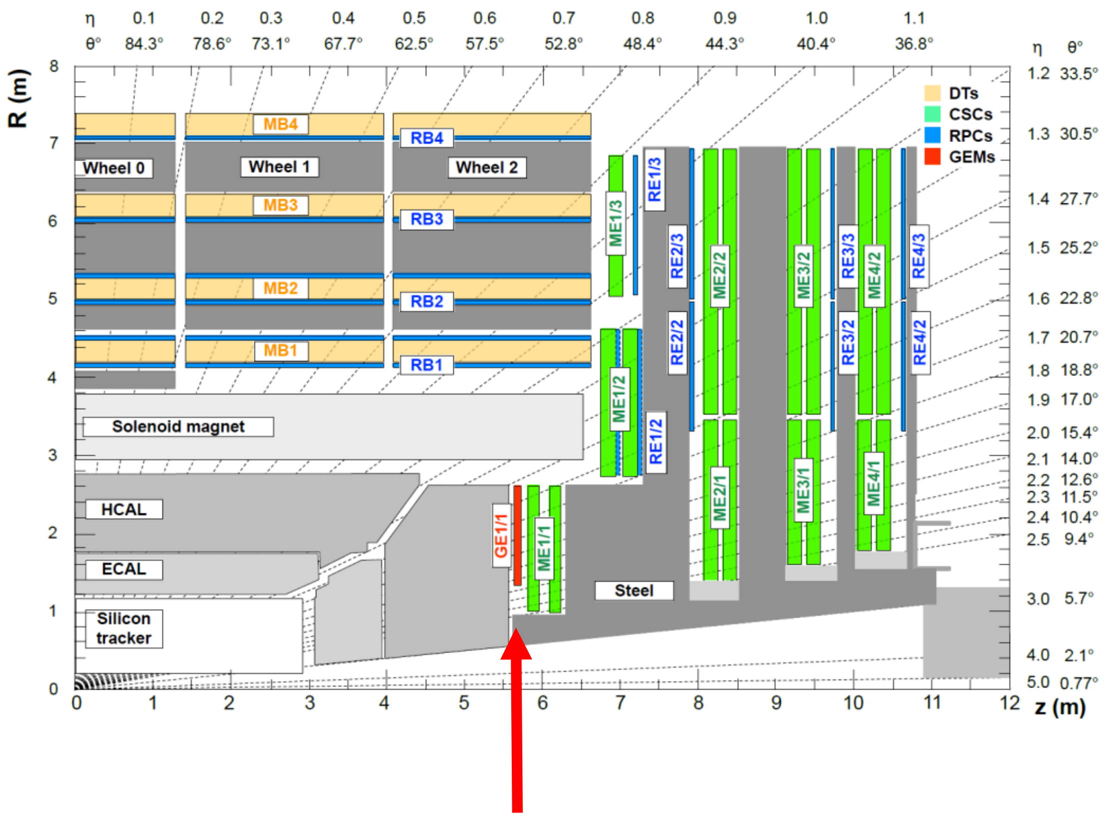


- Prior to the addition of GEMs, the endcap muon system consisted of Cathode Strip Chambers (CSCs) and Resistive Plate Chambers (RPCs).



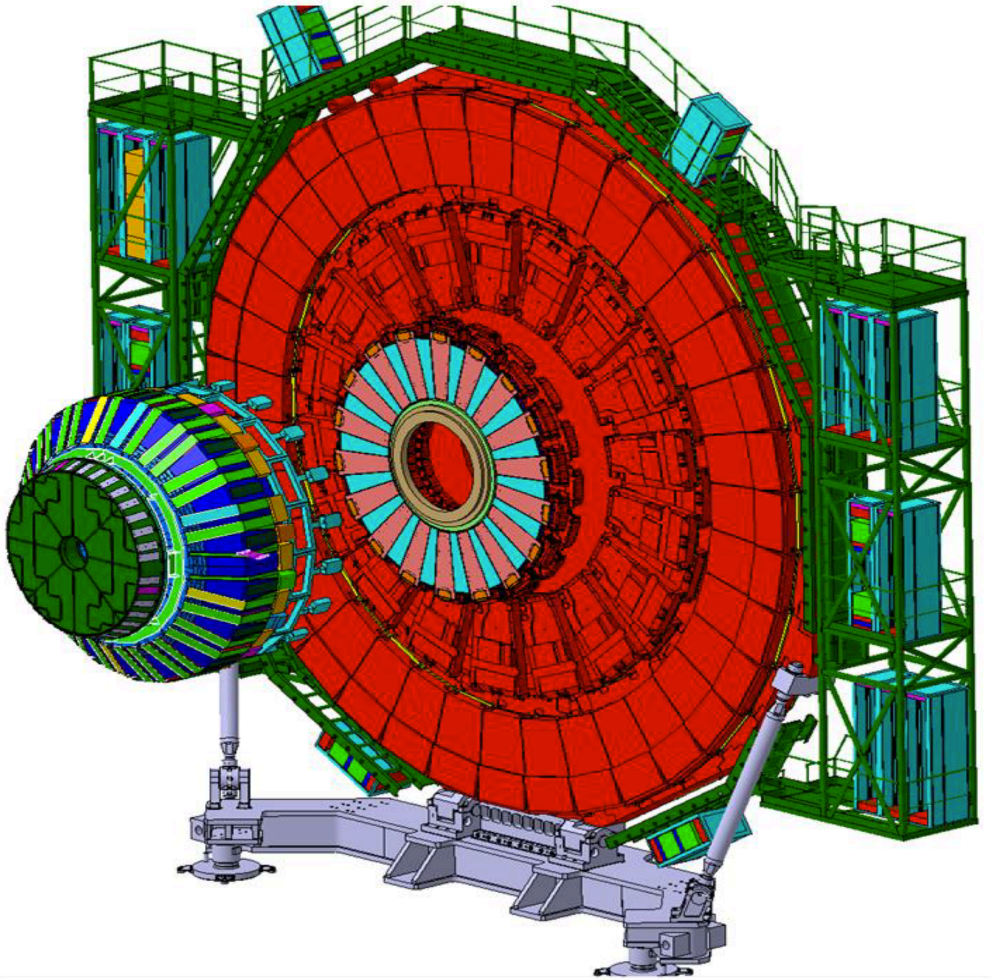
CMS GE1/1 Project

- GE1/1 - GEM detectors in the endcap muon station, 1st muon station from the interaction point, 1st ring of muon chambers radially from the beamline
  - The GE1/1 detectors serve as tracking and trigger detectors and interface with the existing cathode strip chambers
    - Adds redundancy in a difficult η region
    - Allows for better tracking in a high rate / high background environment
    - Allows for the measurement of bending angle at the trigger level
    - Decreases the number of mismeasured muons by lowering the threshold for soft muons



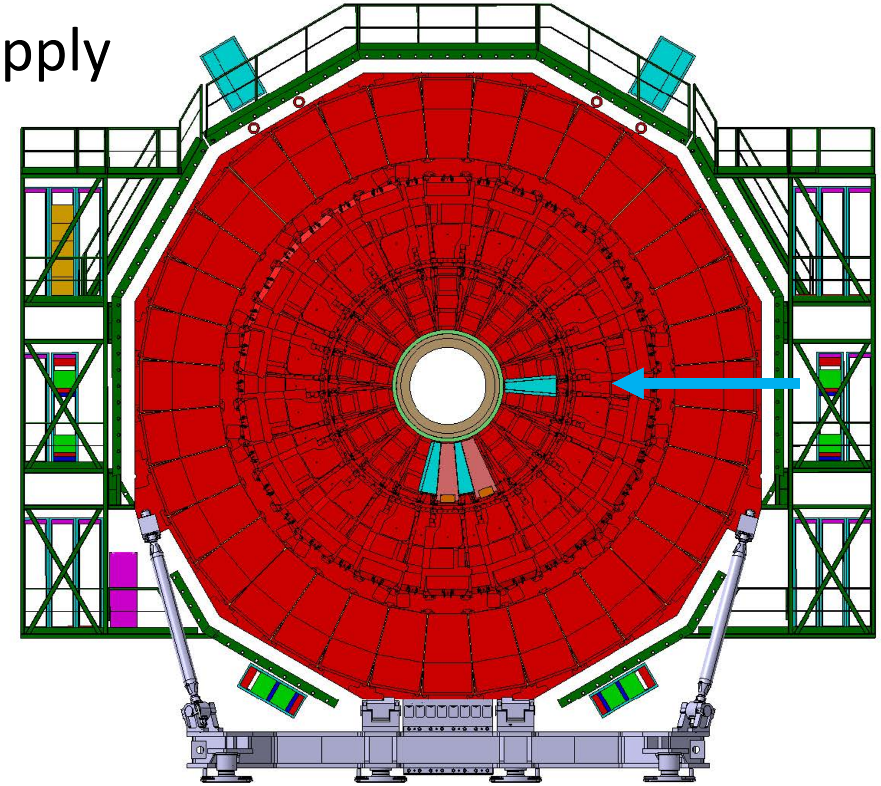
CMS GE1/1 Project

- First completely new subdetector system to be introduced into CMS since it was built!
- This introduces new challenges
  - Mechanical constraints
  - Integration with other existing systems
- 144 GEM detectors make up GE1/1, as 72 two-detector superchambers.
  - 36 short superchambers ($1.61 < |\eta| < 2.18$)
  - 36 long superchambers ($1.55 < |\eta| < 2.18$)



Slice Test

- In 2017, as a proof of concept, 10 detectors were introduced into CMS as the “slice test”
  - 1 short superchamber with a multichannel power supply



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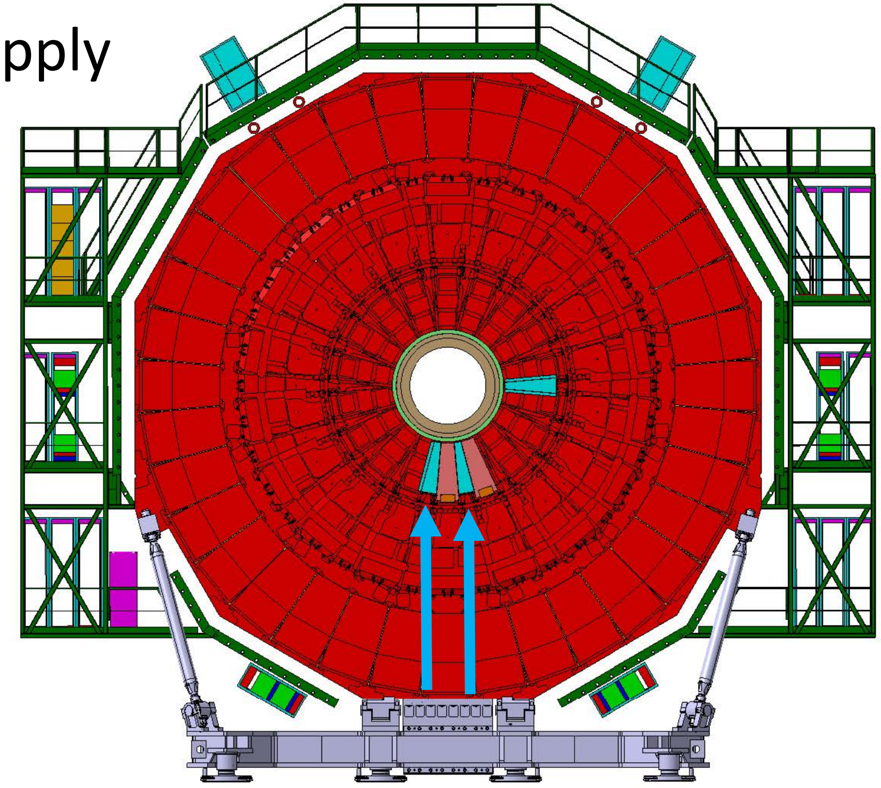
  - 2 short superchambers with an HV divider



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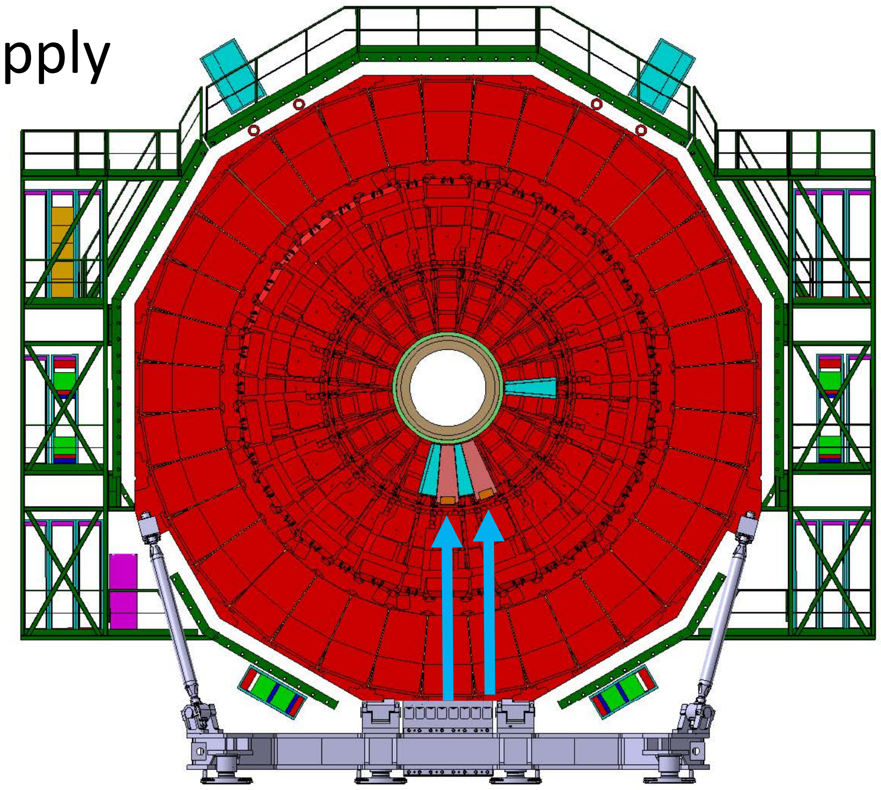

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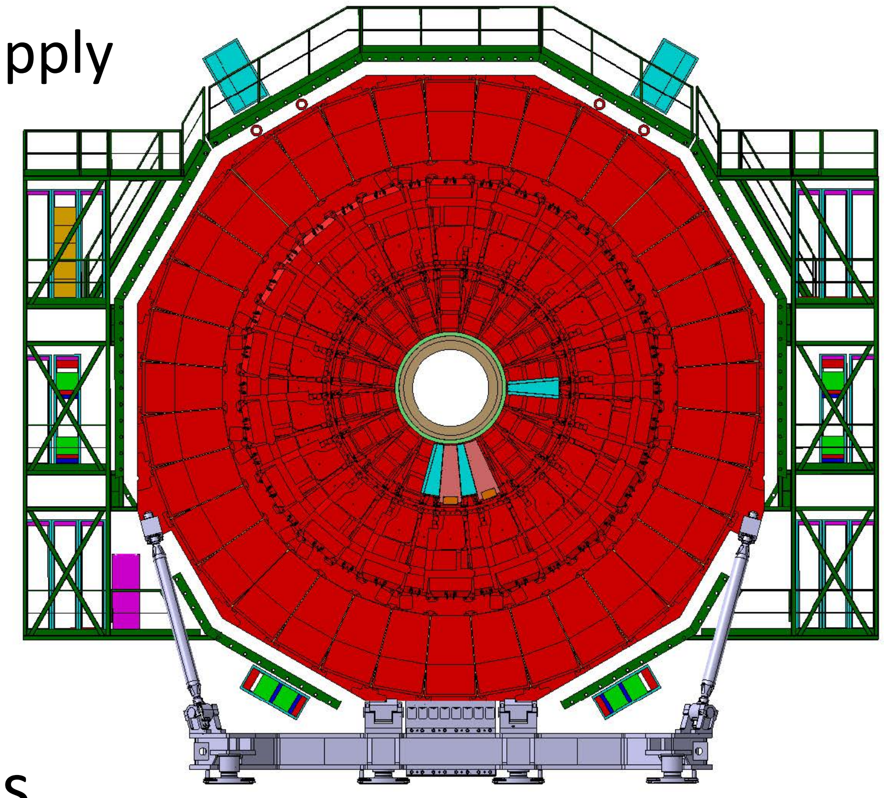
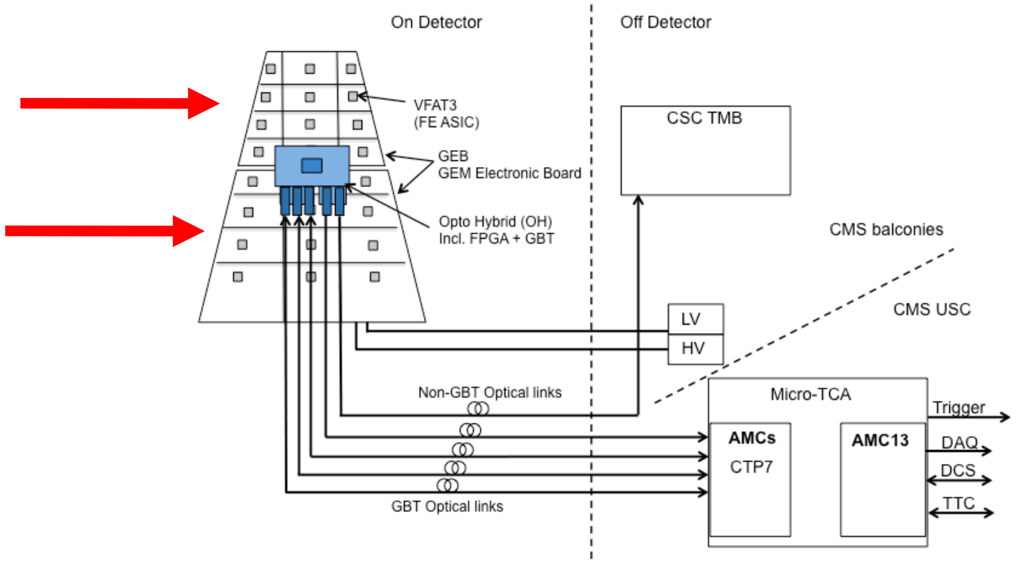


- All detectors had v2b electronics for the 2017 LHC run (VFAT2, single-GEB readout board, wide-end optohybrid)
- In early 2018, the multichannel detector (GEMINIm01) was upgraded with v3b electronics

v3 Electronics - GEB

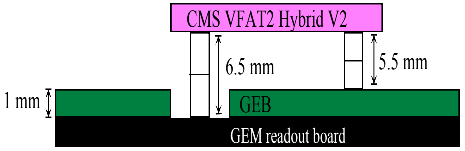
- The GEB is split into two PCBs
- 1m multilayer board was at the manufacturer's limits
- Splitting the board improves signal integrity.
  - Very long track lengths have been seen to cause reflections and distortions of the square signal, rounding out the rising edge.
  - Splitting the board in two allows for shorter track lengths and clearer signal in the simplest manner possible.



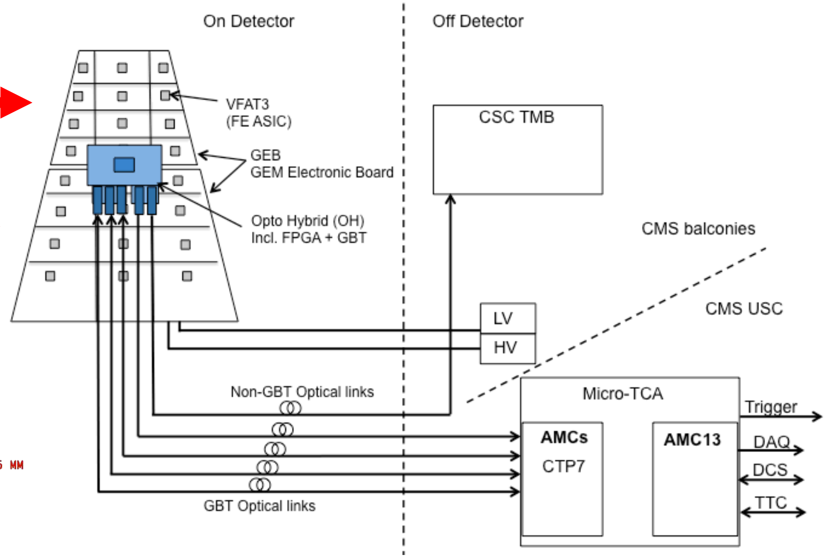
v3 Electronics - GEB

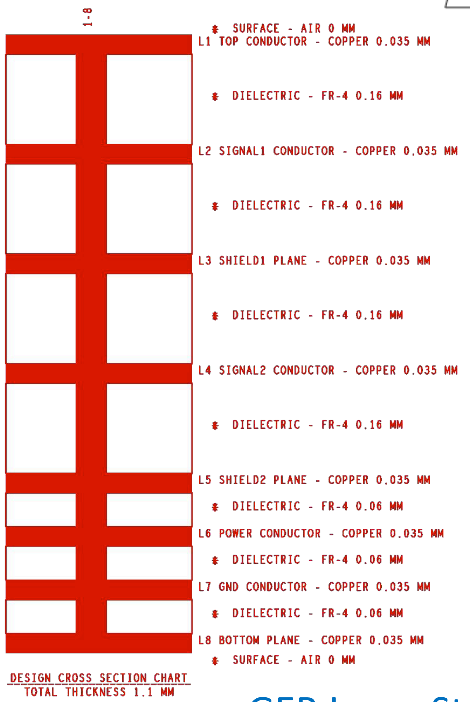
- The GEB is limited to a thickness of ~1mm
- This limits the possible layers:
  - 1 power plane
  - 1 GND plane
  - 2 signal layers
  - 1 shield layer

- The shield layer between the GEB signal lines and the read-out board was added after our experience from the slice test.

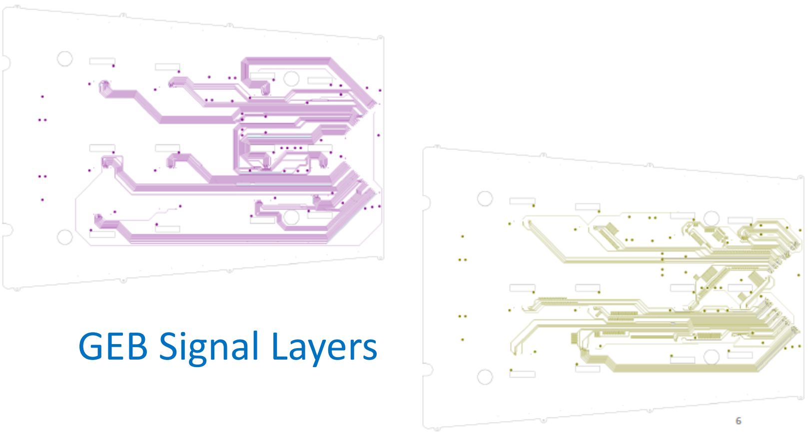


Location of the GEB in the detector





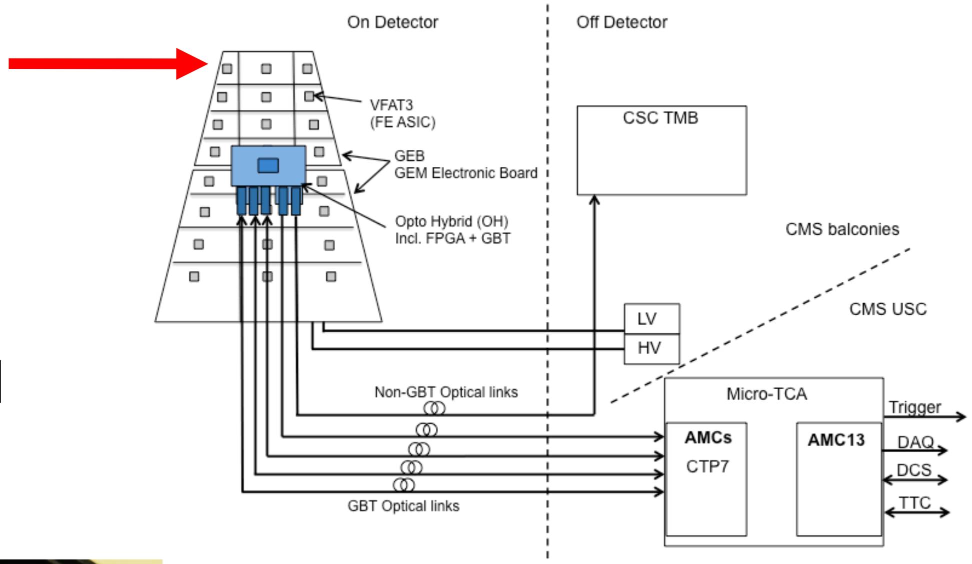
GEB Layer Stack

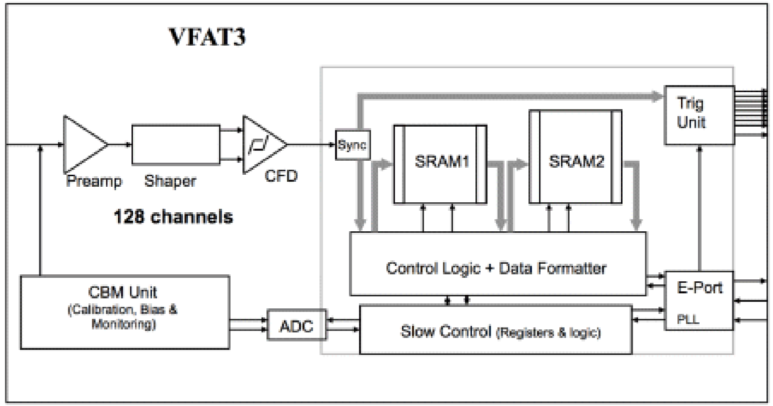


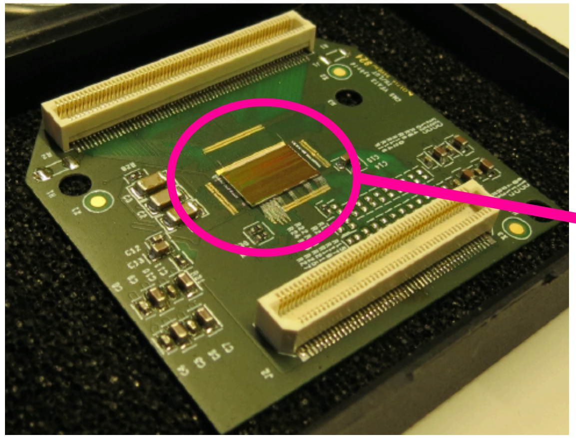
GEB Signal Layers

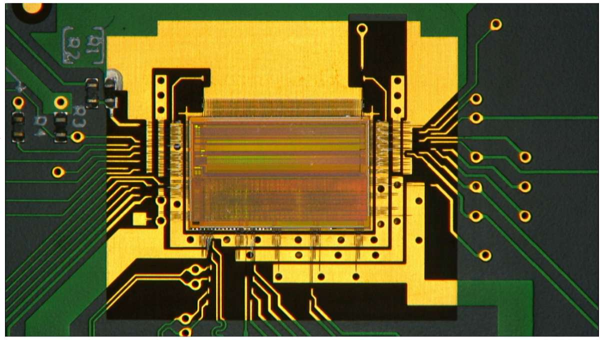
v3 Electronics – VFAT3

- 24 sectors, each routed to an ASIC-based VFAT3 hybrid chip
  - 320 MHz: 4x higher frequency than VFAT2
  - L1 latency up to 12.5 µs
  - Trigger data: 1 bit = OR of two strips (VFAT2 had 1 bit = OR of 16 strips)



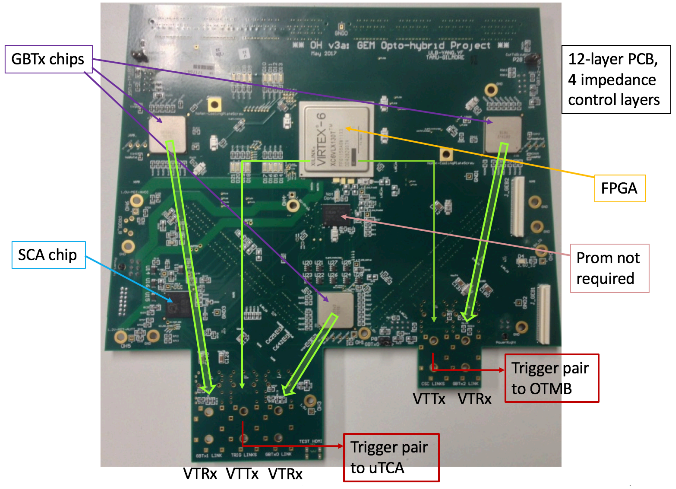




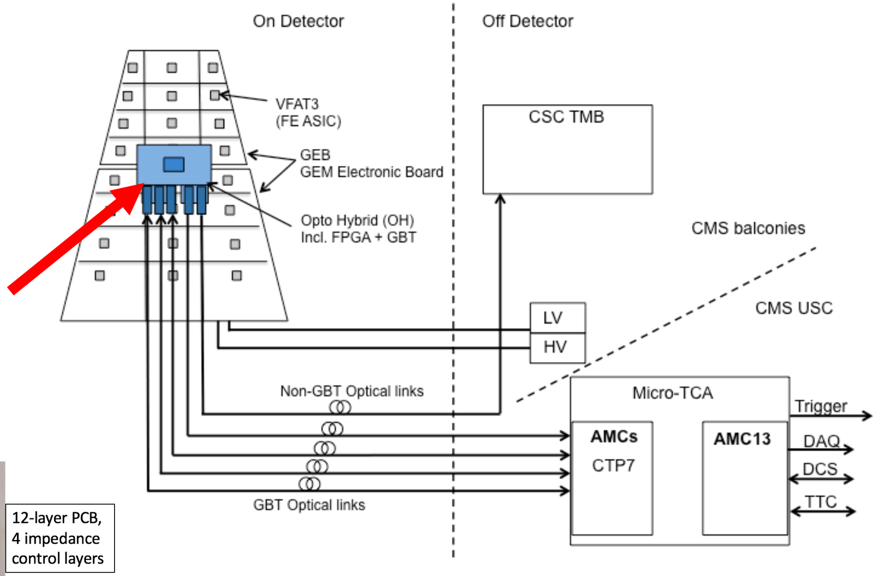


v3 Electronics – Optohybrid

- In the center, attached to both boards, is an optohybrid (OH) mezzanine card, whose main features are a Xilinx Virtex-6 FPGA and three GBTX chips.
- The v3 optohybrid is promless – fast programming of the FPGA directly from the CTP7 is achieved in 70ms. This removes the dependence on a component that has known failures under radiation.

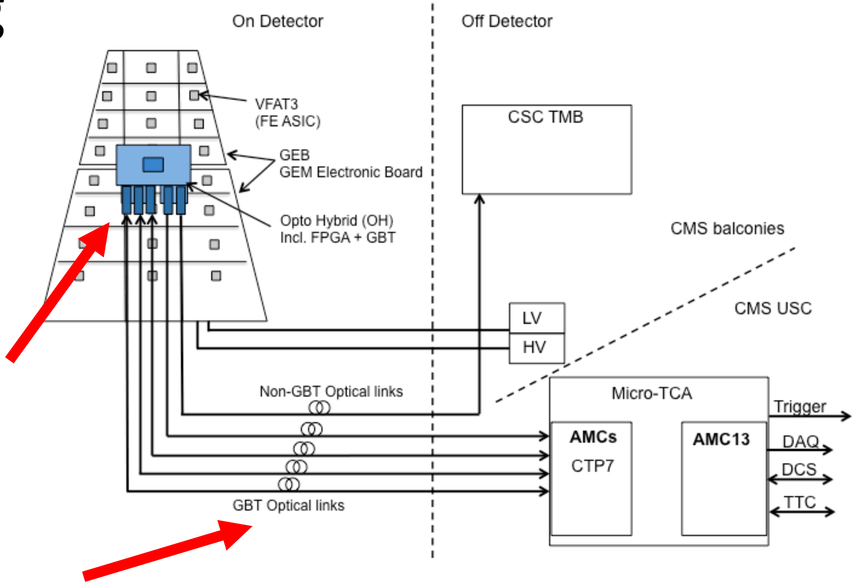


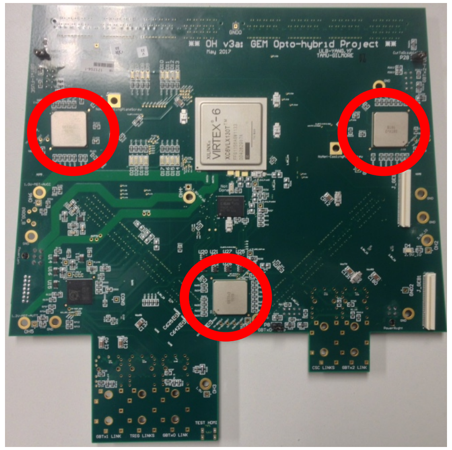
Optohybrid (OH)



v3 Electronics - GBTXs

- The GBTXs are responsible for transmission of tracking and slow control. They drive communication through bidirectional optical links to/from the back-end.
- We have chosen to minimally fuse the GBTXs such that they lock to the fiber link, recover the clock, and keep a certain configuration even after power loss.





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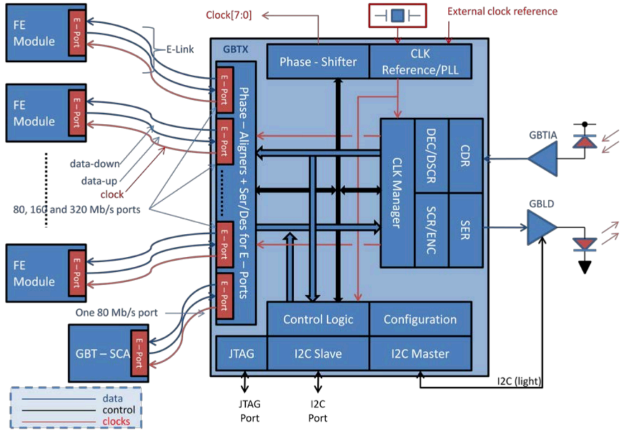
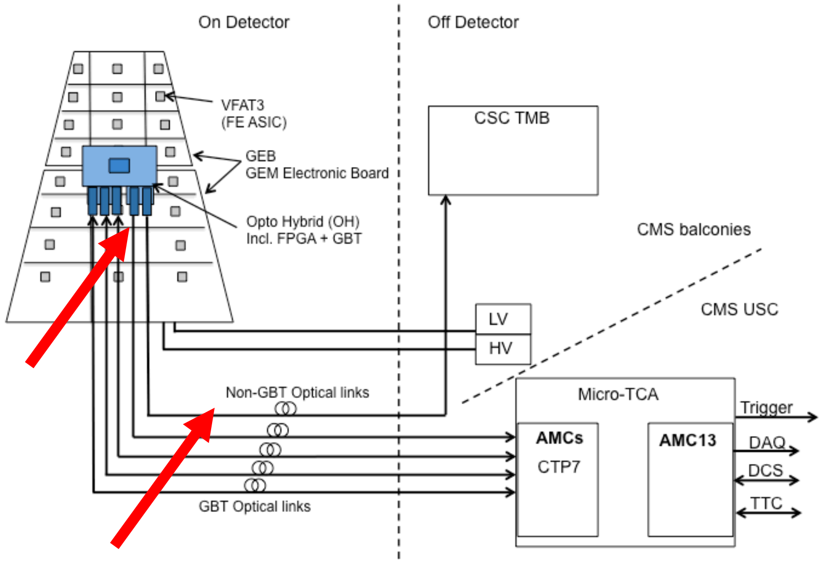


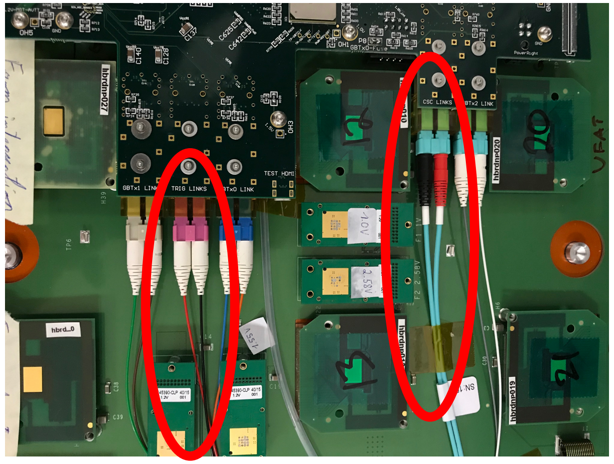
OH Architecture and Interfaces

v3 Electronics - FPGA

- In v3, the FPGA only transmits the trigger data, nothing else.
- A dedicated trigger link is connected to the CSC trigger motherboard.



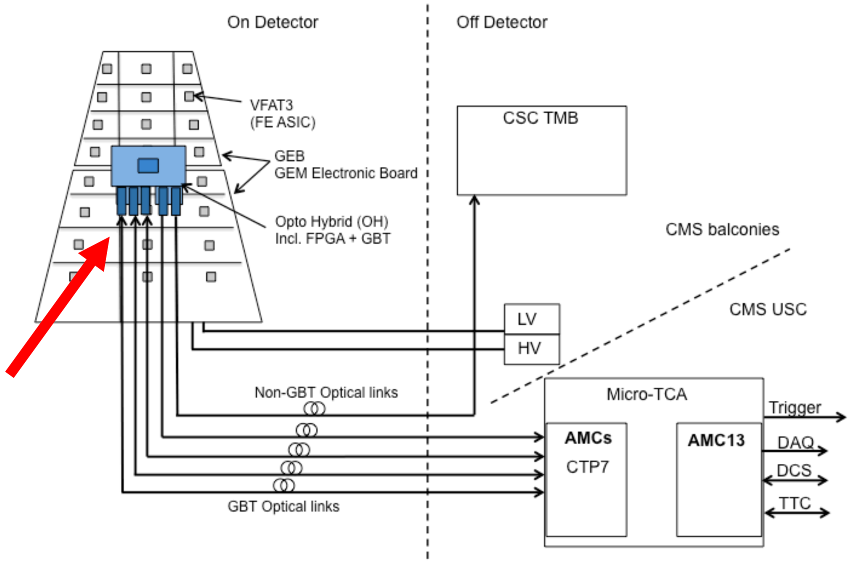
- Same FPGA as used in the CSC ME1/1 chambers (DCFEB), well-tested in the CMS environment.

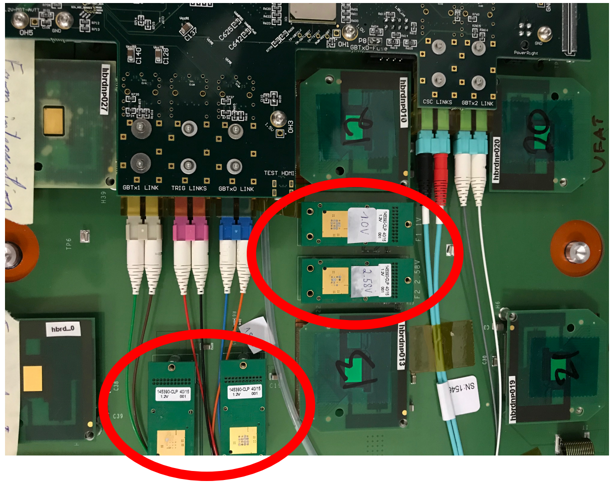


Trigger (L) and CSC trigger (R) links

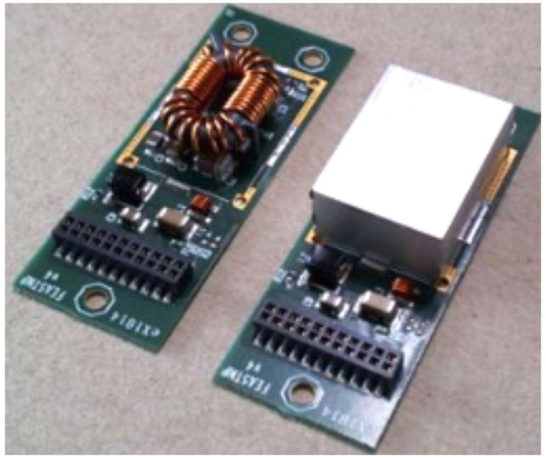
v3 Electronics - FEASTs

- All of the front-end electronics are powered by FEASTs
- There are 10 FEAST slots per detector, but one is not used due to the promless functionality

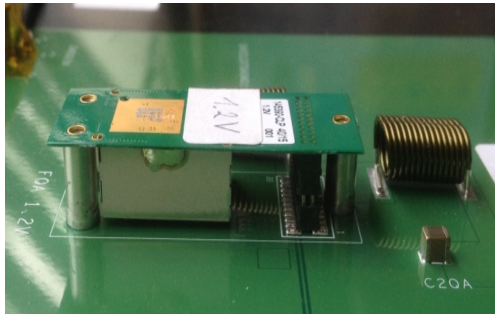




FEASTs next to optohybrid

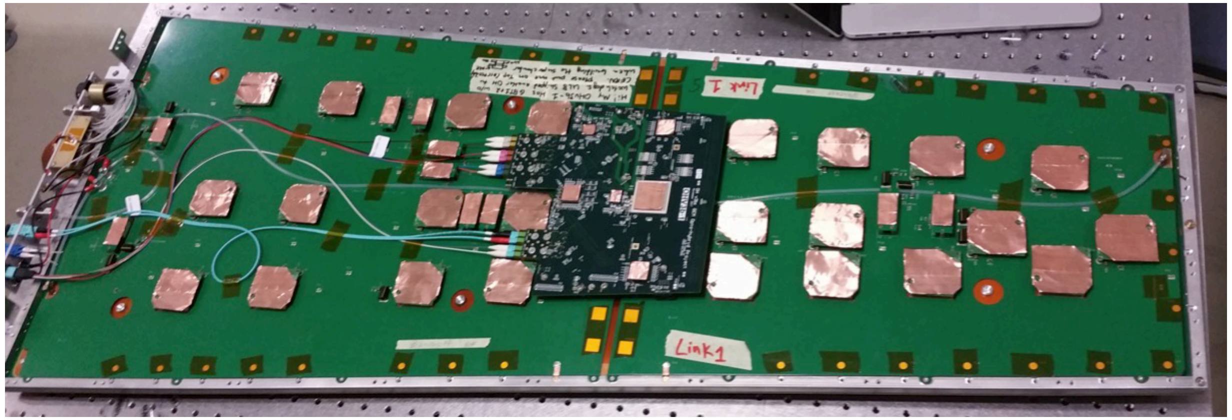


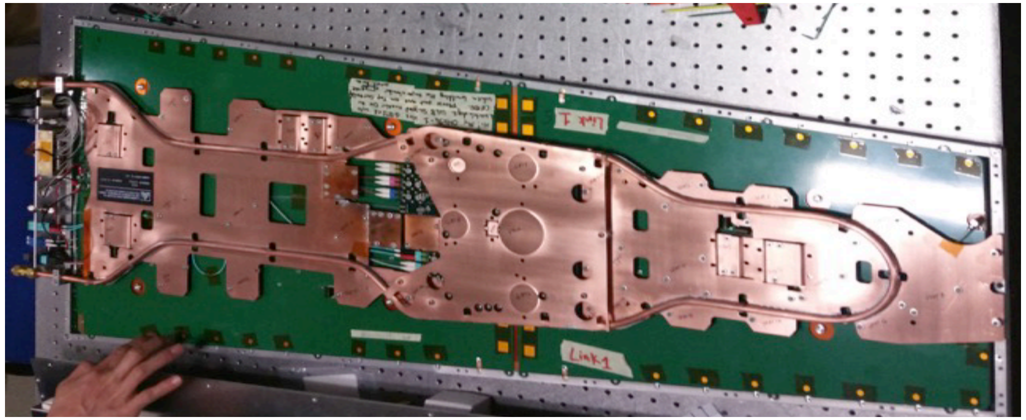
Unmounted FEASTs



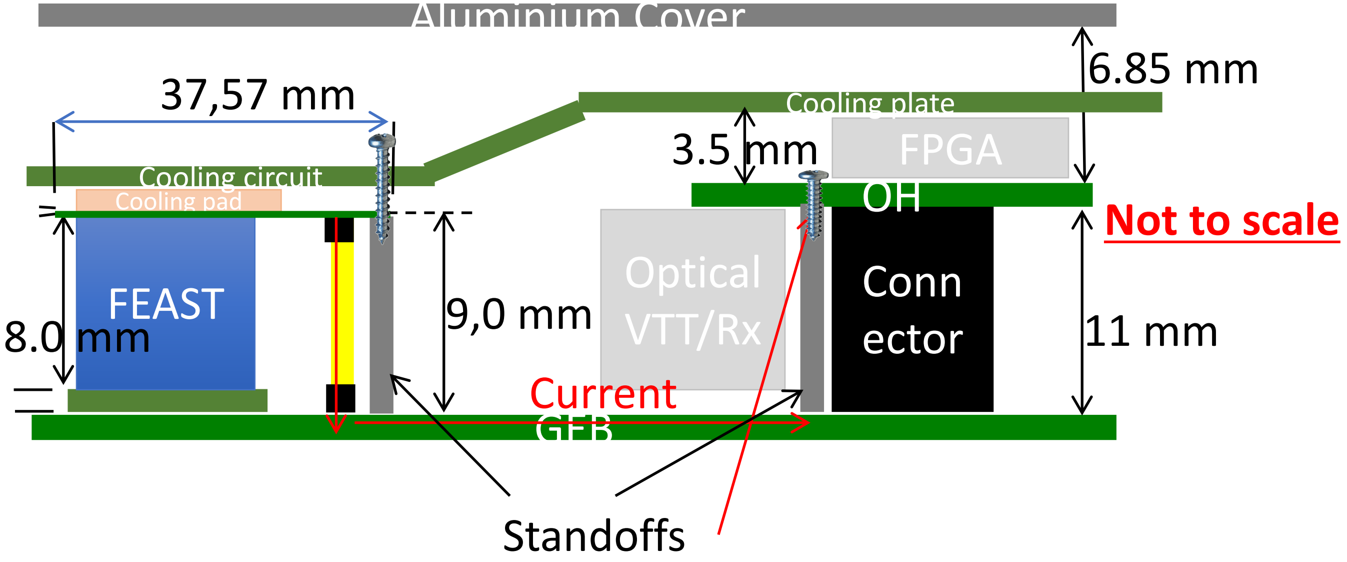
Side view

v3 Electronics - Detector Assembly



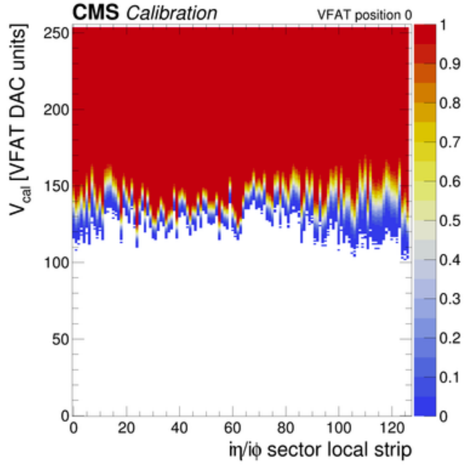


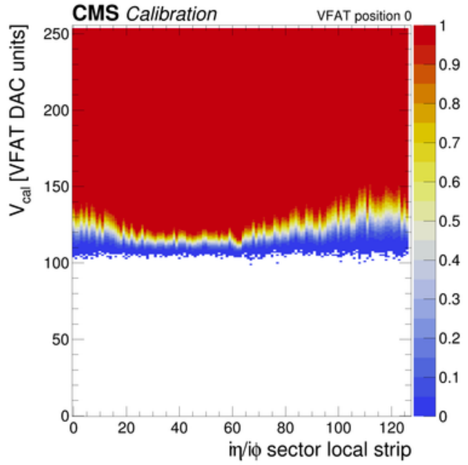
Credit: Gilles De Lentdecker



Noise Measurements: “SCurves”

- SCurve scans show the response of a VFAT chip to the injection of internal calibration pulses.
- A configurable number of pulses are injected, with the size of the pulse determined by the VCAL value.
- The total number of times the comparator fired is recorded. (Top)
- The VFATs can be “trimmed” by adjusting the individual channel registers to trim the 99% response point to the same VCAL value. (Bottom)

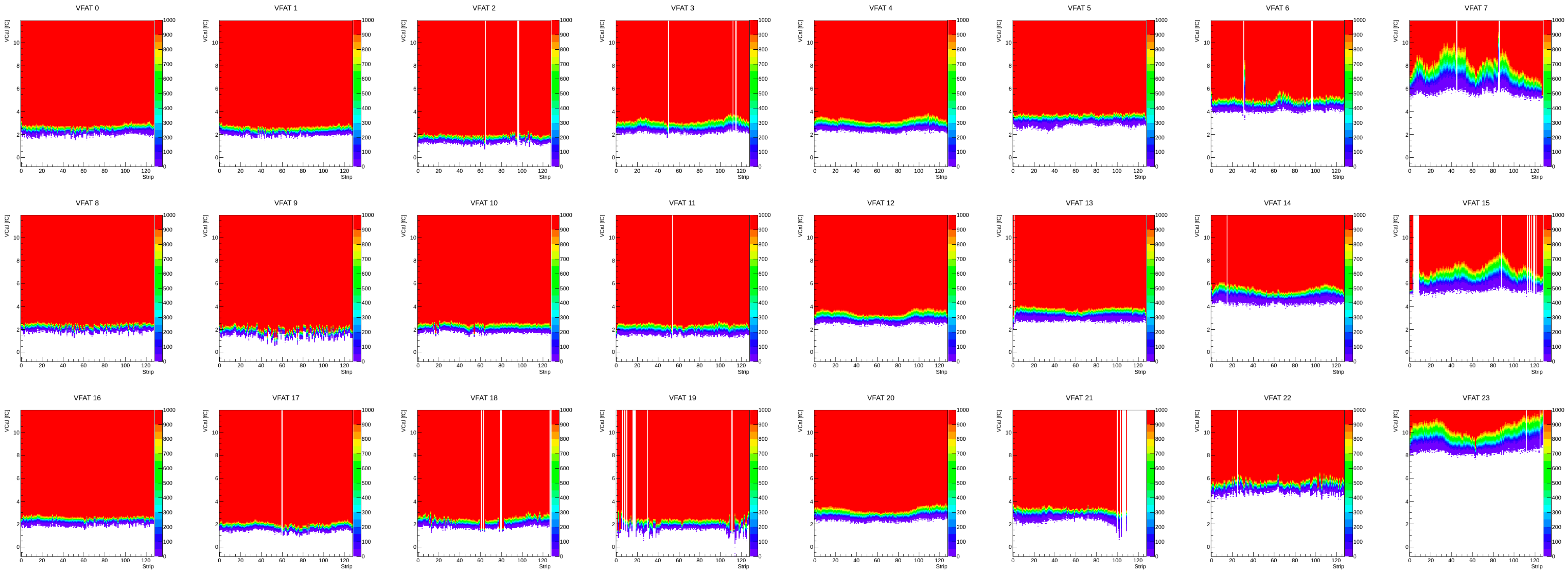




Noise Measurements: "SCurves"

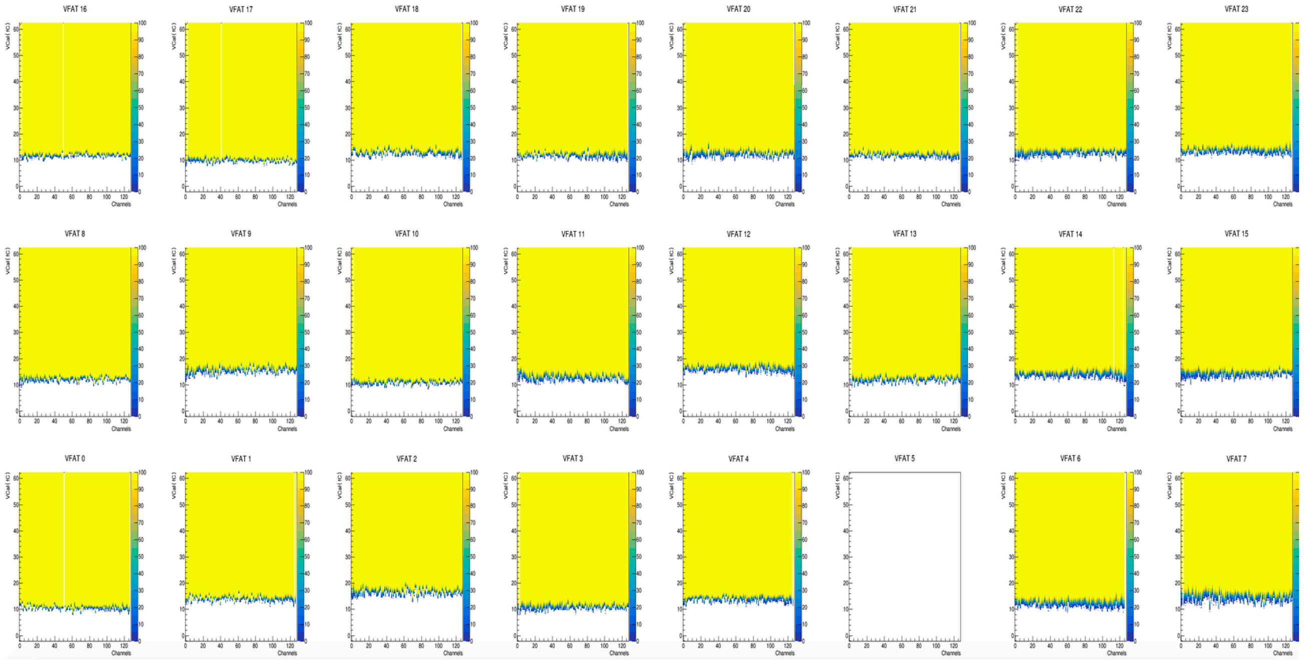
- For v2 chambers, the VFAT2 chips are generally more noisy closer to the optohybrid and the area in which the LV power lines converge. This is not present for v3 chambers.

Noise values in fC

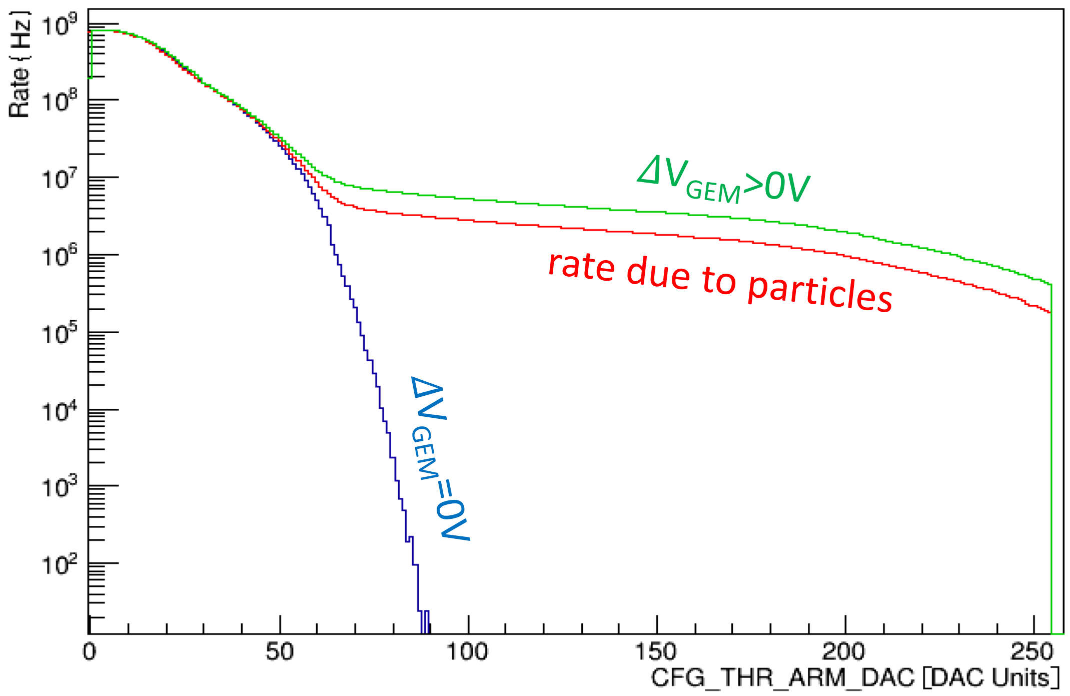


v3 SCurves and Slice Test Results

- The VFAT5 position in the v3 slice test detectors was non-functional due to a mismatch in track length that prevented good communication with the optohybrid. Regardless, we were still able to get good data!

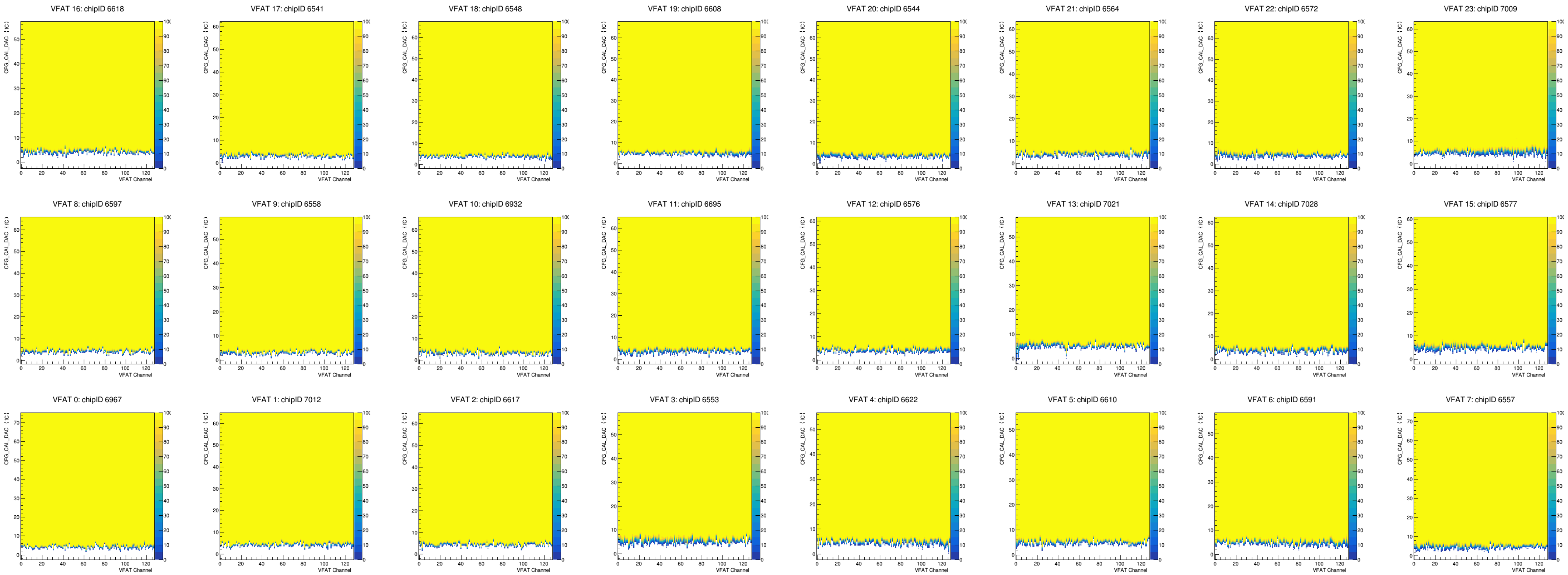


Trigger data rate vs. Threshold



HV3b_v3 GE1/1 SCurves

- For the final GE1/1 electronics, position 5 has been successfully fixed by adjusting the track length. With the new design and VFAT3 chips, we now have low and consistent noise levels.

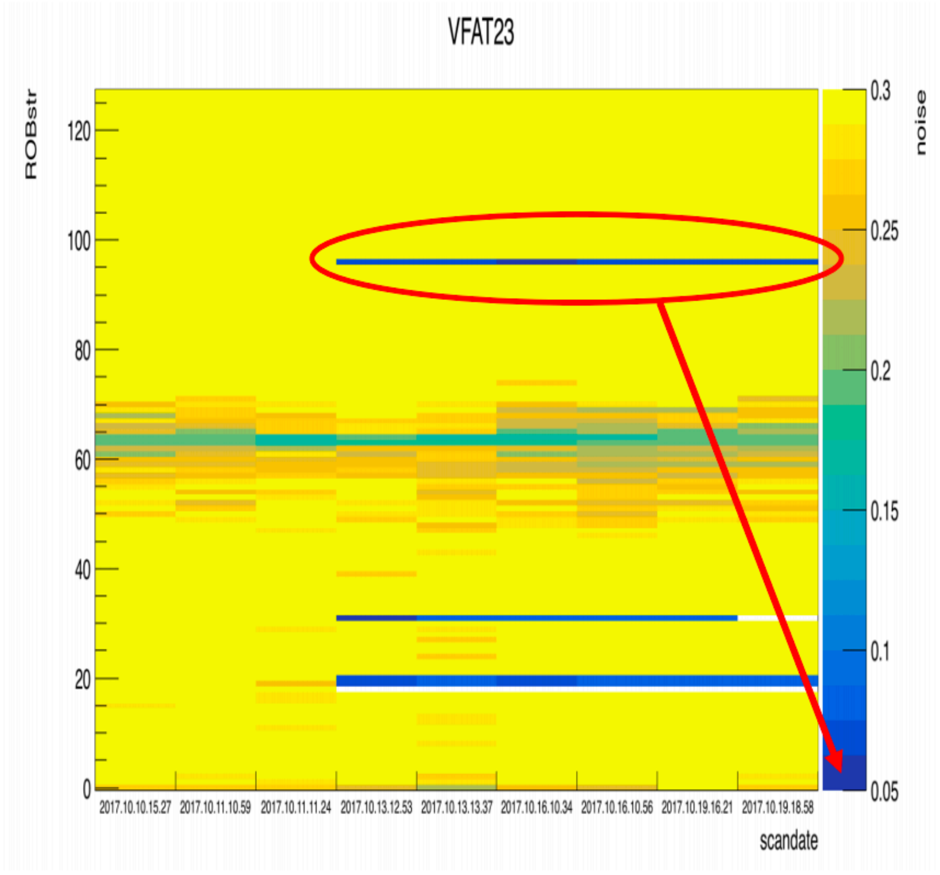


VFAT2 Channel Stability

- Every day, SCurve scans were taken of the installed slice test detectors. This allowed us to see the stability of the VFAT2 channels through “time series” plots.

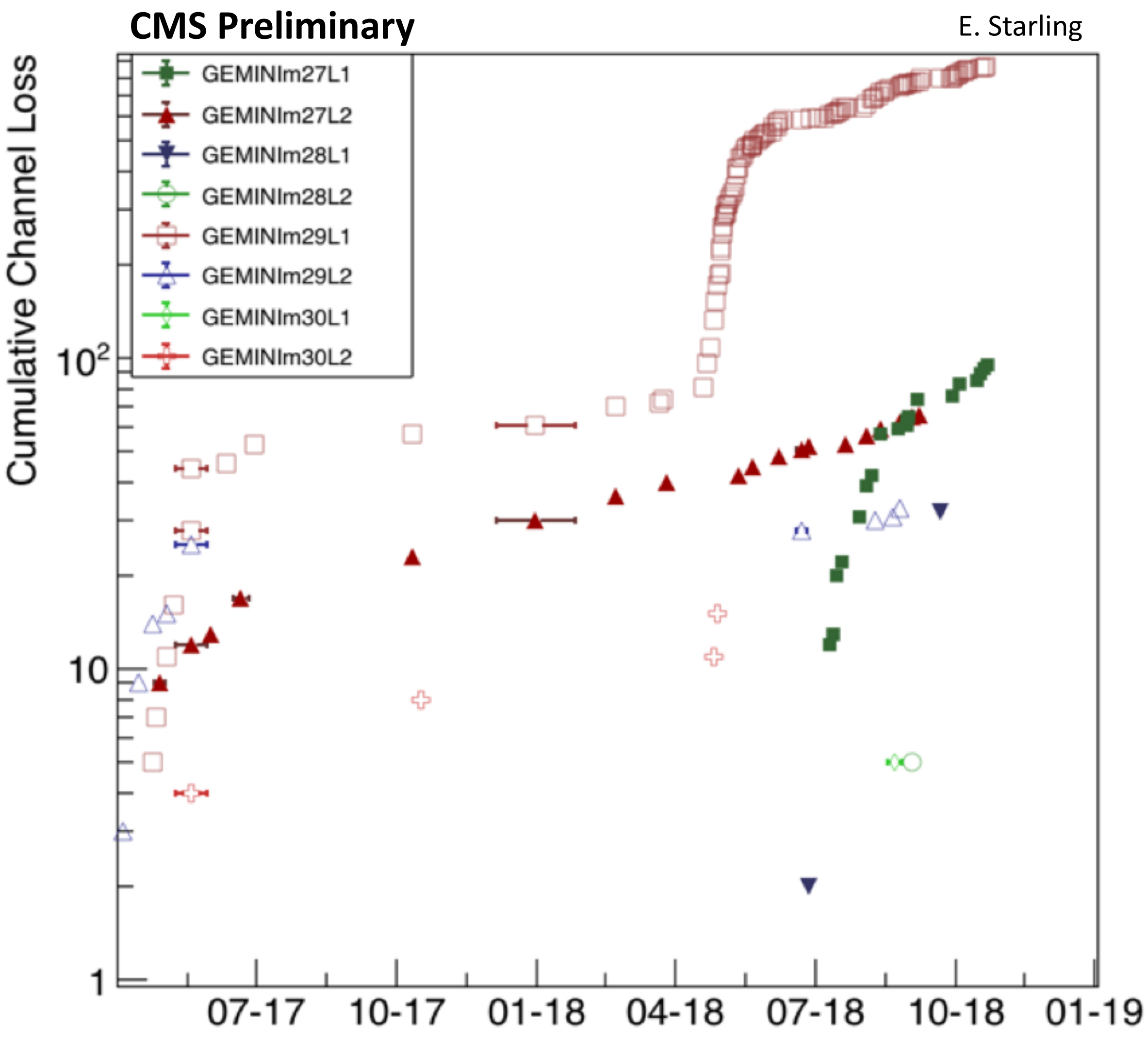
- Channels may be masked for a number of reasons: hot channel, dead channel, high noise, high effective pedestal.

- If a channel has a noise level of 0.0414 – 0.109 fC, it indicates that the capacitance of that strip is no longer being seen and the channel is considered dead.



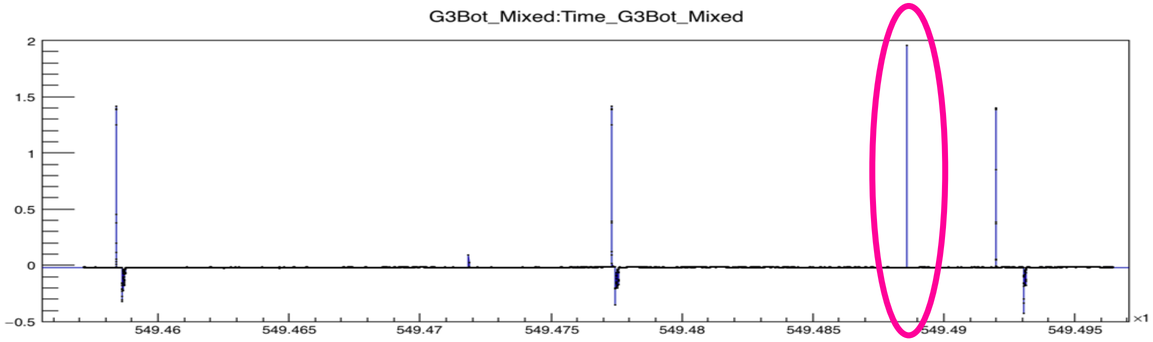
VFAT2 Channel Stability

- Over the lifetime of the Slice Test, there was an overall loss rate of approximately 0.5% of VFAT2 channels per month for the v2 detectors, concentrated mostly in three of the short chambers:
  - GEMINIm29L1 from May 2018
  - GEMINIm27L1 from July 2018
  - GEMINIm27L2 steadily over time

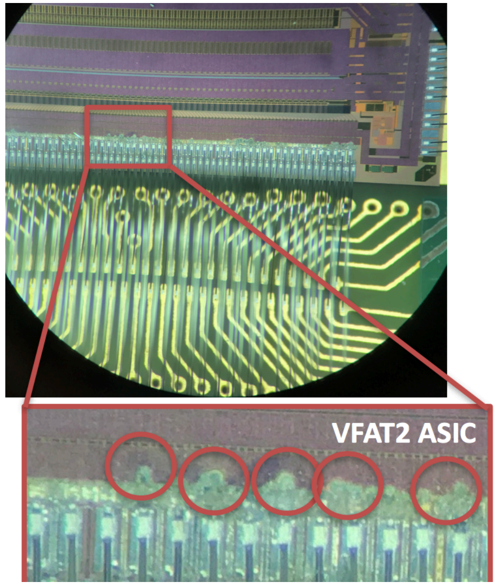


VFAT2 Channel Stability

- This channel loss has been attributed to burn damage as a result of discharges reaching the anode.
  - Ex: Right, G3_bot (foil closest to the anode) exhibiting both leakage currents and a discharge (in pink).



- The energy of these discharges is large - ~410 μJ
- Design changes to the v3 electronics were needed to prevent this for the full GE1/1 system: An additional protection circuit on the VFATs, and changes to the resistance and capacitance of the HV filter on the detector.



Proposed Changes to VFAT Design

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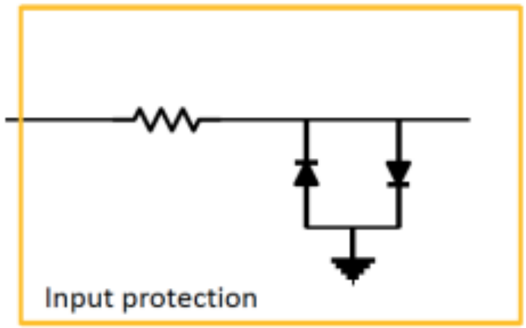
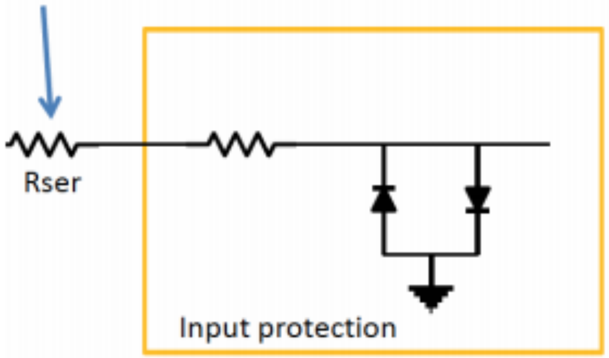
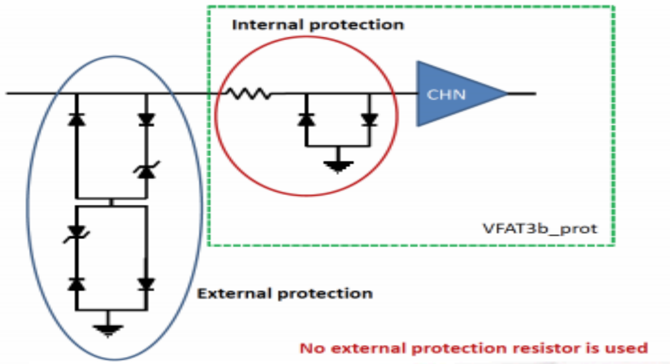
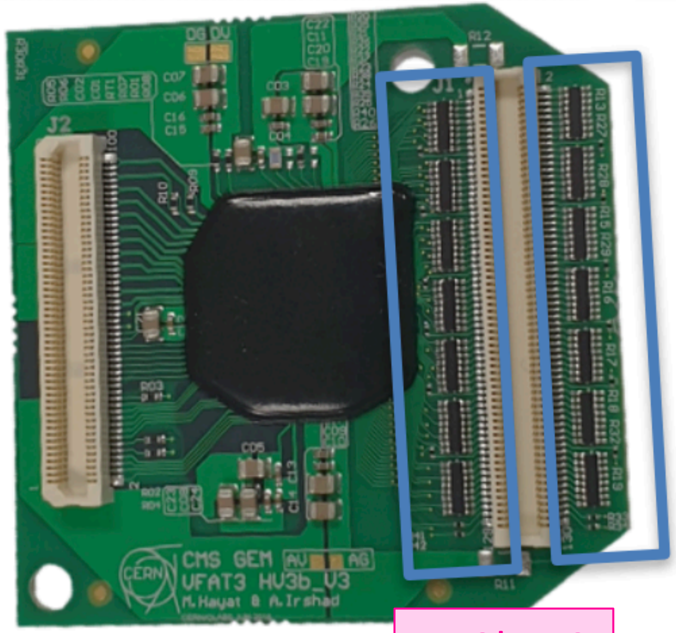


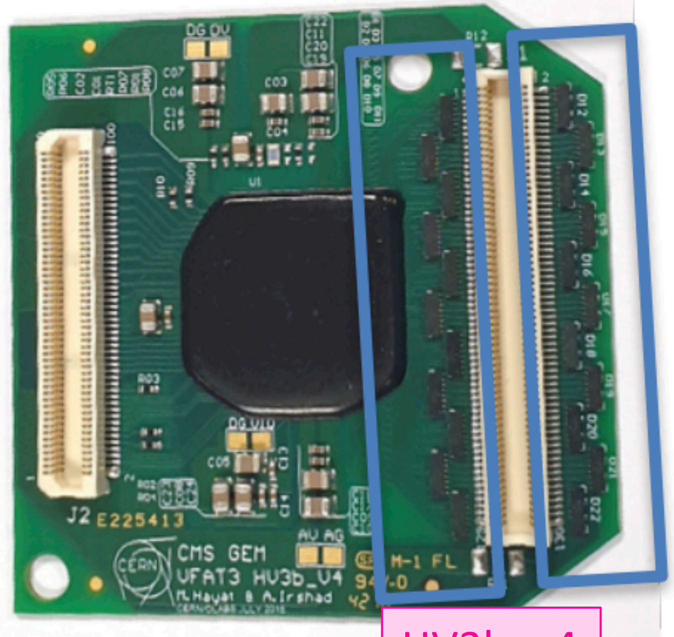




HV3b_v2



HV3b_v3



HV3b_v4

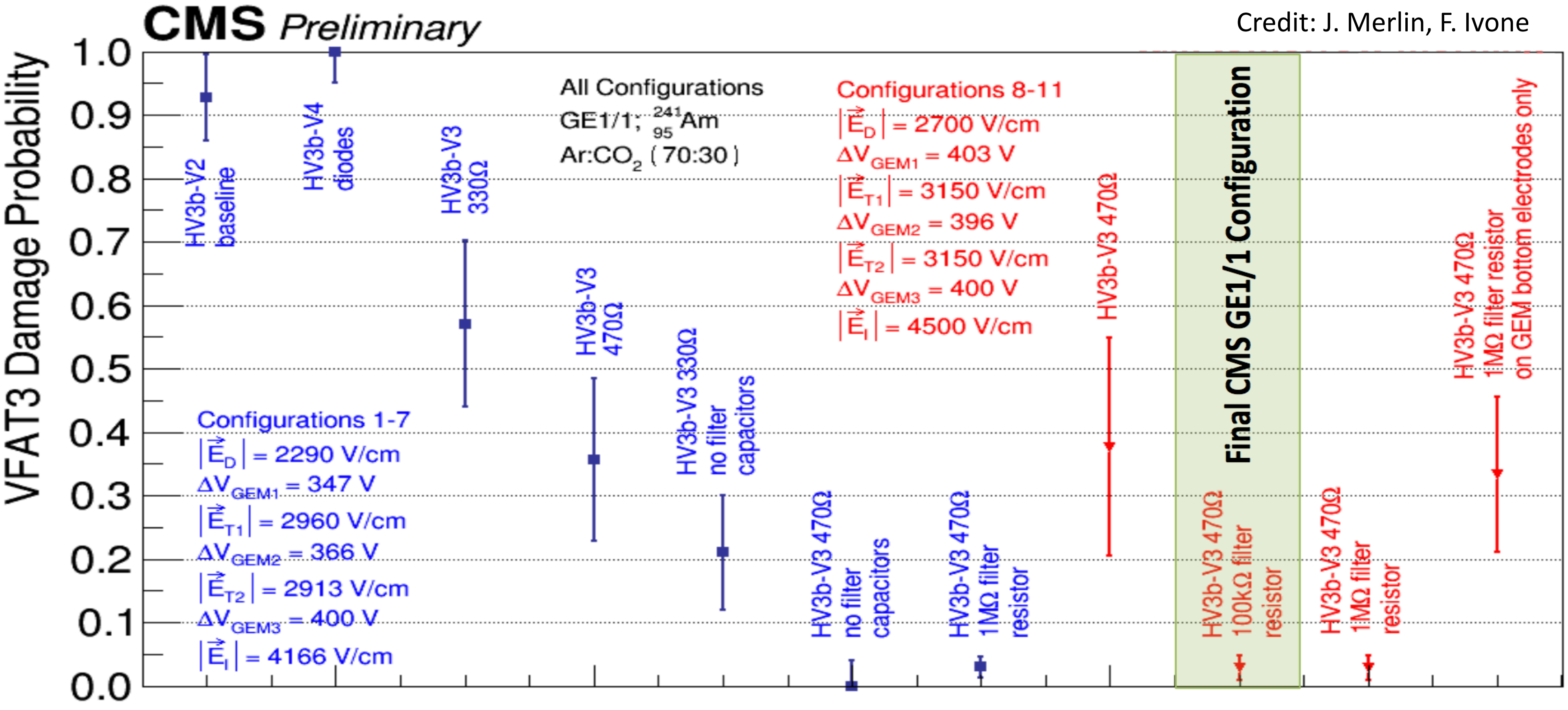
- HV3b_v2 is the baseline hybrid for the v3 electronics
- HV3b_v3 adds additional resistors in series

  HV3b_v4 adds commercial off-the-shelf diodes in parallel

Credit: Paul Aspell

Changes to VFAT Design: Testing

Credit: J. Merlin, F. Ivone



- For more information, see Aamir Irshad's talk: September 6th, 09:25

Timeline – GE1/1

- August 2018: GE1/1 chamber production begins around the world

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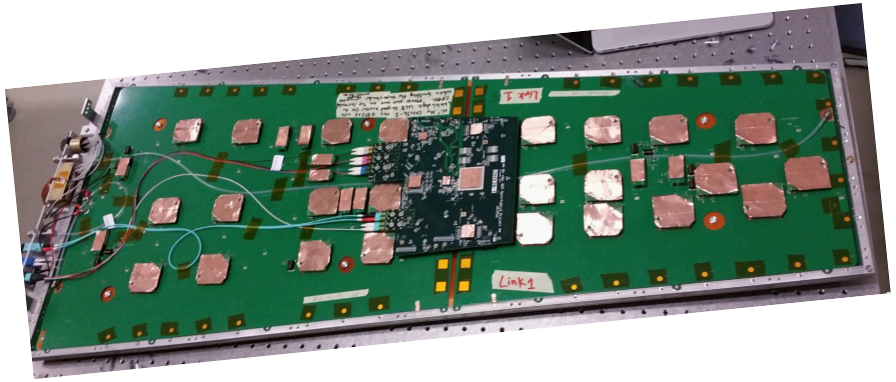
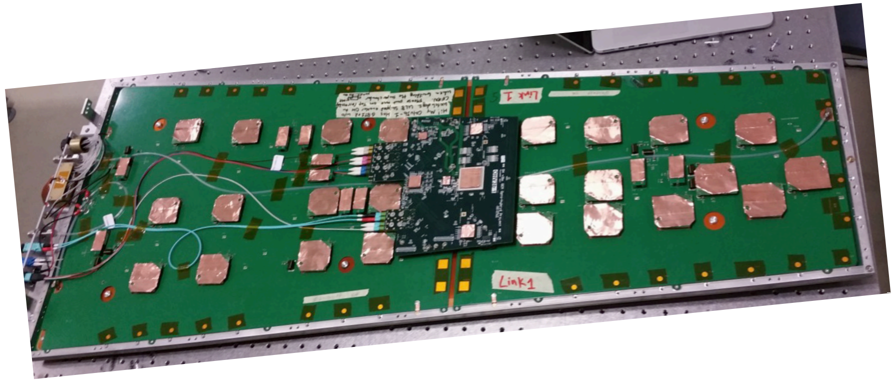
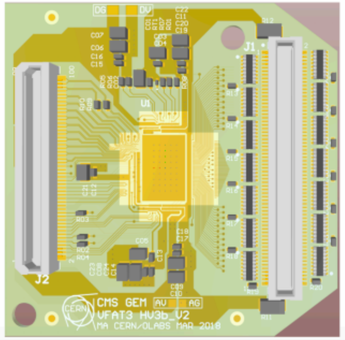


Timeline – GE1/1

- August 2018: GE1/1 v3c superchamber production begins around the world
- December 2018: All 144 GE1/1 chambers have been produced, fully qualified, and validated
- January 2019: HV3b_v3 470 Ω is chosen as the final GE1/1 VFAT design





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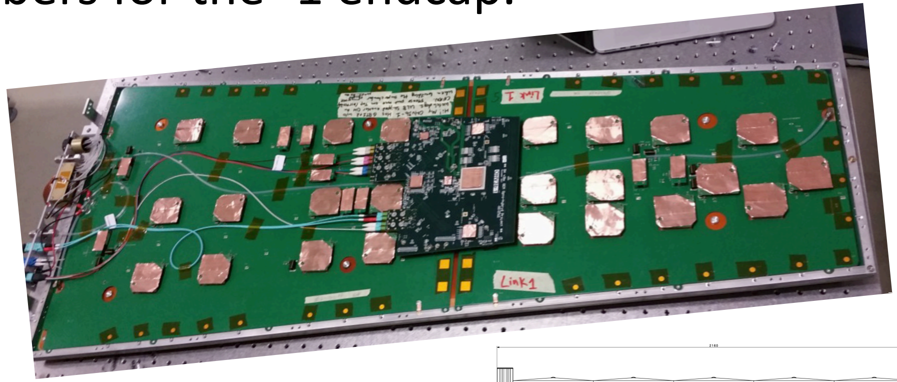
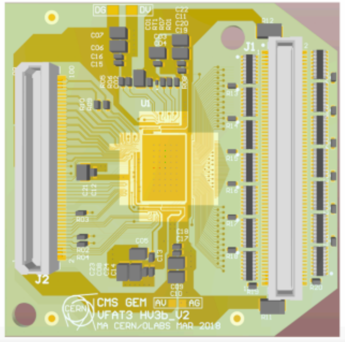
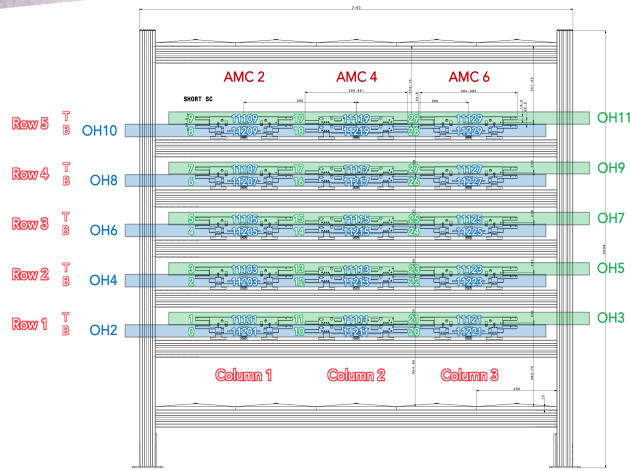
- January 2019: HV3b_v3 470 Ω is chosen as the final GE1/1 VFAT design
- July 2019: QC8 qualification begins on the first short superchambers for the -1 endcap.

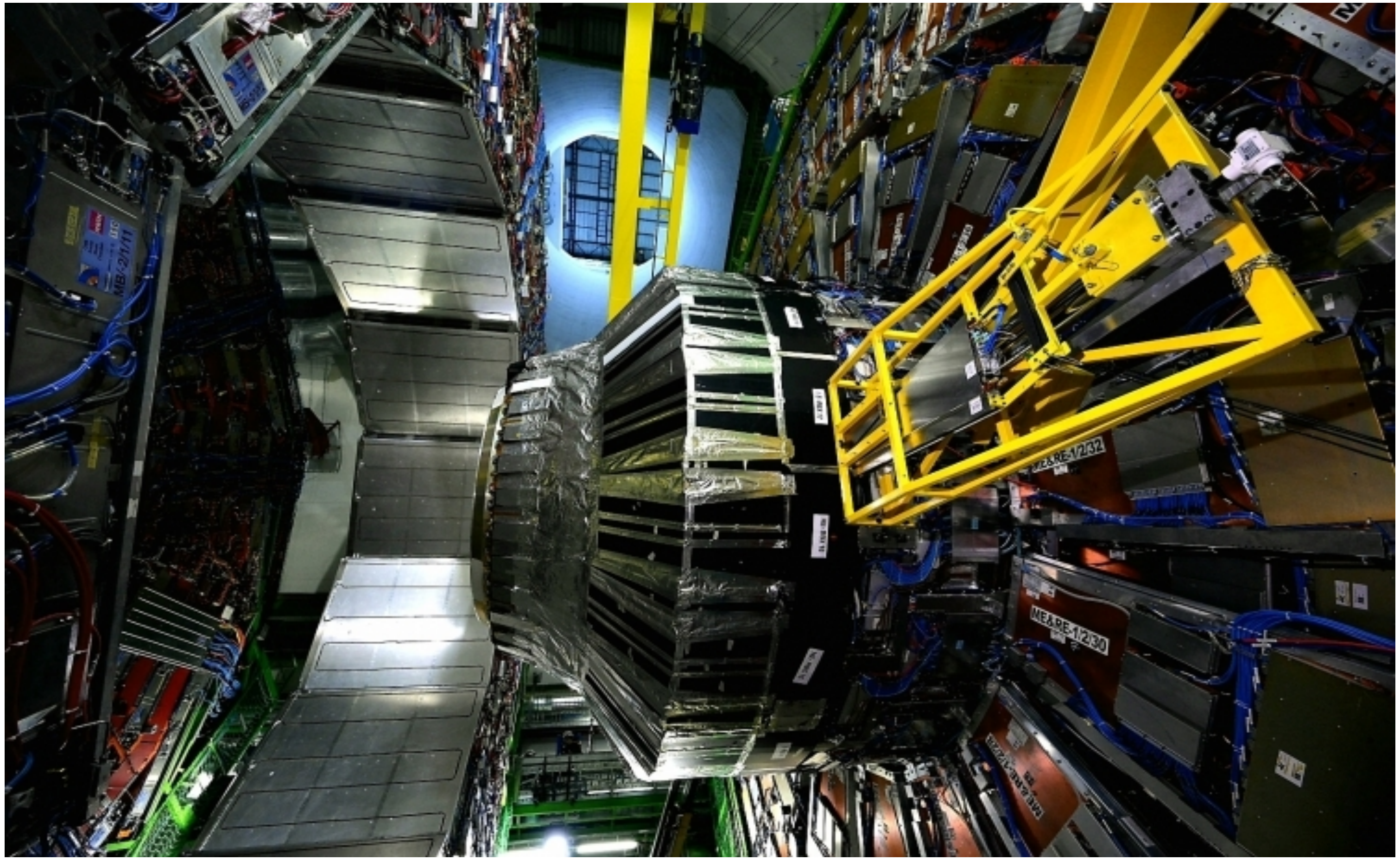


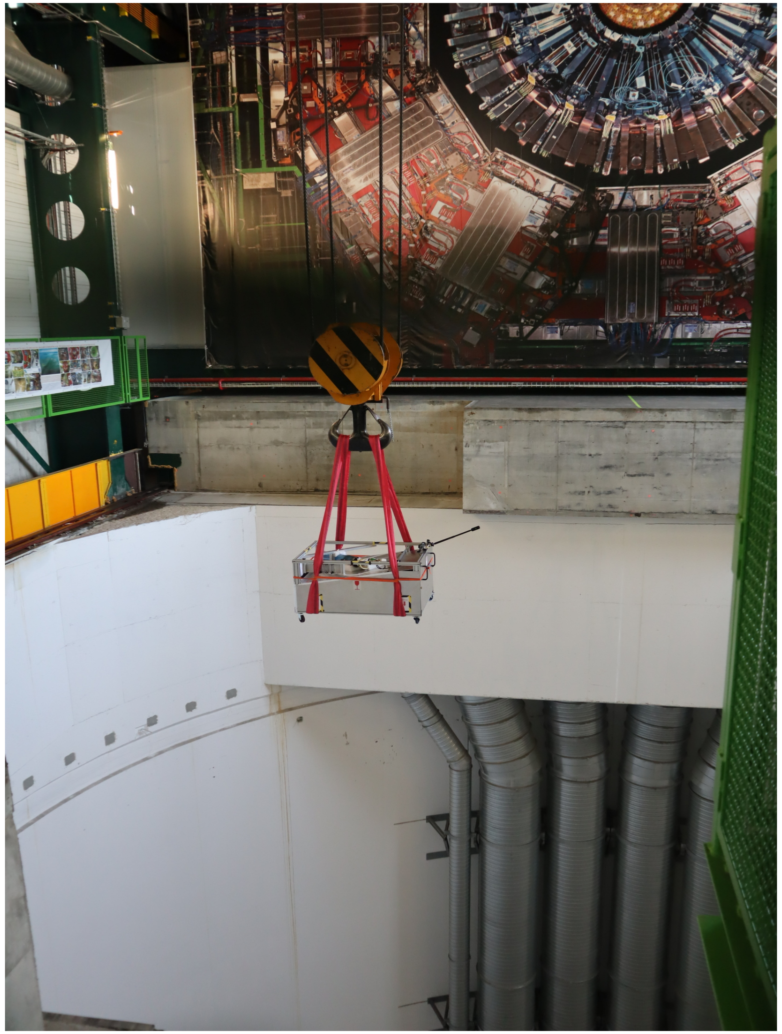




Timeline – GE1/1

- July 25th, 2019: Installation of the first two final GE1/1 superchambers!





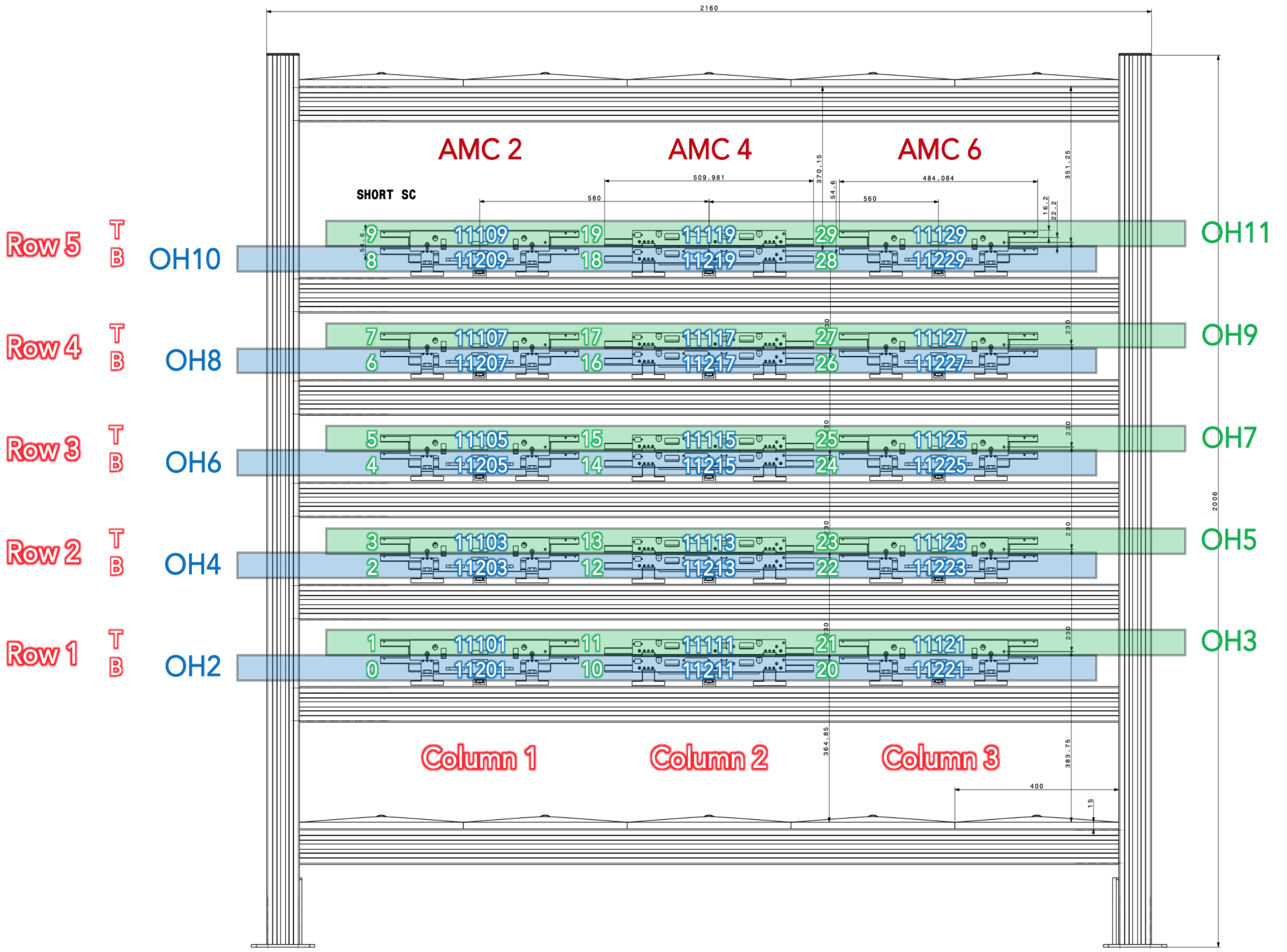
See photo essay: https://cms.cern/news/first-gems-installation

Quality Control Steps

- Throughout the production process, the GE1/1 chambers go through a rigorous series of eight quality control steps
  - QC1: Material inspection
  - QC2: Maximum leakage current measurement for GEM foil quality
  - QC3: Gas leak measurement and gas system calibration
  - QC4: Linear behavior verification and check for defects in the HV circuit
  - QC5: Effective gain and response uniformity
  - QC6: HV stability test
  - QC7: Electronics connectivity test
  - QC8: Cosmic ray data taking and verification
- Quality control steps 1-5 happen at the individual production sites, whereas steps 6-8 happen at CERN in the 904 production lab in Prevessin.

QC8

- QC8 is the final quality control step before the chambers are ready to be installed into CMS
- Data is taken using cosmic muons
- SCurves are taken to ensure the electronics are working properly and to assess the noise
- Efficiency measurements are of particular interest



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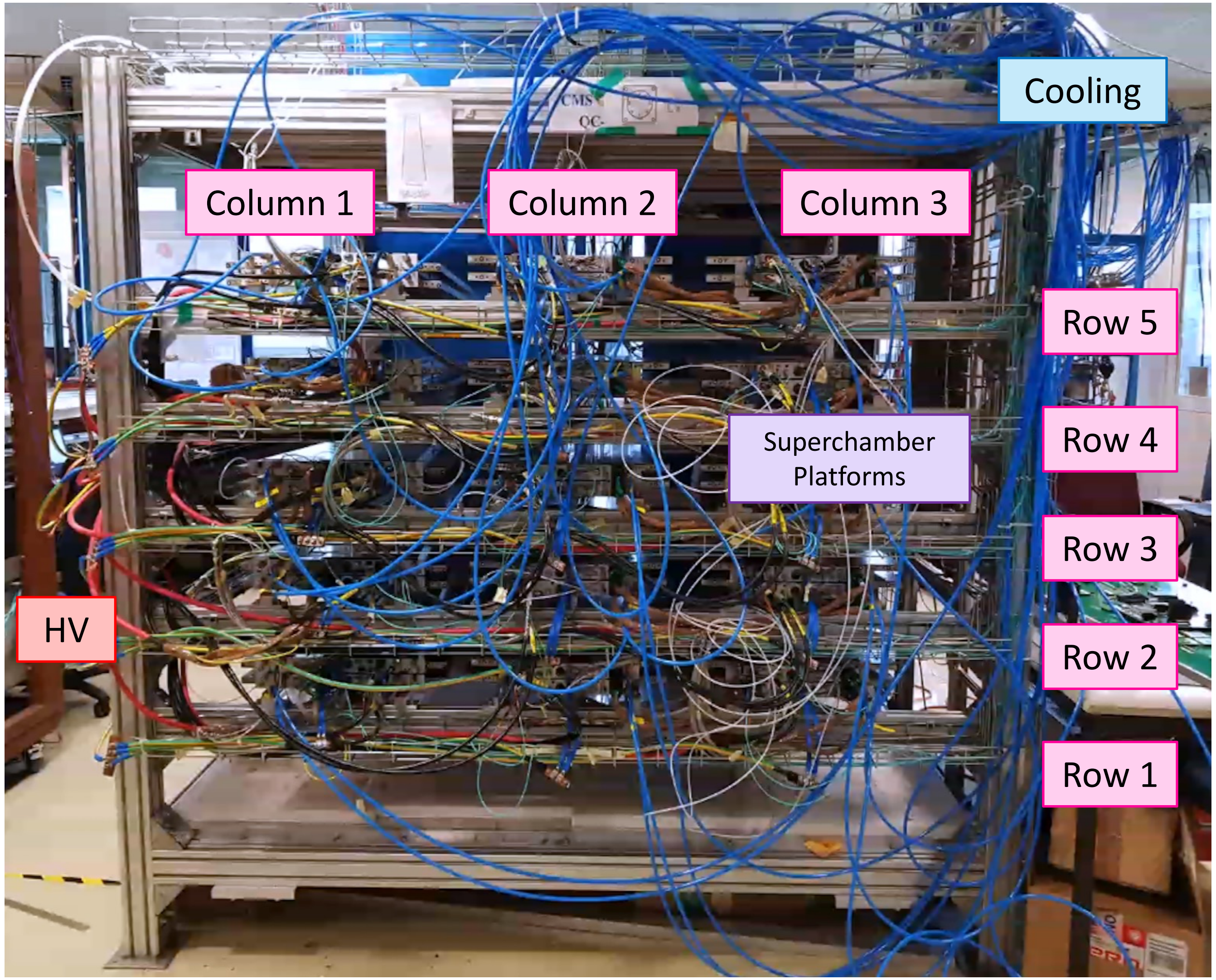
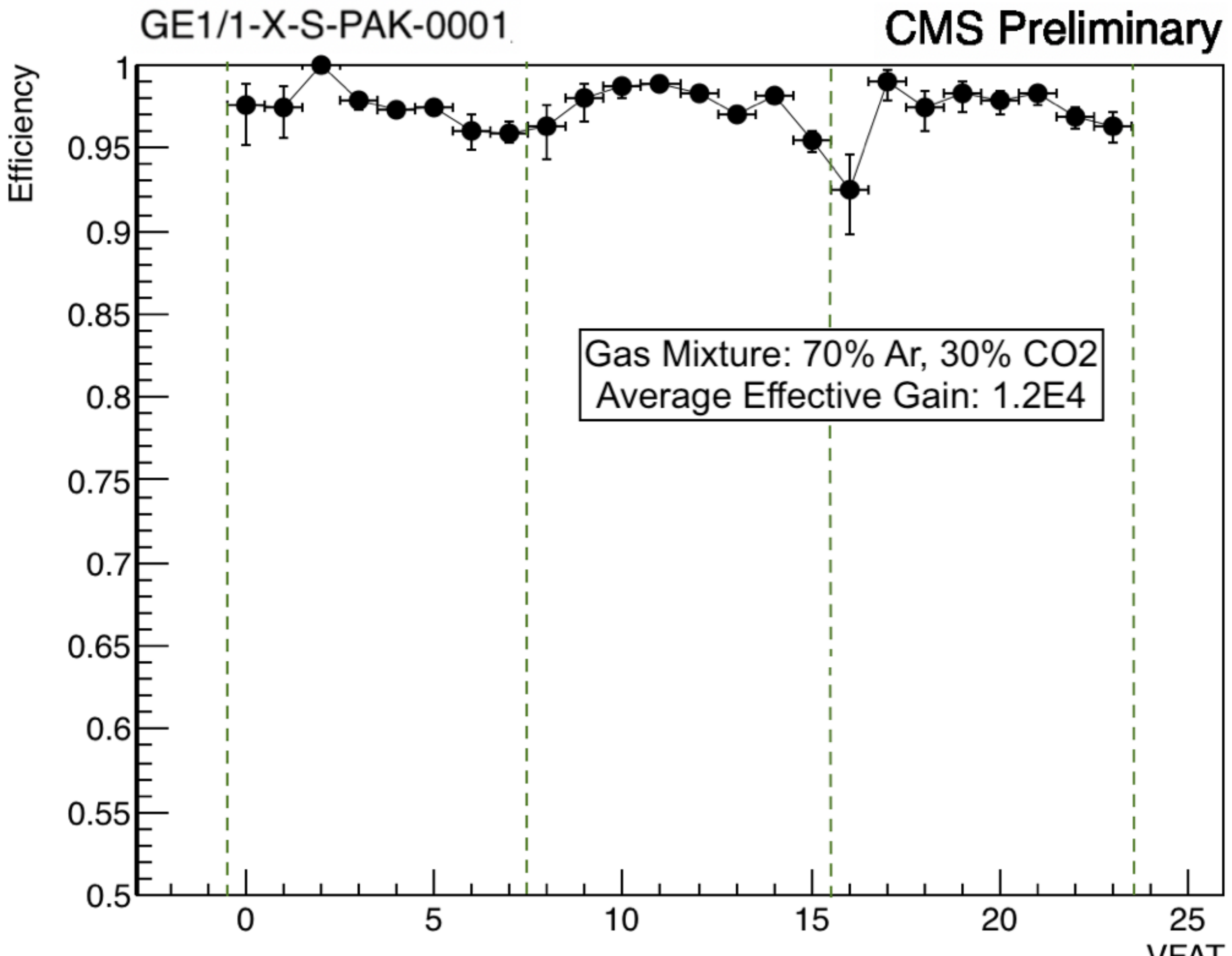
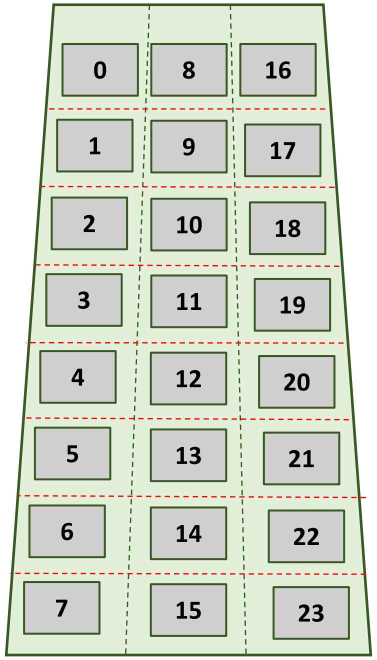


QC8 Results: Efficiency

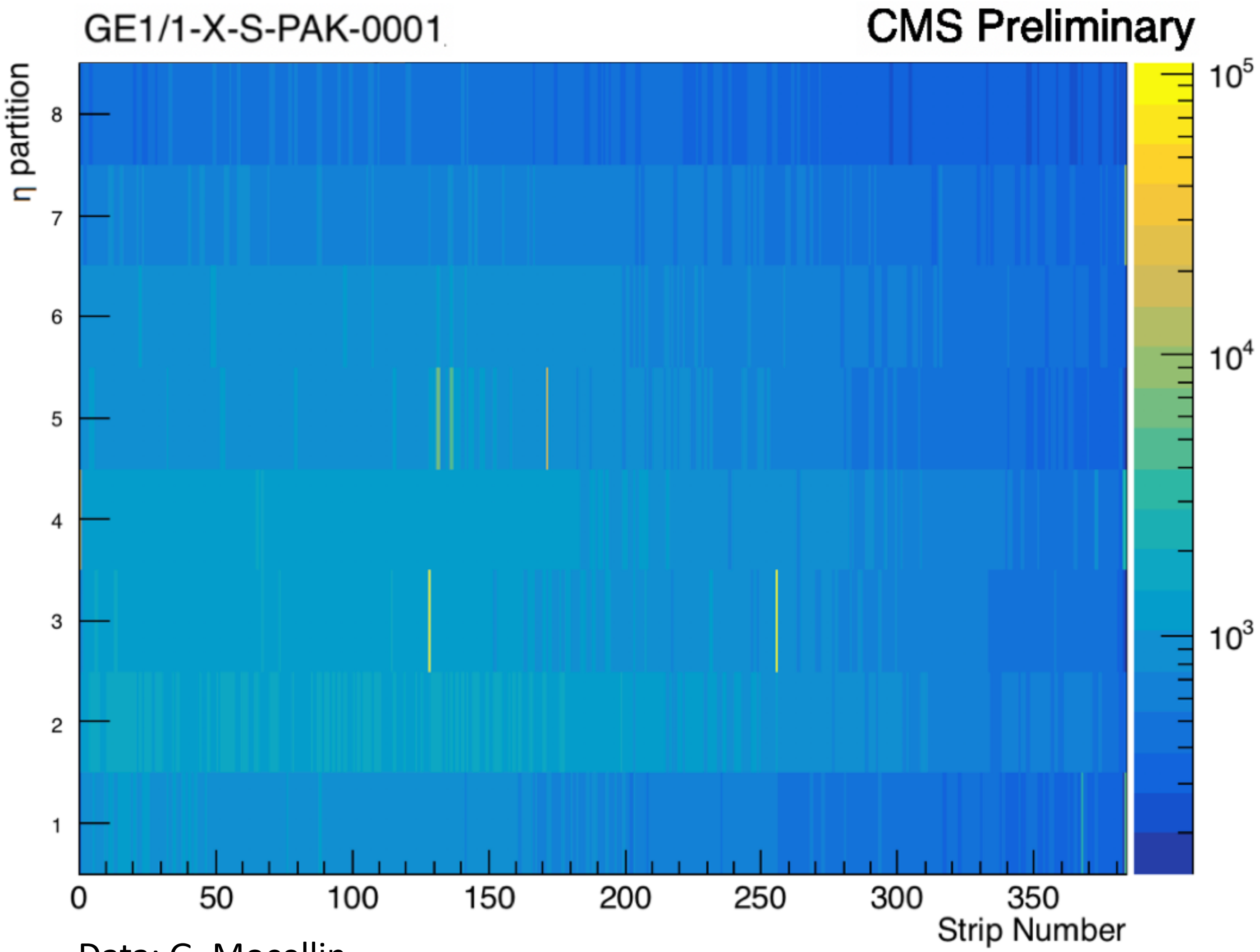


Data: G. Mocellin

- Efficiency of GE1/1-X-S-PAK-0001, one of the detectors that has already been installed in CMS as part of GE1/1, as obtained from QC8 measurements.
- Dotted green lines represent the three (iϕ) regions of VFATS – 0:7, 8:14, and 15:23. The dotted red lines represent the iη regions.



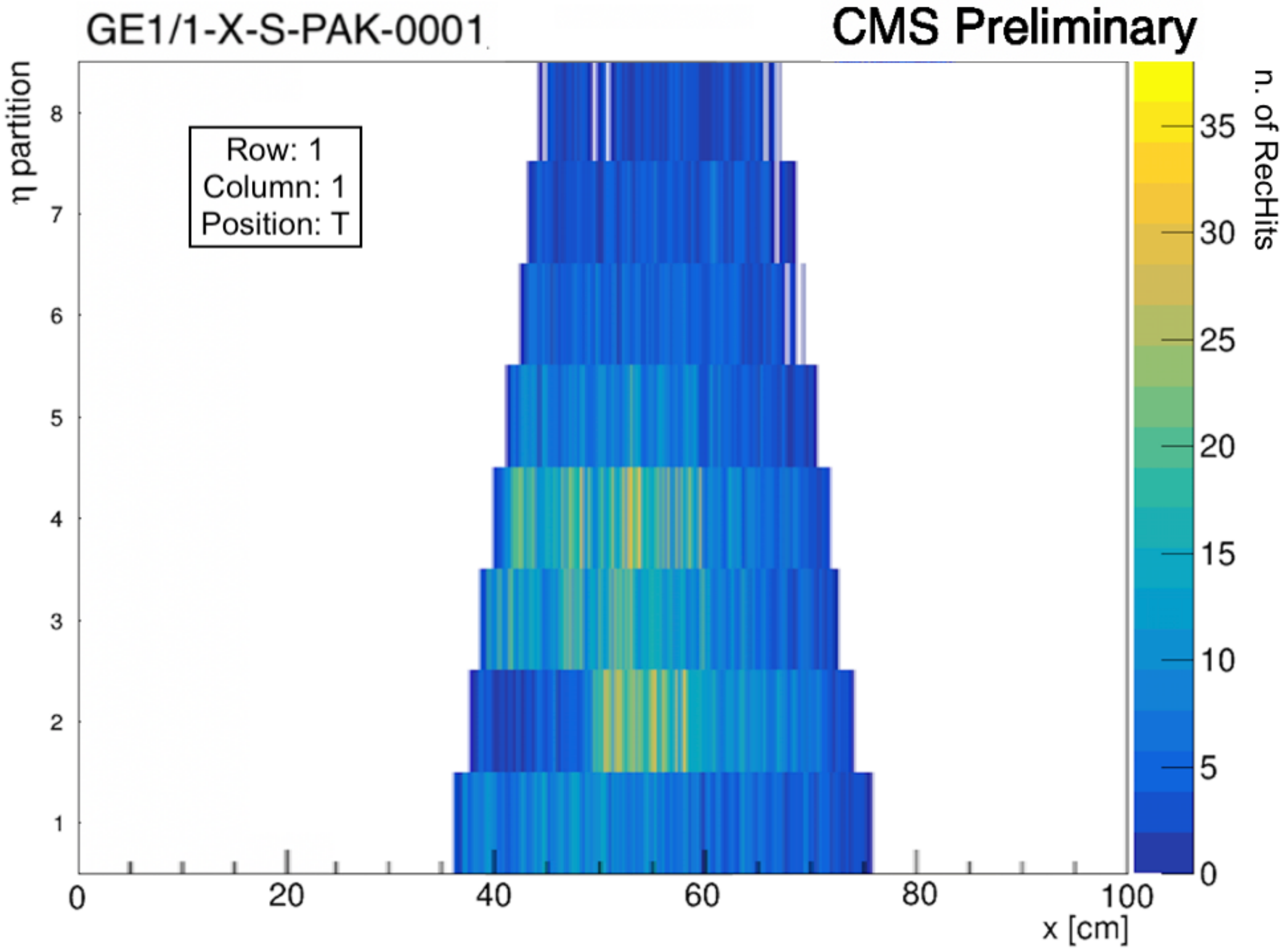
QC8 Results: Digis



Data: G. Mocellin

- Plot of digis for GE1/1-X-S-PAK-0001, run 206 of QC8.
  - Showing the firing of the strips with the highest granularity. If a single strip fires, that is a digi.
  - There are several instances (in yellow/orange) which are clearly noise – this is confirmed by looking at the associated SCurves. These are masked in the final analysis.

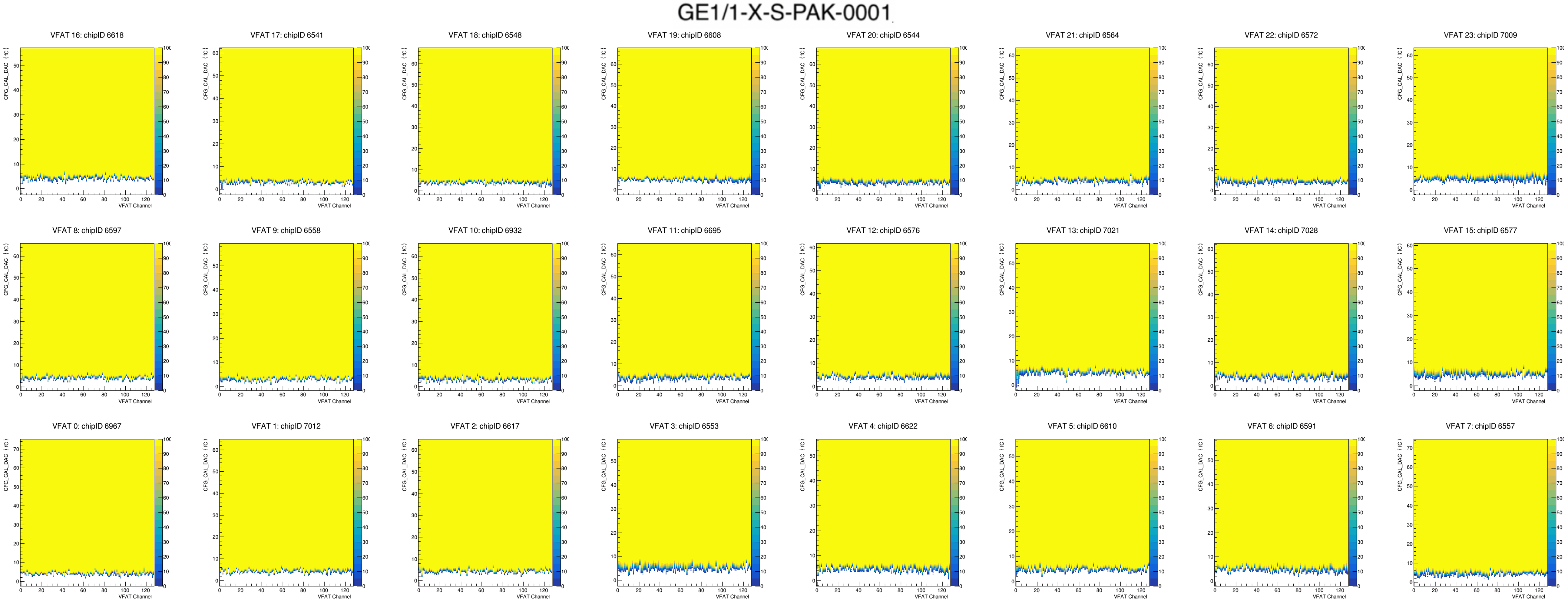
QC8 Results: Occupancy of Associated RecHits



Data: G. Mocellin

- Associated RecHits for the top detectors of Row 1. This plot shows only GE1/1-X-S-PAK-0001, in column 1.
  - For a given test chamber (in this case, GE1/1-X-S-PAK-0001), the other chambers in the stand are taken as reference. For a given event, the muon track is reconstructed using the reference chambers, and then extrapolated to the test chamber.
  - The associated RecHit is a verified hit in the test chamber that matches the extrapolation. This allows us to measure the efficiency of the chamber.
  - Each bin is 1mm wide.

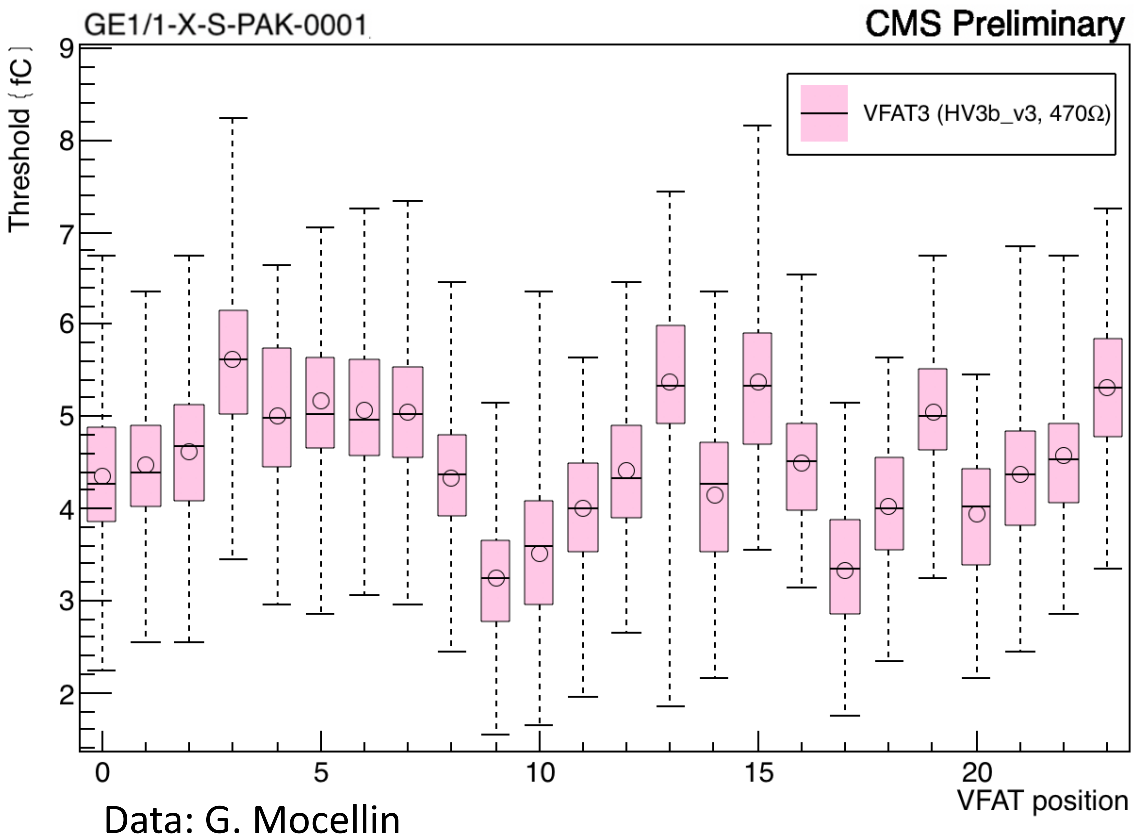
QC8 Results: SCurves

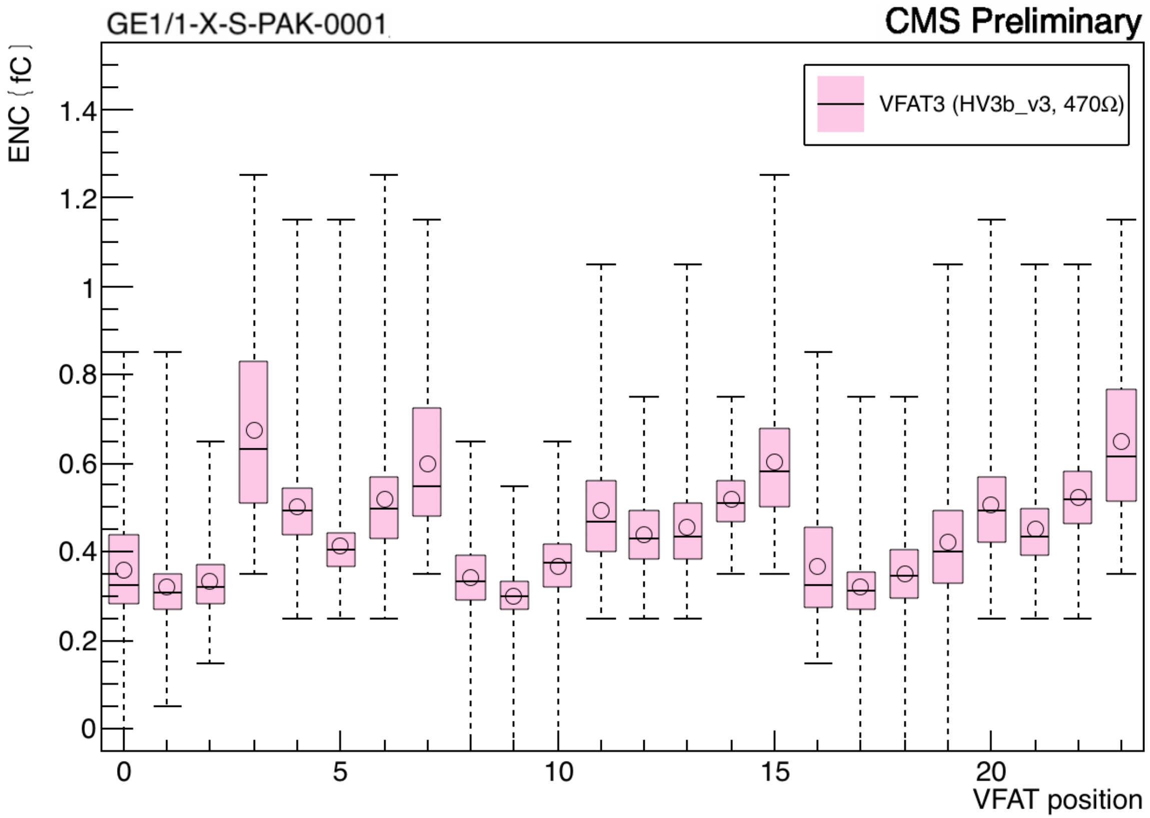


Data: G. Mocellin

Representative SCurves for GE1/1-X-S-PAK-0001

QC8 Results: Threshold and ENC

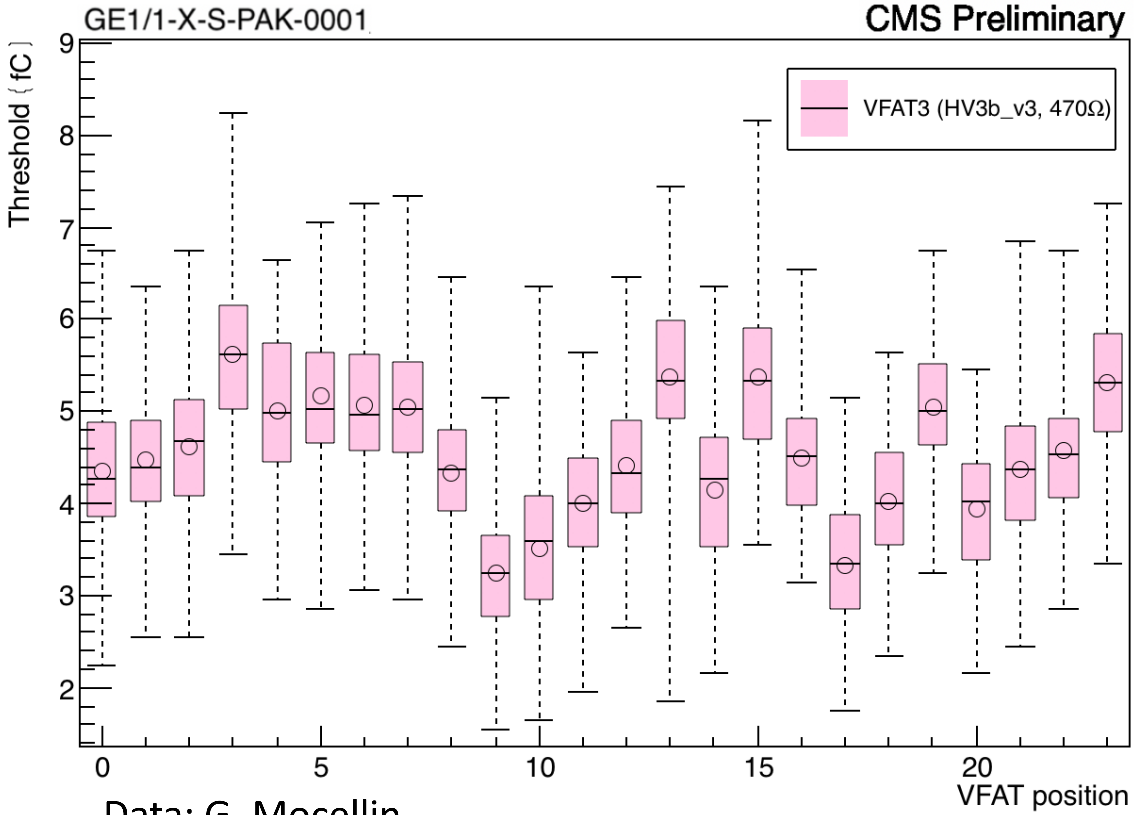




Data: G. Mocellin

Box plots of the mean (threshold) and sigma (ENC) for the SCurves of GE1/1-X-S-PAK-0001
QC8 Run 206

QC8 Results: Threshold



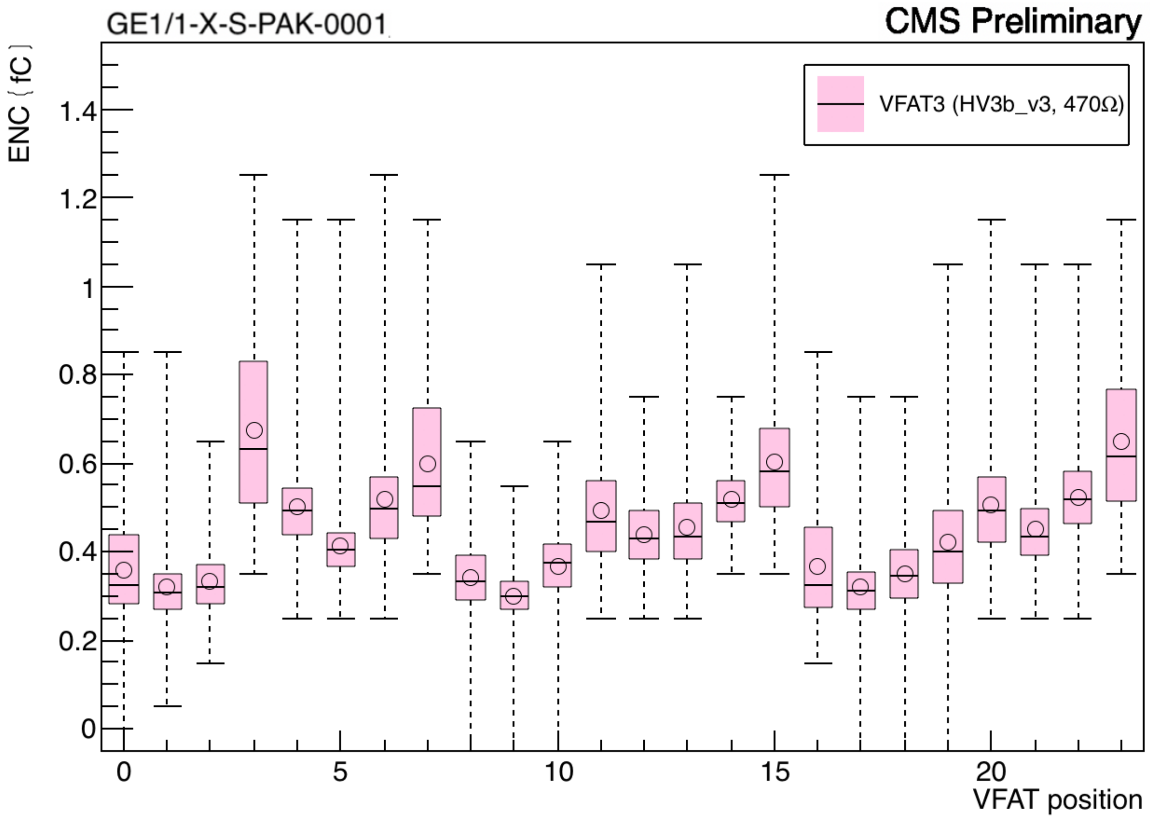
Data: G. Mocellin

- Box plot of the threshold values of GE1/1-X-S-PAK-0001
  - 50% of the channels are within the colored box
  - 100% of the channels are within the range of the dashed line
  - The circle and line in the box represent the mean and median values, respectively.

Box plots of the mean (threshold) and sigma (ENC) for the SCurves of GE1/1-X-S-PAK-0001 QC8 Run 206

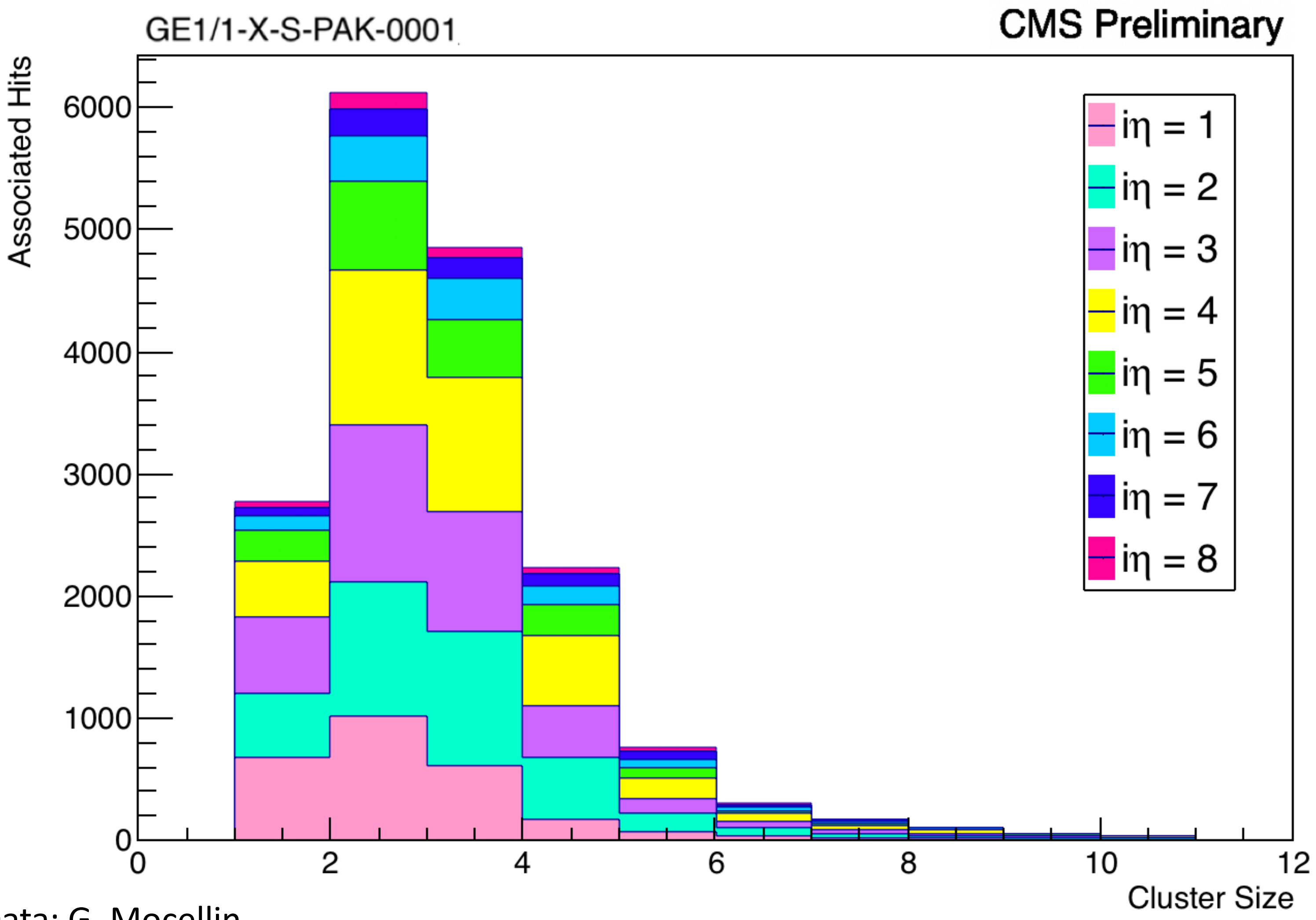
QC8 Results: Threshold and ENC

- Box plot of the ENC values of GE1/1-X-S-PAK-0001
  - Noise increases as we go from the narrow end to the wide end of the GEB due to the increased size / capacitance of the strip
  - VFATs in the eta sectors closest to the optohybrid show an increased noise as well



Box plots of the mean (threshold) and sigma (ENC) for the SCurves of GE1/1-X-S-PAK-0001 QC8 Run 206

QC8 Results: Associated Hits Cluster Size



Data: G. Mocellin

- The hits associated with a reconstructed cosmic muon track for each of the 8 η partitions of GE1/1-X-S-PAK-0001, by cluster size, for run 206.
  - Ex: If three adjacent strips fire from the same event, then that hit has a cluster size of 3.

Current Qualification Progress

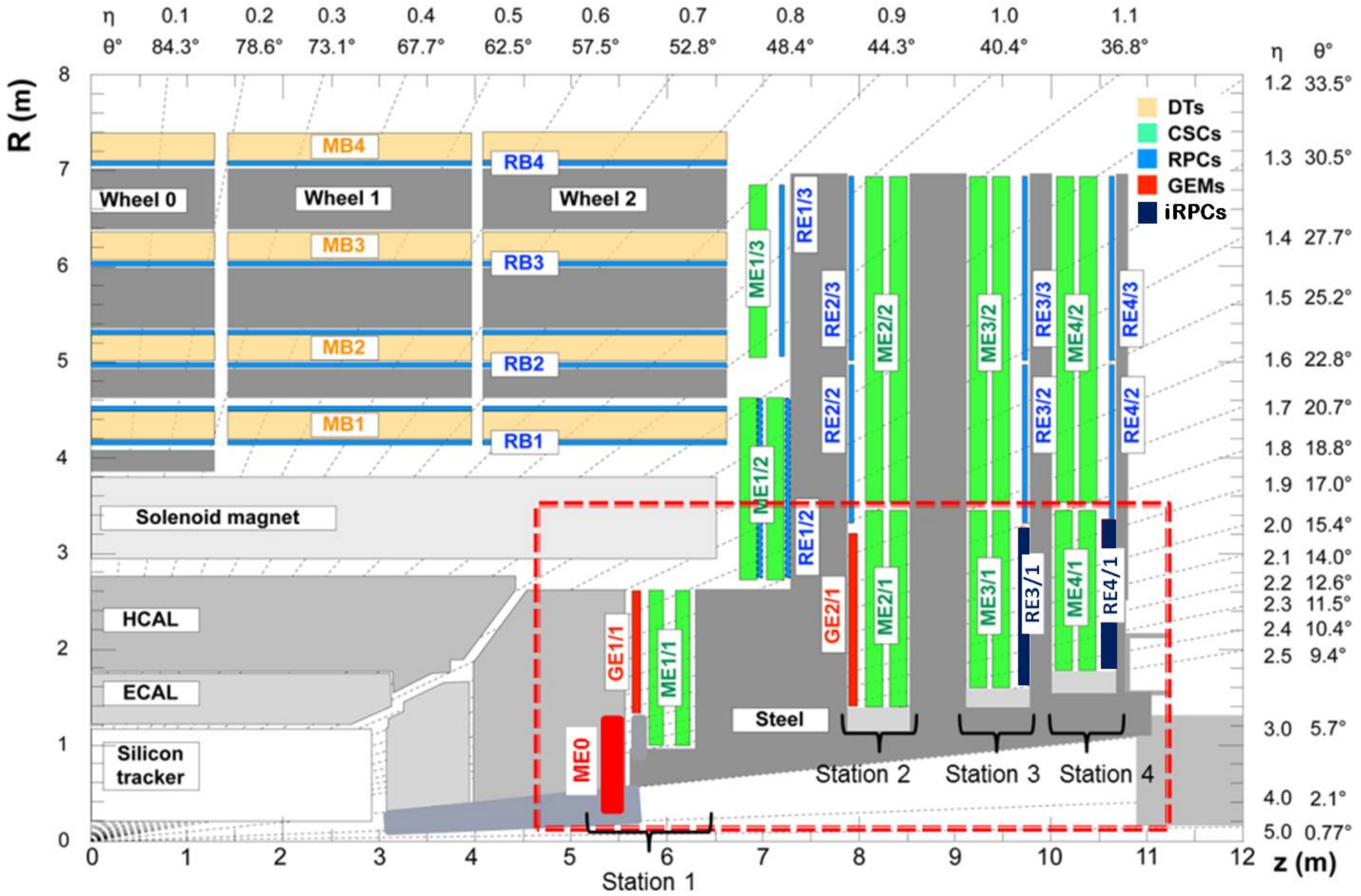
- As of the date of this presentation, 10 chambers have been fully qualified in all of the quality control steps through QC8, and have been deemed ready for installation into the CMS endcap.

- The stand can hold 30 chambers at a time, and is qualifying ~2 per day.

- Our current projected schedule is:
  - 15th September: Finish qualification of -1 chambers
  - 15th October: Finish installation of the 36 superchambers for the -1 endcap
  - End February 2020: Finish qualification of +1 endcap chambers
  - End March 2020: Finish installation of the 36 superchambers for the +1 endcap

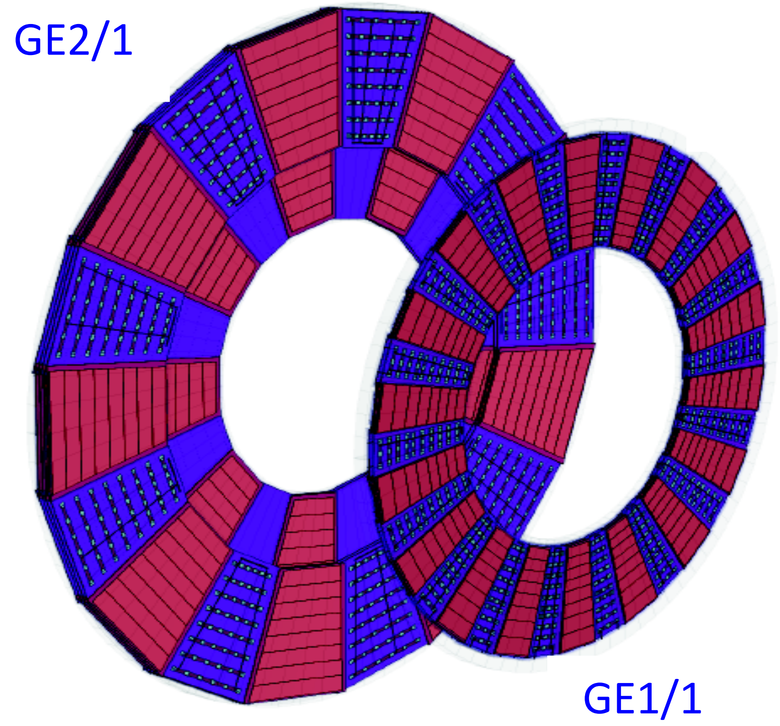
Future CMS GEM Systems

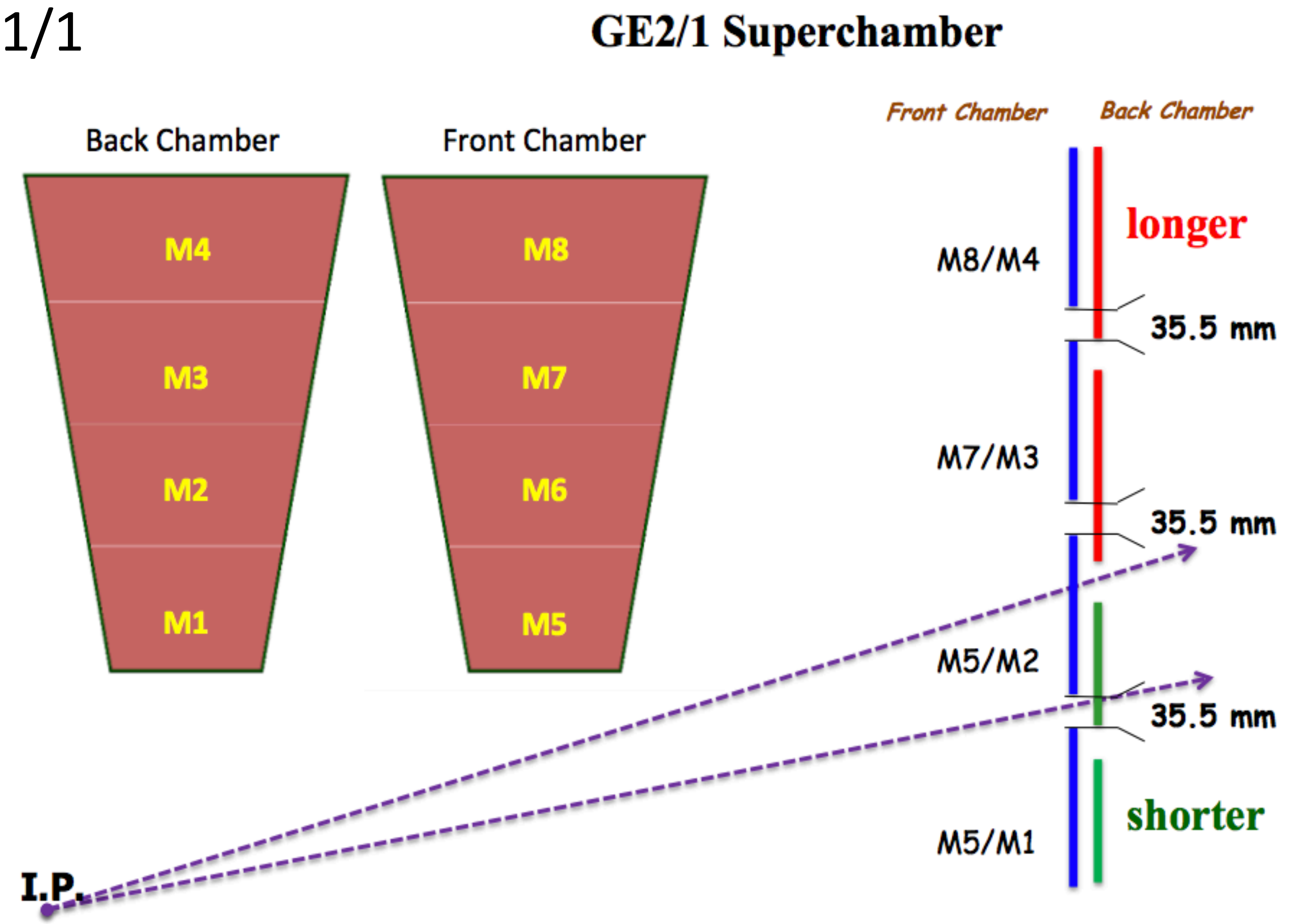
- Following the completion of GE1/1, the focus will shift to the next GEM projects within CMS: GE2/1 and ME0



GE2/1

- 18 staggered superchambers per endcap
  - 442,000 readout channels, like GE1/1
  - Each chamber spans 20°

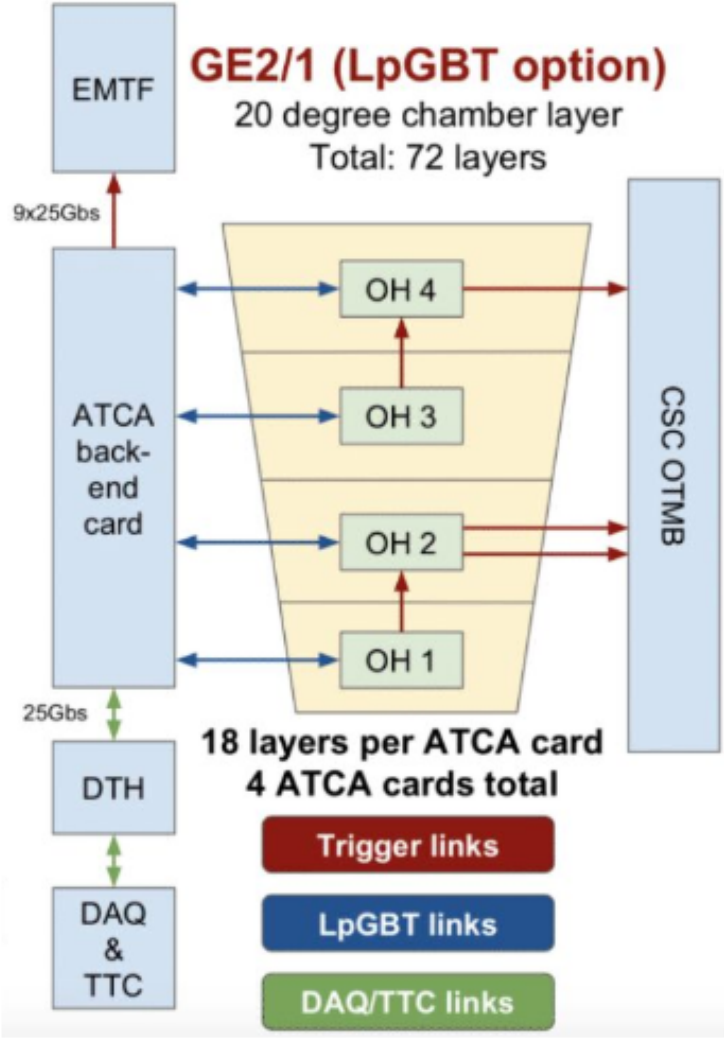


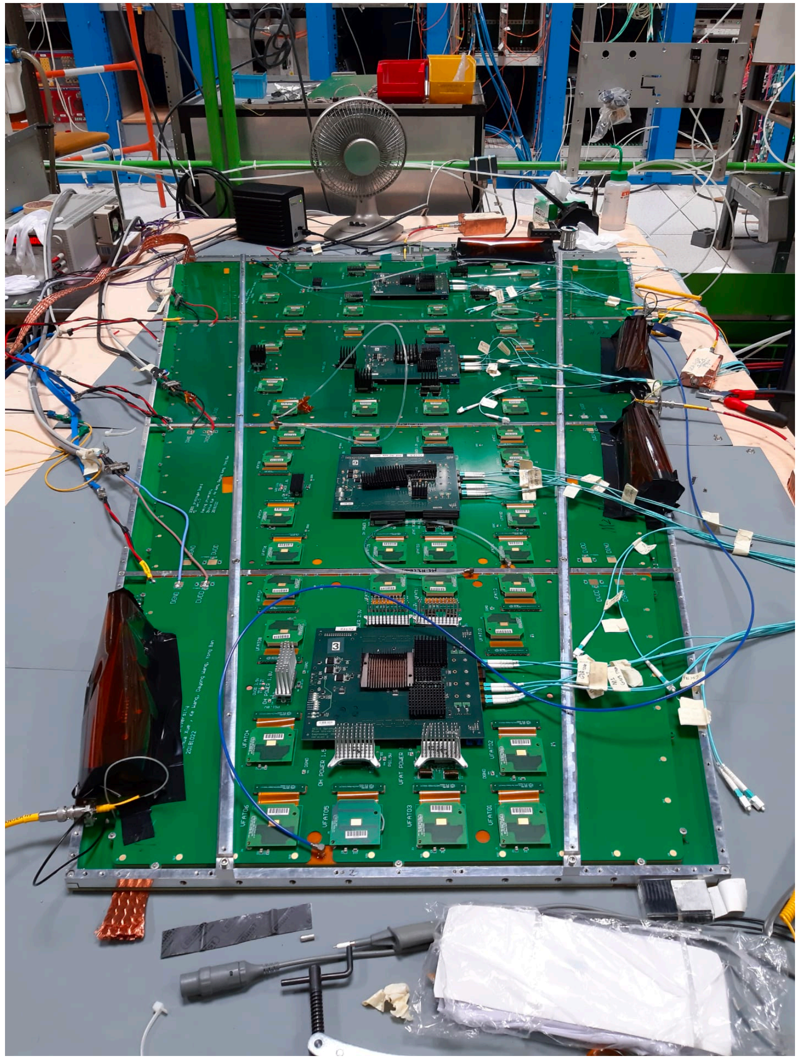


GE2/1

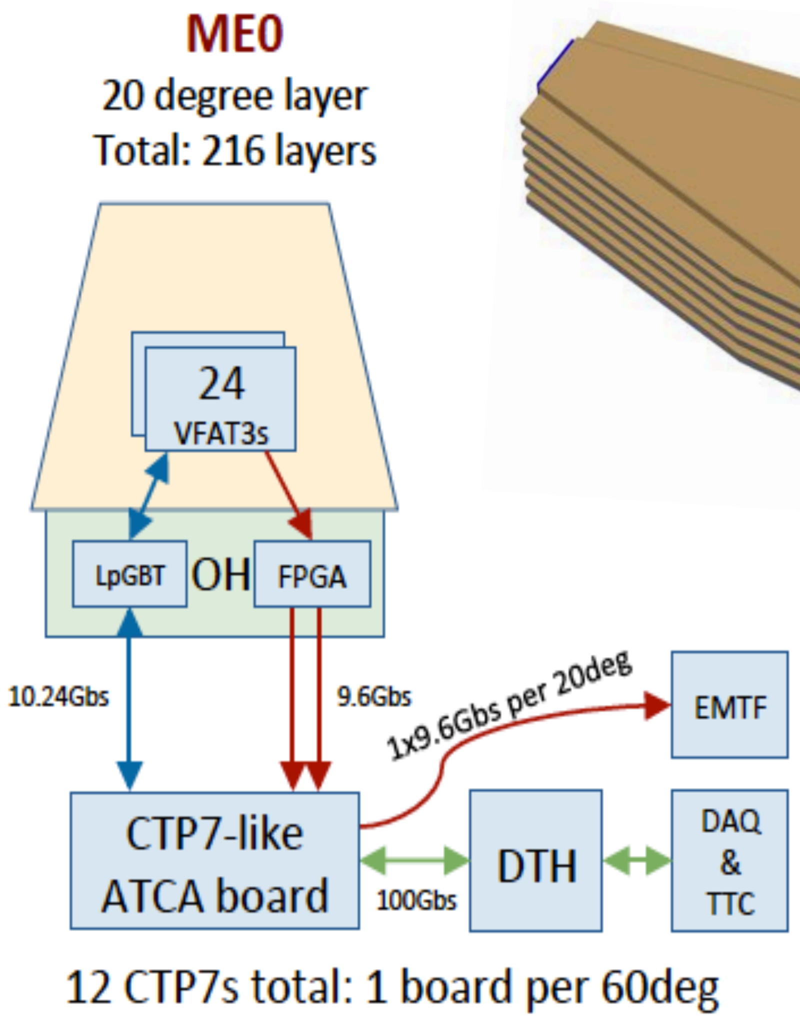
- Production and testing has already begun in earnest

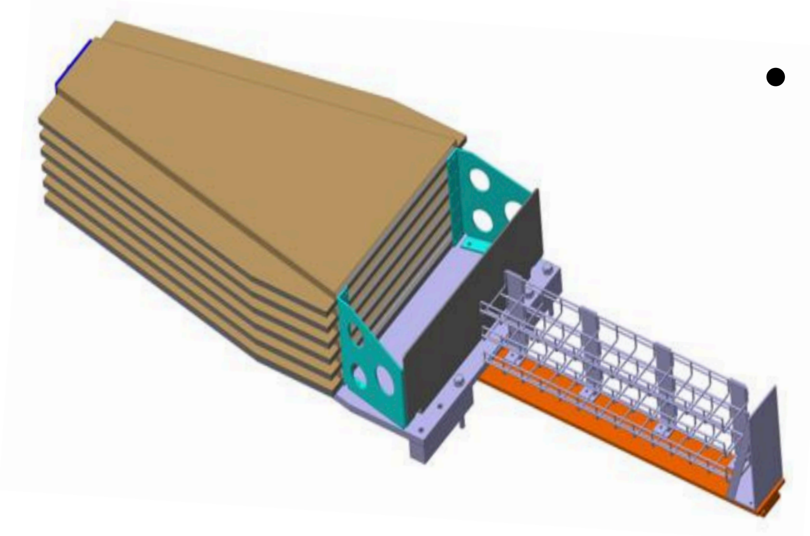
- For more information on GE2/1, see Mike Mateev's poster: September 5th, 16:55



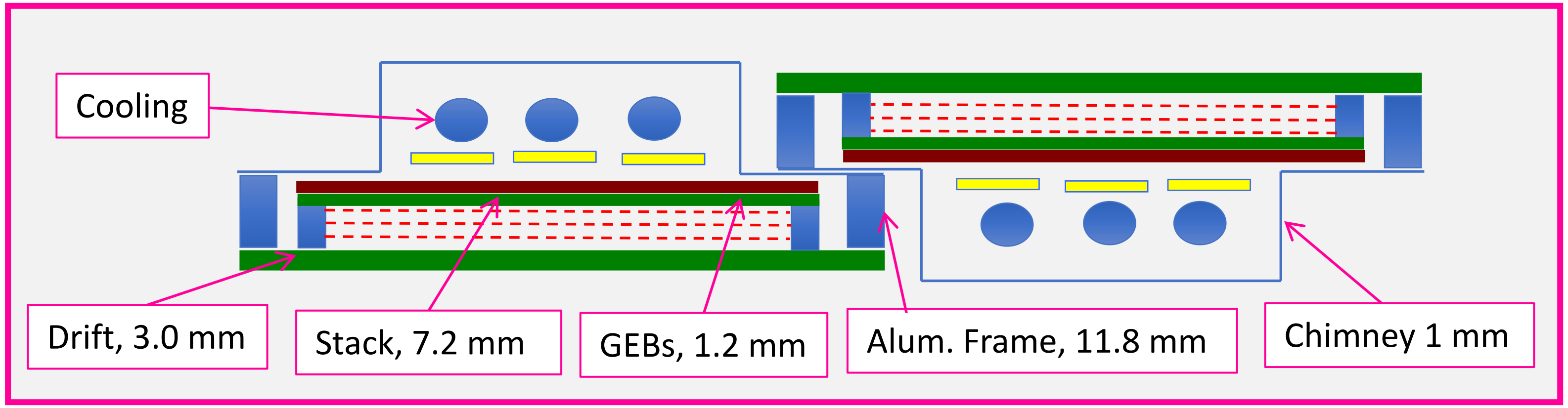


ME0: Very-Forward Muon Tagger





- 18 staggered stacks per endcap
  - Each chamber spans 20°, like GE2/1
  - 6 layers per stack
  - > 650,000 channels
    - 128 strips / 8 eta partitions per chamber



Conclusions

- Experiences from the slice test proved invaluable.
  - Allowed us to identify potential problems in time to update the design of the GE1/1 electronics, before the production and installation of the full system.
- The focus now is on the smooth production, qualification, and installation of the GE1/1 detectors.
- Future electronics development will focus on GE2/1 and ME0 projects.

Questions?

Thank you!