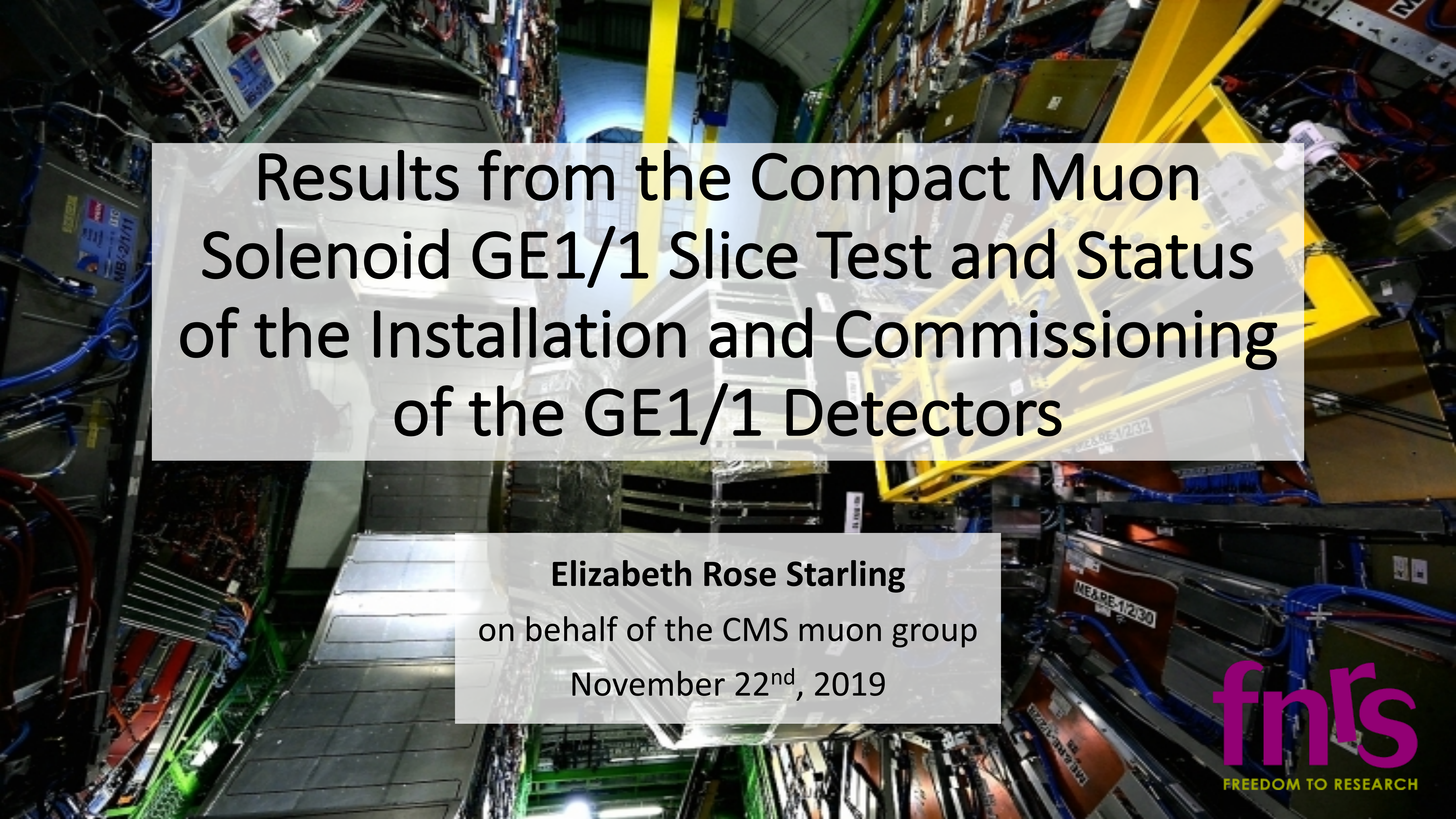


Results from the Compact Muon Solenoid GE1/1 Slice Test and Status of the Installation and Commissioning of the GE1/1 Detectors

Elizabeth Rose Starling

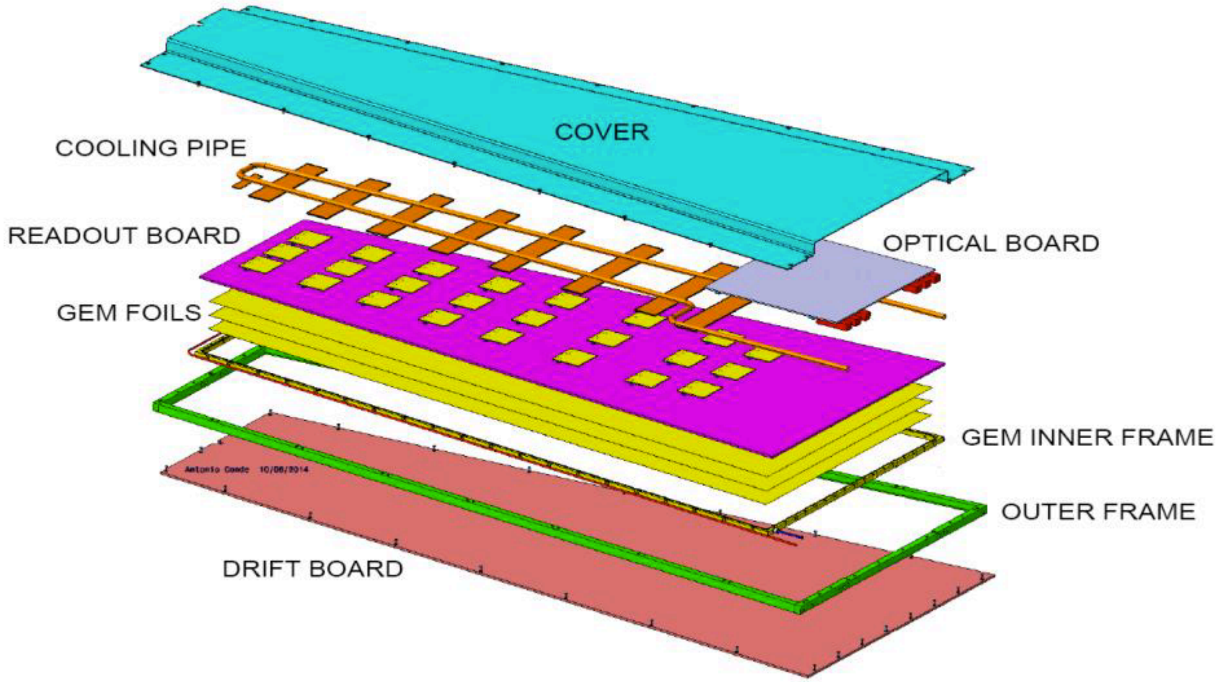
on behalf of the CMS muon group

November 22nd, 2019

Introduction

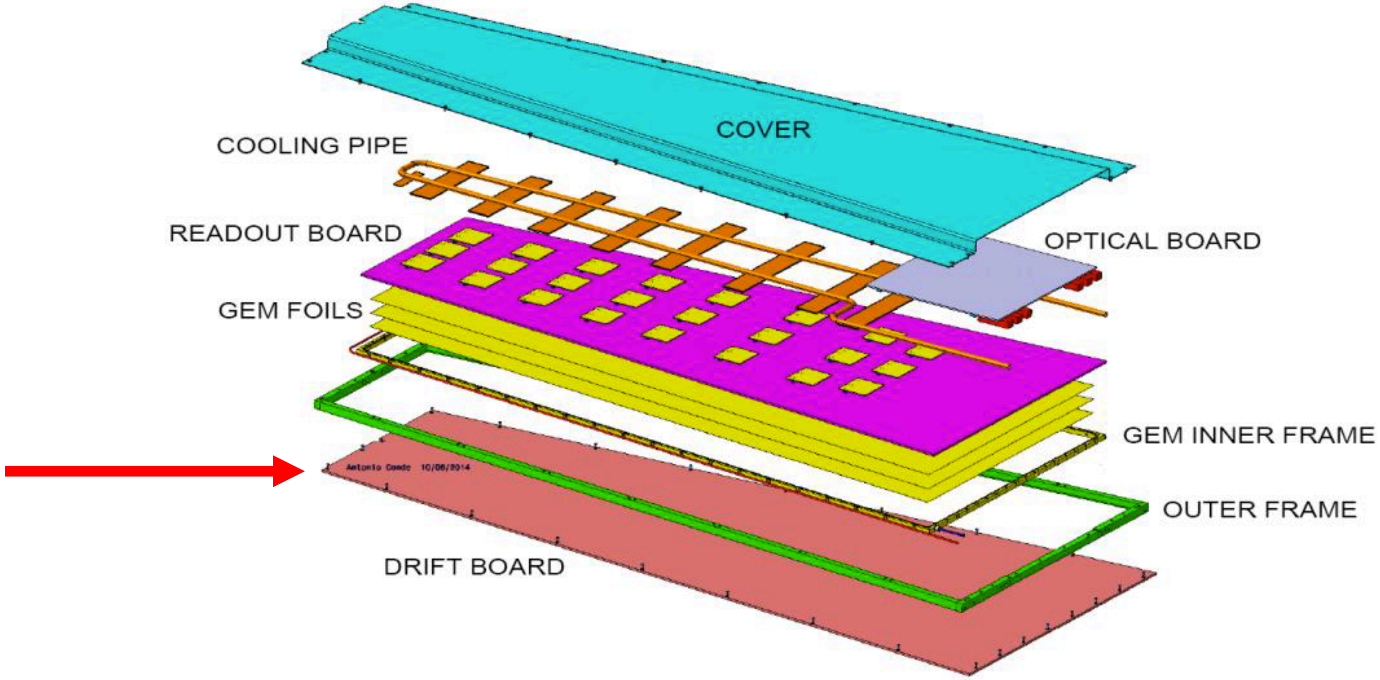
Triple-GEM Detectors

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



Triple-GEM Detectors

- Triple gas electron multiplier (GEM) detectors are composed of five main layers:
  - A drift cathode



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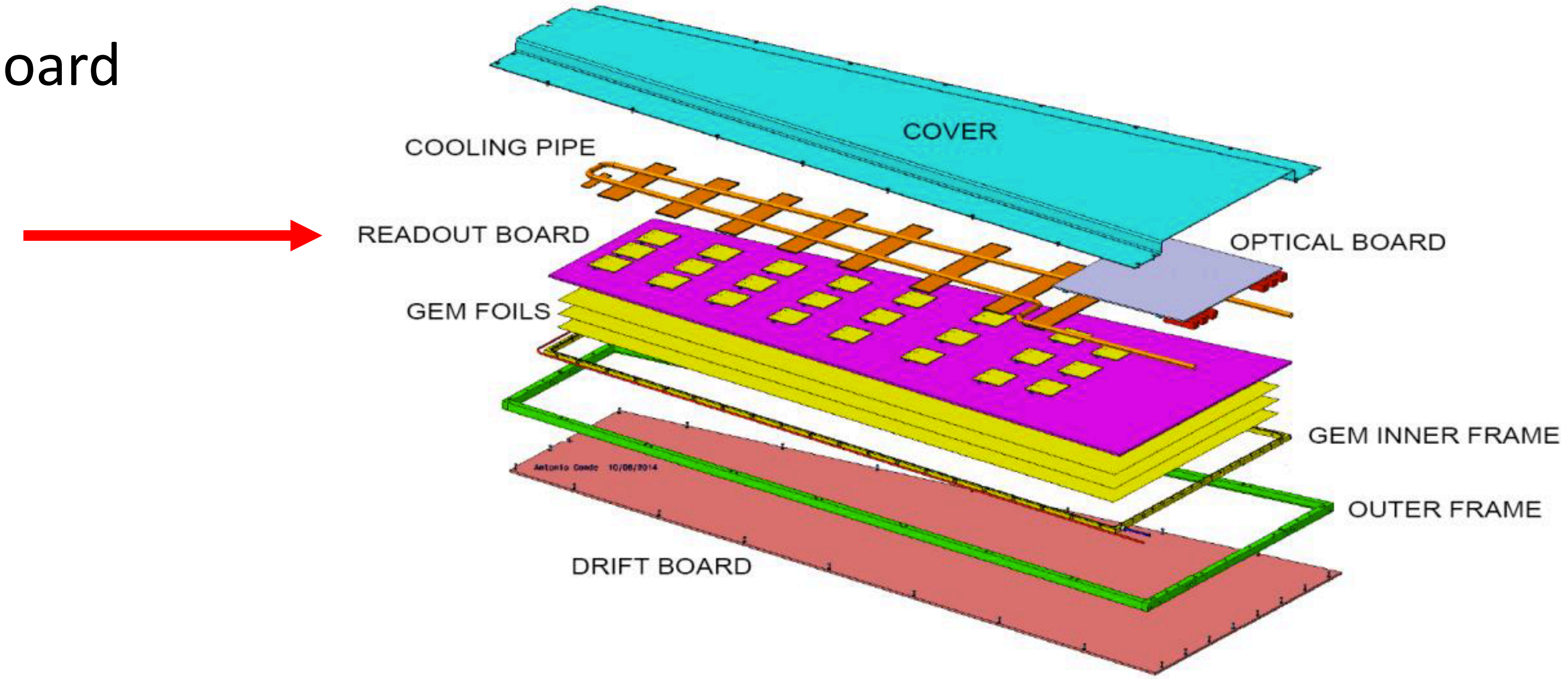
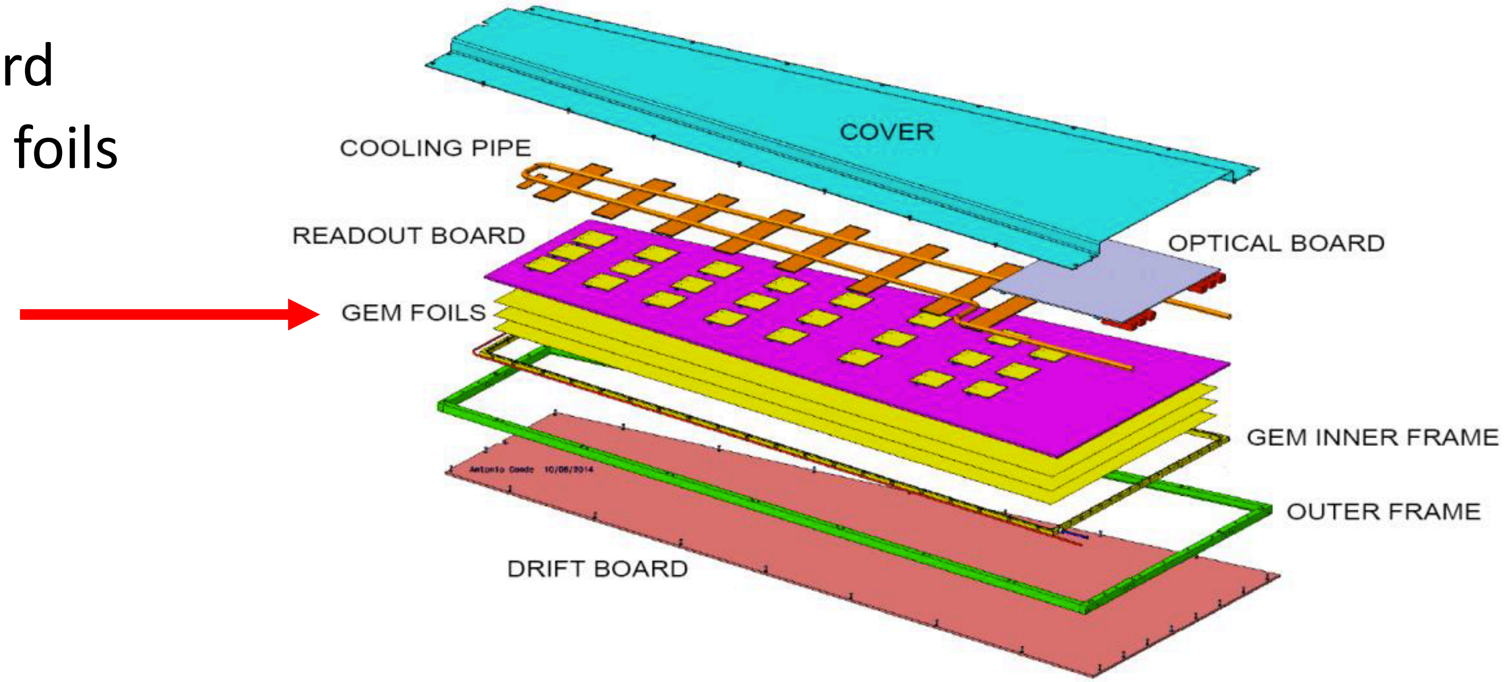
- Triple gas electron multiplier (GEM) detectors are composed of five main layers:
  - A drift cathode
  - A printed circuit readout board



Triple-GEM Detectors

- Triple gas electron multiplier (GEM) detectors are composed of five main layers:
  - A drift cathode
  - A printed circuit readout board
  - Three 50 µm-thick polyimide foils



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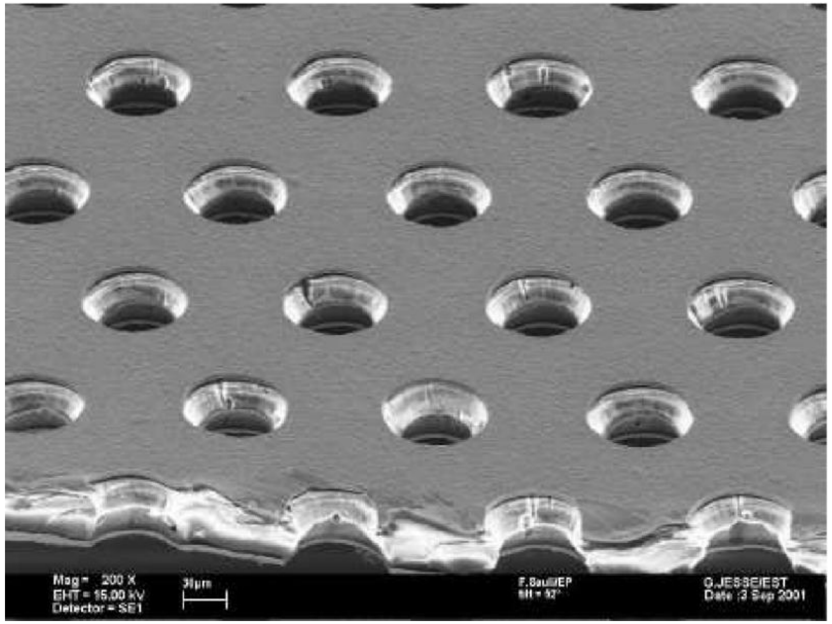
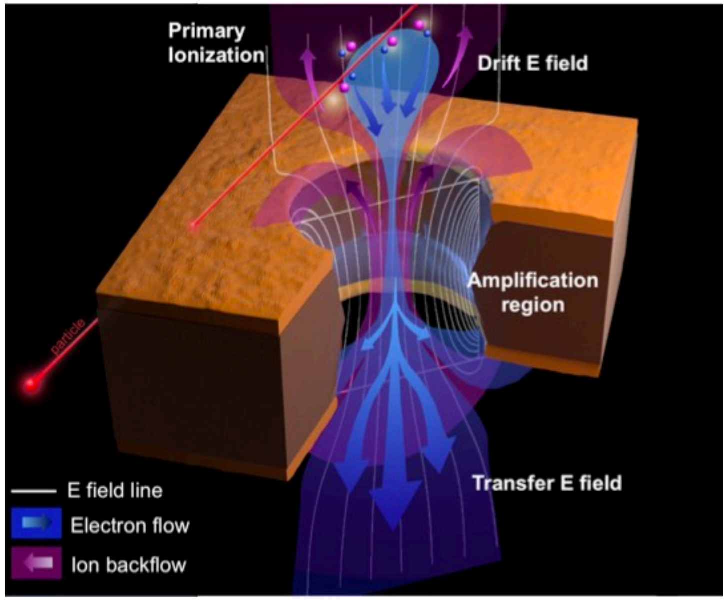


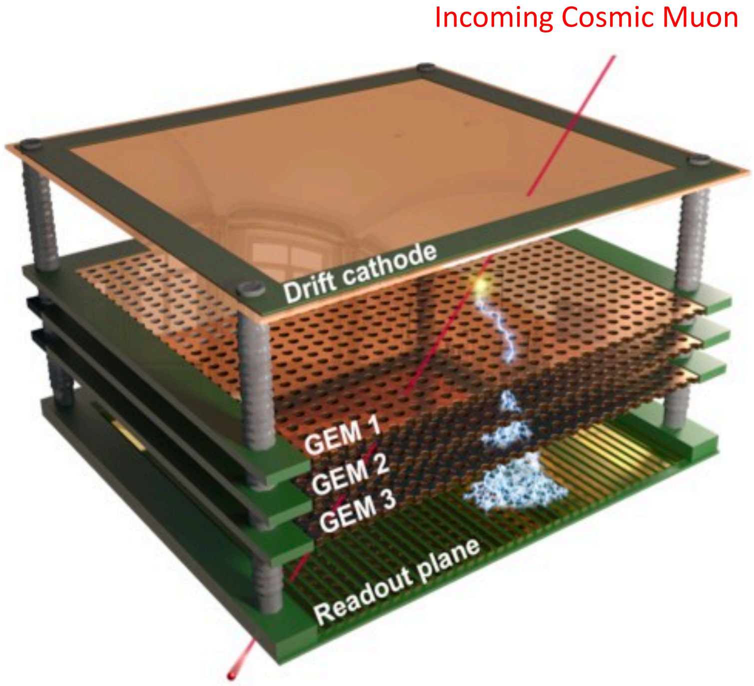
- The foils are coated on both sides with 5 µm of copper and chemically etched with 50-70 µm holes at a pitch of ~140 µm.

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.

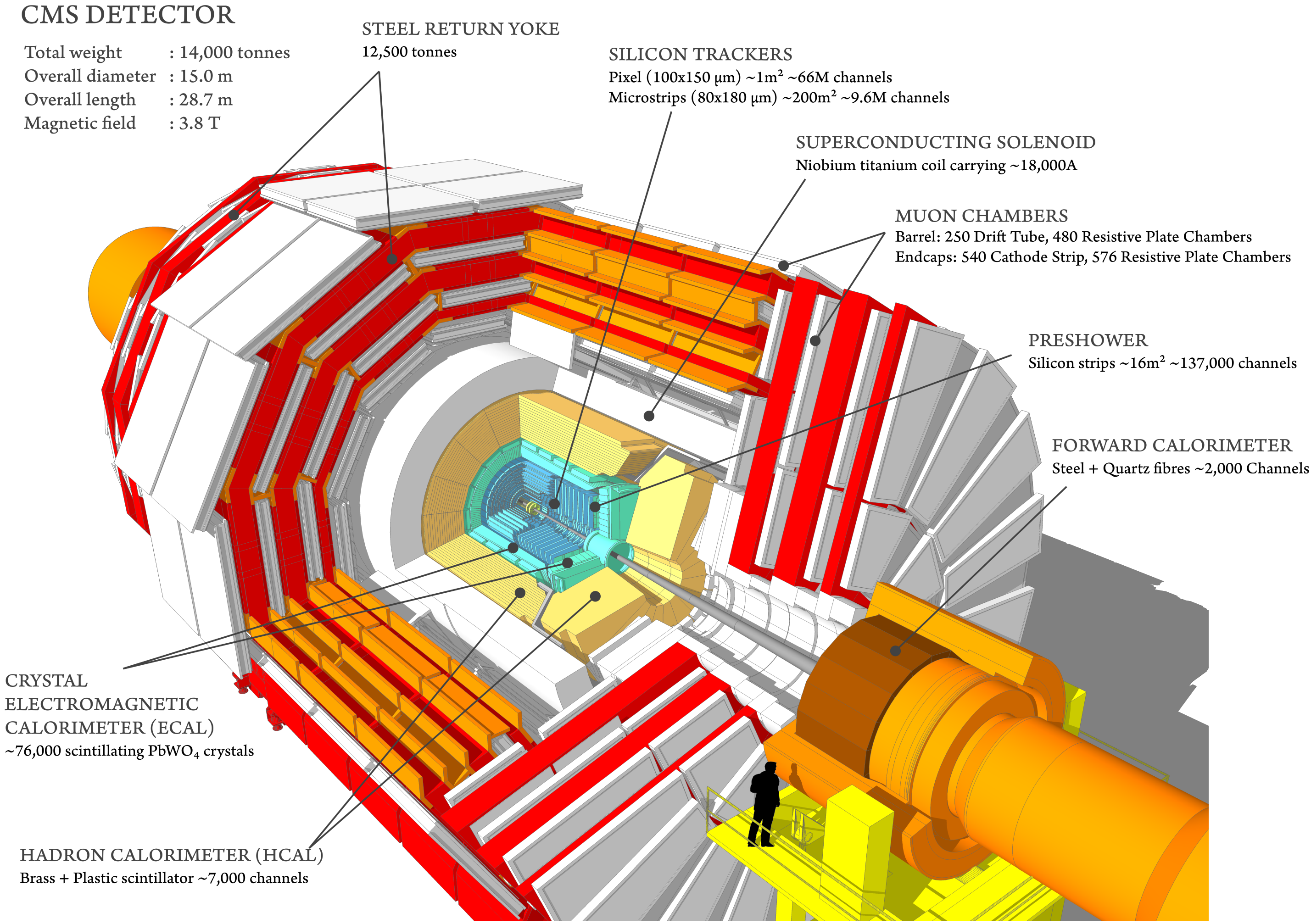


- A muon that enters the detector ionizes the gas, and as those electrons encounter these electric fields, they multiply in an electron avalanche and are read out at the PCB layer at a gain of ~10^4.



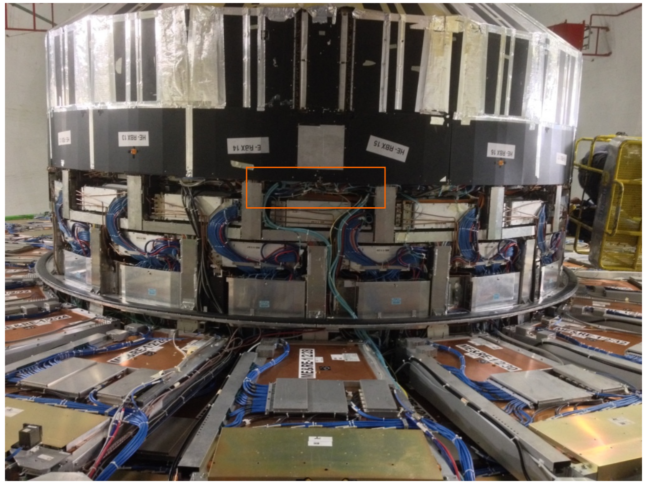
CMS Detector

- General-purpose LHC detector
- Divided into several systems:
  - Silicon tracker
  - Electromagnetic calorimeter (ECAL)
  - Hadron Calorimeter (HCAL)
  - Superconducting solenoid magnet
  - Muon System
    - Cathode strip chambers (CSCs)
    - Resistive plate chambers (RPCs)
    - Drift tubes (DTs)
    - and now…..gas electron multipliers! (GEMS)

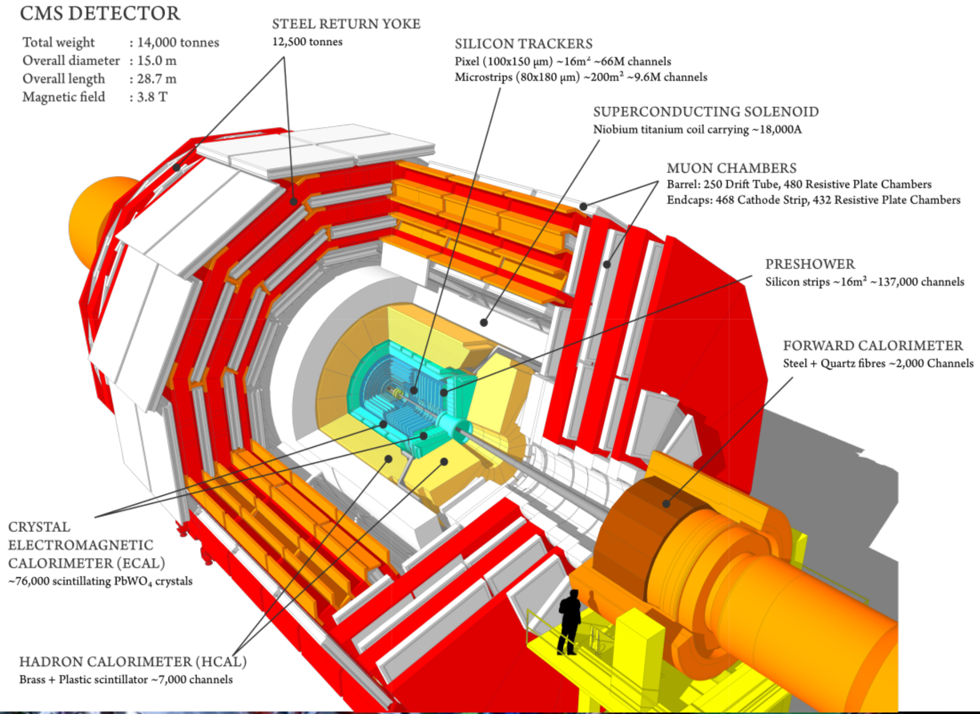


CMS GE1/1 Project

- The GE1/1 project takes place in the context of CMS’ endcap muon system, adding GEMs for the first (but not last – see GE2/1 and ME0) time to CMS.

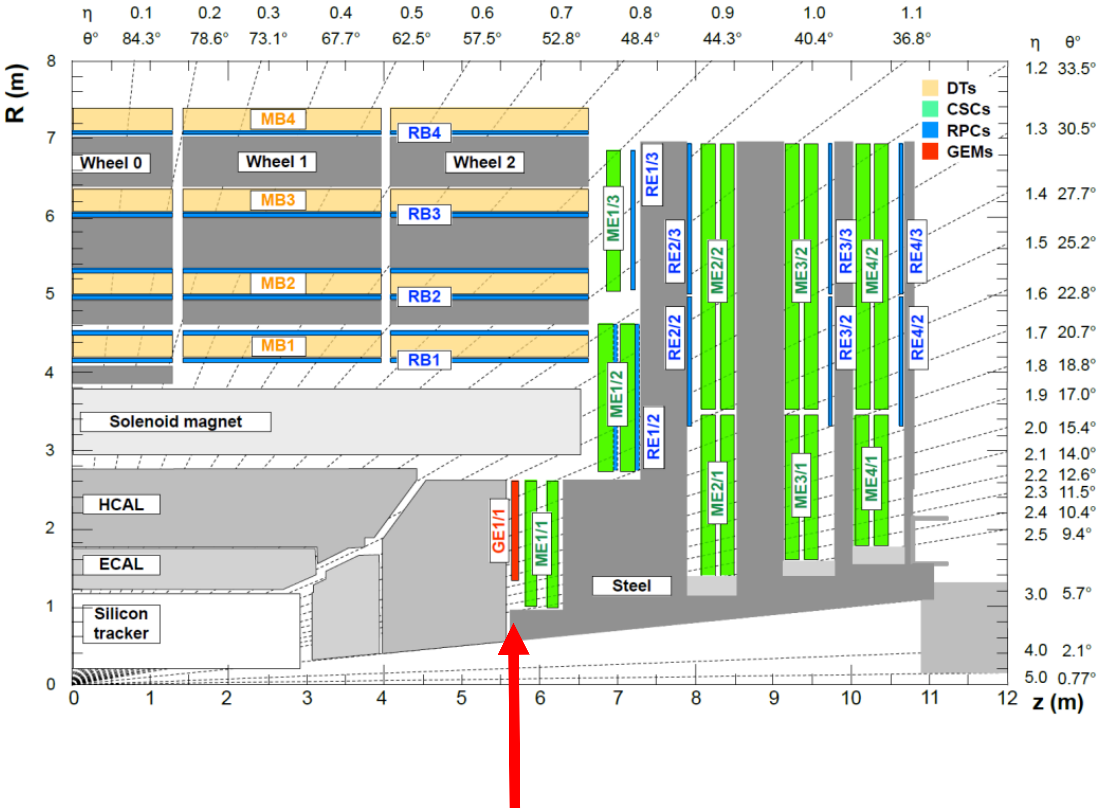


- Prior to the addition of GEMs, the endcap muon system consisted of Cathode Strip Chambers (CSCs) and Resistive Plate Chambers (RPCs).



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

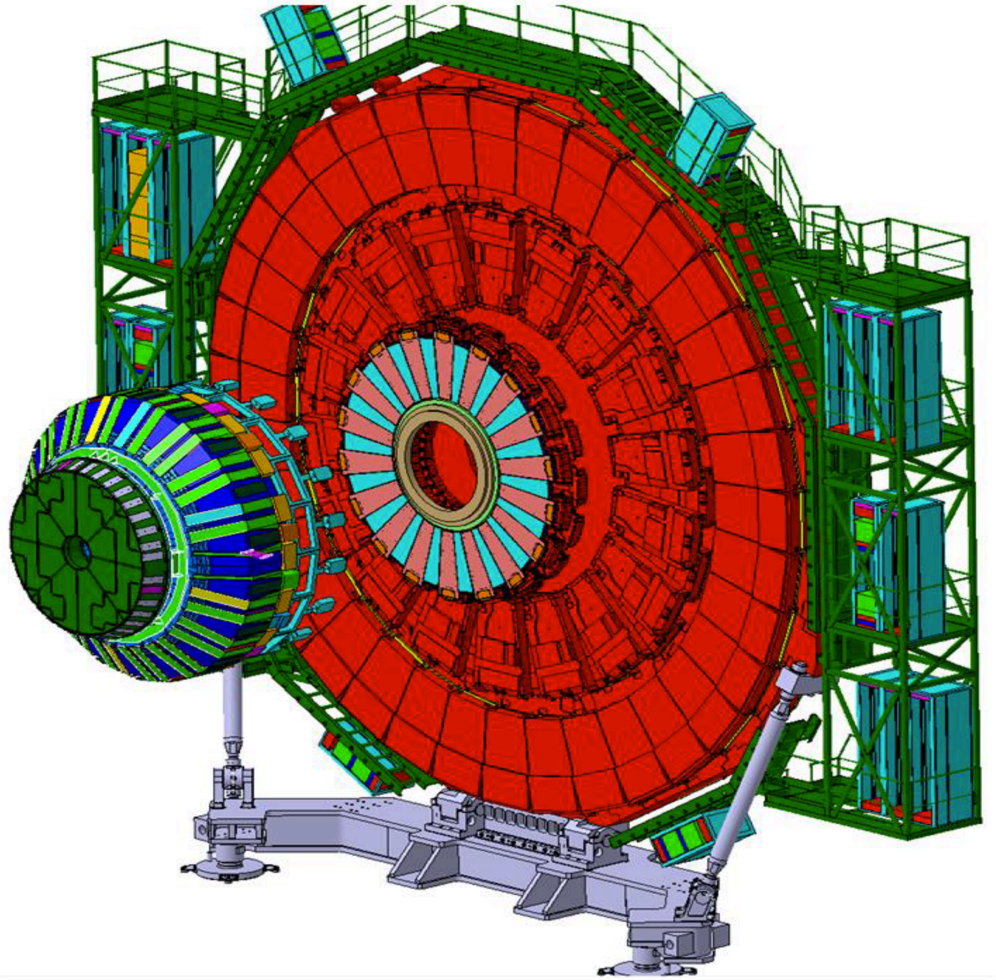


CMS GE1/1 Project

- 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

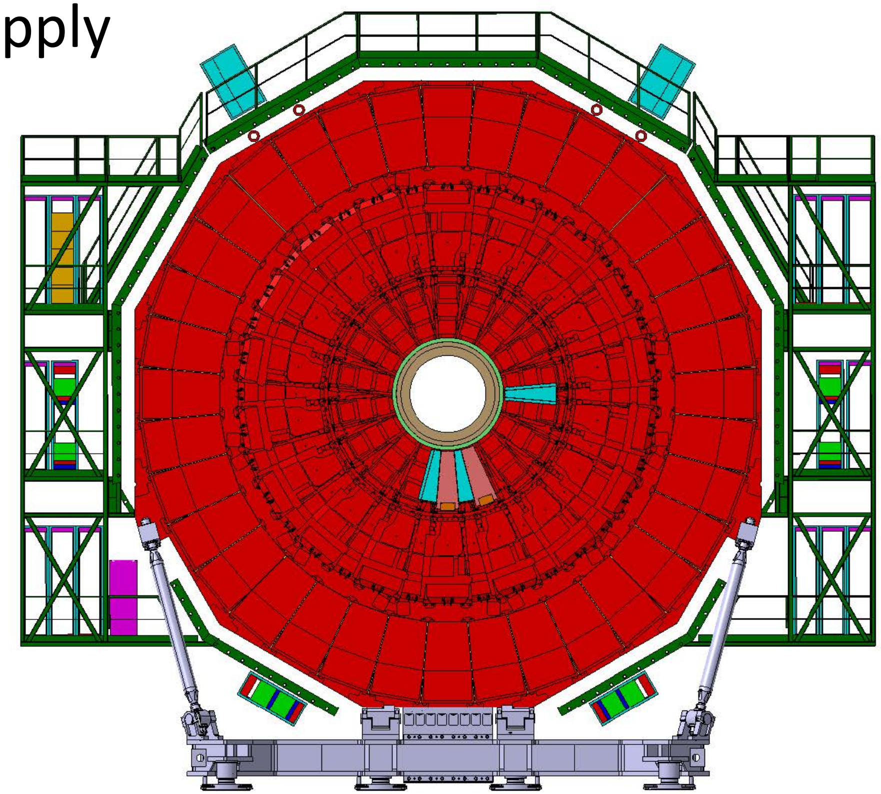
- 144 GEM detectors make up GE1/1, as 72 two-detector superchambers.
  - 36 short superchambers ($1.61 < |\eta| < 2.18$)
  - 36 long superchambers ($1.55 < |\eta| < 2.18$)



Slice Test: Results and Consequences

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
    - Final GE1/1 design uses multichannel power supply
  - 2 short superchambers with an HV divider
  - 2 long superchambers with an HV divider



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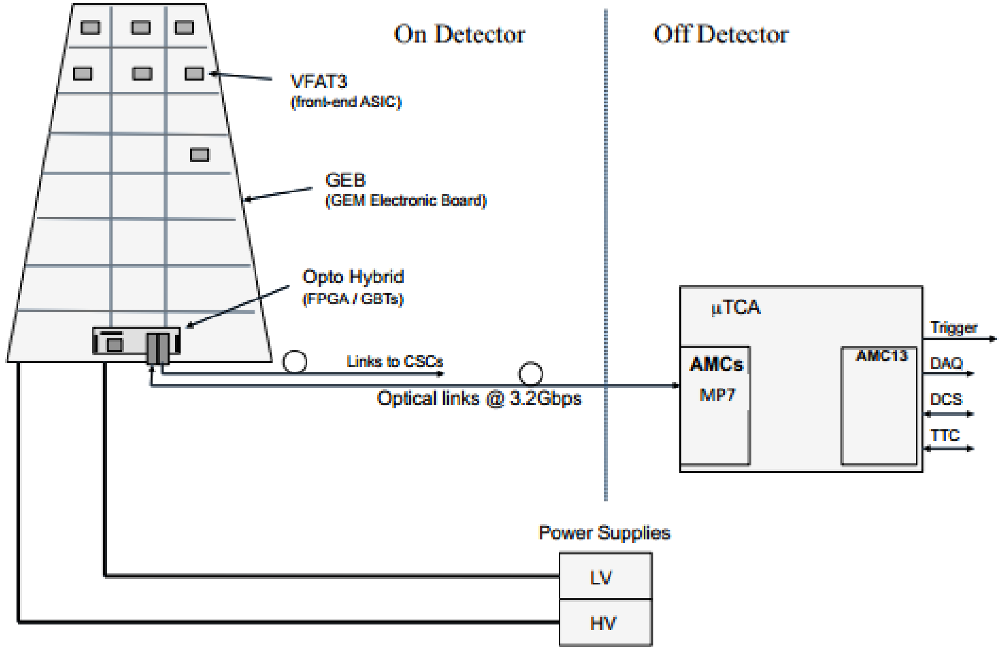
- All detectors had v2 electronics for the 2017 LHC run, as v3 was not yet ready



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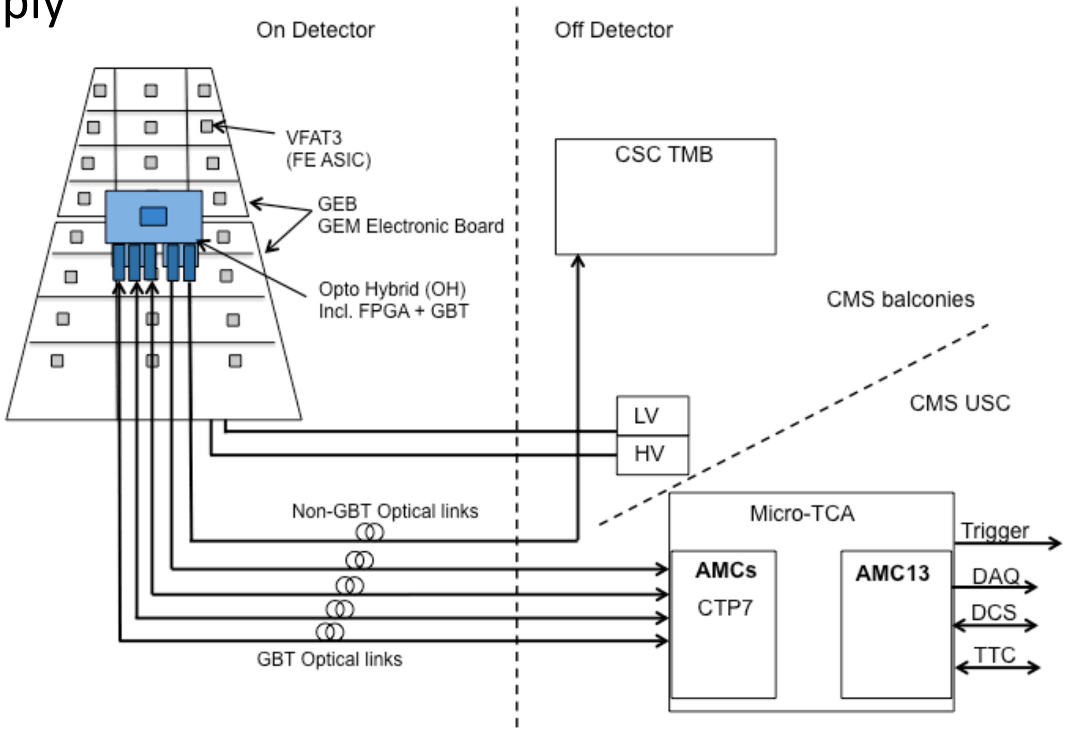
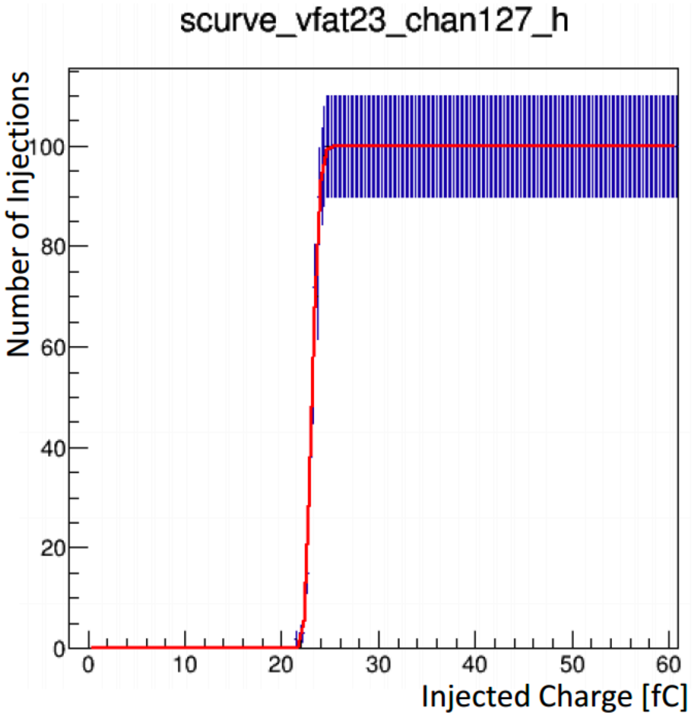
- All detectors had v2 electronics for the 2017 LHC run, as v3 was not yet ready
- In early 2018, the multichannel detector (GEMINIm01) was upgraded with v3 electronics



Noise Measurements: “S-Curves”

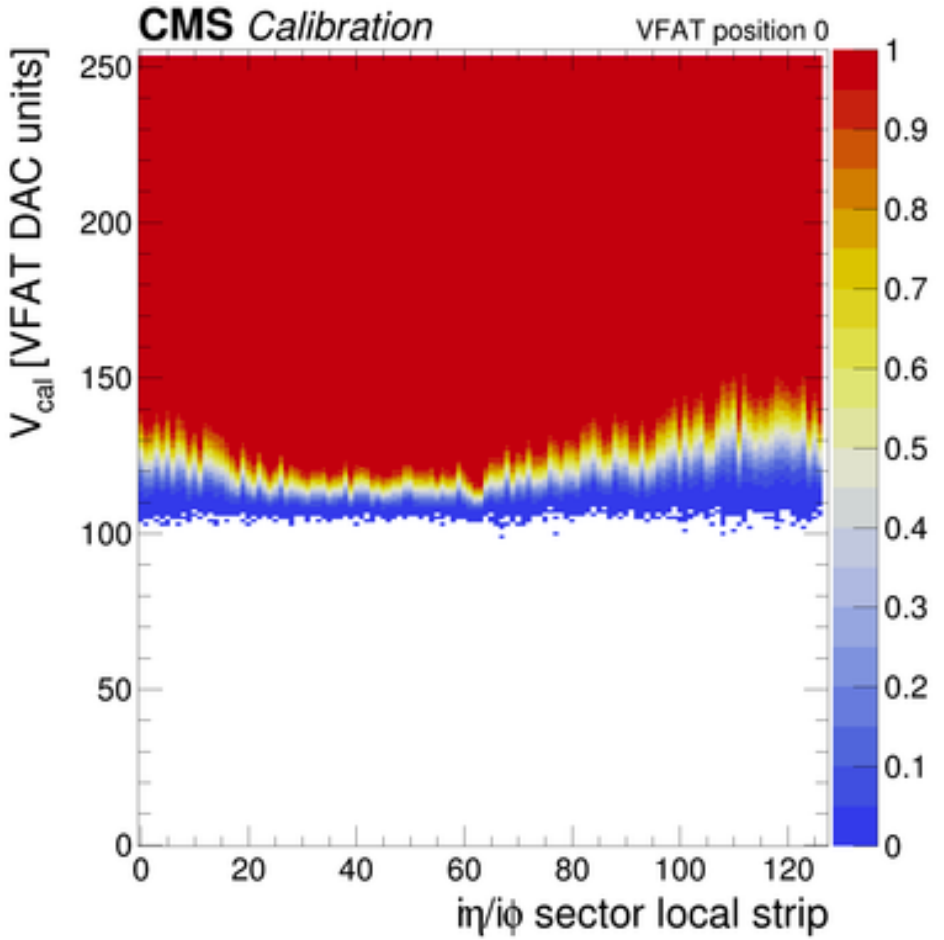
- S-Curve scans help us monitor the health and behavior of the electronics, by showing the response of a VFAT front-end readout chip to the injection of internal calibration pulses.
- A configurable number of pulses are injected, with the size of the pulse determined by the VCAL value.
- The total number of times the comparator fires in response to those pulses is recorded.
- The resulting plot is a step function that is degraded into an “S” shape by the noise of the system.



Noise Measurements: "S-Curves"

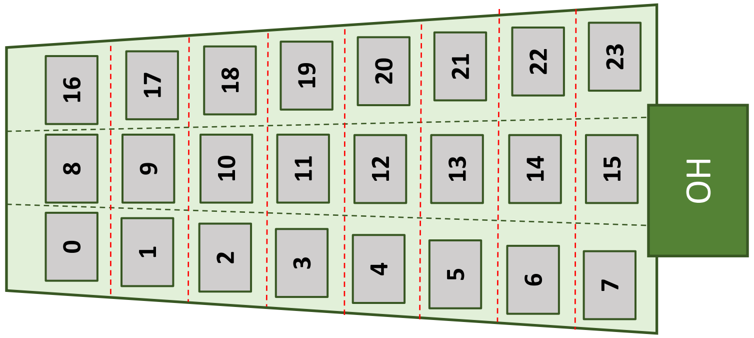
- The S-Curve is then repeated for each channel on the VFAT (0 – 127) and combined into the plot on the right, also called an "S-Curve" in GEM jargon.

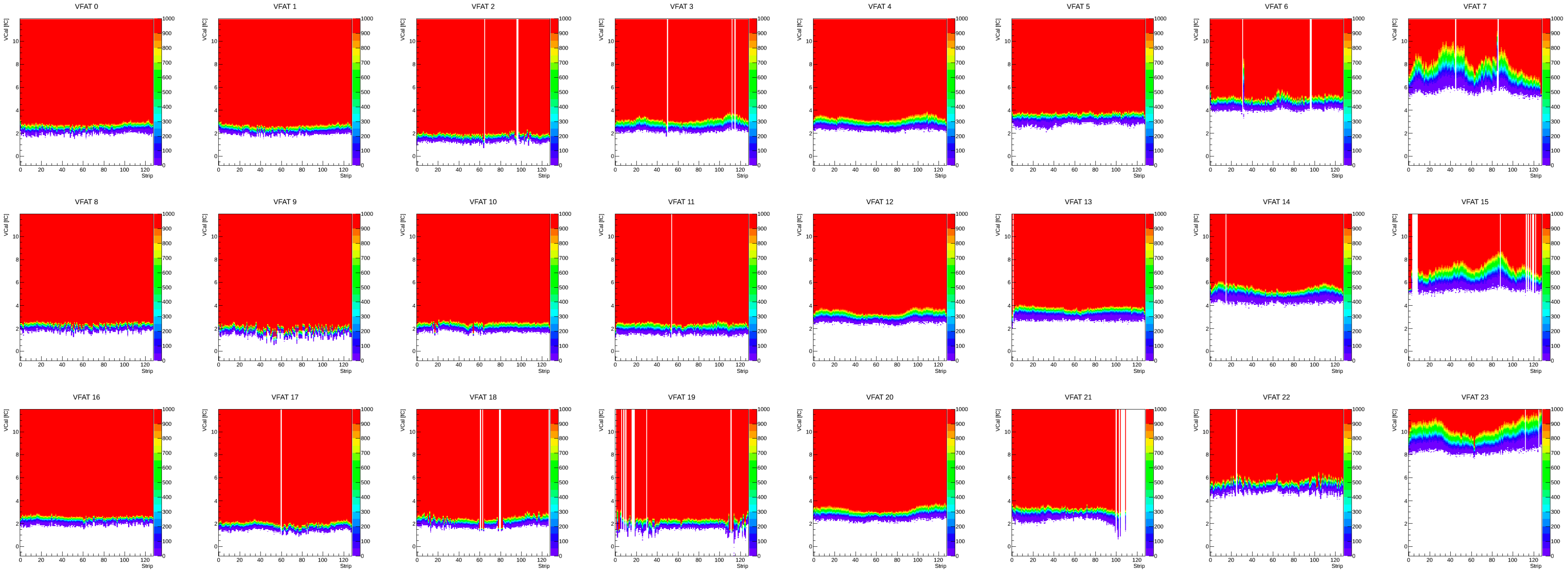
- This plot is trimmed, where the individual channel registers are adjusted such that the 99% response point is the same VCAL value for all channels.



Noise Measurements: “S-Curves”

- For v2 chambers, the VFAT2 chips are generally noisier closer to the optohybrid and the area in which the LV power lines converge.

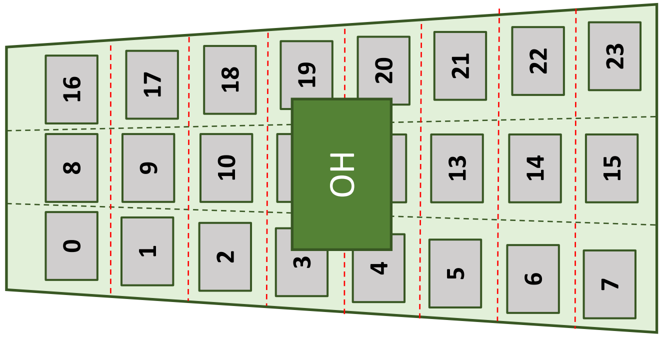


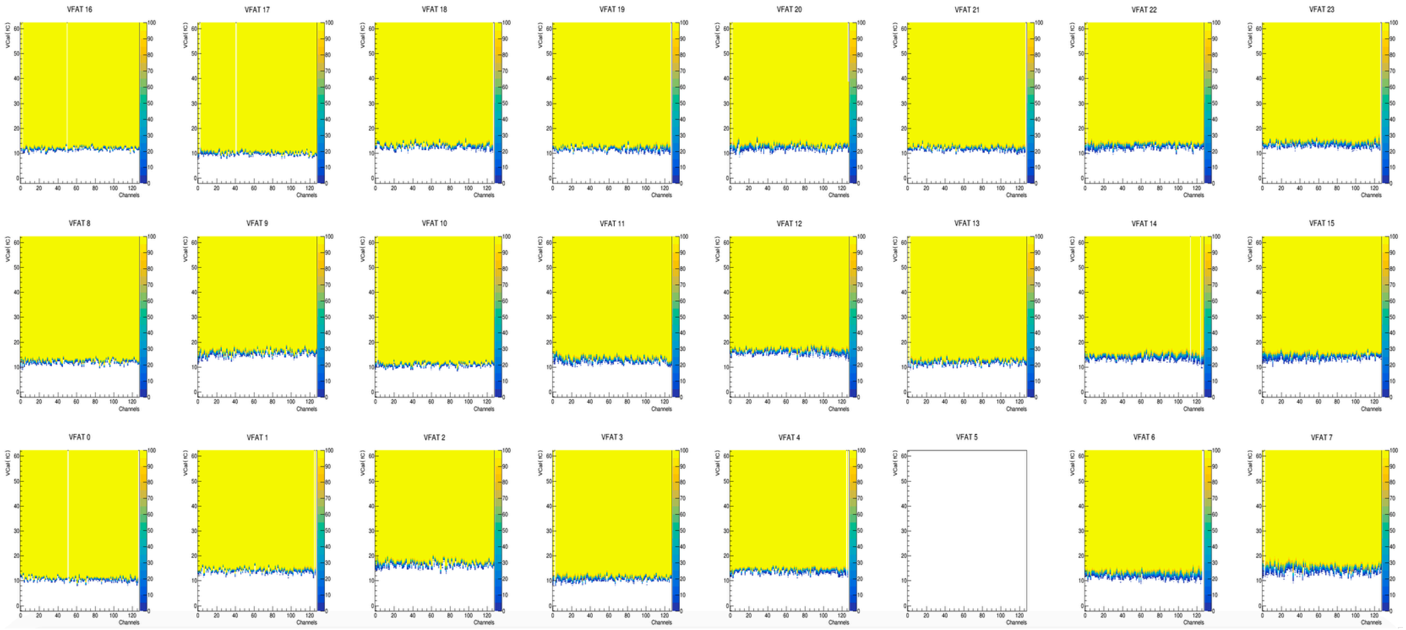


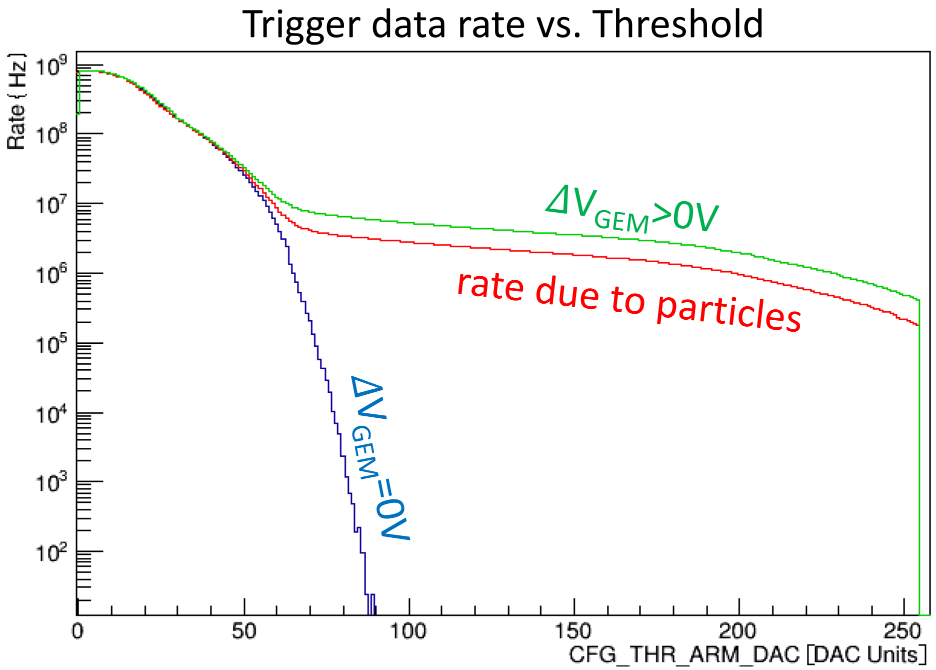
Noise values in fC

v3 S-Curves 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

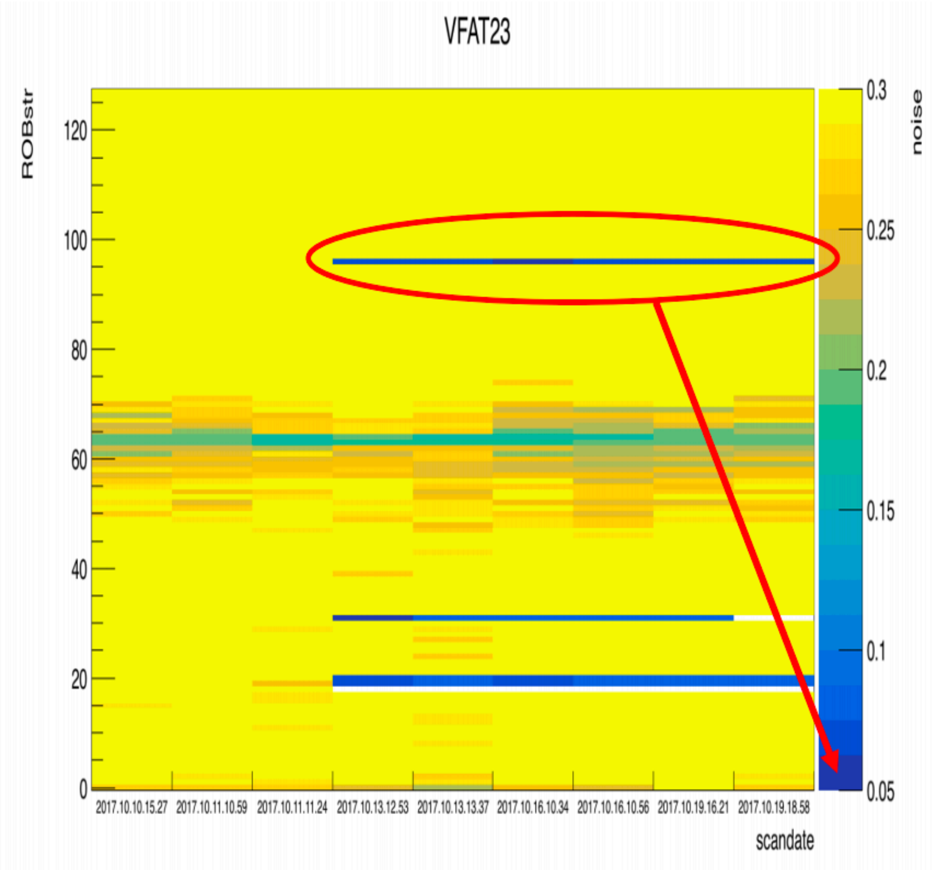
*Color scale changed from v2 to v3

VFAT2 Channel Stability

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

- Each column in a time series plot represents one set of S-Curve scans.

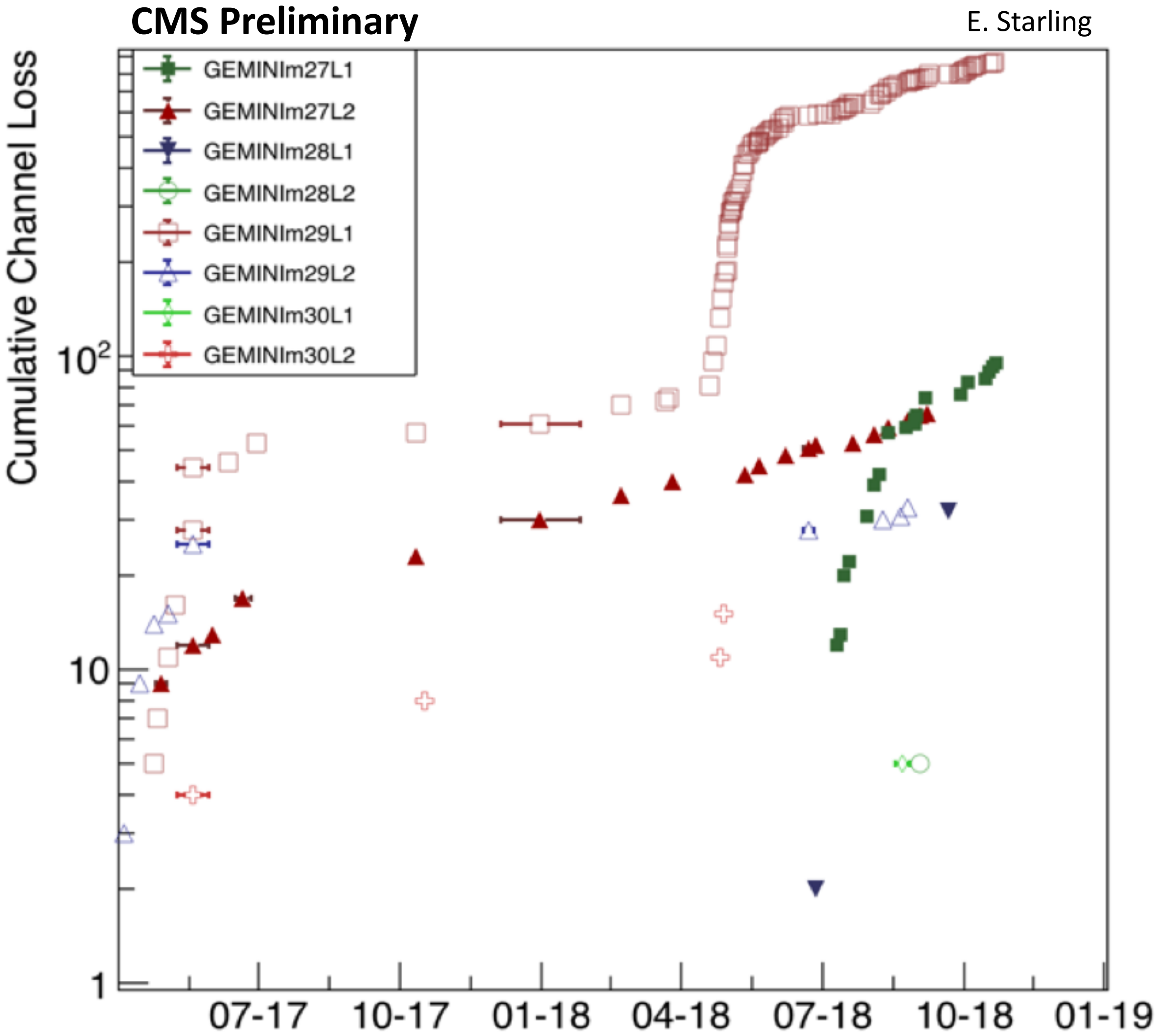
- If a channel has a noise level of 0.0414 – 0.109 fC, it indicates that the capacitance of that strip is no longer being seen and the channel is considered dead.



VFAT2 Channel Stability

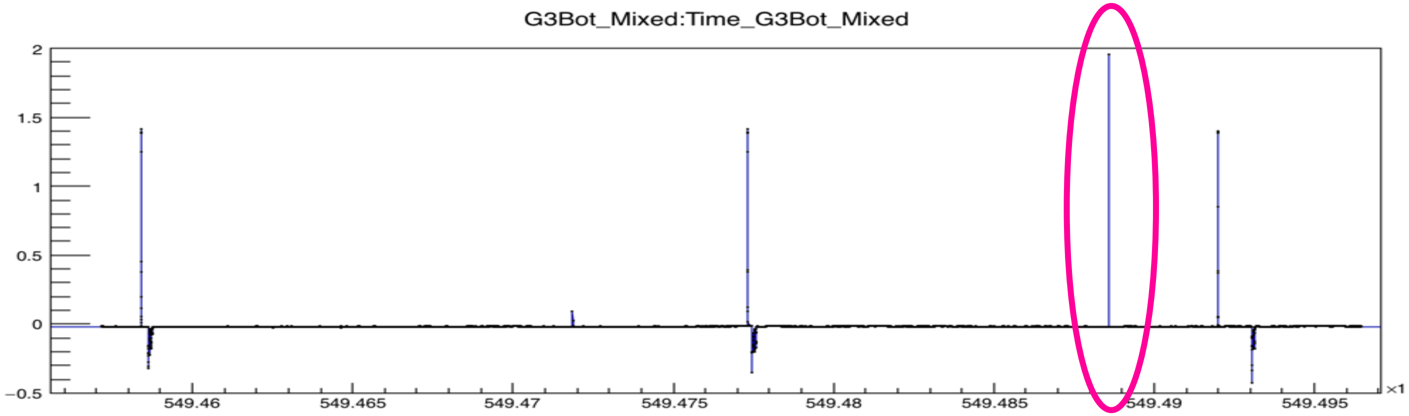
- Over the lifetime of the Slice Test, there was an overall loss rate of approximately 0.5% of VFAT2 channels per month for the v2 detectors, concentrated mostly in three of the short chambers:
  - GEMINIm29L1 from May 2018
  - GEMINIm27L1 from July 2018
  - GEMINIm27L2 steadily over time

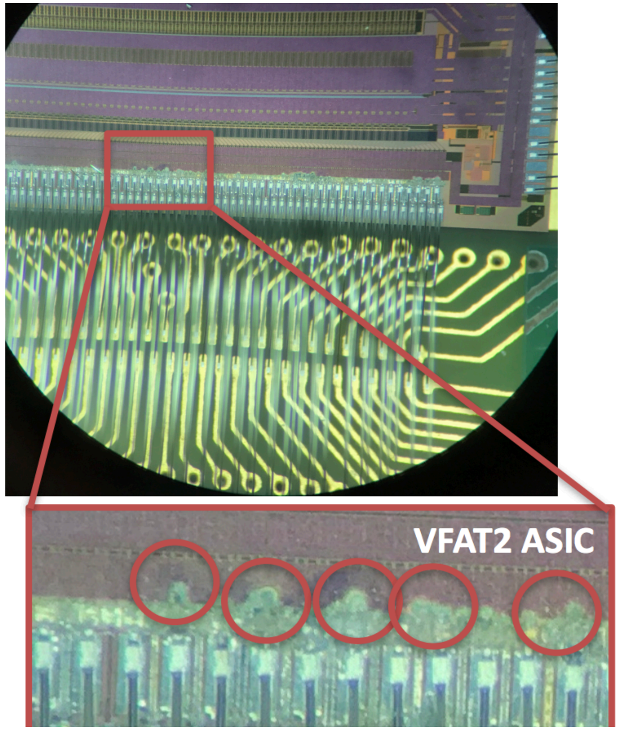
- Changes had to be made to mitigate this damage and preserve the lifespan of the system!



VFAT2 Channel Stability

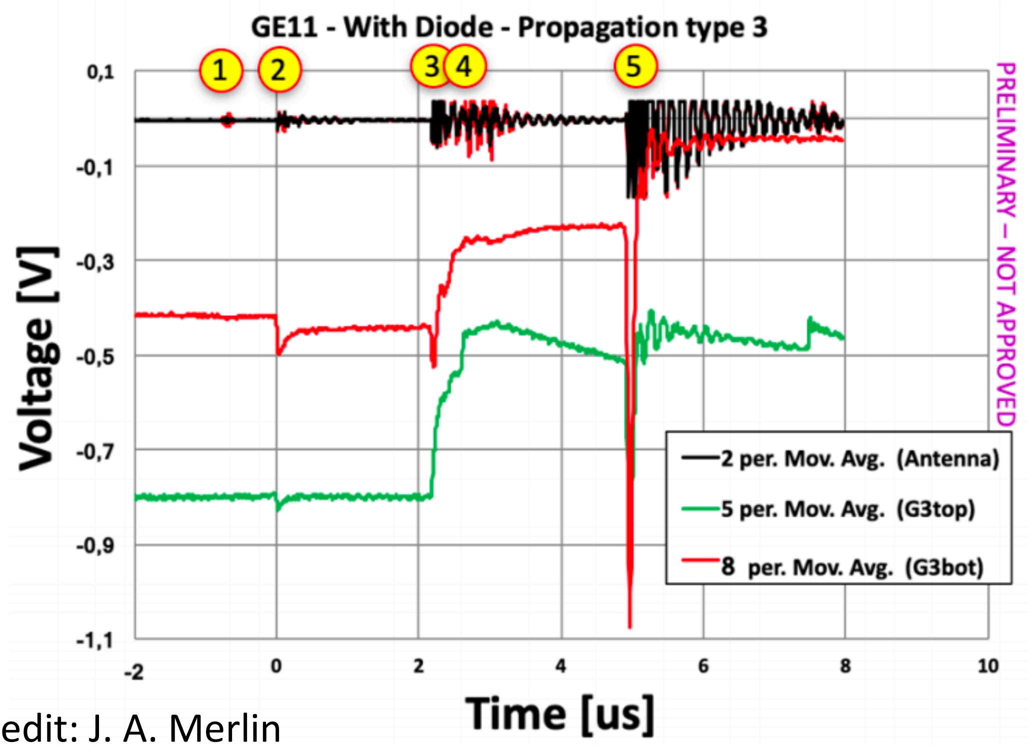
- This channel loss has been attributed to burn damage as a result of discharges reaching the anode.
  - Ex: Bottom, G3_bot (foil closest to the anode) exhibiting both leakage currents and a discharge (in pink).
- The energy of these discharges is large - ~410 µJ





Propagating Discharges

- Discharge propagation in large detectors (such as GE1/1) is more complex than in smaller detectors (ex: 10x10 cm^2).
- Discharges may travel up and down the GEM foil stack, accumulating energy

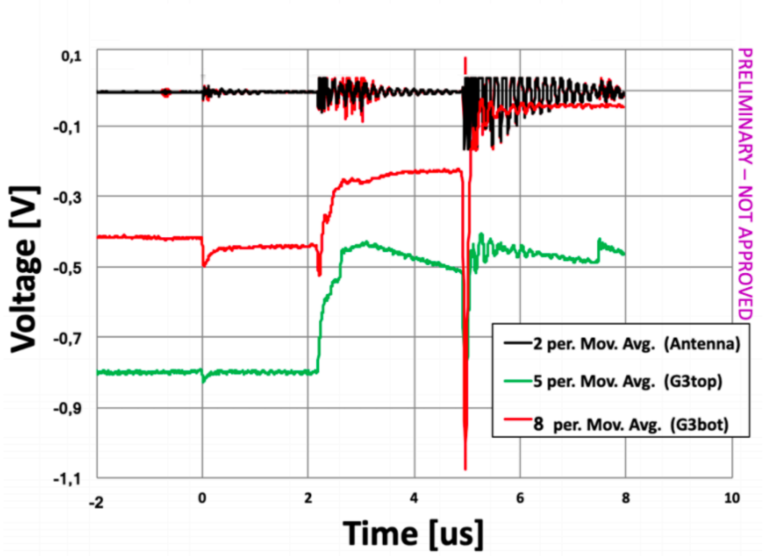


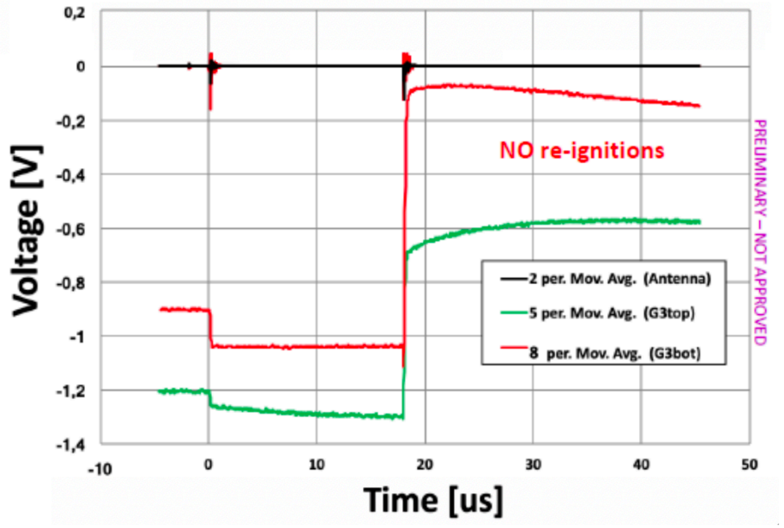
Credit: J. A. Merlin

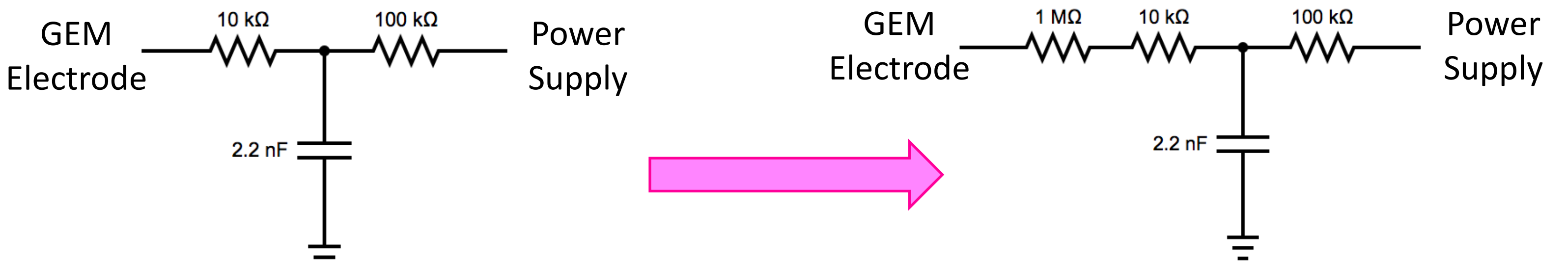
1) Primary discharge in GEM3
2) Backwards propagation in GEM2
3) Forwards propagation in GEM3
4) Forwards propagation from GEM3 to readout board
5) Re-ignition of the propagation

Proposed Changes to HV Filter

- Re-ignitions are fed by the energy stores in the HV filter. This can be mitigated by tuning the filter capacitance.







- Adding a 1MΩ resistor lowers the probability of re-ignitions.
- However, it also lowers the rate capability, negatively effecting detector operation

Credit: J. A. Merlin

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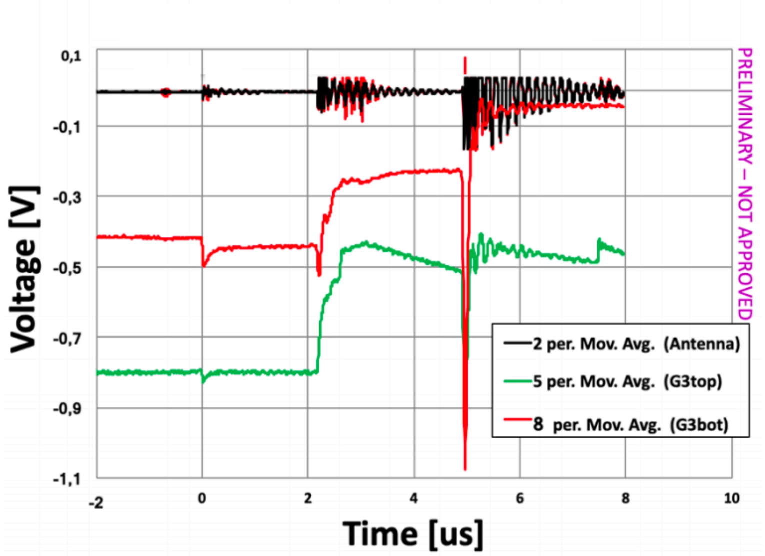
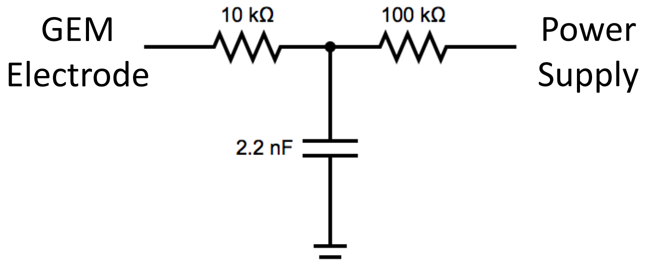
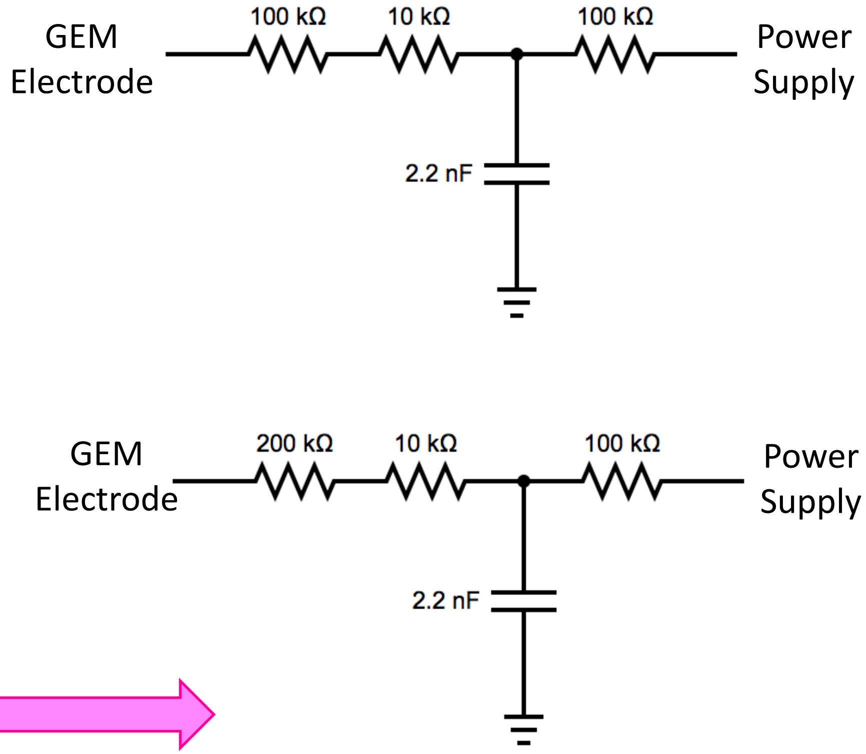


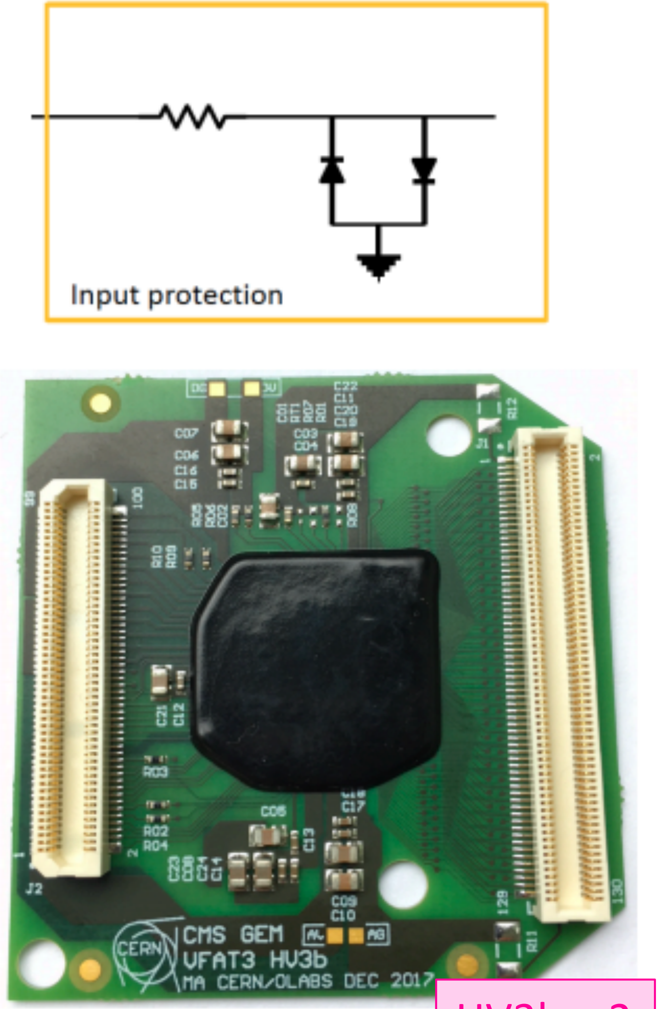


Credit: J. A. Merlin

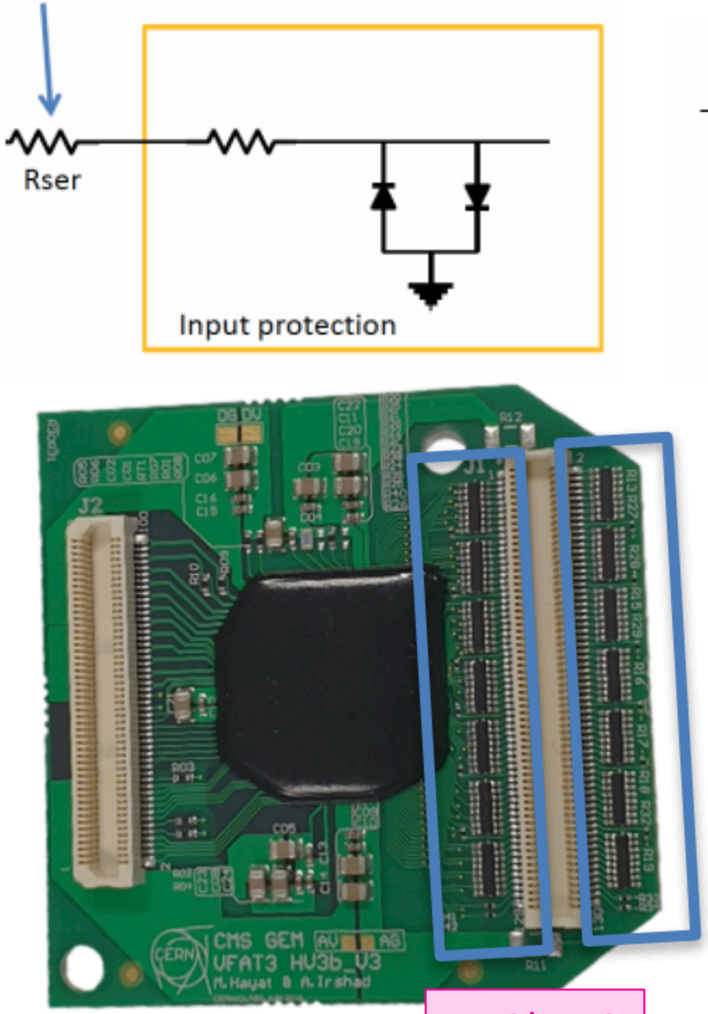


- Adding a 100kΩ resistor still dramatically reduces the re-ignition probability without lowering the detector rate capability.
- 200kΩ was chosen as the best middle-ground value.

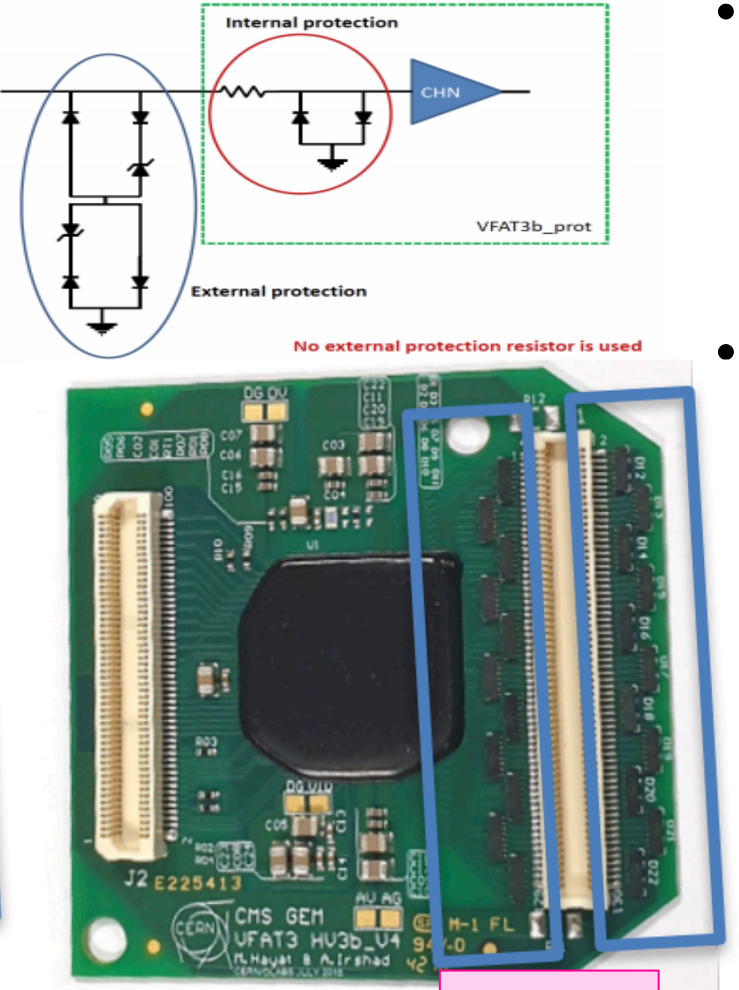
Proposed Changes to VFAT Design



HV3b_v2



HV3b_v3



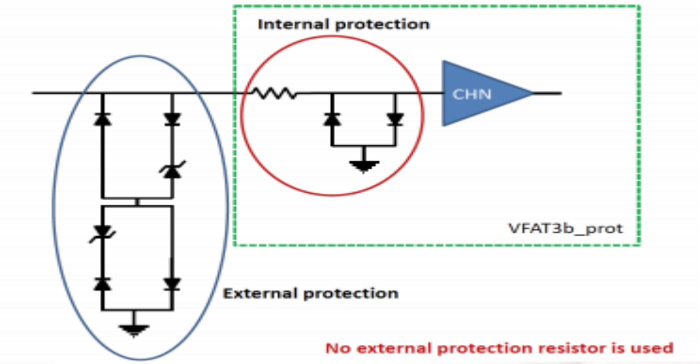
HV3b_v4

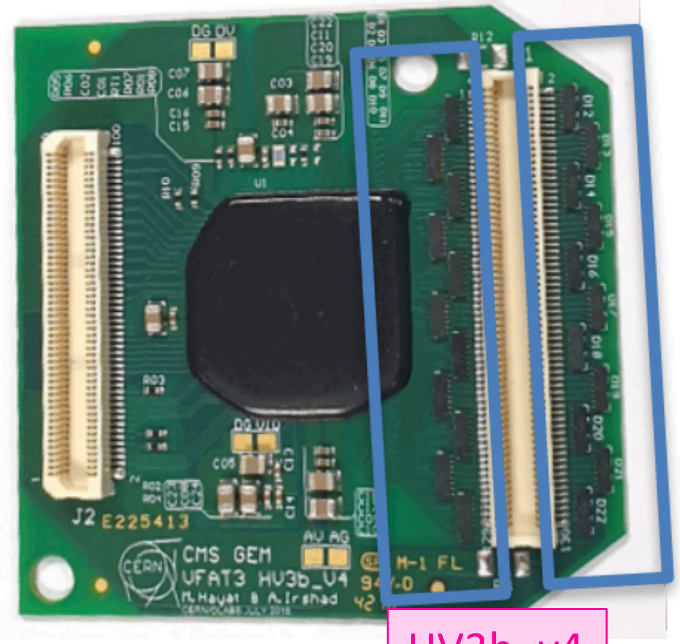
- HV3b_v2 is the baseline hybrid for the v3 electronics
- HV3b_v3 adds additional resistors in series

HV3b_v4 adds commercial off-the-shelf diodes in parallel

Credit: Paul Aspell

Proposed Changes to VFAT Design



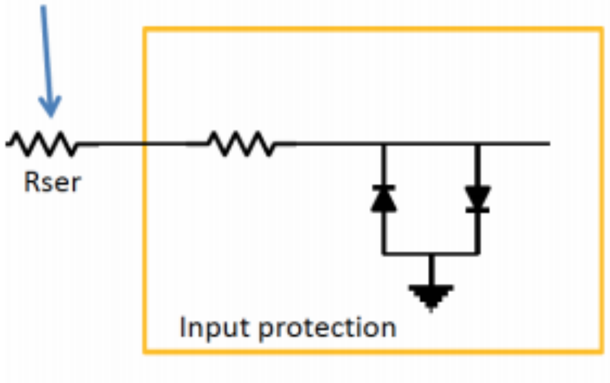


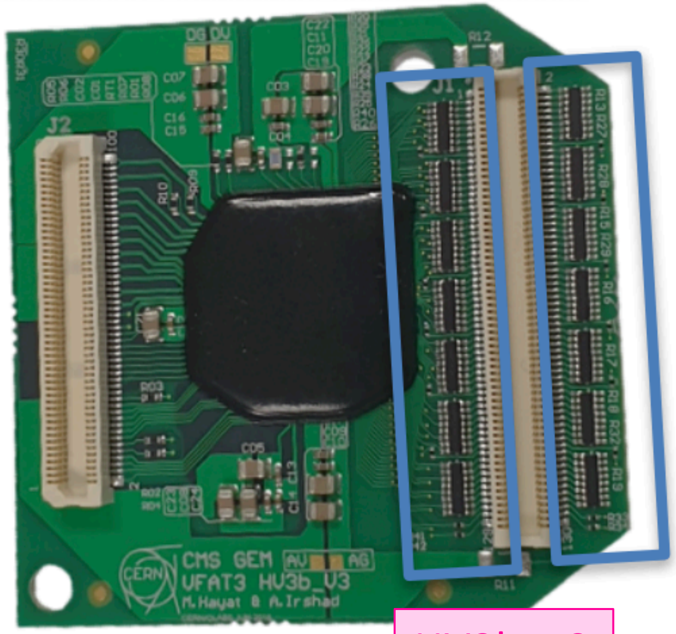
HV3b_v4

- HV3b_v4 would add no additional noise or cross-talk into the system.
- The radiation tolerance had to be tested, and was deemed good up to 10 MRad.
- Survived 540 electrostatic discharges via an injection circuit at ~470 µJ per discharge.
- When put on a GE1/1 detector, one discharge resulted in the destruction of ALL channels → solution REJECTED.

Credit: Paul Aspell

Proposed Changes to VFAT Design



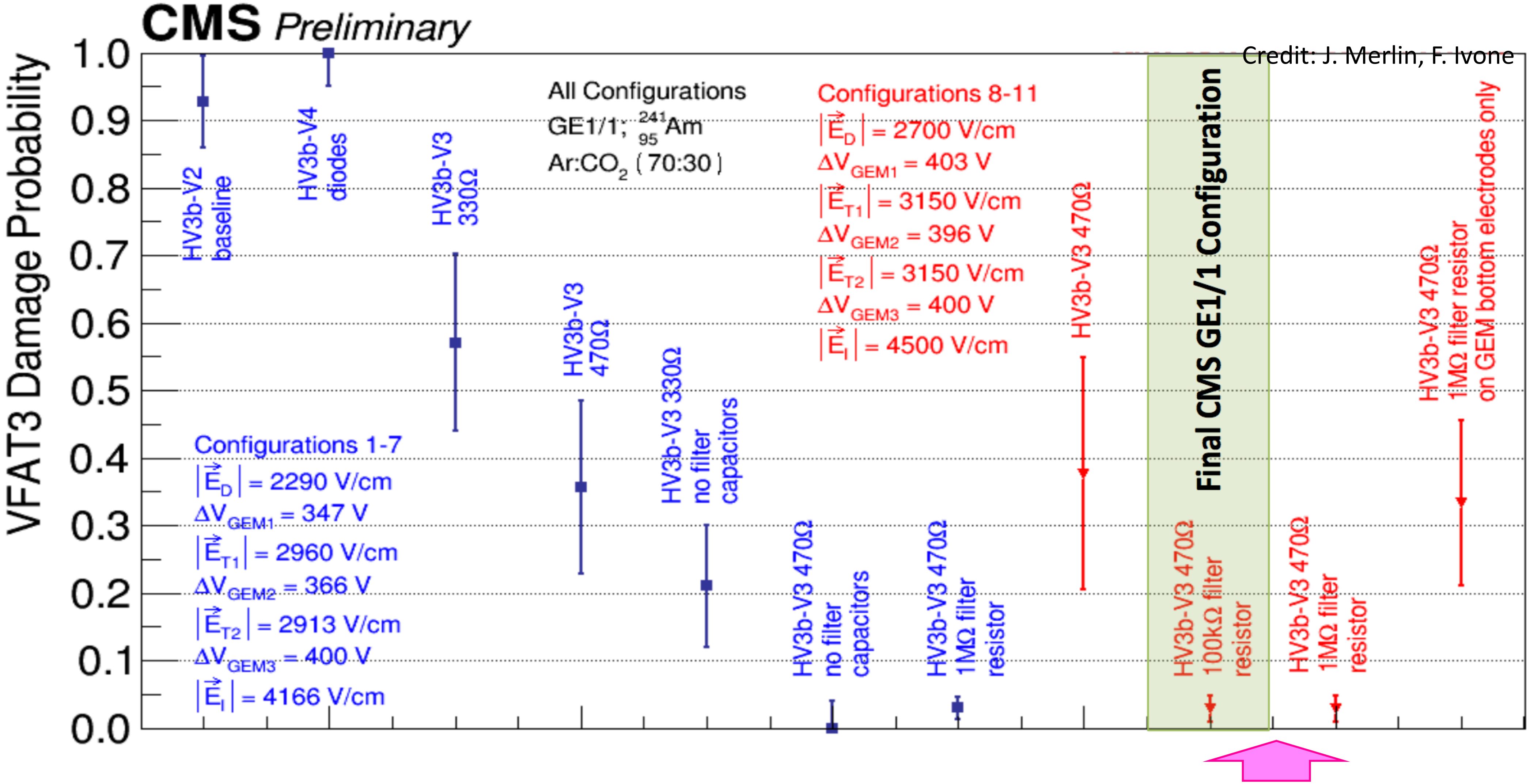


HV3b_v3

- The series resistors of HV3b_v3 dissipate part of the discharge energy.
- But…adds 20% noise and 15% cross-talk into the system.
- The radiation tolerance is well-known, as these have been used in HEP experiments before.
- Different resistances were tested: 330Ω and 470Ω.
  - 470Ω is appropriate for discharge energies up to 1.5 mJ.
- Tested different resistors for resiliency
  - Chosen array: Panasonic EXB2HV471JV

Credit: Paul Aspell

Changes to VFAT Design: Testing



Credit: J. Merlin, F. Ivone

Chosen value: 200kΩ. Good protection without lowering rate capability.

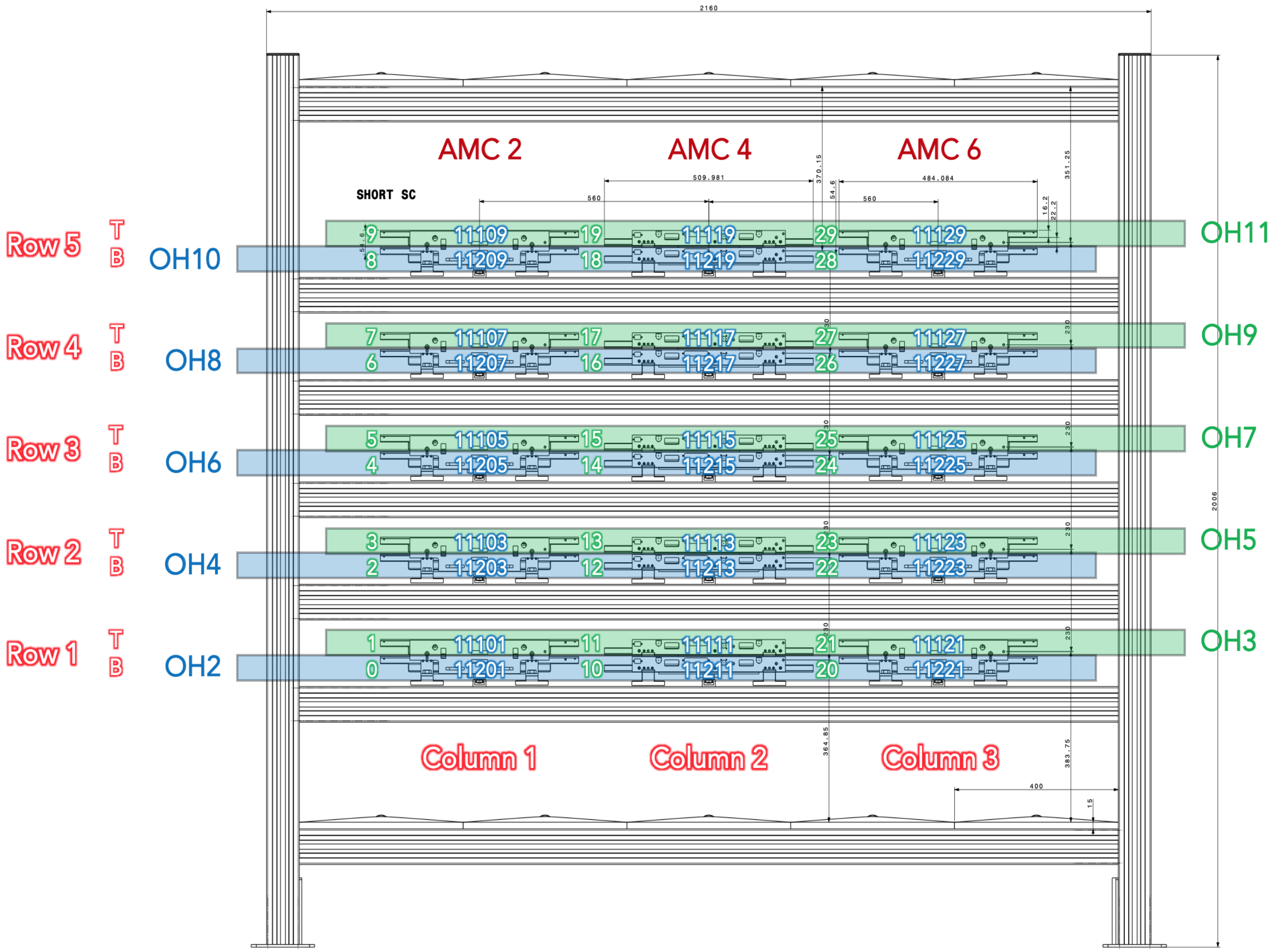
GE1/1 Production and Installation

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
- S-Curves are taken to ensure the electronics are working properly and to assess the noise
- Efficiency measurements are of particular interest



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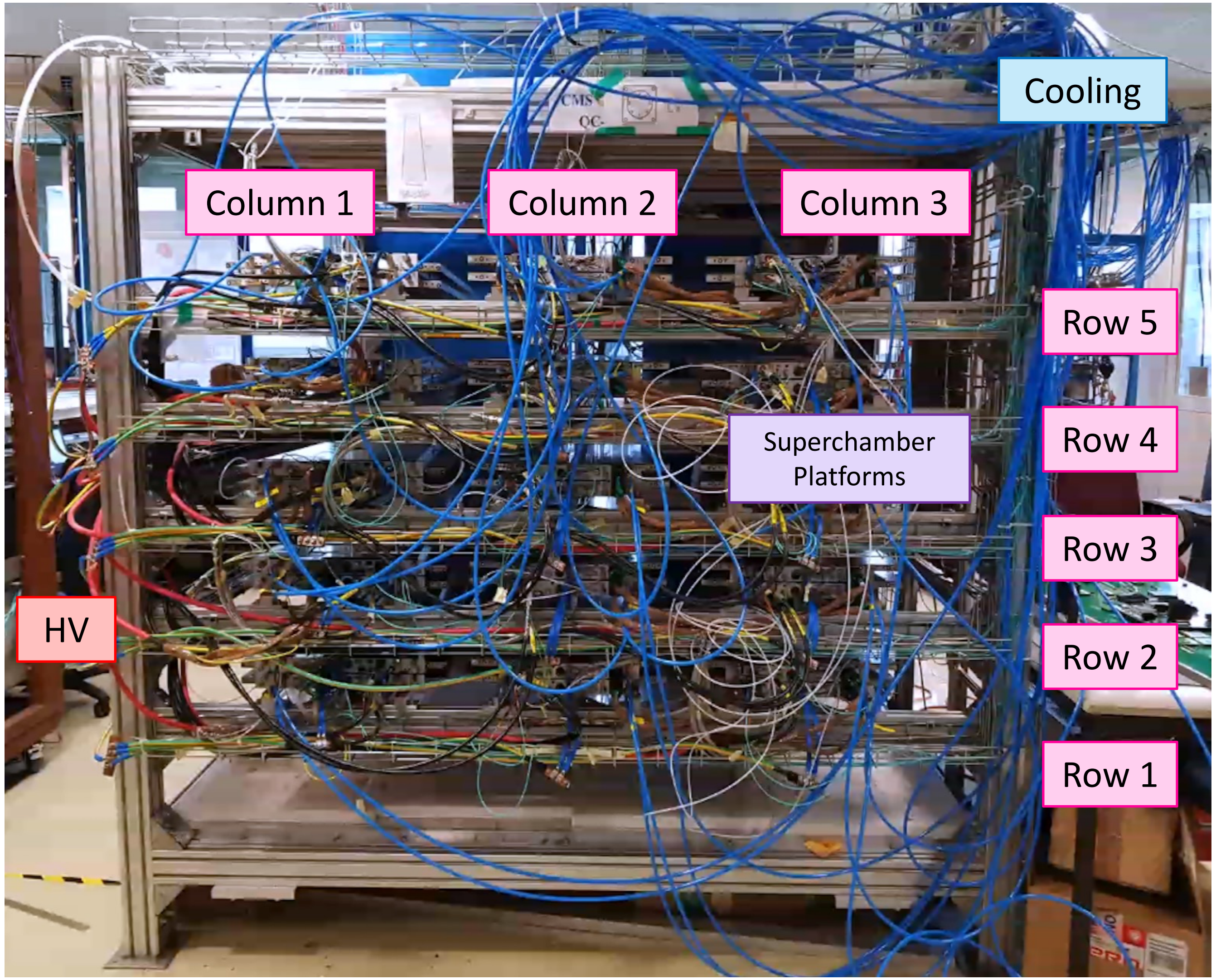
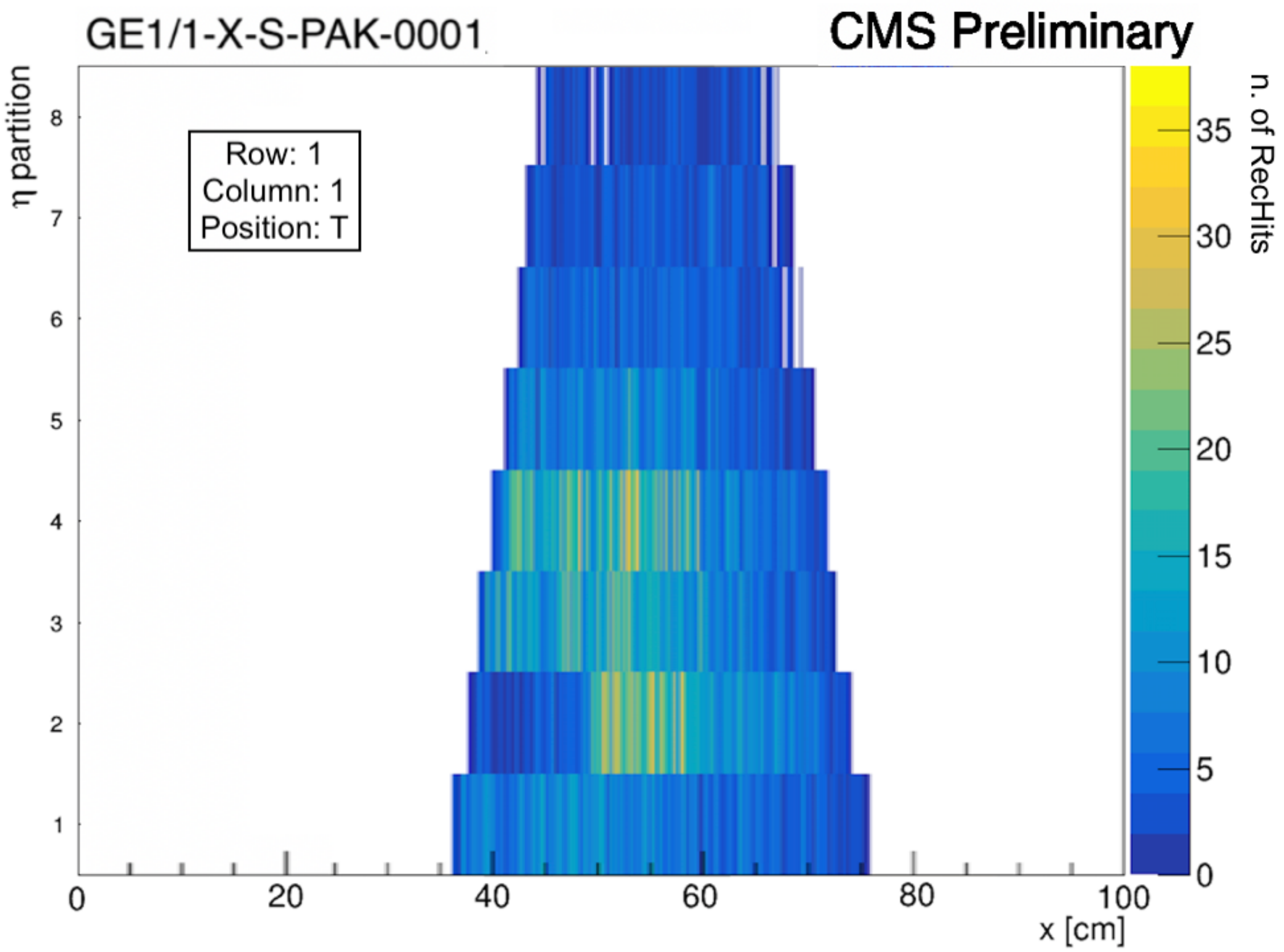


QC8 Results: Occupancy of Associated RecHits

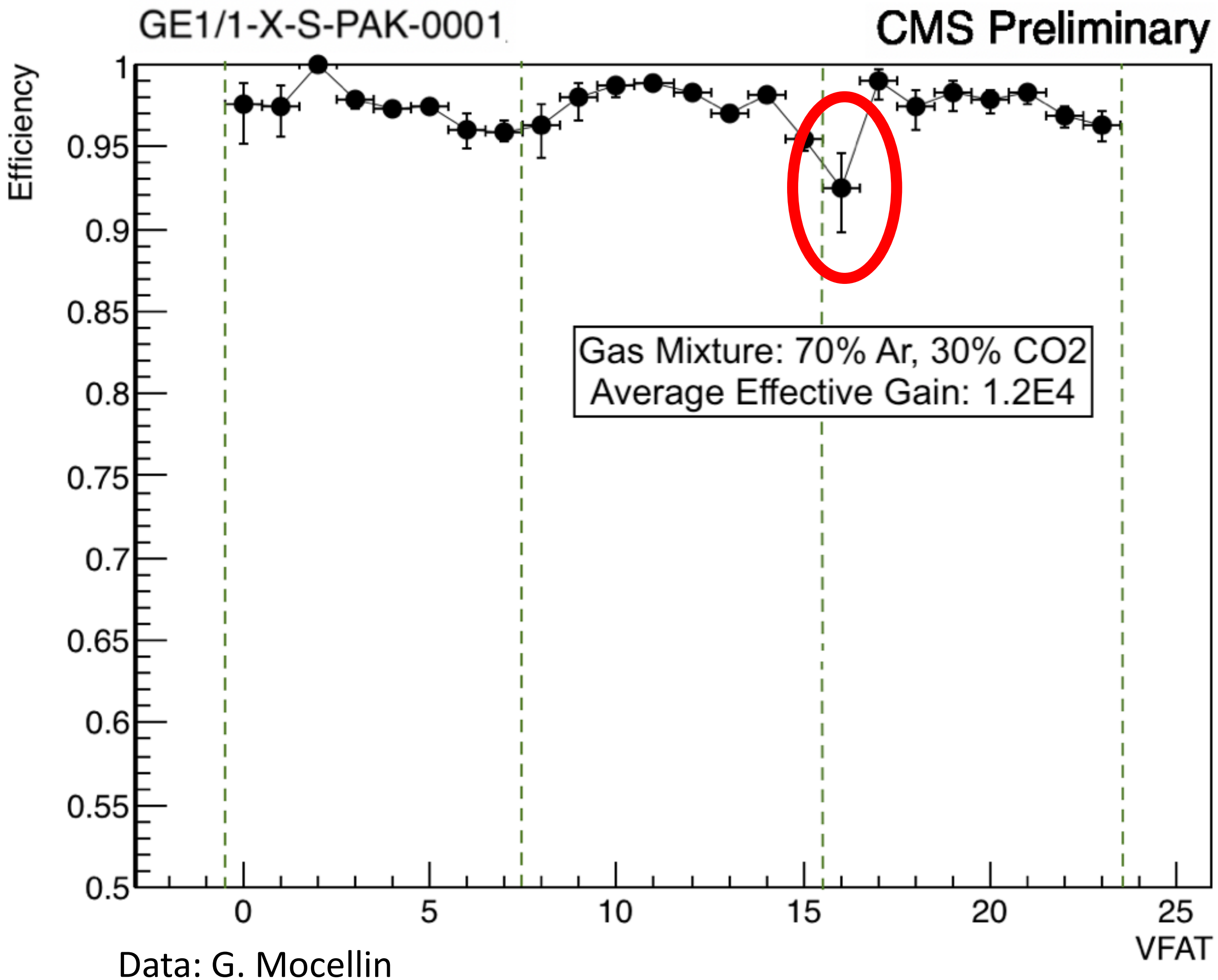


Data: G. Mocellin

Associated RecHits for GE1/1-X-S-PAK-0001.

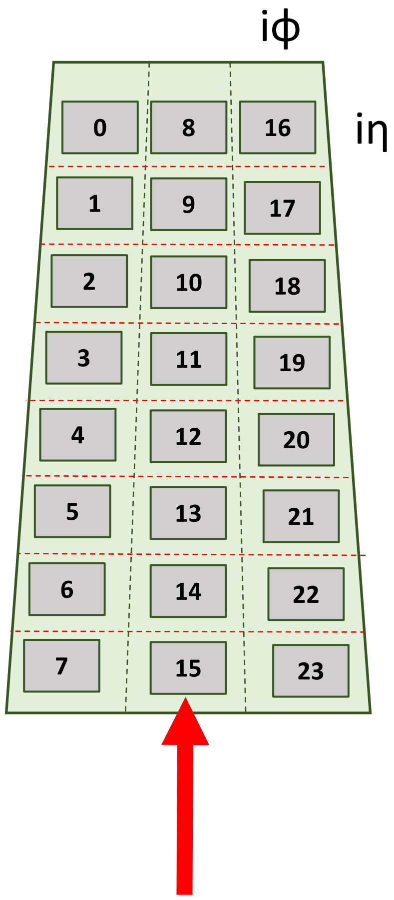
- For a given test chamber (in this case, GE1/1-X-S-PAK-0001), the other chambers in the stand are taken as reference. For a given event, the muon track is reconstructed using the reference chambers, and then extrapolated to the test chamber.
- The associated RecHit is a verified hit in the test chamber that matches the extrapolation. This allows us to measure the efficiency of the chamber.

QC8 Results: Efficiency



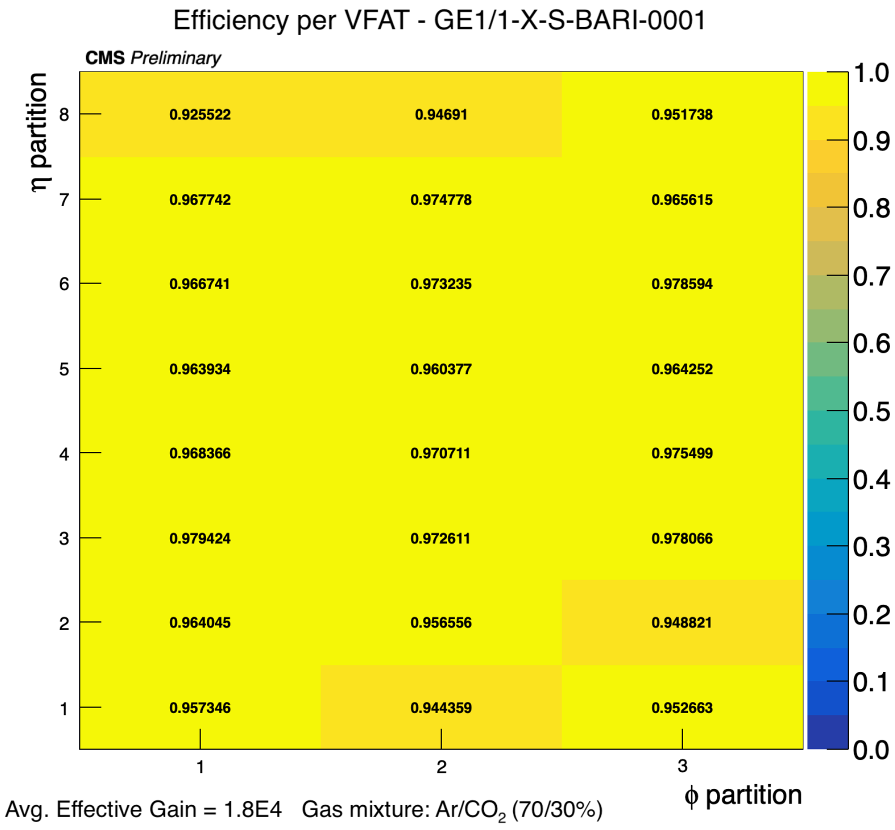
Data: G. Mocellin

- In some cases, the efficiency is lowered by the geometrical acceptance of the stand.
- This is due to an imperfect alignment of the detectors and the choice to take a given hit as being directly in the center of its respective iη/iϕ region. It is NOT a characteristic of the detector itself.

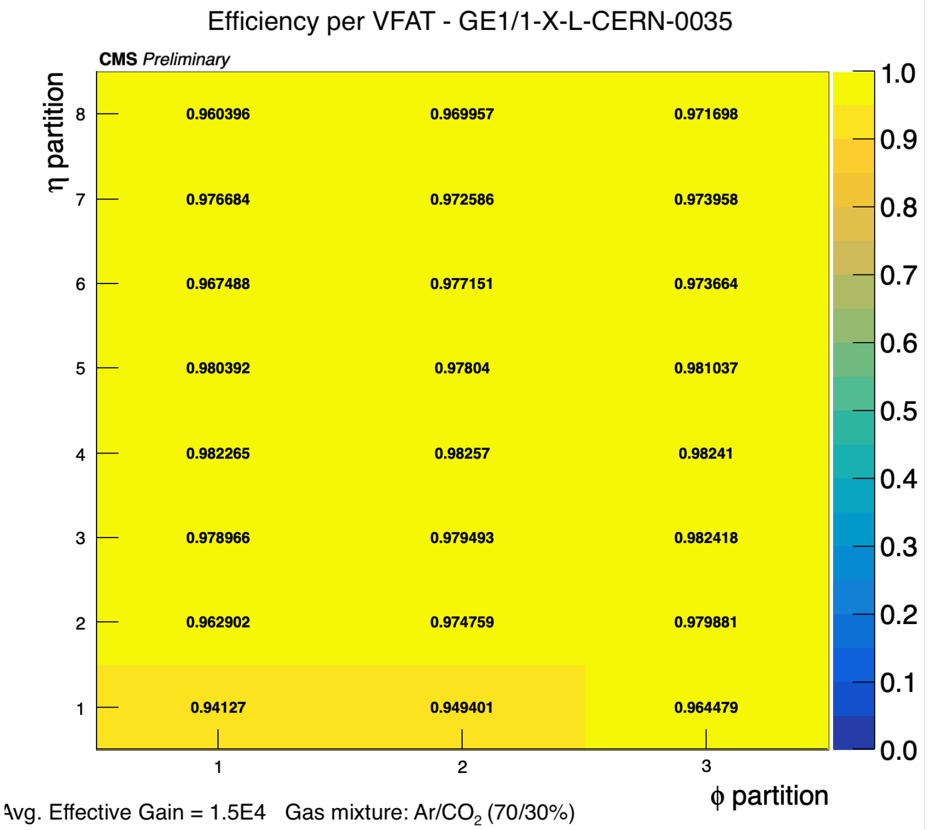


QC8 Results: Efficiency

- Examples of short (left) and long (right) chambers that were qualified as being ready for installation.
- Geometrical acceptance issues seen on the edges of the detectors, but overall efficiency is >95%.

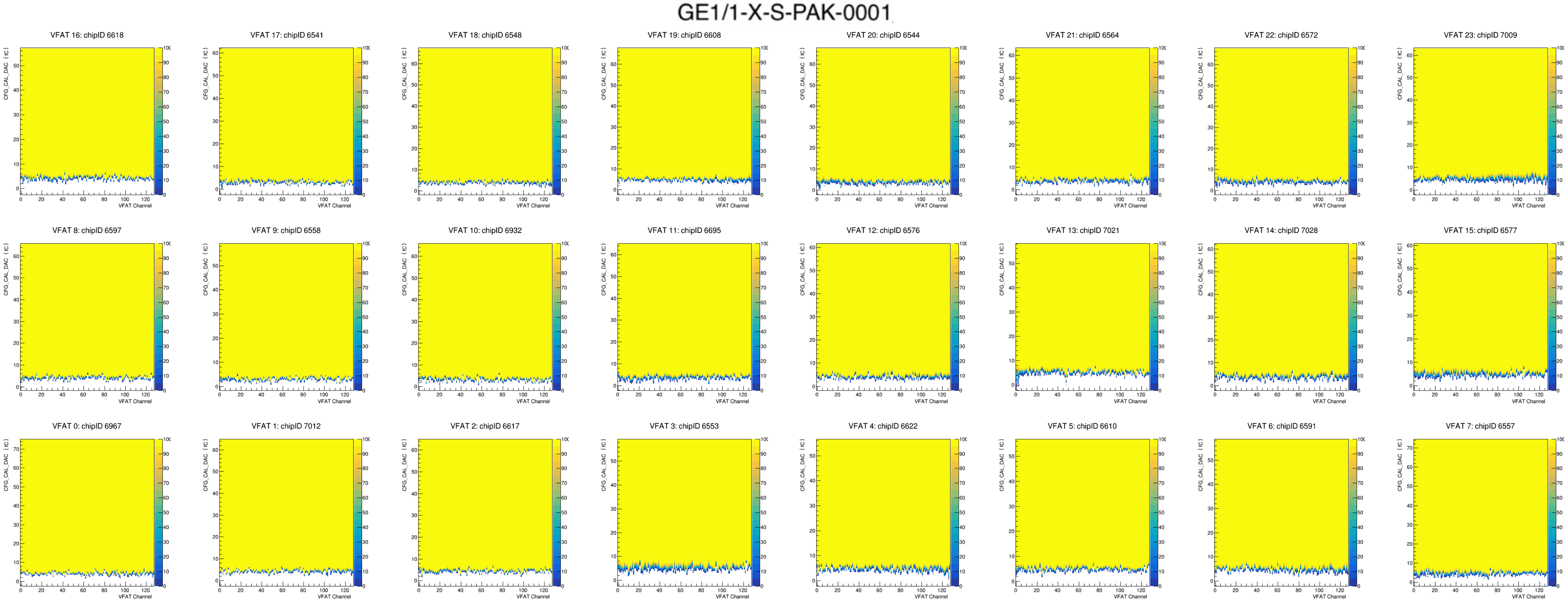


Avg. Effective Gain = 1.8E4 Gas mixture: Ar/CO_2 (70/30%)



Avg. Effective Gain = 1.5E4 Gas mixture: Ar/CO_2 (70/30%)

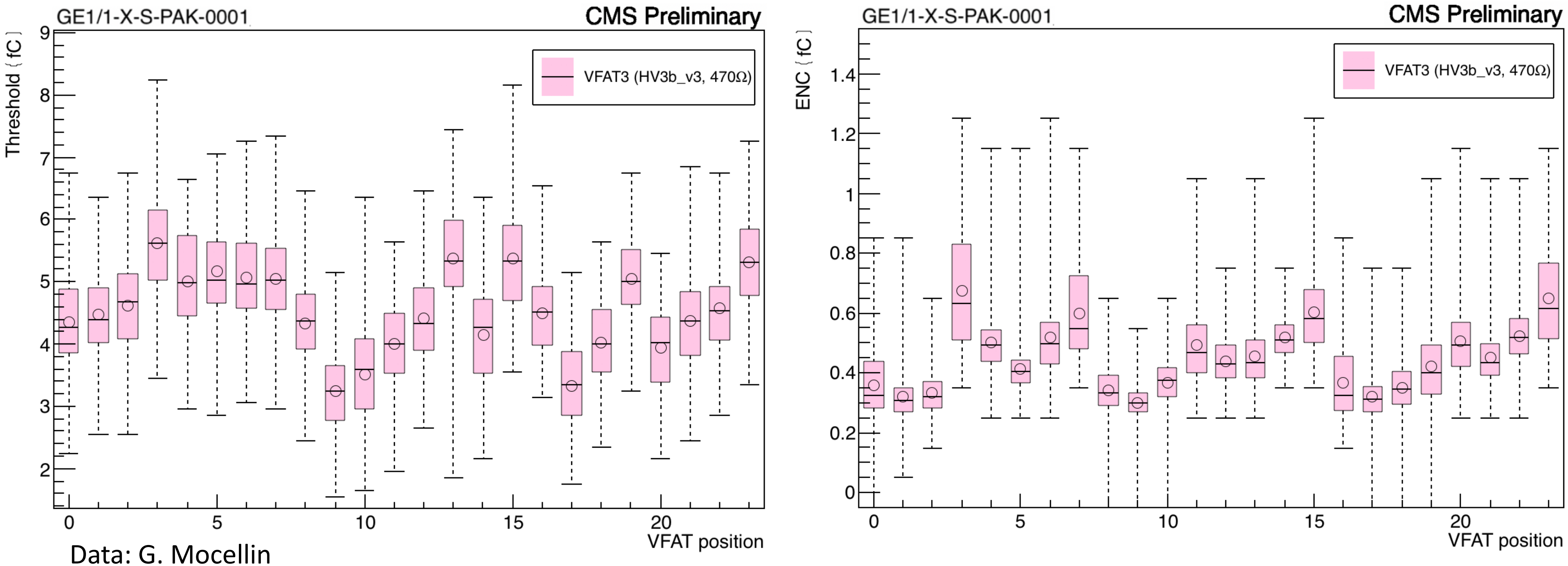
QC8 Results: S-Curves



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

Data: G. Mocellin

QC8 Results: Threshold and ENC

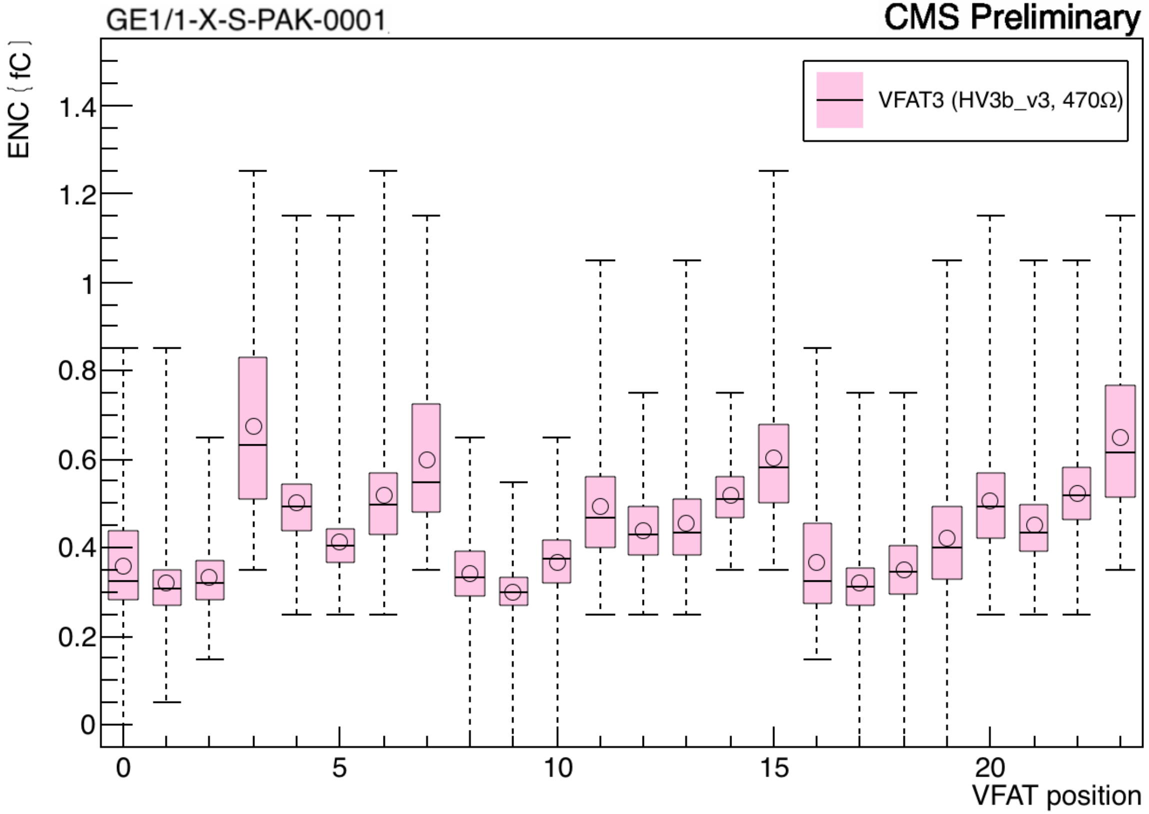


Data: G. Mocellin

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

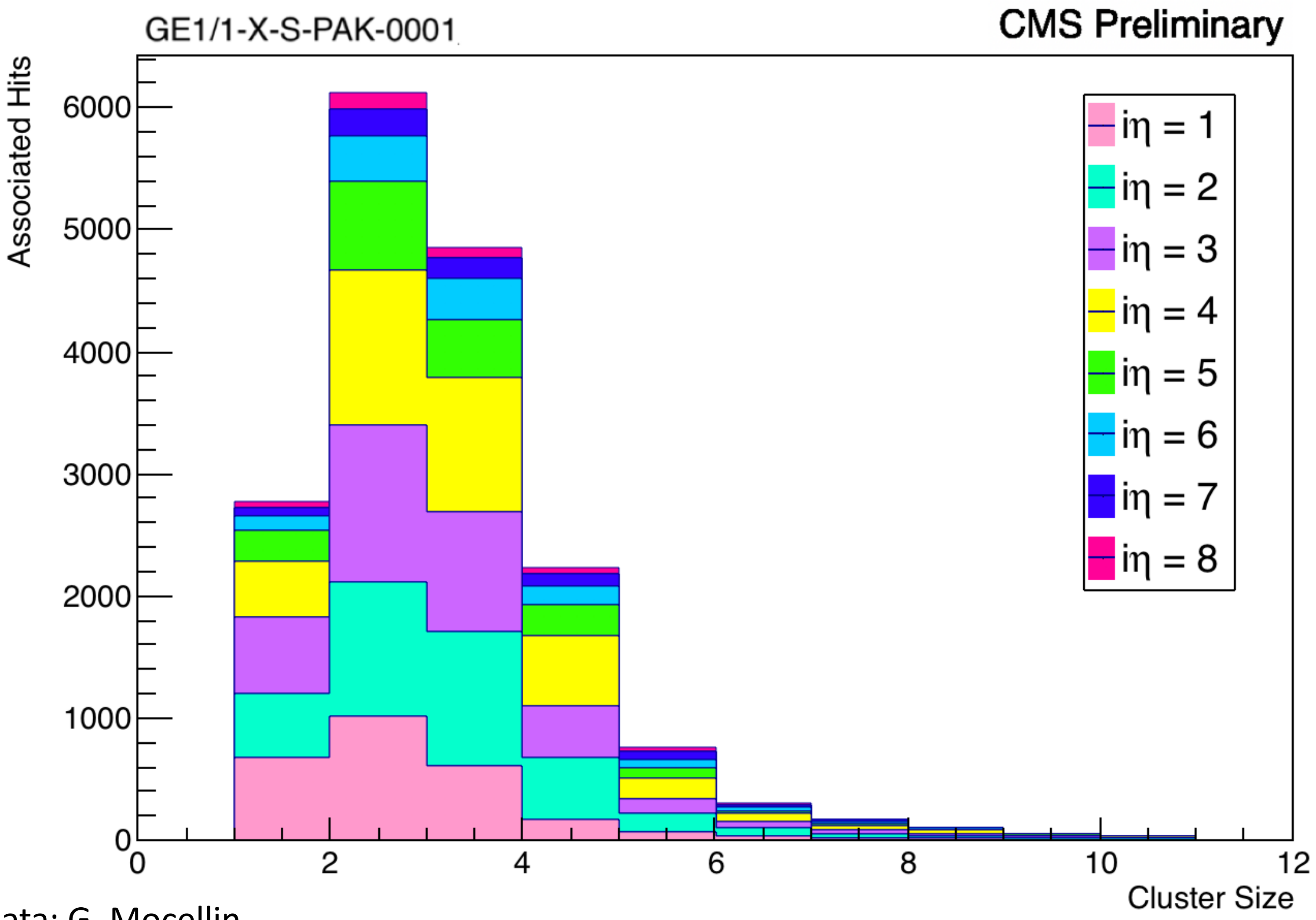
QC8 Results: Threshold and ENC

- 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 S-Curves 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.
- The distribution leans towards larger cluster sizes due to the presence of cross-talk.

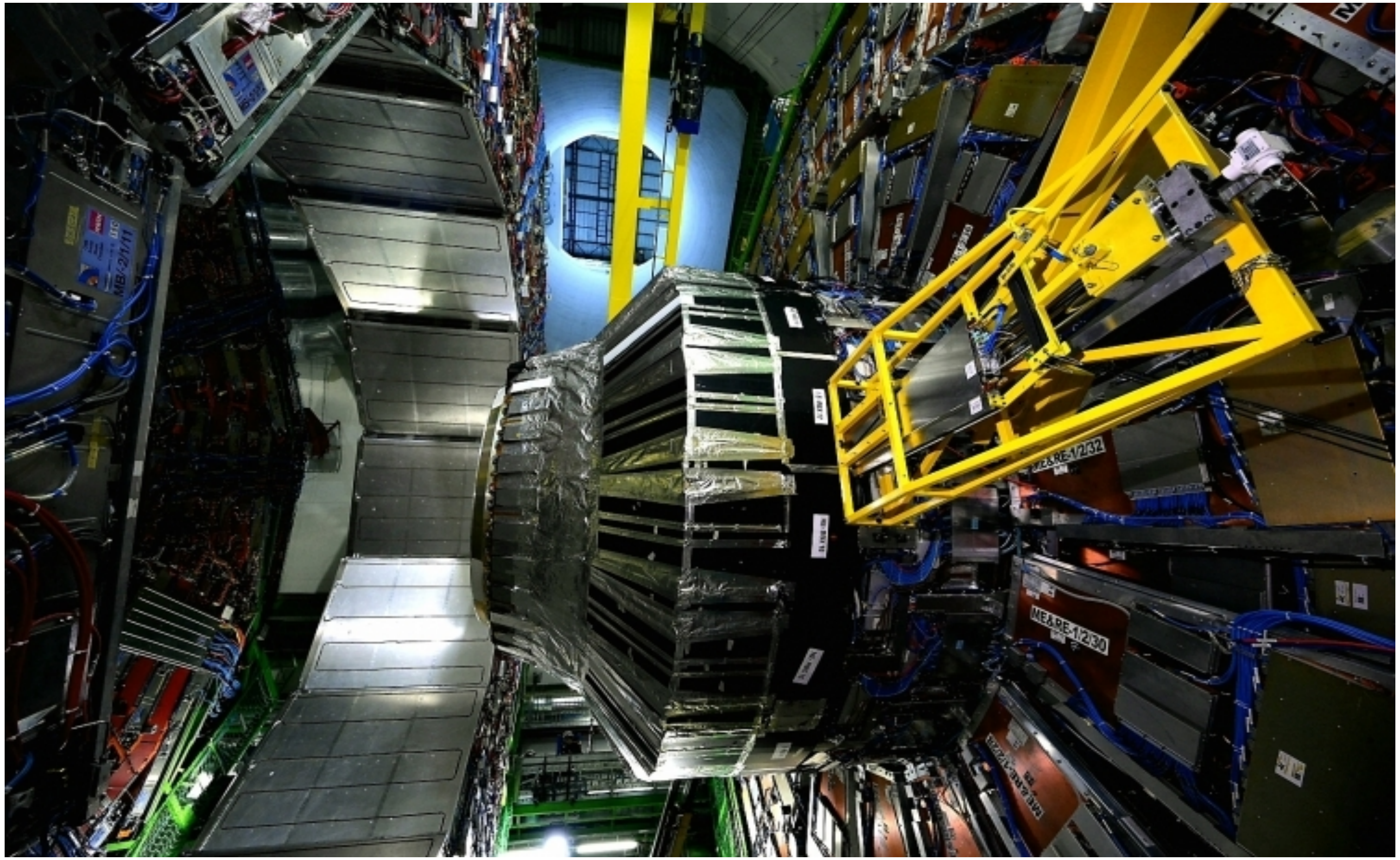
Installation Progress

October 24th:

the installation of the YE-1 endcap is complete!

Facebook live video of the final chamber installation:
https://www.facebook.com/cern/videos/417995299115192/

CMS News Articles:
https://cms.cern/news/first-gems-installation
https://cms.cern/news/cms-continues-shine-new-gems



GE1/1 Commissioning

- The chamber installation is finished, but there’s still a lot of work to do!

- Before cooling is operational, only short checks can be done (for the safety of the electronics)
  - First communication check –
    - Make sure the fibers are routed correctly
    - Make sure we can communicate with the front-end electronics

- Cooling is operational as of last week!
  - Longer tests are now possible
  - Noise studies, S-Curves, DAC scans, etc.

Future Timeline

- Negative endcap
  - Commissioning: November 2019 – February 2020
- Positive endcap
  - Gas services installation: March 2020
  - Cooling services installation: March – April 2020
  - Chamber installation: April – May 2020
  - Cable / fiber installation: May – June 2020
  - Commissioning: June – August 2020
- Mid-week global runs: September 2020 – April 2021
  - Multi-day cosmic data taking with all CMS subsystems running together
- Proton physics in CMS: May 2021 – LS3

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.

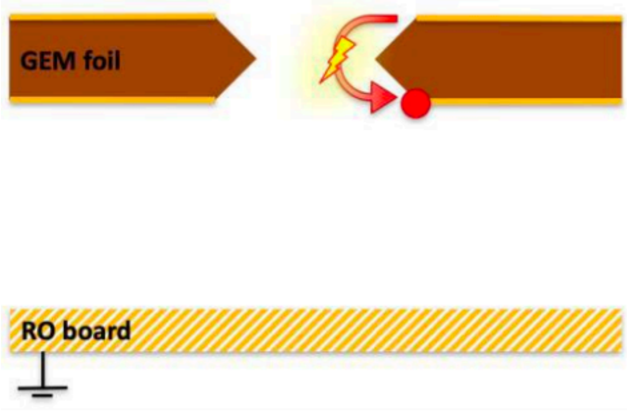
Questions?

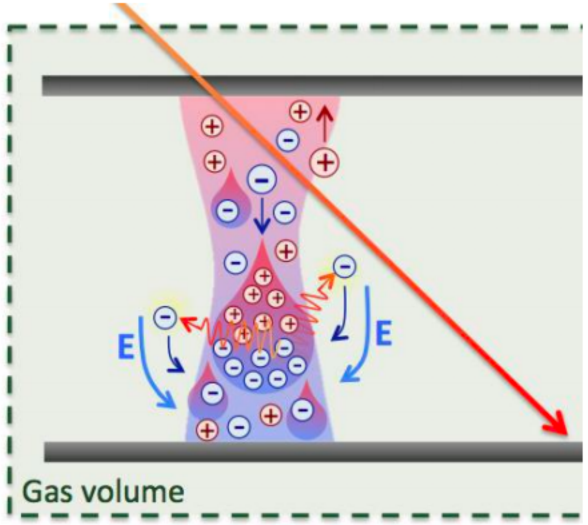
Thank you!

Backup Slides

Backup Slides!

Propagating Discharges



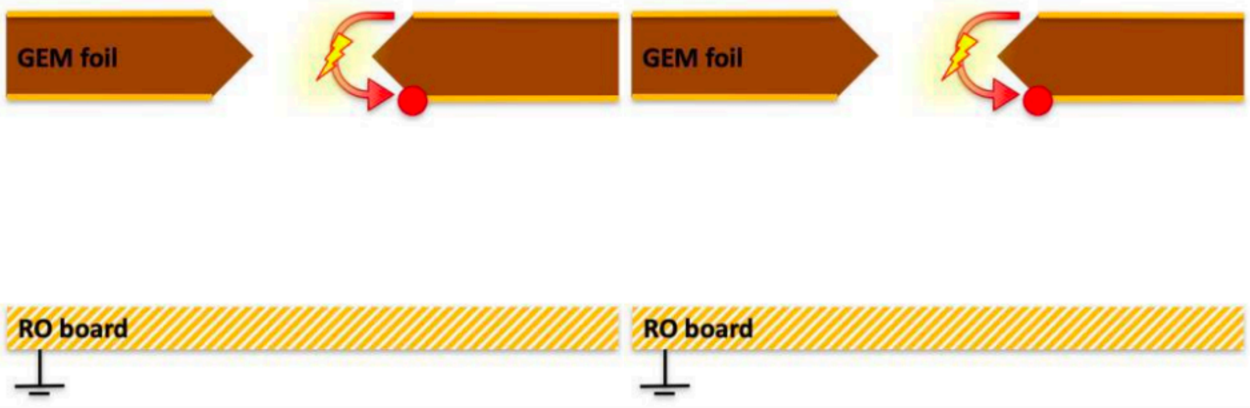


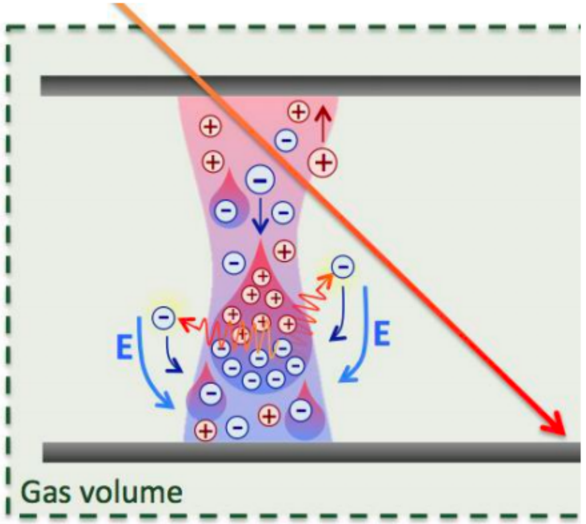
Typical developement of avalanche into a streamer

Credit: J. A. Merlin

- A primary discharge is caused by the high charge density within a given electron avalanche

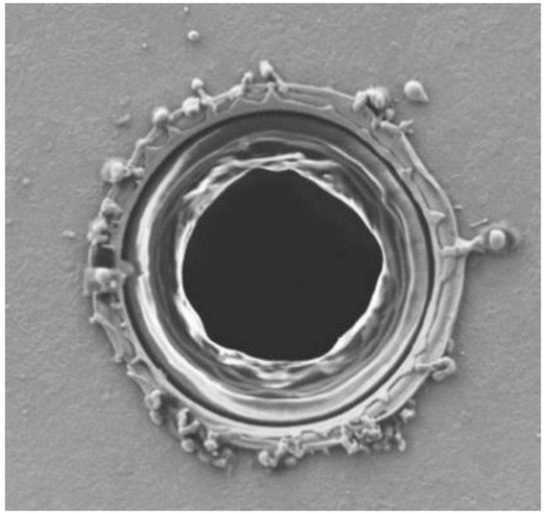
Propagating Discharges





Typical developement of avalanche into a streamer

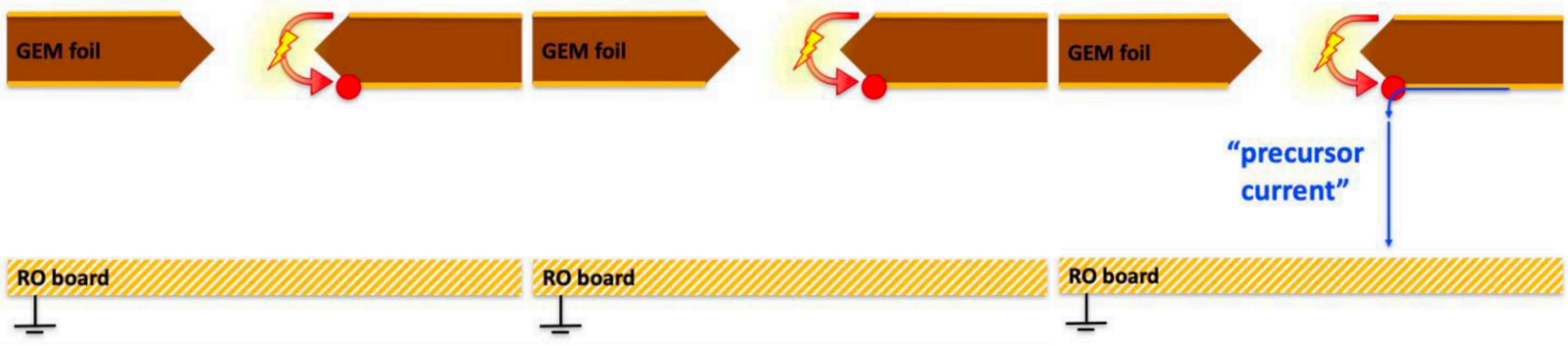
Credit: J. A. Merlin

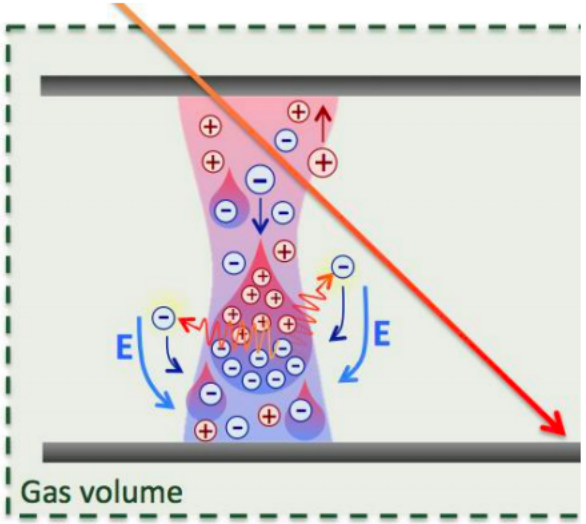


SEM picture of a GEM hole (bottom) after a 2mJ discharge

- A hot spot is created on the copper near the rim of the hole (> 2500℃)

Propagating Discharges





Typical developement of avalanche into a streamer

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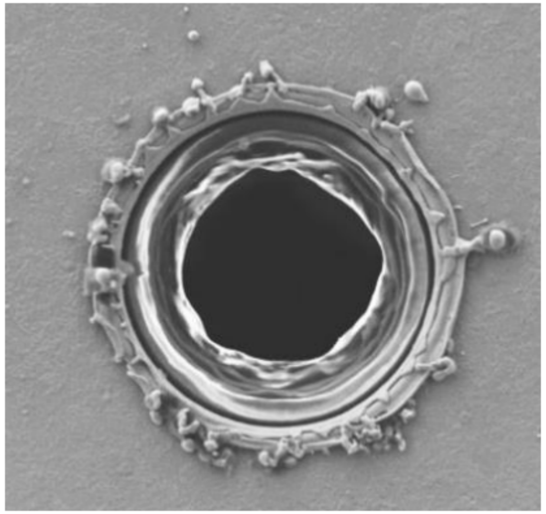
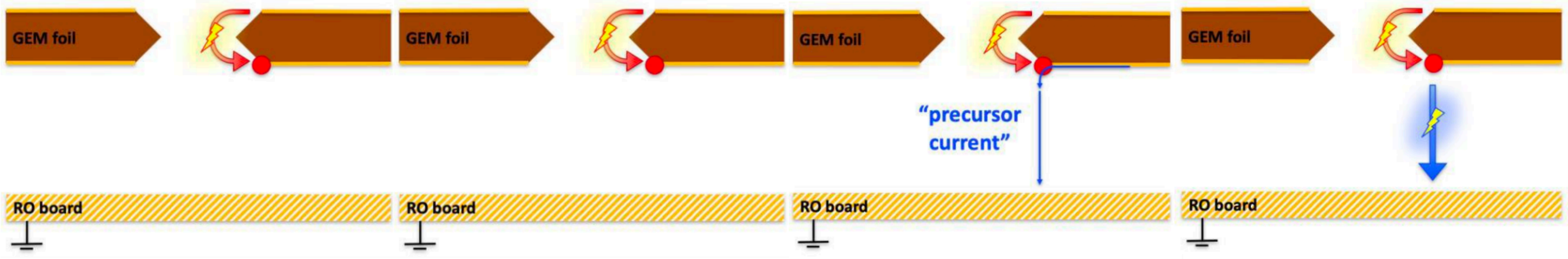


SEM picture of a GEM hole (bottom) after a 2mJ discharge

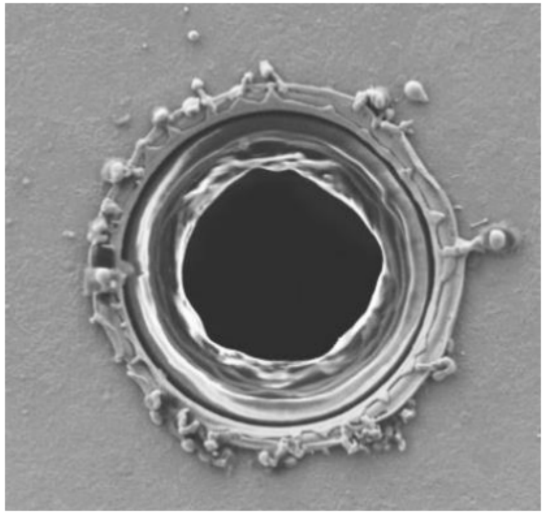
A. Utrobičić et al. (University of Zagreb), MPGD Stability Workshop, June 2018

- Thermionic emission of electrons in the gas by the local electric field (Schotty effect)

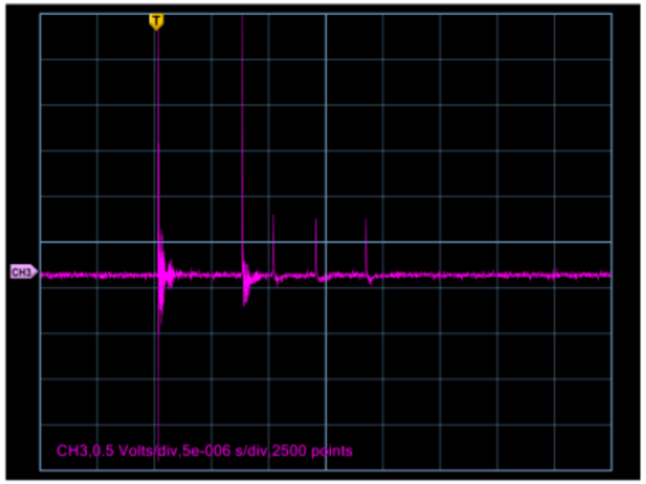
Propagating Discharges



- The development of the precursor current into a streamer which causes a second discharge.


SEM picture of a GEM hole (bottom) after a 2mJ discharge

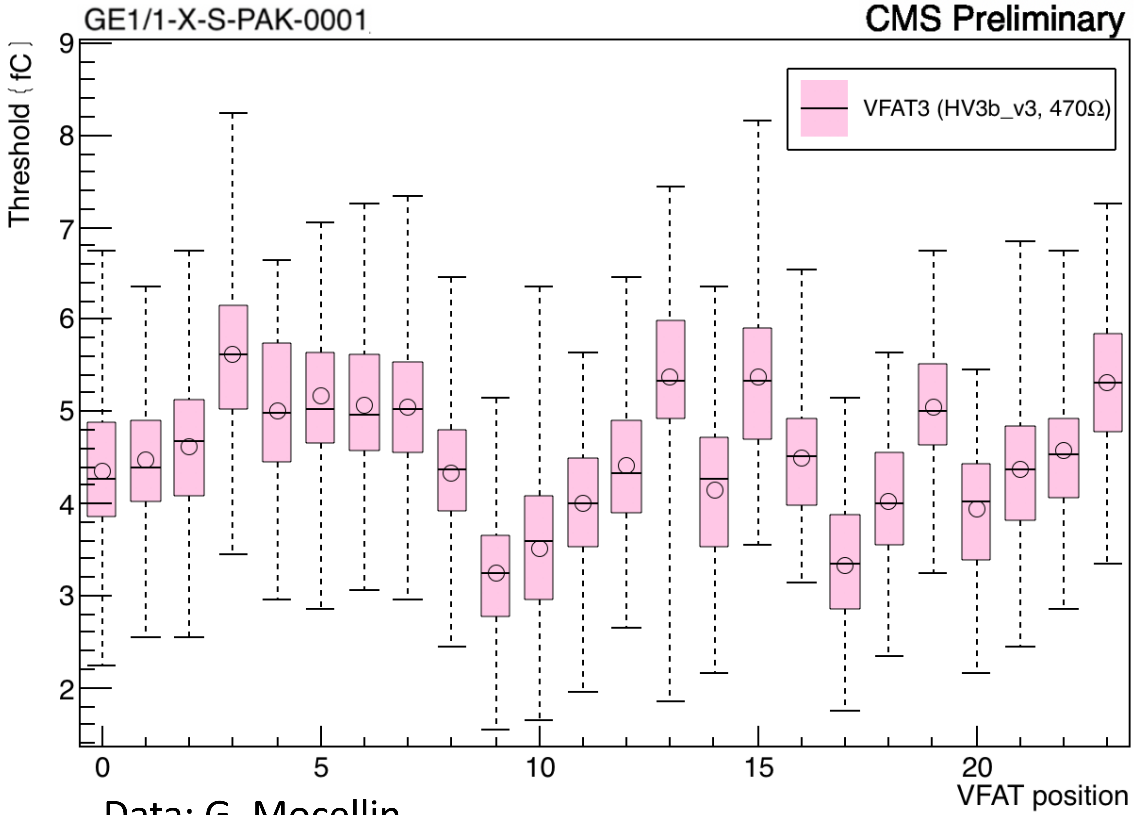

A. Utrobičić et al. (University of Zagreb), MPGD Stability Workshop, June 2018



Typical EM interferences caused by propagating discharges in GEM detectors

Credit: J. A. Merlin

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.

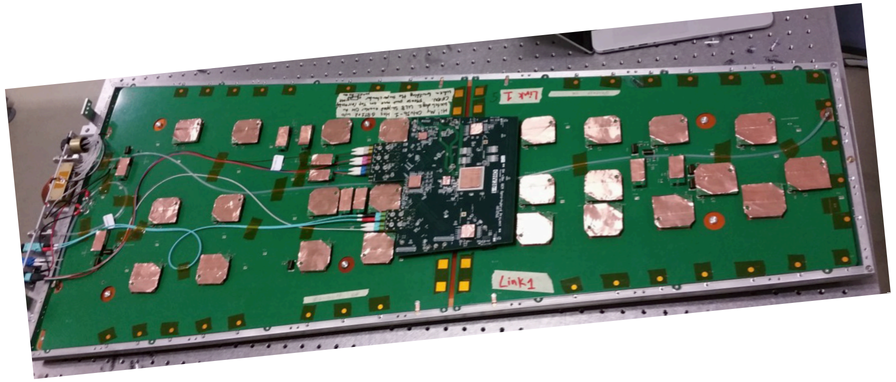
Box plots of the mean (threshold) for the S-Curves of GE1/1-X-S-PAK-0001 QC8 Run 206

Timeline – GE1/1

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

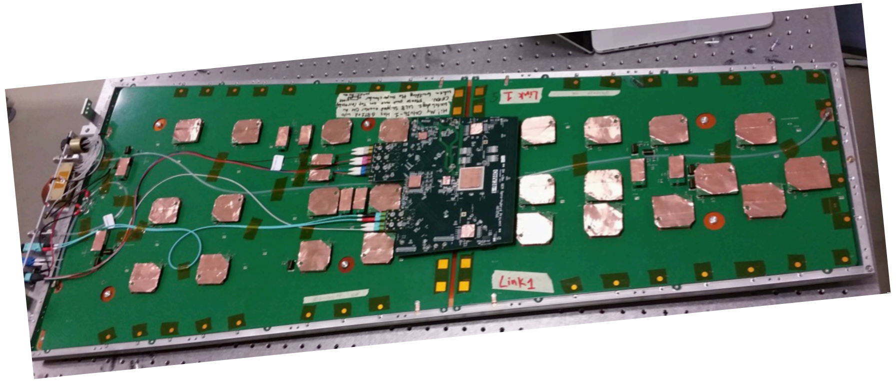
Timeline – GE1/1

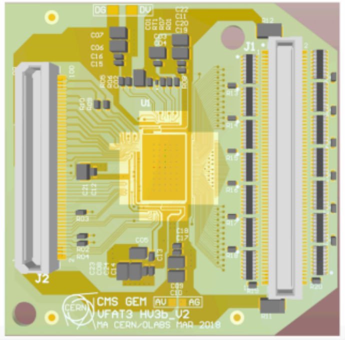
- August 2018: GE1/1 v3c superchamber production begins around the world
- December 2018: All 144 GE1/1 chambers have been produced



Timeline – GE1/1

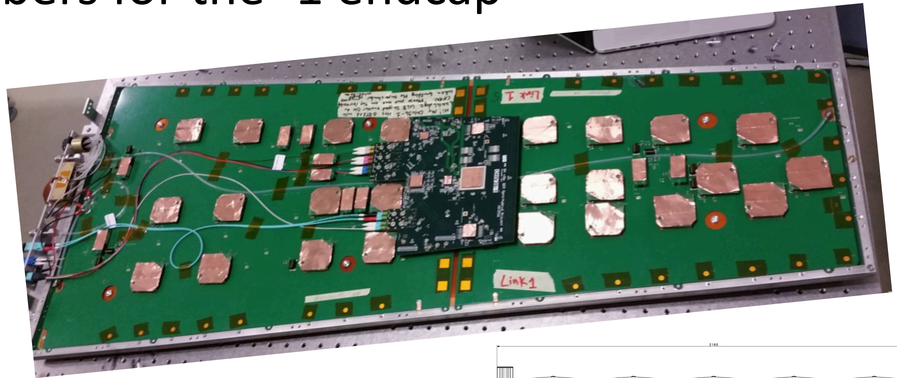
- August 2018: GE1/1 v3c superchamber production begins around the world
- December 2018: All 144 GE1/1 chambers have been produced
- January 2019: HV3b_v3 470 Ω is chosen as the final GE1/1 VFAT design

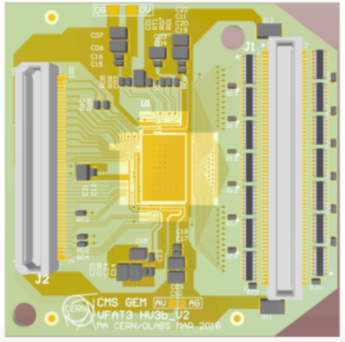


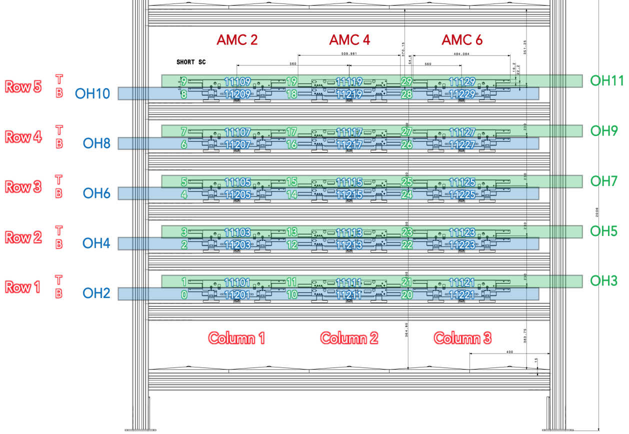


Timeline – GE1/1

- August 2018: GE1/1 v3c superchamber production begins around the world
- December 2018: All 144 GE1/1 chambers have been produced
- 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

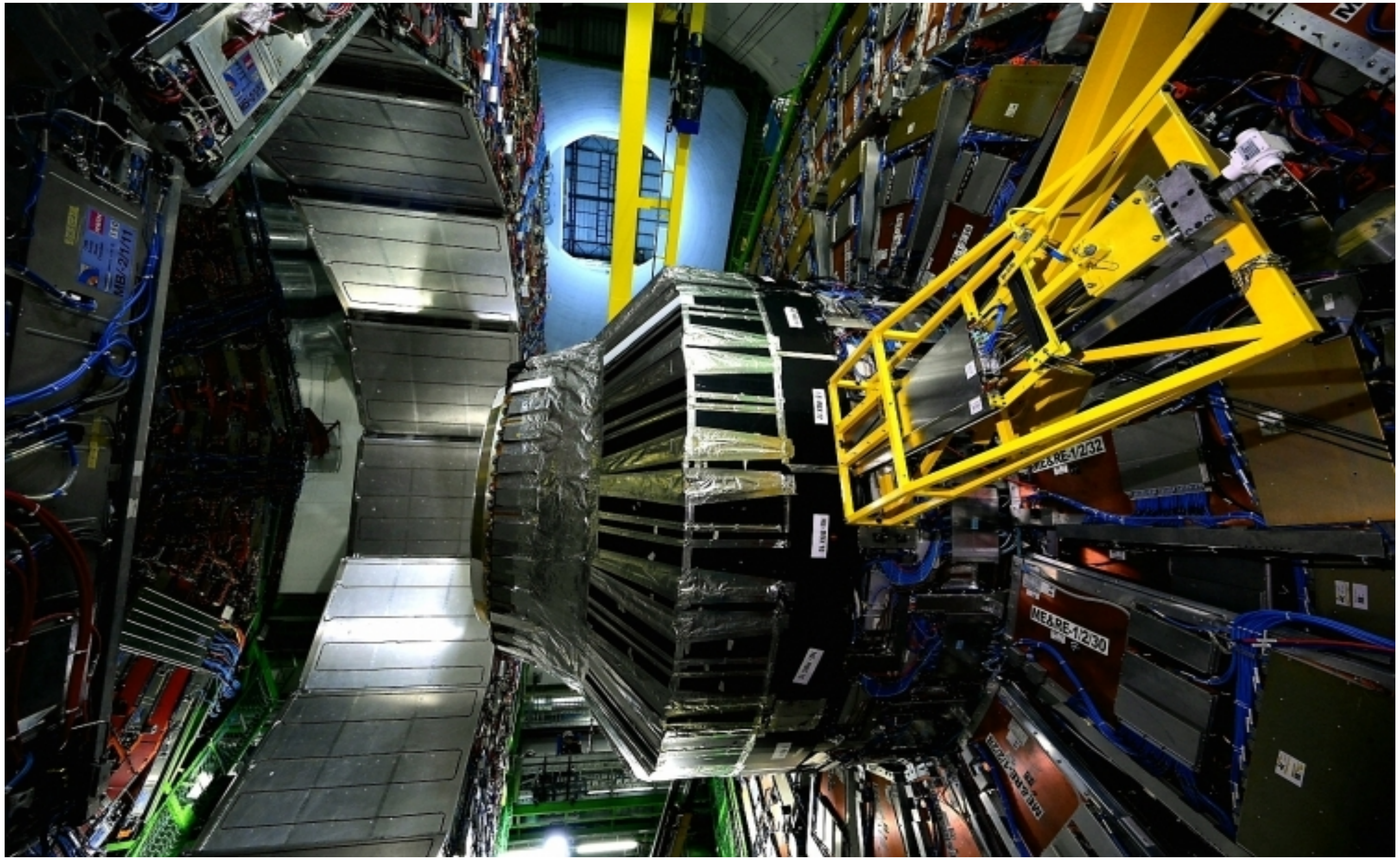


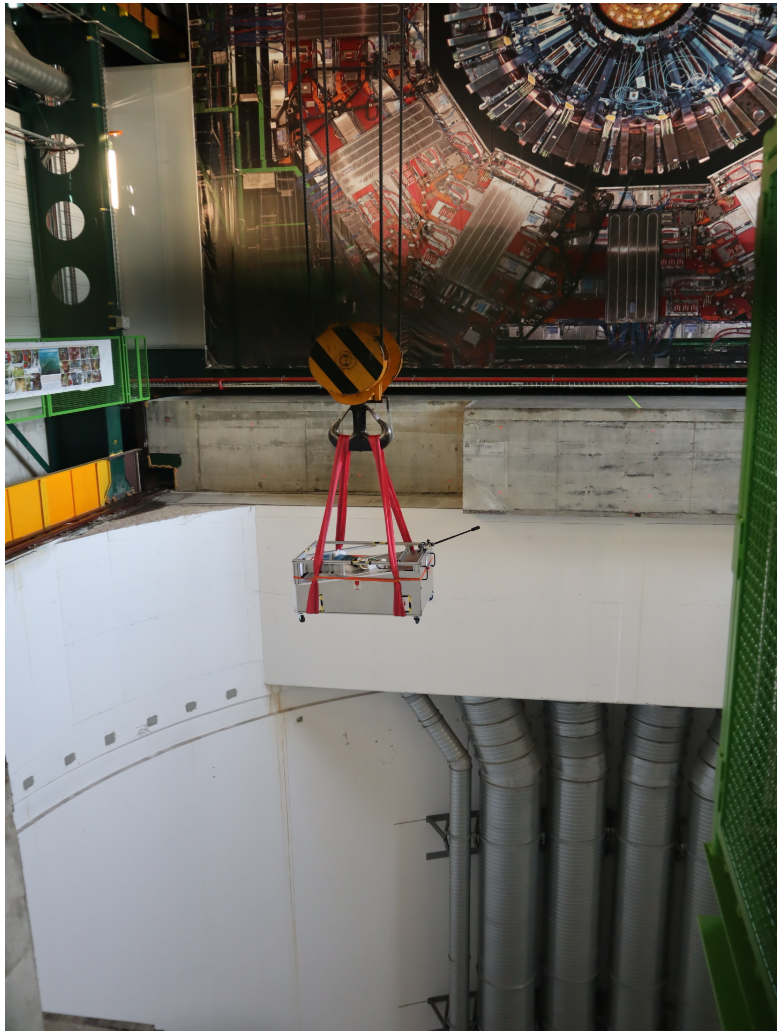




Timeline – GE1/1

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

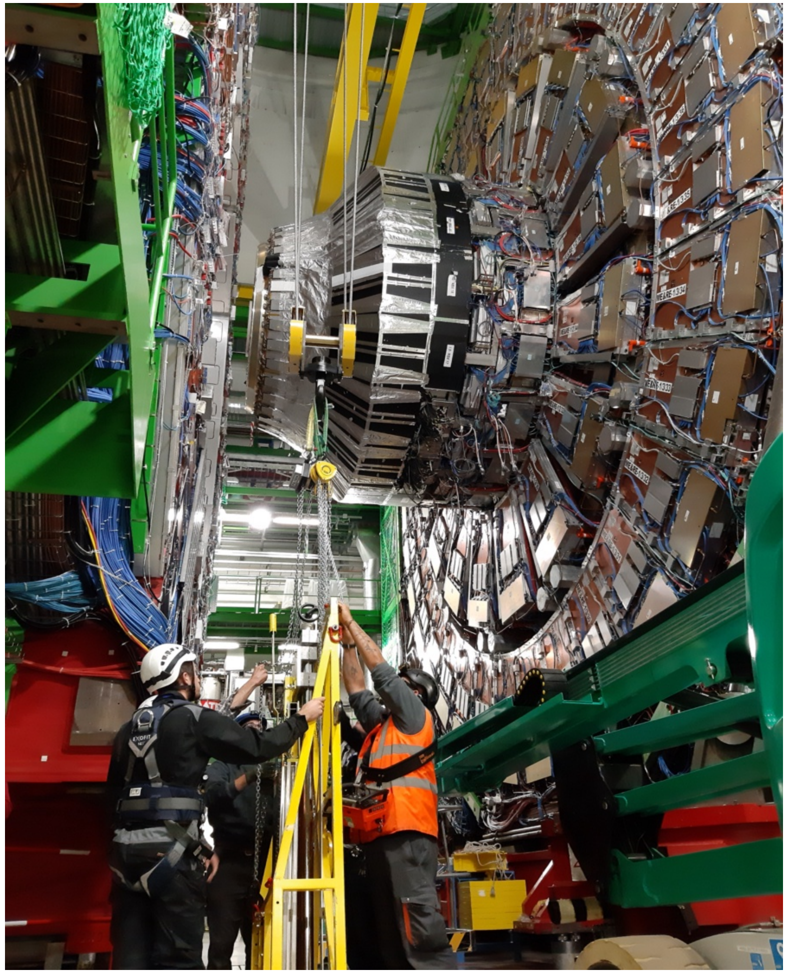




See photo essay: https://cms.cern/news/first-gems-installation

Timeline – GE1/1

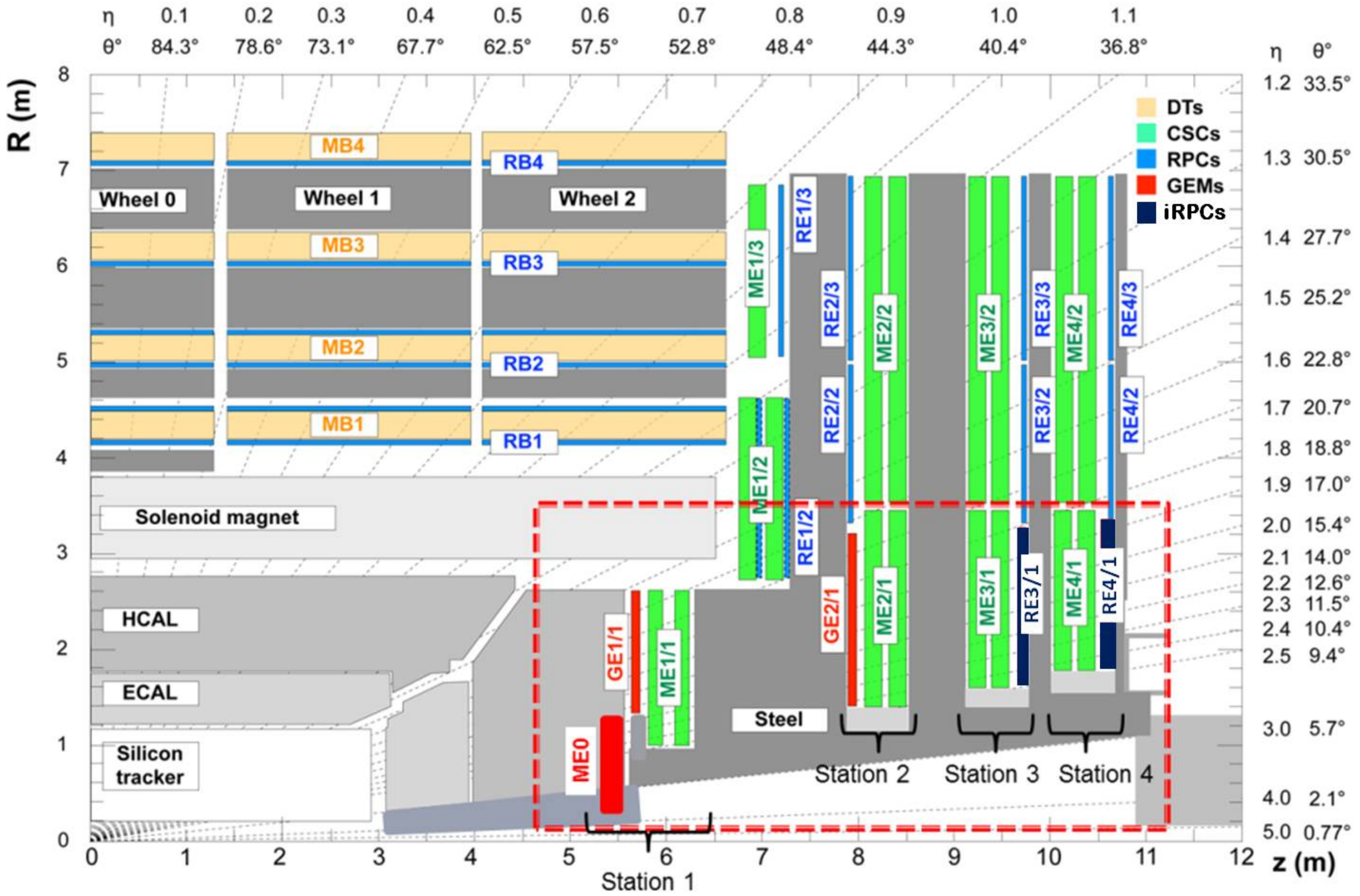
- October 24th, 2019: Installation of the YE-1 endcap is completed! Commissioning now begins…



See news update: https://cms.cern/news/cms-continues-shine-new-gems

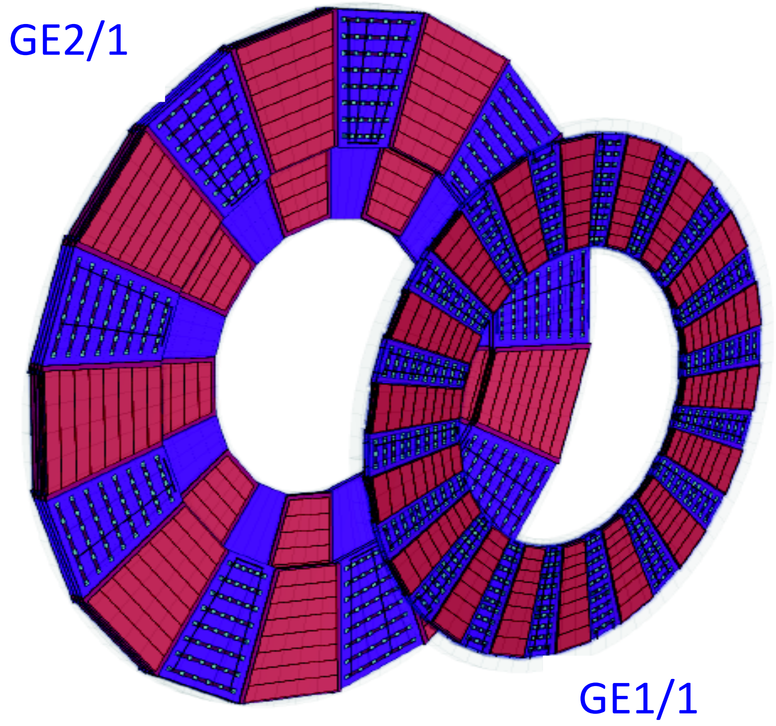
Future CMS GEM Systems

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

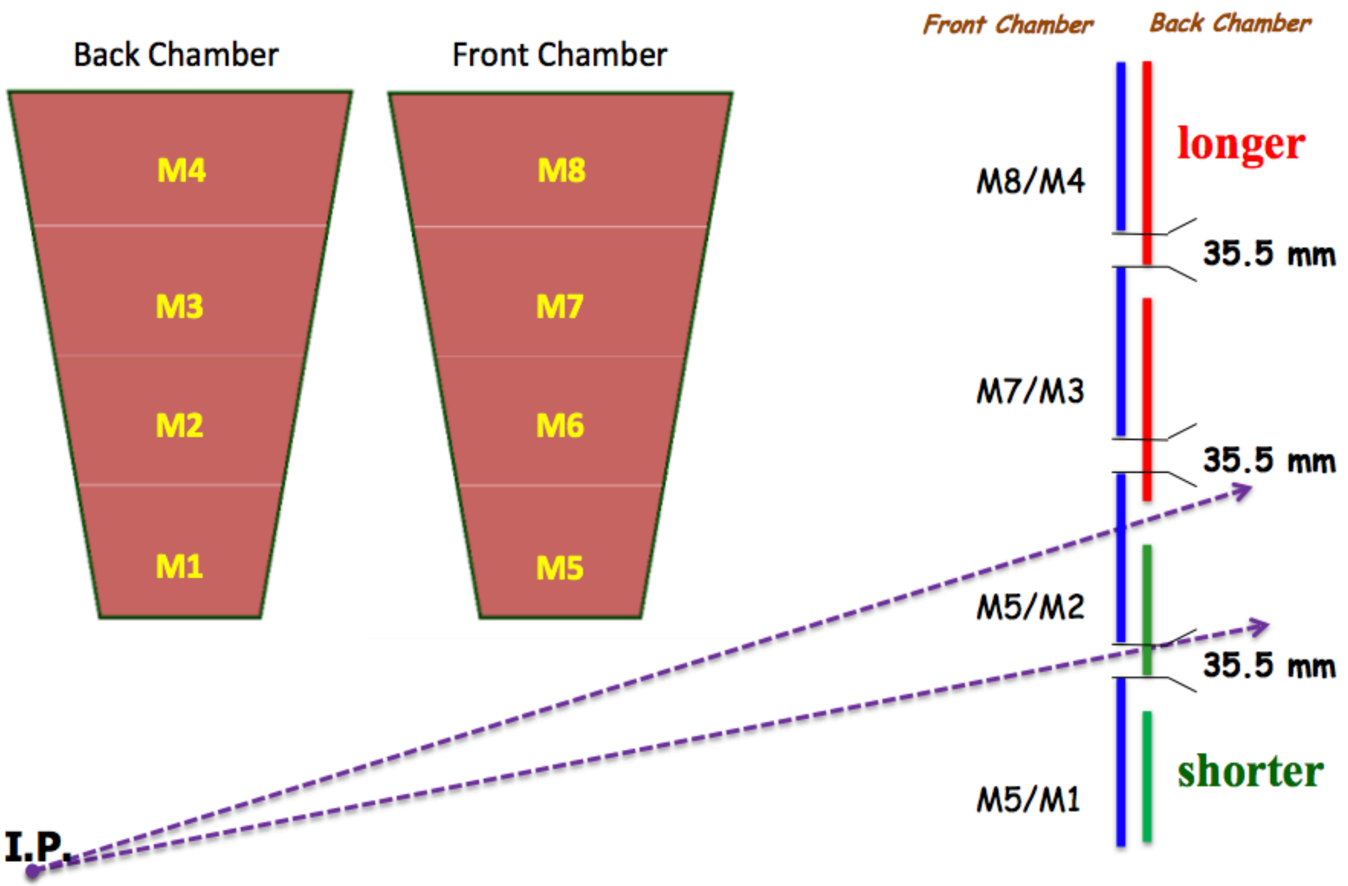


GE2/1

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



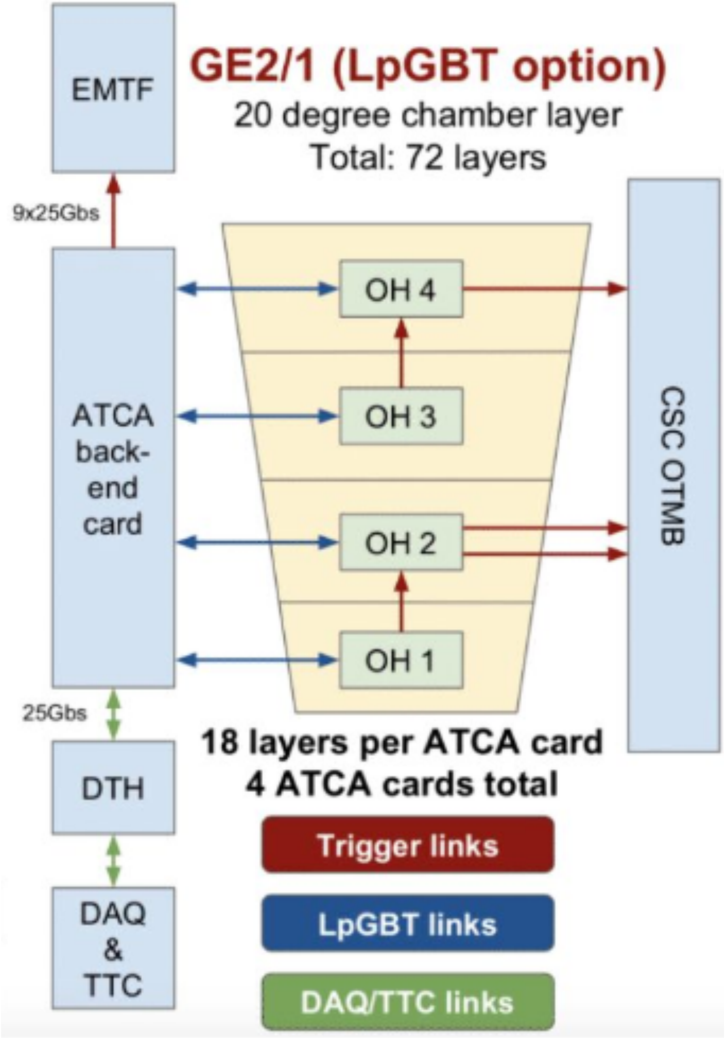
GE2/1 Superchamber



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



GE2/1 (LpGBT option)

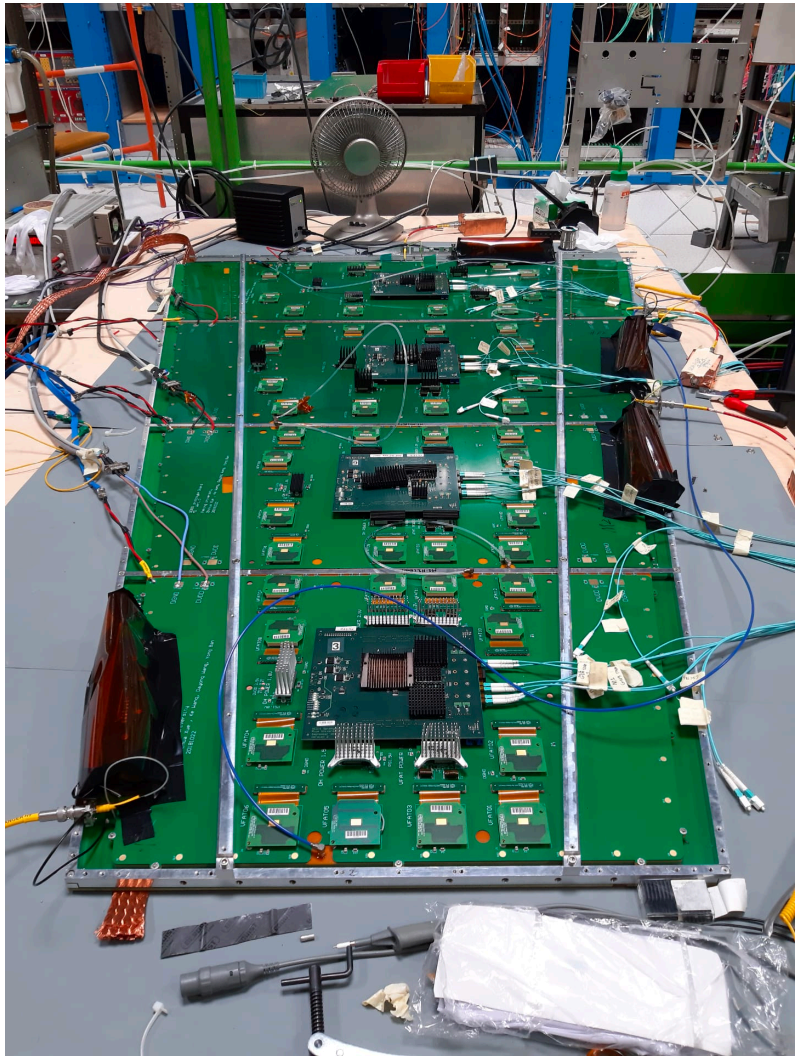
20 degree chamber layer

Total: 72 layers

18 layers per ATCA card

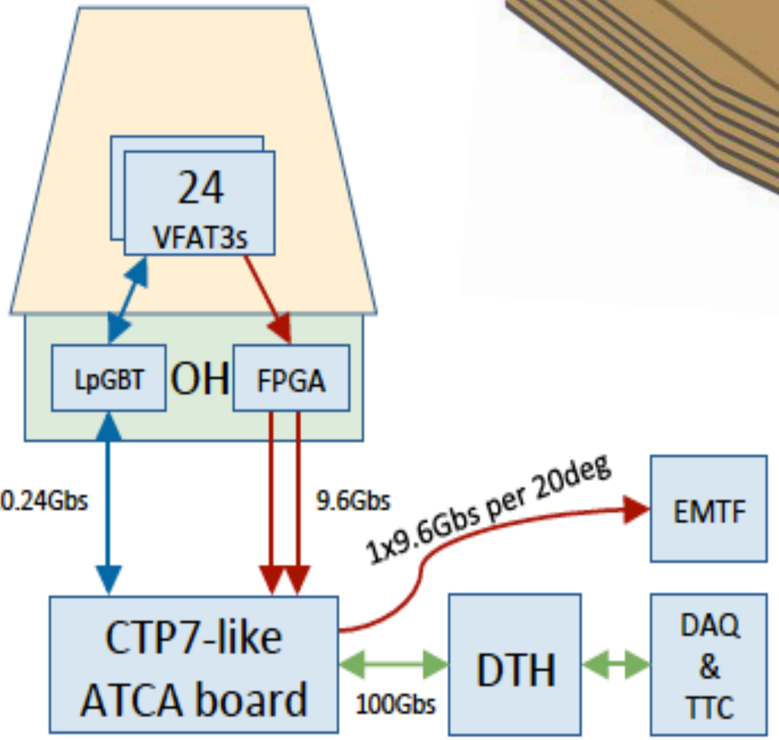
4 ATCA cards total

- 🟥 Trigger links
- 🟦 LpGBT links
- 🟩 DAQ/TTC links

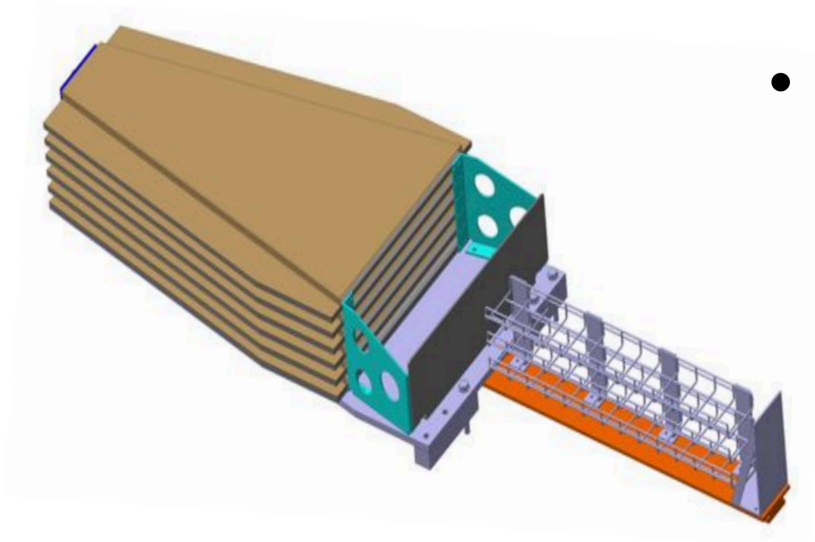


ME0: Very-Forward Muon Tagger

ME0
20 degree layer
Total: 216 layers



12 CTP7s total: 1 board per 60deg



- 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