GEM Detectors for the CMS Endcap Muon System: status of three detector stations

Yanwen Hong

on behalf of the CMS Muon Group

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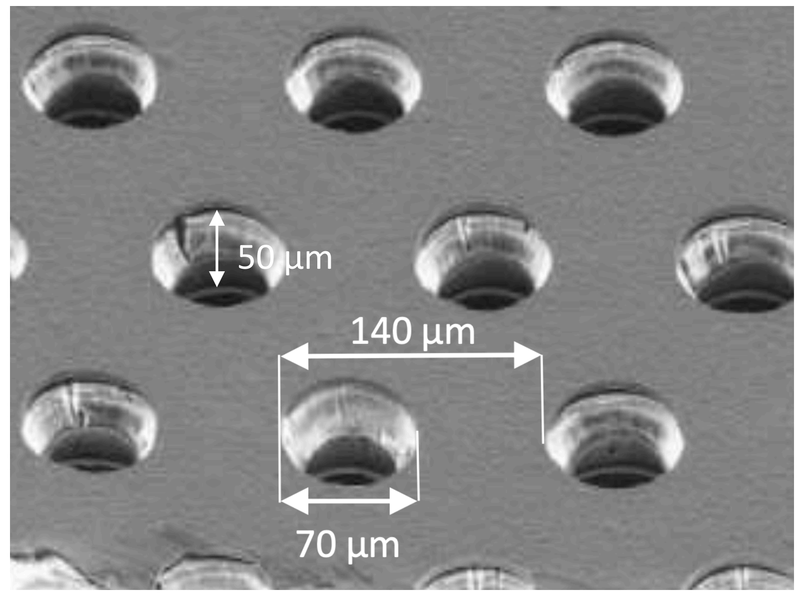
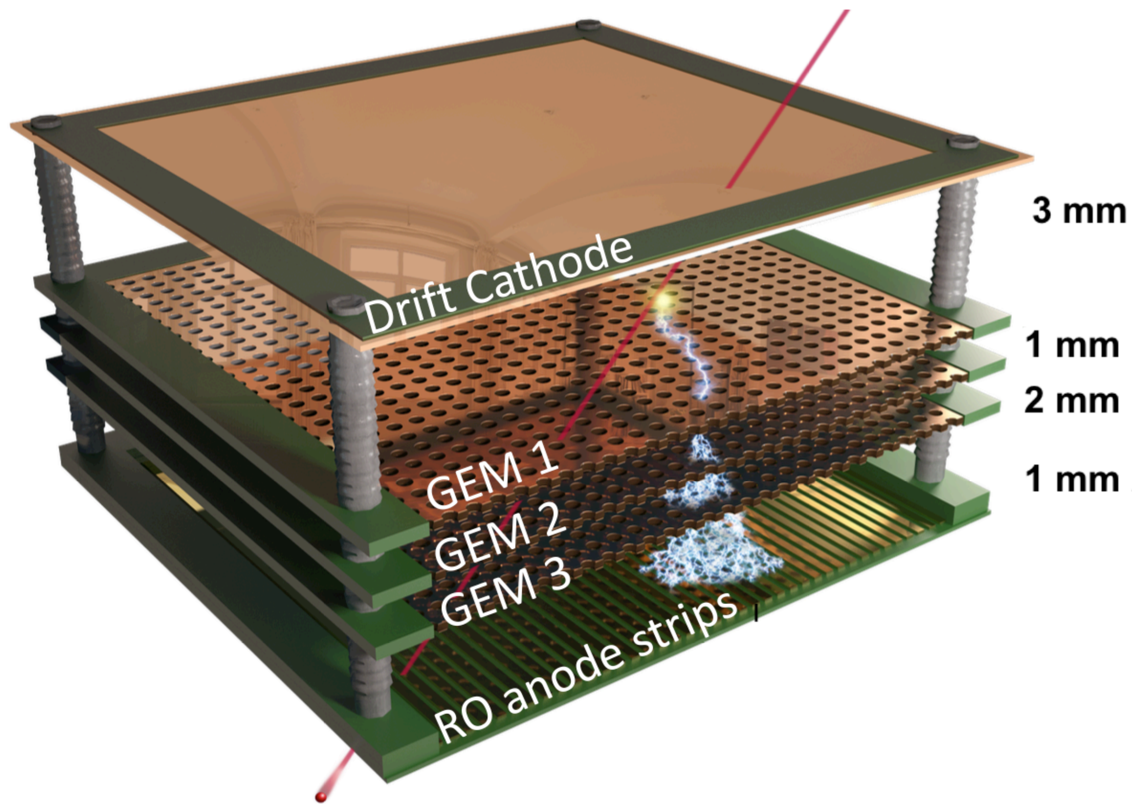
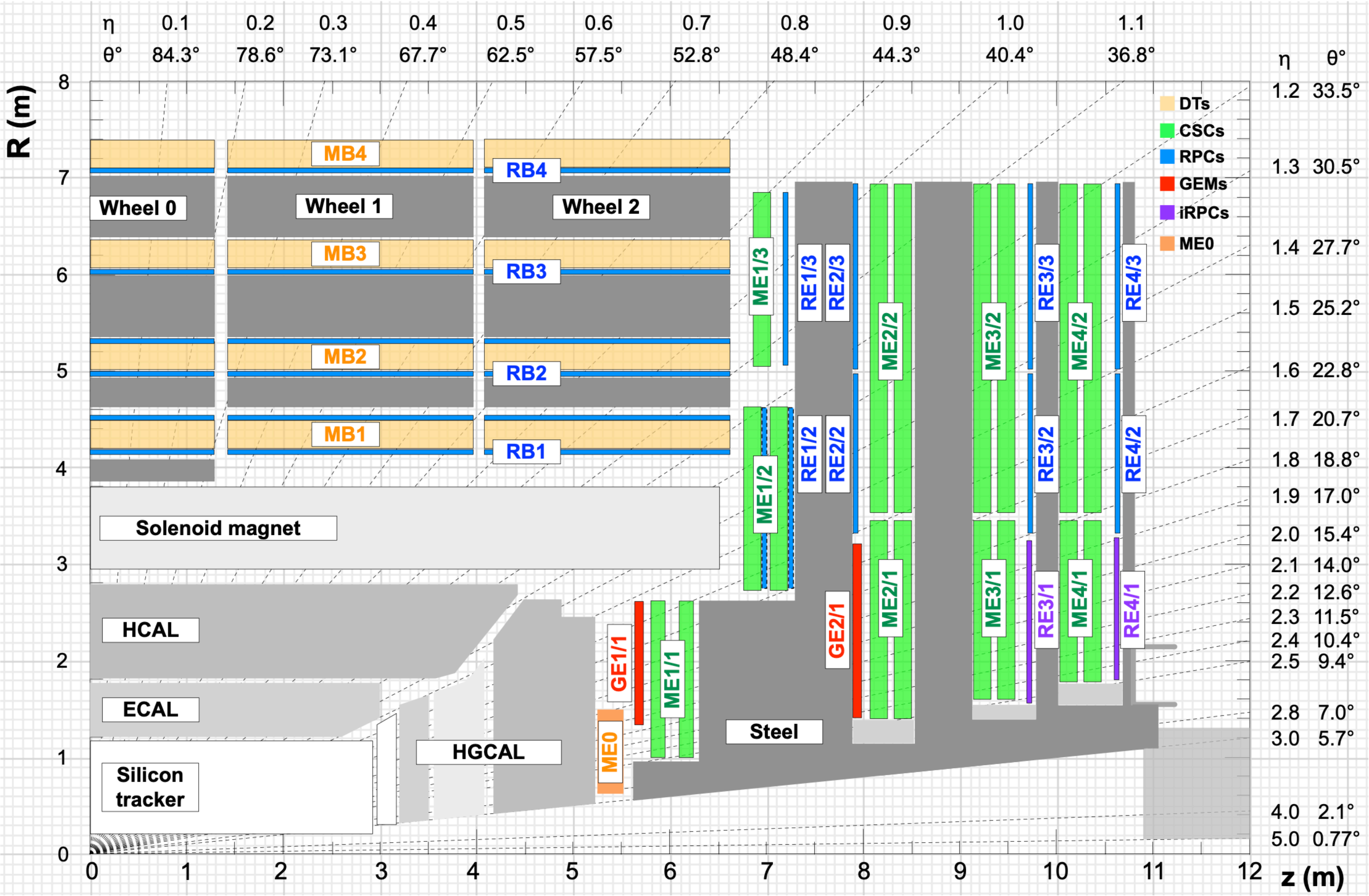
The CMS GEM Project

- Triple GEM technology, 3/1/2/1 configuration.
- To cope with High Luminosity-LHC environment, which will deliver proton-proton collisions at 5-7.5 times the nominal LHC luminosity.







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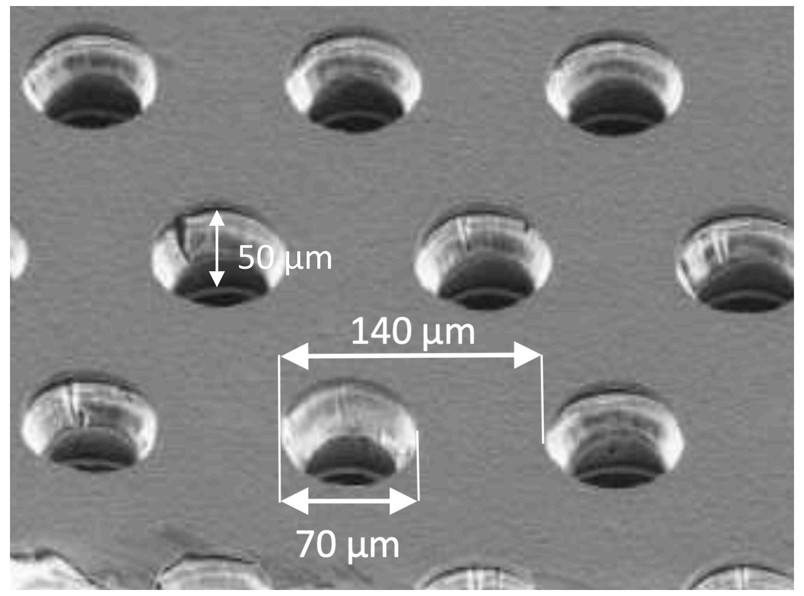

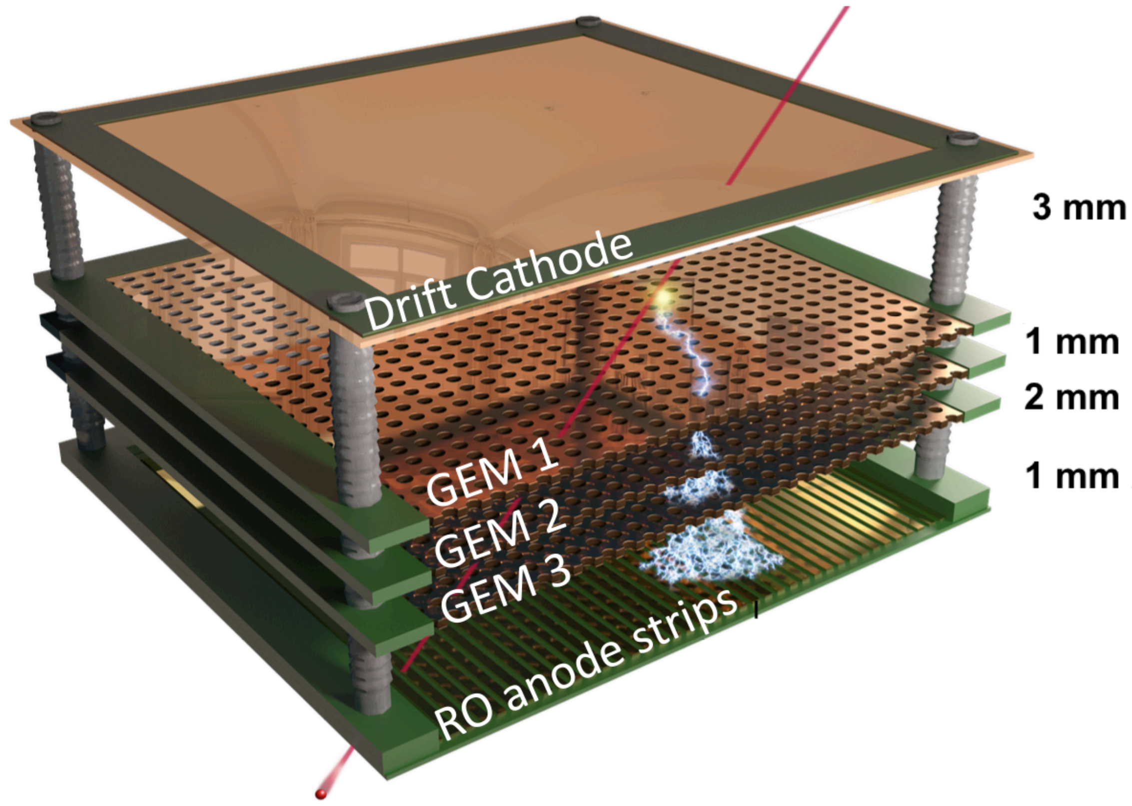

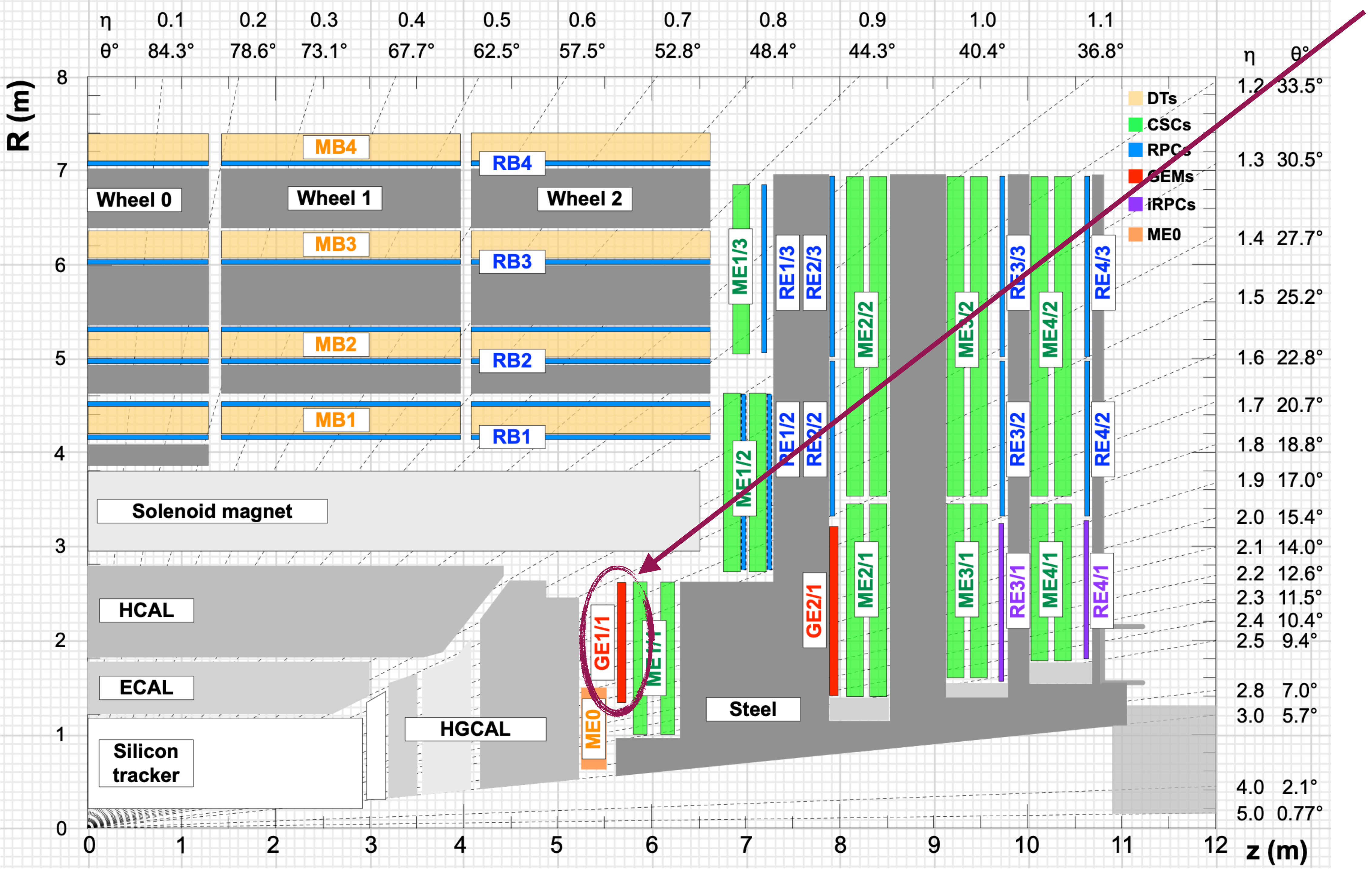

Phase-1 upgrade : GE1/1

- $1.55 < |\eta| < 2.18$
- 36 staggered chambers per endcap, each chamber spans 10°
- Installed in 2019-2021, recording LHC Run-3 data since 2022

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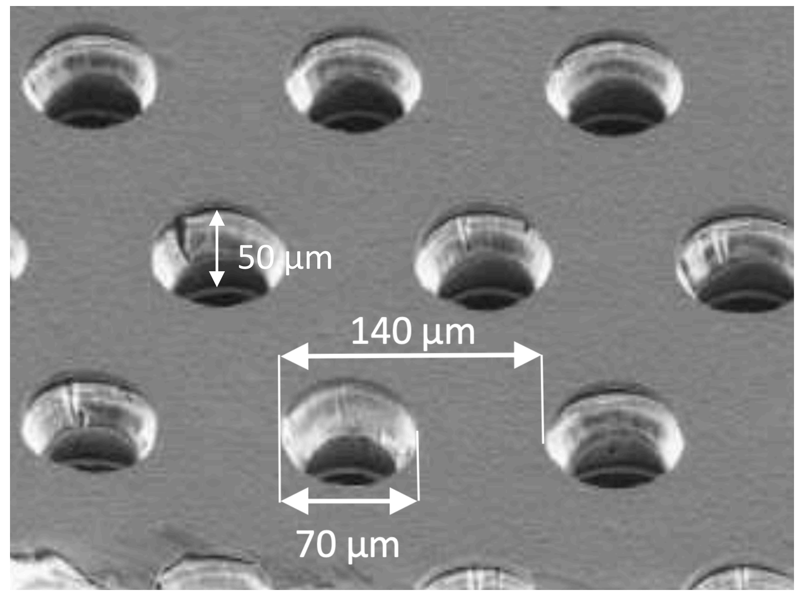

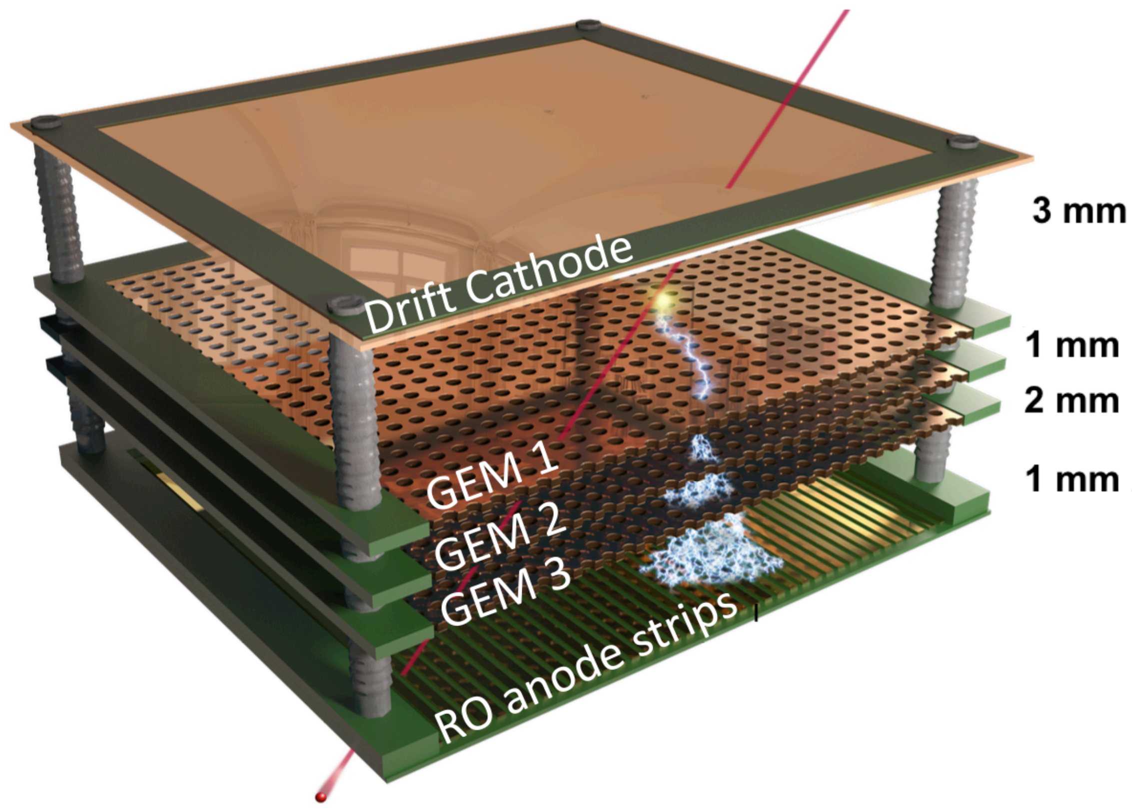

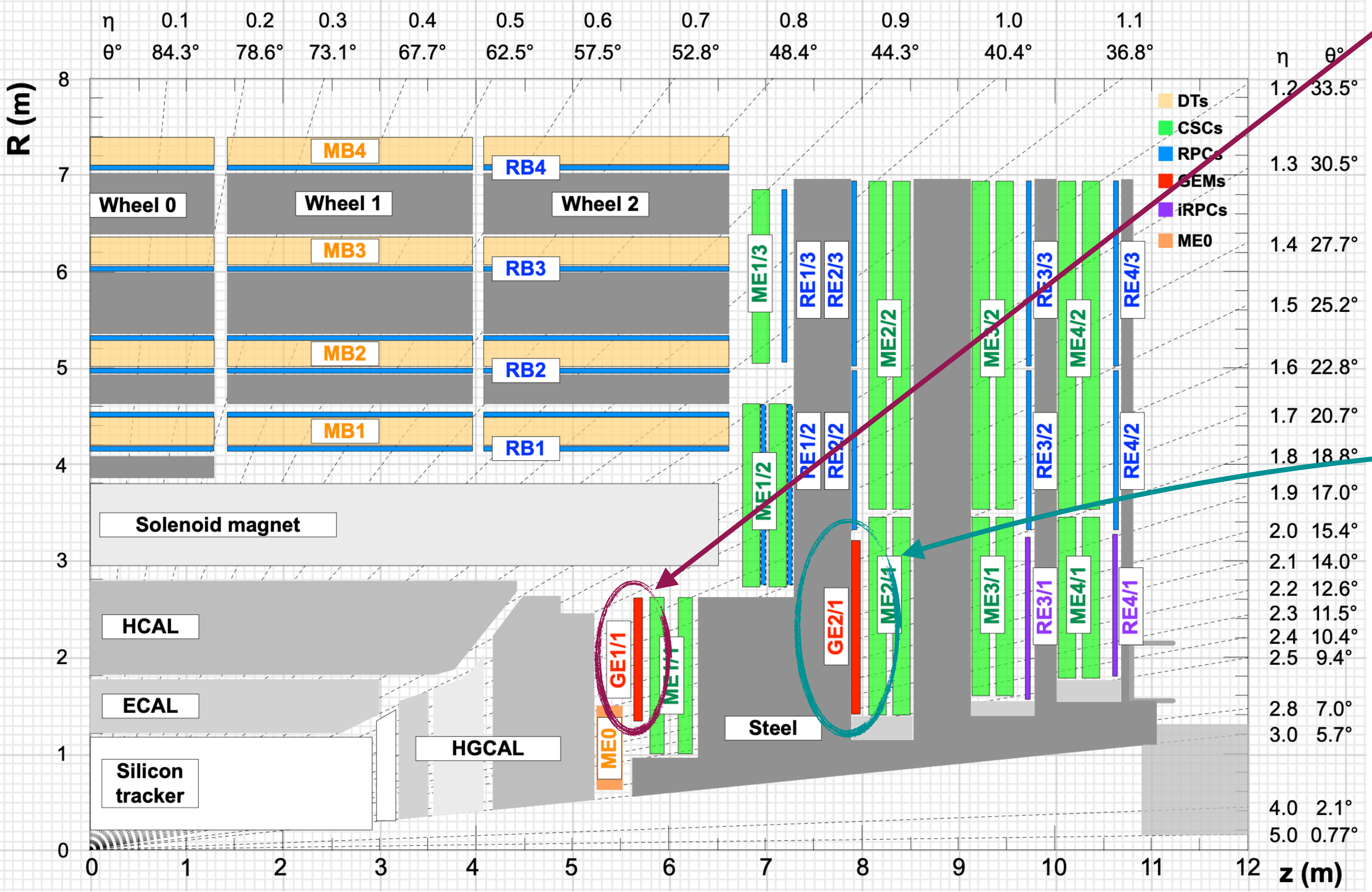

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- $1.55 < |\eta| < 2.45$
- 18 staggered chambers per endcap, each chamber spans 20°
- Few chambers installed, fully installation: after LS3

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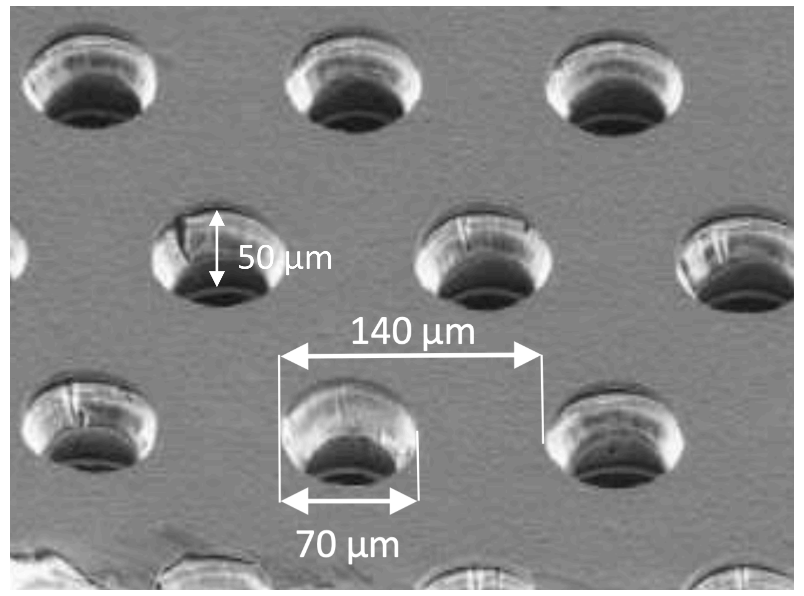

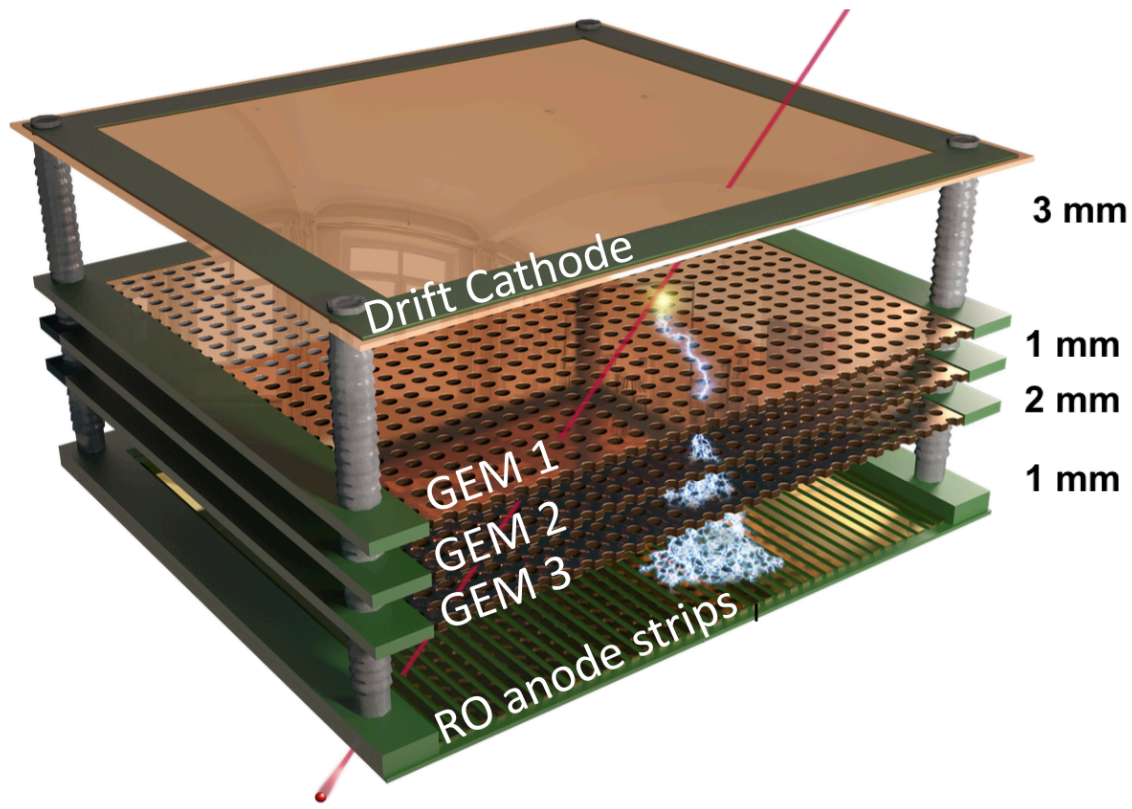

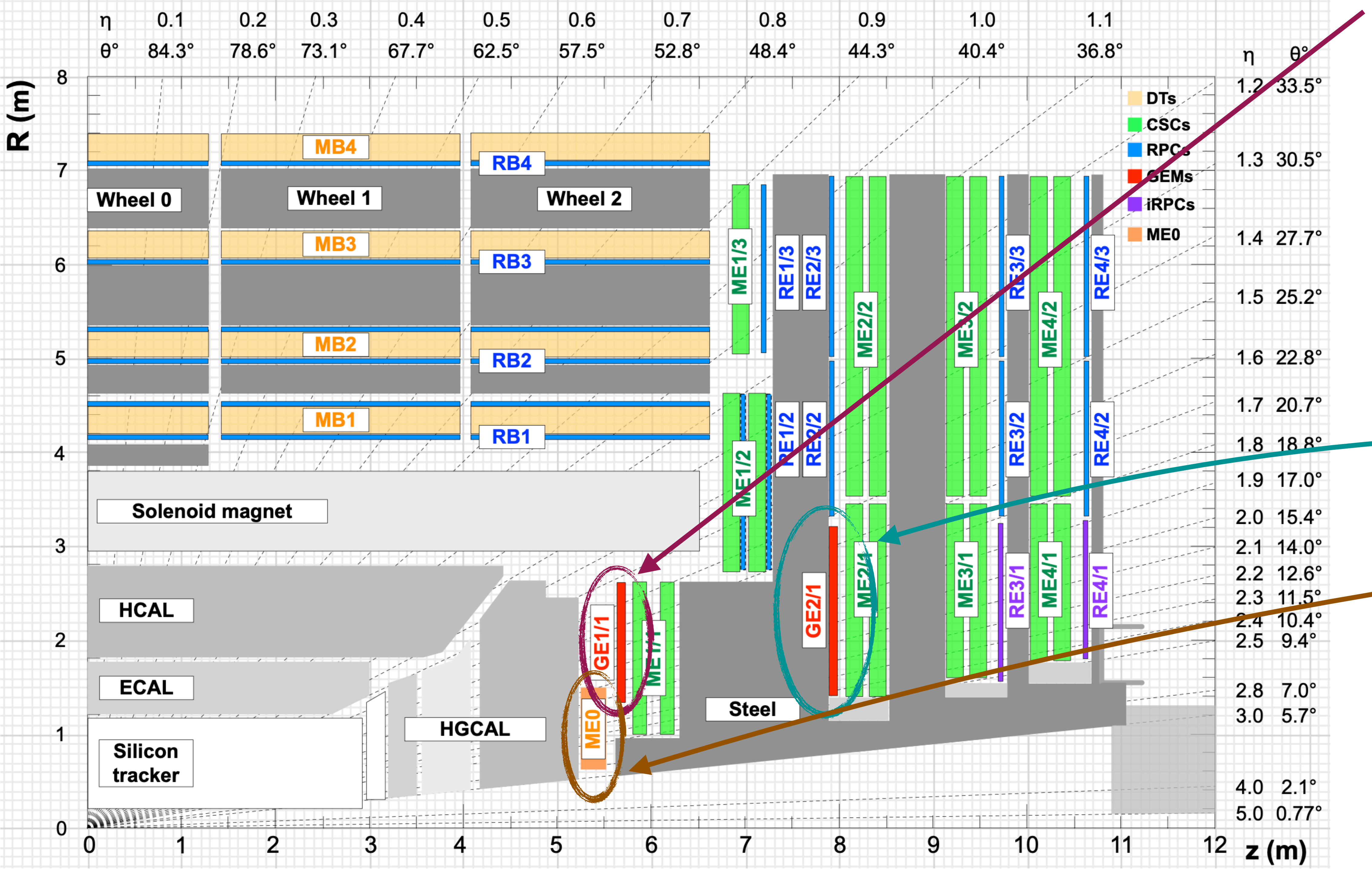

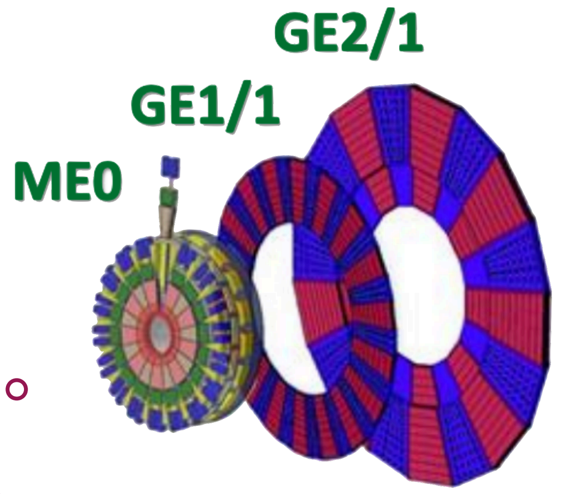

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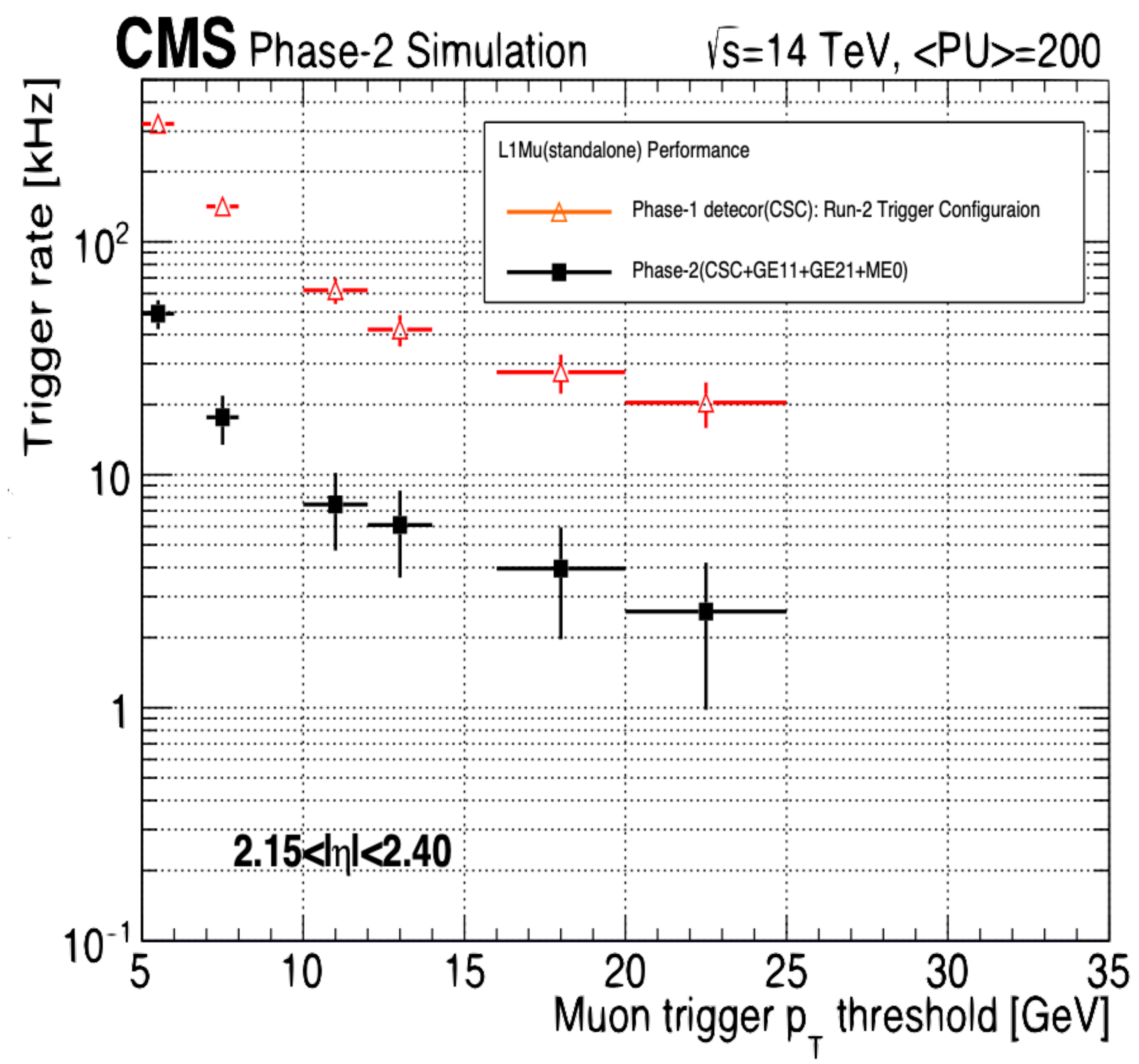
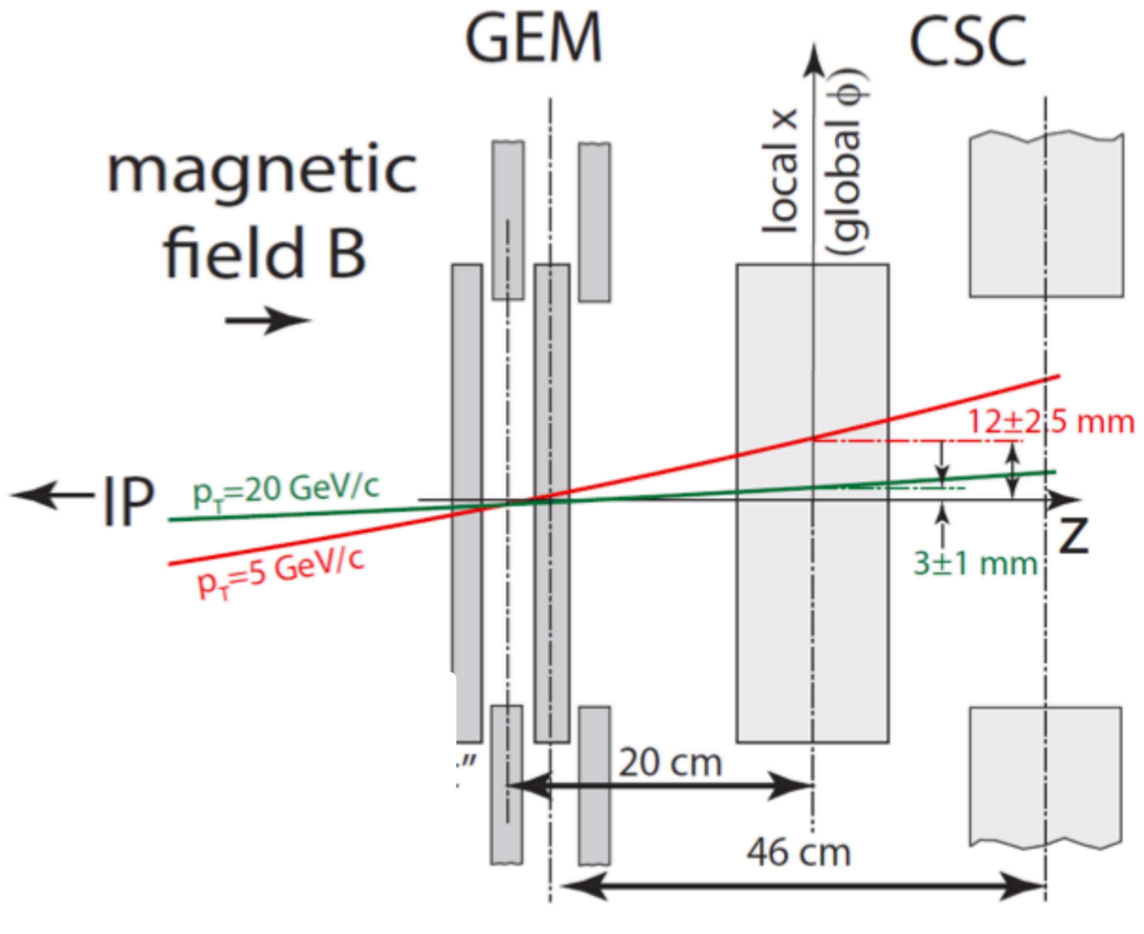
- Few chambers installed, fully installation: after LS3

- the only Muon station at the highest η: 2.0 < |η| < 2.8.
- 6 layers of Triple-GEM, each chamber spans 20°
- Installation: LS3 (2027)

Objectives & Specifications

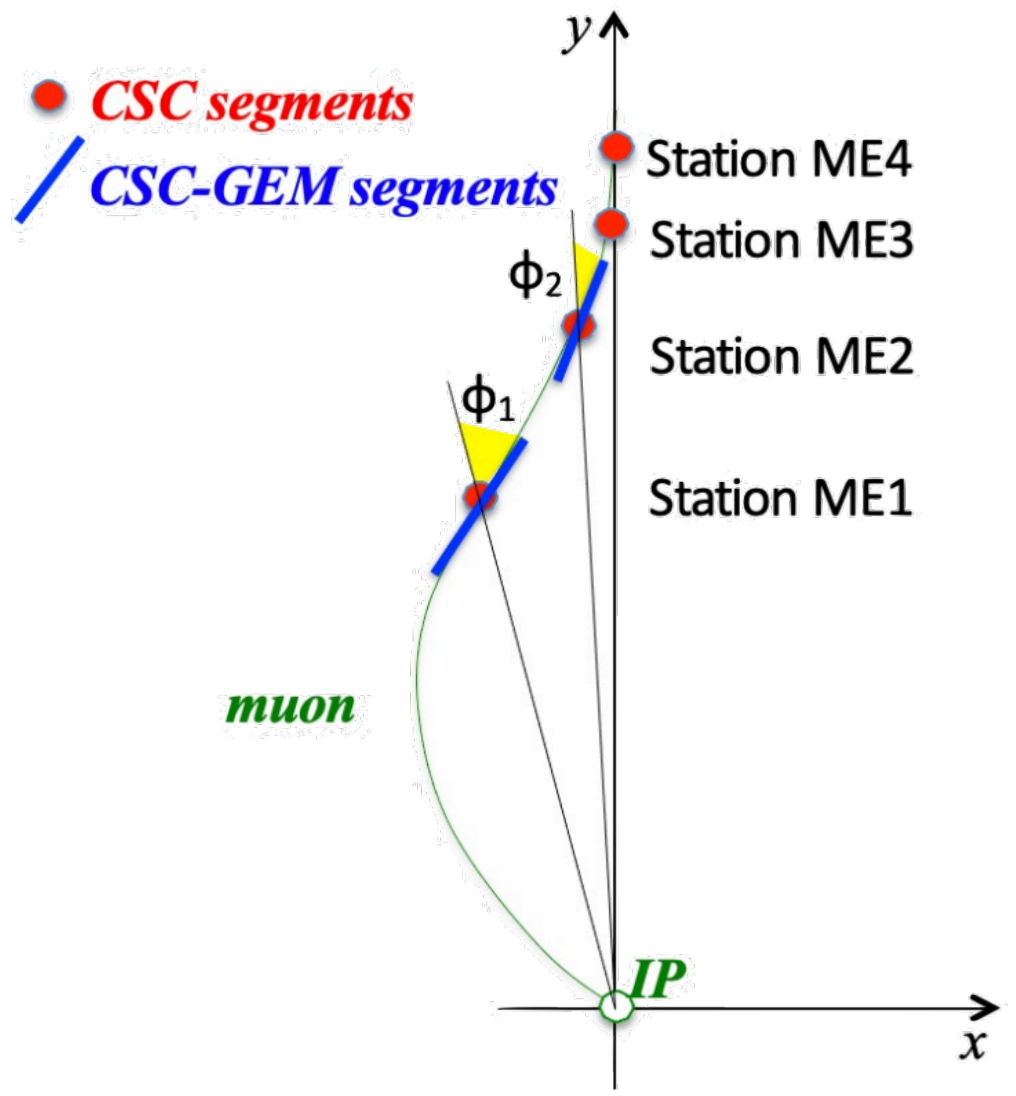
- To improve muon tracking and triggering performance in the most forward region of the CMS muon spectrometer.
- With ME0: extend the muon coverage beyond η = 2.4.





GE1/1 + GE2/1

CONCEPT
(axial view)



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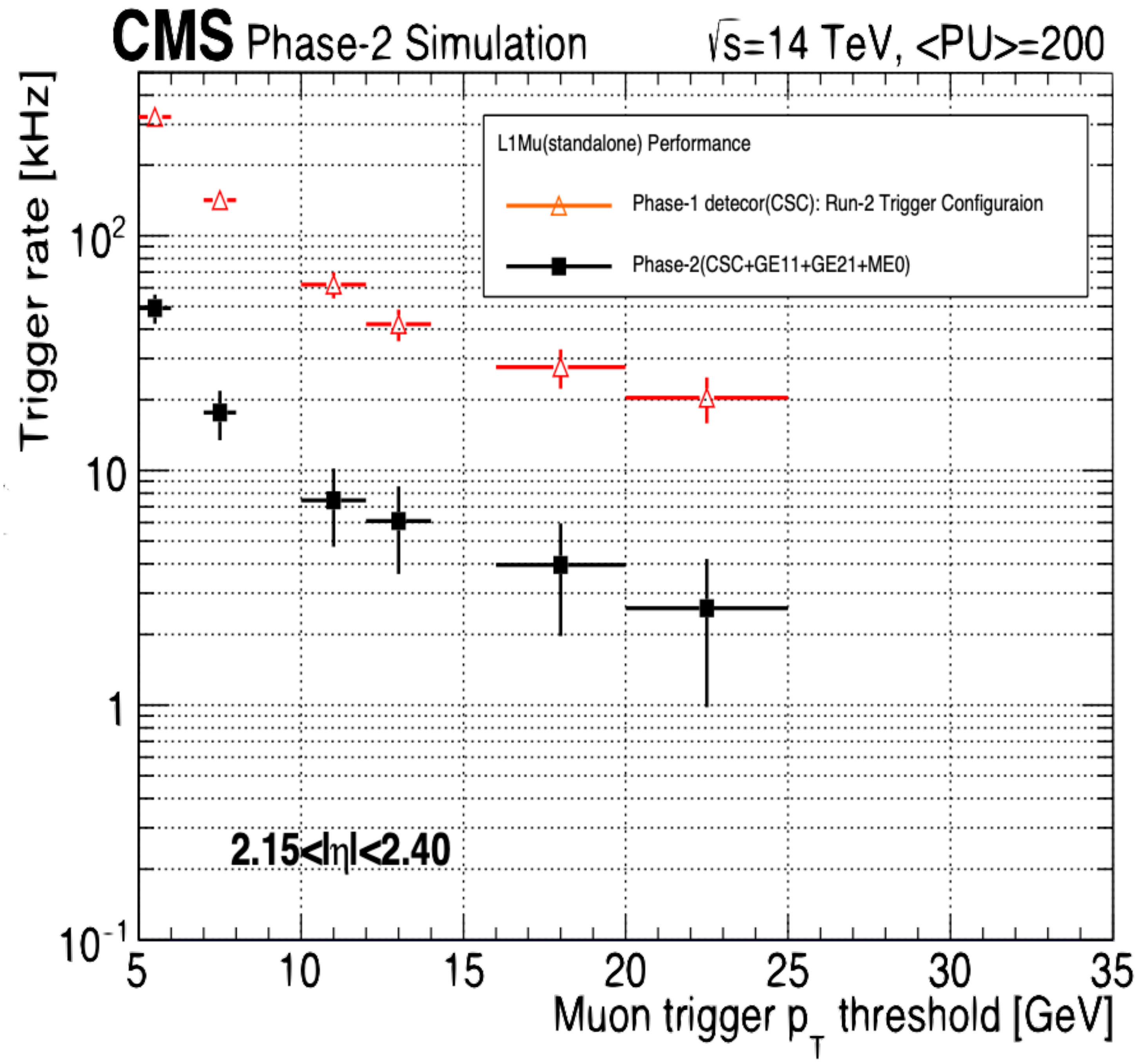

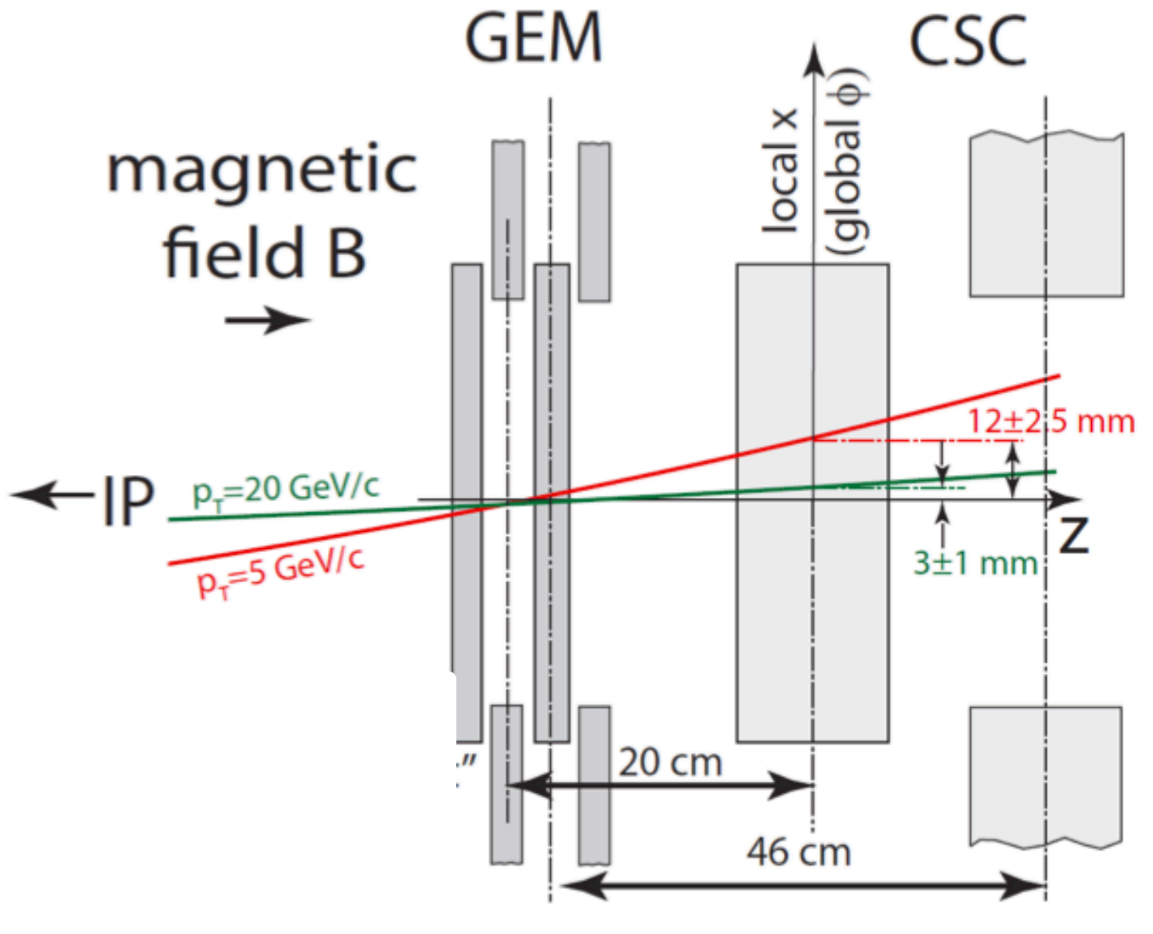

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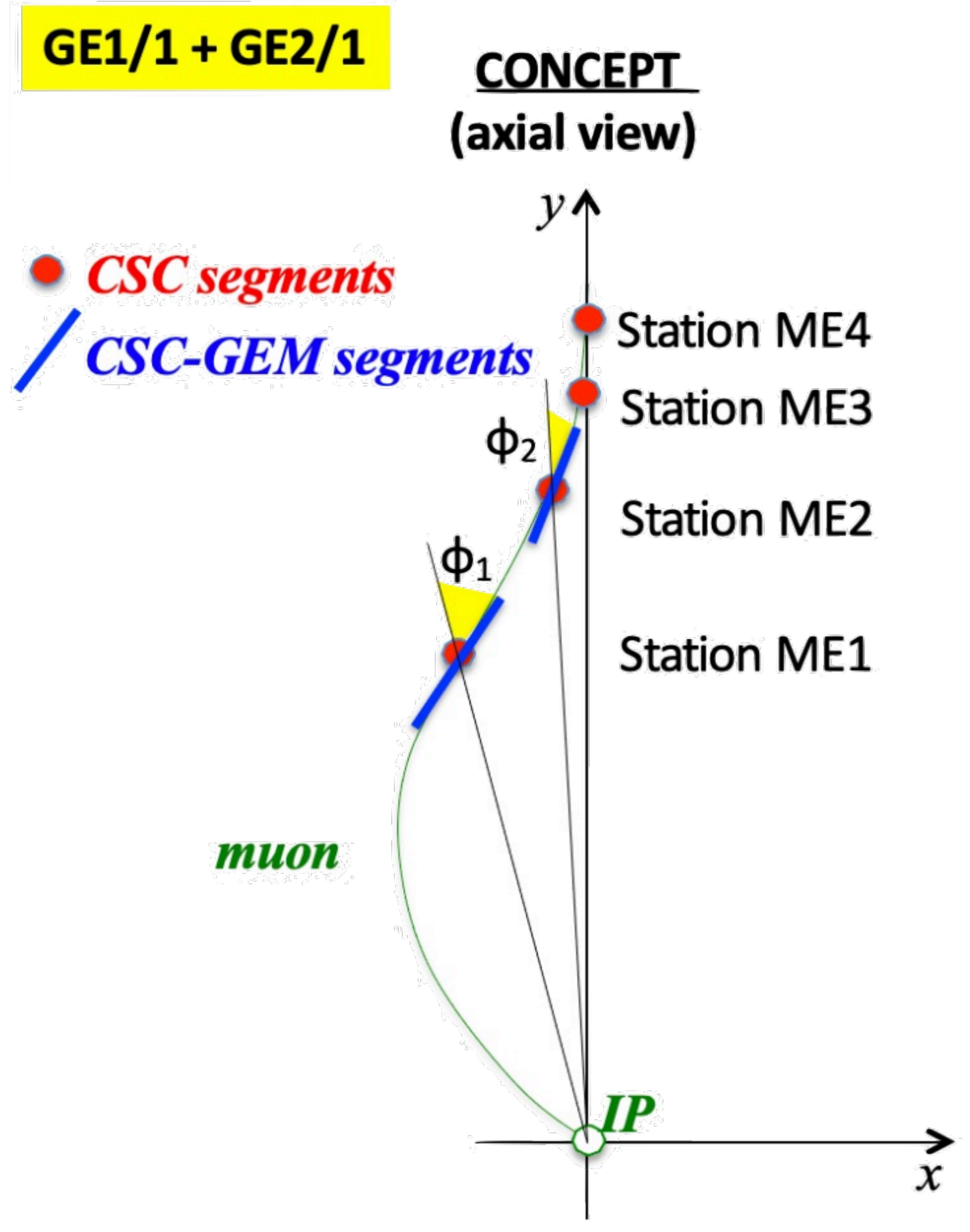
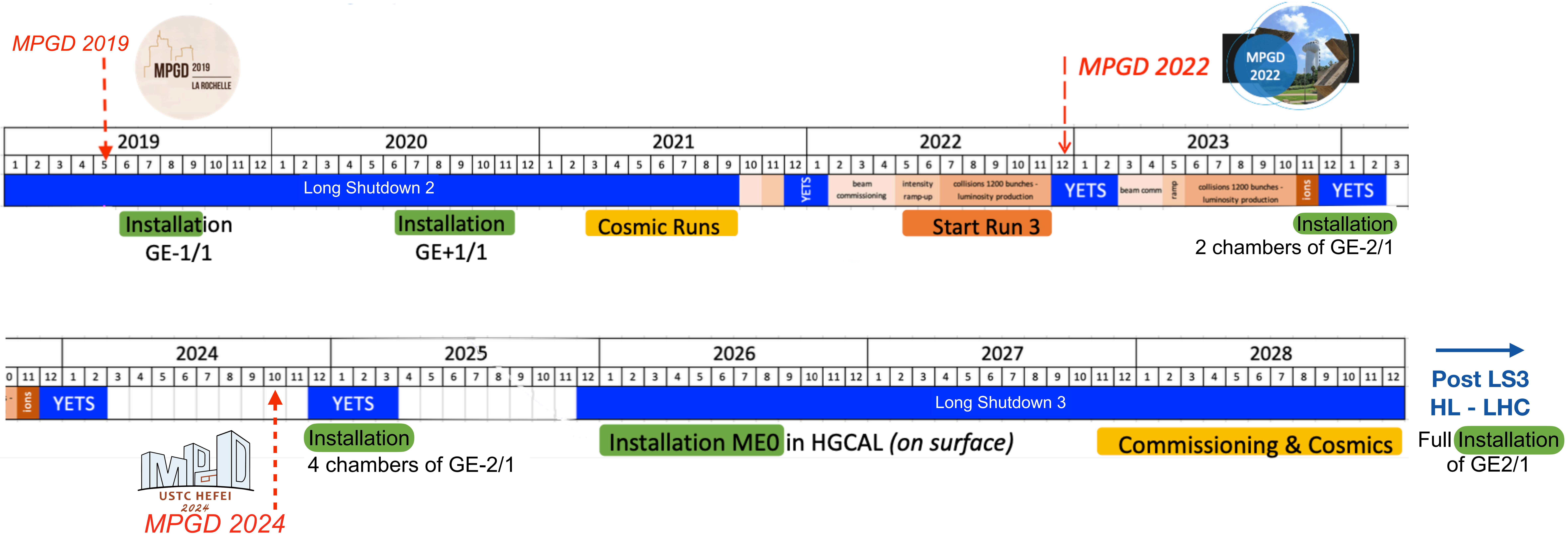


- GE1/1 specifications
  - Particle rate: a few kHz/cm²
  - Spatial resolution: better than 300 μradian
  - Time resolution per chamber: 8-10 ns
  - Good longevity.

GEMs Project Timeline



MPGD 2019

Long Shutdown 2

Installation GE-1/1

Installation GE+1/1

Cosmic Runs

Start Run 3

MPGD 2022

Installation 2 chambers of GE-2/1

Installation 4 chambers of GE-2/1

Installation ME0 in HGCAL *(on surface)*

Long Shutdown 3

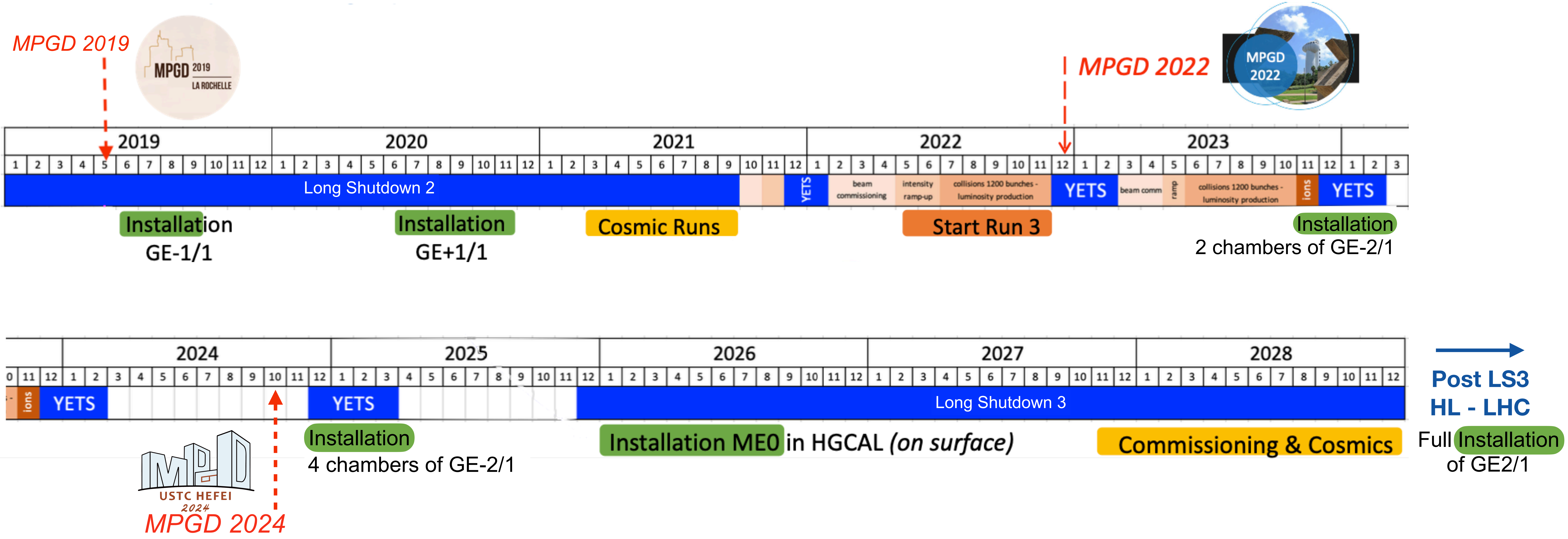
Commissioning & Cosmics

Post LS3 HL - LHC

Full Installation of GE2/1

MPGD 2024

GEMs Project Timeline



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Long Shutdown 2

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Installation
GE+1/1

Cosmic Runs

Start Run 3

Installation
2 chambers of GE-2/1

MPGD 2024

Installation
4 chambers of GE-2/1

Long Shutdown 3

Installation ME0 in HGCAL *(on surface)*

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Full Installation
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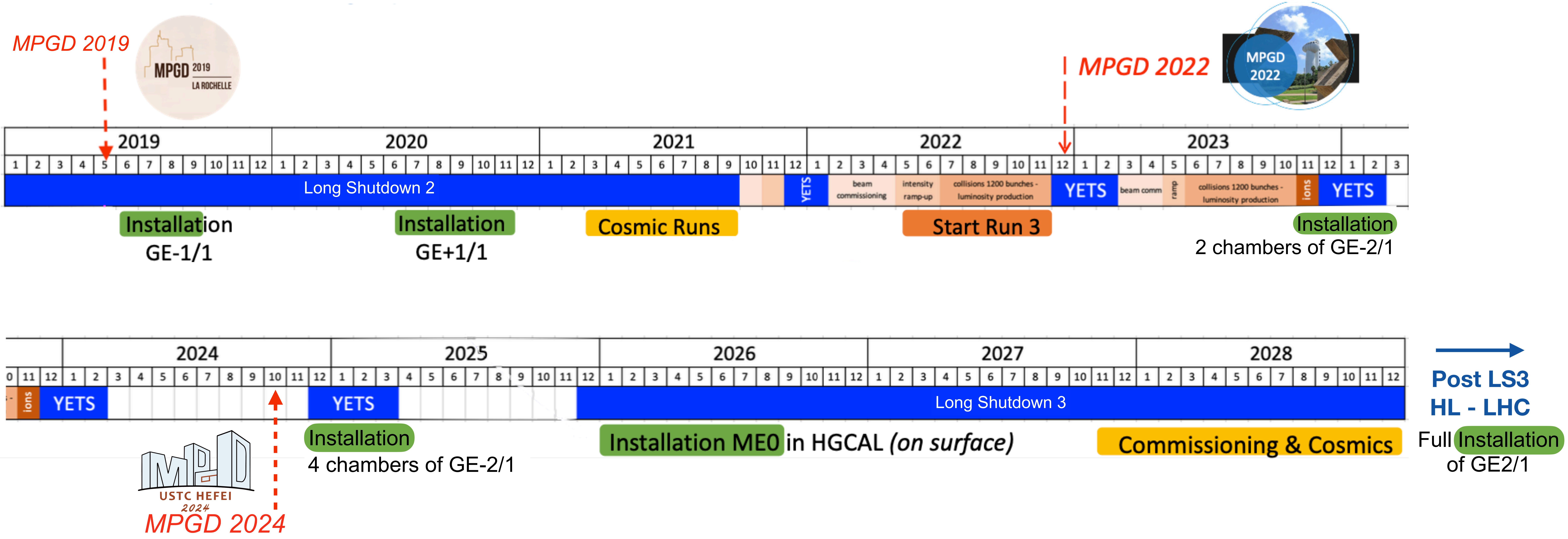
Today's Outline

GEMs Project Timeline



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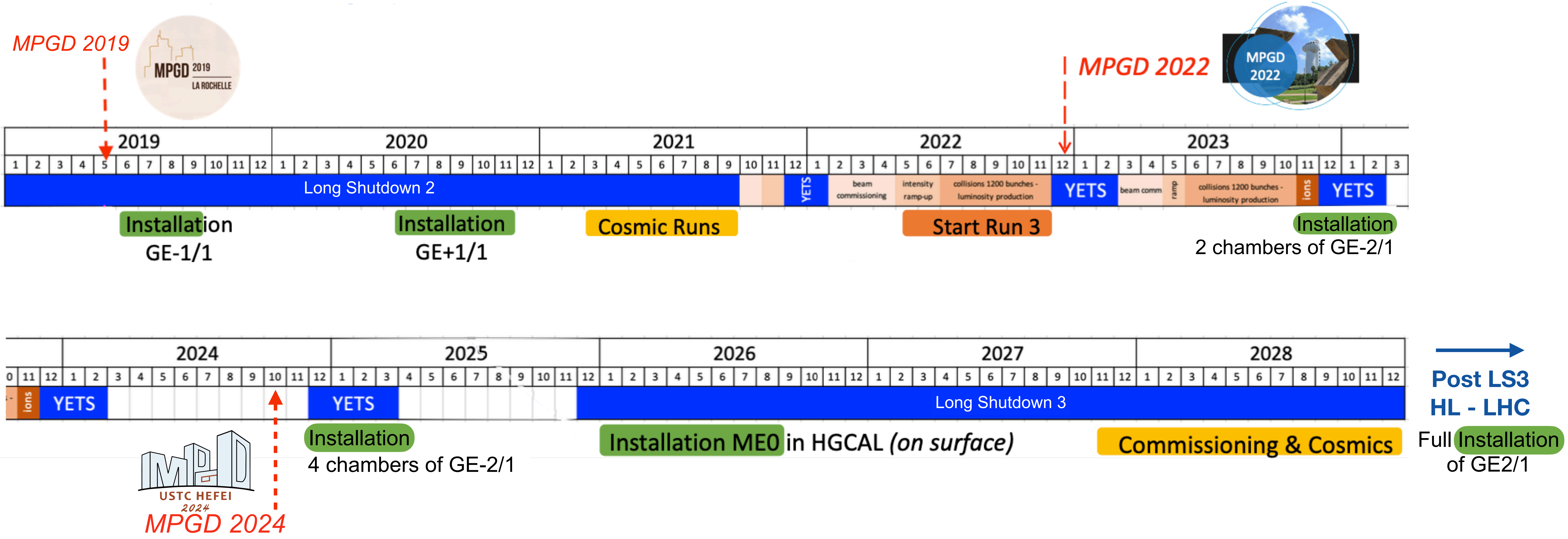

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- GE2/1 Production & Issues - Experience Learned

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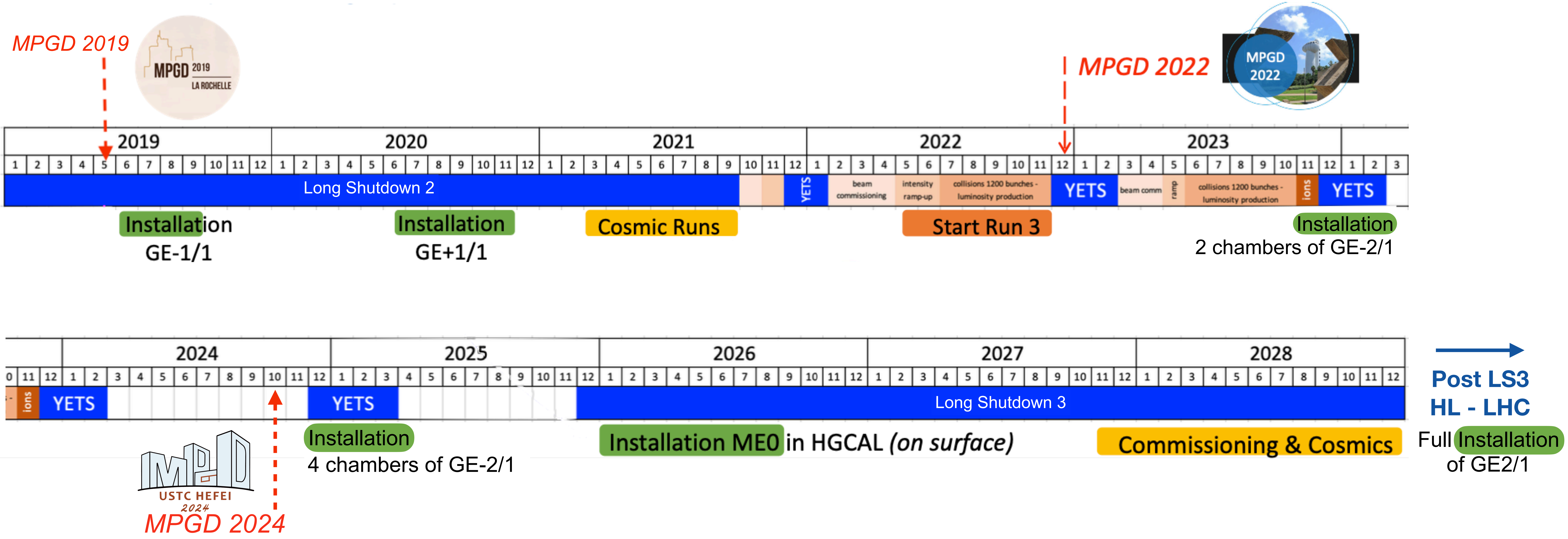

MPGD 2019

MPGD 2022

2019 | 2020 | 2021 | 2022 | 2023

Long Shutdown 2

YETS

beam commissioning

intensity ramp-up

collisions 1200 bunches - luminosity production

YETS

beam comm

ramp

collisions 1200 bunches - luminosity production

ions

YETS

Installation GE-1/1

Installation GE+1/1

Cosmic Runs

Start Run 3

Installation 2 chambers of GE-2/1

2024 | 2025 | 2026 | 2027 | 2028

ions

YETS

YETS

Long Shutdown 3

Installation 4 chambers of GE-2/1

Installation ME0 in HGCAL *(on surface)*

Commissioning & Cosmics

Post LS3
HL - LHC

Full Installation of GE2/1

MPGD 2024

Today’s Outline

- GE1/1 Operation & Performance with 2023/24 Data
- GE2/1 Production & Issues - Experience Learned
- ME0 Project - Looking Into the Future

GE1/1 Operation & Performance with 2023/24 Data

- 144 active detectors, 2 GEM detectors define a GE1/1 Super-Chamber.
- 36 SC per end cap installed in CMS in staggered fashion.
- installed in CMS during LongShutdown2 of LHC between 2019 and 2020.
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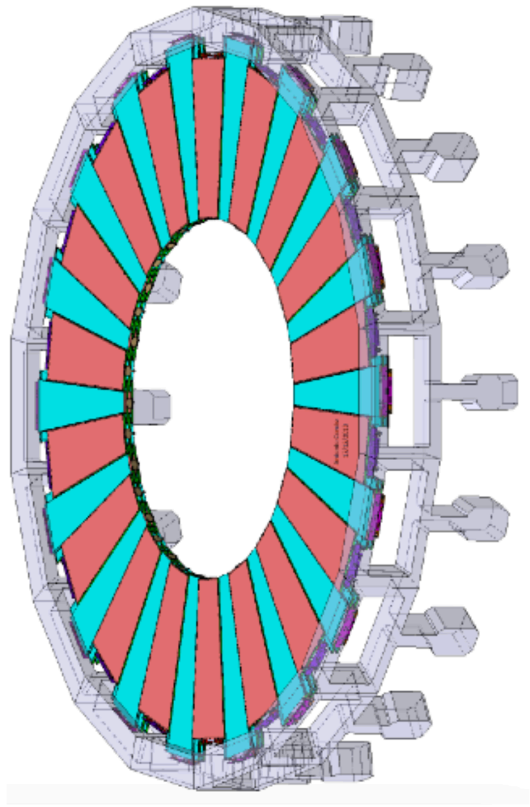

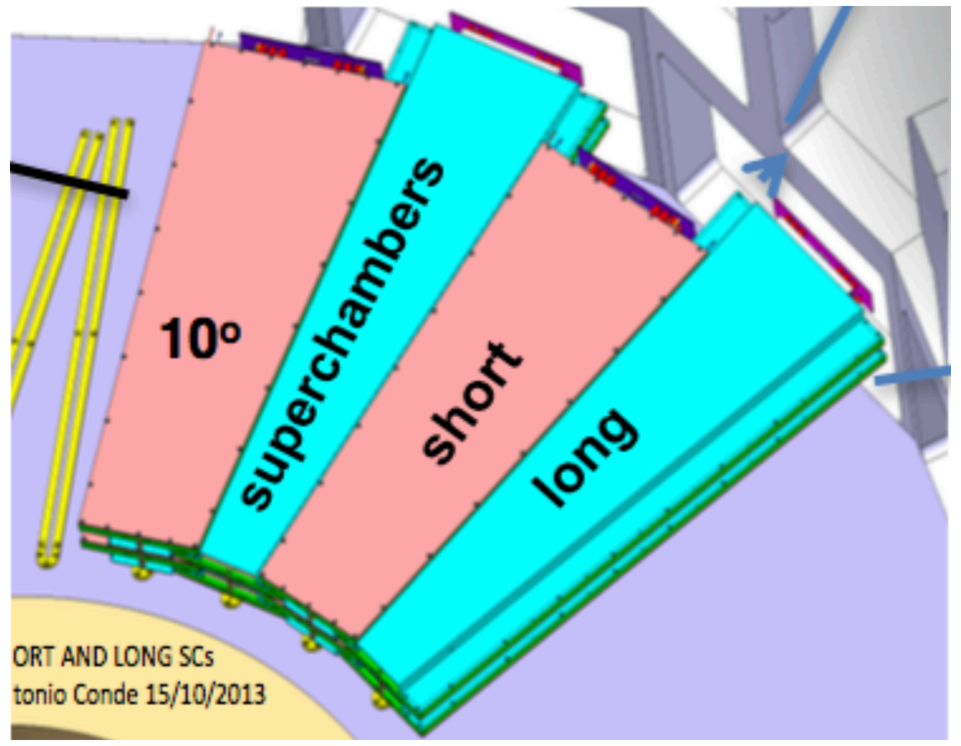

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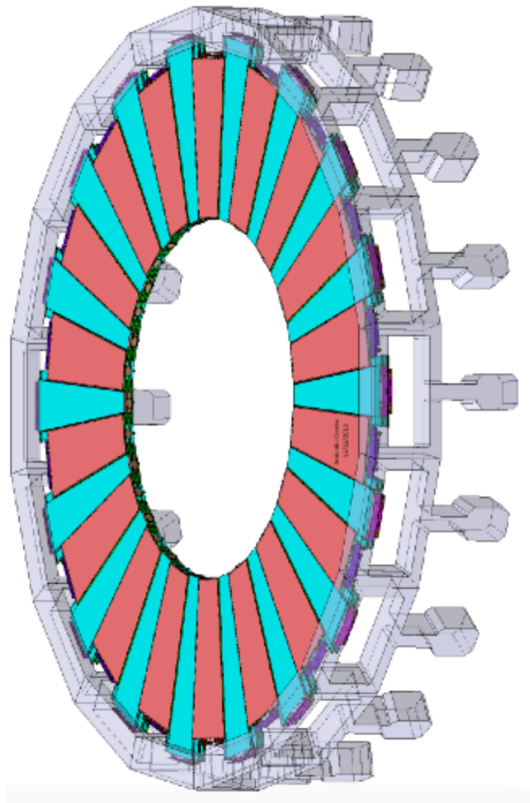

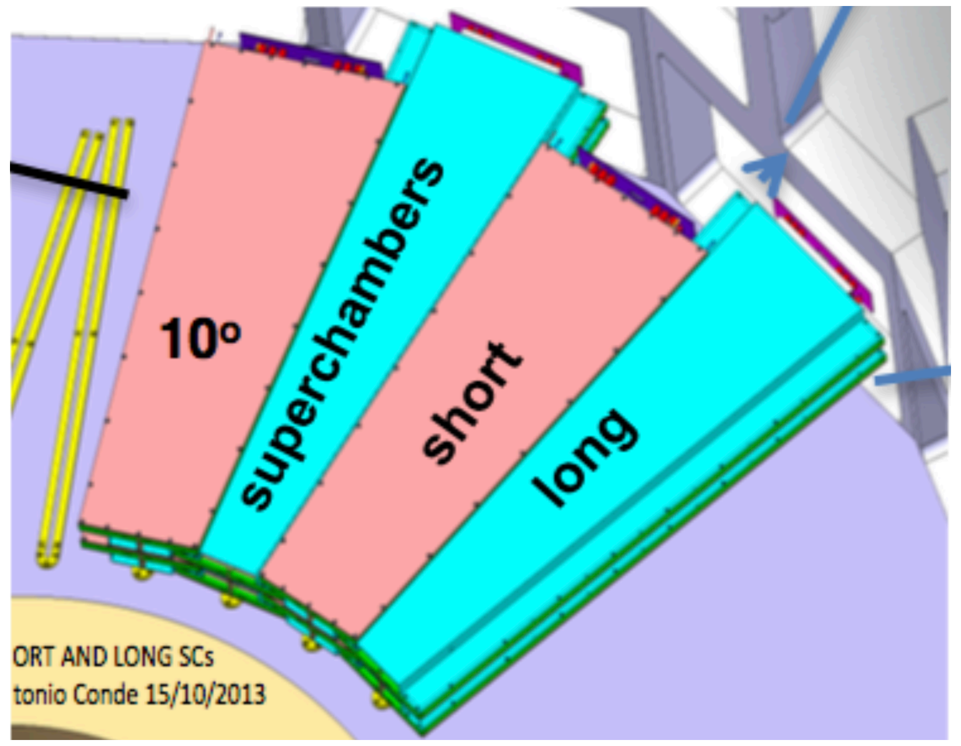

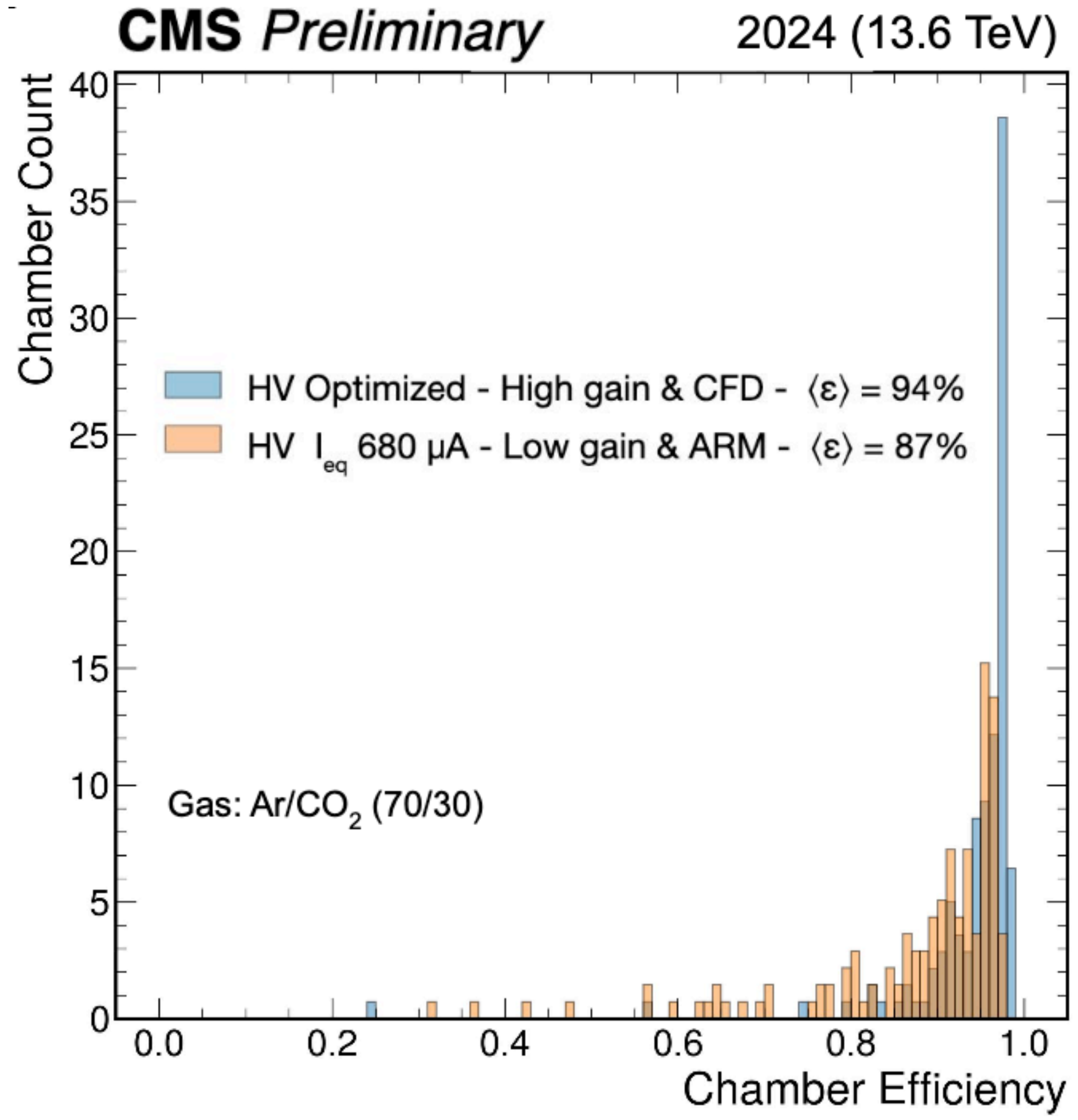

Commissioning optimising the efficiency:

Tested HV point: I_{eq} = 650–700 μA

Tested electronics configurations: ARM, CFD, different VFAT gains (High, Medium, Low)

Achieved efficiency -> 94 %: Compromise between high efficiency and low discharge rate

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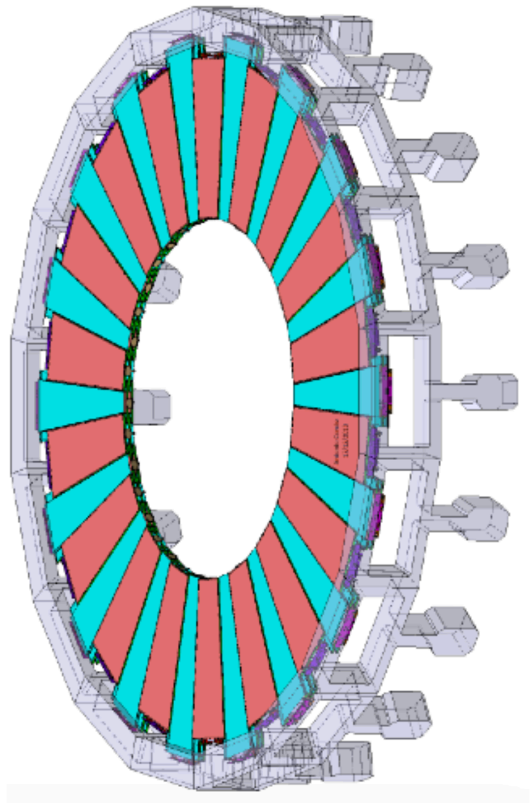
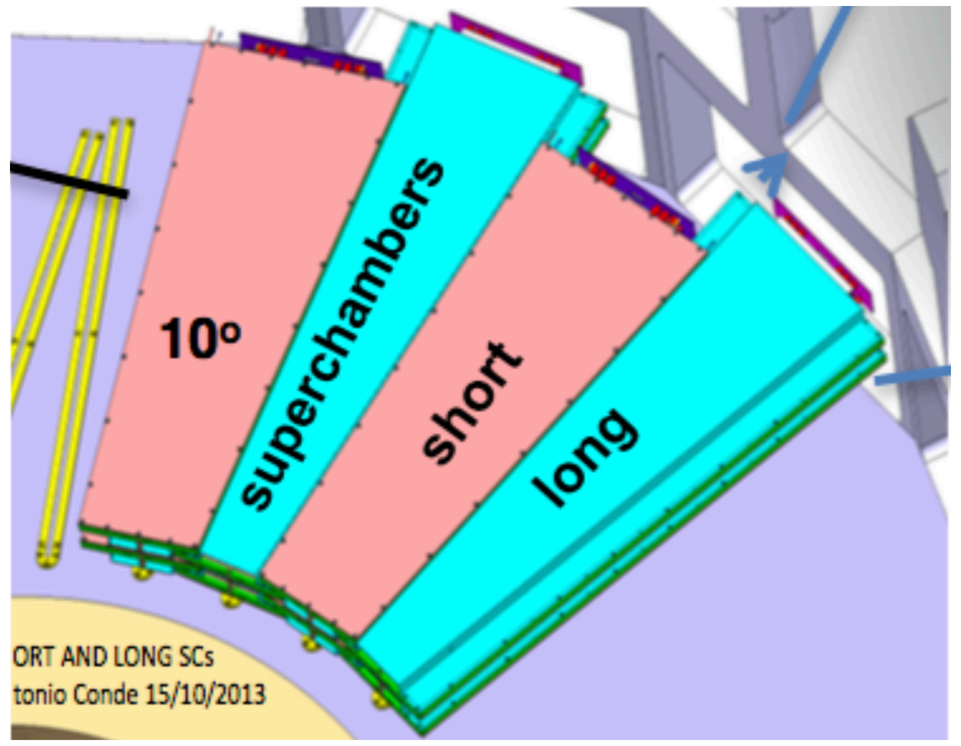
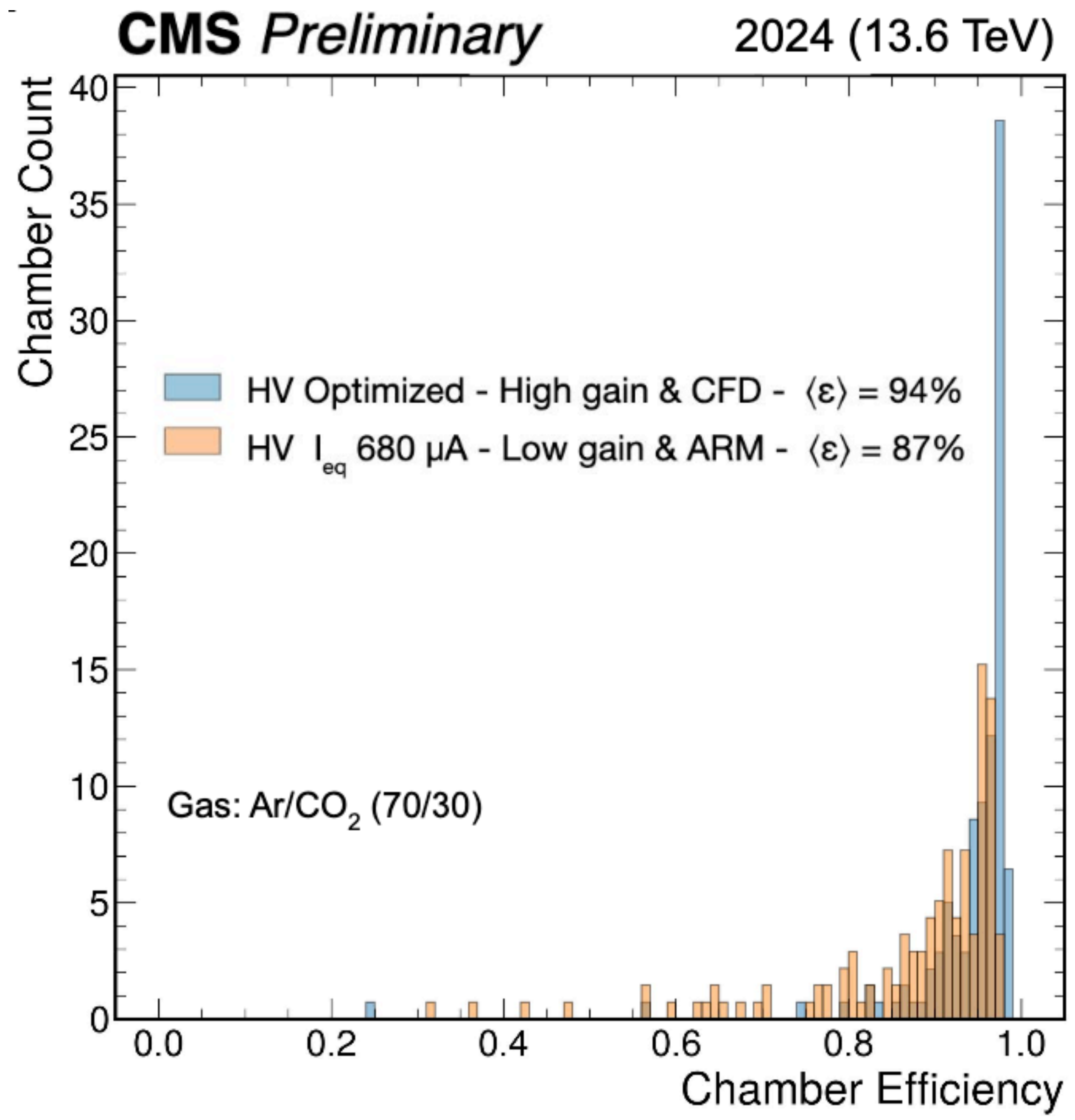
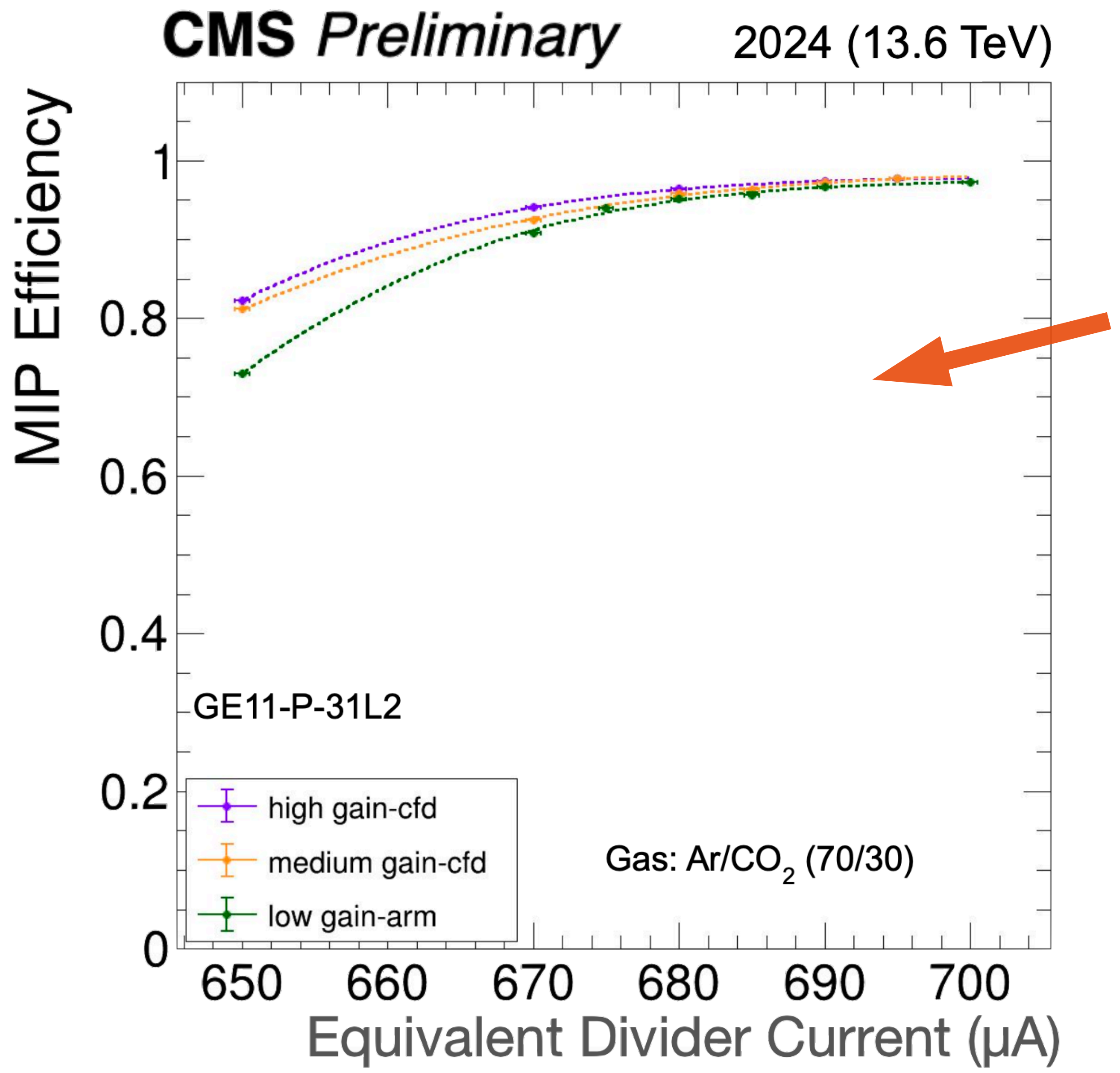
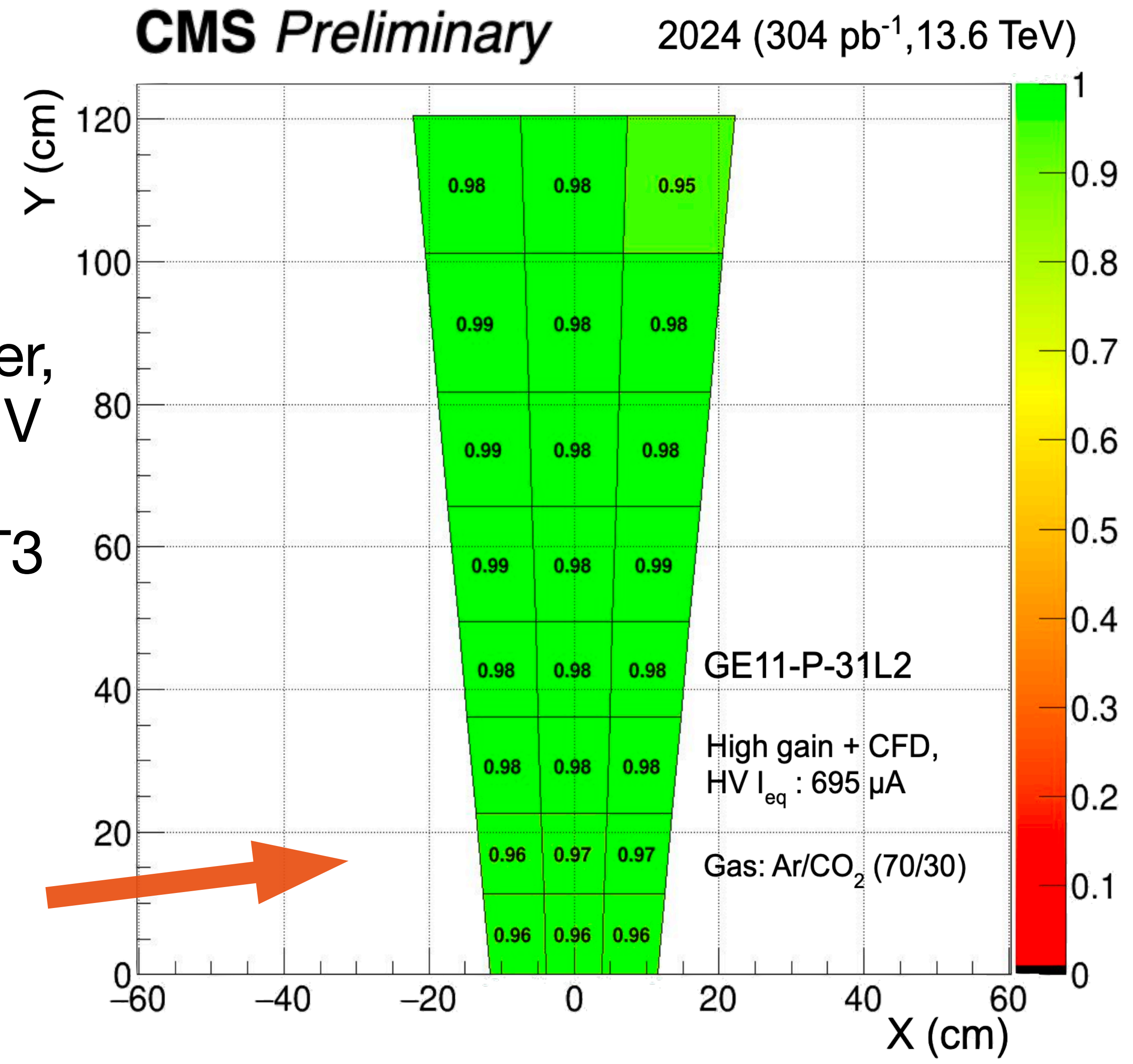








- Efficiency of one representative chamber, operating at various HV settings & certain front-end VFAT3 chip configurations.
- Efficiency map, segment according to readout regions.



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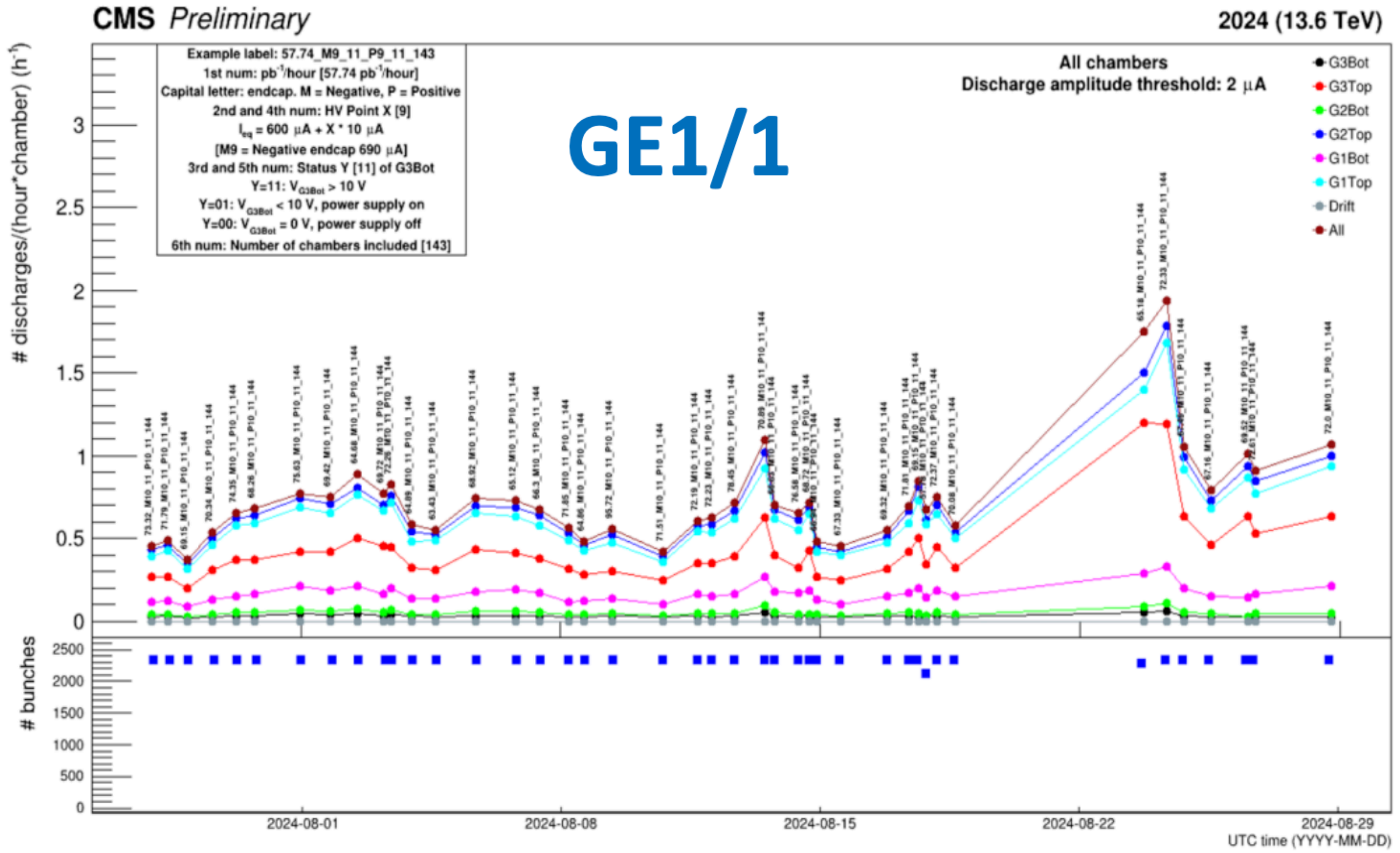

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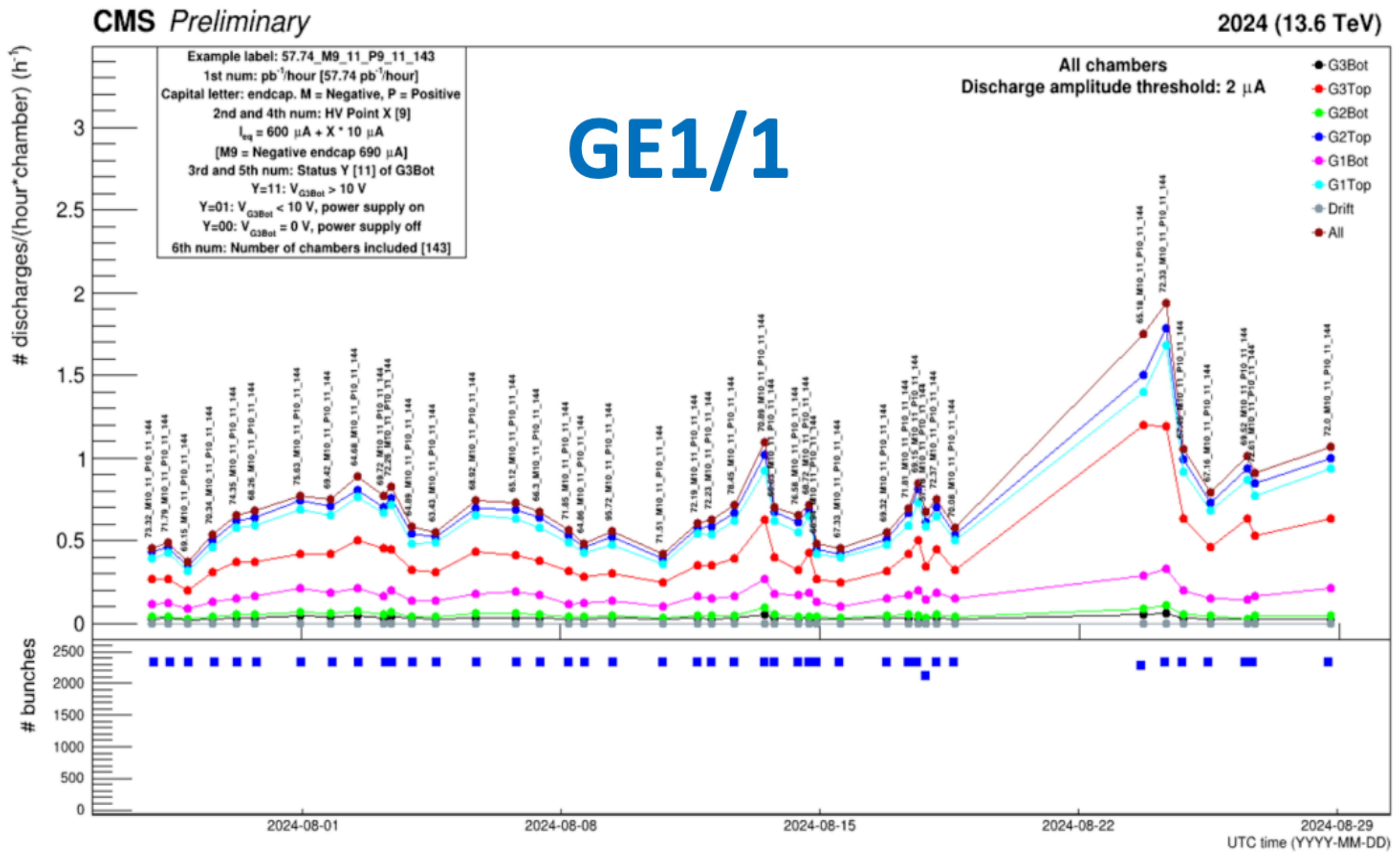
    - Damaged VFAT3 biasing circuit



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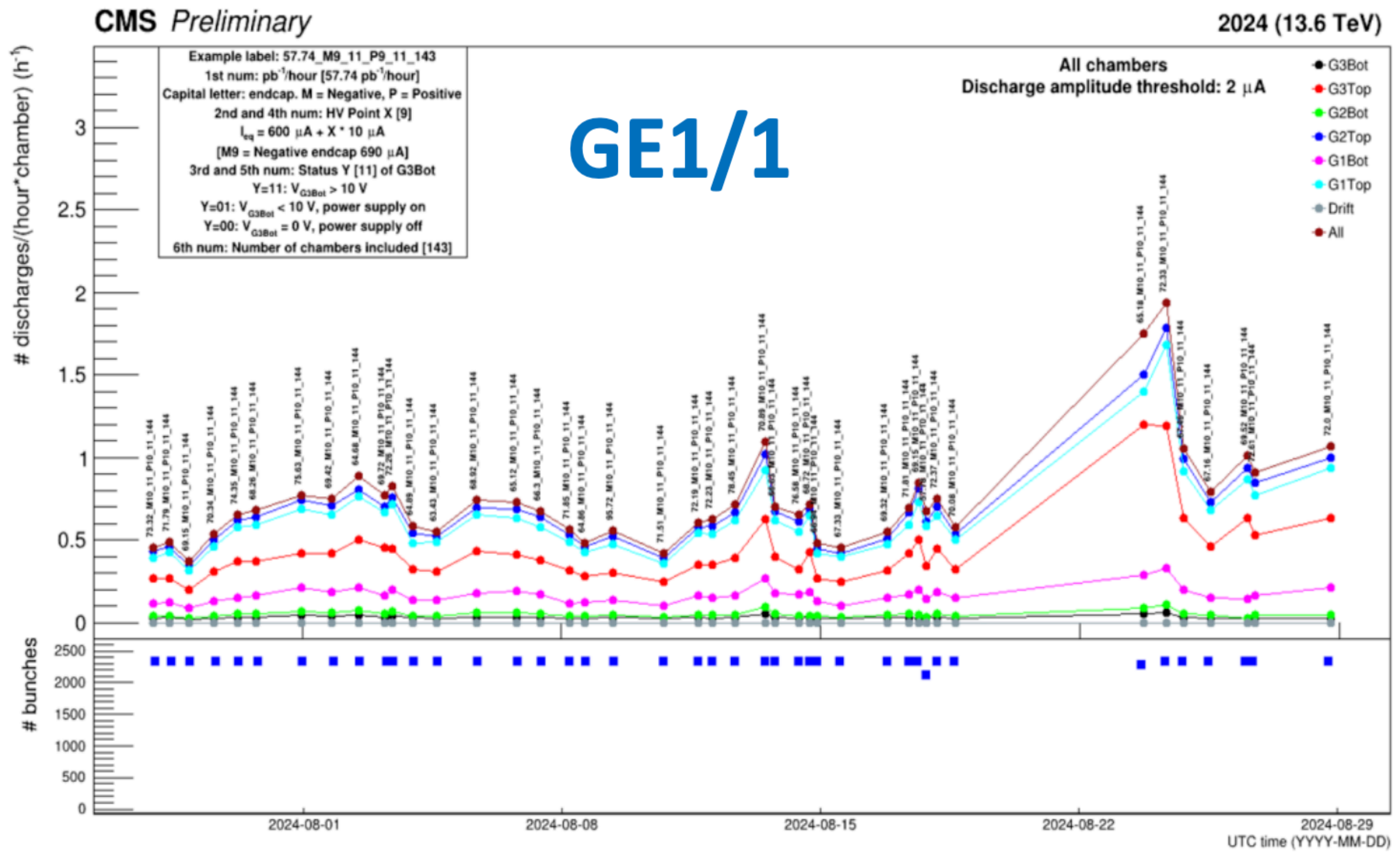
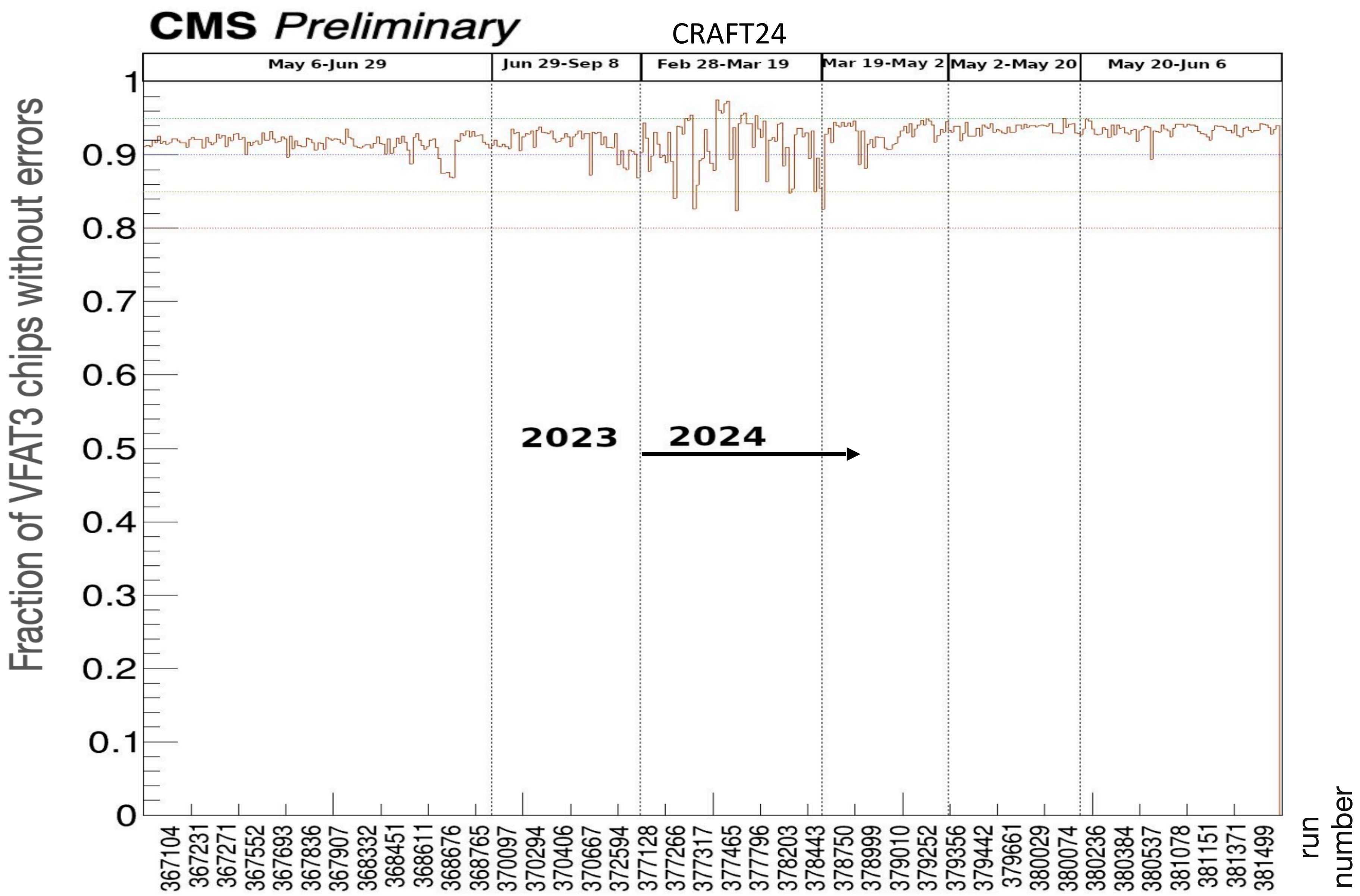
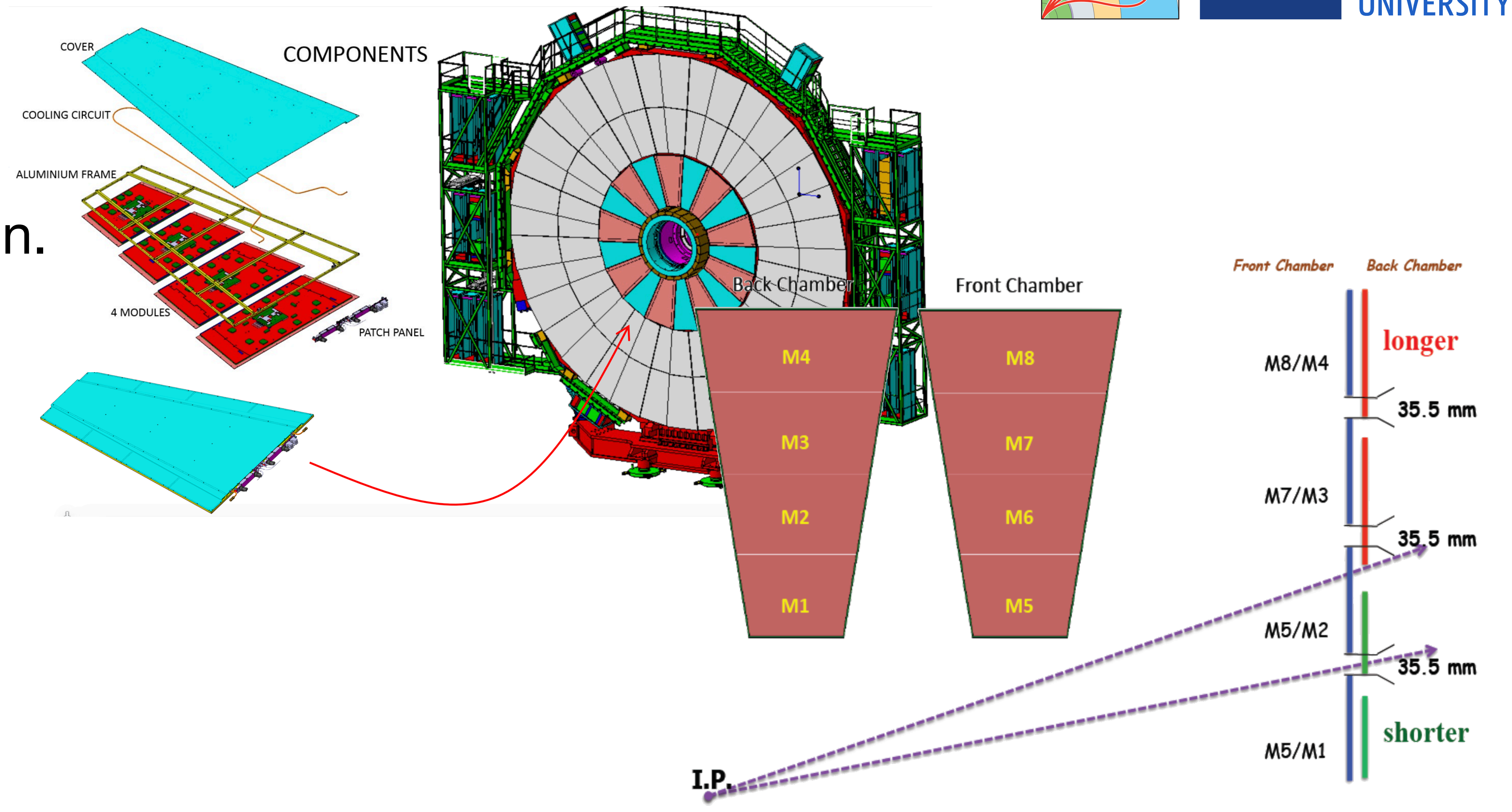


- **VTRx outgassing,** not a new issue known since 2021.
- after GE1/1 installation not enough time to rework the 144 Opto-hybrids.
- how to operate: interplay between DAQ and DCS (Detector Control System) to automatically power cycle and re-configure the affected Opto-Hybrid at each run.
- ~ 7% of VTRx are not communicating properly, rather stable now.
- Electronics refurbishment: all GE1/1 chambers will be extracted from CMS during LS3.
  - Add VTRx cooling (~6% efficiency gain)
  - Better grounding cables
  - Replace problematic components (broken FEAST, VFATs)
  - Improve monitoring,...



GE2/1 Project

- Triple-GEM technology, same as GE1/1, with 3/1/2/1 configuration.
- The full system: 72 chambers, 36 per endcap.
    - The chambers are arranged in two layers.
    - 4 triple-GEM modules per layer (288 modules in total).



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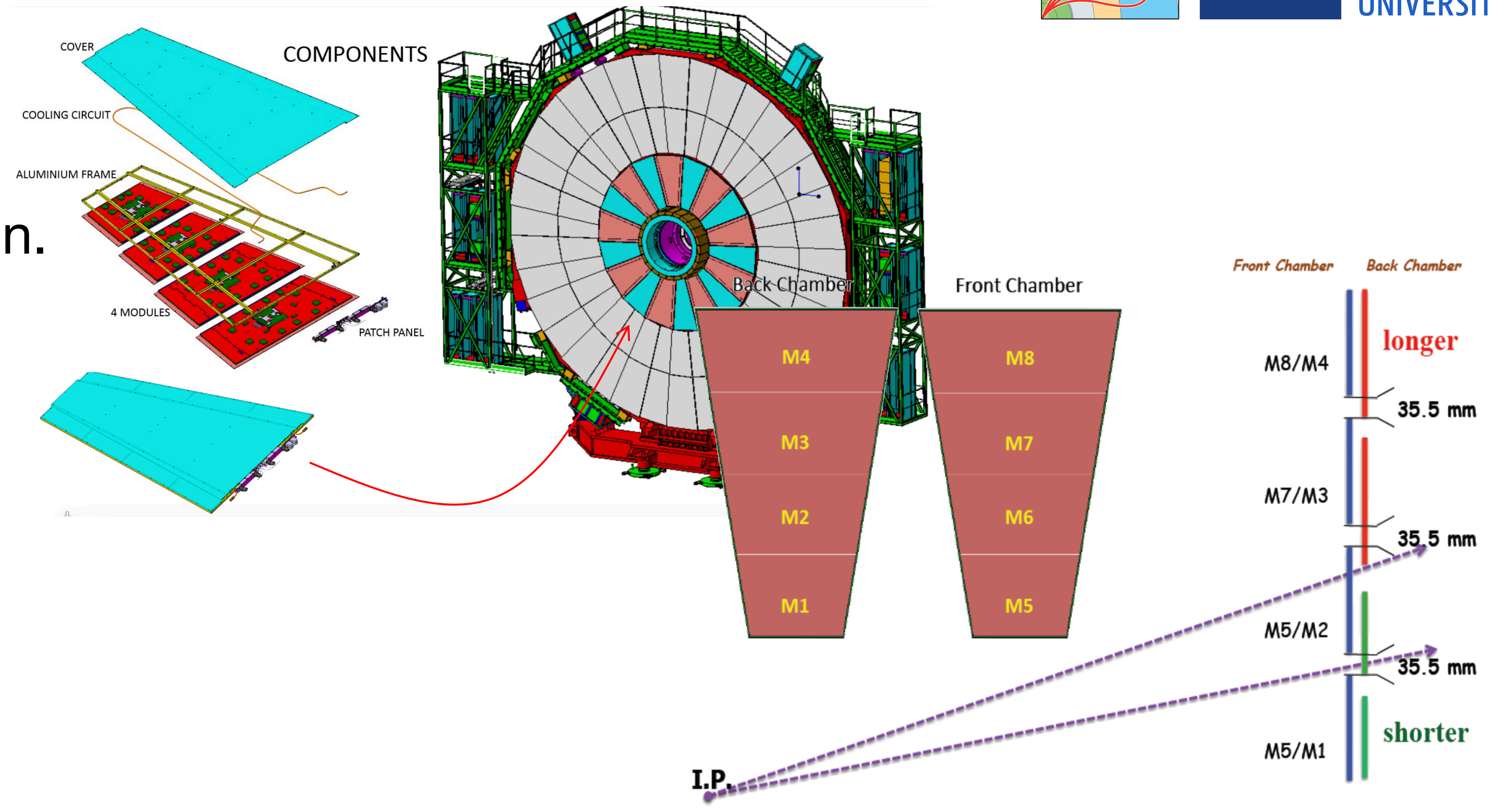

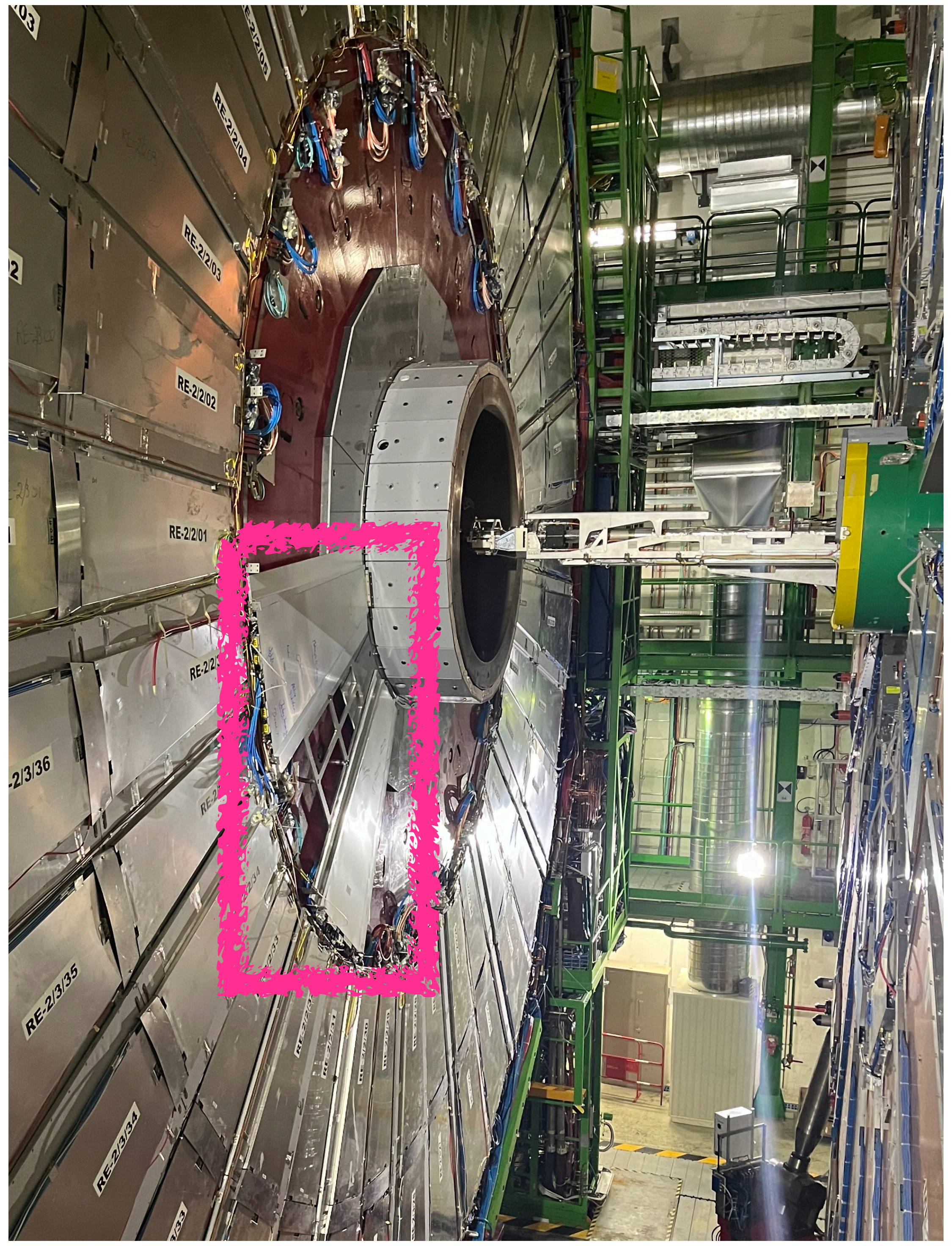

- A demonstrator was installed in November 2021, for the purposes of
  - gain operational experience: DCS & DAQ, DQM, ...
  - experience with new double segmented foil design in GEM1 & GEM2 (see last talk at MPGD 2022 given by Piet Verwilligen).
  - exercise detector integration & mechanical installation tools…
- 2 chambers were installed during YETS23/24.
- will install 4+1 (replacement) chambers at coming YETS24/25.

GE2/1 Production

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Assembly training at CERN GEM lab


First GE2/1 triple GEM foil stack built in Ghent lab summer, 2023

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- The GEM project experienced difficulties in assembling module due to dust pollution of the gas volume.
- On 1st Sep 2023, central site at CERN identified the presence of microscopic (a few μm) copper dust between strips, with the help of the CERN MPT Workshop.

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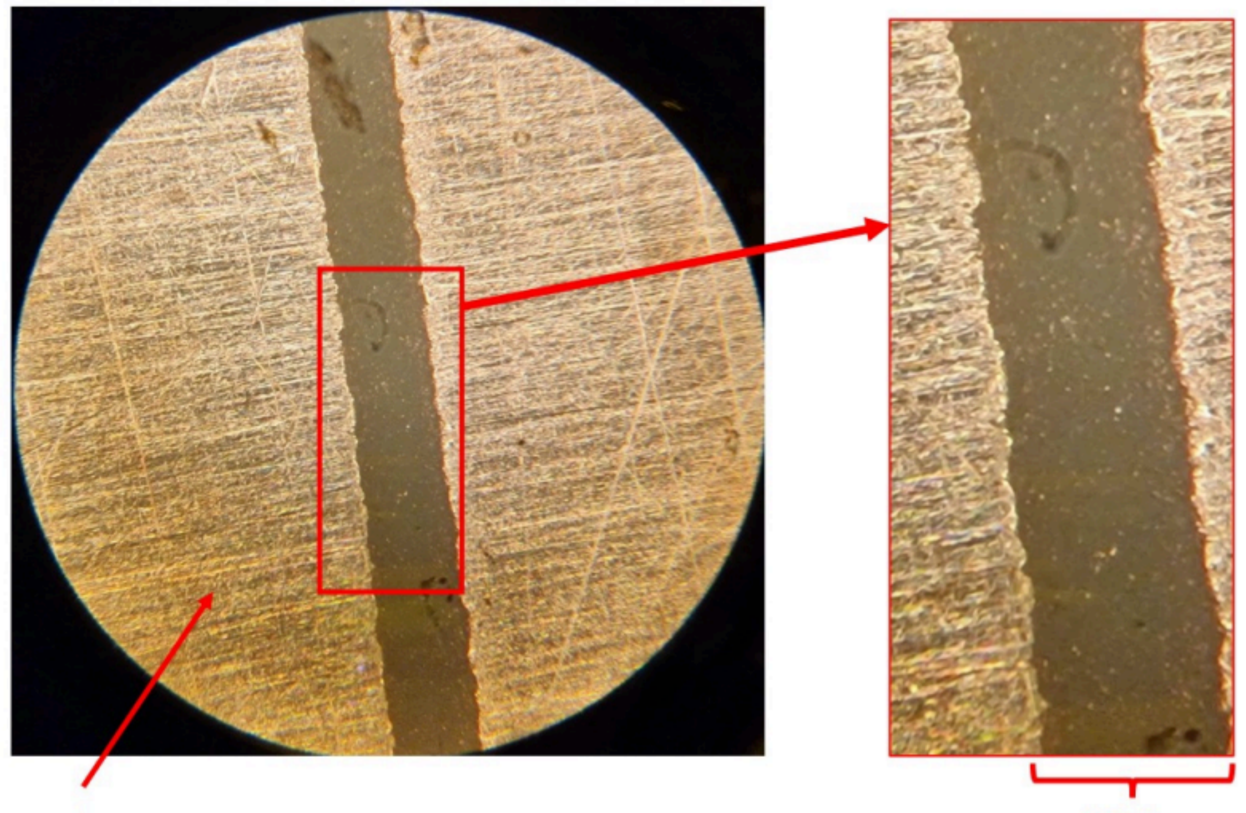

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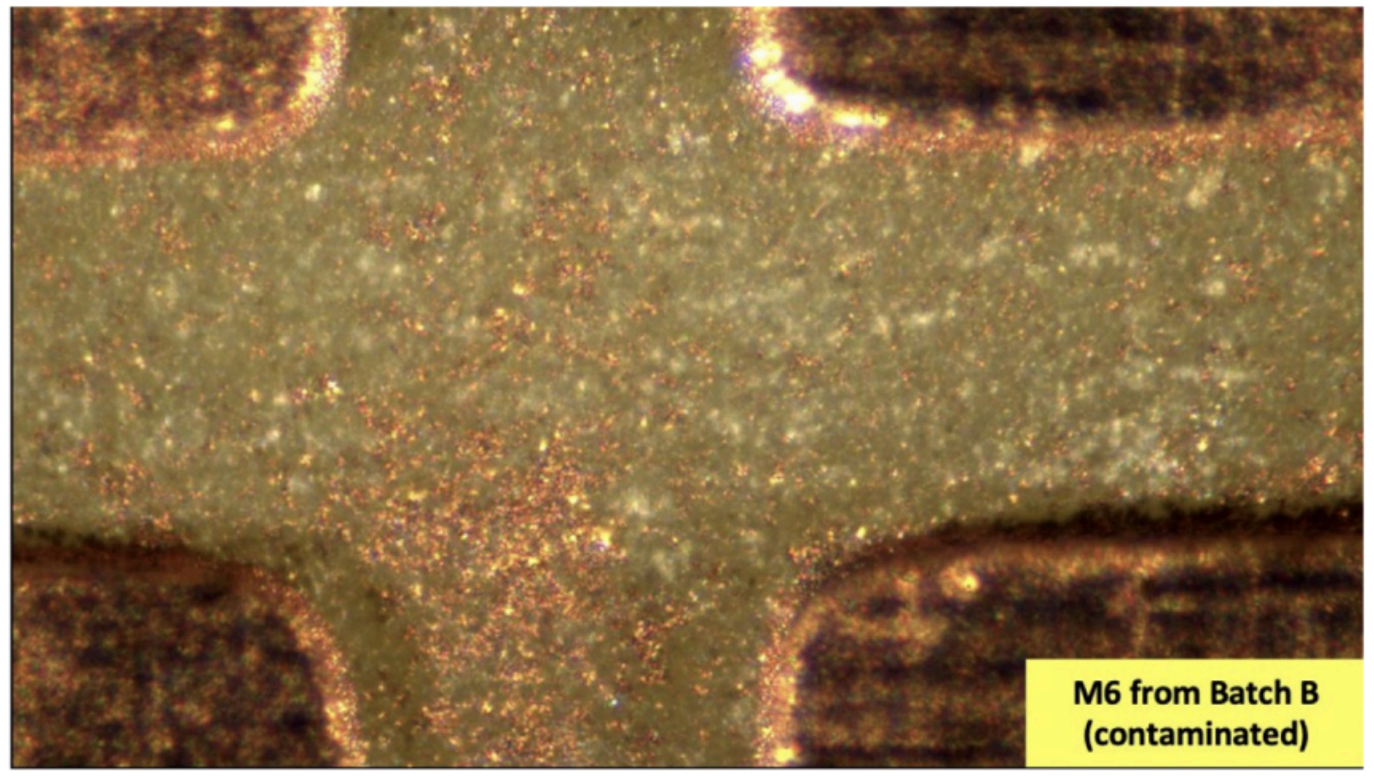

from higher magnification microscope (x25)

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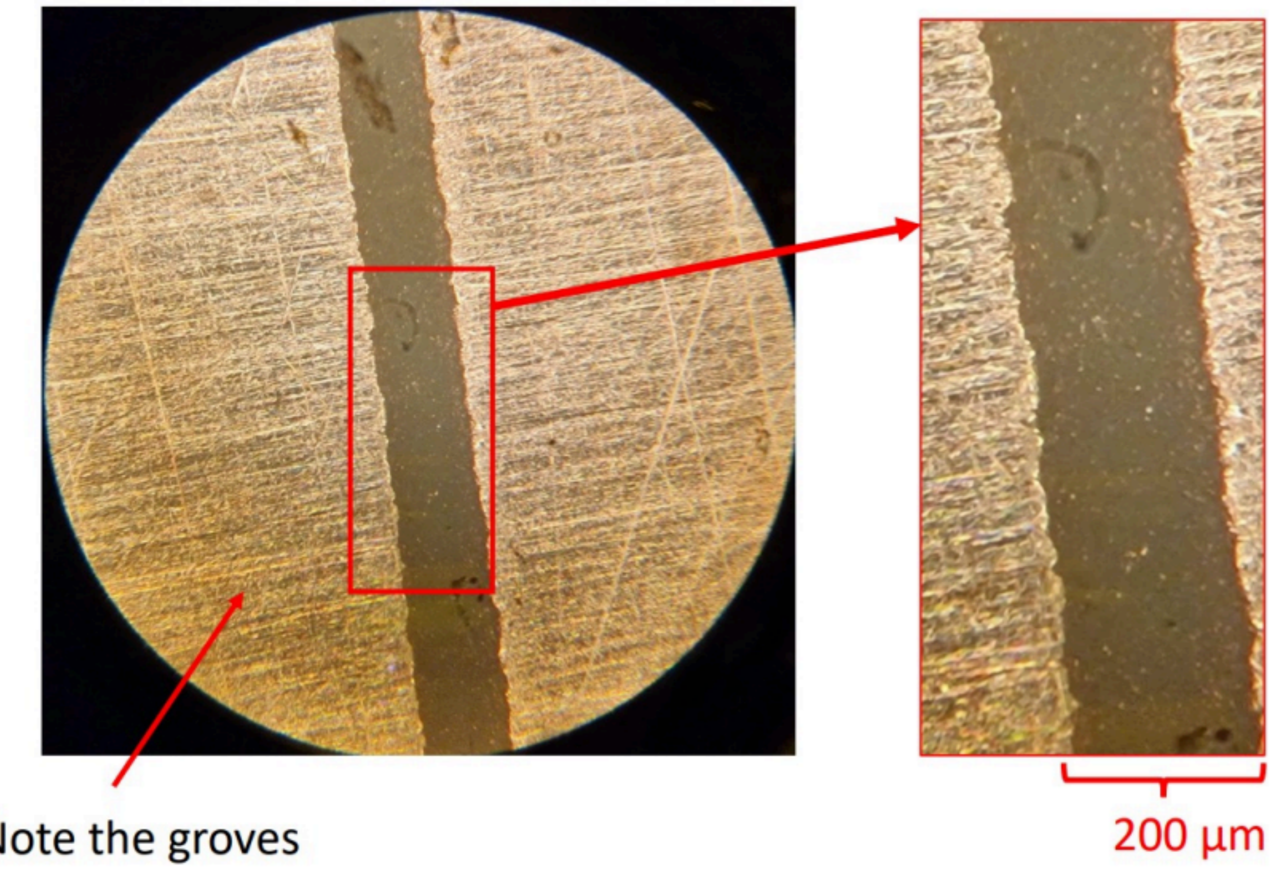

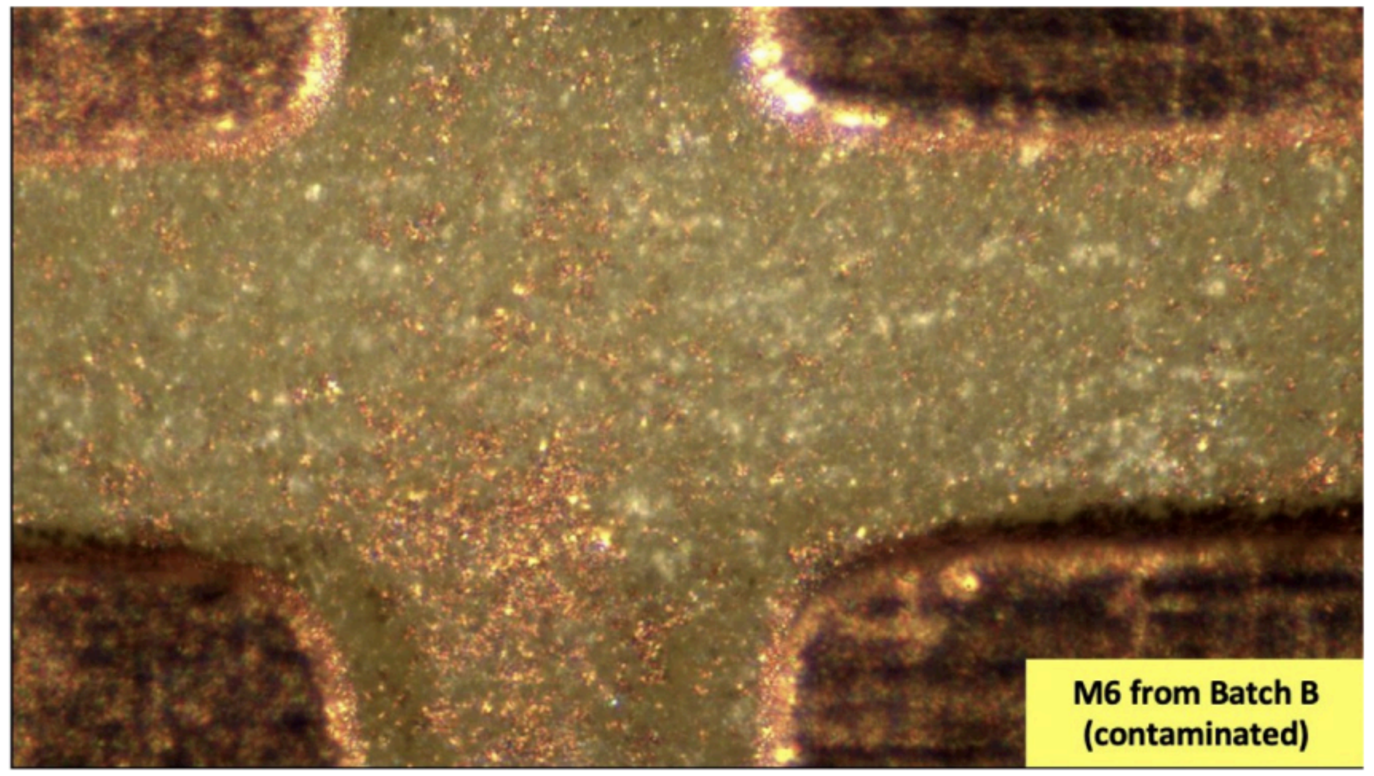

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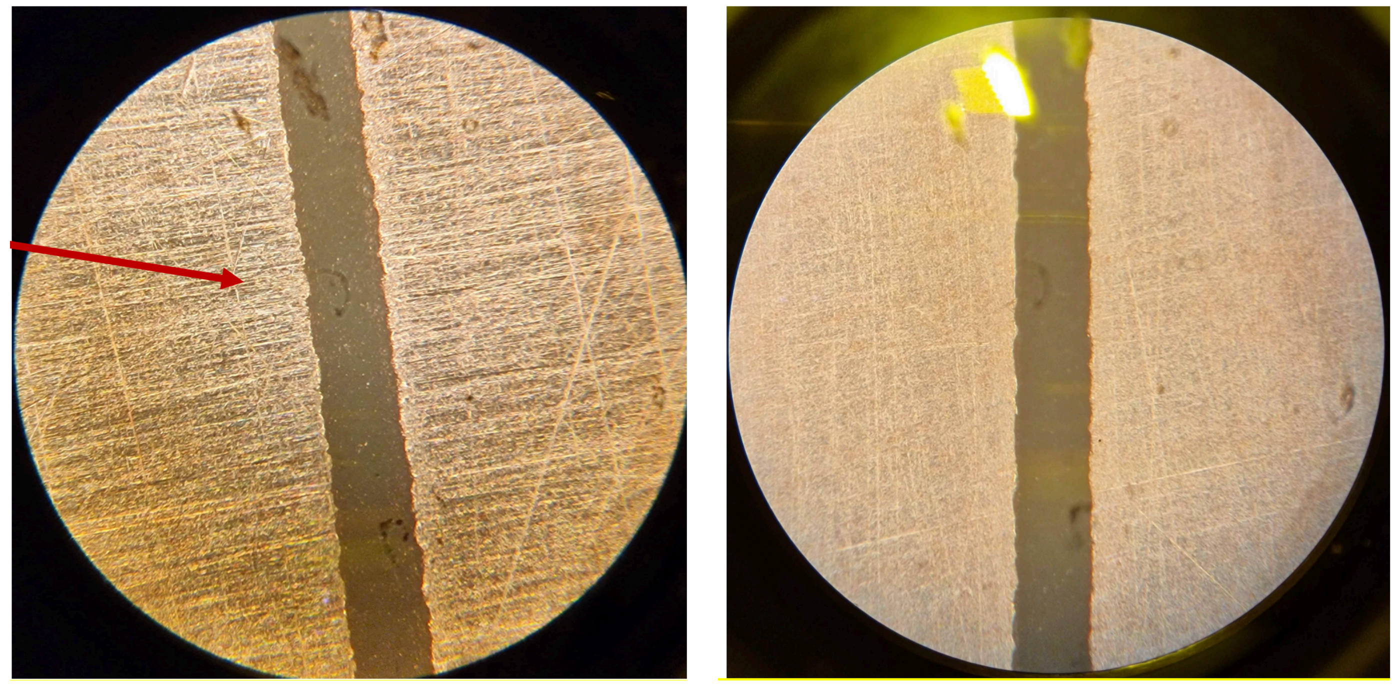
Consequence:

- The 96 modules (among them 52 already used to build 13 GE2/1 chambers) will have to be retrofitted.
- All the PCBs should be cleaned and passivation layers should be applied on them, new assembly of GE2/1 work stopped.
- A cleaning procedure must be set for the foil stack.
- A new additional step for PCB validation was introduced.

GE2/1 Refurbishment

- A retrofitting procedure was established with the help of the CERN MPT Workshop:

Mechanical cleaning with tissue soaked with pure ethanol or isopropyl alcohol -> Water jet cleaning -> Micro-etching -> Chromic-acid passivation



RO inter-strip after chemical cleaning at CERN MPT workshop, micro copper residues between RO strips are increasingly reduced.

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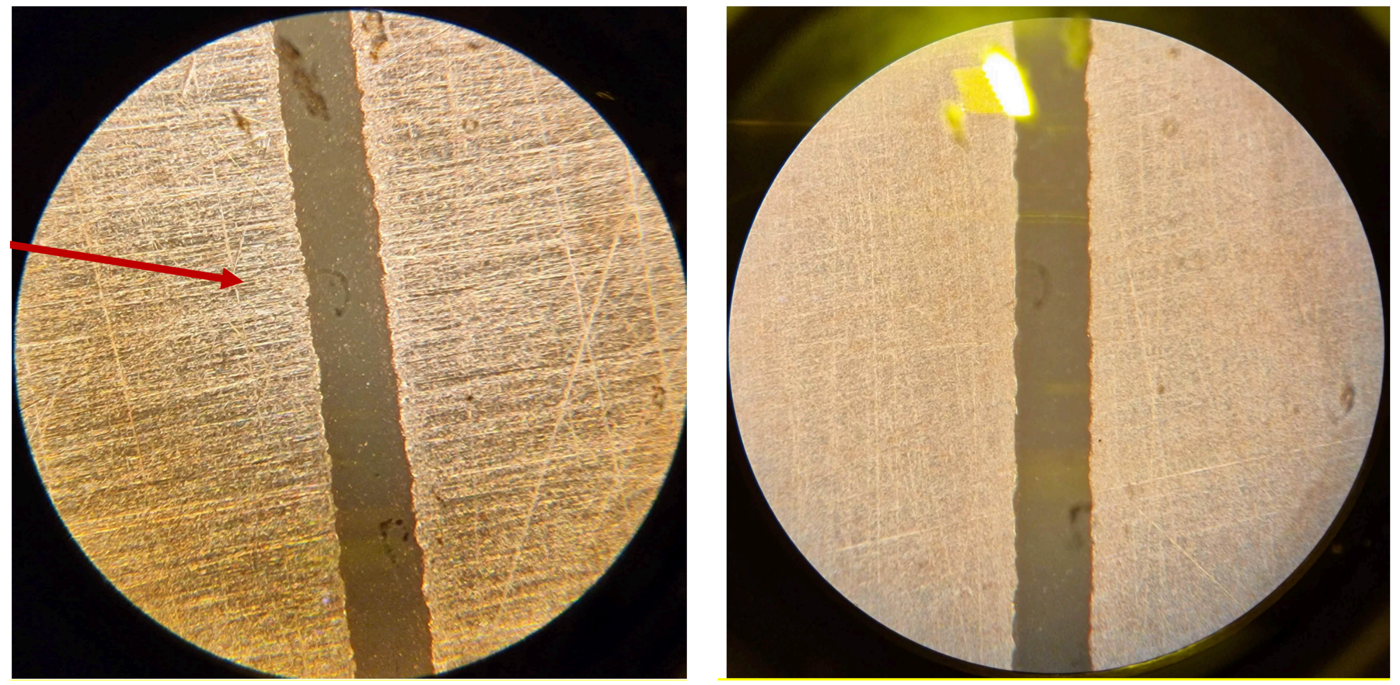

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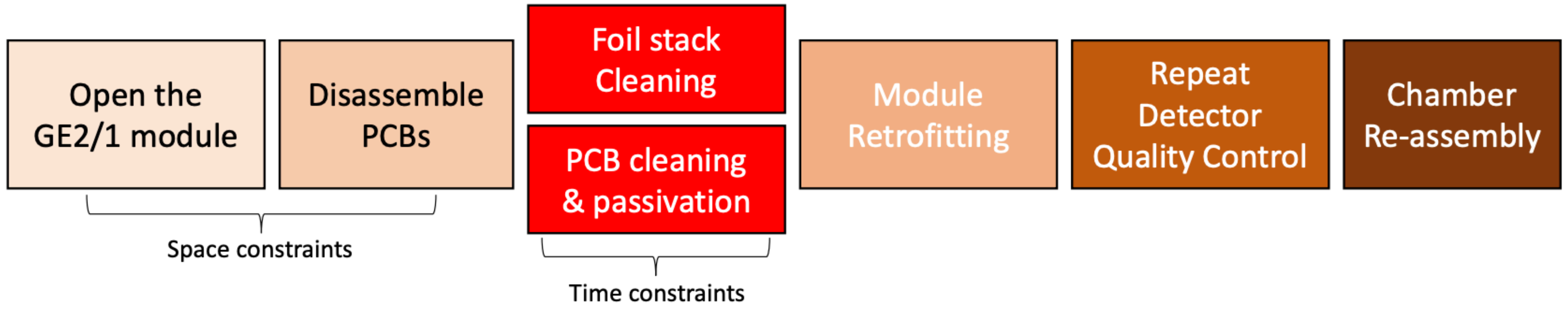

Open the GE2/1 module → Disassemble PCBs → Foil stack Cleaning / PCB cleaning & passivation → Module Retrofitting → Repeat Detector Quality Control → Chamber Re-assembly

Space constraints

Time constraints

- Considering workflow, lab space limits and MPT workshop availability, ~**1.3** year to complete the refurbishment of assembled 96 GE2/1 modules.
- Estimation time for 190 new modules to be assembled ~**1.8** years.

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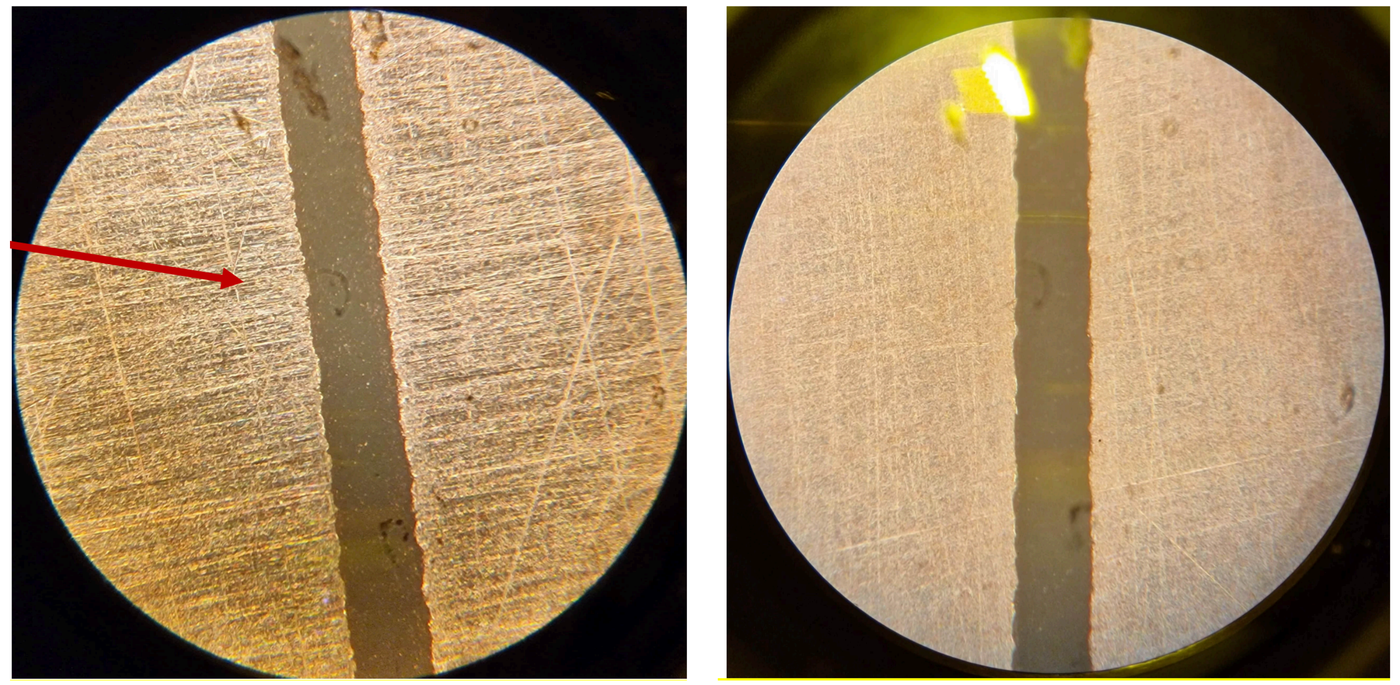

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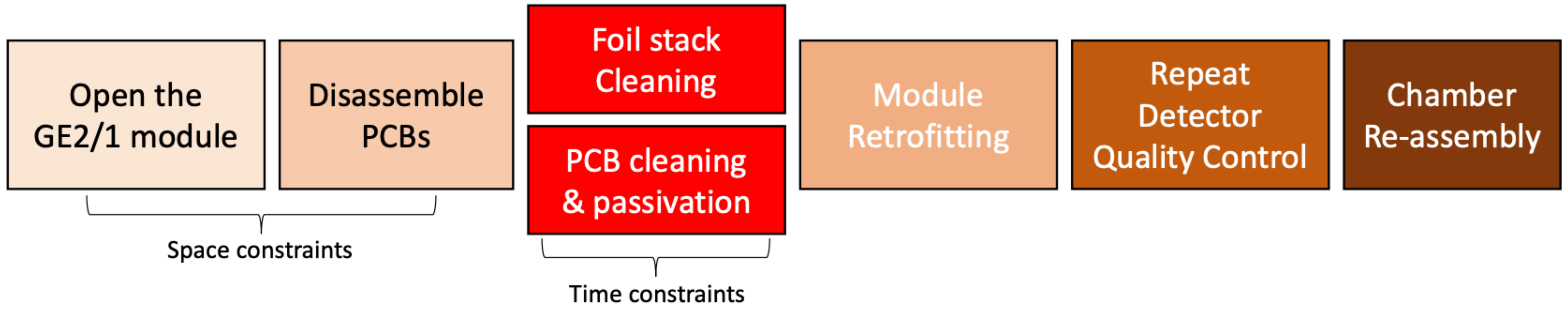

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Disassemble PCBs

Foil stack Cleaning

PCB cleaning & passivation

Module Retrofitting

Repeat Detector Quality Control

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Plans in LS3

2026

2027 ~ 2028

2029

2030

ME0 Production

- Stack for 1st endcap ready in Aug 2025
- Stack for 2nd endcap ready in Oct 2026

Feb 2027
ME0 disk-1 completed & ME0 disk-2 completed

Mar 2028
GE2/1 module production complete

Beginning of 2029
GE2/1 disk-1 completed

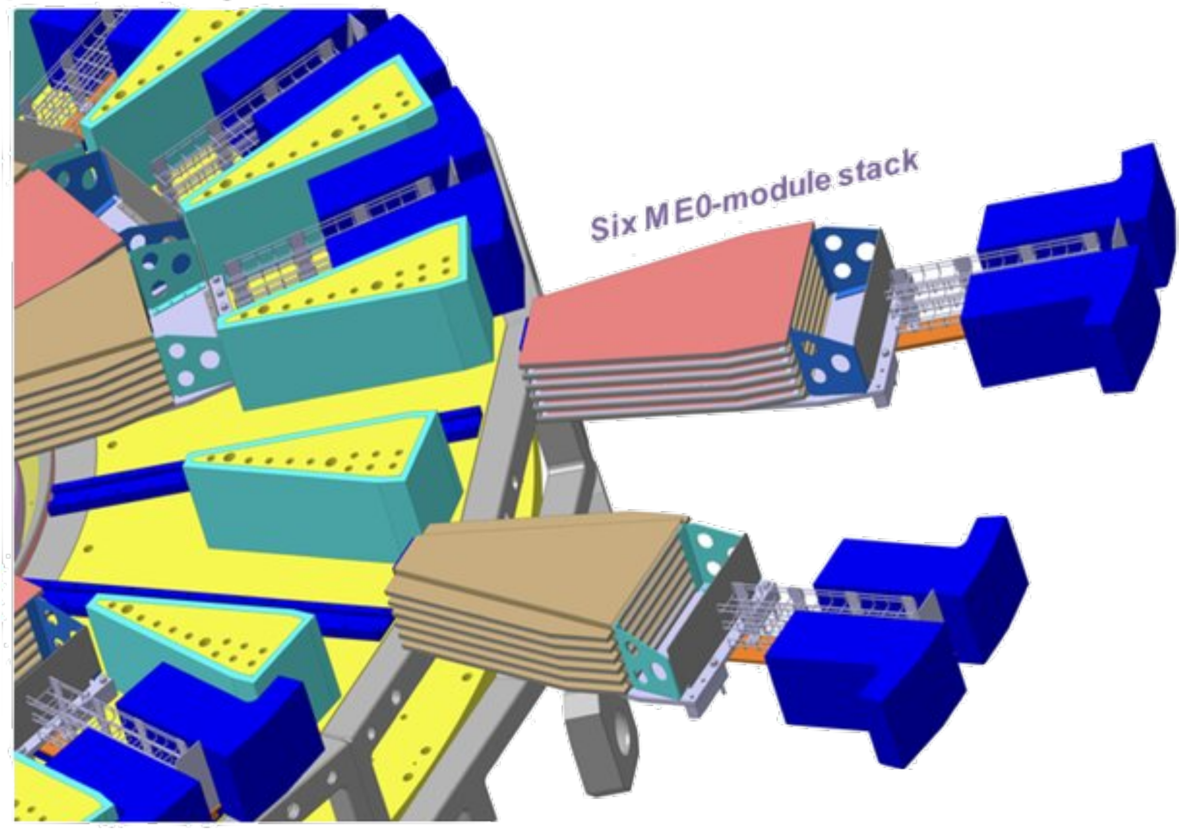
Beginning of 2030
GE2/1 disk-2 completed

- Give priority to ME0

ME0 Project

- 18 ME0 stacks per endcap, each made of 6 layers of Triple-GEM detectors
- Will be installed in the endcap nose directly behind the new HGCAL (high-granularity calorimeter).

  ->no access after installation during all HL-LHC
- Motivation:
  - increases CMS muon coverage to: $2.0 < |\eta| < 2.8$.
  - improve the trigger system, enabling more efficient and accurate event selection and event reconstruction.
  - current detector challenges: aging infrastructure, detector efficiency, resolution and accuracy in higher collision rates and high-radiation environments.



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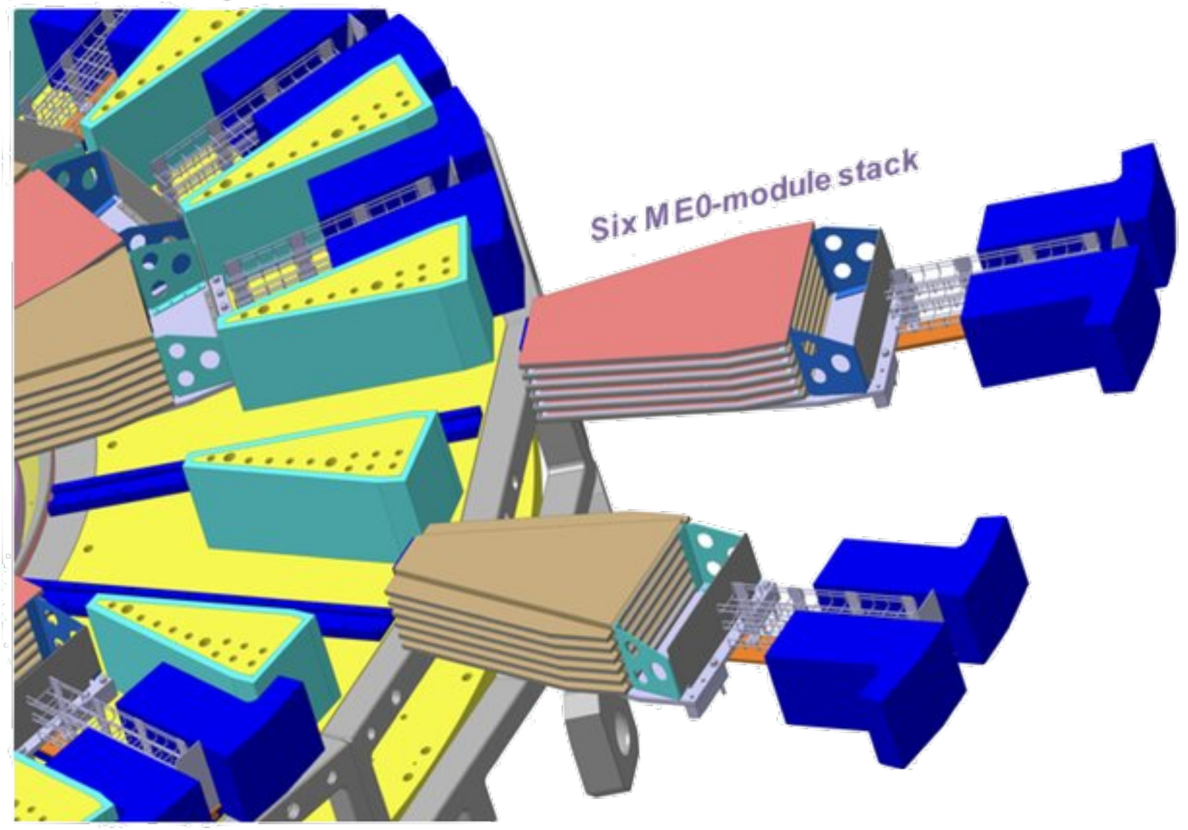
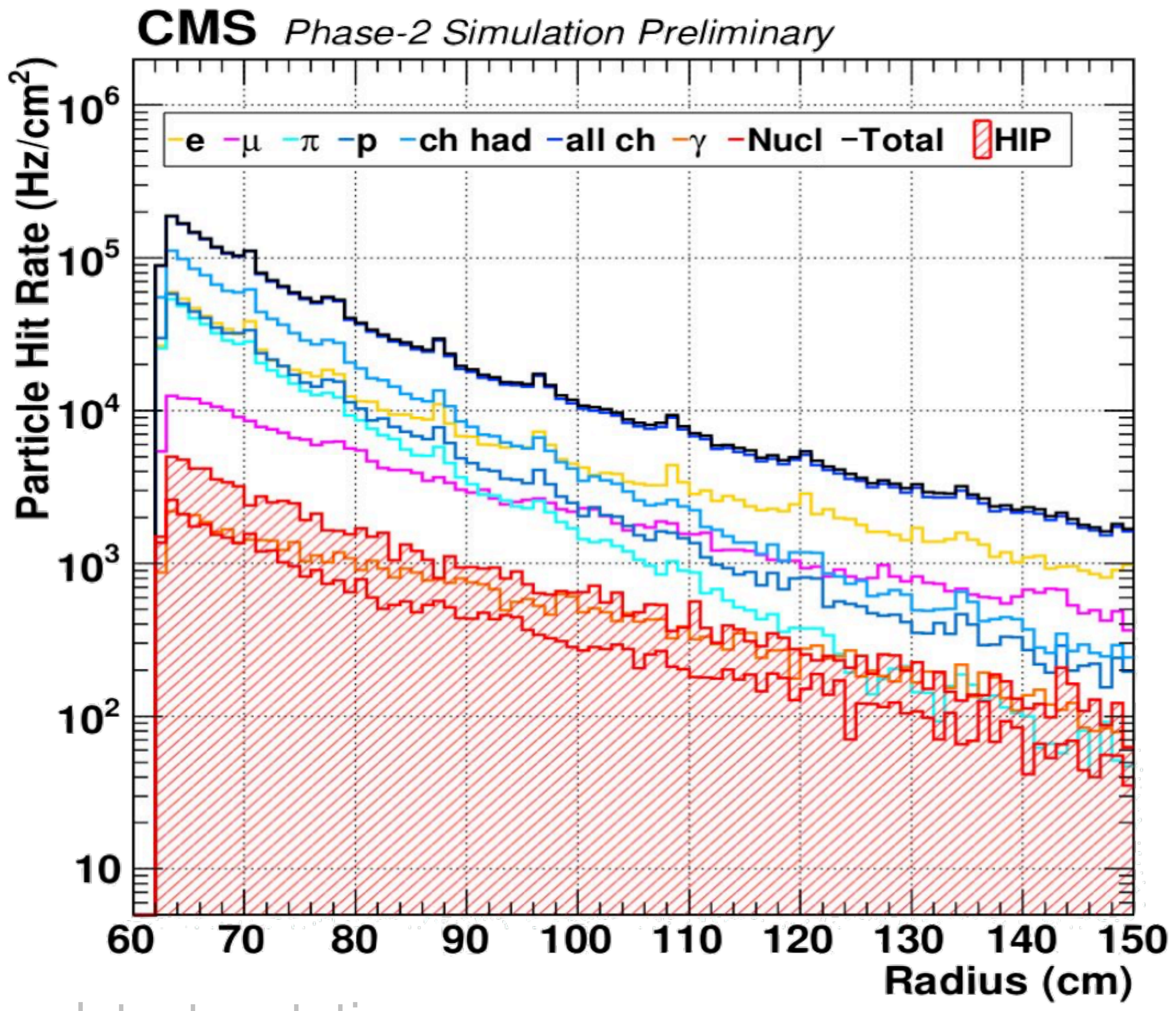
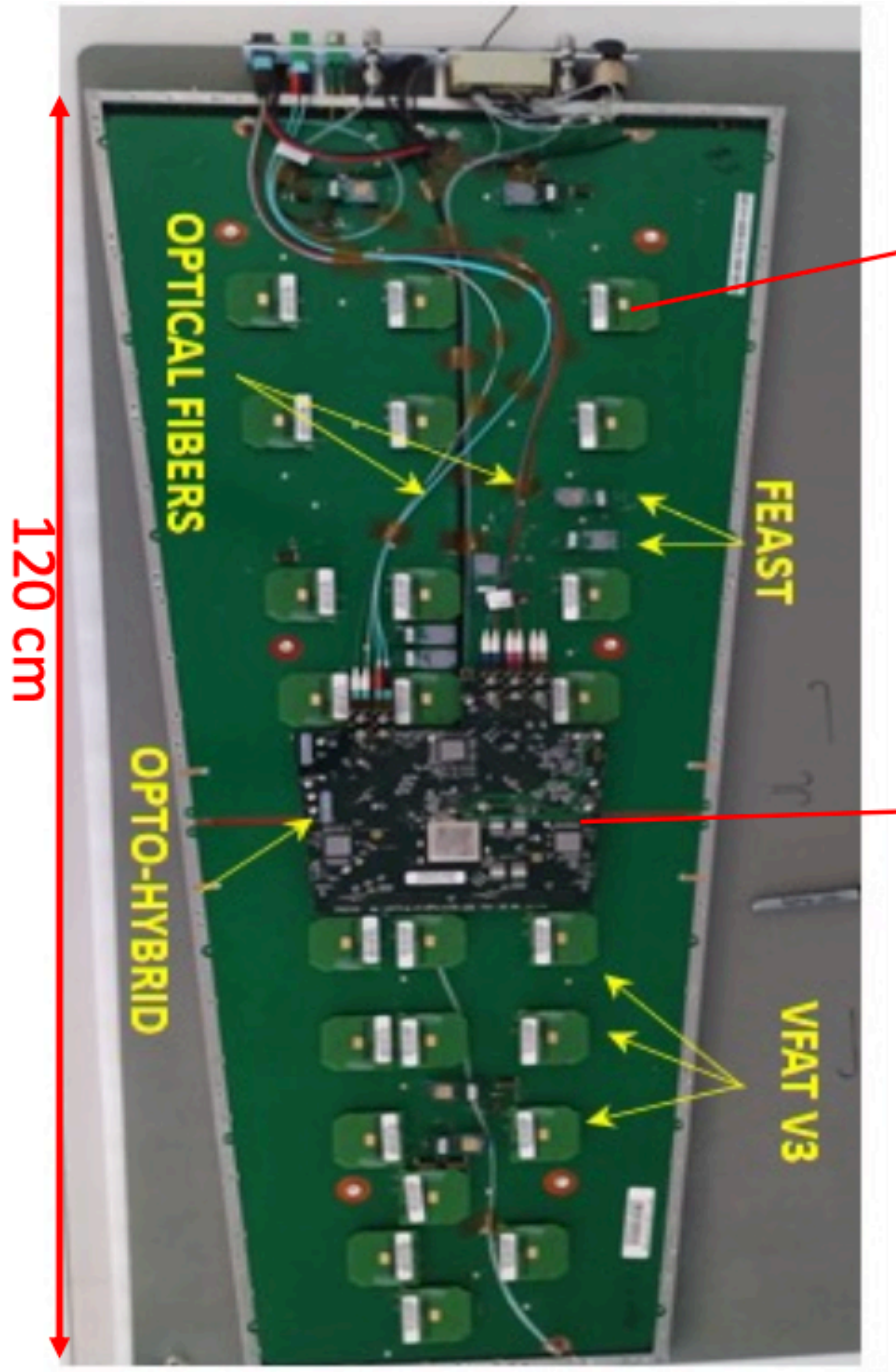


Performance Expectations:

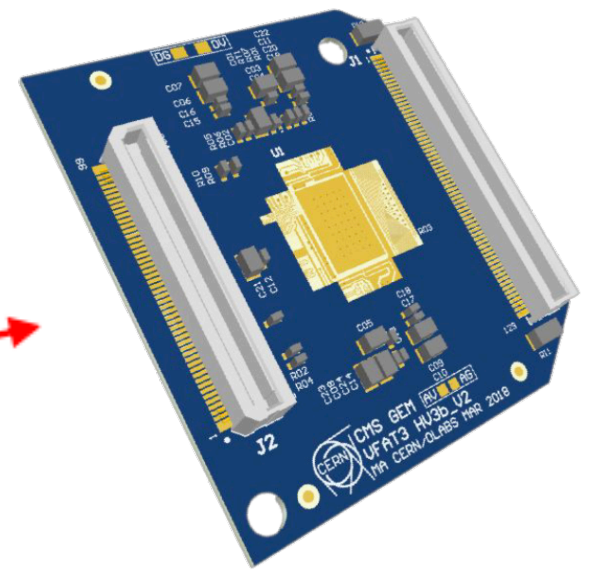
- **Rate Capability:** at least 150 kHz/cm^2.
- **Timing Resolution (per chambers):** 8 –10 ns.
- **Gain Uniformity:** ≤15% across and between modules.
- **Longevity:** No gain loss after 840 mC/cm^2 of integrated charge. Survive harsh radiation environment: 7.9 C/cm^2.



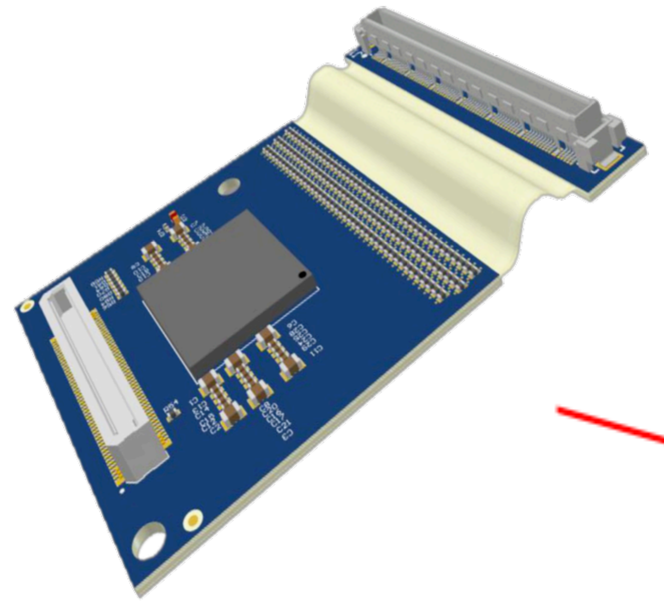
Electronics from GE1/1 to ME0



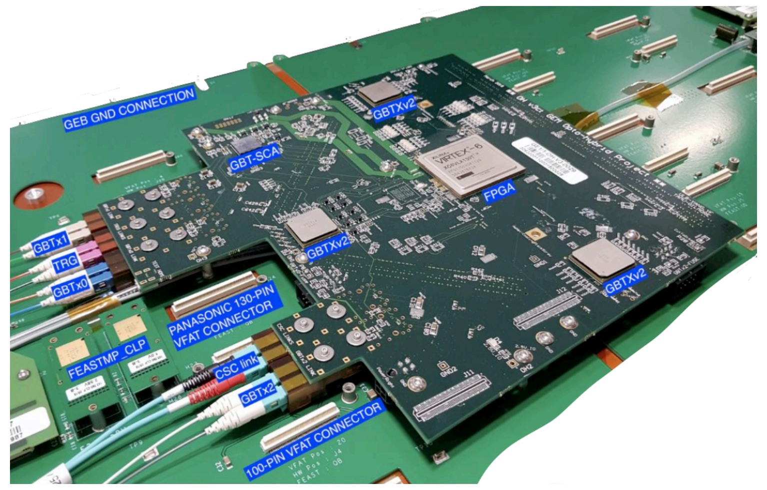
24 VFAT3s



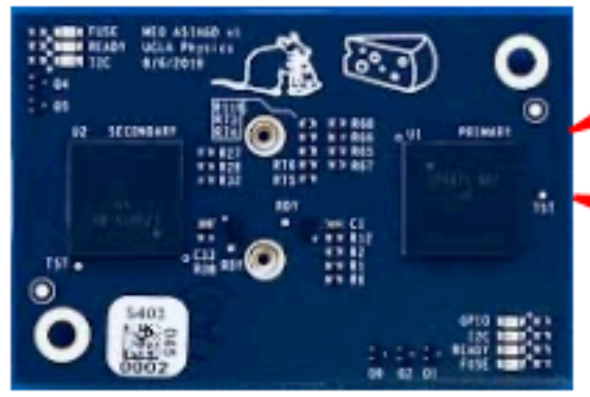
VFAT3 Hybrid (rigid)



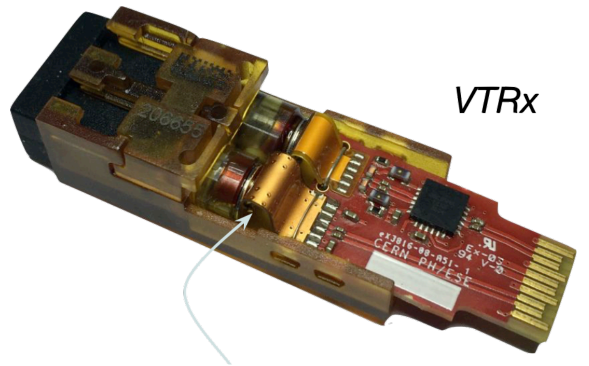
VFAT3 Plug-in card
(incl. flex part)



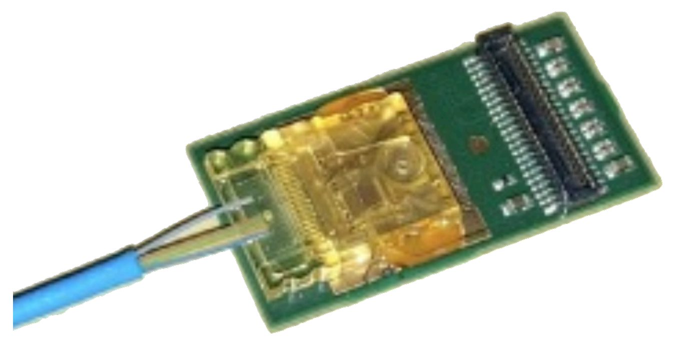
Opto-Hybrid incl. FPGA



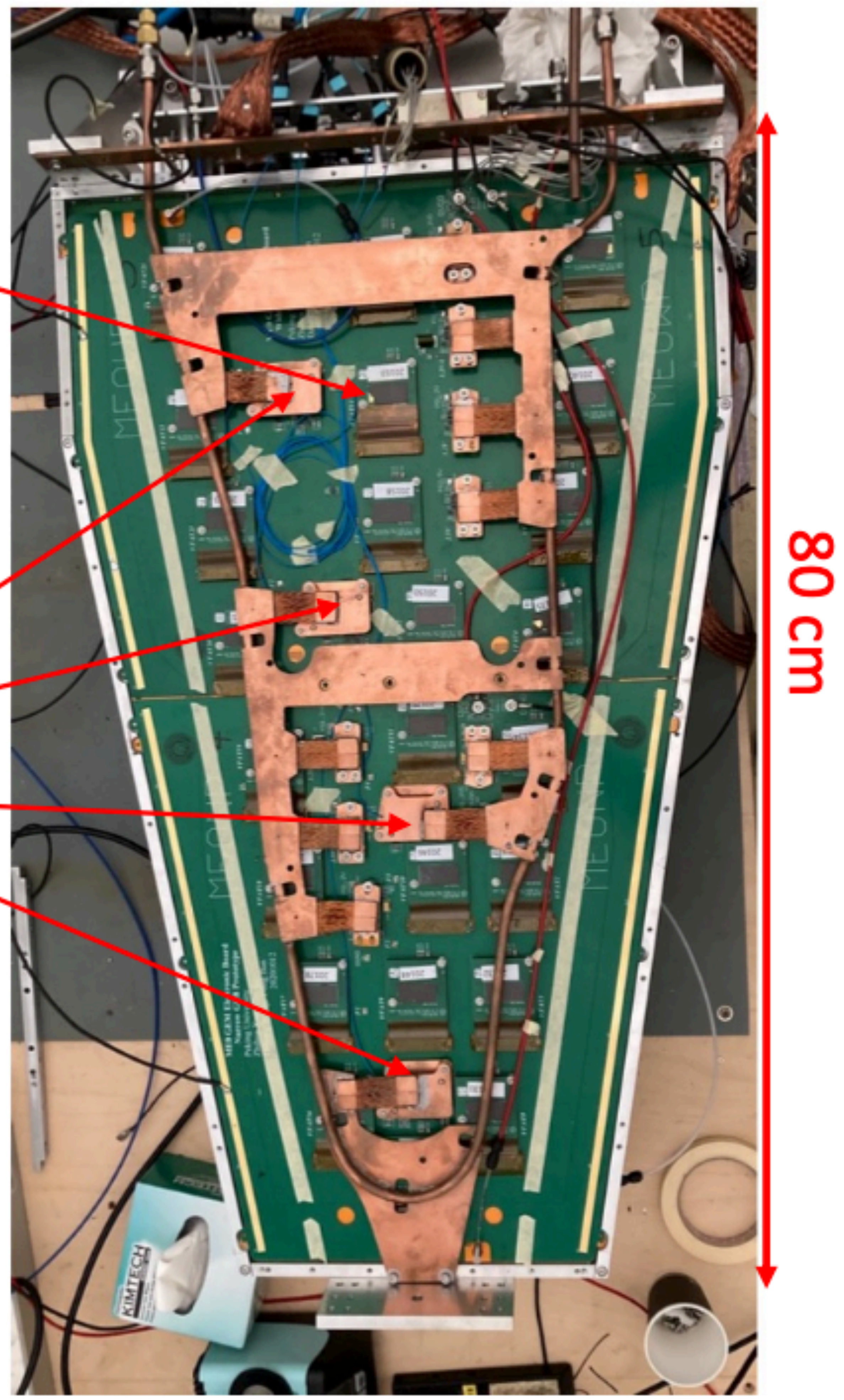
FPGA-less Opto-Hybrid
with 2 LpGBTs



VTRx



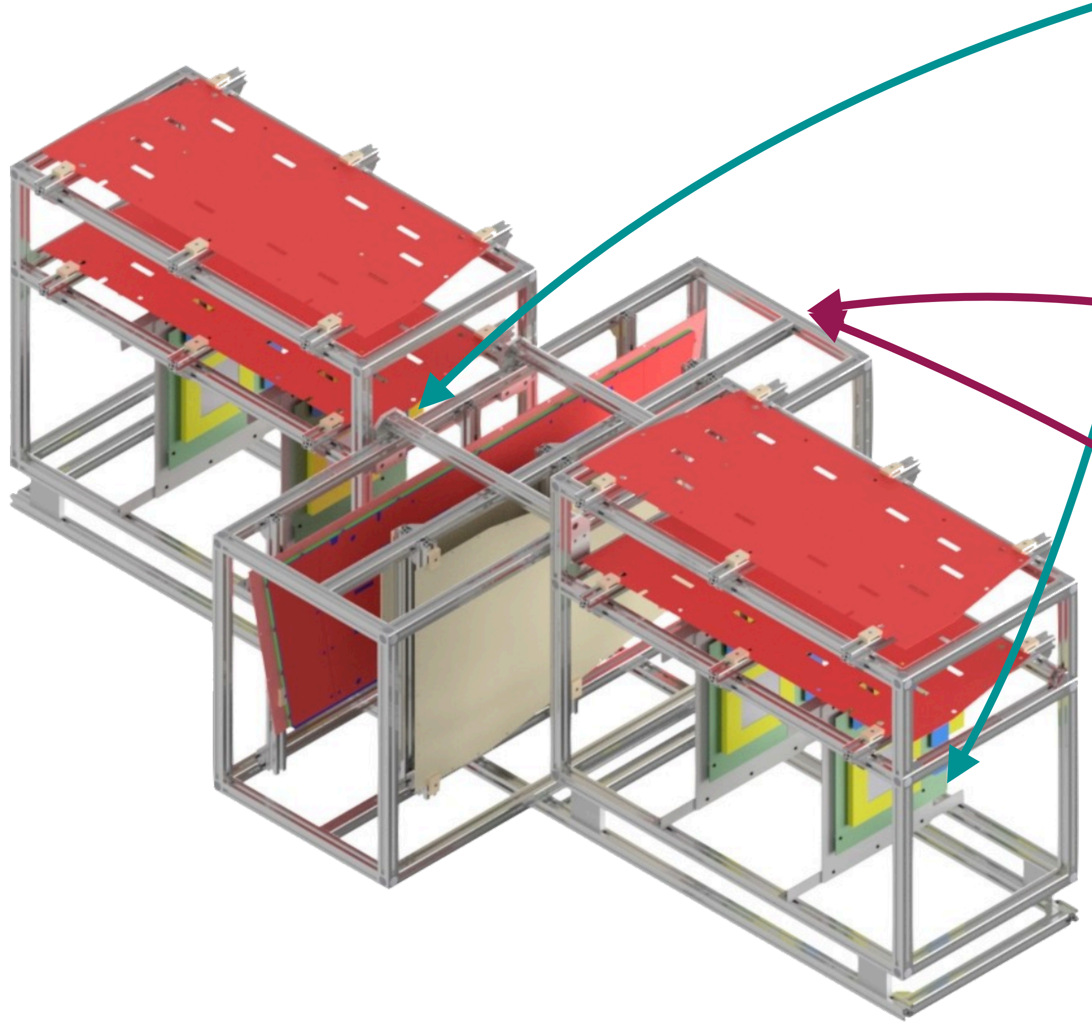
VTRx+



24 VFAT3s

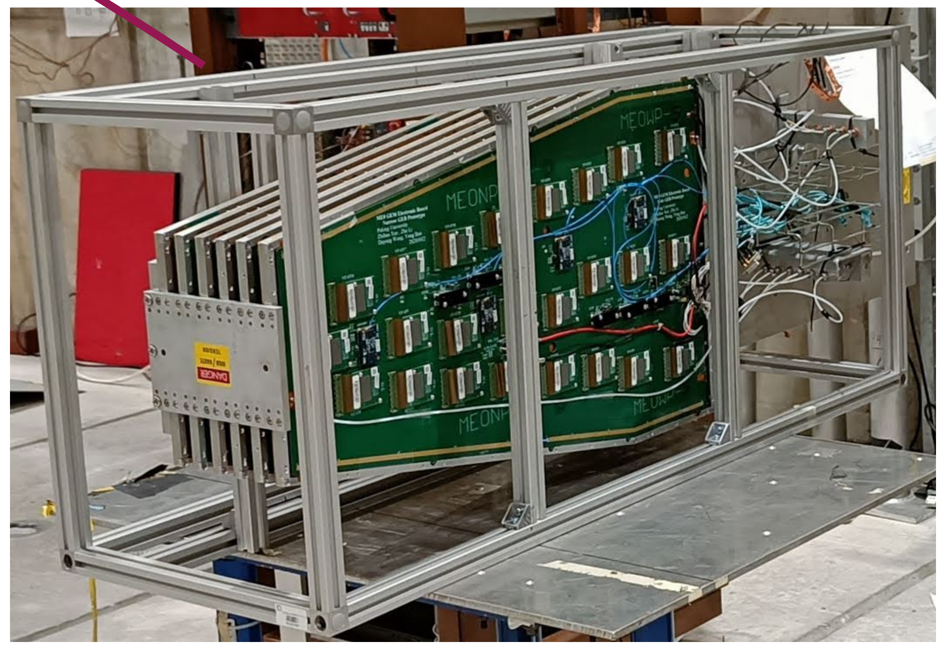
Latest Result: Time Resolution of ME0 Stack in GIF

- First R&D and tests results were give by Piet Verwilligen at MPGD2022, includes:
new foil design, new technique during GEM foil etching, rate capability tests at GIF with 2 layers ME0, effective gain and efficiency measurements.



Tracker:
4 * 10 × 10 cm^2 tripel-GEM detector

ME0 stack under test would be placed here.



- A prototype was used in Test Beam study this year summer at CERN **Gamma Irradiation Facility (GIF)**:
muon beam with momentum up to 100 GeV/c & background from Cs-137 source.

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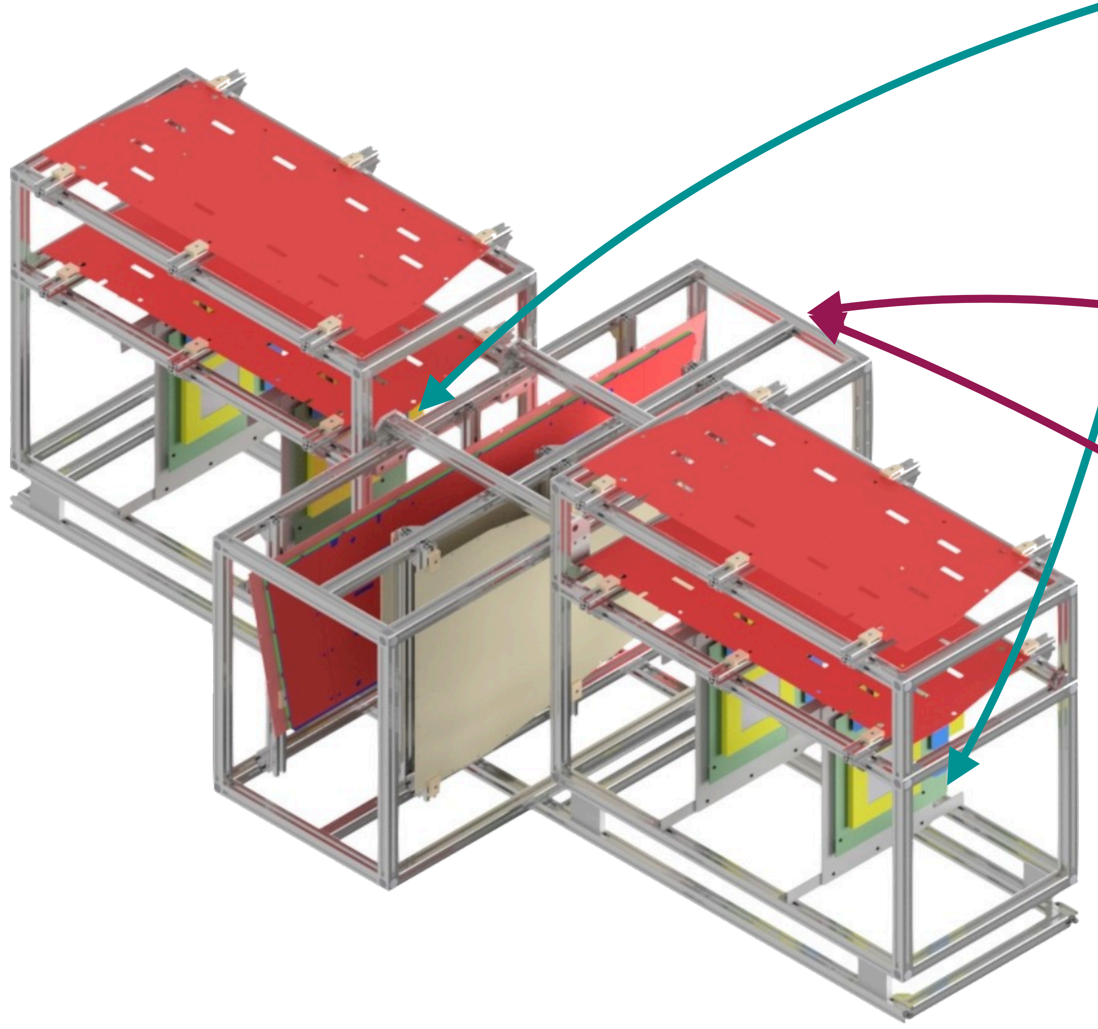

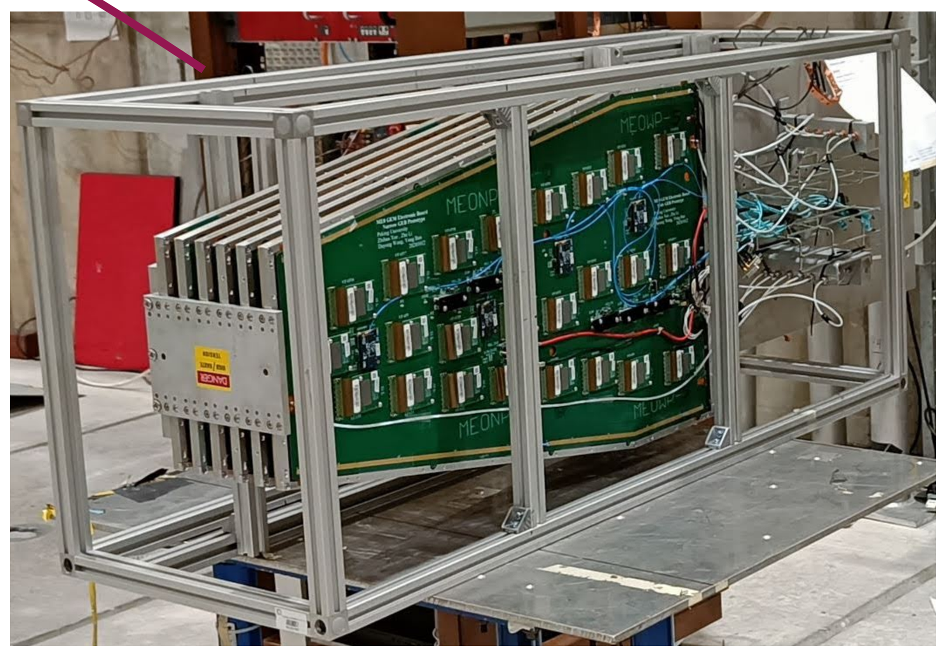

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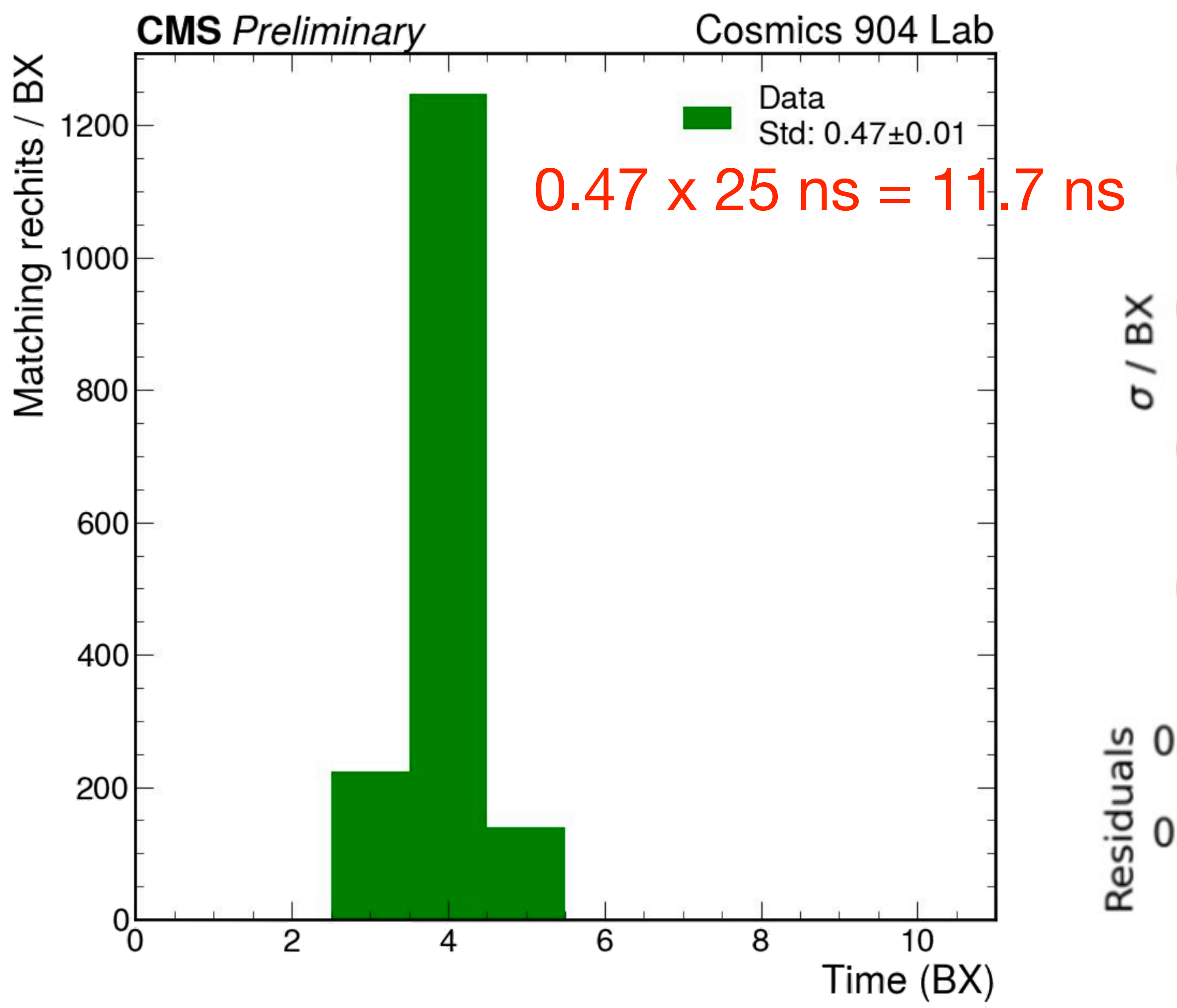
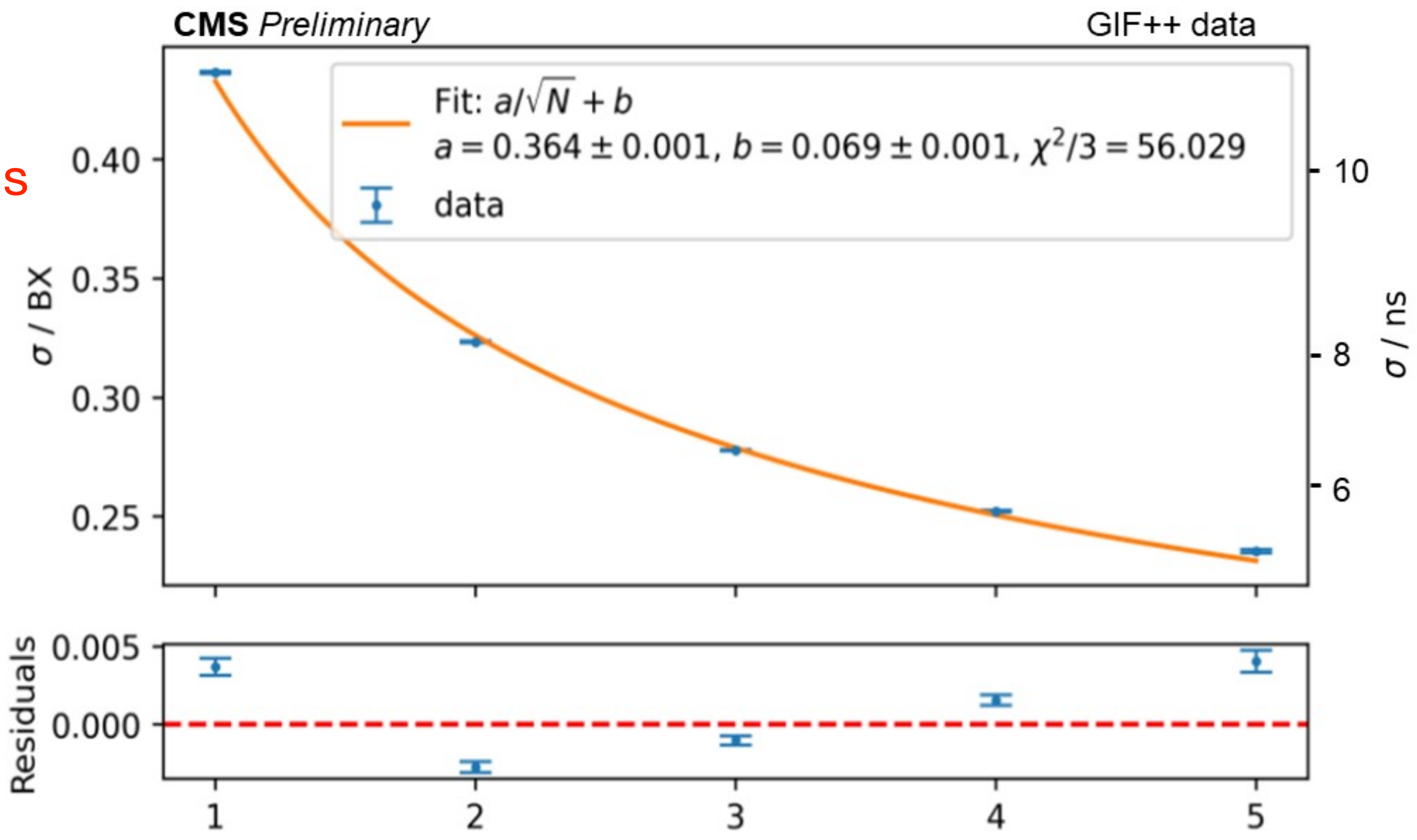


Distribution of the arrival times of the matching rechits for one of the six chambers in the stack

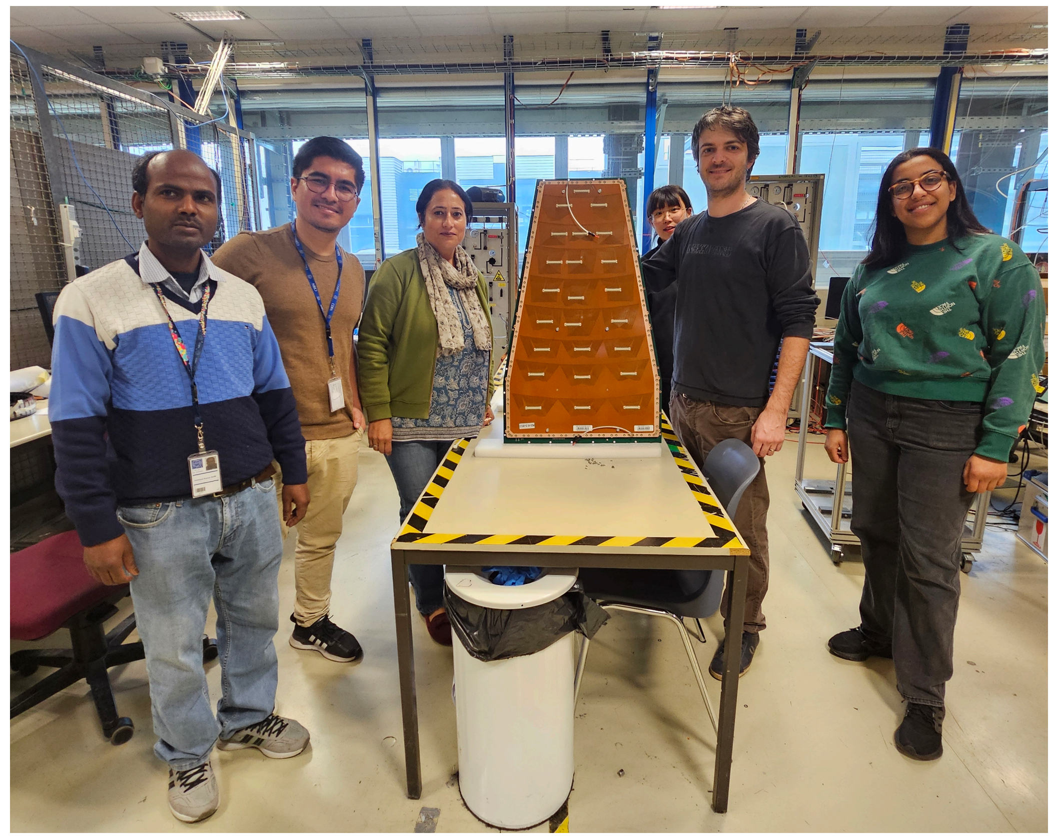


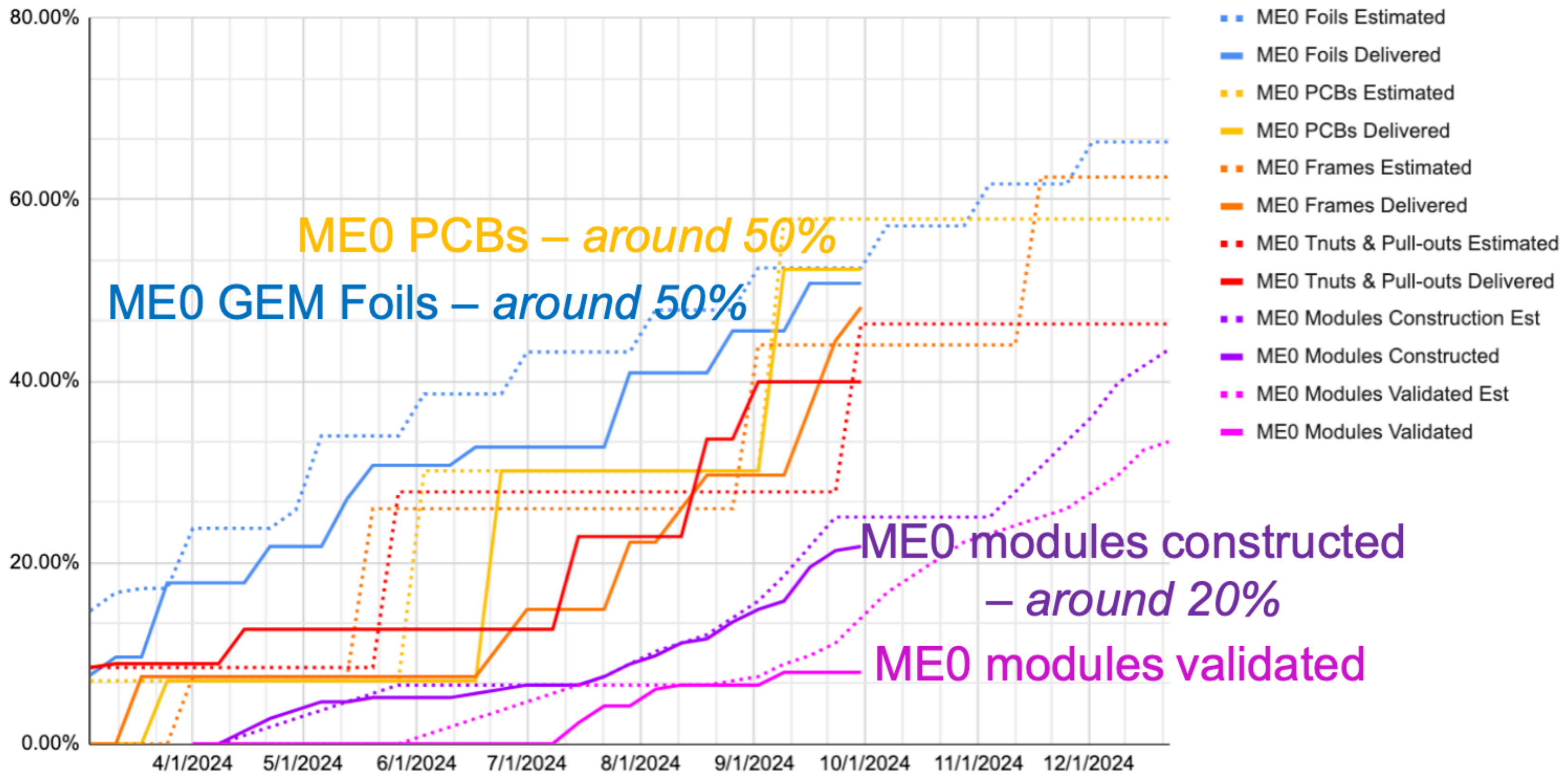
Average time resolution of track segments as a function of the number of ME0 chambers (layers) used to reconstruct the segment.

- A prototype was used in Test Beam study this year summer at CERN **Gamma Irradiation Facility (GIF)**:
muon beam with momentum up to 100 GeV/c & background from Cs-137 source.
- Time resolution: 0.24 BX corresponding to **6 ns**.
- More Test Beam results are under approval: Cluster size distributions, Average rate per strip, Residual distribution, Efficiency, Track slope, Rate capability.

ME0 Production

- A prototype was made for Test Beam in April 2024.
- Then **38** modules assembled since April 2024 in different production sites.
- Beside the GE2/1 approved production sites: CERN, Bari, Frascati, Ghent/Aachen and Peking, 6th & 7th sites Panjab and Delhi are going through Site Approval.
- Module Quality Control tests going smoothly.
- Stack production components status being closely monitored.





ME0 PCBs – *around 50%*

ME0 GEM Foils – *around 50%*

ME0 modules constructed – *around 20%*

ME0 modules validated

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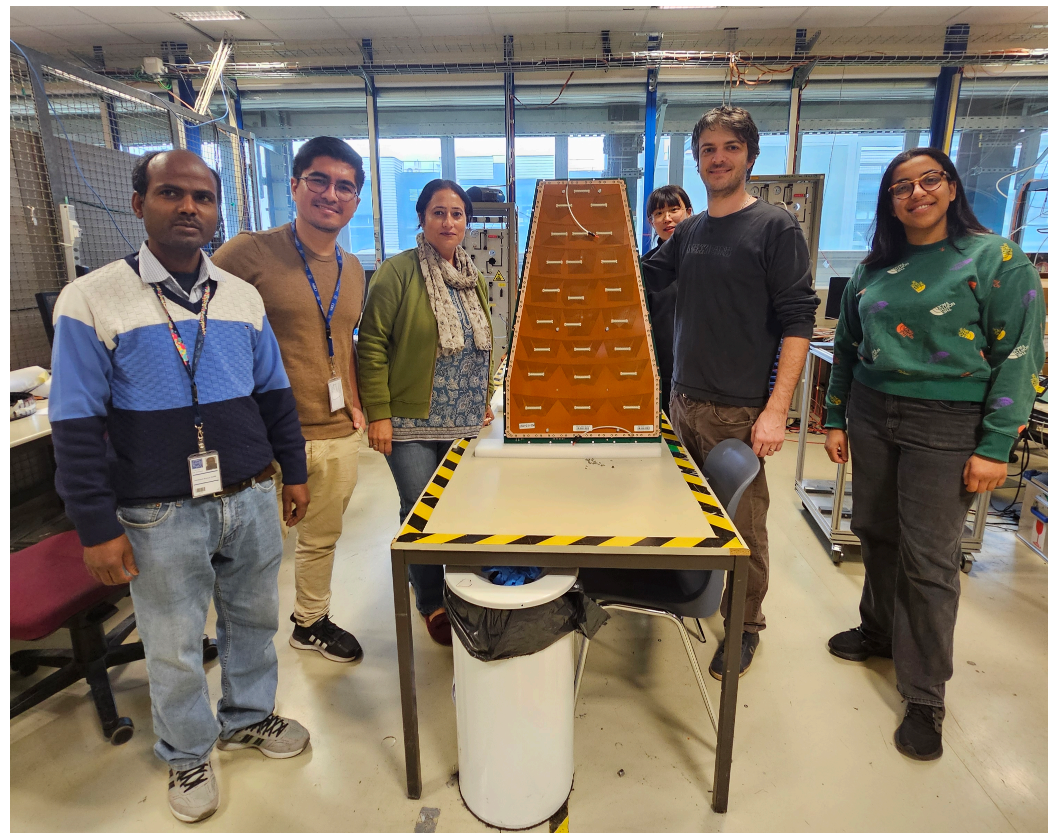
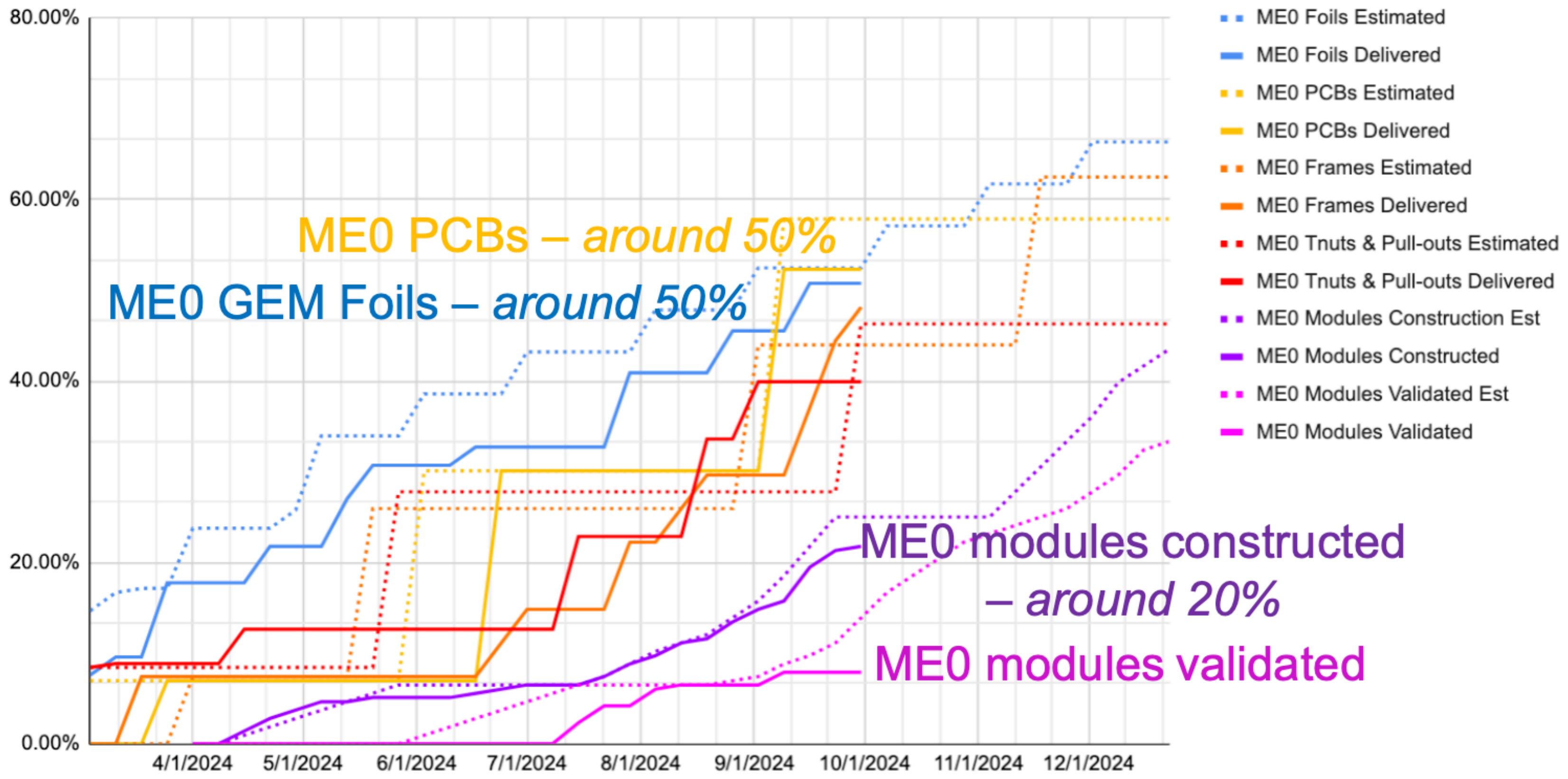
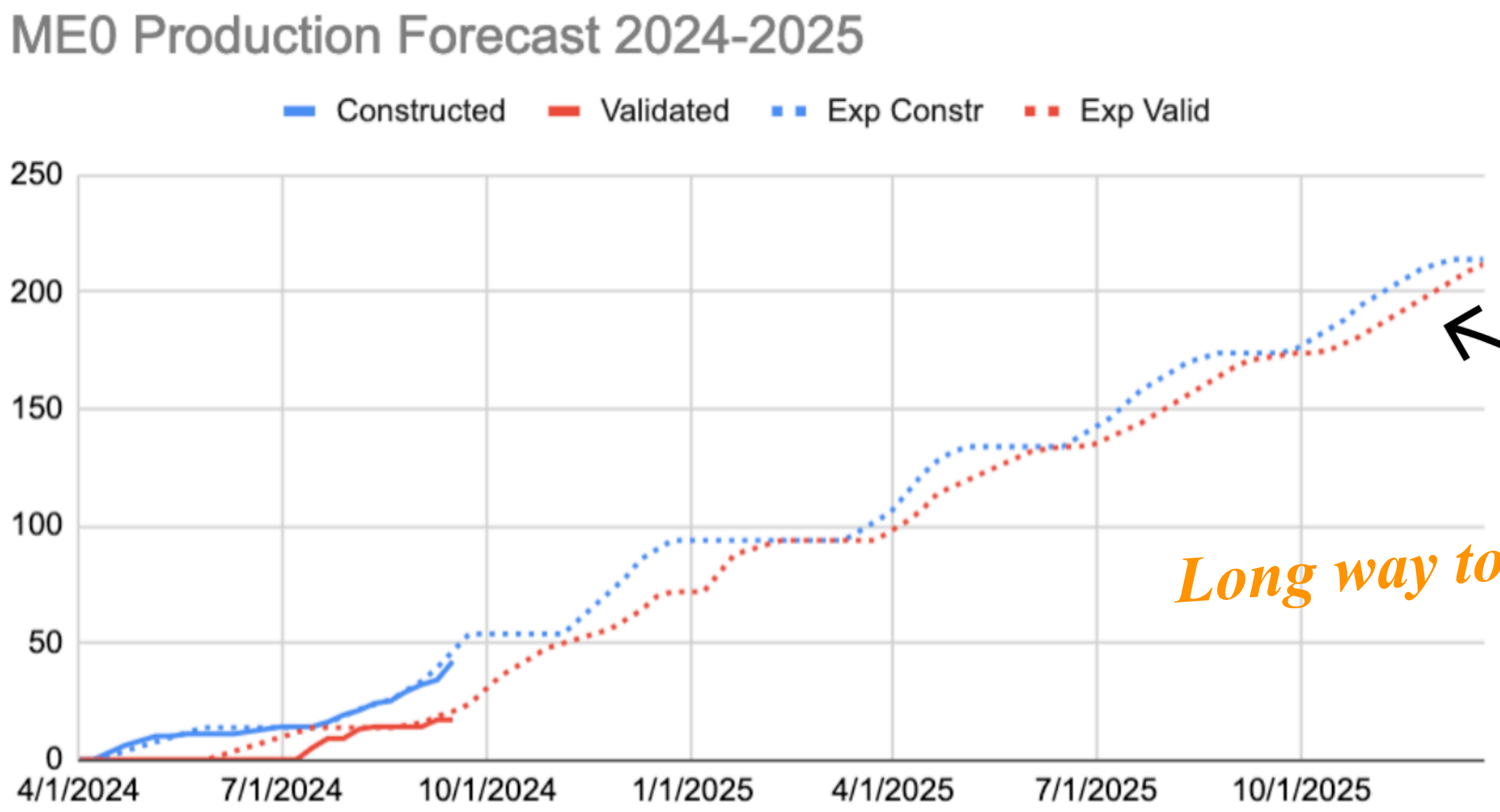


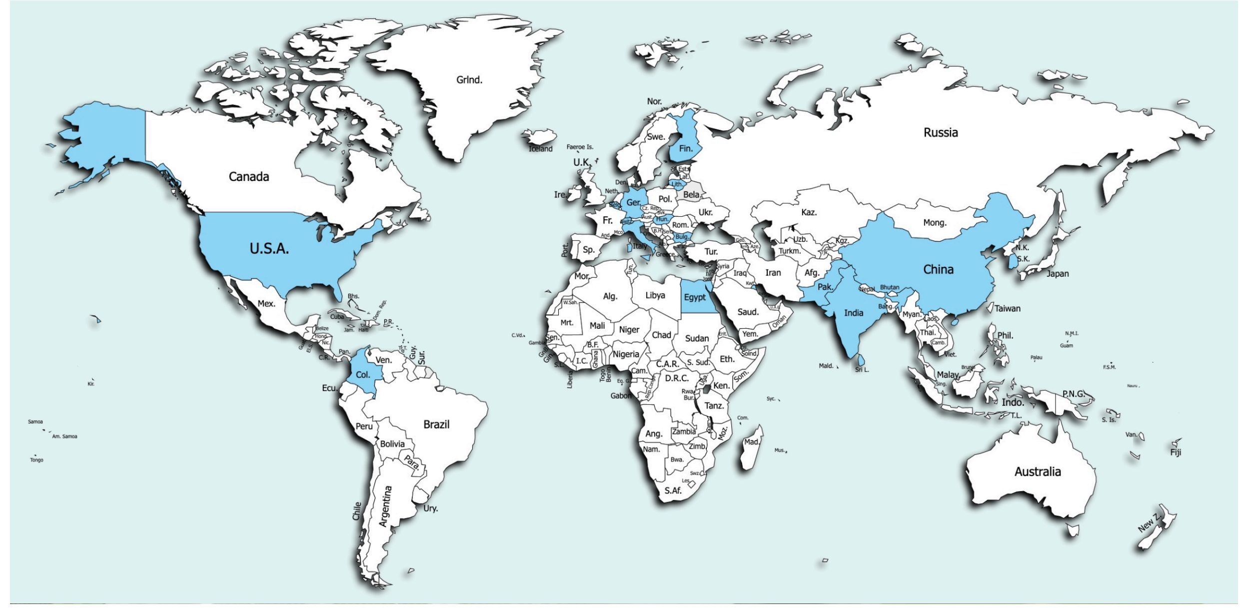


- **Plan before LS3:**
  - Maintain module assembly and validation rate.
  - Start stack production in 2024.
  - Assemble & validate all 18 stacks by End of 2025!



Long way to go but we will be there!

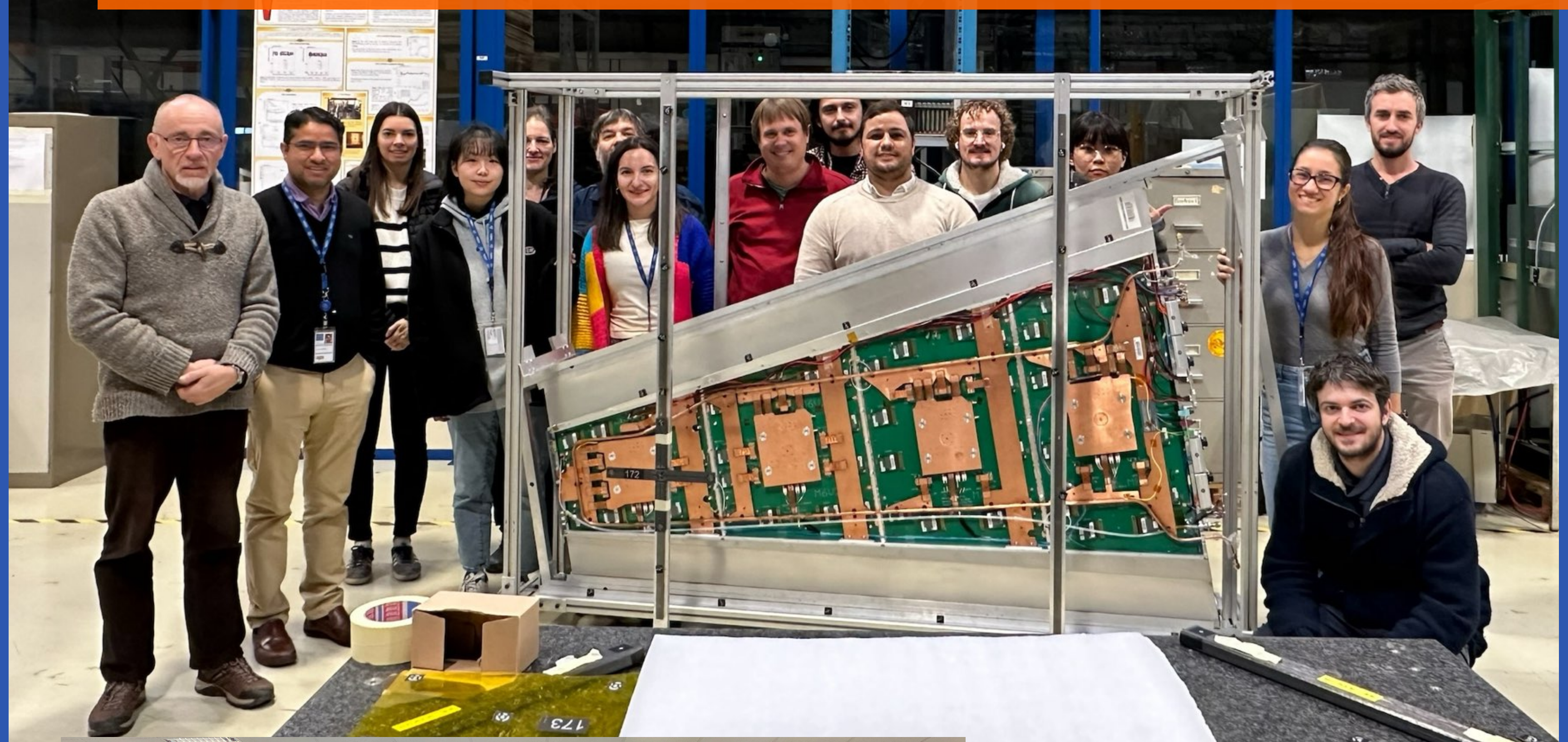
Outlook

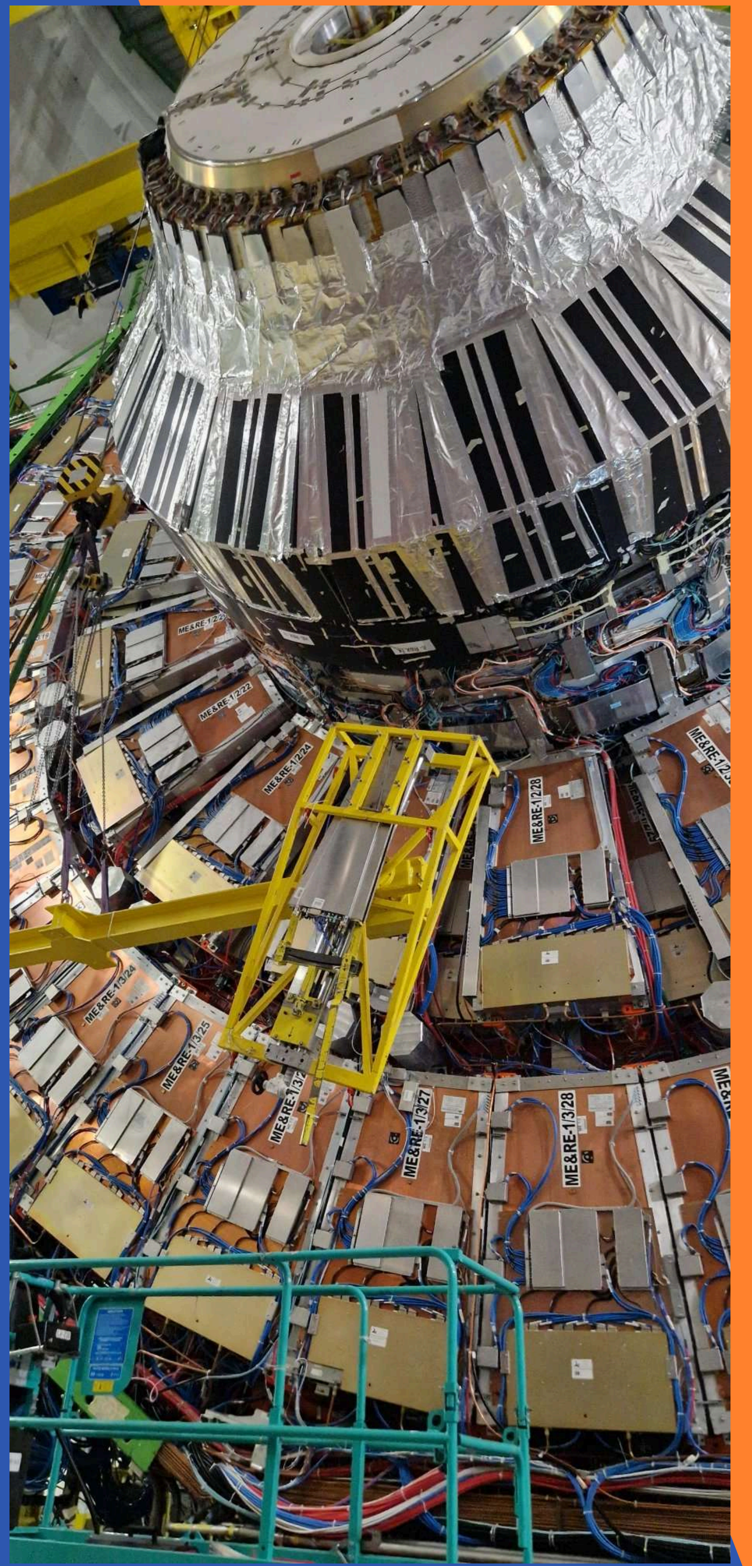
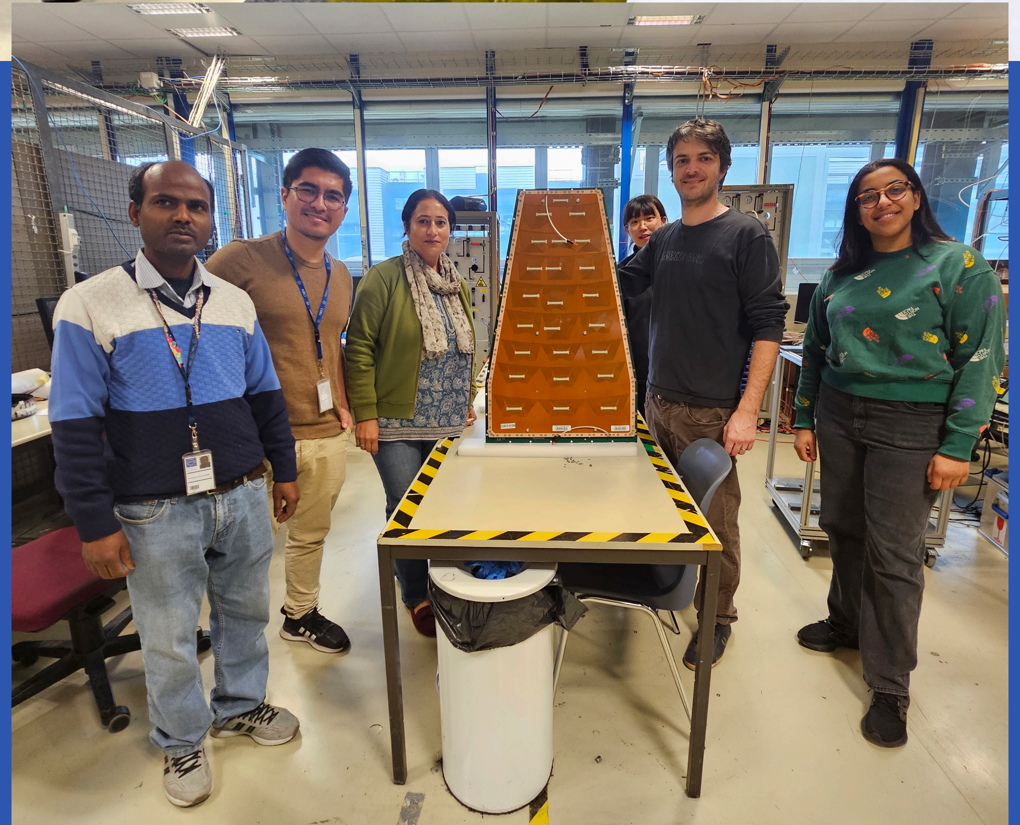


- **CMS GEM collaboration has 190 authors, from 38 institutes and 15 countries.**
- GE1/1:
  - stable operating since Run3 in 2022, collected total ~180 fb-1 (until Sep 2024) .
  - at them same time we are gaining experience, tuning the detector to have better performance.
  - intervene in LS3 to have electronics refurbishment.
- GE2/1:
  - first 6 chambers will finish installation by early 2025, rest is postponed till after LS3 to give priority to ME0.
- ME0:
  - validated prototype detectors to have the final performance, started production.



THANK YOU FOR YOUR ATTENTION!

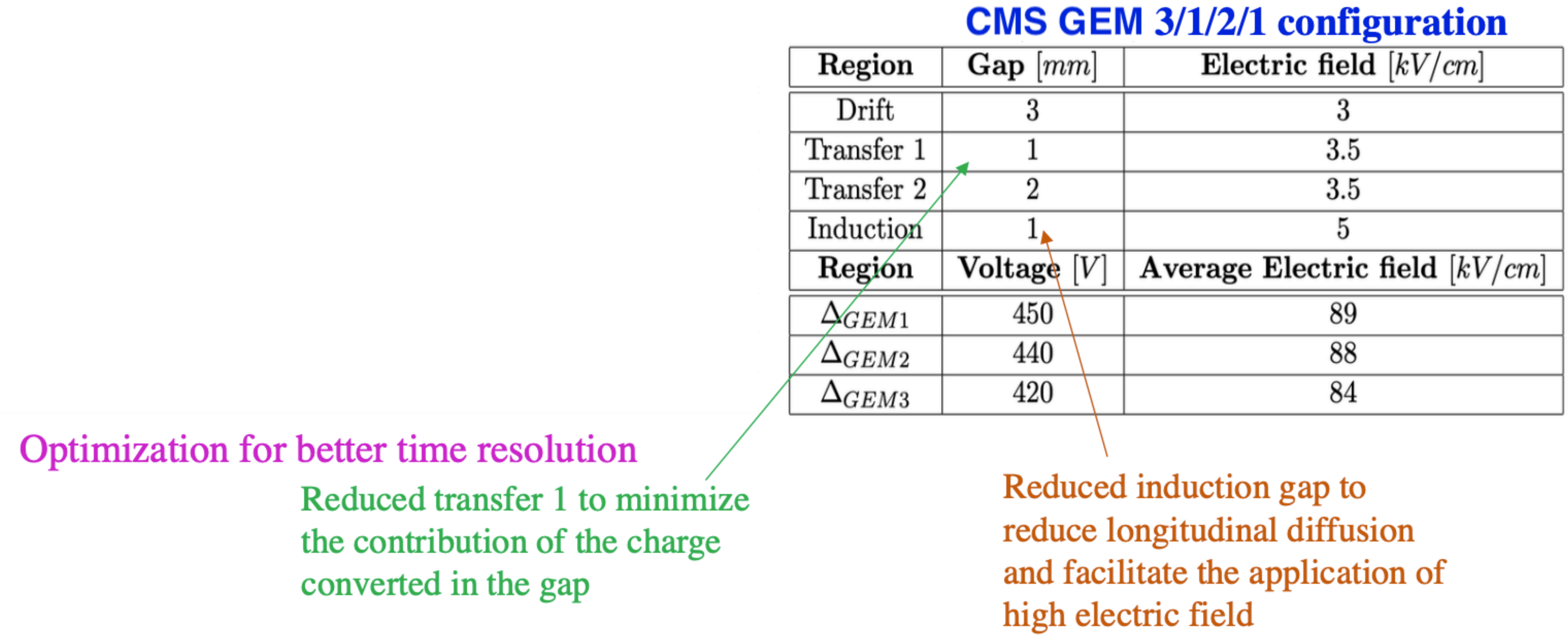



Acknowledgement: Simone Calzaferri, Pieter Everaerts, Johny Jaramillo, Seulgi Kim, Gilles De Lentdecker, Antonello Pellecchia, Jeremie Merlin, Giovanni Mocellin, Piet Verwilligen.

CMS Triple GEM

- Drift gap is usually larger (e.g. 3mm) to maximize the sensitivity to incoming particles (and ensure sufficient number of primary charges).



CMS GEM 3/1/2/1 configuration

Region	**Gap** $[mm]$	**Electric field** $[kV/cm]$
Drift	3	3
Transfer 1	1	3.5
Transfer 2	2	3.5
Induction	1	5
Region	**Voltage** $[V]$	**Average Electric field** $[kV/cm]$
Δ_{GEM1}	450	89
Δ_{GEM2}	440	88
Δ_{GEM3}	420	84

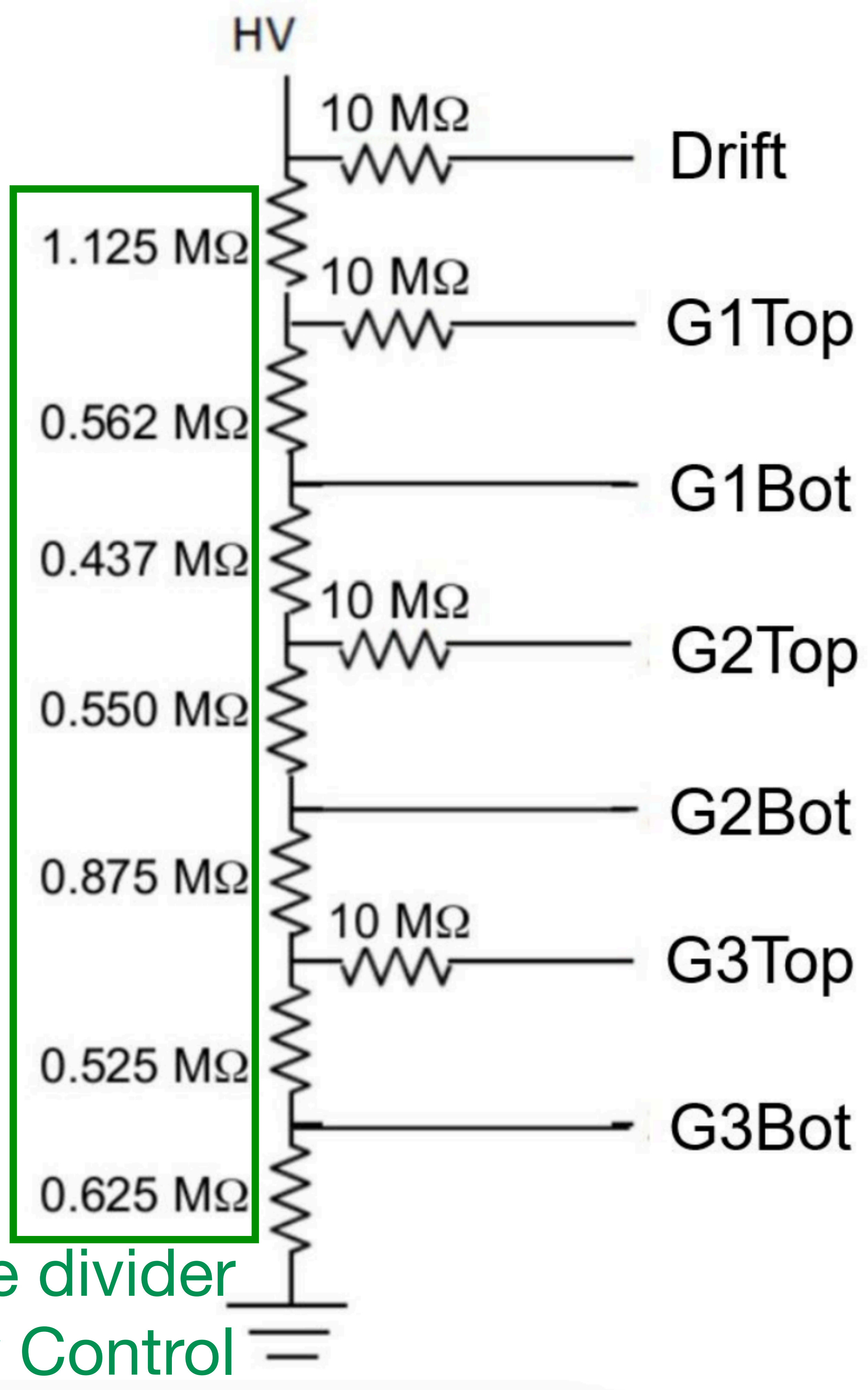
Optimization for better time resolution

Reduced transfer 1 to minimize the contribution of the charge converted in the gap

Reduced induction gap to reduce longitudinal diffusion and facilitate the application of high electric field

GEM Working Point & I_{eq}

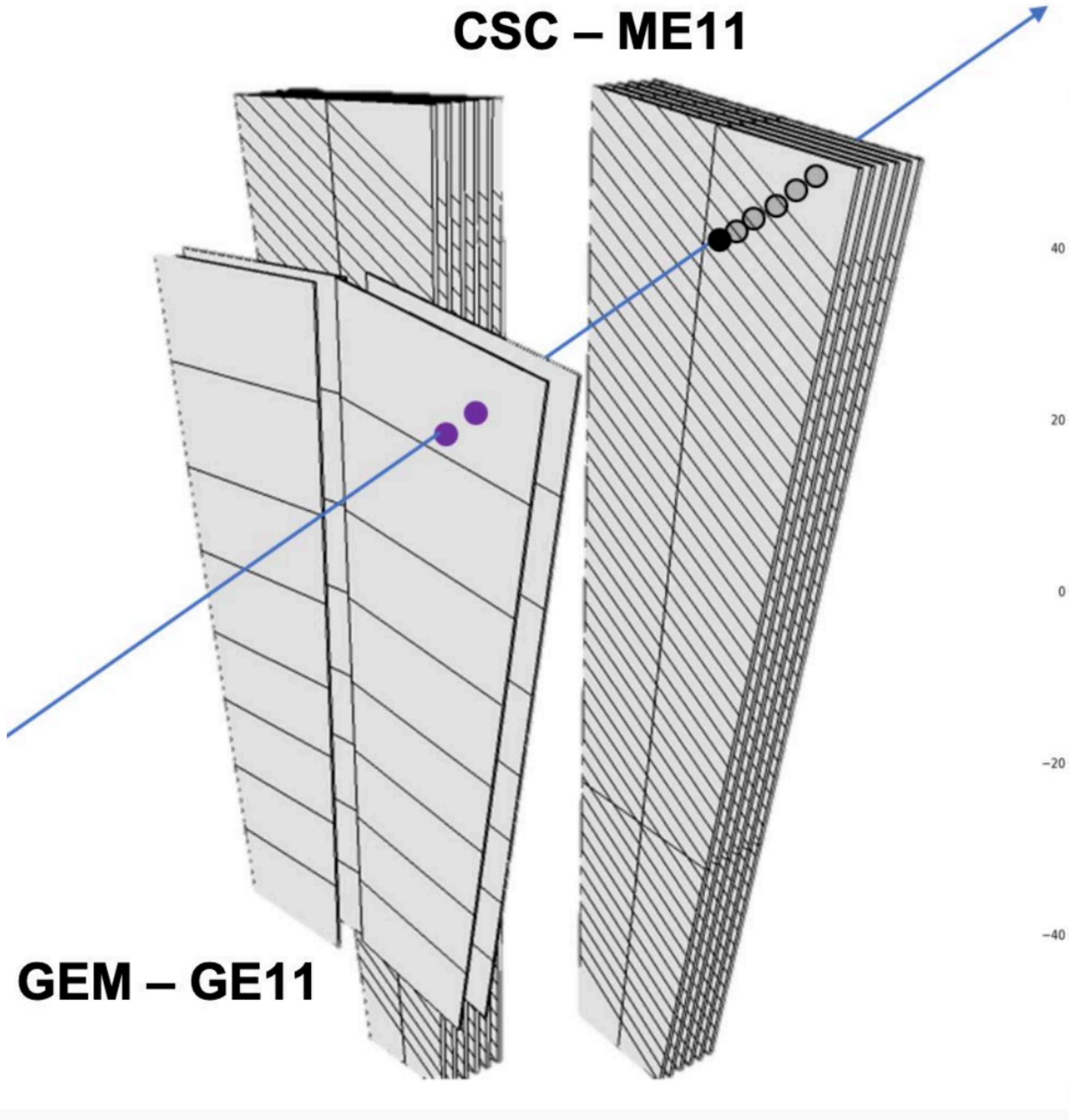
- High Voltage working point in GEM Triple GEM GE1/1 detectors in CMS are powered by customer-made CAEN A1515BTG multichannel boards.
- During operations in CMS, the voltage of the 7 electrodes needed to power the detector are fixed taking as reference the resistor divider in the figure. This divider was just used during the quality control in the phase of production of the detectors.
- To easily identify with a single number the set of 7 voltages set on the detector, we use the equivalent current I_{eq} that would flow in the reference resistive divider.

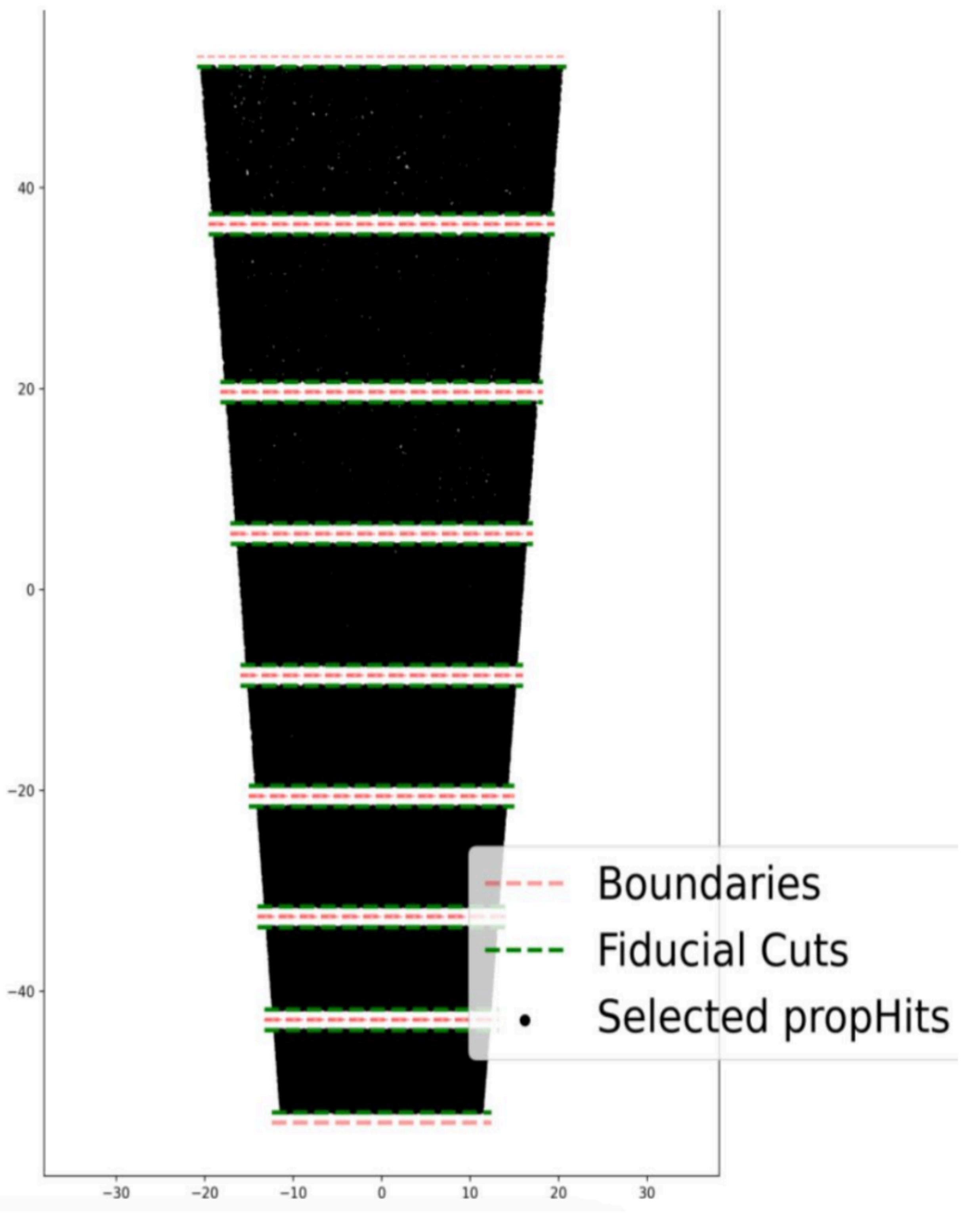


reference divider
during Quality Control

Efficiency analysis

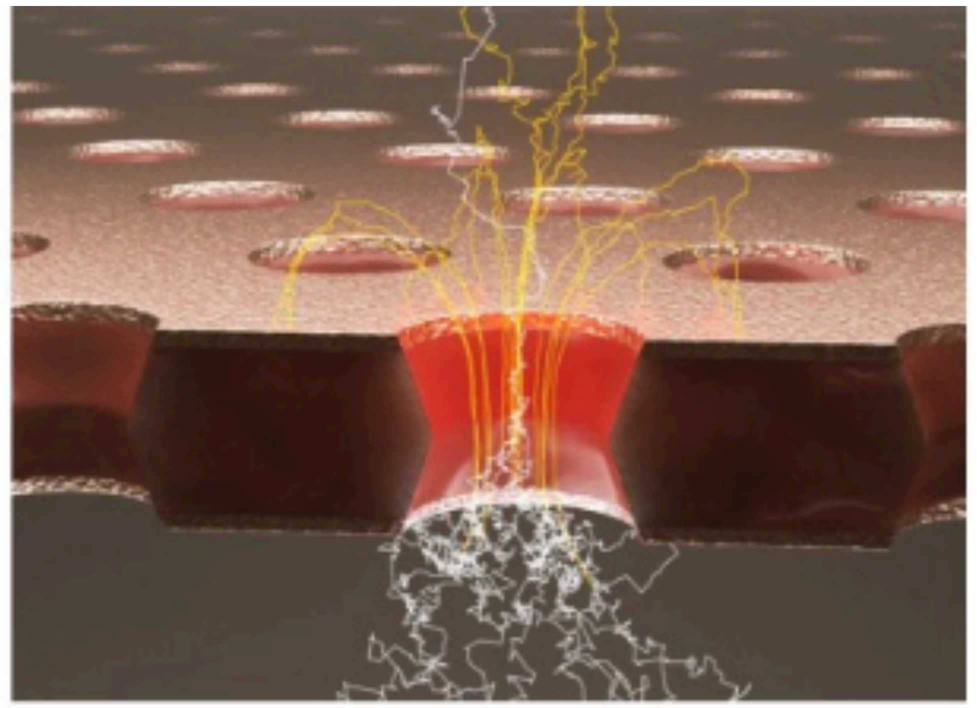
- Analysis based on events with standalone (STA) muons (with beamspot constraint):
  - Selected with $p_T > 10$ GeV, at least 15 hits in the muon system, and $\chi^2 < 5$.
  - Only consider muons with hits in the CSC companion station (i.e. accept a track through GE1/1 only if it contains ME1/1 hits).
  - Propagation cuts:
    - Propagation Error ϕ <0.005 rad;
    - Propagation Error R < 1 cm;
  - Fiducial Cuts:
    - 0.0075 rad along chamber from lateral edges;
    - 1.5 cm along local Y;

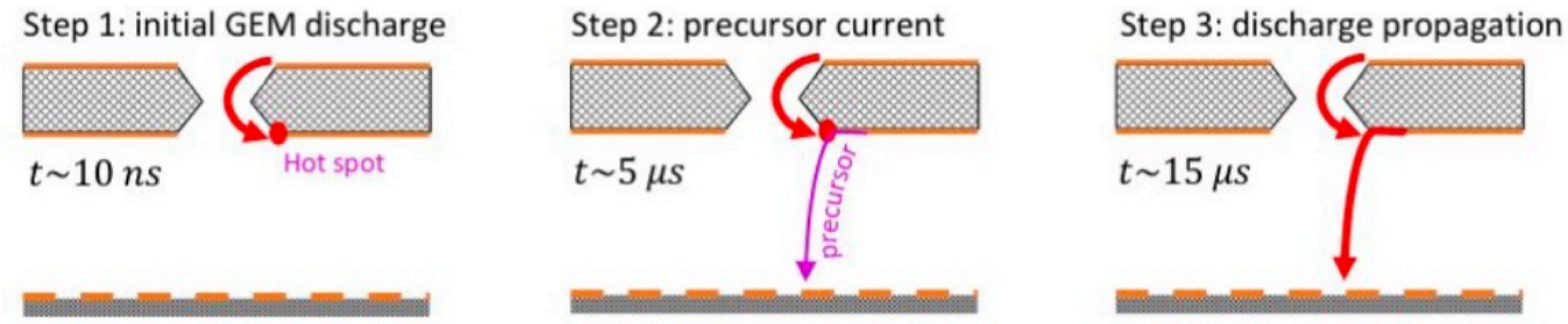




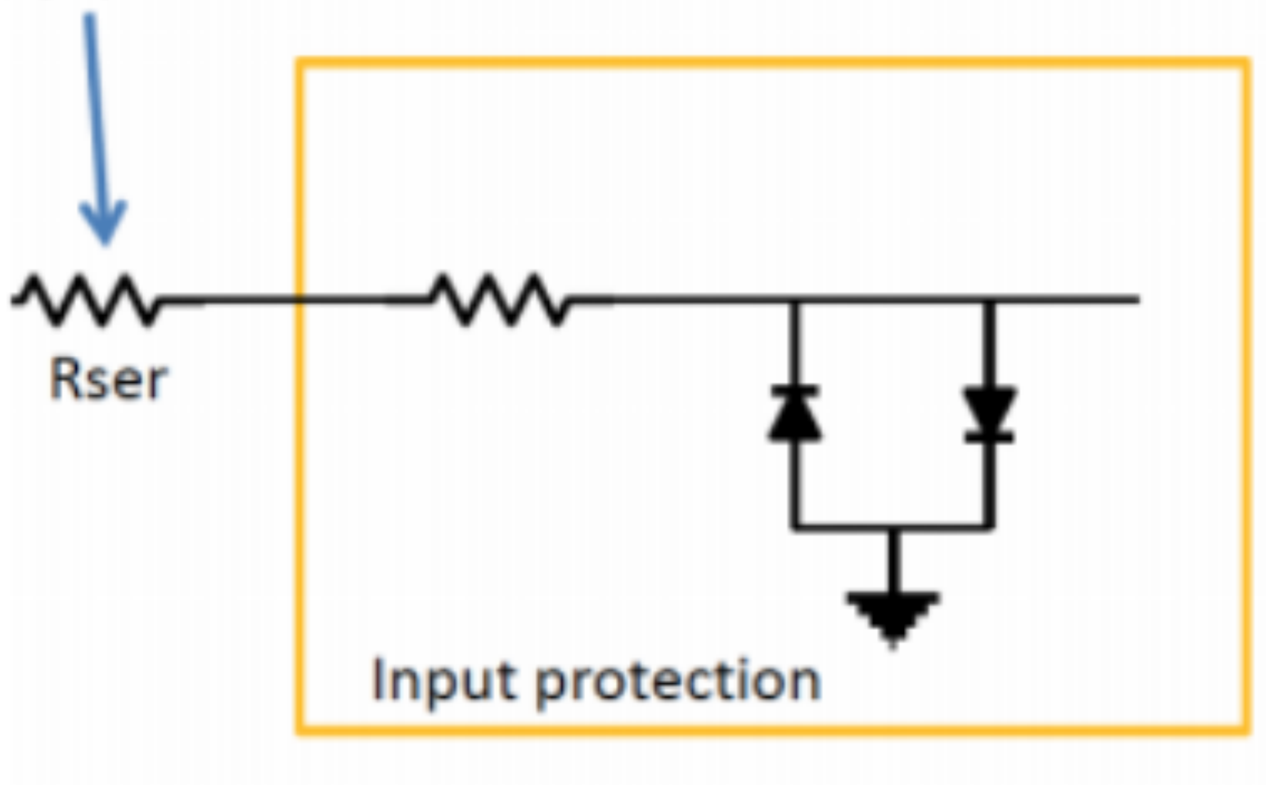
- Definition: the efficiency is calculated as the fraction of events where a reconstructed hit is found near a propagated track, for chambers correctly communicating and powered with certain HV settings.
- The segments are according to front-end chip (VFAT3) readout regions (128 channels per chip).
- The chamber was powered on at HV 695 μA equivalent divider current & using the VFAT3 pre-amplifier in high gain + CFD comparator settings.

6. Damages on electronics due to discharges



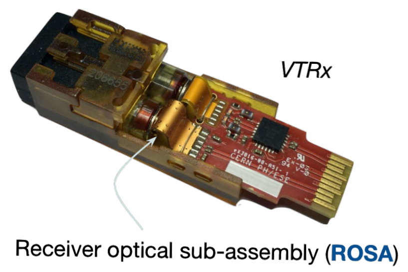


VFAT3 channel input protection:
430 **Ω**



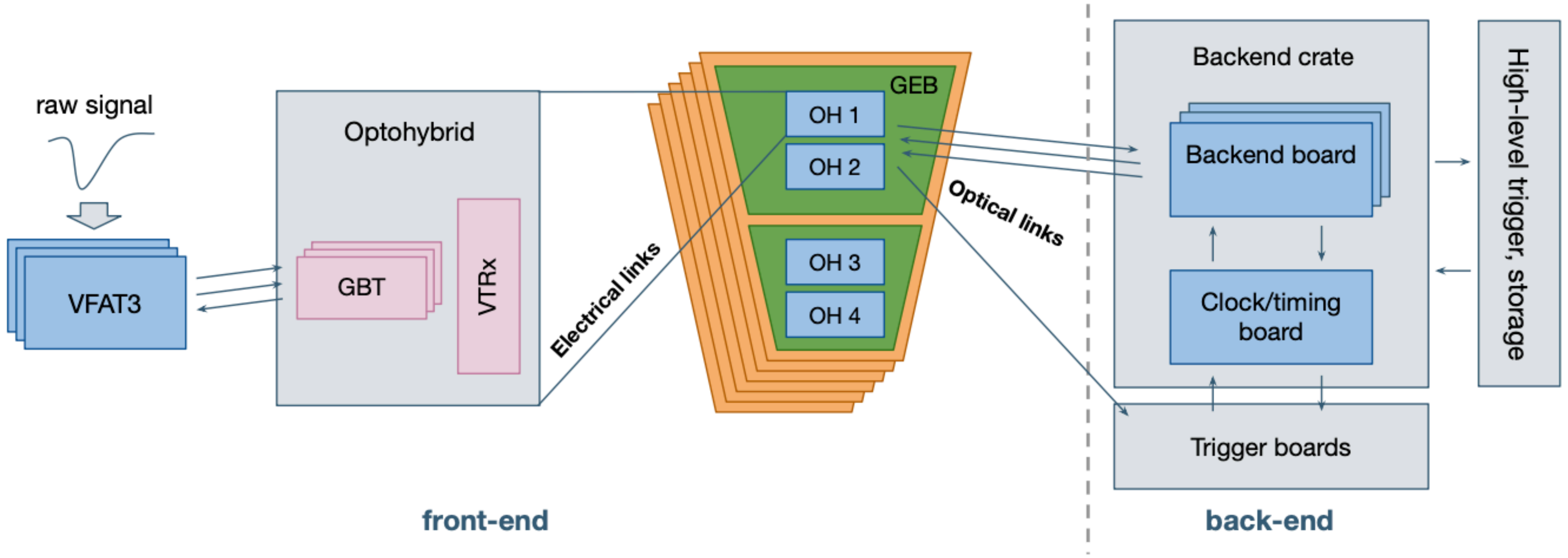
VTRx Outgassing issue

- STA alone muon
- VFAT high CAD ARM



: outgassing of epoxy glue in the ROSA shields the light coming from the fibers, -> communication with back-end becomes unstable.

6. GEM Readout Architecture



VFAT3: Front-end ASIC to read out, discriminate and send data to optohybrid.

The OptoHybrid: a concentrator board providing interface for the VFAT3 readout and trigger.

- Gigabit transceivers (GBT): receive and transmit data from the VFATs and communicate with the back-end through the VTRx .Each GBT “controls” more than one VFAT.
- Versatile transceiver (VTRx): communicate with back-end and GBTx; convert optical data to electrical data
- FPGA (only on GE1/1 and GE2/1): clusters VFAT s-bit data and compresses them to send to trigger board . Not present on ME0 due to radiation hardness requirement.
- Slow control ASIC (SCA): handles the VFAT slow control

GE2/1 PCB Issues

1. Copper dust (RO PCB)

- The GE2/1 boards are sanded to remove small excess of adhesive which slipped through the vias during the manufacturing process.

-> Many microscopic copper residues between strips (not accessible with mechanical cleaning in lab).

2. No surface finish (RO and Drift PCBs)

- Organic Solderability Preservative (OSP) surface finish treatment did not applied at manufacturer for both GE1/1 and GE2/1 boards.

-> Absence of the passivation layer supposed to protect the metal against oxidation.

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Inspection of GE1/1 used for ageing test and 3 production chambers extracted from CMS, showed poor copper condition and strong signs of unusual oxidation in various regions.

GEM PCB Issues

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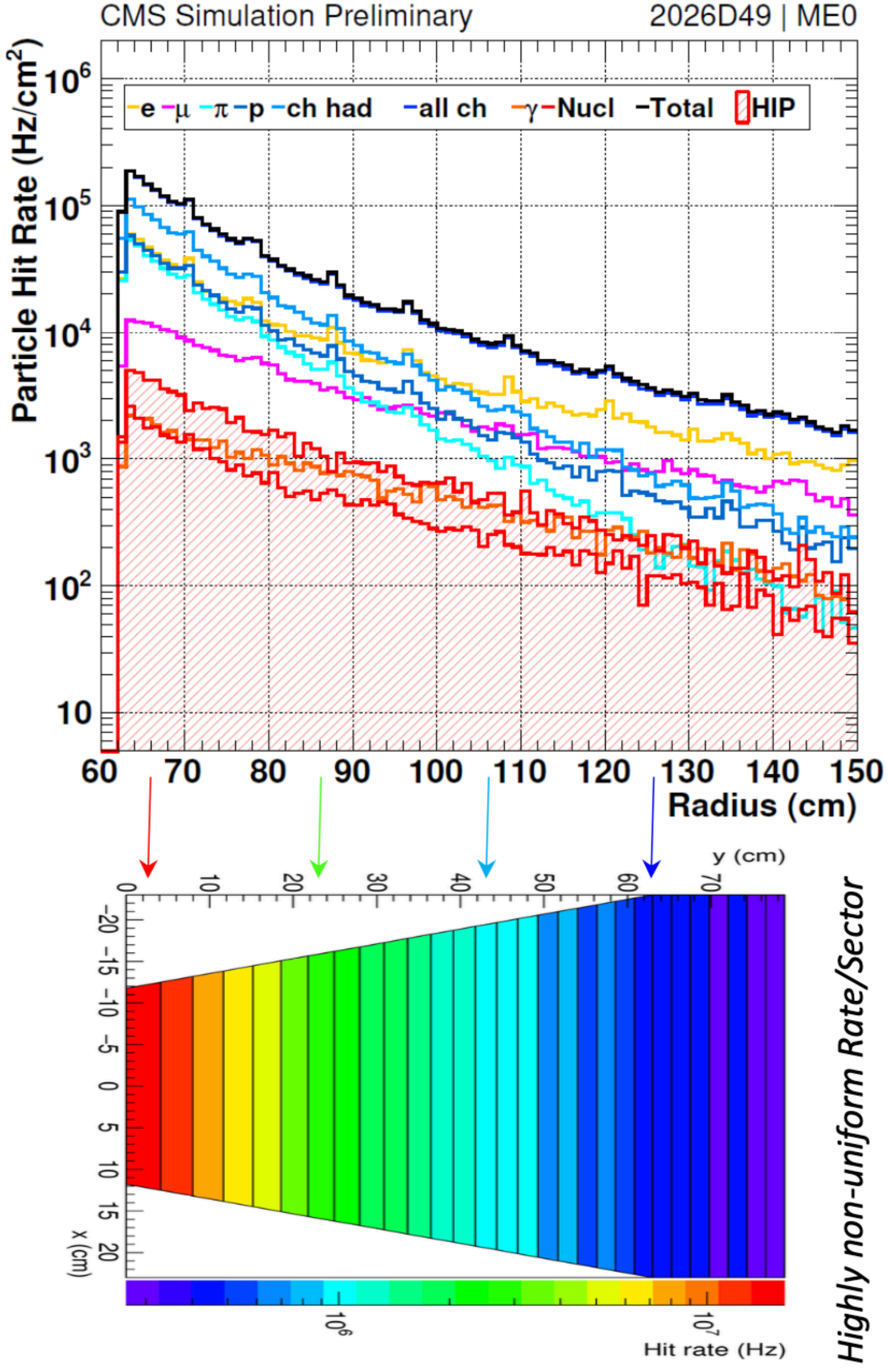
Consequence:

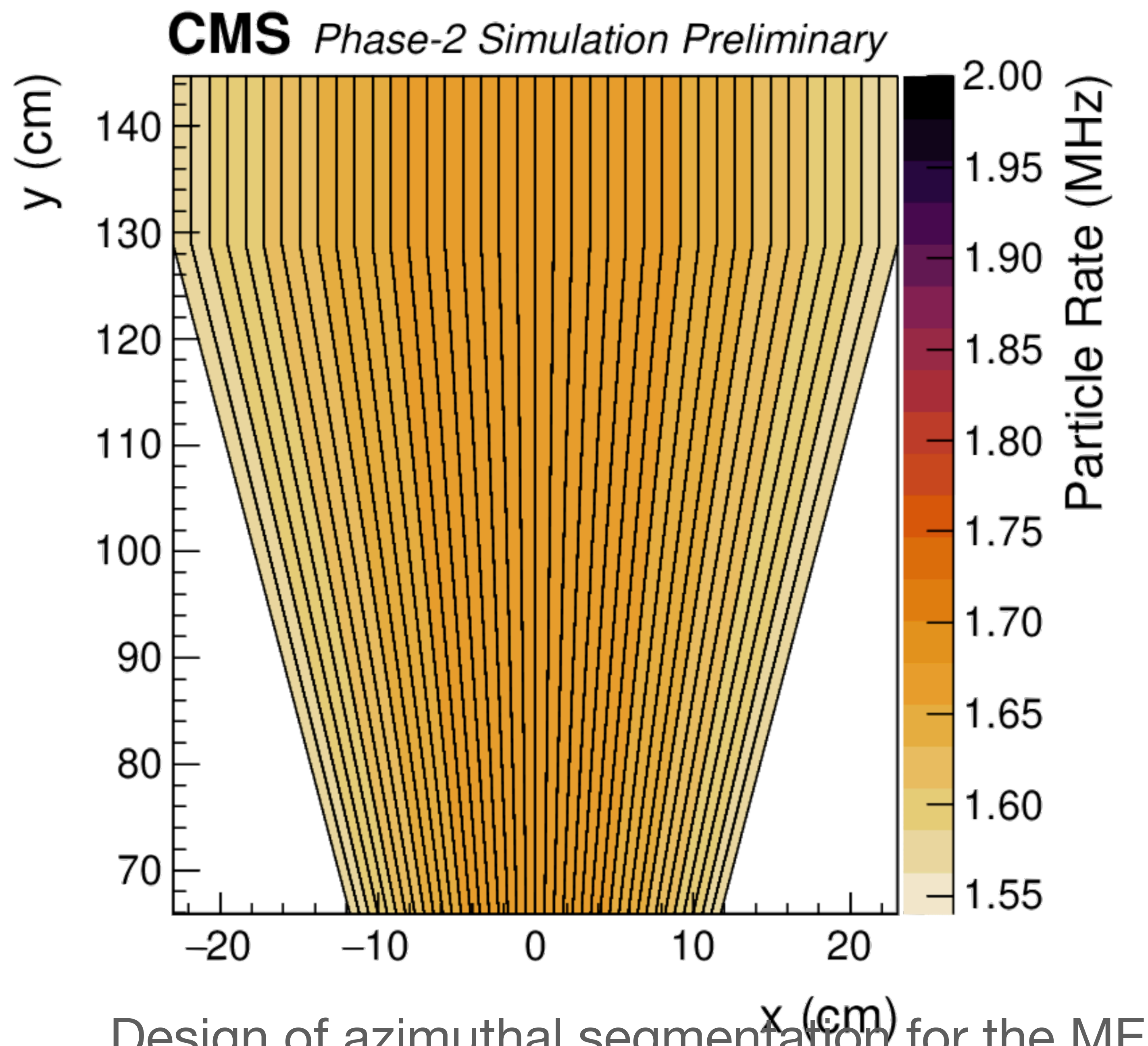
- The 96 modules (among them 52 already used to build 13 GE2/1 chambers) will have to be retrofitted.
- All the PCBs should be cleaned and passivation layers should be applied on them.
- A cleaning procedure must be set for the foil stack.
- A new additional step for PCB validation was introduced.

New Foil Design ME0

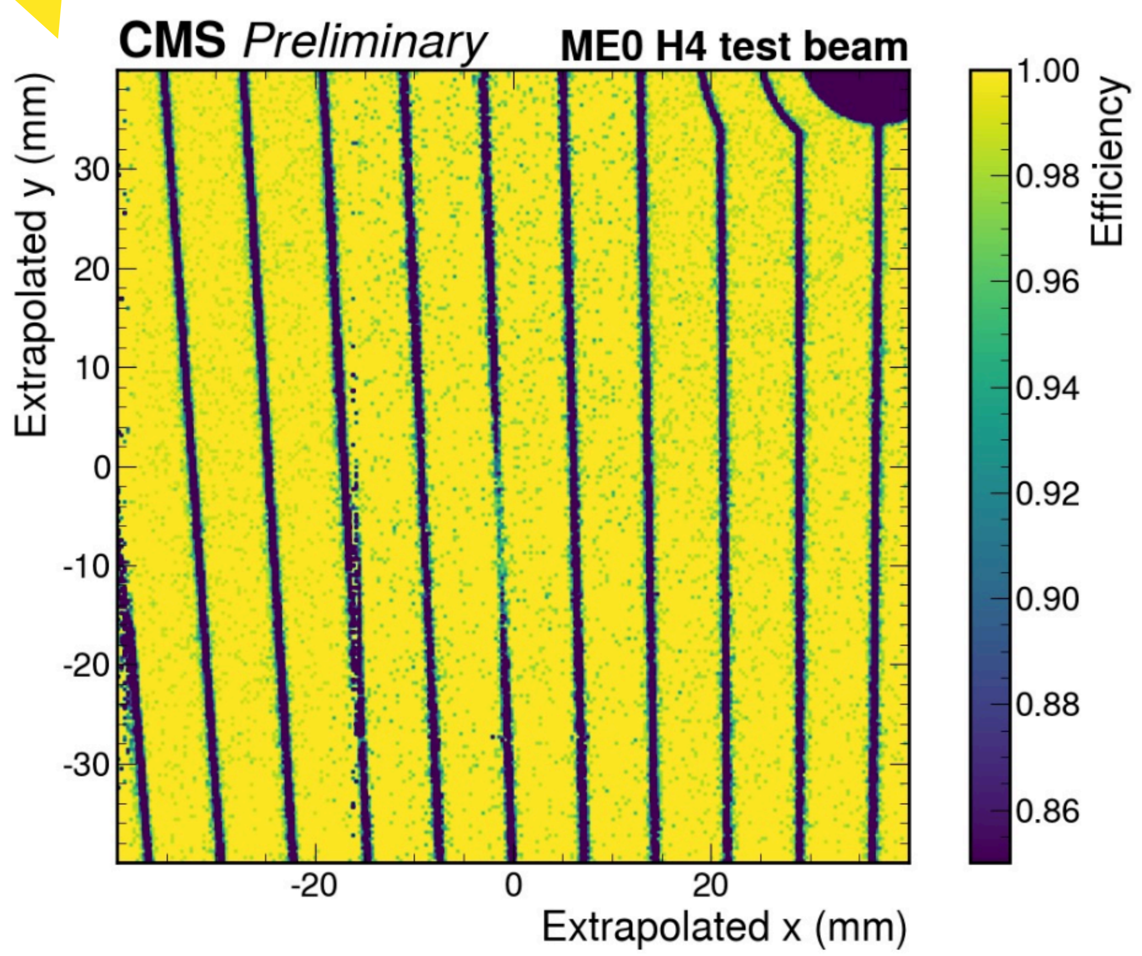


Highly non-uniform Rate/Sector

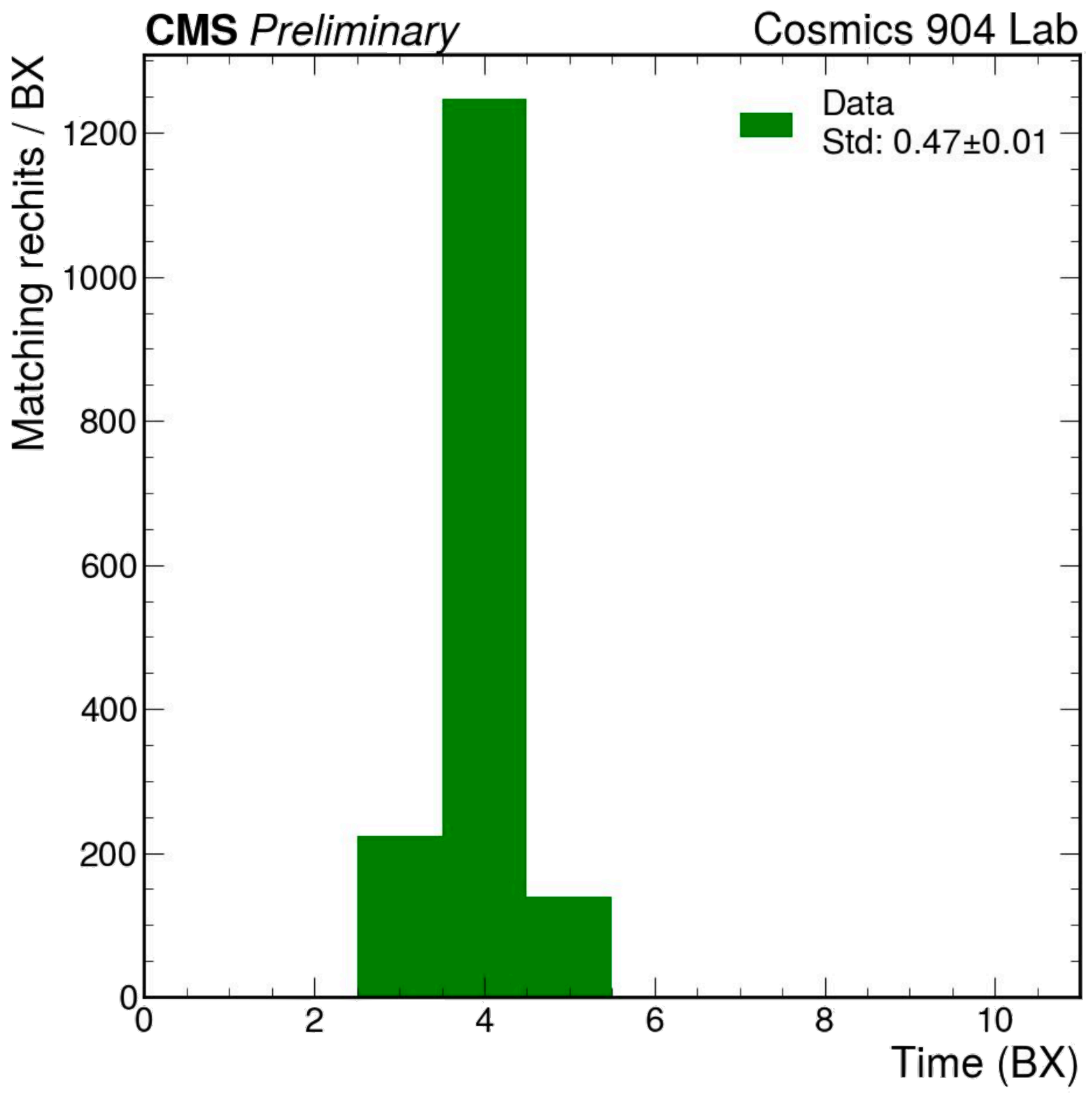
- Azimuthal segmentation for the ME0 foil.
  - for equalizing the gain drop across different GEM foil sectors.
  - and minimizing the average gain
- Prototype with radial HV segments validated with beam: Excellent efficiency



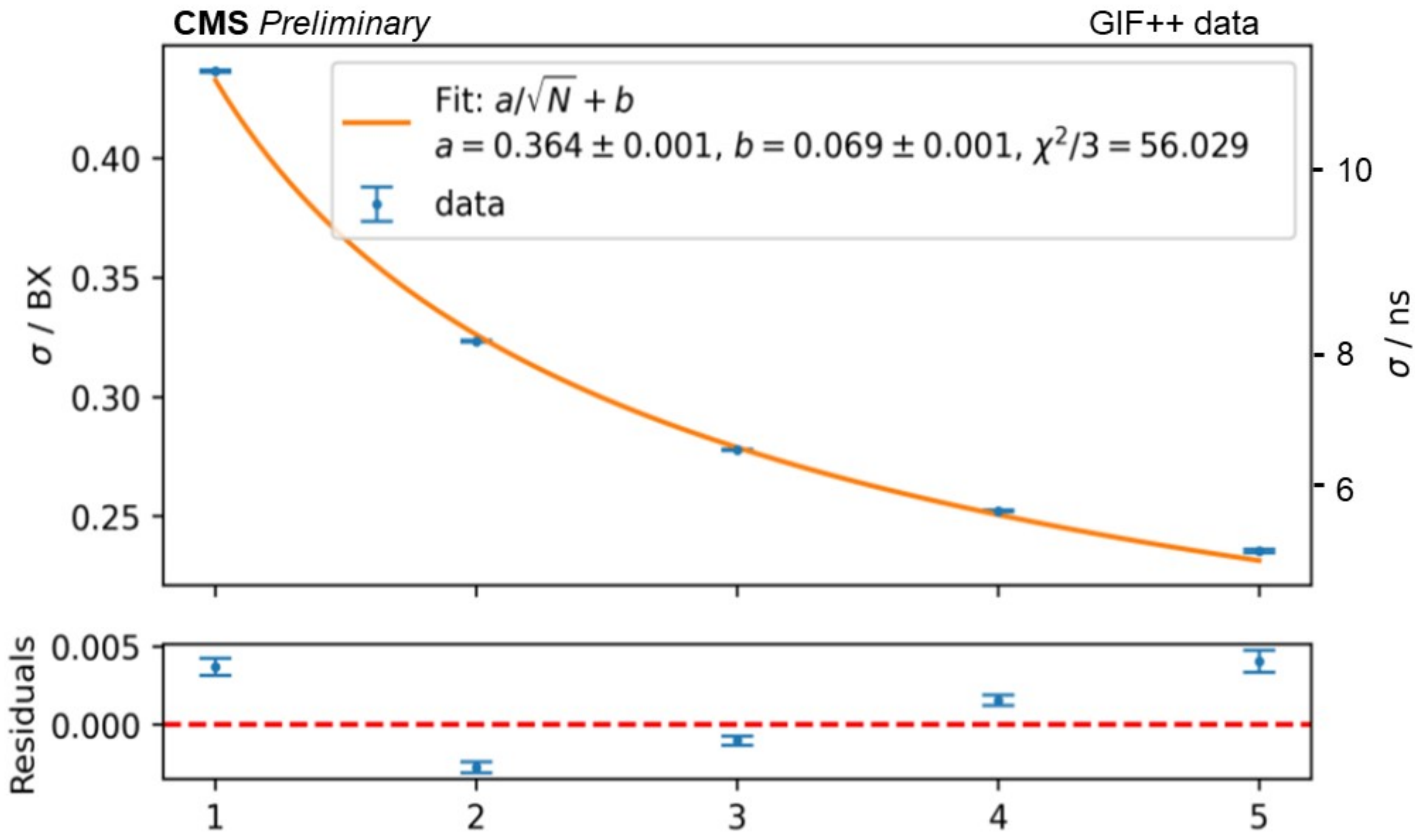
Design of azimuthal segmentation for the ME0 foil, showing the expected background particle rate per sector in the CMS environment.



Test Beam Results



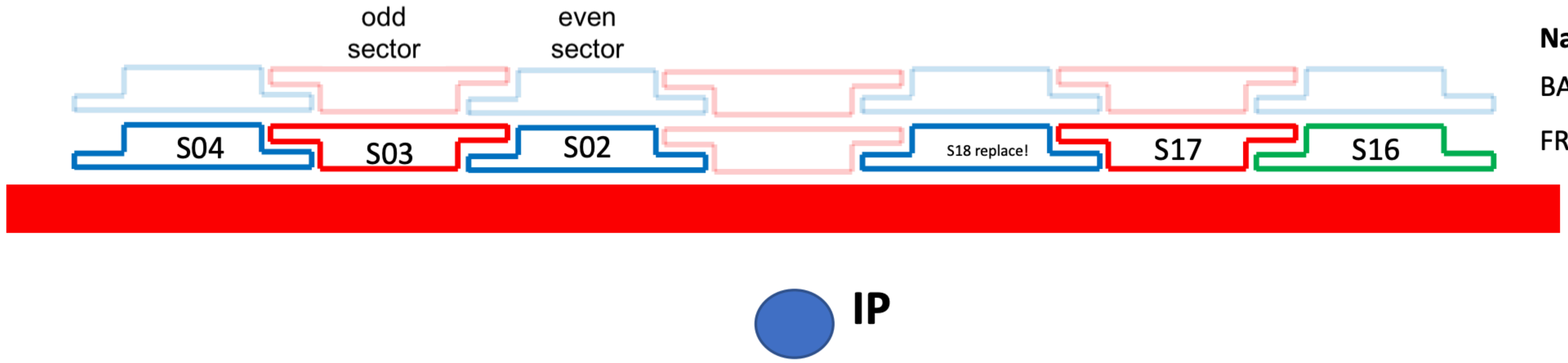
- Example distribution of the arrival times of the matching rechits for one of the six chambers in the stack. An individual chamber has a lower time resolution than the combination of all six chambers on the next page. The data is fit with a Gaussian distribution and the matching window is defined as five times the sigma of the residual distribution within the same readout partition. The arrival time of the rechits is chosen as the one of the last firing strip in the cluster.
- Time is expressed in units of bunch crossing timing (BX). One BX corresponds to 25 ns. The centering on a specific BX (here BX=4) is arbitrary and depends on the chosen latency. The detector has a time granularity of BX.



- Fitting a segment using 5 of the chambers and search for a reconstructed hit (rechit) matching the propagated position of the track on the chamber not used in the segment finding (where the matched hit is the closest to the track and required to pass selections to ensure high quality tracks). The time of the matched rechit is used for the calculation of the time resolution.

GE2/1 extension chambers installation at YETS24/25

- GEM plans to install 4+1 (replacement) Layer 1 GE2/1 chambers on Negative EndCap during YETS24/25.

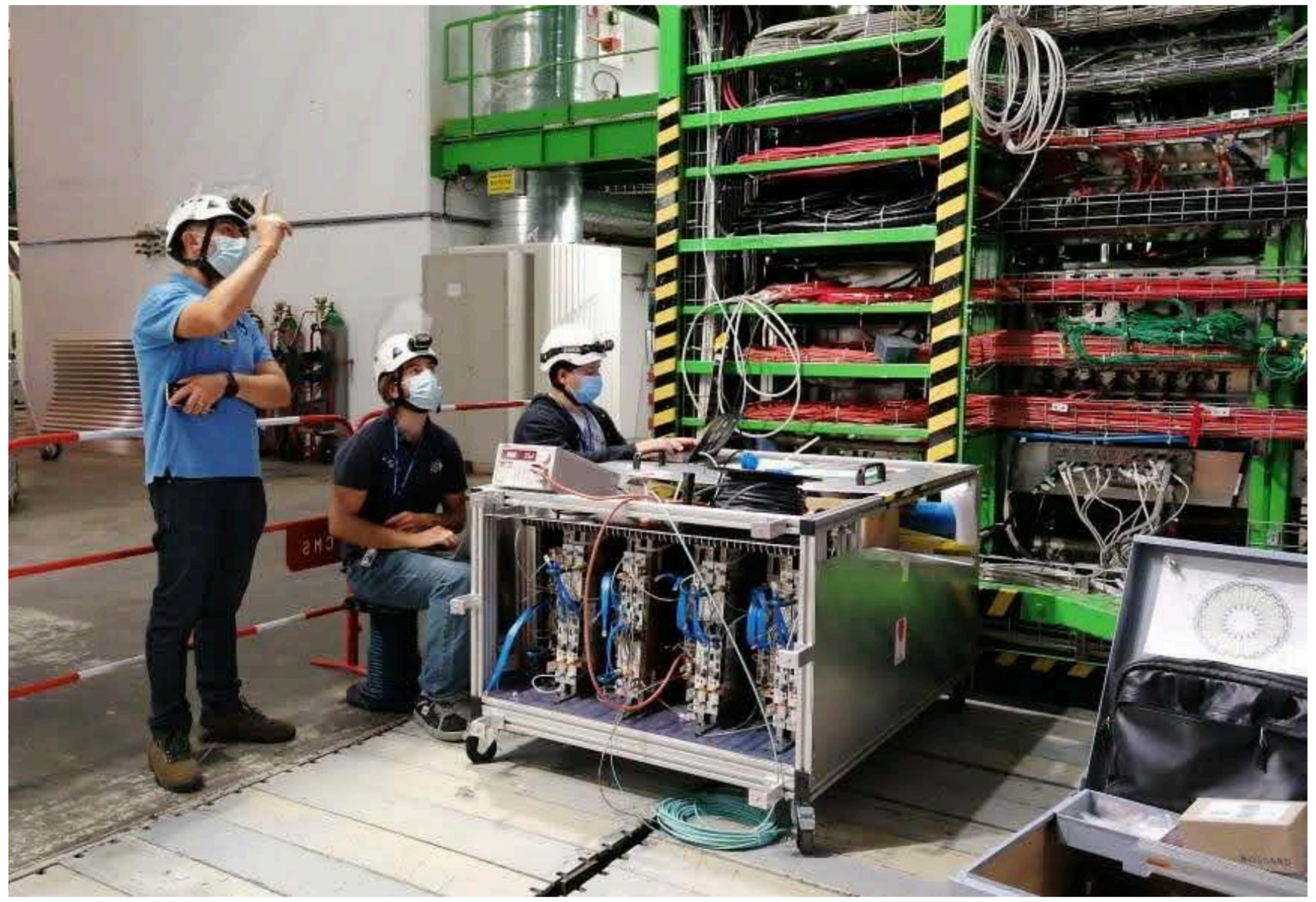


Naming convention:

BACK – Layer 2 – off-disk, M1-M4

FRONT – Layer 1 – on-disk, M5-M8

- Before installation of chambers in UXC, quick acceptance test is needed – procedure was set up during GE1/1 and GE-2/1 installations so far. Even gas flushing procedure was established.
- Final decision on installation or rejection of the given chamber



Technical Coordinations of Installation of GE2/1 Extension Chambers YETS24/25

- Transport b904 - P5
  - According to the expected installation scenario one transport will be needed.
- Lesson learned during GE1/1 transport and the YETS23/24:
  - Chambers are not enough to be bounded by cable ties, but rather mechanical stoppers needed!
  - Gas bottle on the trolley → transport of dangerous goods procedure!
  - Special transport (vmax <= 30 km/h, early morning hours, probably escorted by GEM TC) needed! – organization with Transport Service is mandatory!
  - GEM TC will prepare all EDH documents needed for transport and handling and contracts the field responsible to ensure smooth operation.
- GE2/1 Pre-installation activities
  - N2 flushing of chambers during transport and until installation, in case during full Xmas period.
- Acceptance test (UXC)
  - Acceptance test equipments were setup in UXC for GE1/1, will be very similar.
  - Every GE2/1 chamber will be tested as soon as it arrives to UXC and before installation
  - This quick test will identify potential damage or electronics disconnections due to the transport and manipulation.
  - Connects to the back-end electronics and LV
  - No cooling available → quick test (<20 mins) only*
  - Quick QC7 like test • Connectivity • S-bits • Threshold scan
  - use Megger to check for shorts