Status of operation of the CMS GEM system

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Simone Calzaferri
University of Pavia (Italy)
On behalf of the CMS Muon Group

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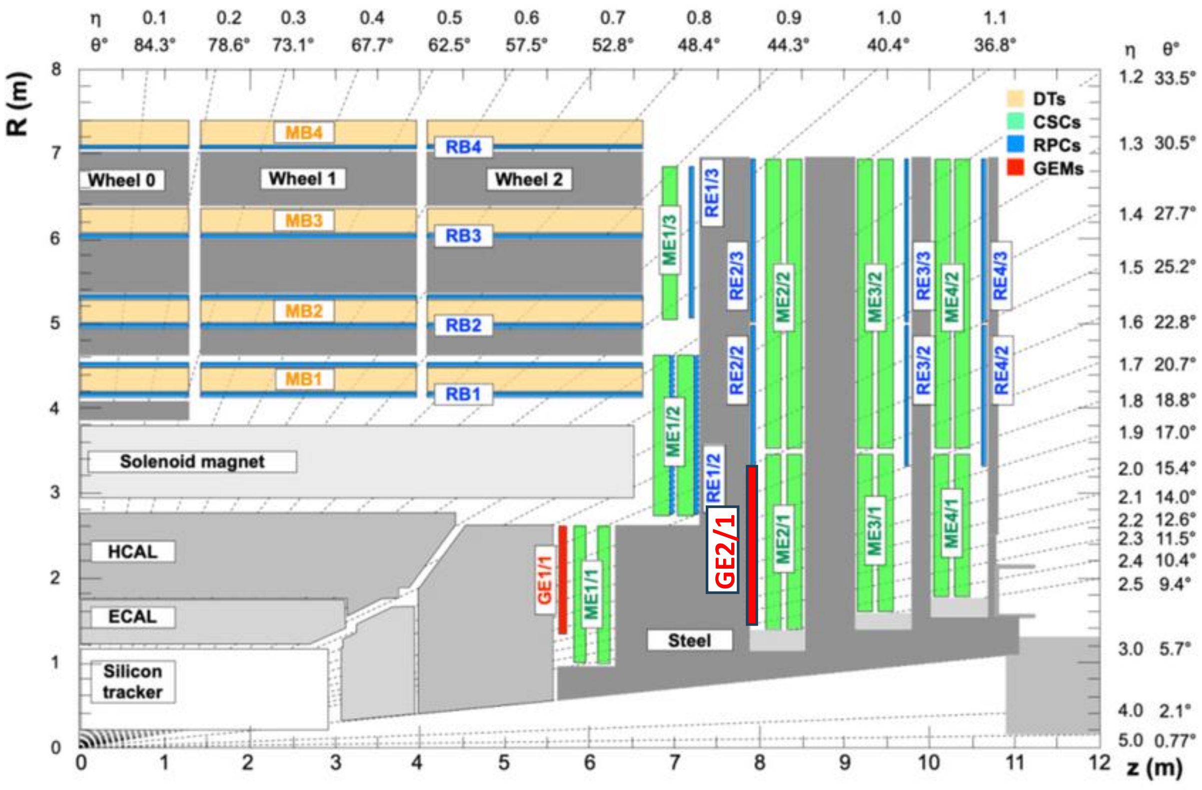
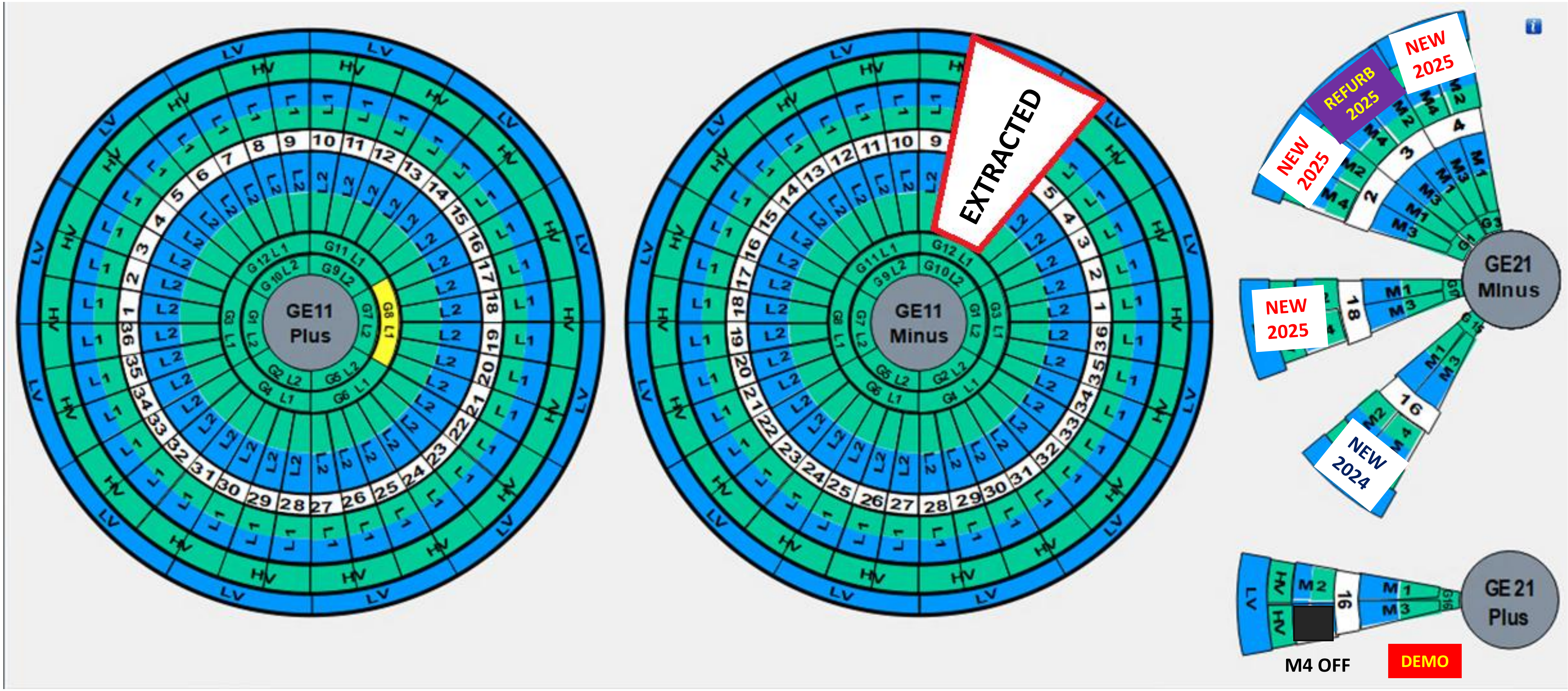
GEM detectors installed in CMS in 2025



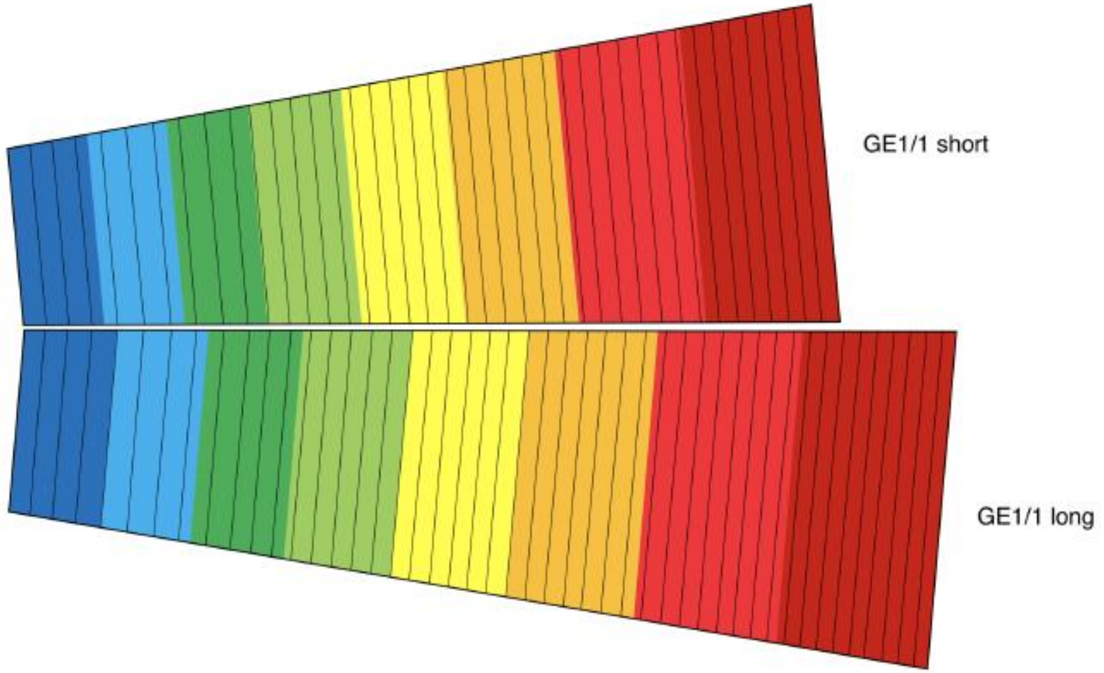
GEM: Gas Electron Multiplier

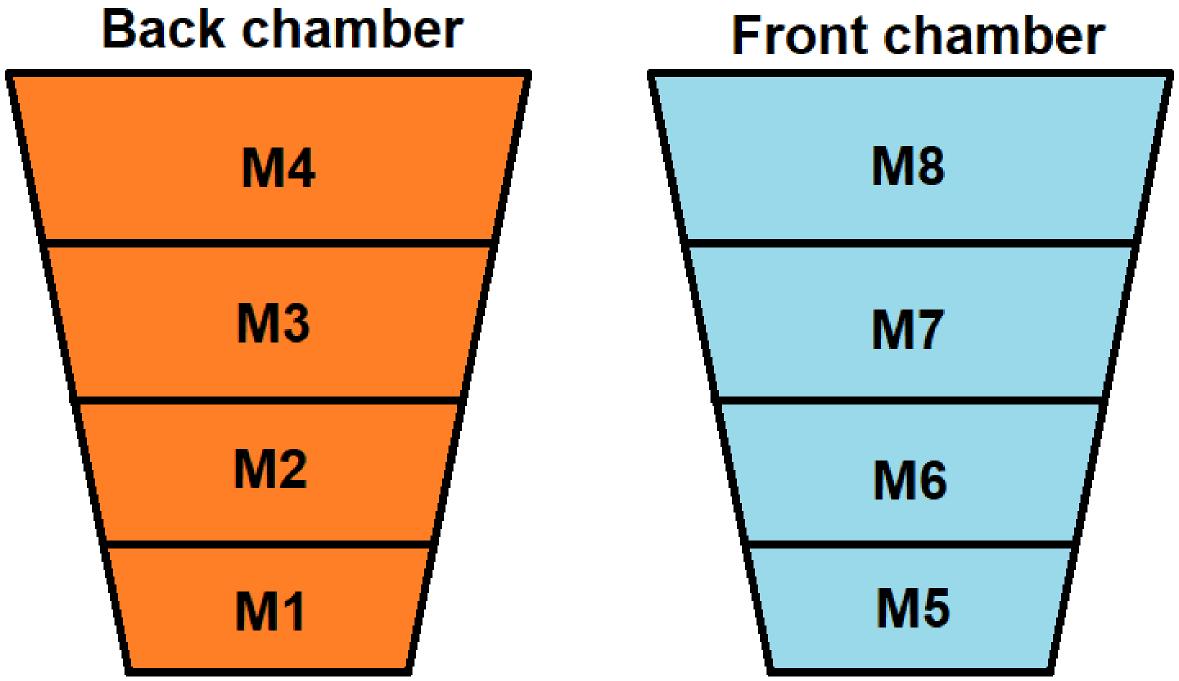
- **Triple-GEM** detectors in CMS
- **Gas mixture:**
  - Datataking: Ar/CO_2 (70/30)
  - Year End Technical Stop: pure CO_2
- **GE1/1:**
  - η coverage: 1.55 < | η | < 2.18
  - 138 detectors installed
  - Angular coverage: 10° with two chambers stacked
  - **Timeline:**
    - Installed in LS2, operated from the bennining of Run-3
    - Lessons learned after 3 years
    - 6 detector extracted at the beginning of 2025
- **GE2/1:**
  - η coverage: 1.62 < | η | < 2.43
  - 6 chambers installed, 24 modules installed in total (entire GE2/1 system: 288 modules)
    - Angular coverage: 20° with two chamber stacked
  - **Timeline**
    - **Demonstrator:** operated from the beginning of Run 3 (3 years)
    - **Chambers in negative endcap:** installed in YETS23/24 and YETS24/25

In one picture: status April 2025



GE1/1 vs GE2/1

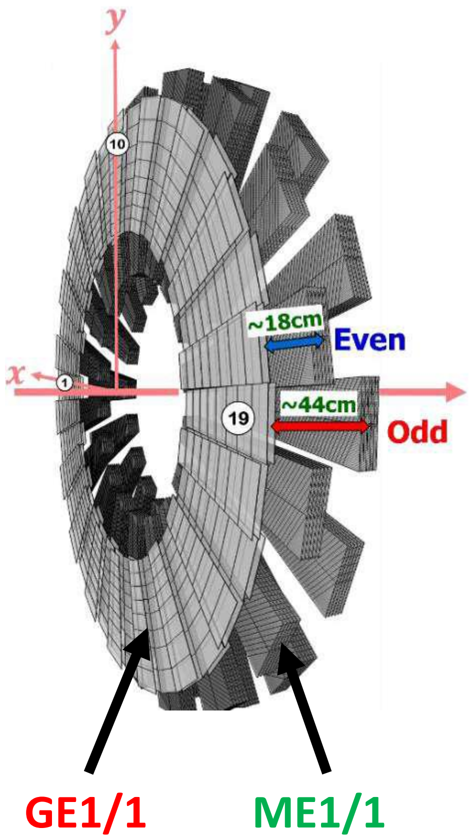




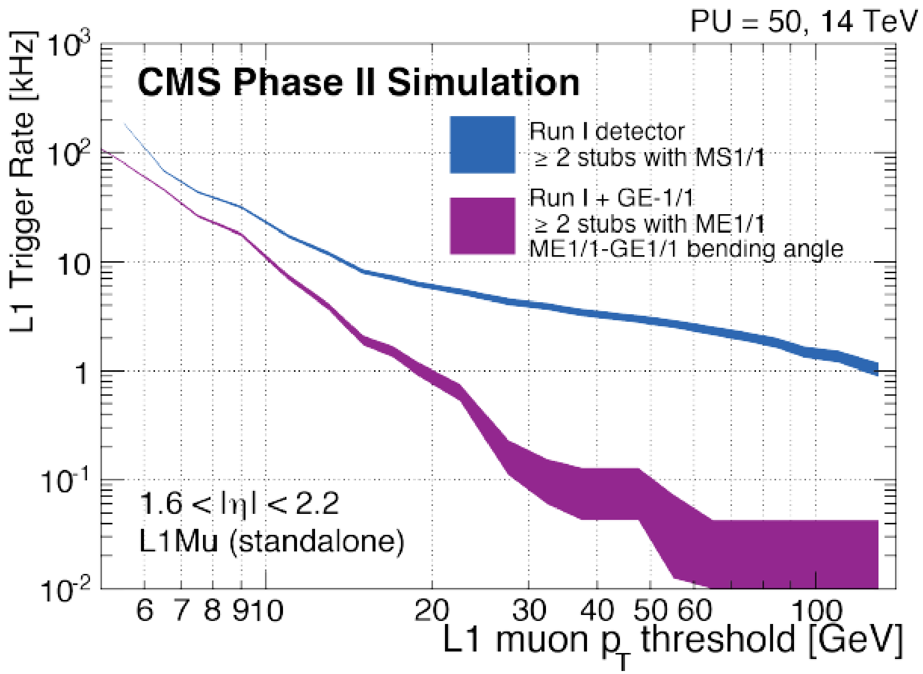
GE11
- 2 kind of modules
- GEM foils: all manufactured with single mask etching

GE21
- 1 chamber is made of 4 modules
- 8 kind of modules
- GEM foils: some manufactured with single mask etching, some with double mask

Goal of GE1/1 and GE2/1

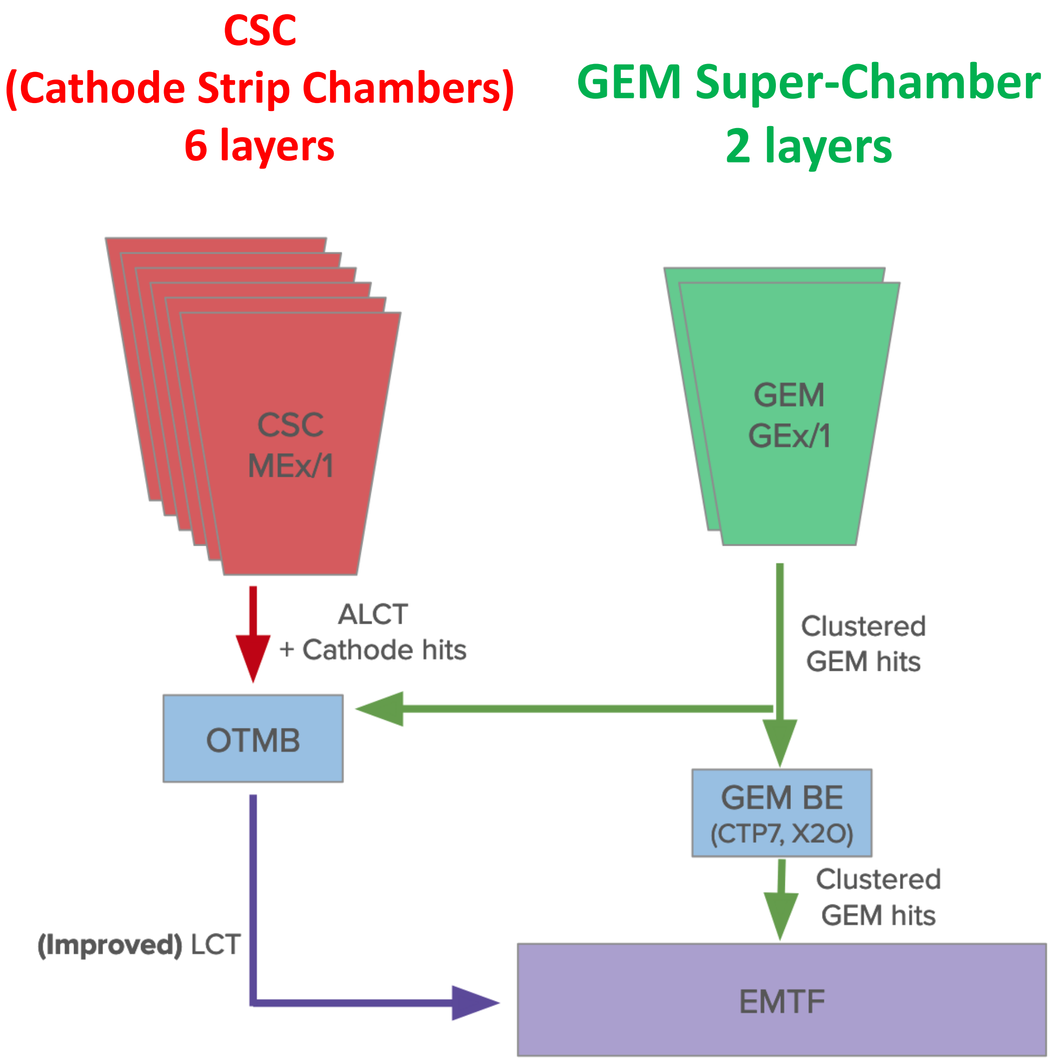


- Increase the muon spectrometer redundancy to
  - Sustain high radiation flux
  - Keep under control the trigger rate in the endcap region



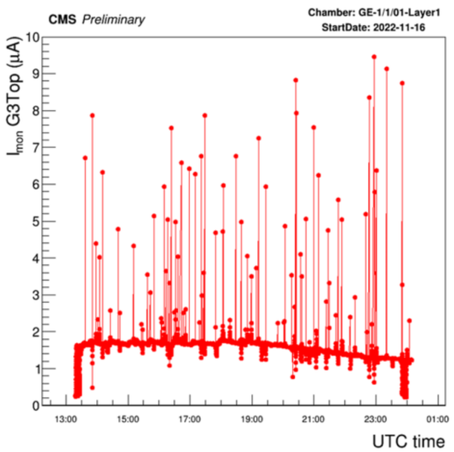
- The addition of GEM can help in improving the evaluation of the muon transverse momentum
  - How: **exploit the increase of the lever arm** available for muon local bending between GEM and CSC
    - GE1/1 pairs with the CSC chambers ME1/1
    - GE2/1 pairs with the CSC chambers ME2/1

Integration of GEM in Level-1 Trigger

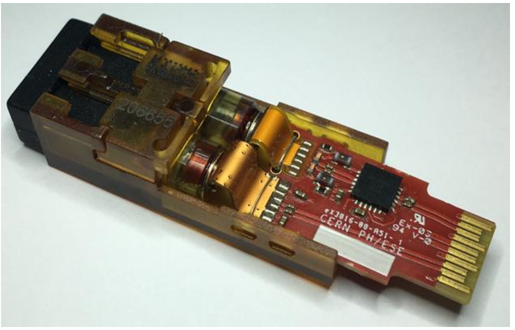


- Activated the correction of the slope of the local muon bending between CSC and GEM
  - GEM offer additional hits which can be combined with CSC
  - Combination of the CSC Local Charged Track (LCT) with GEM hits
  - The improved LCT is sent to the Endcap Muon Track Finder (EMFT)
- Deployed in CMS on 30th September 2024
  - No increase of trigger rate in the region covered by GE1/1
  - Work ongoing on timing of GEM at the EMTF level

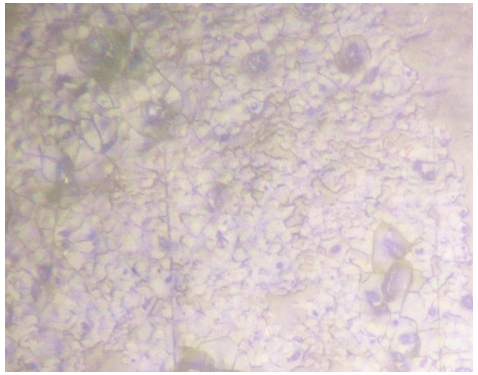
Issues summary



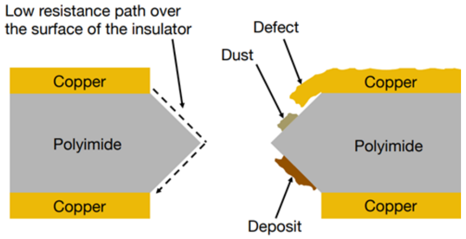
DISCHARGES
Impact:
HV instability, short circuits in GEM foils, reset and dead channels in electronics



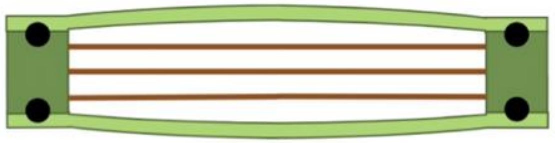
VTRx instability
Impact:
Areas of electronics (part or full detectors) not read



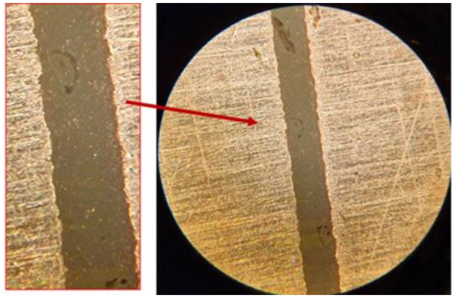
Non passivation of PCBs copper
Impact:
Oxidation signs



SHORT CIRCUITS IN GEM FOILS
Impact:
Inefficient areas, lower voltage applied to the whole foil



PCB bending
Impact:
Local difference in electric fields (and so lower efficiency).
Degradation of hit time of arrival (and so time resolution)

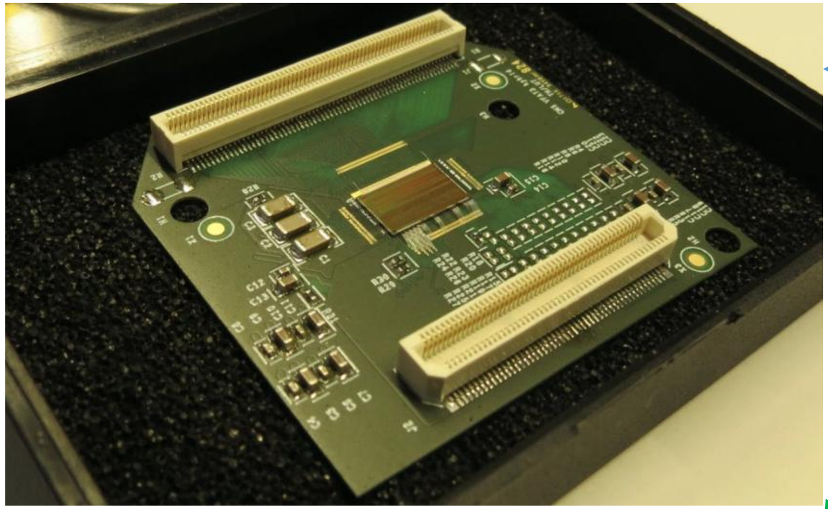


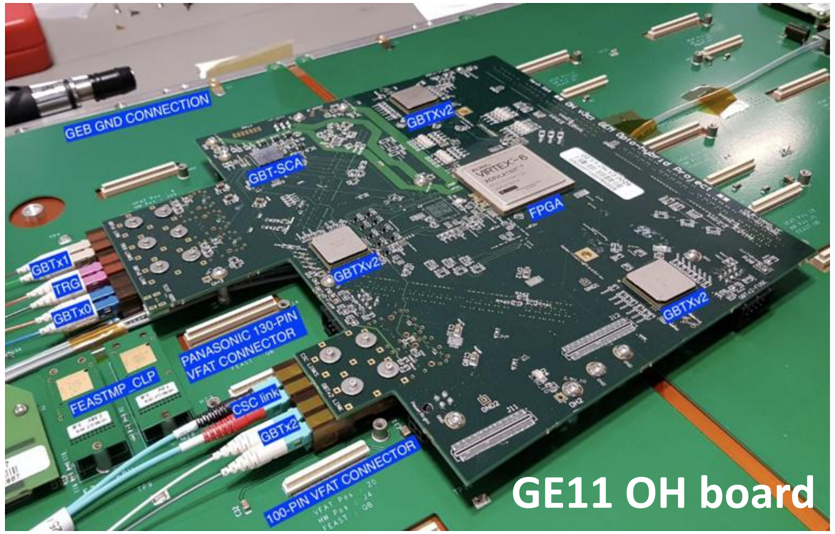
Copper dust on GE2/1 PCBs
Impact:
Generation of short circuits

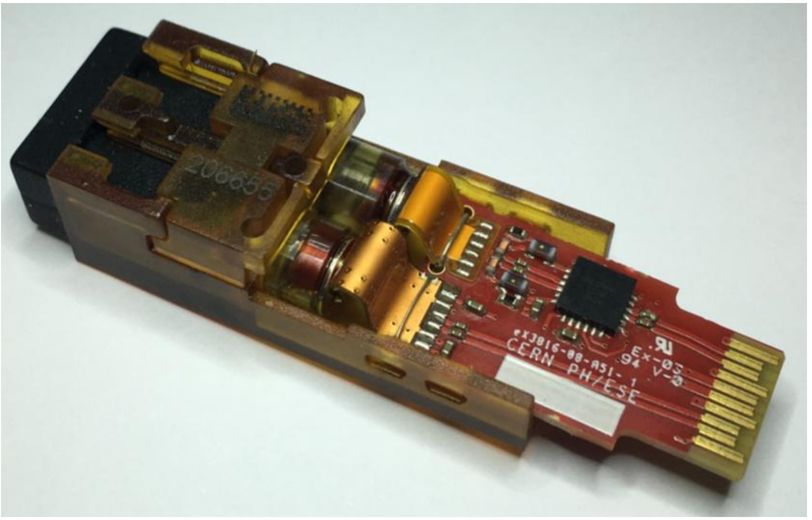
Detectors' efficiency

Electronics

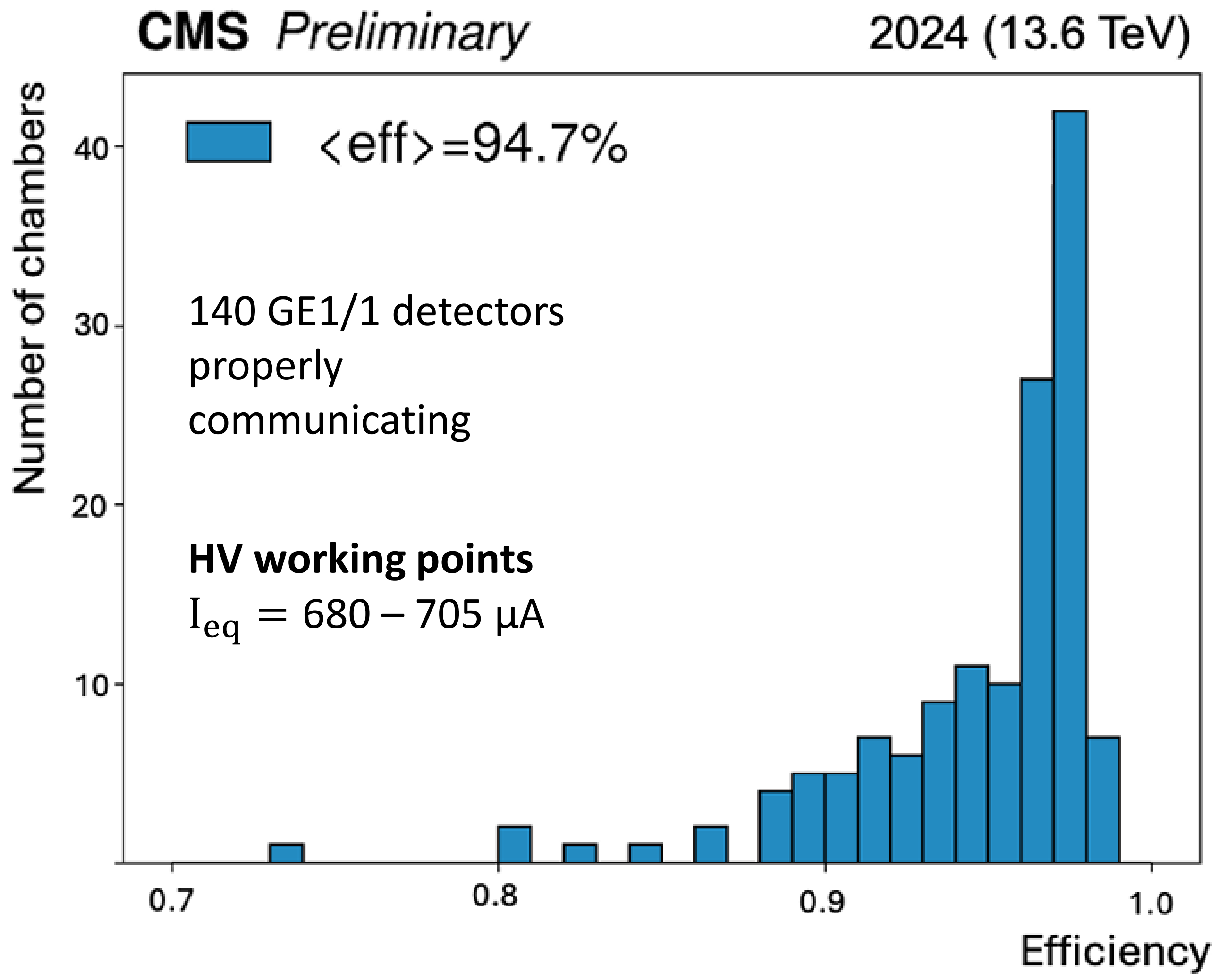
- Front-end electronics: VFAT3 chips
  - GE1/1: 24 per detector
  - GE2/1: 12 per detector
- Groups of VFAT3 chips read by GBT (Giga Bit Transceivers)
- OptoHybrid board on the detector hosting GBTs and FPGA
  - FPGA: Virtex 6
- Data sent by the OH to the backend electronics by VTRx optical transceivers





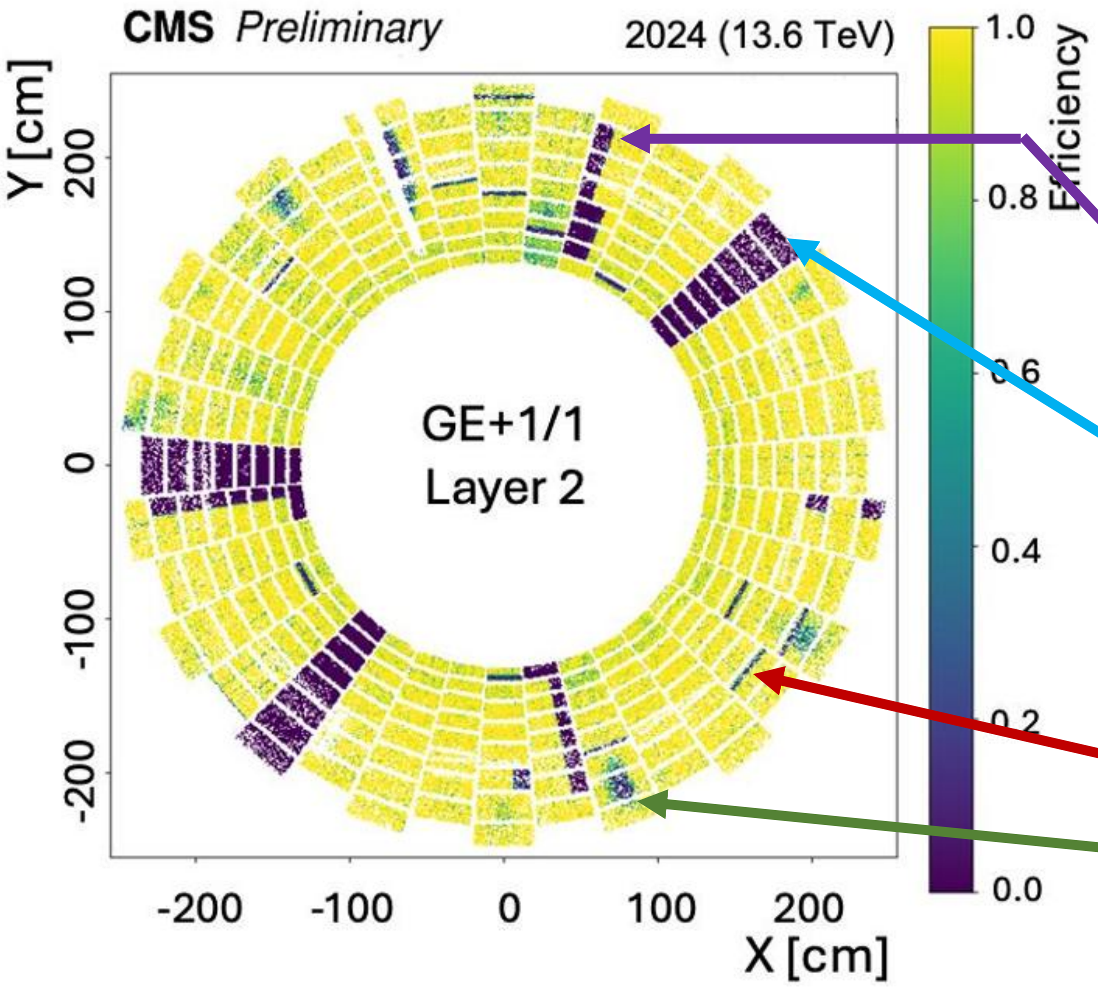


Efficiency after HV scan 2024



- **HV working point optimized**
  - Tuned chamber by chamber to maximize the detector efficiency and minimize its discharge rate
- Tested several **electronics configurations** for the **VFAT** front-end chip
  - **Adopted:**
    - VFAT chip pre-amplifier in High gain
    - VFAT Constant Fraction Discriminator (CFD) enabled
- **Efficiency:**
  - Before HV scan 2024: 87%
  - End of 2024: 94.7 %
- **Automation:**
  - Produces efficiency results for each LHC fill in few days
    (limited by transfer time of data to Tier-0)

Detectors' efficiency in detail

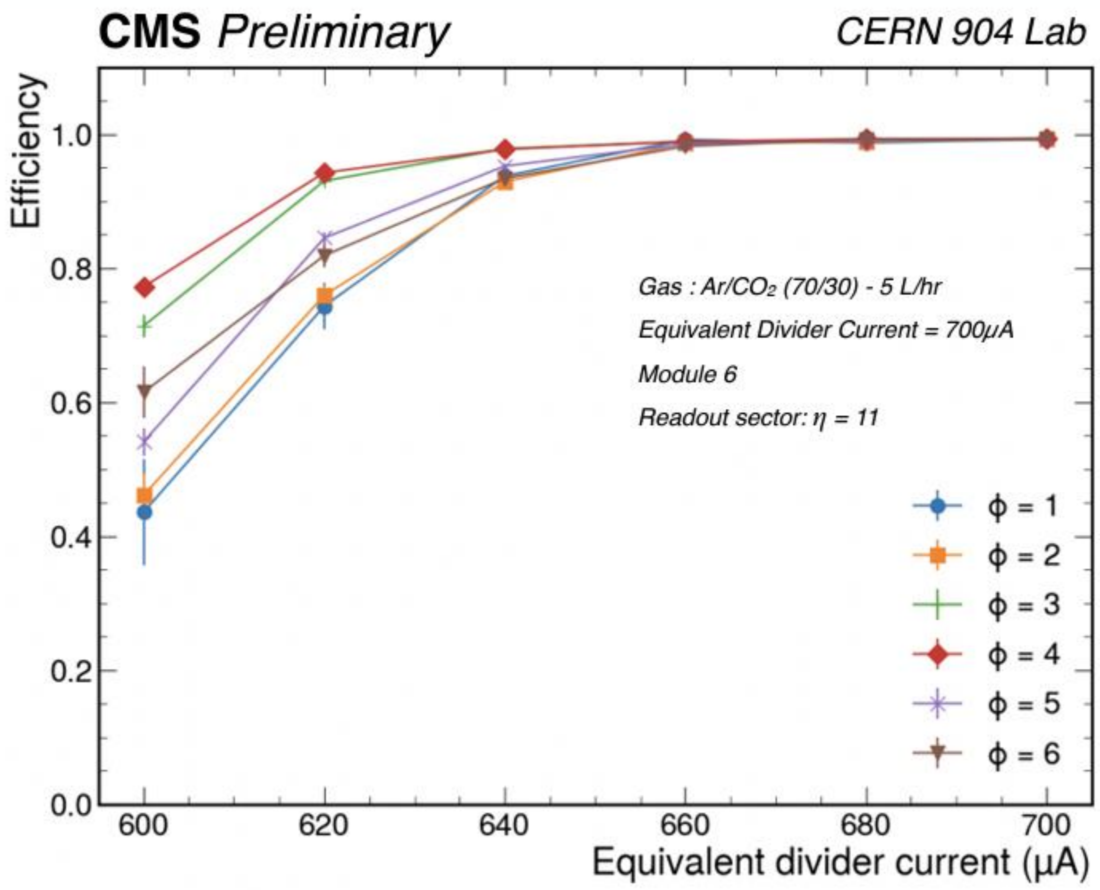


High resolution efficiency plot of the GE+1/1 layer 2 chambers in 2024.

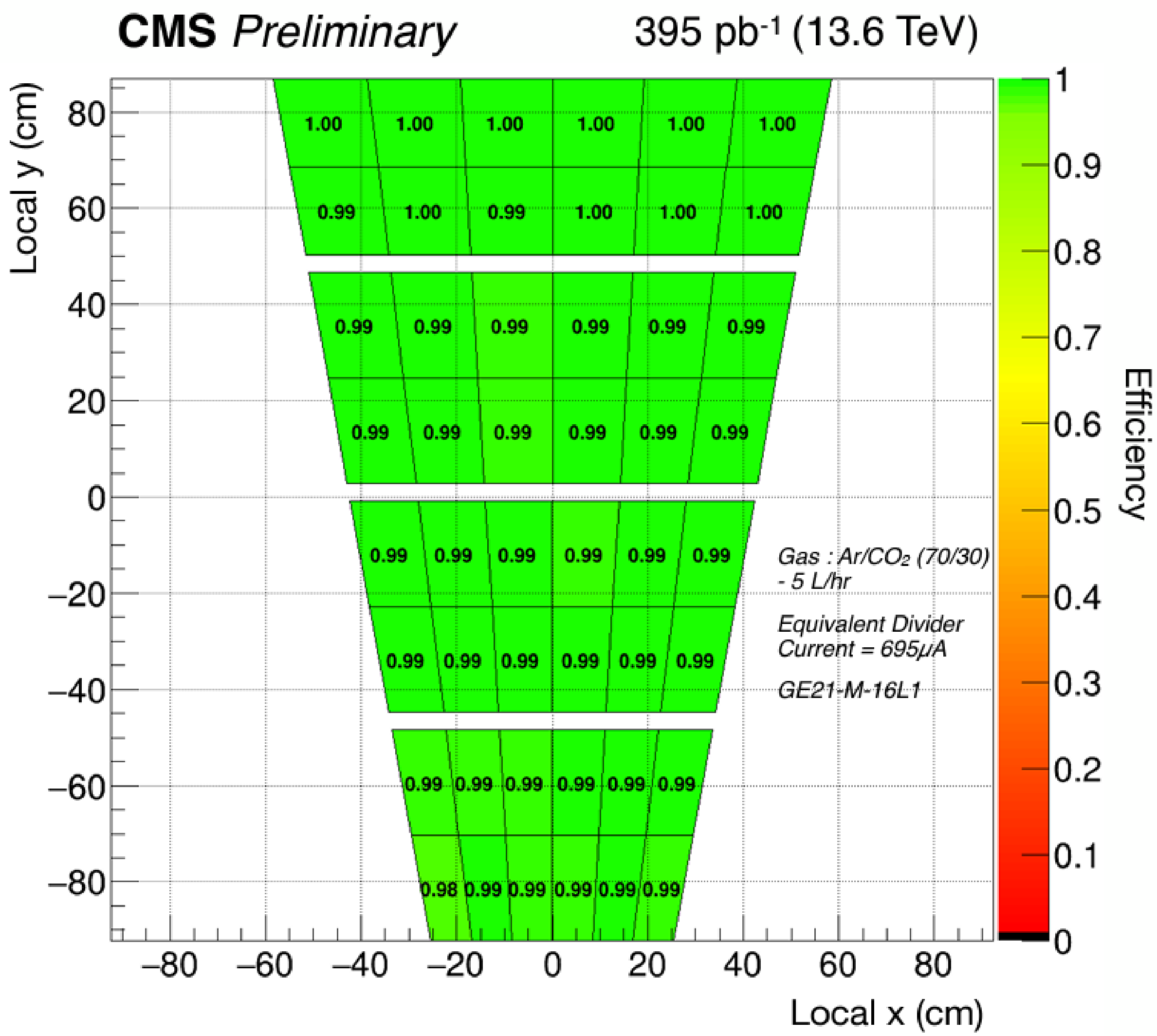
- The overall efficiency is high (Average: 94.7 %)
- **Issues:**
  - chambers with communication issues
    - Due to:
      - Outgassing of the VTRX optical transceiver [3]
      - This makes unstable the Giga Bit Trasceiver (GBT) reading the front-end electronics
    - Can result in:
      - All the front-end connected to **one GBT is not read**
      - **Electronics fully off** if GBT publishing the FPGA temperature is affected (safety power off of the LV)
    - Electronics refurbishment during LS3
  - **Short circuits in GEM foils** (purple lines)
  - On some of the long chambers one can also see an efficiency drop at the wide side due to the **bending of the PCBs**.

GE2/1 efficiency

Chamber: GE21-M-16-L1
Status: not contaminated by copper dust



Cosmic stand

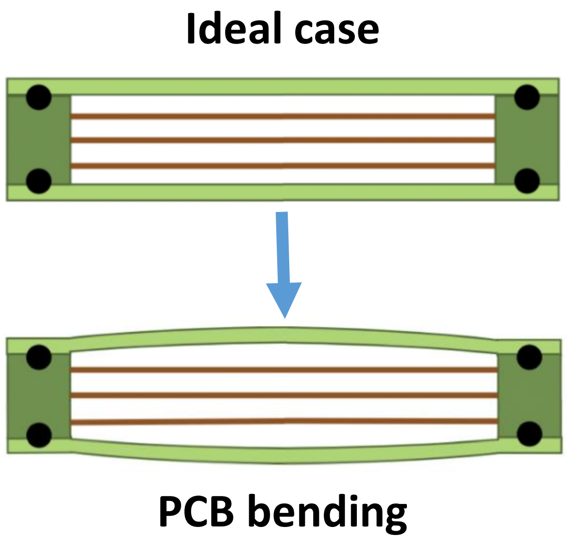


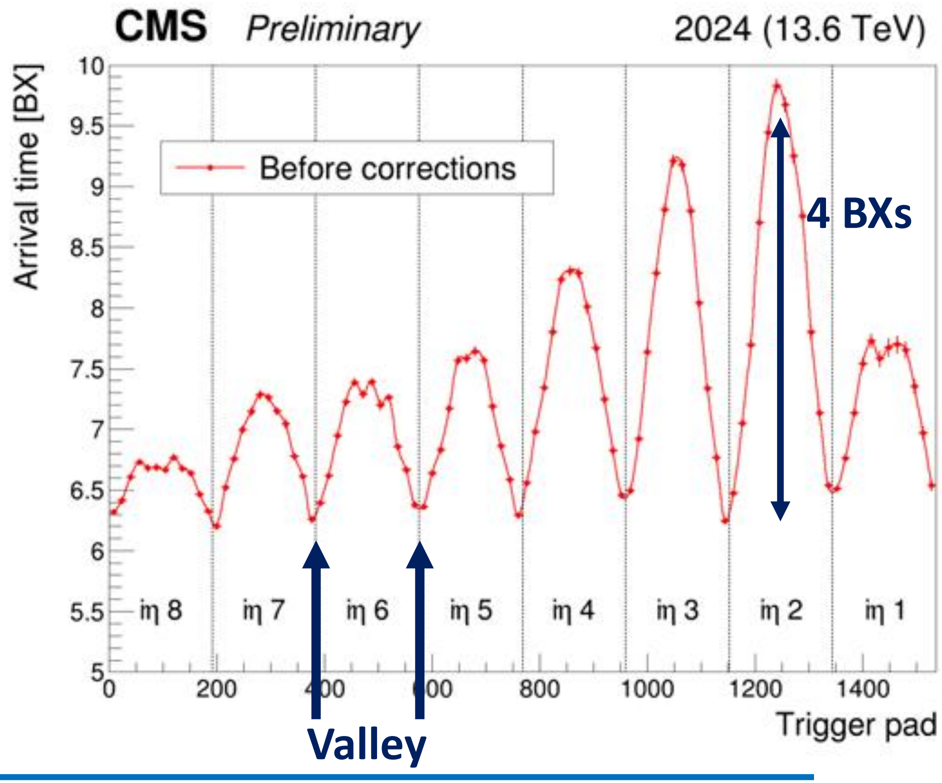
p-p collisions in CMS

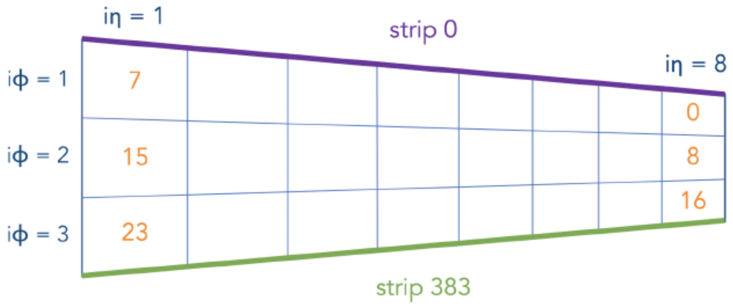
Timing and trigger performance

Timing: GE1/1 detectors

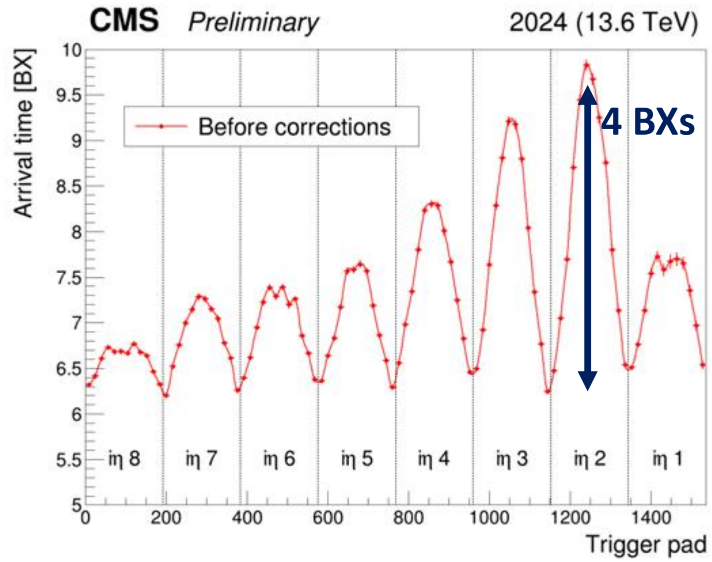
- Affected by: **mechanical bending** of the PCBs
- What happens:
  - A. The time of arrival of one hit depends on its position in the chamber
  - B. The time resolution per strip is degraded proportionally to the time of arrival
- Effect:
  - Modulation per eta partition on the time of arrival, resulting in degradation of time resolution in general
  - **Valley:** edge of the chamber
  - **Peaks:** center of the chamber (the PCB is distant to planar scenario)
    - On the wide side of the chamber the bending effect is more important
    - This effect is more important on long GE1/1 detectors
  - GE1/1 can reach time resolution 10 ns **where the detector is flat** ([12], page 94)

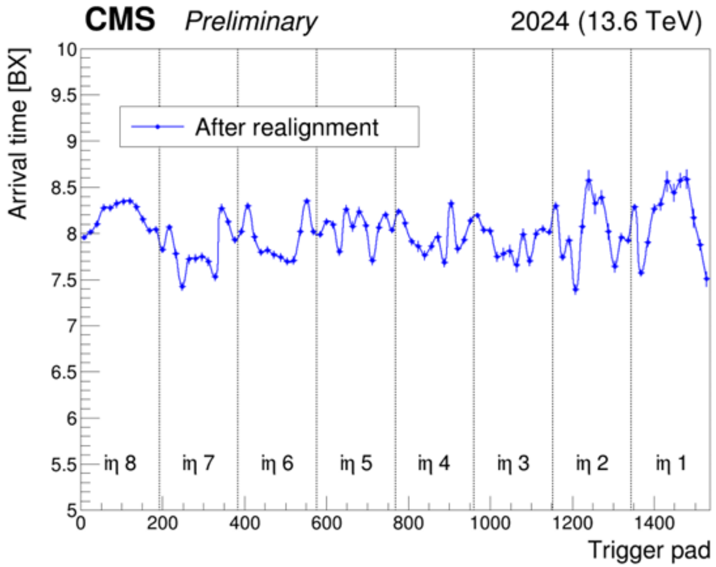






Timing of GE1/1: delayed signal



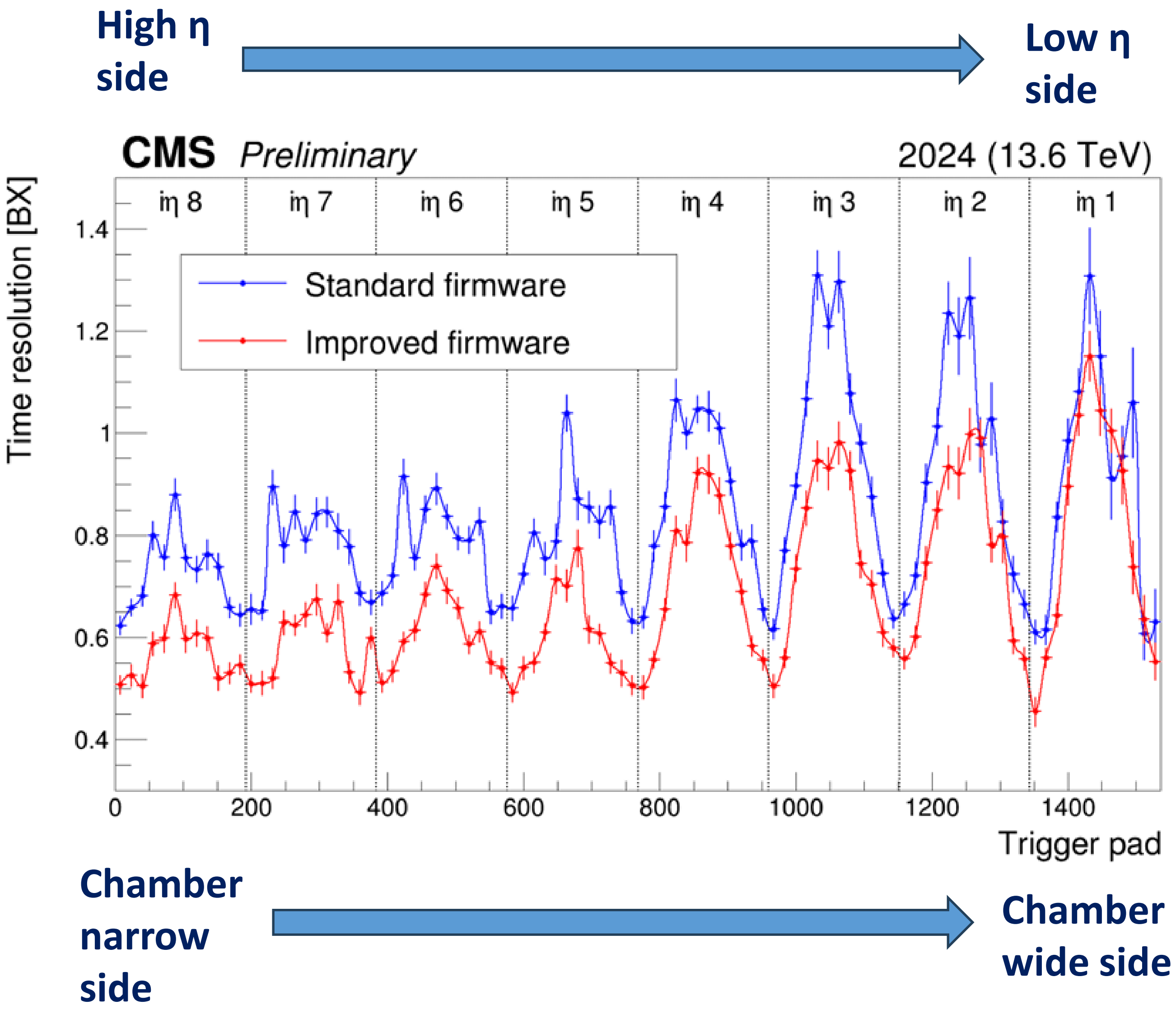


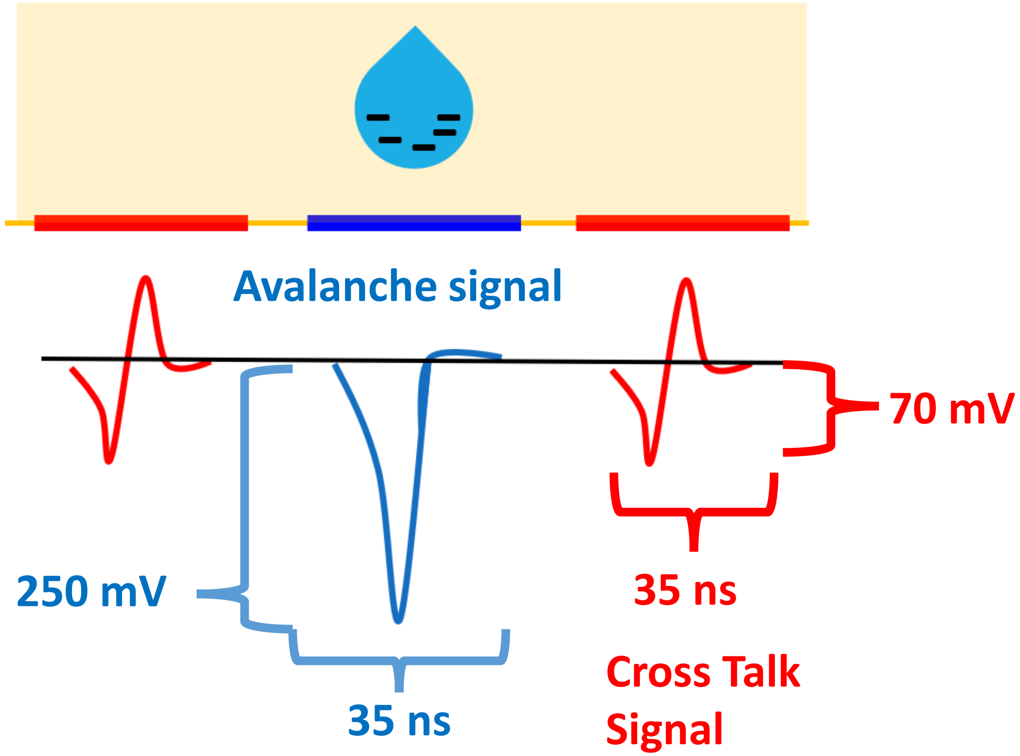
- Improvement of effect A
  (time resolution function of position in the chamber)

- Implemeted by:
  - Slowing the delayed hits to the slower ones, applying to a group of strips a delay with Bunch Crossing (BX) granularity

- Result:
  - Average arrival time within 1 BX

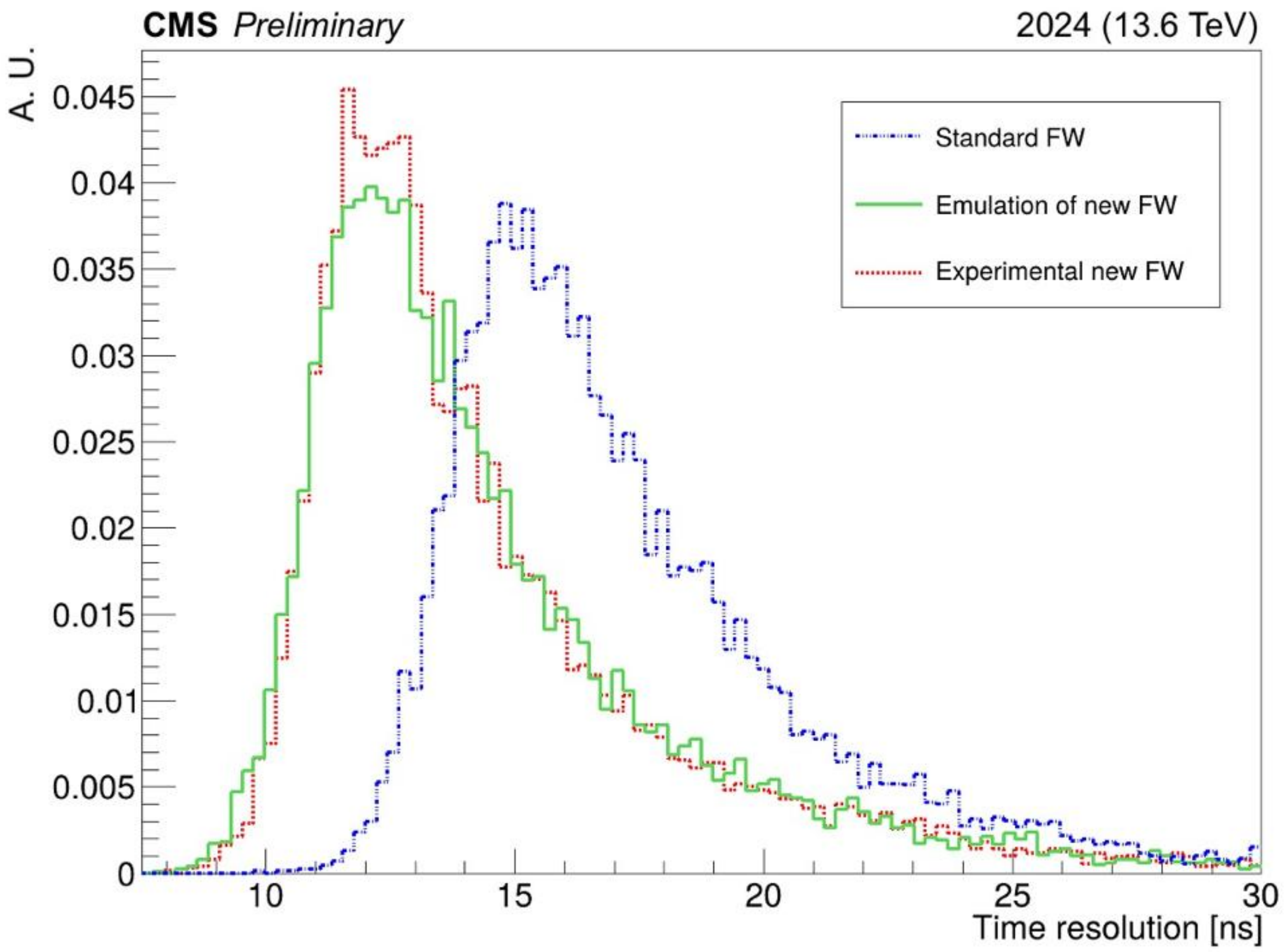
Timing in GE1/1: improved cluster timing





- Improvement of effect B (time resolution function of hit time of arrival)
  - Fact:
    - To properly identify the muon time of arrival you need to **catch the center of the cluster** of strips firing
    - Time resolution per strip is affected by cross-talk bipolar induced signals on neighbouring strips (early firing)
  - Improved by:
    - Using Constant Fraction Discriminator (CFD) of VFAT3
    - Removed cross talk signal of the strips at the edge of the cluster in firmware

Time resolution: global improvement

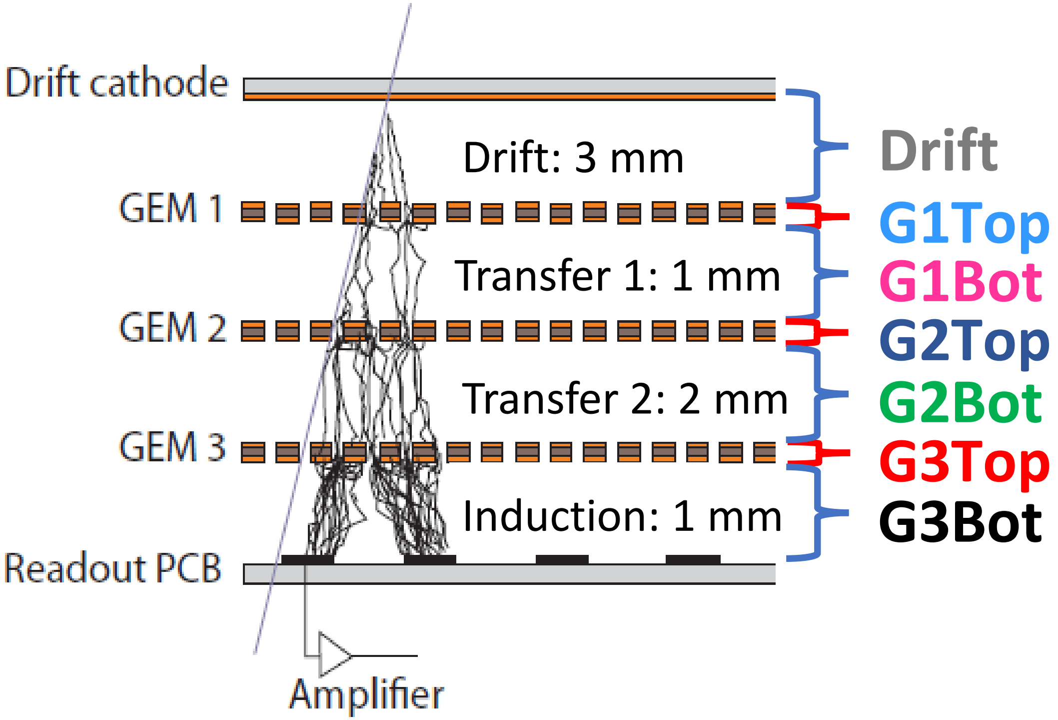


- Improvement of mode value
  - Old firmware: 15.3 ns
  - New firmware: 12.3 ns

- Cost:
  - Increased Level 1 Trigger (L1T) latency in input to the Endcap Muon Track Finder (EMTF)
  - 2 BX for the CFD
  - 1 BX for the cross talk cancellation

HV stability

HV: How we power the detector



Power full GEM stack:
7 electrodes needed

Configuration $I_{eq} = 690\ \mu A$ (Gain ≈ 10^4)			
Drift	776 V	**G1Top**	387 V
G1Bot	302 V	**G2Top**	379 V
G2Bot	604 V	**G3Top**	362 V
G3Bot	431 V		

- **Proportions among stack voltages**
  Fixed by a reference resistive divider used in quality control in laboratory → the current flowing in the divider identifies a set of voltages (I_{eq})
- Multichannel power supply boards used in CMS (A1515BTG)

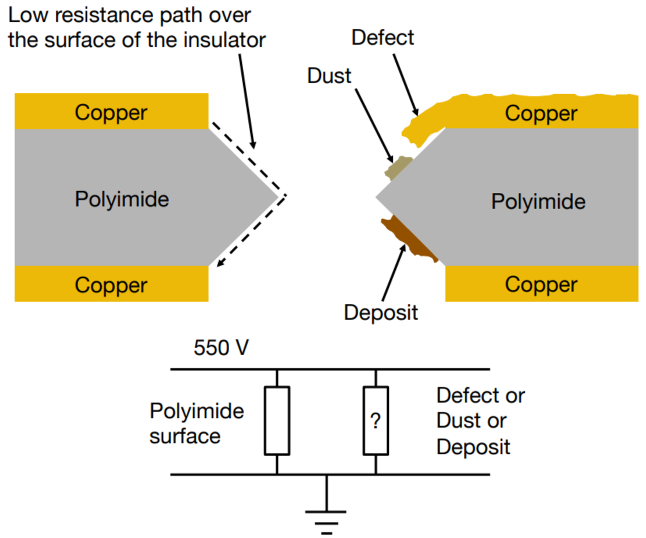
Discharges

- **What is a discharge:** transient transfer of charge between detector planes
- **When:** mainly during LHC pp collisions
  - HV working point in 2024: 680-705 μA
    - Tuned chamber by chamber to maximize the detector efficiency and minimize its discharge rate
  - 2024 p-p collisions
    - Instantaneous Luminosity: $O(10^{34})\ cm^{-2}s^{-1}$
    - Average rate of discharges: < 3 discharges per detector per hour
  - 2023 Pb-Pb collisions
    - Instantaneous Luminosity: $O(10^{27})\ cm^{-2}s^{-1}$
    - Average rate of discharges by the whole system (143 GE1/1 detectors): 5 discharges per LHC fill
- **Impact:**
  - Can create damages to the foils (short circuits)

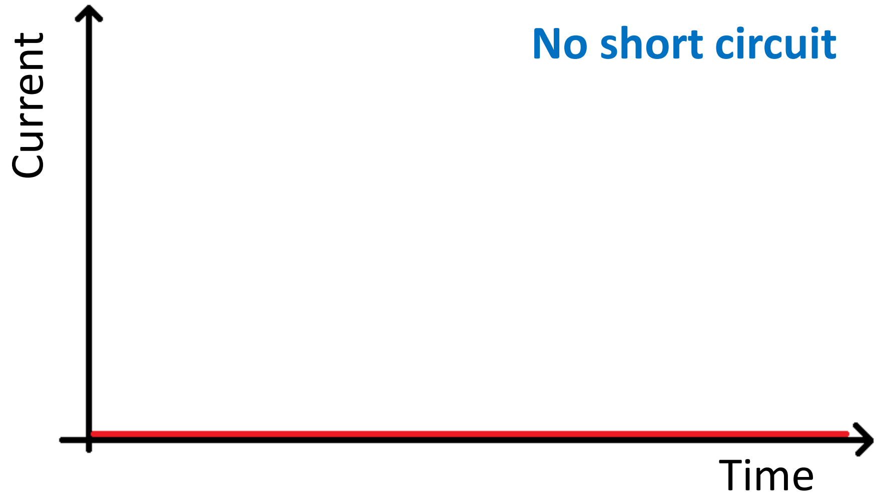
Shorts at 2024-11-25	HV sectors	Foil	Detectors
GE11_M	28	23	20
GE11_P	27	24	20
GE11 total	**55**	**47**	**40**
GE21_M	4	4	3
GE21_P (M4 disconnected)	6	3	2

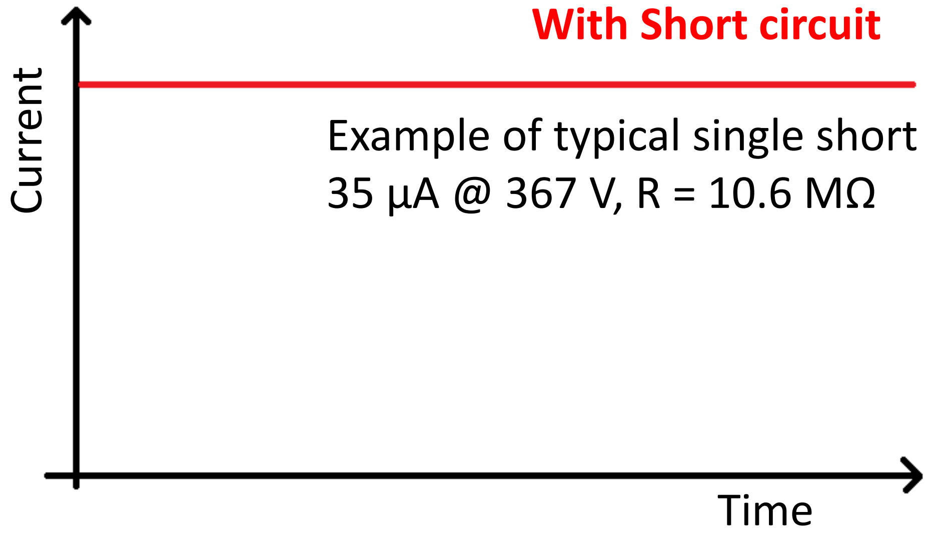
  - Can create resets or damages to the **electronics**: currents find the least resistance path through the electronics
    - Channels at the end of 2024:
      - Active: GE1/1: 93 %, GE2/1: 100 % (all VFATs communicate)
      - Damaged: 0.3%, Noisy & permanently masked: 1.5%

Short circuit in a GEM foil?



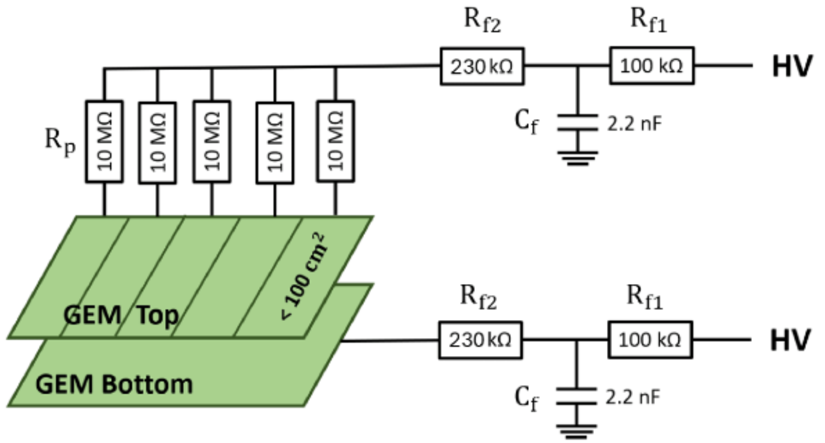
- What is:
  - Connection between top and bottom face of a GEM foil
- Why:
  - **Defects or depositions on GEM foil** can create temporary or permanent short circuit between top and bottom electrode
- How does it look like?:



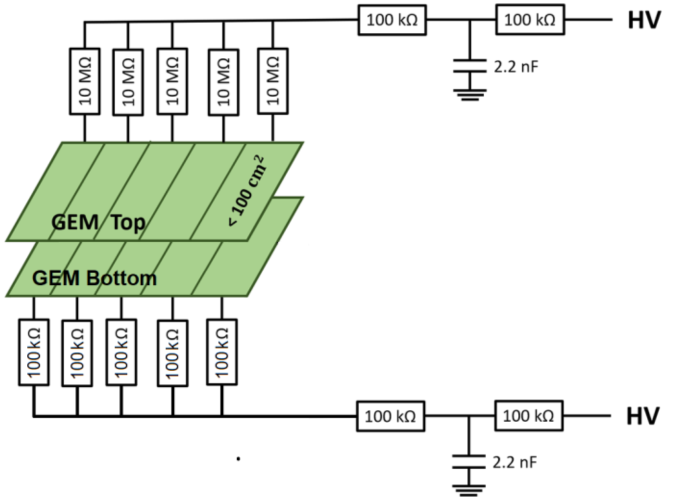


Design of HV distribution on the detector

GE1/1: used for all three GEM foils



GE2/1: used for foils GEM1 and GEM2

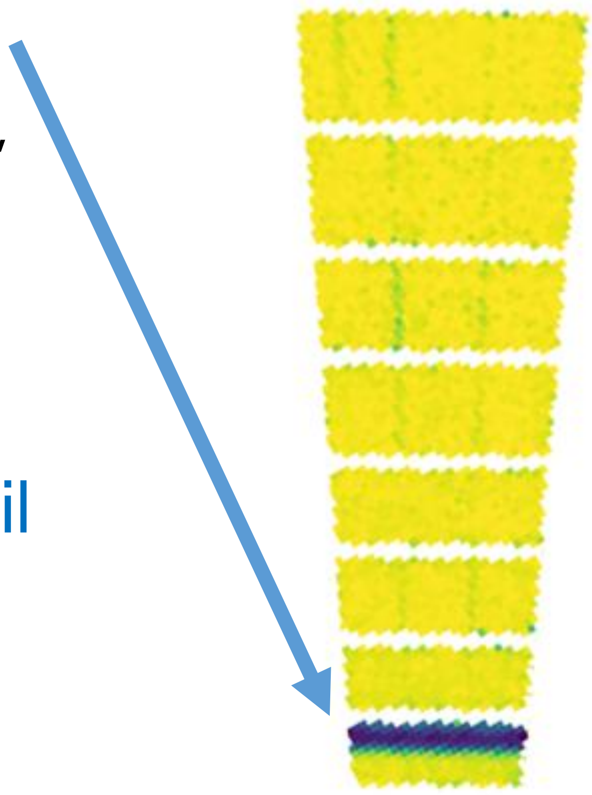


- **GE1/1**
  - 40 (47) HV sectors in short (long) GE1/1 chambers
  - HV sectors just on the top face of the GEM foil
- **GE2/1**
  - HV sectors on both sides of the foil
  - The number of sectors depends on the kind of GE2/1 module (19-46 HV sectors)
  - 100 kΩ resistor applied on the bottom of foils GEM1 and GEM2
  - No resistor applied on the bottom of foil GEM3, just the HV filter

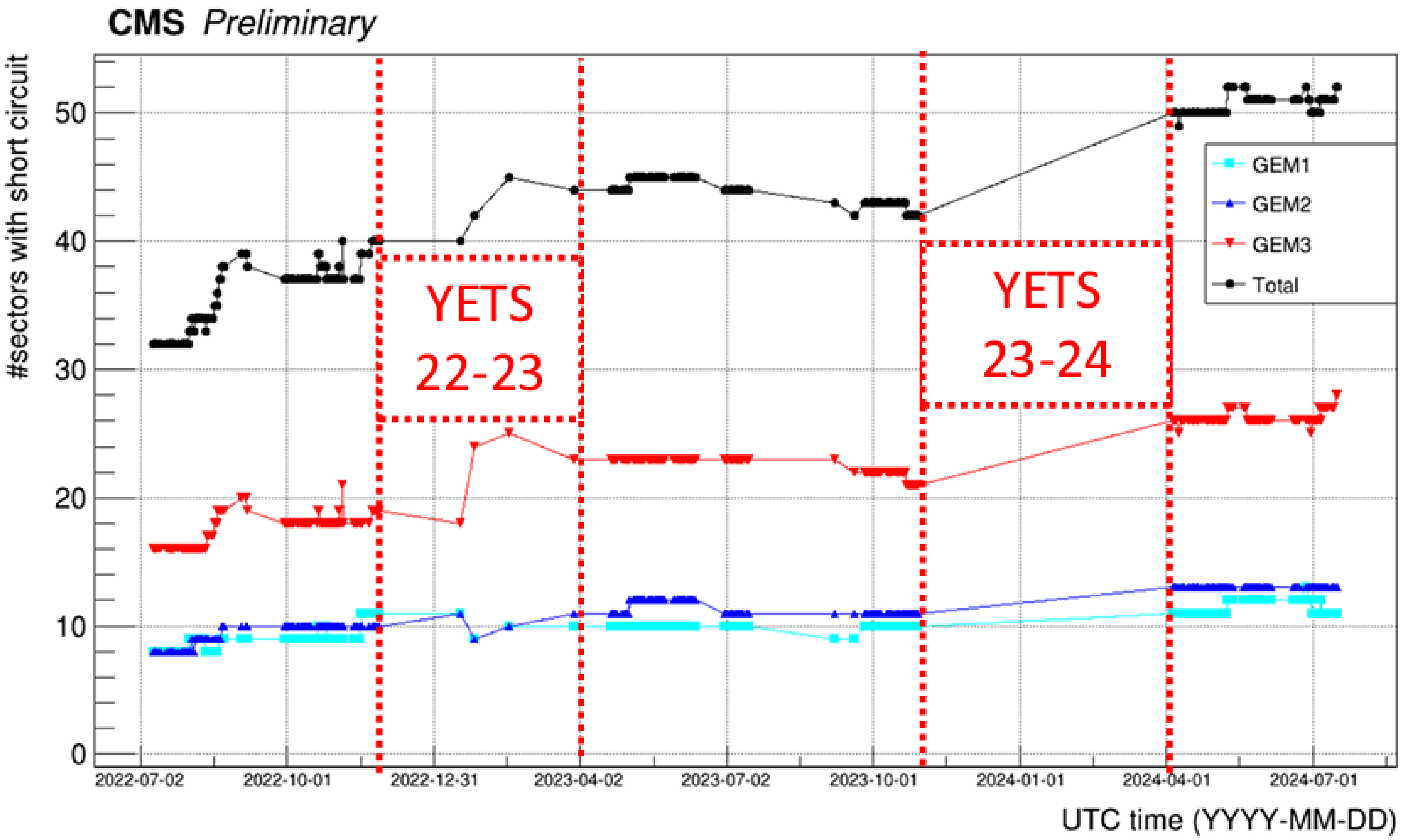
Impact of a short circuit

1. Zero efficiency in the HV sector affected by the short circuit
   - **GE1/1**: 2.5 % of area per HV sector in a short detector, 2.1 % for a long detector
     - 40 (47) HV sectors per GEM foil in GE1/1 short (long) detectors

2. Drop of the voltage effectively applied to the foil
   - The voltage drops on the HV filter resistors, globally lowering the whole foil, around 6% in GE1/1
   - This second effect starts to become relevant if more than one short is present in the same chamber.
     - Evaluations are ongoing thanks to special runs taken in 2024



Evolution of short circuits in Run-3



Mainly affected foil: GEM 3

- Closest to the readout and crossed by the highest charge during avalanche multiplication of primary ionisation electrons

Conditions of short circuits generation:

- Mostly due to discharges, voltage ramp up and magnet ramps

Conditions of short circuits healing:

- Mostly due to discharges, voltage ramp, magnet ramp, slow consumption of the short circuit

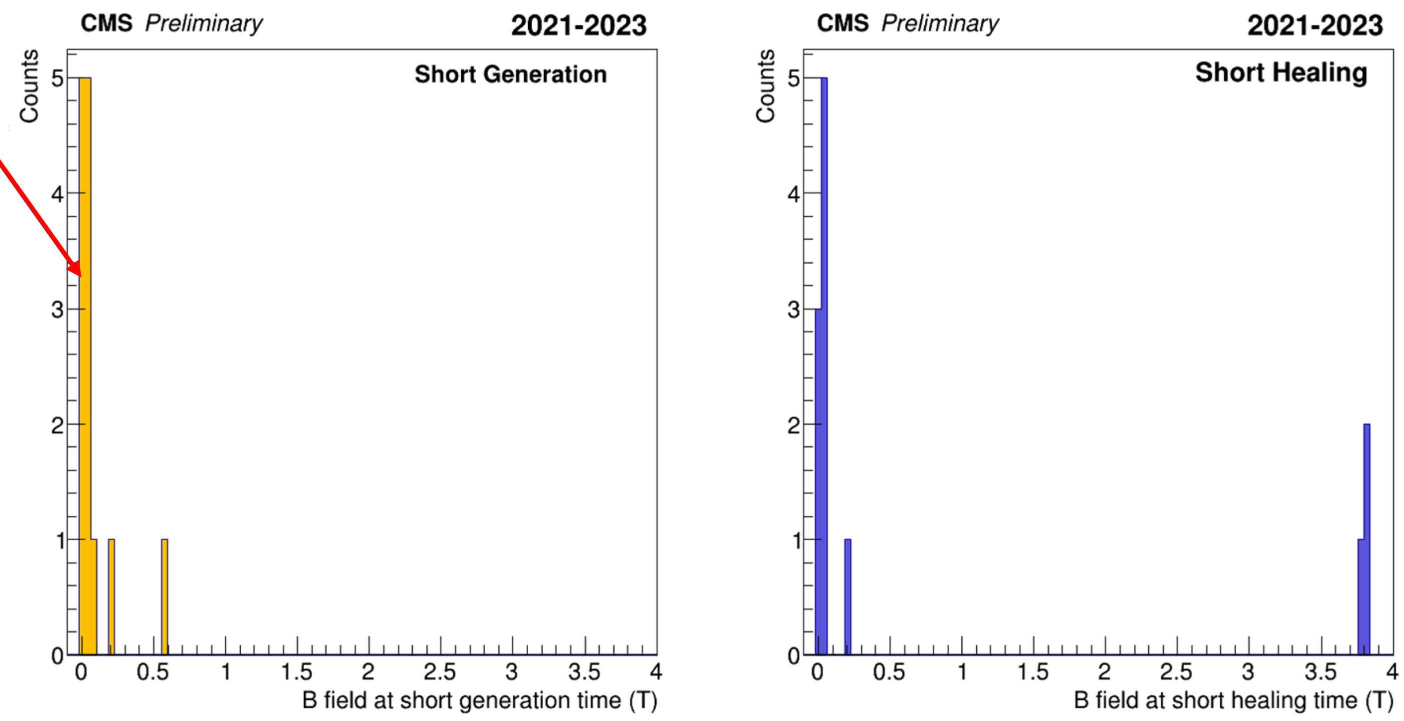
YETS24/25

- Keep minimal HV on GE1/1 during the whole YETS (300 V on the foils, gaps OFF), to mimize the stress at the repower and the contribution of diffusion of oxides in the generation of short circuits

Short circuits: Magnet operations

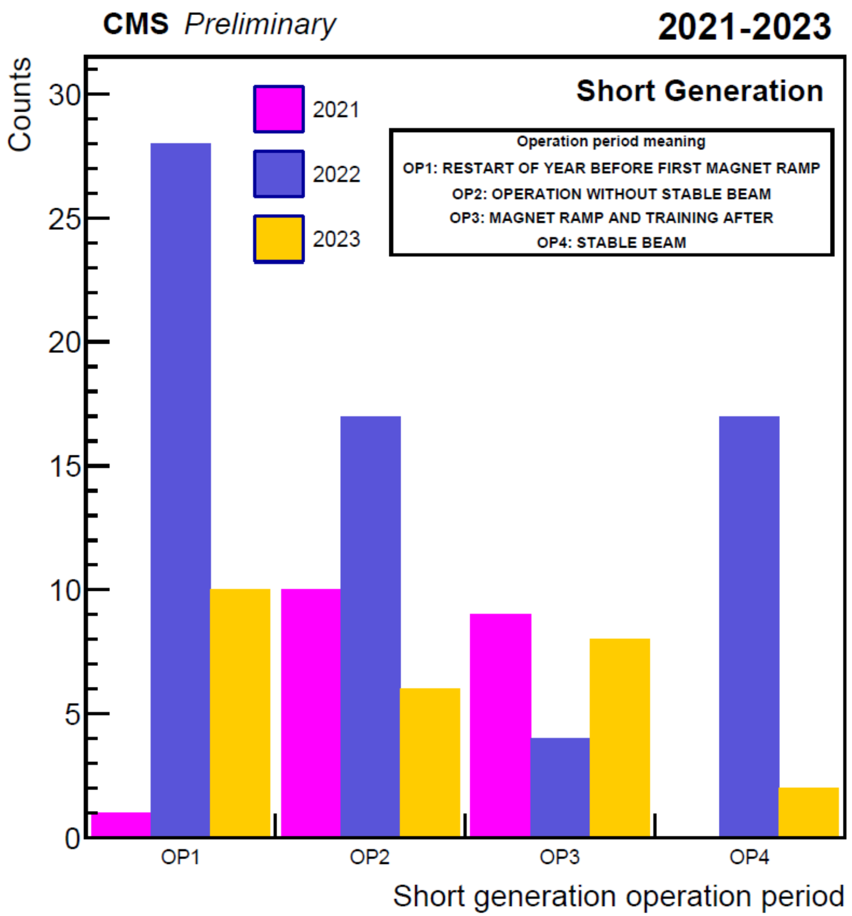
- **During a magnet ramp:**
  - Short circuits mostly generate in the **low field region** (very beginning of a magnet ramp up or at the very end of a magnet ramp down)
  - Article on discharges and short circuits during Run 3 [10.1088/1748-0221/20/05/P05035](10.1088/1748-0221/20/05/P05035)

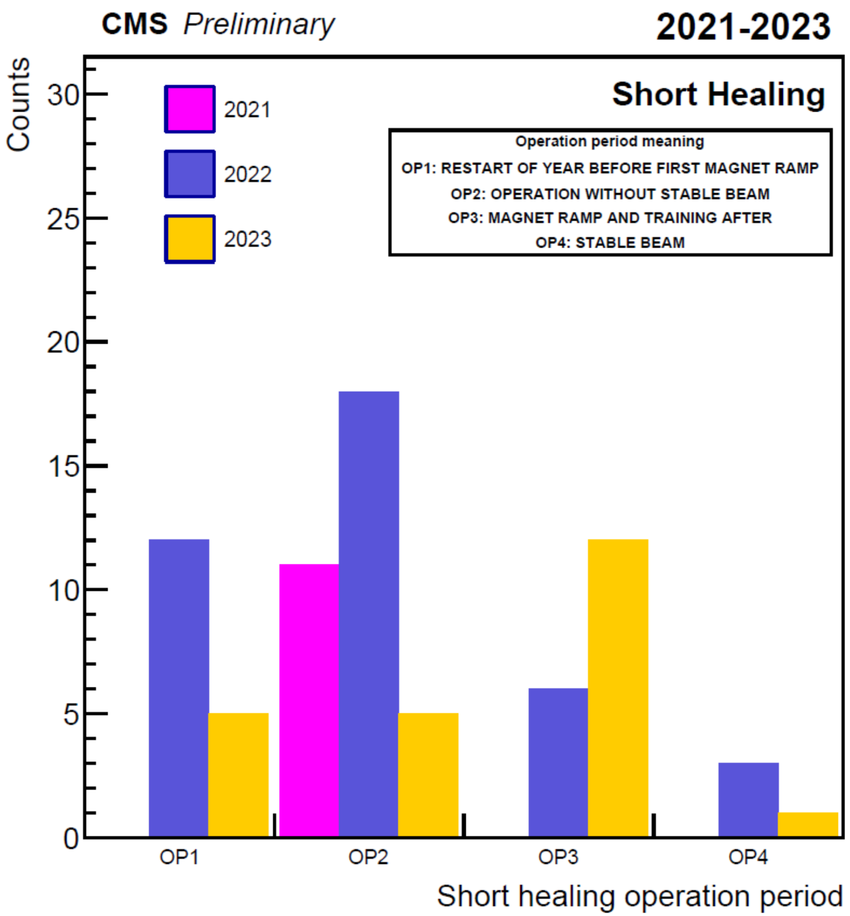
- **Implemented HV protection for magnet operations**
  - HV on GEM foils set to 420 V, gas gaps turned OFF
  - Article on tests done with Goliath Magnet in CERN North Area in 2021 [10.1088/1748-0221/18/11/P11029](10.1088/1748-0221/18/11/P11029)



Events in the plot: magnet ramp ongoing and HV ON

Operative context for short generation and healing



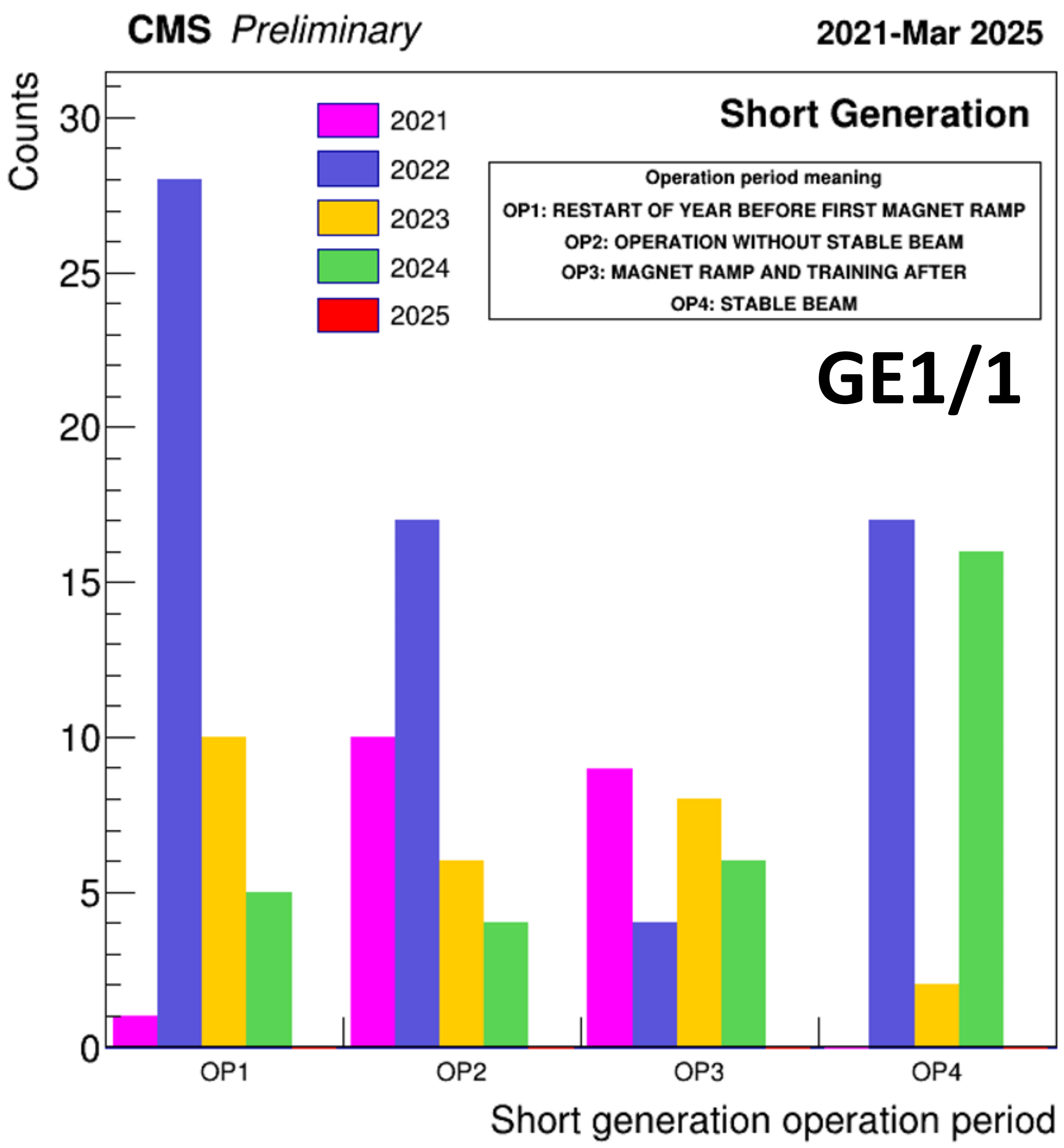


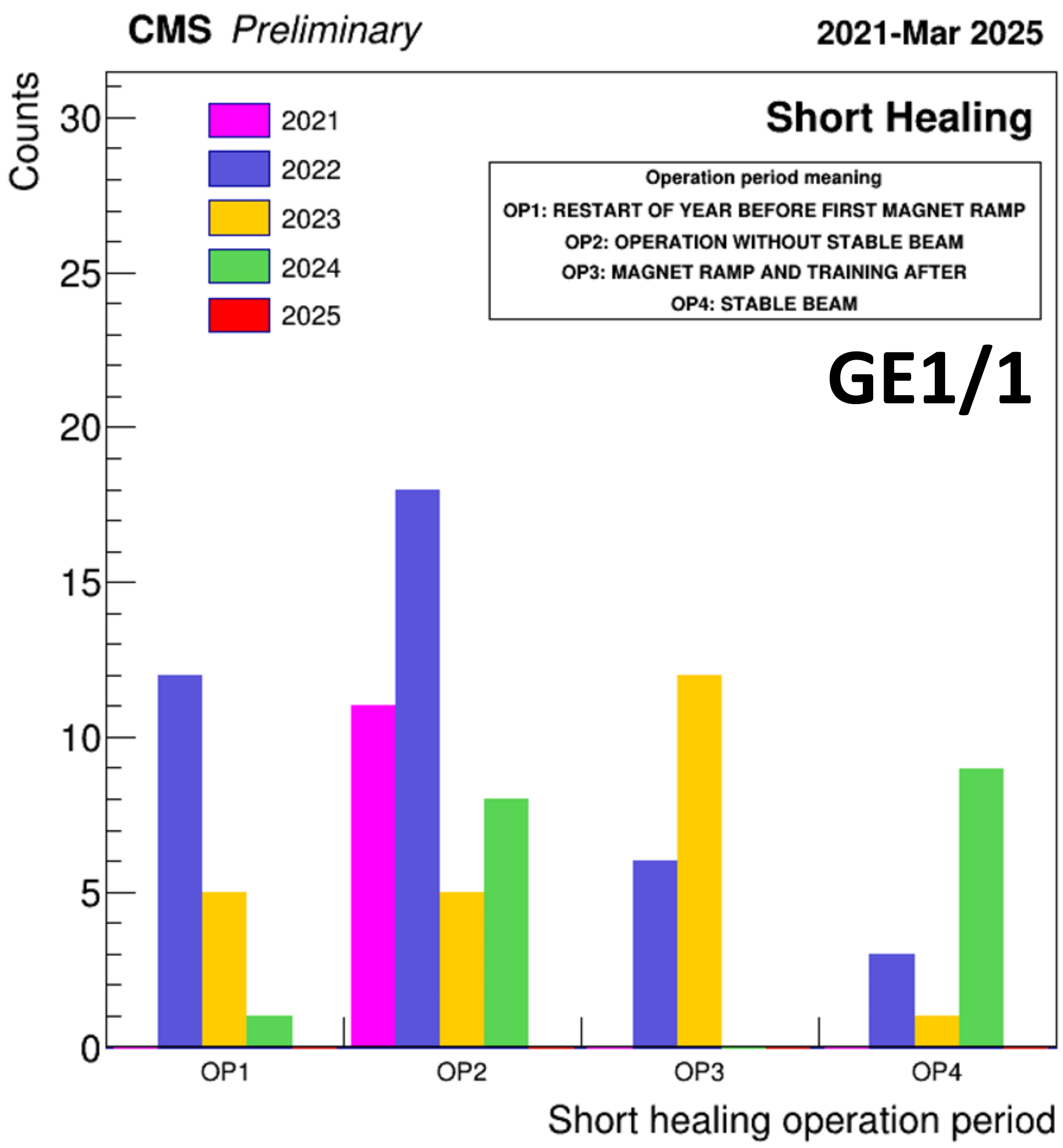
Conditions of generation:

- Mostly due to discharges, voltage ramp up and magnet ramps

Conditions of healing:

- Mostly due to discharges, voltage ramp, magnet ramp, slow consumption of the short circuit


CMS Preliminary
2021-Mar 2025
Counts
Short Generation
2021
2022
2023
2024
2025
Operation period meaning
OP1: RESTART OF YEAR BEFORE FIRST MAGNET RAMP
OP2: OPERATION WITHOUT STABLE BEAM
OP3: MAGNET RAMP AND TRAINING AFTER
OP4: STABLE BEAM
GE1/1
OP1
OP2
OP3
OP4
Short generation operation period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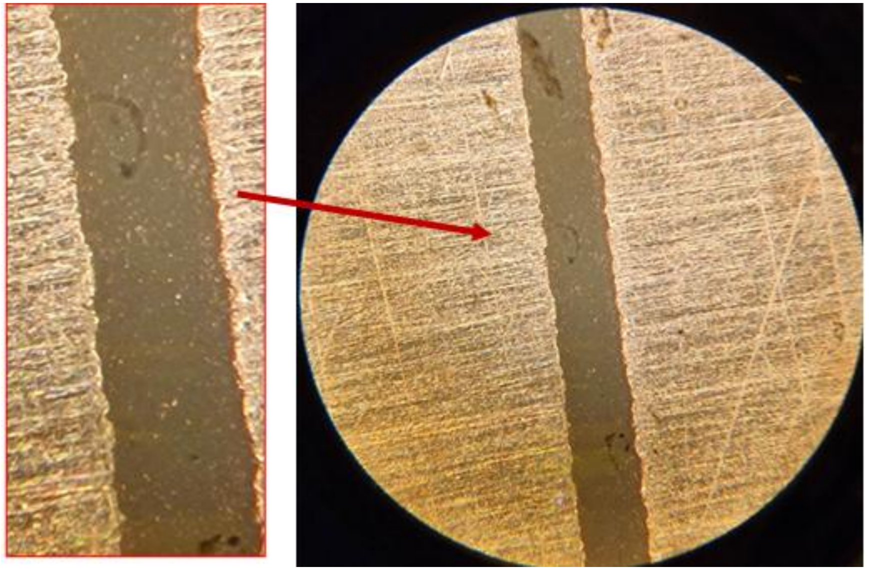
OP2
OP3
OP4
Short healing operation period

Detectors’ production

Production of PCBs

- In summer 2023 it was discovered an issue in the production of PCBs
  - GE1/1 PCBs were not passivated
  - GE2/1 PCBs were not passivated and sand blasted → copper dust in the detectors

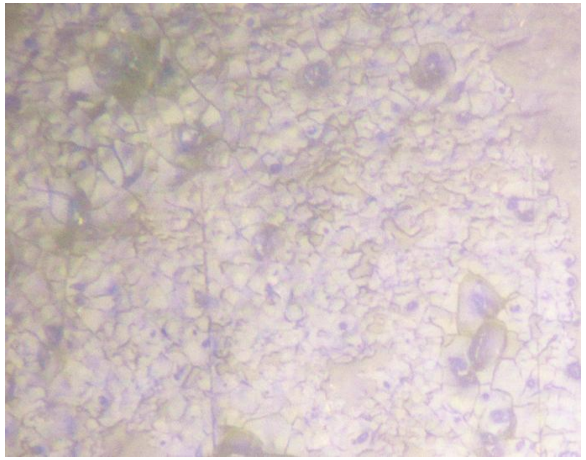


More details:
RD51 collaboration meeting (7 December 2023) [10]

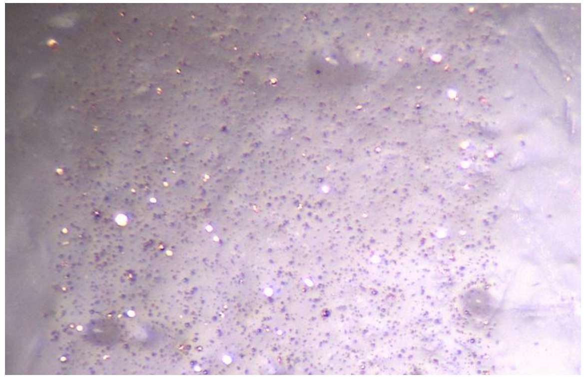
Investigations and actions

Ageing detector

GE1/1 extracted from CMS



Green stains



Brown stains

- Signs of oxidation in irradiated area in the GE1/1 ageing detector
  - White and blue stains
- Exctracted and replaced 4 GE1/1 detectors from CMS
  - Found **signs of oxidation** in 2 of the 3 inspected detectors (green and brown stains)
- Actions:
  - Started cleaning both of GE2/1 GEM foils stack and PCBs
    - How: chromic acid bath
  - Tests in magnet MNP22 in North Area
  - Extraction from CMS in January 2025
    - 6 detectors (3 GE1/1 Super-Chambers)
    - Why: investigation on oxidation

Conclusion

- Summary on 2024 operations
  - Operations team tried to squeeze all the efficiency obtainable so far
    - HV compensation of short circuits: needed improvements in the Detector Control System (DCS)
  - Time resolution: 12.3 ns
  - GEM included in L1 Trigger
    - Next step of integration in the hands of Endcap trigger group
    - GEM team will continue to assist the integration from the detector side

- Investigations on detectors ongoing
  - Cleaning of GE2/1 detectors
  - Role of oxidation
  - Digging further on role of magnetic field ramps in generation of discharges and short circuits (performed 4 tests in magnetic field from 2021)

- Many more aspects investigated
  - There are references and material in backup for the interested auditorium

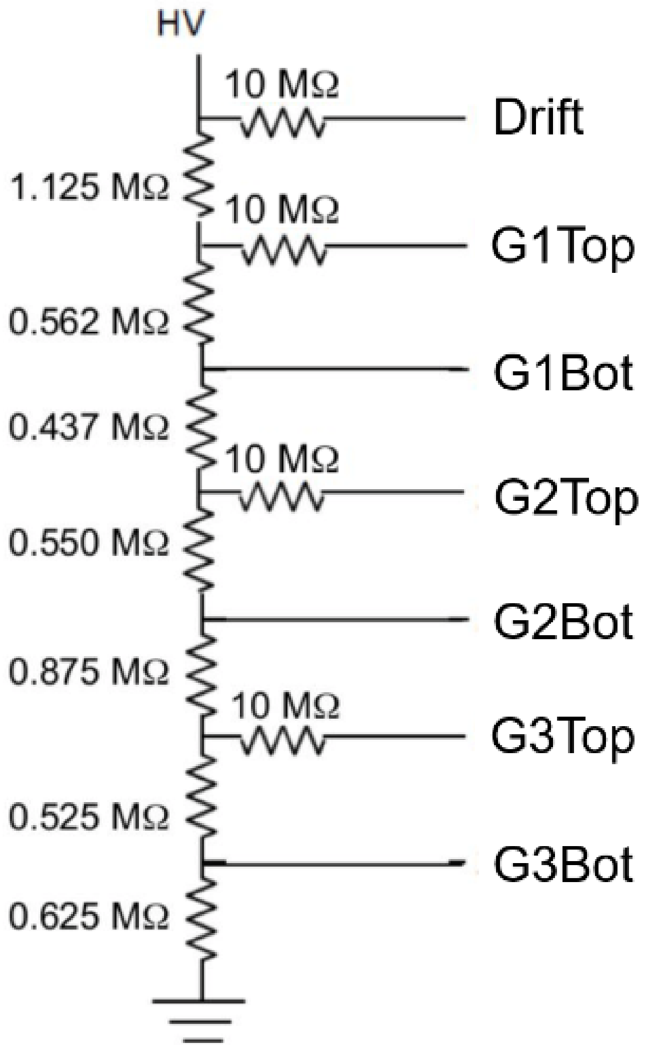
References

- [1] CMS Collaboration, The history of GEM foil short circuit generation and healing (2021-2023), CMS-DP-2024-050, https://cds.cern.ch/record/2904363.
- [2] CMS Collaboration, GE1/1 discharges plots, CMS-DP-2023-091, https://cds.cern.ch/record/2883614.
- [3] EP-ESE Electronics Seminars, The Curious Case of VTRx Receiver Failures, https://indico.cern.ch/event/1099169
- [4] CMS Collaboration, GE1/1 electronics performance, CMS-DP-2024-120, https://cds.cern.ch/record/2917572
- [5] CMS Collaboration, Study of correlation between baseline current and Hit Rate in GE1/1 chambers at the CMS Experiment, CMS-DP-2024-117, https://cds.cern.ch/record/2916757
- [6] G. Mocellin, Performance of the GE1/1 detectors for the upgrade of the CMS muon forward system, CERN-THESIS-2021-327
- [7] CMS Collaboration, Performance and quality control of the first CMS GE2/1 muon production chambers, CMS-DP-2024-075, https://cds.cern.ch/record/2908777
- [8] CMS Collaboration, Measurements of pT Dependent Bending Angles in the CMS GE1/1-ME1/1 System, CMS-DP-2024-047, https://cds.cern.ch/record/2904360
- [9] CMS Collaboration, GEM performance results with 2024 data, CMS-DP-2024-073, https://cds.cern.ch/record/2908775
- [10]A. Pellecchia, Status of CMS GEM Production, RD51 Collaboration Meeting, 7 December 2023 https://indico.cern.ch/event/1327482/contributions/5686633/attachments/2767175/4820306/CMS%20GEM%20production%20status%20-%20RD51%20Dec%202023%20(5).pdf
- [11] M. Abbas et al., Impact of magnetic field on the stability of the CMS GE1/1 GEM detector operation, 2023 JINST 18 P11029, DOI: 10.1088/1748-0221/18/11/P11029
- [12] F.Nenna, Performance in a high-rate environment of triple-GEM detectors for the Phase-2 upgrade of the CMS detector, CERN-THESIS-2024-114, https://cds.cern.ch/record/2906703

Backup

Backup for HV

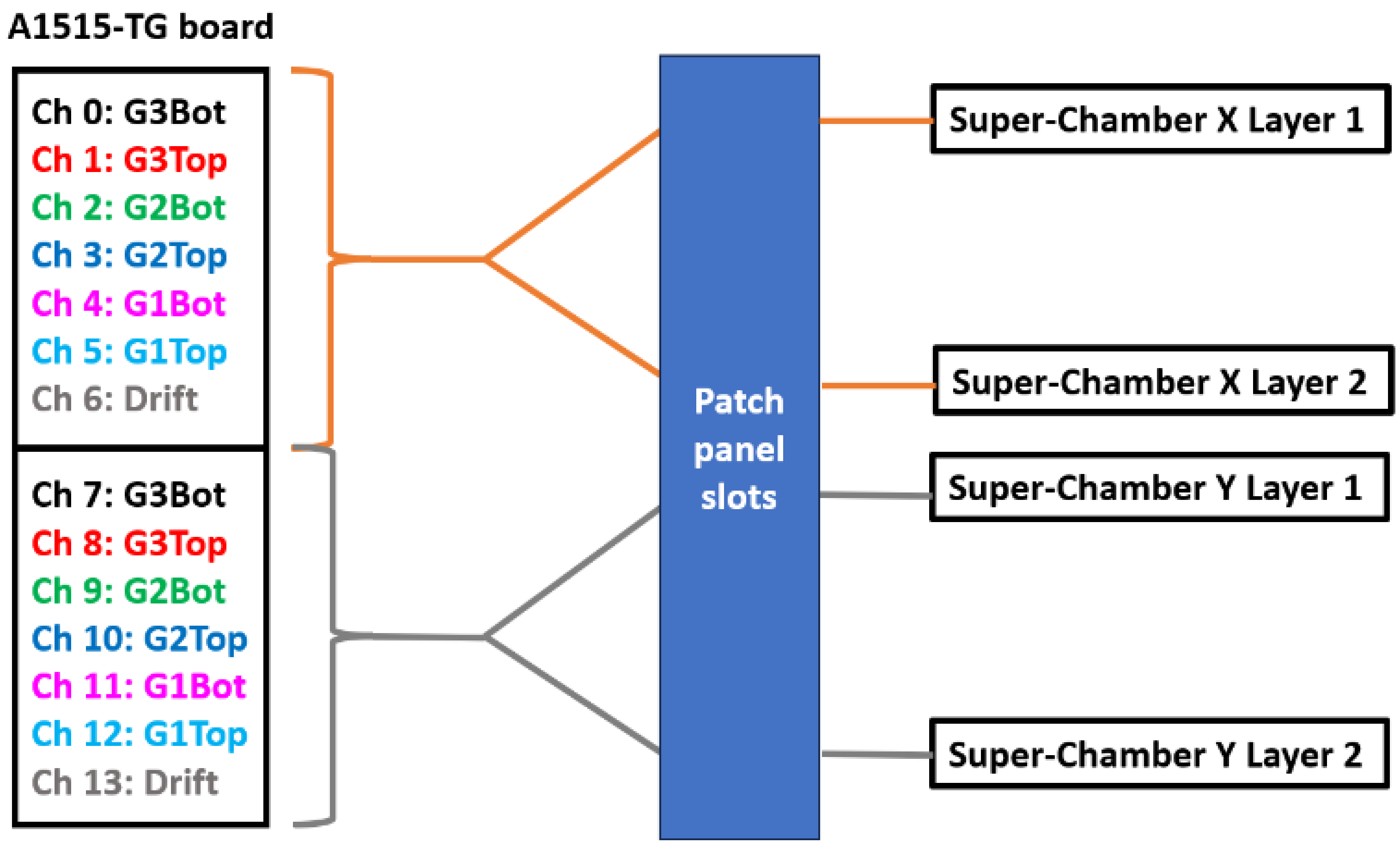
The HV working point



- **How to fix the voltages on the single channel:** these numbers are determined by a reference resistive divider used for the quality control of the detectors
- **How to have flexibility:** in CMS (P5) a multichannel power supply board (A1515BTG) is used, applying the voltage settings aforementioned and allowing to modify each of the 7 channels
  - This voltage configuration is equivalent to that obtained by a given current flowing the referece resistive divider. So a voltage setting ($\mathbf{I_{eq}}$) is identified by this current

Configuration $\mathbf{I_{eq}} = \mathbf{690}\ \mu\mathbf{A}$ (Gain ≈ 10^4)			
Drift	776 V	**G1Top**	387 V
G1Bot	302 V	**G2Top**	379 V
G2Bot	604 V	**G3Top**	362 V
G3Bot	431 V		

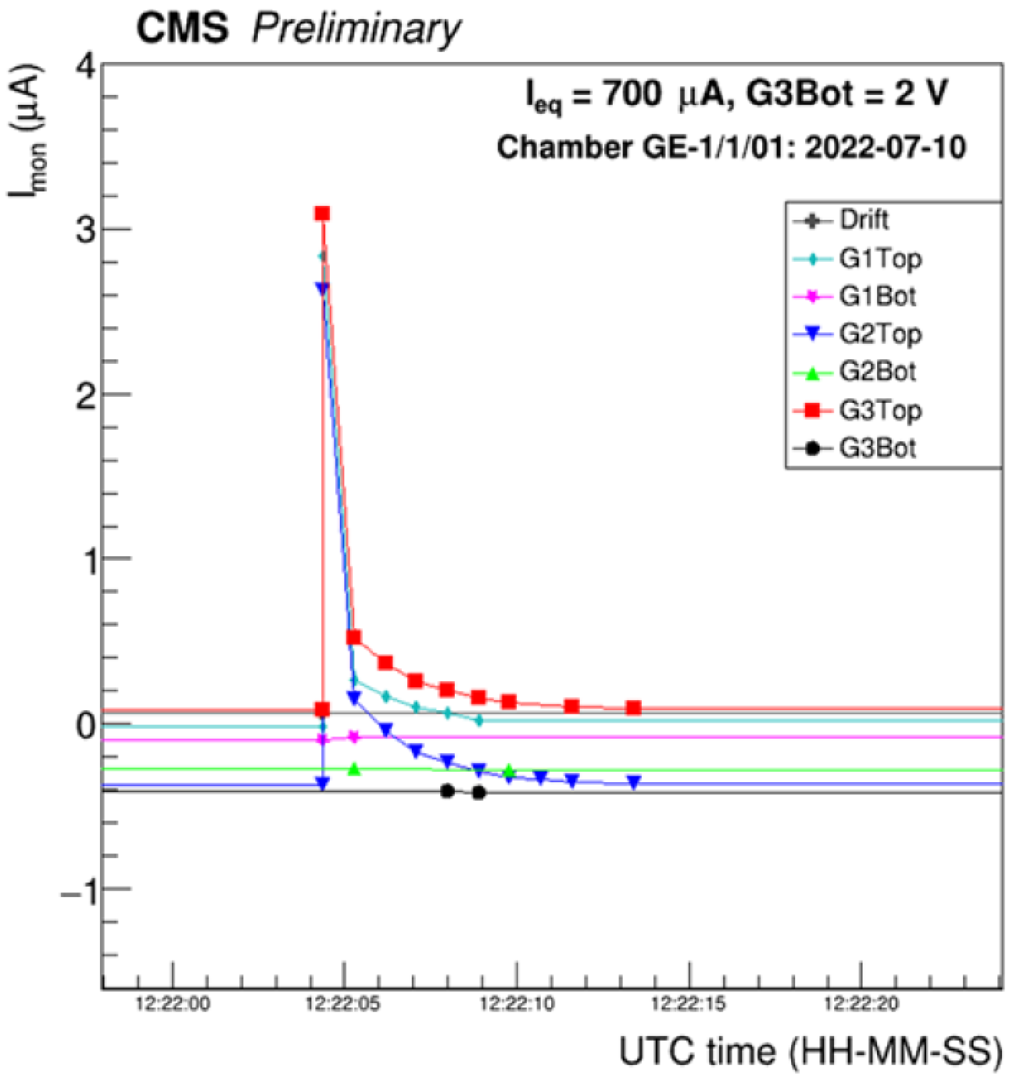
HV patch panel



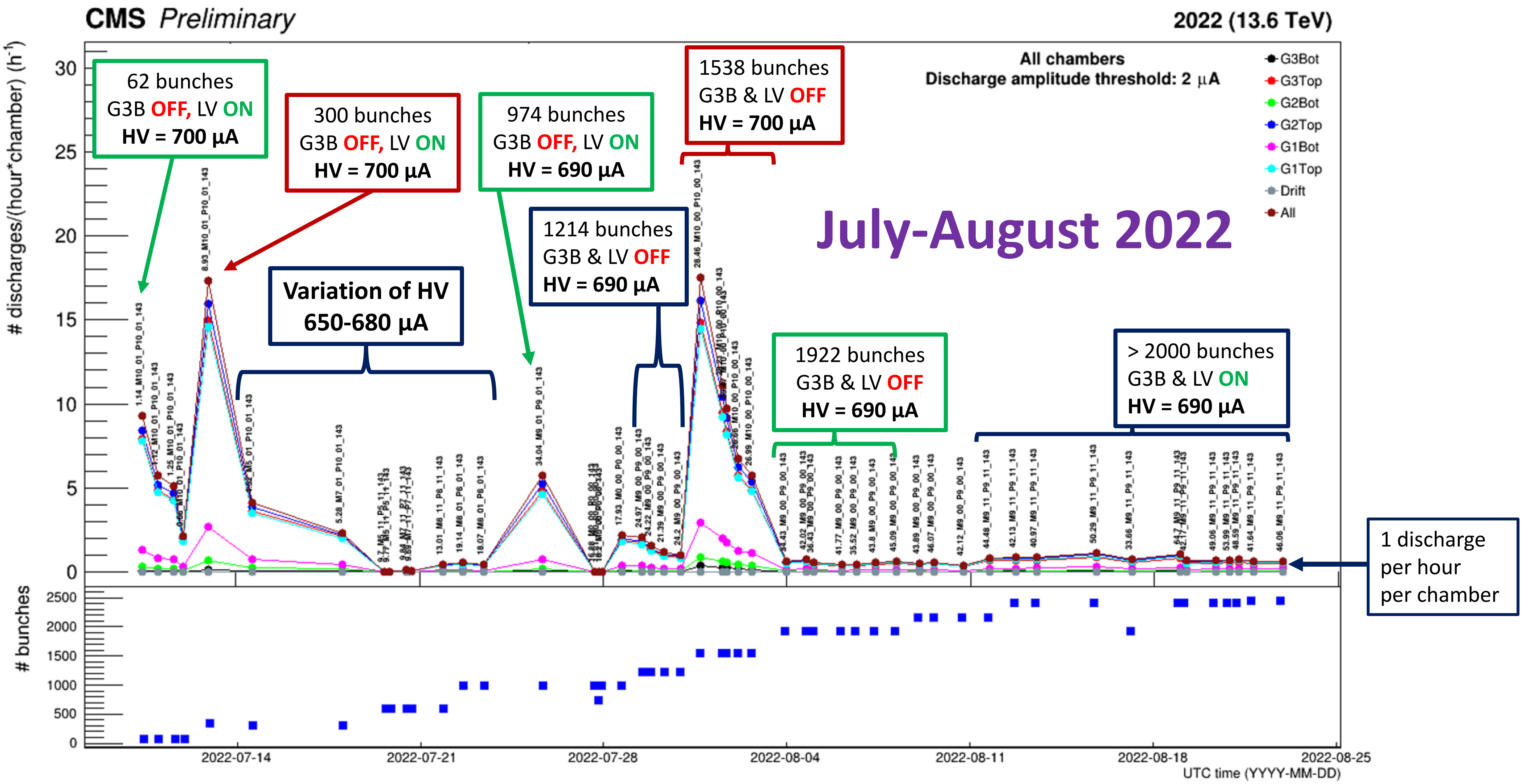
Voltage settings

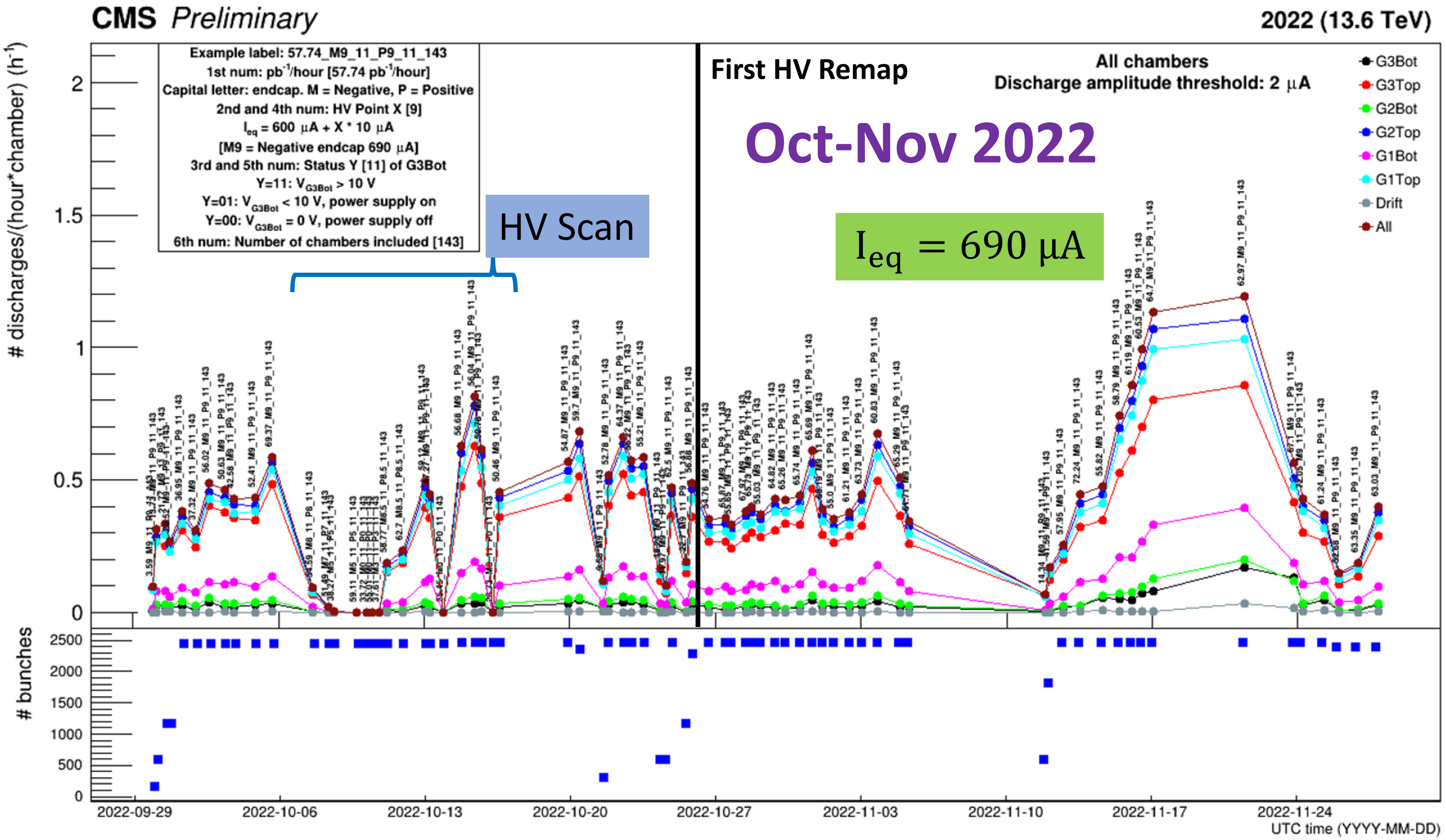
Equivalent divider current I_{eq} [µA]	580	690	700	710
Voltage on drift gap [V]	653	776	788	799
Voltage on GEM1 foil [V]	325	387	392	398
Voltage on transfer 1 gap [V]	254	302	307	311
Voltage on GEM2 foil [V]	319	379	385	391
Voltage on transfer 2 gap [V]	508	604	613	621
Voltage on GEM3 foil [V]	305	362	368	373
Voltage on induction gap [V]	363	431	438	444
Electric field in drift gap [kV/cm]	2.18	2.59	2.63	2.66
Electric field in GEM1 foil [kV/cm]	65.0	77.4	78.4	79.6
Electric field in transfer 1 gap [kV/cm]	2.54	3.02	3.07	3.11
Electric field in GEM2 foil [kV/cm]	63.8	75.8	77.0	78.2
Electric field in transfer 2 gap [kV/cm]	2.54	3.02	3.07	3.11
Electric field in GEM3 foil [kV/cm]	61.0	72.4	73.6	74.6
Electric field in induction gap [kV/cm]	3.63	4.31	4.38	4.44
Total gain	$(3.99 \pm 0.14) \cdot 10^2$	$(1.98 \pm 0.08) \cdot 10^4$	$(2.83 \pm 0.11) \cdot 10^4$	$(4.05 \pm 0.17) \cdot 10^4$

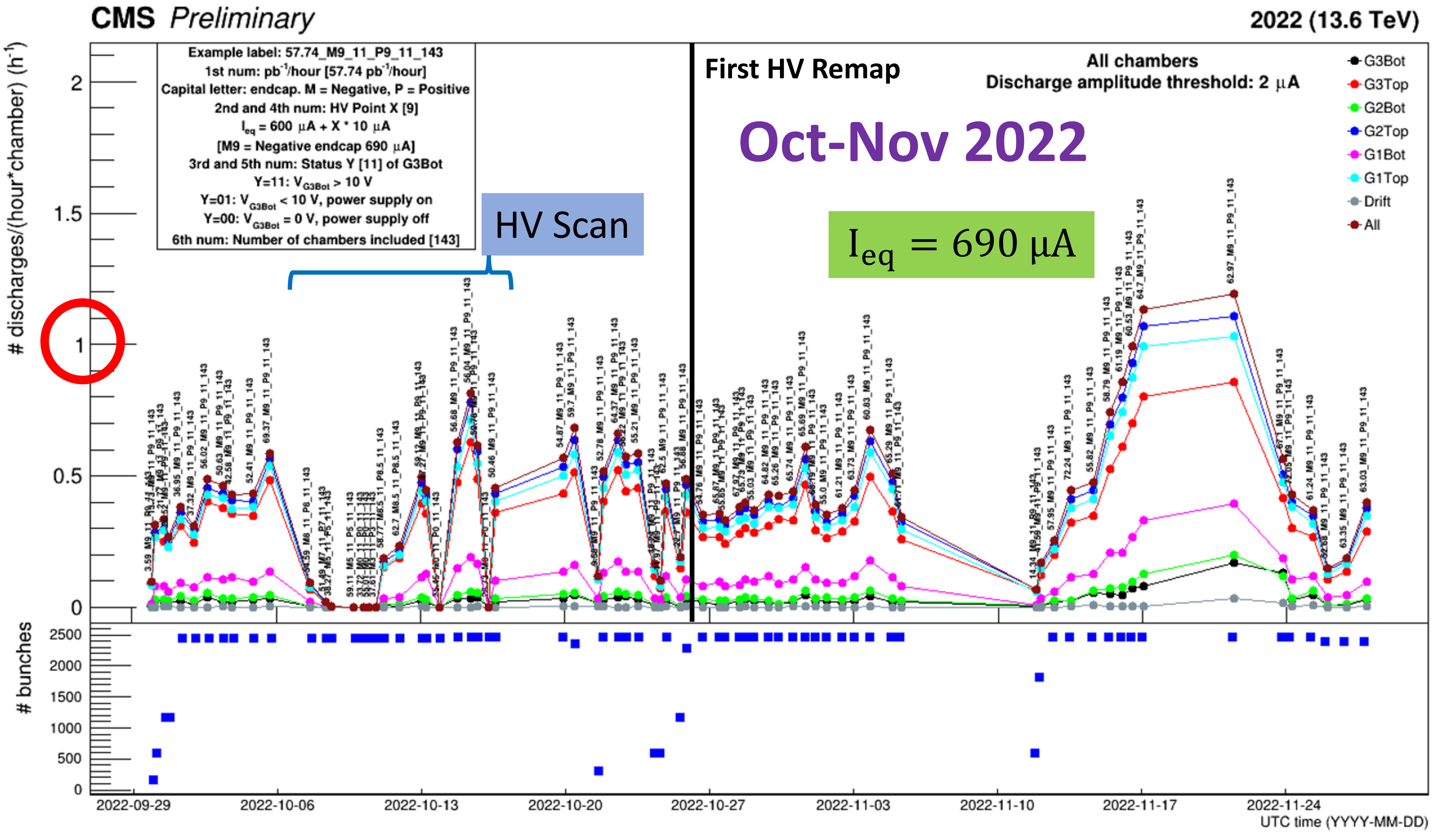
Discharges



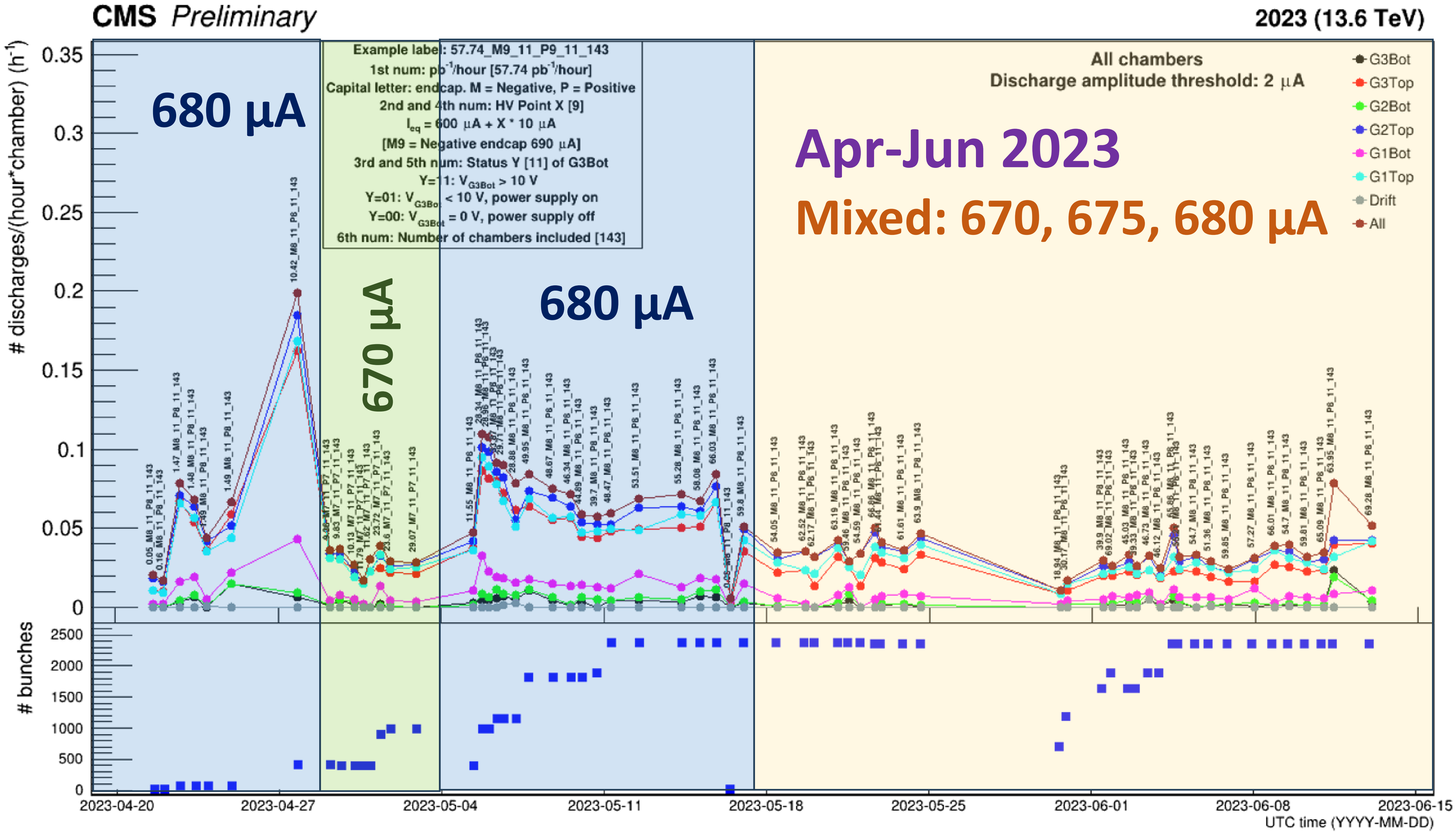
- What is a discharge?
  - Transient transfer of charge between the detector planes
- How it looks like?
  - Spike in current above the baseline current
- Impact?
  - It can trigger HV trips → the current spike can overcome the current limit of the HV channel
  - It can damage channels of the front-end electronics, if the discharge propagates towards the readout plane


CMS Preliminary
2022 (13.6 TeV)
All chambers
Discharge amplitude threshold: 2 µA
G3Bot
G3Top
G2Bot
G2Top
G1Bot
G1Top
Drift
All
July-August 2022
62 bunches
G3B OFF, LV ON
HV = 700 µA
300 bunches
G3B OFF, LV ON
HV = 700 µA
974 bunches
G3B OFF, LV ON
HV = 690 µA
1538 bunches
G3B & LV OFF
HV = 700 µA
1214 bunches
G3B & LV OFF
HV = 690 µA
Variation of HV
650-680 µA
1922 bunches
G3B & LV OFF
HV = 690 µA
> 2000 bunches
G3B & LV ON
HV = 690 µA
1 discharge
per hour
per chamber
discharges/(hour*chamber) (h⁻¹)
bunches
2022-07-14
2022-07-21
2022-07-28
2022-08-04
2022-08-11
2022-08-18
2022-08-25
UTC time (YYYY-MM-DD)


CMS Preliminary
2022 (13.6 TeV)
Example label: 57.74_M9_11_P9_11_143
1st num: pb^-1/hour [57.74 pb^-1/hour]
Capital letter: endcap. M = Negative, P = Positive
2nd and 4th num: HV Point X [9]
I_eq = 600 µA + X * 10 µA
[M9 = Negative endcap 690 µA]
3rd and 5th num: Status Y [11] of G3Bot
Y=11: V_G3Bot > 10 V
Y=01: V_G3Bot < 10 V, power supply on
Y=00: V_G3Bot = 0 V, power supply off
6th num: Number of chambers included [143]
First HV Remap
All chambers
Discharge amplitude threshold: 2 µA
Oct-Nov 2022
HV Scan
I_eq = 690 µA
G3Bot
G3Top
G2Bot
G2Top
G1Bot
G1Top
Drift
All
discharges/(hour*chamber) (h^-1)
bunches
UTC time (YYYY-MM-DD)
2022-09-29
2022-10-06
2022-10-13
2022-10-20
2022-10-27
2022-11-03
2022-11-10
2022-11-17
2022-11-24



CMS Preliminary
2022 (13.6 TeV)
Example label: 57.74_M9_11_P9_11_143
1st num: pb⁻¹/hour [57.74 pb⁻¹/hour]
Capital letter: endcap. M = Negative, P = Positive
2nd and 4th num: HV Point X [9]
I_{eq} = 600 µA + X * 10 µA
[M9 = Negative endcap 690 µA]
3rd and 5th num: Status Y [11] of G3Bot
Y=11: V_{G3Bot} > 10 V
Y=01: V_{G3Bot} < 10 V, power supply on
Y=00: V_{G3Bot} = 0 V, power supply off
6th num: Number of chambers included [143]
HV Scan
First HV Remap
All chambers
Discharge amplitude threshold: 2 µA
Oct-Nov 2022
$I_{eq} = 690\ \mu A$
G3Bot
G3Top
G2Bot
G2Top
G1Bot
G1Top
Drift
All
discharges/(hour*chamber) (h⁻¹)
bunches
UTC time (YYYY-MM-DD)


CMS Preliminary
2023 (13.6 TeV)
680 µA
670 µA
680 µA
Apr-Jun 2023
Mixed: 670, 675, 680 µA
Example label: 57.74_M9_11_P9_11_143
1st num: pb^{-1}/hour [57.74 pb^{-1}/hour]
Capital letter: endcap. M = Negative, P = Positive
2nd and 4th num: HV Point X [9]
I_{eq} = 600 µA + X * 10 µA
[M9 = Negative endcap 690 µA]
3rd and 5th num: Status Y [11] of G3Bot
Y=11: V_{G3Bot} > 10 V
Y=01: V_{G3Bot} < 10 V, power supply on
Y=00: V_{G3Bot} = 0 V, power supply off
6th num: Number of chambers included [143]
All chambers
Discharge amplitude threshold: 2 µA
G3Bot
G3Top
G2Bot
G2Top
G1Bot
G1Top
Drift
All
discharges/(hour*chamber) (h^{-1})
bunches
UTC time (YYYY-MM-DD)

Discharge rate during Pb-Pb collisions

- Low discharge rate during Pb-Pb collisions

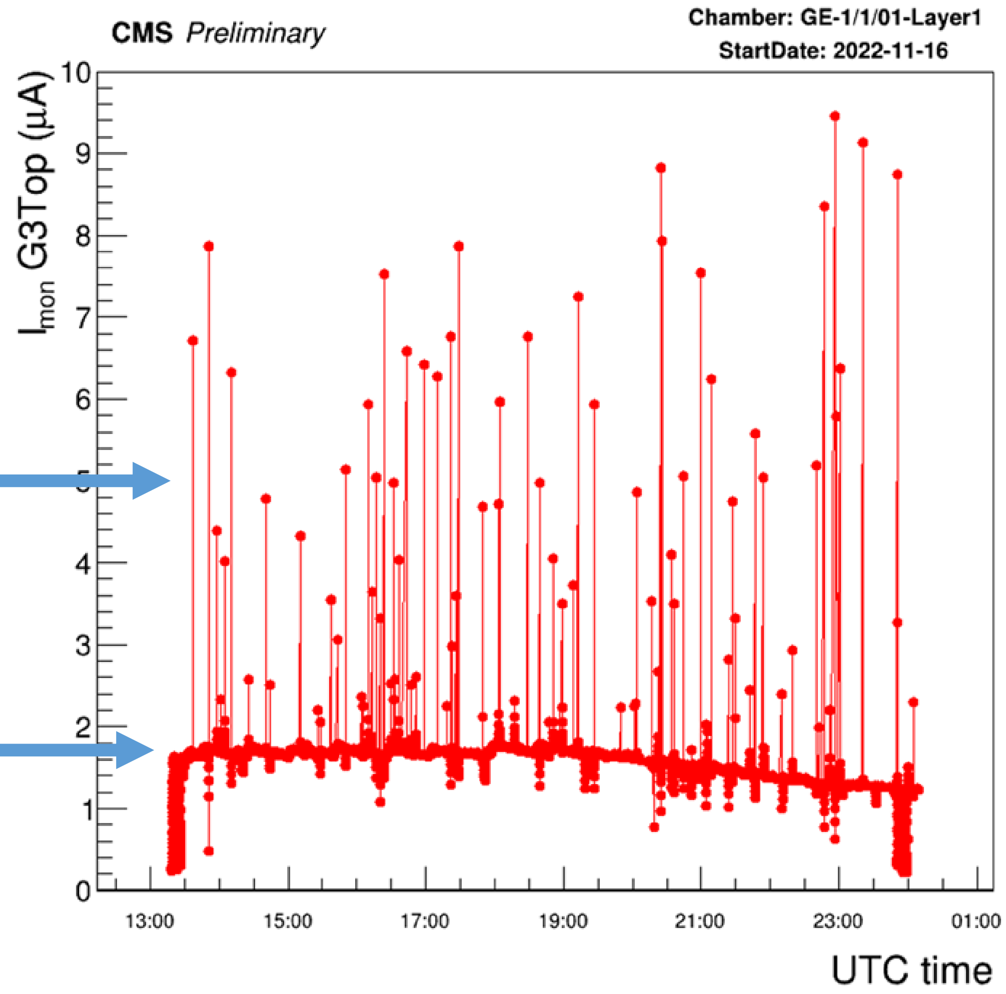
- Much lower instantanous luminosity from the LHC
  - p-p collisions: $\sim 10^{34} cm^{-2} s^{-1}$
  - Pb-Pb collisions: $\sim 10^{27} cm^{-2} s^{-1}$

Quantity	Average per fill	Total
Discharges (143 detectors)	5.9 ± 0.7	347
Delivered luminosity	34.0 ± 2.7 μb^{-1}	2005.7 μb^{-1}

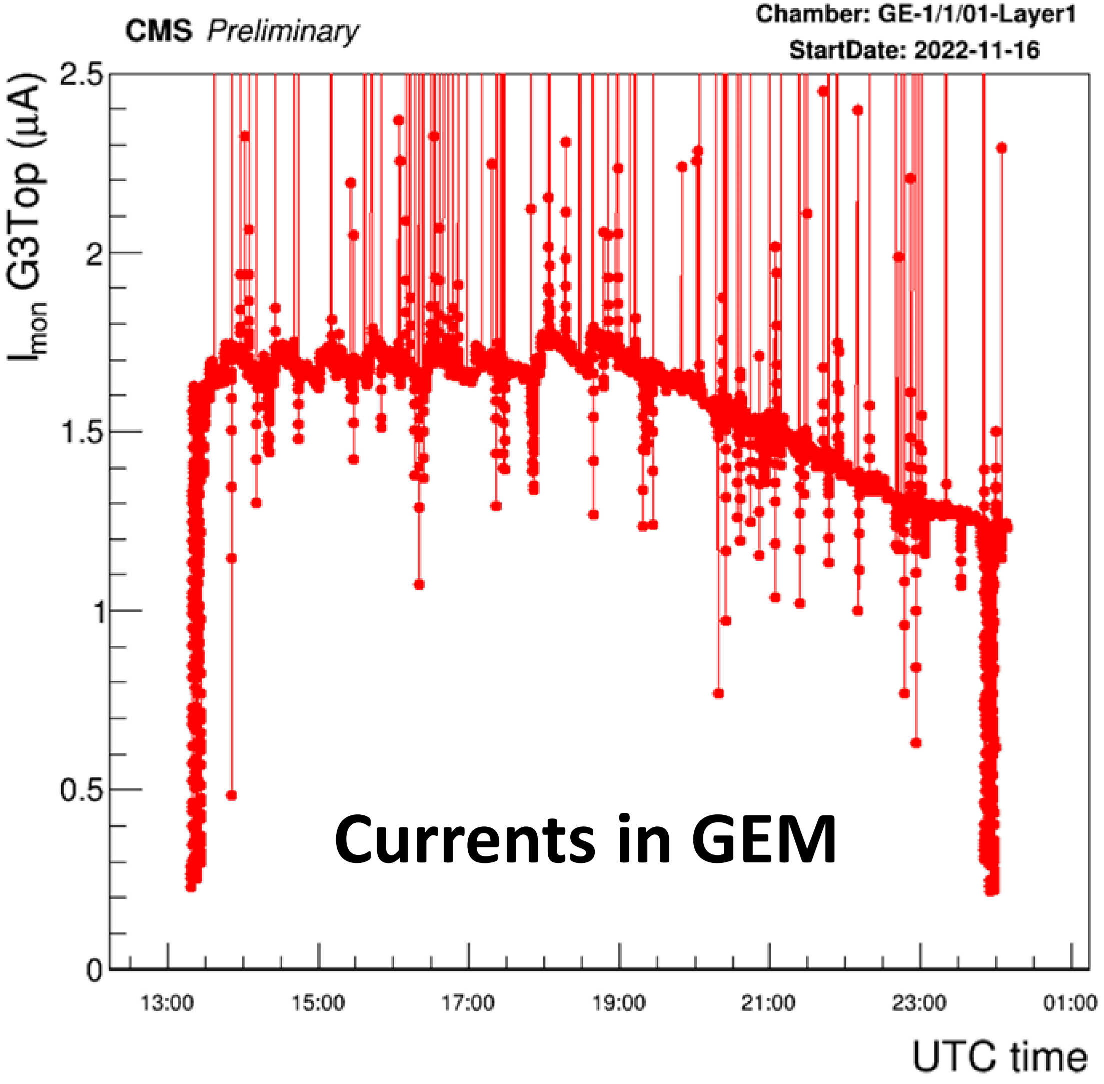
Baseline current in presence of beam

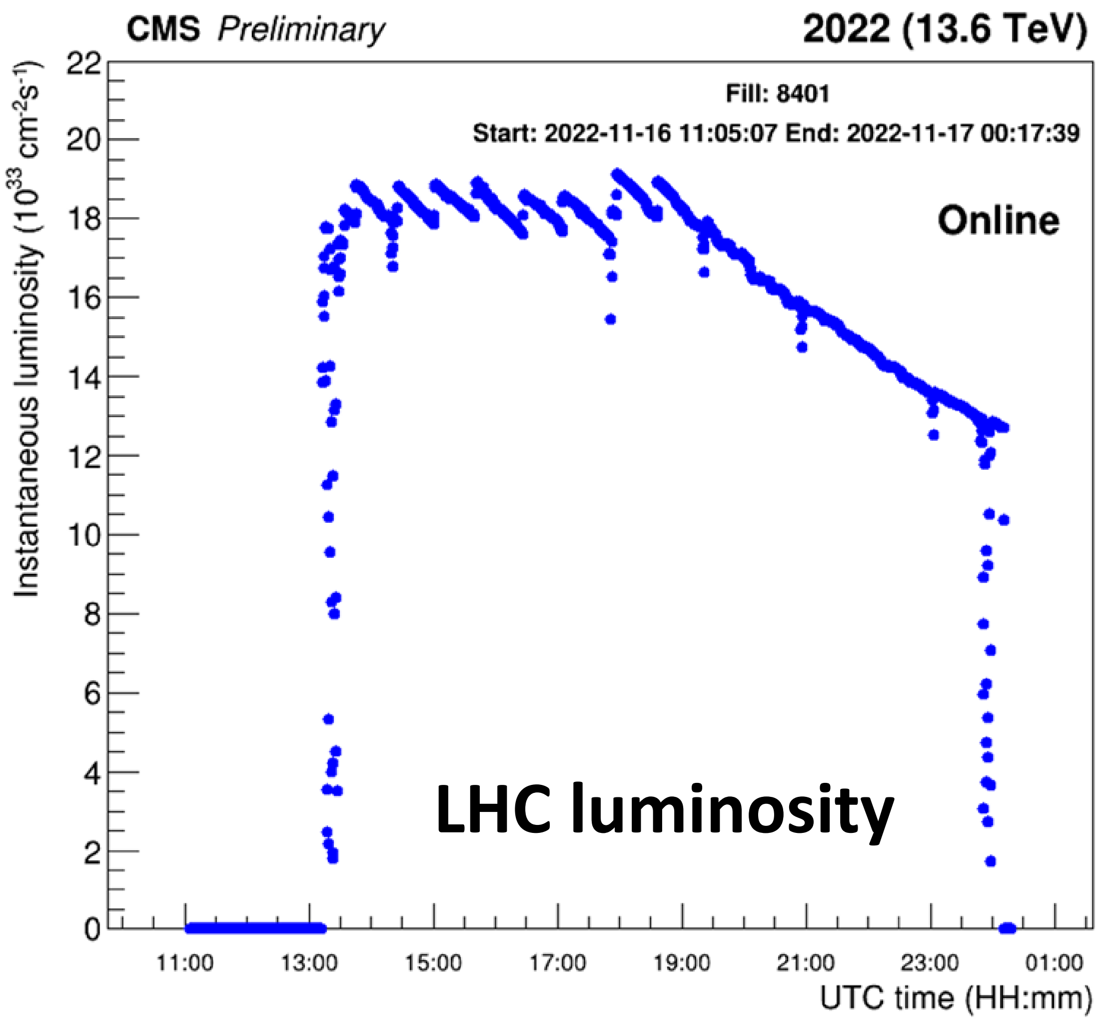
Discharges

Baseline current

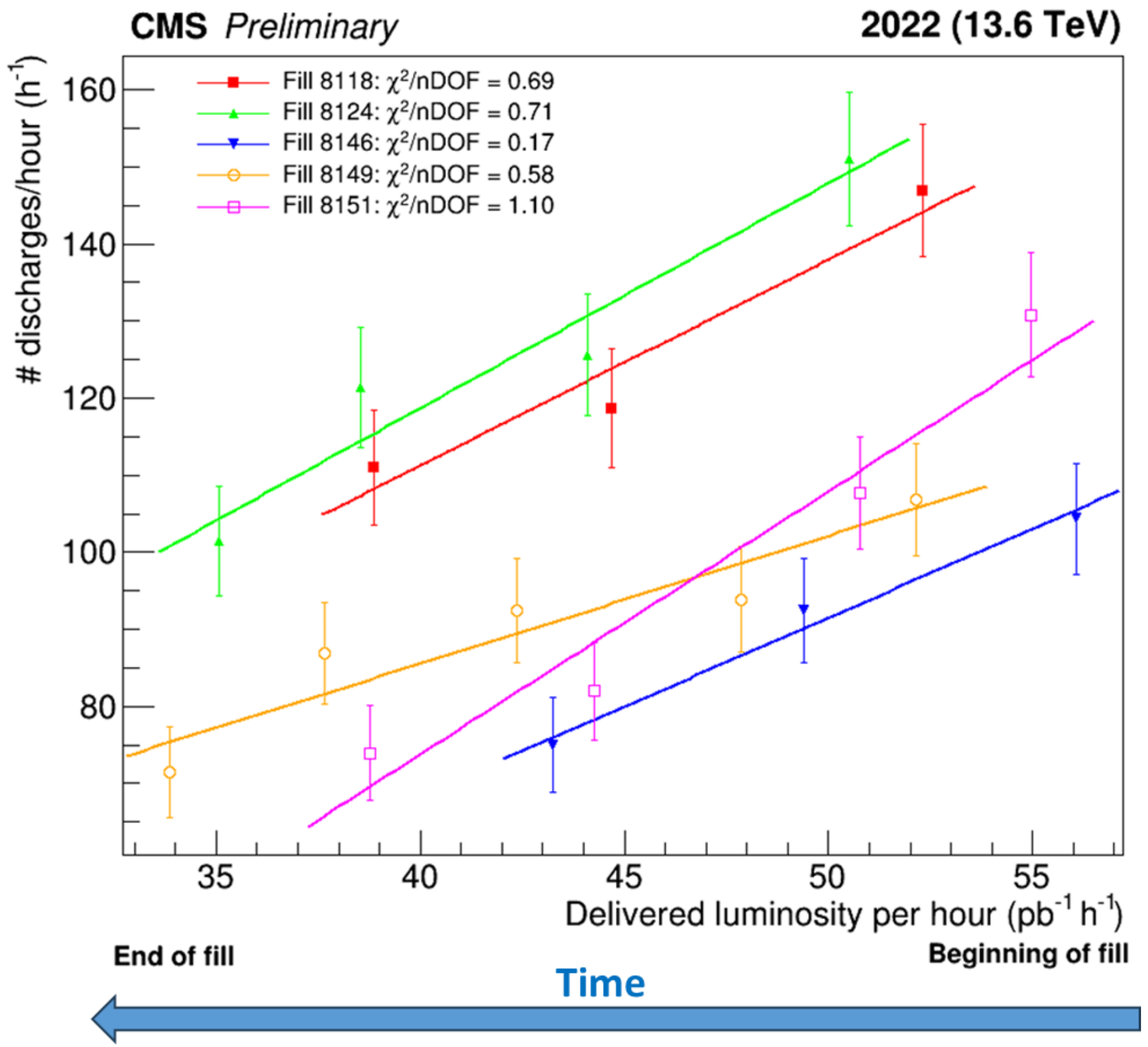


Baseline current vs LHC luminosity





Discharge rate Vs Luminosity



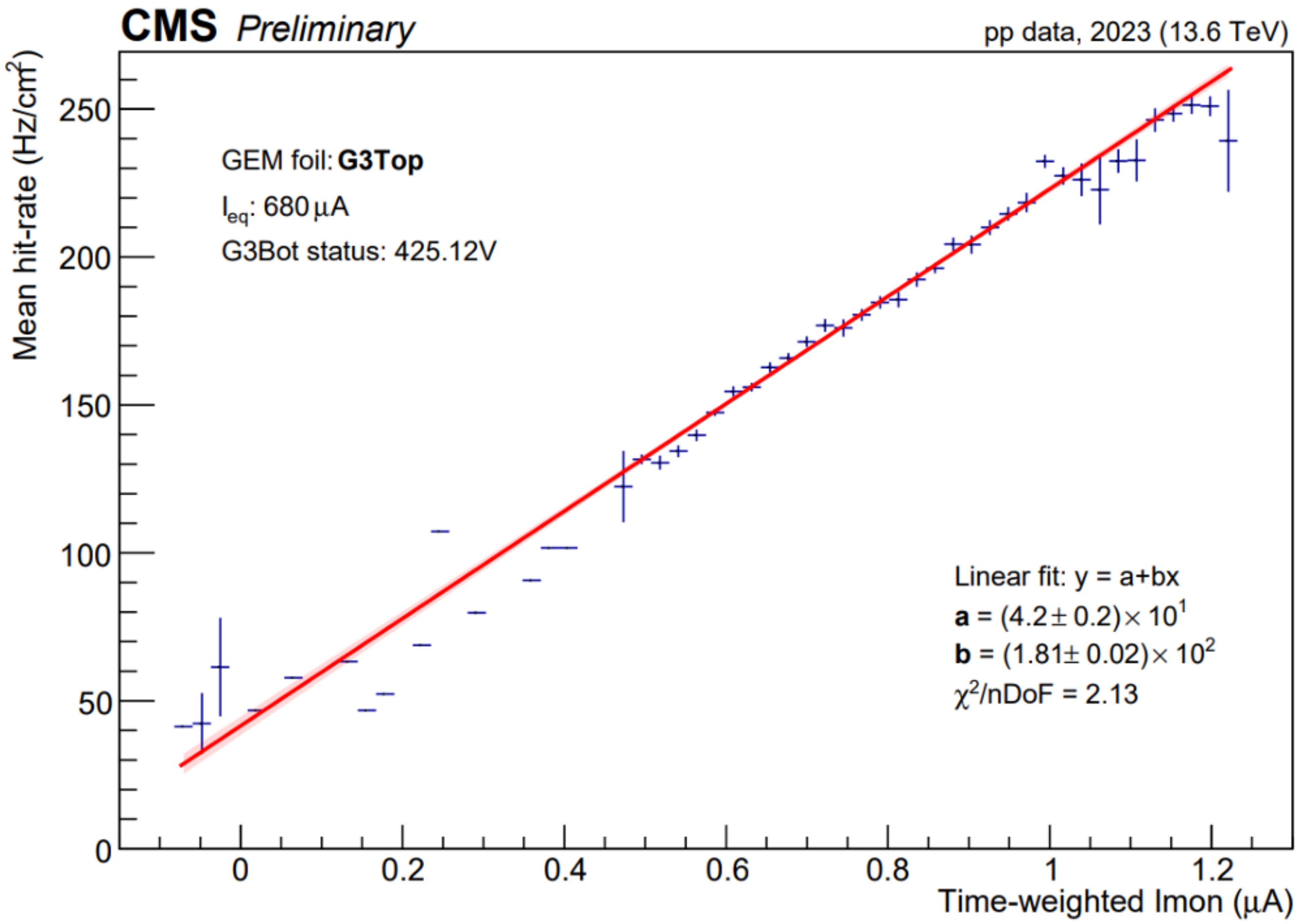
- Data of 5 LHC fills analysed
  - Fixed HV working point: $I_{eq} = 690\ \mu A$

- **Correlation between discharge rate vs luminosity of the LHC**

- Complications:
  - **Conditioning effect:**
    The discharge rate for a given chamber can change in time → generation or removal of imperfections in the GEM foil which generate the discharges
  - **Damages in the foils:**
    if a short circuit is generated a lower effective voltage is applied to the foil

- To study:
  - Dependence of the discharge rate on the HV working point

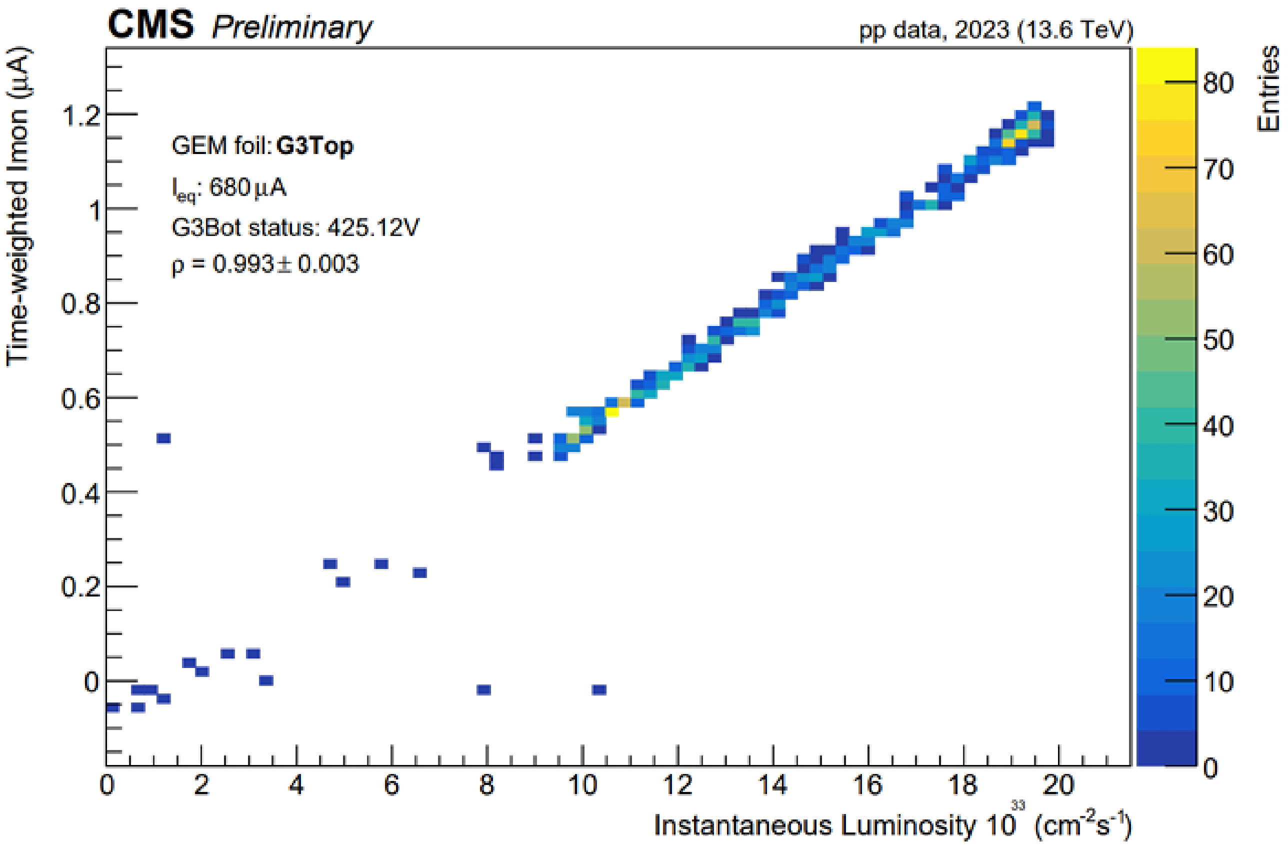
Background current vs Luminosity



- No sign of saturation in the hit rate

- Homework
  - Analyze more fills, in particular of HV scan 2024
  - Study the dependence on the HV working point
  - Study the role of short circuits

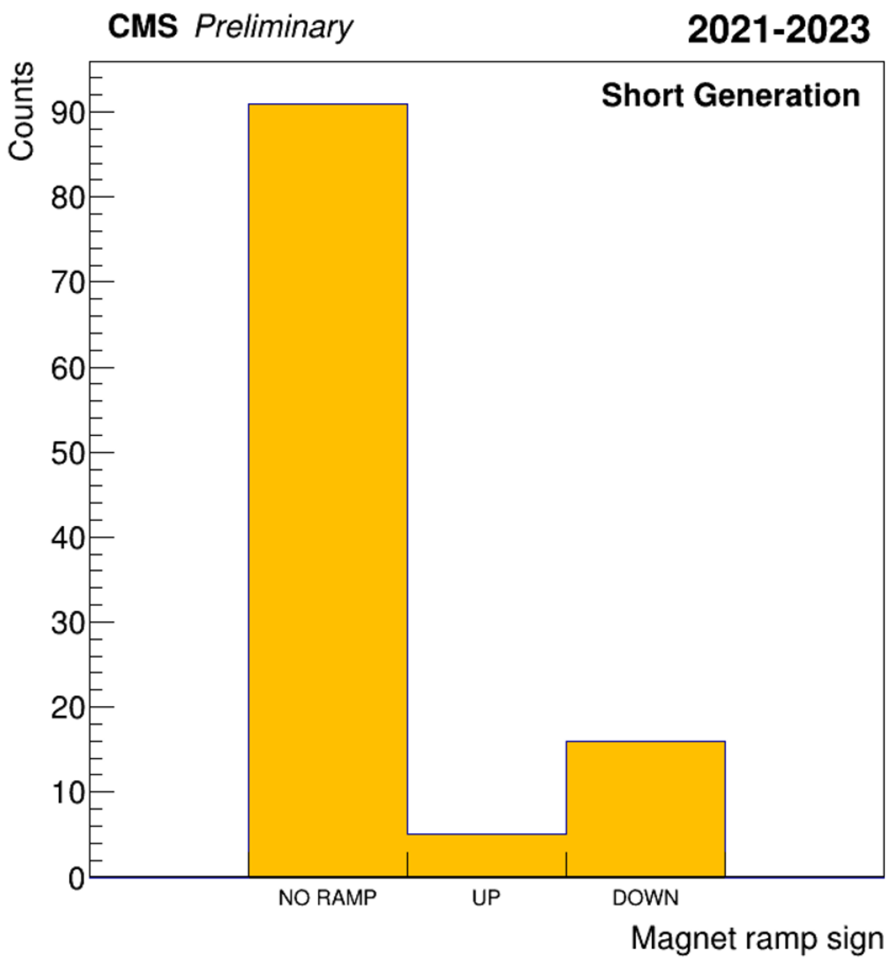
Background Current vs Luminosity

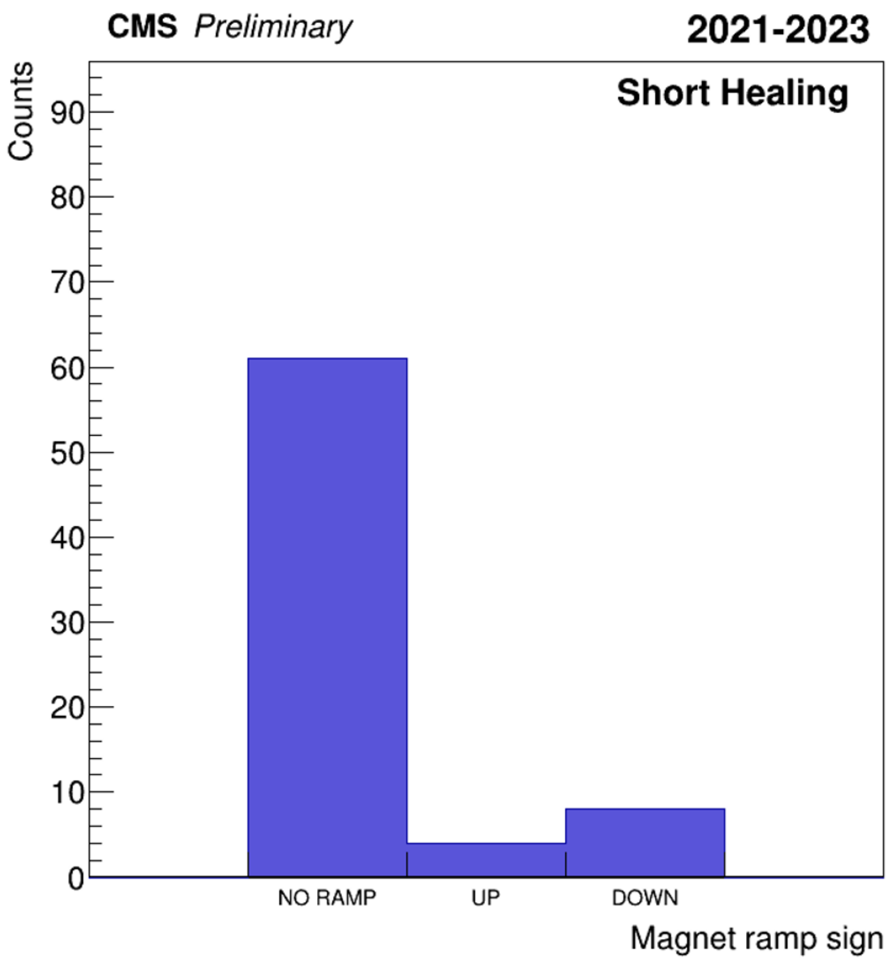


- Two-dimensional binned distribution of the timeweighted baseline current as a function of instantaneous luminosity.
- The current is weighted during the "lumi section" corresponding to the measurement of instantaneous luminosity, where a "lumi section" is a reference time interval used by CMS corresponding to ~ 23 seconds.
- This plot is relative to the chamber GE1/1-P-01-L1, paired in the HV with GE1/1-P-01-L2 (May 2023). This distribution refers to the current in the G3Top channel of A1515 board, powering the GEM3 foil. It is shown the corresponding working-point, the G3Bot voltage status and the linear correlation coefficient ρ, whose error is estimated by $\sqrt{\frac{1-\rho^2}{N-2}}$ where N is the number of all entries.
- The outliers in bottom left part of the plot are due to beam separation ("emittance") scans near the start of CMS data taking, which cause sudden variations in instantaneous luminosity and current.

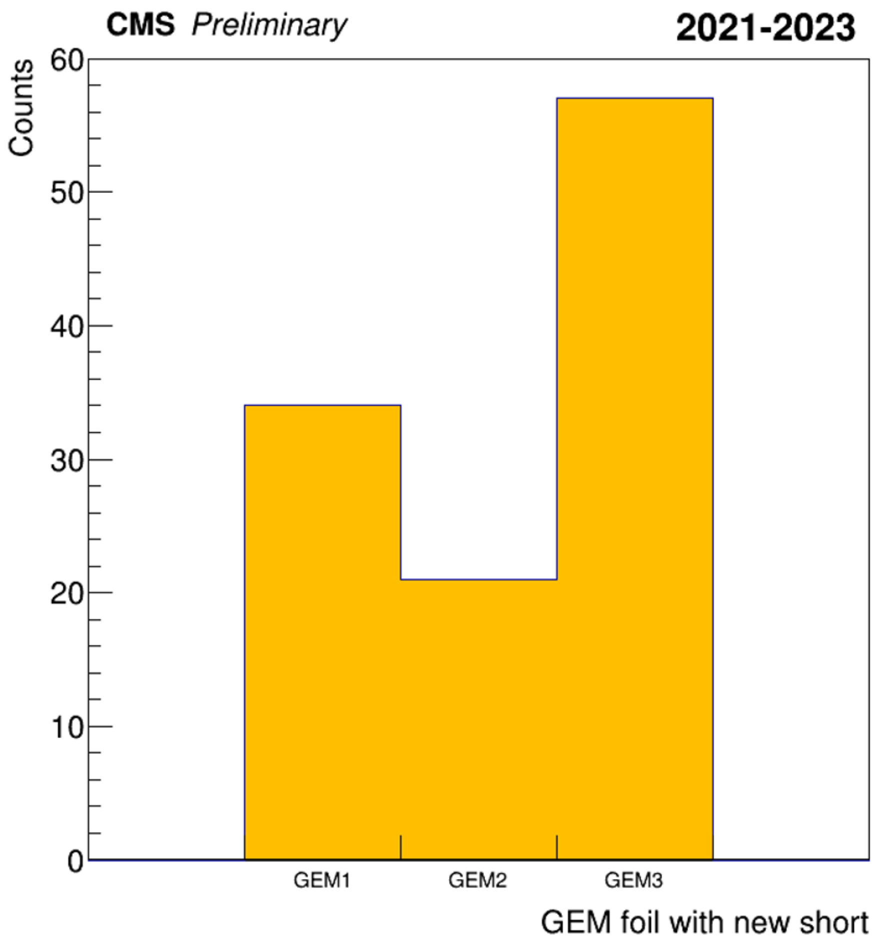
Short circuits in GEM foils

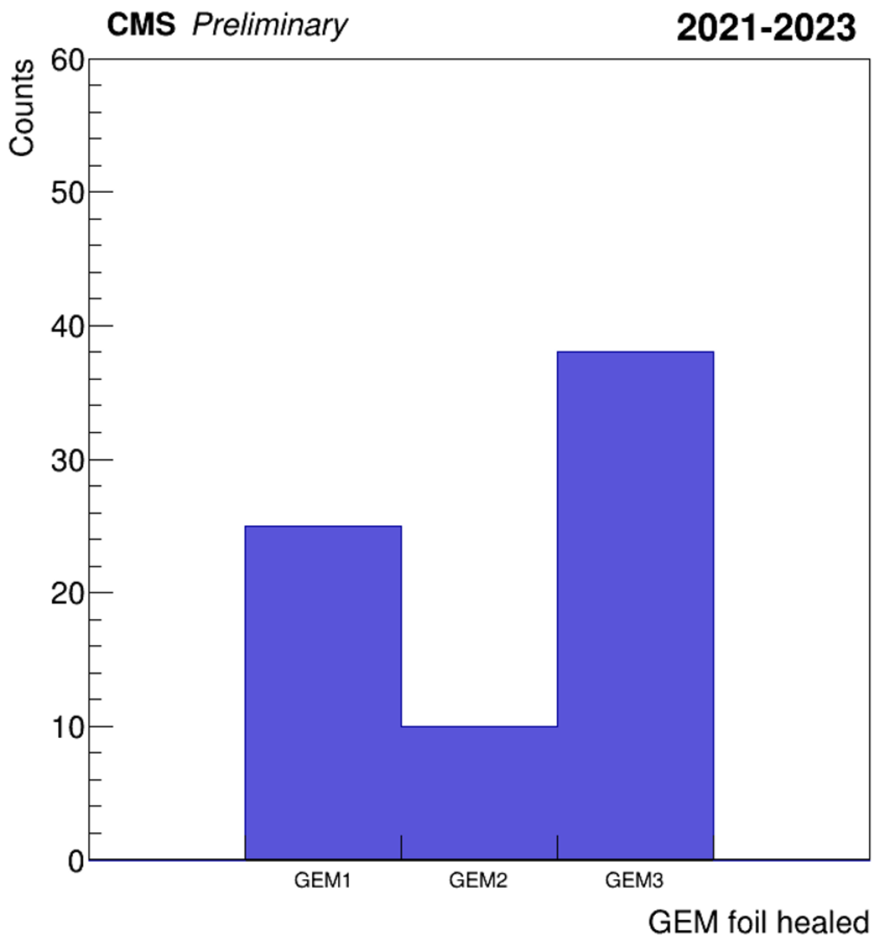
Magnet ramp sign



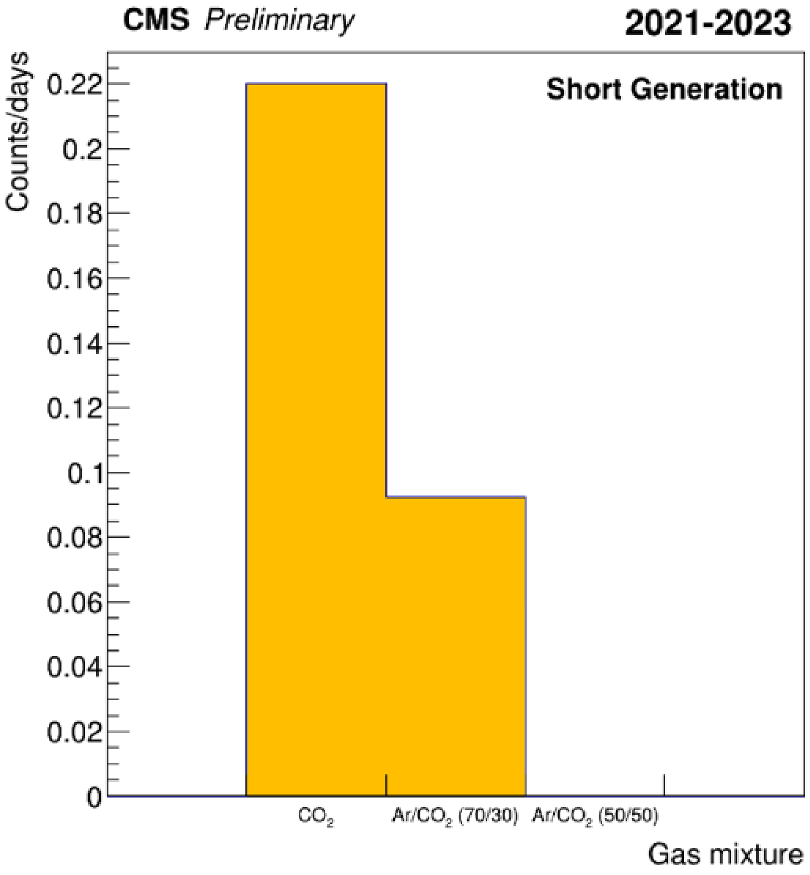


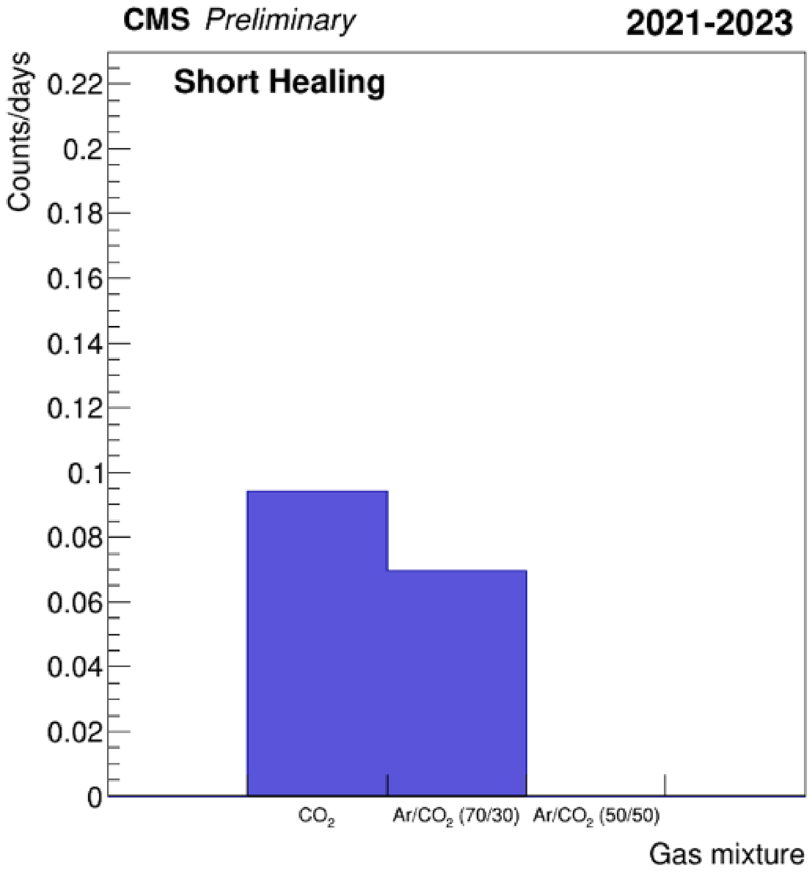
Short circuits generated and healed per foil





Short circuits: gas mixture

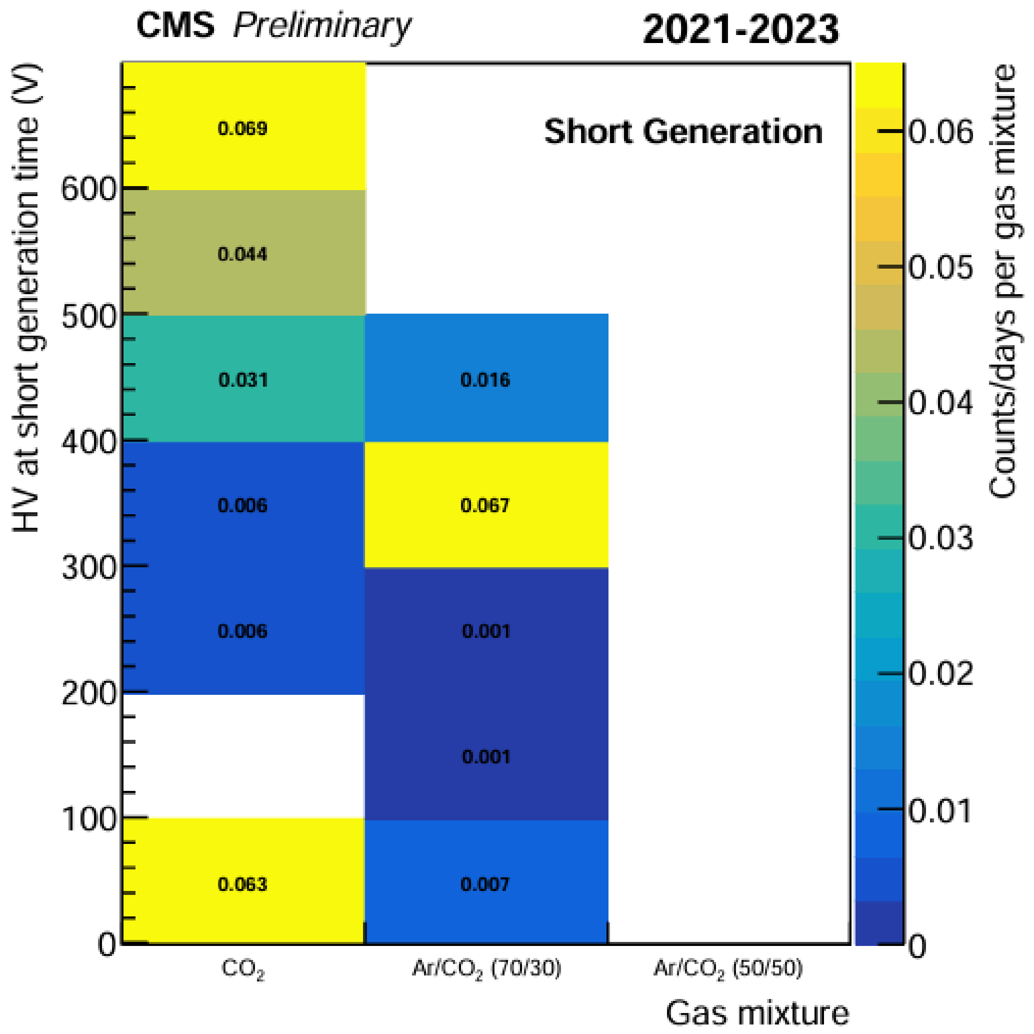


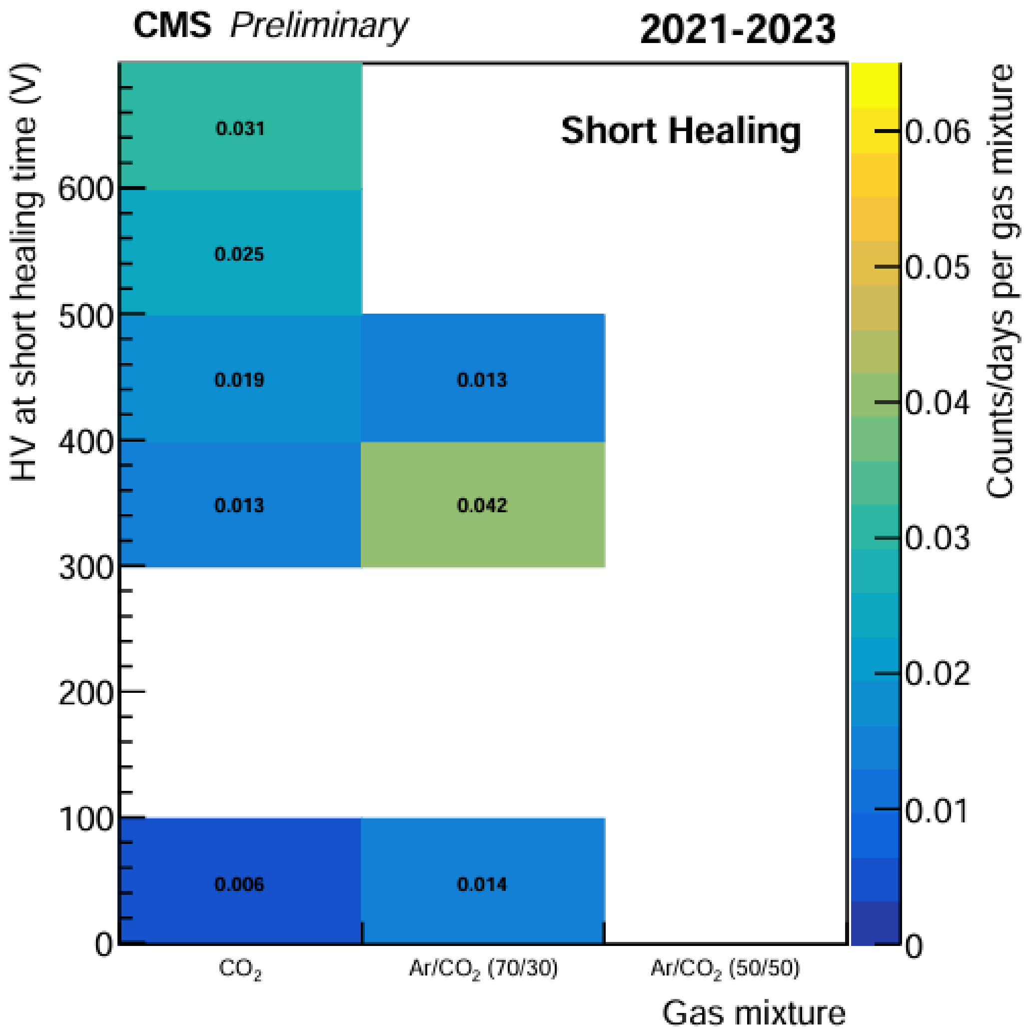


Three years:

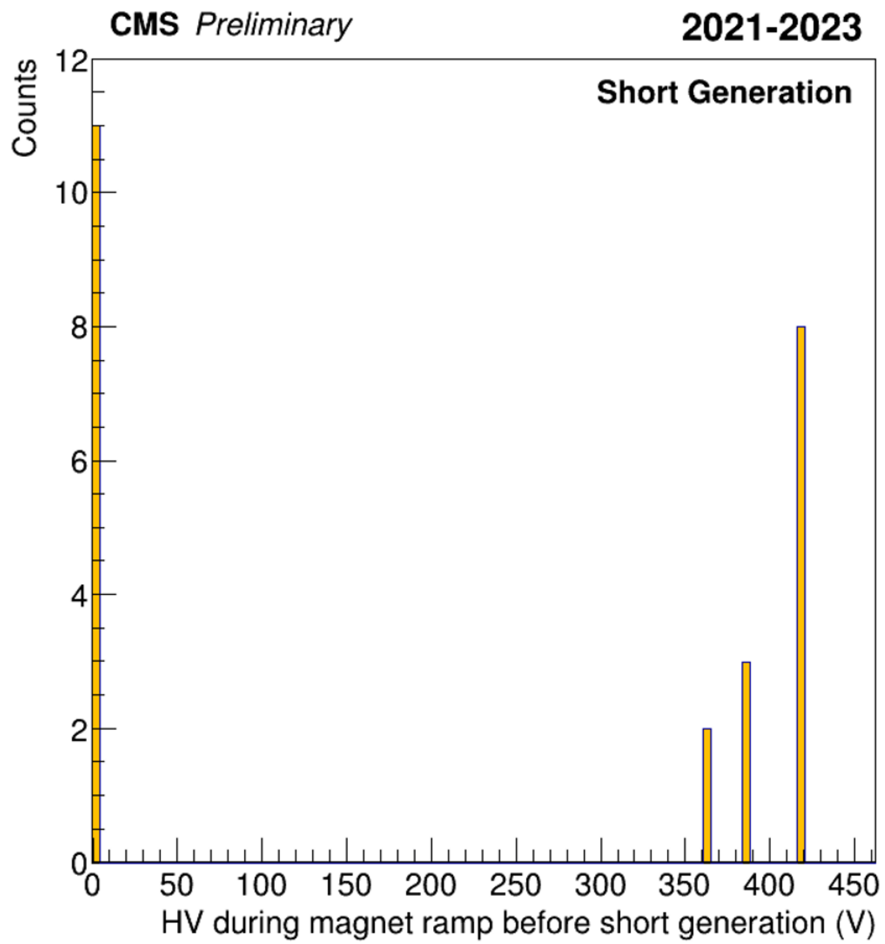
- Pure $CO2$ for 159 days
- $Ar/CO2$ (70/30) for 834 days
- In 2021 they were operated for 41 days in $Ar/CO2$ (50/50)

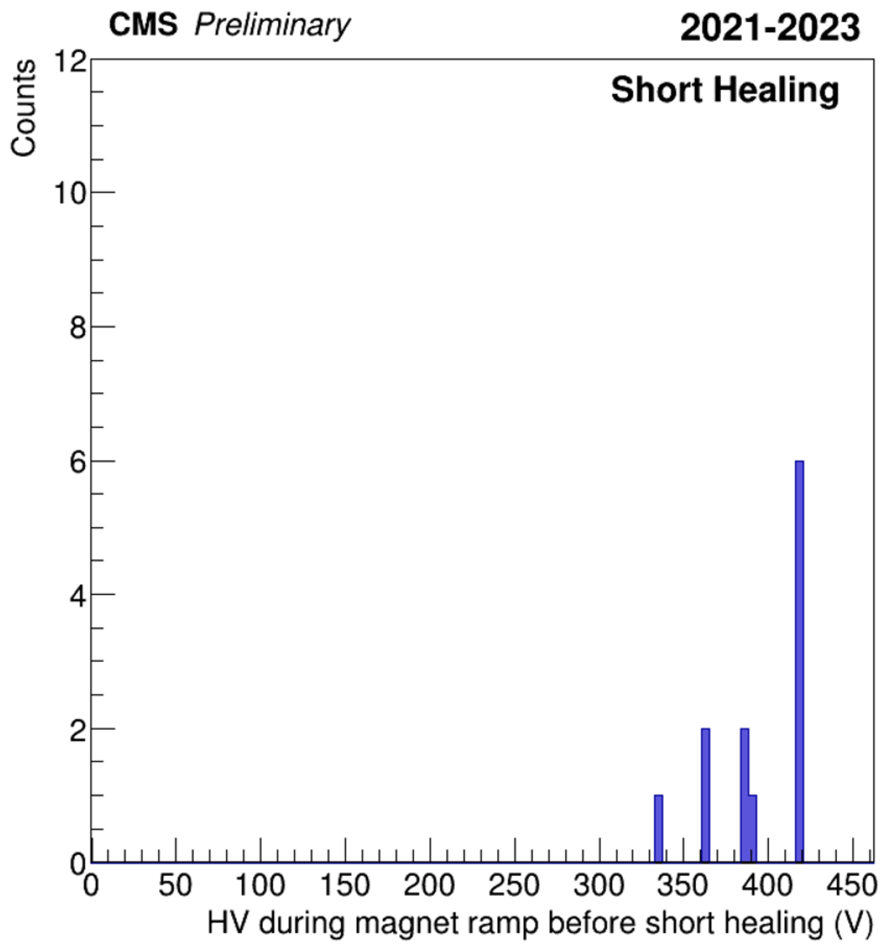
Short circuits: gas vs HV



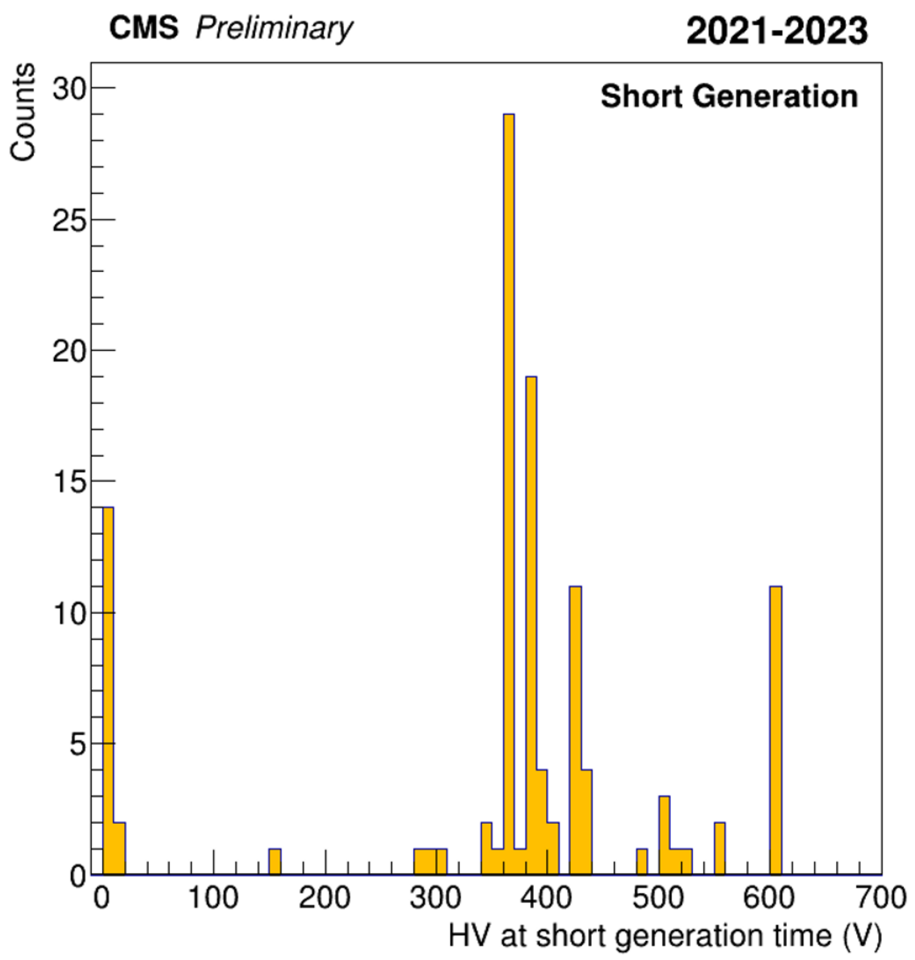


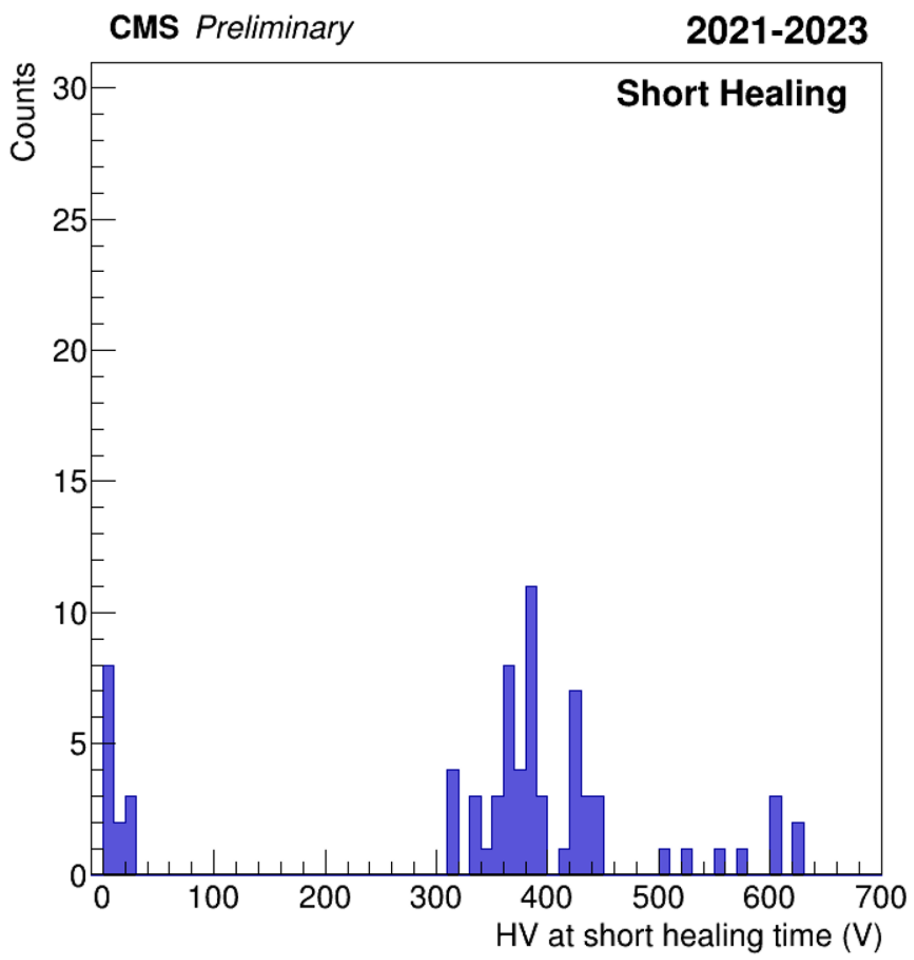
Short circuits: HV during magnet ramp



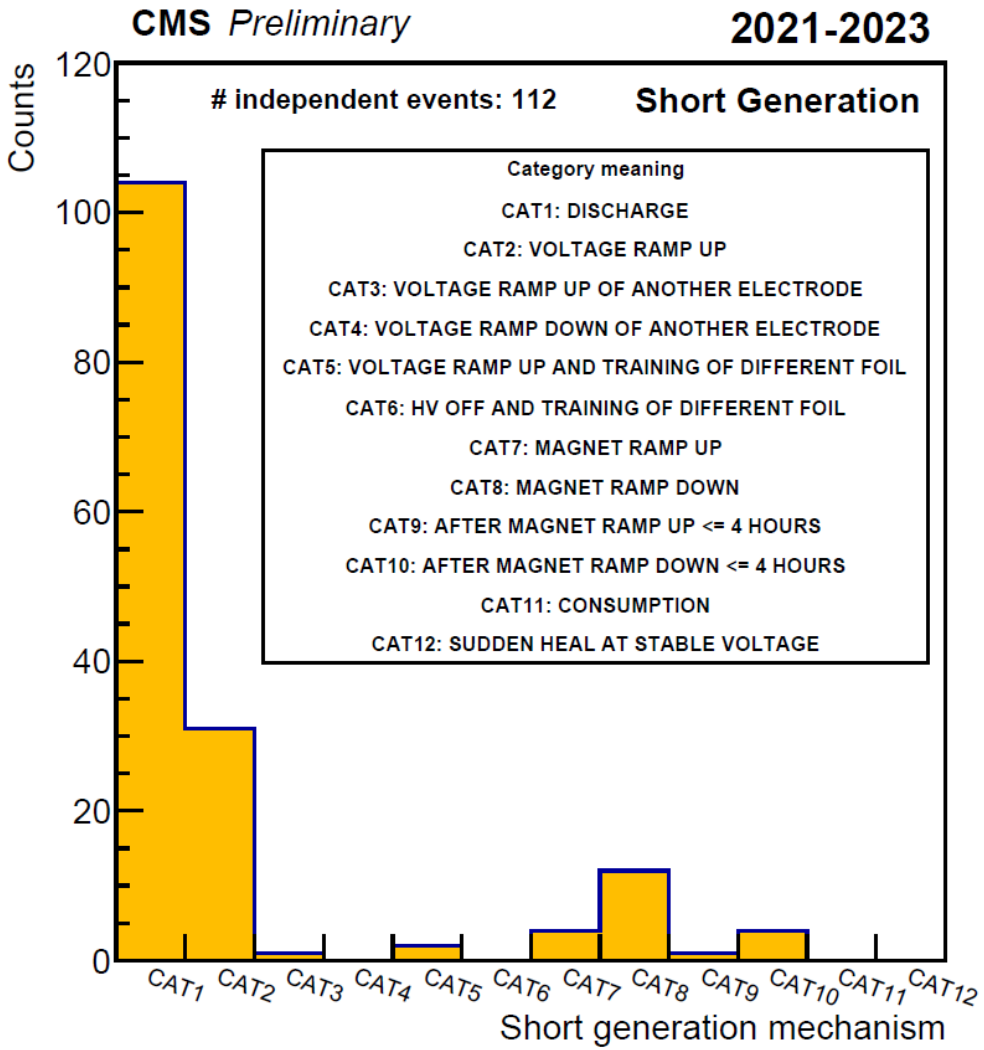


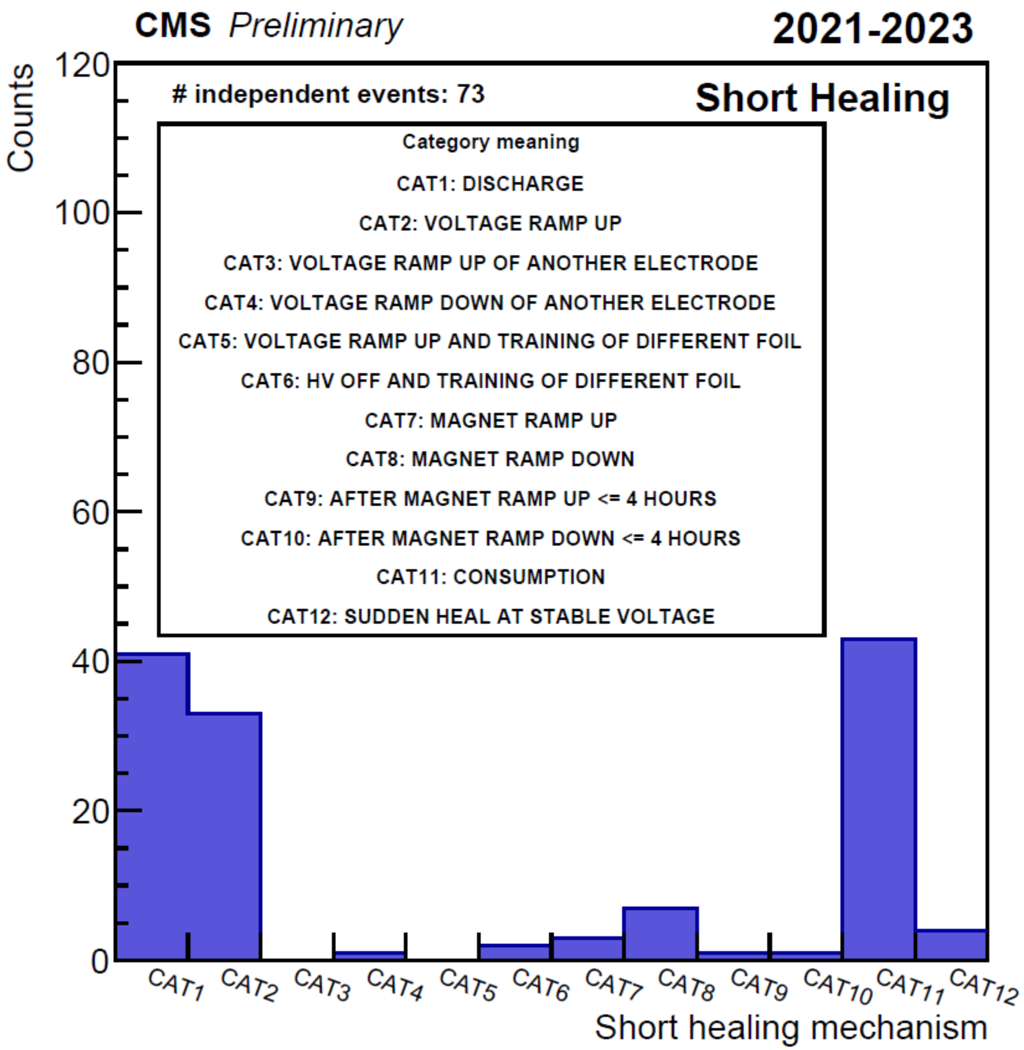
Short circuits: HV value



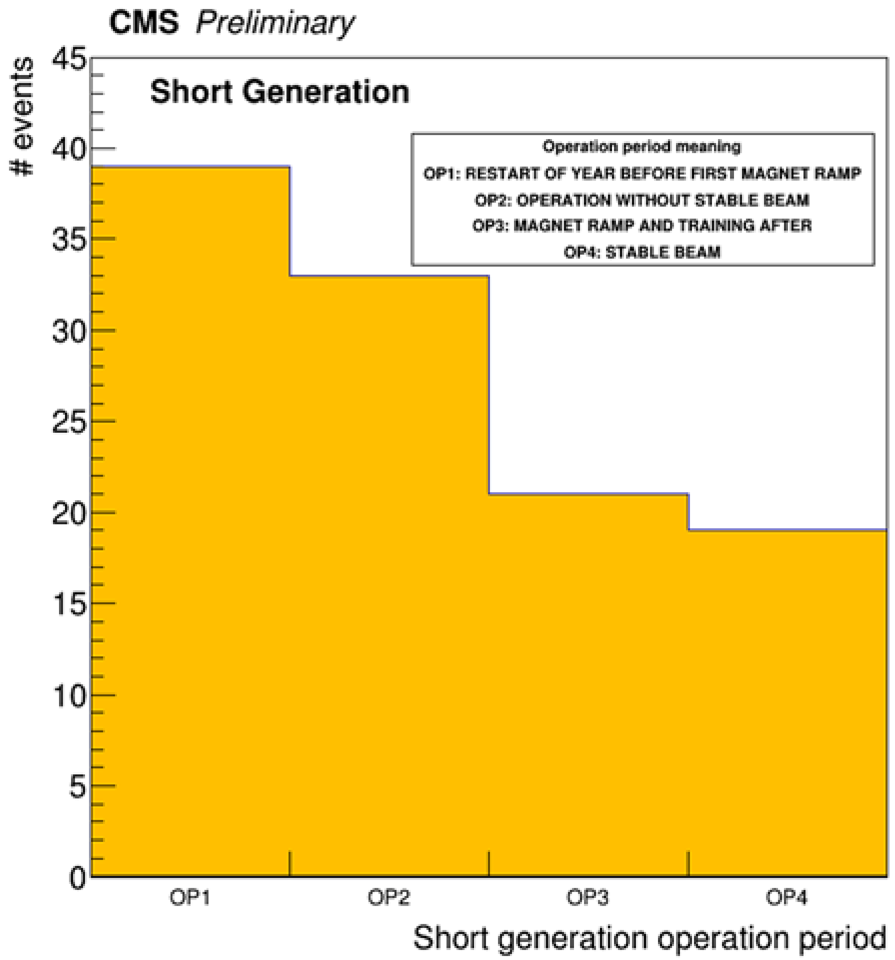


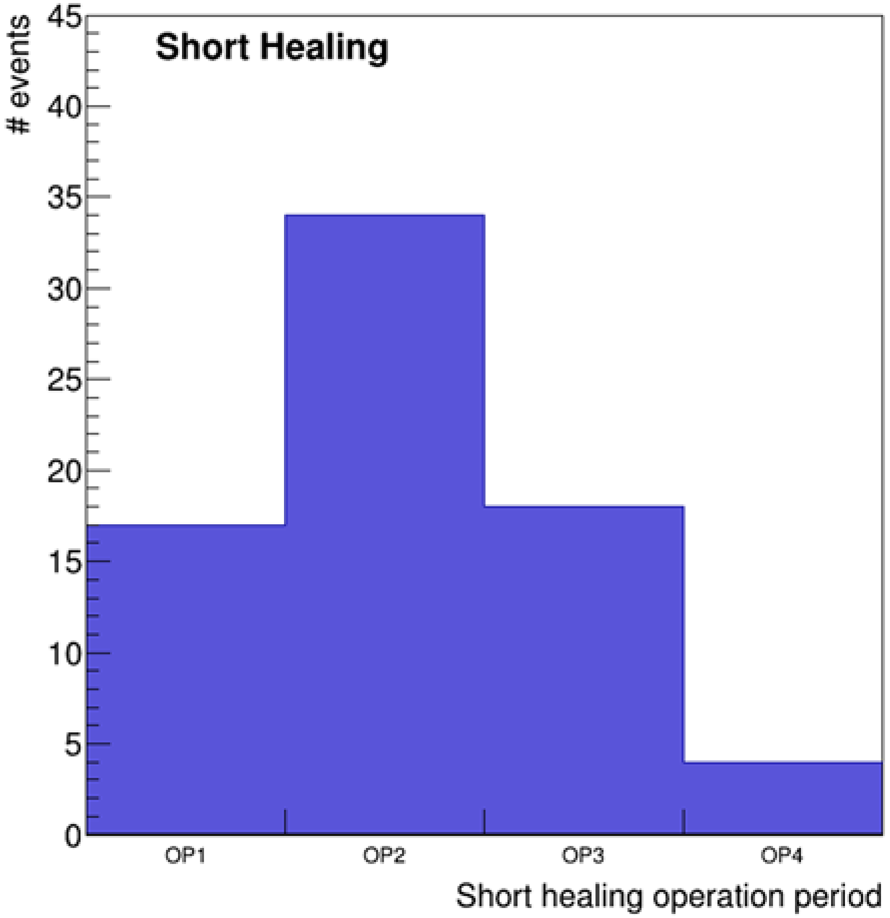
Mechanisms involved in generation/healing of shorts in GE1/1 GEM foils





Short circuits: operation period period





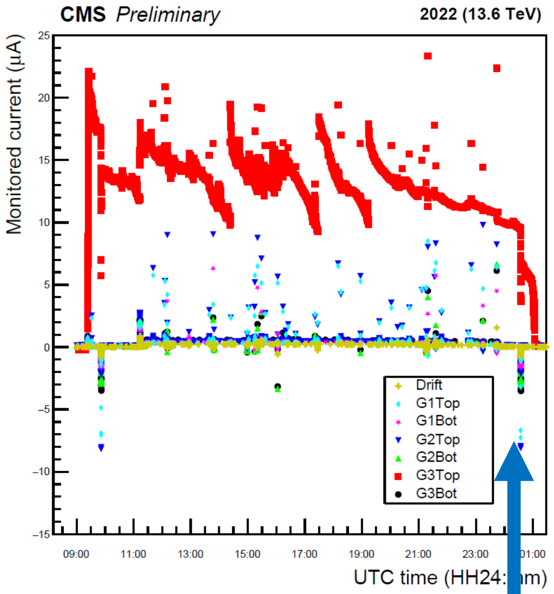
Short circuits: Status at 2024-11-25

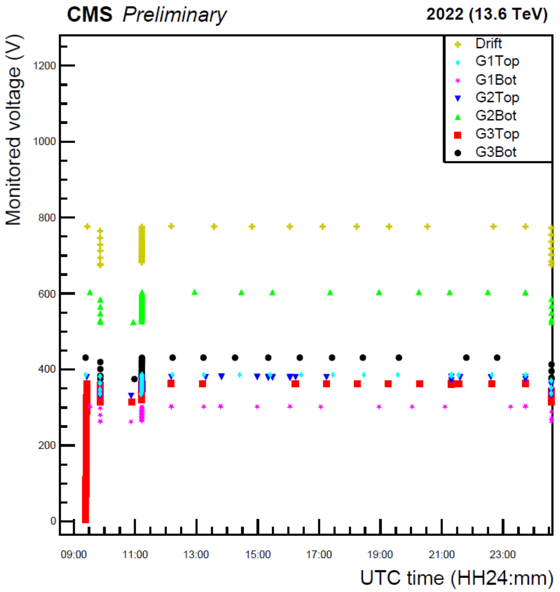
Shorts at 2024-11-25	**HV sectors**	**Foil**	**Detectors**
GE11_M	28	23	20
GE11_P	27	24	20
GE11 total	**55**	**47**	**40**
GE21_M	4	4	3
GE21_P (M4 disconnected)	6	3	2

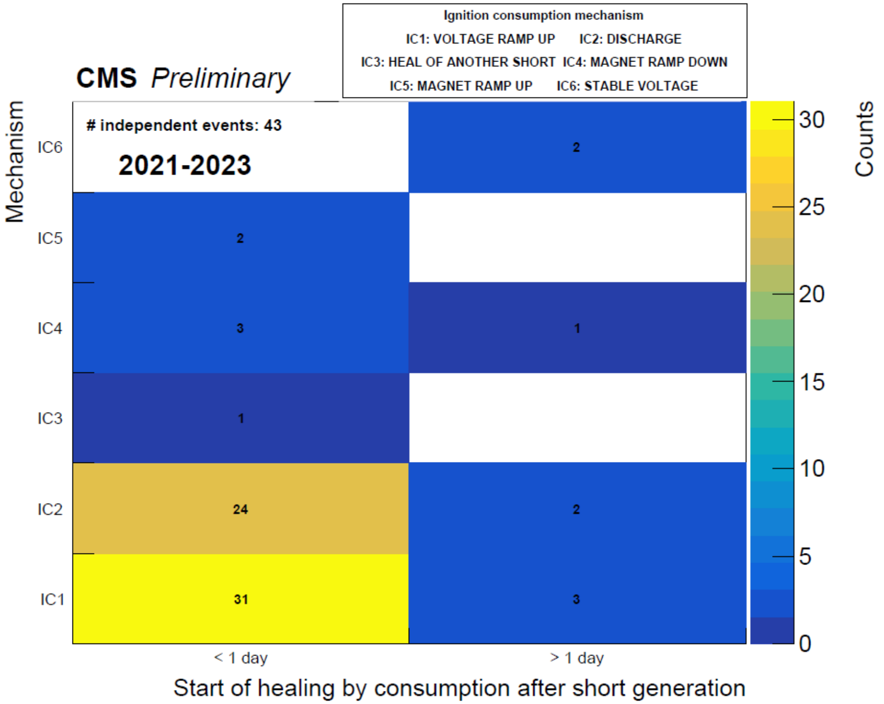
Foils with at least one HV sector affected by short circuit

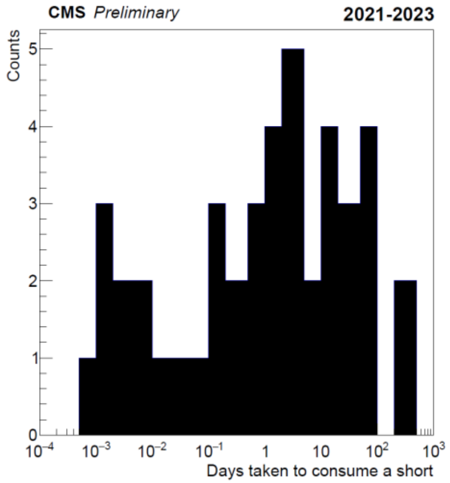
Detectors with at least one foil with at least one HV sector affected by short circuit

Non conductive short circuits





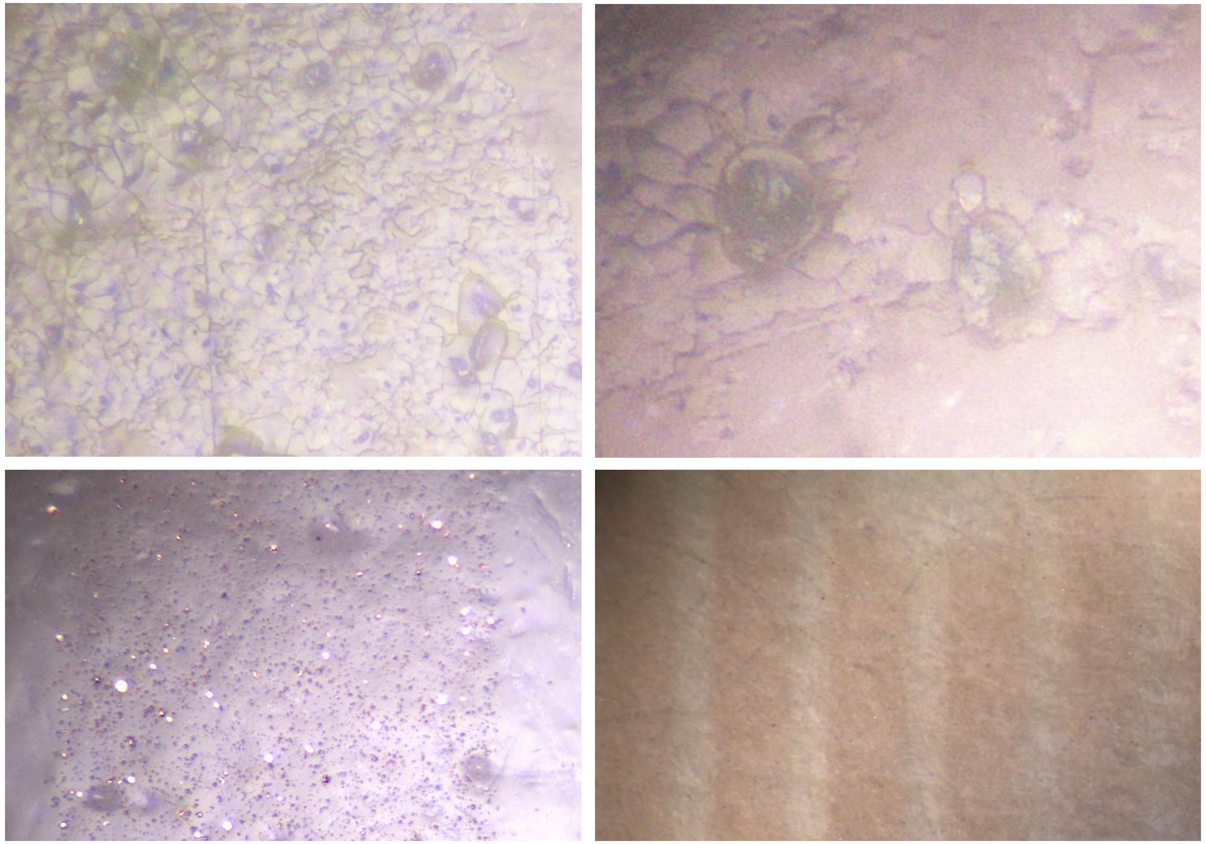




- Not exactly conductive connection for some short between the top and bottom face of GEM foil
  - **Higher resistance**: not compatible with that of the HV distribution schema (10.6 MΩ in GE1/1)
  - **Usual behaviour:** slow consumption, with a **gradual decrease of the drained current**
  - **Mechanisms igniting consumption** of a short
  - **Time** needed to totally heal by consumption

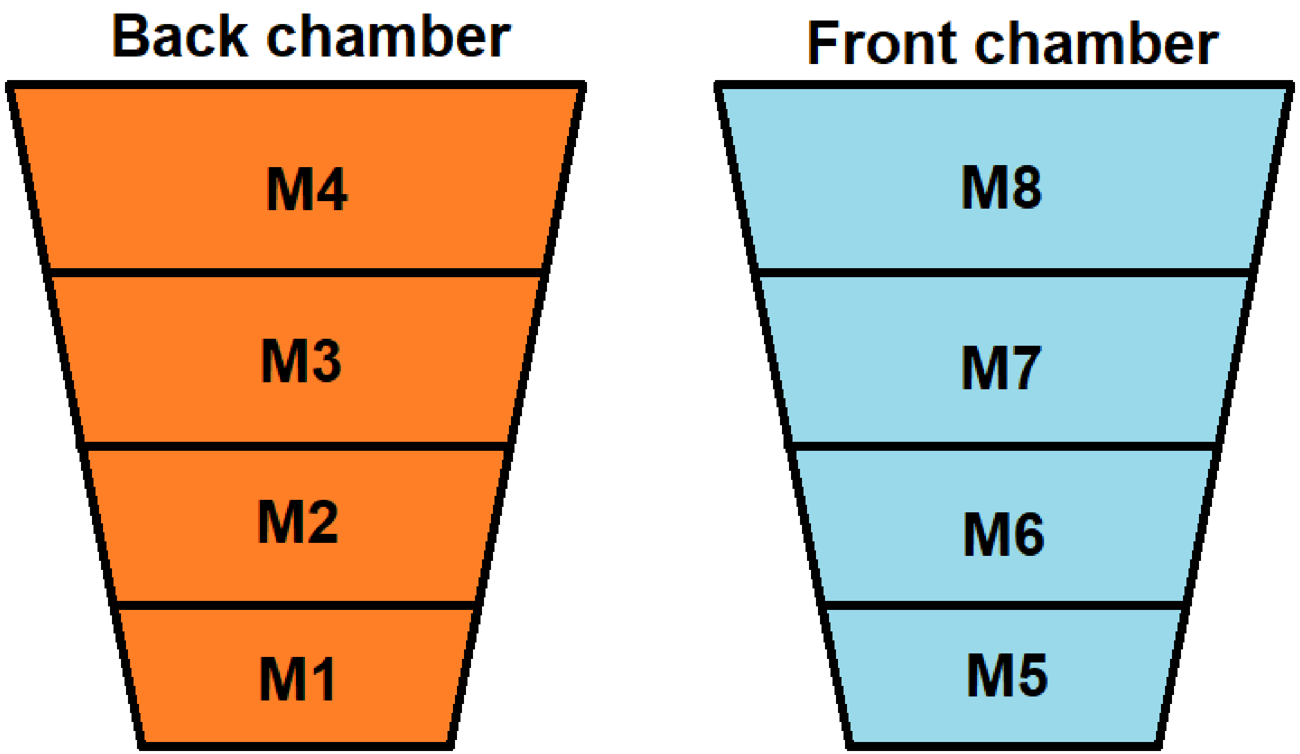
Backup for Hardware in CMS

Investigation on GE1/1



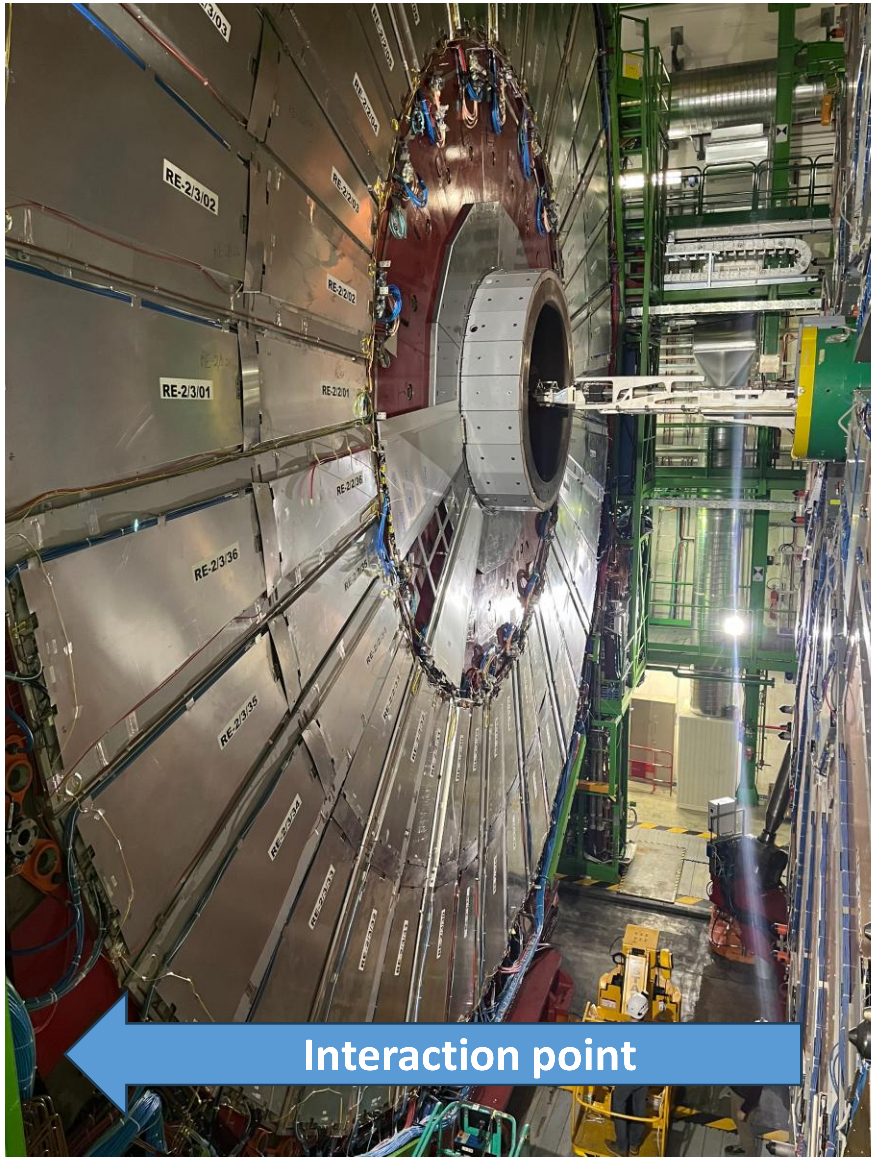
- Exctracted and replaced 4 GE1/1 detectors from CMS
- Found signs of oxidation in 2 of the 3 inspected detectors
- Additional extraction done possible in YETS24/25
  - 6 GE1/1 detectors

GE2/1 naming convention

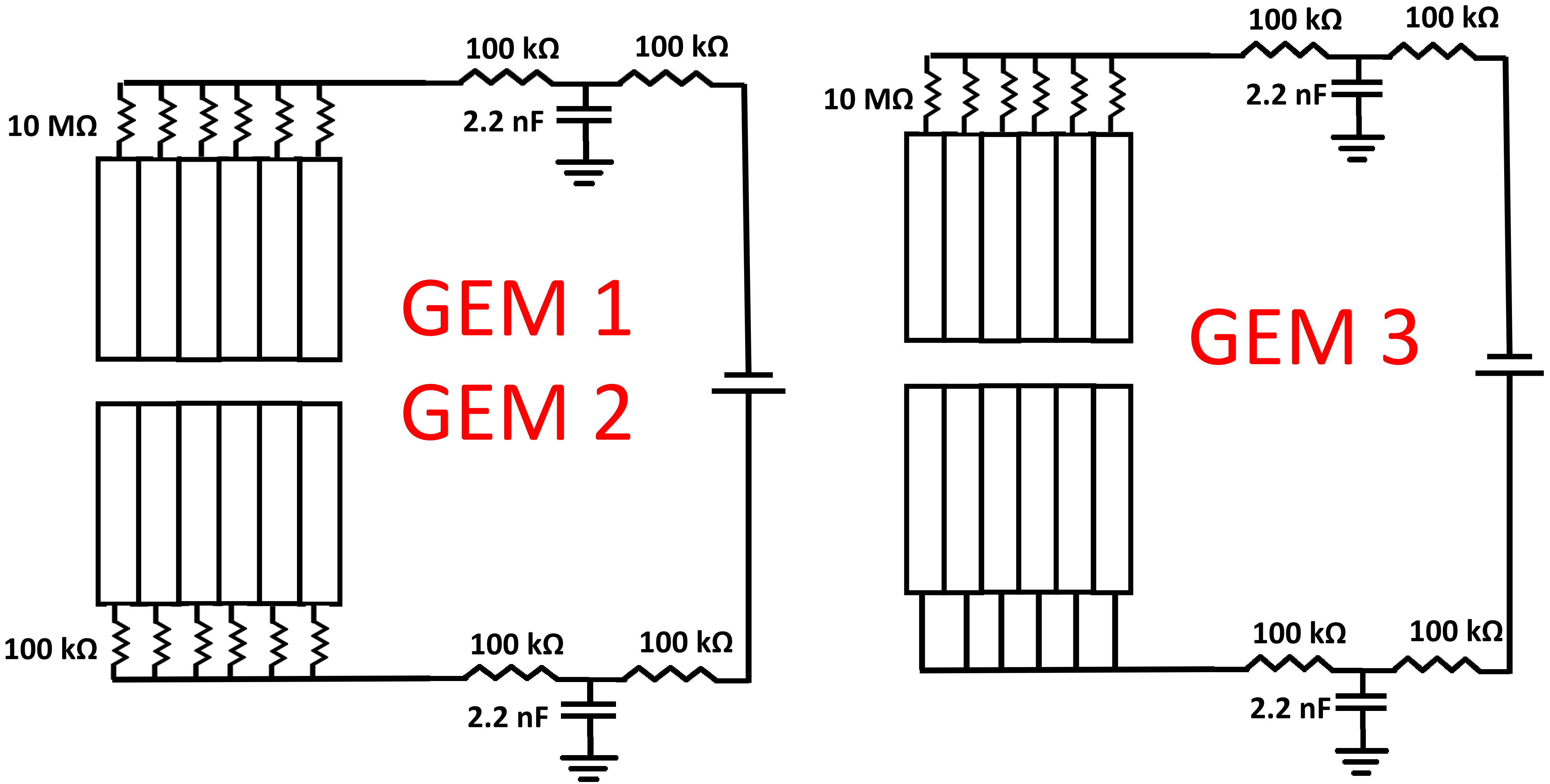


Layer 2
Installed off yoke
Farther from the interaction point

Layer 1
Installed on yoke
Closer to the interaction point



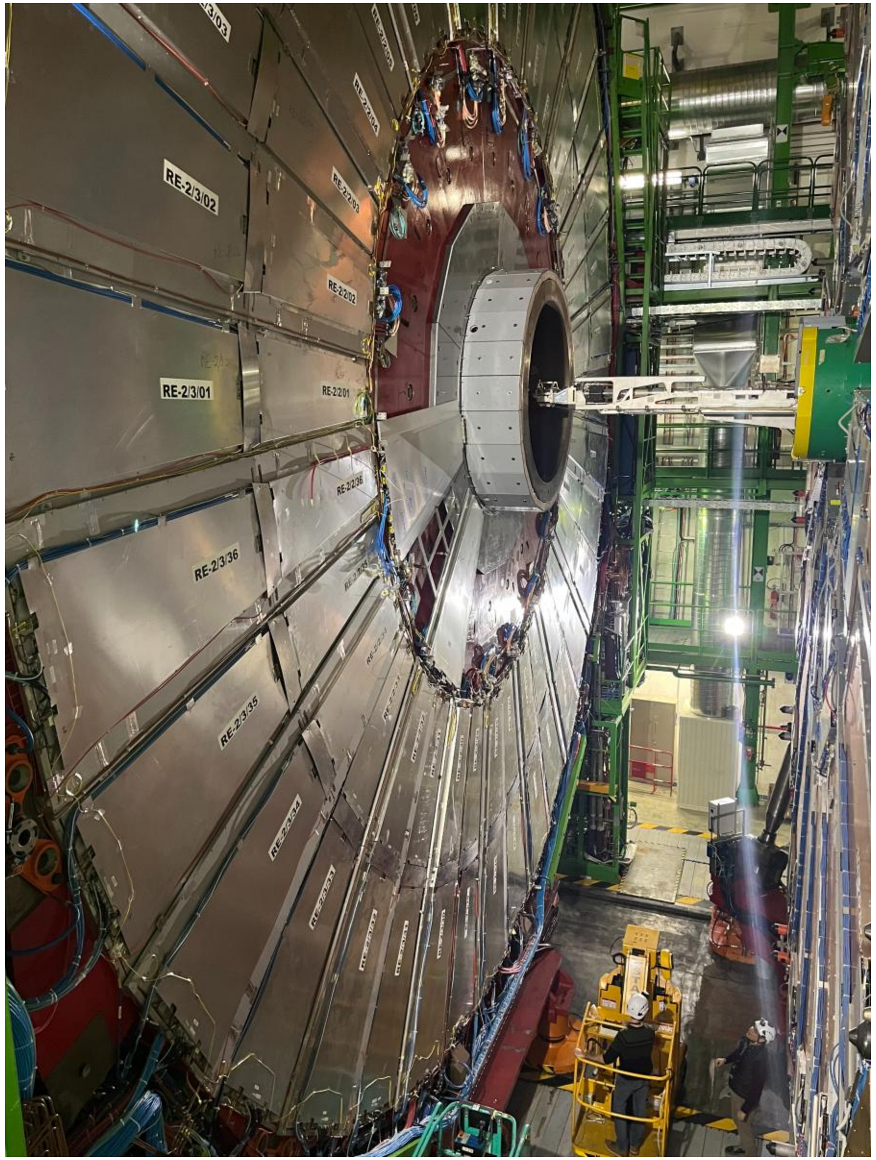
HV distribution GE2/1



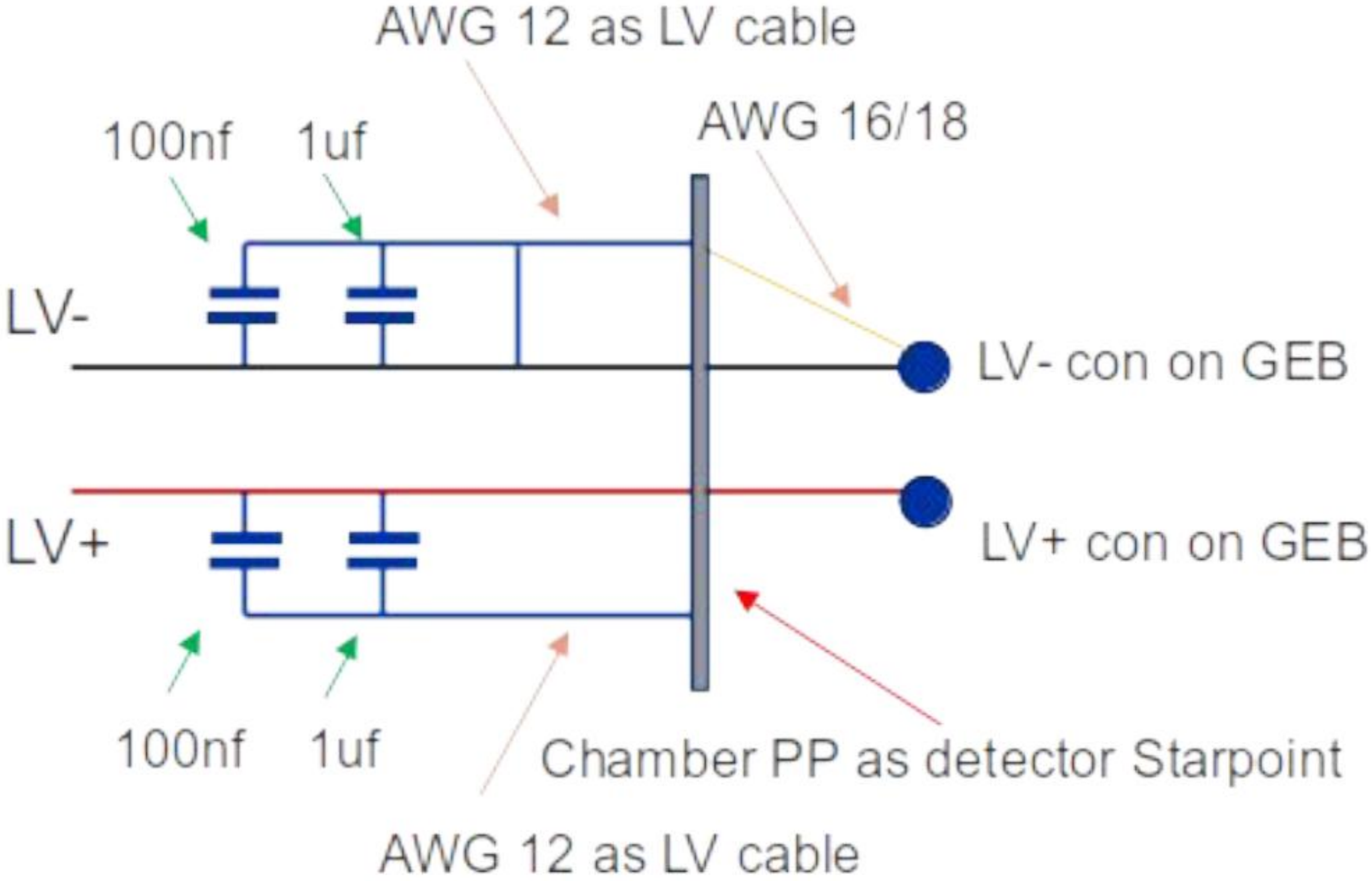
Cleaning of GE2/1

- Recleaning detectors and installed in CMS during YETS23/24
  - One detector never contaminated by dust
    - This detector now has one short circuit in one module
  - One detector with the PCBs recleaned from dust
    - This detector has three short circuits in total among the 4 modules

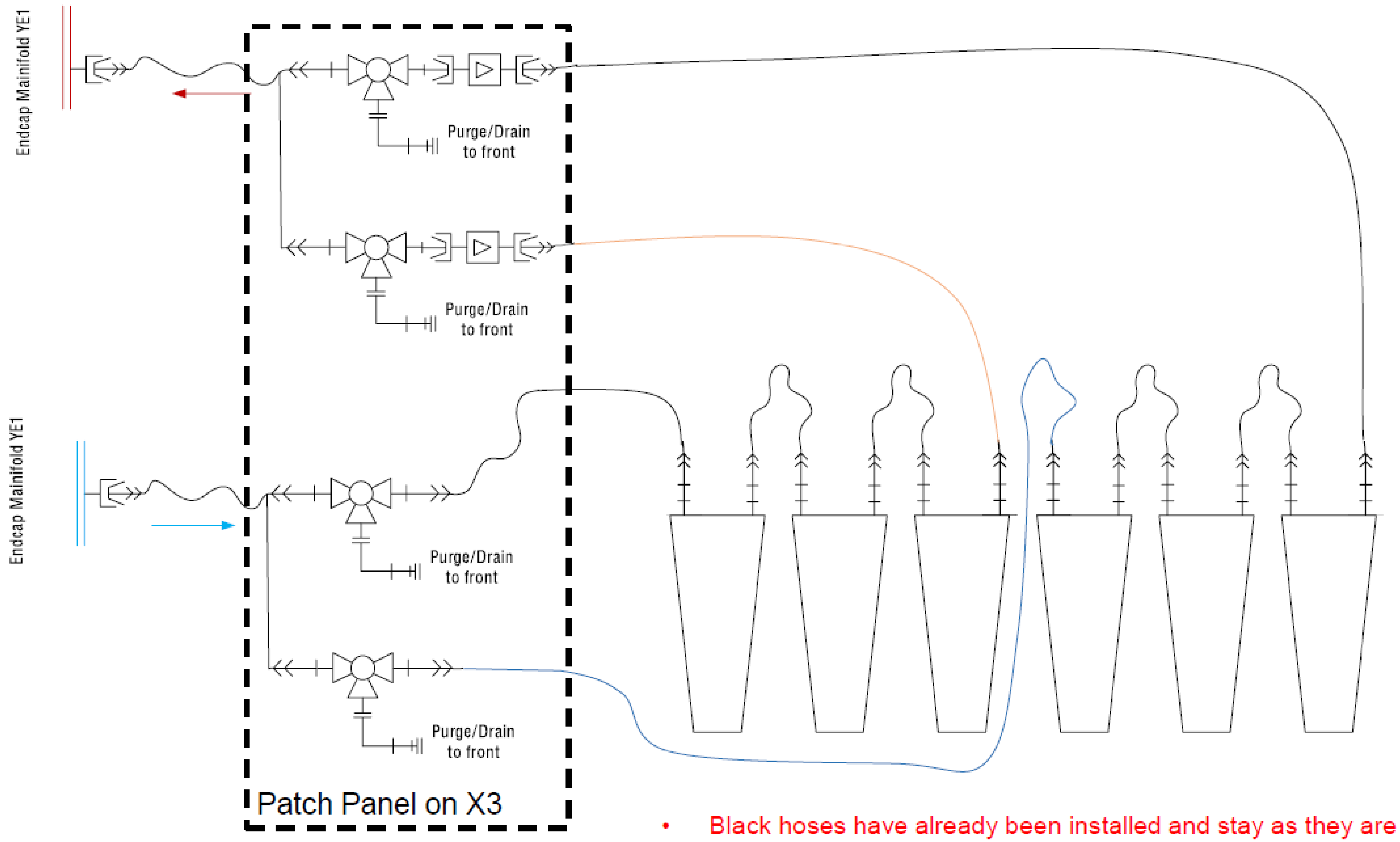
- Started cleaning also the GEM foils stack
  - How: chromic acid bath



LV filter


AWG 12 as LV cable
100nf
1uf
AWG 16/18
LV-
LV- con on GEB
LV+
LV+ con on GEB
100nf
1uf
Chamber PP as detector Starpoint
AWG 12 as LV cable

Cooling manifold

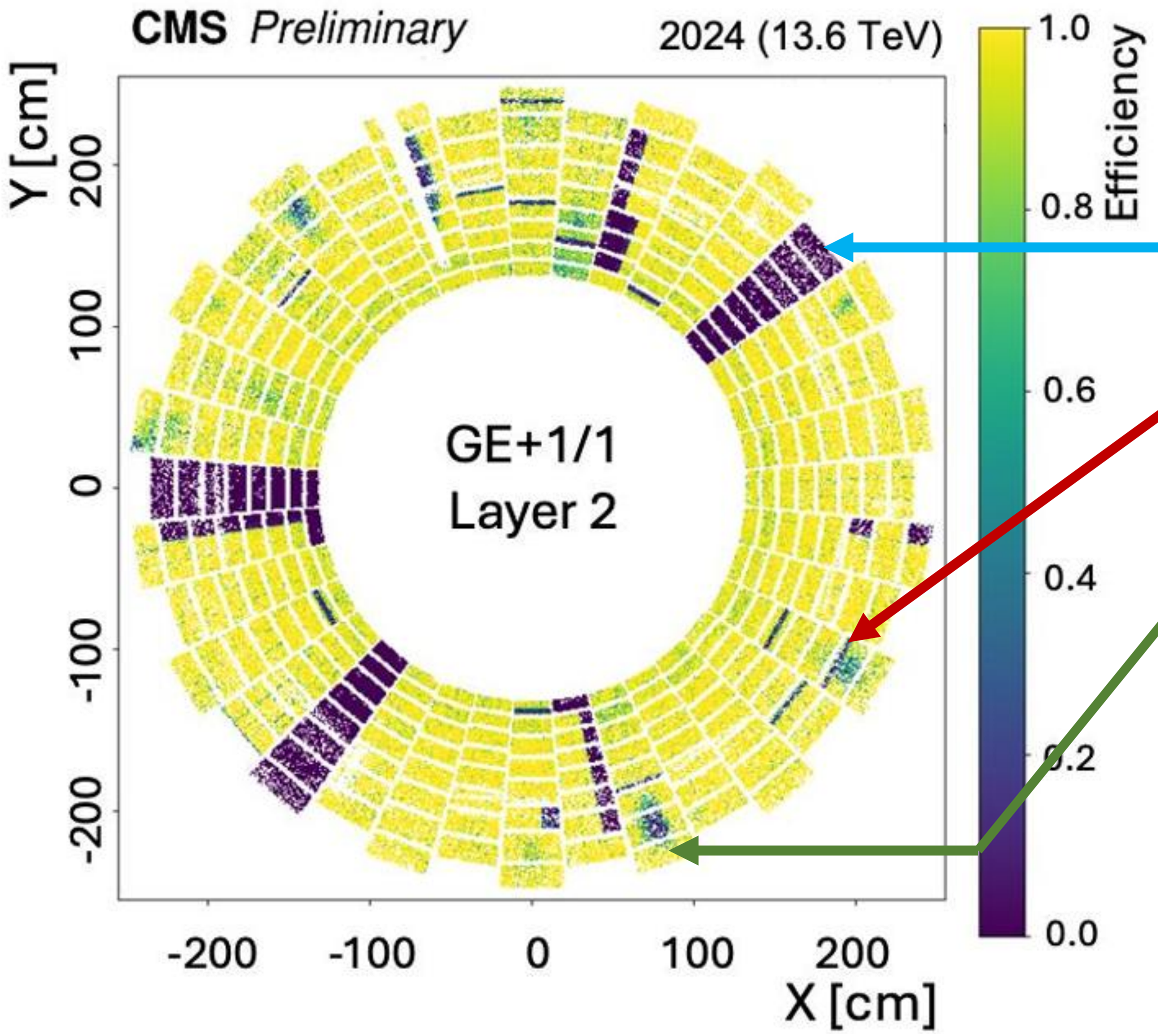


- Black hoses have already been installed and stay as they are
- Colored hoses are to be installed only during YETS 2022 & 2023
- Modified PP is identical to GE1/1 PP → reuse it

Upgraded **cooling manifold** from 6 to 3 chambers per line

Backup for Efficiency

Detectors' efficiency in detail

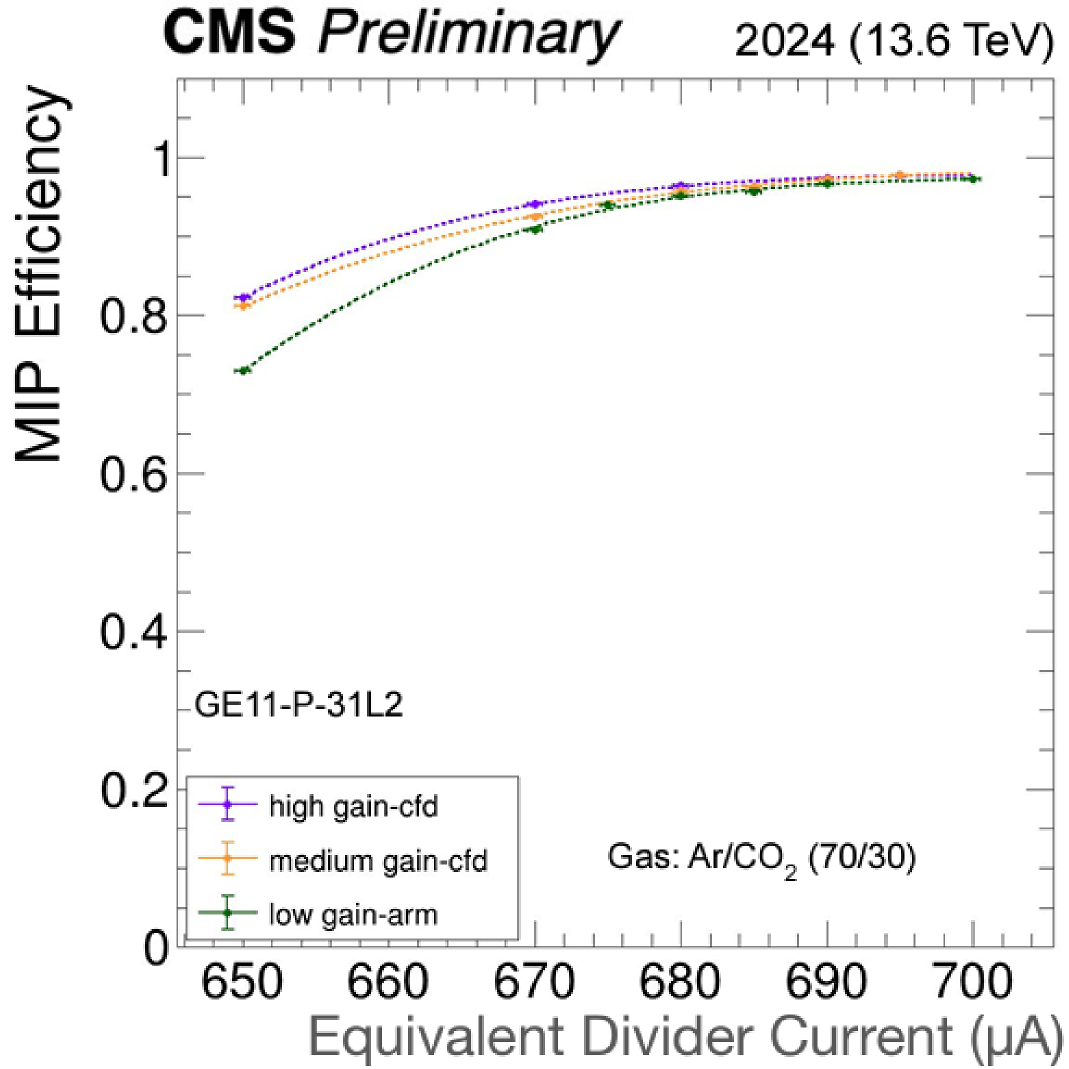


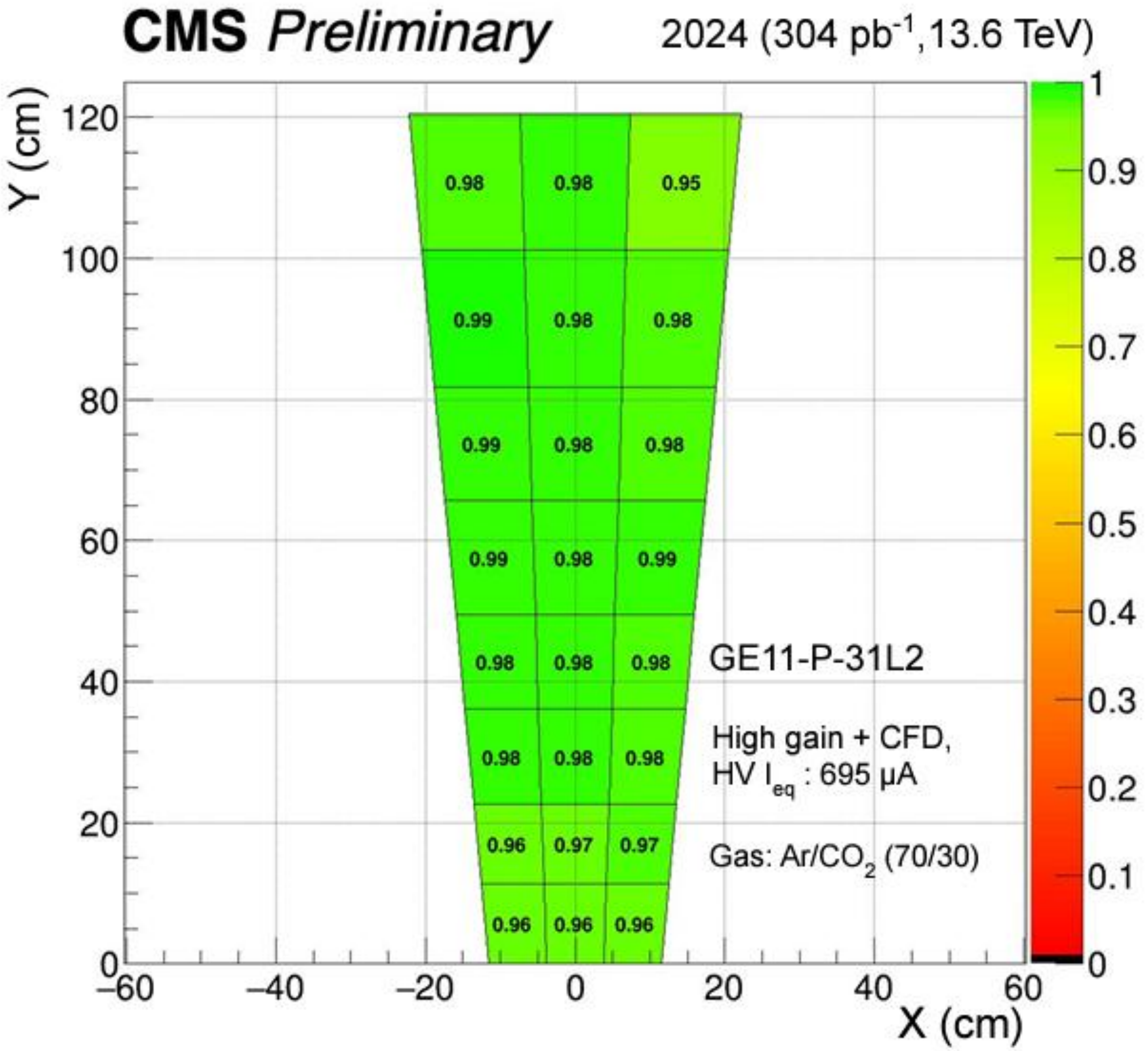
High resolution efficiency plot of the GE+1/1 layer 2 chambers in 2024.

- The overall efficiency is high (Average: 94.7 %)
- Issues:
  - chambers with **communication issues** (fully purple)
    - Electronics refurbishment during LS3
  - **HV shorts** (purple lines)
  - On some of the long chambers one can also see an efficiency drop at the wide side due to the **bending of the PCBs**.

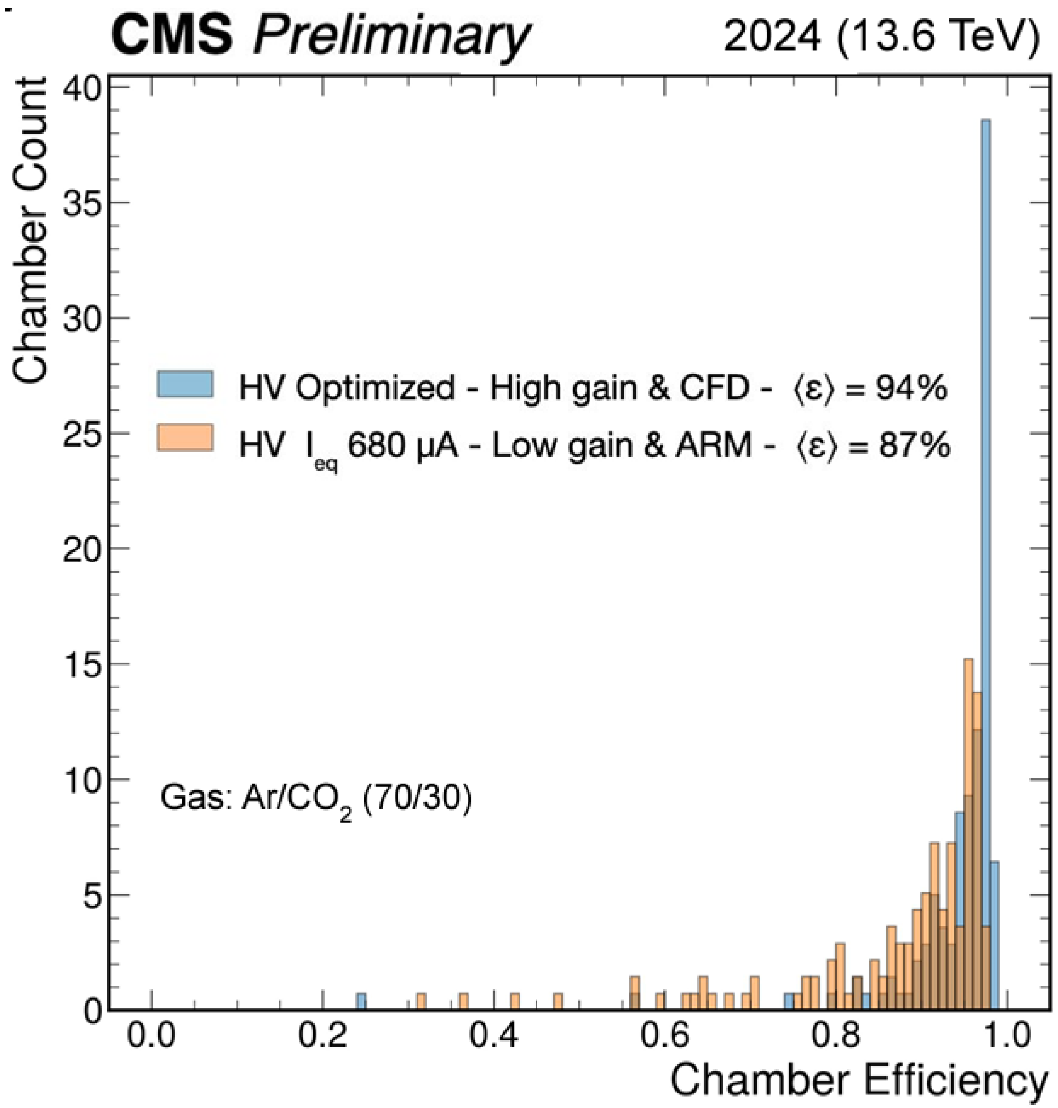
- **Muons used in the calculation:**
  - muons reconstructed by muon detectors only with at least 15 hits (at least 1 in the CSC ME1/1), $\chi^2 < 5$, pT > 10 GeV.
  - Fiducial cuts on the detector : region of 1.5 cm from the border of the iη partition and 0.0075 rad from the lateral edges of the chamber. The position is given by the extrapolated position of the muons to the GE1/1 chambers.

Efficiency vs HV working point





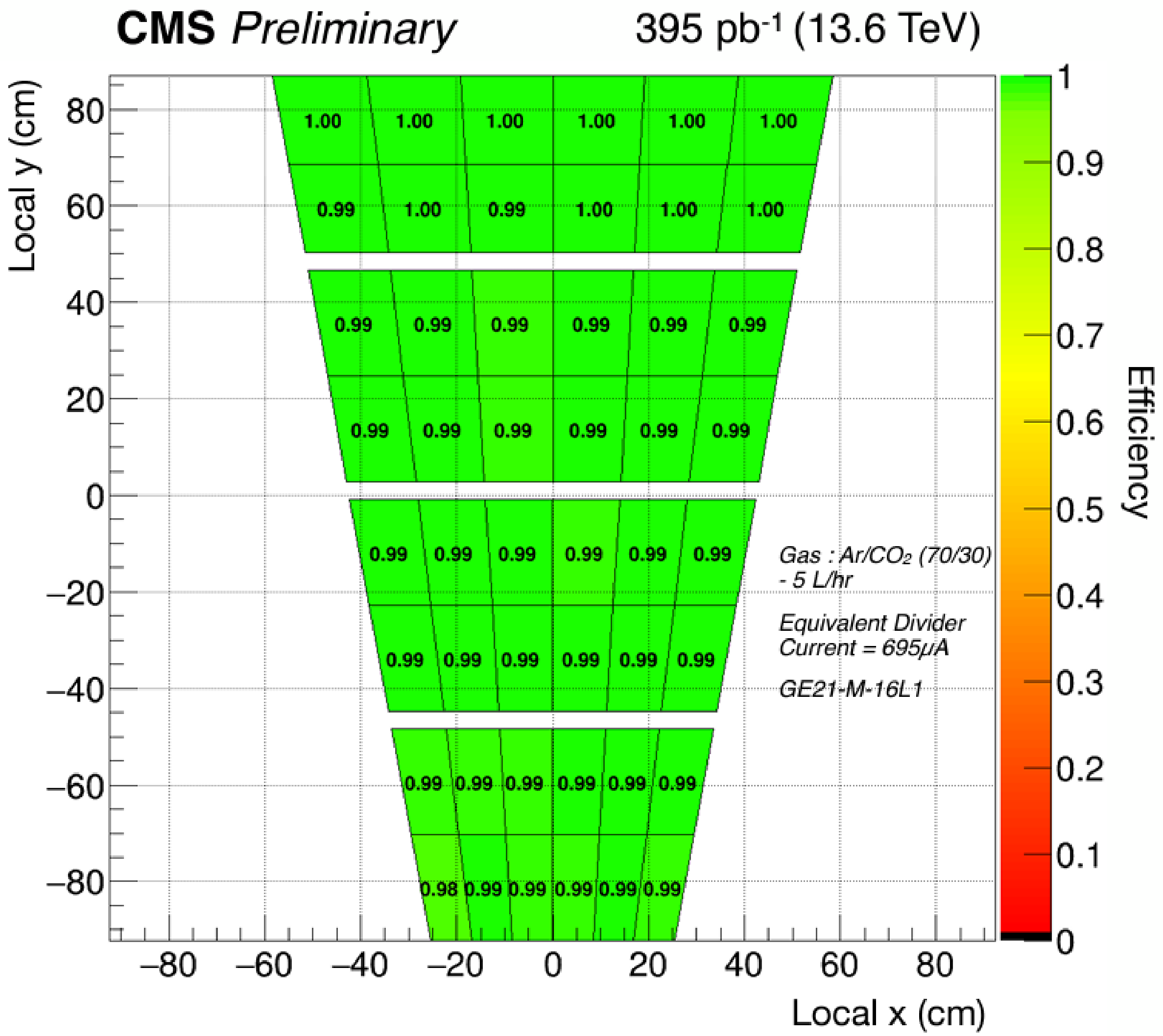
Chamber efficiency



- HV scan 2024
  - Investigated several HV working points
  - Tested several electronics configurations
- New HV working point tuned per chamber
  - Depending on chamber efficiency vs HV curve: look if the chamber is at efficiency plateau at a given I_{eq}
  - Chamber discharge rate
- **Efficiency July 2024:** 94 %
  - Set of working points used:

$$I_{eq} = 685 - 700\ \mu A$$

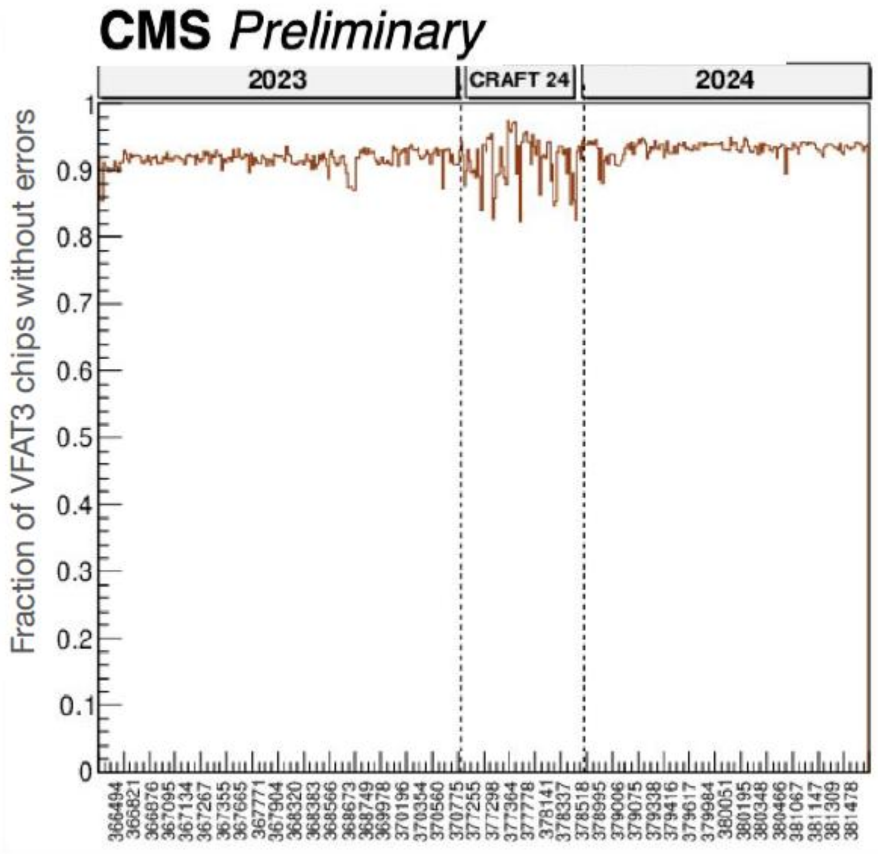
GE2/1 efficiency



- Efficiency map for a GE2/1 chamber installed in CMS, taken from a 2023 run corresponding to Lumi = 395 1/pb.
- This chamber was powered on at HV 695μA equivalent divider current and using the front-end chip (VFAT) preamplifier in medium gain and Constant Fraction Discriminator (CFD) comparator settings.
- The data is divided into VFAT readout regions (128 channels per chip). Plotted is the fraction of events where a reconstructed hit is found near a propagated track on each VFAT, and given in local coordinates.
- Muons used in the calculation : Standalone muons with at least 15 hits (at least 1 in ME2/1), $\chi 2 < 5$, pT > 10 GeV. Fiducial cuts on the detector : region of 1.5cm from the border of the eta partition and 0.0075rad from the lateral edges of the chamber.

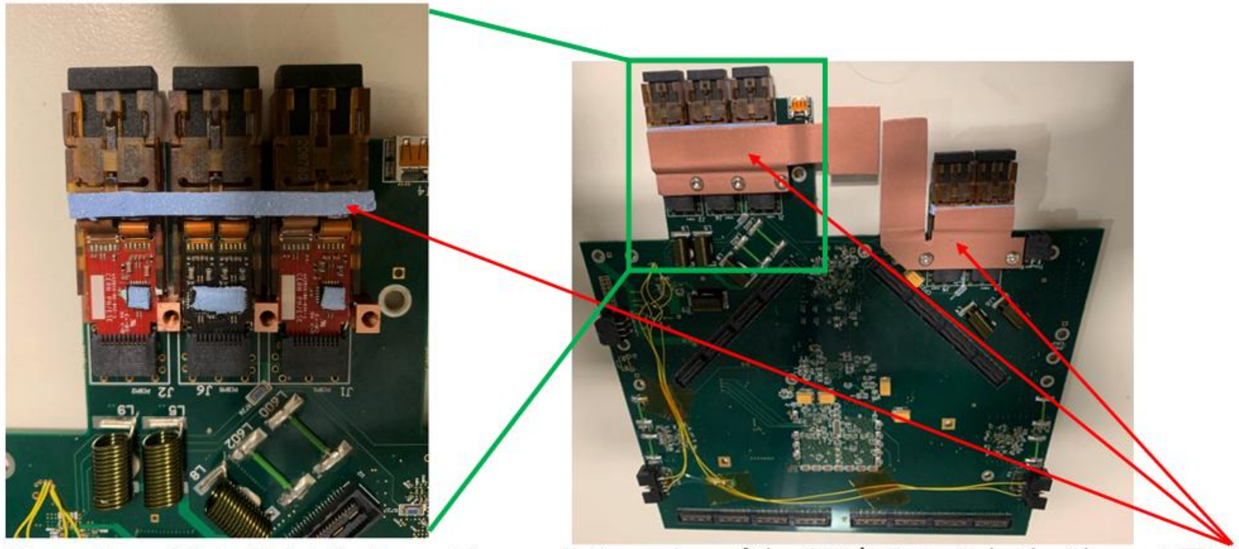
Backup for Electronics

Electronics stability



- Channels:
  - **Active**: GE1/1: 93 %, GE2/1: 100 % (all VFATs communicate)
  - **Damaged:** 0.3%
  - **Noisy & permanently masked:** 1.5%
- Electronics stability issues from:
  - **GBTx not fetching correct configuration** from fuses after power-on
    - **Fixed by:** Interaction with DCS for automatic power cycle
  - **VTRx glue outgassing** → GBT unstable → Lack of publication of FPGA temperature → Safety requirement: power off the electronics
    - Some VTRx are expected to bake in situ during operations
    - LS3: Installation of cooled VTRX on GE1/1
      - 4 GE1/1 detectors with cooled VTRX installed in CMS during YETS23/24: stable
  - **Front-end chips (VFAT) communication issues**
    - Probable consequence of aforementioned issues
  - Minimized by:
    - **During run:** progressive masking of the affected front-end
    - **During interfill:** electronics power cycle and reconfiguration
- Single Event Upset (SEU) → Lack of publication of FPGA temperature for a block of 12 chambers controlled by 1 backend card → Power off of electronics for all of them
  - Mitigated by reprogramming the FPGA in the bakground (during the run) → no power off of the chambers

Electronics stability: VTRx cooling

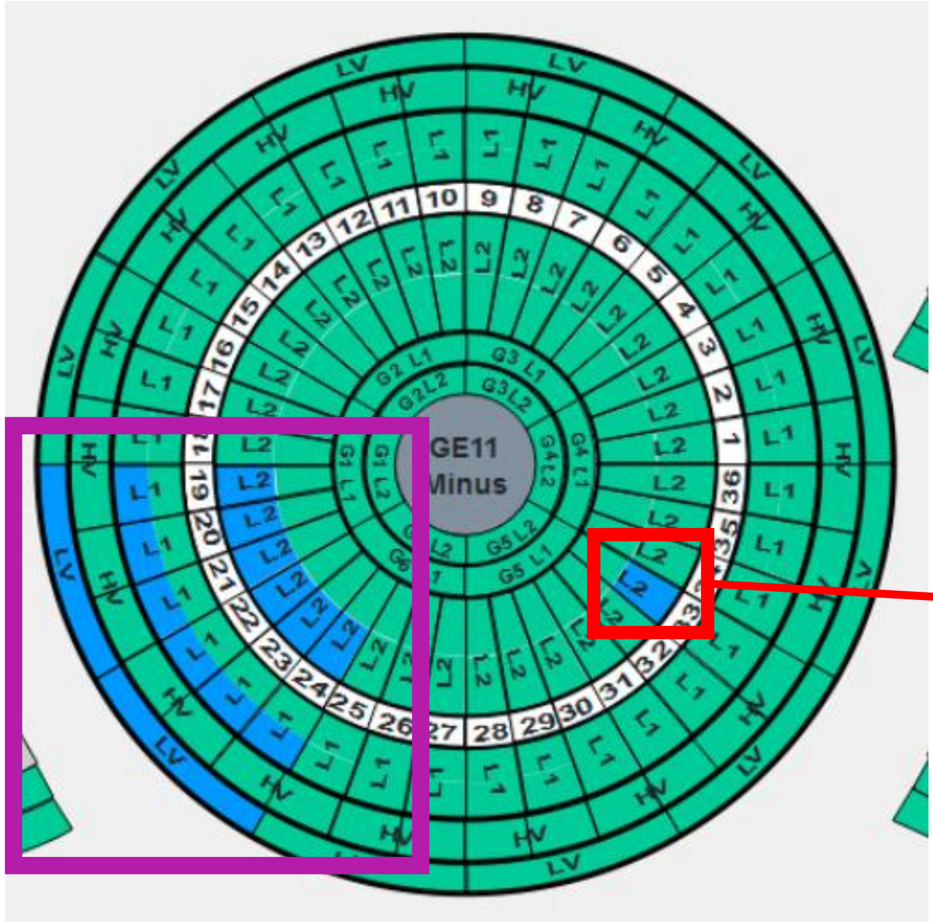


Zoom view of Opto-Hybrid bottom side — *Bottom view of the GE1/1 Opto-Hybrid with new VTRx cooling*

- Installation in YETS-23/24
  - 2 super-chambers (4 detectors) in CMS equipped with cooled VTRx and RSSI (Receiver Signal Strenght Indicator) reading
  - GE11_M_25 and GE11_M_26
- How
  - Thermal pad (Blue strip)
  - Copper plates
- Potential overall improvement in efficiency: ~6 %
  - Why: the electronics is more stable →More electronics in total can be read

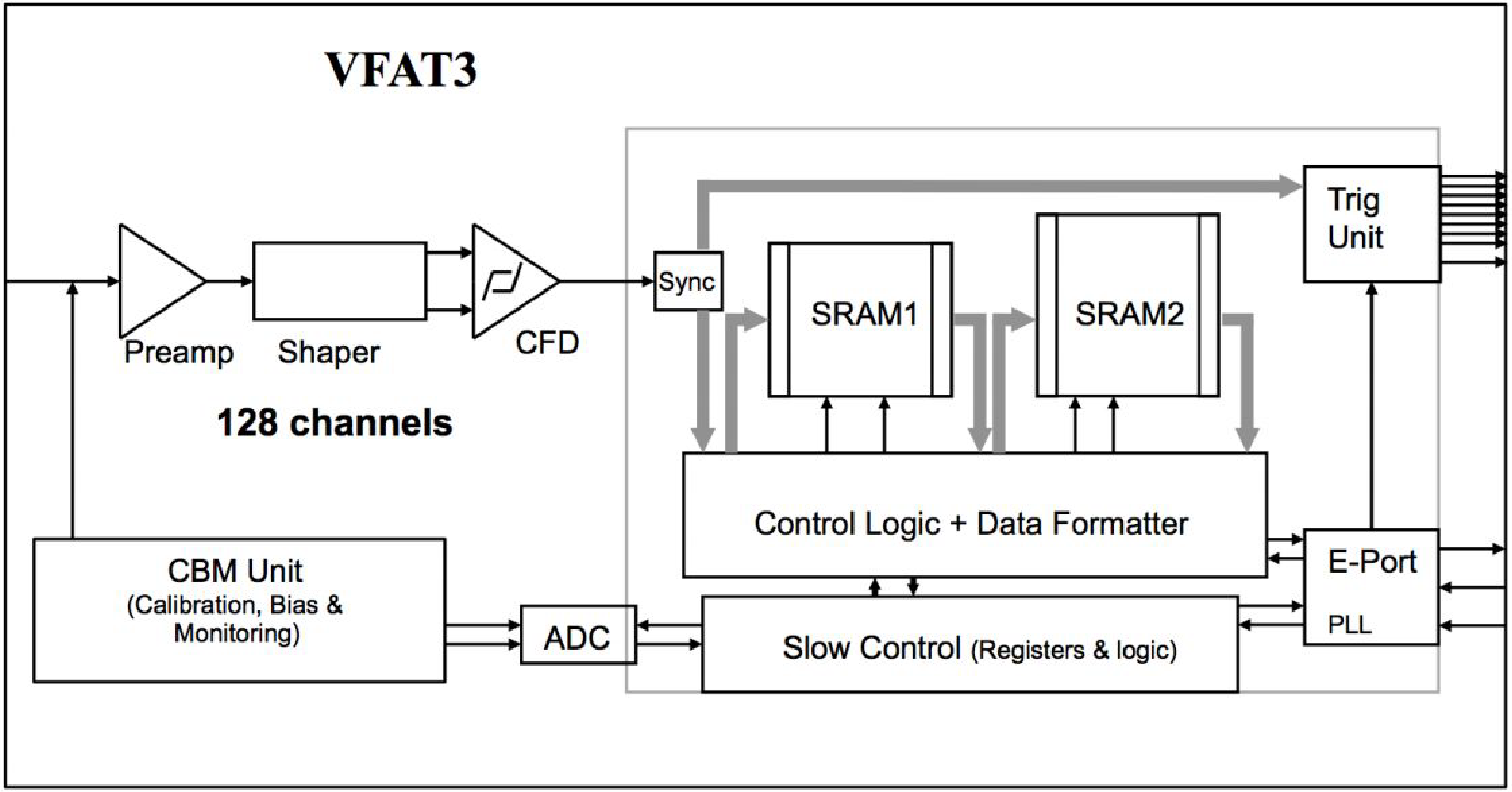
Sigle Event Upset (SEU)

Single Event Upset



Usual chambers due to VTRX

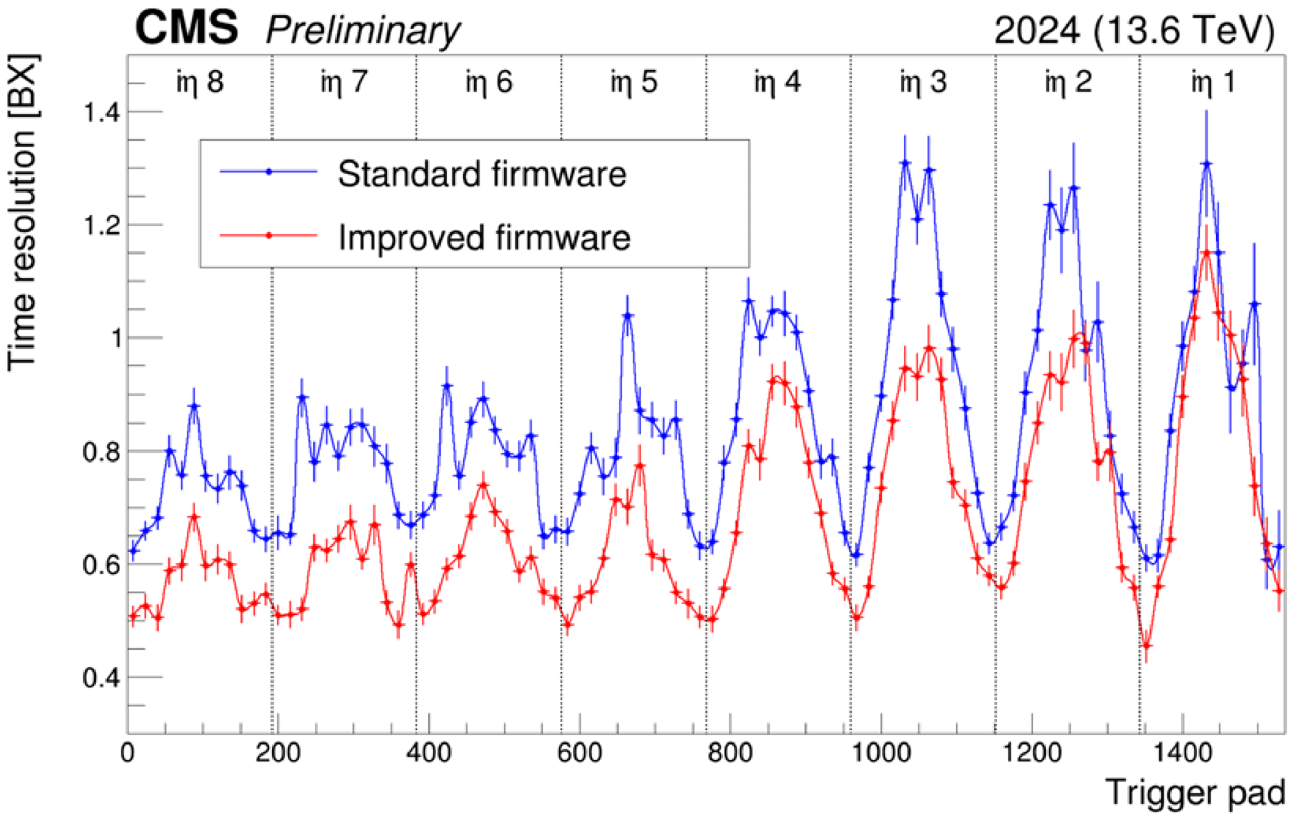
VFAT 3 chip


VFAT3
Preamp
Shaper
CFD
128 channels
Sync
SRAM1
SRAM2
Trig
Unit
Control Logic + Data Formatter
E-Port
PLL
CBM Unit
(Calibration, Bias &
Monitoring)
ADC
Slow Control (Registers & logic)

Backup for Timing and Trigger

Timing in GE1/1: improved FPGA firmware

High η side → **Low η side**

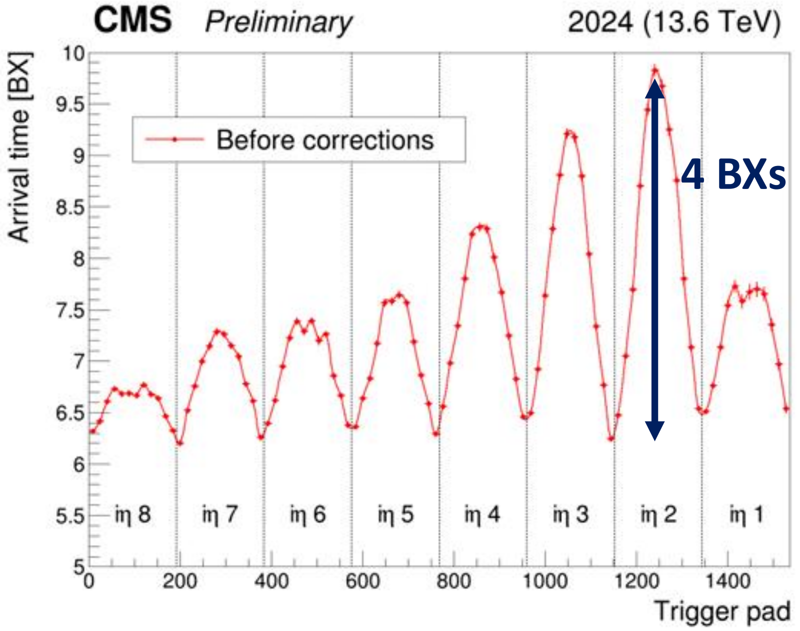


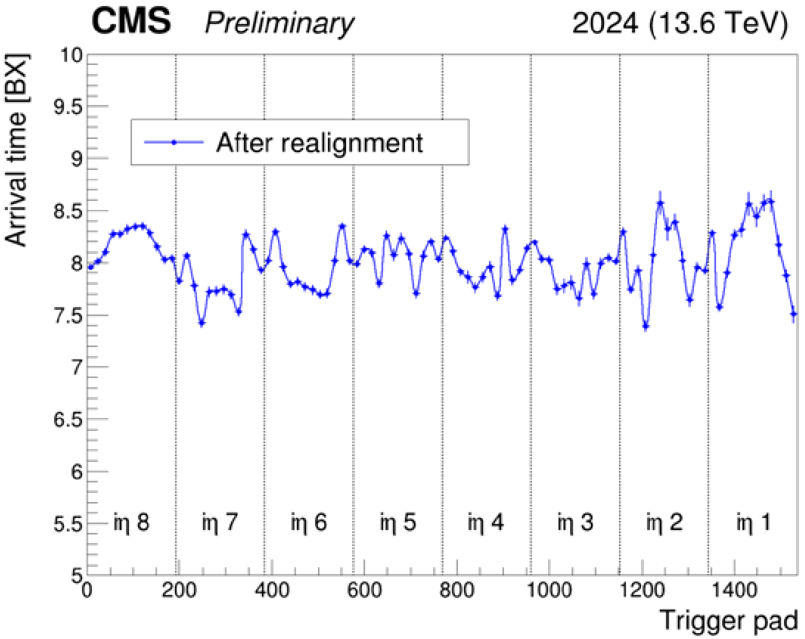
Chamber narrow side → **Chamber wide side**

- Distribution of the time resolution as a function of the trigger pad (pair of two readout strips) for a long GE1/1 chamber, with different firmware versions.
- Each entry represents the width of the time distribution of a group of 16 trigger pads (one quarter of a GE1/1 readout sector).
- The new on-chamber electronics (OptoHybrid) FPGA firmware has a feature that we call "x-talk suppression". It consists in cancelling the hits coming from the interreadout-strip x-talk, which are assigned an earlier Bunch Crossing (BX) with respect to the muon hit.
- The plot shows results from collision runs with both firmware versions. For all runs, the selected GEM hits are the ones matching to a muon track with $p_T > 10$ GeV.
- The time resolution is clearly improved for the new firmware:
- In the low iη area of the detector (wide side), the time resolution worsens significantly, due to the bending of the PCBs in the GE1/1 chambers.

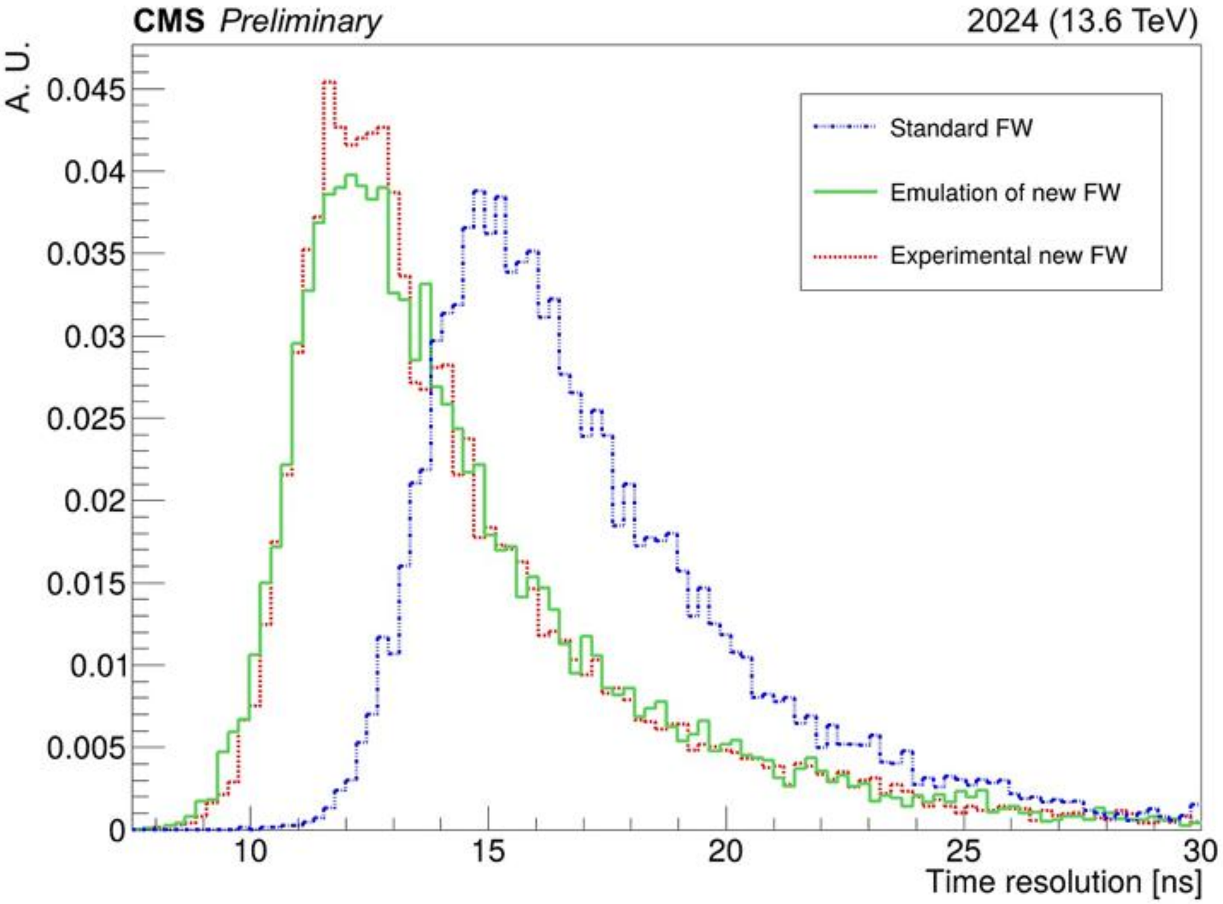
Timing in GE1/1: delays

- **Content:** Distribution of the average arrival time as a function of the trigger pad (pair of two readout strips) for a Long GE1/1 detector
  - Each point in the plot represents the width of the time distribution of a group of 16 trigger pads (one quarter of a GE1/1 readout sector).
- **Kind of run:** collision runs with both firmware versions.
- **Cuts on muons:** For all runs, the selected GEM hits are the ones matching to a muon track with pT > 10 GeV.
- **Implementation of signal delays:** this effect is partially mitigated by delaying earlier hits to later ones. Before we apply any corrections, the arrival times span 4 BXs (of 25 ns). These corrections with BX granularity are applied to groups of 16 strips. Therefore, after applying the corrections, all arrival times end up in the same BX. But the signals are delayed in general and so the latency of the system increased.





Time resolution

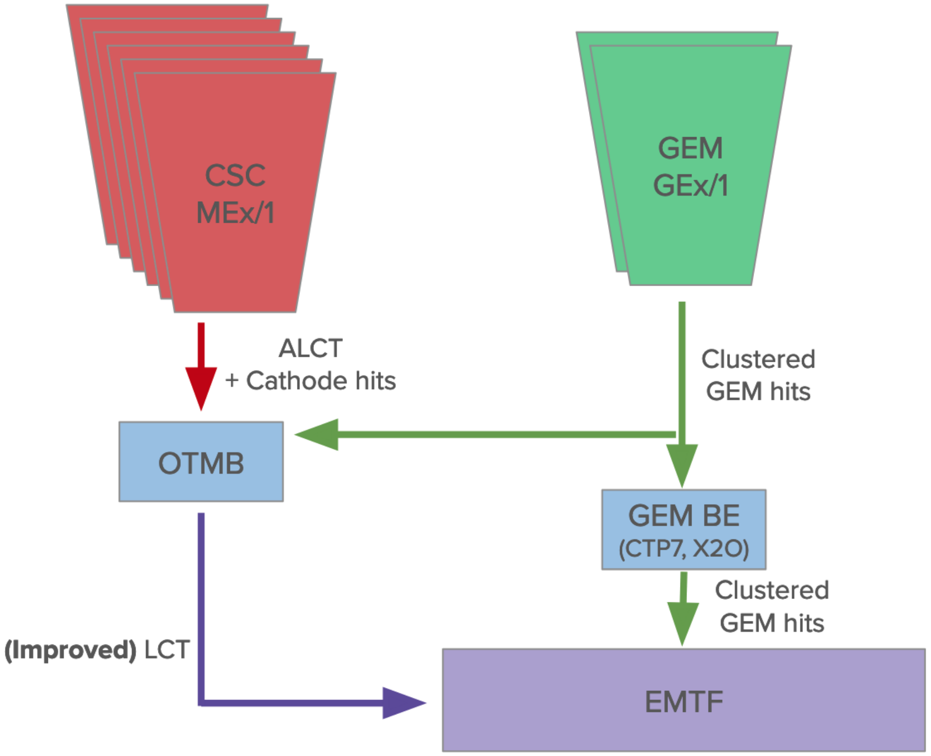


- Distribution of the time resolution of GE1/1, with different Firmware (FW) versions ; each entry represents the width of the time distribution of a group of 16 trigger pads (one quarter of a GE1/1 readout sector).
- Tests with new on-chamber electronics (OptoHybrid) FPGA firmware with the feature “x-talk suppression”. It consists in cancelling the hits coming from the inter-readout-strip x-talk, which are assigned an earlier Bunch Crossing (BX) with respect to the muon hit.
- The plot shows results from collision runs with standard firmware; results from collision runs obtained emulating the behavior of the new firmware; results from collision runs with an experimental version of the new firmware. For all runs, the selected GEM hits are the ones matching to a muon track with pT > 10 GeV.
- Results: the MPV value decreases from 15.3 ns with the standard firmware to 12.3 ns with both the emulator and experimental versions of the new FW.

GEM in Level 1 Trigger (L1T)

CSC
(Cathode Strip Chambers)
6 layers

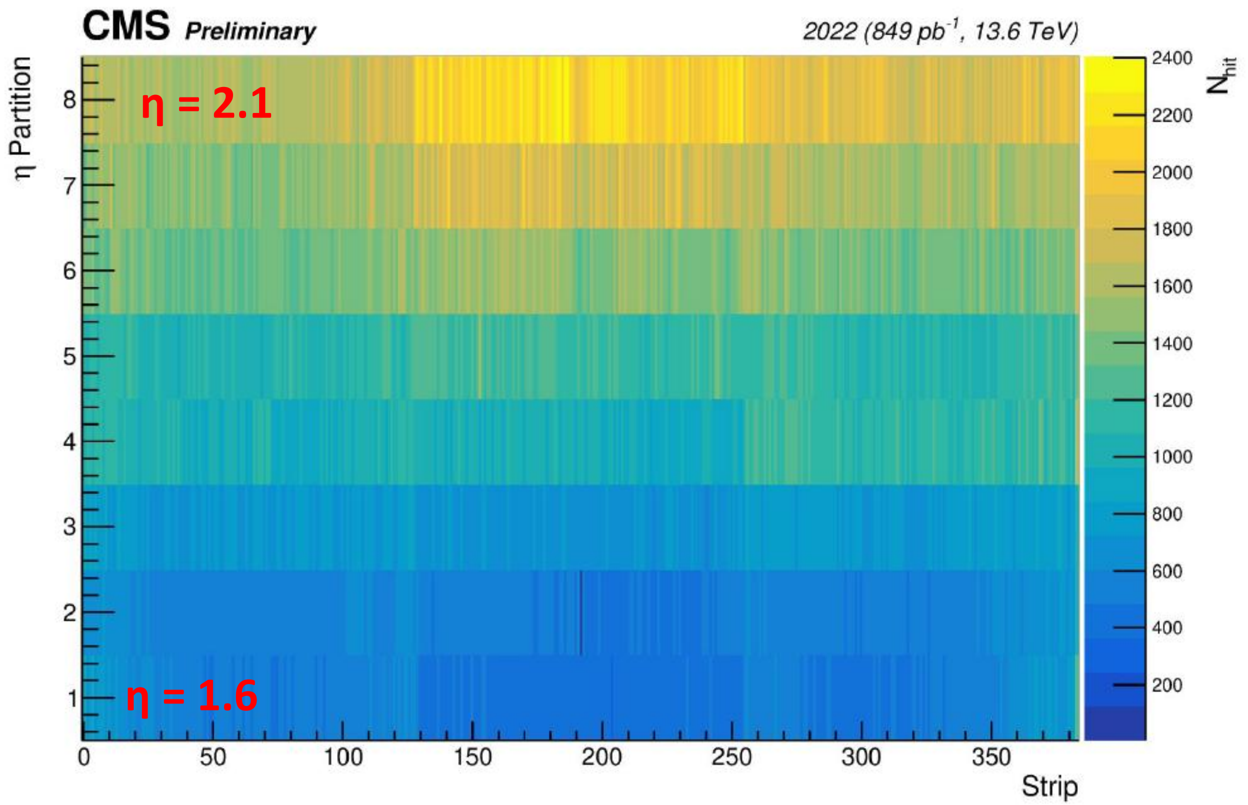
Possible usage (reduction):
- Enhance the single station pT estimation
- Increase the efficiency in case of missing CLCT (Cathode Local Charge Track)



GEM Super-Chamber
2 layers

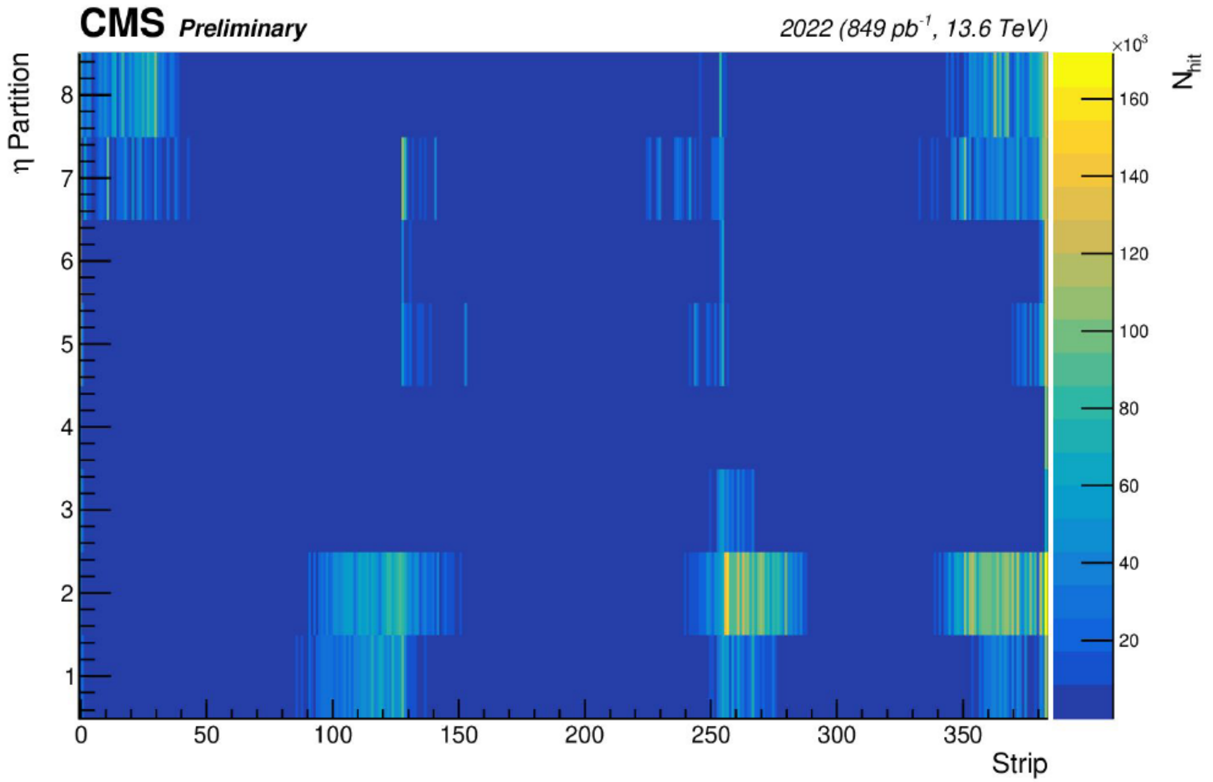
Possible usage (redundancy):
- Replace missing CSC LCT
- Improve efficiency on the edge of the chambers
- Improve track parameters estimation

Hit occupancy plot



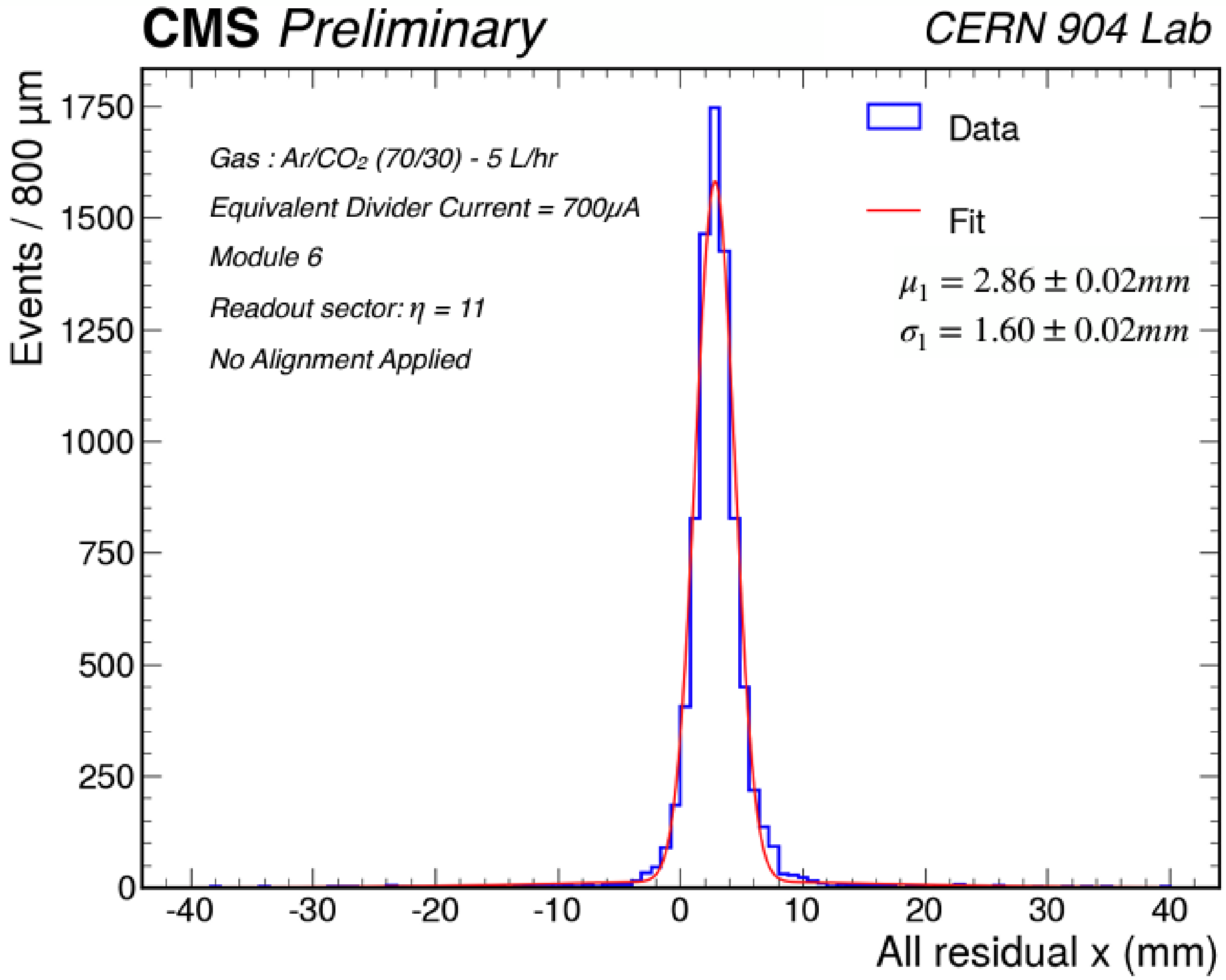
Higher eta → higher number of hits due to background radiation

High Multiplicity event



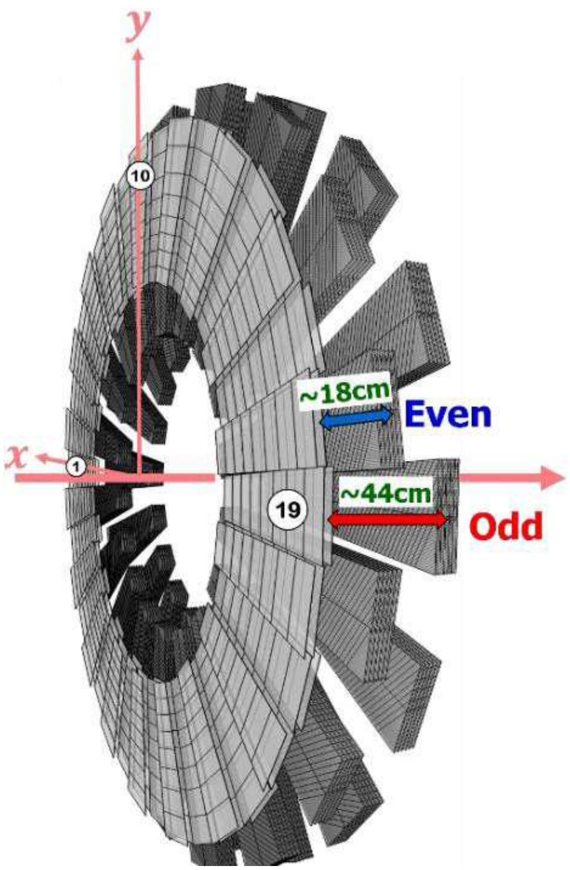
During a high multiplicity event a lot of fake hits are present on top of those due to the background (can be noticed from the scale). In particular the hits concentrate on the edges of VFAT chips, each reading a group of 128 strips

GE2/1 residuals



- Distribution of hit residuals on a GE2/1 module in a GEM cosmic-ray stand, powered on at an equivalent divider current of 700μA.
- The distribution is fit to a Gaussian and the spatial resolution is taken to be the width of the Gaussian.
- The spatial resolution of this particular module and region is 1.60 mm, without alignment.
- The expected spatial resolution is under 300μm.
- The duration of the cosmic run was 69 hours and 46 minutes. This module is a part of the GE2/1 chamber currently installed in CMS (GE21-M-16L1).

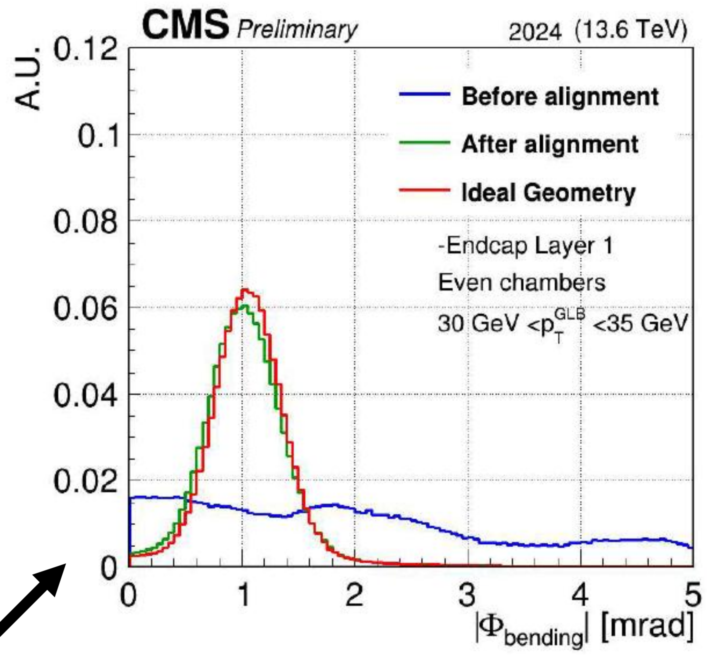
Muon bending angle

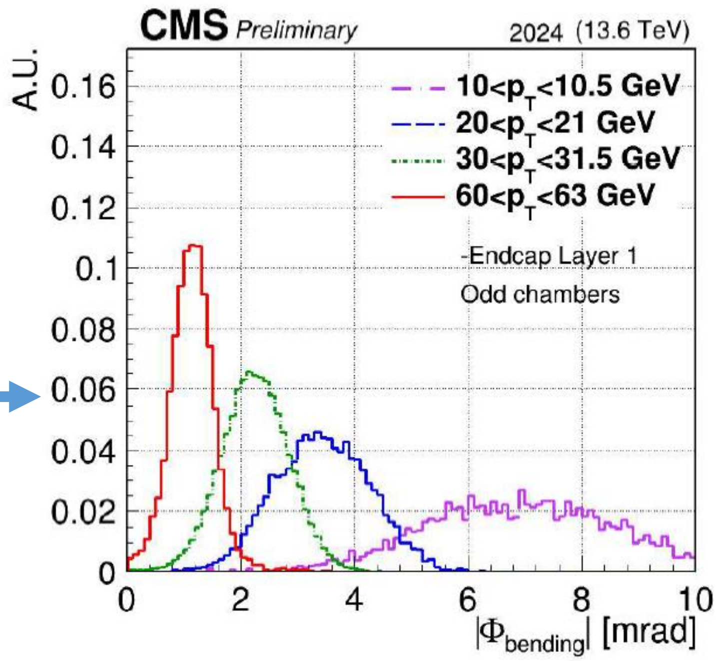


- Implemented alignment between CSC (ME1/1) and GEM (GE1/1) chambers
  - Different distance between ME1/1 and GE1/1
    - Even chamber: 18 cm
    - Odd chamber: 44 cm

- Bending angle distribution with Global muons ($30\text{ GeV} < p_T^{GLB} < 35\text{ GeV}$) $\phi_{bending} = \phi_{ME1/1\,segment} - \phi_{GE1/1\,rechit}$

- p_T dependence of the bendind angle distribution ($\phi_{bending} \propto p_T^{-1}$)



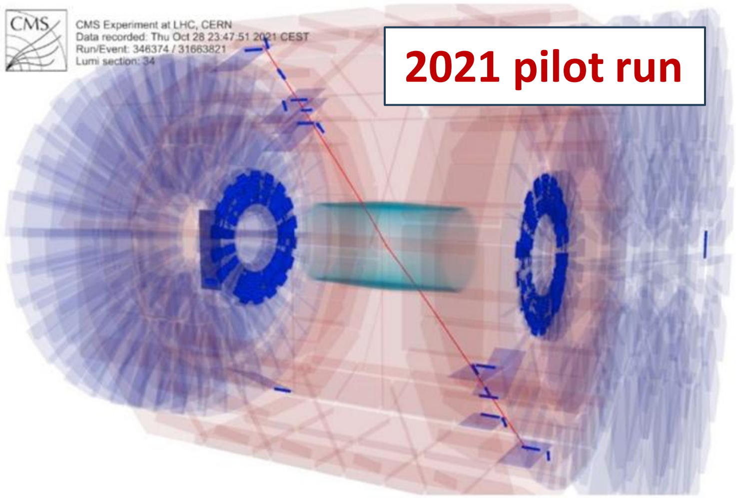


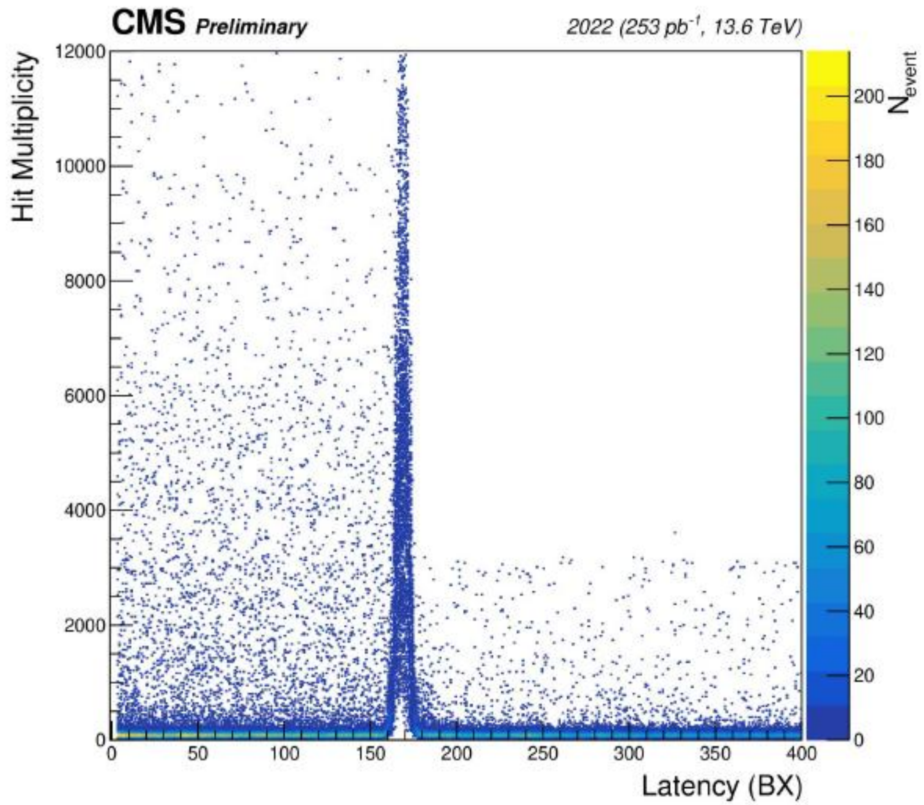
High multiplicity events

- What: high multiplicity events in the GE1/1 chambers

- Why:
  - The L1 trigger signal for accepting an event (L1A) generates a noise signal that can overcome the threshold set in the VFAT3 for the acquisition of data, ~ 160 BX later
  - If a new L1A signal comes data in that time window, the noise signal is acquired

- Minimized by: multi-BX window masking applied at trigger level: 95% of events filtered
  - 5% of events passing, cause of < 2% of GEM deadtime





YETS 24-25

Year End Technical Stop (YETS) 24/25

- Status of detectors
  - **GE1/1:** Keep minimal HV on during the whole YETS (300 V on the foils, gaps OFF)
    - Why:
      - minimize the stress during the repowering in February 2025
      - minimize diffusion of oxide dust without HV
    - When HV OFF: during mechanical movements of CMS yokes, disruptions in power or gas system, human activity on the disk where GE1/1 is installed
  - **GE2/1:** HV OFF
  - Both GE1/1 and GE2/1 flushed in **pure CO_2** during the YETS
- Installations
  - 5 new GE2/1 chambers
    - 4 chambers never contaminated by copper dust
    - 1 chamber with both PCBs and foils cleaned from copper dust
- Extractions
  - 1 GE2/1 chamber (the one with just the PCB recleaned from copper dust)
  - 6 GE1/1 detectors
    - Why: to understand more on the **oxidation** of GE1/1 **non-passivated PCBs**