Production of CMS GEM detectors for the GE2/1 and ME0 stations

With lessons learnt from GE1/1

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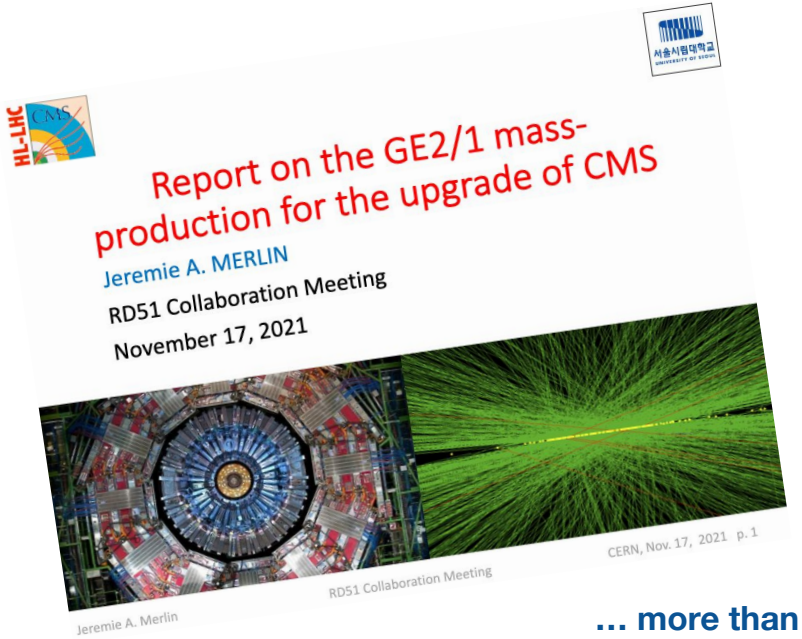
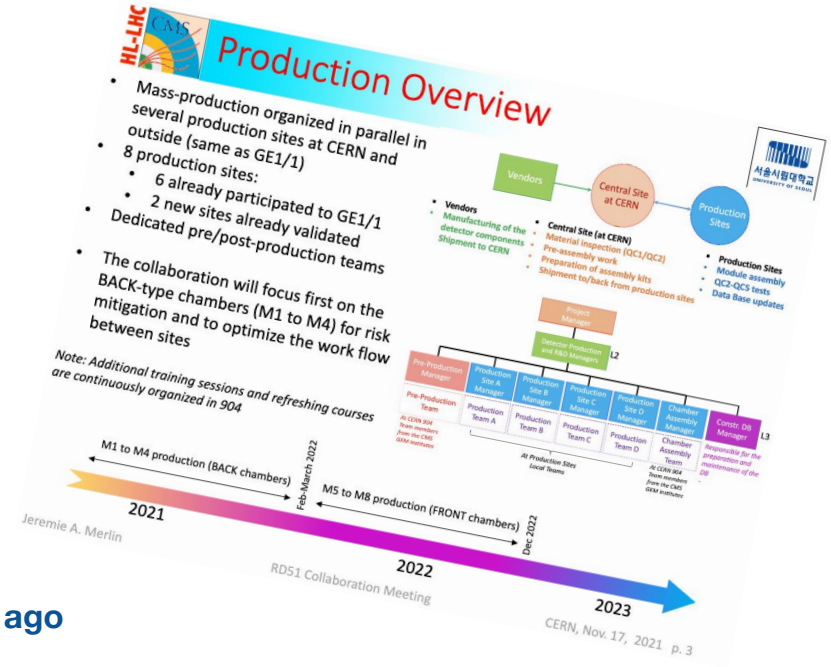
RD51 collaboration meeting - Dec 4-8 2023

Last update on CMS production…



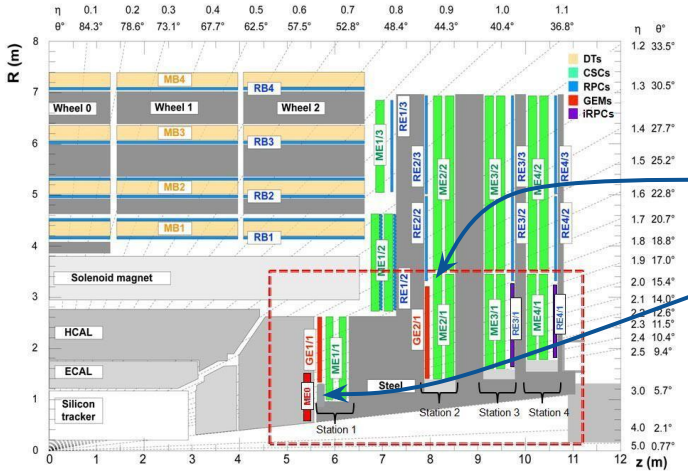


… more than 2 years ago

Meanwhile:

- Production has continued
- First validation results are available
- Priorities have shifted
- New lessons learnt, still more to understand

CMS GEM project

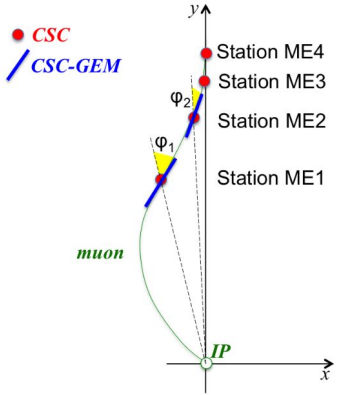


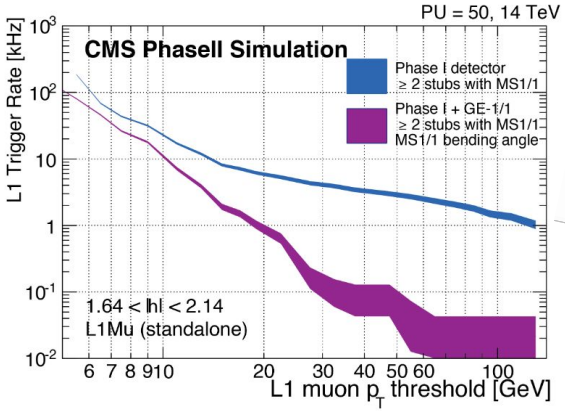
- **GE1/1:** Complementing CSC system in $1.6 < |\eta| < 2.15$

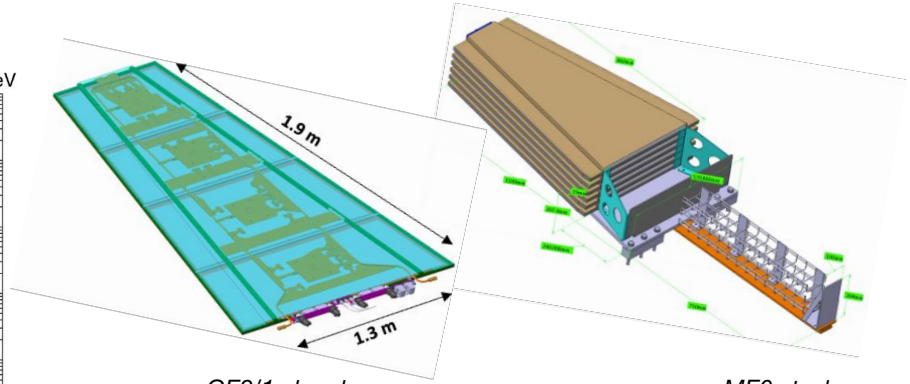
  *Early Phase-2 upgrade: **already installed** in 2019-2020, commissioned and taking data during Run 3*

- **GE2/1:** Complementing CSC system in $1.6 < |\eta| < 2.4$
- **ME0:** Complementing other GEMs and CSCs in $1.6 < |\eta| < 2.4$, extending muon system coverage to $2.4 < |\eta| < 2.8$

In this presentation: GE2/1 production status and outlook on ME0



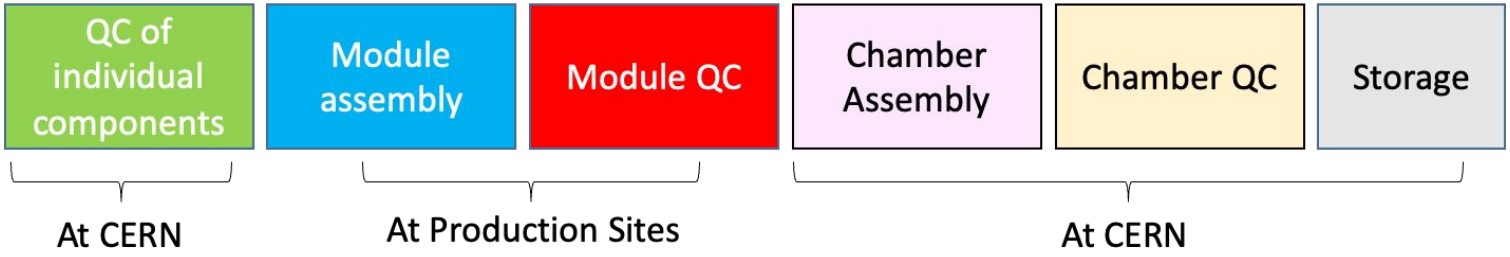


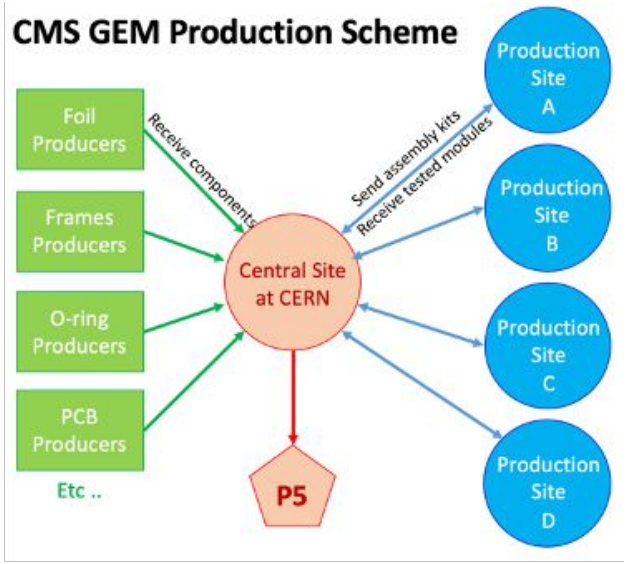


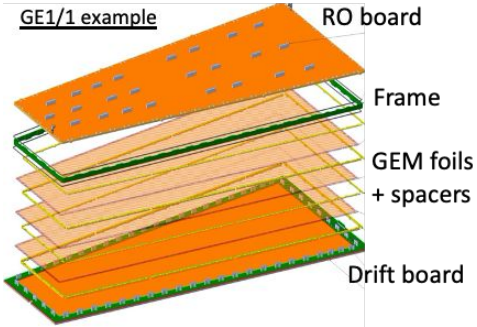
GE2/1 chamber (made of four modules)

ME0 stack (made of six detectors)

Production overview







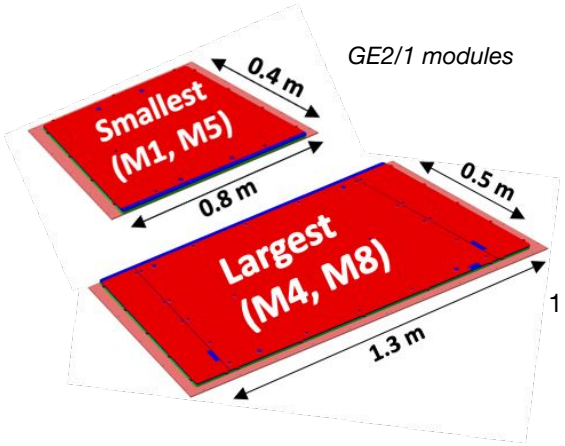
Production scheme as for GE1/1:

- **Component** QC at CERN
- Five **production sites** (Bari, CERN, Ghent+Aachen, Frascati, PKU) for **individual modules**
- Electronics, chamber assembly (4 modules together) and final validation with cosmics at CERN

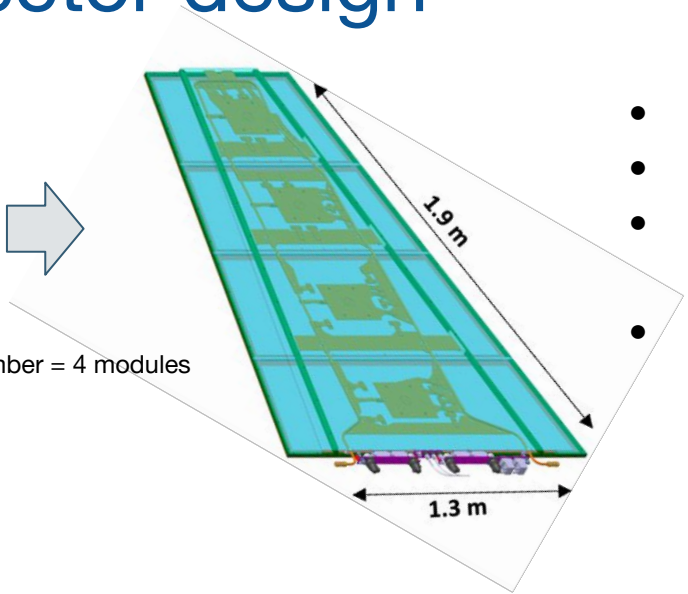
What do the detectors look like?

And how have they changed?

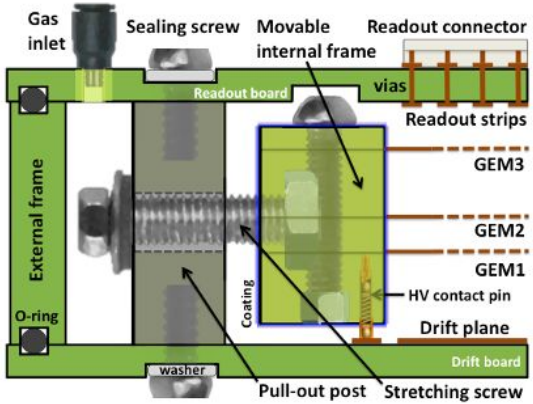
GE2/1 detector design



1 chamber = 4 modules



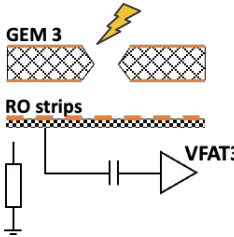
- 2 GE2/1 **endcaps**
- **18 "super-chambers"** per endcap
- **2 chambers** per "super-chamber"
  "Front" and "back" type
- **4 modules** per chamber
  Front modules (M5, M6, M7, M8)
  Back modules (M1, M2, M3, M4)

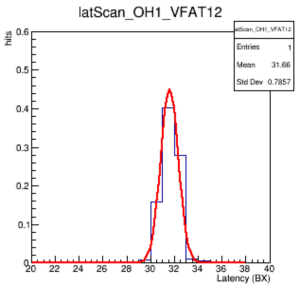


Mechanical stretching scheme

Detector and electronics design **inherited from GE1/1**, but with **lessons learnt**:

- Noise
- Protection for readout electronics
- Planarity and response uniformity
- Intrinsic time resolution



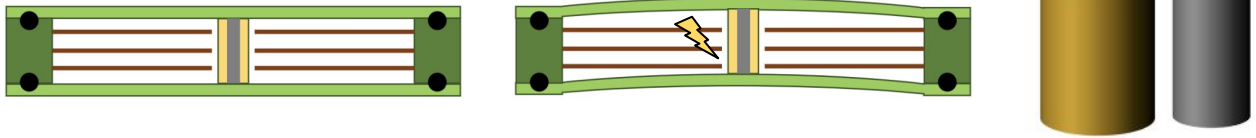


Lesson: detector planarity

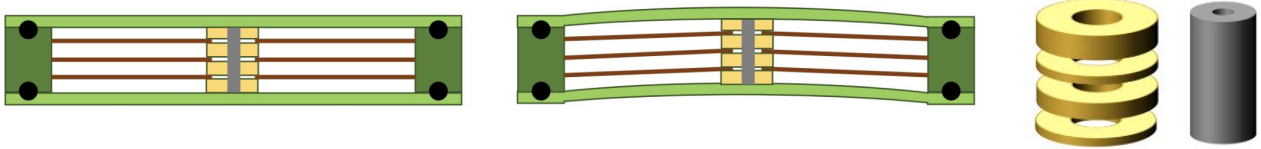
Problem: in GE1/1, drift and R/O **PCBs tended to bend** under stretching force

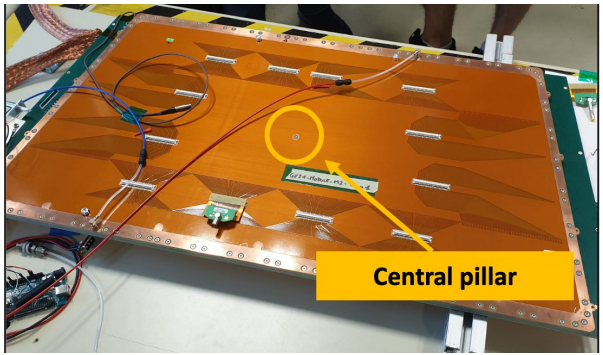
→ **dishomogeneity** of gain, efficiency and timing

1st GE2/1 solution: pillars (sensitive to deformation on drift)

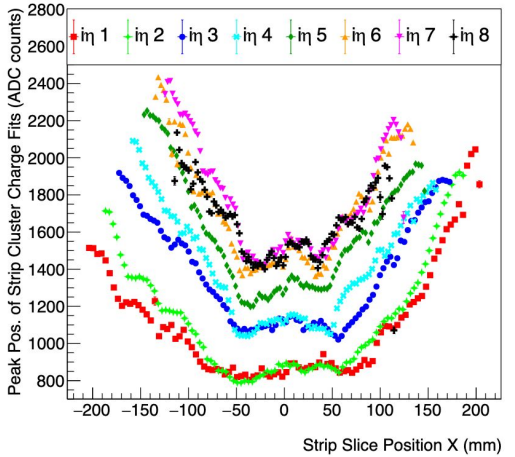


2nd GE2/1 solution: rings

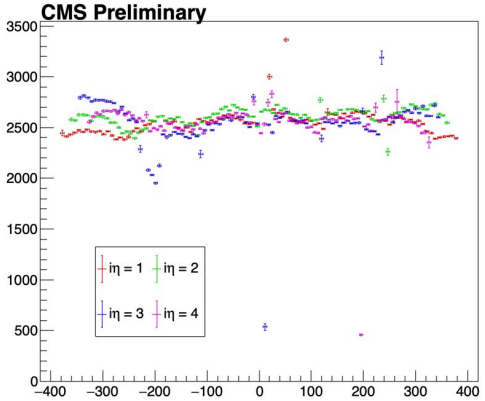




- **Much improved** gain uniformity and efficiency uniformity
- **Reduced risk of sparks** by weak spots in induction gap



Top: GE1/1 "long" detector
Bottom: GE2/1 M4 module

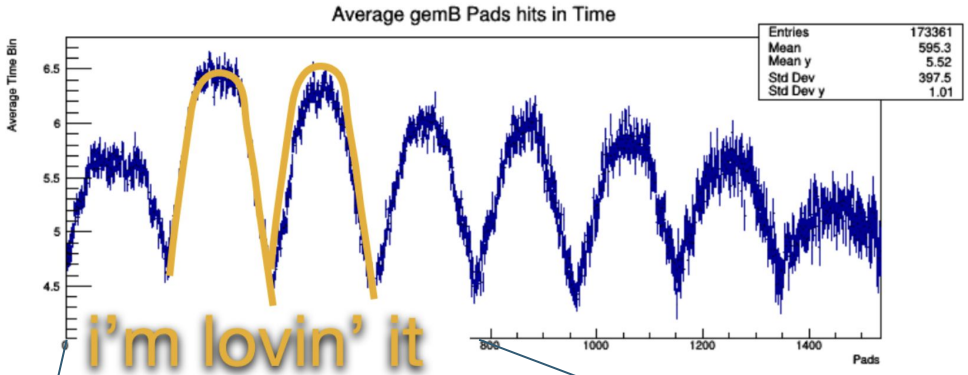


J. Merlin, GE2/1 production, in November 2021 RD51 collaboration meeting

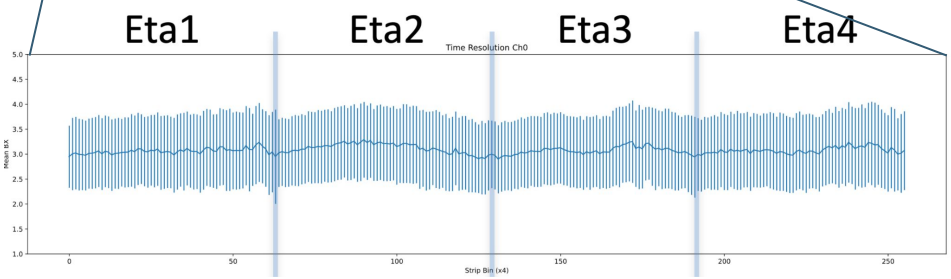
Lesson: time resolution and planarity

The **PCB bending** was impacting the **time response uniformity** of the detector.

GE1/1 cosmics



ME0 SPS test beam



In GE1/1, this caused **non-uniformity in signal** rise time → timing modulation with strip position ("basin effect")

- **Fixable in GE1/1** by applying different delays to trigger primitives in GEM front-end FPGA

Fixed in GE2/1 and ME0 design by using pillars to ensure uniformity of induction gap:

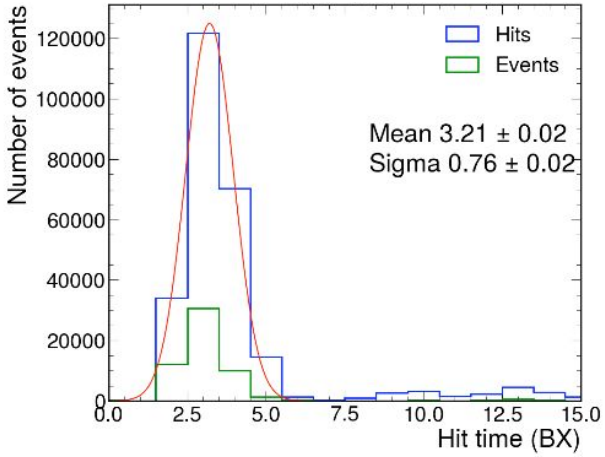
- SPS test beam results: good timing **uniformity over 4 eta partitions**

Not a problem in ME0
(Should also be ok in GE2/1)

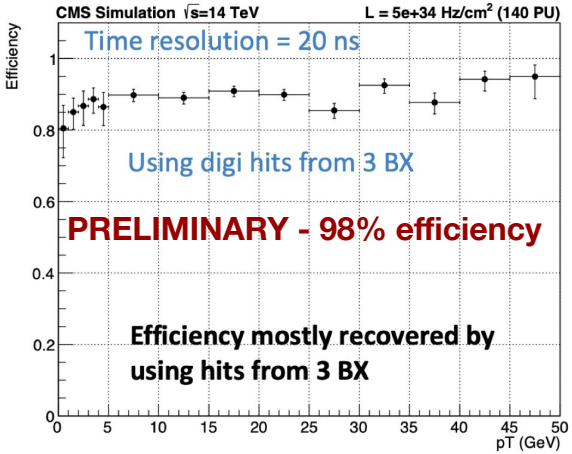
Surprise: time resolution and electronics

Our **time resolution with front-end electronics** is 15 - 19 ns, not 8 - 10 ns

- Common issue between GE1/1, GE2/1 and ME0: **analog front-end** not optimized for GEM signal shape and duration
- We cannot improve the time resolution*, but **we can mitigate effect** on online physics performance:
  - Reading out **multiple BXs readout** in back-end firmware
    Implemented in emulator, under development in GEM firmware
  - From first simulations, online segment efficiency **recovered with matching window 3 BX**
    Slight worsening in bending angle resolution only at "hypothetical" pile-up 300



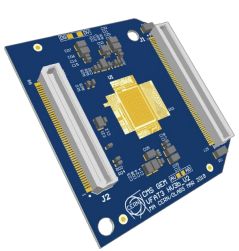
Time resolution of ME0 detector measured in test beam



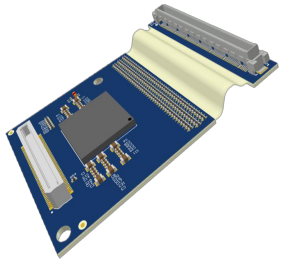
Simulated online segment efficiency with 3-BX readout

**unless maybe we change gas mixture… we are starting an R&D to check*

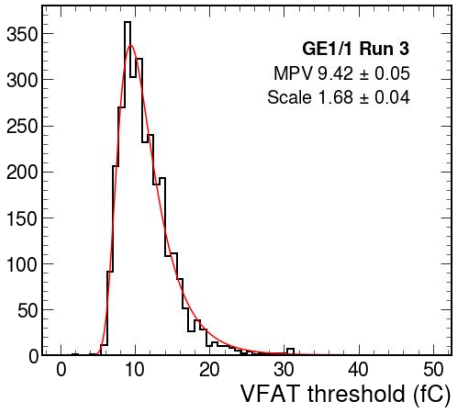
Lesson: noise

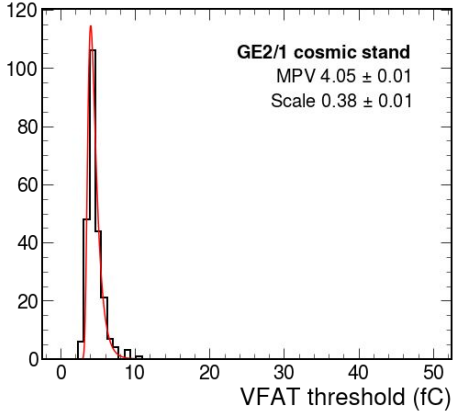


GE1/1 hybrid



GE2/1 plugin card

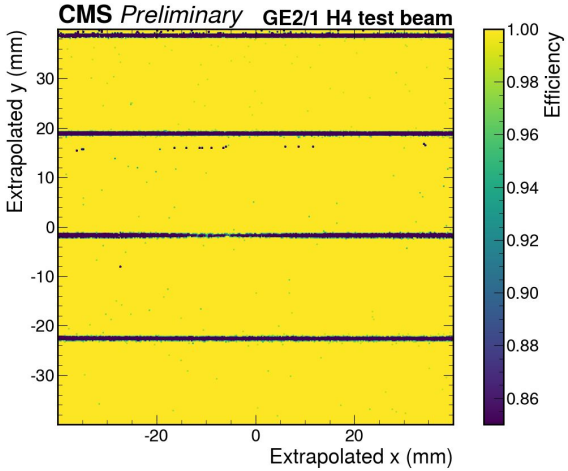




Very **good S/N ratio** verified with high-granularity efficiency measurement in test beam →

Same front-end ASIC (VFAT3), new PCB

- Chip is now **packaged**, bump-bonded (higher yield compared to hybrids)
- **Flex PCB** for easier alignment between readout board (ROB) and GEM electronics board (GEB)
- **HRS 140** connector to R/O strips provides more grounding pins → ~x2 lower noise



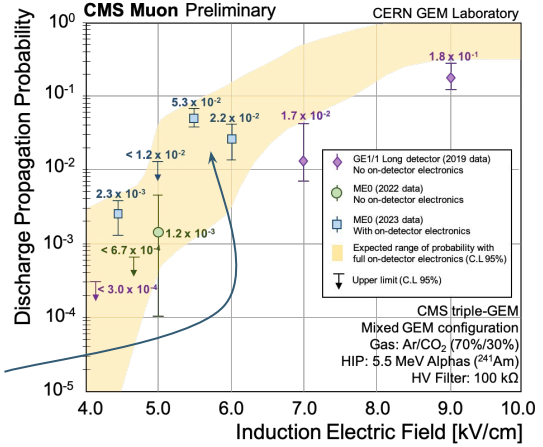
Lesson: readout damage

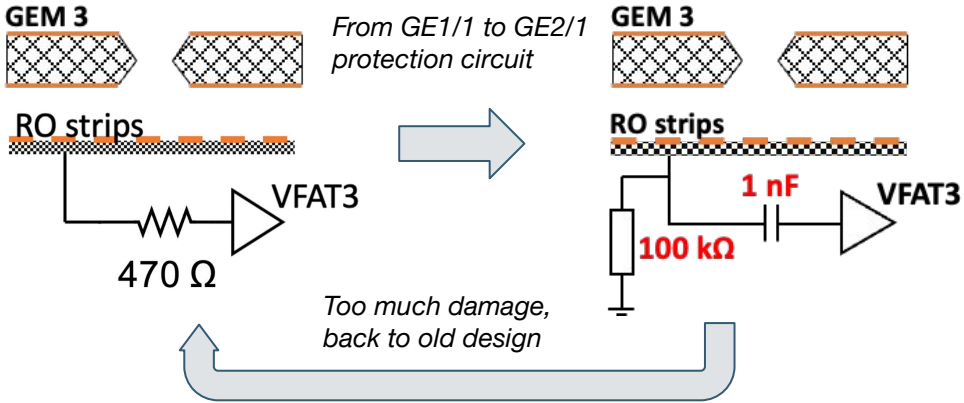
GE2/1 plugin card included new **“decoupling” circuit** to prevent discharge propagation to front-end

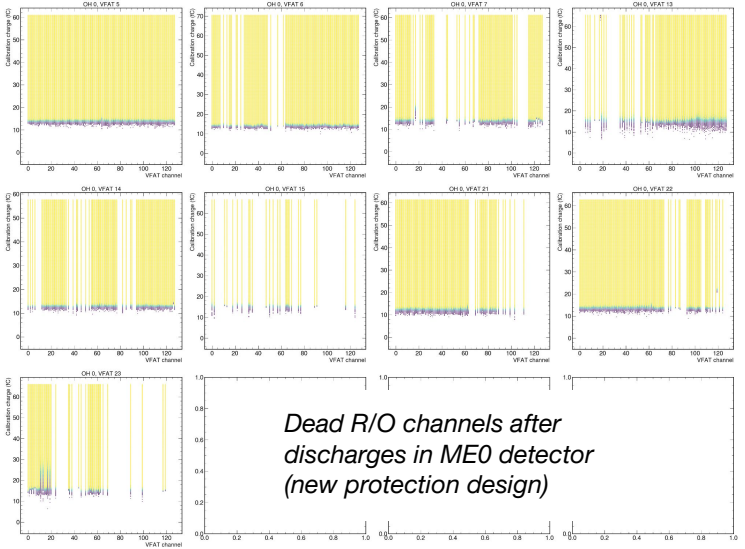
- Operations with GE2/1 and ME0 detectors (demonstrator in CMS, test beam, lab measurements) showed too **high probability of discharge damage**
- We changed the **protection circuit back to the GE1/1** design (470 Ω series resistor)

*Discharge studies now show **no damage***
(expected damage probability per chip < 3×10^{-3})

Discharge propagation more likely with front-end electronics attached







Dead R/O channels after discharges in ME0 detector (new protection design)

How is the production going?

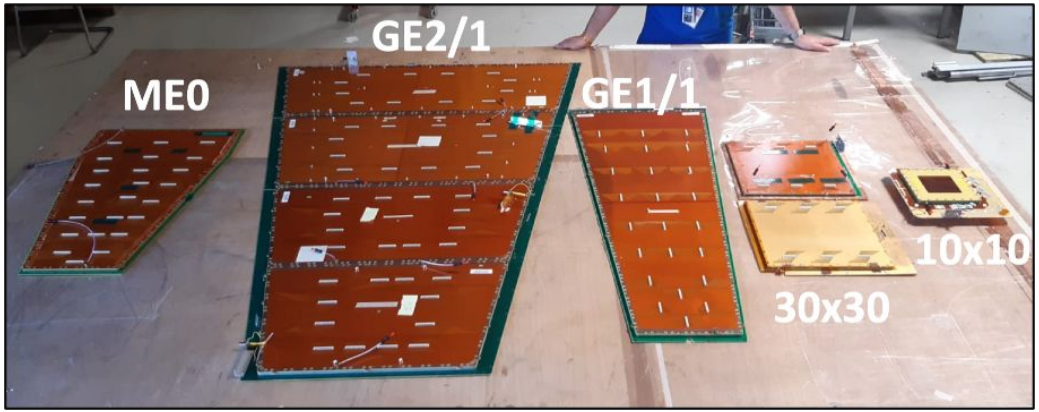
GEM production schedule

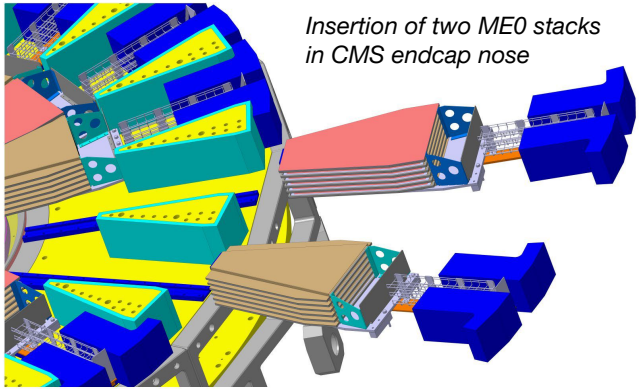
Production schedule **approved by CMS** in GE2/1 manufacturing progress review (MPR), May 2023:

- Install **30 chambers out of 36** (almost one endcap) in year-end technical stop (YETS) 2023-2024
- **Complete** production by **October 2024** (no float)
- Start **ME0** production in **November 2024**
- Complete full GE2/1 system **installation in YETS 24-25**

In short: complete mass production of GE2/1 before ME0

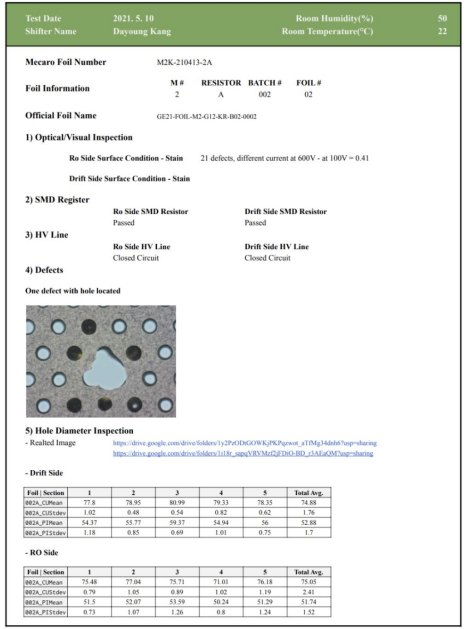
Note: ME0 installation is constrained to January 2027 by HGCAL schedule





Insertion of two ME0 stacks in CMS endcap nose

GEM foil production



Test Date 2021. 5. 10 — Room Humidity(%) 50
Shifter Name Dayoung Kang — Room Temperature(°C) 22

Mecaro Foil Number M2K-210413-2A

Foil Information

M #	RESISTOR	BATCH #	FOIL #
2	A	002	02

Official Foil Name GE21-FOIL-M2-G12-KR-B02-0002

1) Optical/Visual Inspection

Ro Side Surface Condition - Stain: 21 defects, different current at 600V - at 100V = 0.41

Drift Side Surface Condition - Stain

2) SMD Register

Ro Side SMD Resistor: Passed — Drift Side SMD Resistor: Passed

3) HV Line

Ro Side HV Line: Closed Circuit — Drift Side HV Line: Closed Circuit

4) Defects

One defect with hole located

5) Hole Diameter Inspection

- Realted Image

- Drift Side

Foil | Section	1	2	3	4	5	Total Avg.
002A_C|Mean	77.8	78.95	80.99	79.33	78.35	74.88
002A_C|Stdev	1.02	0.48	0.54	0.82	0.62	1.76
002A_P|Mean	54.37	55.77	59.37	54.94	56	52.88
002A_P|Stdev	1.18	0.85	0.69	1.01	0.75	1.7

- RO Side

Foil | Section	1	2	3	4	5	Total Avg.
002A_C|Mean	75.48	77.04	75.71	71.01	76.18	75.05
002A_C|Stdev	0.79	1.05	0.89	1.02	1.19	2.41
002A_P|Mean	51.5	52.07	53.59	50.24	51.29	51.74
002A_P|Stdev	0.73	1.07	1.26	0.8	1.24	1.52

Original plan: two GE2/1 foil producers

- **MPT workshop (CERN)**: M1, M4, M5, M8
- **KCMS/Mecaro (Korea)**: M2, M3, M6, M7

Mecaro produced **300 foils with 99% yield**
Each foil delivered with in-depth QC results

→ In 2022, Mecaro **sold** its chemical lab away

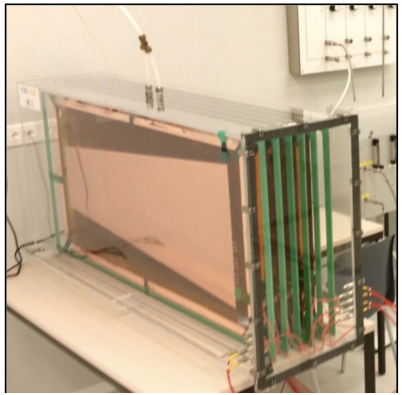
→ Production **stopped** in August 2022

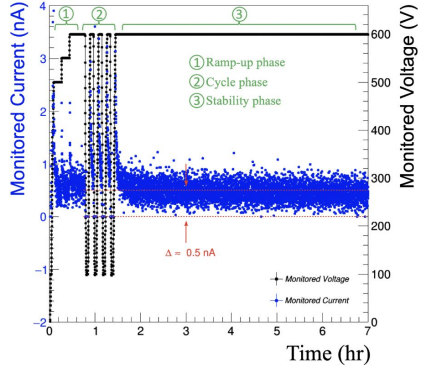
→ Equipment and expertise to be **relocated to KCMS**

→ GE2/1 foil production not continuing at KCMS: will **start again for ME0** foils

New plan: remaining foil production **to complete at MPT workshop**

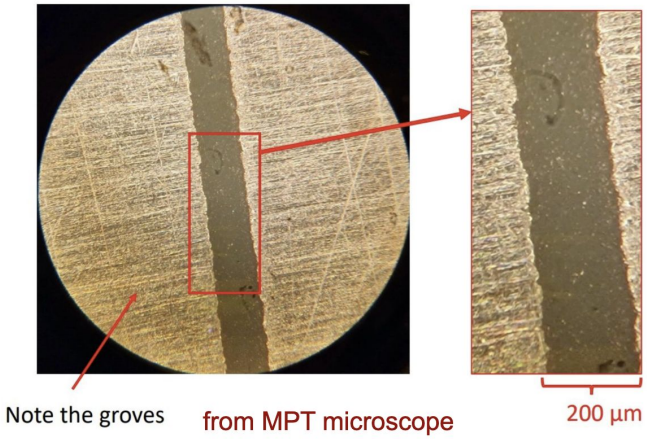
- Restarted in July 2023
- Expected end in April 2024

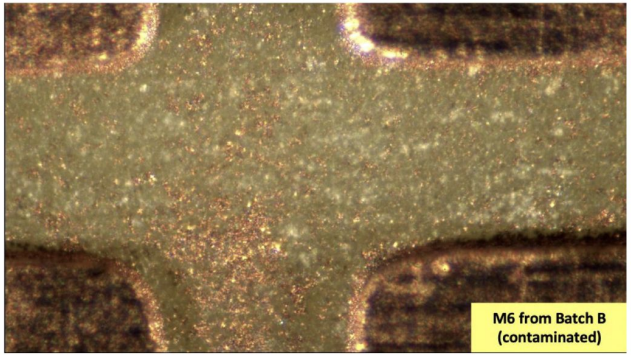




PCB production issue

- At end of summer 2023, **98 modules** assembled (24 chambers)
  36 needed for 1 endcap
- In summer, assembly team had **issues with 80%** of production modules
  - Many **cleaning iterations** needed during assembly
  - **Shorts** forming while closing detectors
- Could not see issues in drift and R/O PCBs with microscope in QC lab
- However, MPT workshop lab showed **copper dust** (few μm) in PCBs
  Cannot be removed by mechanical cleaning

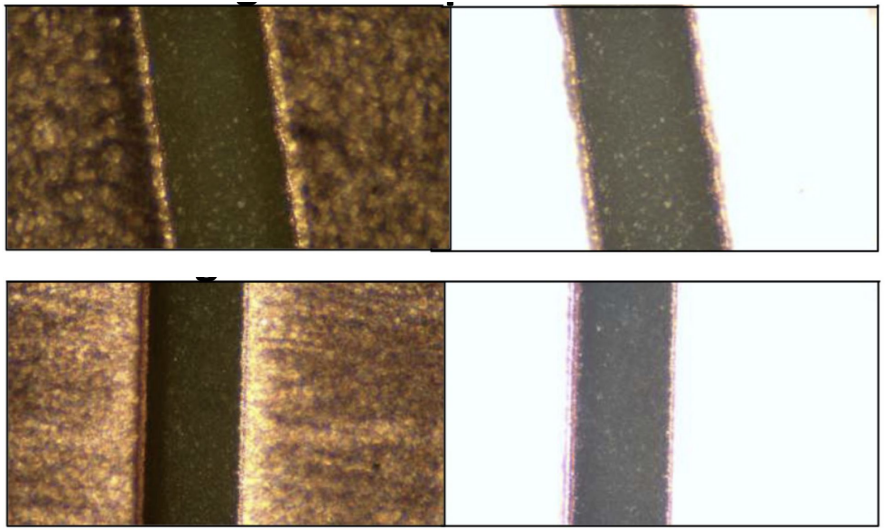




Investigation on PCB quality (September 2023):

- Dust **came from sanding** done by PCB manufacturer (Micropack) on last PCB batch
  Issue only for GE2/1
- Copper **passivation was not applied** in all PCBs:
  No protection against copper **oxidation**
  Affects both GE1/1 and GE2/1; impact on performance yet unknown
- We decided to **refurbish all GE2/1 modules** and redefine PCB validation

PCB refurbishment



Refurbishment procedure established with the help of the **MPT Workshop**:

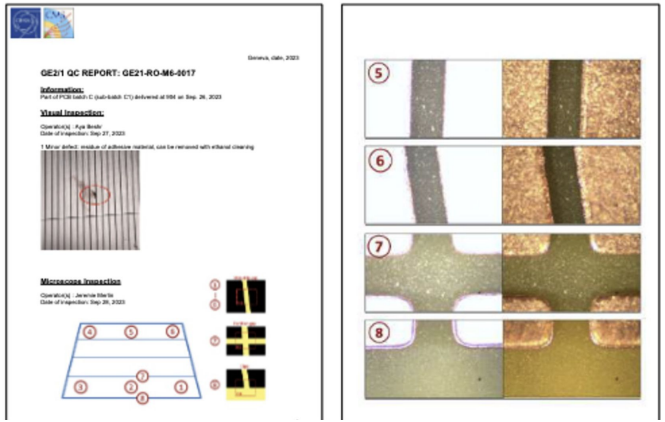
- Mechanical cleaning with tissue soaked with pure ethanol or isopropyl **alcohol**
- **Water jet** cleaning
- **Micro-etching**
- Chromic-acid **passivation**

Procedure also **applied successfully** by Micropack.
No visible difference now between MPT and Micropack refurbished PCBs

A **validation procedure** is now required **for all new PCBs**:

- Visual inspection
- Microscope inspection **(new)**

  Inspection on several points on the PCBs with different light intensity
- Strip continuity/shorts **(updated)**



Still investigating on how to fix contaminated GEM foils

New production plan

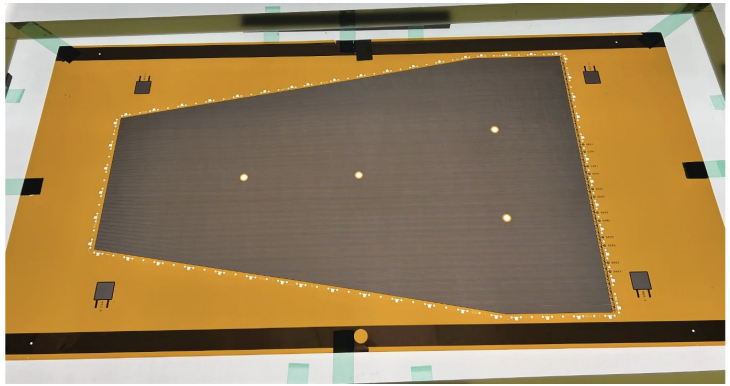
GE2/1 refurbishment plan:

- **Opening** all 98 modules
- PCB **refurbishment** at CERN MPT workshop
- **Re-assembly** and QC

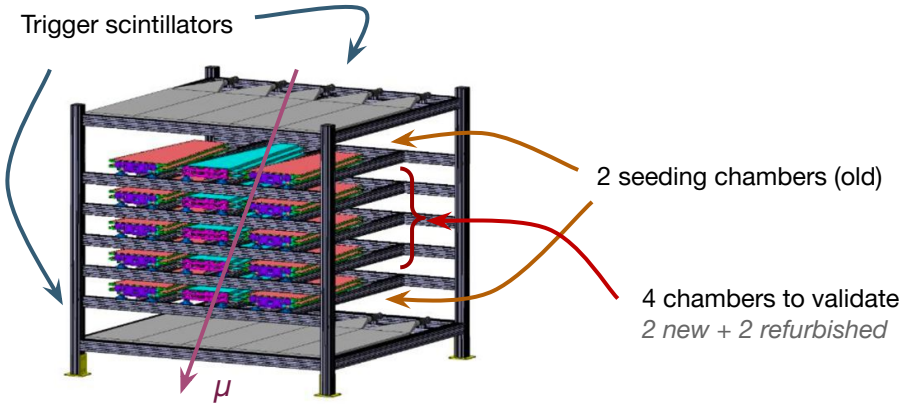
Estimated time to complete production: **2.6 to 3.1 years**

Priority shifts to ME0:

- Stopping GE2/1 foil production at CERN and **start with ME0** (2024)
- **KCMS has started** the ME0 foil production already
- Beginning of ME0 **detector production in March** 2024



First production ME0 foil at KCMS

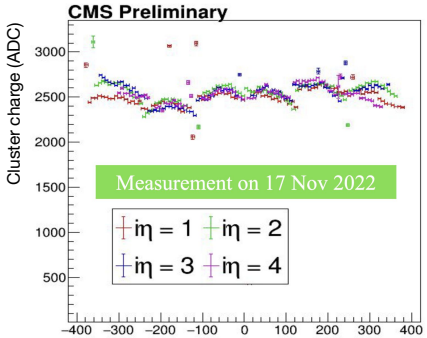


Until ME0 components arrive, **GE2/1 production continues**:

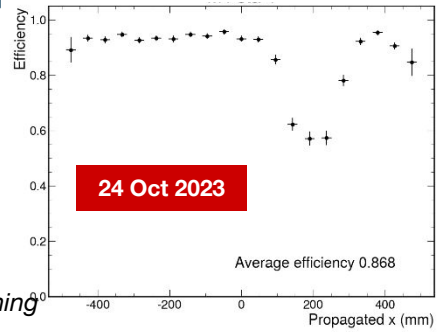
- Assembled **4 GE2/1 chambers**
  2 with new modules, 2 refurbished
- Tested at CERN in "**cosmic stand**"
  Telescope using final electronics and services
- We will **install the two best** chambers in CMS this year
  1 new + 1 refurbished

Outlook on GE2/1 chamber validation

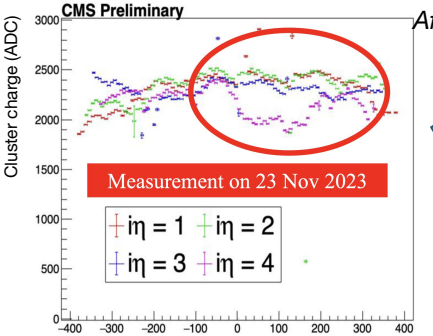
We did a **test round** of chamber validation with cosmics for **non-refurbished** chambers: **still a few surprises** to be understood



Sitting idle 1 year

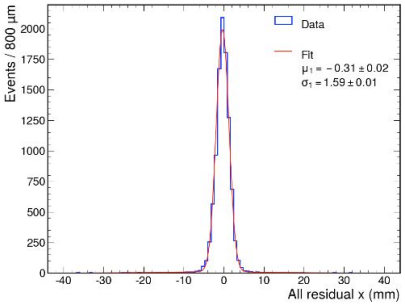


After opening

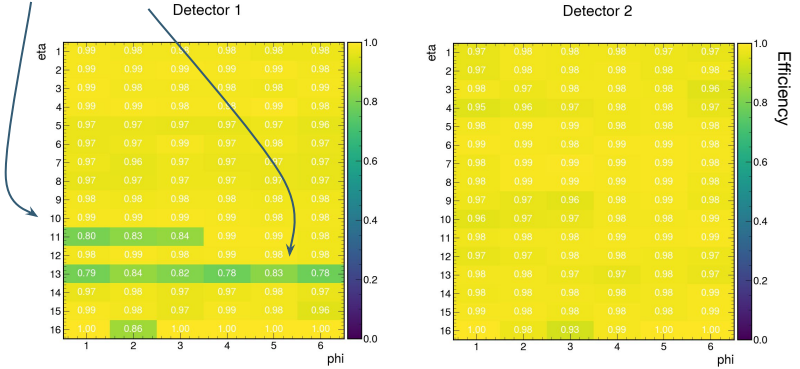


Gain dips found in 4 modules 1 year after production (but seems to disappear after opening the detector and flushing)

Instead the **refurbished and new** chambers show good stability and efficiency **uniformity**



Disconnected HV sectors



Fist chambers almost ready for installation

In conclusion

Long way since beginning of Phase-2 GEM production:

- **GE1/1 lessons** applied to GE2/1 production:

  noise, cross-talk, readout protection, efficiency uniformity

  Or learning to live with: timing…
- Initially produced **almost 1 GE2/1 endcap**
- PCB **quality issue**: rescheduling project to prioritize ME0
- Defined a GE2/1 refurbishment procedure and first chambers will be installed **this year**

Still training the next generation of experts…

Thank you