ME&RE-1/2/32
ME&RE-1/2/30
HE-RBX 16
HE-RBX 15
MB/-2/1/11

GEM Detectors for the CMS Endcap Muon System

Status of three new detector stations

Piet Verwilligen

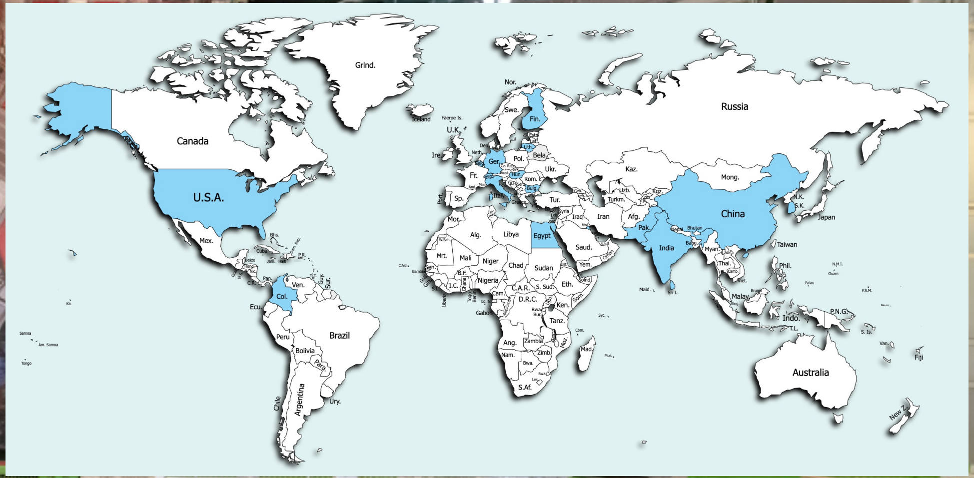
for the CMS Muon Group

MPGD 2022

December 12th 2022

Weizmann Institute of Science - IL

CMS GEM group:
180 authors - 40 Institutes
17 countries
2 ½ year of work since MPGD'19



GEM Detectors for the CMS Endcap Muon System

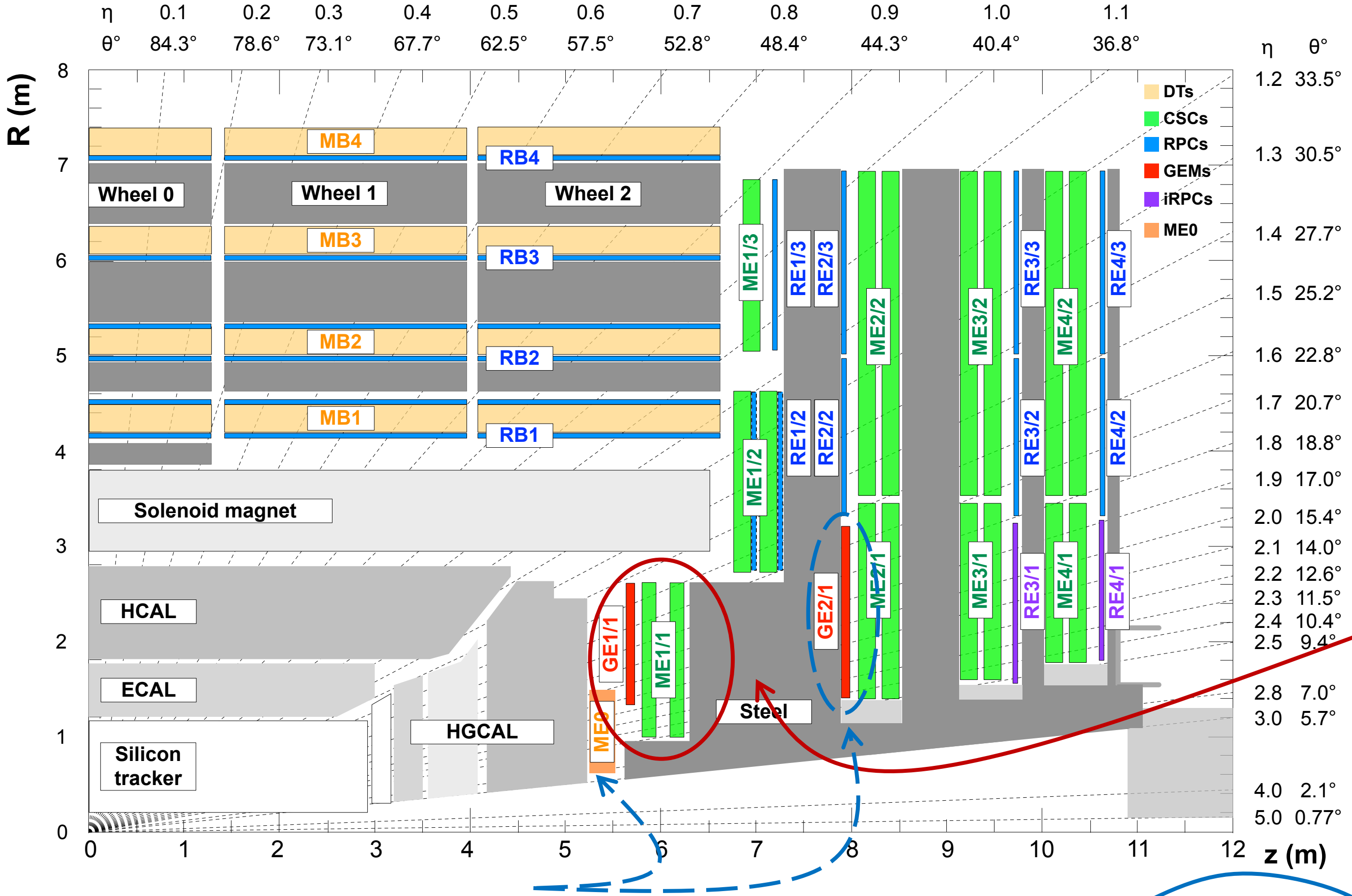
Status of three new detector stations:

I. Installation – Commissioning – Operation – Performance of GE1/1
II. Design & Studies for Phase-2 Triple-GEM detectors in CMS

Small fraction of CMS GEM group involved with installation and commissioning on-site during COVID-19

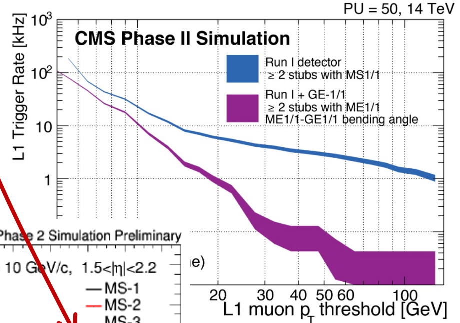
Upgrade of the CMS Muon System

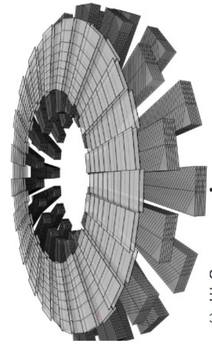
prepare CMS for unprecedented high luminosity at a hadron collider

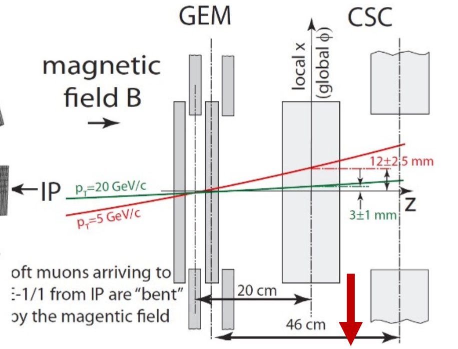


- Improved electronics for existing detectors:
  Drift Tubes, *Cathode Strip Chambers* & *Resistive Plate Chambers*
  - Deal with: Increased L1A (750kHz), latency (12.5us),…
- Instrument Forward spectrometer
  - Highest background – fewest measurements
  - Reduce steeply increasing trigger rate at L1
  - Add Features:
    - *Trigger on Long-lived particles with improved RPCs*
    - *Trigger on Displaced Muons with GEM-CSC tracklets*

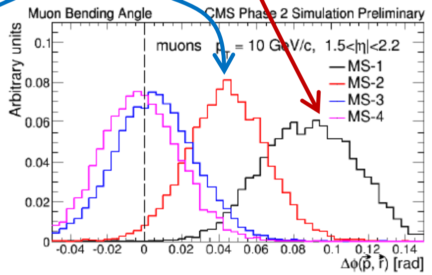
• Phase-1 upgrade :: GE1/1







Increased Bending-angle leverage (20-45cm) improves pT measurement at L1 Trigger and leads to Trigger rate reduction in high background



• Phase-2 upgrade :: GE2/1 & ME0

- GE2/1: Exploit good bending angle @ 2nd station
  Complement CSC & improve Trigger Primitive
- ME0 extends coverage muon system up to $\eta \leq 2.8$

Timeline of the GEM upgrades in CMS

the past, the present and the future

MPGD 2022
we are here

2019	2020	2021	2022	2023
1 2 3 4 5 6 7 8 9 10 11 12	1 2 3 4 5 6 7 8 9 10 11 12	1 2 3 4 5 6 7 8 9 10 11 12	1 2 3 4 5 6 7 8 9 10 11 12	1 2 3 4 5 6 7 8 9 10 11 12 1 2 3

LS 2 | YETS | beam commissioning | intensity ramp-up | collisions 1200 bunches - luminosity production | YETS | beam comm | ramp | collisions 1200 bunches - luminosity production | ions | YETS

MPGD 2019

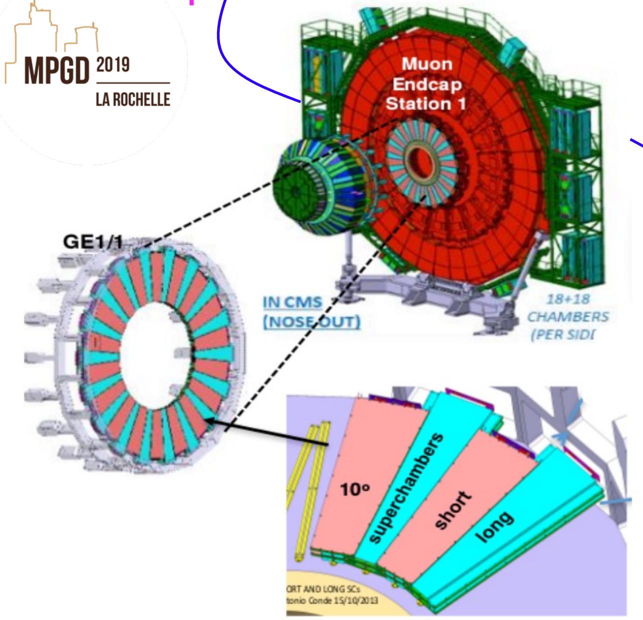
Installation GE-1/1

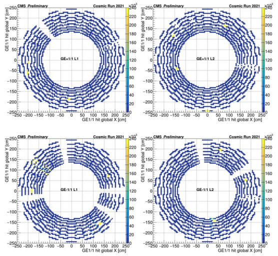
Installation GE+1/1

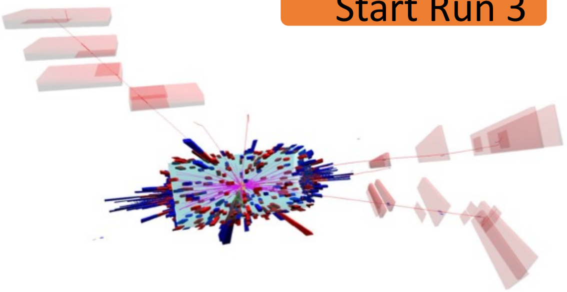
Cosmic Runs

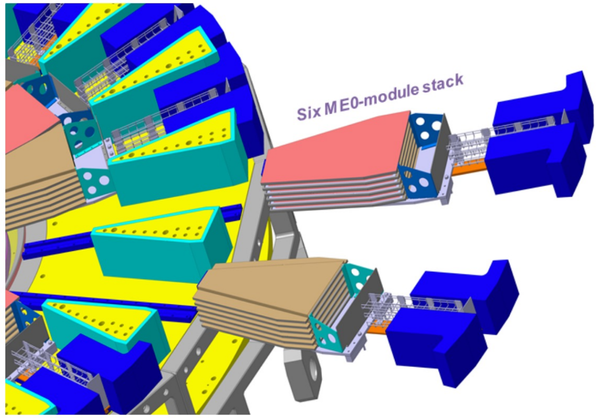
Start Run 3

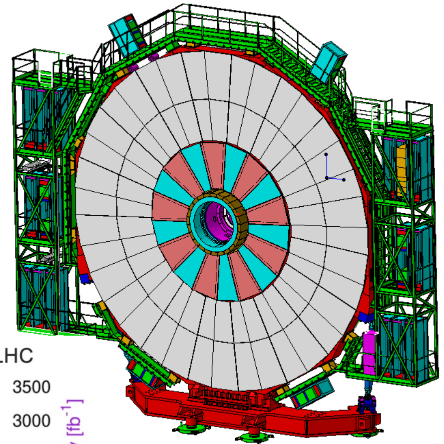
Installation GE-2/1

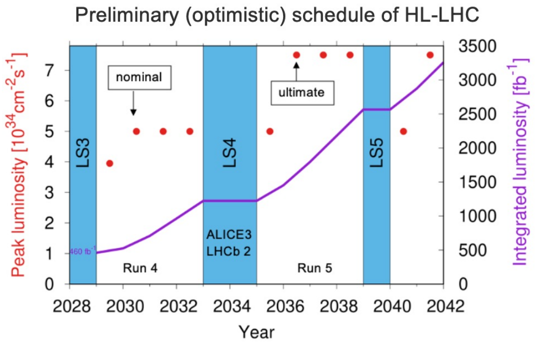












Post LS3
HL - LHC

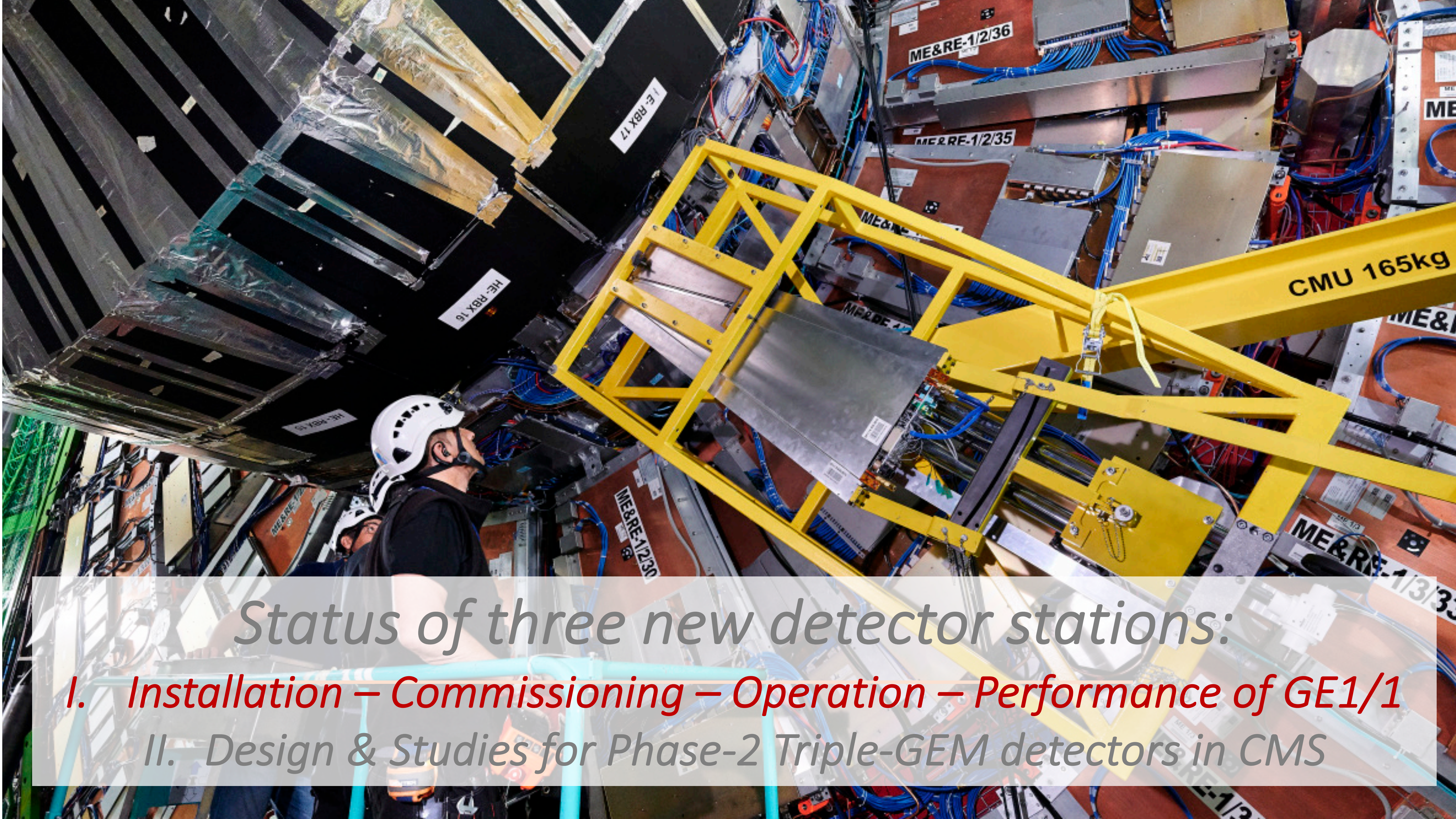
2024	2025	2026	2027	2028
10 11 12 1 2 3 4 5 6 7 8 9 10 11 12	1 2 3 4 5 6 7 8 9 10 11 12	1 2 3 4 5 6 7 8 9 10 11 12	1 2 3 4 5 6 7 8 9 10 11 12	1 2 3 4 5 6 7 8 9 10 11 12

ions | YETS | YETS | LS 3

Installation GE+2/1

Installation ME0 in HGCAL *(on surface)*

Commissioning & Cosmics



Status of three new detector stations:

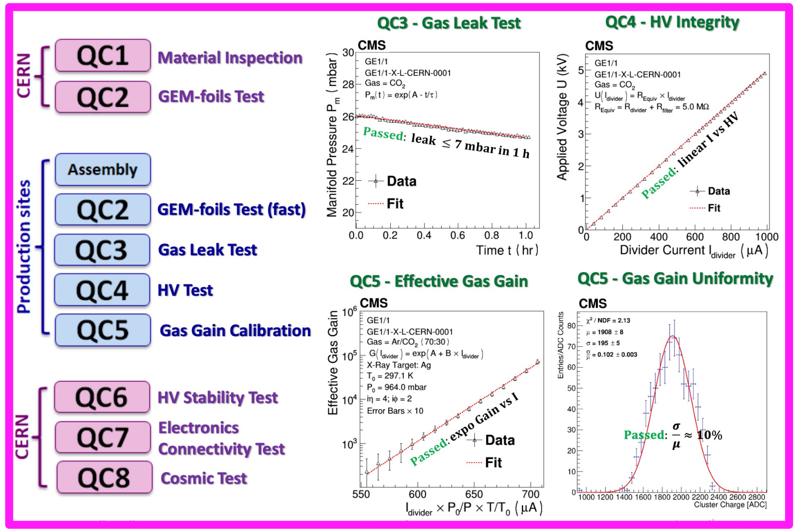
I. Installation – Commissioning – Operation – Performance of GE1/1

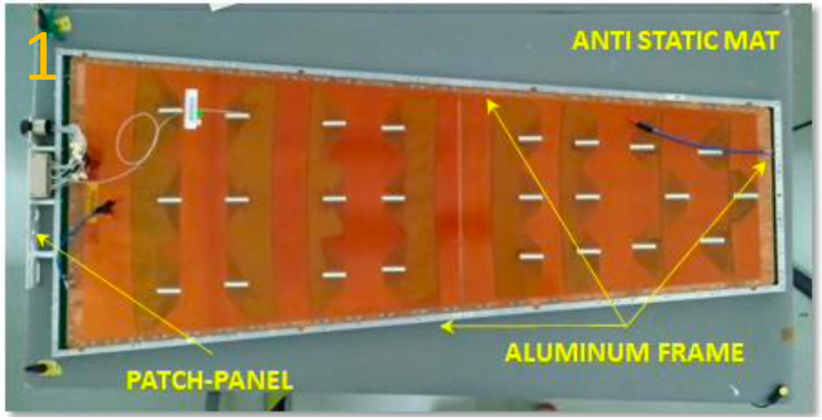
II. Design & Studies for Phase-2 Triple-GEM detectors in CMS

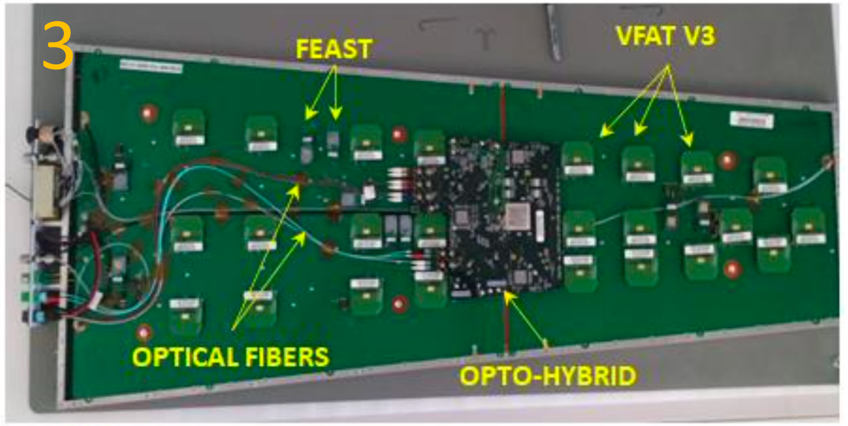
GEM Production and Quality Test

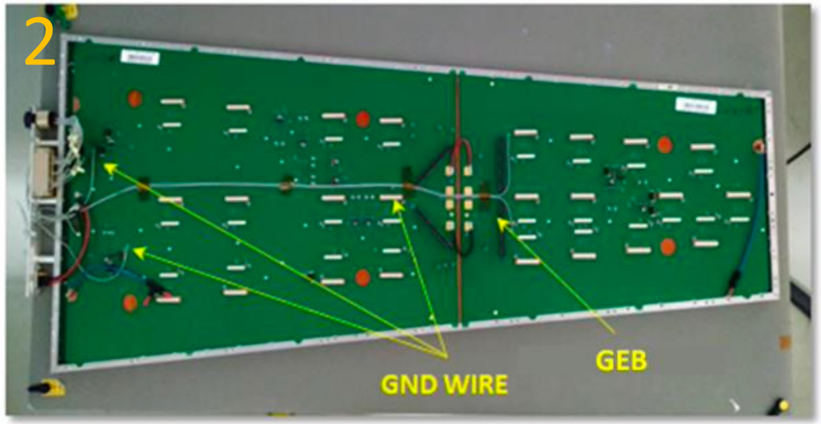
where were we in May 2019 and what did we do up to the installation 2019-2020?

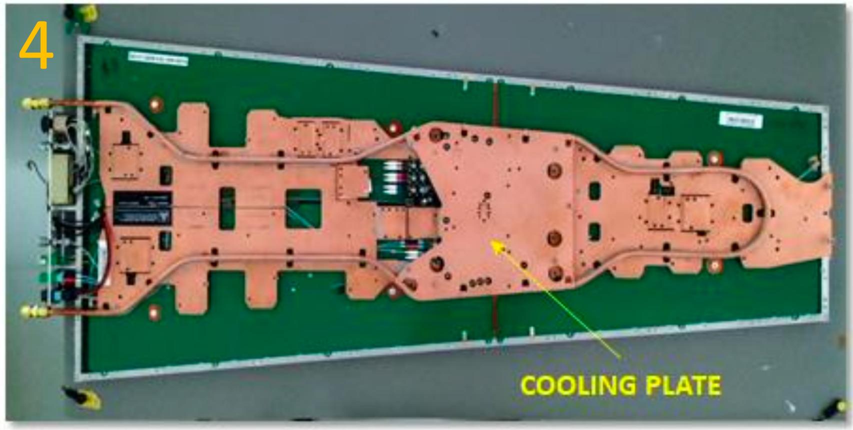
MPGD 2019:
All detectors passed QC1-5





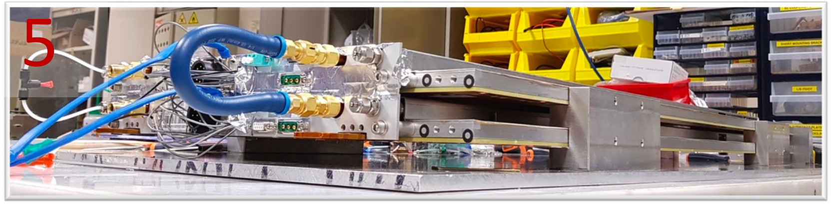






Dressing of GEMs with Electronics:

1. Alu Frame + Patch Pannel
2. GEM Electronics Board (GEB)
3. VFAT3 + FEAST + OptoHybrid
4. Cooling Plate
5. Aluminium Cover, PP & Services

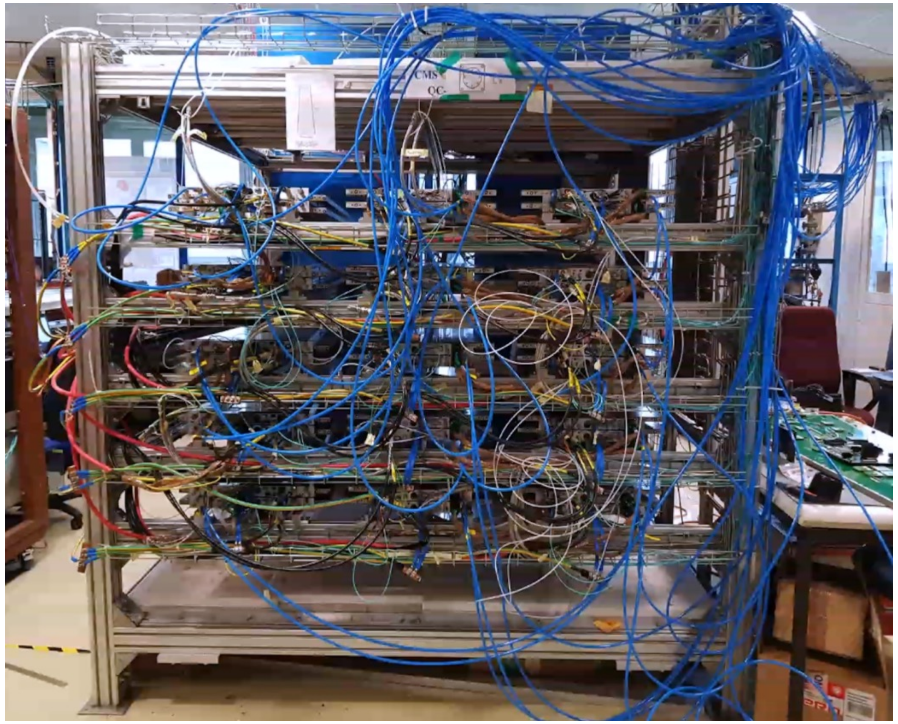


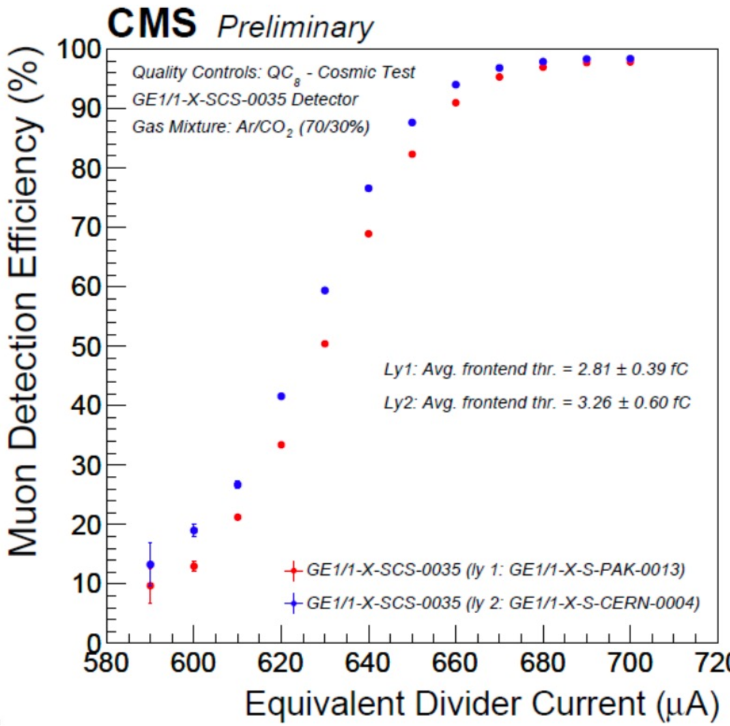
QC7 : Front-End calibration & Test

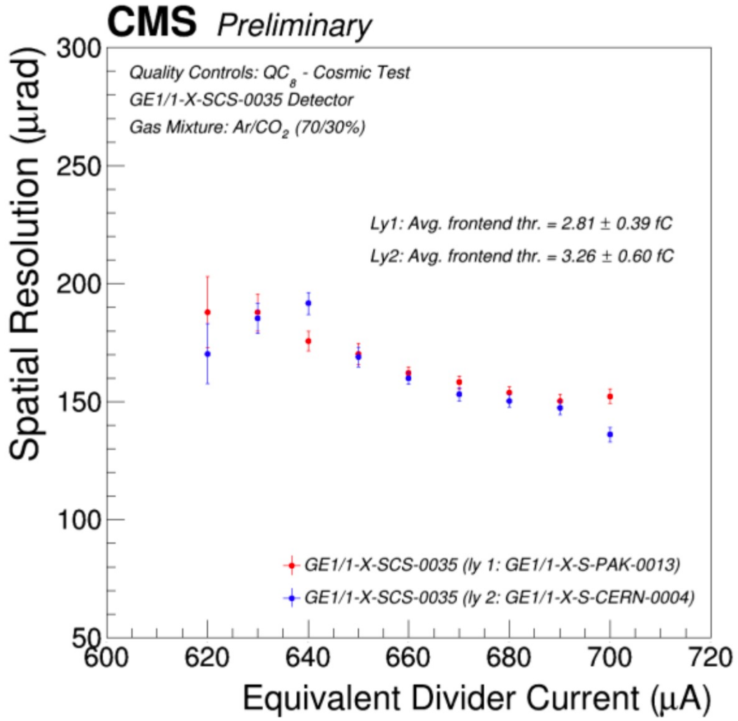
- Connectivity & Communication tests
- Noise (ENC) measurement

GEM Production and Quality Test

quality Control 8 – The Cosmic Stand – a medium scale experiment in the lab!

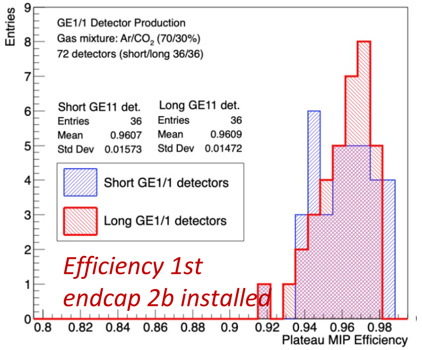






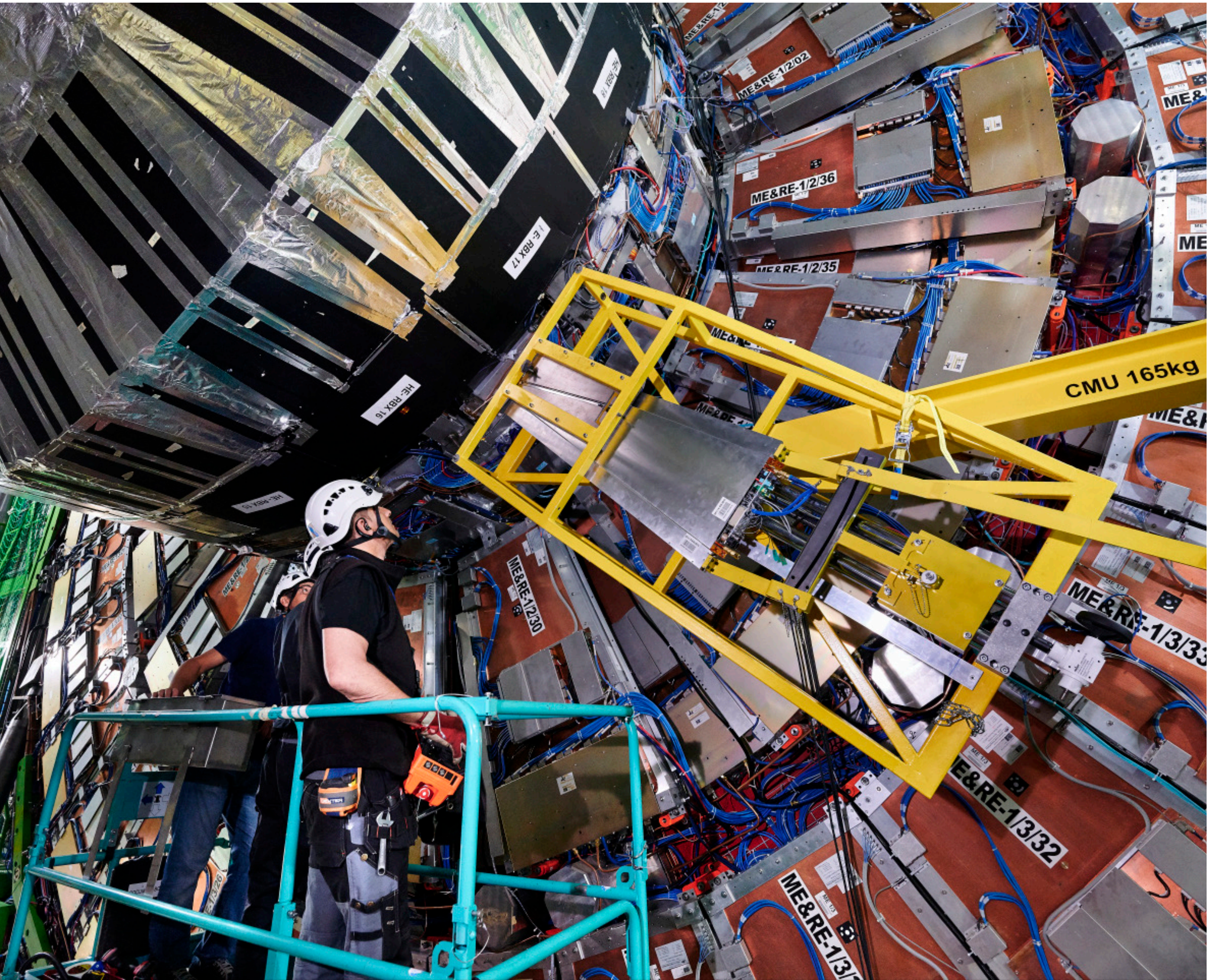
- 15 super-chamber slots *(144 chambers needed - 154 chambers tested)*
- 92k readout channels with CMS DAQ *(uTCA based)*
- $5m^2$ of scintillator trigger *(90Hz total rate)*
- 12h runs per HV-point *(4M muons)* <1% precision on ε
- Services (HV, LV, cooling, gas) as in CMS experiment

- Detector Control System (DCS) as in CMS
  - HV,LV control & monitoring (data stored in DB)
  - Environmental (p,T) gas mixture monitoring (data in DB)
- Data Quality Monitoring (DQM) as in CMS
- Full Simulation & Reconstruction in CMSSW
- *Efficiency > 97.5% and 150 urad spatial resolution*



Installation and Commissioning

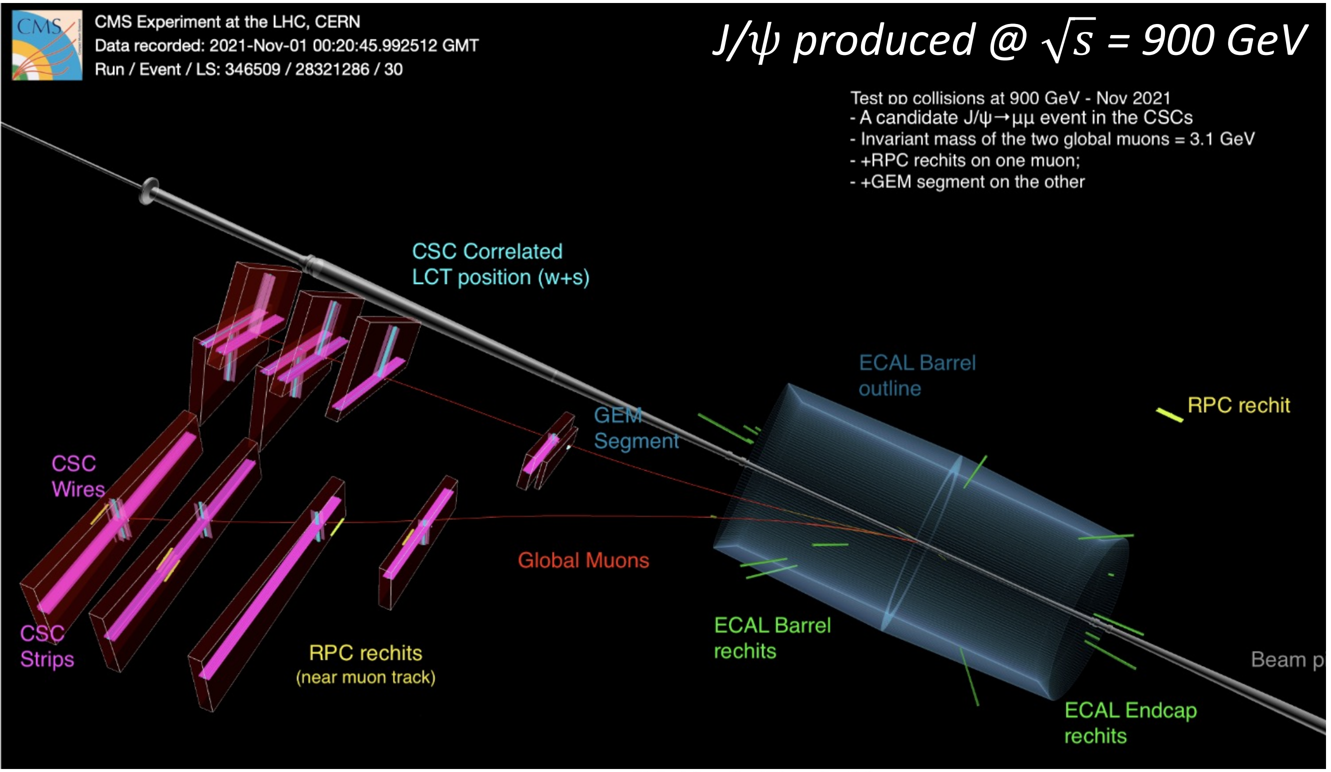
new home in CMS and cosmic runs *2019-2020*

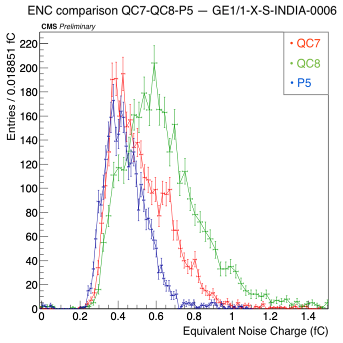


- **144 GE1/1 chambers installed in two slots in 2019 and 2020** *(GE-1/1 @ 07-10/19) (GE+1/1 @ 07-10/20)*
  - Installation rate: 2 super-chambers / day
  - Before & After installation QC2 $_{fast}$ to check foils
  - Fast connectivity test (w/o cooling)
  - Succesful powering, communication & calibration
  - GE+1/1 installation & commissioning during Covid
  - In total 8 chambers replaced (HV, LV, Fibers, …)
- **Integration in central CMS**
  - GEM DCS included in central DCS
  - DCS Action Matrix Review – LHC Handshake
  - DAQ stress tests – configuration – zero suppression
  - Latency scan with cosmics – timing in VFAT3s
- **Early Commissioning**
  - HV Training GEM foils in CO_2 followed by $Ar:CO_2$
  - Extensive use DCS during HV training
  - Full scale development new GEM DAQ Sep 2020
- **Participation to Mid-Week Global Runs (MWGRs)**
  - MWGR #3 (09/20) GEM first time in Global DAQ

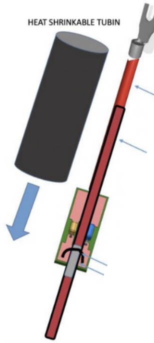
Cosmic Runs and First Beams

regular running – experiencing B-field – pilot beams $\sqrt{s}$ = 900 GeV *2021*

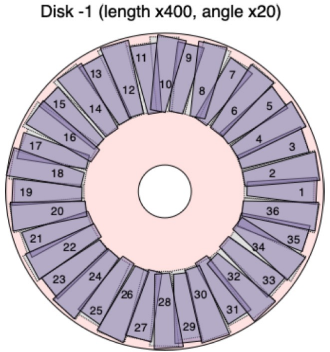




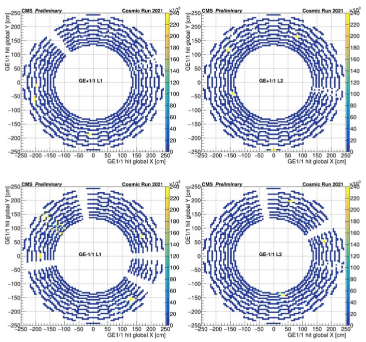
Improved LV-filter – GE1/1



Preliminar Alignment CRuzet



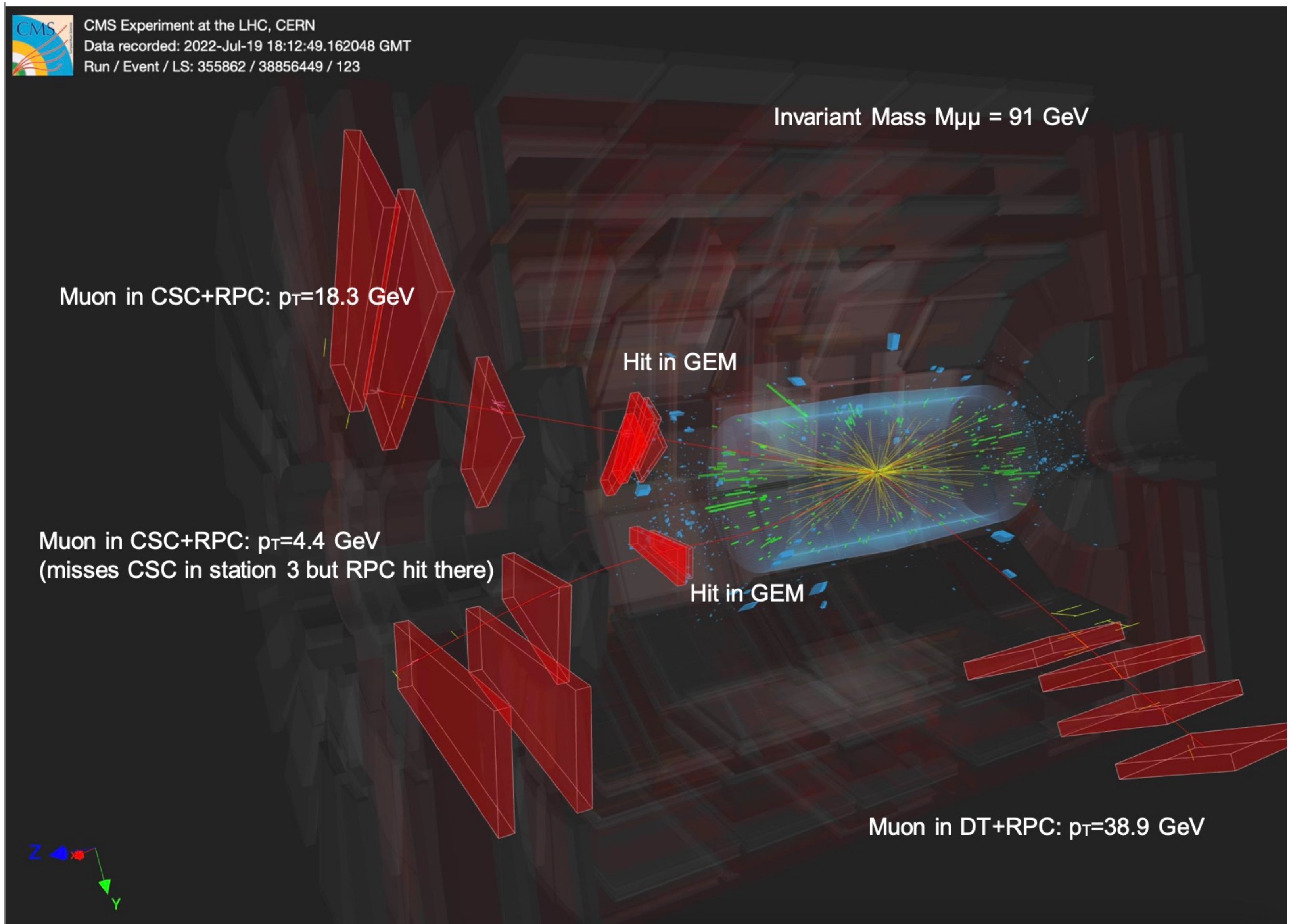
Detector Occupancy CRuzet

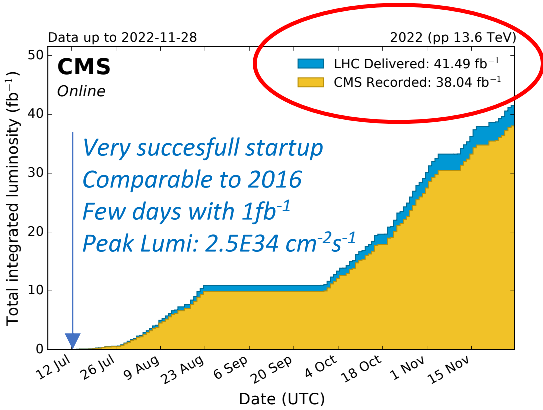


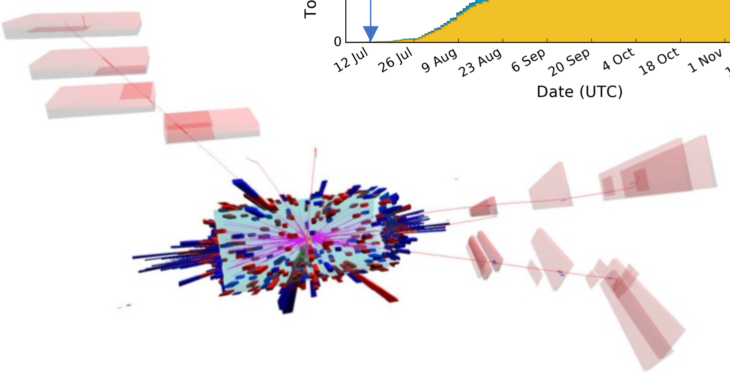
- Participation to all centrally organized global runs
- First observations of unstable GBTs due to VTRx issue
  - GE1/1: 432 VTRx (3 per chamber) 5-10% affected
  - Will require intervention in LS3 *(not accessible earlier)*
- Rework of on-detector LV filters to lower the noise
  - *Now all detectors < 1fC noise level*
- *Summer:* **Cosmic Run at Zero Tesla (CRuZeT):**
  - Smooth configuration and running: 250h
  - Enough statistics to calculate efficiency, HV-scan
  - 1st trial alignment: test of procedures for collisions
  - Progress on GEM-CSC trigger *(Studies, FW-updates)*
  - Monitor detector over long periods
- *Fall:* **Cosmic Run At Full Tesla (CRAFT):**
  - *First experience with GEMs in B-field - CMS closed*
  - *Verified system behaviour*
  - *Found chambers discharging due to metallic dust reproduced in Goliath magnet tests – filters in CMS*
- *Fall:* **Pilot Beams**
  - Splashes, circulating beams, pp at $\sqrt{s}$ = *900 GeV*

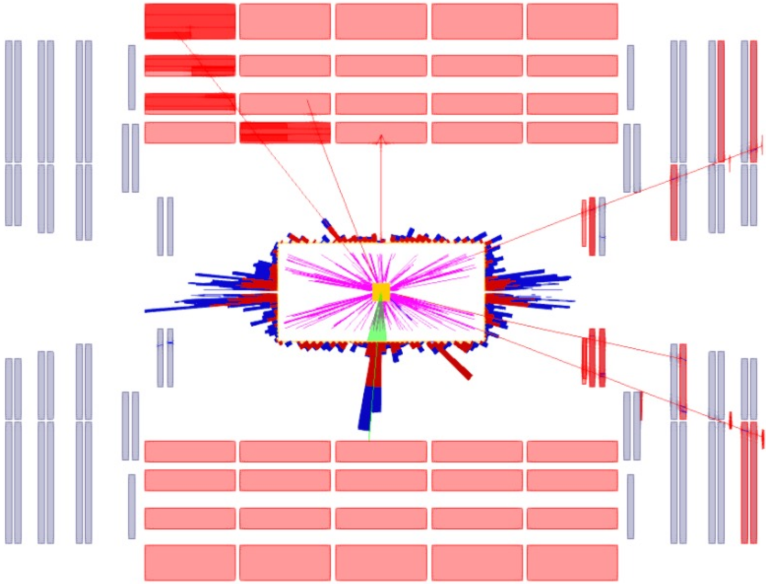
Operation and Collisions

finally collisions and high luminosity running! *2022*



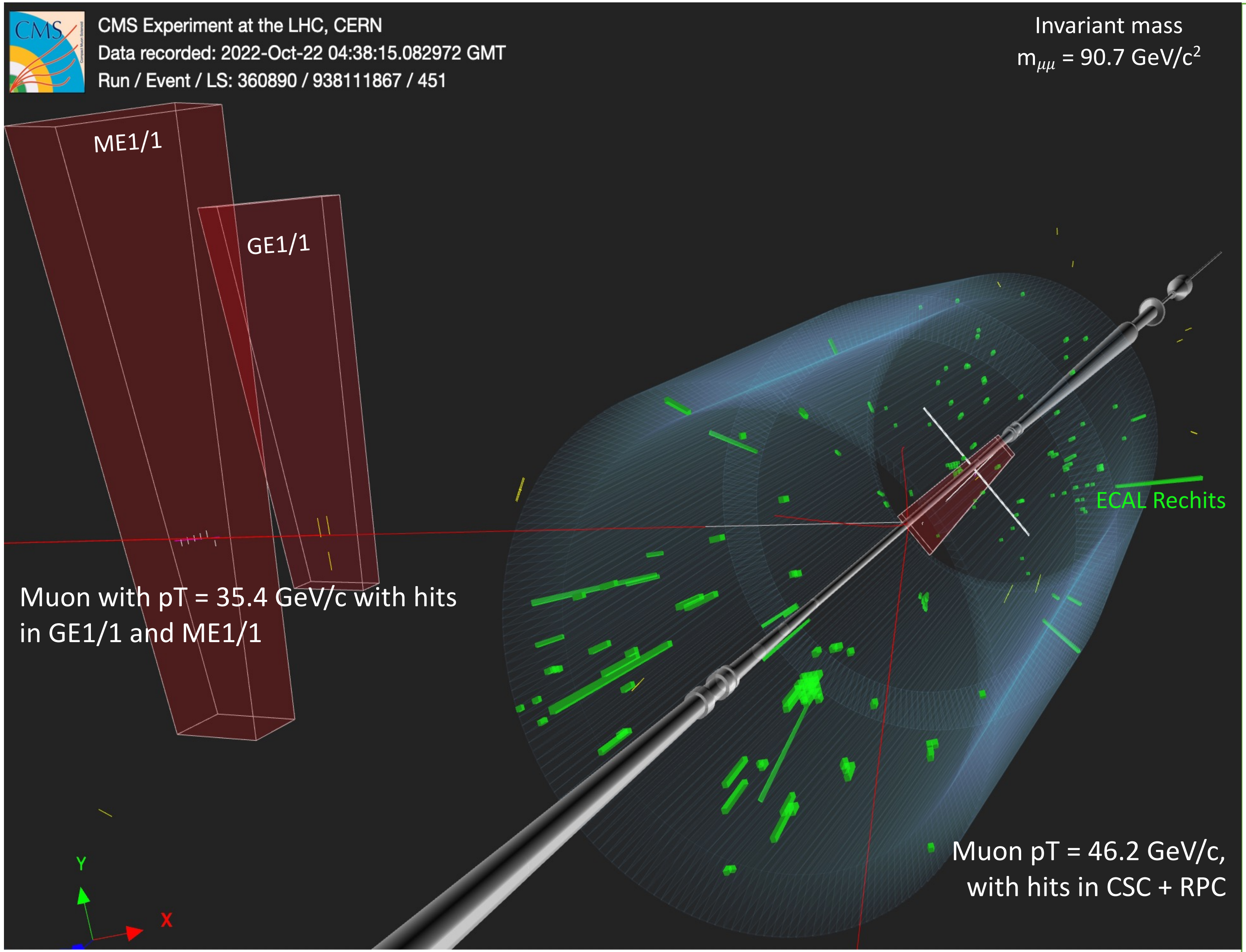






Operation and Collisions

Very succesful start of Run 3 *2022*

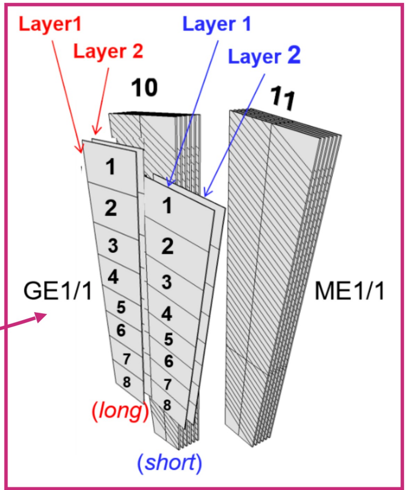


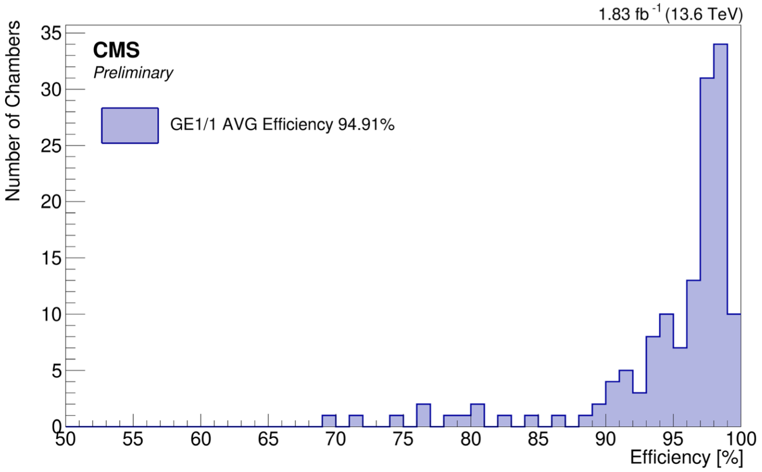
- **High number of Trips observed @ High Intensity LHC**
  - Due to increased background (HIPs) creating discharges in foils with residual imperfections
  - Overcome with HV conditioning – procedure in place – afterwards stable operation at 690uA
  - So far 34 HV sectors in short (0.5% of system)
  - HV hospital system is being setup to power
  - See talk on discharges Friday - Simone Calzaferri
- **Monitoring carefully loss of channels due to discharges propagating to anode plane**
  - Calibration (CalPulse) to monitor health FE
  - Damaged channels < 0.2%
- **Electronic communication issues**
  - GBT not correctly configured
  - VTRx outgassing causing unstable GBT
  - Fraction of live channels 80% -> 90%
- **Excellent performance GEM DAQ SW**
  - <1% lumi lost due to GEM
  - Automatic power on FE during interfill
- **GEM-CSC Trigger – towards inclusion in 2023**
  - Improved quality of GEM Trigger Primitive
  - Trigger Motherboard (OMTB) FW updated
  - High-Granular Timing corrections (GEM time resolution differences due to "ballooning")

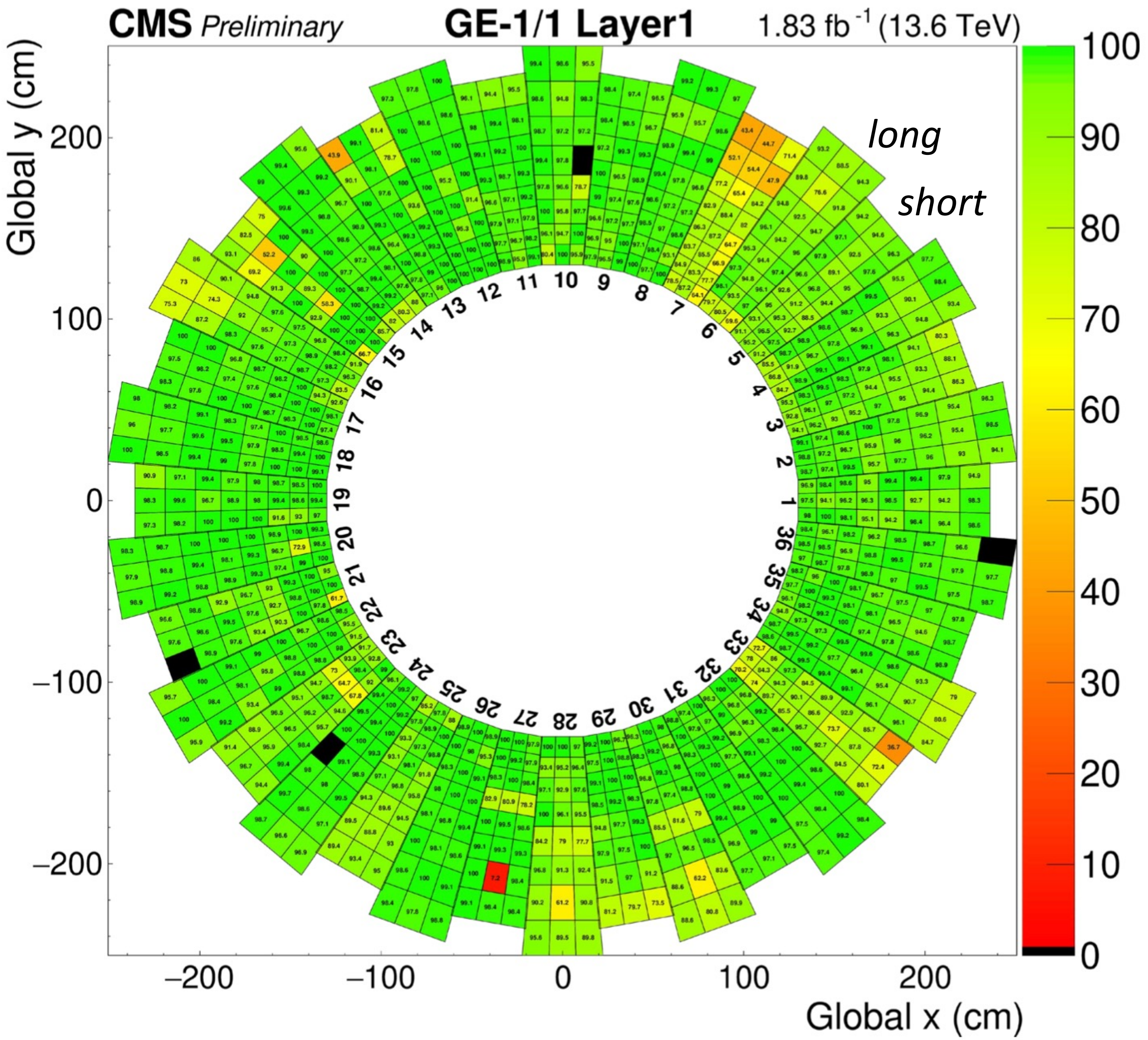
Performance of GE1/1 detectors

overview of 2022 data taking

- *Early assesment* of detector efficiency in Sep 2022
  - Muon tracks reconstructed in Muon detector with $p_T > 20$ GeV/c, $0.5 < \chi^2/ndf < 2$ and with track segment in nearby CSC (ME1/1)
  - *Still 15 chambers below 90%*
  - 30 chambers with $90\% < \varepsilon < 95\%$
  - More than 90 chambers with $\varepsilon > 95\%$
- *"Global Detection Efficiency"* : Detector + FE/BE
  - Communication loss between FE and BE
  - We want to separate intrinsic detection efficiency and efficiency loss due to electronics
    - *Important to define optimal working point* per chamber
    - Updated for next iteration *(see next slide)*



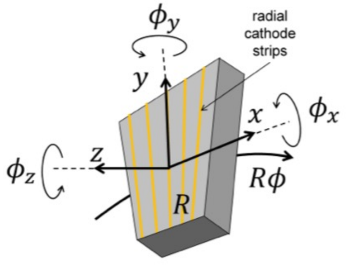


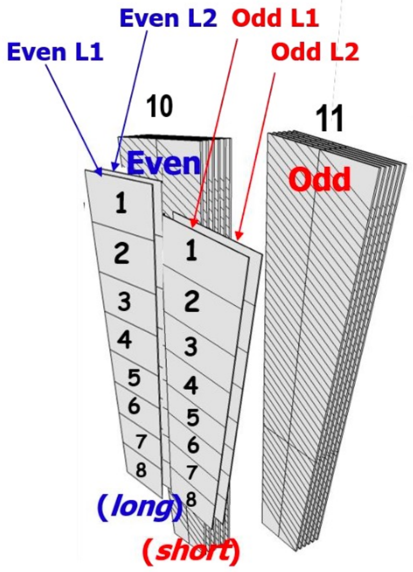


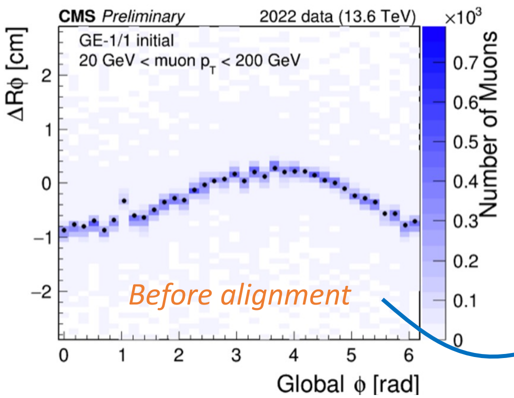
Performance of GE1/1 detectors

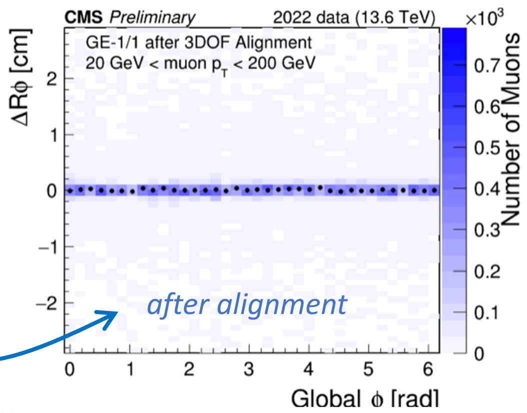
overview of 2022 data-taking

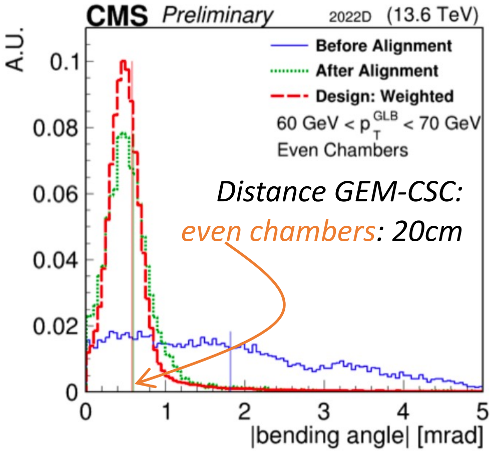
- Performed HV-scan to establish individual detector working points (*for 2023*) – *now detector only efficiency*
- Implemented Detector Alignment
- Bending Angle *(BA)* GEM-CSC measured – *Spatial Res ongoing*
- Alignment & BA important steps for GEM-CSC Trigger in 2023

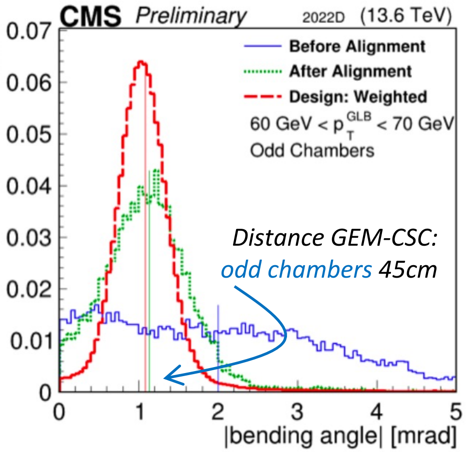


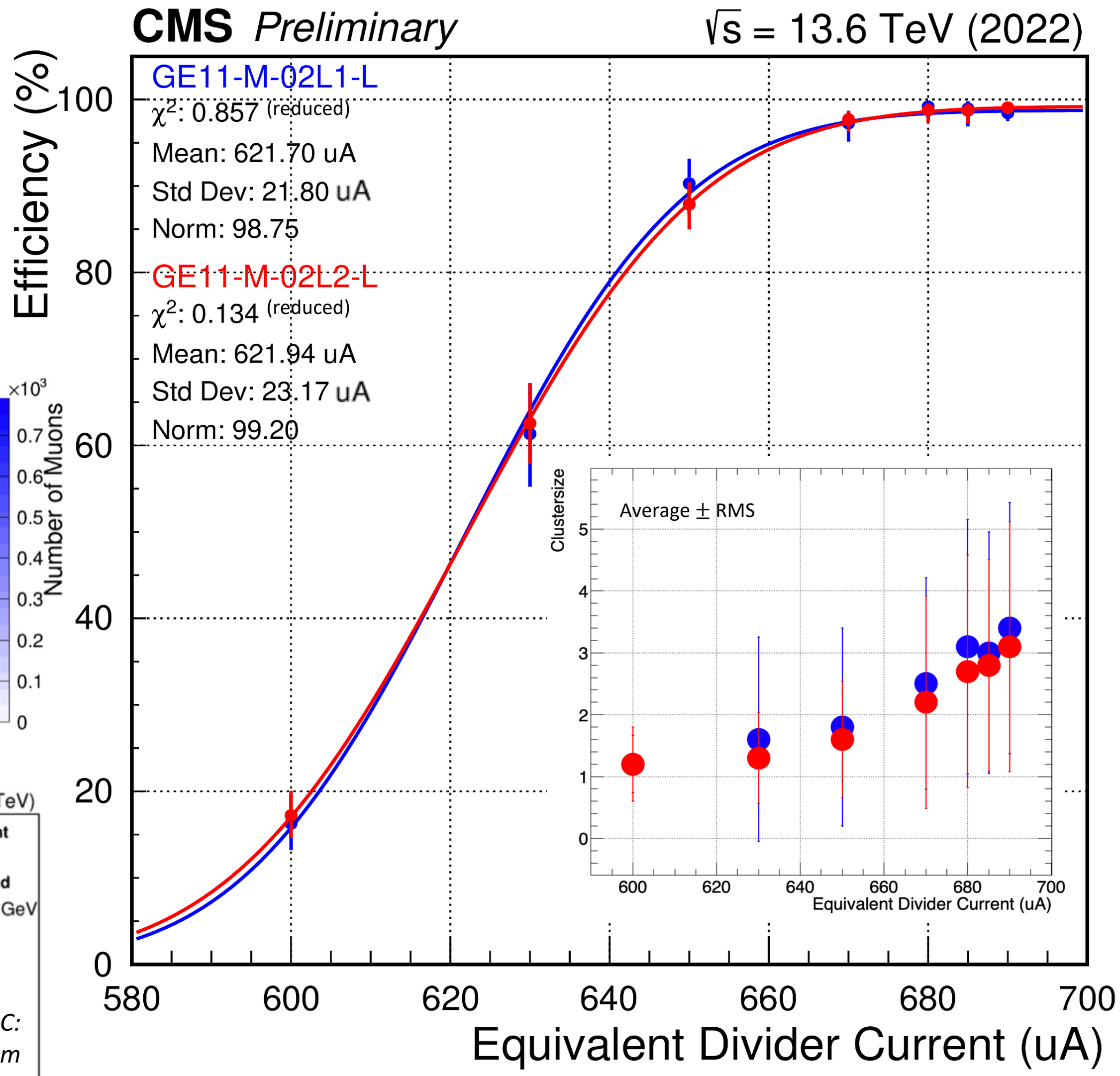












High-Voltage Scan in October 2020

data: Z-Mu skim (2pb^{-1} / point) - curve fitted with Erf(x)

Norm = ε @ Plateau – Mean = I @ 50% ε - Std Dev = width

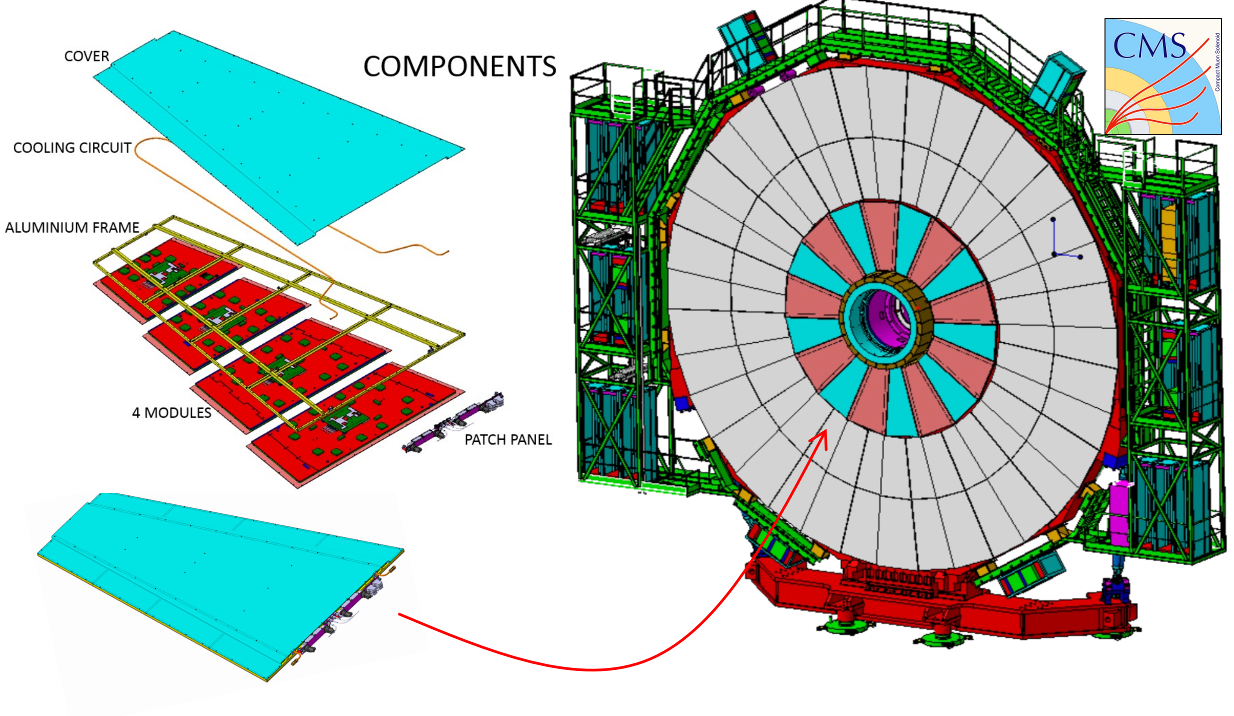
Status of three new detector stations:

I. Installation – Commissioning – Operation – Performance of GE1/1

II. Design & Studies for Phase-2 Triple-GEM detectors in CMS

The GE2/1 project

System overview – lessons learnt from GE1/1

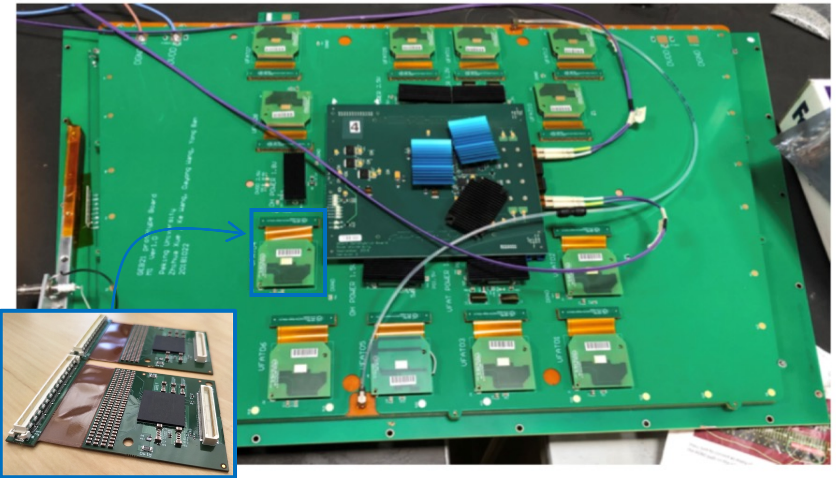


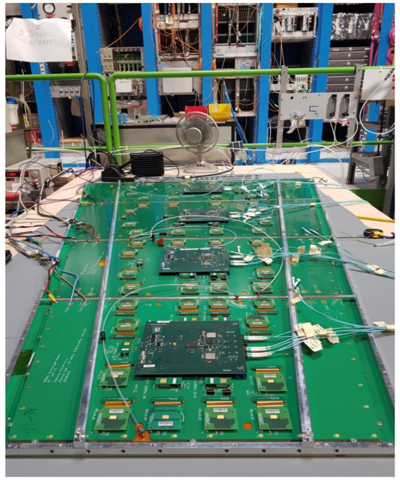
GE21 Detector System

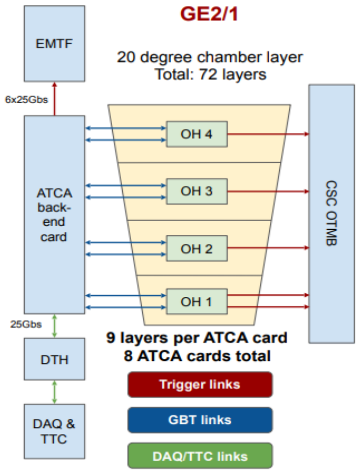
- 72 chambers arranged in 2 layers (Front & Back chamber)
  - 4 triple GEM modules per chamber *(8 different modules for overlap)*
  - 20° chambers (small overlap) – Large area 185 x 115 cm $1.6 < \eta < 2.4$
  - Button spacer in large modules to prevent “ballooning”
- Same solution as for GE1/1 (3/1/2/1 mm gaps – Ar:CO2 70:30)
- FE: wire-bonded hybrids with glob-top -> packaged VFAT3 chip
- Plugin-card with VFAT3 chip and flex to HRS 140 connector
- Improved grounding in Readout board and Electronic board
- Each detector module has own Opto-Hybrid with GBT chip
- *50% GEM Foils produced by Mecaro (Korea) – 50% CERN MPT Workshop*

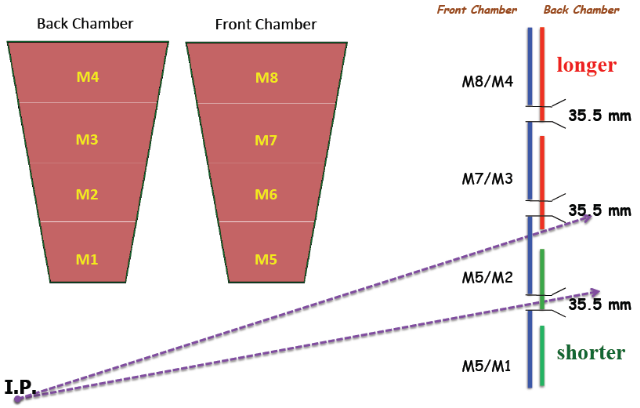
- **GE2/1 currently under construction**
  - Installation Negative Endcap in EYETS 23-24
  - Installation Positive Endcap in EYETS 24-25
  - Currently 51 modules produced (144 needed / Endcap)

See Poster Balashangar Kailasapathy



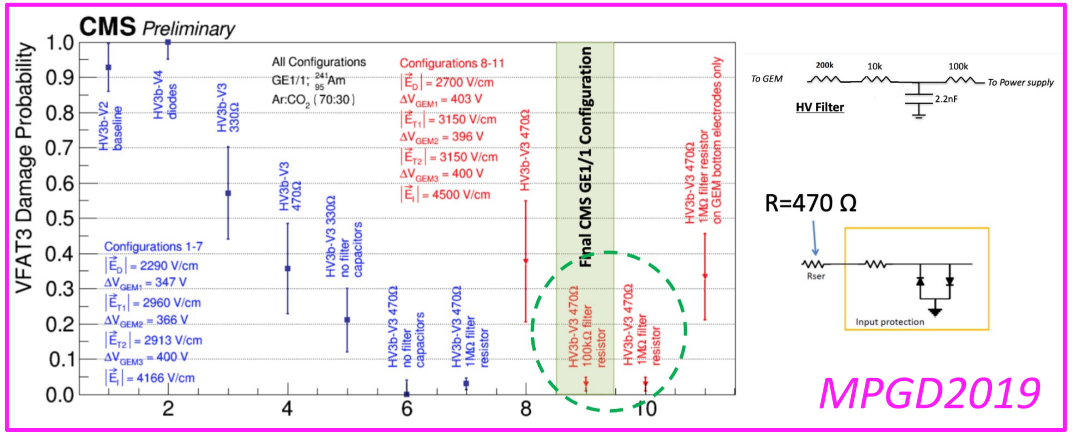






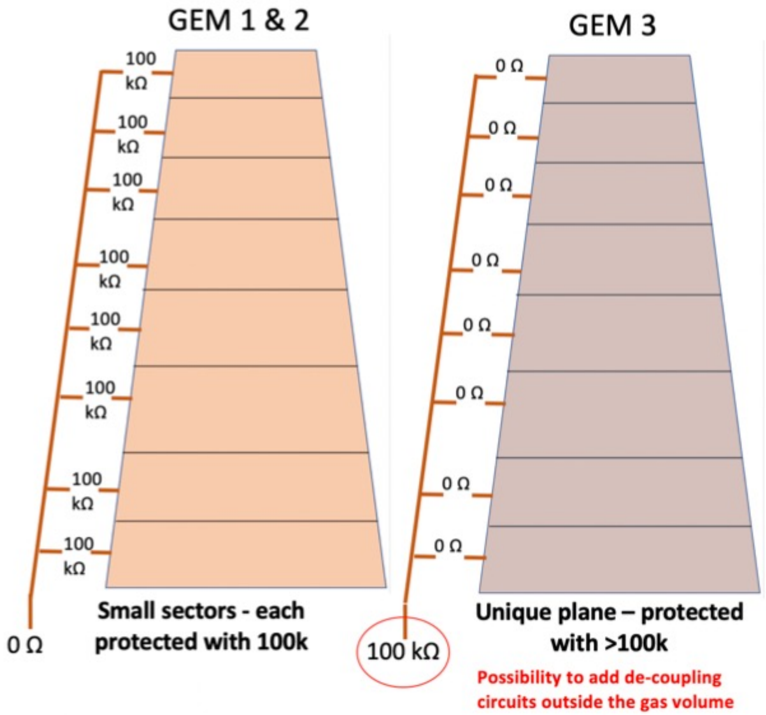
The GE2/1 project

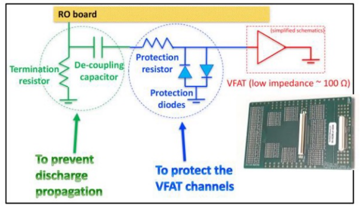
Design modifications for discharge protection and cross-talk mitigation



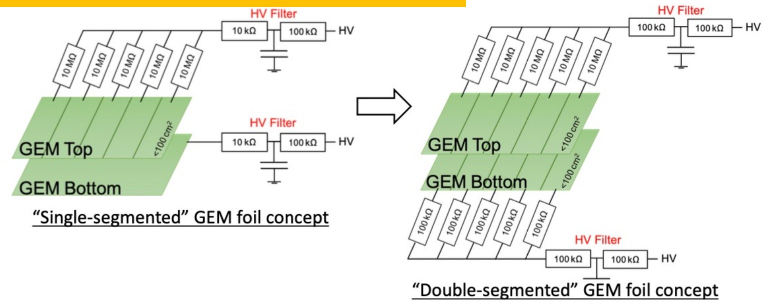
- 2018-2019 repeat channel loss in labo
  - VFAT3 protection and HV filter for GE1/1
  - Double-segmented GEM foils for GE2/1
  - *Presented by J.Merlin & B.Dorney MPGD 2019*
- 2020 discovered increased cross-talk in double-segmented GEM foils
  - Final solution: **mixed design**
  - GEM1&2 double seg'ted: prevent discharge propagation
  - GEM3 single-segmented: suppress cross-talk

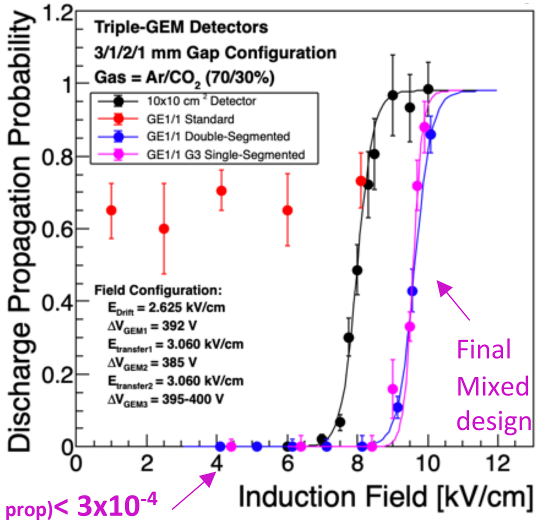
See Poster on Foil mass production in Korea
Inseok Yoon





Basic principle:
- HV segments on the top: GEM protection against regular discharges
- HV segments on the bottom: protection against discharge propagation



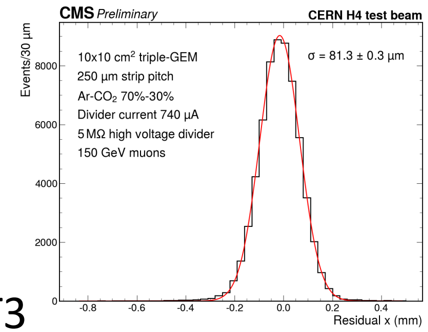


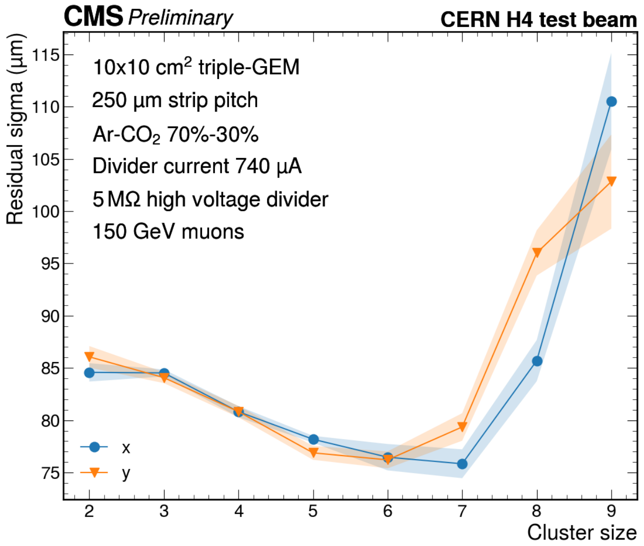
Upper limit at 4.12 kV/cm: $P_{(disch\ prop)} < 3\times10^{-4}$

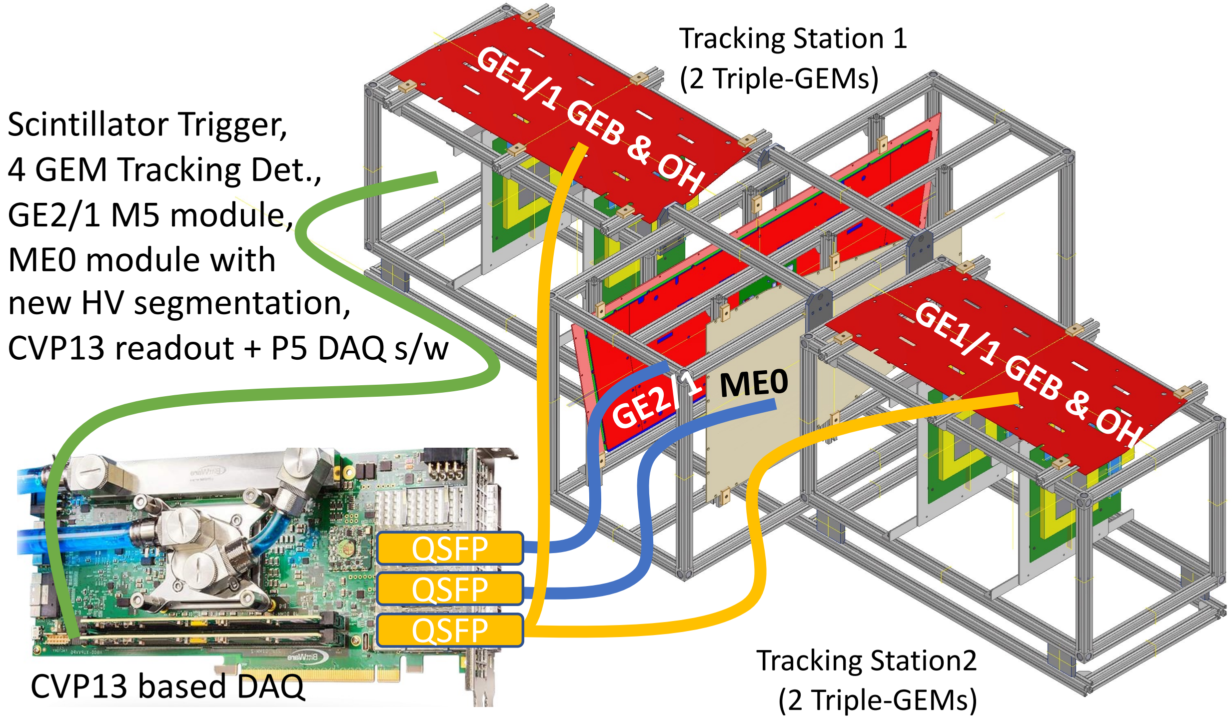
The GE2/1 project

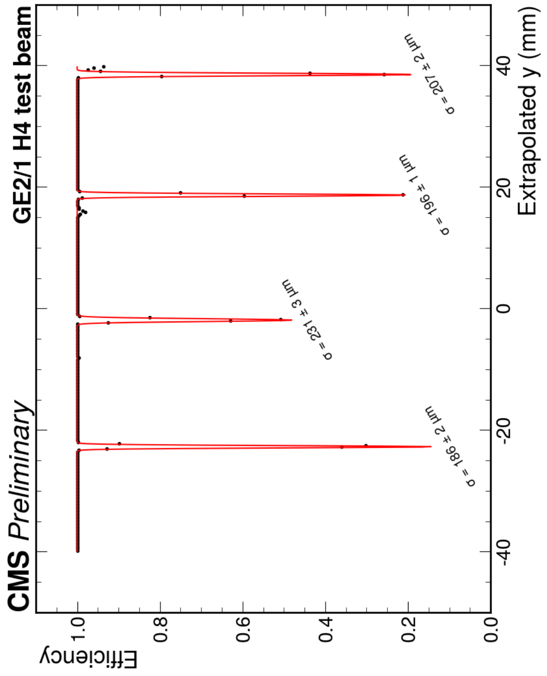
Integration: Test-beam & Demonstrator

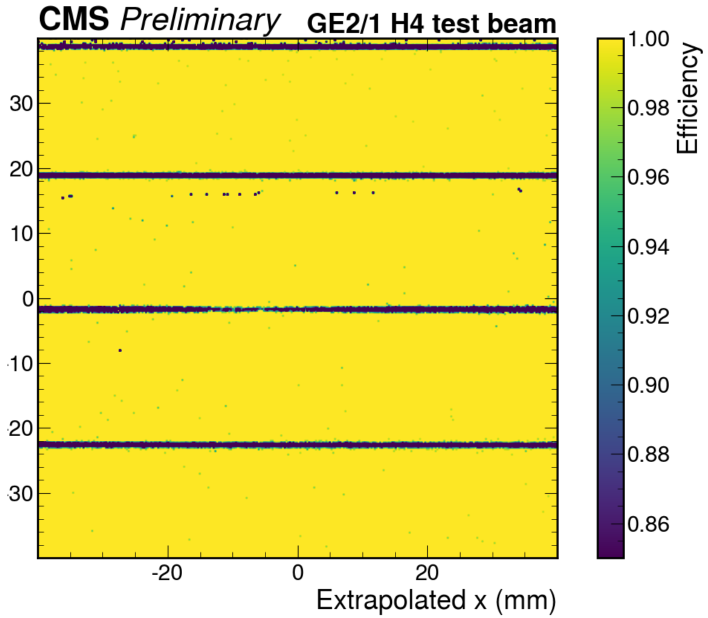
- **Motivation**
  - **Test GE21 and ME0 chambers with final electronics**
  - Measure efficiency, spatial resolution Phase-2 chambers
  - high rate (10-100 kHz L1A rate) test with π-beam
  - Test 9x9cm^2 Tracking GEMs 250um pitch (σ = 75um) with VFAT3
- **Participated in RD51 Test Beam October 2021 & May 2022 at SPS H4**
  - 150 GeV/c low-intensity μ (large beam spot) and high-intensity π (small beam spot)





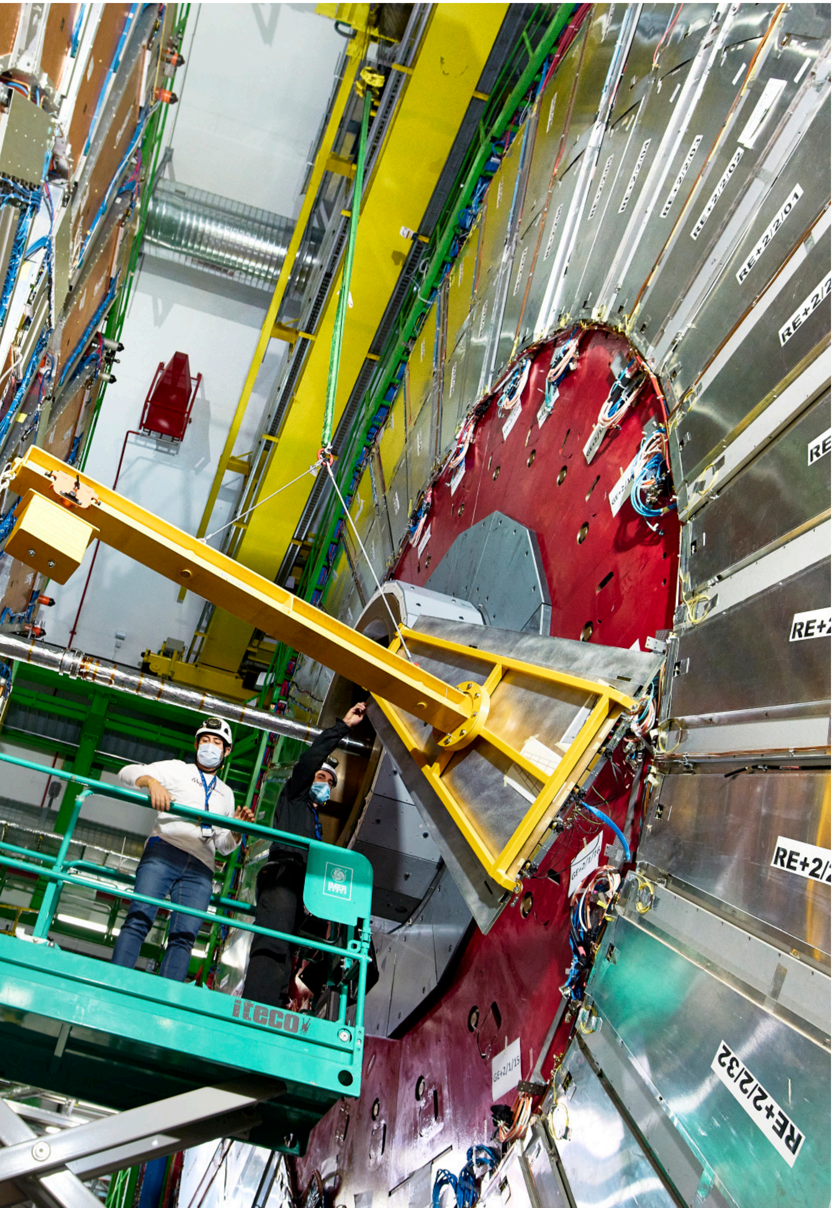






See Poster Nimantha Perera

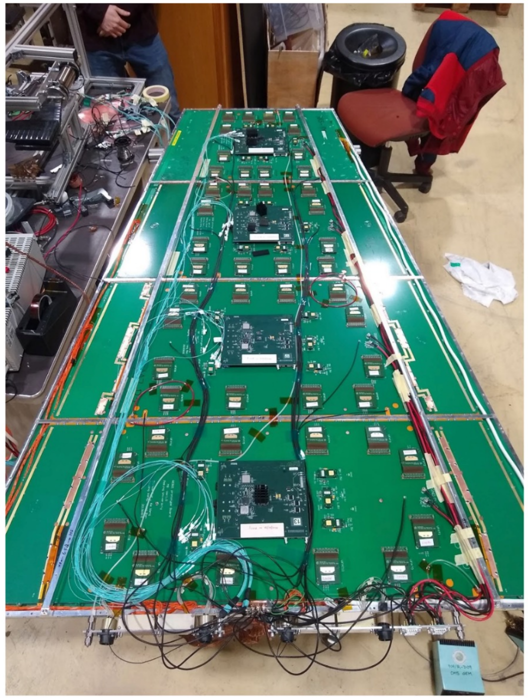
The GE2/1 project *Integration: Test-beam & Demonstrator*



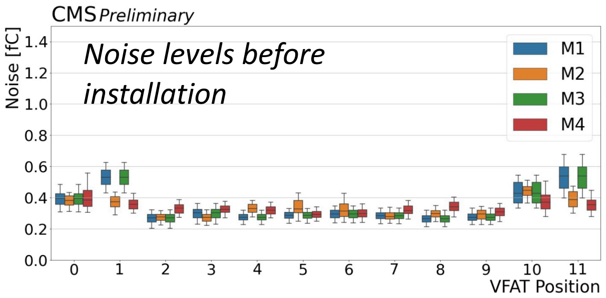
GE2/1 Demonstrator Motivation

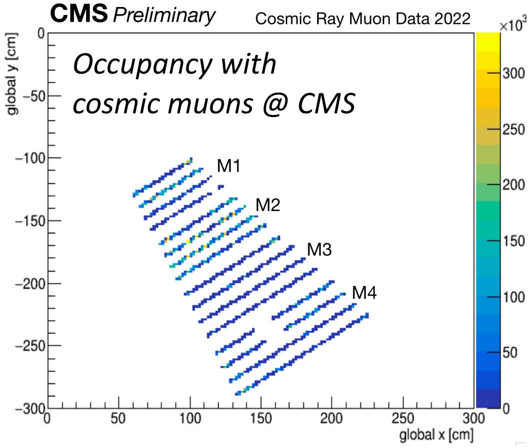
foster GE1/1 experience

- Exercise detector integration & mechanical installation tools
  - Verify detector envelope → found protruding RPC gas pipes (2008)
- Gain operational experience: DCS & DAQ, DQM, …
  - Experience with new foil design (double segmented) in GEM1 & GEM2
  - Verify grounding, noise levels, measure dead channels, cross-talk
- Confirm GE2/1 performance in CMS environment: ε, noise, bkg rate



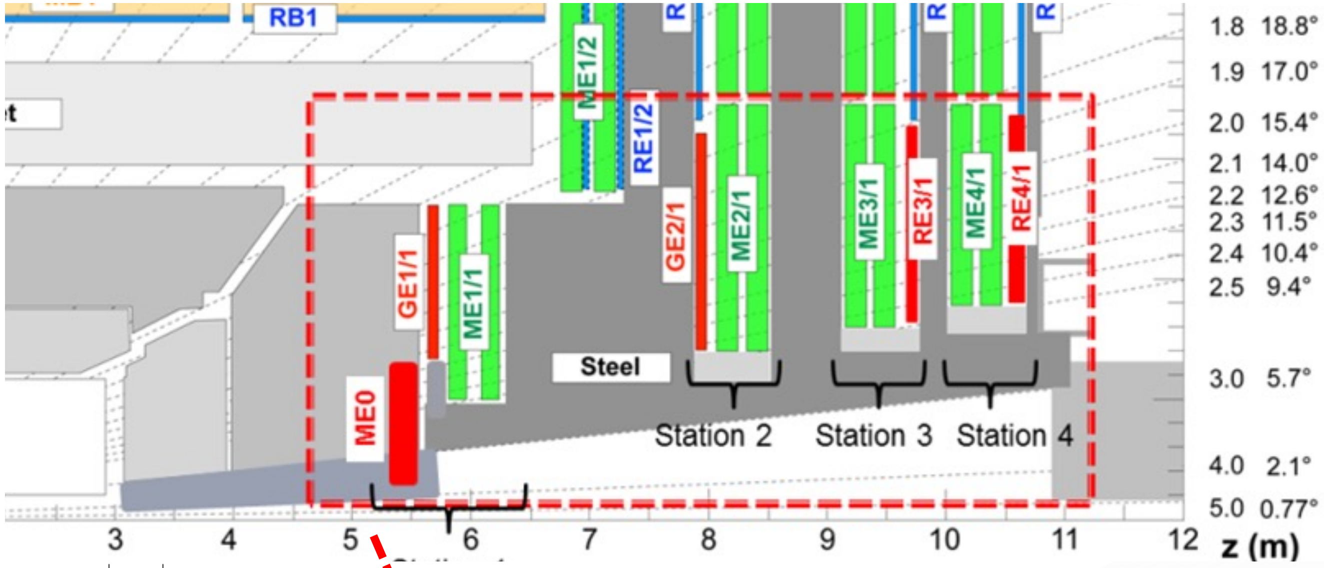
- GE1/1 slice test taught us valuable lessons that we were able to integrate in final GE1/1 chambers
- GE2/1 prototype chamber with final electronics *improved w.r.t. 2019 and 2020 prototypes*
- Installed November 2021
- Backend: uTCA (GE1/1 like)



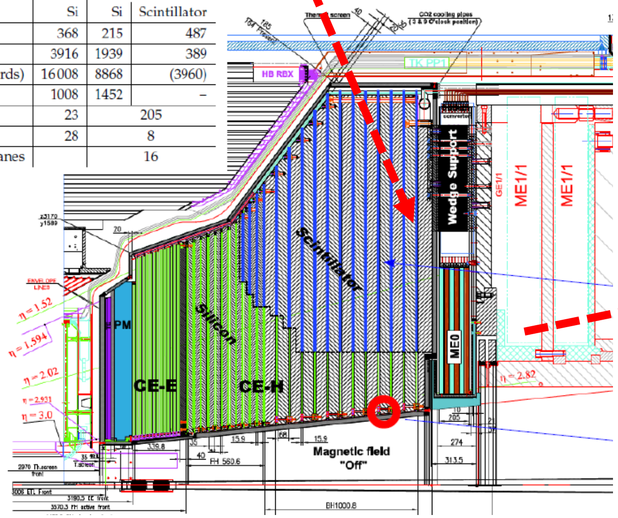


The ME0 detector

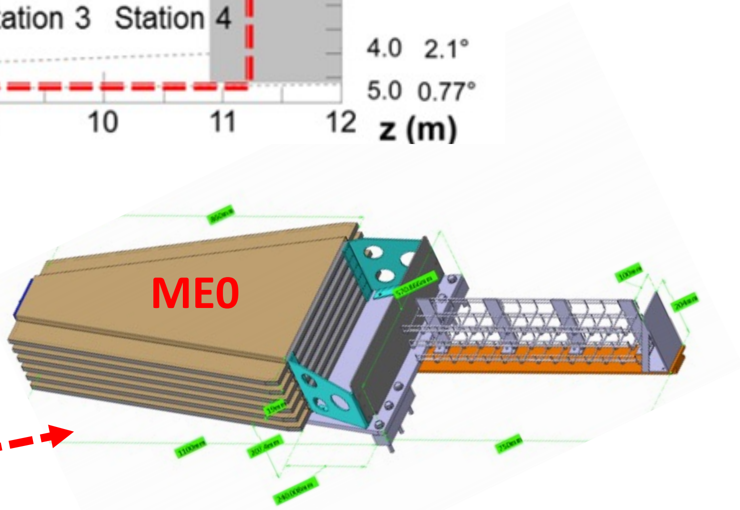
Designing Triple-GEM detectors for the highest rates



	CE-E	CE-H	
	Si	Si	Scintillator
Area (m^2)	368	215	487
Channels (k)	3916	1939	389
Si modules (Tileboards)	16008	8868	(3960)
Partial modules	1008	1452	–
Weight (t)	23	205	
Si-only planes	28	8	
Mixed (Si+Scint) planes		16	

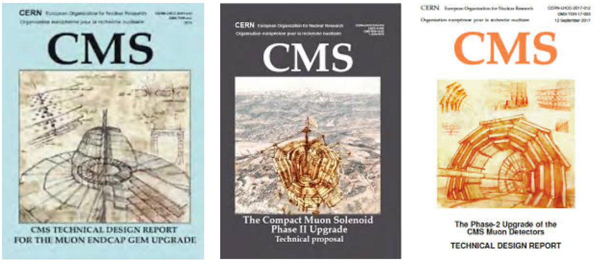


New High-Granular Calorimeter (HGCAL) CMS



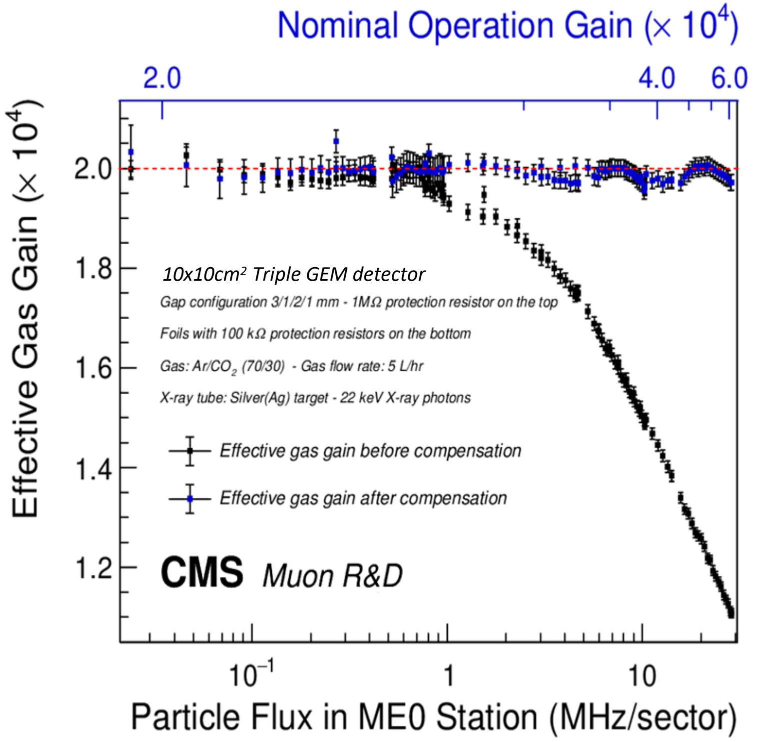
- Requirements:
  - 97% module efficiency
  - $< 500\mu$rad resolution
  - 8-10 ns time resolution
  - $\leq 15\%$ gain uniformity
  - *Work in high-rate environment: 150kHz/cm^2**
  - *Survive harsh radiation environment: 7.9C/cm^2**
  - *Discharge rate that does not impede performance or operation*
  - ** updated w.r.t. CMS Upgrade Technical Proposal & Muon Upgrade TDR*

- 6-Layer stack of Triple-GEM
  - Install behind HGCAL (complex environment)
  - 18 stacks (20°) for each endcap
  - Coverage: $2.0 < \eta < 2.8$



The ME0 detector

Rate capability limitations due to large-area irradiation



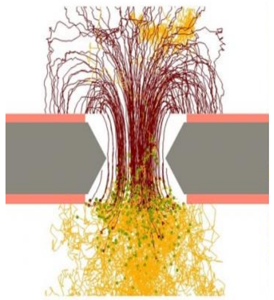
GEM Rate capability studied for decades – on different geometries and detectors

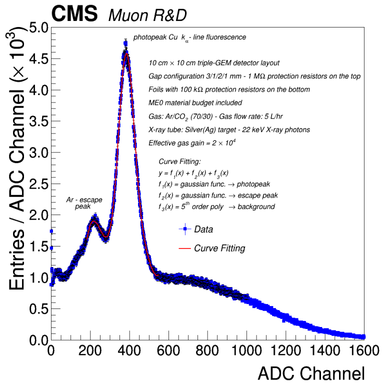
- Common procedure: soft X-rays focussed on mm^2
  - reaching very high X-ray flux
  - Gain stable above MHz/cm^2
  - Proves efficient space charge evacuation
- However: low Ion current flowing through R_{prot}
  - As consequence negligible voltage drop and high rate capability up to $100MHz/cm^2$
  - Low ion current not representative for real experiment with global irradiation on $3000cm^2$
- Gain Loss already observable on $10x10cm^2$ detector with **global irradiation**
  - Compensation of gain by countering voltage drop – increasing operating voltage

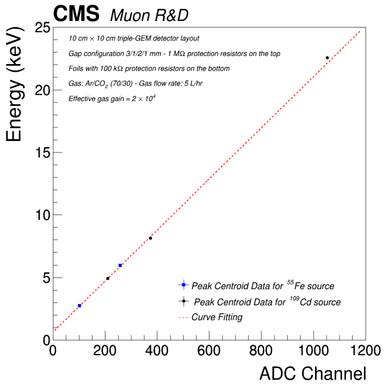
Intrinsic rate capability of a triple-GEM chamber:

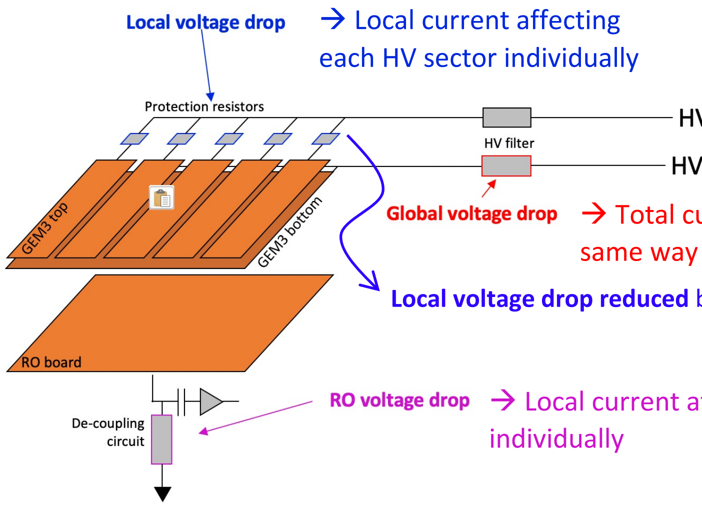
$10^4 – 10^5$ Hz/cm²

The limit can move by tuning the design parameters









→ Local current affecting each HV sector individually

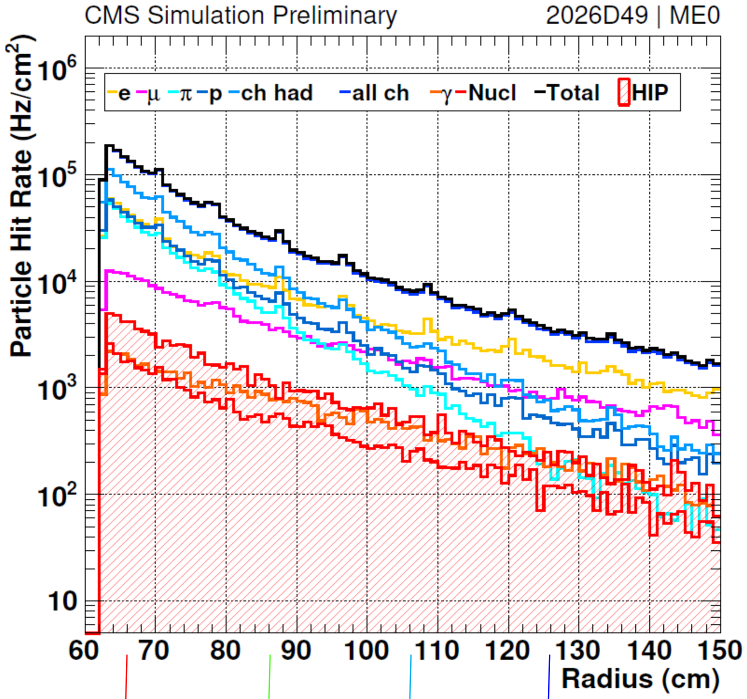
→ Total current affecting all the HV sectors in the same way

Local voltage drop reduced by changing R_{prot} from 10MΩ to 1MΩ

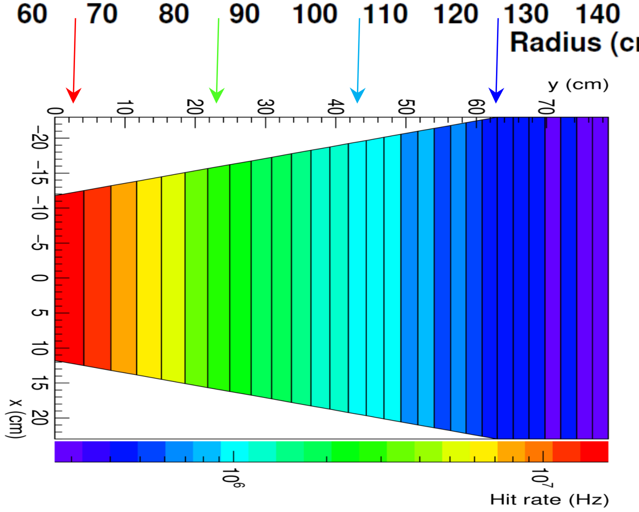
→ Local current affecting each RO strip individually → Negligible effect (few mV) even with the new RO protection circuit

The ME0 detector

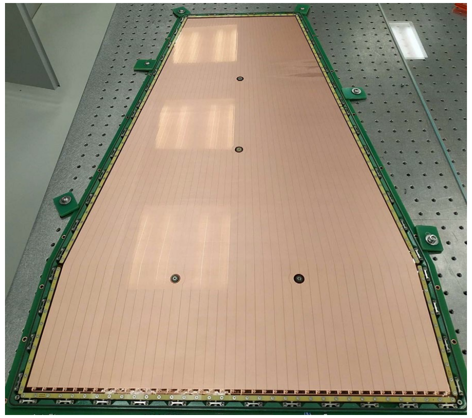
Optimalization of ME0 GEM Foil HV sectors

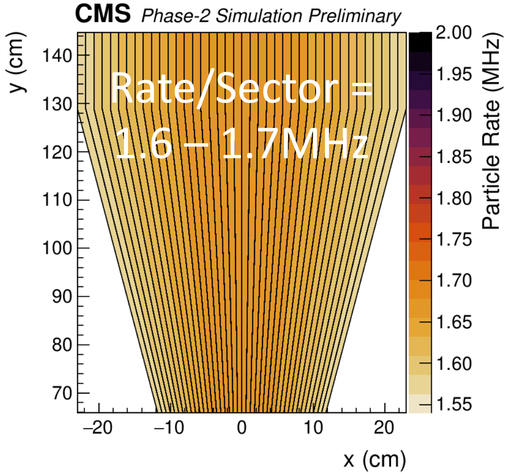


- **Expected Particle Rate on ME0 is Exponential**
  - Highest rate: 150kHz/cm² – Lowest rate: 2kHz/cm²
  - Optimization of horizontal sectors would depend on functional form of background chosen – which is only known from simulation - Uncrt?
- **New HV segmentation paradigm: Radial sectors**
  - Rate on each HV sector is equalized => also current through protection resistors will be equalized
  - Allows for uniform Gain compensation by ΔV on GEM foils
- **Prototype with radial HV segments validated with beam**
  - Excellent efficiency – *However Large # segments => Large Dead Area*

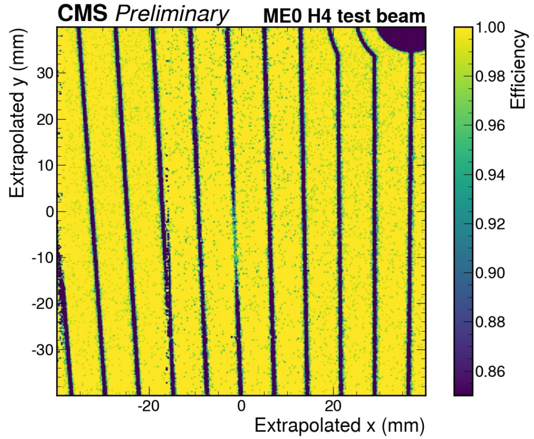


Highly non-uniform Rate/Sector





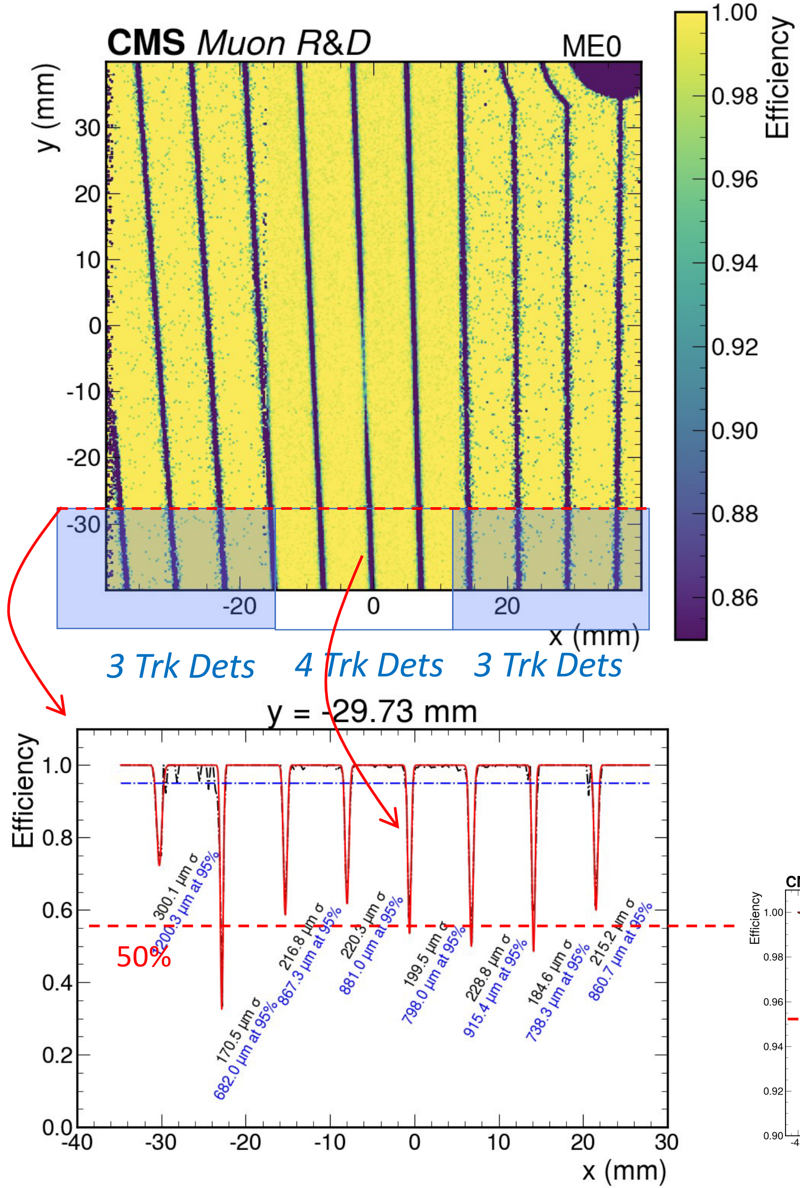
Equalized particle rate per HV sector



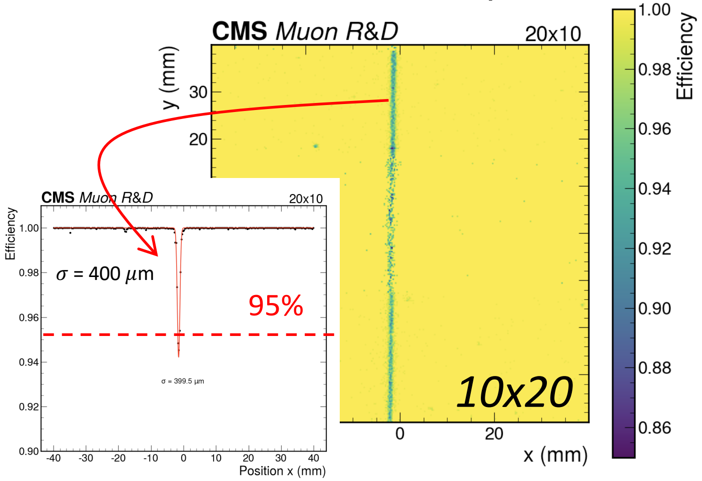
Radially segmented ME0 in TB

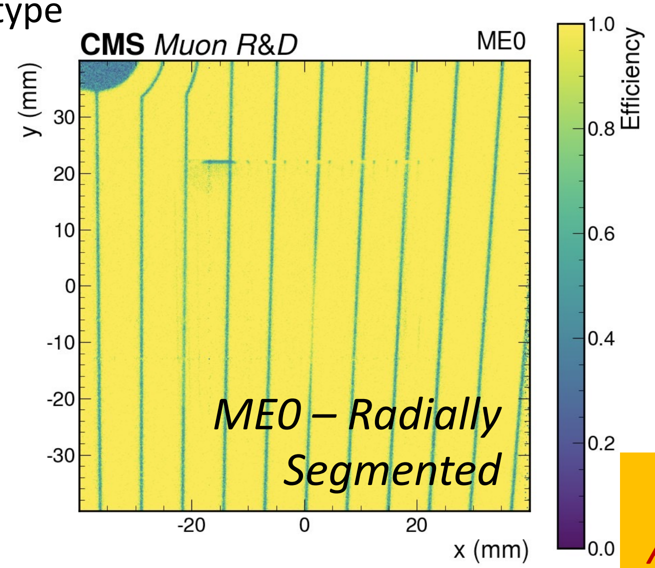
The ME0 detector

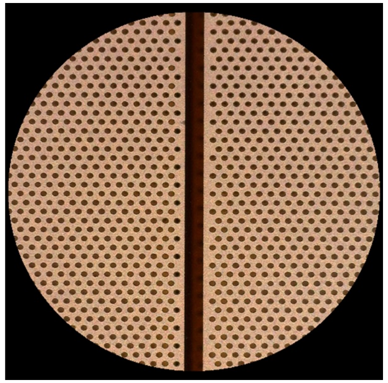
Adoption of “Random hole” sectors technique during GEM Foil Etching

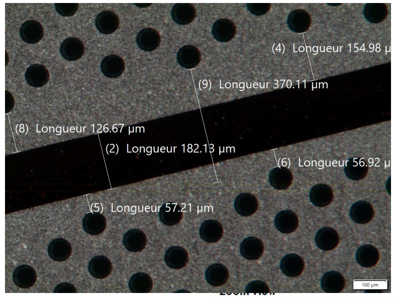


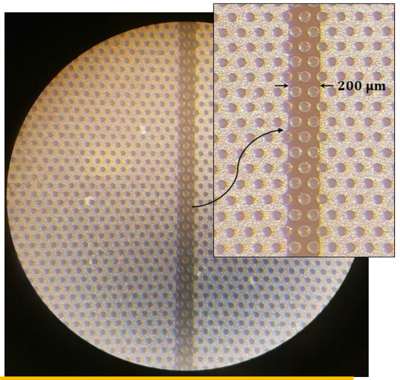
- Traditional segmentation (horizontal)
  - leads to dead area of A= 200um x ℓ
- Radial segmentation leads to a variable distance hole-to-hole
  - Dead area extends to A = 500um x ℓ
  - Test beam observes Efficiency drops < 50% at segmentation line
- New technique Rui / CERN MPT workshop: “Random hole”
  - GEM foil perforated everywhere
  - Subsequent removal of 200um Cu strip
  - creates holes w/random Cu border around
- Tested in testbeam – *Efficiency drops in ‘dead area’ to 95%*
  - October ‘21 with 10x20 prototype chamber (4 segments)
  - May ‘22 with full ME0 prototype
  - R&D and TT required







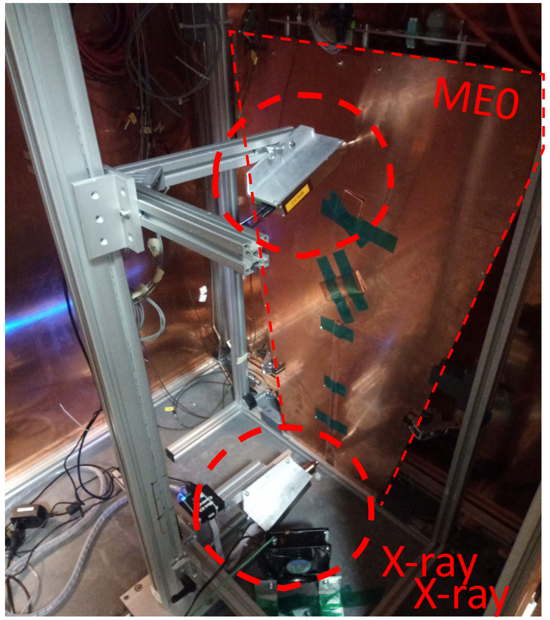




See Poster Antonello Pellechia

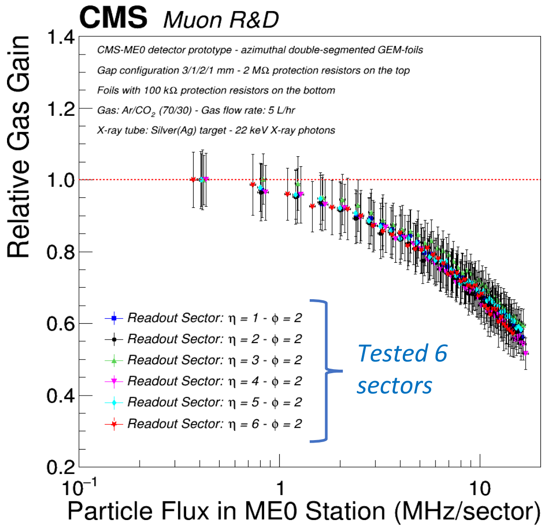
The ME0 detector

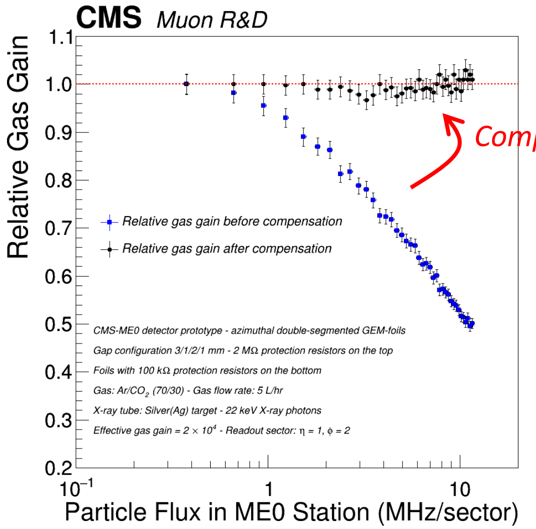
Rate capability tests with X-rays



Verify Validity of new ME0 design and Gain compensation with asymmetric X-ray irrad

- Global X-ray irradiation entire detector + Intense X-ray irradiation of highest η partition of ME0
- ME0 detector without HV-Filter
  - Correct behaviour of filter on rate-capability can only be established with uniform irradiation of chamber
- Measure gain on <u>all</u> η partitions
- All partitions lose gain in same way
  - consequence of radial segmentation – currents are running now along entire detector
- Compensation demonstrated up to 10MHz/sector: *(cfr: CMS: expect 1.7 MHz/sector – 200 e-)*
  - increase V on each electrode according to current flowing through it until desired ΔV reached



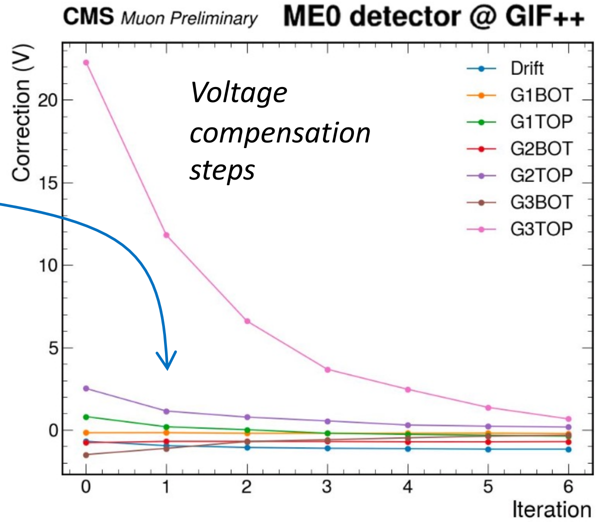


$$V_{eff} = V_{set} - R_{electrode} \times \varphi \times G \times n_0$$

(Flux on the electrode: φ; Number of primaries: n_0; Global electrode resistance: $R_{electrode}$; Effective gain: G)

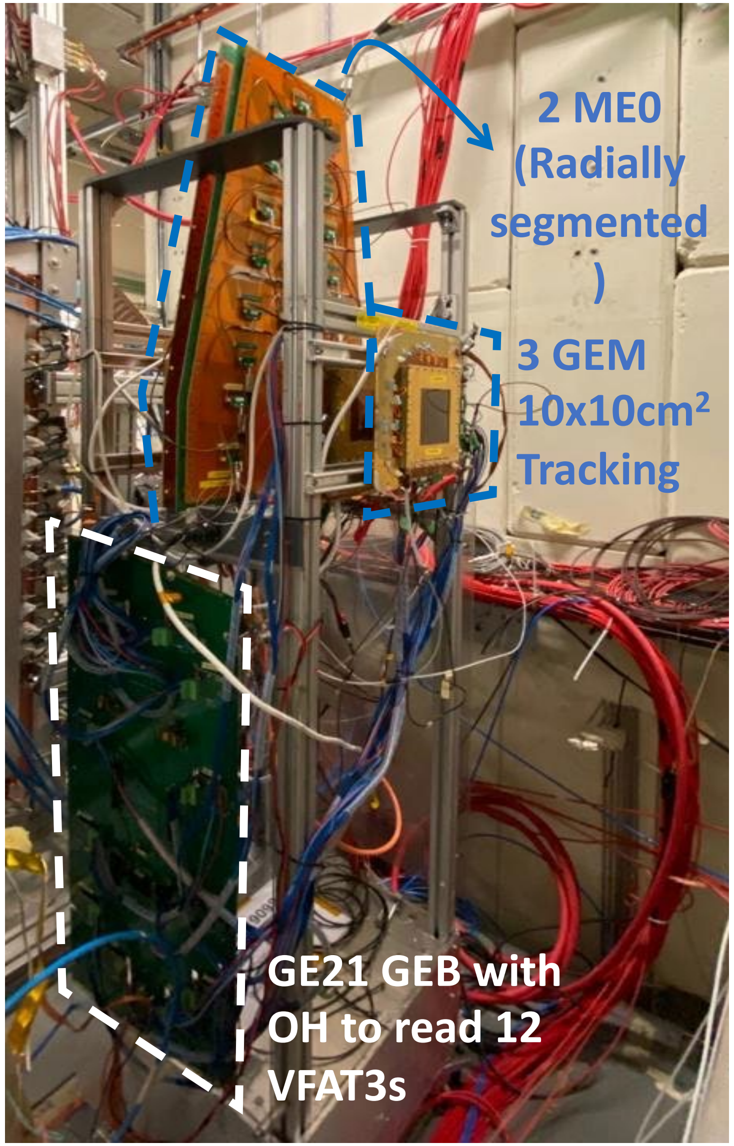
1 – 10V in the ME0 BKG range

- Gain restored in all η parts!
- At 140PU we expect 1.6 MHz/sector
- Demonstrated up to 10 MHz/sector!
- Check effect of HV filter with uniform irradiation @ GIF++ *(see next slide)*

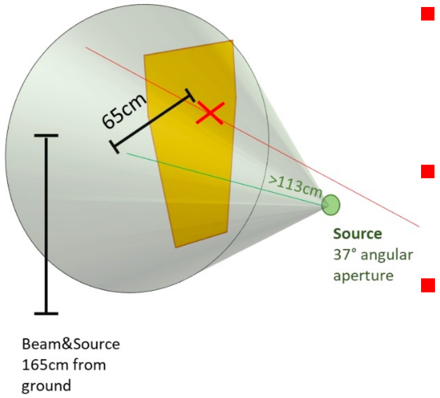


The ME0 detector

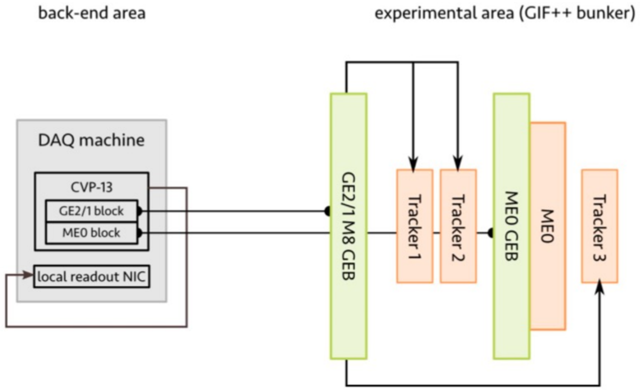
Rate capability tests with γ-rays at GIF++ - - - Gain



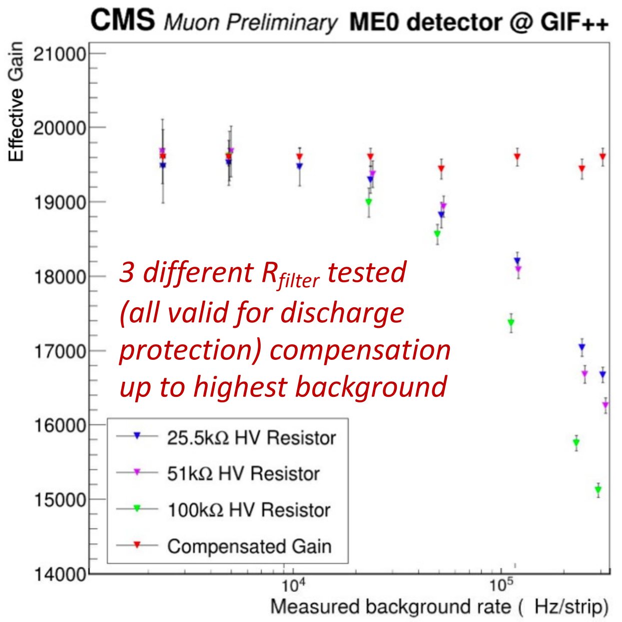
- Goal 1 :: Demonstrate Compensation
  - Uniform ϕ => test HV filter with realistic current
  - Tested 25.5k, 51k, 100k – all ok for compensation
  - *Current required from PS for 100k = 4 x Current 25k*
  - *ME0: High Power version of A1515TG: 3ch w/ 3mA*
- Goal 2 :: Measure Efficiency under irradiation

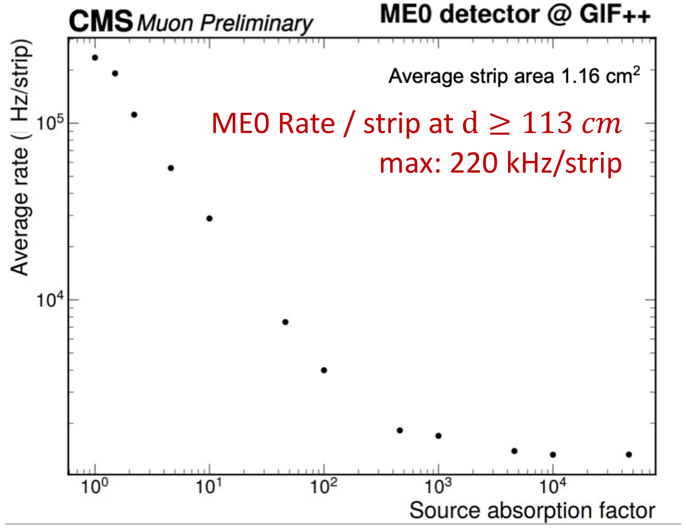


- GIF++ source:
  - 137 Cs (14TBq) - γ (662 keV)
  - 37° aperture
- SPS Particle beams
  - Pions & Muons > 100 GeV
- ME0 at d $\geq 113\ cm$
  - Max current: 250uA
  - Number of Primaries < P5



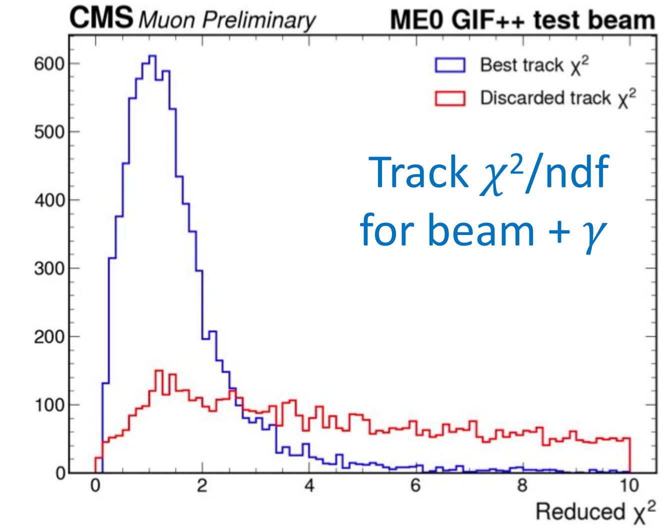
However powerful GIF++ source … we cannot test up to HV current expected @ P5



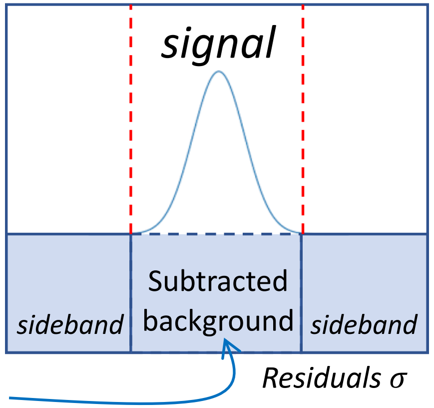


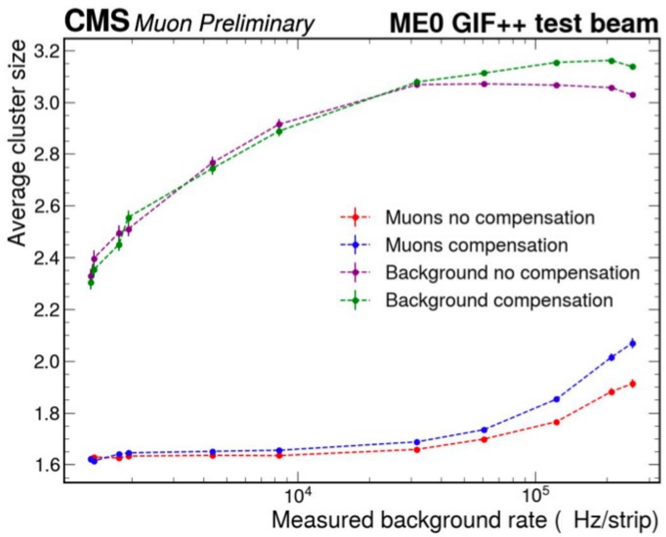
The ME0 detector

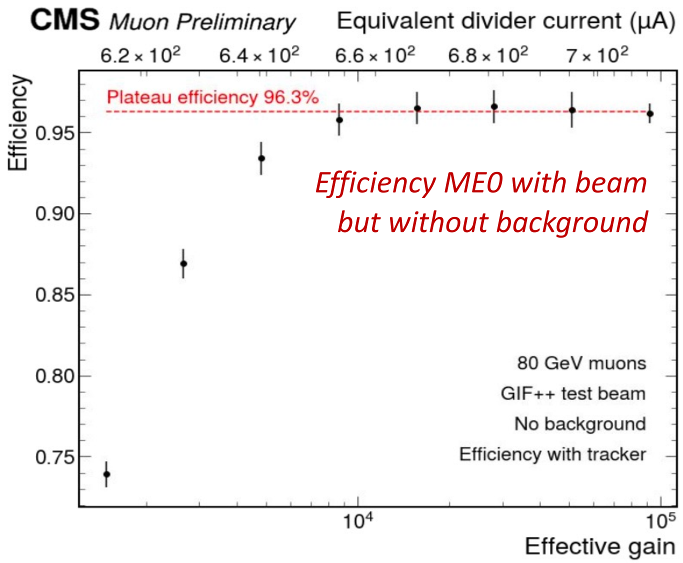
Rate capability tests with γ-rays at GIF++ - - - Efficiency

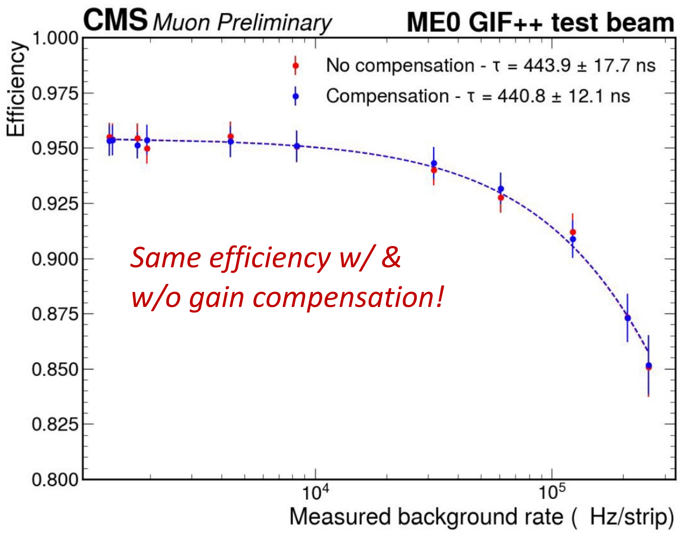


- **Tracker with 3 Triple-GEMs (400um pitch) – *VFAT3 & CVP13 BE***
  - Reconstruct good tracks with 3 x-y points
  - *However does not allow alignment (need 4th detector)*
- **Good Track reconstruction in background environment**
- **Clustersize increases with background** (add γ hits in μ cluster)
- **Efficiency Measured > 95% without beam** (blank segmentation)
- **Efficiency Measurement with background** *requires bkg subtraction*
  - γ hits are added to μ cluster leading to worse spatial resolution
  - Random γ hits matched to muon track – early γ hits creates deadtime for late μ hit
- **Intrinsic limitation of current design** → *need to reduce strip size of ME0 at highest rate*









Efficiency decrease with 10% at 300kHz/strip

Compatible with 400ns deadtime VFAT3 – confirmed also in Lab X-ray measurements

VFAT3 designed with saturation at 2.5MHz/strip

Conclusions

the work is not finished yet

The first Triple-GEM Station in CMS – GE1/1

- *Installed & commissioned during LS 2 (2019-2021)*
- *Shakey start with discharges due to B-field and increased background*
- *From middle of august running stably at highest luminosities*
- *First performance presented today*

The Phase-2 upgrade of CMS with Triple-GEM: GE2/1 & ME0

- *Lessons learnt from GE1/1 lead to improved design Phase-2 detectors*
- *GE2/1 & ME0 detectors tested with final electronics in test beam 2021*
- *GE2/1 in production – First disk to be installed in Winter 2023*
- *ME0 design being adapted and tested for the high expected rates*
  - *Several improvements implemented – now knocked with head on Front-End limitations*
  - *Will continue to improve design to mitigate maximally high rate effects*

Status of three new detector stations:

I. Installation – Commissioning – Operation – Performance of GE1/1

II. Design & Studies for Phase-2 Triple-GEM detectors in CMS

III. Back-up

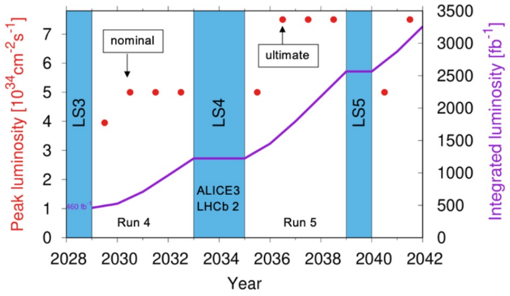
Upgrade of the CMS Muon System

prepare CMS for unprecedented high luminosity at a hadron collider

In the High-Luminosity Phase of the LHC (HL-LHC) (2029 - 2042) LHC will provide collisions at 5 – 7.5 times the original design luminosity (1E34$cm^{-2}s^{-1}$)

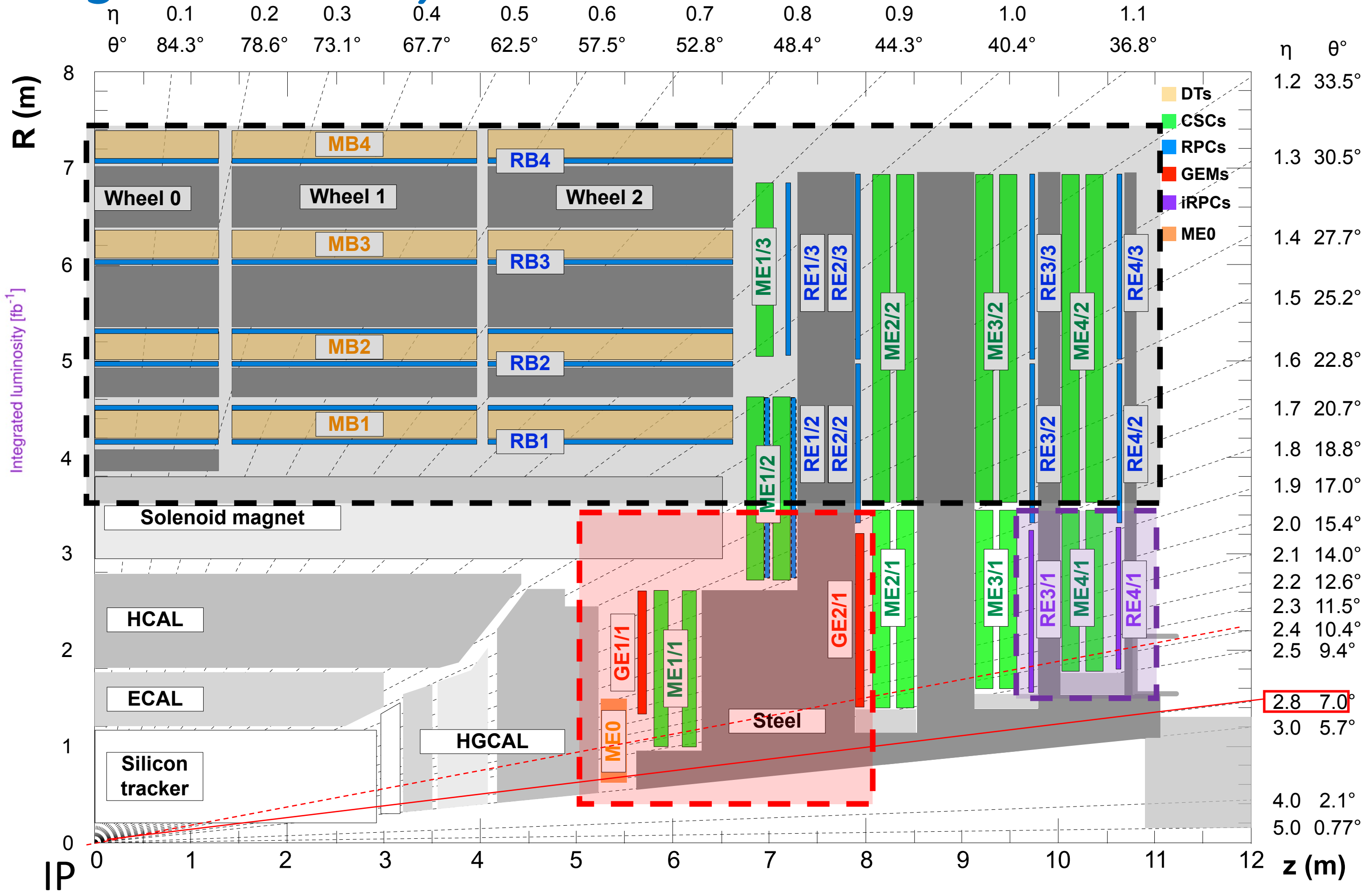
- Integrate 3 ab^{-1}
- HH, %-level measurement of Higgs-boson couplings

Preliminary (optimistic) schedule of HL-LHC



To cope with the high rate Muon System upgrade:

- **Improved electronics for existing CSC, DT & RPC:**
  - Readout w/ high BW, exploit σ_t
  - Longer trigger Latency 12us
  - Higher L1A rate: 100 → 750kHz
- **Gaseous Electron Multiplier (GEM) detectors** for precise (150um) muon reconstruction and triggering in B-field and high background (few kHz/cm^2 – 100 kHz/cm^2 rate)
  - GEx/1 : $1.6 \leq \eta \leq 2.4$ and ME0: $2.0 \leq \eta \leq 2.8$
  - 432 chambers, ~150 m^2 - 1.2M channels

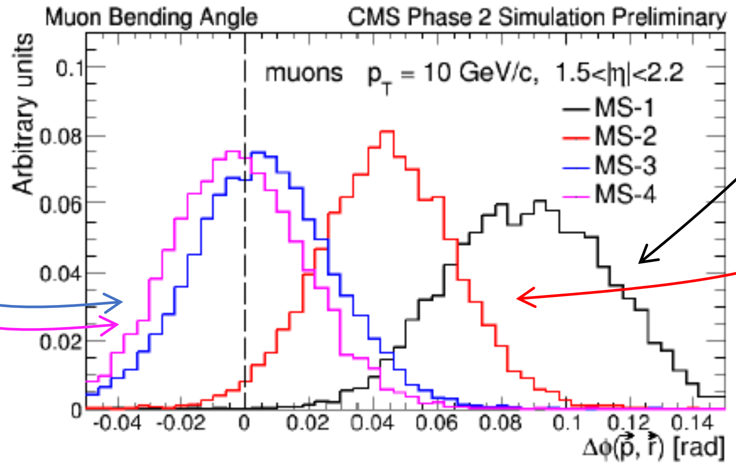


- **Improved Resistive Plate Chambers (iRPC)** for fast triggering (1.5-2ns) and redundant tracking (<1cm) in medium background (< ~1kHz/cm^2)
  - RE3/1 and RE4/1: $1.8 \leq \eta \leq 2.4$ - 72 chambers, ~100 m^2 - 7k channels
- **Gas recuperation plant + search for GWP friendly gas mixtures (for operation > 2033)**

Motivation for GEM Upgrade CMS

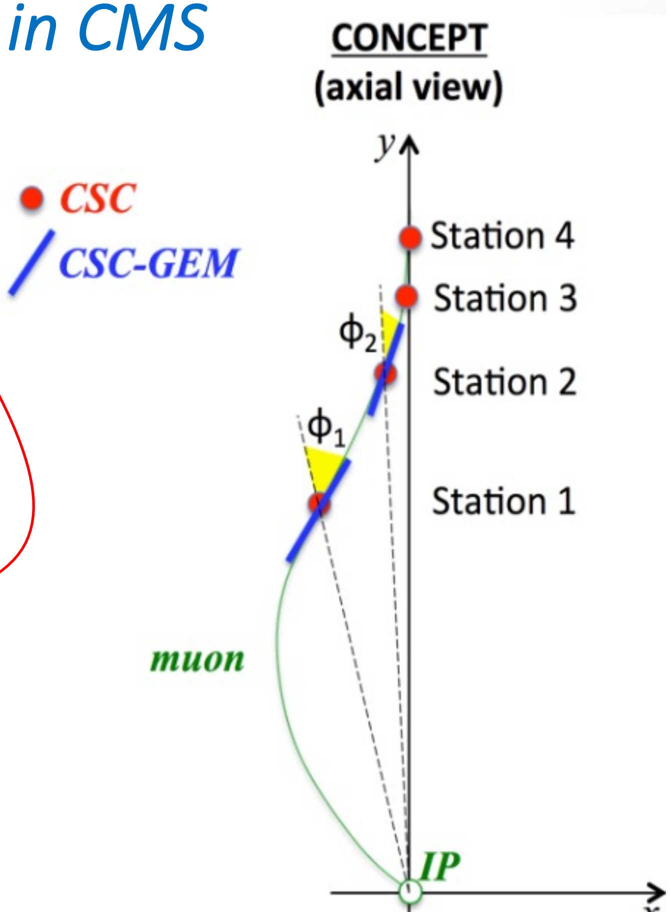
the birth of the GEM project in CMS

- **Good Bending Angle measurement possible in Endcap 1st & 2nd muon station** *(feel B-field)*
  - 1st & 2nd Install Detectors with good spatial σ
  - 3rd & 4th muon station with *i*RPC detectors

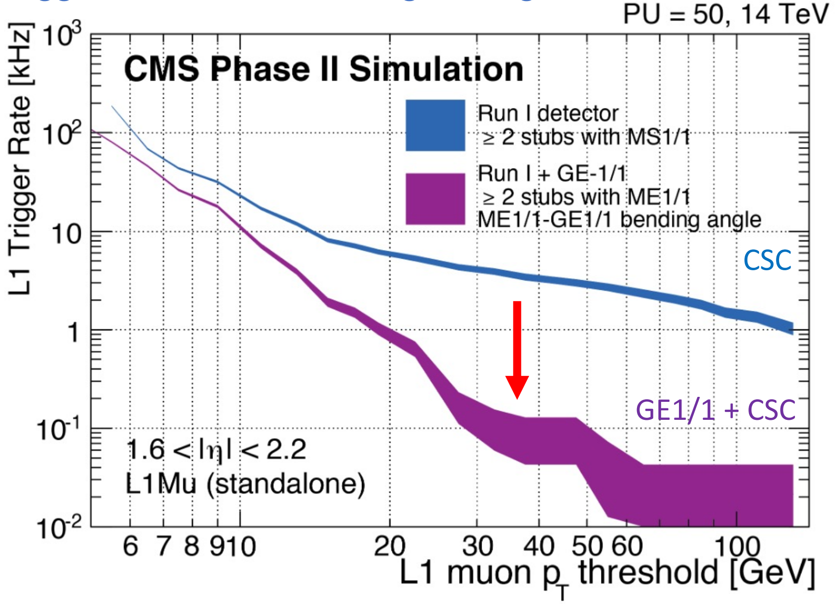


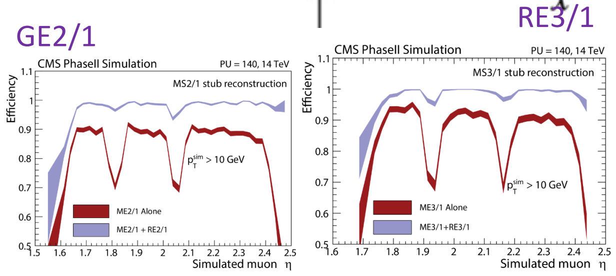
- **GE1/1 is early Phase-2 upgrade:**
  - reduce Trigger rate by using $\Delta\phi$(GEM,CSC) *before track trigger becomes available in Run 4*

- **Bending Angle GE2/1 + CSC → displaced muon triggering**
- **Improve local trigger primitives CSC + GEM/RPC**
  - improve Muon Track Finder Trigger
- *Increase redundancy where background is highest*

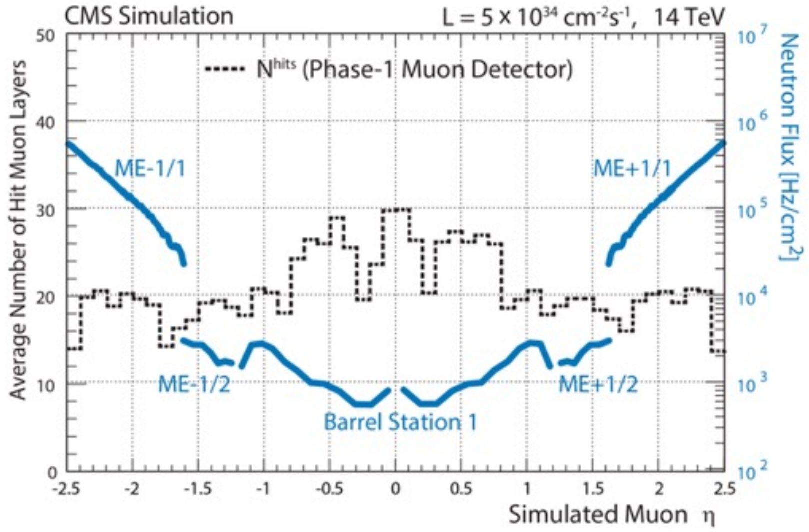


Trigger rate reduction in high background



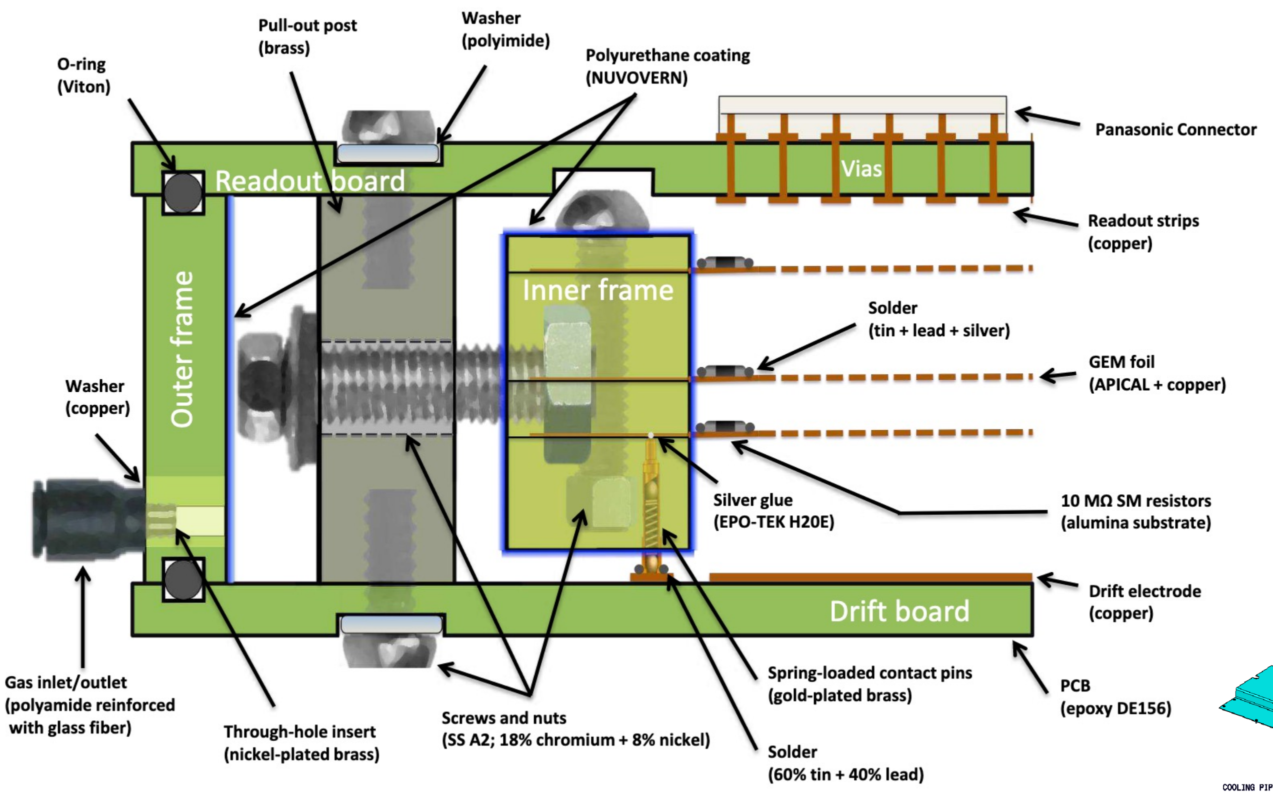


Improved local trigger primitives



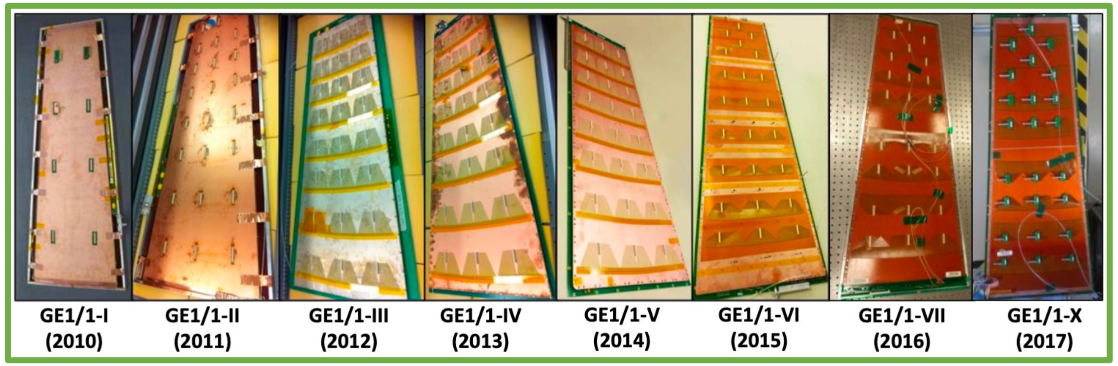
Increase redundancy where bkg is highest

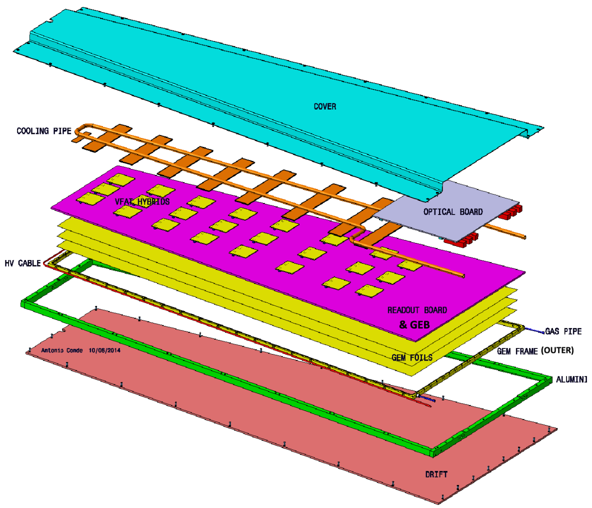
CMS GEM (GE1/1) Detector



- Construction Technique: Stretching, no glue
- Gap config: 3/1/2/1 mm - Ar:CO2 70/30 – Gain = 20,000
- Spatial Resolution < 300 urad
- Rata Capability up to 10 kHz/cm^2
- Two types of Chambers:
  - Long ~4000 cm^2 (l x b_1/b_2: 121cm x 23/45cm)
  - Short ~3000 cm^2 (l x b_1/b_2: 106cm x 23/42cm)
- All Chambers have 24 $\eta \ x \ \varphi$ sectors – 3072 R/O channels
  - Each sector 128 strips – read by VFAT3
  - Chamber has 8 η partitions
- Strip pitch 600um – 1200 um (460 urad)

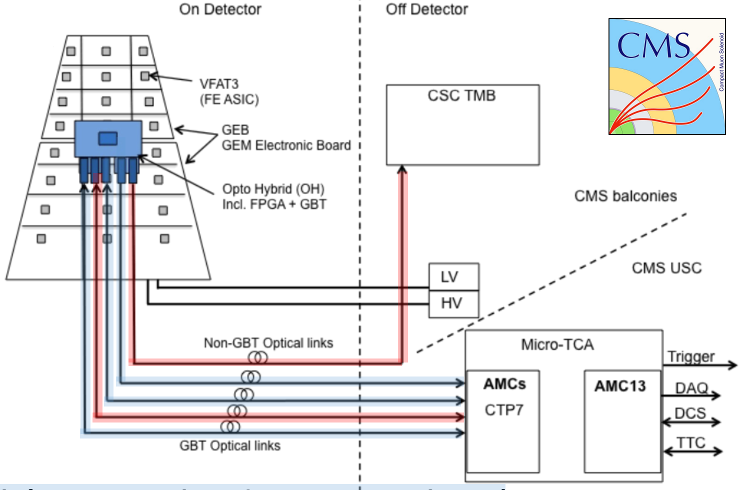
Prototypes: 10 generations





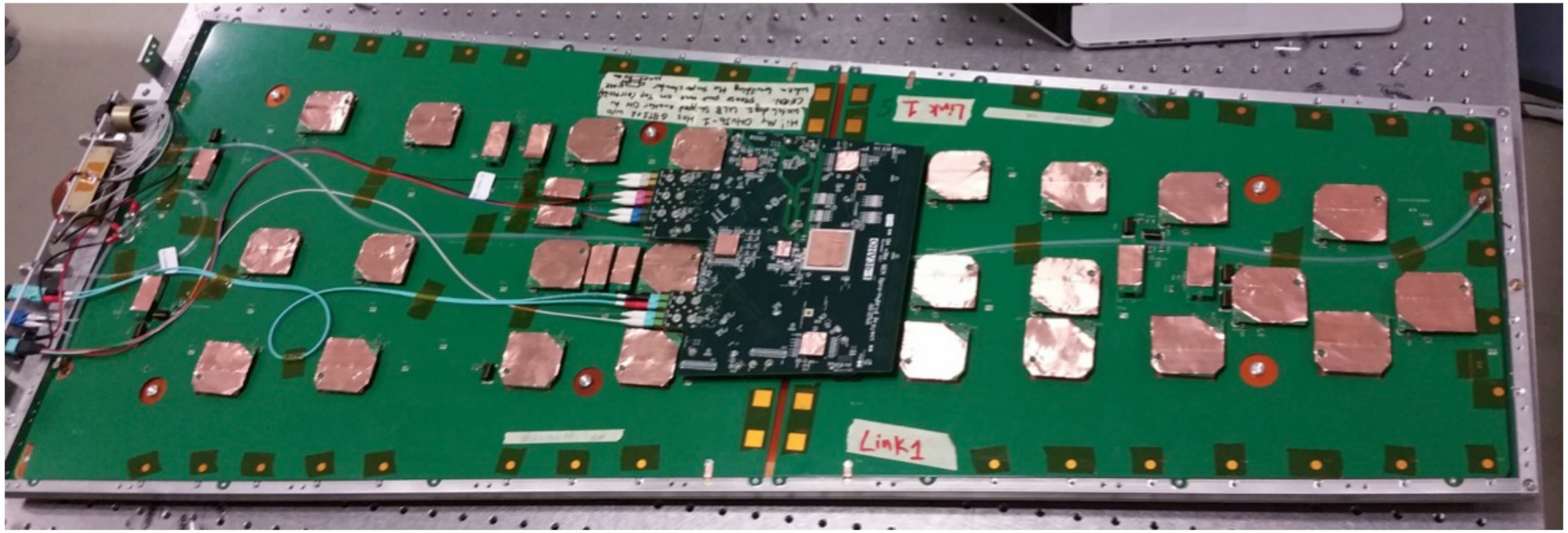
Specification / Parameter	GE1/1
Detector technology	Gaseous detector; micro-pattern gas detector (MPGD)
Charge amplification element	GEM foil (triple, cascaded, tensioned at ≈ 5 N/cm)
Number of chambers in overall system	144 (72 in each endcap)
Chamber shape (active readout area)	Trapezoidal; opening angle 10.15^o
Active area overlap in adjacent chambers	2.6 mrad (corresponds to 5.7 readout strip pitches)
Short chamber dimensions (active vol.)	L: 106.1 cm (center line), W: (23.1 - 42.0) cm, D: 0.7 cm
Long chamber dimensions (active vol.)	L: 120.9 cm (center line), W: (23.1 - 44.6) cm, D: 0.7 cm
Total chamber thickness	D: 3.5 cm
Active readout area	0.345 m^2 (short ch.); 0.409 m^2 (long ch.)
Active chamber volume	2.6 liters (short ch.); 3 liters (long ch.)
Radial distance from beam line	130.2 cm (at inner edge of active readout area)
Geometric acceptance in η	1.61 - 2.18 (short ch.); 1.55 - 2.18 (long ch.)
Signal readout structure	Truly radial readout strips
Readout strip dimensions	230 μrad angular strip width; 463 μrad angular pitch
Number of η-segments in readout	8
Number of readout strips per η-segment	384
Number of readout strips per chamber	3,072
Counting gas mixtures	Ar/CO_2 70:30 or $Ar/CO_2/CF_4$ 45:15:40
Nominal operational gas flow	1 chamber volume per hour
Number of gas inlets	1
Number of gas outlets	1
Nominal HV applied to drift electrode	3200 V (Ar/CO_2); 4000 V ($Ar/CO_2/CF_4$)
Nominal operational gas gain	1-2 × 10^4
Demonstrated rate capability	100 MHz/cm^2

CMS GEM (GE1/1) Electronics

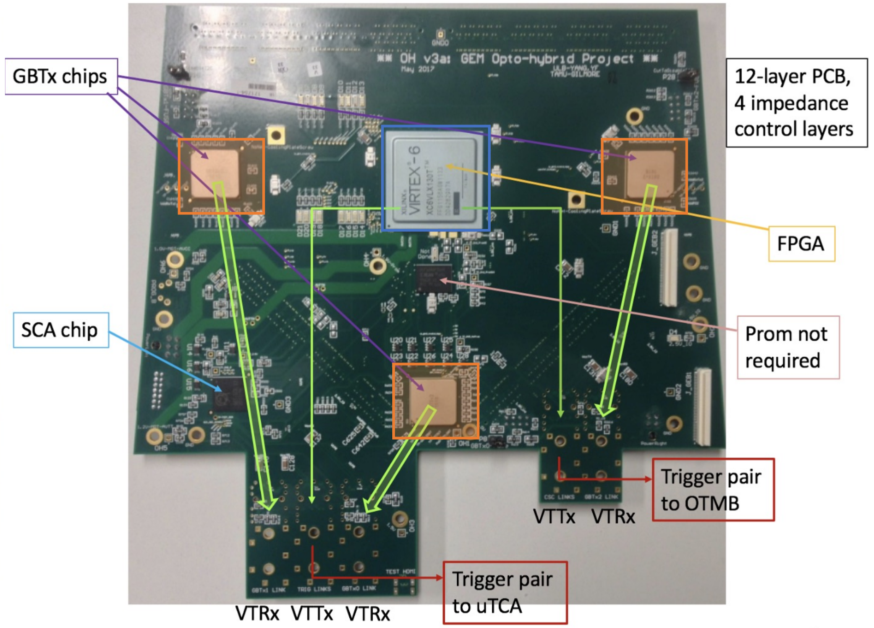


- **VFAT3 Front-End ASIC**
  - 128 ch – 320 MHz – ≥12.5us buffers
  - Trigger data = OR 2 strips
- **GEB = GEM Electronics Board** (8 layer, 1mm)
  - 2 PCBs to avoid long track lenghts
  - 1 power, 1 shield , 1 GND, 2 signal
- **FEAST DC-DC convertors** (#9, 1.2V, 2.5V, 3.2V)

- **Opto-Hybrid (OH) mezzanine card**
  - Xilinx Virtex-6 FPGA (promless)
    - *Only to send trigger data*
  - 3 Gigabit GBTx chips
    - *3 x Tracking & slow control (VTRx = bi-directional OL)*
    - *2 x Triggering (VTTx = mono-directional OL)*



GE1/1 detector with 2 GEBs, 1 OH, 24 VFATs, 5 Ols, 10 FEASTs



GE1/1 Opto-Hybrid board

GEM Detectors for the CMS Endcap Muon System

Status of three new detector stations

Piet Verwilligen

for the CMS Muon Group

MPGD 2022

December 12th 2022

Weizmann Institute of Science - IL