



RIVELATORI A TRIPLA GEM PER L'UPGRADE DEL SISTEMA A MUONI DELL'ESPERIMENTO CMS

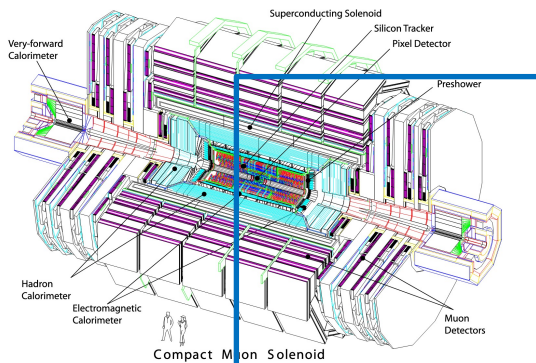
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Per la collaborazione CMS

Incontri di Fisica delle Alte Energie

Catania – 13 aprile 2023



UPGRADE DEL SISTEMA A MUONI DI CMS



Luminosità $5 - 7.5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1} \rightarrow$ aggiornamento tecnologie a muoni esistenti:

- **Upgrade dell'elettronica per CSC, DT, RPC** [1]
Per gestire rate di 750 kHz nel trigger L1
- **Nuove stazioni di (improved) RPC** nella regione ad alto η
Per complementare le CSC e trigger su particelle a vita lunga

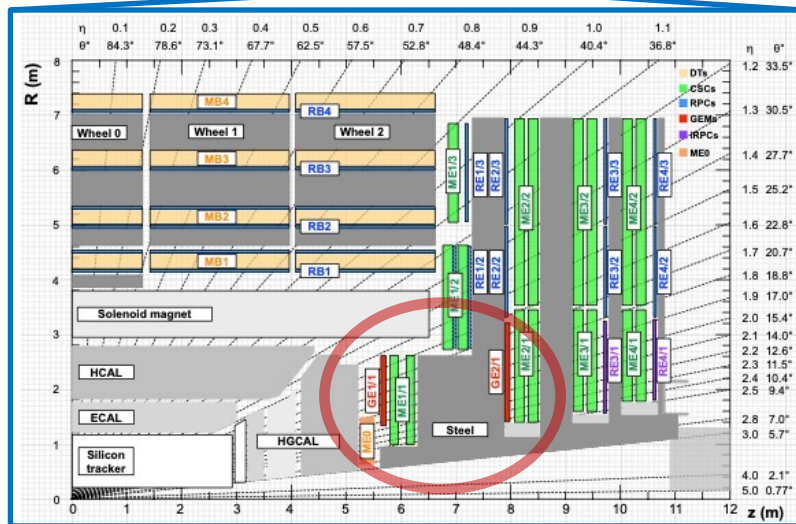
Tre nuove stazioni a tripla-GEM [2]

per mantenere e migliorare la sensibilità per tutti i processi in avanti:

- **Complementare e sostituire le CSC** nella misura dell'impulso nella regione $1.6 < |\eta| < 2.4$
- Trigger su vertici "displaced"
- **Estendere l'accettazione del sistema a muoni** e complementare l'inner tracker in $2.4 < |\eta| < 2.8$

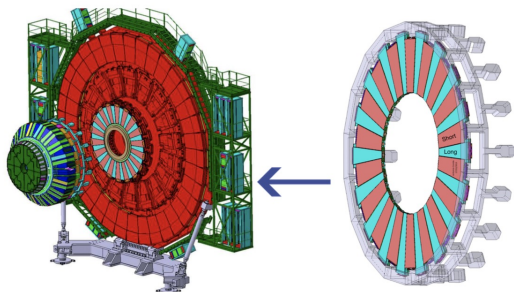
Perché rivelatori a tripla GEM?

- Risoluzione spaziale $O(100 \mu\text{m})$
- **Rate capability** intrinseca $> 1 \text{ MHz}/\text{mm}^2$
- Longevità a **cariche integrate** $\leq 8 \text{ C}/\text{cm}^2$

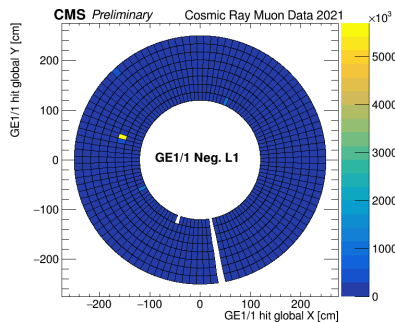




PROGRAMMA DEL PROGETTO GEM



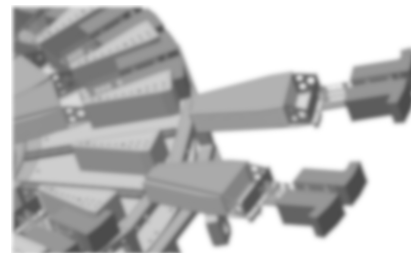
Installazione di GE1/1



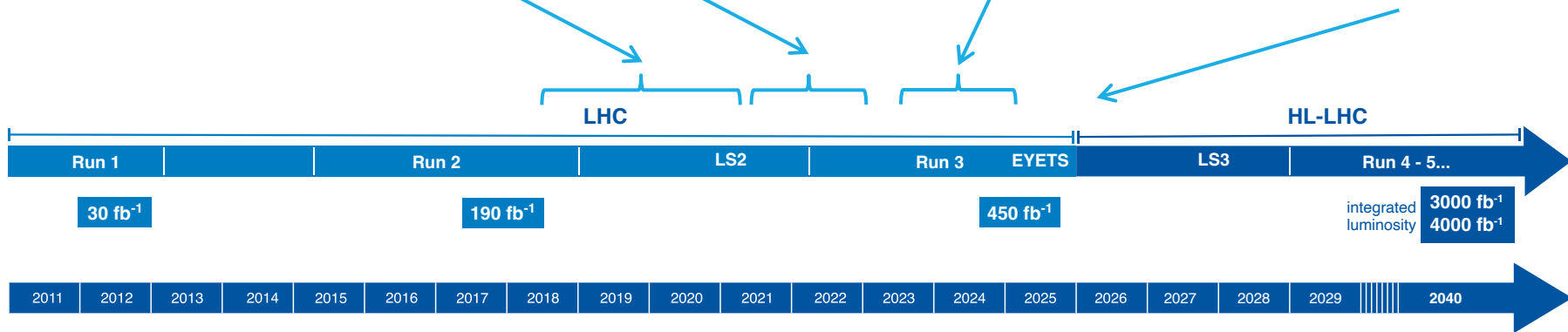
Commissioning di GE1/1



Installazione di GE2/1

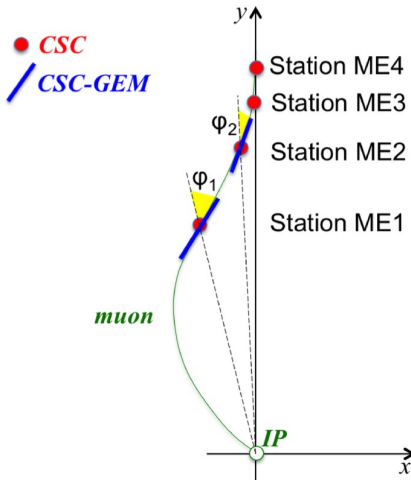


Installazione di MEO





MOTIVAZIONI DI GE1/1 E GE2/1



Motivazione: complementare le stazioni CSC vicine, ME1/1 e ME2/1

→ Maggiore **lever arm** per la misura del bending angle dei muoni

→ Miglior **risoluzione p_T** a livello trigger

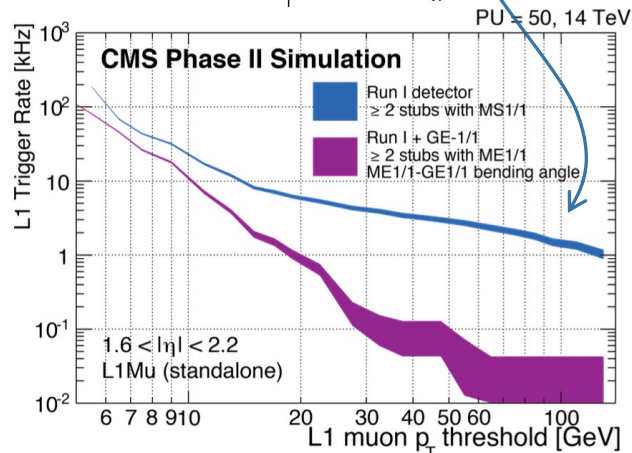
→ Rate di **L1 trigger** ridotta $\times 10$

Per ogni stazioni **un disco per endcap**

- **GE1/1: 36 super-camere** per endcap (apertura 10°)

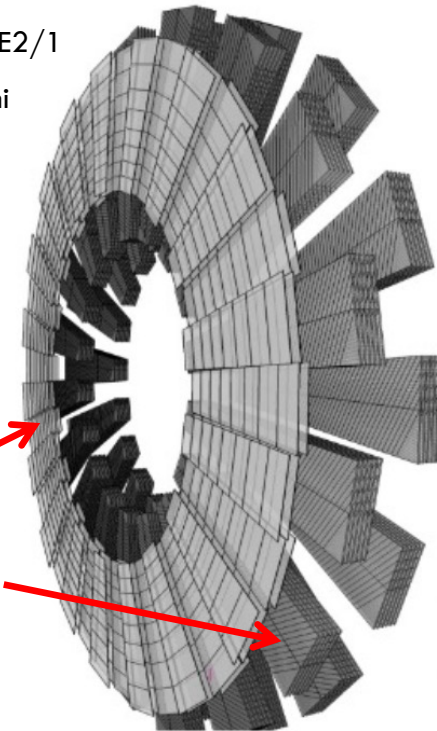
- **GE2/1: 18 super-camere** per endcap (apertura 20°)

Ogni super-camera è uno stack di 2 rivelatori a tripla GEM



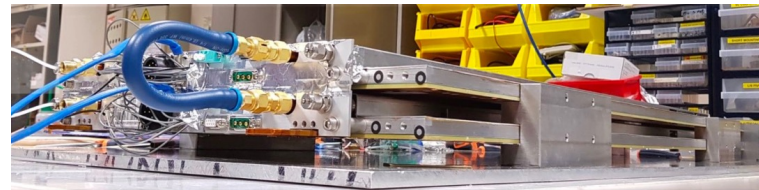
GE1/1

ME1/1



In basso: super-camera GE1/1

A destra: disegno dei dischi di GE1/1 e ME1/1

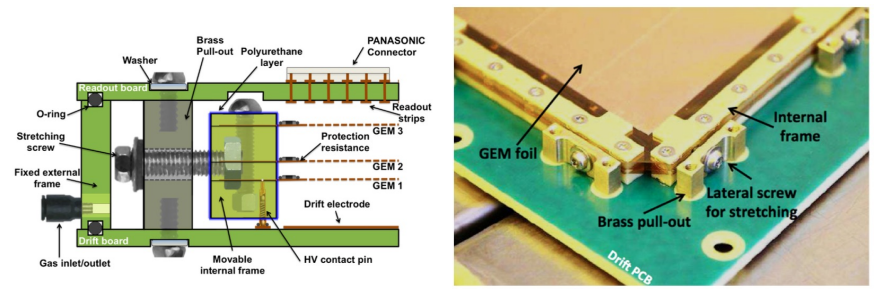




R&D ED ELETTRONICA DI GE1/1

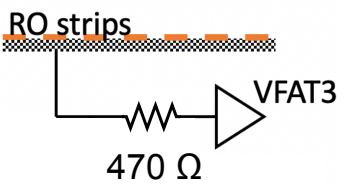
Meccanica del rivelatore

Gap 1-3 mm su aree $\sim m^2$: tecnica di **assemblaggio self-stretching sviluppata** per evitare colla o frame interni



Stabilità e protezione da scariche

R&D per prevenzione di propagazione di scariche e probabilità di danneggiamento dell'elettronica:

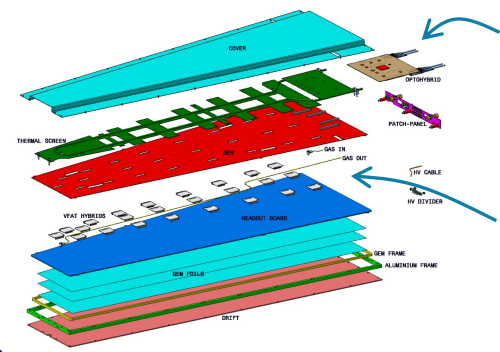
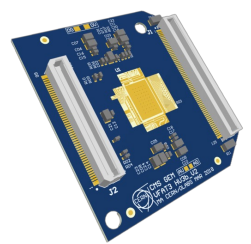
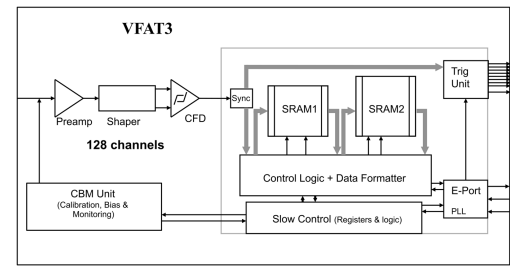


- **Elettrodi GEM segmentati**
- Circuito di protezione in input all'elettronica [4]
- Circuiti di **filtro e protezione ai fogli GEM**

Elettronica di front-end

ASIC di front-end VFAT3 sviluppato per readout digitale [3]

- Integrazione "lenta" (50-70 ns) ai segnali GEM
- CFD per risoluzione temporale < 10 ns



Front-end OptoHybrid concentrator board

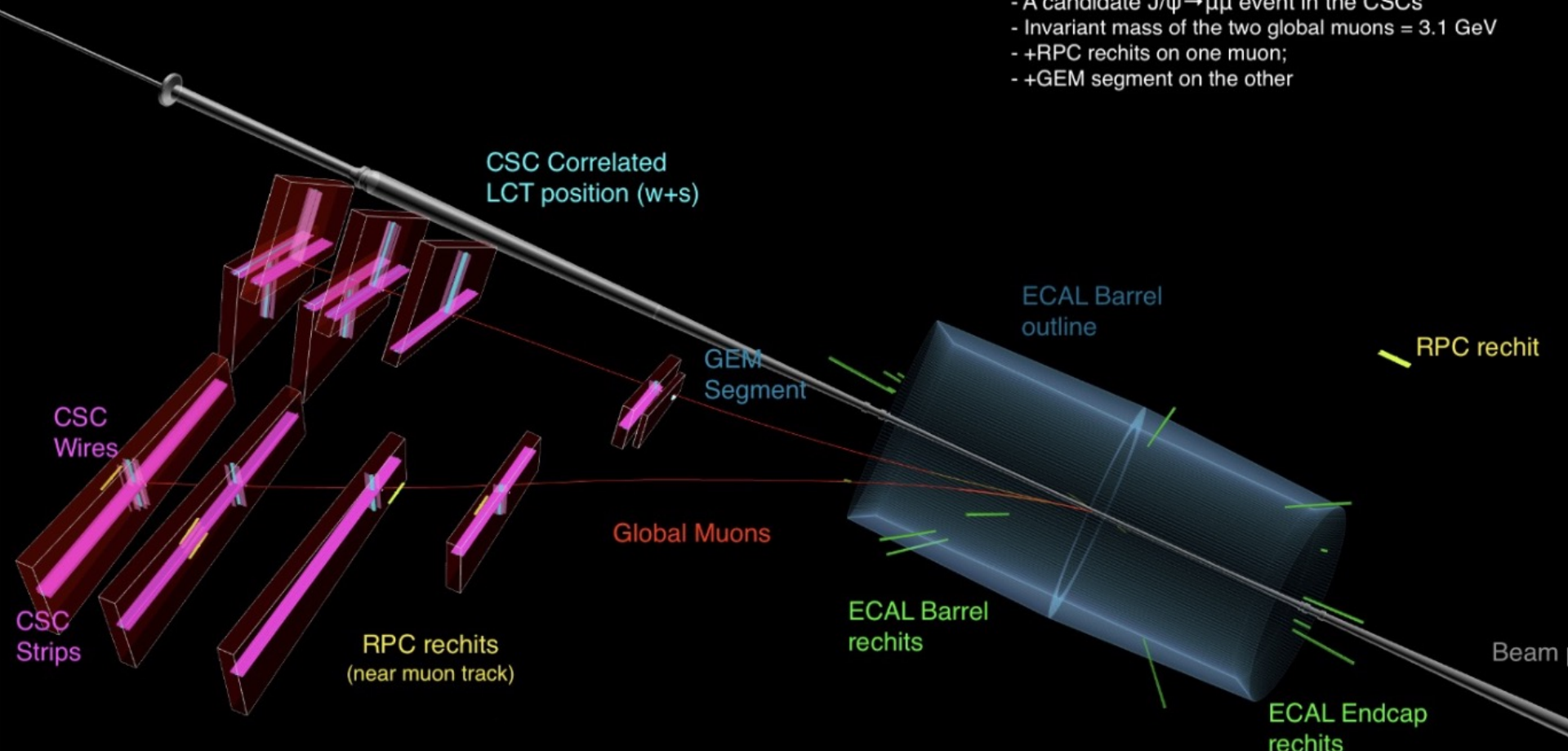
Comunicazione on-detector e back-end basata sul protocollo GBT



J/ψ produced @ $\sqrt{s} = 900$ GeV

Test pp collisions at 900 GeV - Nov 2021

- A candidate $J/\psi \rightarrow \mu\mu$ event in the CSCs
- Invariant mass of the two global muons = 3.1 GeV
- +RPC rechits on one muon;
- +GEM segment on the other





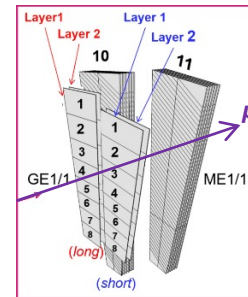
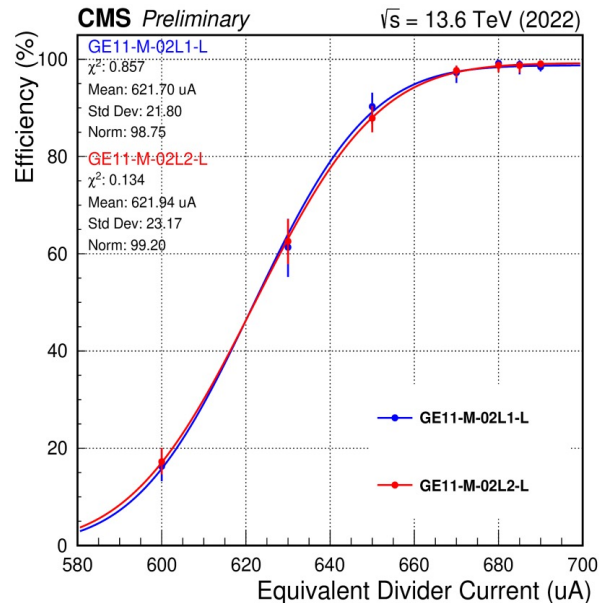
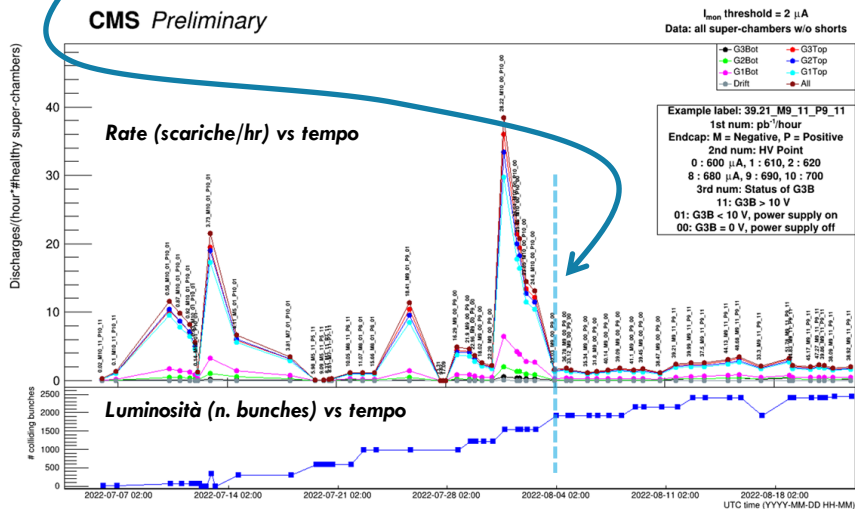
COMMISSIONING E OPERAZIONE DI GE1/1

Commissioning di GE1/1 nei run con cosmici in LS2 e nelle prime collisioni nel 2022

Primi sforzi: stabilità HV e di comunicazione con elettronica

- Raggiunto **>90%** del sistema in comunicazione durante i run
- Sviluppata procedura di **protezione durante il ramping del magnete** di CMS al sicuro da scariche e corti circuiti
- Monitorata la rate di scariche nel tempo. Osservata **crescita nella rate di scariche con la luminosità**

→ risolto abbassando il punto HV nel plateau di efficienza



A sinistra: efficienza di un rivelatore GE1/1 dell'endcap negativo ai muoni [5]

In alto: schema della propagazione del segmento da ME1/1 a GE1/1

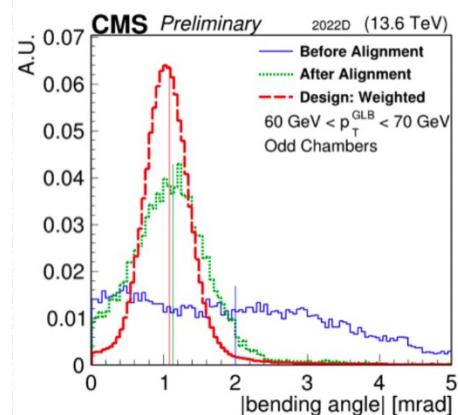
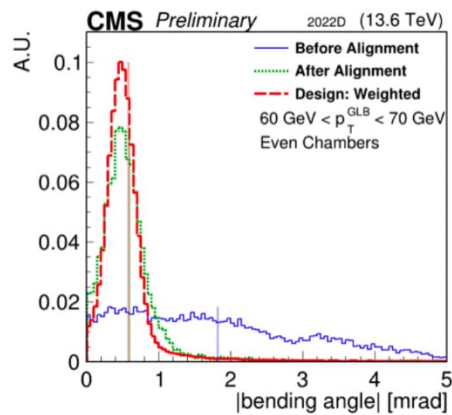
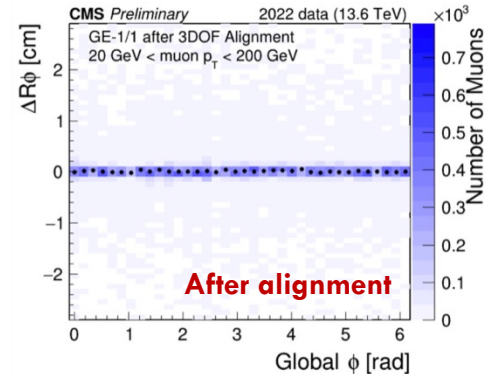
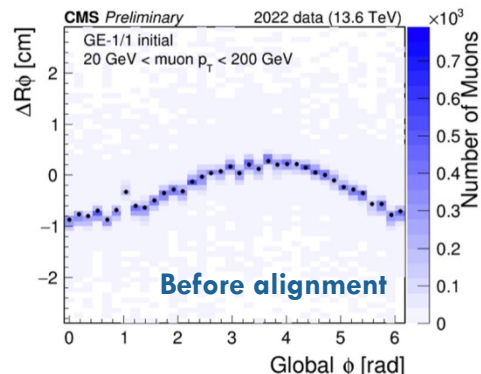
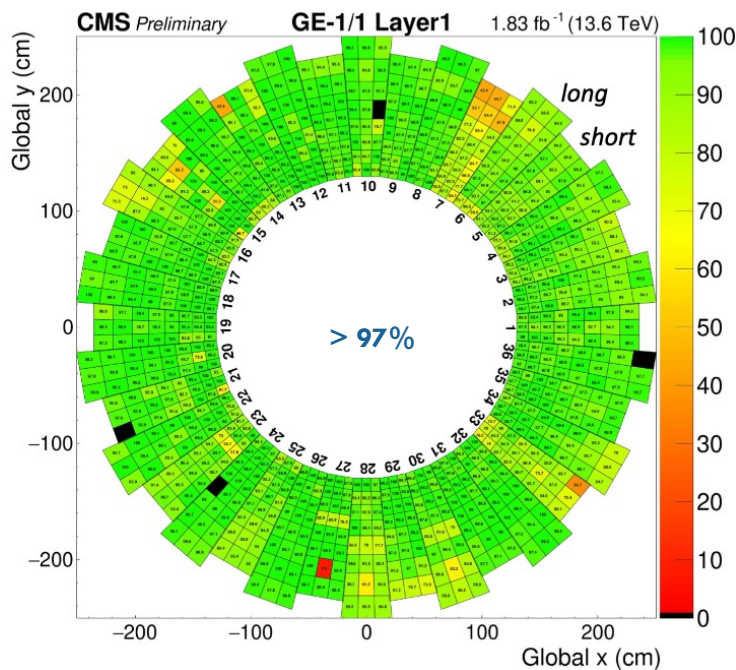
Performance del rivelatore

- Efficienza misurata con muoni cosmici e da collisioni usando propagazione del segmento da ME1/1
- Scan HV per tutti i rivelatori per determinare il **punto di lavoro al plateau di efficienza**



PERFORMANCE GE1/1

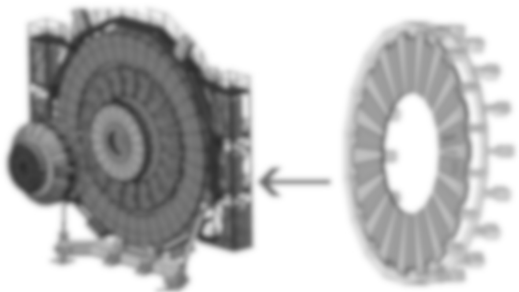
- **Efficienza al plateau** misurata per tutti i rivelatori [5]
- Cause principali di **inefficienza: HV** (corti circuiti) **ed elettronica** (perdita di optical power in VTRx)



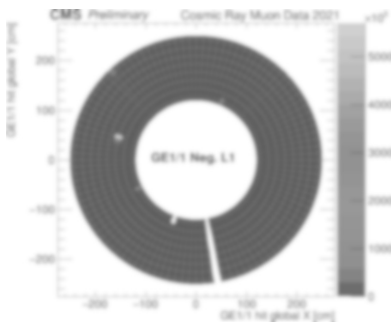
- Rivelatori GEM **allineati rispetto a CSC** con dati da collisioni
- **Bending angle dei muoni** $\phi_{CSC} - \phi_{GEM}$ misurato offline
→ Dipendenza osservabile dal p_T dopo allineamento
- Principale obiettivo del 2023: misura del bending nel **trigger**



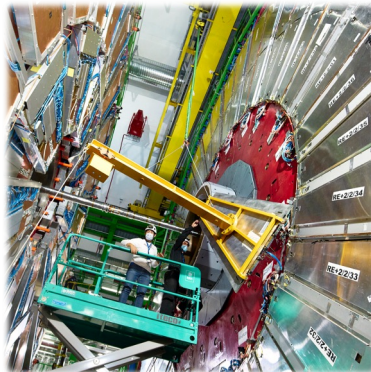
PROGRAMMA DEL PROGETTO GEM



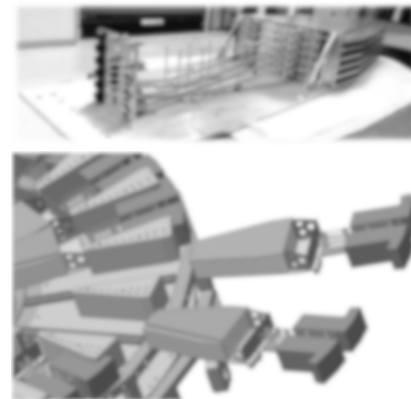
Installazione di GE1/1



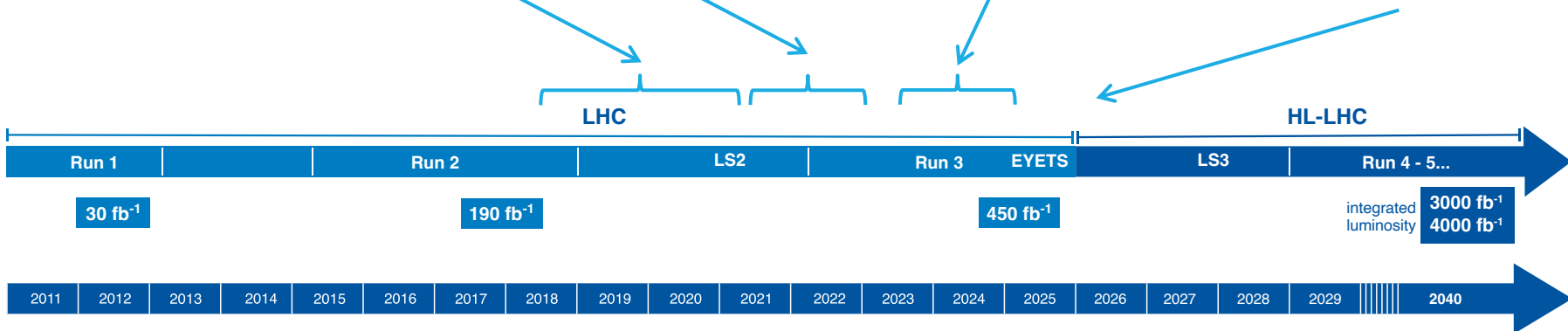
Commissioning di GE1/1



Installazione di GE2/1



Installazione di ME0



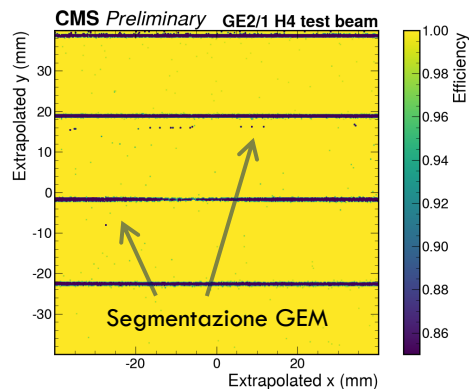
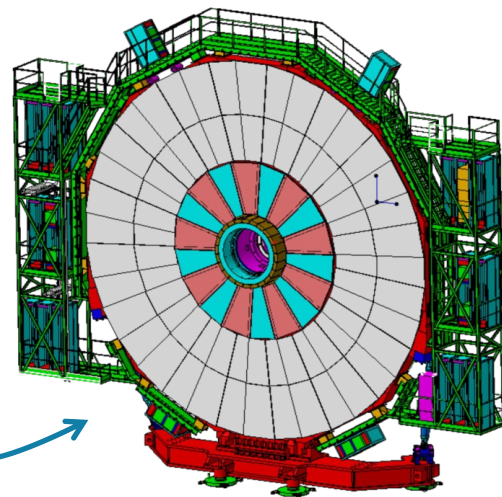
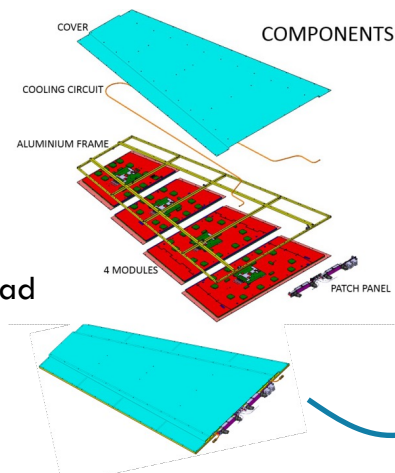
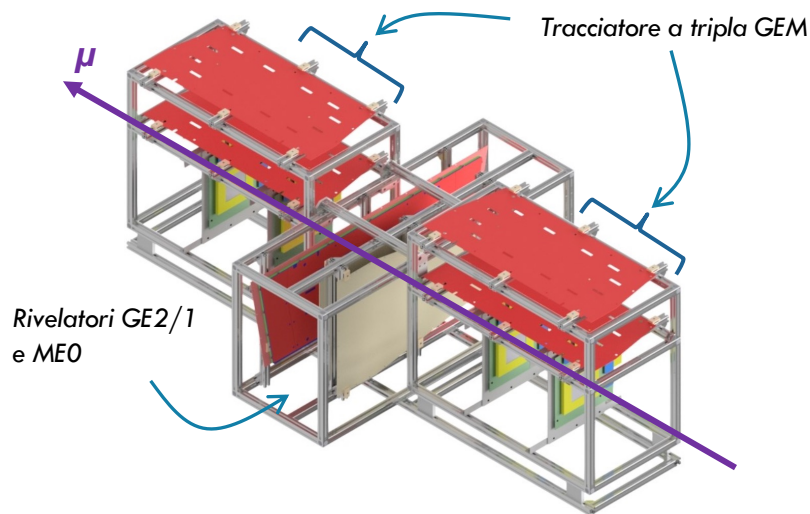


PRESTAZIONI DEI RIVELATORI GE2/1

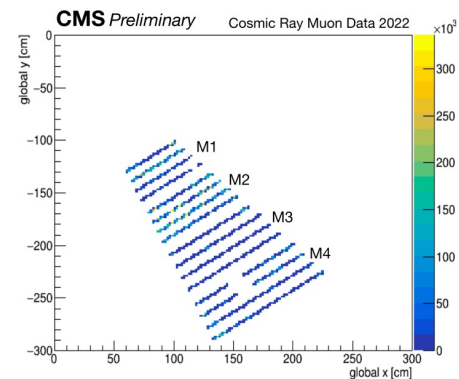
Dettagli sulla produzione di GE2/1: poster [R. Campagnola](#)

Design del rivelatore GE2/1 simile a GE1/1

- **Ottimizzazione** nel rumore elettronico e uniformità di efficienza e di timing
- **Prestazioni del rivelatore misurate in test beam** [6]
 - **Efficienza molto alta** ($> 99\%$ escludendo la segmentazione dei fogli) e **risoluzione spaziale** $< 300 \mu\text{rad}$
- **Dimostratore GE2/1** installato e integrato in CMS



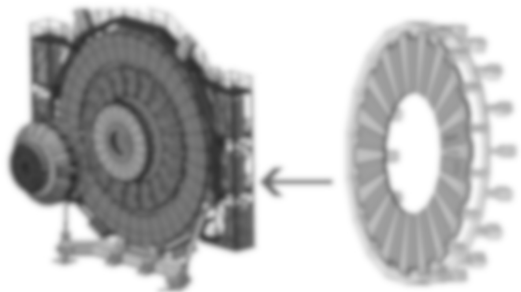
Mapa di efficienza di rivelatore GE2/1 misurata in test beam [6]



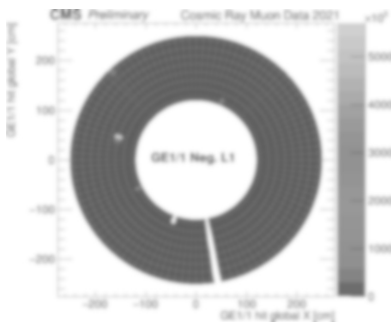
Occupancy nel dimostratore GE2/1 run cosmico in CMS



PROGRAMMA DEL PROGETTO GEM



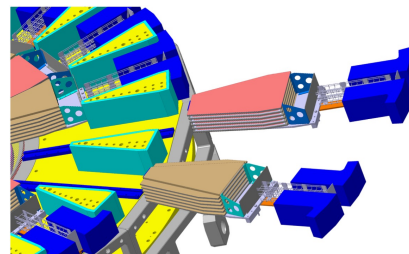
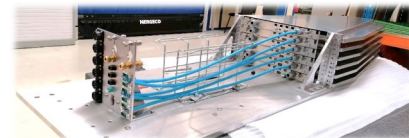
Installazione di GE1/1



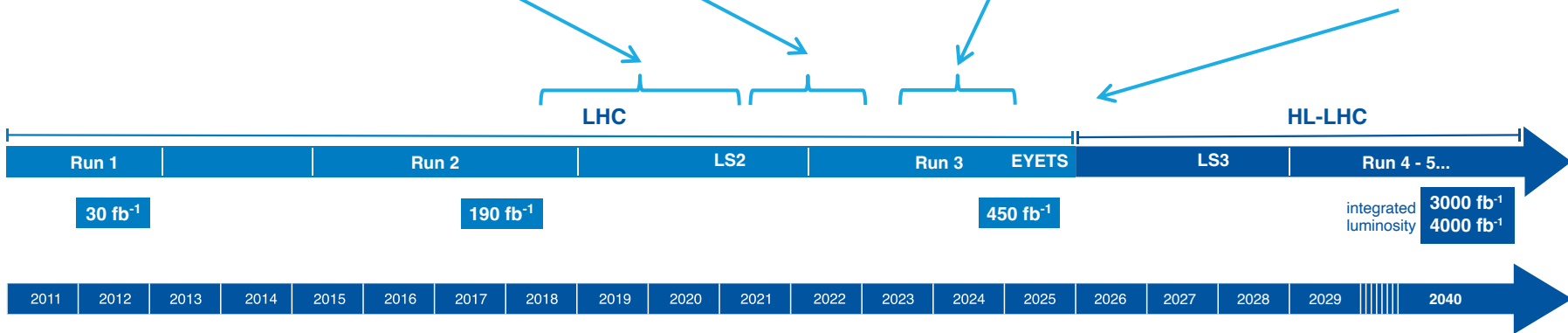
Commissioning di GE1/1



Installazione di GE2/1

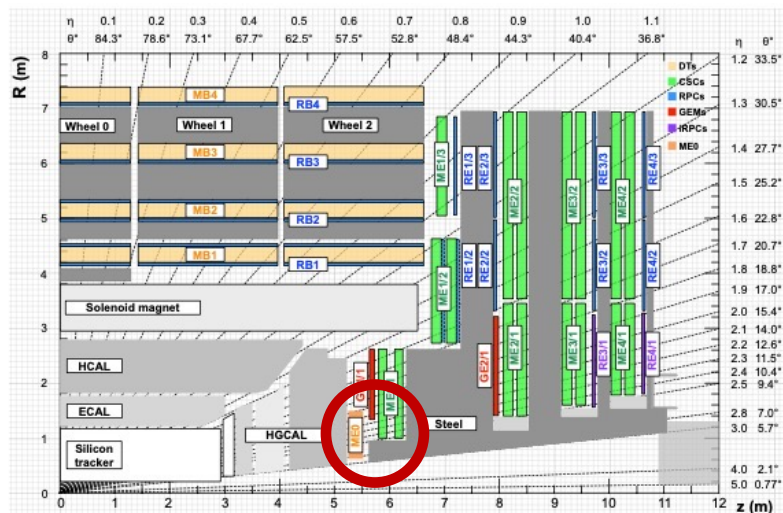


Installazione di ME0





PROSPETTIVA SU MEO



Stazione a muoni più vicina alla linea del fascio di LHC: $2 < |\eta| < 2.8$

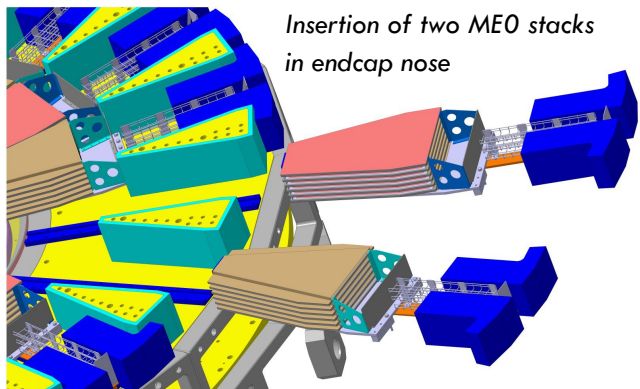
- **Complementa GEM/CSC** per p_T in $2 < |\eta| < 2.4$
- **Estensione accettazione sistema a muoni** in $2.4 < |\eta| < 2.8$

Installata nella meccanica di HGAL

- 18 stack per endcap
- Ogni stack è composto da sei rivelatori a tripla GEM
Nom complementata da nessuna stazione CSC
- Apertura per stack $\delta\phi = 20^\circ$, $\delta\eta = 0.8$

Requisiti di performance del rivelatore:

- Efficienza $> 97\%$ per rivelatore
- Risoluzione puntuale in ϕ $\sim 100 \mu\text{rad}$
- Risoluzione temporale $< 10 \text{ ns}$
- Flusso di particelle di fondo fino a 200 kHz/cm^2
Flusso più alto per una stazione di rivelatori a gas su grande area
- Longevità fino a carica integrata 7.9 C/cm^2



Insertion of two MEO stacks
in endcap nose



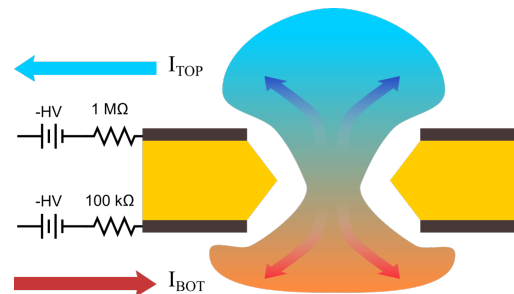
R& ALTA RATE MEO

Flusso di particelle di fondo, disuniforme, fra 2 e 200 kHz/cm²

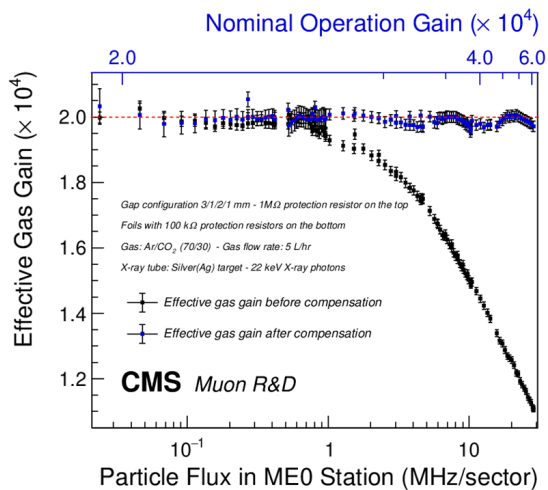
- **Rate capability di triple GEM limitata** dalle resistenze di protezione dalle scariche [7]

Risultati R&D per alta rate:

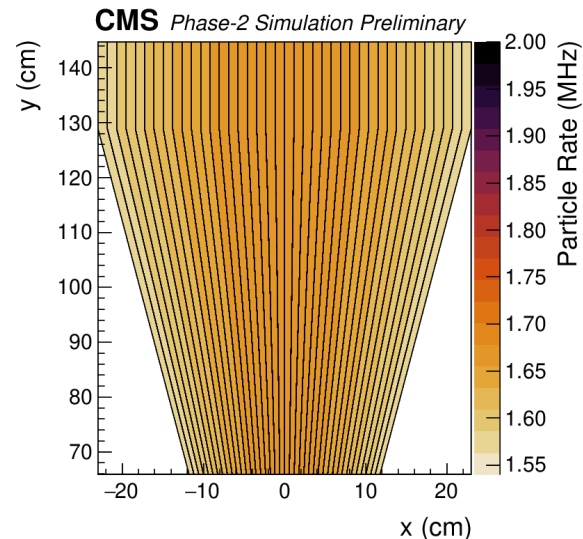
- **Perdita di guadagno del 50%** per rate di 10 MHz/settore
- Mitigazione: **segmentazione dei fogli GEM in direzione radiale** rispetto alla linea del fascio
- ✓ **Equalizza e limita** le perdite di guadagno
- ✓ **Permette di applicare una "compensazione di tensione"** per recuperare alti guadagni



Moltiplicazione di carica in foglio GEM con correnti che scorrono nelle resistenze di protezione



Rate capability di un rivelatore MEO misurata con x-rays



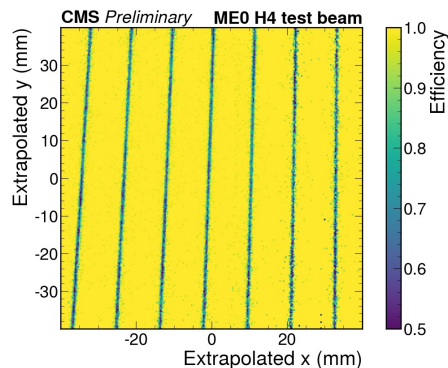
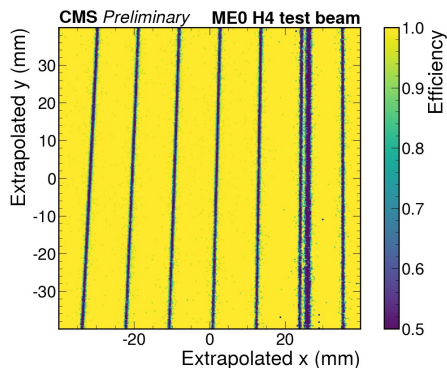
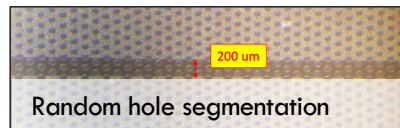
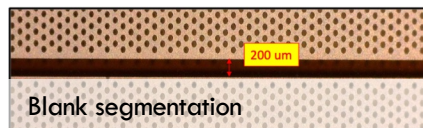
Rate simulate di fondo per GEM settore in rivelatore MEO [7]



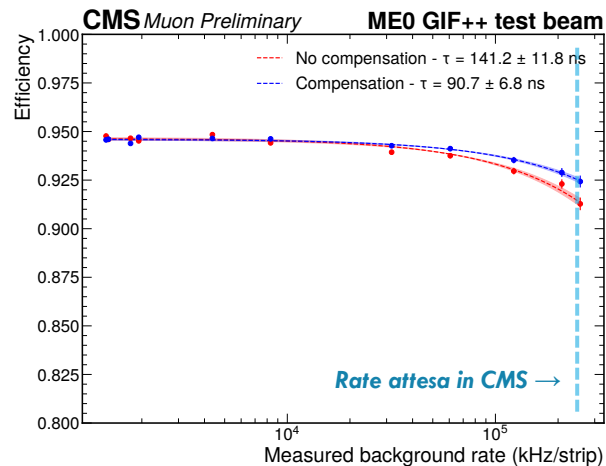
PRESTAZIONI RIVELATORE ME0

Performance del rivelatore misurata in test beam al CERN SPS:

- Risoluzione spaziale 240 μrad
- Efficienza **localmente >99%**
- Perdita di **efficienza per segmentazione** più alta che in GE2/1
- Tecnica di produzione alternativa (**segmentazione random-hole**) **sotto studio** per mitigare la perdita di efficienza mitigate efficiency loss [8]



Mappe di efficienza di rivelatori ME0 con segmentazione blank e random-hole misurate in test beam [9]



Prestazioni con elettronica finale sotto irraggiamento misurate in test beam alla GIF++:

- Muoni 80 GeV/c + fondo gamma da ^{137}Cs a bassa energia
- Perdita di efficienza sotto irraggiamento **non coerente con rate capability del rivelatore**
- Ricondotta al **tempo morto dell'elettronica di front-end** (400 ns)
- Perdita **contenuta al 3%**. Impatto trascurabile atteso nelle performance di fisica in CMS



CONCLUSIONI

Stato delle tre stazioni GEM in CMS:

- **Commissioning di GE1/1 completato, presa dati in corso**
 - Performance verificata con **efficienza e angolo di bending**
 - In corso **integrazione nel trigger di CMS**
- **Produzione GE2/1 in corso**
 - Performance misurata in **test beam**
 - **Installazione attesa** fra 2023 e 2024 nei technical stop di LHC
- **R&D sul rivelatore ME0 completata**
 - **Rate capability** misurata e strategie di mitigazione sviluppate
 - Design **in revisione finale**
 - Produzione attesa **in coda a GE2/1**



RIFERIMENTI

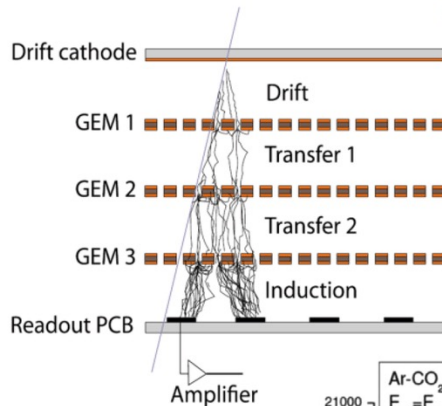
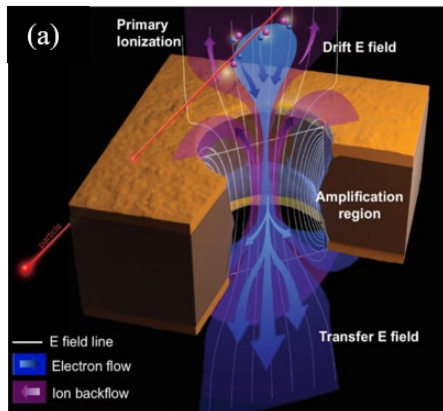
1. CMS collaboration, *The Phase-2 Upgrade of the CMS Muon Detectors*, CERN Tech. rep. 2017. <https://cds.cern.ch/record/2283189>
2. A. Colaleo et al., *CMS Technical Design Report for the Muon Endcap GEM Upgrade*. Tech. rep. 2015 <https://cds.cern.ch/record/2021453>
3. P. Aspell et al., *VFAT3: A Trigger and Tracking Front-end ASIC for the Binary Read-out of Gaseous and Silicon Sensors*. In: 2018 IEEE Nuclear Science Symposium and Medical Imaging Conference Proceedings (NSS/MIC). 2018, pp. 1–8. doi: 10.1109/NSSMIC.2018.8824655
4. F. Ivone, *Discharge mitigation strategies for the CMS GE1/1 Triple-GEM detectors*. In: *Journal of Instrumentation* 15.05 (May 2020), p. C05009. doi: 10.1088/1748-0221/15/05/C05009
5. F. Ivone, *GE1/1 detection efficiencies at 13.6 TeV*. In: (2022). url: <https://cds.cern.ch/record/2837105>
6. A. Pellecchia et al., *Performance of triple-GEM detectors for the CMS Phase-2 upgrade measured in test beam*, *NIM A* 1046 2023, 167618, <https://doi.org/10.1016/j.nima.2022.167618>
7. A. Pellecchia et al., *Rate capability of large-area triple-GEM detectors and new foil design for the innermost station, ME0, of the CMS endcap muon system*, *IEEE NSS MIC 2021*, 10.1109/NSS/MIC44867.2021.9875626
8. F. M. Brunbauer et al., *Minimizing distortions with sectored GEM electrodes*, *NIM A* 961 2020, 163673, <https://doi.org/10.1016/j.nima.2020.163673>
9. A. Pellecchia et al., *Production and characterization of random electrode sectorization in GEM foils*, [arXiv:2303.06355](https://arxiv.org/abs/2303.06355)



BACKUP



TRIPLE-GEM DETECTORS

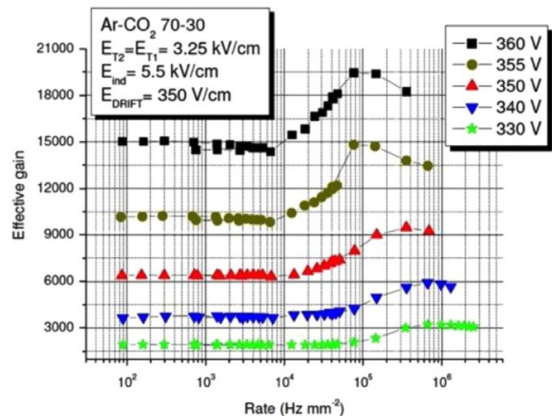


Triple-GEM: micro-pattern gaseous detector (MPGD) based on cascade of three GEM foils

Gas Electron Multiplier (GEM): thin amplification foil covered by electrodes and patterned with holes

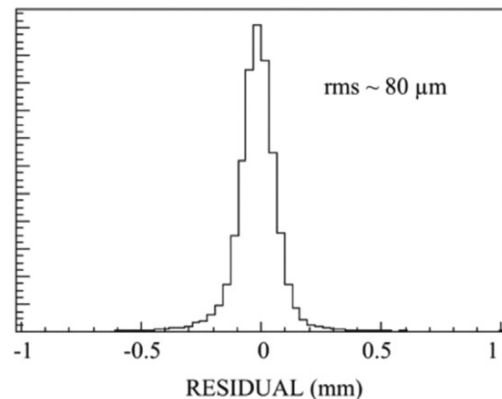
Triple-GEM detector performance:

- Efficiency close to 100% per MIP
- $O(100 \mu\text{m})$ point resolution
Translatable to $O(100 \mu\text{rad})$ resolution in ϕ
- **Intrinsic time resolution** 5-10 ns
- **Intrinsic rate capability** $> 1 \text{ MHz}/\text{mm}^2$
- **Longevity up to several C/cm^2** integrated charge



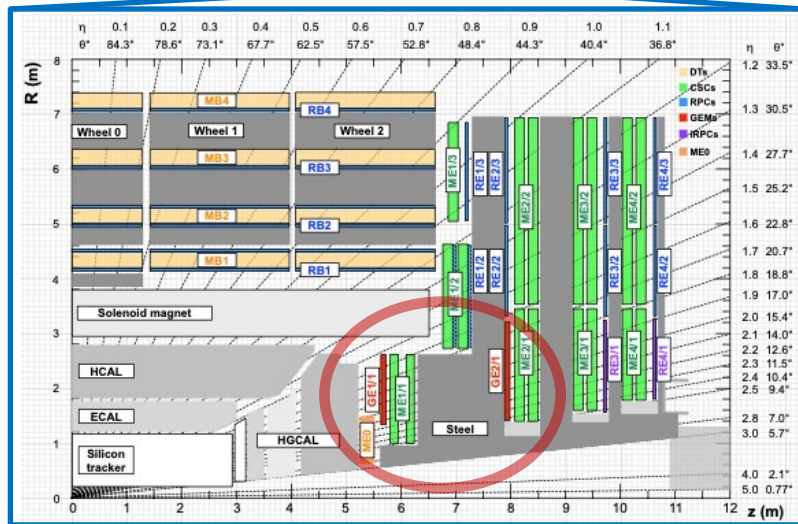
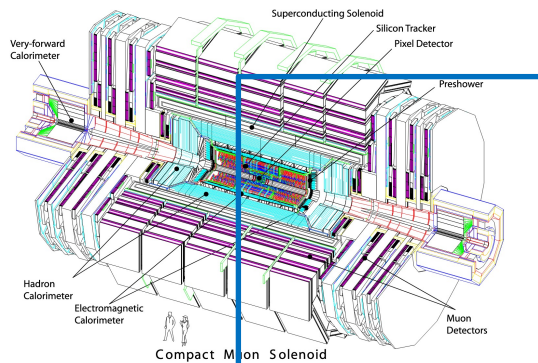
Left: Rate capability of triple-GEM detector measured with x-rays

Right: space resolution of triple-GEM detector measured with MIP





UPGRADE DEL SISTEMA A MUONI DI CMS



Aggiornamento delle tecnologie a muoni esistenti:

- **Upgrade dell'elettronica per CSC, DT, RPC**
Per gestire rate di 750 kHz a trigger L1
- **Nuove stazioni di (improved) RPC nella regione ad alto η**
Per complementare le CSC e trigger su particelle a vita lunga

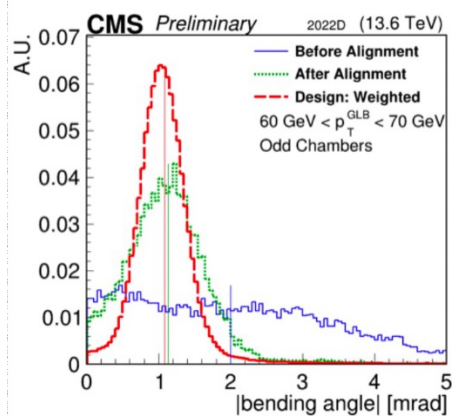
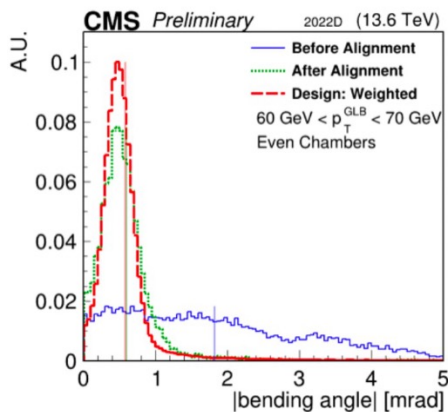
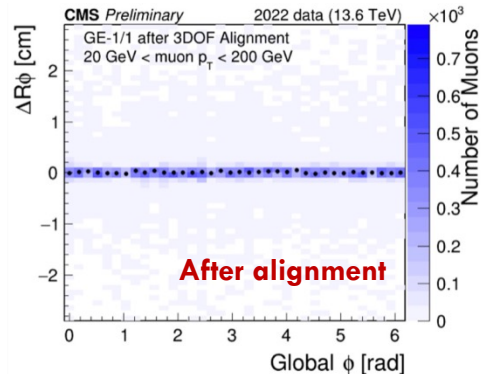
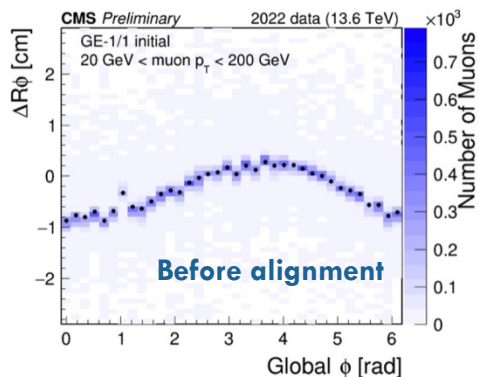
Tre nuove stazioni a tripla-GEM

per mantenere e migliorare la sensitività per tutti i processi in avanti:

- **GE1/1 e GE2/1:**
 - **Complementare e sostituire le CSC** nella misura dell'impulso
 - Trigger su vertici "displaced"
- **ME0:**
 - **Complementare CSC** for misura di impulso nella regione $1.6 < |\eta| < 2.4$
 - **Estendere l'accettazione del sistema a muoni e** complementare l'inner tracker in $2.4 < |\eta| < 2.8$



PERFORMANCE GE1/1

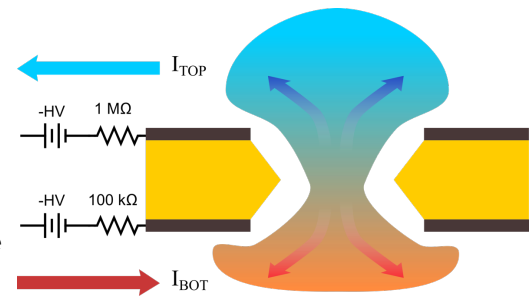




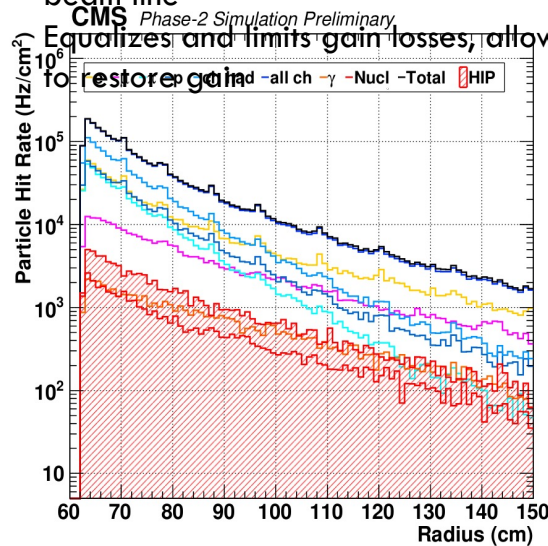
MEO HIGH-RATE R&D

Flusso di particelle di fondo, disuniforme, fra 2 e 200 kHz/cm²

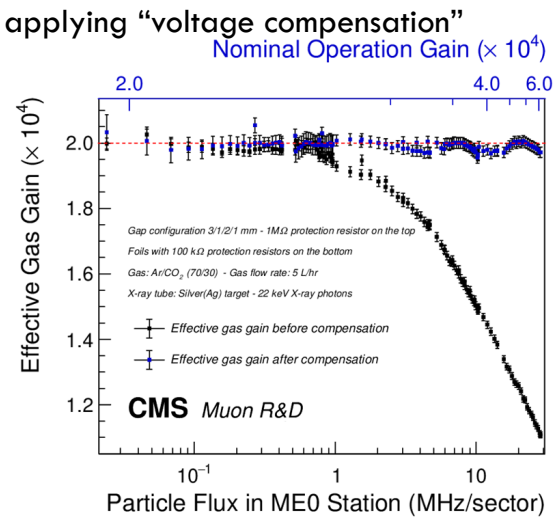
- **Rate capability di triple GEM limitata** dalle resistenze di protezione dalle scariche
- **Expected efficiency drops** below few MHz/sector
- Mitigation: GEM foil **segmentation in radial direction** with respect to beam line



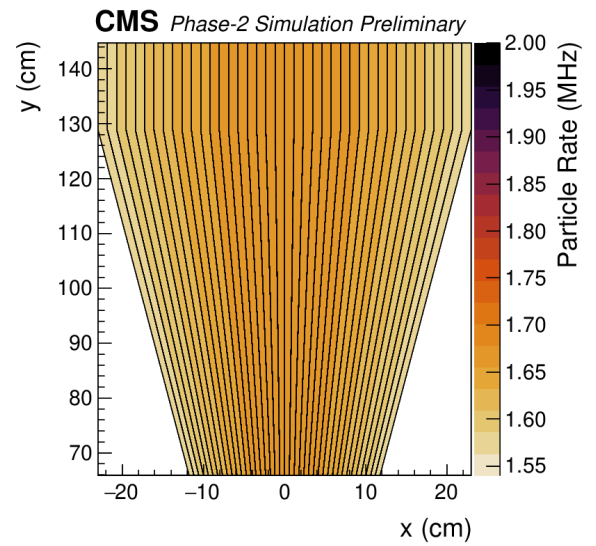
Avalanche in GEM holes with the currents flowing through the resistive protection circuits.



Simulated interacting particle flux in MEO detector in the CMS environment



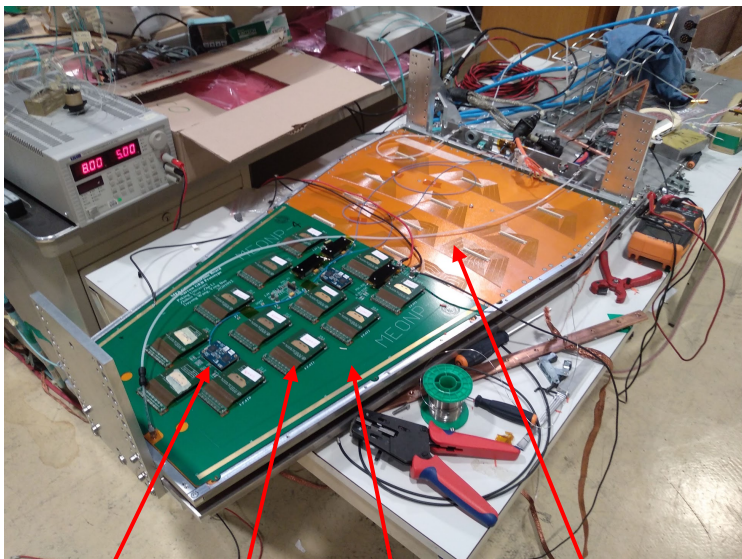
MEO detector rate capability measured with x-rays



Simulated background particle rates per GEM foil sector in MEO detector



ME0 ELECTRONICS



OptoHybrid

VFAT3

GEB

R/O board

bPOL ASIC on
FEAST module

VFAT3: 128-channel front-end ASIC for digital readout

- Common plugin-card format for GE2/1 and ME0
- Ongoing final checks on channel input protection circuit (see later)

GEM Electronic Board (GEB): 1mm 8-layer PCB providing electrical links, powering the front-end and shielding the detector

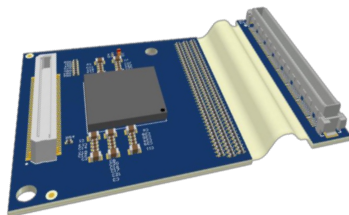
DC-DC converter: FEASTs to be replaced by bPOLs

OptoHybrid: Front-end concentrator, reads out 6 VFATs

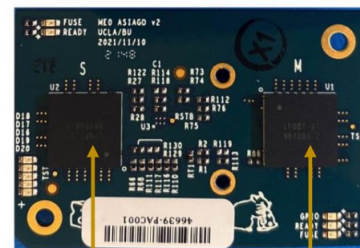
- 2 lpGBT (main/secondary) for front-end, 1 VTRx+ to back-end
- No FPGA, radiation-hard electronics

X2O ATCA board: common back-end for CSC, GE2/1 and ME0

All front-end components in pre-production state and operated extensively in lab & test beam



VFAT3 plug-in card



OptoHybrid

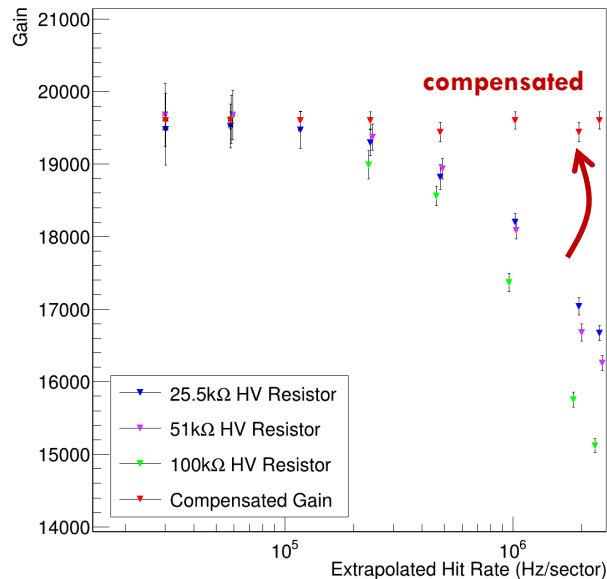
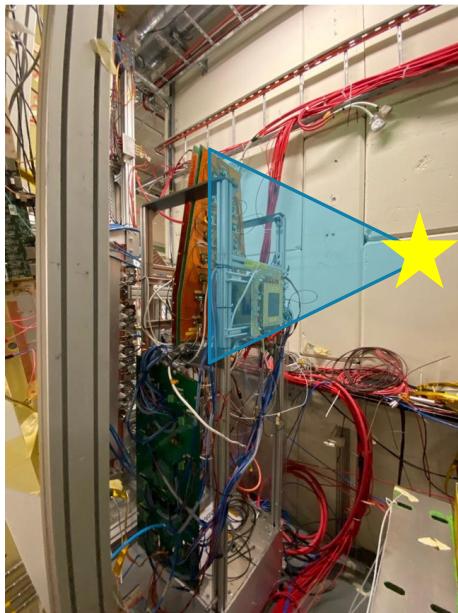
Secondary (S)
lpGBTMain (M)
lpGBT



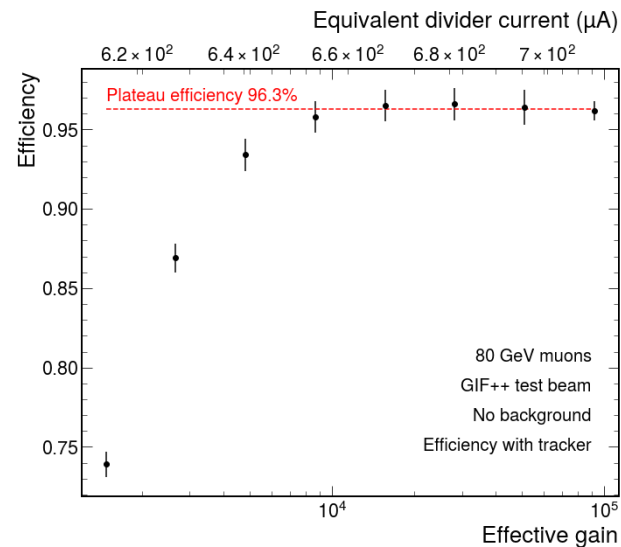
IRRADIATION STUDIES AT GIF++

GIF++ irradiation campaign from March up to September 2022

- Main goal: measurement of rate capability and gain recovery under **uniform and intense irradiation**
- Gain recovery demonstrated **up to 2.2 MHz/sector** (i.e. 250 kHz/strip) and with different HV filters up to 100 k Ω
- Fluxes close to maximum P5 expected rates. However the **charge of the background** at the GIF++ is **lower than in P5**



Measured rate capability and gain recovery at the GIF++ with different filters



Measured efficiency vs gain at the GIF++ test beam (source off)



RATE CAPABILITY WITH FINAL ELECTRONICS

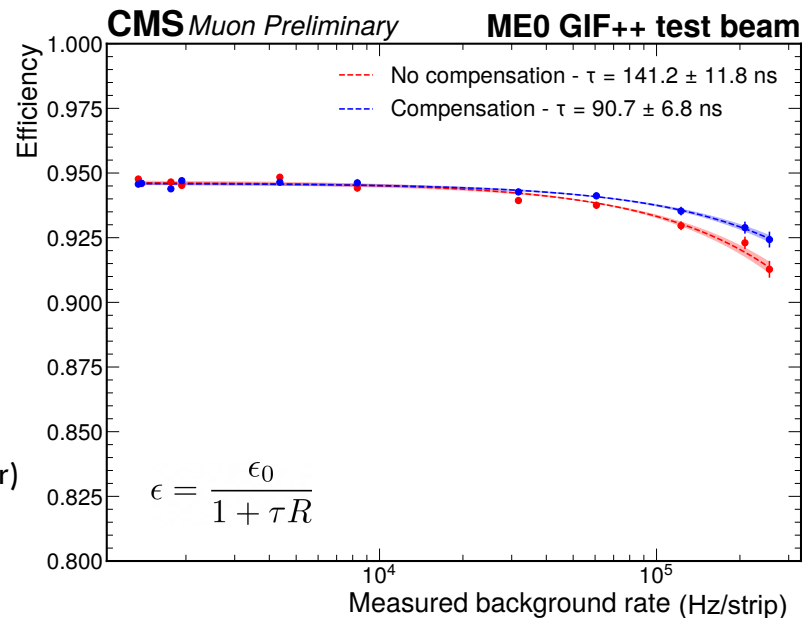
Test beam at GIF++

- Uniform irradiation by low-energy ^{137}Cs source + 80 GeV/c muon beam
- Surprise: compensation does not fully restore efficiency**
- Dead time with compensation 90.7 ± 6.8 ns at rate $1/\tau$, $\epsilon = \epsilon_0/2$**
 - Efficiency loss of **2.5% at 255 kHz/strip**

Efficiency loss not related to detector gain or components (e.g. filter)

Cause of efficiency loss found in front-end electronics

- Initially surprising, **now well understood**
- Confirmed** in both simulations and x-ray measurements in laboratory
In both cases, **dead time in agreement with test beam** efficiency loss (due to comparator recovery time)
- The expected **stack efficiency would drop only by 2%** (for four-layer or more segment) in high η



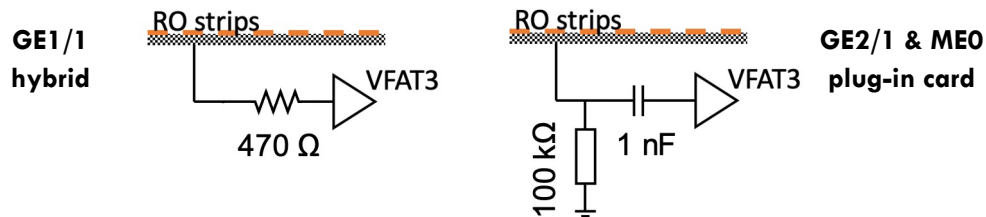
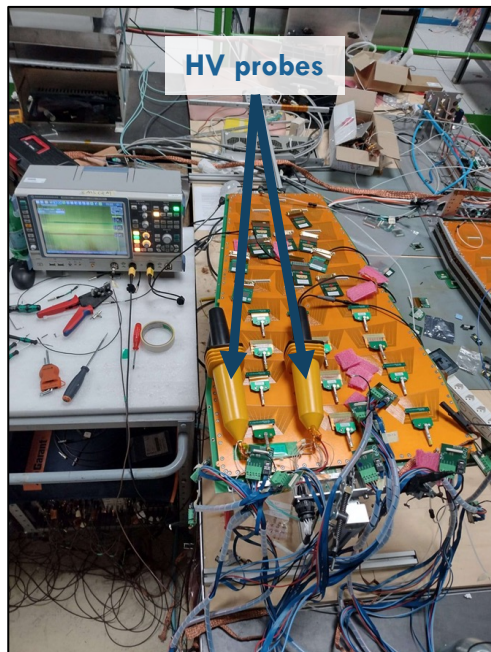
No modifications to detector or readout design needed



READOUT CHANNEL DAMAGE

Observed **dead channels in various setups** (GE2/1 demonstrator, test stands, test beam...) → **new take on discharge studies**

Setup for discharge studies at CERN



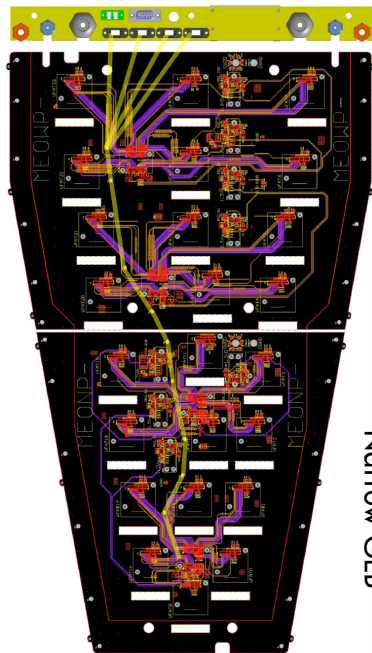
- **VFAT3 input protection** changed between GE1/1 and GE2/1
→ Problem: GE2/1 design **was not preventing discharge propagation**
- Produced batch of VFAT3 **plug-in cards with “GE1/1-style” protection circuit**
 - No damage observed during laboratory tests
 - 12 mounted on GE2/1 demonstrator to check “real-life” operations
 - **Ongoing “sustained operation”** irradiation tests with x-rays

Also: previous measurements done with no GEB → discovered that **GEB increases propagation probability by a factor 10**

With new probabilities, **estimated 1-2 % channels lost in 10 yrs** of operations
Acceptable, working on additional mitigation options

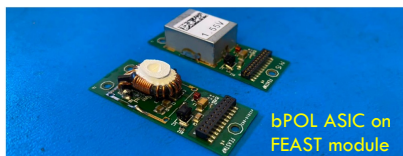


FRONT-END



Wide GEB

Narrow GEB

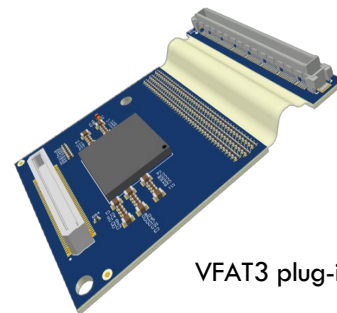
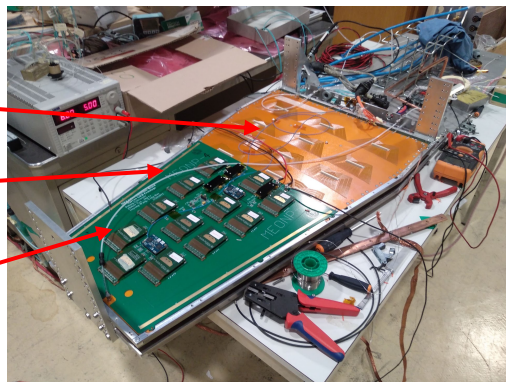


bPOL ASIC on FEAST module

R/O board

GEB

VFAT3



VFAT3 plug-in card

VFAT3: 128-channel front-end ASIC for digital readout

- Already used in GE1/1, new plugin-card format for GE2/1 and ME0
- Ongoing final checks on channel input protection circuit

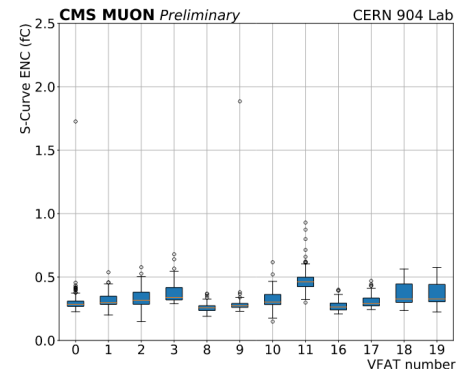
GEM Electronic Board (GEB): 1 mm 8-layer PBC providing electrical links, powering the front-end and shielding the detector

- 11 full pre-production GEBs (5 narrow, 6 wide) tested in PKU, used at CERN, UCLA, FIT

DC-DC converter: FEASTs to be replaced by bPOLs

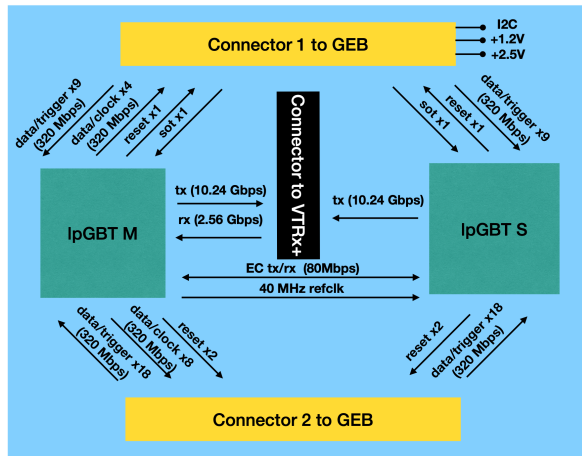
- ASIC from CERN, modules to be produced at ULB
- 9 prototypes tested at UCLA

All front-end operated extensively in lab & test beam





FRONT-END: OPTOHYBRID

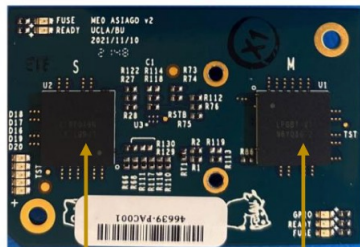


OptoHybrid Reads out 6 VFATs

- 2 IpGBT (main/secondary) for front-end data and slow control
- 1 VTRx+ to back-end
- No FPGA, radiation-hard electronics
- Integrated in final GEM DAQ sw
- 1 OH controls 6 VFATs – 96 ASIAGOs per back-end board

New OHs (v2):

- IpGBT v0 to v1
- Improved **reset and monitoring**
- Mechanical layout changes, halogen-free PCB
- 36 boards tested in UCLA, used in FIT and CERN
Used for both testing and data taking with cosmics and test beam

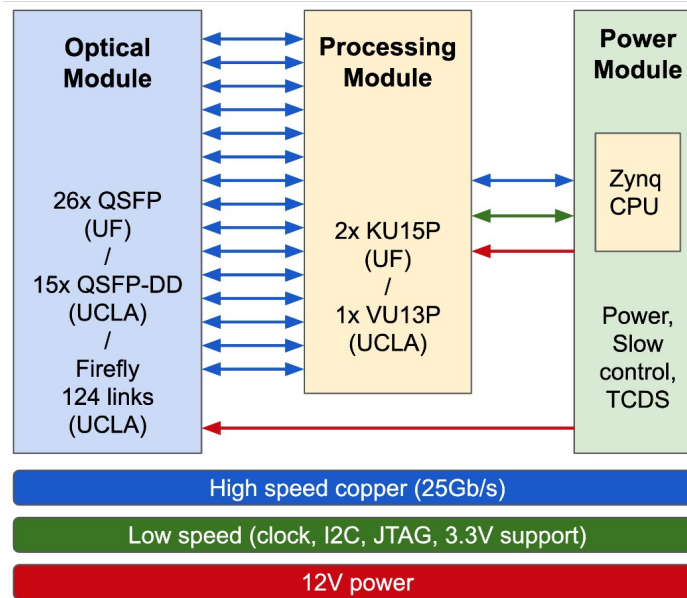
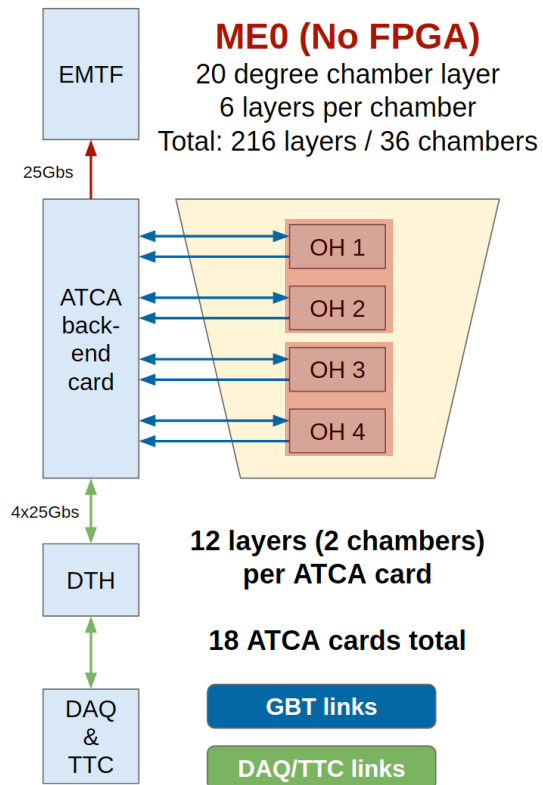


Secondary (S)
IpGBT

Main (M)
IpGBT



BACK-END: X20



X20 ATCA board: common back-end for CSC, GE2/1 and ME0
Developed by UF, UCLA and Vinča

- 18 boards for ME0 (2 ME0 stacks read out by one board)
- Based on VU13P FPGA with CERN-B Fireflies or QSFP
- v1 tested with final front-end in test stands
- Waiting for v2 in early 2023 (updated FPGA, power module)
- Prototype segment finding algorithm implemented, to be tested on first stack

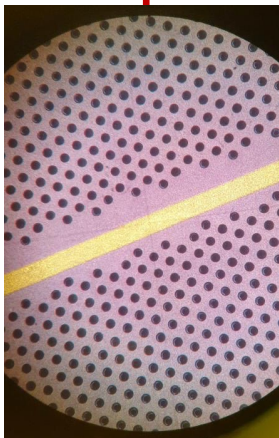


RANDOM HOLE SEGMENTATION

All CMS GEM detectors were manufactured with a **blank segmentation**: sector separation is performed with a manually aligned mask that leaves a wide region (200-600 μm) on uncovered polyimide

Random hole segmentation

Sector separation performed with random alignment between gap and sector holes



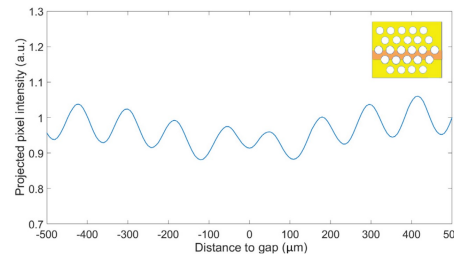
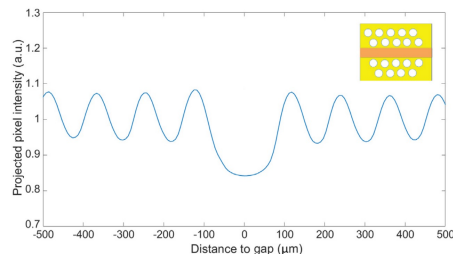
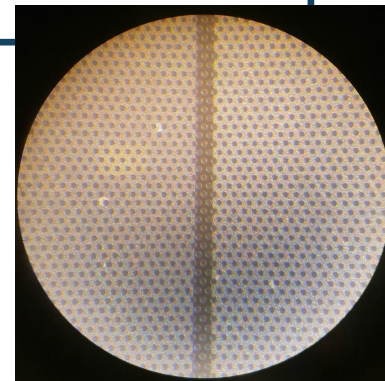
Drawbacks:

- Large dead area
- Signal distortions
- Technically difficult for many oblique sectors (ME0 2nd gen)

ME0 2nd-gen prototype with random hole segmentation

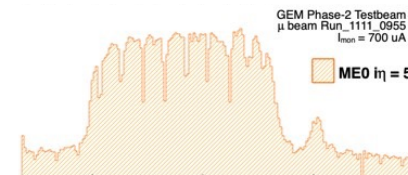
planned for next year

So far, random segmentation only mastered with single-mask technique: R&D needed for double-mask production



Sector separation regions observed in blank and random segmentation detectors

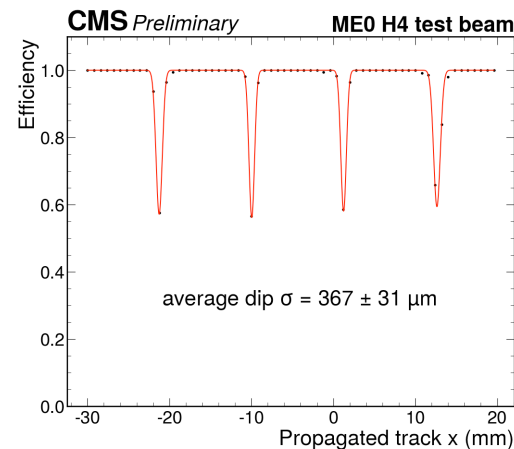
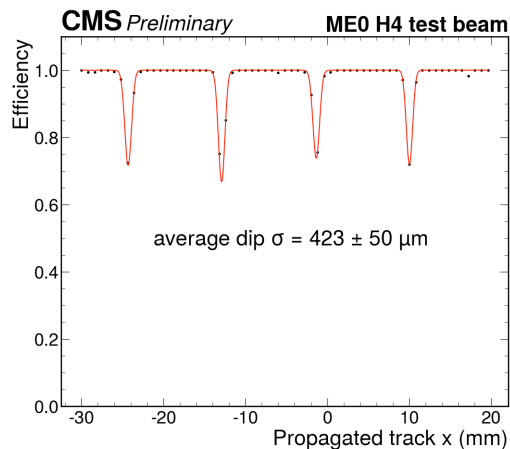
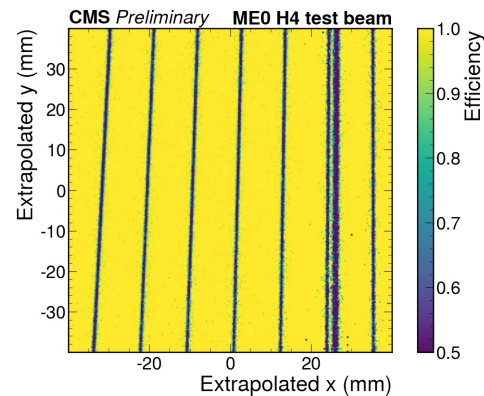
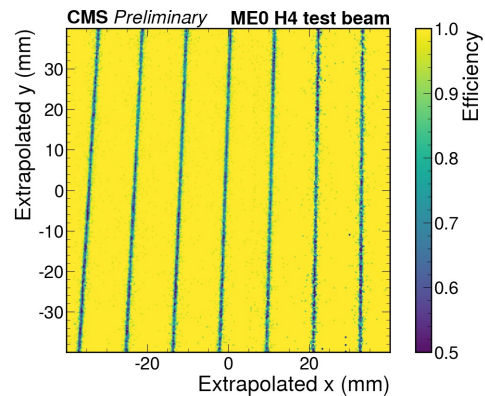
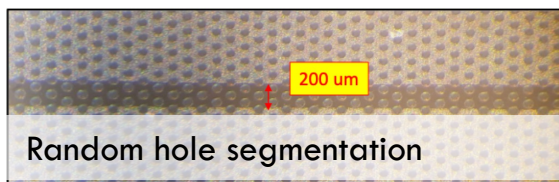
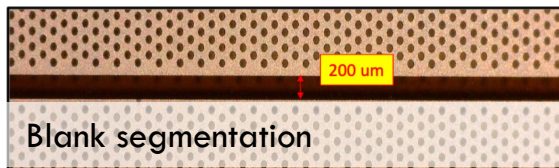
More information on random hole segmentation by [E. Fallavollita](#) and [F. Brunbauer](#)



ME0-II-CERN-0001 beam profile observed in Fall 2021 test beam (see Piet's talk)



EFFICIENCY AND RANDOM HOLE SEGMENTATION



Random hole

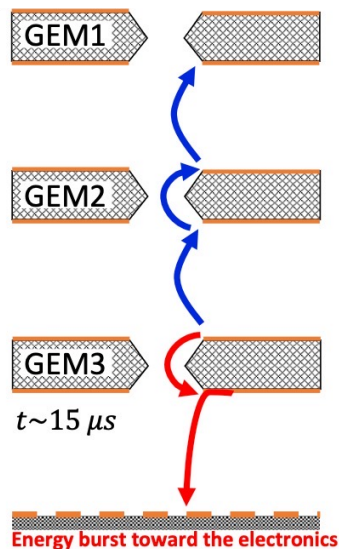
Blank segmentation



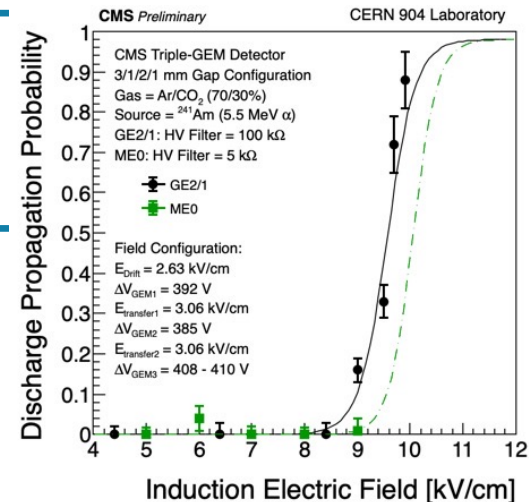
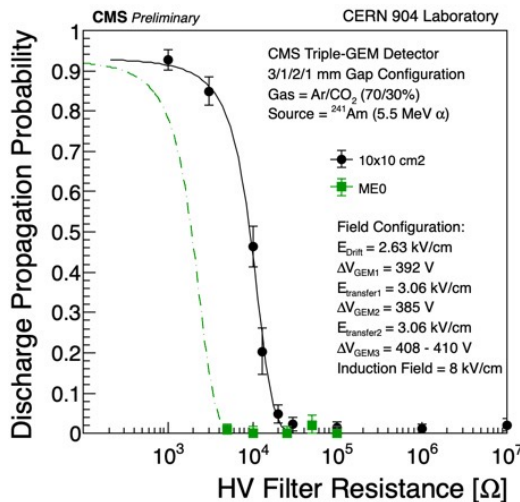
DESIGN VALIDATION: DISCHARGE PROPAGATION

For **ME0 detectors** expected lower discharge propagation than GE2/1
active sector area $\sim 60 \text{ cm}^2$

- Preliminary measurements in line with expectations
- Discharge propagation probability gap $O(10^{-4})$



Confirmed improvement
w.r. to GE2/1. Negligible
propagation at highest
induction field measured



No significant dependence of
discharge probability on filter
resistance observed. However higher
re-ignition rates observed with 5 and
10 kΩ filters
→ picked 50 kΩ as filter for ME0

Discharge propagation towards readout