The upgrade of the CMS muon system for the High Luminosity LHC

September 25th, 2023

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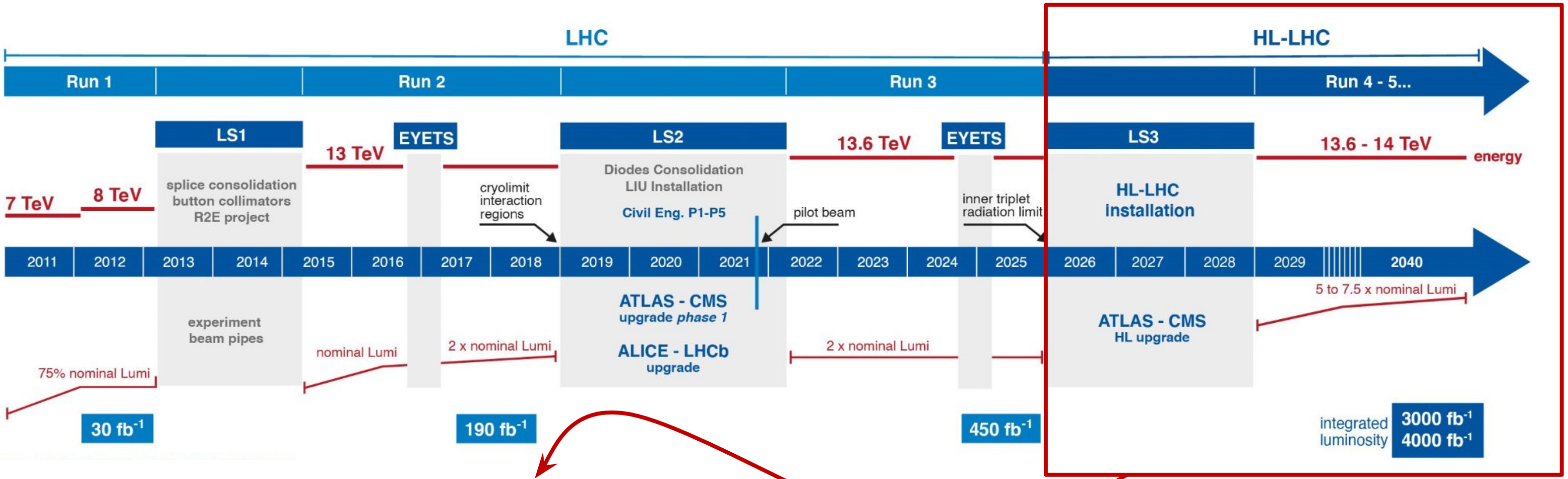
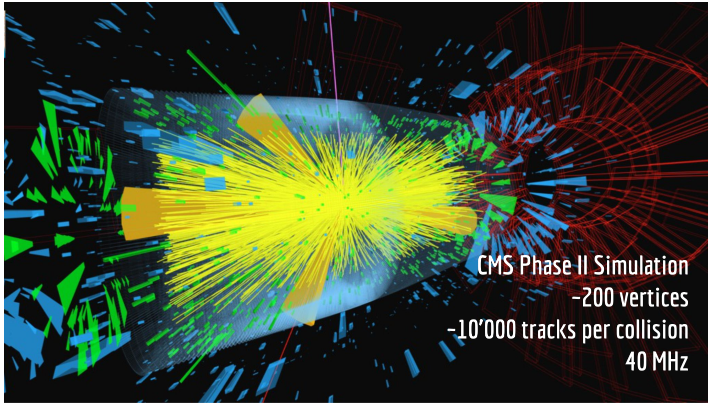
High-luminosity LHC





→ **Integrated luminosity** up to 4000 fb^{-1}

→ Precision tests of **standard model, Higgs physics, new physics** via loops:

- ↳ Higgs couplings
- ↳ Di-Higgs production
- ↳ Rare decays

CMS muon system upgrade

Drift tubes (DT)

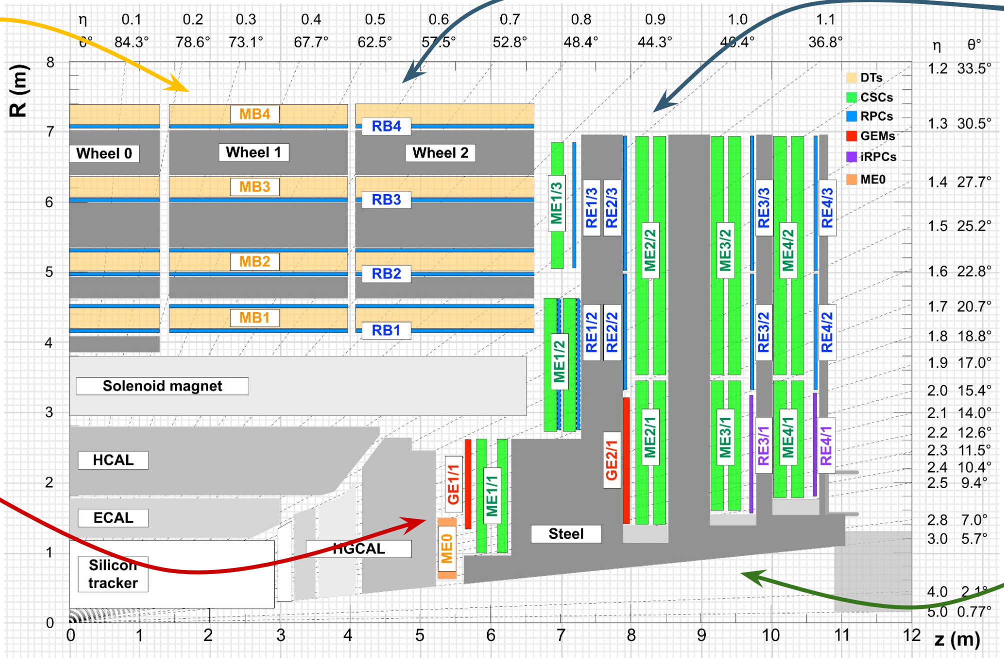
→ On-detector and backend electronics upgrade

Gas electron multiplier (GEM)

NEW

→ Complementing CSC in forward region (GE1/1, GE2/1)

→ Extending muon system acceptance (ME0)



Resistive plate chambers (RPC)

NEW

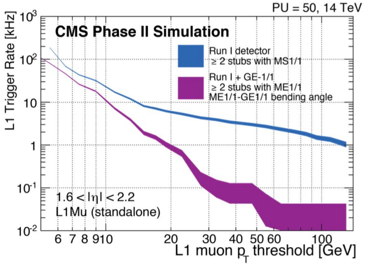
→ Link system upgrade

→ Complementing CSC in forward region (RE3/1, RE4/1)

Cathode strip chambers (CSC)

→ On-detector electronics replacement

→ Back-end upgrade

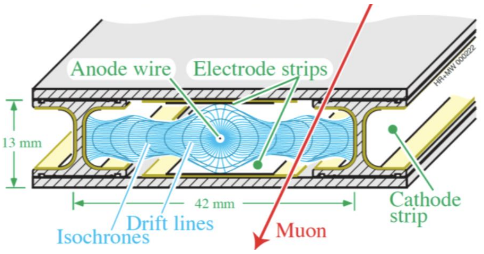


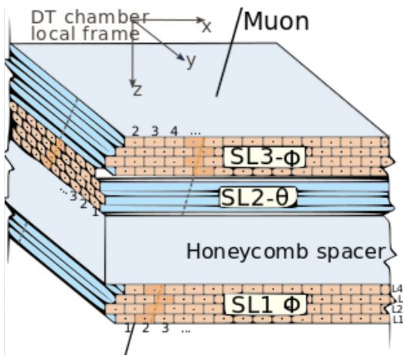
Upgrade goals: sustaining higher trigger rates and background dose in **High-Luminosity LHC**, redundancy in the **forward region**, extending the acceptance in the **very forward region**

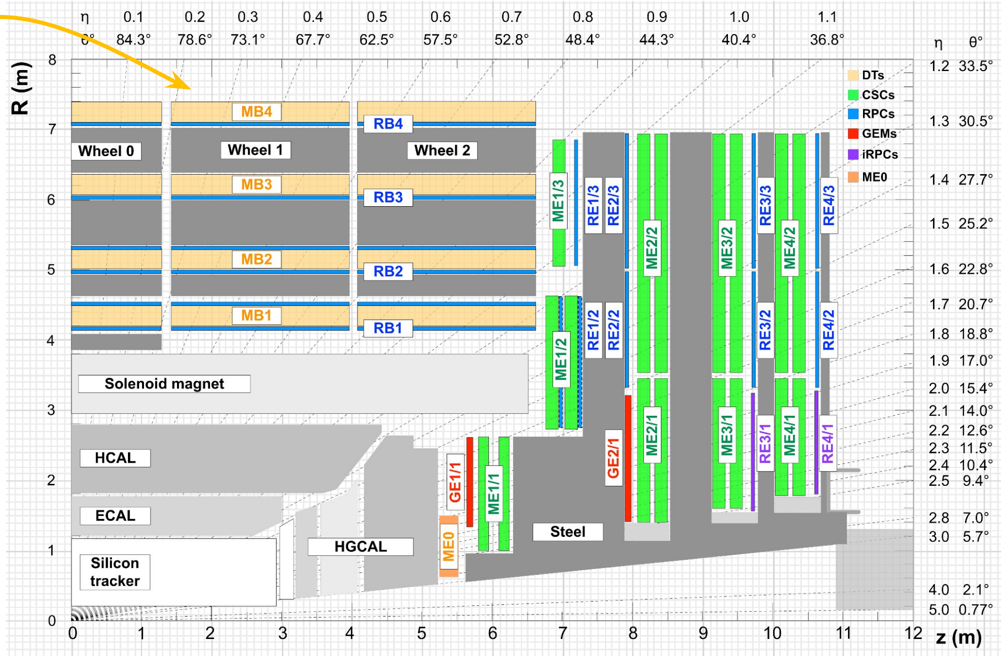
DT upgrade

Drift tubes (DT)

→ On-detector and backend electronics upgrade







DT electronics upgrade

See poster by A. Bergnoli

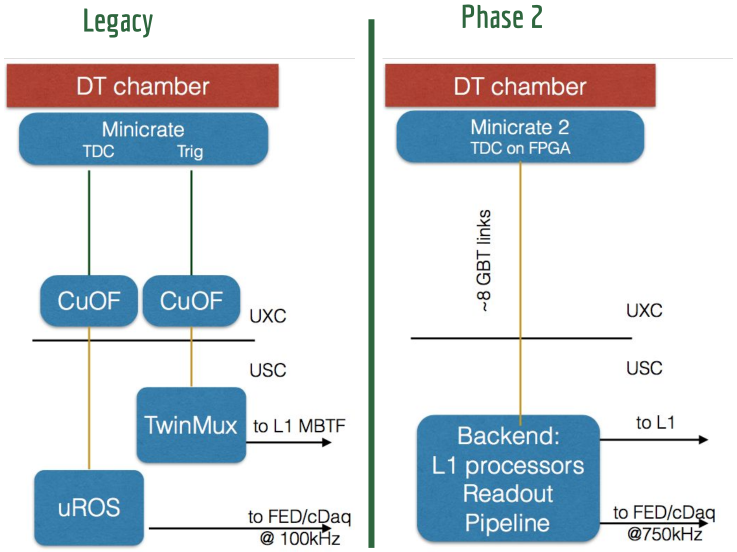
Motivations for **upgrade of MiniCrate** electronics:

→ Allow L1 rate up to 750 kHz

→ Enhance reliability by moving components to USC

Trigger primitives generated in **back-end**

Allows for higher complexity, exploit full DT timing



DT electronics changes foreseen in the upgrade

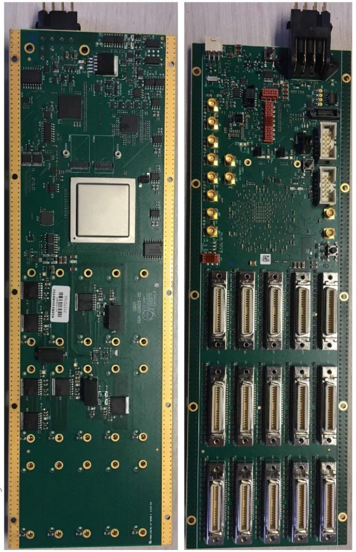
The core of the upgraded **MiniCrate 2 is the OBDT:**

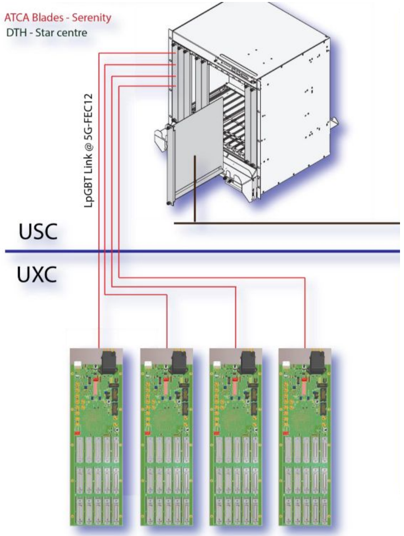
→ 2 board types (**theta/phi**)

→ **240 TDC channels** implemented in FPGA (σ_t<1ns, DNL<2%)

→ 1/3 power of MiC1, higher channel density

→ Two versions: v1 with front-end over **GBTx** and **SFP+** to backend v2 upgrades to **lpGBT** and **VTRX+**





DT demonstrators

First slice test: **YB+2 S12**

→ 13 OBDT v1 installed, integrated and active doing **cosmics and first collisions**

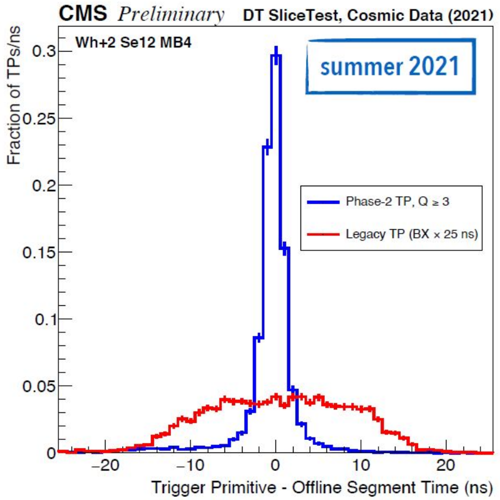
→ Slice test read out in **parallel between legacy and Phase 2** electronics

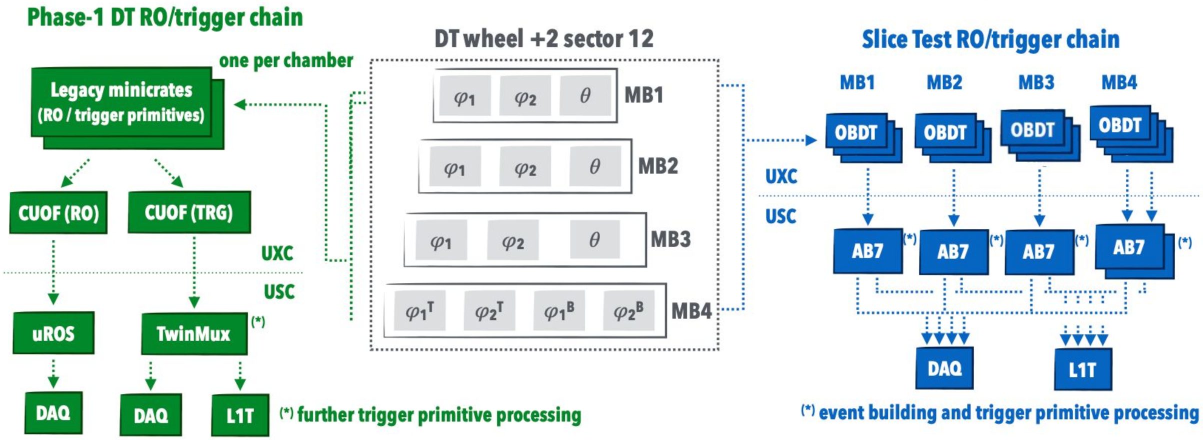
*1 Phase-2 back-end also tested: trigger primitives with **full granularity***

Second **slice test in YB+2 S1:**

→ Installed in **2022/23 YETS**, tested with cosmics

→ Uses OBDTv2 and monitoring and safety system (MONSA)





DT longevity

DTs use Ar/CO_2 85%:15%. **Aging** mostly due to **wire deposits** during avalanche

→ Ongoing **irradiation at GIF++** since 2017

→ Irradiated 3 layers of a DT SuperLayer (SL), other 2 SLs kept as reference for **muon efficiency** measurement

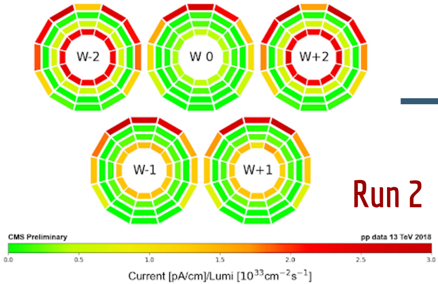
Results from aging measurements:

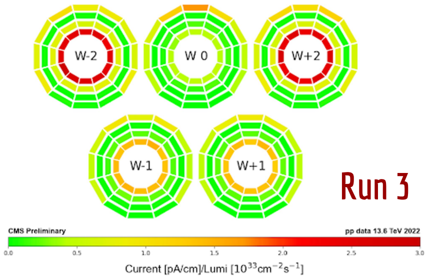
→ Layers installed **before 2018** show **larger gain drop** than later ones

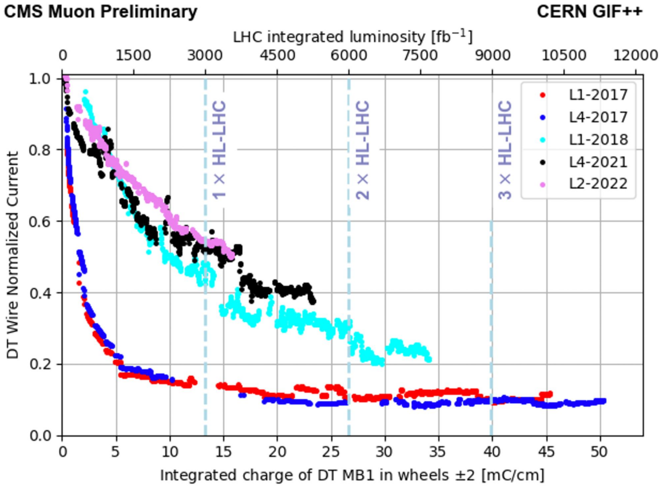
Aging seems correlated to ***carbon peak*** *in observed with spectroscopy*

→ However, integrated charges tested will **only be reached in high-η wheels** of MB1 during HL-LHC (mitigation strategies also implemented)

The redundancy there is already high also thanks to RPC and CSC: negligible impact on physics performance is expected

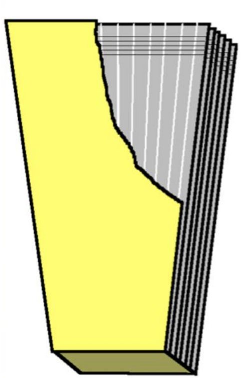


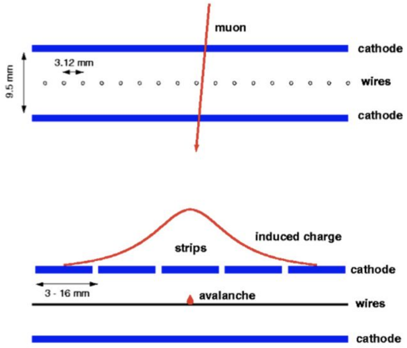


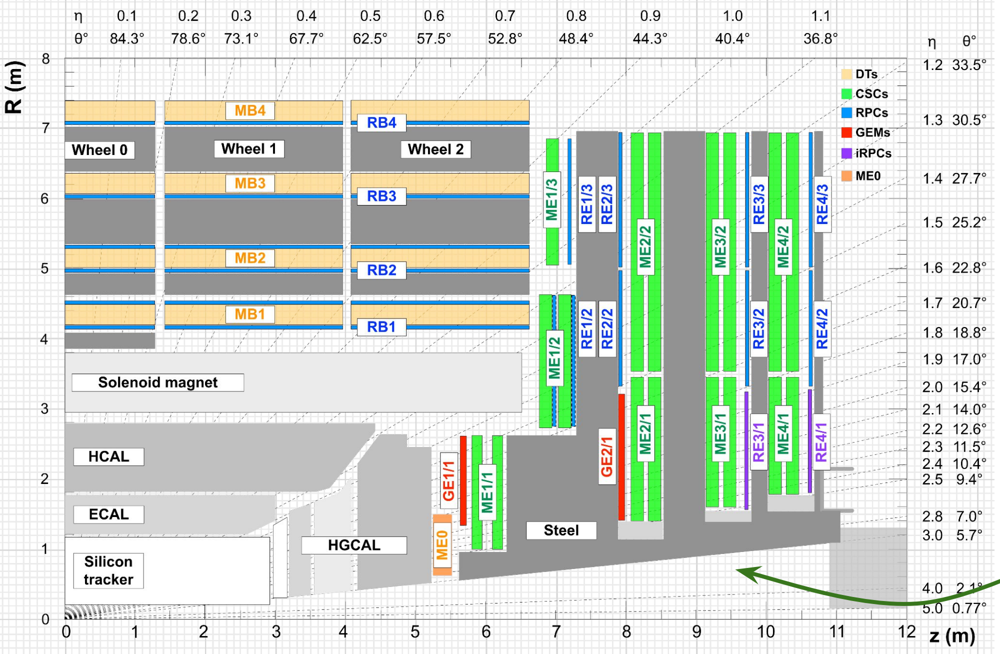


CMS

CSC upgrade





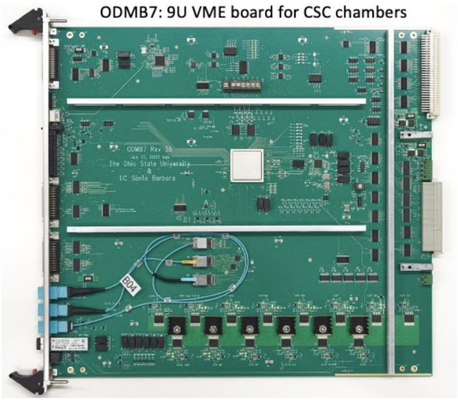


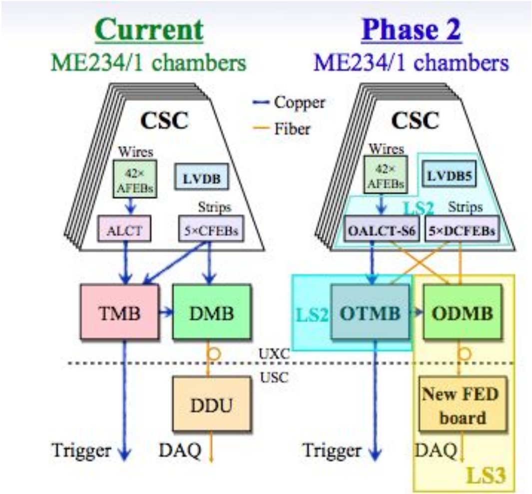
Cathode strip chambers (CSC)

→ On-detector electronics replacement

→ Back-end upgrade

CSC electronics upgrade





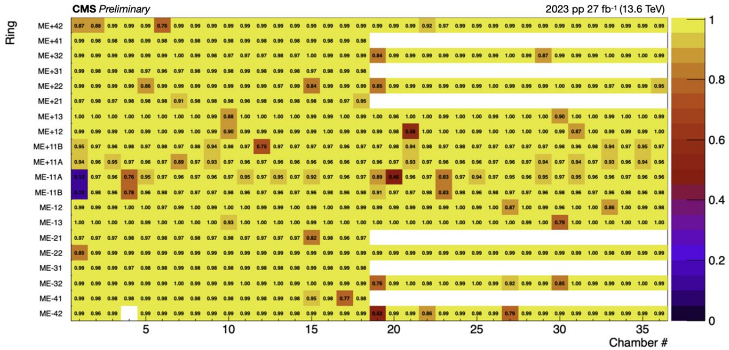
CSC upgrade involves all of electronics:

→ On- and off-chamber **front-end boards** (FEBs)

→ **Front end driver** (FED) & EMTF

→ **Power** systems

Most upgraded during LS2 and validated during Run 3. Excellent trigger primitive **efficiency, mostly > 98%**



To be added in LS3:

→ 180 upgraded off-chamber Optical Data MotherBoard (ODMB7/5) boards

Passed electronics status review in May 2023

→ Common FED with GEM (X2O) for production readiness review in fall

CSC longevity

CSCs use $Ar/CO_2/CF_4$ 40%:50%:10%. Ongoing **optimization to reduce CF_4** fraction

→ **5% and 2% CF_4** mixtures tested at GIF++

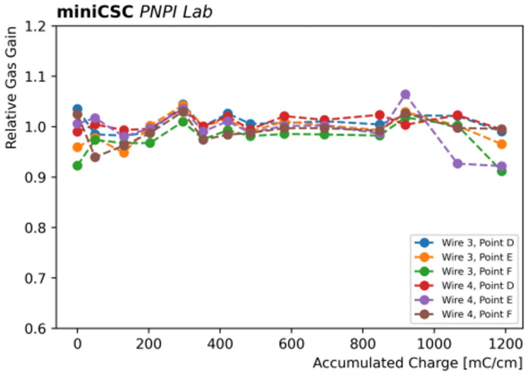
→ No gain drop observed, but **pollution** visible at microscope

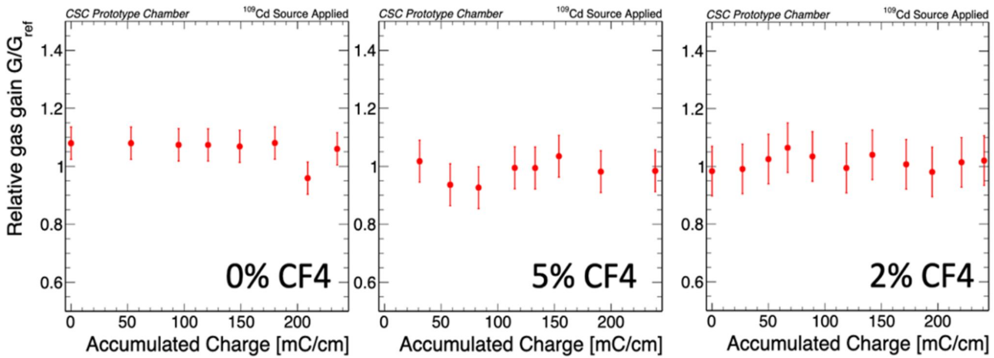
Ongoing studies, 5% CF_4 looks more promising

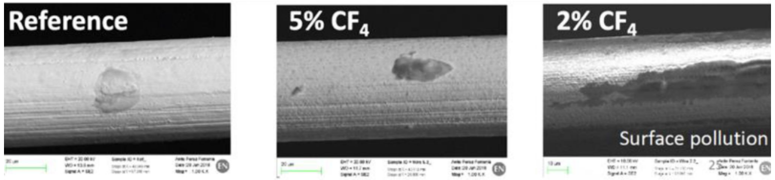
Tested also mini-CSC with **HFO-1234ze** mixture:

→ No gain drop after 10× HL-LHC integrated charge

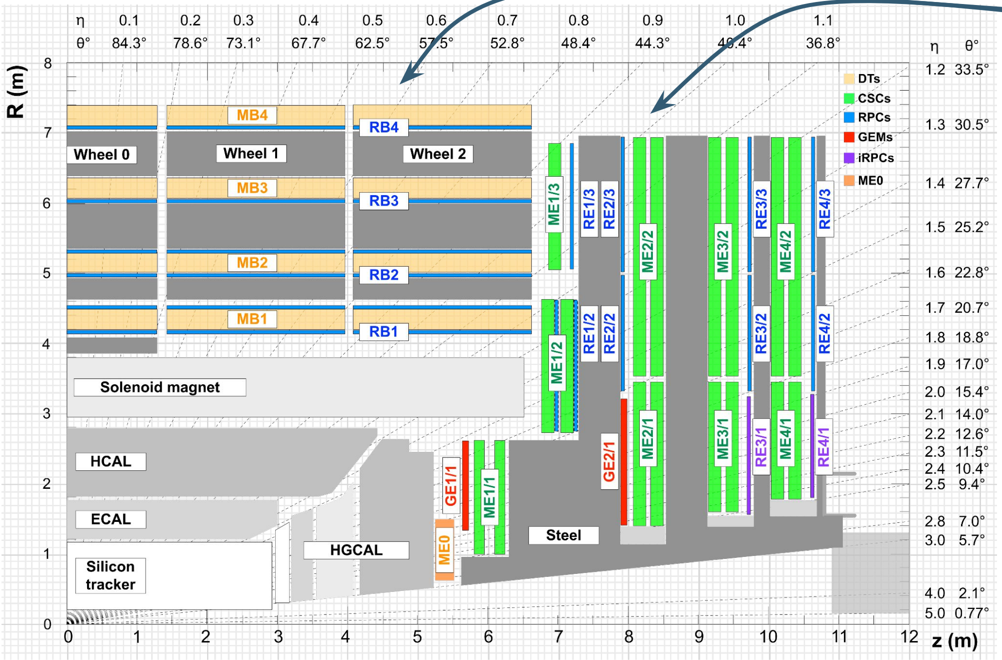
Dark current increase observed, to be-retested on full-size CSC







RPC upgrade

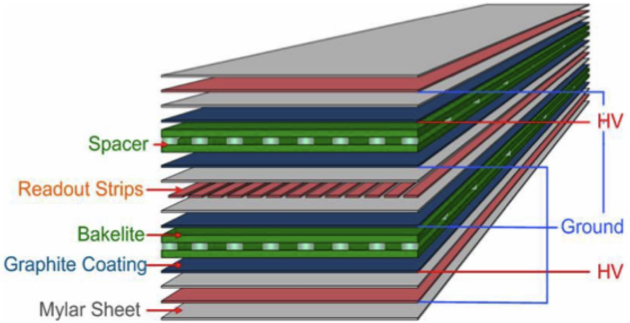


Resistive plate chambers (RPC)

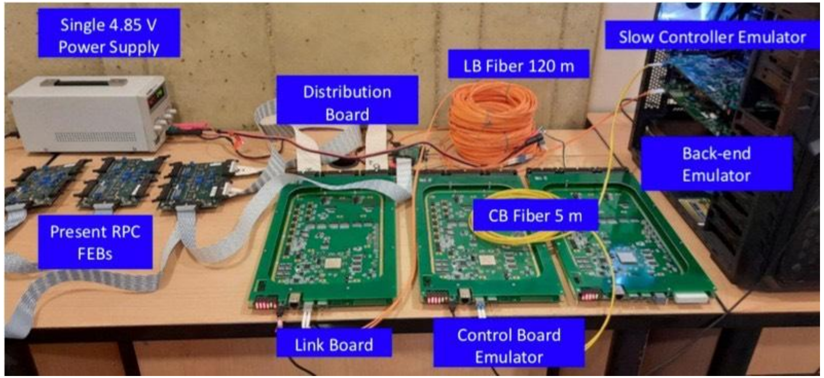
→ Link system upgrade

→ Complementing CSC in forward region

RE3/1, RE4/1



RPC link system upgrade



Run 2 RPC link system is sensitive to **possible failures**:

→ Non **rad-hard** to HL-LHC rates

→ Uses **discontinued** ASICs and FPGA

New link system uses upgraded **link board and control board**:

→ Sub-BX timing at 2.5 ns to **improve background rejection**

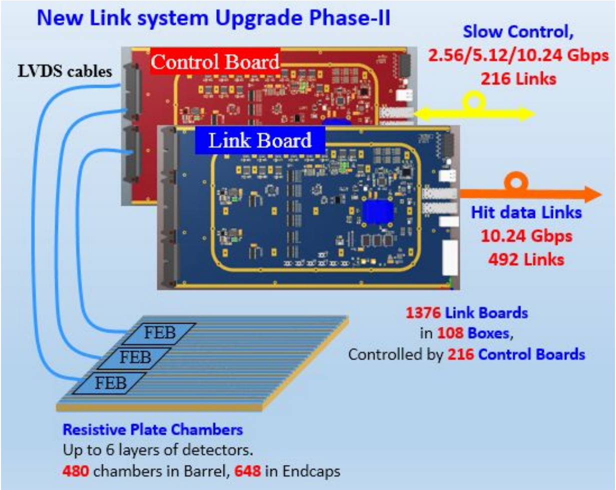
→ Compliance with **lpGBT** standard

Test stands for link system at CERN:

→ Prototypes of production-design version available
Validated at CHARM irradiation studies

→ Firmware **integration** with slow control emulator and back-end emulator **completed**

→ Pre-production started. **Integration tests at CERN** by the end of the year



RE3/1 and RE4/1 production

Improved RPC (iRPC) design:

→ Uses new front-end: 2 FEBs/chamber, 6 **Petiroc-2C** ASICs per FEB

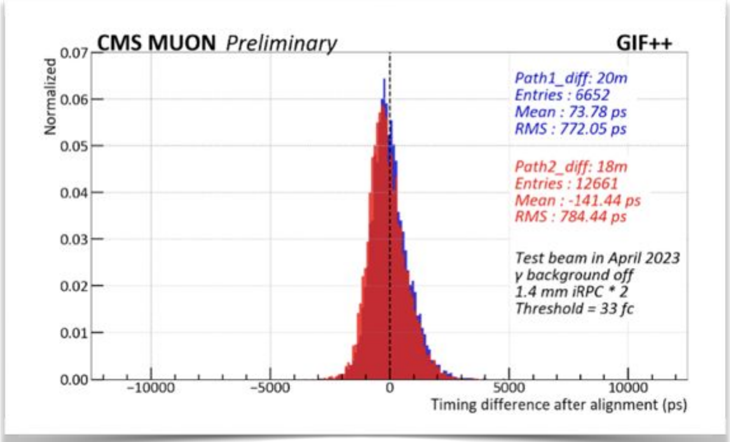
→ 96 strips, readout on both strip sides for **2D position at 2 cm** σ_η

→ On-FPGA TDC for <1 ns timing

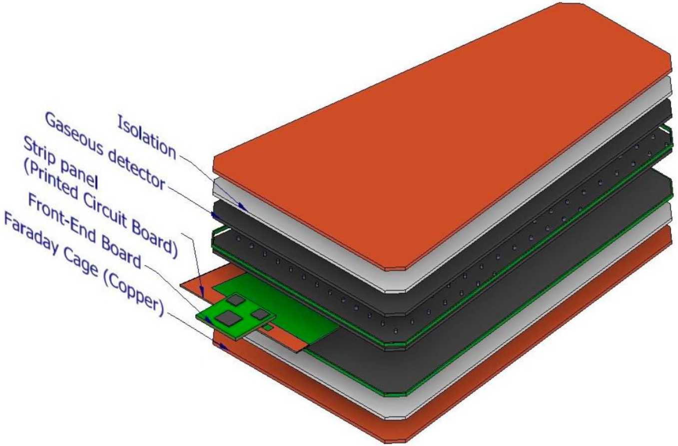
→ **Low-impedence strips + low front-end noise**

↳ Low thresholds (<50 fC) → lower gap amplification

→ Production: 14 RE3/1 and 4 RE4/1 assembled at CERN and Ghent, to be validated with cosmics



	Present	iRPC
HPL Resistivity (Ohm/cm)	$1\text{-}6\times10^{10}$	$0.9\text{-}3\times10^{10}$
Gap thickness	2mm	1.4mm
Electrode thickness	2 mm	1.4mm
Eta coverage	0 – 1.9	1.8 – 2.4
Rate Capability (Safety factor=3 included)	600 Hz/cm²	2 kHz/cm²
Max int. charge@3ab^{-1} (SF = 3 included)	~ 0.8 C/cm²	~ 1.0 C / cm²
Phi granularity	~ 0.3°	~ 0.2°
Eta resolution	~ 20 cm	~ 2 cm
Time resolution	1.5 ns	< 1 ns



RPC longevity

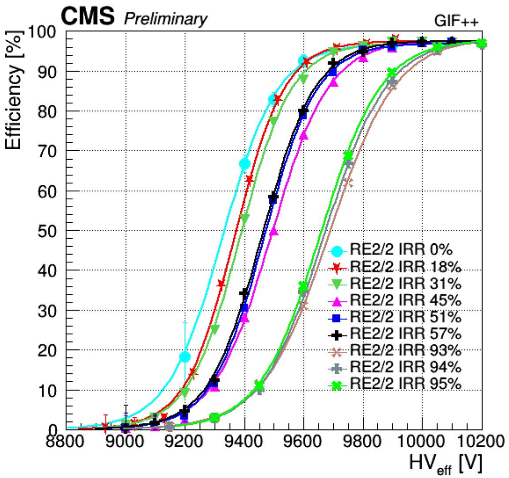
iRPC longevity **to be verified up to 0.8 C/cm²** (safety factor 3 × HL-LHC). Ongoing irradiation at GIF++:

→ Status of the studies: **RE2 up to 96%, RE4 to 57%**

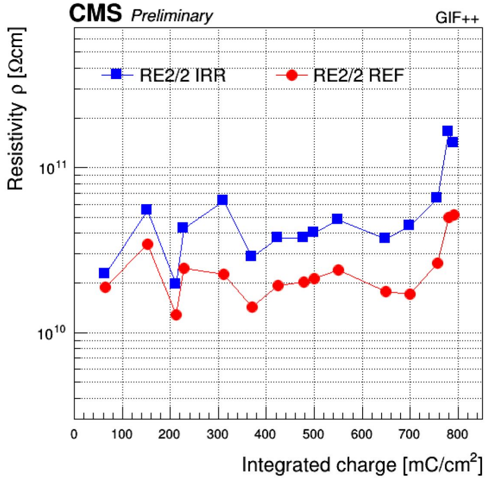
Efficiency measured with μ beam after extended irradiation

→ No ageing observed without background, but **observed shift** up to 200 V in the efficiency turn-on point with source on

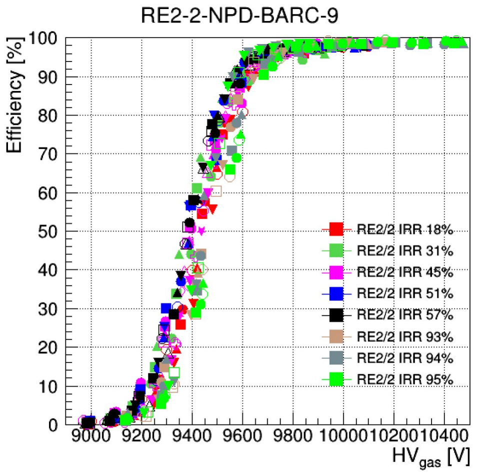
→ Effect ascribed to increase in the **bakelite resistivity** after irradiation.
The **curves overlap by compensating** for the corresponding voltage drop. **Result: no effect of aging observed.**



Efficiency turn-on curve measured at different stages of the irradiation

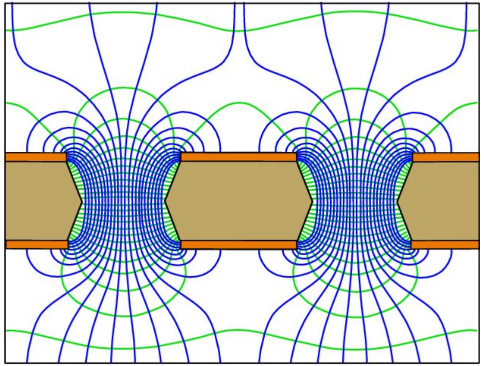


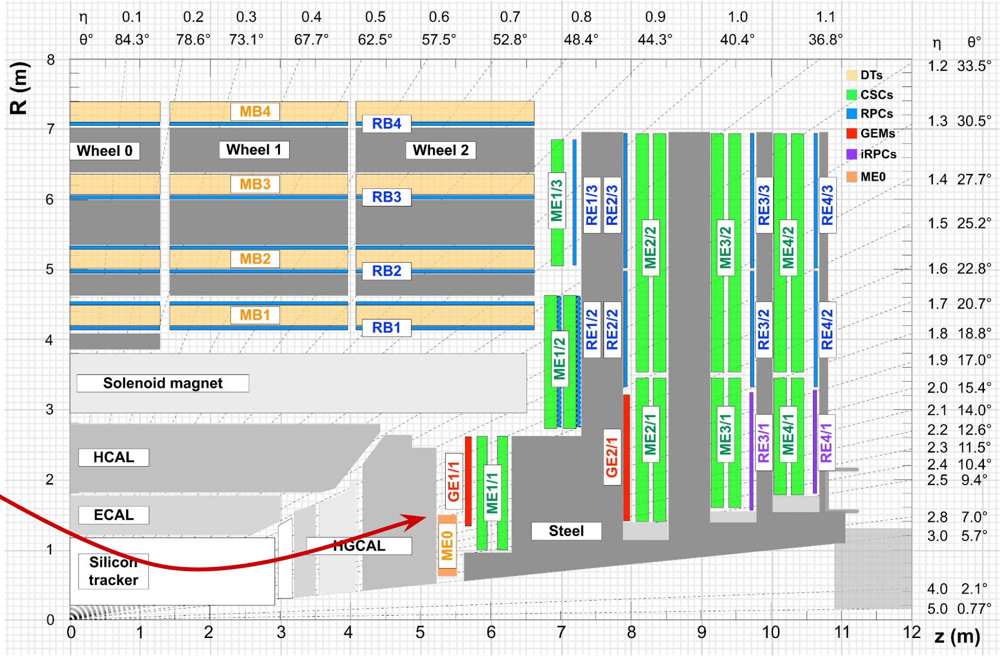
Bulk resistivity of the RPC electrodes as a function of the integrated charge



Efficiency scan after compensating for the voltage drop on the electrodes

GEM upgrade





Gas electron multiplier (GEM)

→ Complementing CSC in forward region

GE1/1, GE2/1

→ Extending muon system acceptance

ME0

GEM upgrade: GE1/1 and GE2/1

Motivation: complementing closest CSC stations (ME1/1 e ME2/1)

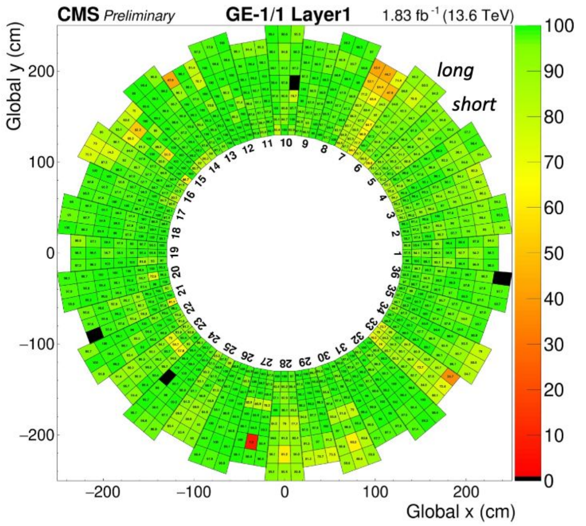
↳ Better **p_T resolution** in trigger ⟶ x 10 trigger rate reduction

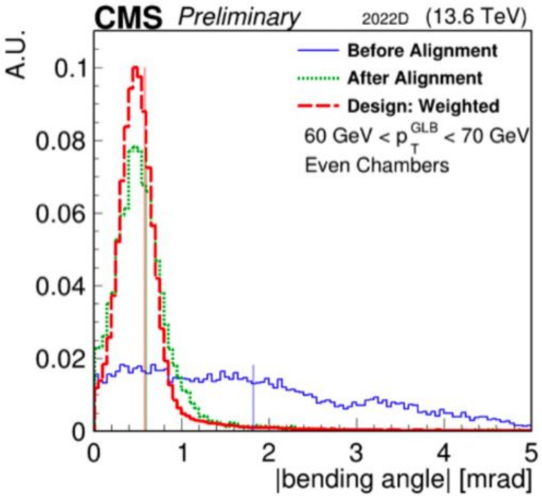
For each station, one disk per endcap:

↳ **GE1/1: 36 super-chambers** per endcap (10° aperture)

↳ **GE2/1: 18 super-chambers** per endcap (20° aperture)

Each **super-chamber is a 2-layer** triple-GEM detector stack





GE1/1 detector installed in LS2, commissioned and operated in cosmic runs and Run 3:

↠ **Plateau efficiency** measured for all detectors [5]

⟶ Main efficiency loss causes: **HV** (short circuits), **electronics** (VTRx optical power loss)

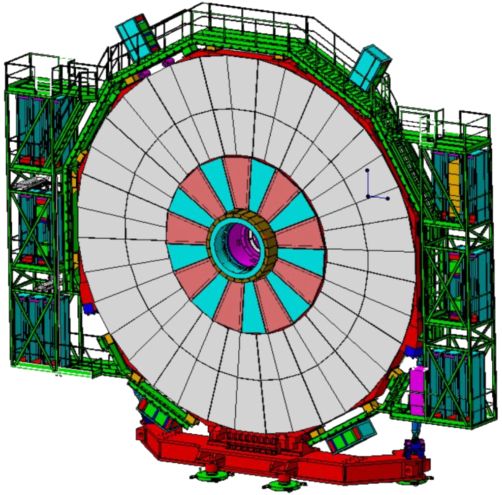
↠ Space and time alignment **with respect to CSC** with collision data

↠ **Muon bending angle** $\phi_{CSC} - \phi_{GEM}$ measured using offline data

⟶ Observable dependency on p_T after alignment

⟶ To be implemented in **trigger**

GE2/1 detector production



GE2/1 detector undergoing production:

→ Design similar to GE1/1, over **larger area**

→ Performance measured in **test beam** [6]

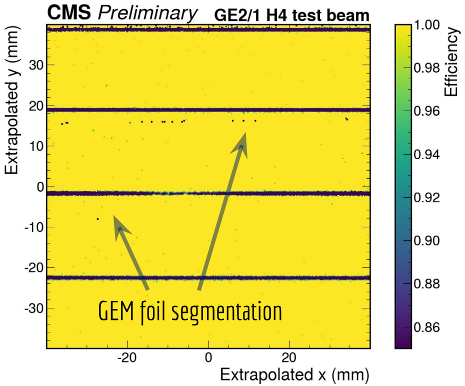
  ↳ **Very high efficiency** (> 99% excluding GEM foil segmentation)

  ↳ < 300 μrad **space resolution**

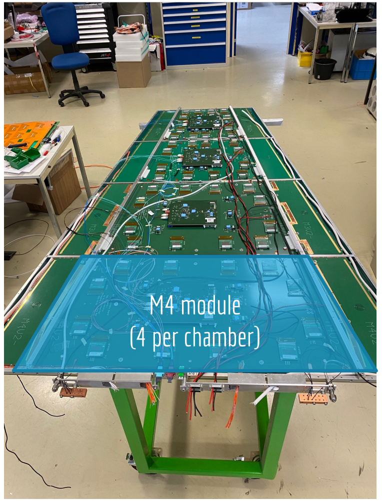
→ **GE2/1 demonstrator** installed and integrated in CMS DAQ / DCS

→ New chambers to be installed **starting 2023 technical stop**

GE2/1 demonstrator during installation

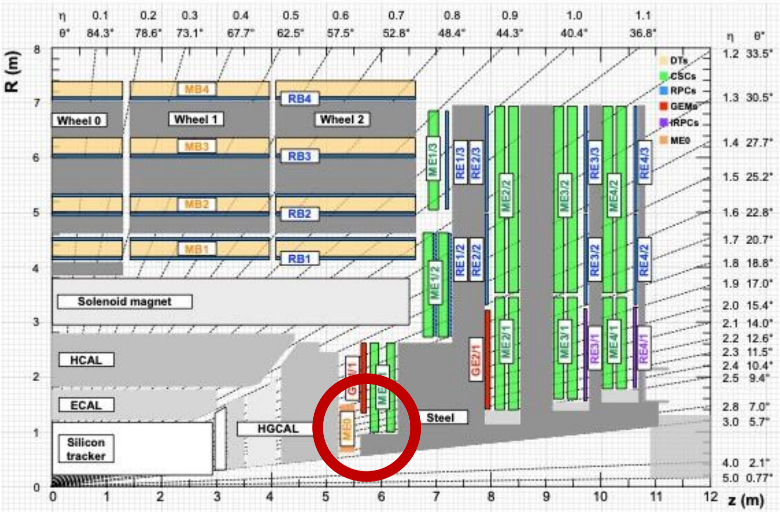


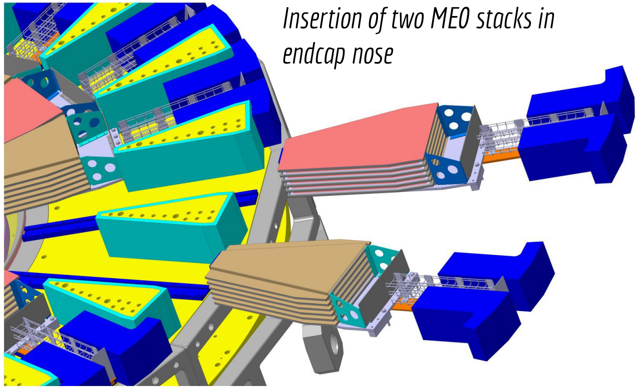
Efficiency map of GE2/1 detector measured in test beam [6]



First GE2/1 chamber assembled at CERN

ME0 system overview





Insertion of two ME0 stacks in endcap nose

Closest muon station to LHC beam line: 2 <|η|<2.8

→ **Complementing GEM/CSC** in p_T measurement in 2 < |η| < 2.4

→ **Extending muon system acceptance** in 2.4 < |η| < 2.8

→ Each stack is made of **six triple-GEM detectors**

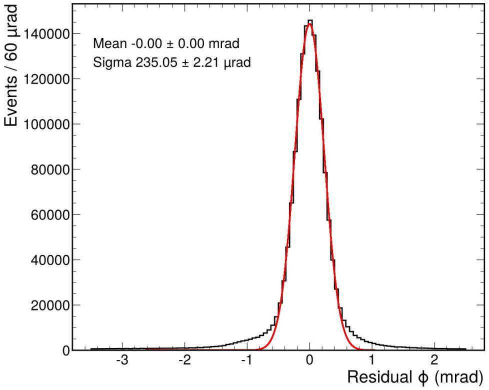
↳ Working **standalone for online segment** reconstruction

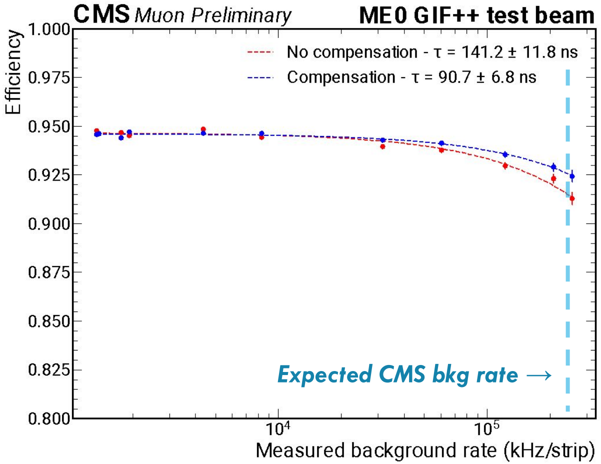
↳ 18 stacks per endcap

↳ Stack aperture $\delta\phi$ = 20°, $\delta\eta$ = 0.8

Design validated in test beams, also with high background *(see F. Simone's talk)*

Pre-production started, installation scheduled early LS3





Conclusions

The CMS muon system is undergoing an **upgrade** in its detectors and electronics **to sustain the HL-LHC rates** and extend its **acceptance**:

- The DT and CSC stations are upgrading their **front- and back-end electronics**; production ongoing
- The RPC stations are upgrading their **link systems**; two **improved RPC** detectors to be installed in the forward region are in mass production
- Three GEM stations will complement the existing system in the **forward region and extend** the muon system acceptance; production of the latter two stations is ongoing

All existing stations are leading **aging studies** to validate the system against HL-LHC integrated charge; from projections of ongoing studies **expect no degradation** of physics performance.