The CMS Muon Spectrometer Upgrade

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On behalf of the CMS Collaboration

ICHEP 2020 - Virtual Conference

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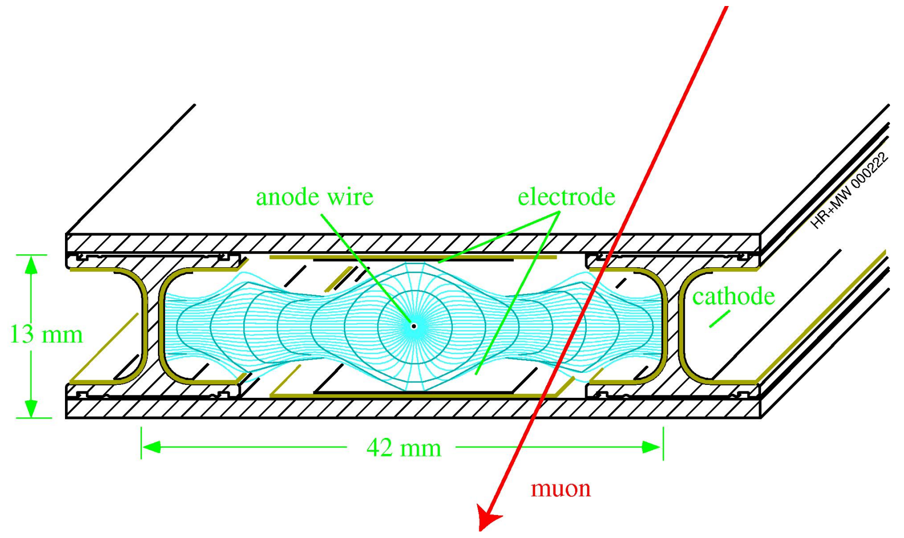
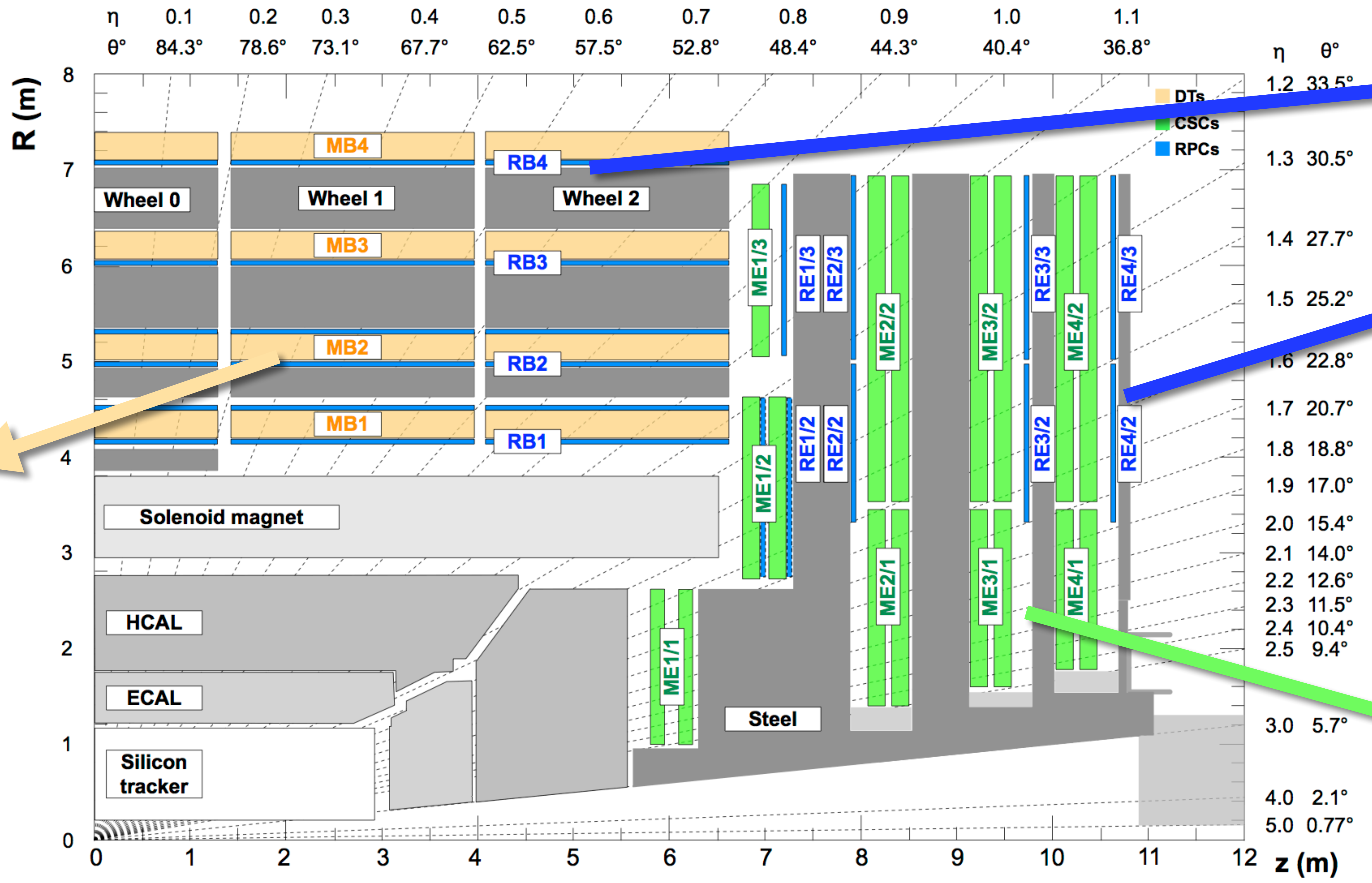
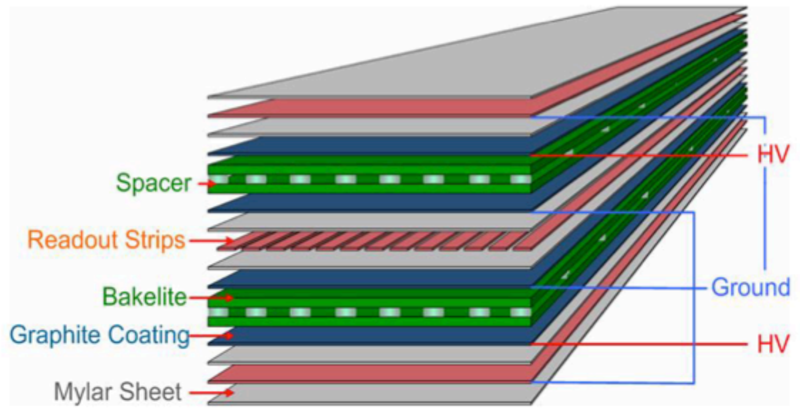
The CMS Muon Spectrometer

Drift Tubes (DT)
|η|<1.2
250 Barrel Chambers

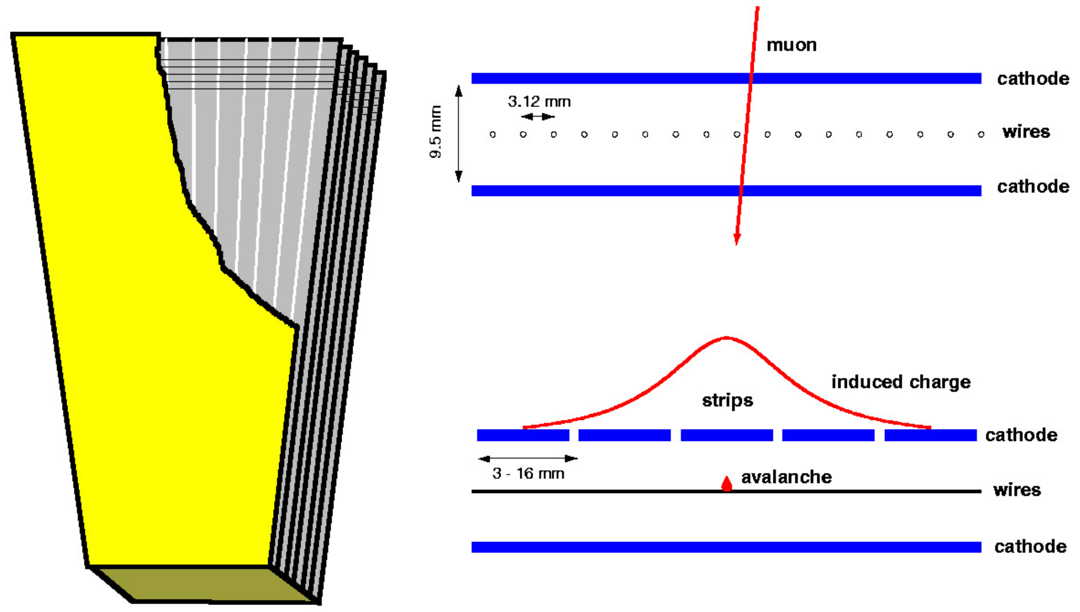




Resistive Plate Chambers (RPC)
|η|<1.9
480 Barrel Chambers
576 EndCap Chambers



Cathode Strip Chambers (CSC)
0.9<|η|<1.9
540 Endcap Chambers

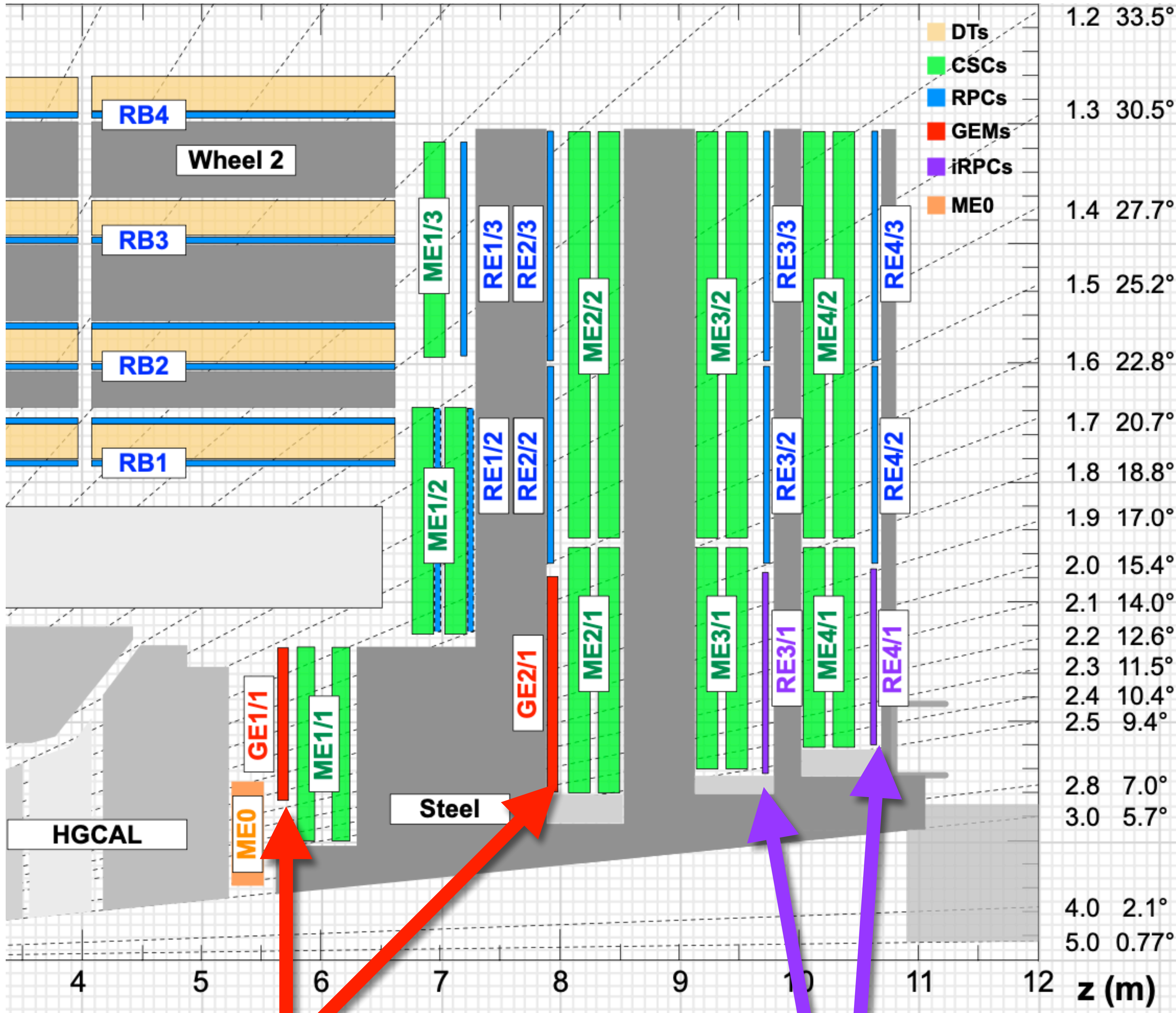


- The Muon Spectrometer cover the Barrel and Endcap of CMS using different gaseous detector technologies
  - It showed **excellent performances** at LHC in triggering, identification and reconstruction of muons
    - See C. Battilana talk “*Performance of the reconstruction and identification of high-momentum muons collected with CMS in 13 TeV data*"

The Upgrade for HL-LHC

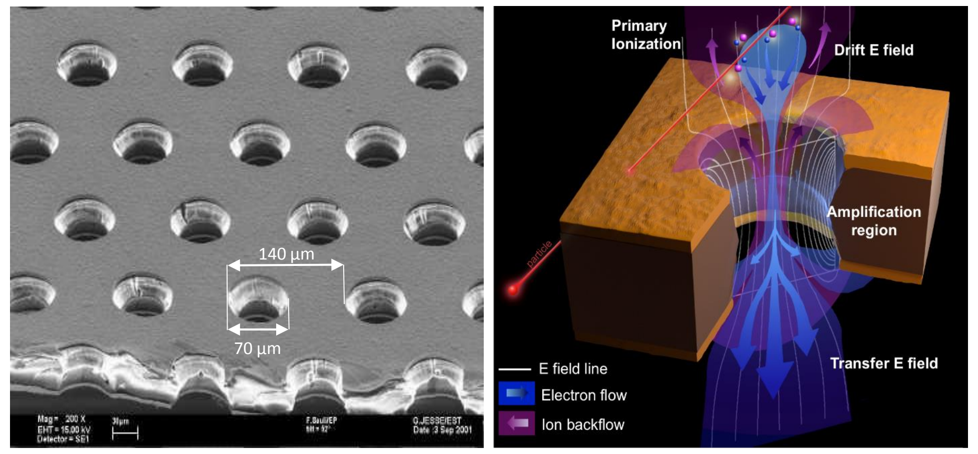
	LHC design	HL-LHC design	HL-LHC ultimate
peak luminosity ($10^{34}\ cm^{-2}s^{-1}$)	1.0	5.0	7.5
integrated luminosity (fb^{-1})	300	3000	4000
number of pileup events	∼30	∼140	∼200

- The ongoing upgrade of the LHC to High Luminosity (HL-LHC) will be challenging
    - **peak luminosities starting at $5 \cdot 10^{34}\ cm^{-2} \cdot s^{-1}$** with ~140 pileup (PU) events
    - **integrated luminosity at least ten times** the LHC design value.
- The **Muon Upgrade** will cope with the new operating condition and **extend** the physics potential of CMS:
    - **New detectors** (GEM and iRPC) in the forward region to extend **acceptance, resolution and redundancy**
    - Upgrade of the **existing detector electronics** with improved radiation hardness to handle the increased rate
    - Test of the Longevity of all the detectors for the new expected integrated luminosity and operational time
- **The Phase-2 Upgrade has already started!**
    - Will be completed at the end of LHC LS3 (~2028)



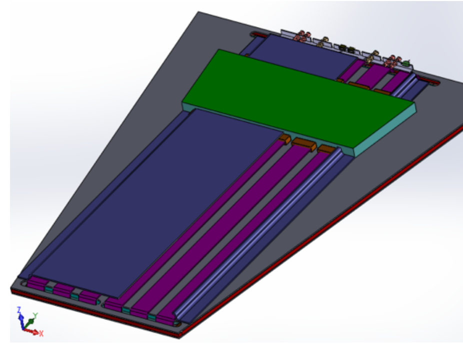
Gas Electron Multipliers (GEM)

72 Endcap Chambers 1.6≤|η|≤2.8



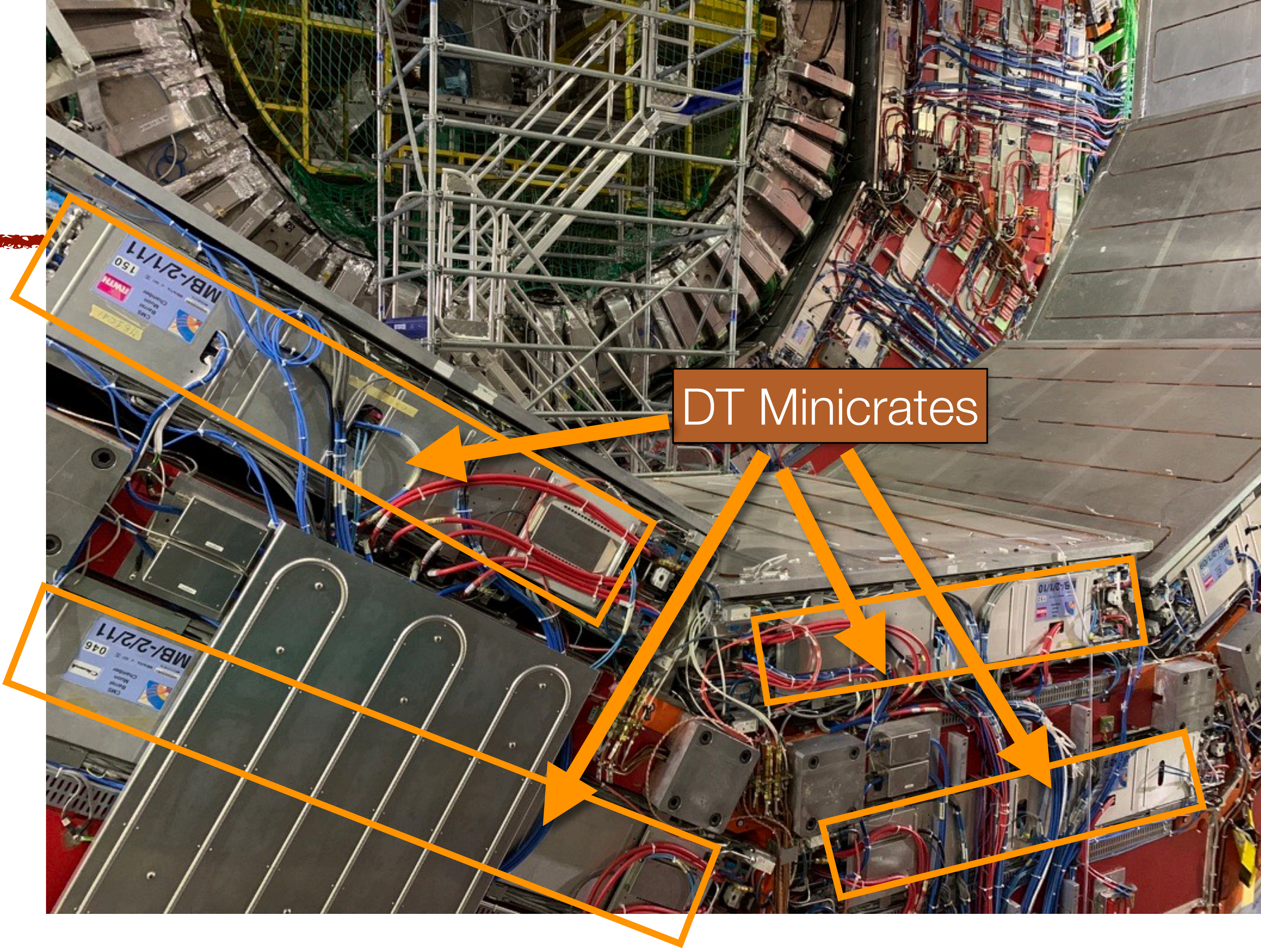
Improved RPC (iRPC)

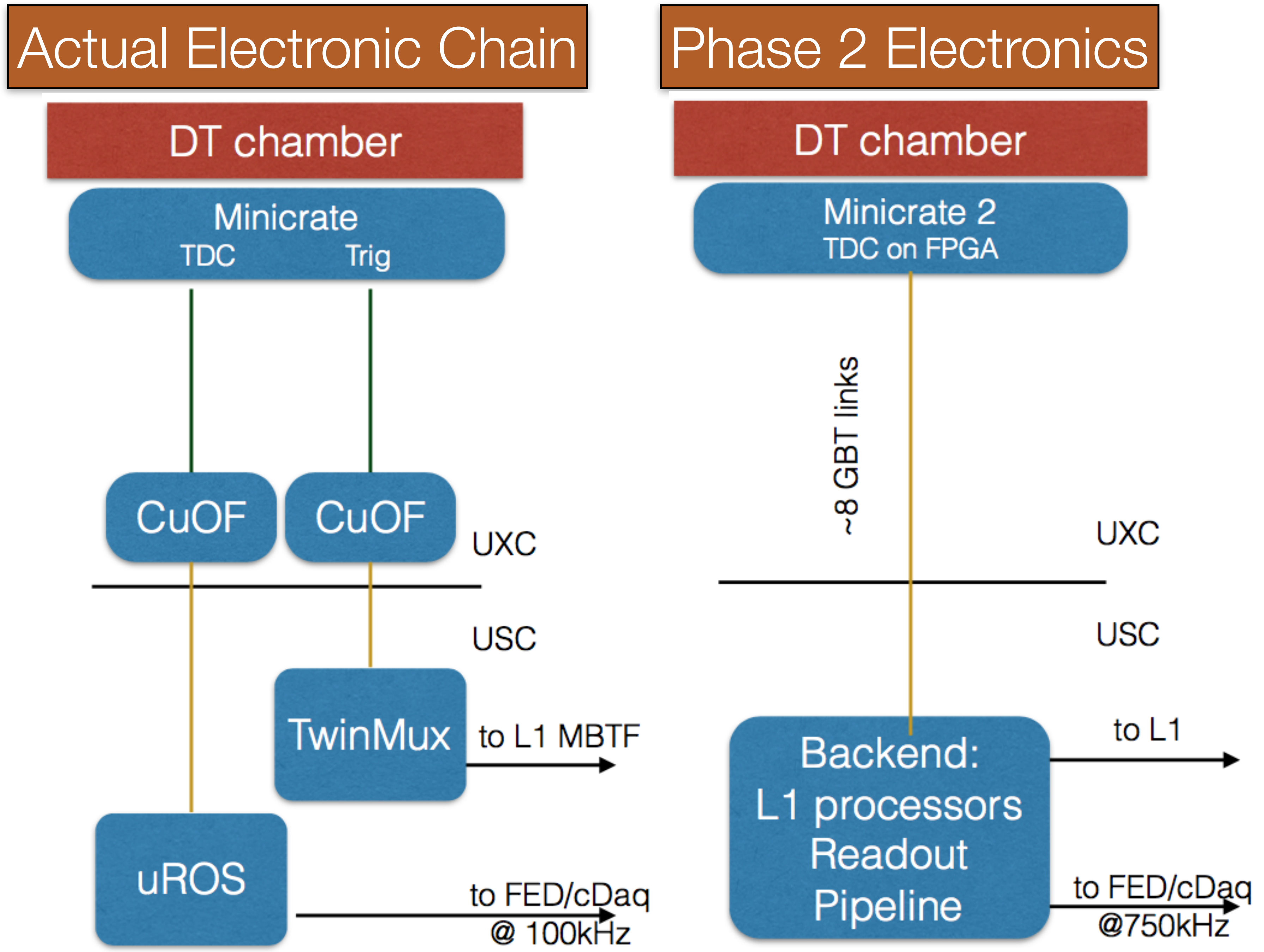
18 Endcap Chambers 1.8<|η|<2.4



The DT electronic Upgrade

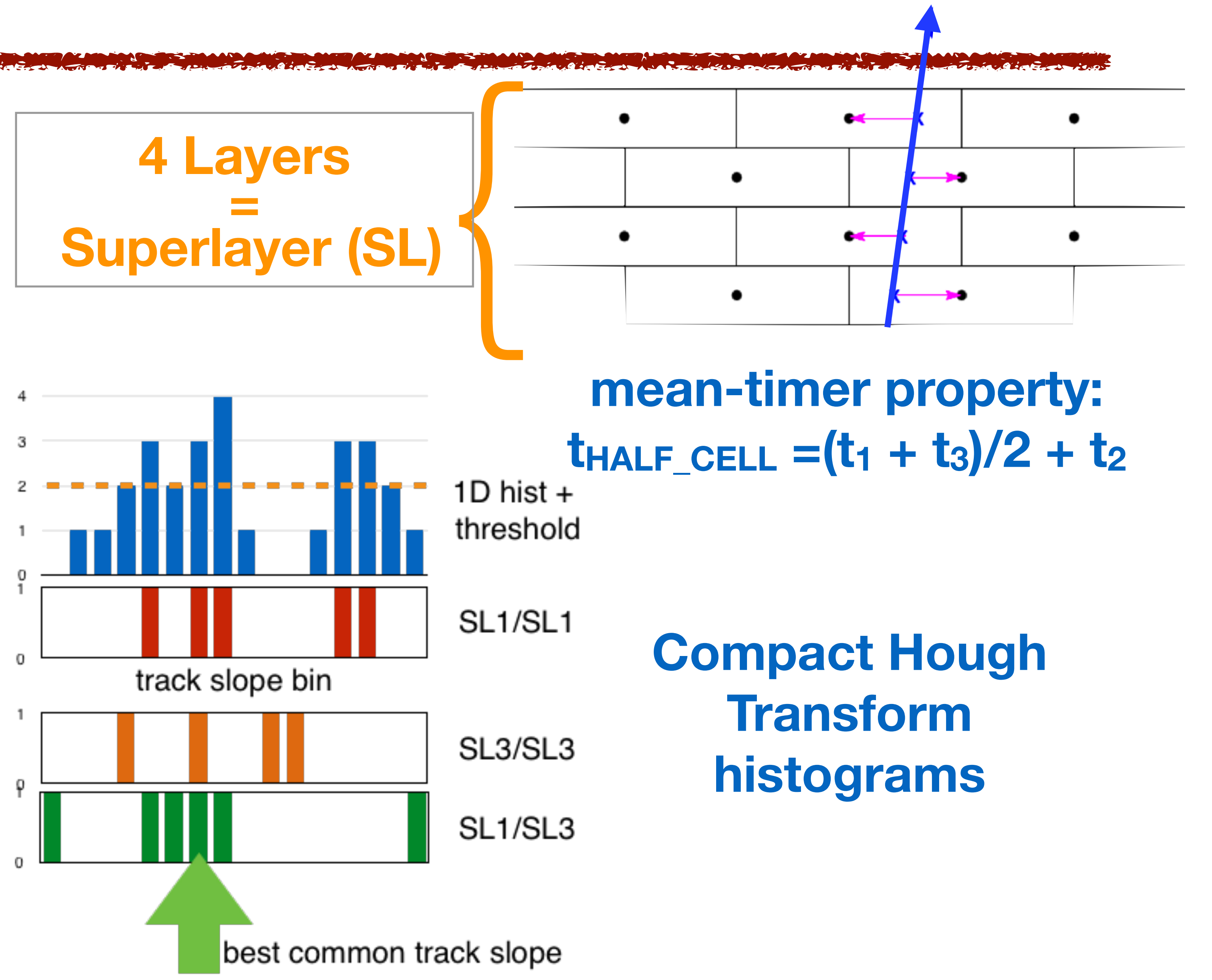
- The signal coming from the DT FE are processed by the **MiniCrate**, a complex system of boards handling trigger and readout
  - **not able to withstand** the expected background rate at HL-LHC
  - **not able to handle** the maximal Level-1 Trigger up to 750 kHz
- **New electronic based on 1 type of board (OBDT)**
  - TDCs implemented of FPGA
  - improved performance, radiation hardness and long time maintenance
  - capability to comply with HL-LHC requirements
- **Trigger logic system moves completely to the back-end** outside of the experimental cavern
  - more flexibility in combining DT and RPC hits to form Trigger Primitives (TP)
  - higher efficiency using more than 4 layers for TP
    - improved resilience to ageing and detector failures
- **Installation will be performed during LS3 (2025-2027)**



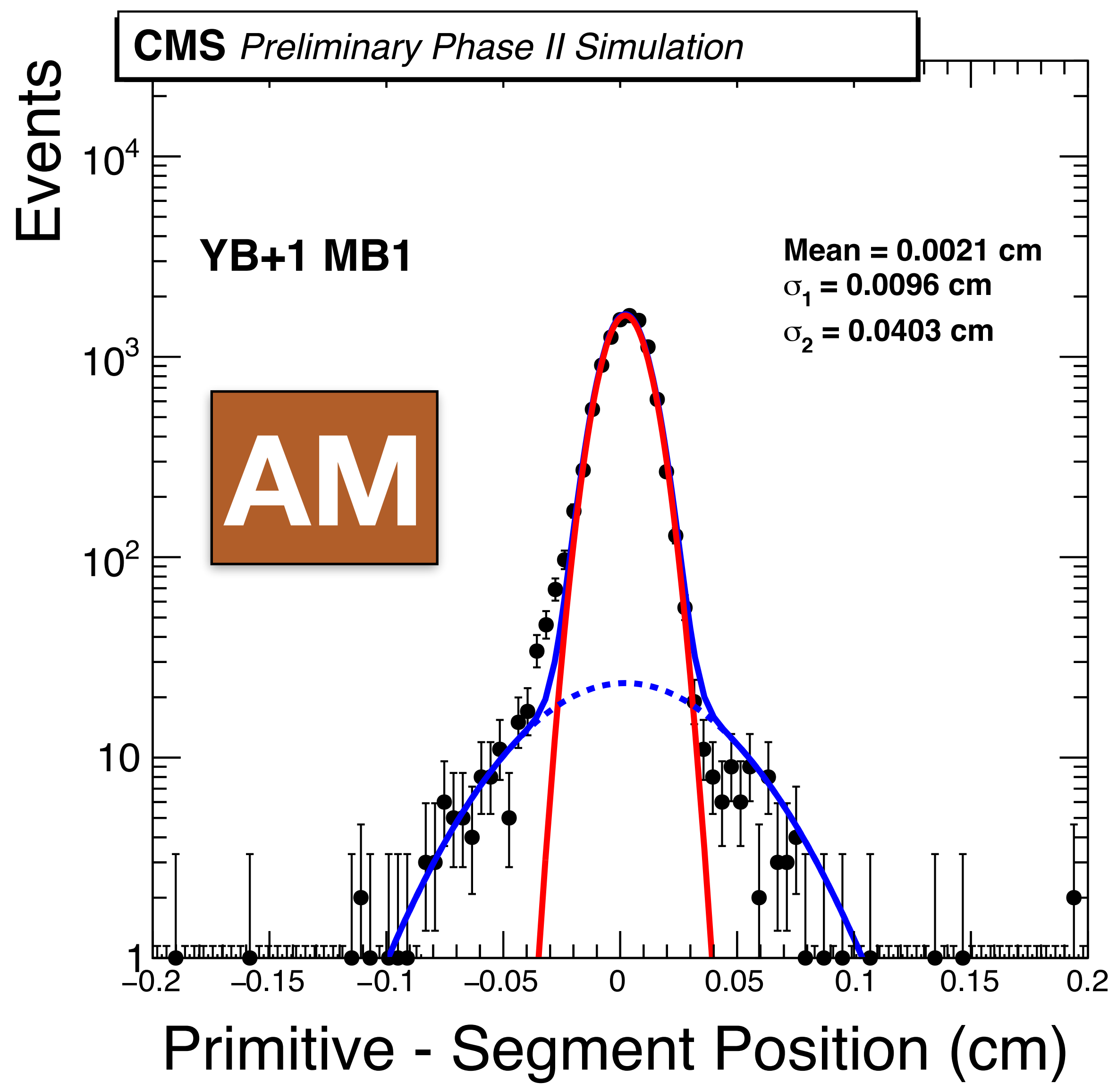


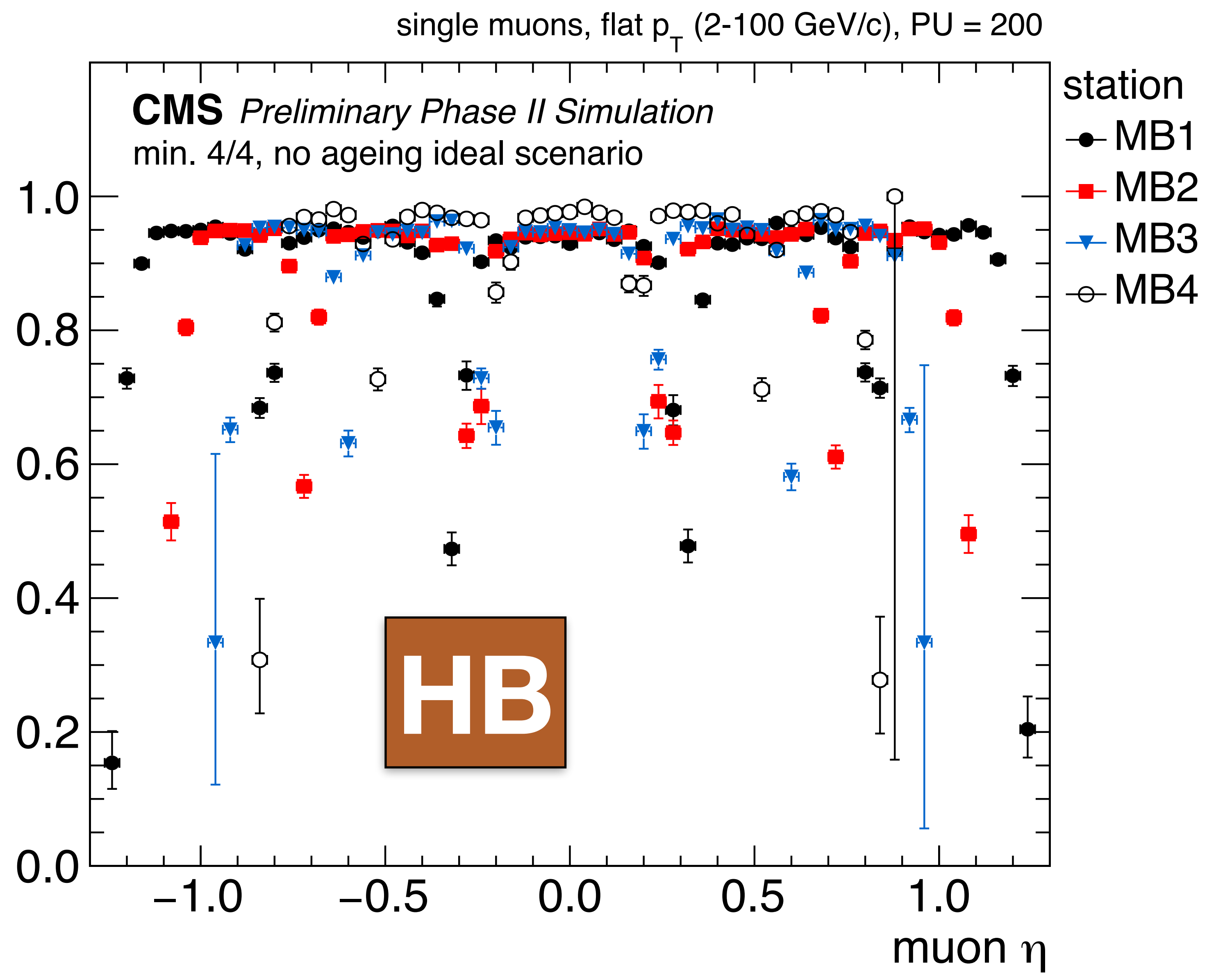
New DT Backend Trigger Algorithms

- **Two different algorithmic approaches** to reconstruct trigger segments are being investigated
  - both assume **straight line tracks** within a chamber and require at least a **triplet of fired layers** within a SL to build a trigger segment
  - one relies the mean-timer property (BX-ID) and does fitting using exact formulas (least squares) [**Analytical-method - AM**]. **AM** has been **implemented in FPGAs** and operated in the DT slice test demonstrator (next slide)
    - *See Jaime Leon Holgado's Poster for additional details*
  - the other is based on **Majority Mean-Timer** (BX-ID) and **Compact Hough Transform** (track building) methods [**Histogram-Based - HB**]



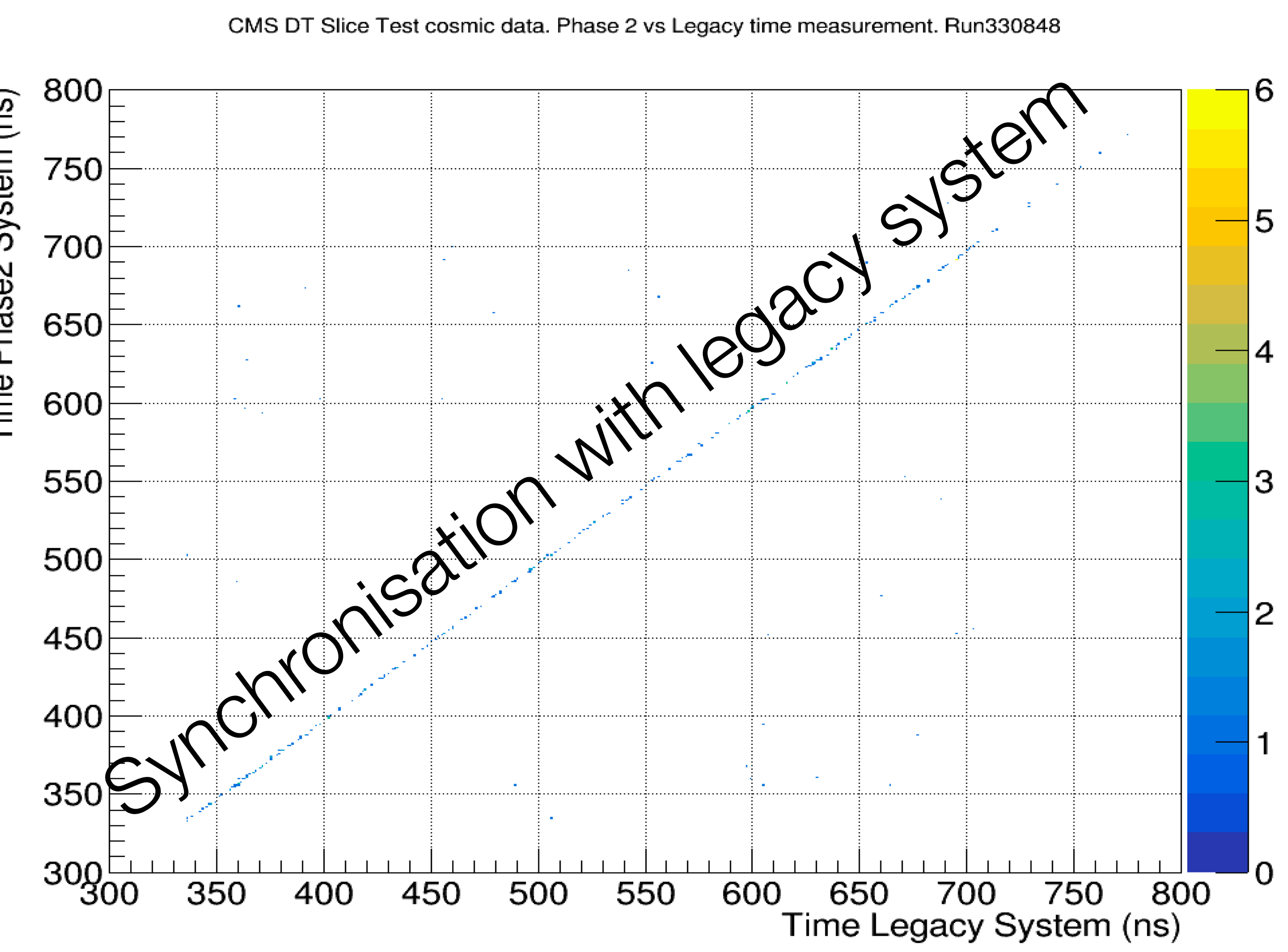
- Performance algorithms measured with simulations and Run-2 data
  - **Stress-test scenarios with 200 PU** collisions per BX
  - **Overall good results**
    - as efficient as present system: **95%**
    - spatial resolution (pos. / dir.) improves

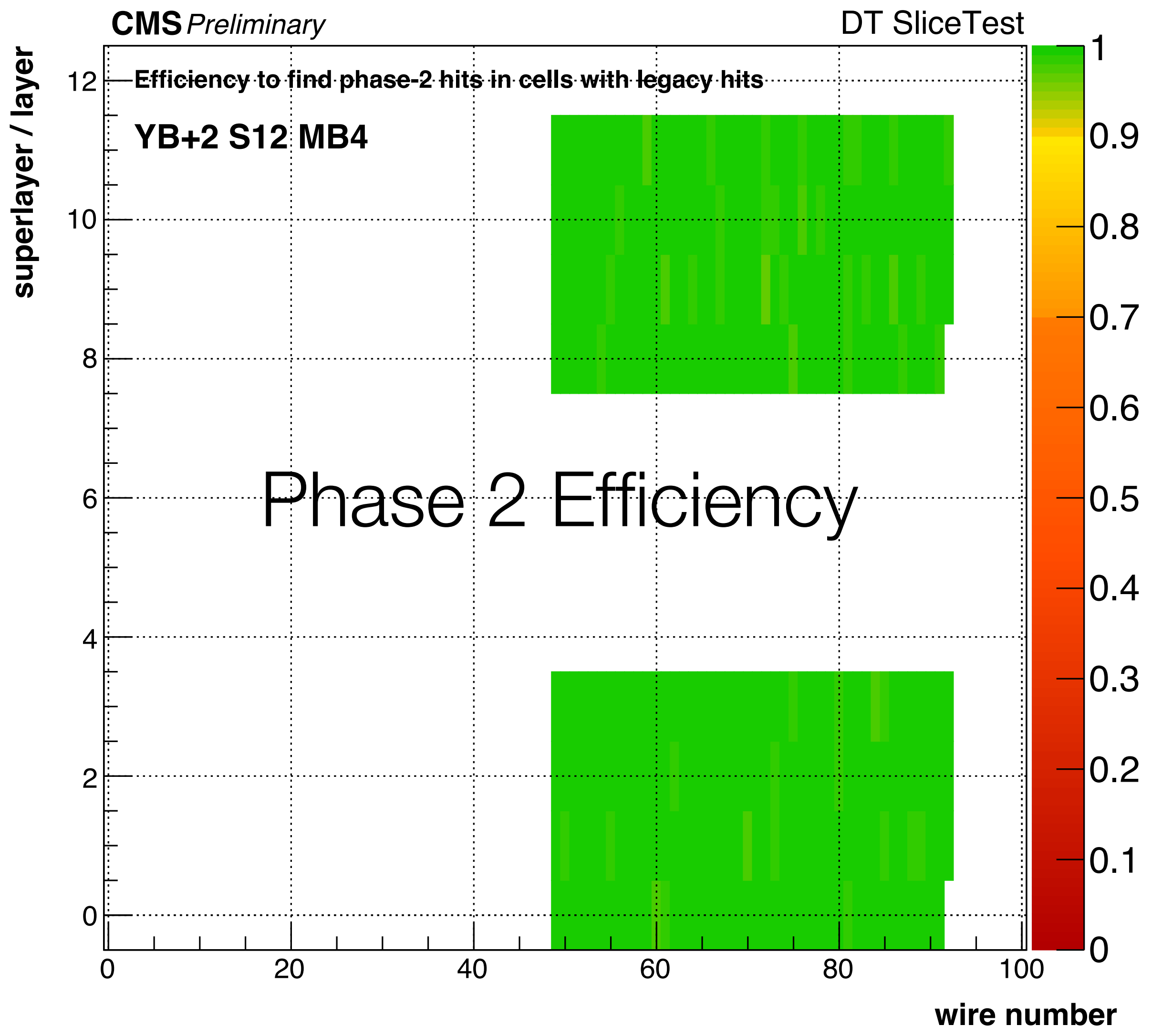


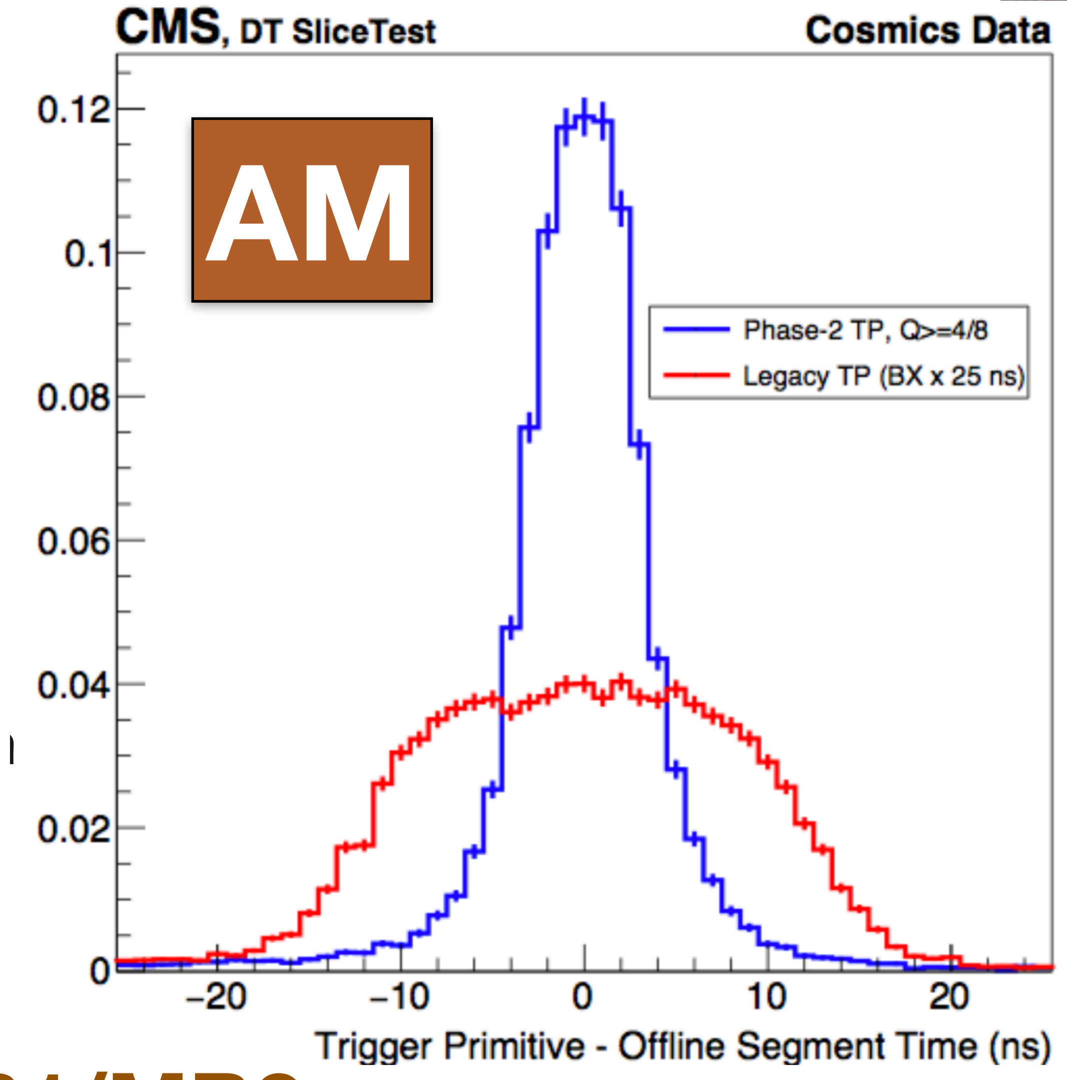


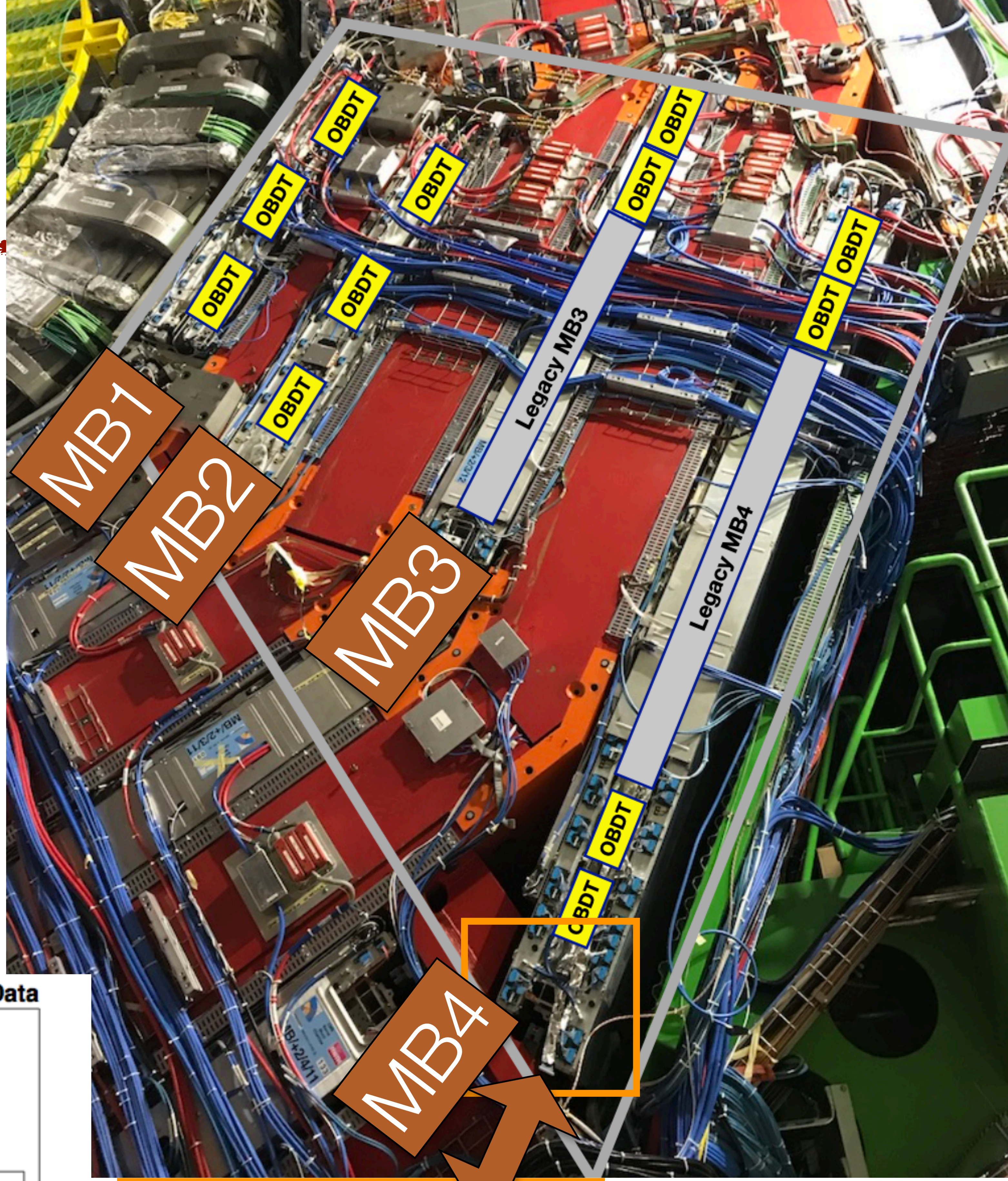
DT LS2 Slice Test

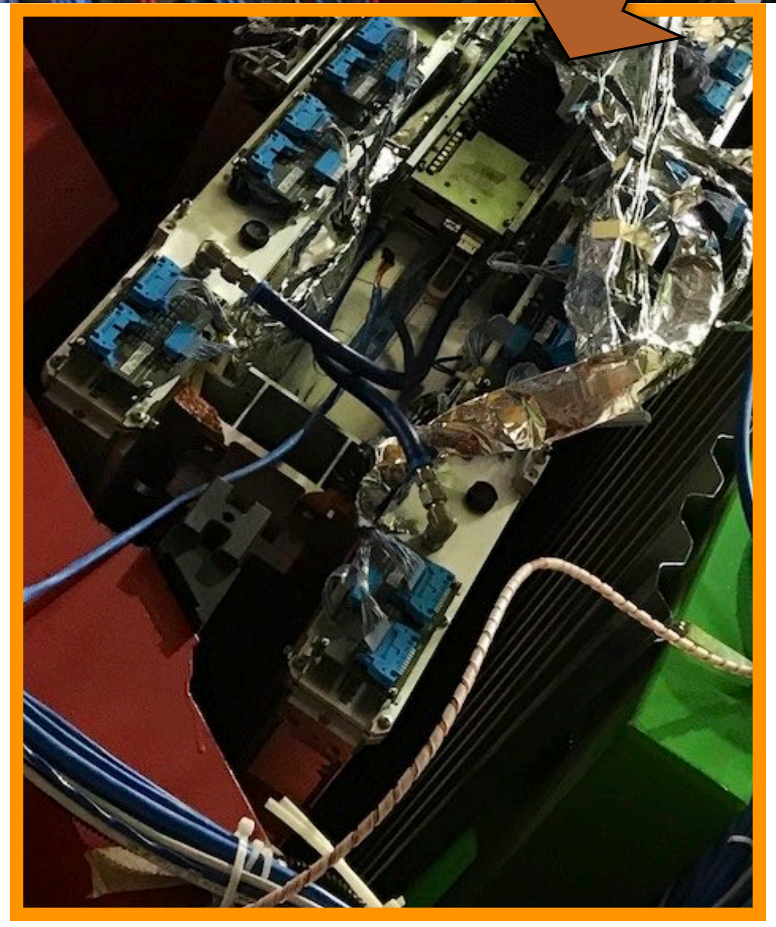
- During LS2 one DT sector has been instrumented with **prototypes of OBDTs and operated with a full Phase-2 electronics demonstrator implemented on Phase-1 HW**
- Different setup in different stations:
  - **MB1/MB2**: perform integration as in Phase-2, with only new electronics
  - **MB3/MB4**: run legacy and Phase-2 chains in parallel to validate Phase-2 data quality using legacy information
- The system has been successfully operated since Summer 2019.









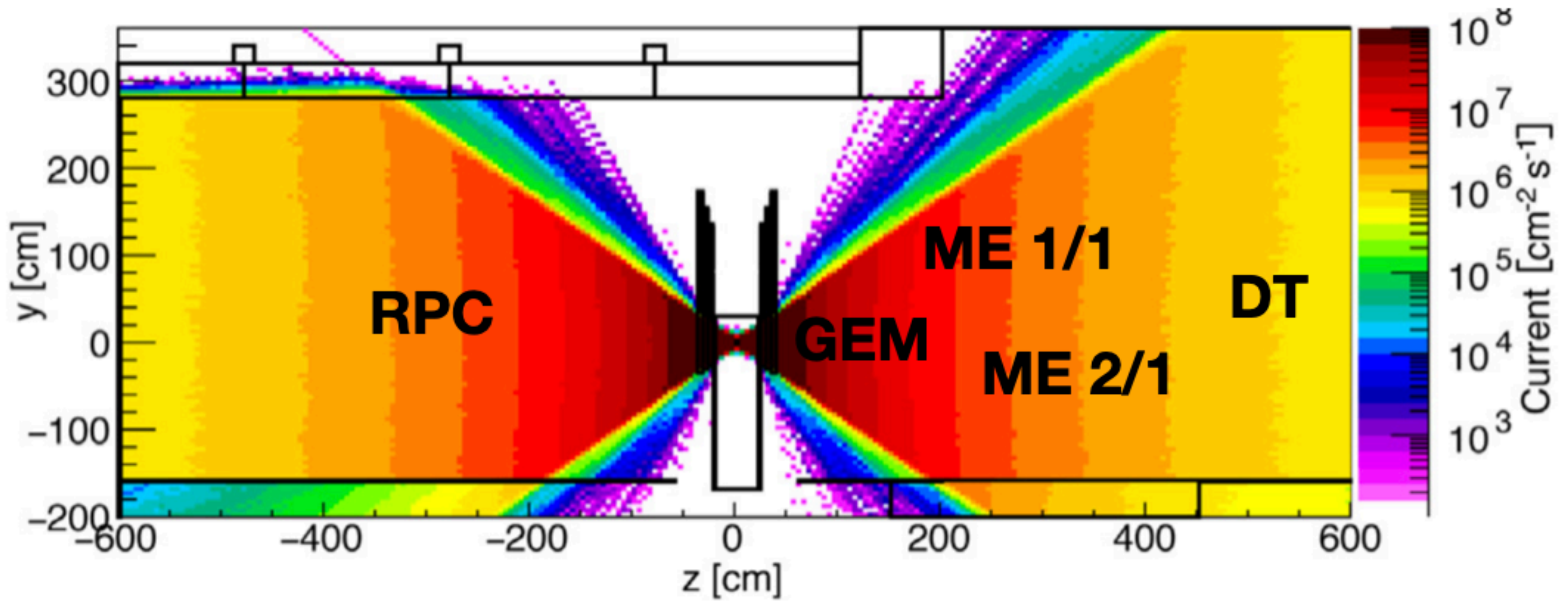


Splitted FE

- At the end of 2020 **legacy system will be reinstalled in MB1/MB2**
- **OBDTs will be kept in Run3** receiving the splitter FE for part of the 4 stations to allow Phase-2 L1 test and development

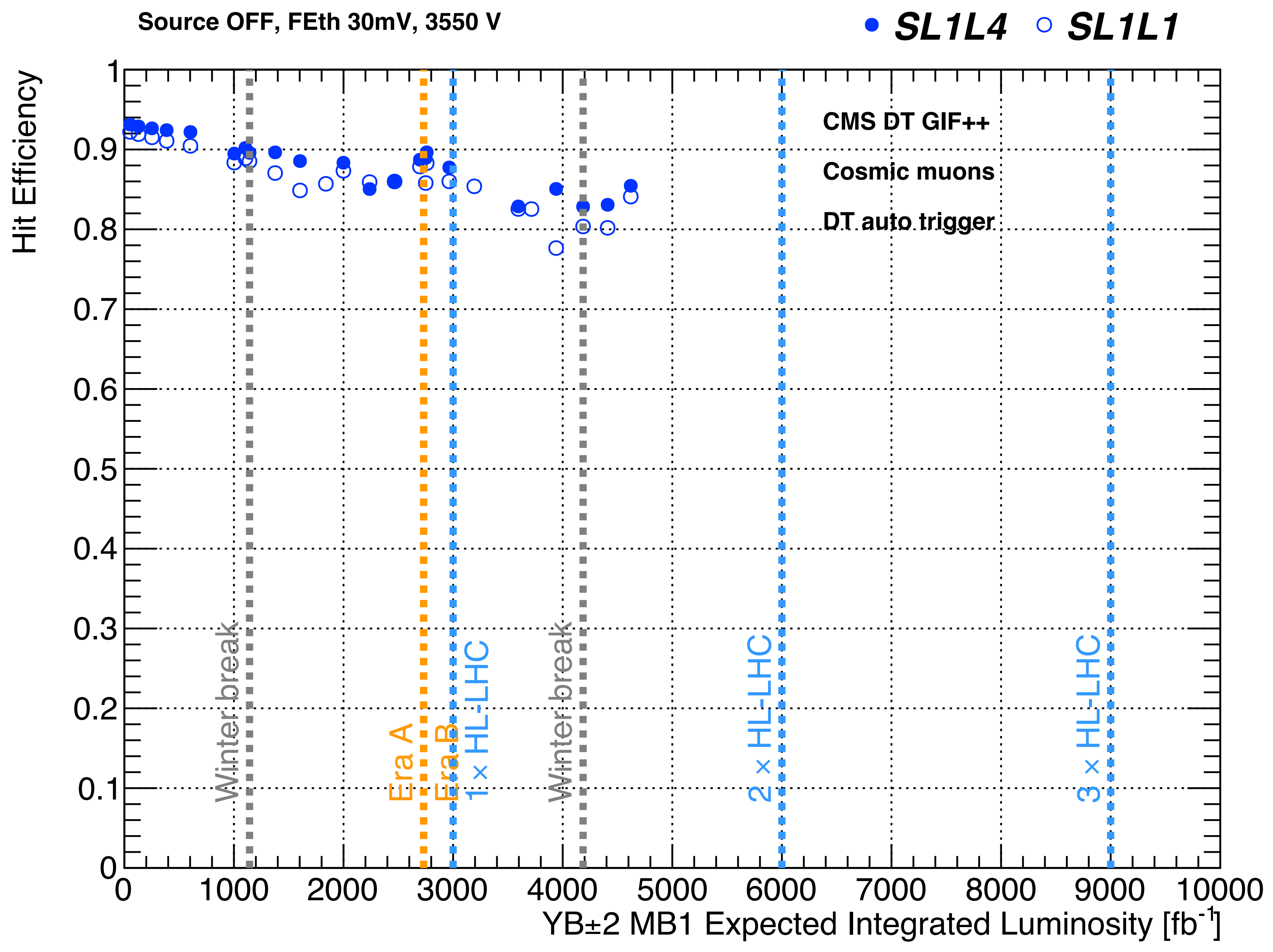
Longevity at GIF++

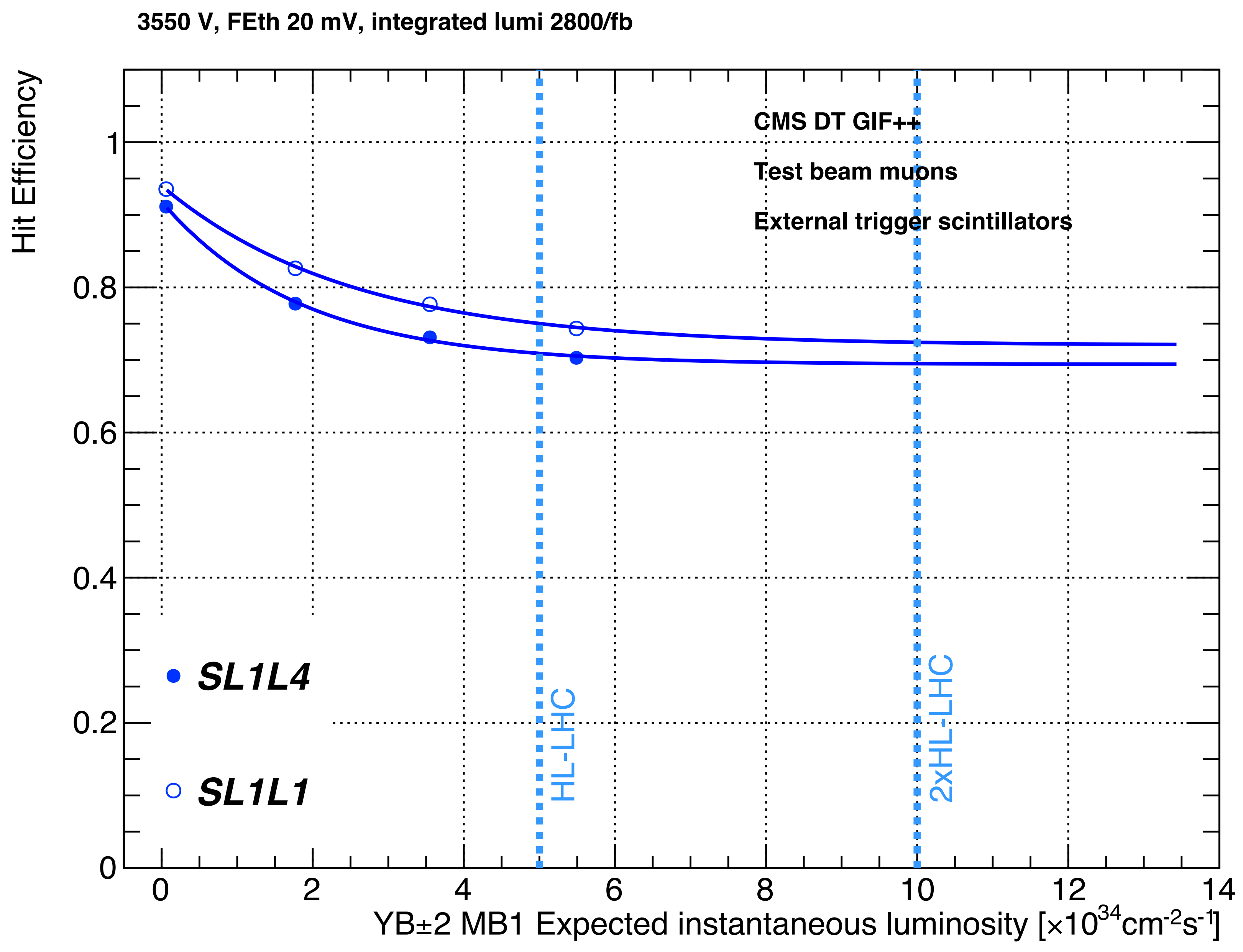
- **GIF++ CERN facility** used to certify existing and new detectors at the estimated HL-LHC conditions
  - **14 TBq ^{137}Cs source** emitting 662 keV photons
    - **realistic environment:** neutron-induced photons have an energy in the range 0.1–10 MeV.
    - long period of irradiation to study ageing
  - periods with **high momentum muon beam** (100 GeV)
    - allows detector performance studies in the presence of high radiation
- Facility extended in 2020 to allow more test space and to have a low intensity area (ideal for DT)



Chambers tested:

- CSCs: 1 ME1/1 and 1 ME2/1
- DTs: 1 MB1, 1 MB2
- GEMs: 1 GE1/1, 1 GE2/1
- RPCs: 1 RE2, 1 RE4, 1 iRPC large prototype

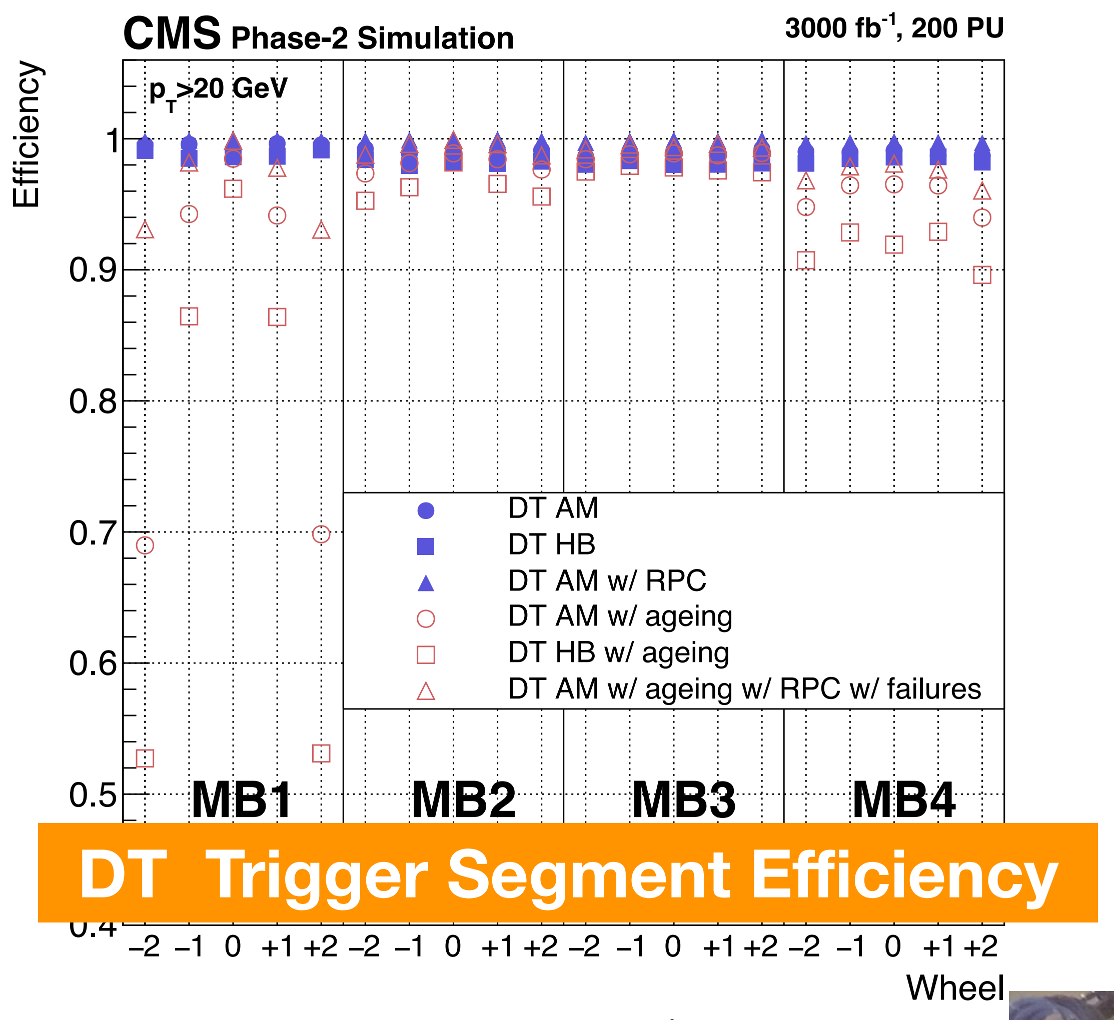


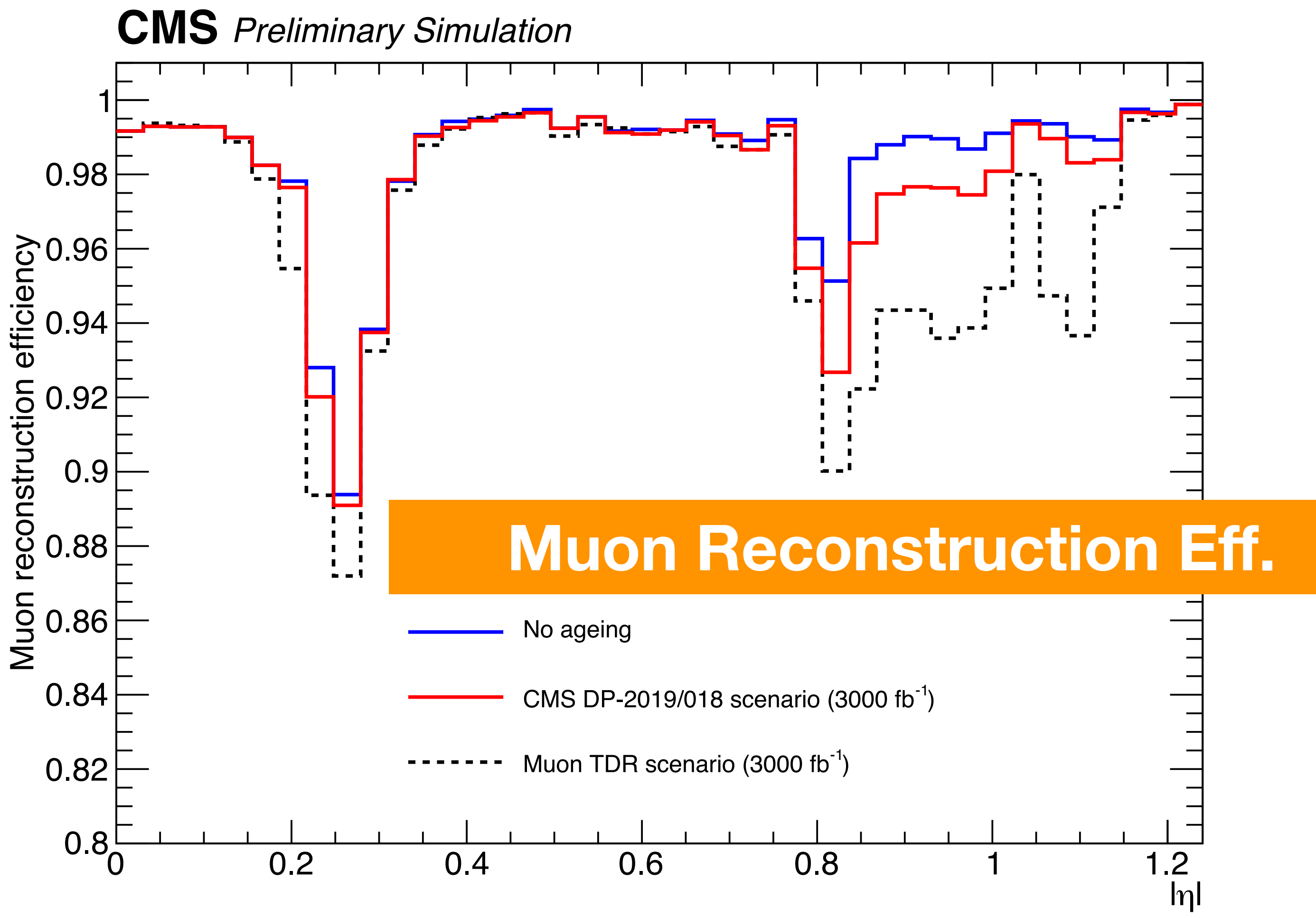


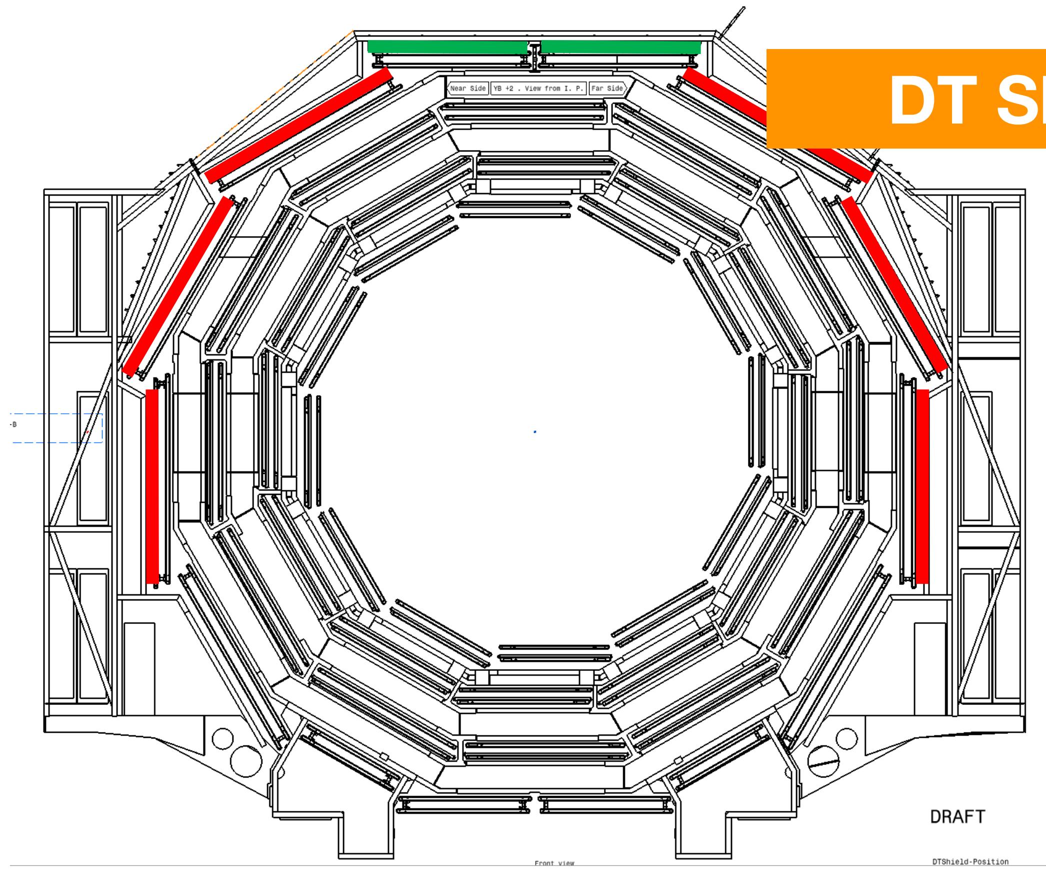
- For DT **irradiated 2 layers** in MB2 and the rest kept for reference
- A **strong decrease of the gain** was observed due to deposition of material on the anode wires
- **Single hit efficiency** in muon beam studies, at approx HL-LHC int. / inst. lumi (3600 fb^{-1} - 5·10^{34} cm^{-2}s^{-1}) **is around 75%**

DT Ageing effects and Mitigation

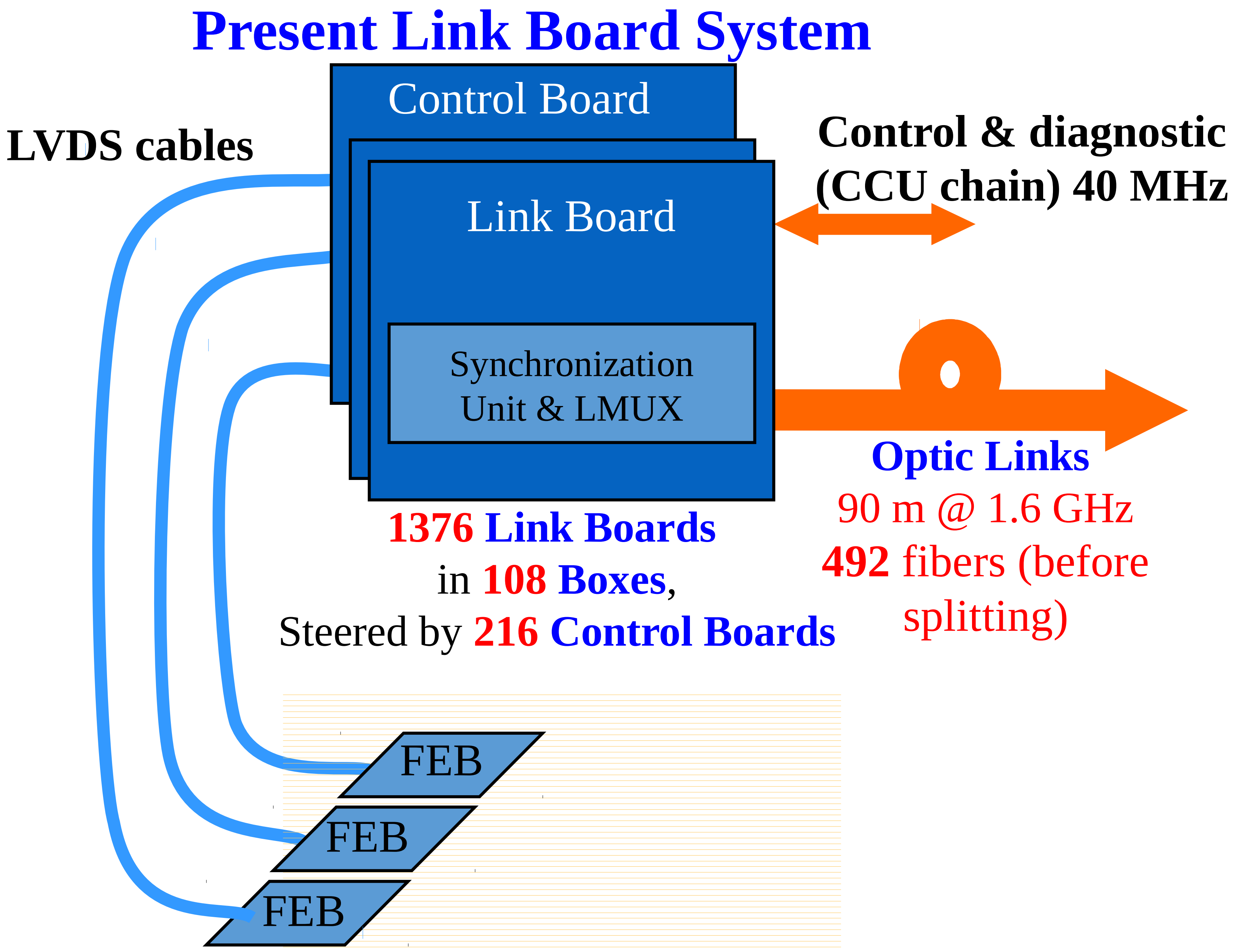
- The measured single hit inefficiency will affect on the **most exposed chambers in the DT detector (~10%)**: YB±2 MB1s and MB4 on the top of the detector
- **This impact is reduced at different levels**
  - Thanks to the **multiple layers of a DT chamber**: out of 8 r-φ layers, ≥ 3 are needed to build an offline segment
  - Thanks to the **handling of TDC hits in the backend** in Phase-2
    - The new algorithm are tested against ageing and failure scenario
  - **Thanks to the redundancy of the CMS muon system**: in the region of the DTs most affected by ageing, there is a coverage of 3 DT/CSC stations + 4-5 RPC layers along the trajectory of a prompt muon
- Loss of hits in YB+/-2 MB1s has hence "just" a **marginal impact on overall standalone muon reconstruction efficiency**
- Additionally, to reduce the neutron background on the top of the detector, a **shielding has been installed during LS2**
  - **Layers of Borated Polyethylene + lead**

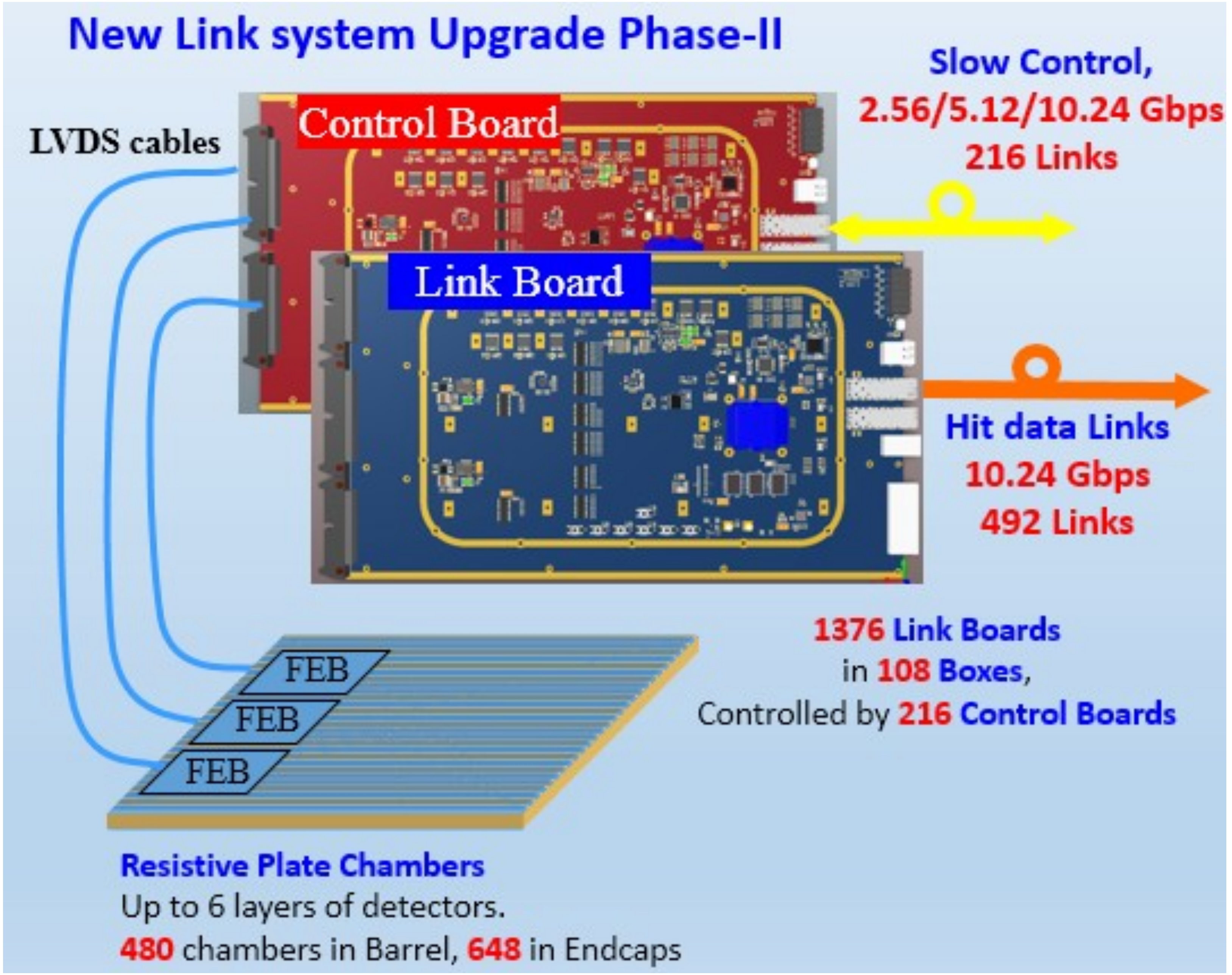






The RPC electronic upgrade



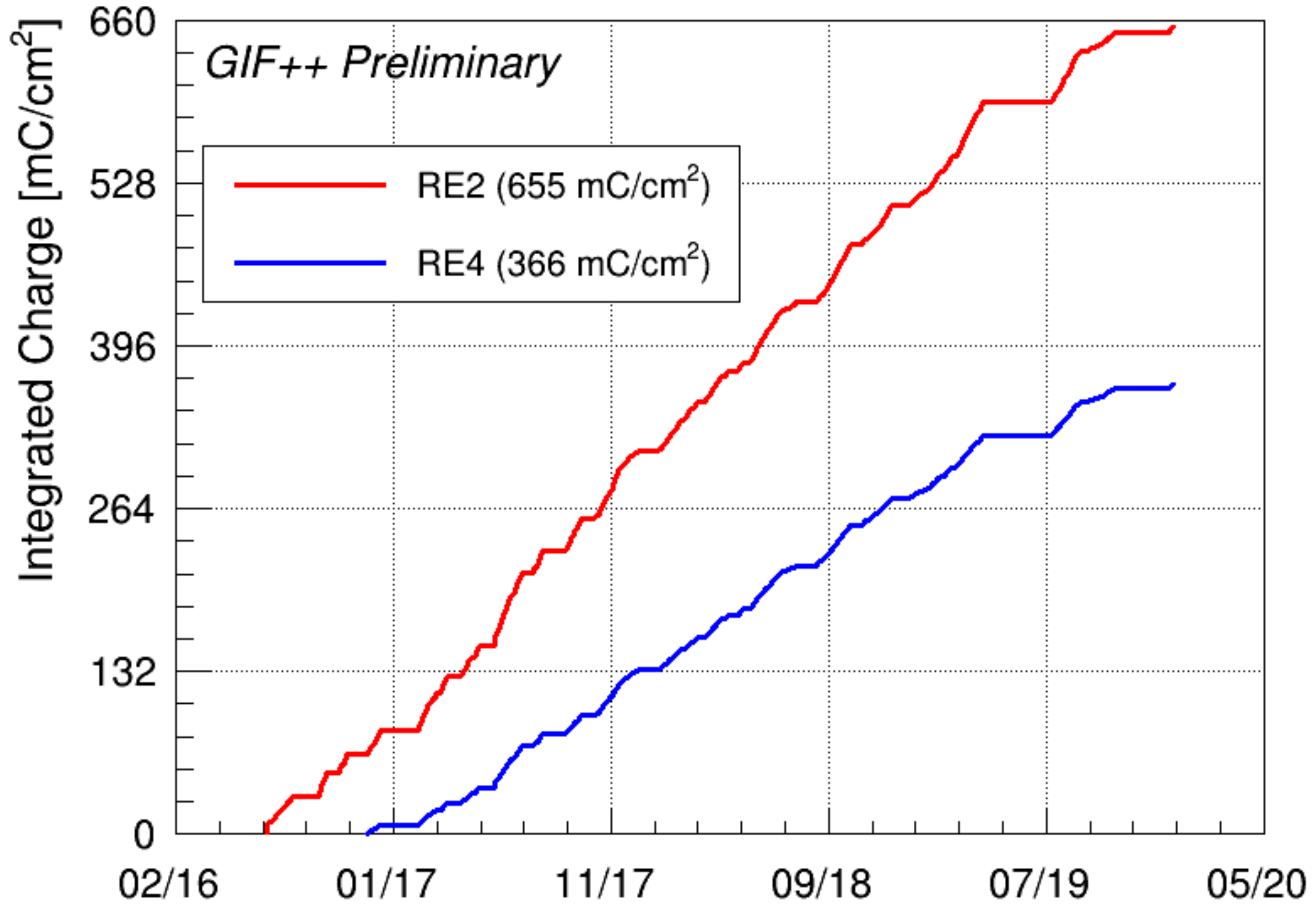


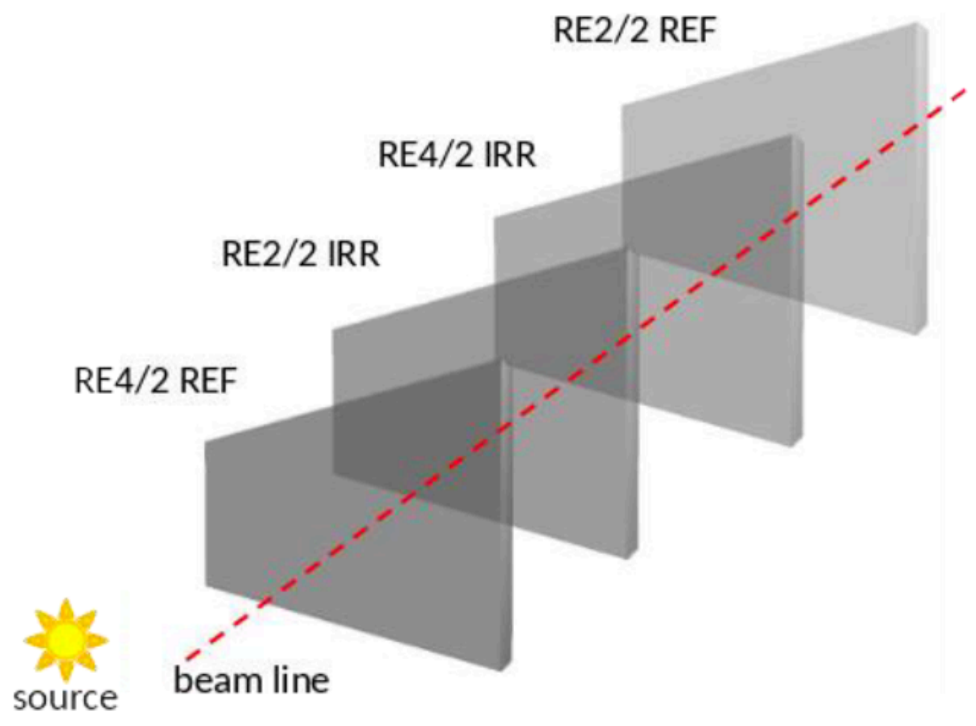
RPC Link system will be replaced in LS3:

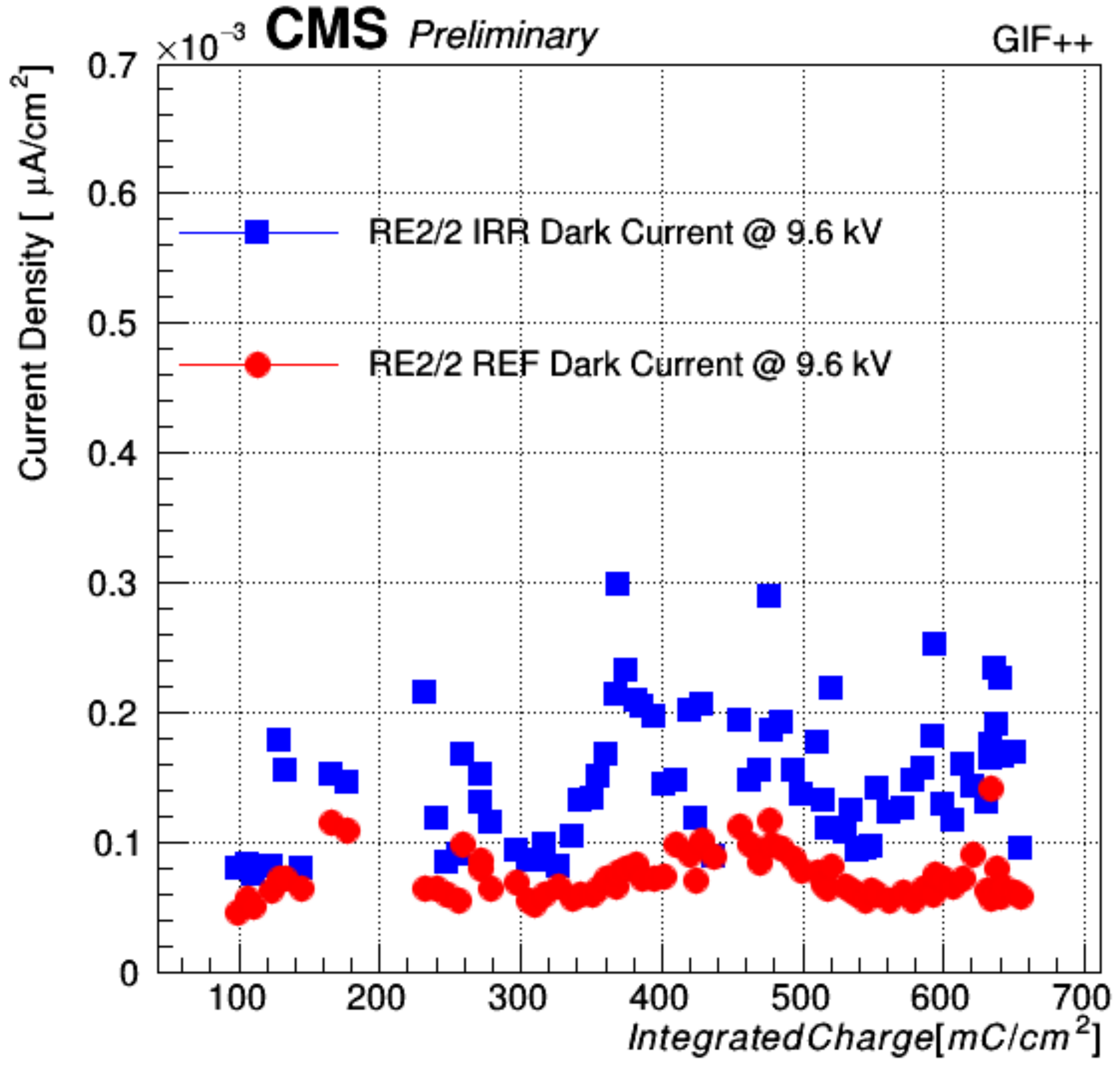
- Replace **obsolete rad hard components** and an **ageing system** (13 years old by end of LS2) with FPGA technologies
  - **Radiation Mitigation** is based on Triple Modular Redundancy (TMR) and internal scrubbing (SEM) techniques from Xilinx.
  - Scrub Rate of entire FPGA (Real time SEU detection and Correction): 13ms (31,770 times faster than the rate of SEU at the Balcony)
- Moving **from 25ns** sampling to recover the intrinsic RPC resolution with **new TDC timing resolution of 1.56 ns**
- Replacing the control, diagnostic and monitoring, based on combination of copper cable and fibers (very susceptible to electromagnetic interference and slow - 40 MHz bandwidth) **to a new slow controller at 0.24 Gbps.**

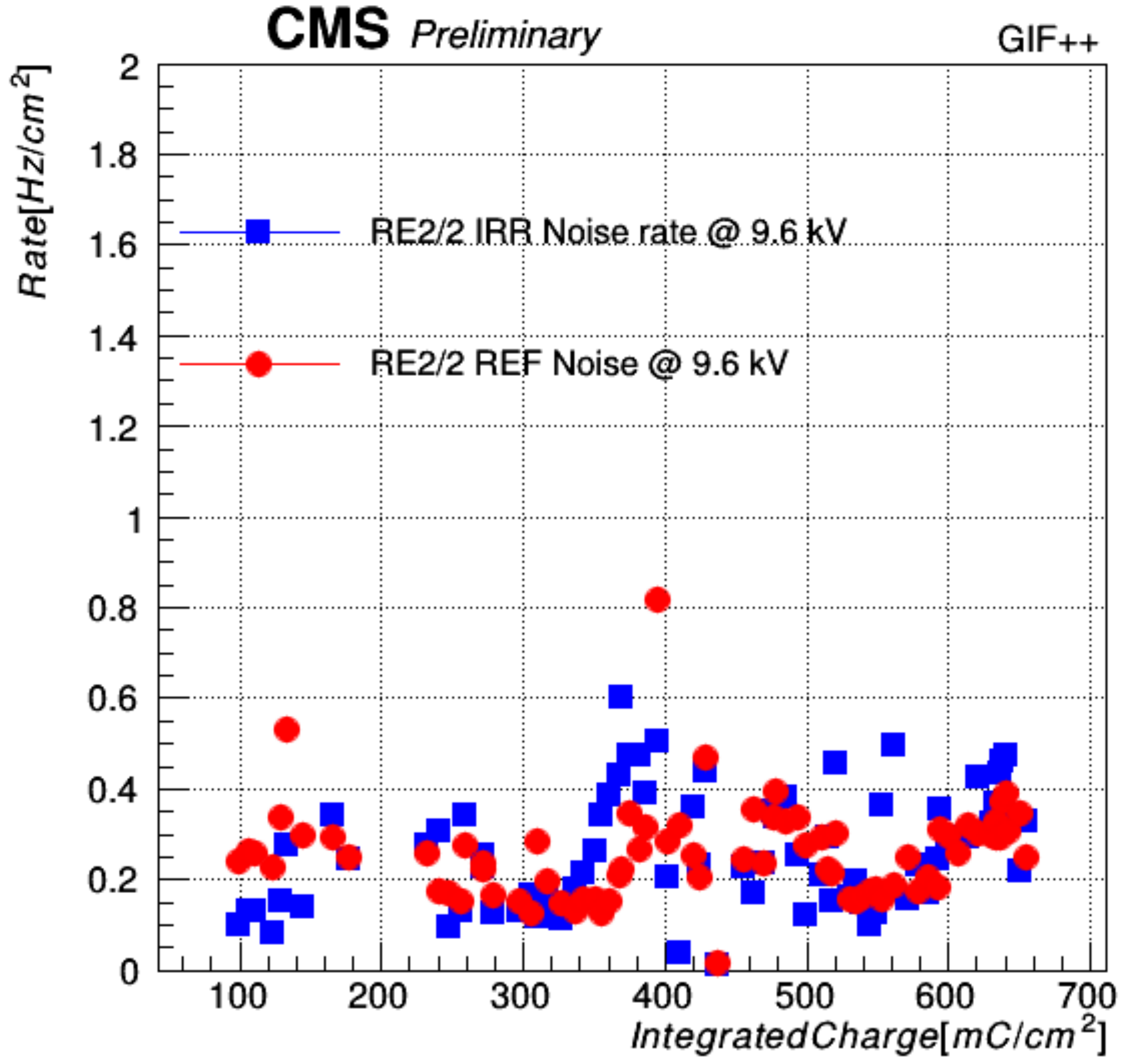
RPC Longevity at GIF++

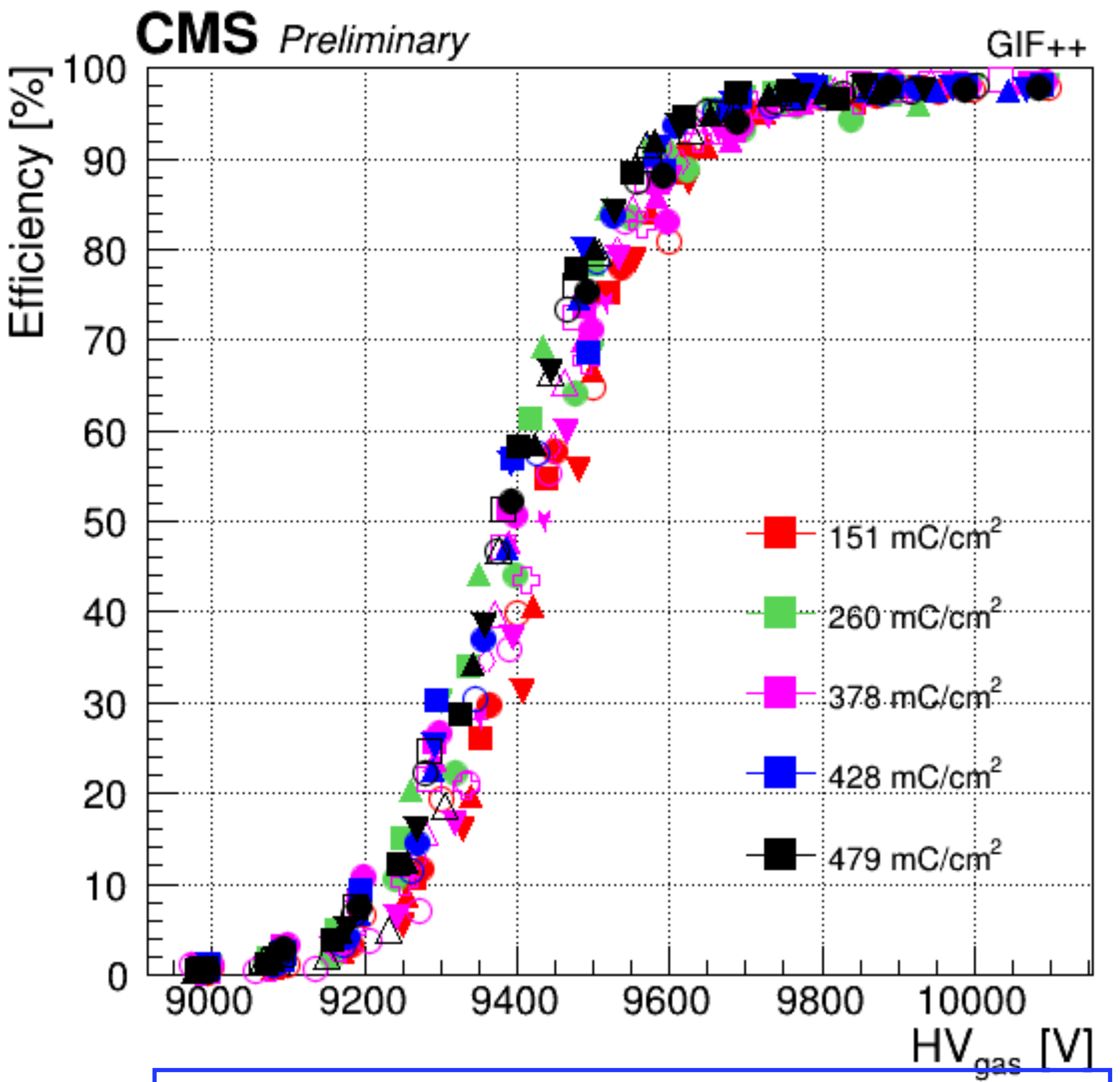
- Two chambers are continuously irradiated with two used as reference.
- Two different types of chambers from old and new production (RE4 produced in 2012- 2014)
- Expected Integrated charge at HL-LHC **840 mC /cm²**
  - **Reached 78% for RE2 and 44% for RE4**
- Different parameters monitored









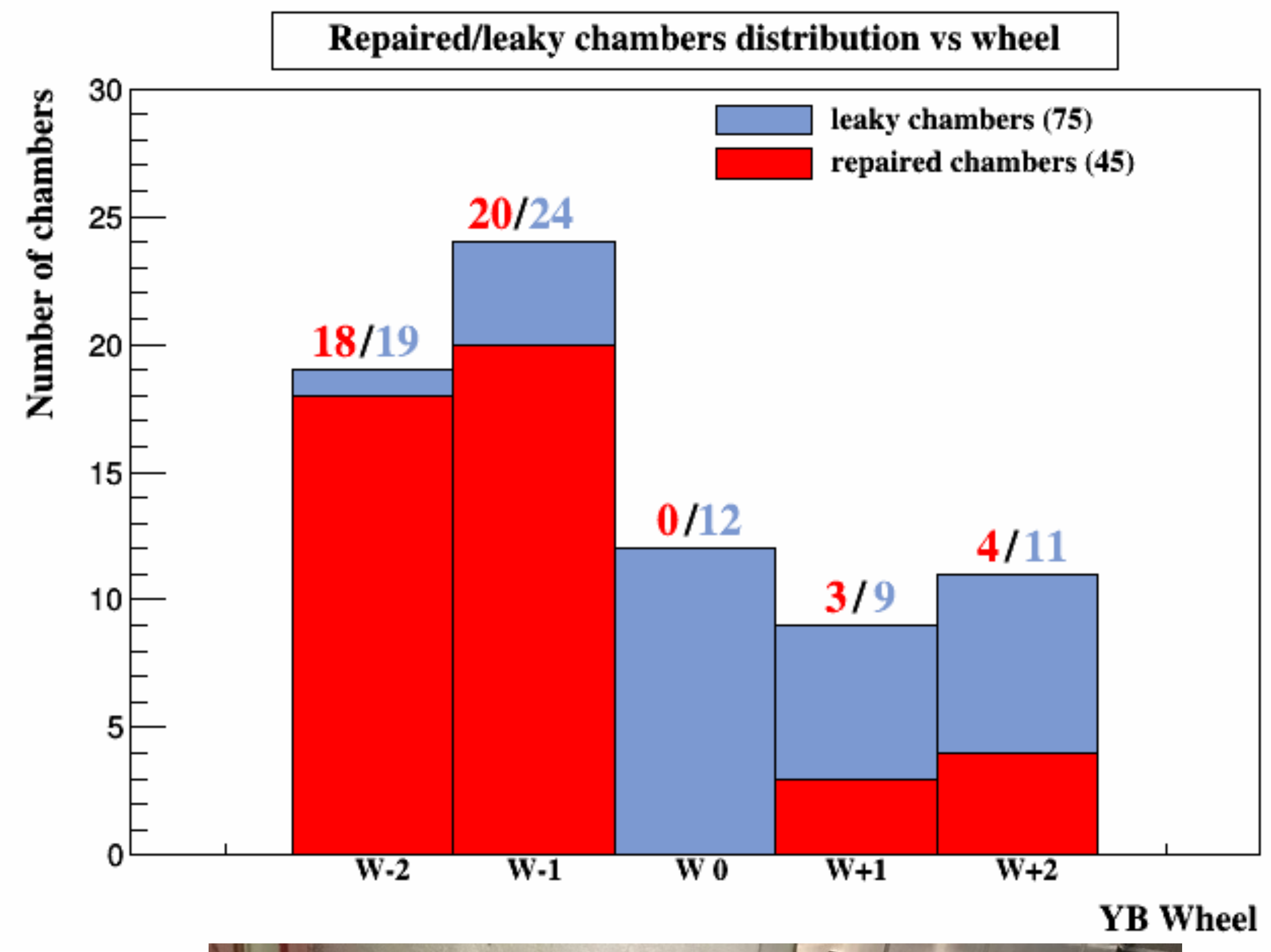


Total **current and noise almost stable** with time and after collecting 650 mC/cm²
Average noise rate less than 1 Hz/cm²

No shift in the efficiency curve observed vs. time and up to **background rate 600 Hz/cm²**

RPC gas mixture

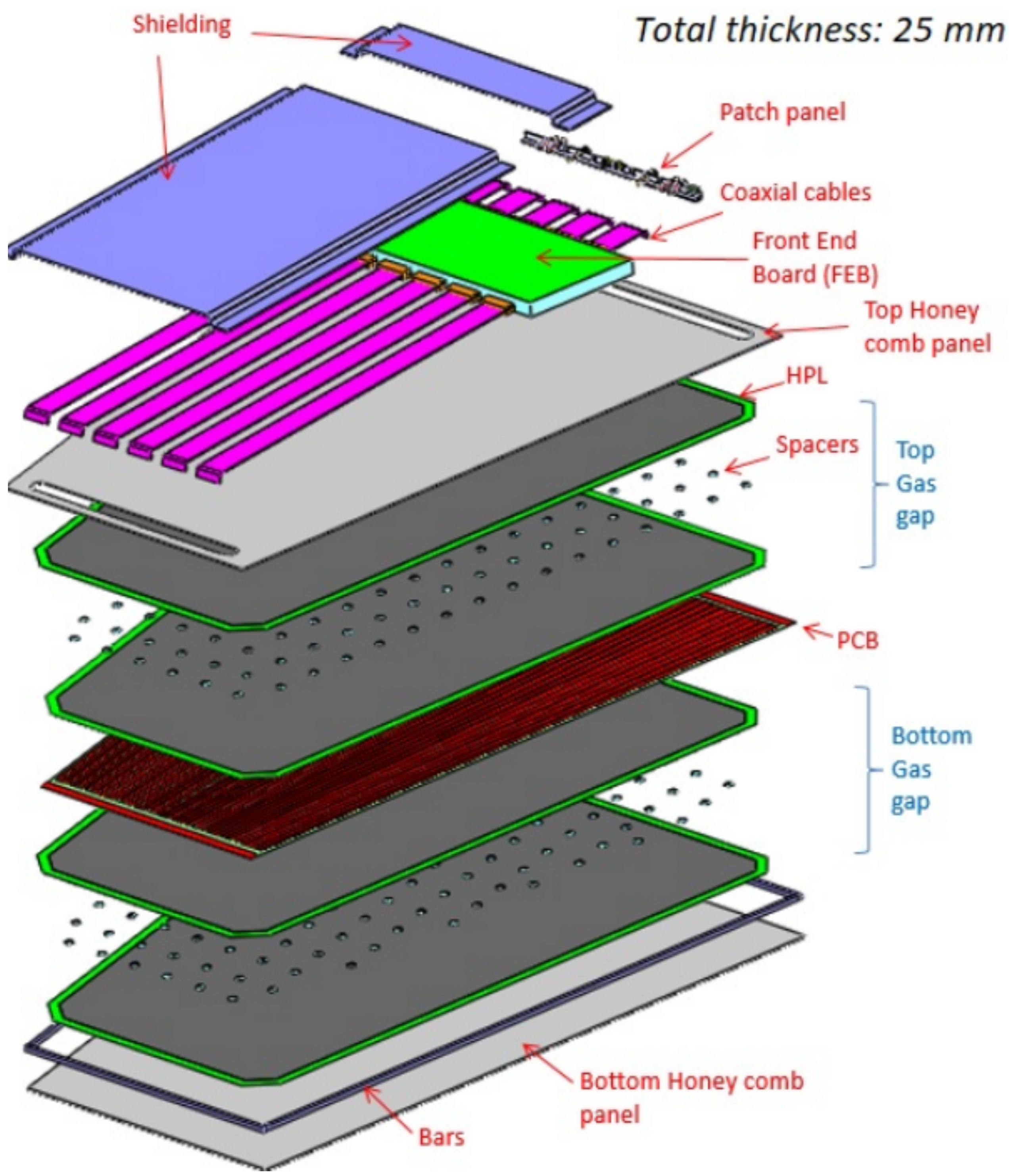
- Gas mixture used in the RPC contains **Tetrafluoroethane ($C_2H_2F_4$), a greenhouse gas**
- Strong commitment from CERN to r**educe greenhouse emission** and expected limited production worldwide in the future
- Solution needed for the longtime operation of the RPC system at HL-LHC
  - **Recirculation system**, to use only a small fraction of fresh gas
  - **Recuperation system** to recover the greenhouse gas from exhaust
    - Prototype0 installed in CMS in December 2019 and connected to RPC exhaust
    - The system is running since January 2020 with an efficiency of about 100%
    - recuperated $C_2H_2F_4$ contains some impurities of iC_4H_{10} or SF_6 (under study)
- For this solution to be effective need to reduce gas leaks
  - **82 Barrel RPC chambers leaky** due to cracked or broken pipes.
  - RPC leak repair campaign has given the highest priority during LS1
    - **About 50 DT/RPC stations partially extracted and repaired**
- Study ongoing on alternative gas mixtures



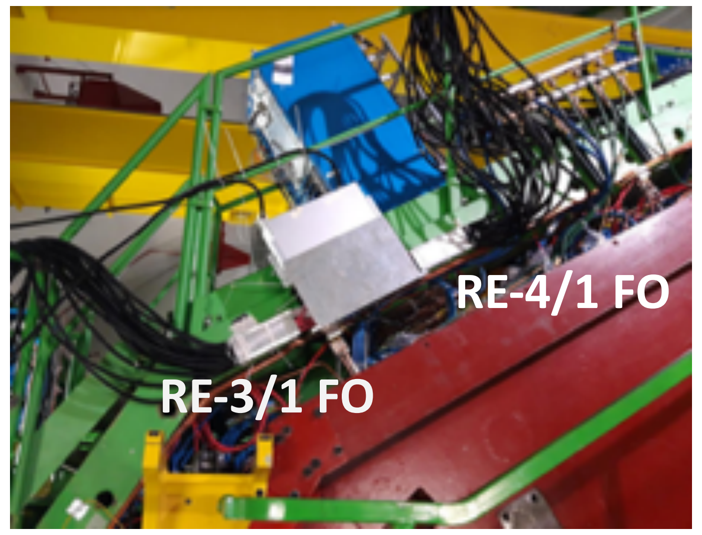
The iRPC Project

Specification	RPC	iRPC
$\|\eta\|$ coverage	0-1.8	1.9-2.4
Max. expected rate (safety factor 3 included)	600 Hz/cm^2	2 kHz/cm^2
Max. Integrated charge (safety factor 3 included)	~ 0.8 C/cm^2	~ 1 C/cm^2
High Pressure Laminate thickness	2 mm	1.4 mm
Number and thickness of gas gap	2 and 2 mm	2 and 1.4 mm
Resistivity (Ωcm)	1 - 6 x 10^{10}	0.9 - 3 x 10^{10}
Charge threshold	150 fC	50 fC

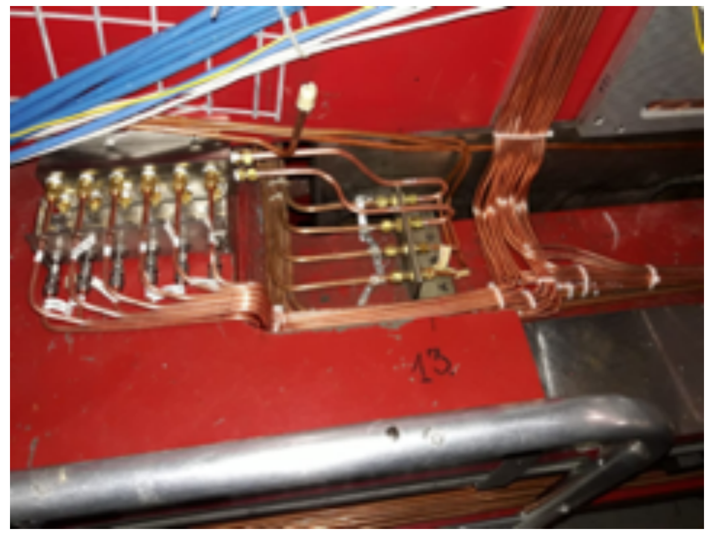
- Installation of 72 iRPC with **increased rate capability** by a factor of ~3:
  - **Lower Electrodes thickess**: 1.4mm
    - Reduce the **recovery time**
    - Increase in efficiency of extracting the pickup charge from the avalanche charge.
  - Decrease **Gas Gap thickness** to 1.4mm
    - **reduces the fast growth of pickup charge** of the ionization avalanches
    - lowers the operational high voltage making system more robust than before
      - less chance of ageing.
  - **Electronic Thresholds at 50 fC**
    - Lower threshold electronic helps to provide better sensitivity to reduce charge
- Improved performance providing **measurements in 2D**
  - strips are readout from both ends

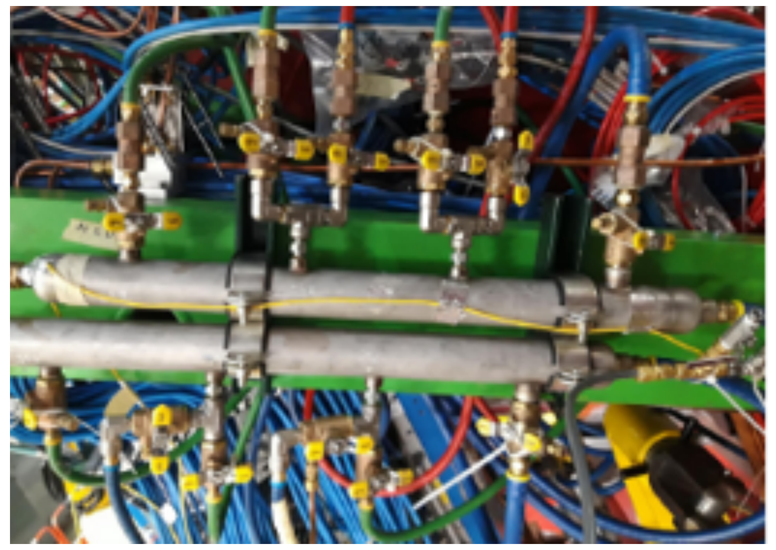


- **Services are being installed in L2**
- Installation possible before LS3 in a YETS 23/24



Fiber optics box installed back of YE-3 and Y+3

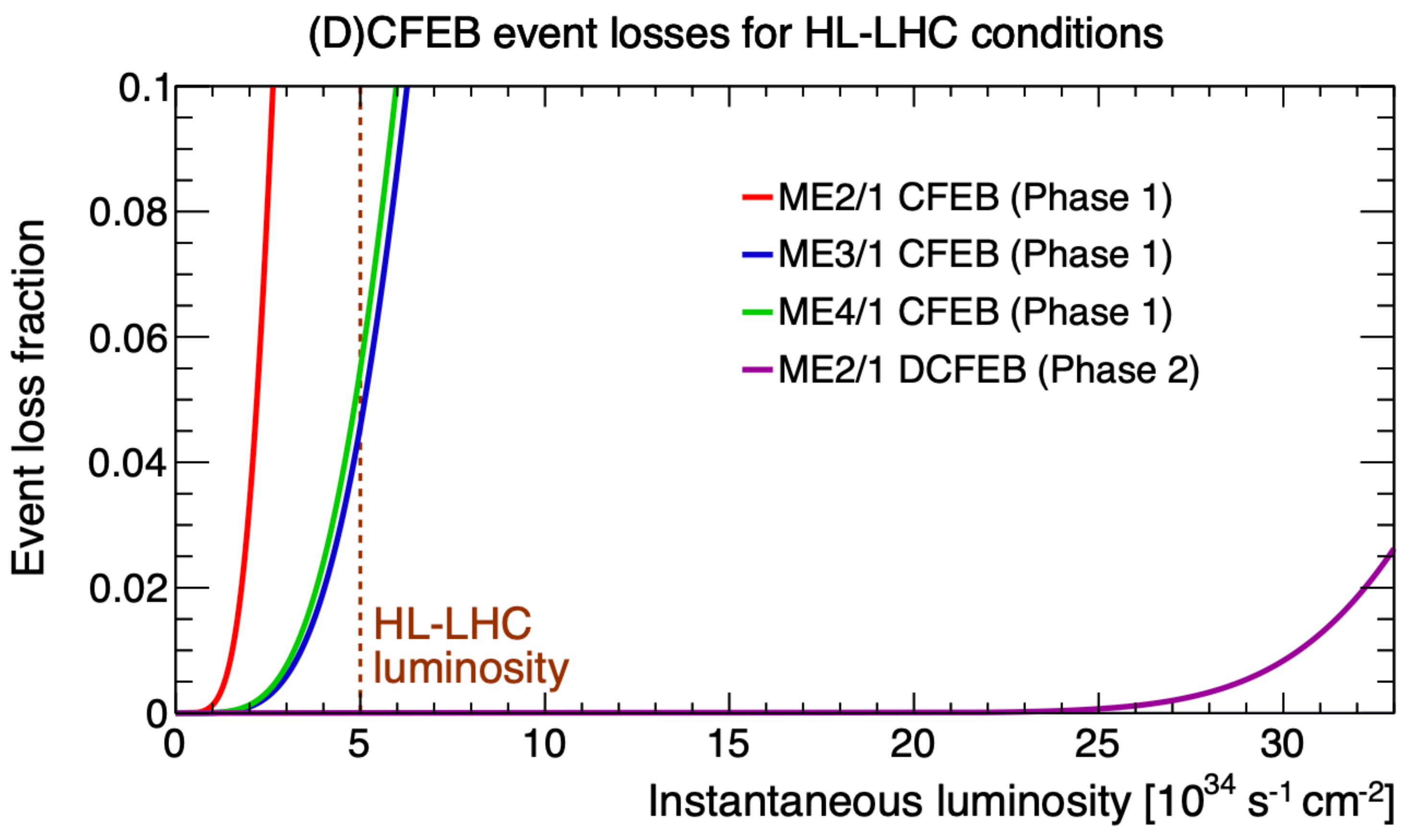

Gas impedance boxes

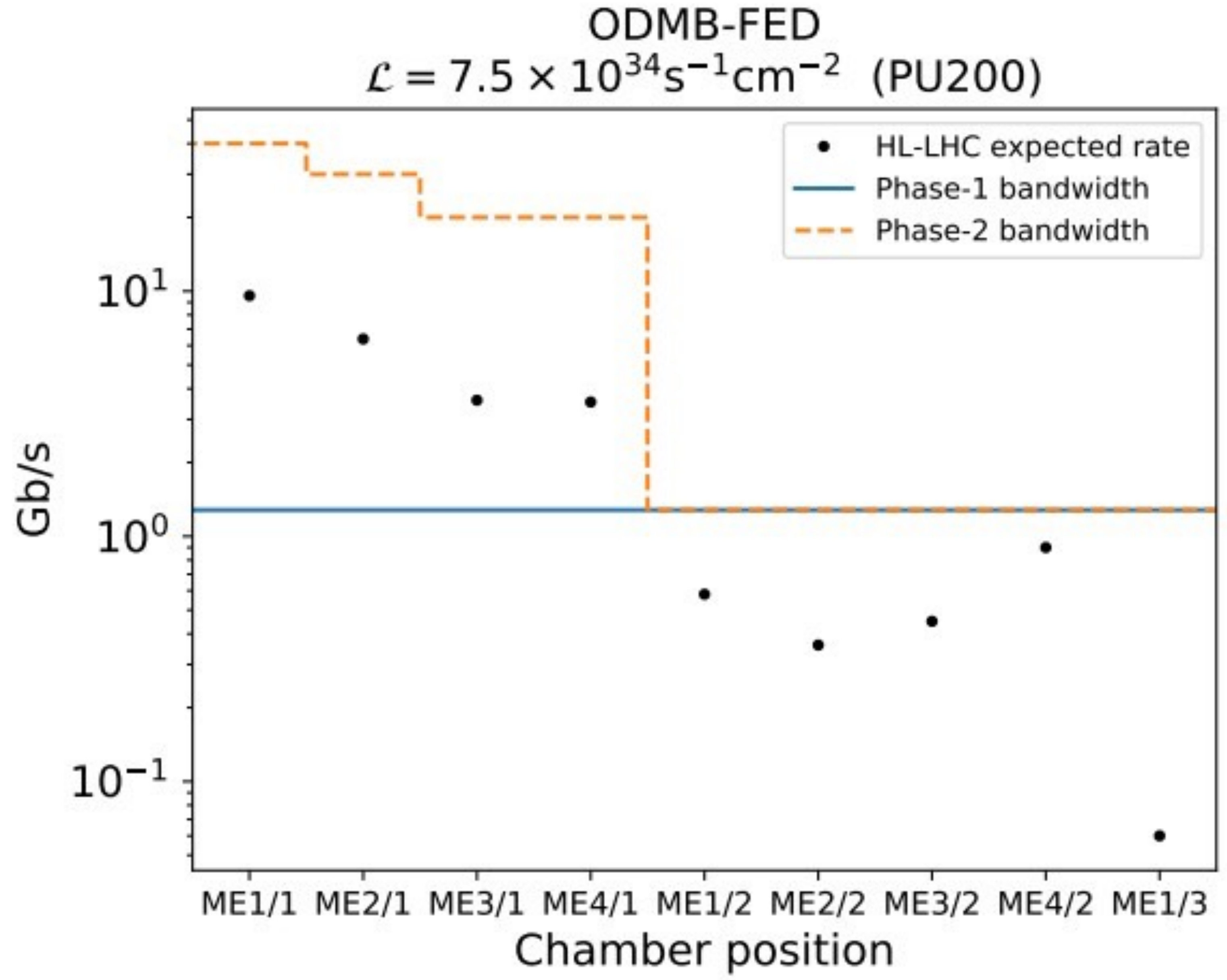

RE4.1 Cooling

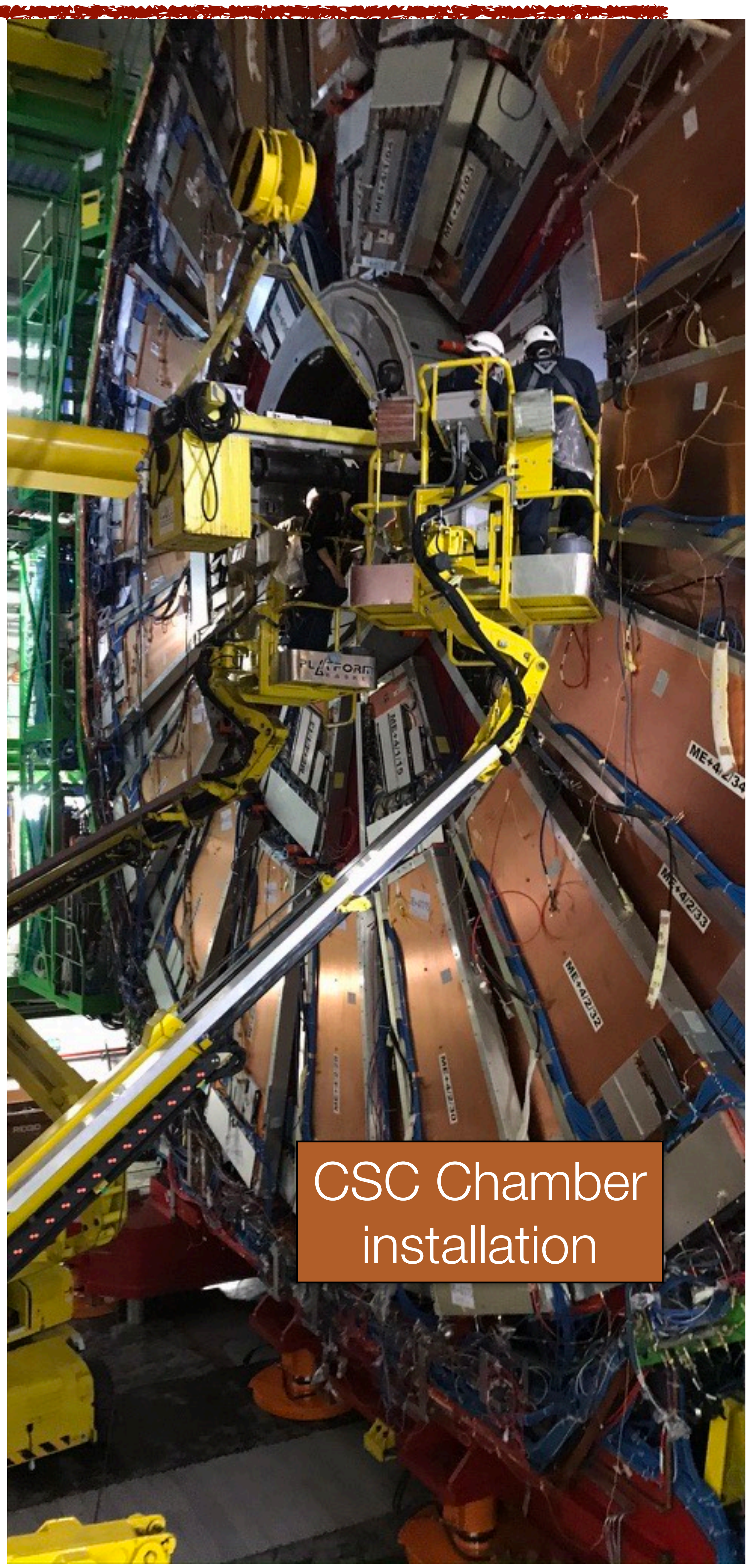
The CSC Upgrade (in a nutshell..)

Dedicated Talk: "Upgrade of the CMS Cathode Strip Chambers for the HL-LHC" by Sven Dildick

- Refurbishment needed of the **detector electronics**
  - **old CFEBs** do not have enough buffering for chambers closest to beamline (180/540 chambers)
  - **Longer L1 trigger latency**: required for new track trigger
  - **Output bandwidth** (ALCT, DCFEB, ODMB, FED) and pipeline length (ALCT) not sufficient
  - GBTx programming to mitigate EEPROM failures experienced in 2017 in high-occupancy CSCs (ME1/1)
- **Upgrade being done mainly in LS2** (2019-2021):
  - On-chamber electronics (DCFEB, ALCT, LVDB)
    - **180 chambers brought to the surface, refurbished and installed back in the detector**
  - Trigger Motherboard (OTMB), Services (LV, HV), GEM-CSC link

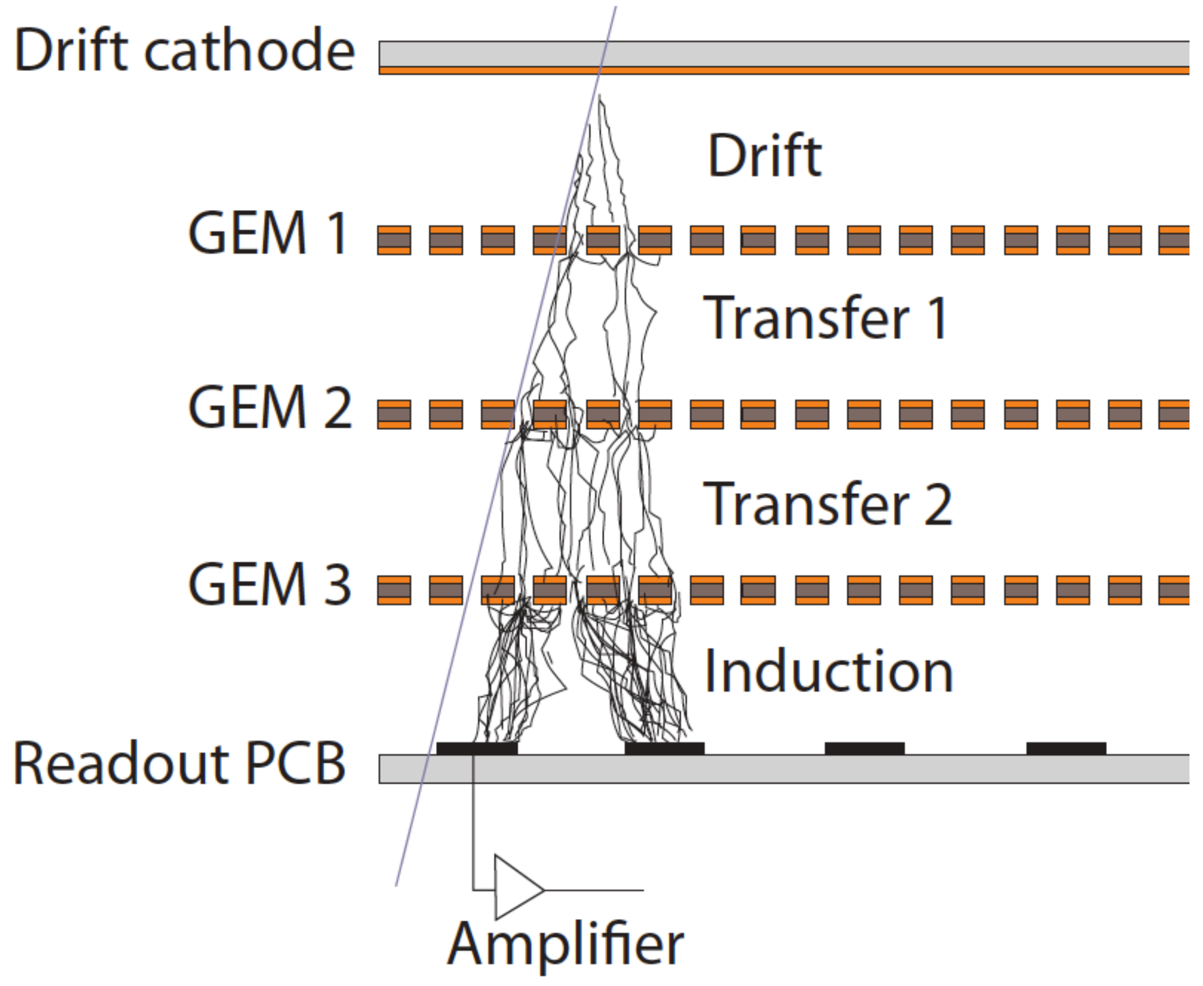




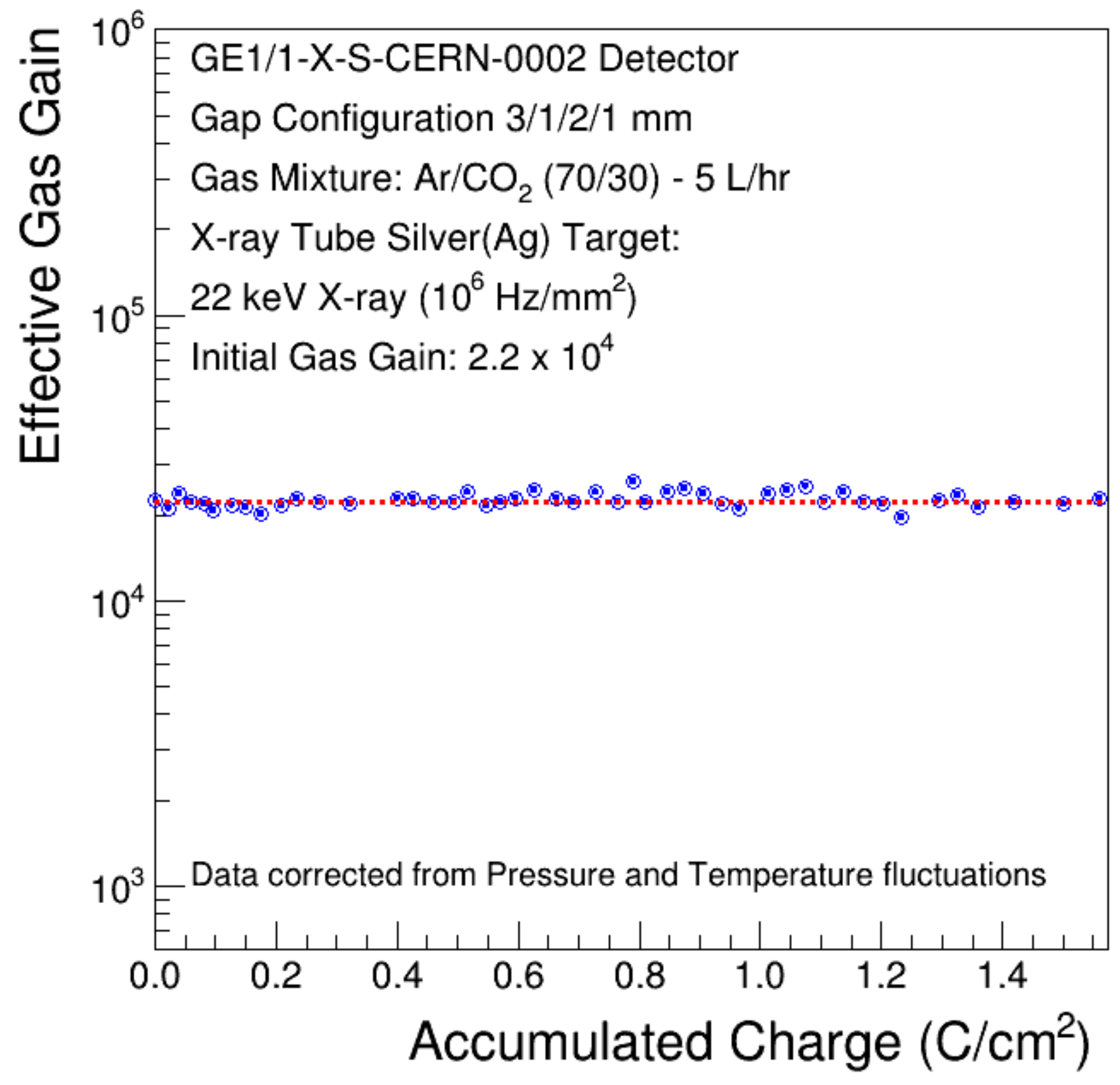


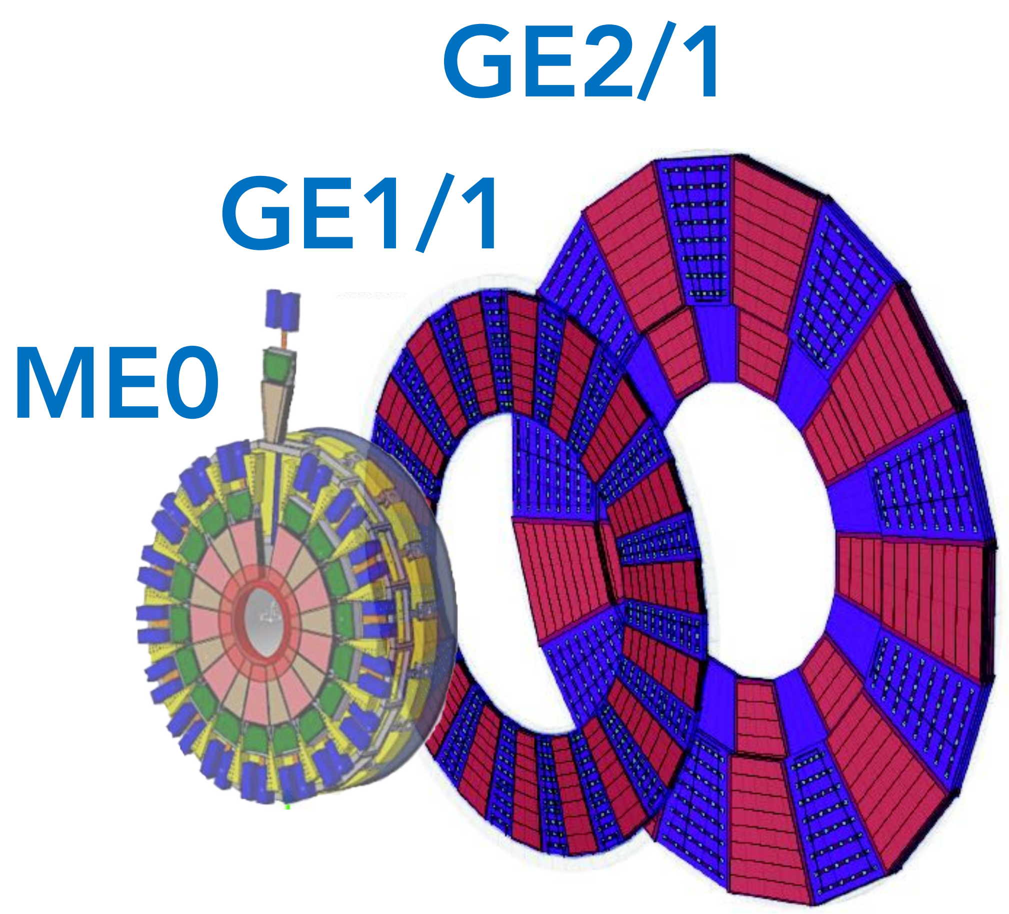
The GEM Upgrade (in brief)

- Micro-Pattern Gas Detectors (MPGD) was chosen as ideal tools for the upgrade Forward Muon Spectrometer in CMS
  - **Rate capabilities: up to O(MHz/cm²)**
  - **Single-chamber efficiency > 97 % for mips**
  - **High spatial and good time resolution**
  - **High resilience to detector ageing**
    - Triple-GEM technology **validated at GIF++** for all the CMS GEM projects with a **Safety Factor 5.5 or higher**



Triple GEM technology

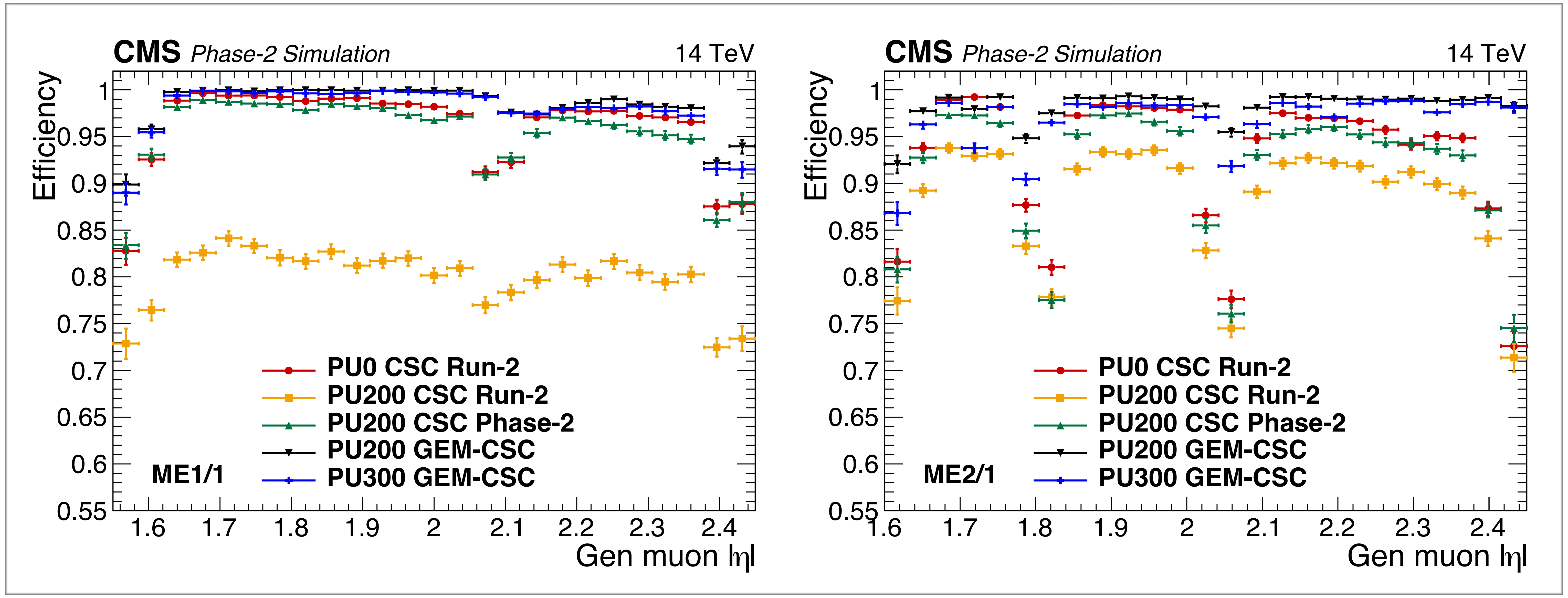


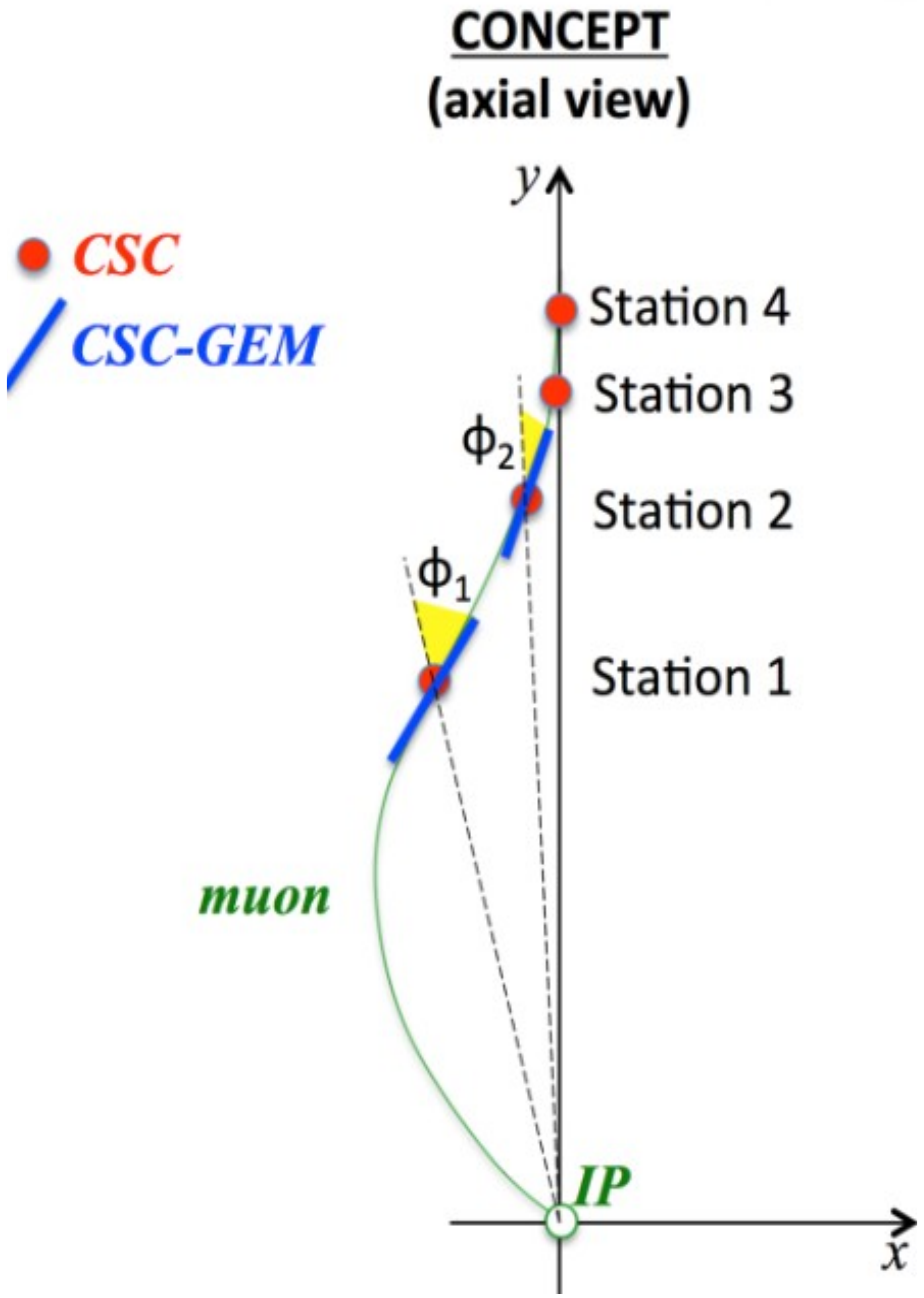


- GE 1/1 is being installed in LS2
  - ***Dedicated talk "Commissioning and prospects of first GEM station at the CMS experiment" by G. Mocellin***
- GE 2/1 and ME0 will be installed in LS3
  - ***Details available in the talk "Electrical Discharge Mitigation Strategies for Future CMS GEM Systems GE2/1 and ME0" by E. R. Starling***

GEM + CSC Trigger

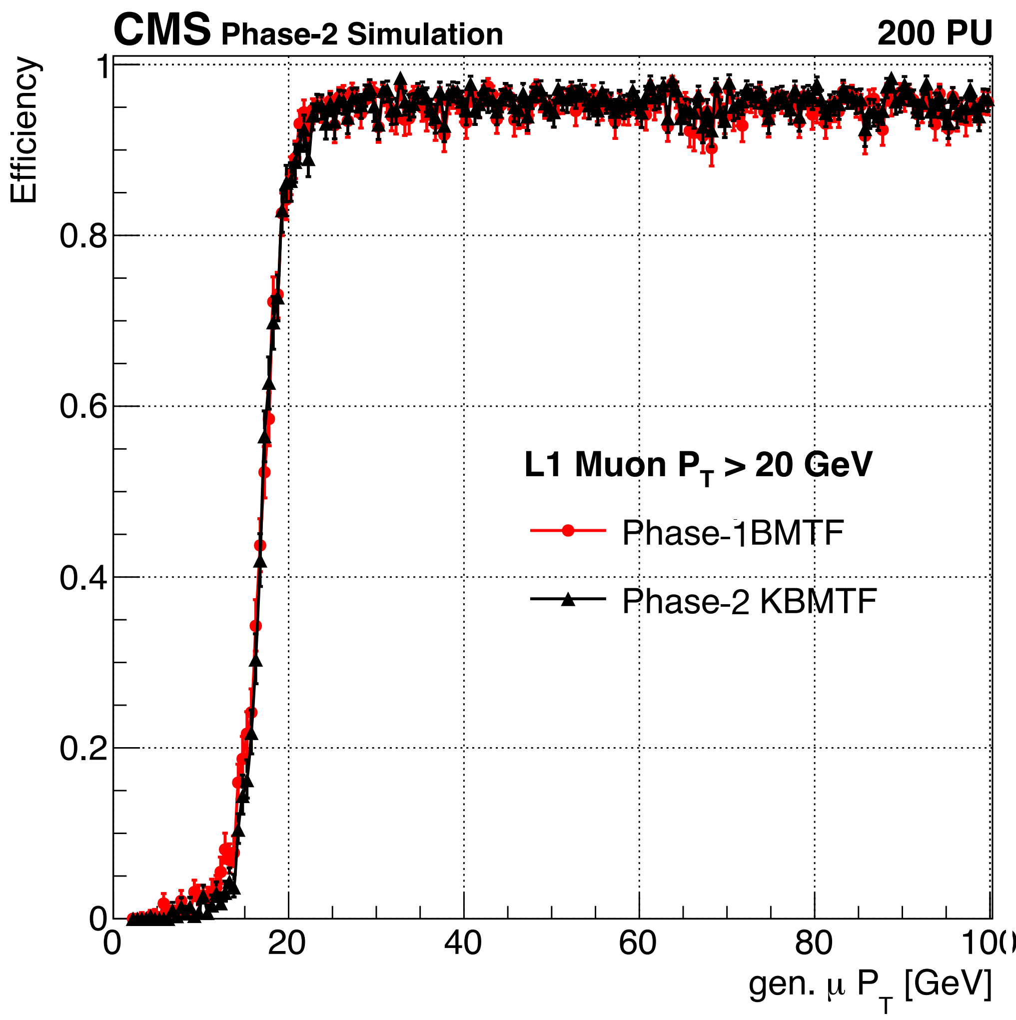
- GEM + CSC upgrade will have a string impact to improve the forward trigger generation
- **Combine CSC and GEM information**
  - New CSC electronic design will allow receiving trigger primitives from GEM neighbouring muon system to form **CSC+GEM “super-primitives"**
  - **boost segment-finding efficiency**
  - disentangle combinatorial “ghosts” in CSCs (short strips in GEMs)
  - improve muon direction within a single station

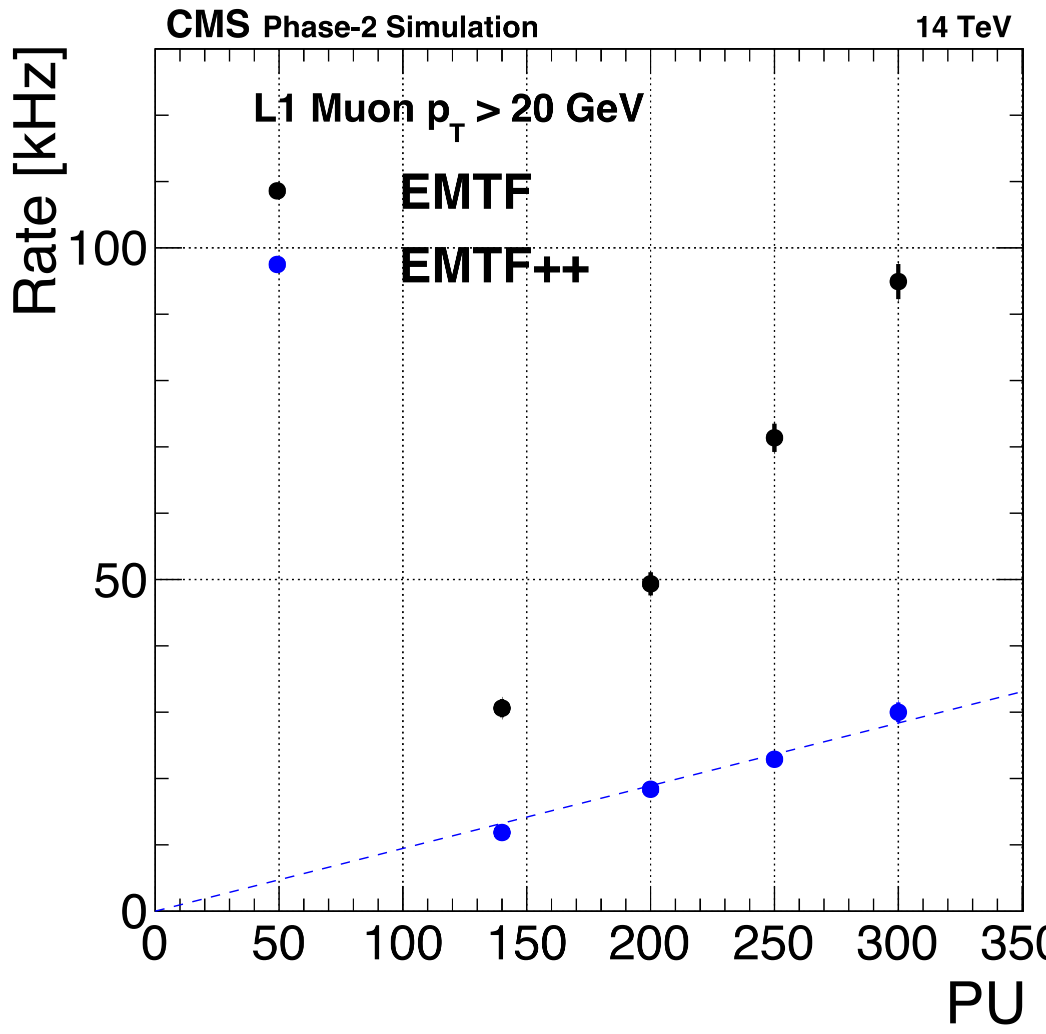


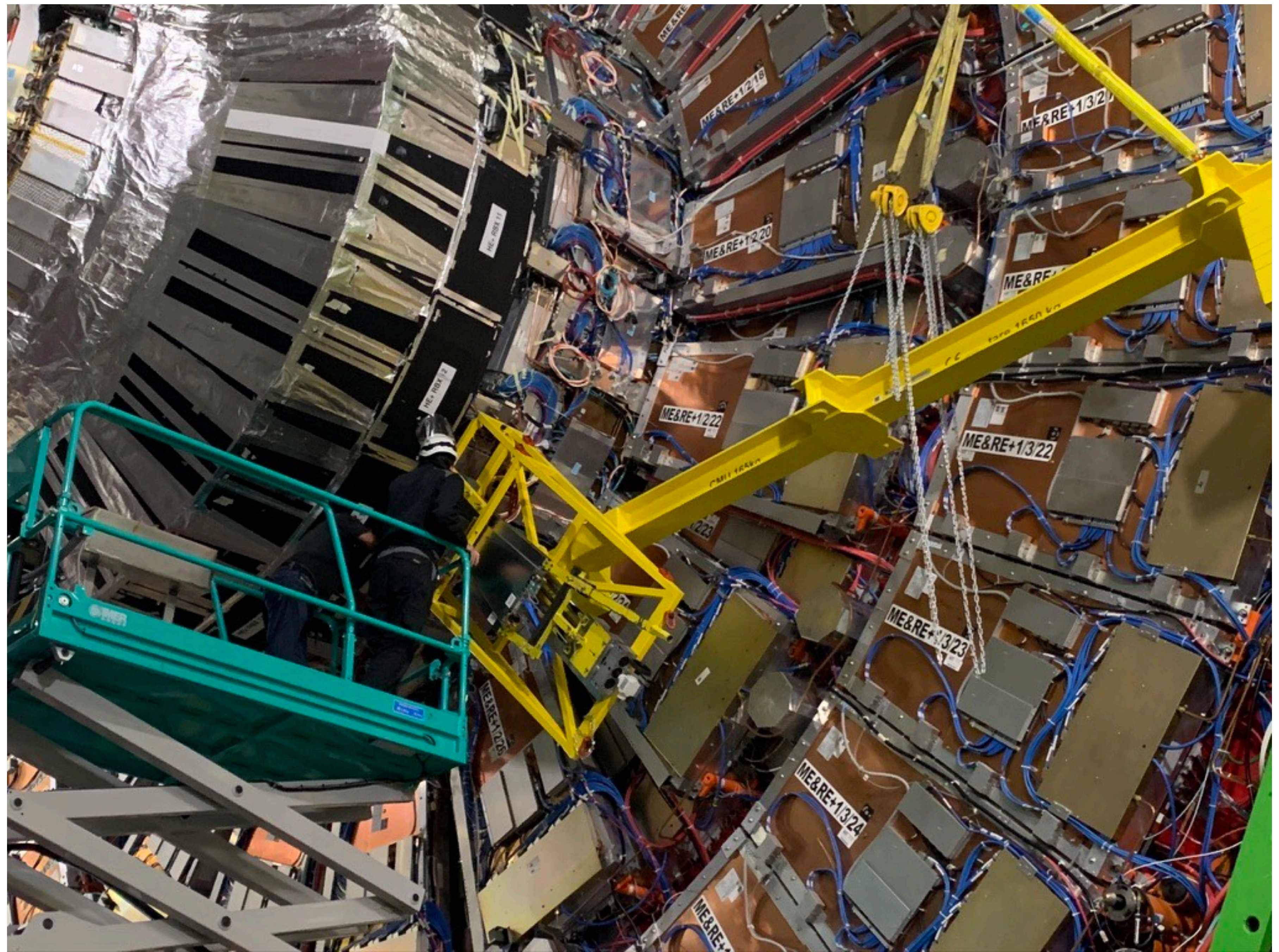


Summary

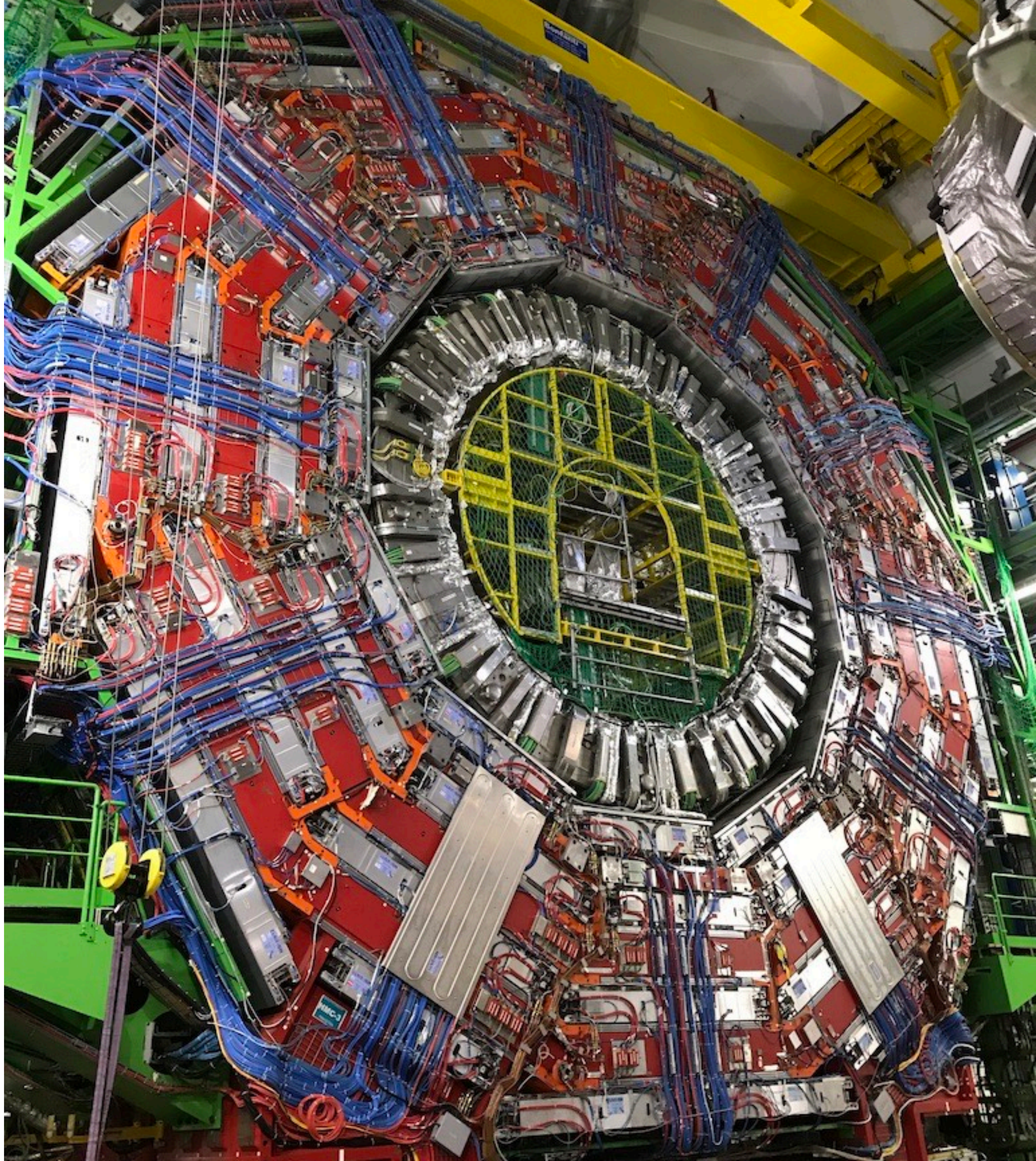
- The **CMS Muon System is ongoing a huge upgrade toward HL-HLC**
  - Addition of **new detectors**
  - Major **electronic upgrade of existing detectors**
  - Ability to withstand the HL-LHC environment, keeping the excellent achievements of the actual system and:
    - improve timing resolution
    - extend η coverage
    - improve triggering
    - improve radiation tolerance
- Longevity of all the detectors assured with long term testing at **GIF++**
- **Part of the Phase-2 Upgrade will be already in place for Run3:**
  - GEM GE 1/1 Rings
  - CSC on-detector electronic refurbishment
  - Services for new iRPC
  - DT Phase-2 demonstrator





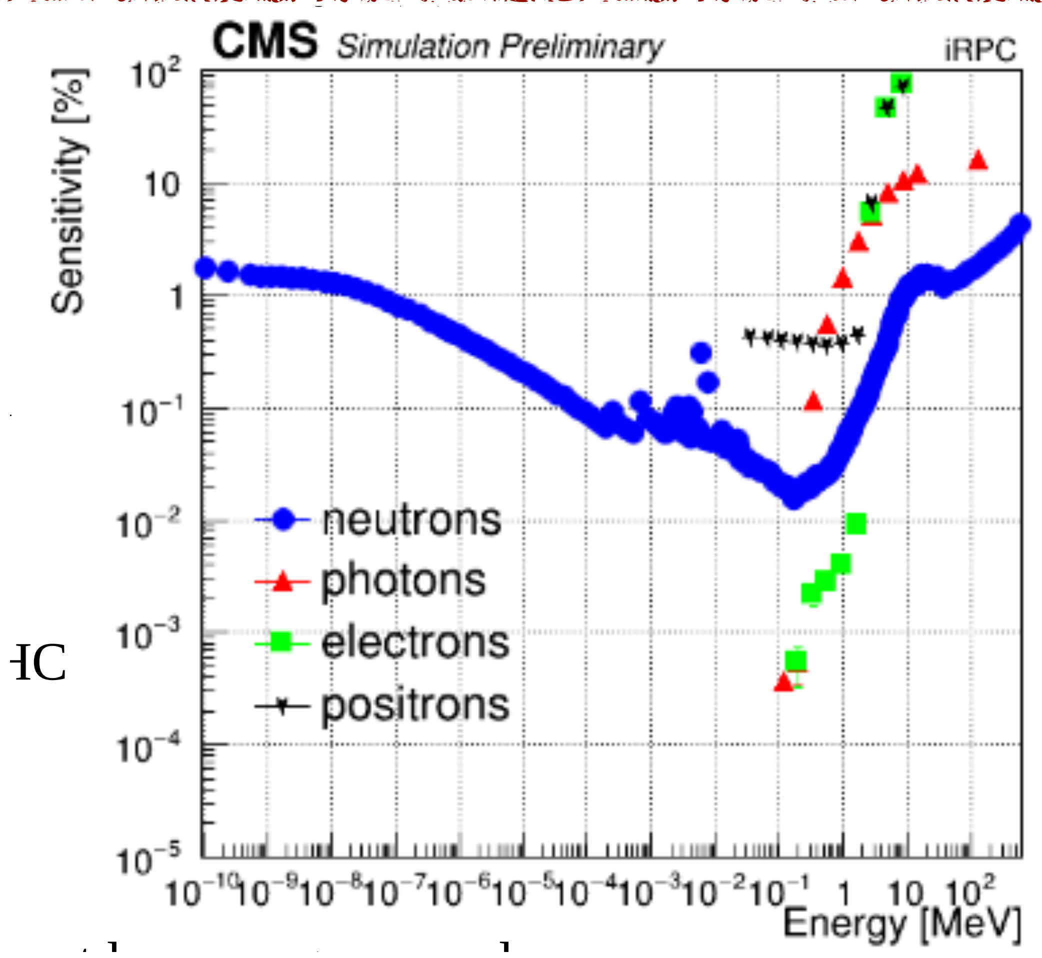


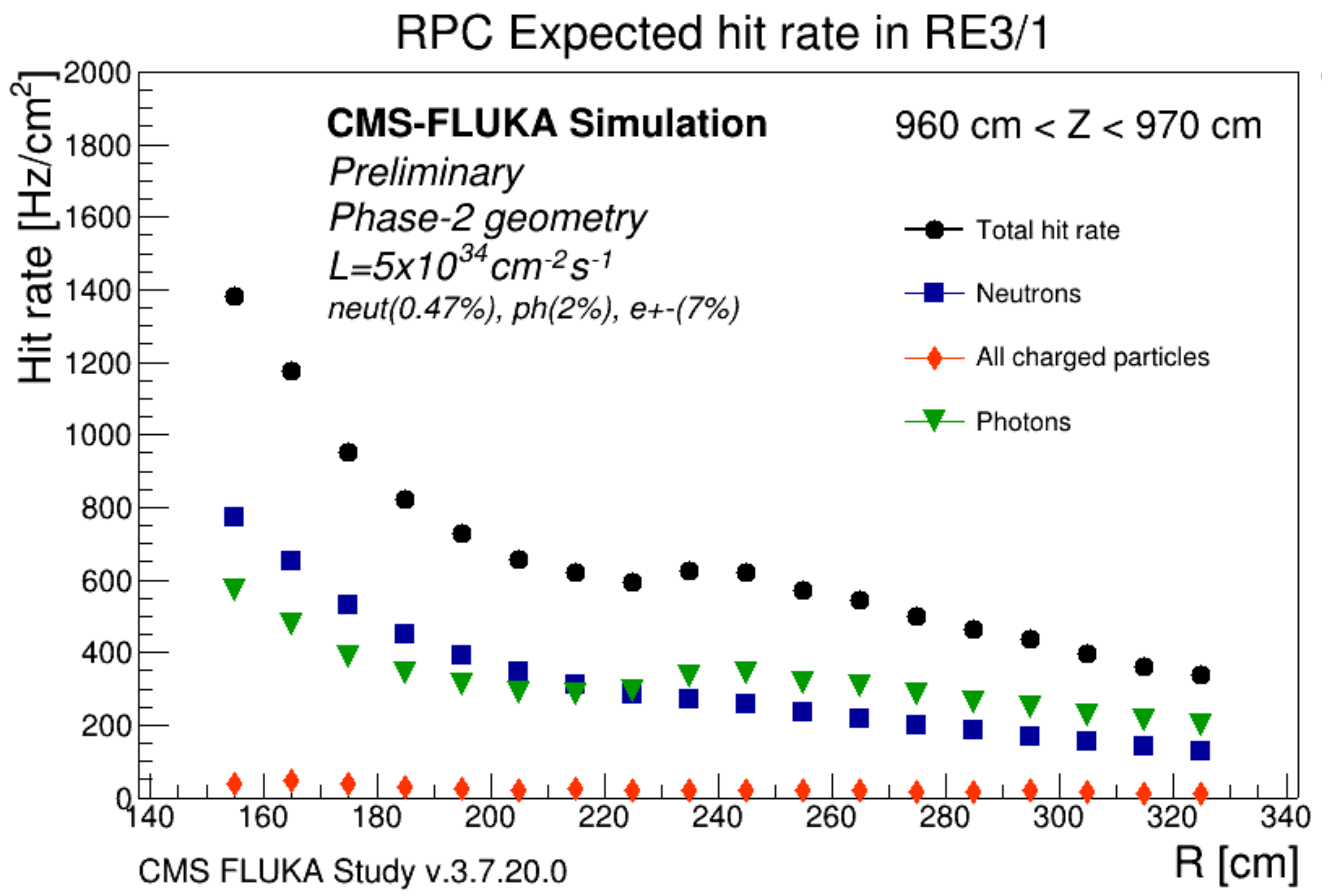
BACKUP

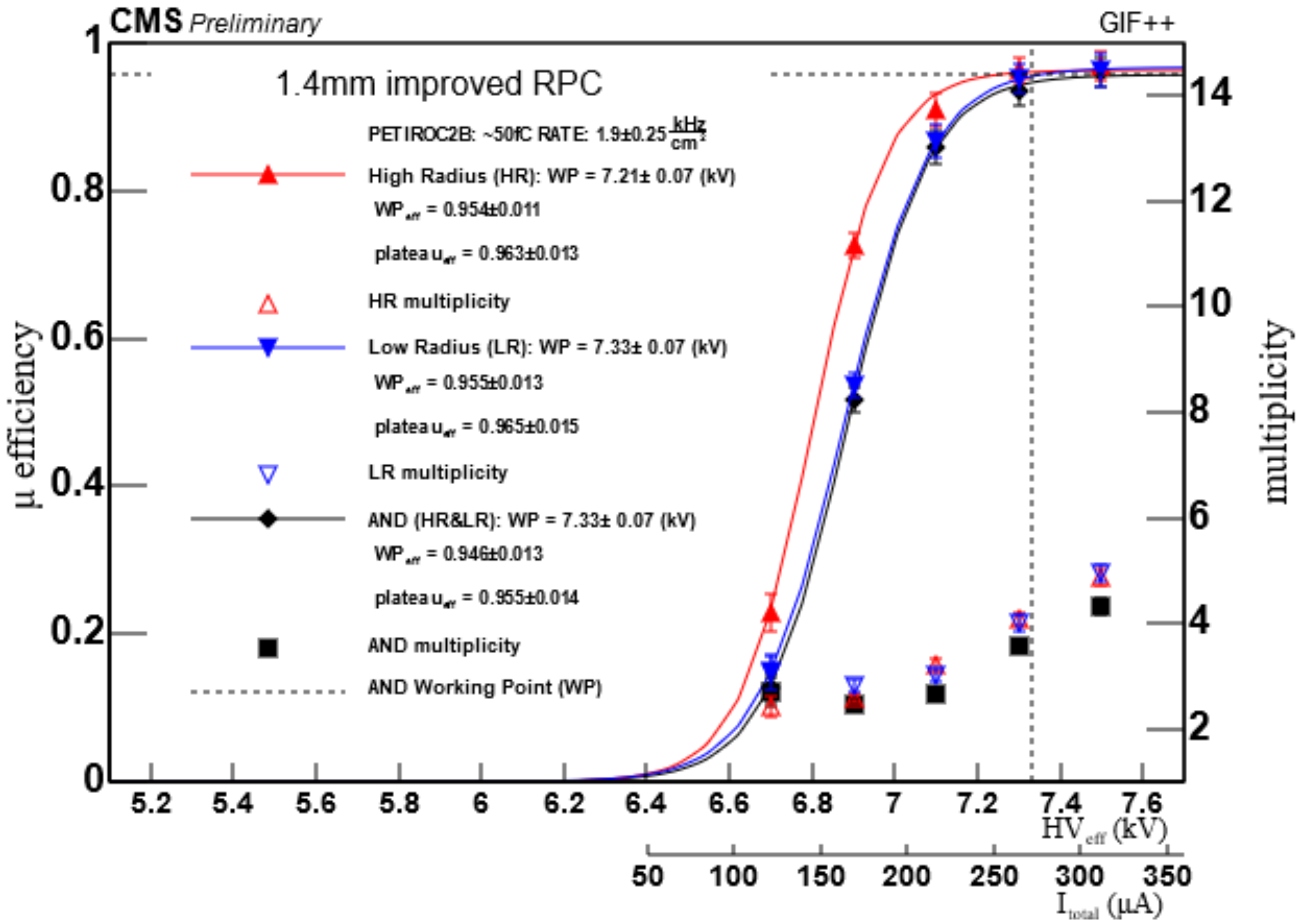


The iRPC electronic

- The detector response to background particles, known as **Sensitivity** S(E) is calculated using **GEANT4** simulation
  - Sensitivity **increases rapidly at high energy** because at low energy secondary charged particles don't have enough energy to reach the gas volume.
- Using Sensitivity and FLUKAs simulation the expected hits rates are calculated
- **iRPC validated at GIF++ with background rate at ~2 kHz/cm2**
- Efficiency of **more than 95%** is obtained.
  - used FEBv1 with FPGA Cyclone V
  - irradiation test are planned for September 2020 and then again in 2021 with the final rad-hard version



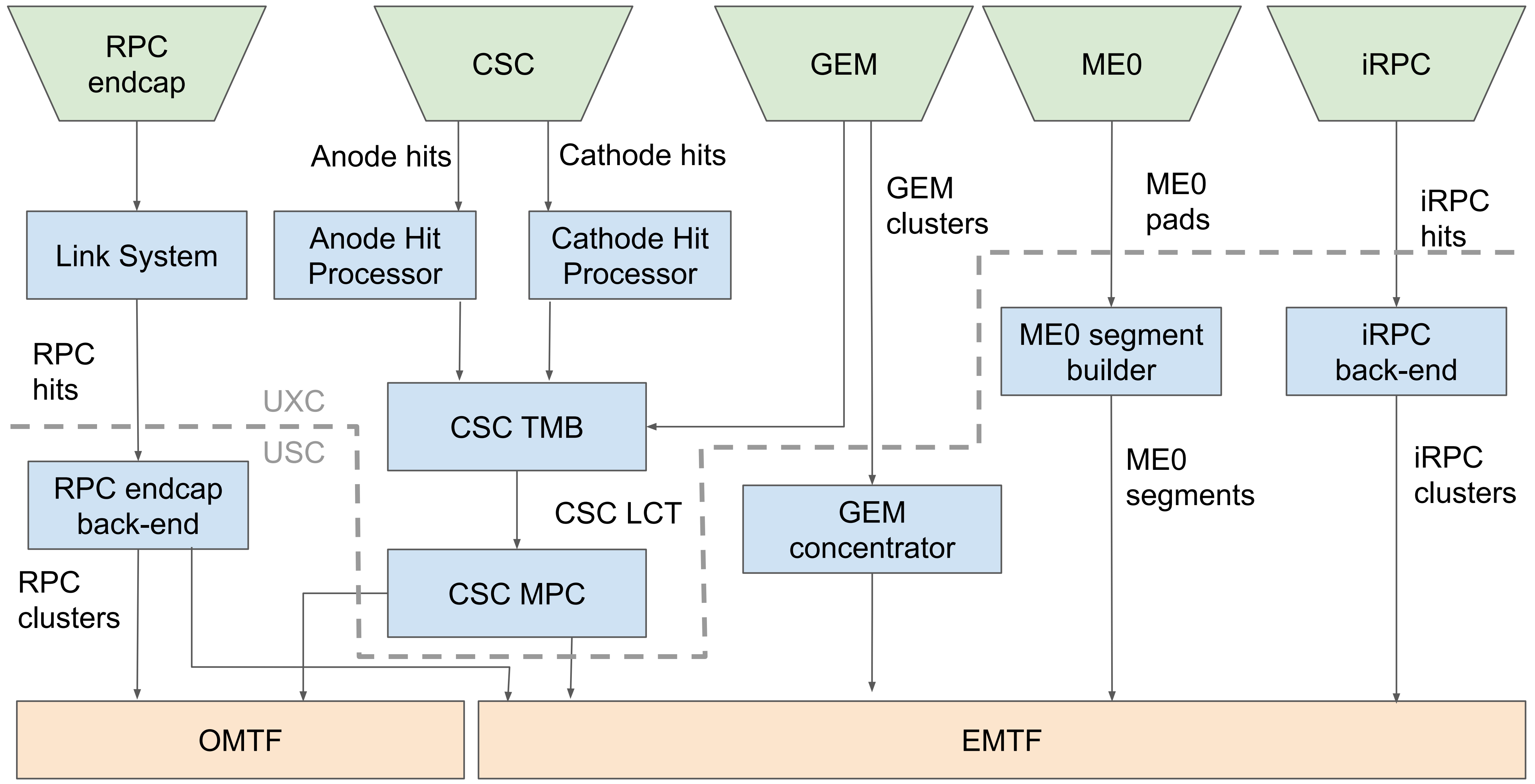


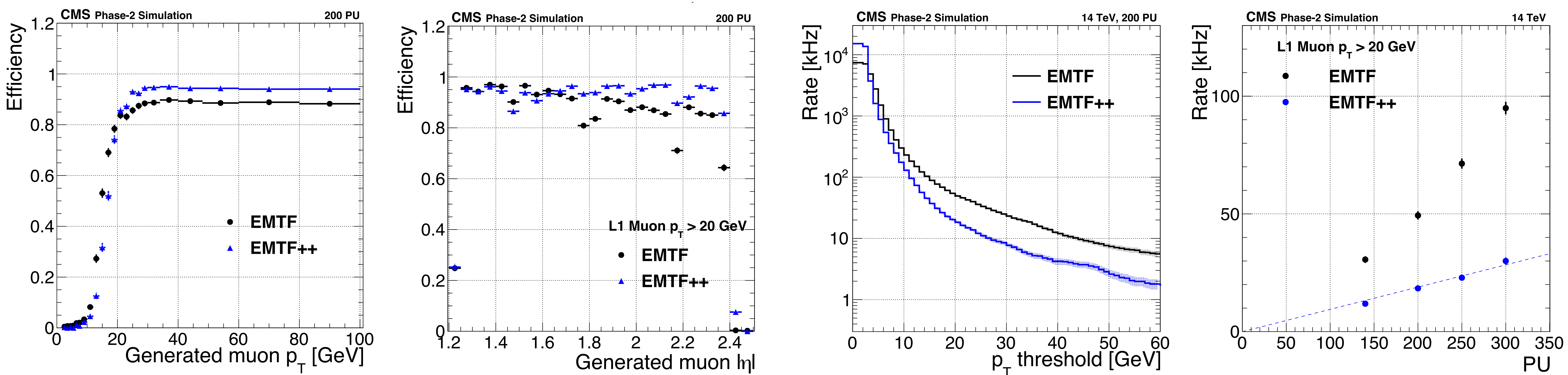


FEBv1

Phase 2 L1 Muon Trigger in the Endcap

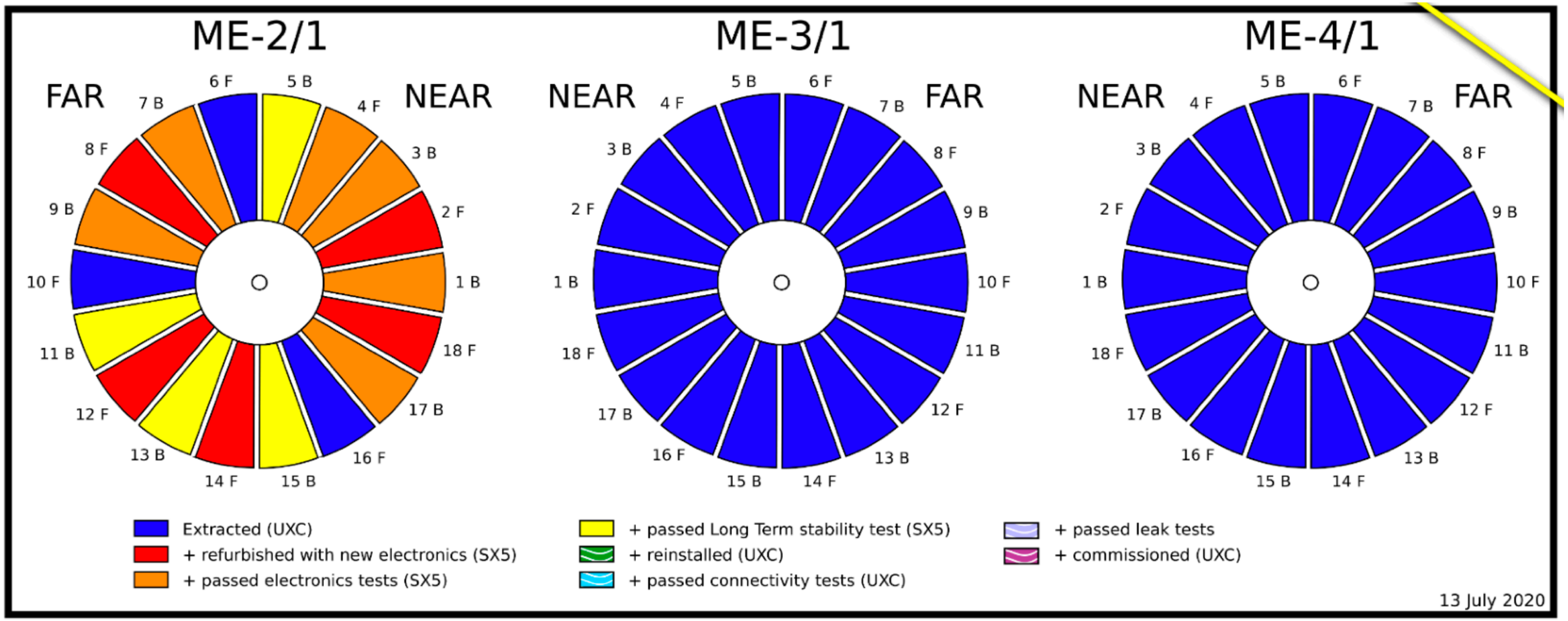
- The final combination of existing detector upgrade and new detectors **strongly enhance the CMS trigger in the forward region**
    - **Improved efficiency**
    - **Linear increase of the rate with PileUp**
- Large physics impaction the CMS physics potential : Higgs, EW measurements and new physics searches (e.g. long-lived particles decaying to muons)





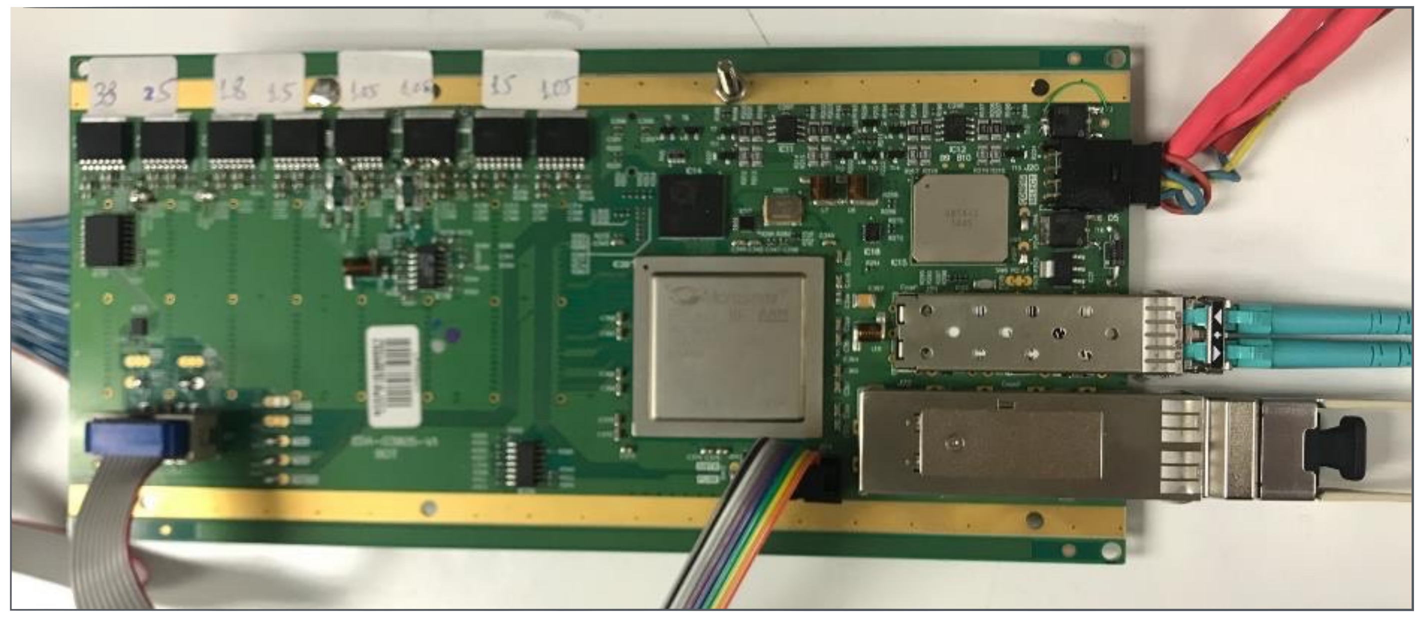
Status of CSC Phase-2 Installation

- ME-X/1 refurbishment was just about to begin at CERN shutdown from March 18th to June 2nd
- CERN starting back up again: ME-X/1 refurbishment will be shifted by 2.5 month and extended by 2 months
- ME-2/1 reinstallation started July 21



DT Slice Test HW components and layout

OBDT: prototype board performing <1 *ns* time digitization in FPGA of chamber signals. Core of the new on-detector electronics.



(Virtex 7 XLXXC7VX330T-3FFG1761E)

Selection of final back-end boards ongoing (most of the ones used for L1T upgrade could work).

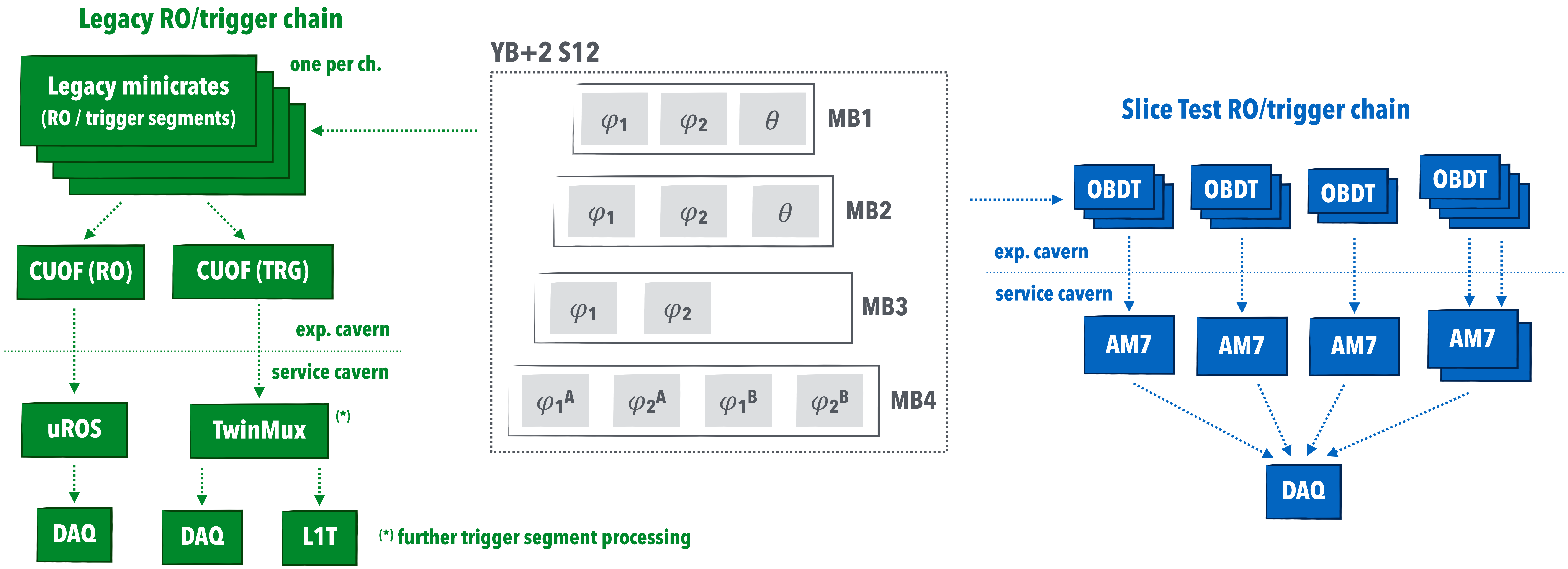
Presently using phase-1 board (TM7) also for phase-2, for two purposes: slow control (**MOCO**) and trigger segment generation (**AM algorithm**) / event building (**AB7**)

AB7 functionalities:

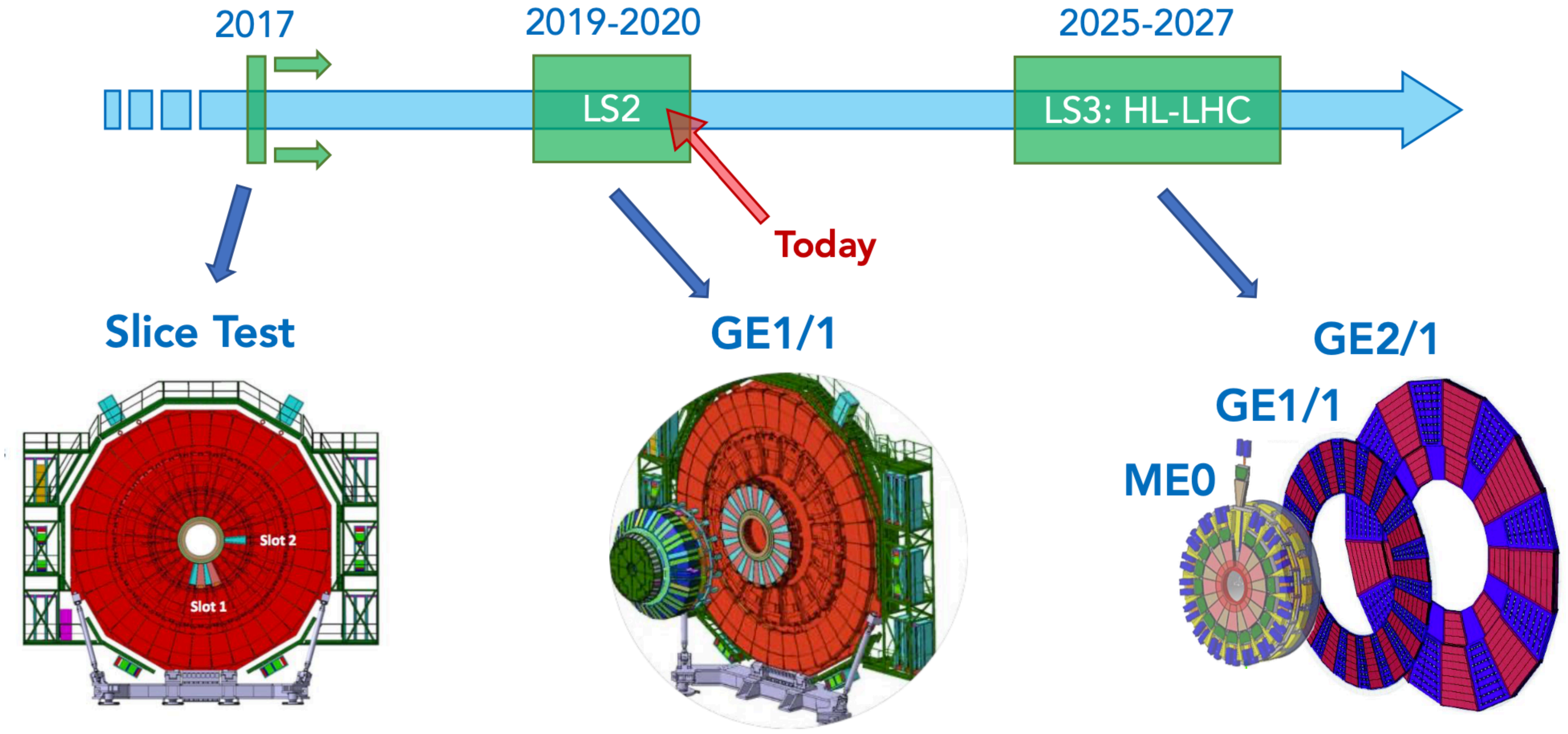
-process data from up to 3 OBDTs

-generates trigger primitives

-performs event matching and



GEM Integration Timeline



Slice Test = commissioning of 5/72 **GE1/1** detectors in CMS

Installation of **GE1/1** during **Long Shutdown 2**

GE2/1 & **ME0** installed by end of **Long Shutdown 3**

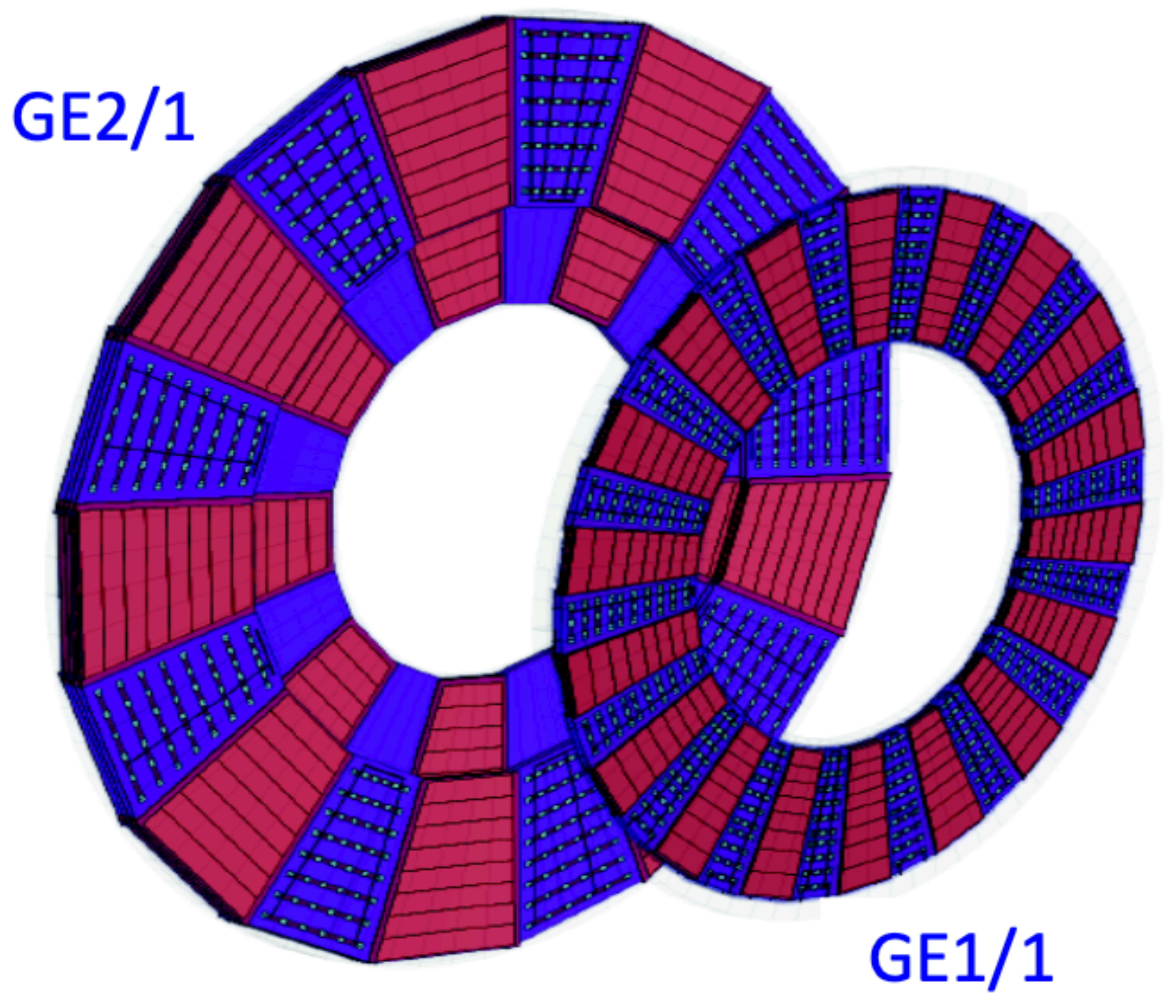
First GEMs in CMS…

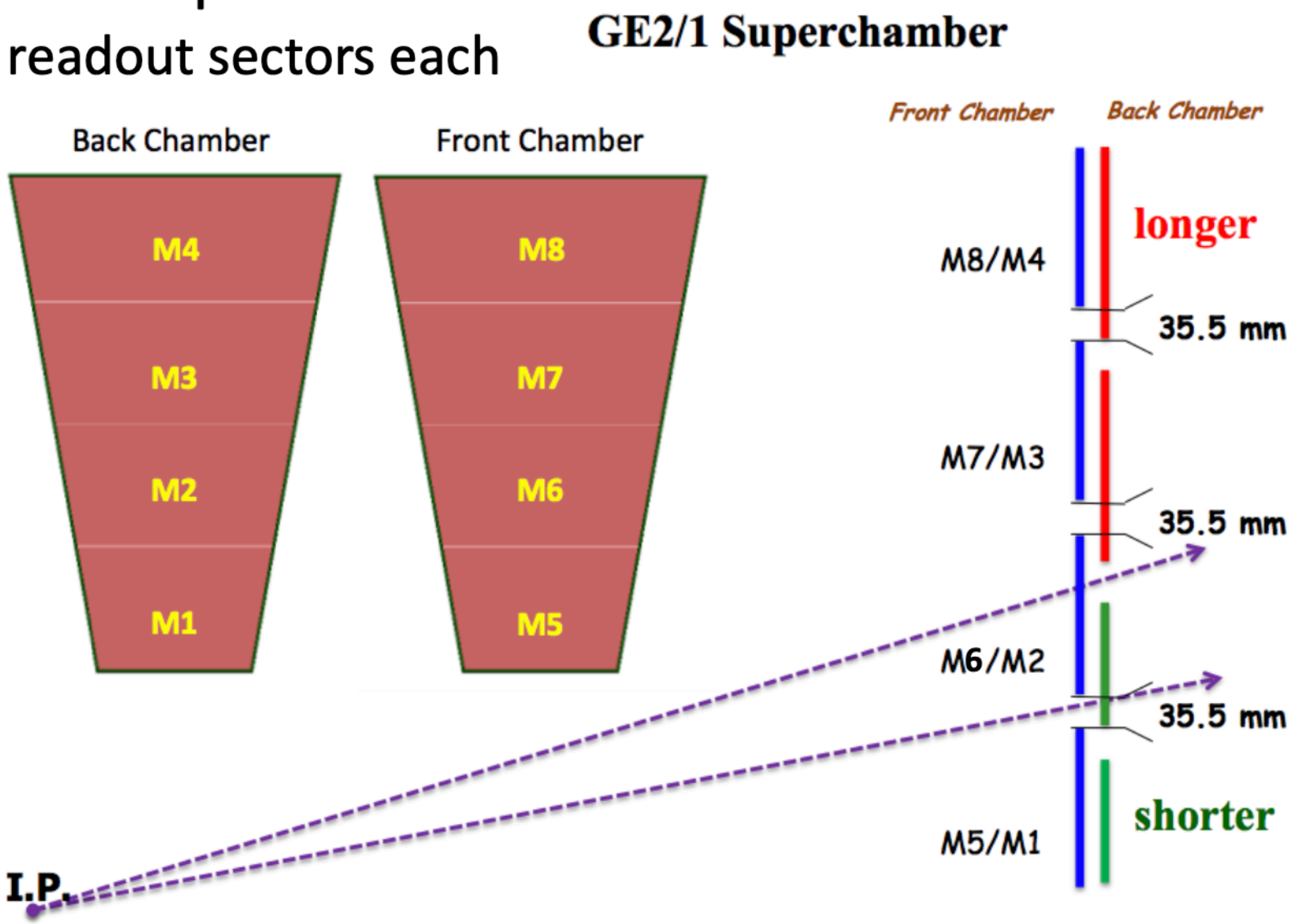
…GEM CMS subsystem…

…GEM expansion pack!

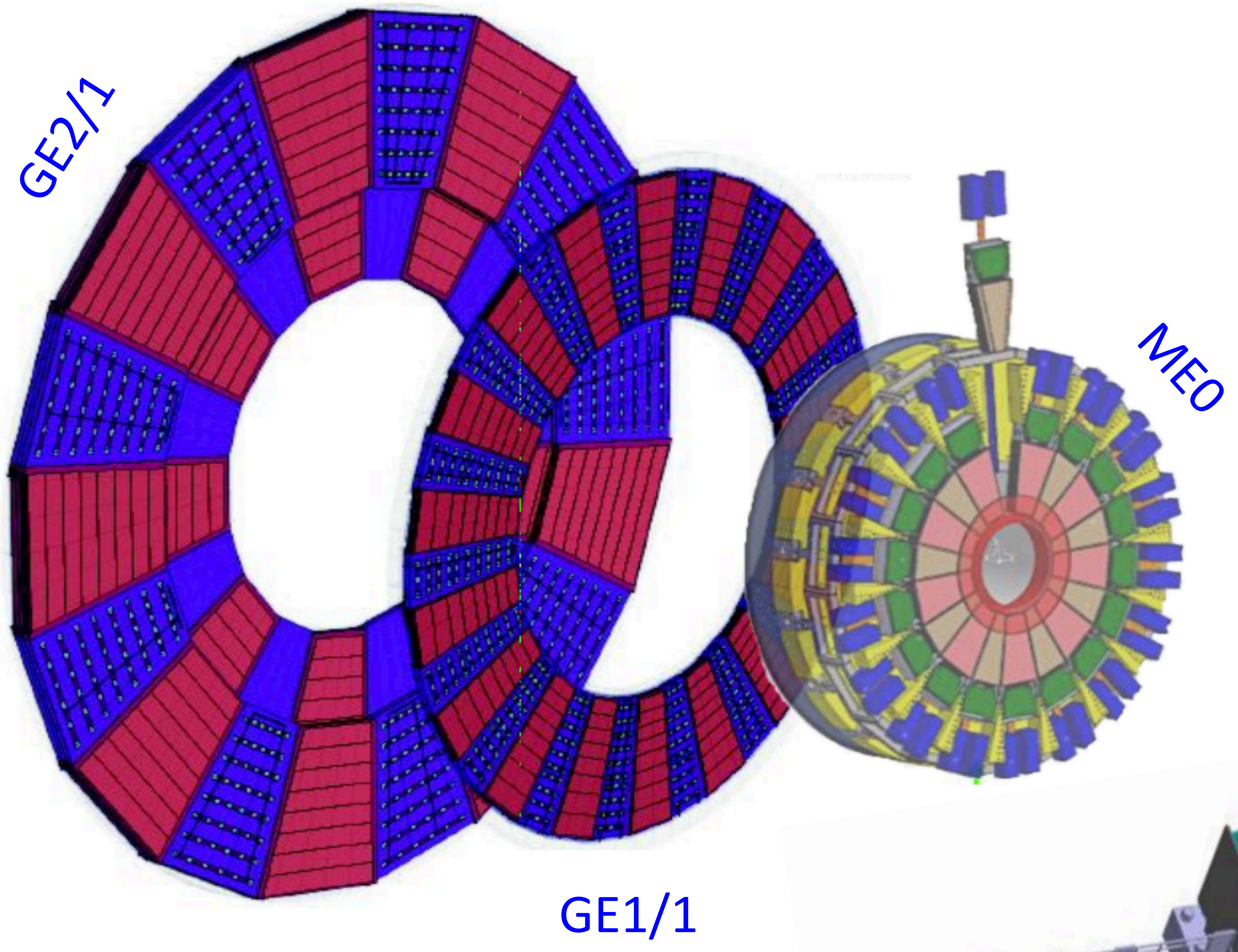
GE 2/1

- 18 staggered superchambers per endcap
  - Each chamber is four modules: 12 readout sectors each
  - 442,000 readout channels
    - Same as GE1/1
  - Each chamber spans 20°





ME0



- 18 staggered stacks per endcap
  - Each chamber spans 20°, like GE2/1
  - Each chamber is a single module with two GEBs, like GE1/1
  - 6 layers / chambers per stack
  - 128 strips / 8 eta partitions per chamber
  - > 650,000 channels