Measurement and simulation of the background in the CMS muon detectors

Cesare Calabria on behalf of the CMS Collaboration

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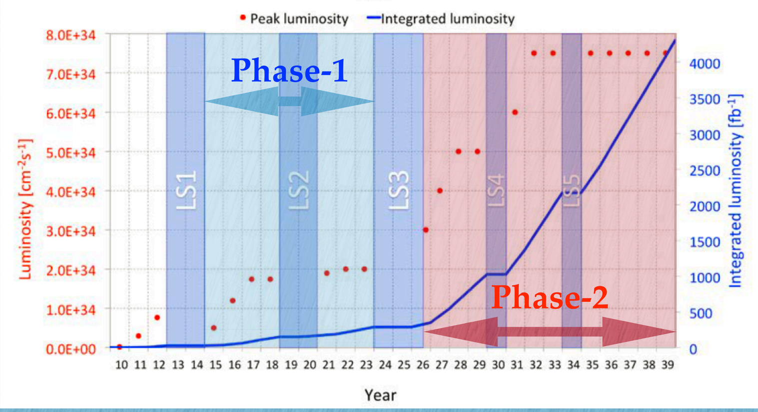
The CMS muon system presently consists of three detector technologies equipping different regions of the spectrometer. Drift Tube chambers (DT) are installed in the muon system barrel, while Cathode Strip Chambers (CSC) cover the end-caps; both serve as tracking and triggering detectors. Moreover, Resistive Plate Chambers (RPC) complement DT and CSC in barrel and end-caps respectively and are mostly used in the trigger. Finally, Gas Electron Multiplier (GEM) chambers are getting installed in the muon spectrometer end-caps at different stages of the CMS upgrade programme. The study of the different backgrounds the muon detectors are exposed to, is fundamental to assess the system longevity and project its performance to the conditions expected for HL-LHC. In this respect, an accurate modeling of the backgrounds in simulation is of prime importance as many studies rely on simulation-based predictions while these future conditions have never been experienced in reality. The state of the art of the work carried out to understand backgrounds observed with data collected during the LHC runs, as well as at CERN high-intensity gamma irradiation facility, (GIF++), will be presented. Furthermore, the effort made to improve the accuracy of FLUKA and GEANT4 based simulations of background will be thoroughly described.

LHC vs. HL-LHC



The High Luminosity LHC (HL-LHC) Upgrade is planned to extend the sensitivity for new physics searches

- The integrated luminosity will increase tenfold with respect to the original design values
- The center-of-mass energy for proton-proton collisions is expected to be raised from the current 13 up to 14 TeV
- The projected integrated luminosity is 300 fb^{-1} for "Phase-1", the current LHC period, and by an order of magnitude to 3000 fb^{-1} in the coming two decades
- The number of pileup (PU) interactions per bunch-crossing is expected to reach 200

	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

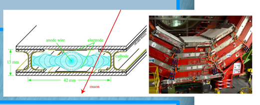
The CMS Muon System and its upgrade

Current Muon System

DT: |η| < 1.2

Trigger and reconstruction

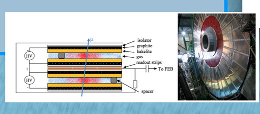
The DTs are segmented in long aluminum drift cells. The position of a traversing muon is determined by measuring the drift time to the anode wire in the center of each cell, with an optimally shaped electric field



RPC: |η| < 1.9

Trigger and reconstruction

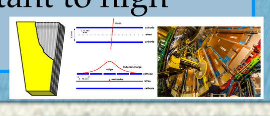
The RPCs are double-gap chambers operated in avalanche mode, at high electric field. They use bakelite electrodes with a high bulk resistivity. RPCs are mainly used for accurate timing and fast triggering and bunch crossing assignment

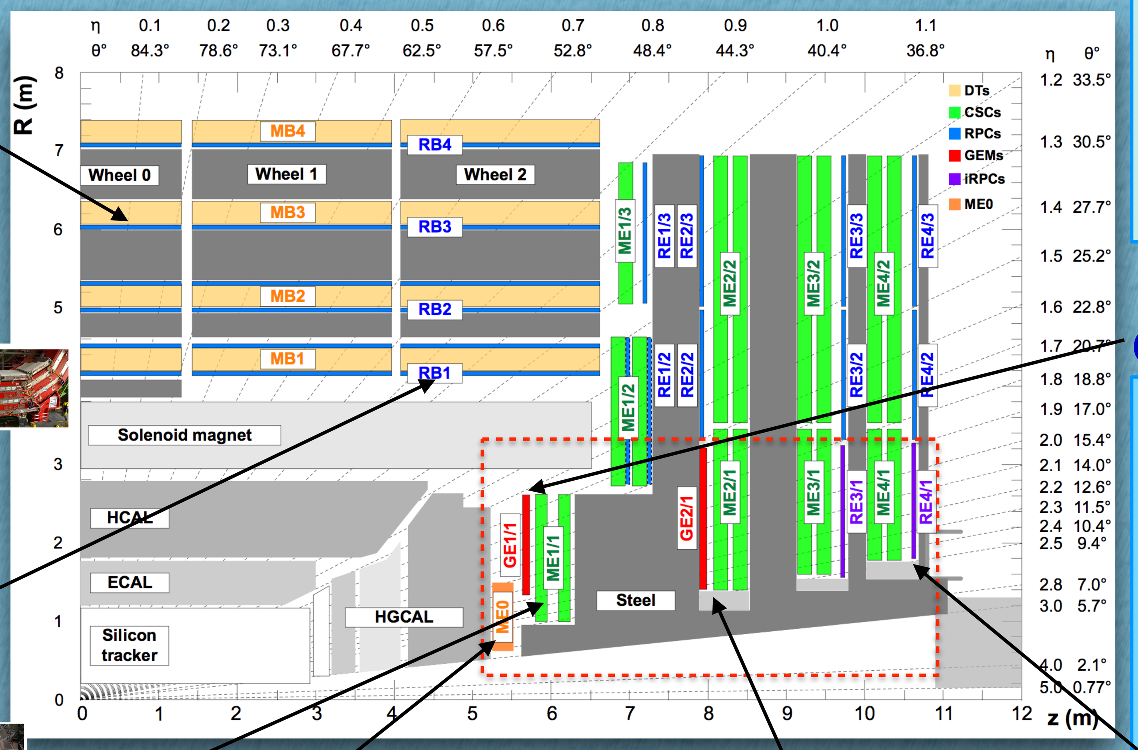


CSC: 0.9 < |η| < 2.4

Trigger and reconstruction

The CSCs operate as standard multi-wire proportional counters with a finely segmented cathode strip readout. The strips run radially outward to measure the muon position in the bending plane, while the anode wires provide a measurement in R. Good performance and resistant to high particle rates



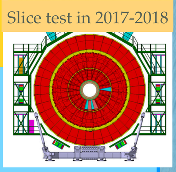


Electronics upgrade

- **DT:** Minicrate (readout, trigger electronics) attached to each chamber to be replaced, to cope with higher rate and radiation
- **CSC:** Selective replacement of electronics for inner ring chambers: high speed optical links, faster processor, deeper buffer
- **RPC:** Replace the Link System (Link and Control Boards) since current system is prone to losing communication

Enhancement of the forward region

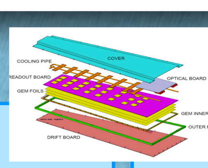
GE1/1



Trigger and reconstruction

- 1.6 < |η| < 2.2
- **Baseline detector for GEM project**
- 36 super-chambers (SC) per endcap, each super-chamber spans 10°
- One super-chamber is made of 2 back-to-back triple-GEM detectors
- **Installation: LS2 (2019-20)**

ME0



Trigger and reconstruction

- 2.0 < |η| < 2.8
- 18 chamber spanning 20°
- 6 layers of GEM-like technology

Further improvement: fast timing MPGD - fully resistive multi-layer design for background and pileup (PU) rejection

GE2/1

Trigger and reconstruction

- 1.55 < |η| < 2.5
- 18 superchambers per endcap, each chamber covers 20°
- 2 layers of GEM-like technology

Further optimization: μ-R-Well as compact and low cost large detector

RE 3/1 – RE4/1

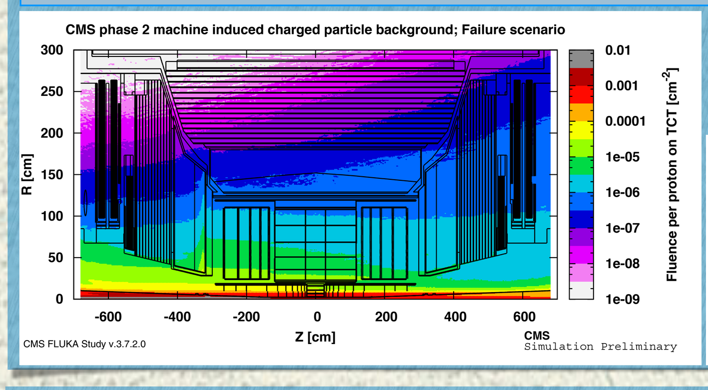
Trigger and reconstruction

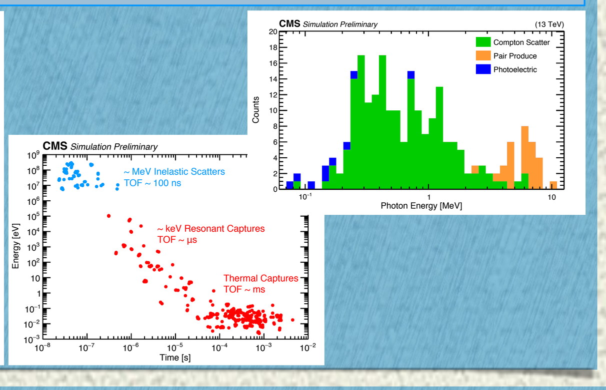
- 1.8 < |η| < 2.4
- 18 chambers per endcap, each chamber spans 20°
- 1 layer (per station) RPC-like technology

Further performance improvement: multi-gap provide high time resolution for background and pileup (PU) rejection

Composition and impact of the background

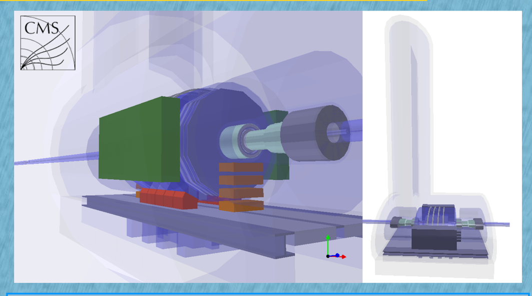
- **The high rate expected at HL-LHC is a major challenge for the particle muon detector longevity and the muon reconstruction**
  - It can decrease the gas gain and increase hit-efficiency losses
  - Radiation damage can lead to noisier electronics performance and even fatal failures of entire electronic boards
- **Neutron induced background is the main source of background:**
  - neutrons are captured in nuclei, emitting a γ of O(0.5-10 MeV)
  - γ produces e± of O(MeV) through Compton scattering or Photo-electric effect
  - hits in muon chambers due to elastic (n,p) collisions (in gas) or from γ → e±



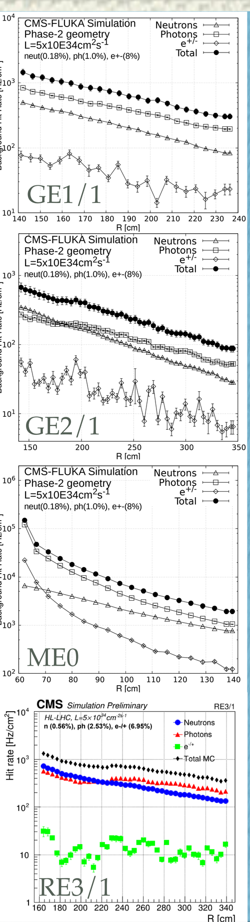


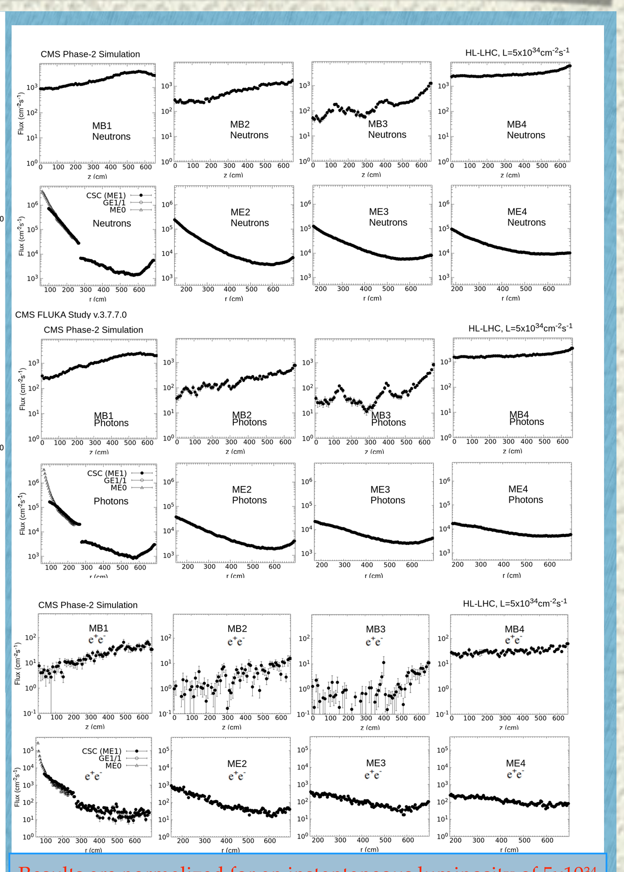
Neutron background simulation

- Background simulation is of primary importance to understand the harsh conditions never faced before at LHC and design properly the electronics and the detectors
- A lot of effort have been spent in CSM to establish a detailed simulation using tools like FLUKA[3] and GEANT4[2]
  - **FLUKA to simulate the p-p collisions and the transport of particles in the CMS detector (including long living neutrons)**
  - **GEANT4 to estimate the probability for these particles to create a spurious signal in the detector (sensitivity)**
- CMS detector and cavern geometry have been carefully simulated



- **A full GEANT4 based Monte Carlo simulation has been also set up to simulate minimum-bias p-p collisions and the neutron background in the CMS analysis framework**
- The standard CMS GEANT4 configuration has been modified in order to address the long lifetime and low energy of the neutron by:
  - increasing tracking time of all particles (to 10 s)
  - removing all energy thresholds where they existed





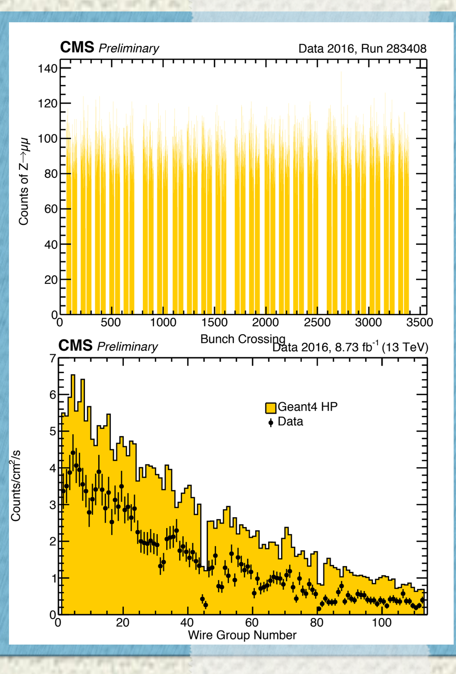
Results are normalized for an instantaneous luminosity of $5x10^{34}$ $cm^{-2}s^{-1}$ assuming an inelastic scattering cross section of 80 mb

Background measured in data

- The Muon community is investigating how to identify neutron-induced hits in CMS data collected in Run2
- The comparison with the simulation is a fundamental step for validating the simulation technique to make correct predictions for HL-LHC

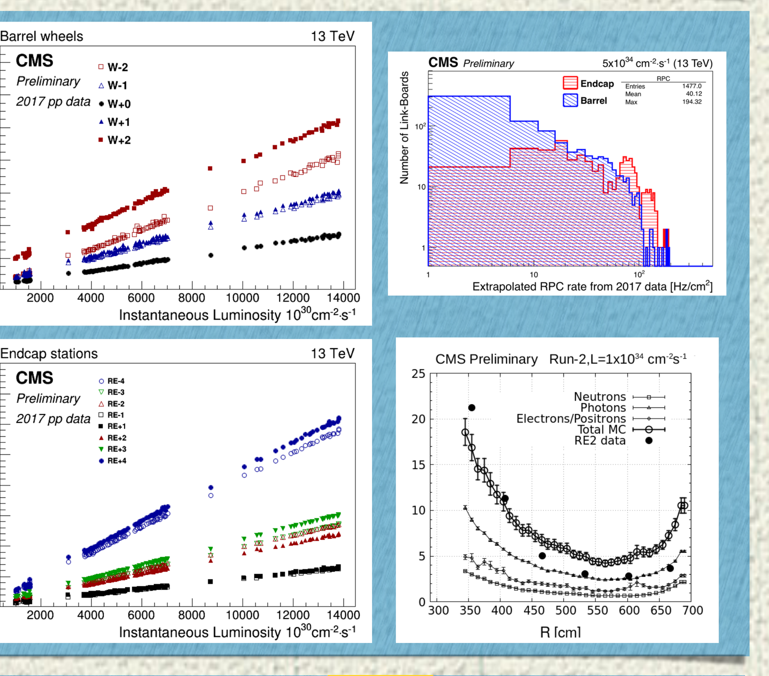
The CSC measurement

- Selecting Z → μμ events and identifying candidate neutron-induced hits by looking away from the triggering muon
- To distinguish neutrons from out-of-time pileup we consider gaps in the LHC proton bunch structure of at least 35 bunch crossings (BX) and use p-p bunch trains with exactly 48 BX to identify p-p collisions occurring just after such gaps
- Considering end-of-gap thermal neutron induced hits and comparing to thermal-neutron induced hits from simulation
- **For all CSCs at various r and z positions, simulation reproduces data to within a factor of 2**



The RPC measurement

- Background in the cavern has been studied in terms of RPC hit rate as function of the instantaneous luminosity (rates were measured during the p-p collision data taking and averaged per run; instantaneous luminosity is also averaged per run)
- The linear dependency allowed to make an extrapolation to the HL-LHC regime
- The background hit rate measured in data has been compared with the FLUKA simulation at an instantaneous luminosity of 10^{34} $cm^{-2}s^{-1}$
- **Background simulations reproduce the measured rates within a factor of two in the worst case**

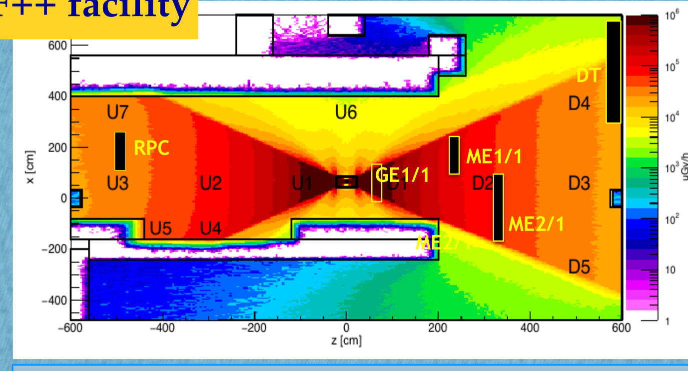


Longevity tests

- All muon subsystems worked with high efficiency and resolution even at $1.7x10^{34}$ $cm^{-2}s^{-1}$, the highest instantaneous luminosities reached by the summer of 2017
- Anyway elements of current system are currently 15-20 years old, eventually may need to last 40 years
- Must re-certify existing equipment to HL-LHC: 6x integrated radiation doses and 5x signal and background rates w.r.t LHC
- Longevity of new detectors (GEM, iRPC) must be also tested
- Accelerated tests are ongoing by exposing detectors and electronics to irradiation sources:
  - accelerated tests are indicative only
  - at least a factor of 3 larger than what we expect to see over the HL-LHC lifetime is considered

NB: No safety factor! |η| range	DT 0-1.2	CSC 0.9-2.4	RPC 0-1.9	iRPC 1.8-2.4	GE1/1 1.6-2.15	GE2/1 1.6-2.4	ME0 2.0-2.8
neutron fluence (10^{12} n/cm^2)	0.4	40	1	7	20	12	200
total ionization dose (kRad)	0.12	10	2	3	3	7	490
hit rate (Hz/cm^2)	50	4500	200	700	1500	700	48000
charge per wire (mC/cm)	20	110	-	-	-	-	-
charge per area (mC/cm^2)	-	-	280	330	6	3	280

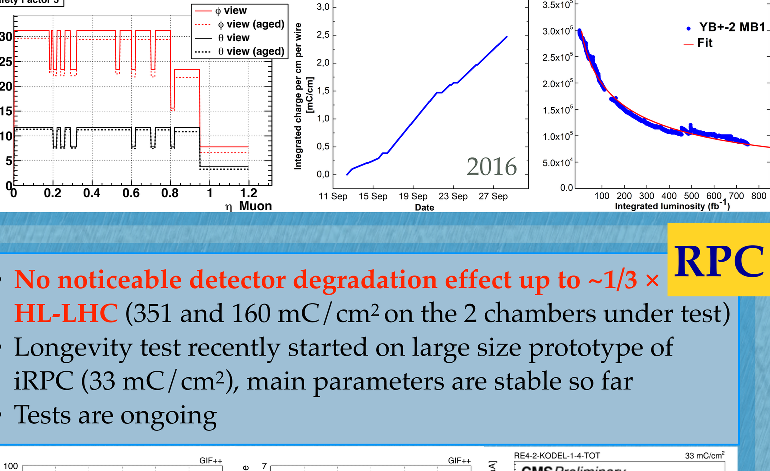
The GIF++ facility



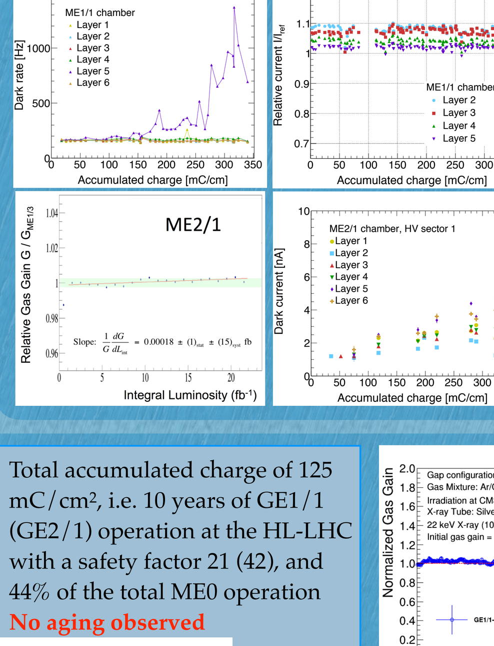
- CERN GIF++[4] provides 662 keV photons emitted by an intense 14 TBq ^{137}Cs source and a high momentum muon beam (100 GeV)
- Neutron-induced photons have an energy in the range 0.1–10 MeV. Thus, GIF++ provides a fairly realistic simulation of the HL-LHC conditions
- The muon beam provides excellent probes for detector performance studies in the presence of high radiation
- Chambers under test:
  - CSC: 1 ME1/1 and 1 ME2/1
  - DT: 1 MB1
  - GEM: 1 GE1/1, 1 GE2/1
  - RPC: 1 RE2, 1 RE4, 1 iRPC large prototype

DT

- **About 15% of chambers, most exposed to background, could see noticeable gas gain loss, but muon reconstruction will remain high, thanks to multiple layers of DTs on the path of a muon**
- Aging mitigation measures are being explored (no gas recirculation, HV adjustment, shielding for chambers, etc.)



CSC



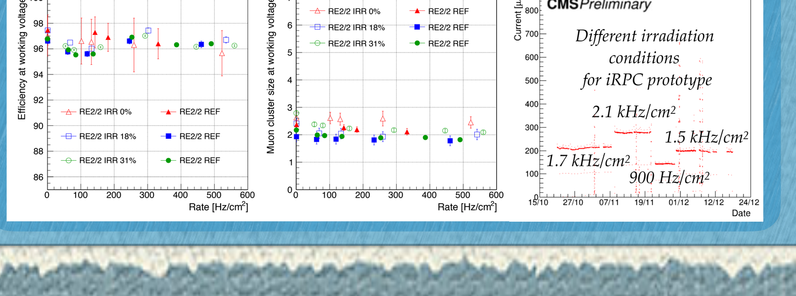
- Total integrated charge of 330 (ME1/1) and 340 (ME2/1) mC/cm
- **No noticeable gas gain loss up to 3 × HL-LHC**
- Tests continue

Typical manifestations of prolonged exposition to radiation:

- a loss of gas gain
- a rise in spurious signal rates ("dark rate")
- an increase in leakage currents ("dark current")
- development of self-sustained discharges set off at high radiation rates (Malter effect)

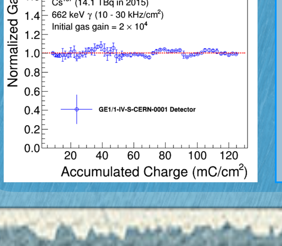
RPC

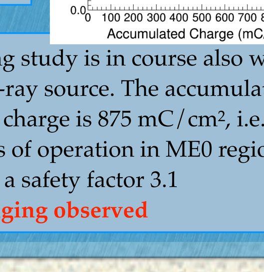
- **No noticeable detector degradation effect up to ~1/3 × HL-LHC** (351 and 160 mC/cm^2 on the 2 chambers under test)
- Longevity test recently started on large size prototype of iRPC (33 mC/cm^2), main parameters are stable so far
- Tests are ongoing



GEM

- Total accumulated charge of 125 mC/cm^2, i.e. 10 years of GE1/1 (GE2/1) operation at the HL-LHC with a safety factor 21 (42), and 44% of the total ME0 operation
- **No aging observed**





- Aging study is in course also with an X-ray source. The accumulated total charge is 875 mC/cm^2, i.e. 10 years of operation in ME0 region with a safety factor 3.1
- **No aging observed**

References

[1] CMS Collaboration, "The Phase-2 Upgrade of the CMS Muon Detectors", CERN-LHCC-2017-012. CMS-TDR-016

[2] Nuclear Instruments and Methods in Physics Research A 506 (2003) 250-303, IEEE Transactions on Nuclear Science 53 No. 1 (2006) 270-278, Nuclear Instruments and Methods in Physics Research A 835 (2016) 186-225.

[3] "The FLUKA Code: Developments and Challenges for High Energy and Medical Applications", T.T. Böhlen, F. Cerutti, M.P.W. Chin, A. Fassò, A. Ferrari, P.G. Ortega, A. Mairani, P.R. Sala, G. Smirnov and V. Vlachoudis, Nuclear Data Sheets 120, 211-214 (2014); "FLUKA: a multi-particle transport code", A. Ferrari, P.R. Sala, A. Fassò, and J. Ranft, CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773

[4] D. Pfeiffer et al., "The Radiation Field in the Gamma Irradiation Facility (GIF++) at CERN", Nucl. Instrum. Meth. A866 (2017) 91, doi:10.1016/j.nima.2017.05.045, arXiv: 1611.00299