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Background in the CMS muon detectors: simulation and measurements with pp collision data

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Abstract: The CMS muon system at the LHC is built of different detector technologies. The measurement of the background hit rates in the different muon detectors during the LHC Run-2 is of prime importance for an assessment of the longevity of the chambers and their on-board electronics, and therefore for the expected performance of the system at HL-LHC. Moreover, an accurate modelling of the backgrounds using simulations is also critical, as an estimation of the expected radiation background for the Phase-2 upgrade can only rely on Montecarlo-based predictions in the regions where new detectors are being installed. The present understanding of the backgrounds measured with data collected during the LHC Run-2, as well as at CERN high-intensity gamma irradiation facility, GIF++, is discussed, together with the work made to improve the accuracy of the background modelling in Fluka and GEANT4 simulations.

Keywords: Muon spectrometers, Performance of High Energy Physics Detectors, Radiation calculations

Contents

1 The CMS muon system and its upgrade

The High Luminosity LHC (HL-LHC) upgrade [1] is expected to increase the sensitivity to new physics by increasing the center-of-mass energy for proton-proton (pp) collisions to 14 TeV and the instantaneous luminosity to $5 \cdot 10^{34}$ cm^{-2} s^{-1} ($7.5 \cdot 10^{34}$ cm^{-2} s^{-1} in the ultimate scenario), with an average number of additional pp interactions (pileup) per bunch-crossing expected to reach 140 (200 in the ultimate scenario). The integrated luminosity will increase in the coming two decades from the design value of 300 fb^{-1}of the present LHC "Phase-1", to 3000 fb^{-1}(or to 4000 fb^{-1}, expected ultimate value) during the so-called LHC "Phase-2", as shown in figure 1.

The detailed description of the CMS detector, together with a definition of the coordinate system used, can be found in Ref. [2]. Muons with pseudorapidity in the range $|\eta| < 2.4$ are measured in gas-ionization detectors embedded in the steel return yoke, with detection planes made of three technologies: Drift Tube chambers (DTs) and Cathode Strip Chambers (CSCs) serve as tracking and triggering detectors respectively in the barrel and the endcaps of the spectrometer, whereas Resistive Plate Chambers (RPCs) complement the DTs and CSCs both in the barrel and in the endcaps, and are mostly used in the trigger. In addition, multiple layers of Gas Electron Multiplier (GEM) [3] chambers are being installed in the muon system endcaps at different stages of the CMS upgrade programme. The present CMS muon system, together with the detectors of the proposed HL-LHC scenario, is shown in figure 2 and described in detail in [4].

2 Expected background in the CMS muon system

The estimation of the dose and rate expected in the muon system from radiation background is essential to choose the appropriate detector technologies for the upgrade, and to design the detectors and electronics that will be able to cope with the HL-LHC conditions. The new detector technologies (the GEMs and the so-called "improved RPCs", referred to as iRPCs in the following) that are to be installed as part of the muon system upgrade, are designed to maintain excellent performance throughout the whole HL-LHC operation. Both the new and the existing detectors

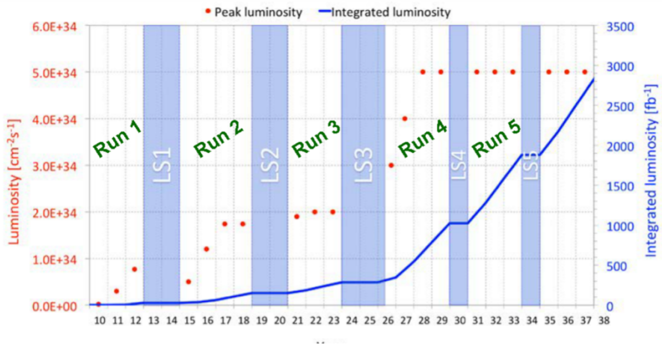

Figure 1. Development of the instantaneous and integrated luminosities vs. time for the design HL-LHC. The present "Phase-1" data taking period will end in 2023, followed by a shutdown for the HL-LHC upgrade. The high luminosity data taking period, "Phase-2", is expected to last from 2026 till 2038.

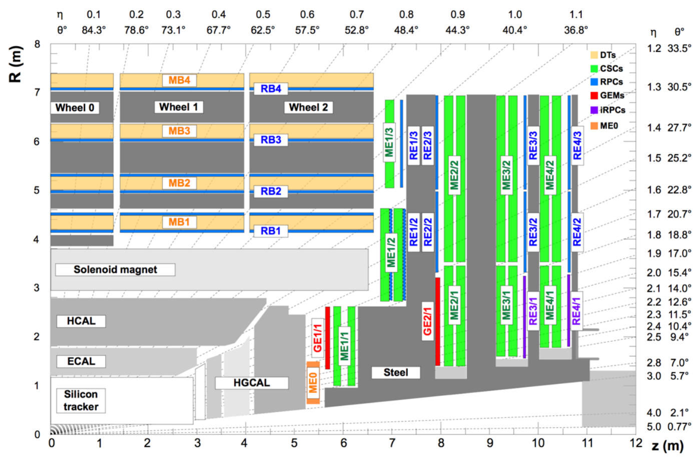

Figure 2. Schematic view, in the R-z plane, of one quadrant of the CMS detector, with the axis parallel to the beam (z) running horizontally and the radius (R) increasing upward. The interaction region is at the lower left corner. The position of the present RPC chambers is shown in blue. The RPCs are both in the barrel ("RB" chambers) and in the endcaps ("RE") of CMS. The DT chambers are labeled "MB"("muon barrel") and the CSC chambers are labeled "ME" ("muon endcap"). The steel disks are displayed as dark gray areas. Also shown in orange and red are the chambers of the proposed upgrade scenario of the CMS Muon system, including Gas Electron Multiplier detectors (labeled "ME0" and "GE") and iRPCs ("RE3/1" and "RE4/1").

(DTs, CSCs, RPCs) are being tested (Section 4) to demonstrate, or confirm, their radiation hardness at the level required to handle the HL-LHC background conditions.

Proton-proton primary interactions and particle transport through the CMS detector are simulated using FLUKA [5, 6], which is also used to estimate the expected fluences, doses and fluxes from neutrons, photons and charged particles. Hit rates are in turn estimated by normalizing the fluxes by the detector sensitivities determined with GEANT4 [7–9]. Very accurate descriptions of the CMS detector and the CMS cavern are implemented in the FLUKA and GEANT4 simulations, well reproducing the Run1 and Run2 measurements as shown in the next Section. As an example, figures 3 and 4 show typical detector sensitivities in the GEM chambers as a function of the particle energies, together with the resulting expected fluxes in the detector.

The DTs, CSCs and RPCs are replacing for Phase-2 their front-end electronics in the chambers exposed to the largest background with new electronics tested to cope with the expected neutron fluences and total ionization doses [1].

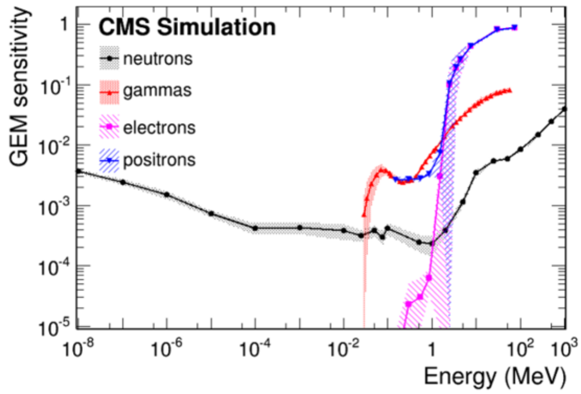

Figure 3. GEM sensitivities in the GE1/1 chambers as a function of the particle energies for neutrons, photons, electrons and positrons. The sensitivities are simulated with GEANT4.

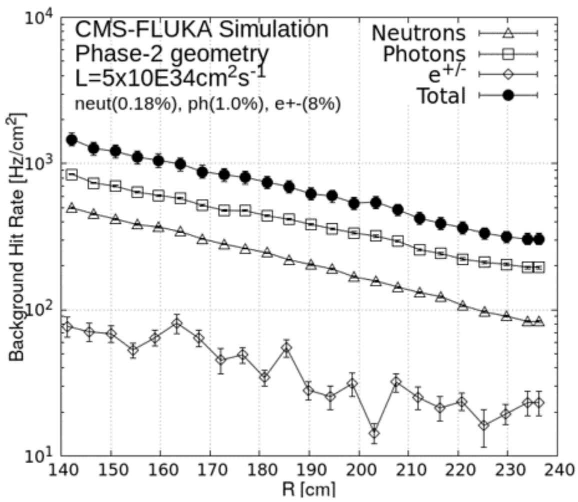

Figure 4. Expected hit rates, at the HL-LHC design luminosity, in the GE1/1 chambers. Rates values are determined normalizing fluxes estimated with FLUKA via average sensitivities obtained with GEANT4 and shown for instance in figure 3.

3 Background measurements

The data collected during the LHC Run1 and Run2 have offered the opportunity to extensively study the radiation background inside the CMS cavern and in the Muon system. A linear dependence as a function of the LHC instantaneous luminosity has been observed by all subdetectors over several orders of magnitude of the instantaneous luminosity, as shown as an example in figure 5. The highest rates are observed in the external endcap chambers, more exposed to the neutrons permeating the CMS cavern. Assuming that the linear dependence on the luminosity, observed from $\approx 10^{29}$ cm^{-2} s^{-1} to $\approx 10^{34}$ cm^{-2} s^{-1}, will hold at $5 \cdot 10^{34}$ cm^{-2} s^{-1}, these measurements can be extrapolated to estimate the expected background rates at the HL-LHC in the existing detectors. Figure 6 shows the RPC measurements in the barrel and endcap compared to the expected hit rates in the detectors. Good agreement is observed in the central (barrel) region of the detector, where the differences are at the level of 10% to 30%. In the endcap regions, the simulation is able to reproduce the shape of the measurements, with a quantitative agreement within a factor of two. A similar agreement, within a factor two, is observed by the CSCs. The RPC average sensitivities determined with GEANT4 are: neutrons (0.26 ± 0.03)%; photons: (1.6 ± 0.2)%; e+/e-: (35 ± 16)%.

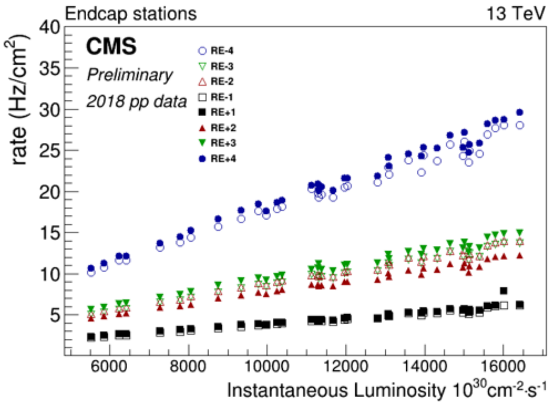

Figure 5. Rates measured in the endcaps of the RPCs as a function of the instantaneous luminosity, at a center-of-mass energy of 13 TeV, for values of the instantaneous luminosities up to $\approx 1.6 \cdot 10^{34}$ cm^{-2} s^{-1}.

4 Irradiation tests at the GIF++ facility

The expected higher background conditions at the HL-LHC are realistically simulated at the CERN Gamma Irradiation Facility (GIF++) [10], where beams of high energy charged particles, mainly 100 GeV muons, are provided with photons from an intense (14 TBq) Cs^{137} source. The dose distribution inside the GIF++ bunker is shown in figure 7 [10]. The energy of the emitted photons, 662 keV, is within the typical range (0.1 to 10 MeV) of neutron-induced photons emitted at the LHC. Accelerated irradiation tests are performed, allowing to study the performance and stability, and to asses the longevity of detectors expected to cope for several decades with the HL-LHC conditions, i.e. with doses and rates of the order of five times the LHC ones (as mentioned in Section 1). Effects of prolonged exposition to radiation may result in loss of gas gain; rise in spurious signal rates (dark rate); increase in leakage currents (dark current); development of self-sustained discharges set off at high radiation rates (Malter effect). Existing and new detectors are therefore being certified for the doses and rates expected at the HL-LHC. Maximum hit rates and charges expected to be accumulated in the chamber gas volume, relevant for the detector longevity, are summarized in table 1 [1].

Chambers of all the muon subdetectors are being irradiated at the GIF++. We refer to [11] for a detailed discussion of the longevity studies performed by the DTs. The CSCs have collected a

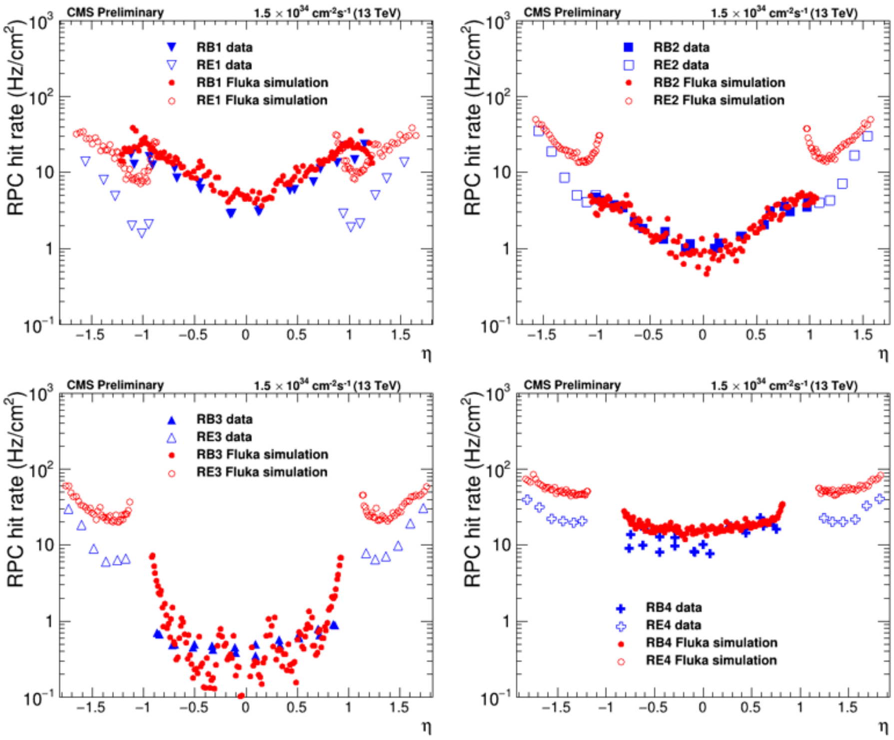

Figure 6. Comparison between measurements and simulation in the barrel and endcap stations of the RPC detector. The stations RB1-RE1 (top left), RB2-RE2 (top right), RB3-RE3 (bottom left) and RB4-RE4 (bottom right) are shown, respectively. The simulation is able to reproduce the shape of the data, with a quantitative agreement at the level of 10% to 30% in the barrel, and within a factor 2 in the endcap.

Table 1. Expected hit rate and accumulated charge for the CMS muon detectors after the Phase-2 upgrades, at the end of HL-LHC running, assuming an instantaneous luminosity of $5 \cdot 10^{34}$ cm^{-2} s^{-1}. Only the worst-case values in the most exposed chambers of each subdetector are given. The numbers shown do not include safety factors. The column RPC refers to the RPC chambers already present during Phase-1, while the new chambers to be installed are referred to as iRPCs.

	DT	CSC	RPC	iRPC	GE1/1	GE2/1	ME0
$\lvert\eta\rvert$ range	0-1.2	0.9-2.4	0-1.9	1.8-2.4	1.6-2.15	1.6-2.4	2.0-2.8
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

total integrated charge of about 330 mC/cm, corresponding to three times the integrated charge per wire expected at the HL-LHC (figure 8) with no evidence of gas gain loss. The average gas gain of the most exposed ME2/1 chambers is normalized to the one of the least exposed ME1/3 chambers, used as a reference. The RPCs (figure 9) see no noticeable effects of detector degradation for values the integrated charge up to 600 mC/cm^2 corresponding to roughly 70% of the ones expected at the HL-LHC. Longevity tests are also performed on large size prototype of Phase-2 RPC detectors, showing stability of the main detector parameters. The GEMs have observed no aging effect with total accumulated charge of 125 mC/cm^2, corresponding to 10 years of GE1/1 (GE2/1) operation at the HL-LHC, and about 45% of the total ME0 operation. Irradiation tests for ME0 have been performed also with an X-ray source, allowing to collect an integrated charge of 875 mC/cm^2, corresponding to 10 years of operation (figure 10). Safety factors of at least 3 are included for all subdetectors.

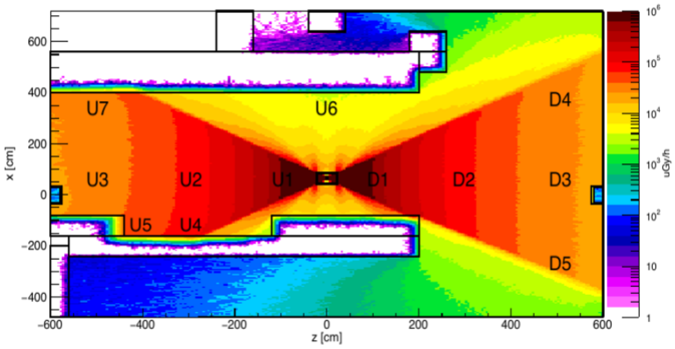

Figure 7. Dose distribution inside the GIF++ bunker. The labels U (upstream) and D (downstream) refer to the two independent irradiation regions of the GIF++ bunker, classified as "upstream" or "downstream" relative to the incoming charged particle beam. The chambers being irradiated are located near the positions labelled as D4 (DTs), U3 (RPCs), D2 (CSCs), and D1 (GEMs).

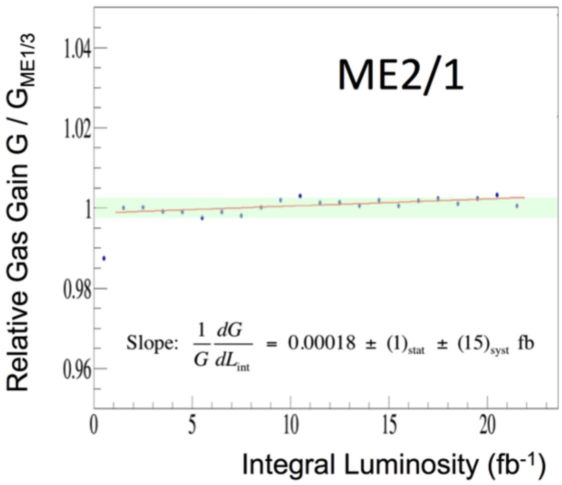

Figure 8. Relative gas gain in the CSC ME2/1 chambers, the most exposed to radiation background, normalized to the least exposed ME1/3 chambers, taken as a reference in the comparison.

5 Conclusions

Extensive measurements have been performed during the LHC Run1 and Run2 data taking periods, leading to an accurate understanding of the radiation background in the CMS Muon system. The simulation, with FLUKA being mainly used for flux and dose estimation, and GEANT4 for sensitivity studies, well describes the data in the central part of the detector, with differences in the

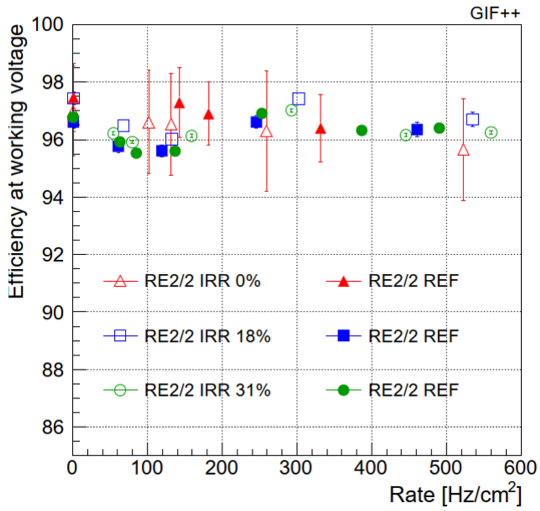

Figure 9. RPC hit efficiency at the working point as a function of the γ background rate per unit area, for values of the integrated charge up to 600 mC/cm^2, for both irradiated (IRR) and non-irradiated reference (REF) chambers. The measurements are shown at different values (0, 18 and 31%) of the total integrated charge expected at the HL-LHC.

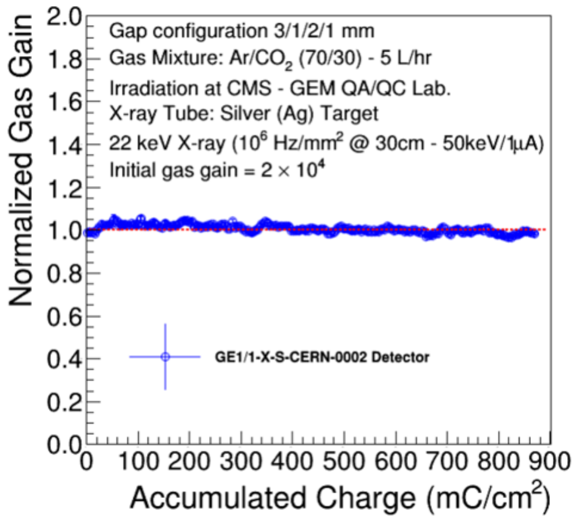

Figure 10. Normalized gas gain in the GEMs as a function of the accumulated charge.

range of 10% to 30%. The agreement between data and simulation is within a factor two in the endcap. The level of agreement with present measurements, in the regions covered by the existing detectors, allows to estimate the expected radiation background where new detectors are going to be installed at the HL-LHC, and it is essential for detector design ad future operation. Longevity tests are being performed at the CERN GIF++ facility. They show no evidence of aging effects at the total integrated charge collected so far.

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