Impact of the GE1/1 upgrade on CMS muon system performance

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Summary. — During the future LHC upgrade planned in 2018, the forward endcap region of the CMS muon spectrometer will be upgraded with GEM chambers. GEM technology is able to withstand the radiation environment expected in the forward region. The GE1/1 station will be included in the muon L1 trigger, allowing to keep low p_T threshold even at high luminosity. Moreover, it will bring detection redundancy in the most critical part of the CMS muon system, along with benefits to muon reconstruction performance.
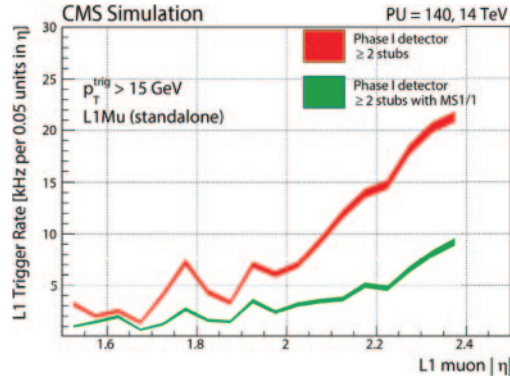
Fig. 1. – L1 trigger rate as a function of the pseudorapidity. The curves correspond to two different configurations of the current muon trigger: the green curve is obtained by requiring the presence of reconstructed hits in the first station (MS1/1) [3, 4].

The Compact Muon Solenoid (CMS) [1] muon spectrometer consists of different kinds of gas-ionization chambers installed in up to four measurement stations placed between the layers of the steel return yoke of the CMS solenoid [2]. Drift Tube (DT) chambers and Cathode Strip Chambers (CSC) detect muons in the pseudorapidity regions $|\eta| < 1.2$ and $0.9 < |\eta| < 2.4$ respectively, and are complemented by a system of Resistive Plate Chambers (RPC) covering the range $|\eta| < 1.6$. The forward region of this system, with pseudorapidity $|\eta| > 1.6$, has currently the least redundancy, being affected by exceptionally high background rates $(1\,\mathrm{kHz/cm^2})$ that are at limit of the RPC rate capability. In spite of this, it is the most challenging part of this system, since the severe background environment and the reduced magnetic field complicate pattern recognition and momentum measurement. After the future upgrades planned in 2018 and 2023, the LHC luminosity will exceed the design value by a factor two and five respectively. Muon trigger studies performed at increased luminosity scenarios [3, 4] show that the inclusive muon trigger rate features a rapid growth with the increasing η, as illustrated in fig. 1. It was shown that already at an instantaneous luminosity $L = 1.7 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$ the rate of the single muon trigger in the high-η region only is expected to approach values of $10\,\mathrm{kHz}$, corresponding to one tenth of the entire Level-1 (L1) bandwidth [3]. In order to maintain acceptable trigger rates during the future LHC operation phases, the installation of an additional set of muon detectors in the first endcap muon station, based on the Gas Electron Multiplier (GEM) technology [5], has been planned for 2018.

During a five-years-long R&D programme, prototypes featuring three cascaded GEM foils, commonly known as triple-GEM detectors, were developed and tested. The new station, named GE1/1, will cover the pseudorapidity region $1.6 < |\eta| < 2.2$ and consists of a ring made of 72 pairs of such triple-GEM chambers. Details about the project can be found in [3]. Dedicated studies were performed in order to assess the capability of these detectors to cope with background fluxes expected in the high η region according to FLUKA simulations (fig. 2, left). The background rate was estimated convoluting the aforementioned fluxes with the chamber sensitivities to background computed through standalone Geant4 simulations and plotted in fig. 2, right, as a function of the kinetic energy of the background particles. The resulting rate is found to be of the order of $1\,\mathrm{kHz/cm^2}$, orders of magnitude below the rate capability of the chambers, whose gain was found to be stable up to $100\,\mathrm{MHz/cm^2}$ [3].
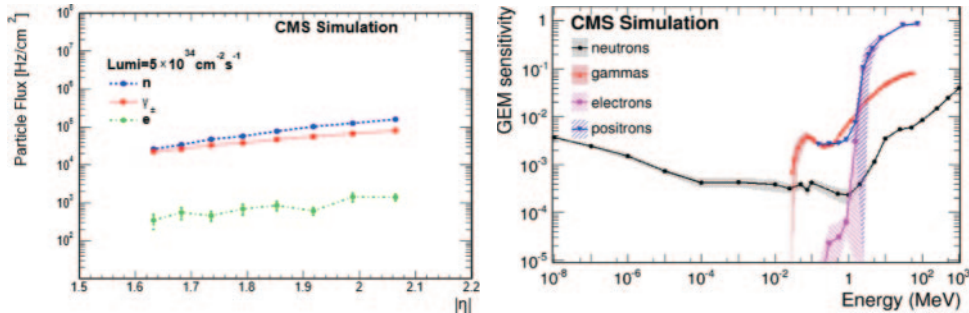
Fig. 2. – Left: particle flux as a function of the pseudorapidity in the GE1/1 region, assuming an instantaneous luminosity of $5 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$. Right: sensitivity of the GE1/1 chambers to background particles as a function of their kinetic energy [3].

The GE1/1 chambers will complement the operation of the CSCs installed in the first muon station, called ME1/1. Specific trigger and reconstruction algorithms combining CSC and GEM information were developed. The impact of the new GEM station on the muon system performance was studied inserting this system in the official Geant-based CMS simulation tool. Figure 3, left, for instance, illustrates the improvement in the trigger efficiency achievable using the CSC-GEM combined trigger.

The major benefit brought by the GE1/1 muon station, however, consists in reducing the L1 muon trigger rates. The muon lever-arm between the GEMs and the adjacent CSCs will allow to determine the muon p_T by measuring the bending angle due to the magnetic field in the first muon station alone. This p_T measurement, independent from the one based on the muon bending through the whole detector, helps in reducing the rate of soft muons that pass the trigger threshold due to p_T mismeasurements. The single muon trigger rate curves before and after the GE1/1 upgrade for the region $1.6 < |\eta| < 2.2$ in fig. 3, right, indicate that GE1/1 will be crucial in maintaining reasonable trigger rates even at not too high transverse momentum p_T thresholds.

This will be of special importance for a broad spectrum of physics analyses whose signatures are characterized by the presence of soft muons. Some examples, ranging from new physics searches to the measurements in the Higgs sector, are shown in fig. 4, left.
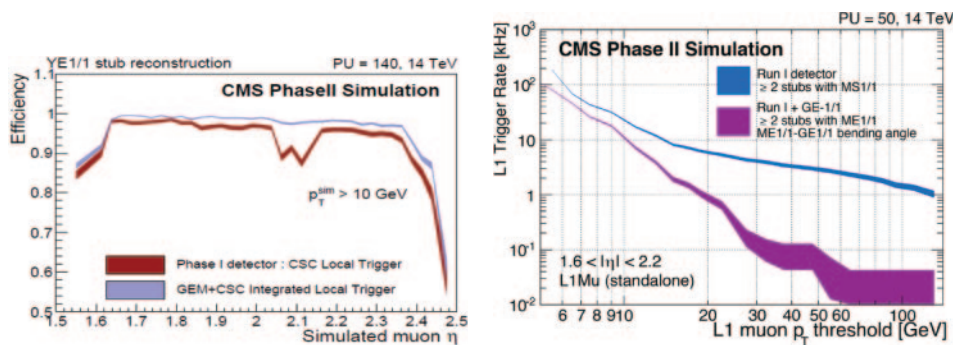

Fig. 3. – Left: muon track segment reconstruction efficiency before and after the GE1/1 upgrade. Right: Level-1 muon trigger rates before and after the GE1/1 upgrade at a luminosity of $2 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$, for constant efficiency of 94% [3].

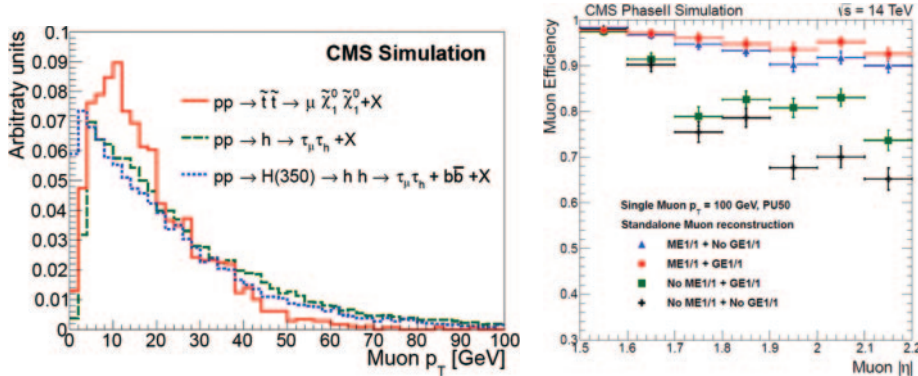Fig. 4. – Left: distribution of muon p_T for illustrative physics processes: production of a standard model like Higgs decaying via $\tau\tau \to \mu + X$, two-Higgs doublet model (2HDM) heavy Higgs production $pp \to H \to hh \to \tau\tau bb$ with H mass of 350 GeV, and supersymmetry stop production. Right: standalone muon efficiency as a function of the pseudorapidity in the 2019 scenario in different operational conditions for the first muon station [3].

In addition to that, it was shown that, once integrated in the CMS muon reconstruction algorithm, GE1/1 chambers will improve muon reconstruction performance, especially in case the CSCs installed in the ME1/1 station start experiencing operational failures due to their long exposure to hostile radiation environment. Figure 4, right, sums up how the standalone muon reconstruction efficiency behaves in different operational scenarios for the first muon station: the presence of GE1/1 in addition to ME1/1 allows to recover the efficiency drop expected at high pseudorapidity; the gain in efficiency becomes even more relevant in the worst scenario where ageing damages make ME1/1 completely inoperable. Similarly, it was also demonstrated that in this scenario GEM detectors will guarantee stability in the muon momentum resolution [3].

In conclusion, huge efforts were spent by the CMS GEM Collaboration to estimate the impact of the muon system upgrade with GEM detectors planned in 2018. Simulation results show that the GE1/1 measurement station is suitable for running in the CMS high η background environment and will be crucial in controlling muon trigger rate and muon reconstruction performance during the future LHC high-luminosity phases.

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