The Fast Simulation of the CMS Detector at LHC

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Abstract. The CMS collaboration has developed a fast Monte Carlo simulation of the CMS detector with event production rates $\sim$100 times faster than the GEANT4-based simulation, with nonetheless comparable accuracy for most of the physics objects typically considered in the analyses. We discuss basic technical principles of the CMS Fast Simulation and their implementation in the different components of the detector: the silicon tracker, the electromagnetic calorimeter, the hadronic calorimeter, the muon system, the Level 1 and the High Level Trigger. A few comparisons of the Fast Simulation results both with the GEANT4-based Full Simulation and with the LHC data are shown.

1. Introduction
A framework for Fast Simulation of particle interactions in the CMS detector has been developed and implemented in the overall simulation, reconstruction and analysis framework of CMS \cite{1}. It produces data samples in the same format as the one used by the GEANT4-based \cite{2} (henceforth Full) Simulation and Reconstruction chain; the output of the Fast Simulation of CMS can therefore be used in the analysis in the same way as other ones. The Fast Simulation can be used in any physics analysis, but it is particularly suited for those that would require prohibitively-large computation times to generate using the Full Simulation and Reconstruction. Examples of these include those analyses needing many samples to scan the extended parameter space of a physics model (e.g. SUSY), or analyses where background samples of manageable size resulting from large cross section processes can only be obtained by the selection of events based on final reconstructed objects.

The Fast Simulation of CMS is an object-oriented subsystem of the general CMS C++ based software \cite{1}. Event production rates are of the order of 100 times faster than the corresponding Full Simulation ones, with nonetheless comparable accuracy for most of the physics objects typically considered in the analyses. Most of the time spent for the production of the events is actually used in the reconstruction step, mostly based on the same modules as used in the Full Simulation and Reconstruction: the simulation part itself is typically 500-1000 times faster than the corresponding Full Simulation one, where the exact improvement in speed is process dependent.

We discuss here the basic technical principles of the CMS Fast Simulation and their implementation in the different components of the detector: the silicon tracker, the
electromagnetic calorimeter (ECAL), the hadron calorimeter (HCAL), the muon system, the Level 1 and the High Level Trigger. Comparisons of the Fast Simulation results both with the Full Simulation and with the LHC data collected at the beginning of the year 2010 at the centre-of-mass energy of 7 TeV are also shown, to demonstrate the level of accuracy achieved.

2. The Physics Processes
The input of Fast Simulation is a list of particles (from an event generator or a simple particle gun) characterized by their momentum and origin vertex, with mother and daughter relationships to follow the various decay chains in the event.

According to the user’s request, each of the (quasi)-stable particles in this list is then propagated in the CMS magnetic field to the different volumes of the various CMS sub-detectors, where it may interact. While propagating, these quasi-stable particles are also allowed to decay according to their known lifetimes, branching fractions and decay kinematics. The particles resulting from the interactions with the detector layers or from the decays in flight are added to the original list and propagated/decayed in the same way. Particles from pile-up interactions in the same bunch crossing as the original event are read from pre-generated files, added to the list according to a Poisson distribution with a user-defined average, and undergo the same treatment.

The interactions considered in Fast Simulation are

- electron Bremsstrahlung;
- photon conversion;
- charged particle energy loss by ionization;
- charged particle multiple scattering;
- nuclear interactions;
- electron, photon, and hadron showering.

The first five interactions are applied to particles crossing the thin layers of the tracker, while the latter is parameterized in the electromagnetic and hadron calorimeters. Muons propagate through the tracker, the calorimeters and the muon chambers with multiple scattering and energy loss by ionization taken into account during the propagation.

3. Simulation of the Tracker
A simplified version of the tracker material geometry, deemed adequate for the required level of accuracy, is considered in the propagation of the simulated particles. As can be seen in Fig. 1, it is made of over 30 thin nested cylinders representing the sensitive layers, interleaved with non-instrumented cylinders with dead material (cables, support, etc.).

Simulation hits are then created at the intersection of the track trajectory with the sensitive areas of the actual instrumented tracker geometry (Fig. 2). To speed up the reconstruction of charged particle tracks, the reconstructed hits belonging to a given simulated charged particle are fit, with the same fitting algorithms as in the complete reconstruction. The features of the full pattern recognition are instead emulated to reproduce the efficiency observed in the data.

The quality of the reconstruction of these tracks can be appreciated by looking (Fig. 3) at a few distributions obtained for Minimum Bias events in Fast Simulation, compared with the first real data collected by CMS at the beginning of 2010 at $\sqrt{s} = 7$ TeV [3, 4].

4. Simulation of the Calorimeters
Electron and photon showers in the ECAL are simulated in two steps. First, the shower is developed according to the well-tuned GFLASH [5] parameterization, as if the ECAL were an homogeneous medium, which is indeed an excellent approximation for crystal calorimeters.
Figure 1. Simulation tracker geometry in Fast Simulation, as given by the position of the reconstructed photon conversion vertices.

Figure 2. Reconstruction tracker geometry, which is the same in Fast and Full Simulations, as given by the position of the reconstructed hits.

Figure 3. Distributions of pseudorapidity and transverse momentum of the reconstructed tracks in the data and in the Fast Simulation of CMS.

In this parameterization, an electromagnetic shower consists of several thousand energy spots, longitudinally distributed according to a $\Gamma$ function, the parameters of which fluctuate from one shower to the next. The deposited energy is integrated over 2 $X_0$-thick longitudinal slices, including uncertainties due to the limited photo-statistics and the longitudinal non-uniformity in the crystals. Then, in each slice the energy spots are distributed in space according to the radial profile and placed into the actual crystal geometry, under the realistic assumption that no energy is lost in the small inter-crystal gaps. Leakage in the HCAL is also taken into account. Noise hits are further added, and zero suppression and selective read-out in the ECAL are emulated.

The quality of such a simulation can be appreciated by looking at the di-photon invariant mass in the ECAL barrel shown in Fig. 4 [3], where the photons are reconstructed with the Particle Flow algorithm of CMS [7]. The $\pi^0$ peak position and width coincide with the corresponding ones obtained with Full Simulation and with the data [8], and they all agree with the expected ones.
Charged and neutral hadrons are propagated to the ECAL and HCAL surfaces after their interactions with the tracker layers. Their energy response is derived from the Full Simulation of charged pions. It is tabulated as a function of the hadron energy and pseudo-rapidity. The mean value and RMS of those distributions are used as the Gaussian mean and sigma respectively to simulate the hadron response in Fast Simulation. Linear interpolation is used for hadron $p_T$ in the range from 1 to 3000 GeV/$c$, while an extrapolation is used for particles with transverse momentum outside this range. This smeared energy is then distributed in the calorimeters using parameterized longitudinal and lateral shower profiles, with shower-to-shower variations, following an approach similar to the one used in GFLASH [6]. Other types of hadrons are simulated as if they were charged pions of the same transverse energy. Also in the HCAL noise hits are added to the signal ones, based on data derived constants read from the offline database.

Fig. 5 [3] shows the quality of the calorimetric jets obtained with Fast Simulation by looking at the distributions of the scalar sum of all jet energies and the missing ET in the event, as measured in the data collected at LHC [9], in Full Simulation, and in Fast Simulation. The agreement between the Fast and the Full Simulations is quite remarkable, over several orders of magnitude, and the small difference with the distributions in the data is due to the event content of the particular tuning of the event generator used for the MC production [9].

Furthermore, the jet response as function of the jet momenta and pseudorapidity is compared between the Fast and the Full simulations in Fig. 6 [3]. Even there, a good agreement between Fast and Full Simulation is demonstrated.
Figure 6. Comparisons of the jet responses as a function of jet transverse momentum and pseudorapidity, in the Full (empty squares) and Fast (full circles) simulations

5. Simulation of the Muon Detectors
A muon, either coming from the main interaction vertex or produced afterwards in the decay of a jet particle, is propagated in the CMS magnetic field through the tracker, the calorimeters, the solenoid and the muon chambers. At the moment, only the multiple scattering and the energy loss by ionization are taken into account as physics processes for muons in Fast Simulation. The actual geometry of the CMS muon chambers (DT, CSC and RPC) is taken from a CMS database, and simulation hits are positioned in the detector whenever the track trajectory crosses an active layer of those chambers. Then, these simulated hits are digitized in the same way as in the Full Simulation chain, and the resulting digis (raw data equivalent) are fed to the standard local and global muon reconstruction packages, and to the L1 muon emulator which provides the quantities used to build the L1 trigger primitives.

If no selection is applied one can observe differences in the reconstructed muon distributions, due to the lack of hadron decays-in-flight outside of the tracker volume and hadron punch-through in the Fast Simulation. For example, if one looks as in Fig. 7 for Global Muons (tracks for which a global fit of tracker and muon hits can be performed) with no further requirements on the provenance from the vertex and/or \( p_T \), Fast Simulation [3] cannot reproduce the data as well as Full Simulation [10], especially at low muon \( p_T \). However, as soon as some cut aimed at selecting prompt muons is applied, Fast Simulation describes the data very well, even in the relatively low \( p_T \) environment of the Minimum Bias events collect by CMS at the beginning of the 2010 running period. In Fig. 8 [3] the data versus Fast Simulation comparison for the Tight Muon selection is shown: Tight Muons are Global Muons with segments associated in at least two muon stations, and with tighter requirements on \( p_T \), impact parameters, \( \chi^2 \) of the fit, number of associated tracker hits.

6. Simulation of the Trigger
L1 trigger primitives are built in the ECAL, HCAL and Muon systems starting from the detector hits produced by Fast Simulation, and are used to generate the L1 decision functions as for Full Simulation and real data. Those L1 primitives serve then as seeds for the subsequent L2/L3 objects, which build up the HLT decision functions. Although there is some customized, Fast Simulation-specific reconstruction of a few L3 objects, the HLT uses the same menus and algorithms as in the real data chain.
7. Conclusions
The Fast Simulation has proven to be a very useful tool for analysis and algorithm design in CMS. Due to its efficient processing and ease of use, it will also be an invaluable tool for LHC physics analysis, either for estimating the contributions of large cross-section backgrounds or in the generation of elaborate sets of physics signals.

The distributions obtained with the Fast Simulation of minimum bias events have been compared with the real collision data collected by CMS in the initial 2010 LHC running. Despite the fact that these low transverse momentum events were not the focus of Fast Simulation design or tuning, the agreement between simulation and data observed for most high-level reconstructed objects is quite good.

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