The Compact Muon Solenoid Experiment

Conference Report

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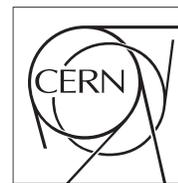
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Fast Simulation of the CMS Detector

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Abstract

The CMS collaboration has developed a fast Monte Carlo simulation of the CMS detector with event production rates 100-1000 times faster than the GEANT4-based simulation, with comparable accuracy. This paper discusses the simulation of particle propagation in the CMS detector and the response of the different parts of the detector: the silicon tracker, the electromagnetic calorimeter, the hadronic calorimeter and the muon system.

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The CMS collaboration has developed a fast Monte Carlo simulation of the CMS detector with event production rates 100-1000 times faster than the GEANT4-based simulation, with comparable accuracy. This paper discusses the simulation of particle propagation in the CMS detector and the response of the different parts of the detector: the silicon tracker, the electromagnetic calorimeter, the hadronic calorimeter and the muon system.

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1 Introduction

By the end of 2009, the Large Hadron Collider will restart collisions and the CMS detector [1] will begin collecting physics data. In order to make sense of the data and search for new physics phenomena, accurate and precise Monte Carlo simulations of the detector are needed. Two different types of simulation are used by the CMS collaboration: a GEANT4-based simulation, colloquially known as the "Full" Simulation, and a detector model which uses simplified geometry, response evaluation and pattern recognition to decrease the processing time per event, the "Fast" Simulation. This report discusses the latter simulation.

To understand the large volume of data expected to be produced at full luminosity, CMS scientists will need an equally large or larger amount of simulated data, on the order of a few billion events. With complex events taking minutes to simulate, the Full Simulation cannot keep up with the data rate. At 100-1000 times faster per event, the Fast Simulation is the only way to produce large statistic data sets necessary for studying background processes and systematic errors.

Using intuitive detector parameters as inputs, the Fast Simulation can quickly and easily be tuned to reproduce the data. Not to be underestimated, the ability to tune the Fast Simulation will allow the data to be understood more quickly during the upcoming start up. At the present time, the tuning of the Fast Simulation is done using parameters derived from the Full Simulation. The agreement between the results from the full-sim tuned Fast Simulation and the Full Simulation is very good, as will be shown in some example plots later on.

Because the Fast Simulation is only a simulation of the CMS detector and not of the physics during the collision, simulated particle decays produced by event generators such as PYTHIA are used as inputs. The resulting particles are then propagated through the detector and all physically relevant material effects are included in the Fast Simulation, which is necessary to accurately model the underlying physics.

The output of the Fast Simulation is designed to be completely accessible to CMS users, containing objects with the same format as the standard offline reconstruction. Analysis code designed to run on data will automatically work on files made with the Fast Simulation; no changes are needed.

One of the main goals of the Fast Simulation is to produce analysis-grade simulated data. Some of the additional features that add realism to the simulation are in-time pile-up, emulations of the Level 1 and High Level Triggers, and mis-calibration and misalignment of the detector.

2 Materials Effects

To accurately model the propagation of the particles through the layers of the tracker, five different material effects are taken into account: bremsstrahlung, photon conversions, multiple Coulomb scattering, energy loss through ionization and nuclear interactions. All of the effects except for nuclear interactions are calculated analytically, using references such as the PDG [2].

Nuclear interactions are simulated in a different manner, because no analytical description is sufficient to describe the effect. Cross sections for various nuclear interactions, such as a pion colliding with a proton, are taken from different measurements and the probability of the interaction is calculated. The kinematics of the resulting daughter particles are derived from single particle collisions using a particle gun in the Full Simulation, saved in files made beforehand.

To save time simulating the material effects, the tracker uses a simplified geometry of nested cylindrical layers (see Figure 1). The thicknesses of the different layers are tuned to create the same amount of material interactions in the Fast Simulation as in the Full Simulation (see Figure 2).
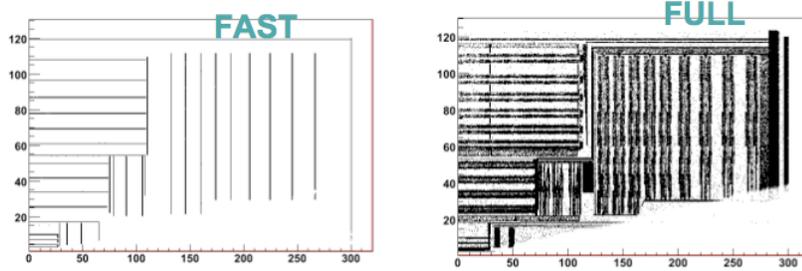
Figure 1: Radiography of tracker by photon pair conversion from electrons in the fast (left) and full (right) simulations.
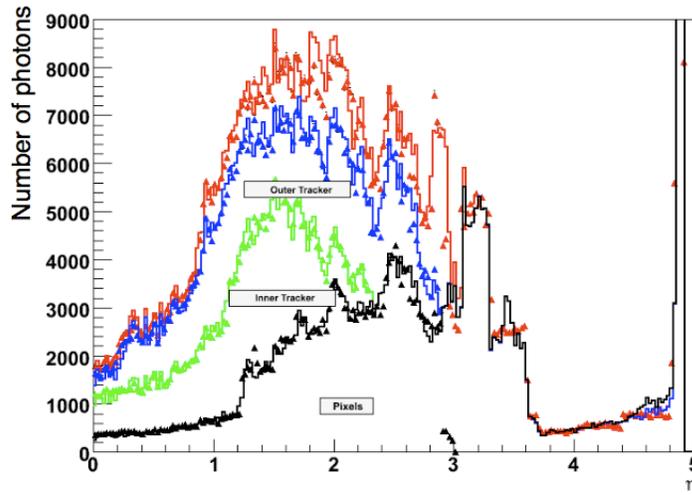
Figure 2: This plot shows the comparison of the number conversion of electrons to photons in tracker between the Fast Simulation (triangles) and the Full Simulations (solid lines) over pseudo-rapidity. The contributions of different parts of the tracker are shown: pixels (black), inner tracker (green), outer tracker (blue).

3   Tracking

The base of the tracking simulation is the reconstructed hits. The local position resolution and efficiencies of the hits are currently parameterized with input from the Full Simulation, and in the future they will be parameterized to match data. For the silicon strip tracker, the local positions are smeared according to a gaussian. The parameterization for the pixel detectors is more complicated, and depends on histograms derived from the Full Simulation, which make use of both the angle of incidence and the multiplicity of the pixel clusters.

To make tracks, the Fast Simulation emulates the different steps of the standard iterative tracking sequence, using only the hits from the simulated tracks to make track candidates. Therefore, each reconstructed track corresponds to a simulated track. For the seeding emulation, only seeds that pass the standard seeding criteria are included. The standard pattern recognition algorithms are too time consuming for the Fast Simulation. Like the standard pattern recognition tracking, the Fast Simulation removes hits that give large contributions to the track χ^2 from the tracks. The final tracking step uses the same fitting algorithms as the standard reconstruction sequence.

High occupancy events may have fake tracks, which are not produced by the Fast Simulation. Hit sharing between different tracks is also not included in the Fast Simulation. For specialized studies, a translation algorithm allow the reconstructed hits made with the Fast Simulation to be input into the full pattern recognition chain.

The plots in Figure 3 show the accuracy of tracking in the Fast Simulation for a variety of particles, from single muon events to more complicated top pair decays with large track multiplicities.
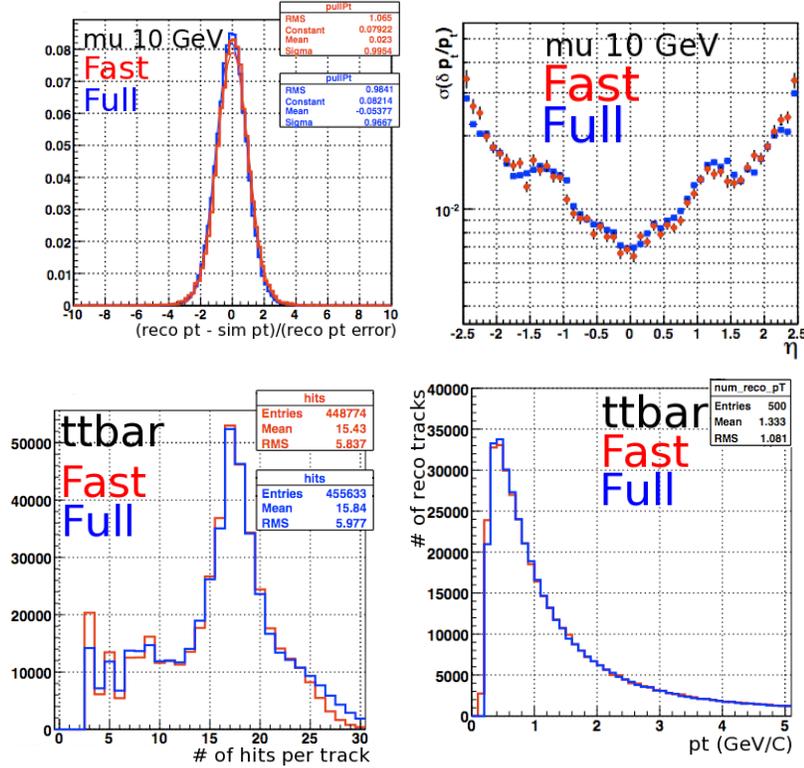
Figure 3: Clockwise from the top left: Pull in p_T comparison for 10 GeV μ. p_T resolution vs η comparison for 10 GeV μ. Comparison for hits per track in $t\bar{t}$ events. Comparison of the number of tracks versus p_T for $t\bar{t}$ events. The Fast Simulation is red and the Full Simulation is blue.

4 Calorimetry

After leaving the layers of the tracker, the particles interact with calorimeters. To simulate electron showers in the EM calorimeter, the Fast Simulation uses the Grindhammer parameterization, similar to GFLASH [3]. The showers are first simulated in a homogeneous medium and then moved to the calorimeter. Detector effects such as energy leakage into the inter-crystal gaps and energy leakage out the back of the EM calorimeter to the hadron calorimeter are then included in the final measured energy. Photons undergo electron pair conversions within the EM calorimeter based on the number of radiation lengths they have traversed. The electron pairs then undergo showering. To simulate the measured energy, zero suppression and electronics noise are included.

Shower simulation in the hadron calorimeter is similar to the simulation in the EM calorimeter. A parameterization of the energy response for different types of particles at a variety of energies and pseudo-rapidities is made from the Full Simulation. Further information on the simulation of the calorimeters is available in [4].

To illustrate accuracy of energy measurements in the calorimeters, both electron and jet comparisons are shown in Figures 5 and 6. The jets are shown with a range of different energies.
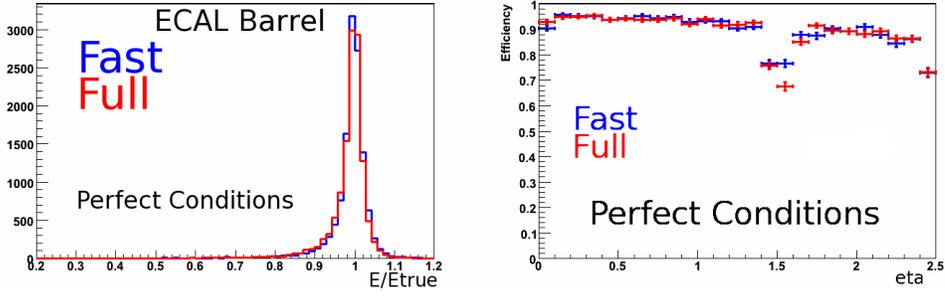
Figure 4: Left: Comparison of electron momentum resolution between the Fast Simulation (blue) and the Full Simulation (red) in ideal detector conditions. Right: Comparison of electron reconstruction efficiency versus η between the Fast Simulation (blue) and the Full Simulation (red) in ideal detector conditions.
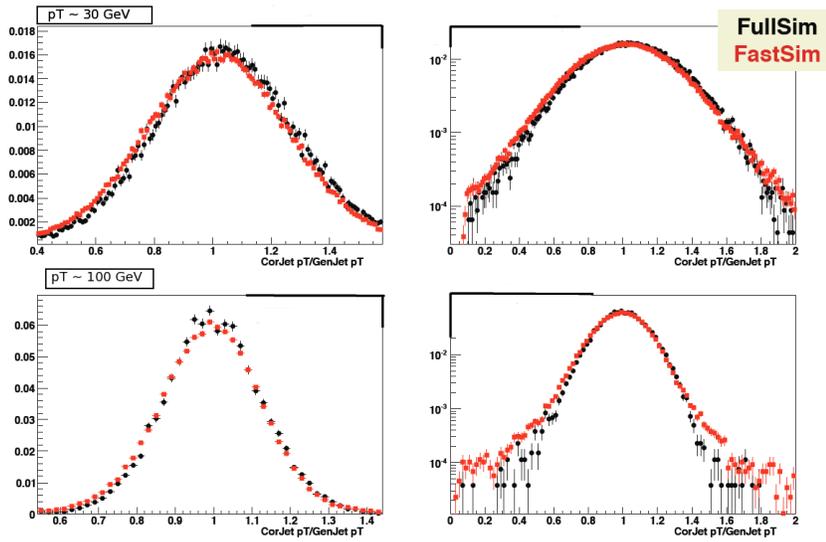
Figure 5: Comparison of corrected jet energies over simulated jet energies for jets with $\hat{p_T}$ of $\sim$ 30 GeV/c (top) and jets with $\hat{p_T}$ of $\sim$ 100 GeV/c (bottom). The Fast Simulation is in red and the Full Simulation is in black.

5 Muons

Muons are propagated in the magnetic field through the material of the tracker and the calorimeters, with average energy loss included, before encountering the muon chambers. To accurately simulate the propagation of muons through the muons system, the Fast Simulation includes $\frac{dE}{dx}$ loss and multiple scattering of muons with the iron yokes of the detector.

The Cathode Strip Chambers, Drift Tubes and Resistive Plate Chamber sections of the muon detector are all modeled in the Fast Simulation. Because the interactions with the detector are included throughout the muon flight path, muons are well modeled. Figure 7 shows the agreement of the Fast Simulation in $1/p_T$ resolution with the Full Simulation when multiple scattering is turned on.
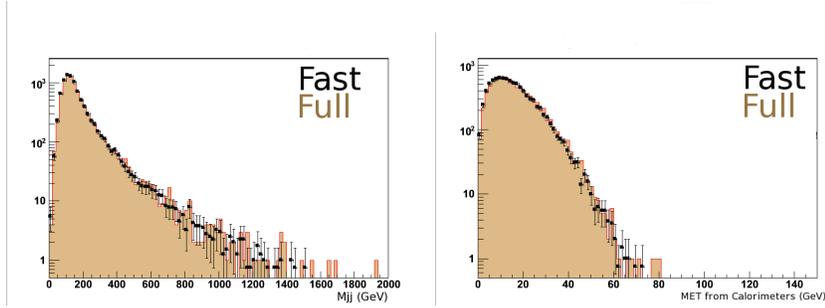
Figure 6: Comparison of M_{jj} and MET for jets from QCD events with $\hat{p_T}$ = 80 - 120 GeV/c. The Fast Simulation is in black and the Full Simulation is in brown.
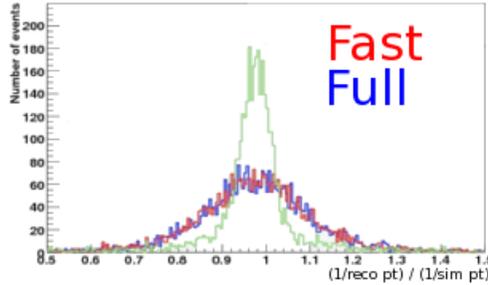
Figure 7: Comparison of $1/p_T$ resolution between the Fast Simulation (red) and the Full Simulation (blue). The green line is the $1/p_T$ resolution when multiple scattering is turned off. Notice the improvement in the Fast Simulation when multiple scattering is turned on.

6   Applications to Physics

The Fast Simulation achieves accurate reconstruction of physics-level objects by following the propagation of the particles through the entire detector and including the materials interactions within the detector. Because the products of τ lepton decays interact with and are detected by various sub-detectors, comparisons in kinematics of the reconstructed taus are good benchmarks for the overall agreement between the fast and the Full Simulations (see Figure 8).

One of the main applications of tracking in physics analyses is b tagging. Strict quality criteria are placed on the tracks used in b tagging, making any of the effects discussed in Section 3, such as fake rates, negligible. For this reason, the Fast Simulations gives a good description of the physics results. The accuracy of one of the b tagging discriminants is shown in Figure 9.

Various features give the Fast Simulation the ability to produce event characteristics and conditions necessary for physics analysis. To simulate conditions in the high luminosity environment of the LHC, in-time pile-up can be turned on for any type of event. The Fast Simulation models in-time pile-up by including minimum-bias events, generated beforehand, along with the decay products from the signal event in the group of particles propagated through the detector. Trigger paths are simulated in the Fast Simulation, filtering and saving events on disk based on the trigger decision. Mis-calibration of the calorimeters and misalignment of the tracker can also be included in the Fast Simulation to simulate events in the detector environment during LHC startup. Plots made with electrons before and after mis-alignment/miscalibration agree well with the Full Simulation, as seen in Figure 10.
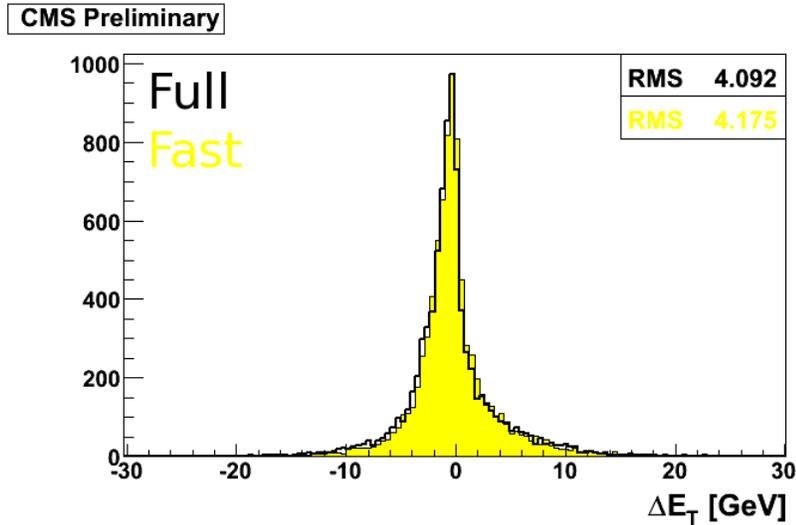
Figure 8: Comparison of reconstructed visible energy - simulated visible energy for τ decays between the Fast Simulation (yellow) and the Full Simulation (black).
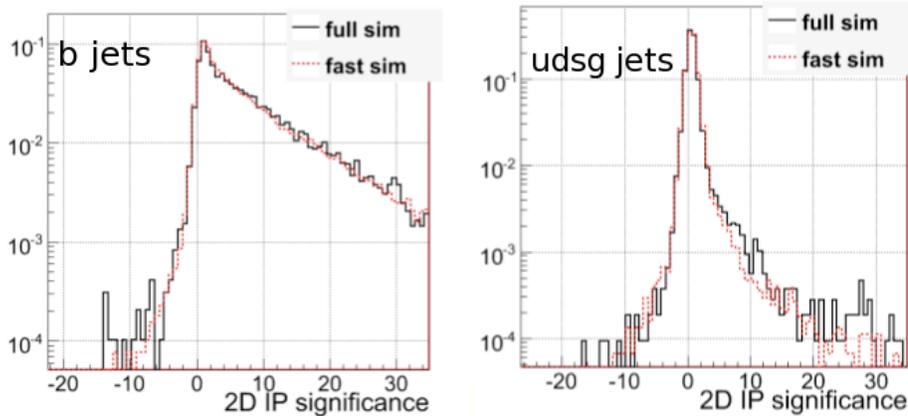
Figure 9: Comparison of the impact parameter significance for the second leading p_T track for jets from b (left) and udsg (right) between the Fast Simulation (red, dotted) and the Full Simulation (black, solid).

7 Conclusion

With the inclusion of all relevant material effects, the Fast Simulation of the CMS detector can accurately and quickly produce events in the standard output format. As a detector model based on intuitive parameters, the Fast Simulation can be adjusted to match data soon after the startup of collisions in late 2009. Currently, the Fast Simulation is tuned to the GEANT4-based simulation and agrees well with the Full Simulation for a variety of particle interactions across a wide range of energies. The Fast Simulation has been utilized for the large scale production of a few billion events and is ready for high statistics studies in the future.
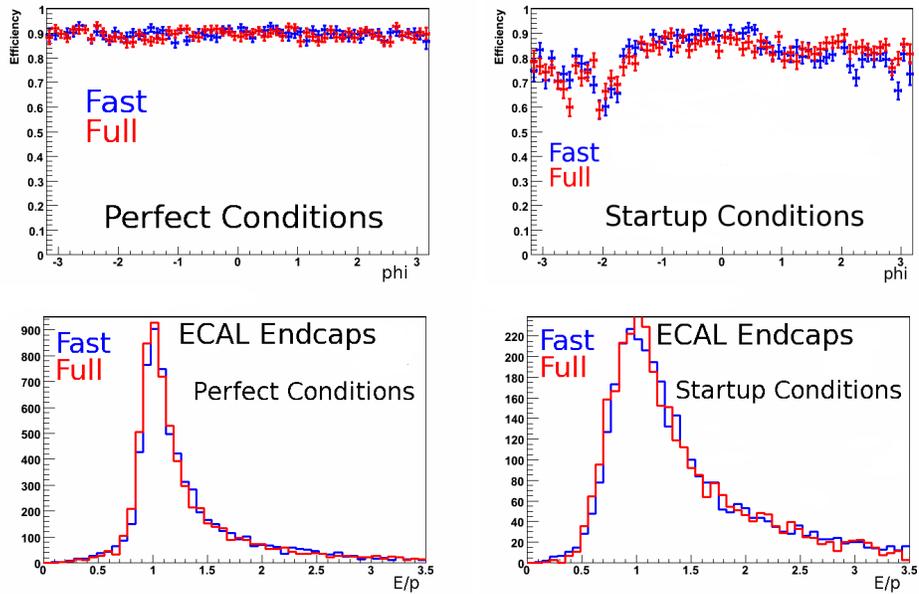
Figure 10: In the top row: Comparisons of electron reconstruction efficiency in ϕ with perfect detector conditions (left) and start up detector conditions (right). In the bottom row: Comparisons of electron energy over electron momentum in perfect (left) and startup (right) conditions. Startup conditions include tracker misalignment and calorimeter mis-calibration. The Fast Simulation is in blue and the Full Simulation is in red.

8 Acknowledgements

References

[1] The CMS Collaboration, "The CMS Experiment at the CERN LHC", JINST **3**, S08004, (2008)

[2] C. Amsler et al., "The Review of Particle Physics", Physics Letters **B667**, 1 (2008)

[3] G. Grindhammer, M. Rudowicz, S. Peters, "The Fast Simulation Of Electromagnetic and Hadronic Showers", Nucl. Instrum. Meth. **A290**:469, (1990)

[4] The CMS Collaboration, "The Physics Technical Design Report, Volume 1" CERN/LHCC 2006-001, (2006) (pp. 55-64)