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Fast Simulations of the ATLAS and CMS experiments at LHC

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Abstract

The fast simulation of a high energy physics experiment is a tool used by experimentalists to quickly assess the potentiality of their detectors on a specific analysis or reconstruction tecnique, before imbarking themselves into a more time- and CPU-expensive detailed study with the full simulation. In some cases, it can also be considered the access point for theoreticians wanting to see "how do their model looks like in the real life". The aim of this contribution is to introduce how fast simulations work in the ATLAS and CMS experiments at LHC, and which are the main differences with respect to a full simulation. A comprehensive comparison of a few results obtained with the full and the fast simulation in CMS is also given, in order to provide an example of application of the two methods.

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1 Introduction

What happens when two particles collide in the center of a detector taking data at a high energy collider? At the interaction point, either the two particles are just scattered away, or new-born particles sort out with a given momentum. If those particles are unstable, they tend to decay with their proper lifetime, and at a distance typical of the size of the detectors only stable, or practically stable, particles survive. The particles coming out from the collision point interact in the detector material. Such a material can be either active, that is a material in which the modifications induced by the passing particle can be recorded somehow and thus give out some sort of signal, or passive, that is a region in which interactions just happen, but locally no signal can be extracted out of them. Sensitive areas of the detector produce analogic electronic signals as result of the particle-material interaction. Those signals get shaped, discriminated and read out by dedicated electronic devices, whose output can be digitized and provided to the subsequent steps of the data acquisition (DAQ). Fast hardware components (triggers) use part of those signals to decide on-line whether to accept the event or not. Only in case of a positive trigger decision, the DAQ reads out the digitized signals and write them onto a permanent support by using an appropriate format (raw data). Typically, before writing the whole raw data on the permanent disks, a further decision is taken by software modules (high level trigger, HLT) which can compute a few physics quantities relevant to the event with fast algorithms. Starting from the raw data one then has to try to reconstruct the particles which originated those signals, that is one has to estimate the trajectory, the momentum, the energy and possibly the mass (if some particle identification is effective) of all particles that generated the digitized output of the data acquisition chain. A complex, detailed, dedicated software, which combines the information contained in the raw data with huge geometry and calibration data-bases, accomplishes this task. First, raw data from a single subdetector are used to extract the hits. Hits are then combined to produce intermediate analysis objects within the subdetector (local reconstruction), which in turn constitute the building blocks for the higher level analysis objects, at different degrees of complexity, used for the final physics analysis.

Thus, to simulate an "event" and take into account all what happens in a high energy physics experiment, one has to provide the following steps:

- event generation;
- simulation of the interaction of the generated particles with the detector;
- simulation of the digitization phase;
- local and global event reconstruction.

While the first part (generation) remains a task of the model builders and phenomenologists, the simulation of the interactions with the detector, digitization and event reconstruction are worked out by the experimental collaborations that design, build and maintain the detectors. In the detector simulation, one tries to simulate the result of all the physics processes and intermediate steps that lead from the four-vectors and vertices of the generated particles to the final analysis objects. If the output of the simulation after the digitization phase has the same format as the really collected raw data, the same reconstruction software as used on the real data can be applied to simulated ones. Effects as electronic noise in the detectors, event overlapping ("pile-up"), instrumental dead-times, etc., must be properly taken into account to provide realistic reconstructed analysis objects.

As experiments get more complex, also their simulations become more complex, CPU-time (and physicist time!) consuming. Therefore, while for several tasks the most possibly detailed simulation is advised, there are many where the required level of precision makes more suitable a less detailed but much quicker simulation. One of the domains in which a fast simulation is certainly more suitable than a full simulation is when a new theoretical model is available and physicists want to evaluate the experimental accessibility of their own scenario: there is no reason to study all the complex details of an experimental apparatus implicit in the use of a full simulation, and wait uselessly for days, weeks, (or even months, if those events have no high priority for the "production teams" of the collaborations) if one just wants to estimate whether a given scenario can be visible, and how.

It is precisely with the "experimental" part of the simulation chain that we will deal in this contribution. In section 2 we will introduce how full simulations are performed in the ATLAS and CMS experiments at LHC, and which are the main differences with respect to a fast simulations. Section 3 describes the fast simulations, and in particular 3.1 and 3.2 summarize and justify the different choices adopted in ATLAS and CMS, respectively. A comparison of those two fast simulations, in terms of speed and correspondence with the results of the full simulations, is provided in section 4. Finally, in section 5 a closer look to the fast simulation in CMS and how it compares with the full detector simulation is provided.

2 Detector simulations at LHC

In a simulation of an event at LHC, in order to obtain realistic final state analysis objects one has to simulate all the relevant processes that happen in the real life, when the particles produced in the p-p collision propagate through the detector volume and interact with its material. Fig. 1 summarizes the various steps leading to the final high level analysis objects of a typical LHC general purpose experiment, starting either from a real collider interaction or from a MC generated event.

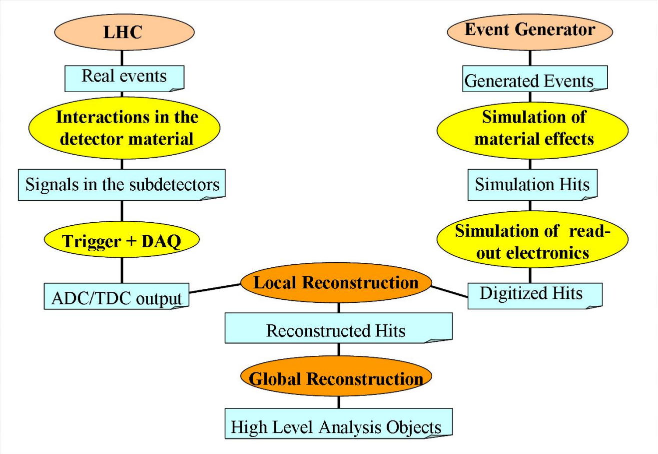

Figure 1: Schema of the parallel physics processes and simulated ones leading to the raw data, first, and to the final high level analysis objects later on.

A particle (a muon, for example, that crosses the whole detector as shown in fig. 2) passes through several layers of different subdetectors, built with different materials; it touches passive material like the cables, the magnet, the mechanical support structure; it enters also regions with different values of the magnetic field. All those effects and materials must be properly taken into account for a precise detector simulation[1]. High level of details and precision can be achieved with an accurate full simulation. Detector responses can further be validated and tuned with: test beam data; *in situ* calibration data (e.g. cosmics, halo muons); calibration data from LHC collisions $(Z \to \mu^+\mu^-, e^+e^-, \pi^0 \to \gamma\gamma...)$.

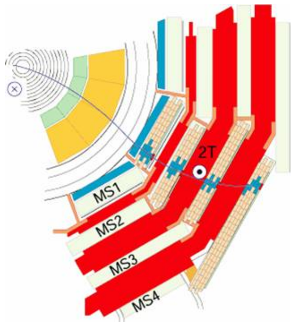

Figure 2: Trajectory of a muon in a slice of the CMS detector. Outside the coil, the magnetic field changes versus, as can be seen by the change of sign in the curvature radius of the trajectory.

The most common components of a high energy physics detector like ATLAS and CMS are the inner tracking, the electromagnetic and hadronic calorimeters, and the muon detectors. In the following sections a few hints will be given on how does simulation act on those components in general, so that it can be compared later on with the methods that use the fast simulations to emulate the same tasks. Details on the two detectors and their simulation and reconstruction software can be found in [1, 2] for ATLAS and [3] for CMS.

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[1] Quite often, the very final arrangement for auxiliary equipements, like cables, shieldings, etc., is not finalized until the detector is fully built and closed, thus leading to some new "final" simulation samples to be produced only when the correct account of the crossed material is known.

2.1 Simulation of a generic inner tracker system

A charged particle crosses the active layers of the inner tracking detectors (silicon strips and pixels in CMS; silicon strips, pixels and an outer transition radiation detector in ATLAS). Propagation is affected by multiple scattering in the detector and surrounding material. Within each detector layer, the particle looses energy along the path between its entry and exit point. The produced charges drift to the detector surface and cause a signal in the dedicated electronics (fig. 3a). Gaussian noise is added on top of those signals, and also to the other channels not touched by this particle trajectory (fig. 3b). In the same event other particles add up, coming from the very same generated event, multiple interactions, in-time or out-of-time pile-up (fig. 3c). All charges are linearly added up in case of overlapping, then discriminated and digitized, ending up with the raw data of the tracking detector layers. Those raw data, separated from the information of the generated particles, are the input for the reconstruction phase (fig. 3d). Tracking algorithms apply pattern recognition and track fit; magnetic field, multiple scattering, material effects are also taken into account. Different use cases can be considered: low/high p_T, searches for displaced verticies, etc. At the end of the reconstruction (as for the real data) the exact 1-to-1 correspondence between generated charged particles and reconstructed tracks is generally lost, and it can only be restored on a probabilistic basis.

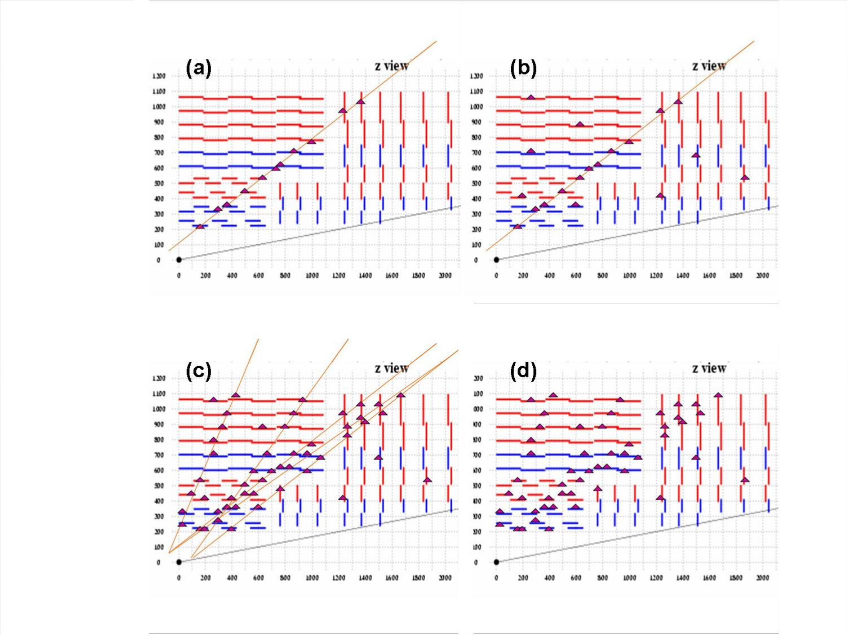

Figure 3: Steps performed in the simulation of charged particles crossing the inner tracking devices (see text).

2.2 Simulation of the calorimeters

Electromagnetic (ECAL) and hadronic (HCAL) calorimeters are coarser grained detector (if compared to the tracking devices). They can be omogeneous, as the ECAL of CMS, made of lead-tungstate scintillating crystals; or sampling calorimeters, as ECAL and HCAL in ATLAS and the HCAL of CMS, all built with different technologies but basically consisting in absorber layers, made of heavy elements, interleaved by either active plastic scintillating tiles (HCAL of CMS and barrel HCAL of ATLAS), or by a liquid argon detector (ATLAS ECAL and endcap HCAL). Light collected in the scintillators is read out by photomultipliers positioned at the detector outer end. Other sensitive volumes before the ECAL can be in the preshower detectors, aimed at discriminating between electron and photon shower and at recognizing $\pi^0 \rightarrow \gamma\gamma$ decays.

Electrons and photons in the ECAL, and hadrons in the ECAL and HCAL, generate large showers, respectively via pair production and bremsstrahlung processes, see fig. 4, and via hadronic interactions. To perform a realistic simulation, several effects must be taken into account: variation of the light collection along the length of the crystal or of the fibers; modified crystal transparency with large integrated doses; noise; electronic thresholds. Simulation parameters must be tuned to reproduce the results of the test beams.

The whole charge collected in one, or even more than one, crystal or tile is read out together. Therefore, in the reconstruction, exact 1-to-1 correspondence between generated and reconstructed particles is lost and cannot be

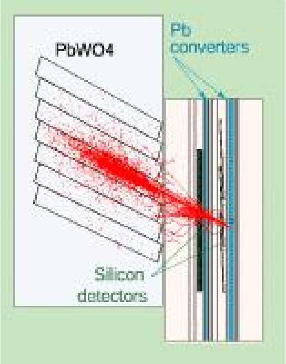

Figure 4: Side view of the ECAL of CMS, with an electromagnetic shower that starts in the preshower and fully develops in the electromagnetic calorimeter.

restored2). Clusters of energy deposits in the HCAL represent the jets, which are the high level analysis objects obtainable starting from the calorimetric showers; different clusterization algorithms and recombination schemes are available, depending on the needs of the specific analysis.

2.3 Simulation of the muon detectors

Muon detectors are tracking devices placed in the outer part of the detector and exploiting the large penetrating power of muons. Passing muons produce ionization charge in the drift cells; charges drift towards the sense wires with a drift velocity which is in general dependent on the impact position, muon direction, residual magnetic field. Contributions from electronic noise, neutron background, halo muons, muons from pile-up events (in-time or from a different beam crossing), punch-through hadrons, must be taken into account. Local reconstruction starts in a single layer and continues by correlating track segments in the different substructures. Global reconstruction matches these local segments with those of the inner tracking system (plus possibly calo signals, that must be compatible with the particle being a minimum ionizing particle). Exact 1-to-1 correspondence between generated and reconstructed muons is formally lost; although, given the lower track density, there is a smaller combinatorial than in the inner tracker.

2.4 Simulation of the trigger

Bunch crossing rate at LHC is planned to be $4 \cdot 10^7$ Hz. Acceptable DAQ read-out and data storage rate is of the order of 100 Hz: only 1 over 10^5 collision can be recorded and used for the physics analysis. Rate reduction is performed in two (CMS) or three (ATLAS) steps:

- First level trigger (L1), with dedicated hardware boards for a fast on-line decision;
- High level trigger (HLT), organized in two levels in ATLAS and one single level in CMS, an (almost) offline analysis based on fast reconstructions algorithms and decision functions and performed by a dedicated farm of pc's.

L1 and HLT decide which events to store on a permanent support: others will get lost forever.

The simulation must reproduce the trigger decision: it is not necessary to actually drop all events that do not pass the trigger, but it must be made clear which can be used for the analysis, and which cannot. Since the HLT reconstruction algorithms are similar but not generally the same as the off-line analysis ones (in particular, they cannot access the whole calibration data-base, they must be quick, some part of the event information can be unusable), to obtain realistic performance in the simulation code specialized trigger modules must be considered.

2.5 Timing

To obtain the high level of details and precision of the full simulations a considerable amount of CPU time is required. As an example, for CMS it was estimated [4] that for a typical LHC high-p_T p-p collision in a 1 GHz

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2) The exception being isolated electrons, photons or hadrons at low luminosity

Pentium III3) the required processing times were:

- less than 100 ms/evt for the MC event generatiom;
- 100-200 s/evt for the simulation of the material effects;
- 1-10 s/evt for the digitization (simulation of the read-out electronics);
- 10-100 s/evt for the reconstruction.

Therefore, the total CPU-time spent before the analysis can start ranges from 3 to 5 minutes per event. Those estimates were done with the previous framework and event data model of CMS, the new framework still being finalized: it is expected, however, that timings will not change that much with the new CMS simulation code.

The CPU time needed for the event simulation in the present release of the ATLAS software can be derived from figure 5 [5], for different types of events and as function of the largest absolute value of the pseudorapidity simulated (in a p-p collider the track density, and therefore the CPU time needed to simulate the complete event, increases strongly with pseudorapidity).

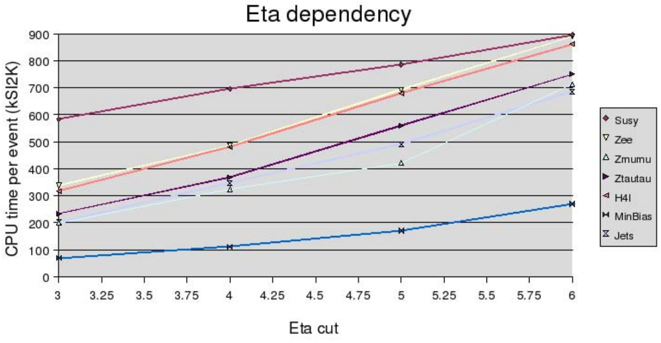

Figure 5: Average CPU time, in kSI2k, needed to fully simulate different kind of events in ATLAS, as function of the upper limit of the interval of pseudorapidity in which particles are propagated and their interaction with the detector simulated.

3 Fast simulations

A fast simulation is not meant to be a replacement of the full simulation. Its purpose is to produce some final analysis object in the shortest possible time, compatibly with the level of accuracy required to satisfy the needs of the task it is used for. Emulation of intermediate quantities, as digitized or reconstructed detector hits, could also be provided. Fig. 6 compares the job done by a fast simulation with what done by a full simulation.

Fast simulation emulates the combined result of detector simulation and reconstruction, and it is therefore generally tuned and validated with the full simulation results (while full simulation is tuned and validated with the real data).

Domains where a fast simulation is more suitable than a full one are:

- quick and approximate estimates of signal and background rates;
- fast development of analysis methods and algorithms;
- test of new generators or new theoretical ideas in a realistic environment;
- scan of complex, multi-parameter spaces (like e.g. SUSY);
- possibly cross-check a few aspects of a full simulation.

In what follows, the different ATLAS and CMS strategies on fast simulation development are summarized.

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3) To obtain the corresponding values in kSI2k-sec, the standard CPU speed normalization between machines based on the SPECint®2000 benchmark for integer calculations, those times obtained with a 1 GHz machine must be multiplied by a factor 0.46.

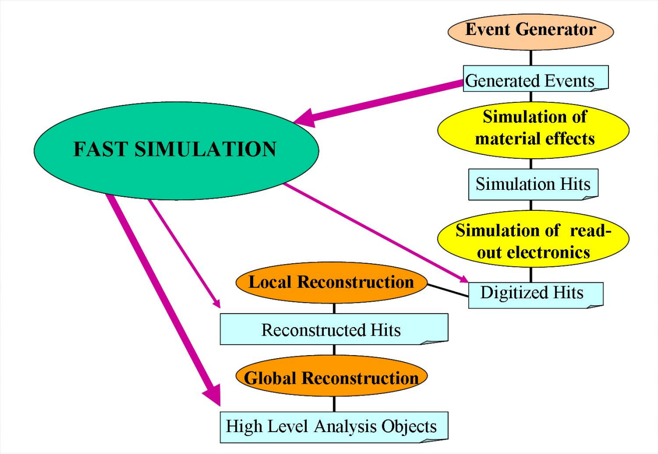

Figure 6: Block diagram of a full and a fast simulation in a typical LHC experiment. They all start from the same MC generated events and aim to produce as similar as possible final analysis objects.

3.1 Fast simulation in ATLAS

ATLFAST [6] is the package for fast simulation developed and used in ATLAS. It includes most crucial detector aspects, as jet reconstruction in the calorimeter, momentum and energy smearing for electrons and photons, effect of the magnetic field, and missing energy. It provides, starting from the generated particles, the list of reconstructed jets, isolated leptons, photons, muons, and missing transverse energy. It provides also (optionally) the list of reconstructed charged tracks. No particle propagation, nor interaction with the detector material is simulated; a coarse detector geometry is considered to define the acceptances. Fast simulation in ATLAS is therefore obtained by smearing directly the MC-truth informations with efficiencies and resolutions as obtained from the full simulation.

3.1.1 Tracking

Emulation of track reconstruction is provided (only optionally) for charged particles inside the inner detector. It is obtained by smearing three-momenta and impact parameters, as indicated in the full simulation studies, with different parameterizations of the smearing and of the reconstruction efficiency for muons, pions and electrons.

3.1.2 Calorimetric clusters

In the present implementation, all electron or photon energy is deposited in one single ECAL cell, and all hadrons energy in one single HCAL cell. A new parameterization has been studied [7] and is ready to be implemented. In this new parameterization, the transverse energy of all undecayed particles is summed up in cells having the same granularity as the calorimetric L1 trigger ($\Delta\phi \times \Delta\eta = 0.1 \times 0.1$), which is coarser than the granularity of the full simulation; the longitudinal segmentation is limited to the separation between ECAL and HCAL. The effect of the 2 T magnetic field is taken into account. Generic calorimetric cluster reconstruction is started from those cells, and an appropriate energy smearing and reconstruction efficiency is applied after cluster identification from MC truth as electron, photon or hadron.

3.1.3 Jets

Calorimetic clusters non associated with isolated e or γ are associated into jets and further smeared, with a parameterization which depends on the presence of quarks of a given flavour in the generated particles that originated the calorimetic clusters. Different parameterizations are also applied for different luminosity scenarios, reflecting the different amount of pile-up. Reconstruction and tagging efficiencies are not included in ATLFAST, but they can be applied “by hand” at a later stage.

3.1.4 Muons

Three possibilities are foreseen for the parameterization of the momentum resolution, depending on the subdetectors used for the muon reconstruction: muon system stand-alone, inner detector stand-alone, or the two combined. Muons can be flagged as isolated or non-isolated. Muon tagging efficiency is not included in ATLFAST, but it can be applied at a later stage.

3.1.5 Trigger

Only primitive trigger routines are considered, not meant to cover all ATLAS triggers and levels. They are aimed essentially at eliminating events which have no chance of passing ATLAS L1 and L2 triggers.

3.1.6 Pile-up

Pile-up events are not simulated in ATLFAST, but a different smearing of jets due to pile-up is provided as function of the luminosity, see fig. 7. Also the parameterization of the trigger selection allows for the low and high luminosity options (2×10^{33} cm^{-2}s^{-1} and 10^{34} cm^{-2}s^{-1} respectively).

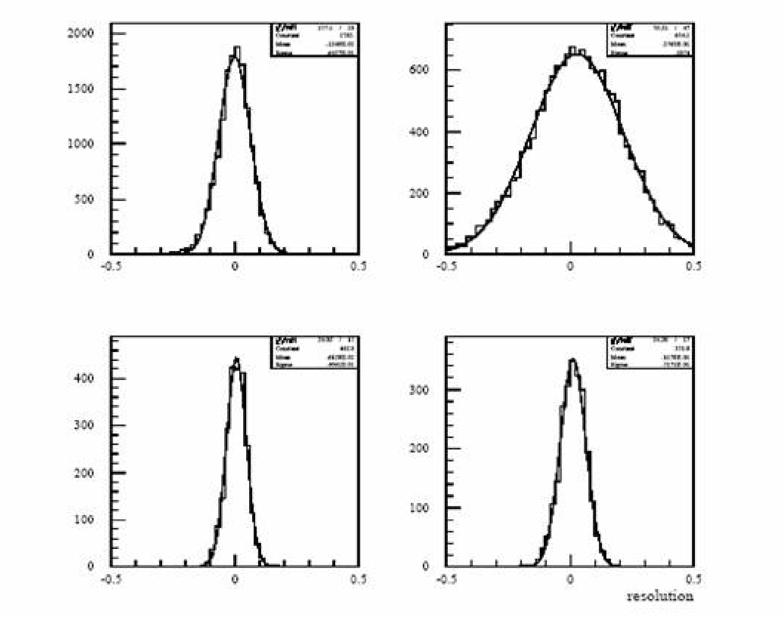

Figure 7: The $p_T^{\rm jet}$ resolution for reconstructed jets with $40 < p_T^{\rm jet} < 50$ Gev/c (top) and $200 < p_T^{\rm jet} < 250$ Gev/c (bottom), obtained in ATLFAST with the default cone algorithm for low (left) and high (right) luminosity.

3.1.7 Timing

A very fast processing is obtained thanks to the approach chosen in ATLFAST of relying on parameterizations of the properties of the final analysis objects, without simulating interactions of particles with the detector material, nor attempting any reconstruction. A gain of about four orders of magnitude is claimed with respect to fully simulated similar events, which corresponds to a computation time of just a few hundred milliseconds per event.

3.2 Fast simulation in CMS

CMS software [3] is currently completing the migration from the previously adopted framework to the present one. We describe here the package FAMOS for the fast simulation of particle interactions in the CMS detector, based on the old framework; its main features will however remain basically unchanged in the new framework.

The output of FAMOS is designed to be as close as possible to the output of the full simulation and reconstruction of CMS. It delivers the same physics objects (calorimetric hits and clusters, tracker hits, and reconstructed tracks and muons), with identical interface: they can be used as inputs of the same higher-level analysis algorithms (b-tagging, electron, muon and tau candidates, jet clustering, lepton isolation, etc.) as the real or fully simulated data.

Particles in FAMOS are propagated in the nominal magnetic field through the inner tracker and up to the entrance in the calorimeters. The following interactions are simulated in the tracker material:

- electron bremmstrahlung;
- photon conversion;

- charged particles energy loss by ionization;
- charged particles multiple scattering.

Electron, photon and hadron showering is allowed in the ECAL and HCAL. Nuclear interactions are not simulated in FAMOS[4], which implies that hadronic showers never initiate before the calorimeters, and there is a lower number of secondary vertices. As will be described in section 5.0.11, this implies in turn a different b-tagging significance with respect to the full simulation, and the correspondence has to be restored with a re-tuning of the output.

3.2.1 Tracking

Charged particles in FAMOS are traced through a simplified detector geometry. The inner part of CMS is treated as composed by thin cylindrical layers of pure silicon, whose thickness is tuned on the number of brehmstrahlung photons with $E_\gamma > 500$ MeV radiated by energetic electrons traversing any such layer. A comparison of the material content of the inner CMS in FAMOS and in the full simulation is shown in fig. 8, where the photon conversion points in the plane R-z are recorded.

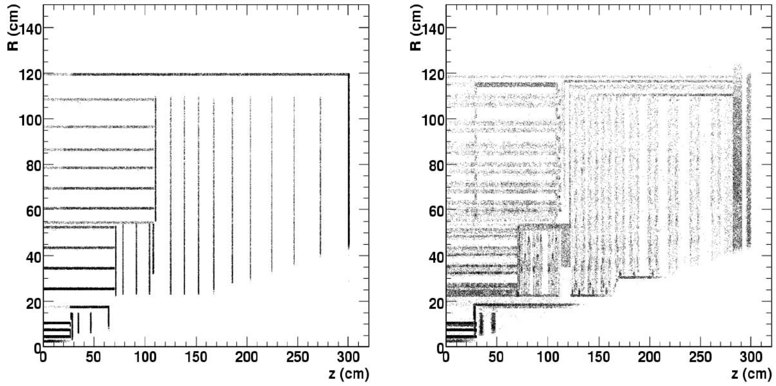

Figure 8: A radiography of the inner part of the CMS detector, were are the tracker layers, obtained by recording the points where a photon converted in the fast (left) and full (right) simulations.

Charged particles in FAMOS propagate in the magnetic field through the tracker layers; multiple scattering and energy loss by ionization are taken into account. Intersections between simulated trajectories and tracker layers give the “simulated hits”; they are then smeared and turned, with a given probability, into “reconstructed hits”. An emulation of seeding and pattern recognition is performed with the reconstructed hits originating from a given propagated particle, followed by a fit of the track done with the same fitting algorithms of the full reconstruction.

3.2.2 Calorimeter response to e and γ

In FAMOS, the simulation of an electron shower makes use of the Grindhammer parameterization [8], implemented in the GFLASH code [9]. The photon case goes back to the electron case after the first $\gamma \to e^+e^-$ splitting. Shower develops as if the whole ECAL were a homogeneus medium. The energy deposits are sliced longitudinally; in each slice energy spots (calorimeter hits) are distributed in space according to the radial profile and placed in the actual crystal geometry. The following effects are simulated: leakage (which is propagated to the HCAL), gaps between ECAL modules, shower enlargement due to the B-field, electronic noise and zero suppression. Starting from the calorimeter hits, clustering is obtained as in the complete reconstruction.

3.2.3 Calorimeter response to hadrons

Charged and neutral hadrons propagate to the ECAL and HCAL entrances. The energy response is derived from a full simulation of single pions generated at fixed p_T values between 2 and 300 GeV$/c$. Smeared energy distributes in the calorimeter cells using parameterized longitudinal and lateral shower profiles. Other hadrons are treated as pions of the same p_T.

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[4] Their implementation is indeed foreseen in the new fast simulation.

3.2.4 Muons

Muons in FAMOS are not propagated until the CMS muon chambers. Their calorimetric response is tabulated in a similar way as for hadrons. The response of the muon chambers is parameterized on samples of fully simulated single muons (with $2 < p_T < 1000$ GeV$/c$) to reproduce efficiencies and resolutions, assuming a gaussian distribution for the final quantities. Different parameterizations are provided for L1 trigger muons, HLT muons, and global muons. HLT and global muons may require a correlation with the reconstructed track.

3.2.5 Trigger

L1 and HLT trigger signals and primitives are obtained as a “by-product” of the fast simulation of the corresponding subdetectors. Decision functions are then reconstructed starting from those trigger primitives with the very same logic as in the real data.

3.2.6 Pile-up

In-time pile-up minimum bias generated events are superimposed to the signal events, and their particles treated as all other particles in the event. No out-of-time pile-up is considered.

3.2.7 Timing

A complete event takes a couple of seconds to be simulated and reconstructed with FAMOS (about 1 s in FAMOS itself, the rest in the analysis and framework ovehead); it is slightly more with the pile-up superimposed. It consists of more than two orders of magnitude gain with respect to the full simulation and reconstruction.

4 Comparison between the fast simulations of ATLAS and CMS

Summarizing what reported in the previous section, one can argue that:

- fast simulation in ATLAS focuses on simplicity and velocity, still maintaining a reasonable agreement with the results of the full simulation;
- fast simulation in CMS focuses on intermodularity with full simulation and reconstruction and on the best possible reproduction of the results of the full simulation, still maintaining a reasonable gain in velocity with respect to the full simulation.

It is possible to compare graphically a full simulation and the fast simulations of ATLAS and CMS, with two other simpler methods usually adopted to emulate the effect of the detector on a set of generated particles: a crude smearing of the generated momenta, plus some efficiency factor on them; and a more optimized way of applying smearing of momenta, detection and reconstruction efficiencies, reconstruction of jets, leptons and trigger objects, as for example in the program PGS [10]. As represented in fig. 9, one can order the different methods in terms of increasing complexity (i.e. correspondence to the “true” detector response) and consequently increasing CPU-time needed to process an event. Roughly speaking, the fast simulation as developed in ATLAS is closer to the theoreticians needs, the one of CMS is instead richer in details and able to better reproduce the actual detector output.

5 A closer look to the fast simulation of CMS

A few comparisons between the former fast and full simulations of CMS (respectively FAMOS and OSCAR, based on GEANT4[9]) are shown here. Although the accord between the results of the two simulations is amazing for most of the relevant observables, emphasis will be given to the remaining discrepancies, with a discussion of the possible causes.

5.0.8 Electrons and photons

In the fast simulation ECAL is represented as a homogenous medium. This allows by itself such a saving of CPU time, that a relatively high degree of realism can be afforded on other aspects:

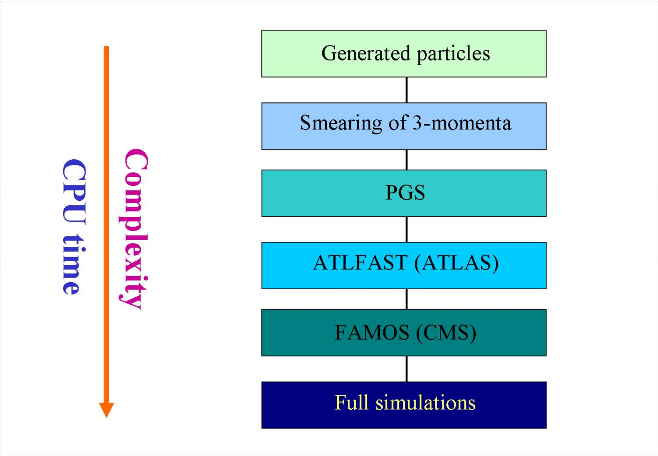

Figure 9: A classification of the fast simulations of ATLAS and CMS, of a full simulation, and of the physics analyses done on bare generated particles, smeared particles, and PGS, as a function of time and increasing development complexity.

- a lot of details are allowed (after optimization, about 1500 hits are calculated per shower of 35 GeV);
- the front and rear leakage, the fraction of signal lost in the inter-module voids, and the shower spreading due to the magnetic field are simulated;
- the calorimetric noise is added to the signals;
- for very high energy electrons, the punch-through into HCAL is also parameterized;
- fake electrons can show up when an ECAL cluster is associated with a simulated seed originating by hits produced by the tracks of the event.

The effect of all this detail can be seen in fig. 10: in general, the reconstructed energies in FAMOS reproduce the corresponding ones from the full simulation with an accuracy at the per mille level in the calorimeter barrel, and at the per cent level in the endcaps.

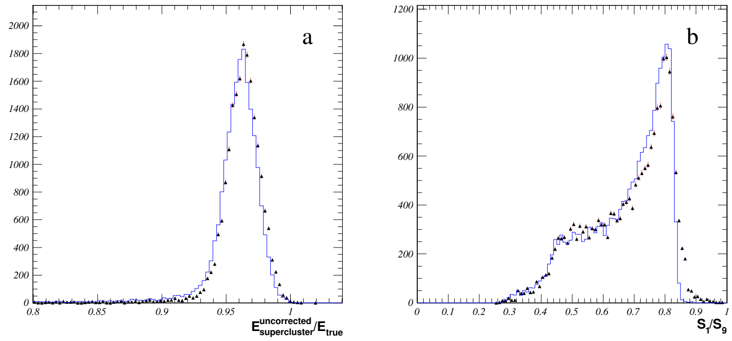

Figure 10: Energy deposited in an ECAL supercluster over true energy (left) and the ratio of the energy in the most energetic crystal to that in the surrounding 3×3 crystals windows (right) for isolated electrons in the CMS fast (dots) and full (histogram) simulations.

5.0.9 Muons

As seen in 3.2, muons are among the objects simulated with the lesser sofistication in FAMOS. In spite of that, the higher-level variables show a remarkable agreement with the full simulation, one example being the invariant mass of a di-muon resonance, shown in fig. 11.

5.0.10 Fake tracks

As explained in Sec. 3.2, the tracks in FAMOS are not currently obtained from a pattern recognition, but from a fit of the hits associated to a “true” charged particle. Because of this use of the Monte Carlo truth during the

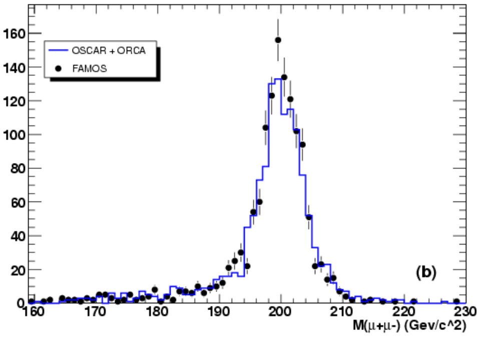

Figure 11: Invariant mass peak of di-muons coming from the decay of a heavy Higgs, in the CMS fast (dots) and full (histogram) simulations.

reconstruction step, no fake tracks (i.e., random combination of hits from more than one track, with or without the contribution of fake hits coming from detector noise) can contaminate the final sample of reconstructed tracks.

Studies in full simulation show that 0.5% of the tracks in the "low luminosity" scenario (2×10^{33} cm^{-2}s^{-1}) are fakes. At that level, the incidence of fake tracks is irrelevant for most of the LHC studies, and a realistic reproduction of this combinatorial background starting from the hits would require a pattern recognition, which would result in a significant increase of CPU time. In spite of that, several possible compromises are under consideration.

5.0.11 Impact parameter and b-tagging

FAMOS applies to the tracks the same b-tagging algorithms applied on data and full simulation. Since the impact parameter is the key ingredient of some of the best performing b-tagging algorithms, the validation of this "low level" variable (shown in fig. 12 for single muons) is of paramount importance. It has to be remarked that the impact parameter was not directly tuned to reproduce the full simulation shape, thus making this full/fast simulation agreement a particularly significant test.

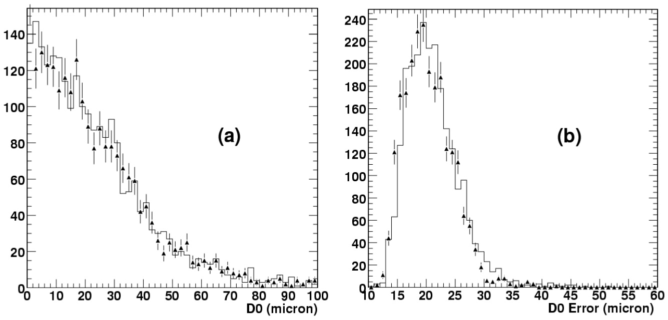

Figure 12: Impact parameter (left) and its error (right) for isolated muons in the CMS fast (dots) and full (histogram) simulations.

Unfortunately, the agreement observed in fig. 12 is not enough to guarantee the complete reproduction of the b-tagging performance on the fast simulated events, as evidenced by the first three plots in fig. 13, which show the output of one high-level b-tagging algorithm mainly based on the impact parameters of the charged tracks, for b-, c- and $udsg$-initiated jets. Actually, the output of this algorithm in the fast simulation reproduces quite well the behaviour of the full simulation for b- and c-jets, while the same is not true for jets originating from lighter partons. This will affect all analyses in which significant sources of background come from processes where some light jets are mistagged as coming from heavy quarks. A common way to describe the performance of a b-tagging algorithm is by showing its misidentification probability as function of the efficiency. Such a representation is shown in the last plot in fig. 13, for the fast and the full simulations of CMS: one can see that over a wide range of cuts, chosen such to fix the rejection factor for the light-flavours related background, the b-tag efficiency in the fast simulation is systematically overestimated by some 5-10%.

In order to understand which, of the many simplifications meant to make FAMOS fast, is the culprit of this situation, a closer look to the variables that enter in the definition of the b-tagging is needed. In fig. 12 we had shown how

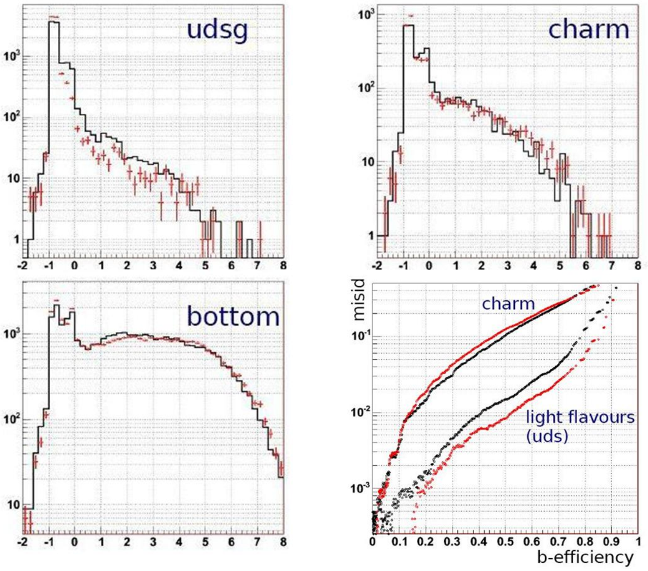

Figure 13: In the first three plots: output of the standard CMS b-tagging algorithm, in the CMS fast (red points) and full (black histogram) simulation. In the last plot: probability of misidentification for non-b jets versus efficiency of identification of true b-jets, in the CMS fast (red) and full (black) simulation.

well the impact parameter was reproduced in FAMOS, in the relatively easy case of isolated muons. Fig. 14 shows instead the largest impact parameter among all the charged tracks (mostly hadrons) in each jet. The comparison with the corresponding full simulation is not satisfactory for jets from $udsg$ partons. The situation improves if one does not consider the tracks with the largest impact parameter: for instance, in fig. 15 the third largest impact parameter in each jet is shown.

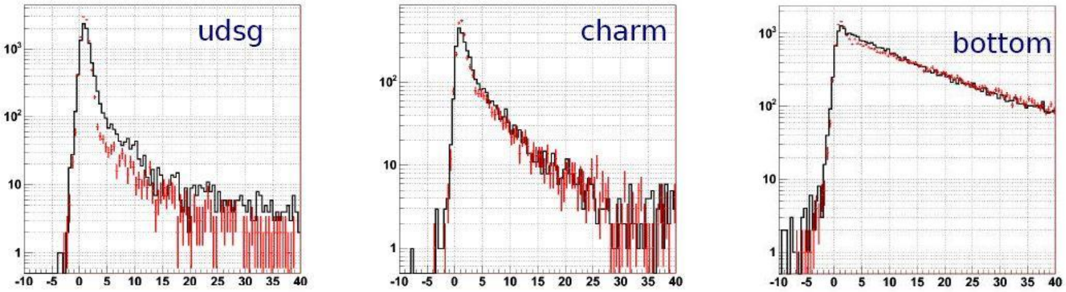

Figure 14: Largest impact parameter for charged particles inside jets, in the CMS fast (red points) and full (black histogram) simulations.

All this suggests that FAMOS lacks the description of some process which is able to seldomly produce a small number of tracks with significant impact parameter. At first, it was thought that the lack of fake tracks (see previous subsection) could have been the responsible of the discrepancy, but at a closer look they were found not sufficient to explain it. Instead, the difference can be attributed to the nuclear interactions of the hadrons with the tracker active and passive materials: they were not simulated in FAMOS, but their implementation is planned for the next release of the fast simulation of CMS.

5.0.12 Hadrons and jets energy

The calorimetric response (ECAL+HCAL) to single pions in FAMOS and in the CMS full simulation is shown in fig. 16a and b. In order to simplify the simulation, all the long-lived hadrons in FAMOS are treated as charged pions. This proves to be enough to obtain a remarkable agreement with the full simulation, as shown in fig. 16c for jets between 80 and 120 GeV in p_T. There are plans, however, to further improve the realism, by treating differently: the long-lived neutral hadrons, since they don't release any signal before the first nuclear interaction; protons and neutrons, whose kinematic is different due to the high mass; anti-protons and anti-neutrons, which in

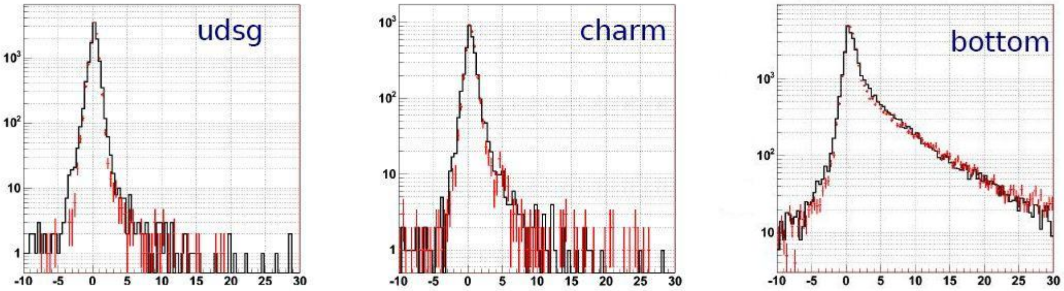

Figure 15: Third largest impact parameter for charged particles inside jets, in the CMS fast (red points) and full (black histogram) simulations.

addition can annihilate.

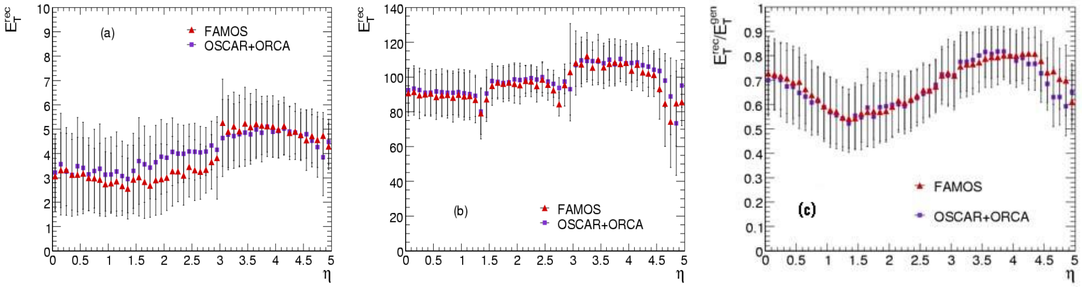

Figure 16: Calorimetric response, as a function of η, to single pions of 5 GeV (a) and 100 GeV (b), and to jetc, reconstructed with the iterative cone algorithm, of p_T between 80 and 120 GeV (c) in the CMS fast (triangles) and full (squares) simulations.

6 Conclusions

Both ATLAS and CMS have developed computer programs for the fast simulation of their detectors. Fast simulations do not have the same level of details as full simulations; they can nevertheless help planning and developping a physics analysis. In the trade between accuracy and time spent to simulate an event, different approaches were chosen by the two experiments. FAMOS, the fast simulation program of CMS, puts its emphasis on having results as close as possible to the full simulation ones. ATLFAST, the fast simulation program of ATLAS, was designed to have results as fast as possible. Both programs were already extensively used for the preliminary studies of the physics technical design reports of the two collaborations.

Fast simulations of the LHC detectors could be the entry point for phenomenologists wanting to test their ideas and MC's in a realistic LHC environment. They are not meant for public use, however, and the interaction with the experimental collaborations is mandatory (and, by the way, this can only be of benefit to both communities of experimentalists and theoreticians).

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