Concepts for fast large scale Monte Carlo production for the ATLAS experiment

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Abstract. The huge success of Run 1 of the LHC would not have been possible without detailed detector simulation of the experiments. The outstanding performance of the accelerator with a delivered integrated luminosity of 25 fb\(^{-1}\) has created an unprecedented demand for large simulated event samples. This has stretched the possibilities of the experiments due to the constraint of their computing infrastructure and available resources. Modern, concurrent computing techniques optimised for new processor hardware are being exploited to boost future computing resources, but even the most optimistic scenarios predict that additional action needs to be taken to guarantee sufficient Monte Carlo production statistics for high quality physics results during Run 2.

In recent years, the ATLAS collaboration has put dedicated effort in the development of a new Integrated Simulation Framework (ISF) that allows running full and fast simulation approaches in parallel and even within one event. We present the main concepts of the ISF, which allows a fine-tuned detector simulation targeted at specific physics cases with a decrease in CPU time per event by orders of magnitude. Additionally, we will discuss the implications of a customised simulation in terms of validity and accuracy and will present new concepts in digitization and reconstruction to achieve a fast Monte Carlo chain with a per event execution time of a few seconds.

1. Introduction
The current ATLAS [1] Monte Carlo production chain (described in Sec. 2) has successfully matched the needs of the experiment during Run I data taking. The great level of detail achieved in the various steps of the chain is on the other hand a clear limitation in case of large scale production, which will be necessary during Run II, when higher centre of mass energy and pileup will come into play. Fast simulation techniques (described in Sec. 3) are designed to exploit the balance between precise simulation and small CPU consumption. They have already been successfully used by ATLAS for the Run I production campaigns and could be further exploited integrating them into a flexible simulator. One of the main ideas presented in this paper is the Integrated Simulation Framework (described in Sec. 4), which uses a dynamic approach to handle different particle interactions within the detector in the same event to significantly speed up the process. A drastic reduction of simulation times calls for fast digitization and reconstruction techniques (described in Sec. 5 and 6) and a more efficient way of managing I/O readout. This goal can be reached by a fast production chain, that can speed up current times to a few seconds per event (described in Sec. 7).
2. Current ATLAS Monte Carlo production chain

The chain to facilitate accurate Monte Carlo production in ATLAS consists of five steps [2], each associated with a specific data format, written out to disk. The final format is shared by both recorded data and simulated events, to allow for a direct comparison between the two.

The five steps, represented by the scheme in fig. 1, are the following:

**Event Generation.**
It is responsible for the precise simulation of different processes that can take place during collisions. These events are stored in EVGEN file formats.

**Detector Simulation.**
This step produces HITS files, where the resulting energy deposits of the generated particle interactions with the sensitive detector material are stored.

**Digitization.**
This is the stage at which pileup is handled as well as the conversion of the HITS to the detector response, as a raw data object (RDO). The content of RDO is equivalent to the bytestream data recorded by the detector.

**Reconstruction**
During reconstruction RDO files are processed to find physics objects subsequently stored either in ESD (event summary data files), containing information on detector measured or reconstructed quantities and physics objects, or a reduced version them, AOD (analysis object data), containing only physics object information. These two file formats are used for both data and simulation.

**Rootification**
To allow for fast ROOT [3] analyses on the simulated and collected data, the ESD and AOD files are further reprocessed to obtain N-tuples (D3PD, derived physics data).

The Monte Carlo production using the described chain is the biggest user of the ATLAS grid resources, as can be seen in fig. 2. The most time consuming step is the full detector simulation performed using Geant4 (see Sec. 3), as can be seen in fig. 2.

Figure 1. The current ATLAS Monte Carlo production chain. At each stage a specific output file is stored and passed to the following step for processing. The digitization step is used to handle correctly both in- and out-of-time pileup effects by overlaying pileup events with the simulated main event.
3. The detector simulation step: available technologies

Several developments to speed up the simulation step are currently available as standard ATLAS production tools. The final aim is to obtain a good balance between accuracy and speed, because high accuracy implies a very slow simulation.

A list of the possible technologies that can be employed for detector simulation is given in the following, describing the performances of both full and fast simulation techniques.

**Geant4**

The Geant4-based simulation [4],[5], is the most accurate simulation tool available in ATLAS. It computes interactions of all the particles produced, including secondaries, with the detector materials. This is the cause for the significant CPU consumption, particularly in the electromagnetic calorimeters.

**Frozen showers**

This [6] is a fast simulation technique and is designed to solve the problem caused by the large amount of high energetic particles interacting with the forward calorimeters and slowing the simulation significantly. It consists of libraries storing pre-computed shower developments for given particles at specific energies.

**FastCaloSim**

It consists of a parametrized calorimeter simulation. It computes calorimeter energy deposits for all the particles in the event, apart from muons, that are handled by Geant4. The parametrisation is based on pre-computed tables derived from existing ATLAS Geant4 detector simulation. FastCaloSim [7] can be tuned to data, allowing for good description of the physics treated.

**Fatras**

It is a fast tracking engine [8],[9], based of the geometry used for track reconstruction [10]. The detector in this case is described as a set of thin layers, instead of volumes, where all the interactions take place and are modelled by fast algorithms. The gain in speed with respect to Geant4 is of approximately two orders of magnitude.

**ATLFAST**

It consists of a fully parametric description of the ATLAS detector [11],[12], used to perform studies during the detector design phase. It is based on smearing the generator inputs for each particle and directly producing physics object output to be analysed.

The ATLAS production chain default setup is based on Geant4 simulation combined with frozen showers for the forward calorimeters. It can optionally be substituted by the ATLFASTII simulation engine, where the calorimeter simulation is handled by FastCaloSim. An analogous technique to ATLFAST has been recently used for ATLAS upgrade physics studies.
performance of the different engines are summarised in table 1. It is not used in the current ATLAS production framework, but similar techniques have been employed for future upgrade studies.

During the last production campaign, ATLAS simulated 3.9 billion events using the full simulation approach (combining Geant4 and frozen showers) and 3 billion events with ATLFASTII instead. The difference in speed between the two is of an order of magnitude.

4. Future prospects: the Integrated Simulation Framework

The recent developments in fast simulation techniques in ATLAS, lead to the need for a common framework, able to combine these different approaches. The Integrated Simulation Framework (ISF) is currently being implemented and tested by the collaboration to meet these requirements. It allows for the combination of different simulation techniques within the same event, based on particle types and characteristics or selected regions (generally cones around particles) in a dynamic way, as shown in the example in fig. 4. Therefore, detailed simulation can be exploited for only certain particles of interest to the particular physics analysis and the rest can be simulated using fast algorithms. Such flexibility improves considerably the speed of the simulation step, still maintaining a high level of accuracy (see table 1).

Table 1. Comparison of different simulation flavours using the ISF setup for \( gg \rightarrow H \rightarrow \gamma\gamma \) simulated events without pileup contributions. Significant speedups can be reached when only partially simulating the event.

| ISF Simulation Setup                      | Speedup | Accuracy                          |
|------------------------------------------|---------|-----------------------------------|
| Full Geant4                               | 1       | best possible                     |
| Geant4 with FastCaloSim                  | \( \sim 25 \) | approximated calorimeter          |
| Fatras with FastCaloSim                  | \( \sim 750 \) | all subdetector approximated      |
| Fatras with FastCaloSim, only simulating particles inside cones around photons | \( \sim 3000 \) | approximated and partial event simulated |

Figure 4. A scheme of a possible event simulated using the ISF. The picture shows the flexibility of the infrastructure, allowing for different simulators for the same event.

Figure 5. Core ISF representation, showing the working chain and the functioning of the SimulationKernel, ParticleBroker and SimulationSelectors.
The ISF core is integrated into the ATLAS Athena [13] framework and consists on two main components, as shown in fig. 5: the SimulationKernel and the ParticleBroker. The first is responsible of the particle loop, and sends the particles to the various simulators that produce secondaries, subsequently passed back via the ParticleBroker. The latter also chooses which simulator to assign each particle to, using chains of SimulationSelectors. The selectors make a decision on whether the particle has to be simulated with that specific technology or not. Each particle can be simulated by only one technology, namely the one relative to the first selector accepting it. Each ATLAS sub-detector has a different SimulationSelector chain associated. The described functionality is a routing algorithm to keep track of all the particles in the event and simulate them consistently. There are two different routing possibilities: a static and a dynamic routing. Static routing consists in an initial decision based on particle types and kinematic features that is kept constant through the full simulation process. For example, a static decision can be: all muons with a transverse momentum higher than 30 GeV are simulated with Geant4. In the case of dynamic routing instead, specific particles and the regions surrounding them are simulated with one simulator, thus all the particles falling in the surrounding cone of an interesting particle belong to this category no matter what type or kinematic feature.

5. Towards fast digitization

Significant speedups in simulation call for speed improvements also in the digitization step, the next bottleneck in the production chain, together with reconstruction. The conversion of simulated HITS into detector readout format and the pileup treatment are currently handled with high accuracy and independently for each sub-detector technology. This is particularly intensive in terms of CPU in the Inner Detector case. Fast digitization methods are thus being studied to be applied to the different technologies present in the ATLAS Inner Detector: silicon and transition radiation.

Fast digitization for silicon trackers

The approach for silicon technologies directly converts particle path lengths into readout signals by projecting it on the readout surface (see fig. 6). A correction for Lorentz angle drift [14] is implemented as well as a random smearing on the projected path length to account for multiple scattering. The final readout signal will be proportional to the smeared path length.

Figure 6. Fast digitization method for silicon detectors: the particle path length is projected on the readout surfaces, corrected for Lorentz angle drifts and smeared.

Fast digitization for the transition radiation tracker

The Transition Radiation Tracker (TRT) fast digitization converts the calculated closest approach radius in a straw into the drift radius at reconstruction level (see fig. 7), taking into account its measurement from the simulated HITS, giving an estimate for the drift radius \( r_D \) used at reconstruction level.

Figure 7. Fast digitization method used for the TRT: the closest approach radius is computed together with the uncertainty on its measurement from the simulated HITS, giving an estimate for the drift radius \( r_D \) used at reconstruction level.
account the uncertainty on the measurement. This technique skips the calculation of the time-over-threshold information performed in the default digitization. The response of the transition radiation is parametrised to allow for particle identification.

6. Fast reconstruction techniques
The most time-consuming reconstruction step is the tracking, because of the combinatorics involved in the pattern recognition step. The identification of tracks out of detector hits grows rapidly with the increase of in time pileup. Thus a fast, truth-seeded, tracking algorithm has been developed [15], bringing significant speed improvements to this production step. The fast method uses truth information on hits from the simulation step to identify the tracking hits relative to each particle. Thorough studies have been carried out to cross-check the performance of truth-seeded tracking compared to standard ATLAS tracking, with excellent results showing very good agreement between the two (see figs. 8, 9).

Figure 8. Comparison of the longitudinal primary vertex resolution using tracks found with the standard tracking and truth tracking at $\mu = 80$, where $\mu$ represents the average number of collisions per bunch crossing.

Figure 9. Transverse momentum spectrum of reconstructed tracks with standard and fast tracking for different pileup scenarios.

7. Prospects for a fast production chain
The improvements presented in the previous sections on the various production steps introduce a new bottleneck in the chain: the output storage consumption. Output files are currently saved at each stage of the chain, but for a future fast production chain only one final output is foreseen, to avoid I/O overhead. The project of a fast production chain [16], combining fast simulation, digitization and reconstruction with a single output file at the end of the process is illustrated in fig. 10.

A significant improvement is foreseen thanks to this approach, speeding up production to a few seconds per event, making adequate MC statistics possible also in case of limited resources.

8. Conclusions
Monte Carlo production has been so far the main consumer of ATLAS computing resources. With the high luminosity and pileup foreseen for Run 2 it is necessary to develop fast technologies to limit the CPU consumption and keep up with the physics programmes. The different approaches developed in ATLAS during the past years to achieve significant speedup in simulation, digitization and reconstruction processes are presented in this paper.

Fast simulation has already been widely employed in ATLAS physics studies, via frozen calorimeter shower libraries and parametrised calorimeter response. The Integrated Simulation Framework (ISF) is designed to dynamically combine the different technologies available for
The fast MC production chain, producing directly ROOT output files from EVGEN inputs via fast simulation digitization and reconstruction steps.

ATLAS simulation, based on particle types and features or specific regions. Tests performed on different ISF configurations show a significant speedup of simulation, the most consuming step of the production chain. Fast digitization and reconstruction techniques and their performances are also described.

A redesigned fast production chain will be introduced, allowing to go in a single step from generated events to ROOT files, via fast simulation, digitization and reconstruction, significantly increasing the speed. This can allow for large scale MC production at high luminosity.

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