# GFlash - parameterised shower in CMS

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*Abstract*

An object-oriented package for parameterising electromagnetic showers in the framework of the Geant4 toolkit has been developed. This parameterisation is based on the algorithms in the GFLASH package (implemented in GEANT3 / FORTRAN), but has been adapted to the new simulation context of Geant4. The package substitutes the full tracking of high energy electrons/positrons (normally form above 800 MeV ) inside Geant4 with the probability density function of the shower profile. A mixture of full simulation and fast parameterisation is also possible. This new implementation of the GFLASH package leads to a significant gain in simulation time for pp events at 14 TeV at the LHC, without sacrificing too much the simulation accuracy and can be used for any calorimeter. GFLASH has been also included into the GEANT 4.7 release and the CMS detector simulation OSCAR, which is based on Geant4. Some GFLASH parameters have been also tuned to achieve better agreement with the CMS electromagnetic calorimeter. Comparisons between GFLASH and full simulation in timing and physics performance will be presented as well.

## INTRODUCTION

The CMS detector simulation is based on the Geant4 package [1]. Geant4 simulates detector effects on physics events using a detailed microscopic description of the interactions between particles and matter. It is very accurate, but it can be very time consuming. In particular the simulation of electro-magnetic cascades in calorimeters is expected to account for a considerable amount of the total simulation time, since it increases almost linearly with the energy absorbed in the detector. Consequently, at LHC energies of 14 TeV fully simulating one event, using individual particle tracking, may take several minutes, depending on the event type and topology. This approach is often not viable, especially when a large number of simulated events are needed for physics analyses. An alternative is the CMS stand-alone fast simulation [4], which is, however, less accurate. The running of past HEP experiments like CDF or H1 proved the importance of an intermediate level of simulation, faster than full simulation, but integrated in the same framework so that it could provide the same kind of output as full simulation on which the full reconstruction chain could be run. A set of equations, derived from the H1 parameterisation (implemented in FORTRAN/GEANT3), can be used to parameterise the electro-magnetic shower development in different calorimeters [2]. In this paper we present the implementation of an electro-magnetic shower parameterisation inside the Geant4 framework[1].

Shower parameterisations based on this approach has been also integrated in the simulation framework of CMS to speed-up the simulation inside its lead tungstate electromagnetic calorimeter.

## PARAMETERISED DESCRIPTION OF SHOWER PROFILES

The spatial energy distribution of electromagnetic showers is given by three probability density functions (PDF),

$$dE(\vec{r}) \;=\; E\, f(t)dt\, f(r)dr\, f(\phi)d\phi, \qquad (1)$$

describing the longitudinal, radial, and azimuthal energy distributions. Here $t$ denotes the longitudinal shower depth in units of radiation length, $r$ measures the radial distance from the shower axis in Molière units, and $\phi$ is the azimuthal angle. It is assumed that in $\phi$ the energy is distributed uniformly due to symmetry: $f(\phi) = 1/2\pi$. The mean longitudinal profile of a shower is described by a gamma distribution:

$$\langle \frac{1}{E}\frac{dE(t)}{dt} \rangle = f(t) = \frac{(\beta t)^{\alpha-1}\beta e^{-\beta t}}{\Gamma(\alpha)} \qquad (2)$$

where $t$ is $E$ the shower energy. The longitudinal position of the shower maximum is $T = (\alpha - 1)/\beta$. The mean and the sigma of $\ln(T)$ and $\ln(\alpha)$ are used to parameterise the longitudinal profile, as they are Gaussian distributed variables. For an homogeneous calorimeter they parameterise as a function of the critical energy, the material of the calorimeter, and the direction. For the radial distribution, $f(r)$, a two-component Ansatz is chosen.

$$f(r) \;=\; p f_C(r) + (1-p) f_T(r) \qquad (3)$$

$$\;=\; p\frac{2rR_C^2}{(r^2+R_C^2)^2} + (1-p)\frac{2rR_T^2}{(r^2+R_T^2)^2} \qquad (4)$$

More details are described in the references mentioned above [2]. The shower profiles had to be partially tuned to achieve better agreement with the full simulation - this is especially true for the radial profiles and for high energetic particles.

### *Shower parameterisation in Geant4*

The new implementation of the shower parameterisation(GFlash) has been intergrated into Geant4 and is

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available from version 7.0 on. [1] The following table shows the performance of the shower parameterisation package in a simple test setup: a block of matrial, in this case lead tungstate, the material of the CMS calorimeter. The parameters needed for the parameterisation are calculated on the fly for the considered material. Electrons and Positrons are fully tracked by Geant4 until they reach the calorimeter volume and are then parameterised if the shower is expected to be contained in the envelope (technically a G4LogicalVolume [2]) and certain dynamic conditions are satisfied. Photons are parameterised as soon as they have converted; Fully contained secondaries are parameterised as well, if they satisfy the conditions described above. The speed-up obtained with this set-up is significant and reaches a factor 100 and more for electrons above 50 GeV, as can be seen in table 1.

Table 1: Speed-up of single electrons and positrons in a pure lead tungstate cube in Geant4 version 4.7.0. The numbers obtained for photons are similar.

| **Electron Energy** | **Time/event full Geant 4** | **Time/event parameterisation** | **Speed-up factor** |
|---|---|---|---|
| 1 GeV | 0.10 | 0.006 | 16 |
| 5 GeV | 0.46 | 0.009 | 48 |
| 10 GeV | 0.92 | 0.013 | 67 |
| 50 GeV | 4.60 | 0.045 | 102 |
| 100 GeV | 9.37 | 0.080 | 117 |
| 500 GeV | 46.50 | 0.312 | 149 |
| 1000 GeV | 91.75 | 0.566 | 162 |

Typical longitudinal and radial profiles in $PbWO_4$ are shown in figure 1. Further tests performed on this calorimeter model have shown that the performance is independent of the angle between the electron trajectory and the calorimeter surface. The relative entry position in the crystal does not show an influence either: the performance is equally good near the crystal border and in the centre of the crystal. Only if the particle enters exactly in the crack the performance gets worse. This case is, however, not very likely. Critical regions of the calorimeter can be excluded from triggering the parameterisation. The presence of the magnetic field does not show a significant influence on the shower shape. A detailed comparison of the shower shapes shows in general a worse agreement with Geant4 than with GEANT3 - especially for the radial profiles. This is on the one hand due to technical differences and implementation details between Geant4 and GEANT3. On the other hand, the parameterisation obtained from GEANT3 does not always describe Geant4 shower profiles with sufficient accuracy. Here a retuning may be necessary. In the case of CMS the radial profiles were retuned, as described in the next section.

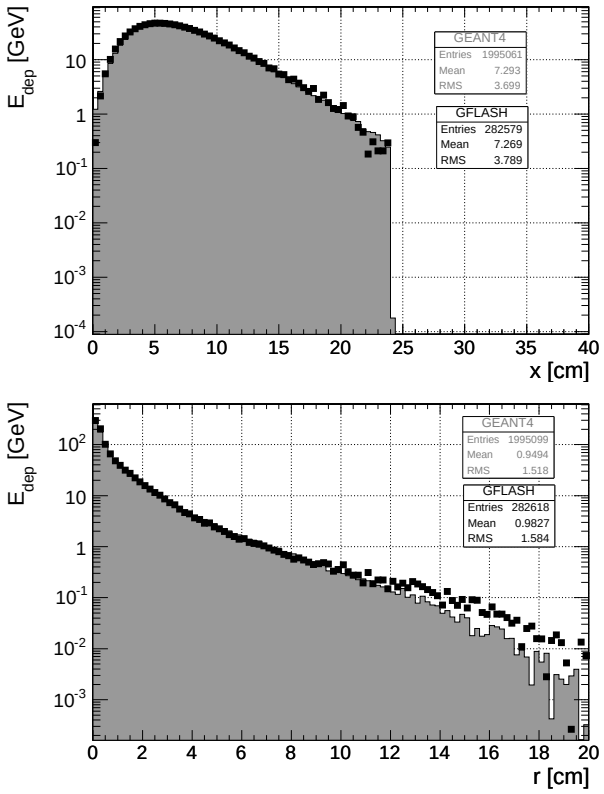


Figure 1: Longitudinal (top) and radial shower profile (bottom) for 50 GeV photons in pure lead tungstate ($PbWO_4$). The points correspond to the parameterisation (radial profile retuned), the histogram to the full Geant4 simulation.

## *Tuning of the radial profiles*

Detailed studies of the GFlash performance and a comparison with GEANT3 indicates that especially the parameterisation of the radial profiles might need adjustment when moving to Geant4 and using a $PbWO_4$ calorimeter, a material, which has not been considered explictly in [2]. Furthermore, the energy range at the LHC is much higher than the range explored by H1. From the direct comparison of the energy deposit in the crystal one can see, that GFlash tends to deposit too much energy in the central crystal. In order to stick as close as possible to the original GFlash parameter and get at the same time a better agreement for the transversal profile a correction factor k for the weight p was introduced in equation 3 leading to the modified form:

$$\begin{aligned} f(r) &= (p*k)f_C(r) + (1-(p*k))f_T(r) \qquad (5) \\ &= (p*k)\frac{2rR_C^2}{(r^2+R_C^2)^2} + (1-(p*k))\frac{2rR_T^2}{(r^2+R_T^2)^2} \end{aligned}$$

[1] Since version 4.8.0 sampling calorimeters are also supported, see Geant4 manual for details.

[2] From the Geant4 version 8.0 the envelope is defined by a G4Region

In other words, the core and tail component of the radial profile are reweighted. In figure 2 the tuning procedure, as well as the core and the tail components of the radial profile are visualised.

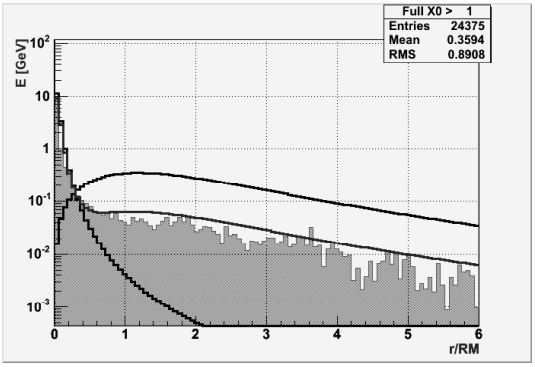


Figure 2: The radial function is fitted to the full simulated radial profile (histogram). Left the core and right the tail component of the radial function are plotted

The procedure has been as follows:

1. The radial profile is plotted in bins of the longitudinal shower profile with the size of one $X_0$ in the range from $X_0 < t < 20X_0$ (t being the longitudinal shower coordinate).

2. For each longitudinal interval the radial profile function is fitted with only $k$ as free parameter and all others parameters fixed.

3. The obtained correction factors $k_1 ... k_{20}$ are now fitted as a function of the longitudinal coordinate. As a first approach a linear function was taken for $k(t)$

4. At the end, the energy dependence of $k$ is studied and parameterised.

In figure 2 the tuning procedure, as well as the core and the tail components of the radial profile are visualised. With this procedure a better agreement of the radial profiles could be achieved. The energy deposit in the crystals after retuning showed an agreement to the one $1\%$ level in $PbWO_4$.

## *Performance for single electrons in CMS*

The performance of the shower parameterisation has been tested for single electrons and positrons in the CMS detector simulation OSCAR [3] with the full geometry. For this purpose electrons with a flat distribution in $\eta$ were shot from the centre of the detector into the barrel and endcap region of the calorimeter and the energy deposit in the central crystal, the $3 \times 3$ and the $5 \times 5$ matrix was compared. The same tests were also performed with photons, which in this model are parameterised after they have converted into an electron-positron pair. The speed-up factor gained due to shower parameterisation is presented in table 2, a plot illustrating the physics performance in the crystals can be seen in figure 3.

The speed up is still significant. It is less explicit than in pure lead tungstate since with a complex geometry and material in front of the calorimeter not all electrons are fully contained and parameterised and produced secondaries may be fully tracked, which slows down the simulation. Similar results has been found for photons. Another

| Energy (GeV) | Speed-up factor |
|---|---|
| 50 GeV | 2.0 |
| 100 GeV | 3.8 |
| 500 GeV | 11.8 |
| 1000 GeV | 7.0 |

Table 2: Speed-up for single electrons in OSCAR 5.0.0

problem encountered is the fact that inside a complex geometry it may be difficult to find an adequate parameterisation envelope, since besides the active matrial (here $PbWO_4$ ) also other volumes and materials may be contained in the mother volume. This possibility is neglected in the parameterisation and has an impact on the agreement between full and fast simulation. If one shoots an electron directly into the calorimeter starting from the crystal surface the difference between full and parameterised simulation is below one percent. If, on the other hand, the electron comes from the detector centre the difference increases to 2 - 3 %. This is most likely due to the not ideal shower envelope. The parameterisation deposits the energy spots assuming that the whole envelope consists of $PbWO_4$, which leads to energy losses if this is not the case. Full tracking handels this situation correctly, since the electron is basically propagated through the (usually thin and not very dense) support material and is still able to deposit energy in the active material. This problem is currently under consideration. The new region based parameterisation concept in Geant4 8.0 may improve the situation, since it allows for a more accurate description of the envelope.

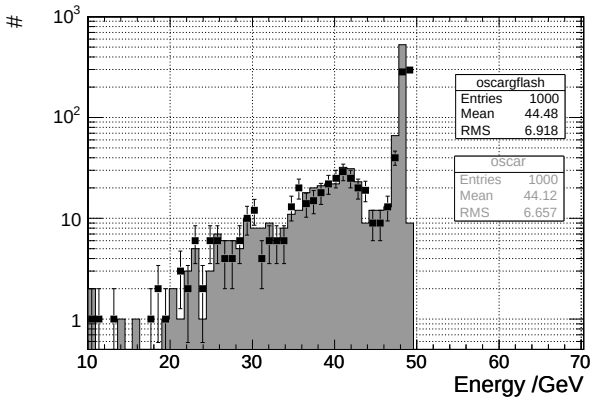


Figure 3: Energy deposit in the $5 \times 5$ crystal matrix. The points correspond to the parameterisation (radial profile retuned), the histogram to the full Geant4 simulation.

### *Performance for Full LHC events*

Physics studies for the LHC require a large number of simulated proton-proton collisions. So the relevant question from the CMS physics point of view has been how much parameterised showers can speed- up the complete simulation of full events, where only electromagnetic subshower are parameterised. The speed up will depend on the event topology and the final state particles. As a sample, two event types were studied where the contribution from electromagnetic showers dominates the simulation time: the decay of a Higgs boson to 4 electrons and the production of a high energetic photon together with a graviton in the Arkani-Hamed, Dvali and Dimopolous(ADD) Large Extra Dimension model. The results can be seen in table 3. The studies have shown that the gain in computing time using the parameterised shower technique can significantly speed-up full events. The speed-up can still be increased if

| Event | Speed-up factor |
|---|---|
| Higgs $\rightarrow$ 4e, | 2.0 |
| ADD Gamma + Gravition | 3.3 |

Table 3: Speed-up of full LHC events in OSCAR 5.0.0; For the Higgs a mass of $m_H = 300$ GeV is assumed, in the case of the ADD process the photon has a $p_T > 1000$ GeV.

the electromagnetic sub showers in the hadron calorimeter are parameterised. This has, however, not been done in this work.

### *Conclusion and Outlook*

The parameterisation concept and equations of GFLASH from H1 has been successfully ported and object-oriented redesigned in the simulation framework of Geant4. This new parameterisation package has been contributed to the Geant4 collaboration and is available since version 7.0 for homogeneous calorimeters and for sampling calorimeters since version 8.0, featuring also an example to illustrate the usage of the package inside Geant4. Detailed tests of the performance have been carried out on simple and complex geometries. The radial profiles have been retuned to achieve better agreement with fully simulated shower profiles in Geant4. In the next step, the parameterisation has been fully intergrated into the current CMS detector simulation suite OSCAR. Comparisons of the energy depositions in the central crystal, the 3x3 and 5x5 crystal matrices performed with the GFlash based and the full OSCAR simulation show good agreement to the $> 1\%$ level. The transverse and longitudinal shower profiles are also well modeled to within 1-3$\%$. The shower parameterisation concept allows for a significant performance gain in timing, with speed-up factors in the range of a 3-10. The gain for a simulation including the full detector geometry depends on the event type, the particle energy and the detector $\eta$ region. A better physics performance may be achieved by using the new Geant4 region concept once the CMS simulation will be ported to Geant4 8.0, since then a more accurate definition of the shower envelope is possible. The speed-up for full events can be increased by using the parametrisation as well for the electromagnetic components inside the hadronic calorimeter. CMS is currently rewriting its framework (CMSSW), so the porting of GFlash to the new simulation environment is another important task to be accomplished in this year. In CMSSW a comparison with the test beam is planned in 2006 which would finally also offer the possibility of a comparison and potential tuning of GFlash to test beam data.

## REFERENCES


[1] Geant4, see http://wwwinfo.cern.ch/asd/geant4/geant4.html and documentation therein. and paper NIM A 506 (2003), 250-303

[2] G.Grindhammer, M.Rudowicz and S.Peters, NIM A290(1990)469 and G.Grindhammer and S.Peters, hep-ex/0001020

[3] OSCAR: CMS Simulation Package see http://cmsdoc.cern.ch/oscar

[4] FAMOS: CMS Simulation Package see http://cmsdoc.cern.ch/famos