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Calorimetry Task Force Report

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Abstract

In this note we summarize the progress made by the calorimeter simulation task force (CALOTF) over the past year. The CALOTF was established in February 2008 in order to understand and reconcile the discrepancies observed between the CMS calorimetry simulation and test beam data recorded during 2004 and 2006. The simulation has been significantly improved by using a newer version of GEANT4 and an improved physics list for the full CMS detector simulation. Simulation times have been reduced by introducing flexible parameterizations to describe showering in the calorimeter (using a GFLASH-like approach) which have been tuned to the test beam data.

Contents

1 Introduction

The Calorimeter Simulation Task Force (CaloTF) was established by the CMS management in February 2008 with the following charges:

- For the full simulation ("FullSim") of the electromagnetic (ECAL) and hadronic (HCAL) calorimeter systems:
  - Evaluate and "fix" or tune the shower models used by GEANT4 [1] to improve the agreement between the simulation and the test beam data for the linearity of the response, the energy resolution, and the shower shape;
  - Simulate saturation effects (Birks' law [2]) which occur in the scintillators;
  - Implement the contribution of Cerenkov light for the ECAL response;
  - Develop a GFLASH [3] based parameterization for the electromagnetic and hadron shower shapes which are tuned to the test beam data.
- For the fast simulation ("FastSim") of the calorimeter system:
  - Tune the parameterization of the electromagnetic and hadron showers to FullSim with the goal of achieving better than 1% agreement;
  - Tune the shower parameterization to the available test beam data.
- Usage of collider data for tuning the simulation:
  - Provide a strategy to tune both FullSim and FastSim to collider data. The strategy should include the specification of trigger paths to record the necessary data as well as the tools for the analysis and tuning of the simulation.

The first deliverables of the task force are summarized in the earlier report [4] and have been included in the CMS Software (CMSSW) version 2_1_0 and subsequent software releases. The agreement between test beam data and Monte Carlo (MC) was greatly improved for FullSim as well as FastSim and the first implementation of a parametrized shower description was implemented within the FullSim framework. However the agreement in FullSim was achieved after sacrificing some of the performance quantities such as execution time and memory usage. There has been an ongoing effort to improve the simulation not only in terms of the physics description but also in terms of the computing performance.

This note summarizes the work that has been done over the past year in the following three areas: (1) FullSim using GEANT4 where the simulation quality as well as computing performance has been improved; (2) parametrization of electromagnetic and hadron showers using GFLASH where good agreement between the simulation and test beam data is obtained for electron and pion beams; (3) understanding events with abnormally large signals in the forward hadron calorimeter (HF) due to punch through and extending the FullSim framework to simulate such anomalous events. The work described here has been implemented in the CMSSW software for versions 3_1_0 and its successors. A strategy to use collision data to tune the simulation is still being developed, and therefore has not been addressed in this report.

2 Recent GEANT4 Improvements

Significant improvements have been incorporated in the GEANT4 toolkit [5, 6] since the previous report of the CaloTF [4]. Improvements have been made to the standard electro-magnetic (EM) [7] and hadronic [8] physics packages of GEANT4. These improvements are being used for the CMS detector simulation starting with the CMSSW_3_1_X version of CMSSW. Configuration of the GEANT4 physics models is specified by the Physics Lists [9]. For CMSSW_3_1_X the QGSP_BERT_EML Physics List has been selected for the Monte Carlo production used for the start of the LHC. The QGSP_BERT_EML Physics List is a customized version of GEANT4 reference Physics List QGSP_BERT_EMV which has been modified for CMS. Highlights of the GEANT4 developments relevant to CMS are discussed below.

2.1 GEANT4 Electro-Magnetic Packages

The new ultra-relativistic bremsstrahlung model [10] for electrons and positrons above 1 GeV is included in the EM package. This model includes a completely revised method to simulate suppressed response due to the Landau-Pomeranchuk-Migdal and density effects. The new model results in a simulation which fits the experimental results much better than the previous GEANT4 model [5]. New GEANT4 processes and models of bremsstrahlung and e^+e^- pair production by hadrons are created on the basis of existing GEANT4 models for muons [11]. Only modifications of the differential cross sections are required to take into account mass and spin differences between muons and hadrons. The cross sections of new processes are small compared to the total hadronic cross section but a visible effect on the MIP fraction in ECAL for π^- above 100 GeV is observed in [4]. The probability of a large energy deposition in ECAL is larger with increasing pion energy due to high energy pion bremsstrahlung.

The GEANT4 multiple scattering model (MSC) has been under development for the last several years [7, 12] with a focus on providing the best balance between accuracy and CPU performance. Recent modifications concentrate on implementing and tuning of MSC models specific to the particle type, with electrons as the first priority. The description of the tail of the electron scattering distribution is improved and the single scattering model is applied to electrons in the vicinity of geometry boundaries. This allows us to double the default value of the parameter specifying the MSC step limitation, $F_R = 0.04$, resulting in slightly fewer steps in the electron tracking and hence faster execution time.

A cubic spline interpolation across the transition of physics tables is provided, which is an alternative to the former linear interpolation. Physics tables for EM processes are created during initialization and a table of look up values for the stopping powers and ranges is saved, which helps to reduce the overall execution time. These tables, however, require significant memory. The accuracy of the interpolation depends on the number of bins. Usage of the spline interpolation method increases simulation precision while keeping the size of GEANT4 applications the same.

By default, the GEANT4 production thresholds (cuts) are applied only for ionization and bremsstrahlung processes. The option *ApplyCuts* enables production thresholds for other EM processes (Compton scattering, photo-electric effect, ...) speeding up the simulation time. However, enabling this option may affect the response of calorimeters since part of energy will be absorbed locally. This option has never been used in the past and a careful validation has been performed.

An initial check is performed using a simplified simulation of the CMS combined calorimeter allowing to study the response of physics processes for the ideal setup which excludes digitization and other detector effects. ECAL is represented by 5×5 matrix of $\mathrm{PbWO_4}$ crystals. The transverse shape of EM showers can be characterized by the relative value of the energy deposition in the central crystal to the total energy deposition in the matrix (Fig. 1). Because of the upgrade of MSC this value is reduced by 0.5% in comparison with previous GEANT4 versions yielding a result that is closer to the measured values from the data of the CMS H4 test beam. Other major modifications, namely the new bremsstrahlung model, the spline interpolation and the *ApplyCuts* option do not affect EM transfer shower shape.

In contrary, the response of the HCAL becomes more sensitive to GEANT4 cut values if the *ApplyCuts* option is enabled (Fig. 2). For high cuts values the response of a sampling calorimeter becomes very sensitive to the choice. This can be expected since the mechanism of energy transition by low-energy gammas is suppressed. Thus, to insure the stability of the simulation of the detector response for the CMS HCAL sampling calorimeter the cut value should not exceed 3 mm. The default cut value of 1 mm both for ECAL and HCAL allows us to use the *ApplyCuts* option safely and provides about 20% speedup of the simulation.

2.2 GEANT4 Hadronic Models

As mentioned in the previous section, the configuration of GEANT4 hadronic models for CMSSW_3_1_X based on QGSP_BERT Physics List has been adopted for the simulation. In this Physics List the high energy hadron-nuclear interactions (above 12 GeV) for protons, neutrons, pions and kaons are simulated using the quark-gluon string (QGS) model with the Pre-Compound model for the nuclear cascade [8]. Below 10 GeV the Bertini cascade is used. For the remaining hadrons and energy interval the parameterized models are used. A refinement of the cross section for the quasi-elastic scattering is essential to reproduce the longitudinal shower shape for high energy pions [4]. Recently the quasi-elastic model has been updated by including Fermi-motion for target nucleons providing a smooth spectrum of recoil nucleons.

As shown in [4] the Bertini cascade model is needed for the CMS simulation. The hadronic calorimeter response is mainly determined by the production of π^0 and protons and the model can be validated using thin target data for

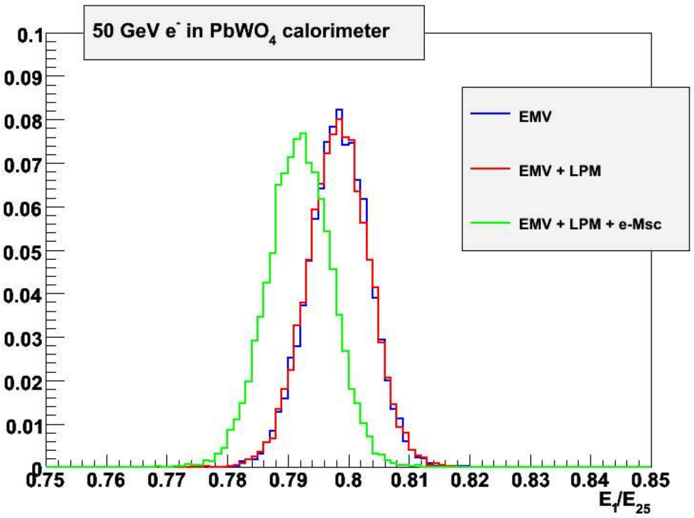

Figure 1: Transverse shower profile of 50 GeV e^- in a 5×5 matrix of $\mathrm{PbWO_4}$ crystals. The beam is pointed to the center of the matrix, the ratio of energy deposition in the central crystal to the total energy deposition is shown for different variants of EM physics table: EMV - default configuration, (EMV + LPM) - a new bremsstrahlung model is used, (EMV + LPM + eMSC) - a tuned multiple scattering model for electrons is added.

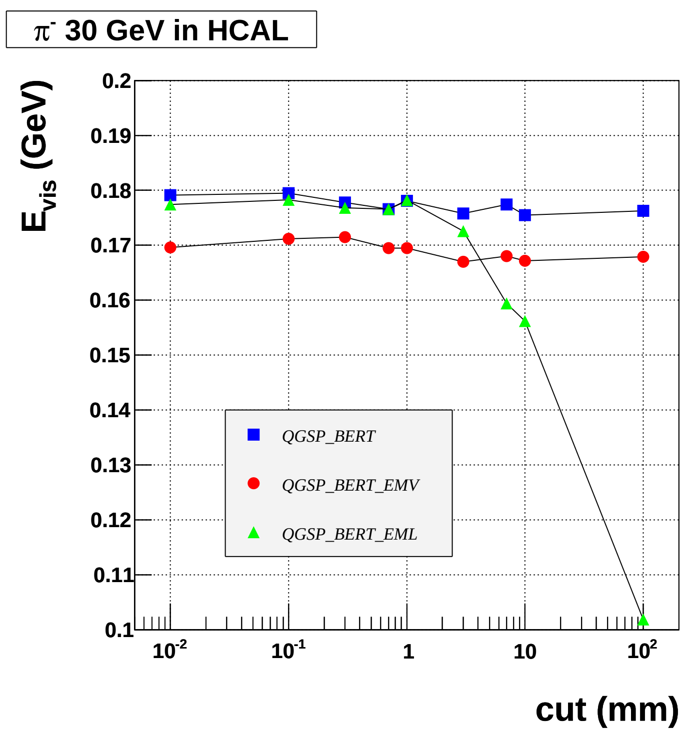

Figure 2: The response of a simple sampling calorimeter for 30 GeV π^- beam as a function of the GEANT4 cut in range. The structure of the simulated calorimeter is a close approximation to the CMS HB geometry. The response is sensitive to cut values above 1 mm if the *ApplyCuts* option is enabled (QGSP_BERT_EML Physics List) and is stable otherwise for lower choices.

$\pi^{\pm}$ and proton production. The following improvements are introduced into the Bertini cascade [6]:

- correct normalization of the quasi-elastic cross section is used;
- partial cross sections shape is improved;
- Coulomb barrier effects are added in the pre-compound and cascade phases;
- pion absorption cross section is tuned to the thin target data.

A review of the native GEANT4 Pre-Compound and de-excitation models is also carried out [13]. An important characteristic of the simulation in the cascade energy range is the description of inclusive neutron production, which is reproduced by GEANT4 cascades [6]. The tuning of the probabilities of neutron, proton, deuteron, triton, and alpha production as well as the probability of nuclear fission are performed.

The main limitation of QGSP_BERT is in the simulation of diffractive processes and in the discrepancy between the cascade and string models around 10 GeV. To address these issues an alternative string model (FTF) is further developed [6]. The main advantage of the updated FTF model is its ability of simulating down to 5 GeV, because of the natural sampling of the diffractive processes dominating the moderate energy region. CHIPS is a quark-level event generator for the fragmentation of hadronic system into hadrons [14]. This model is significantly improved and can be used to simulate the cascade both for primary protons and neutrons as well as for the intra-nuclear cascade simulation with the QGS model.

2.3 New GEANT4 Physics Lists

A CMS custom Physics Lists (QGSP_BERT_EML) has been introduced starting from the reference QGSP_BERT_EMV Physics List. The following modifications are made:

- The upper energy of the EM tables for energy loss, ranges, and cross sections is reduced from 100 TeV to 10 TeV;
- The number of bins is reduced from 84 to 77 decreasing the total memory required for these tables;
- Hadron bremsstrahlung and $e^{+}e^{-}$ pair production are applied also to kaons (by default these processes are enabled only for pions and proton);
- the *ApplyCuts* option is enabled.

A number of new Physics Lists are also included as an alternative for the baseline QGSP_BERT combination of hadronic models. The goal is to provide better agreement with the test beam data and future collision data, in particular, in the transition energy range 5-20 GeV. FTF_BIC and QGSP_FTFP_BERT are created as possible future alternatives, in which the transition between cascade and string models is moved down from 10 GeV to 5-7 GeV. Additional Physics Lists QGSC_CHIPS and QGSC_QGSC are included.

3 Quality Improvements of FullSim

The quality of the shower simulation in FullSim is tested against measurements made with hadron beams of different energies in several test beam runs [15, 16]. The energy response and resolution are measured for the combined calorimeter system (or the hadron calorimeter) for different hadron beams of momenta ranging between 2 and 300 GeV/c. Measurements are also performed for the lateral and longitudinal shower profiles and the fraction of minimum ionizing particles (MIP) in the ECAL as a function of the beam energy.

In CMSSW version 2_1_X, a major discrepancy between the data and simulation has been in the description of the fraction of MIP events as a function of beam energy. As seen in Figure 3, GEANT4 predicts a larger MIP fraction at momenta between 4-10 GeV/c and it also does not show the drop above 100 GeV/c. The large fraction at low momenta is found to be due to inadequate description of quasi-elastic process in the Bertini model while the constant fraction at large momenta is due to absence of considering bremsstrahlung and pair production due to high energy charged hadrons. Both these inadequacies are addressed in the 9.2 version of GEANT4. The agreement between data and FullSim improves with the new version as seen in same figure.

A study of the impact of varying the electromagnetic Physics List of GEANT4 is performed. The default electromagnetic Physics List (_EMV) is modified to include bremsstrahlung and pair production for charged hadrons.

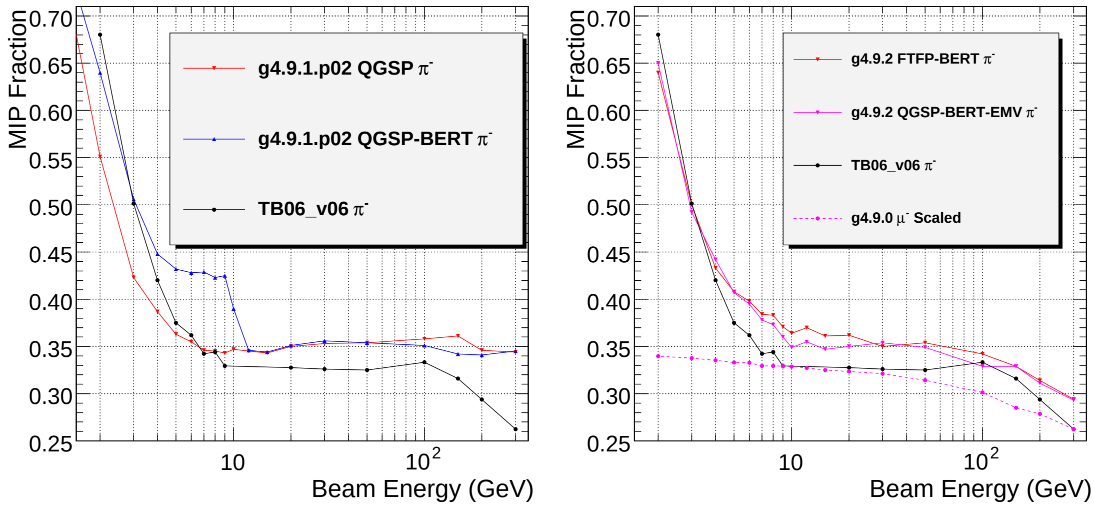

Figure 3: The fraction of π^- with a MIP like signal in ECAL as a function of beam momenta in the 9.1.p02 version of GEANT4 is shown in the left figure. The right figure shows the result obtained using the new 9.2 version of GEANT4 with the modified EM physics list described in the text.

Restricting the hadronic physics list to QGSP_BERT, the electromagnetic physics list is extended to include the *ApplyCuts* option (_EMLX), improved multiple scattering model in the region for HCAL (_EMLY), improved multiple scattering model for HCAL together with reduced range for the physics table (_EMLZ) and with all these options together (_EML). Figure 4 shows the mean energy response as a function of beam momentum for incident π^- and p in the combined calorimeter system and in the HCAL (where the beam has response like a MIP in ECAL). The test beam data are compared with the four variations as mentioned above together with the old default _EMV which does not use *ApplyCuts* option, nor any improved multiple scattering model. As can be seen from the figure, the EM versions _EMV and _EMLX are similar and agree better with the data. The other 3 options, _EML, _EMLY and _EMLZ, have very similar predictions and give somewhat smaller value of mean energy response. These physics lists have very similar predictions for all other variables like resolution, shower profile, etc. Although the versions _EMV and _EMLX give very similar results, the version _EMLX is 20% faster. These considerations lead to the choice of the modified physics list with *ApplyCuts* option, reduced range for physics tables but keeping the default multiple scattering for electrons and positrons in all regions. The combined physics list is referred to as QGSP_BERT_EML in all future references.

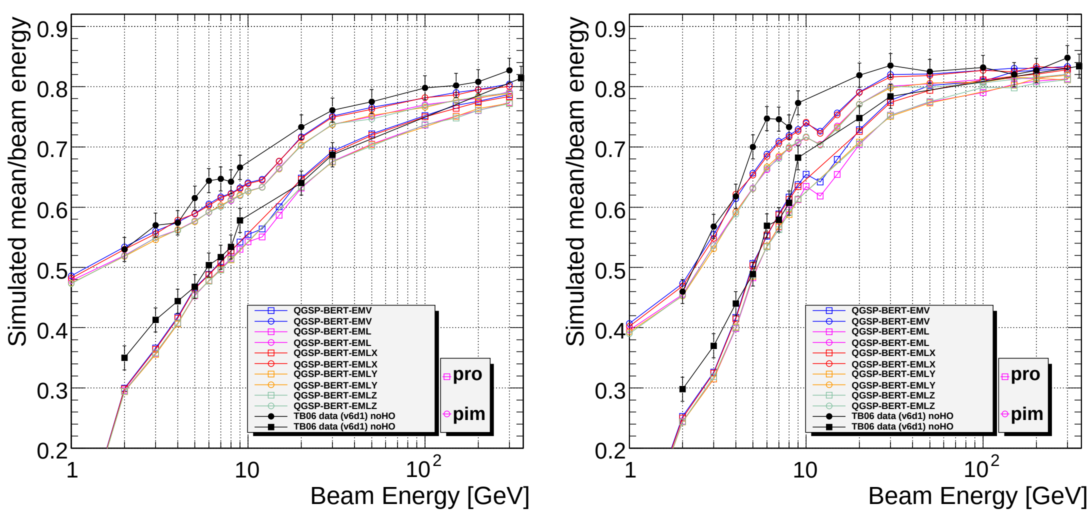

Figure 4: Mean energy response of the combined calorimeter (left) and HCAL (right) to π^- and p beam as a function of beam momenta compared to predictions of different physics lists as described in the text.

The release of the beta version of GEANT4 9.3 provides a few more options. Several new physics lists for the hadronic model are now available. The usage of the parametrized model LEP in intermediate energies for $\pi^{\pm}$, $K^{\pm}$ and nucleons is replaced by a different microscopic model FTF in the physics list QGSP_FTFP_BERT. The cross section at high energies can now be improved using a parametrization based on Glauber-Gribov model. Also synchrotron radiation can be activated for electrons/positrons in the electromagnetic physics list. Several combinations of these new features are tested.

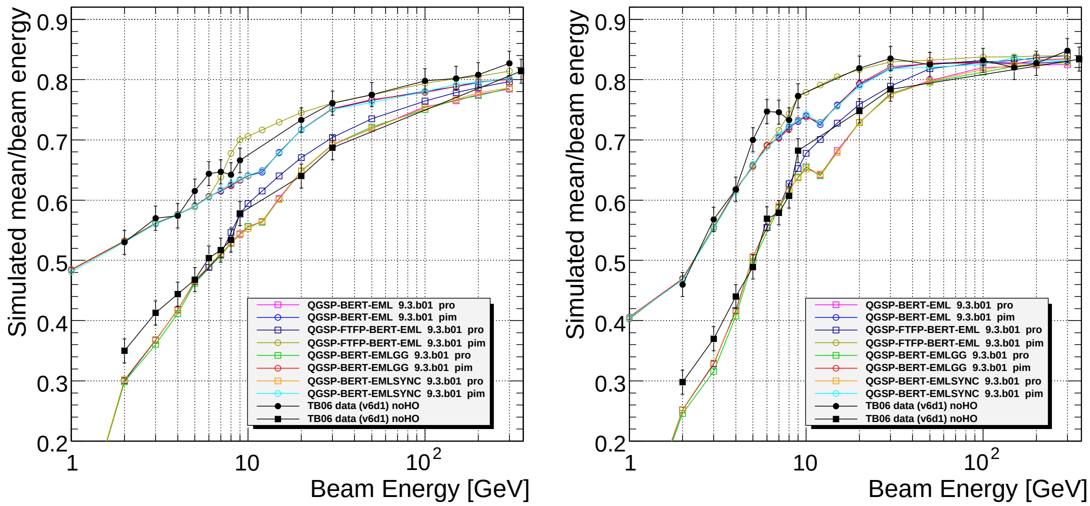

Figure 5: Mean energy response of the combined calorimeter (left) and HCAL (right) to π^- and p beam as a function of beam momenta compared to predictions of different physics lists as described in the text.

Figure 5 shows the mean energy response for π^-s and protons as a function of beam momenta for the combined calorimeter and for HCAL alone compared with more recent physics lists available in GEANT4 9.3. As can be seen from the figure the new physics list QGSP_FTFP_BERT provides an interesting alternative and gives better (worse) agreement with data for HCAL alone (combined calorimeter).

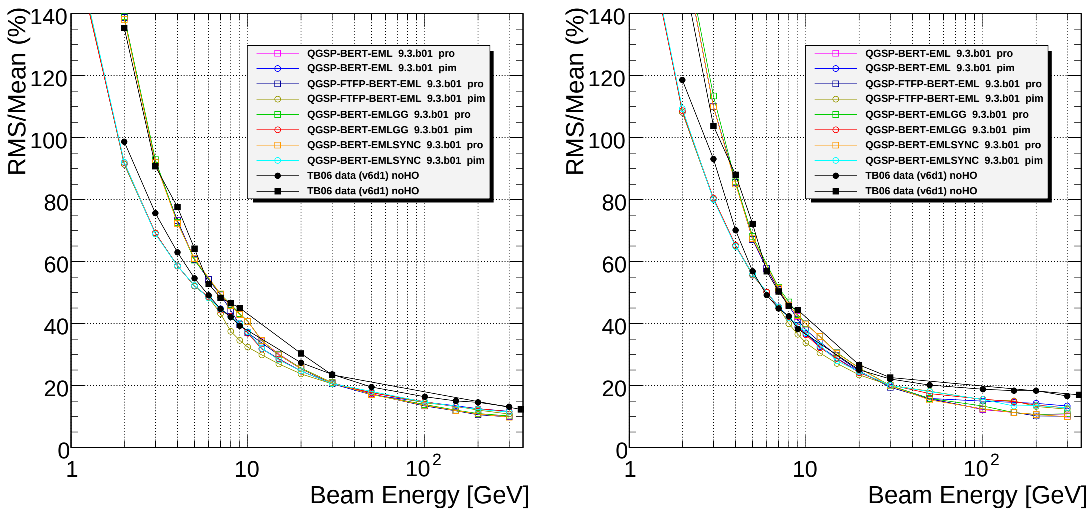

Figure 6: Energy resolution of the combined calorimeter (left) and HCAL (right) to π^- and p beam as a function of beam momenta compared to predictions of different physics lists as described in the text.

Figure 6 shows the energy resolution of the combined calorimeter system and HCAL alone as a function of beam momenta for π^- and protons. For both the systems, FullSim provides better energy resolution which is most pronounced at high energy data in HCAL alone system. This difference is still not understood.

Figure 7 shows the fraction of events with MIP like signal as a function of π^- momentum compared with the new

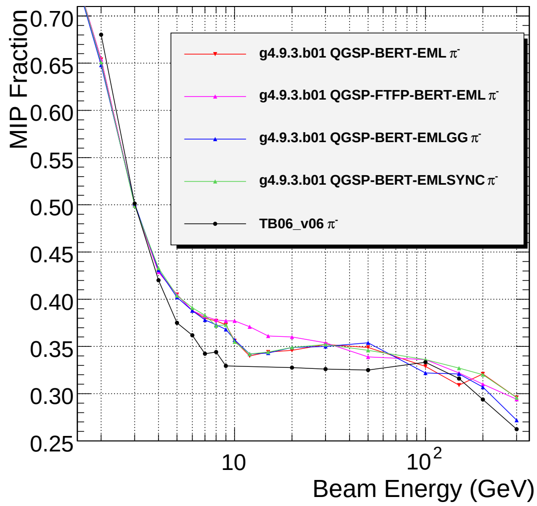

Figure 7: Fraction of π^- with MIP like signal in ECAL as a function of beam momenta in the 9.3.b01 version of GEANT4.

variation of physics lists. Here one sees QGSP_FTFP_BERT predicts a larger fraction at momenta between 10 and 20 GeV/c while the usage of Glauber-Gribov cross section improves the agreement at higher energies.

Considering all the comparisons, the best physics list for CMS would be QGSP_BERT_EML with Glauber-Gribov cross section. However, this version will be available only with the 9.3 version of GEANT4. In absence of that the list QGSP_BERT_EML in version 9.2.p02 will be a good choice for FullSim production of CMS.

4 Computational Performance Improvements in FullSim

The work done to tune the CMS GEANT4-based full simulation presented in ref. [4] resulted in an improvement of the agreement of the simulation with the test beam data, but this was obtained at the price of a serious deterioration of its computational performance. As reported in the note, the adoption of the QGSP_BERT_EMV physics list caused the CPU time to be increased by about 50%, and the data output size was increased by a similar proportion. The usage of the "_EMV" option for the electromagnetic physics description allowed to limit the increase of CPU time to about 15% without any significant impact on the physics quality of the simulation, and was therefore chosen as the baseline option.

It was immediately felt that an optimization, balancing physics quality and computational performances, is highly desirable. The increase in the simulated event size is traced back to a significant increase in the number of hits in the calorimeter produced when using the Bertini cascade model, compared to the QGSP one. The executable memory is also significantly increased due to the memory allocated when creating temporary calorimeter hits during the shower development. Two areas of possible improvements are identified: large values of time of the hits (compared to the event t_0) and very low hit energies.

Long lived thermal neutrons can travel for periods greatly exceeding 1 μs in the detector, creating secondary particles when interacting with the material of the calorimeter. Since the interactions occur outside of the digitization window of the CMS detector and do not contribute to the physics signal, it is not necessary to simulate these long lived interactions. The CMS digitization window is set such that interactions occurring $\sim$500 ns after the interaction time, t_0, can be safely discarded. The Muon Drift Tubes have the longest readout times and the digitization chain can safely fit in the 500 ns window. For the simulation of out-of-time pileup events in the range of [-5,3] LHC clock ticks (period 25 ns) around the t_0 are considered, in practice shifting the times provided by GEANT4 by the corresponding amount when merging different simulated events together before the digitization step. Background processes resulting from slow neutrons can occur at times long after the interaction producing them and will need to be simulated separately from the standard event. Such interactions will appear essentially as a very long-time pileup superimposed on events happening thousands or even millions of bunch crossings later than their origin.

A time cut-off is defined on a `G4Region` basis to both stop particle tracking after the cut-off time (in the `SteppingAction`) and prevent the insertion of particles produced after the cut-off into the GEANT4 stack (in the `StackingAction`). In a similar way a cut-off is defined for each calorimeter sensitive detector class

CaloSD to reject temporary calorimetric hits (CaloG4Hit) from being considered to build the persistent ones (PCaloHit). These cuts are defined as G4Region dependent to accommodate in the same mechanism both the sub-detectors in the central part of CMS, and the calorimeters placed along the beam pipe far away the interaction region, like the Zero Degree Calorimeter which is located about 140 meters away from the nominal CMS center. The cuts are set to 500 ns for the central part of CMS, and 2000 ns for ZDC. A positive side-effect of applying these cuts is to boost to the CPU performances, by suppressing the simulation of slow neutrons beyond the cut-off times.

The Bertini cascade is found to produce an increased number of very low energy (keV and sub-keV) calorimeter hits compared to the pure QGSP model. These low energy hits are responsible for the increased size of the persistent output, through the addition of many PcaloHit objects, as well as increasing the memory usage through the creation of corresponding CaloG4Hits objects during the sensitive detector simulation. This makes the problem even worse, since the size of a PCaloHit is 26 bytes while the size of a CaloG4Hit is 118 bytes. Moreover, while a selection is possible at the PCaloHit creation time, this is not true for the CaloG4Hit, whose energy is increased step-by-step during the tracking provided the cell identifier and the time slot (1 ns granularity) remain the same.

A study is performed to assess the impact of the low energy hits on the final physics performances of the simulation. For this purpose, single muons, electrons, pions and protons beams of energies 1, 10, 50 and 100 GeV are simulated in the calorimetric setup. The Bertini cascade of course matters in hadronic interactions, the lepton beams are used to cross check the impact of possible cuts on the simulation of electromagnetic showers. Figure 8 shows the distribution of the logarithm base 10 of the hits' energy in the ECAL barrel crystals, the fraction of the total energy deposited in the crystal as a function of the single hit energy and the similar distribution for 5×5 crystal matrix around the highest energy deposit. These type of plots are used to define minimum thresholds to be applied to the PCaloHit energy in order to create it. Similar plots are made for the reconstructed hits, and it is verified that cutting the energy deposits at the simulation level below the chosen threshold does not impact the reconstructed energy. As a result of the study, thresholds of 15 and 10 keV are applied respectively to the ECAL barrel and

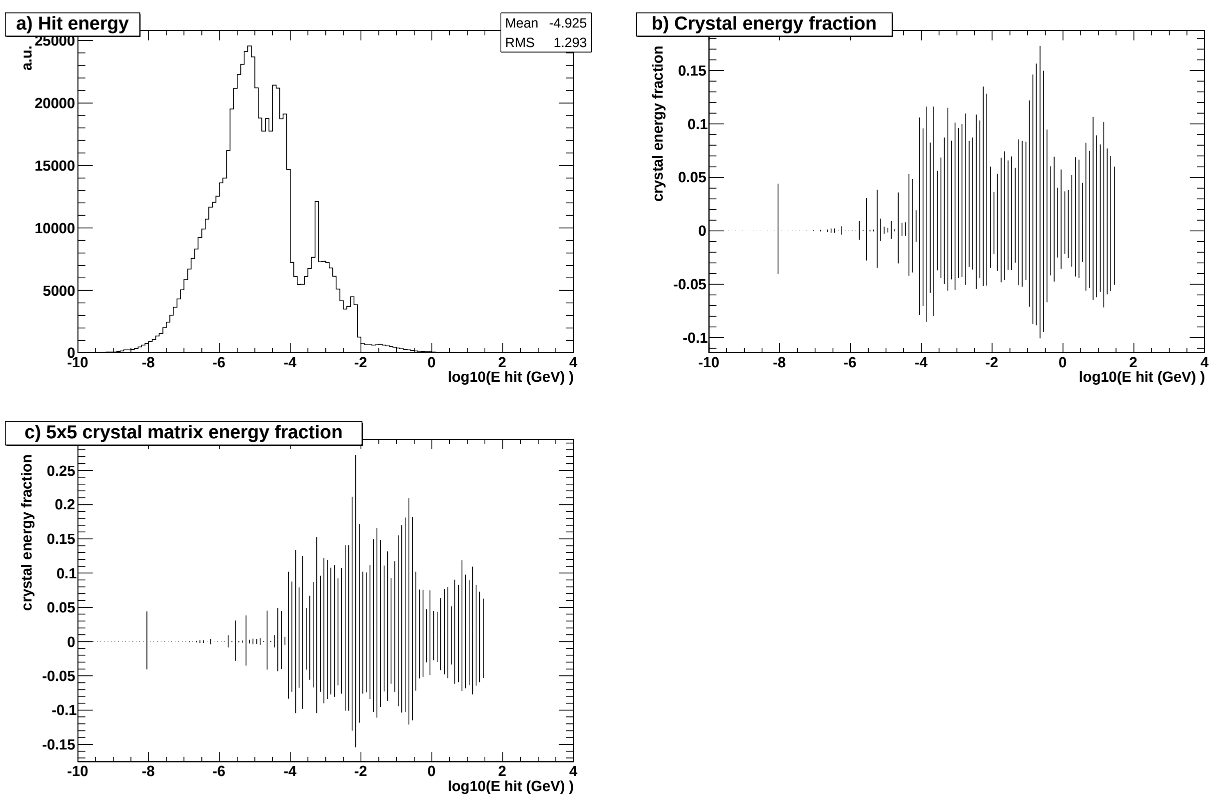

Figure 8: Study of the energy spectrum of hits in the ECAL barrel crystals: a) distribution of the logarithm base 10 of the hit energy; b) fraction of the total energy in a crystal taken by hits of a given energy; c) fraction of the total energy in a matrix of 5×5 crystals around the most energetic one taken by hits of a given energy.

endcap hit collections. The energy distribution in the preshower, and HO is such that this mechanism would cut a marginal fraction of hits. The number of hits in HB and HE is also smaller than the one in ECAL, and therefore no cut is applied (although some gain could be reached with a 0.1 keV cut). The hits for HF effectively store the number of photoelectrons, therefore cannot be treated in a parallel way to the other calorimetric components. The impact on the `RAWSIM` event content size for a $t\bar{t}$ event sample is a reduction of 26% compared to the original QGSP_BERT_EMV case. The virtual memory VSIZE is marginally reduced by 4 MB.

The applied cuts on time and energy of the hits prove to be a useful tool to reduce the number of objects produced. Parallel studies on simulation performances are done using several profiling tools available in CMSSW [17], ranging from basic measurements of time and virtual memory consumption (`Timing` and `SimpleMemoryCheck` services of CMSSW) to a detailed analysis of the memory allocation made with `IgProf`. The conclusion is that a significant gain in the memory usage, both in terms of memory footprint and in number of allocation/deallocation cycles, can be achieved by moving the use of the cuts on calorimetric hits to the transient `CaloG4Hit` objects. As previously explained this cannot be trivially done at creation level, but can be done only a posteriori.

In CMSSW the GEANT4 particle stack is always used in the last-in first-out approach. Therefore any generated physic event to be simulated can be idealized as an array of primary particles which will be simulated independently in a sequential way. In this way, any operation on the results of the simulation of a primary particle can be performed at the end of the simulation of that particle without waiting for the end of the whole event. In particular, the selection of `CaloG4Hit` objects, which can build `PCaloHit` and which cannot, can be done at this stage. The rejected `CaloG4Hit` objects can be reused for the needs of the next primary particle, instead of deleting and re-creating the same object. The map used to order the `CaloG4Hit` according to the `CaloHitID` they contain is replaced by the old mechanism of sorting them in a vector since this operation is moved from the whole event to a single particle level. The sorting algorithm can work much faster (its speed is approximately proportional to $\mathcal{O}(N \log N)$ if N is the number of objects to be sorted), making the CPU loss minor compared to the search in the map, but allowing much more efficient memory handling compared to the one provided by the map.

This optimization makes the calorimetric sensitive detector a bit more complex. It is tested on a 100 $t\bar{t}$ event sample and found to reduce the memory footprint of the simulation job by about 30 MB. As a fall-out of the experience gained in this work, a similar approach is adopted in the handling of tracks in the `SimTrackManager`, moving them to a primary by primary basis. Of course the gain provided by this approach on the standard one depends on the number of primary particles contained in the generated events, ranging from one for the single particle gun case to larger values as the event multiplicity increases. In this respect, very high p_T QCD events or Heavy Ion events are those maximally benefiting from this re-organization of the code.

With the adoption of GEANT4 version 9.2.patch01 another possible optimization studied is the use of the *ApplyCuts* option for the electromagnetic processes. Standalone GEANT4 studies on a simplified CMS calorimetric model shows that this option can significantly boost the CPU performance with little or no impact on physics output provided the parameter cuts are set no bigger than 1 mm. This option is implemented as the default in the QGSP_BERT_EML model, and the parameter cuts across the CMS description are reviewed accordingly, lower values than 1mm in the tracer support structure and in the muon chambers structure are used.

A comparison of the performances obtained with different options for 1000 simulated 50 GeV pions in the CMS calorimeters (with no other CMS part, the "calorimeters only geometry") in the release CMSSW_3_1_2 is shown in Table 1.

Physics list	⟨CPU⟩ (s/ev)	⟨EBHits⟩ (B/ev)	⟨EEHits⟩ (B/ev)	⟨ESHits⟩ (B/ev)	⟨HcalHits⟩ (B/ev)
QGSP_EMV no cut	0.94	2701.02	2454.51	45.919	1220.87
QGSP_BERT_EMV no cut	1.45	8233.88	6039.22	53.688	5541
QGSP_BERT_EMV cuts	1.38	3304.85	2934.21	51.403	4734.78
QGSP_BERT_EML cuts	1.13	3297.68	3077.16	47.111	4726.4

Table 1: Summary of the computing performance of the CMS detector simulation for different physics lists and cuts. The results are for a sample of 1000 single pions of energy 50 GeV simulated using the CMS calorimeter only geometry using CMSSW_3_1_2. The average CPU per event is measured in seconds on a Intel Xeon 5160 @ 3 GHz dual-process dual-core setup (a CERN build machine). The average size per event of the `PCaloHit` collections is the compressed one provided by the `edmEventSize` utility of CMSSW.

5 Updates on GFLASH Shower Models for CMS

GFLASH as a parameterized simulation of electromagnetic (EM) and hadron showers has been successfully introduced to the CMS detector simulation since CMSSW_2_1_X version of CMSSW. It takes over GEANT4 tracking at the first inelastic interaction inside the CMS calorimeters and simulates the energy deposition of particles passing through specified detector envelops. After preliminarily tuned, both EM and hadron shower models have been further refined in parameterizations and their parameters are tuned to test beam data taken in 2006 (H2 and H4). In this section, updates on GFLASH after CMSSW_2_1_X are summarized. Performance and validation with various physics processes as well as the single particle are also presented.

5.1 EM Shower Model

The EM shower model has been re-validated with CMSSW_3_1_X with the latest EM physics list (EML). Updates on the EM shower include 1) validation for the photon shower, 2) fine tuning to the 2006 electron test beam data (H4) with a new beam profile, 3) validation with high level objects (basic cluster and super cluster) and $Z \rightarrow e^+e^-$, and 4) performance measures for single electrons (CPU and output file size).

5.1.1 EM Parameterization

The current GFLASH EM shower model is applicable only to electrons and positrons. Since photons are also following the EM cascade, $\gamma \rightarrow e^+e^-$ (the pair production) and followed by $e^\pm \rightarrow e^\pm\gamma$ (bremsstrahlung), it is pertinent to study whether a separated parameterization for the photon shower should be implemented. Intuitively, the EM shower initiated by the photon will be delayed around 1 radiation length (X_o) until photons undergo the pair production. For the longitudinal profile with the $\Gamma(\alpha, \beta)$ distribution, the mean position of the shower maximum, $(\alpha - 1)/\beta$ is swifted around $+1X_o$, which may be parameterized independently for photons. An alternative question is whether convolution of electron and position showers using the current EM shower model is equivalent to the resultant shower profile by photons. Shooting single photons, the shower profile obtained by GFLASH (convolution of electron and position parameterization after the pair production) is compared to that by GEANT4 (photon shower). Figure 9 shows that longitudinal shower profiles of 50 GeV γ simulated by GEANT4 and GFLASH are nearly identical, which indicates that it is not necessary to have a separate parametrization for photons.

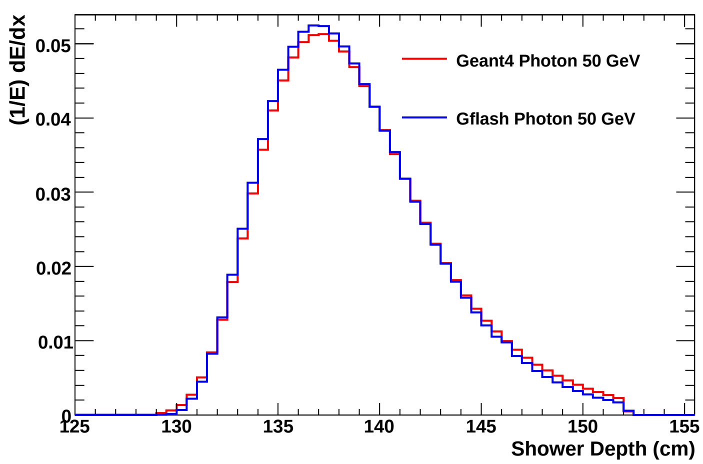

Figure 9: The longitudinal shower profile of 50 GeV γ: GEANT4 (red) vs. GFLASH (blue). The longitudinal profile of GFLASH is the convolution of electron and position showers parameterized by GFLASH after the pair production ($\gamma \rightarrow e^+e^-$).

5.1.2 Tuning to 2006 H4 test beam data

The EM shower model has been re-tuned with CMSSW_3_1_0 to take into account changes in recent releases of CMSSW as well as GEANT4. Following exactly the same analysis path used for the H4 test beam setup, the nominal energy response in $N \times N$ crystals (absolute response) is measured for each beam energy. Since the absolute response may be sensitive to the calibration scale and the containment correction, the ratio of $N \times N$

crystal response (relative response) is a scale–independent measure of the energy response. The relative response is also a good measure for the lateral spread of the shower. Figure 10 shows an example of energy shape comparison between GFLASH and the test beam data for the 50 GeV electron beam. Both absolute response ($N \times N$ crystal responses) and relative response (ratio of $N \times N$ responses) are in good agreement. It turns out that the low tail in the 1×1 crystal response is sensitive to the beam profile. Energy responses of $N \times N$ crystal are tuned for all

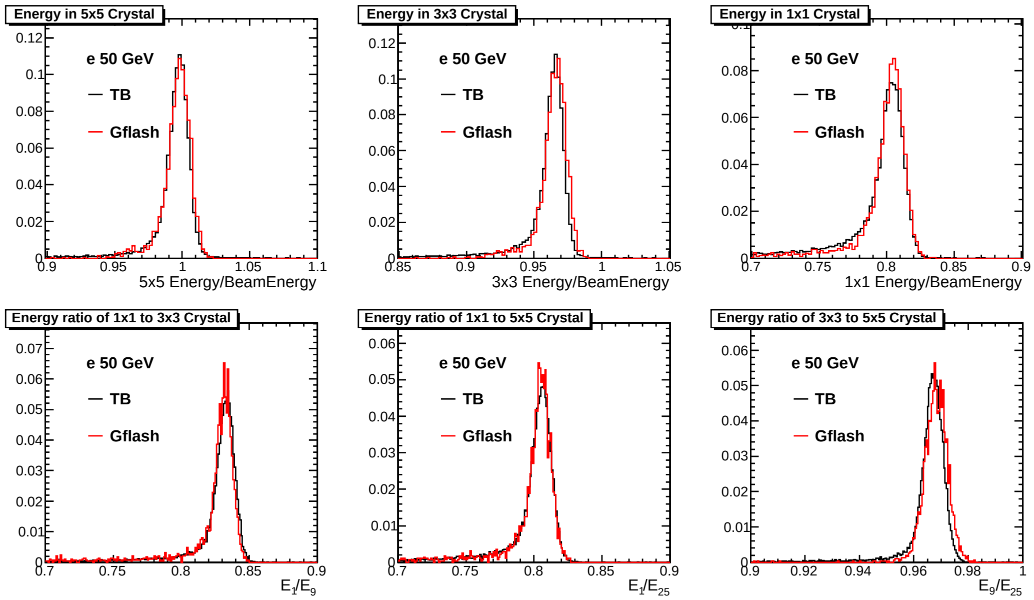

Figure 10: The energy response of 50 GeV e^- by GFLASH (red) and test beam data (black). The top row shows the fraction of energy measured in $N \times N$ crystals to the electron energy for (N = 1, 3, 5). The bottom row shows the ratio of $N \times N$ crystal response.

available beam energies of the 2006 test beam data ($E_{\rm beam} = 20, 30, 50, 80, 120, 150$ GeV). Figure 11 shows the mean energy response and resolution (iteratively fitted with Gaussian within 2σ) as the beam energy.

5.1.3 Validation and Performance

The invariant mass of Z, M_Z obtained from $Z \to e^- e^+$, is a good probe of Monte Carlo energy scale as well as calibration of ECAL. The average mean energy response, $\langle E \rangle / P$ will be studied with data for electron triggers ($Z \to ee, W \to e\nu$). Lateral shower shapes (along η and ϕ near the target crystal) will also be extensively scanned with data. Figure 12 shows 1) the invariant mass of $Z \to e^+e^-$ (PYTHIA without $\gamma^* \to e^+e^-$) with the standard CMS geometry, 2) E/P for electrons and positions from Z decay.

In general, GFLASH provides a significantly faster calorimeter simulation than detailed GEANT4 based simulation. Figure 13 shows the CPU time (sec) and the size (kB) of output file per event for single electrons. In most beam energy range shown in the plot, the CPU time by GFLASH is around a factor 10 faster than that by GEANT4, which may be further improved optimizing the number of GFLASH EM hits used in the EM parameterization. However, timing for the EM shower may not be an issue in most physics processes since many other underlying hadrons are present in the event.

5.2 Hadron Shower Model

The GFLASH hadron shower model has been significantly improved recently and the relevant changes on both methodology of parameterization and tuned parameters are updated into CMSSW_3_1_X version of CMSSW. The hadron physics list QGSP_BERT of GEANT4 is used for tuning to the 2006 test beam data or any new development in the hadronic parameterization. Updates on the hadron shower model include 1) new parameterization for the lateral shower profile, 2) longitudinal parameterization by particle types, 3) parameterization for the HO response, 4) fine tuning to 2006 test beam (H2), 5) validations with physics processes ($t\bar{t}$ and QCD), and 6) performance measures (CPU and memory usage).

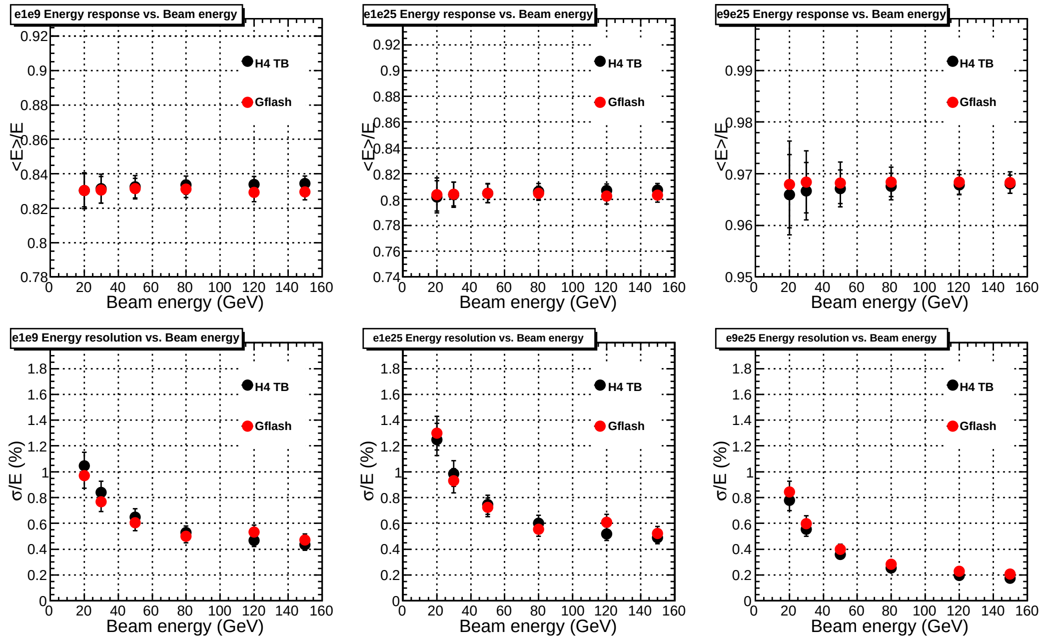

Figure 11: The mean energy response (top row) and energy resolution (bottom row) of e^- as a function of beam energy as measured in the test beam (black) and as predicted by GFLASH (red).

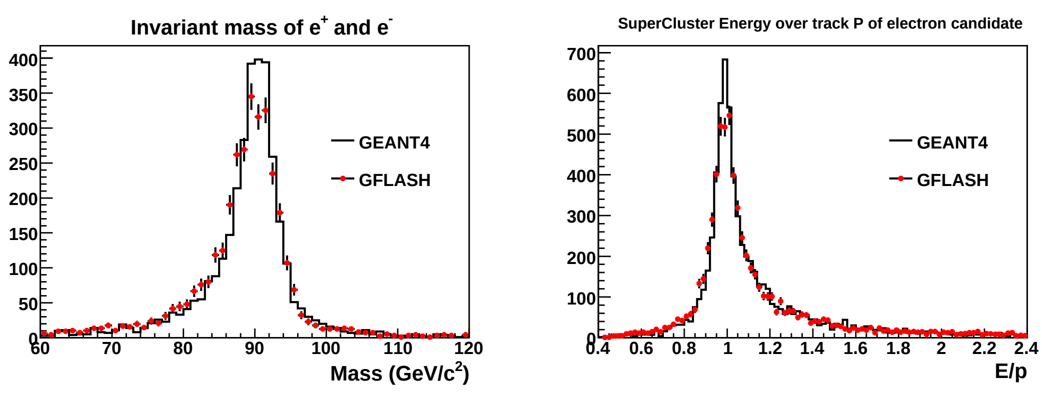

Figure 12: The invariant mass of the e^+e^- system and the mean energy response, E/P of electrons and positrons from $Z \to e^+e^-$ by GFLASH (red marks) and GEANT4 (black histogram)

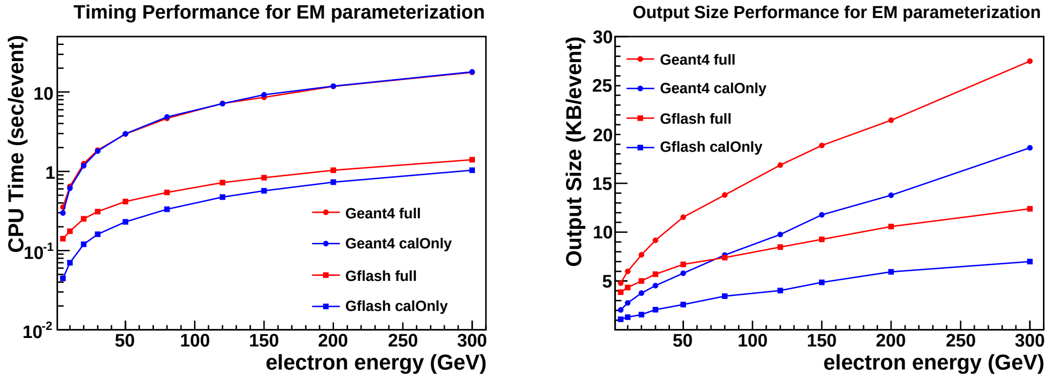

Figure 13: The computing performance measured with single electrons: the CPU time (sec) and the size of output file (kB) per event. The performances are shown both with the standard CMS geometry and with a calorimeter only geometry.

5.2.1 Hadronic Shower Parameterization

The hadron shower model has undergone significant changes in the code structure as well as parameterizations. Partly these changes reflect results of studies using the 2006 test beam data. For an example, a new log-normal parameterization instead of the Gaussian parameterization for the mean energy responses used the longitudinal profile, is introduced to reproduce the detailed energy shape of H2 test beam data better, especially in low momentum region ($E < 10$ GeV). In the code structure, GflashShowino class is introduced to centralize managements of the shower development along the shower depth. Also the hadron profile class adapts polymorphism of implementing one method of parameterization but virtual methods of loading parameters for different particles. In parameterization, the lateral profile is completely re-parameterized and the HO parameterization is newly added into the model.

The lateral profile is newly parameterized based on the probability density function (p.d.f) of the lateral energy distribution obtained from GEANT4. For hadron showers, the radial distribution of energy can be well modeled by

$$f(r) = \frac{2rR^2}{(r^2+R^2)^2}$$

where R is assumed to be a log-normally distributed with the mean (μ) and standard deviation σ related to the expected value of R (R_0) and its variance (V),

$$\mu = \ln R_0 - \sigma^2, \qquad \sigma^2 = \ln(V/R_0^2 + 1).$$

To parameterize R_0 and V statistically based on GEANT4, the radial p.d.f of $f(r)$, E_i^{jk} was constructed by using the i-th lateral interval (r_i) and the j-th depth for the k-th beam energy. Then R_0 and V are calculated using the built-in p.d.f.;

$$R_0^{jk} = \frac{2}{\pi}\sum_i E_i^{jk} r_i,$$
$$V^{jk} = \sum_i E_i^{jk}(r_i - R_0^{jk})^2$$

and R_0 and V are parameterized as the shower depth (z) and the energy in the following form,

$$R_0 = R_c(E) + R_s(E)z,$$
$$V = [S_c(E) + S_s(E)z]^2 R_0^2.$$

There is one parameterization for ECAL while multiple parameterizations are constructed for HCAL depending on the shower starting point. An initial set of reconstructed lateral parameters is validated comparing profiles of simulated hits of GFLASH to those of GEANT4. Figure 14 shows an example of the lateral profile of 20 GeV pions at different shower depths integrated over ϕ.

The average lateral leakage in relative η-tower and ϕ-tower will be tuned using *in-situ* collision data when available or the test beam data with a proper beam profile.

The hadron shower parameterization was used to work only for charged pions and now is extended for other charged particles. In the current implementation, there are three separate parameterizations for 1) $\pi^\pm$ and $K^\pm$, 2) p, 3) $\bar{p}$. Following the same procedure of parameterizations for pions, the initial set of parameters of longitudinal and lateral shower profiles for p and $\bar{p}$ are

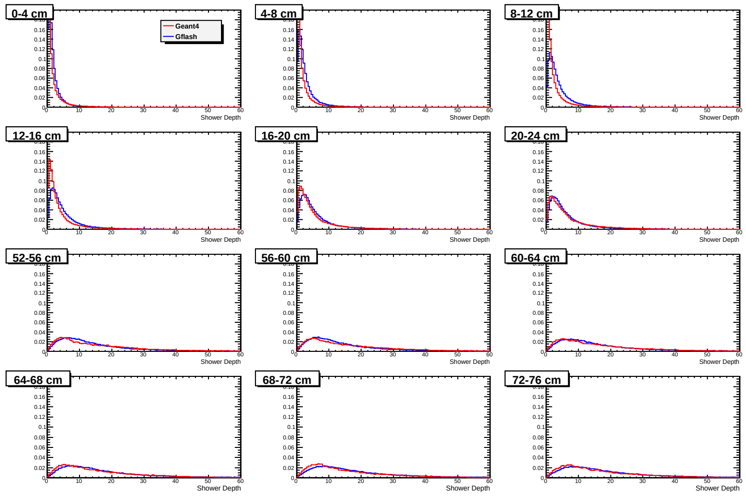

Figure 14: Lateral shower profile for 20 GeV pions in the CMS Calorimeter.

obtained using GEANT4. In principle, the shower profile of K^- passing through particle detectors is different from those of K^+ or $\pi^\pm$. For the moment, it is assume that K^- has the same profile as K^+.

In the central region, the (EB+HB) effective thickness is $(1.1 + 5.82/\sin\theta)\lambda_I$ of material, which may not provide sufficient containment for hadron showers, especially for energetic particles. The HO is designed to catch the shower leakage after HB, which may be important to improve the measurement of missing transverse energy ($\not\!\!E_T$). In the earlier version of GFLASH, the response of HO was handled by GEANT4 only for the case that hadron showers start later than 10 cm from the back of HB. If the shower starts earlier, the HO hit deposition was not simply attempted. In the current hadron shower model, the GFLASH envelope is now extended to include HO layers and a detailed hit deposition is also modeled to reproduced the HO response obtained from the test beam data ($E > 50$) or GEANT4 ($E < 50$). Since HO is an array of 10 mm thick scintillator tiles for one (or two) ring configuration, it is spatially not thick enough to parameterize hits as the usual approach and difficult to parameterize the energy shape and response. Even though depositing sensitive hits inside HO trays requires detailed treatment of the HO geometry, we assume that the longitudinal profile follows a simple form, $exp(-c \cdot x)$ where x is the shower depth from a reference point along the trajectory and $c^{-1} = 1.4 \sin\theta\lambda_{int}$. The profile also contains a weight factor associated with the shower starting point, $(s_{HO} - s_0)/(s_{HO} - s_{\mathrm{ref}})$ and a HO energy scale, $\propto (E_{inc} - E_{\mathrm{dep}})$ where E_{dep} is the total energy deposited in ECAL and HCAL (energy correlation). For the lateral parameterization of HO, the current hadronic lateral parameterization is temporarily used with a constraint that the maximum shower depth for the median of the lateral arm is 10 interaction length). If necessary, HO lateral parameterization based on the layer-by-layer response from GEANT4 may be developed. With the functional assumption, the mean energy scale and shape tuned to the H2 test beam or GEANT4 taking into account individual fluctuations based on the Poisson distribution. The parameter GflashHcalOuter is introduced to toggle the HO parameterization. Comparisons to H2 will be shown in the following subsection.

5.2.2 Tuning to the H2 Test Beam Data

To tune hadronic response of GFLASH, the reference response of the 2006 test beam data are used. For the nominal energy response, the result of GFLASH are compared to the sum of energy in EB (7×7 matrix), HB (4×3), HO (3×2) and their correlations. For the lateral shower, the energy in each η-tower or ϕ-tower are compared using tower-by-tower energy matrix of EB (9×9) and HB (4×3). Using the test beam geometry and the default configuration of GEANT4 simulation with GFLASH tuned on, we follow exactly same procedure that was used for tuning the GEANT4 simulation of the test beam. Calibration scales (EB = 1.02, HB = 120) are applied to calorimeter hit energy from GFLASH.

For each energy of each particle type, the energy shape is tuned with the first four momenta of 1) pure hadronic response (hadronic energy for $E_{ECAL} < 0.8$ GeV), 2) EM (ECAL) energy response 3) hadronic (HCAL) energy response. The total energy response is not attempted to be tuned, but used only as the final measure of tuning. Figure 15 shows examples of the energy shape tuning for 100 GeV π^- beam and 20 GeV p beam, respectively.

With the physics list QGSP_BERT_EML, the measured mean energy as the beam energy ($\langle E\rangle/P$) for all available π^- and p beams are shown in Figure 16 and Figure 17, respectively.

For tuning HO response to the test beam data, we again follow the standard test beam analysis with calorimeter hits from HcalOuter with additional weight factor 2.3 in 3×2 response and the estimated noise used in the HB analysis. Since the HO response was measured only in the runs with high energy beams ($\pi^- : 50, 100, 150, 200, 300$ GeV, p : 350 GeV and $\bar{p} : 50, 100, 150, 200$ GeV) we tune to the HO response to GEANT4 responses in the low energy region ($E < 50$ GeV). Figure 18 shows an example of very preliminary tuning of the HO response for 100 GeV π^- beam.

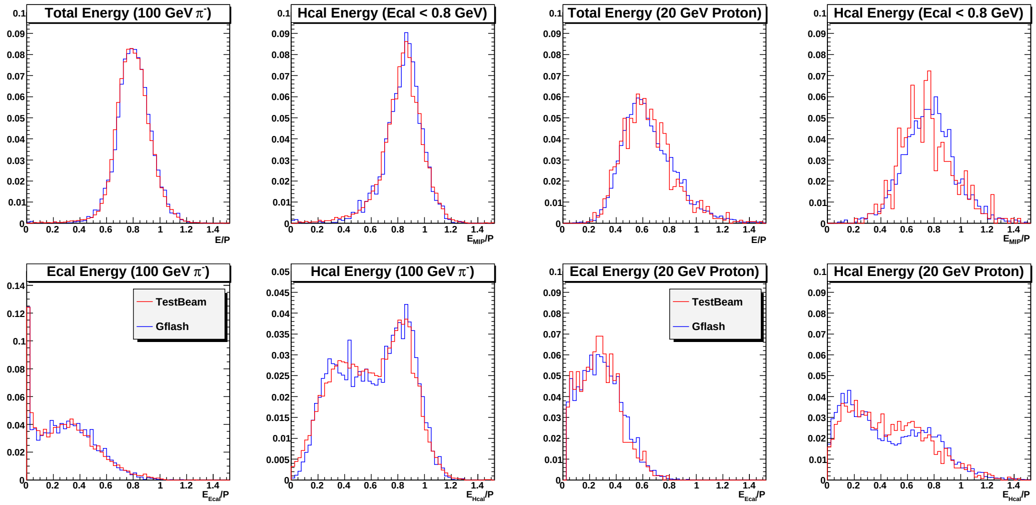

Figure 15: Distribution of energy measured in the combined calorimeter and separately in the ECAL and the HCAL for 100 GeV π^- (left) and 20 GeV p (right). Red lines correspond to test beam measurements and the blue lines are predictions from GFLASH.

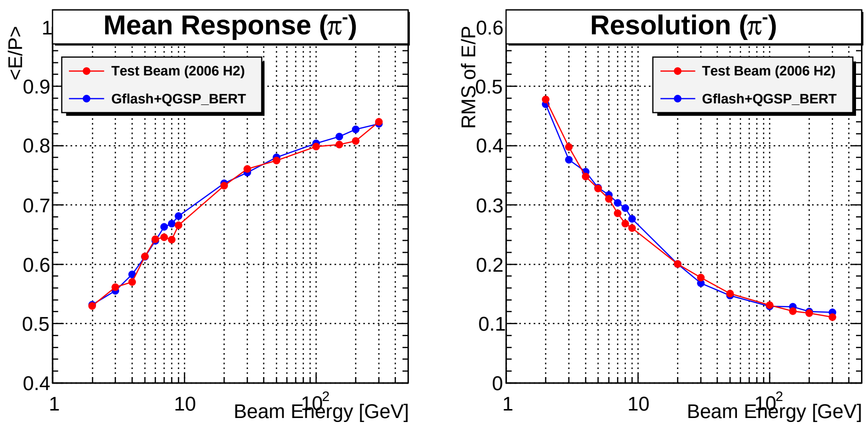

Figure 16: Mean energy response and resolution as a function of beam energy for pions measured in the test beam compared to GFLASH predictions.

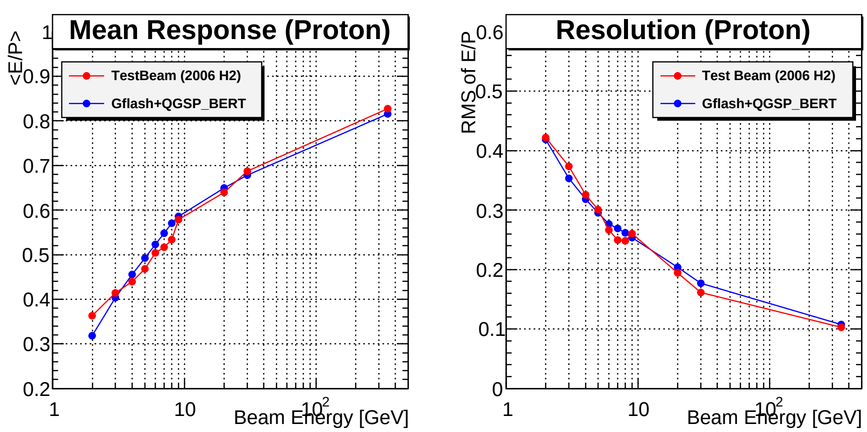

Figure 17: Mean energy response and resolution as a function of beam energy for protons measured in the test beam compared to GFLASH predictions.

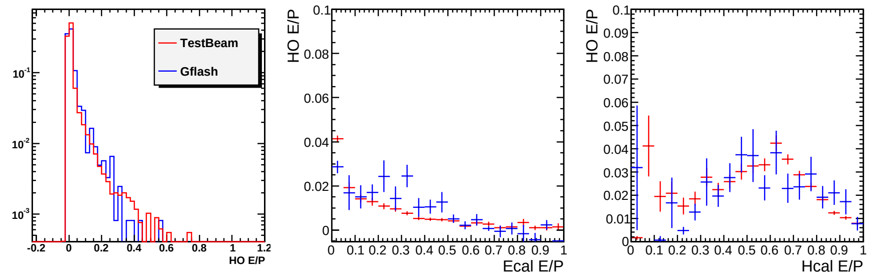

Figure 18: Comparison between tuned GFLASH predictions (blue) and test beam data (red) for energy measured in HO and also for mean energy deposit in HO as a function of energy measured in the ECAL and the barrel HCAL detector.

5.2.3 Validation and Performance

Figure 19 shows the CPU time per event and the size of output file from GFLASH and GEANT4. The CPU gain using GFLASH with respect to GEANT4 is around factor 2 at low energy (2 GeV) and factor 10 at high energy (300 GeV). GFLASH will not be triggered for the low momentum track ($p < 1$ GeV/c) that hardly reach to the face of calorimeter due to the strong magnetic field ($3.8T$). As a result, the CPU time is totally attributed to tracking particles inside the tracker by GEANT4.

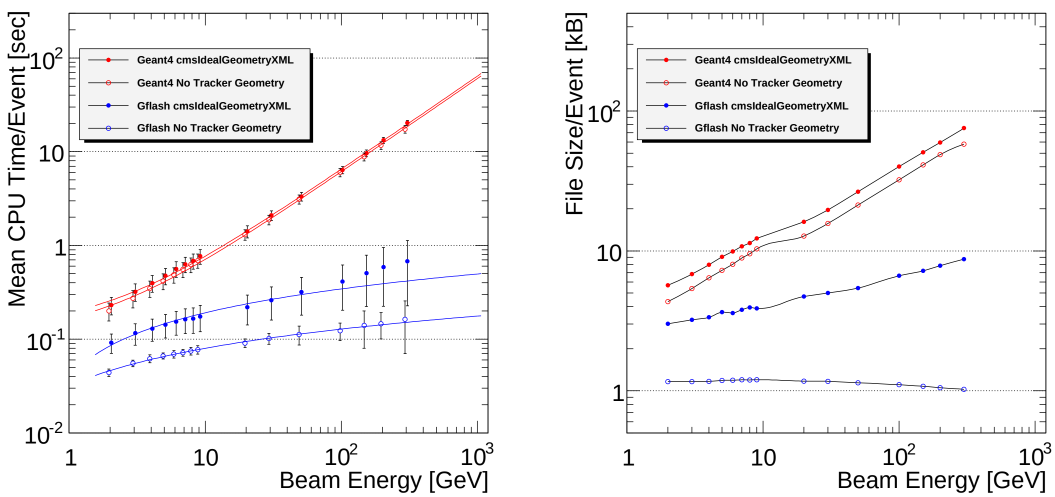

Figure 19: CPU performance and size of the output file for single pions.

In the general physics process, CPU gain will be moderate since there are two sources of irreducible CPU used for tracking low momentum tracks trapped in the tracker (handled by GEANT4 only) and secondaries produced inside the tracker (handled by both GEANT4 and GFLASH). Table 2 summarizes CPU performance for various physics processes.

The memory usage is also checked with the full chain of simulation. Compared to GEANT4, there is only marginal increment in both RSS and VSIZE as shown in Figure 20

6 Simulation of Forward Hadron Calorimeter

The CMS Hadronic Forward (HF) Calorimeter covers the pseudorapidity region of approximately $2.9 \leq |\eta| \leq 5$. It is composed of quartz fibers of two different lengths embedded in steel absorbers, with the PMT readout box assembly sitting behind the calorimeter at roughly $3 \leq |\eta| \leq 3.2$, see Figure 21. More information on HF is available in [18].

Abnormally high energy events were observed during the HF test beam in 2004. These events were present for both muon and pion beams, and although a very few events were also seen in electron runs, the electron events were rare enough that it was likely due to beam contamination. Detailed information on the test beam and analysis of these events are available in [19].

The steel absorber of HF is 165 cm long ($\sim 10\lambda_I$), and contains about 95% of hadronic longitudinal showers. However, some of the hadronic shower may leak out the back of HF. In addition, muons can pass directly through HF. When muons strike the PMT directly, or some component of the hadronic shower from pions hits the PMT, particles may pass through the PMT window. As the particles pass through the window, Cerenkov radiation is generated, and an abnormally large (several hundred GeV) signal is registered in the PMT.

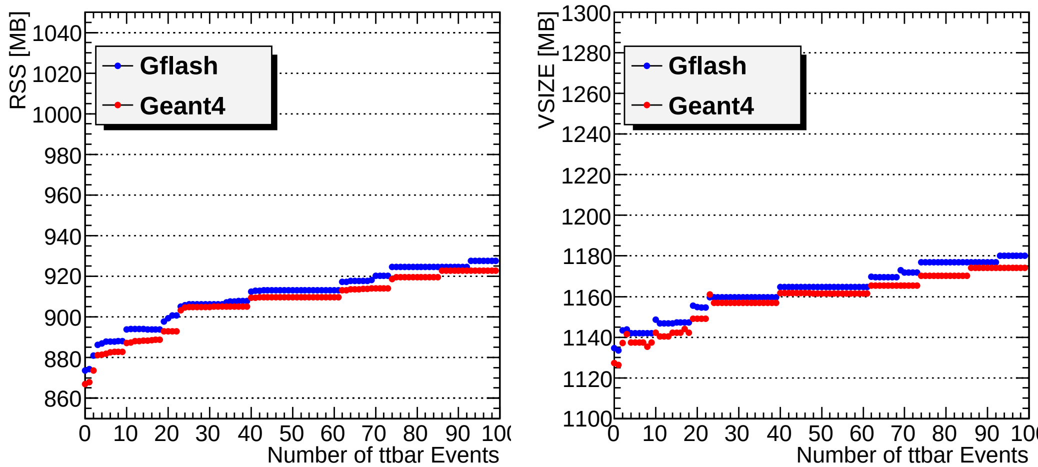

Figure 20: Memory usage in simulating $t\bar{t}$ events using GEANT4 and GFLASH as a function of number of events. Resident memory is shown on the left plot and the virtual size is on the right.

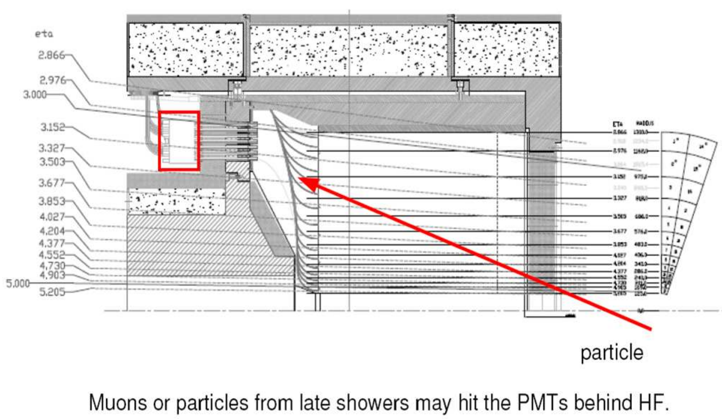

Figure 21: Diagram of HF. The readout box is located at $3 \leq |\eta| \leq 3.2$. Particles hitting the PMTs may cause anomalously large signals.

Process	GEANT4	GFLASH	Tracker Only
MinBias	9.8	9.2	5.3
$t\bar{t}$	84.0	60.5	26.1
QCD_Pt_80_120	70.4	54.2	23.4
QCD_Pt_3000_3500	322.9	73.9	16.4

Table 2: CPU time (measured in second/event) used in simulating events of various processes.

6.1 Simulation of PMT Events using CMSSW

The abnormal events in HF are simulated by modeling the PMT windows inside the full simulation setup and treating these as sensitive detectors. Production runs of CMS detector simulation utilize shower libraries for hadronic as well as electromagnetic showers. In this approach any hadron, electron, positron or photon entering the forward calorimeter volume is removed and it is substituted by a number of photo-electrons which are obtained from a pre-generated shower kept in a library. This approach needs to be modified to take care of shower leakage in case of hadronic showers.

A new approach is followed to do the parametrization of showers in HF. The electrons, positrons or photons are treated as before using the shower library while the hadrons are transported using standard GEANT4. There are different options for electromagnetic component of the hadron showers: (1) to be transported using GEANT4, (2) to be replaced using the shower library or deposited at a single point; (3) to be parametrized using GFLASH approach.

In the current simulation the PMT windows are incorporated as disks of uniform thickness. The windows of the PMTs currently installed on HF are plano-convex and the varying thickness will have an impact in the distribution of Cerenkov photons produced in the windows.

6.2 Long and Short Fiber Energies

The simulated results for the number of photoelectrons seen by the long (depth 1) and short fibers (depth 2) are shown in Figure 22 for 100 GeV pions. The simulated number of photoelectrons is seen to be low for pions as compared to the test beam data and work is under way to improve the understanding there.

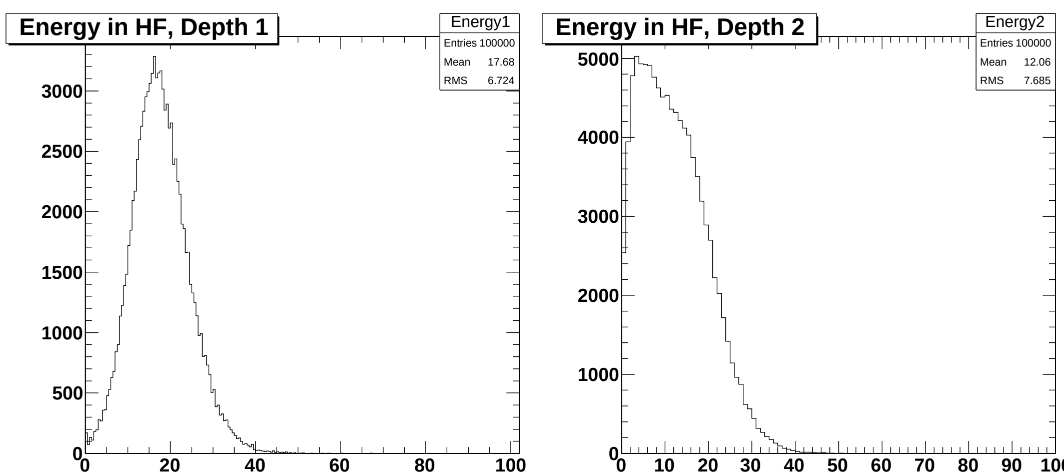

Figure 22: Number of photoelectrons in the long and short fibers (depths 1 and 2, respectively) for 100 GeV pions.

6.3 Signals from Punchthrough

In the simulation, hits are seen in the PMTs for both 150 GeV muons and 100 GeV pions (Figure 23), in agreement with the data from the Test Beam 2004 analysis. For both muons and pions, there is a peak at about 50 photoelectrons. In datasets with 100,000 simulated events, 19.9% of muon events have PMT hits, while 0.9% of pion events have PMT hits. Note that the numbers in Figure 23 indicate the number of PMT windows which have hits.

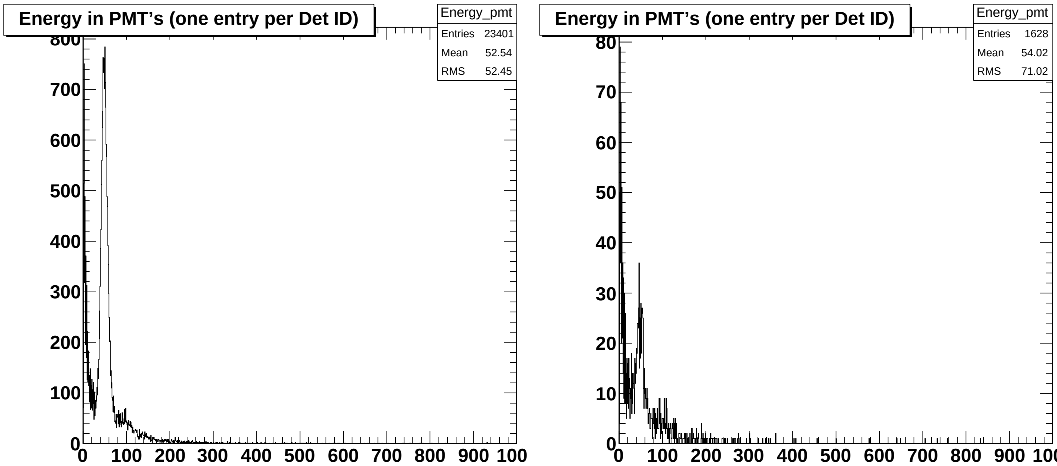

Figure 23: Number of photoelectrons in PMTs for 150 GeV Muons and 100 GeV pions.

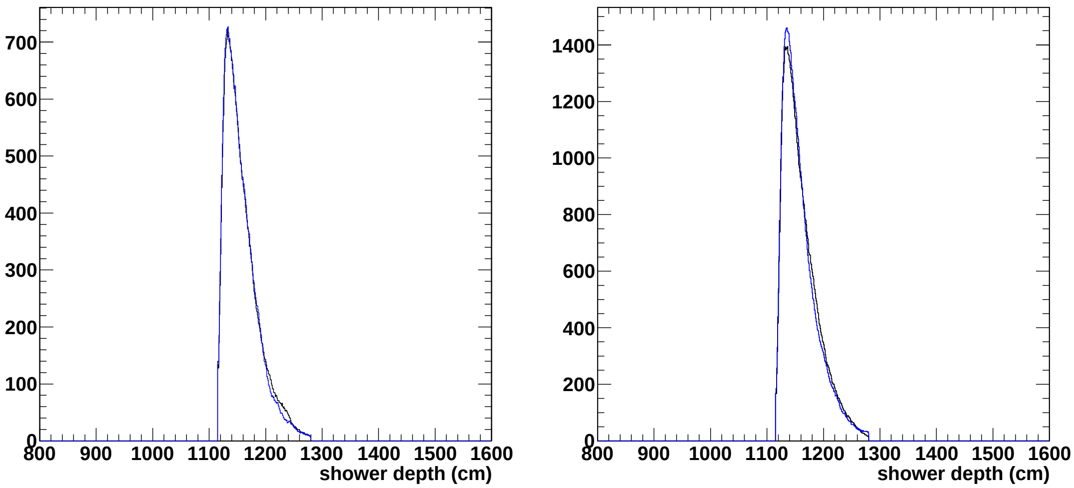

Figure 24: Longitudinal shower profiles of charged pions of 50 GeV (left plot) and 100 GeV (right plot) produced using the shower library (black) and the GFLASH (blue) options.

Particles traveling through the HF absorber travel at close to the speed of light, while the light signal through the HF fibers travels at a reduced speed that is dependent on the index of refraction of the fiber material. Signals resulting from PMT hits will thus occur at an earlier time than the signal from particles losing energy within the HF absorber. For both muons and pions, the PMT hit times peak at 46-47 ns, while normal hits occur several ns later. This timing structure can be used to filter out the PMT hits.

6.4 GFLASH for the HF Shower Simulation

The successful application of GFLASH in other parts of the calorimeter, especially EB and HB, has led to its adaptation for the simulation of HF. As has been mentioned earlier, only the electromagnetic part of the shower is either parametrized or substituted by a pre-generated shower from a shower library. The same parametrization as used for the central detectors is used here. The list of particles which are substituted through the parametrization includes π^0 in addition to $e^{\pm}$ and γ. Simulated energy deposits are distributed between long and short fibers depending on the z-position of the hit.

Samples of 5000 charged pions are simulated at 50 GeV and 100 GeV using the GFLASH option. The longitudinal and lateral shower profiles of these charged pions are compared to those obtained using the shower library option for the electromagnetic part of the shower. Figures 24 and 25 show the longitudinal and lateral shower profiles respectively for the two samples of charged pions. As can be seen from the figures, the GFLASH parametrization is in good agreement with the results from the shower library approach.

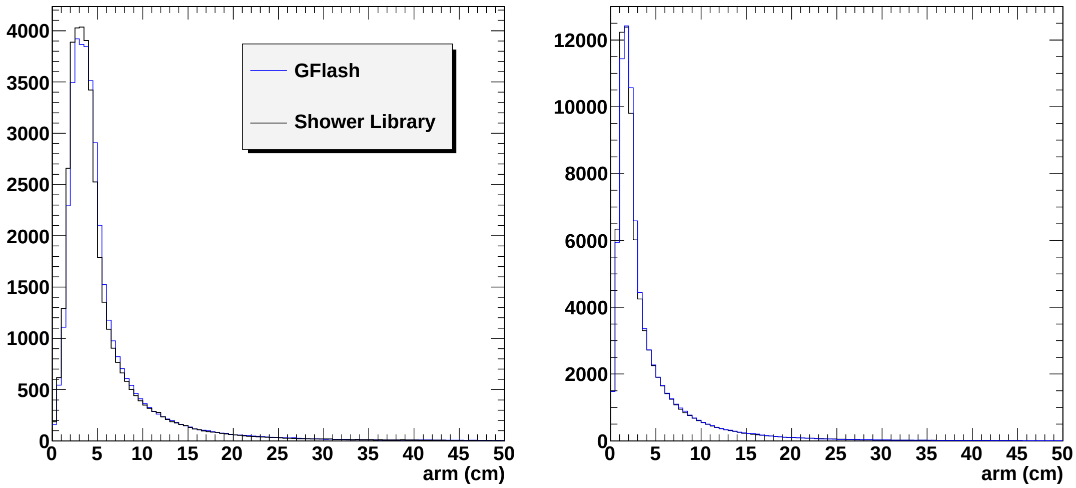

Figure 25: Lateral shower profiles of charged pions of 50 GeV (left plot) and 100 GeV (right plot) produced using the shower library (black) and the GFLASH (blue) options.

Time Summary	GEANT4	Shower Library	Parametrization using	
			GFLASH	Shower Library
50 GeV pions				
Minimum	0.269	0.015	0.041	0.031
Maximum	5.411	2.016	2/943	2.273
Average	2.139	0.124	0.271	0.269
100 GeV pions				
Minimum	0.312	0.050	0.030	0.049
Maximum	7.553	5.186	6.122	7.800
Average	4.402	0.128	0.455	0.454

Table 3: Summary of the CPU time usage for different options of simulation in HF for 50 and 100 GeV pions.

Hadronic showers in the HF can be generated with 4 different options: (a) using GEANT4 for the complete shower generation, (b) substituting the incident hadron using a shower library, (c,d) using GEANT4 for hadronic component and (c) shower library or (d) GFLASH for the electromagnetic component. the relative performance of the 4 approaches are summarized in Table 6.4 for 50 and 100 GeV pions. It is clear that usage of shower library to replace the complete hadronic shower is the most attractive approach from the point of view of performance, but it will lack in explaining the punch through effect. Options (c) and (d) are equally performing and can be used to explain abnormal events in HF.

7 Conclusions

Significant improvements have been made to the calorimeter simulation resulting in better agreement between simulation and test beam results.

- Improvements to the EM and HAD packages to GEANT4 have been implemented in the simulation starting with CMSSW_3_1_X.
- A tuned physics list is used (QGSP_BERT_EML) for the CMS simulation.
- Improved parameterizations for GFLASH have been implemented.

- The execution time has been improved by not simulating processes that occur outside the CMS digitization window and would not contribute to the physics signal and by usage of *ApplyCuts* option of the GEANT4 electromagnetic package.
- Code optimization has led to significant improvements to the execution time and has reduced the memory required used.
- A simulation of PMT punch through events has been developed for HF.
- A GFLASH parametrization has been extended to HF.

The lateral shower profile for electromagnetic showers are described to an accuracy better than 0.5% and the agreement between data and Monte Carlo is better than 3% for mean hadronic response. The computing performance of the full simulation regarding CPU, memory and data size are now in well acceptable limits. GFLASH parametrization is now ready to be used for full simulation. More detailed simulation of the forward region is now available with a very little penalty for performance.

Collecting large samples of isolated charged particles will be essential for tuning the response of the MC simulation to agree with Data. Isolated charged particles are important for several calibration purposes, for instance calorimeter calibration, jet calibration, etc. Each application has different needs and requires samples of isolated charged particles with different momenta ranges and isolation criteria. A common strategy for collecting isolated charged particles is being worked upon.

References

[1] GEANT4: S. Agostinelli *et al.* , Nuclear Instruments and Methods **A506** (2003) 250;
J. Allison *et al.* , IEEE Transactions on Nuclear Science **53** (2006) 78.

[2] J. Birks, Theory and Practice of Scintillation Counting, Pergamon Press, 1964; J. B. Birks, Proc. Phys. Soc. **A64** (1951) 874.

[3] G. Grindhammer, M. Rudowicz, and S. Peters, *The Fast Simulation of Electromagnetic and Hadronic Showers*, Nuclear Instruments and Methods **A290** (1990) 469.

[4] S. Abdullin *et al.* , CMS Calorimetry Task Force, *Calorimetry Task Force Report*, CMS-NOTE 2008-025.

[5] V. Ivanchenko *et al.* , *Recent Progress of Geant4 Electromagnetic Physics and Readiness for LHC Start*, Progress of Science (ACAT08) 108.

[6] V. Ivanchenko *et al.* , *Hadronic Physics in Geant4: Improvements and Status for LHC Start*, Progress of Science (ACAT08) 111.

[7] J. Apostolakis *et al.* , Journal of Physics Conference Series **119** (2008) 032004.

[8] D. H. Wright *et al.* , AIP Conference Proceedings **896** (2007) 11.

[9] A. Ribon *et al.* , *Geant4 Physics Lists: improvements and status*, contribution to IEEE NSS 2008 conference, NSS N02-89, to appear in the proceedings.

[10] A. Schaelicke *et al.* , *Improved description of bremsstrahlung for high-energy electrons in Geant4*, contribution to IEEE NSS 2008 conference, NSS N37-1, to appear in the proceedings.

[11] A. Bogdanov *et al.* , IEEE Transactions on Nuclear Science **53** (2006) 513.

[12] L. Urban, *A multiple scattering model in Geant4*, Preprint CERN-OPEN-2006-077 (2006).

[13] J. M. Quesada *et al.* , *Improvements of preequilibrium and evaporation models in Geant4*, contribution to IEEE NSS 2008 conference, NSS N02-97, to appear in the proceedings.

[14] P. V. Degtyarenko, M. V. Kosov and H. P. Wellisch, European Physical Journal **A8** (2000) 217.

[15] G. Baiatian *et al.* , *Energy Response and Longitudinal Shower Profiles Measured in CMS HCAL and Comparison With Geant4*, CMS-NOTE 2006-143.

[16] S. Abdullin *et al.* , European Physical Journal **C60** (2009) 359.

[17] P. Elmer, *CMS Software Performance Strategies*, contribution to CHEP09, to appear in the proceedings.

[18] G. L. Baiatian *et al.* , *CMS Physics TDR: Volume I (PTDR1), Detector Performance and Software*, CERN-LHCC-2006-001 (2006).

[19] S. Abdullin *et al.* , *Design, Performance, and Calibration of CMS Forward Calorimeter Wedges*, European Physical Journal **C53** (2008) 139.