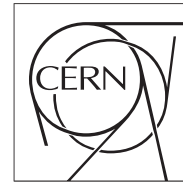


The Compact Muon Solenoid Experiment
Conference Report

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Validation of Geant4 Physics Models with LHC Collision Data

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Abstract

The CMS experiment has designed a strategy to validate Geant4 physics models using collision data from the LHC. Isolated charged particles are measured simultaneously in the tracker as well as the calorimeters. These events are selected using dedicated triggers and are used to measure the response in the calorimeter. Measurements of mean response, resolution, energy sharing between the electromagnetic and hadron calorimeters, shower shapes are directly compared with predictions from the various physics models in the Geant4 description. The broad range of energies available in collision data allows stringent tests of the accuracy of the models in reproducing the observed distributions.

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1 Introduction

CMS experiment has been validating the physics models of GEANT4 [1, 2] using an elaborate set of measurements in dedicated test beam setups. The single particle response in the prototype CMS calorimeters has been measured in these experiments using hadron beams over a large range of energy. Measurements of the single particle response from collision data at the Large Hadron Collider are also used in testing the predictions of GEANT4.

The CMS calorimeter system consists of Electromagnetic (ECAL) and Hadronic (HCAL) calorimeters. The ECAL uses an array of lead tungstate crystals providing an excellent measurement of the response of electrons, positrons and photons. The HCAL is situated behind the ECAL and is constructed of alternating layers of brass absorber and plastic scintillator which sample the energy response of charged and neutral hadrons. This composite system has a non-linear response for low energy hadrons due to the non-compensating nature of both these detectors and to the non-matching electron/hadron response between them. CMS has an all silicon tracking device in front of the calorimeter system. This, together with the large magnetic field provided by the Superconducting solenoid, measures momenta of the charged particles with a high degree of accuracy.

Isolated charged particles can be used to validate various aspects of the shower code in GEANT4. The momenta of these particles are well measured by the tracker. The electron candidates are used in testing the lateral profile of electromagnetic showers. Response and resolution for charged hadrons can be compared to predictions from GEANT4. For these studies, one needs to ensure that there is no contamination due to other nearby particles.

CMS experiment has observed some isolated abnormal energy deposits in the calorimeter system. GEANT4 physics models are also used to understand the source of these events on a qualitative as well as on a quantitative basis.

2 Response Measured at the Test Beam

Dedicated measurements were carried out with prototypes of the CMS calorimeter in the test beam facility at CERN [3]. Two production wedges of the barrel hadron calorimeter (HB), one prototype module of the hadron endcap (HE), and eighteen trays of the outer hadron calorimeter (HO) were exposed to hadron beams in the H2 beam line of the Super Proton Synchrotron (SPS). Two sets of runs were used to tune the simulation of hadronic showers. The runs during 2004 used a prototype electromagnetic calorimeter assembled by putting together 49 lead tungstate crystals in a matrix of 7×7 . During 2006, this matrix was replaced by a super-module of the barrel electromagnetic calorimeter (EB). The platform holding the modules could be moved along the ϕ and η directions allowing the beam to be directed onto any tower of the calorimeter in order to mimic a particle trajectory from the interaction point of the CMS experiment. Monochromatic secondary and tertiary beams were used having a momenta between 2 and 350 GeV/c. Auxiliary beam counters were used to select pure beam interactions.

Both calorimeters were calibrated using 50 GeV/c electron beams. The energy response, resolution, and shower profiles were measured for different beam momenta. Figure 1 shows plots of the energy response (ratio of the energy measured in the calorimeter to the incident momentum of the beam) for incident π^- and proton beams as a function of momentum. Four different physics lists QGSP_BERT_EML, QGSP_FTFP_BERT_EML, QGSP_BERT_CHIPS_EML and FTFP_BERT_EML are used in these comparisons. The first three physics lists utilize the QGSP model of GEANT4 to describe the high energy interaction of hadrons while the fourth list uses the FTFP model. The Bertini cascade code is used for the low energy interactions of pions, kaons, protons and neutrons. The intermediate energy component is described by LEP, FTFP and CHIPS in the first three physics lists while the fourth list does not require any different physics model for the intermediate energy region. As can be seen from the figure, the Monte Carlo simulation agrees with the data to a level of 3% for π^- . For low energy protons, the difference become larger ($\sim 10\%$) at low energies.

3 Electromagnetic Showers

LHC collision data are used in commissioning various components of the CMS detector. In that process, emphasis is given to the set of observables which are directly dependent on GEANT4 shower code. Isolated electromagnetic showers are selected from the data (and also from Monte Carlo samples) on the basis of matching energy and momentum measurements and energy sharing between ECAL and HCAL. Widths of such showers in the electromagnetic calorimeter are compared between data and Monte Carlo.

Figure 2 shows a comparison of widths of electromagnetic shower (in the non bending plane) between data and Monte Carlo. The width is narrower in the barrel calorimeter which corresponds to lower noise level. The Monte Carlo distributions match very well with those observed in the data.

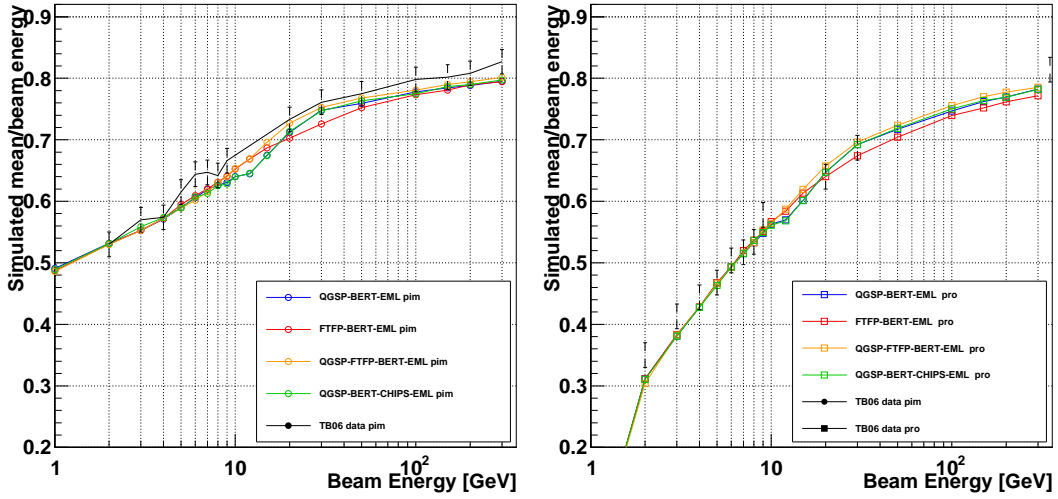


Figure 1: Mean energy responses for π^- (left) and protons (right) as a function of incident particle momentum. Predictions of the four physics lists QGSP_BERT_EML, QGSP_FTFP_BERT_EML, QGSP_BERT_CHIPS_EML and FTFP_BERT_EML are also shown.

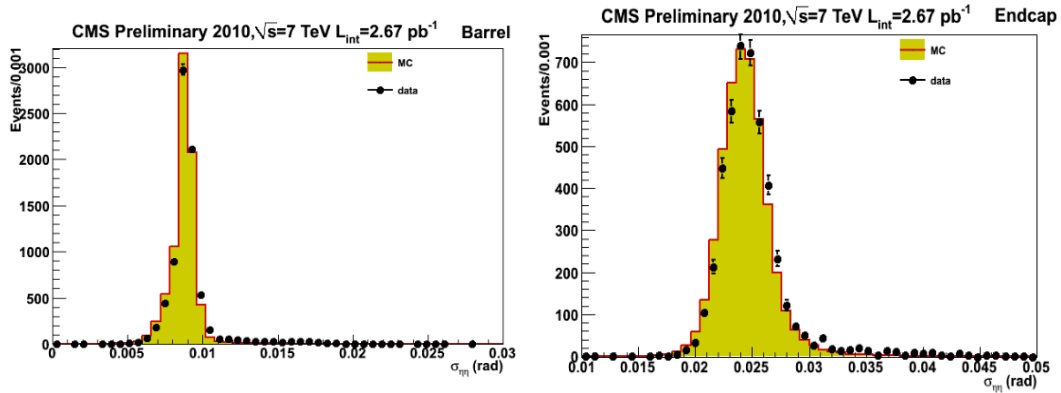


Figure 2: Comparison of widths of electromagnetic showers (along η direction) between data and Monte Carlo in the barrel and in the endcap electromagnetic calorimeter.

4 Isolated Hadrons from Collision Data

Isolated charged particles are selected from the data collected using the minimum bias trigger (with the help of the beam scintillators). As the luminosity increases, the minimum bias trigger are highly suppressed by prescaling the rate. This makes this path less useful for the collection of isolated charges particles. The high level trigger provides a trigger path of minimum bias events and this is used in the high luminosity runs.

Events are selected to have only one well reconstructed primary vertex which is close to the nominal interaction point. Good track candidates are then selected and tested if these are well isolated from other charged and neutral particles. Tracks are first selected on the basis of closeness of the track to the primary vertex in the transverse (xy) plane as well as along the beam axis, the χ^2 of the track fit and number of tracker layers used in the measurements. It is important that the tracks do not interact before reaching the calorimeter surface. This is checked by looking at the number of missing hits in the inner and outer hit patterns of the reconstructed hits. All tracks with missing hits in the inner and outer hit patterns are rejected.

The tracks are extrapolated to the calorimeter surface and the calorimeter cell corresponding to the impact point is identified. A matrix of $n \times n$ cells, corresponding to the granularity of the calorimeter cells, around the impact point is defined as signal zone and consequently a matrix of $N \times N$ (with $N > n$) is defined as isolation zone. From a study of lateral shower profile of hadrons in the test beam and in simulation, signal zone is chosen to be a matrix of 11×11 crystals for the ECAL and 3×3 towers for the HCAL.

The extrapolated cell needs to be well isolated from all other charged and neutral particles. Isolation with respect to charged particles is obtained by extrapolating other charged particles (selected with slightly looser criteria) and examining if the extrapolated point is within a matrix of 31×31 crystals for the ECAL and 7×7 towers for the HCAL. Isolation against neutral particles is assured from a study of energy deposited in an annular region around the signal region. The energy in the annular region in the ECAL (between 15×15 and 11×11 crystals) is required to be smaller than 0.5 GeV and in the HCAL (between 7×7 and 5×5 cells) is required to be less than 3 GeV. The purity of the signal is found to be better than 90% from a study of Monte Carlo sample of minimum bias events.

Energy response is measured as the ratio of energy of the isolated track in the signal zone to the momentum of the track. Comparisons are done using the full spectrum of the energy responses or using the arithmetic mean of the distributions. Measurements are done for the mean energy response as a function of the track momentum in the barrel ($|\eta| < 1.131$), the endcap ($1.653 < |\eta| < 2.172$) and the transition ($1.131 < |\eta| < 1.653$) region. The granularity of the detectors and background conditions are different in these three regions.

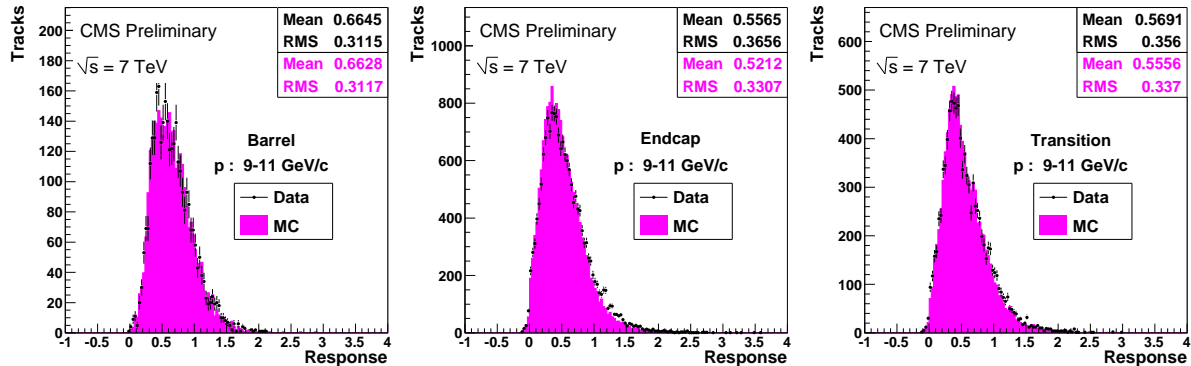


Figure 3: Response measurements as a function of track momentum in three different regions of the calorimeter. Data distributions for tracks with momentum between 9 and 11 GeV/c are compared with results from the simulation.

Figure 3 shows the combined calorimeter response for tracks of momenta between 9 and 11 GeV/c. These measurements, done in the three different η regions, are compared with the Monte Carlo. There is a reasonable agreement in the barrel. The figure shows a slightly broader peak in the data in the endcap region (see the middle plot in Figure 3) suggesting possible discrepancy in the scale setting for the endcap region.

Figure 4 shows the measurements of mean calorimeter response of isolated tracks as a function of the track momentum. The same measurements from data and minimum bias Monte Carlo sample are shown on the same plot. While the agreement is quite consistent between data and Monte Carlo in the barrel and in the transition region, there is some systematic difference in the endcap region.

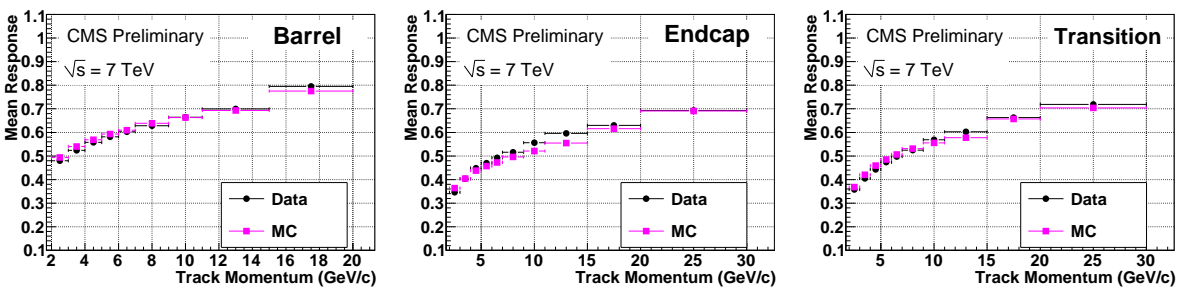


Figure 4: Mean response measurements as a function of track momentum in three different regions of the calorimeter. Monte Carlo prediction is compared with the data. The three columns refer to barrel (left), endcap (middle) and transition region (right). The top row is $z+$ and the bottom row is $z-$.

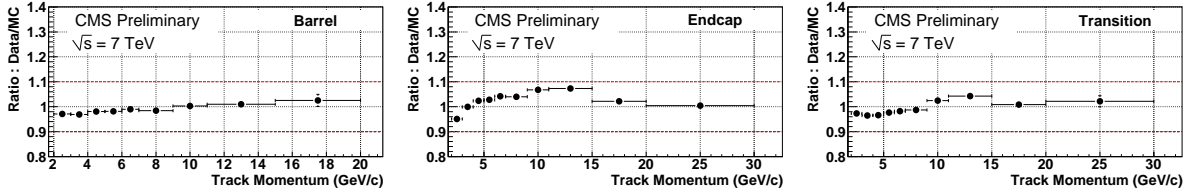


Figure 5: Ratio of mean response measurements between data and Monte Carlo as a function of track momentum in three different regions of the calorimeter. The three columns refer to barrel (left), endcap (middle) and transition region (right).

Figure 5 shows the ratio of the response between data and Monte Carlo as a function of track momentum in the three calorimeter regions. As can be seen from the figure, the agreement in the barrel region is well within 2-3%. In the transition region, the agreement is at the level of $\pm 5\%$ while in the endcap, the ratio is systematically above 1.

5 Abnormal Calorimeter Hits

Rare but anomalous high energy deposits are observed in the calorimeters. Isolated single crystal hits are seen in the barrel ECAL calorimeter (EB) and long tails are observed in the distributions of energy deposit in the forward hadron calorimeter (HF). These tails are seen in either short or long fibres. Figure 6 shows evidence of two types of anomalous energy deposits. The plot on the left shows distributions of energy deposits in the barrel electromagnetic calorimeter where a clear excess is seen at the high energy tail. The plots on the right show the correlation of energy deposits between the long and the short fibres where large tails are seen with only one of the fibres fired.

Filters based on topological properties and timings are developed to remove these abnormal hit events. These tools are very effective in eliminating the abnormal hits from the data sample. For example, the left plot of Figure 6 shows the data distribution after the noise filter where one observes good agreement between data and Monte Carlo. However, one needs to understand the source of the hits and the effect of these in a crowded environments.

Anomalous crystal hits in the barrel electromagnetic calorimeter are identified to be due to energy deposits in the thin silicon layers of the APD's (induced by heavily ionizing particles produced in the epoxy layers by neutrons). Anomalous hits in the forward hadron calorimeter are due to Cerenkov light produced by the penetrating component of hadron showers in the fibres and in the windows of the Photo Multiplier tubes sitting behind the absorber.

The silicon layers in the APD and the PMT window material (together with the fibre bundle behind the HF absorber) are treated as sensitive detector in the simulation. An improved neutron transport code is used from GEANT4. The resulting simulation code could explain the distribution sensitive to spikes in EB. This variable which compares the energy of 2×2 matrix versus the energy in the trigger crystal has a spike in the data which could not (could) be explained by Monte Carlo without (with) inclusion of energy deposit in the APD (see Figure 7).

The showers in the forward hadron calorimeter are produced by transporting all hadrons within HF using GEANT4

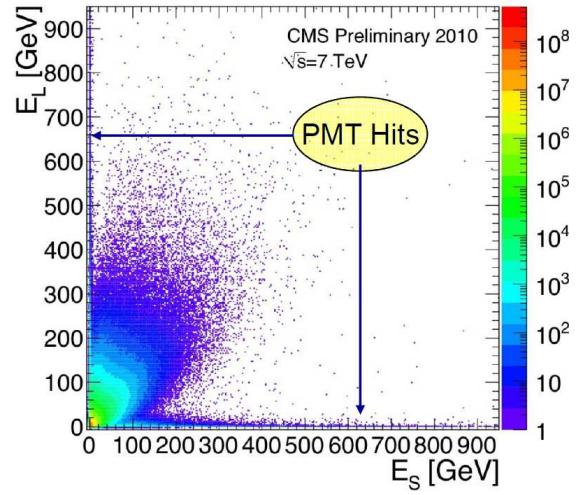
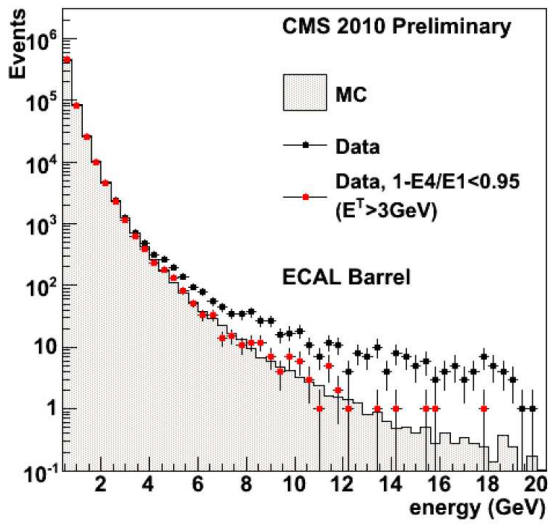


Figure 6: Distributions of energy deposit in the barrel ECAL (left) compared to the prediction of Monte Carlo. The red points refer to the data after the application of the noise filter. The plot on the right refers to a scatter plot of energy deposits in the long and in the short fibres.

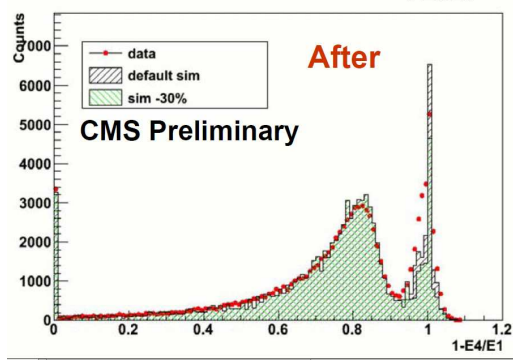
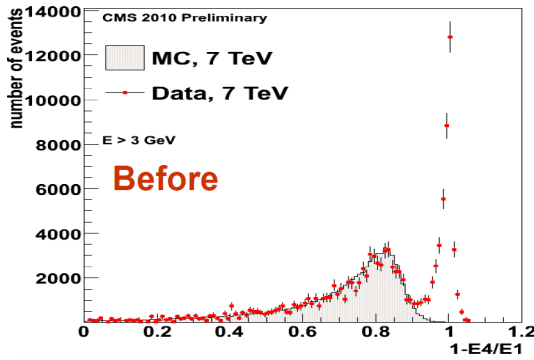


Figure 7: Comparison of data and Monte Carlo for the ratio of energy deposit in a 2×2 crystal matrix to the energy in the most energetic crystal. The Monte Carlo distributions are obtained without (left plot) and with (right plot) the inclusion of energy deposits in the thin silicon layer of the APD.

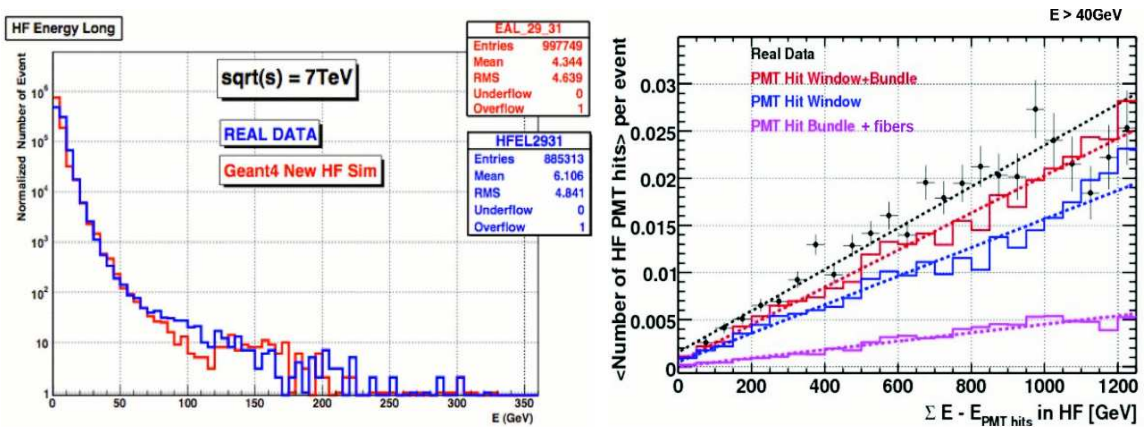


Figure 8: The left plot refers to energy measured by the long fibres in HF for collision data at 7 TeV compared to Monte Carlo predictions with hits produced in the absorber, PMT window and fibre bundles. Plot on the right shows the correlation of mean number of PMT hits with energy in the absorber.

hadronic models. The electromagnetic components of showers in HF are replaced using a parametrization. The resulting simulation code explains the measured energy spectrum as well as anomalous hit rates in HF rather well (see Figure 8).

6 Summary

CMS has been validating the physics models inside GEANT4 using its test beam as well as collision data. Several physics lists inside the most recent version of GEANT4 provide good agreement of the energy response, resolution of π^\pm and protons. More work is needed to improve the physics for K^\pm , \bar{p} and hyperons.

Electromagnetic physics in GEANT4 gives a good description of shower shapes for electron and photon candidates in the collision data. Isolated charged particles are used to measure calorimeter response of hadrons as a function of particle energy. These are used to compare data with Monte Carlo predictions. There is an impressive agreement between GEANT4 predictions and data in the barrel region. The agreement worsens in the endcap region. This is currently under investigation.

Rare anomalous hits in the calorimeter can be explained using the present transport codes in GEANT4. Thus bulk as well as rare events can be handled by the physics models within GEANT4.

References

- [1] GEANT4: S. Agostinelli *et al.*, Nuclear Instruments and Methods **A506** (2003) 250.
- [2] J. Allison *et al.*, IEEE Transactions on Nuclear Science **53** (2006) 278.
- [3] Energy Response and Longitudinal Shower Profiles Measured in CMS HCAL and Comparison with GEANT4, G. Baiatian *et al.*, CMS Note-2006/143.