Fermilab FERMILAB-CONF-06-473-E

CMS validation Experience: Test-beam 2004 data vs Geant4

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Abstract. A comparison between the Geant4 Monte-Carlo simulation of CMS Detector's Calorimetric System and data from the 2004 Test-Beam at CERN's SPS H2 beam-line is presented. The overall simulated response agrees quite well with the measured response. Slight differences in the longitudinal shower profiles between the MC predictions made with different Physics Lists are observed.

Keywords: Monte-Carlo Simulation, Geant4 Validation, Physics Lists, Calorimeters, Test-Beam, Hadronic Showers, Longitudinal Shower Profiles
PACS: 29.40.Vj,07.05.Tp

INTRODUCTION

A series of Test-Beam measurements has been performed on the calorimetric system of CMS over the last few years in order to optimize the design and study its performance. Detailed Monte-Carlo simulations of the test-beam configuration in 2004 have been made and the results compared with the test-beam measurements. Presented here is a comparison between the results from the 2004 Test-Beam and the Geant4-based Monte-Carlo simulations performed at the same time.

The CMS detector

The Compact Muon Solenoid detector (CMS)[1] is one of the general purpose detectors for the Large Hadron Collider (LHC) that is being assembled at CERN. A cross-section of the detector (Fig.1) identifies the major sub-systems of the apparatus. The Pixel Detector, Silicon Tracker, Preshower, Electromagnetic Calorimeter (ECAL) and Hadronic Calorimeter (HCAL) are positioned inside the superconducting solenoidal magnet generating the strong 4T magnetic field. Outside of the solenoid are the Muon Detectors embedded into the magnet's return yoke, and the Very-Forward Calorimeters.

Following the cylindrical symmetry of the apparatus, most sub-detectors consist of a Barrel and End-cap parts, labeled with a "B" or "E" respectively in further references.

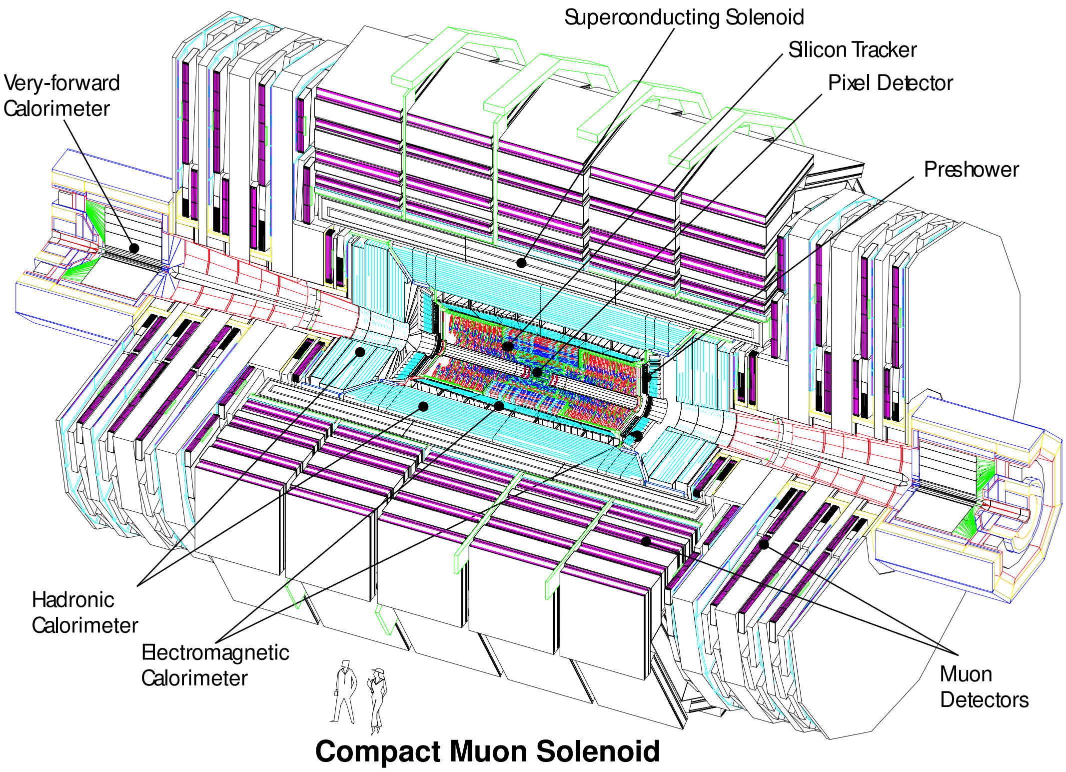

FIGURE 1. CMS - detector subsystems

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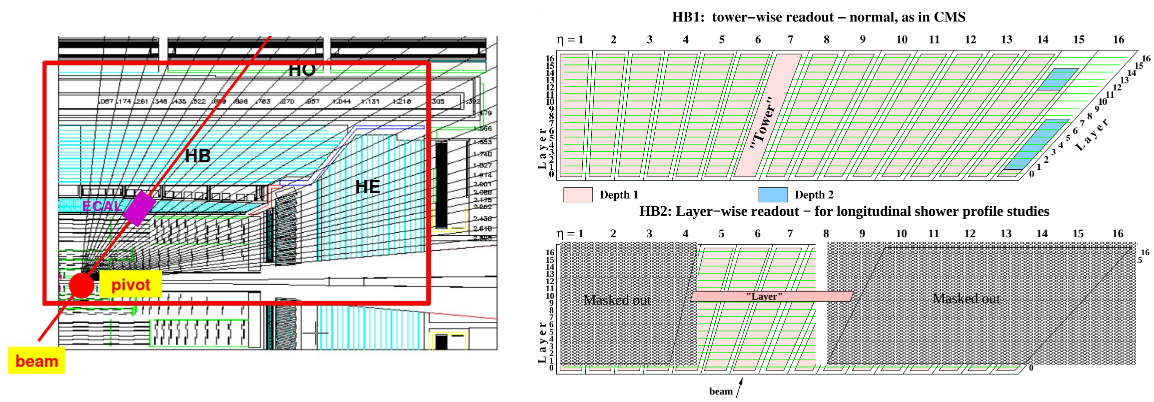

a) b)

FIGURE 2. a) Calorimetric systems present on main moving table of Test-beam 2004 (framed). Pivot point corresponds to beam-crossing point in CMS; b) Two different read-out schemes for the HB wedges: Tower-wise (top) and Layer-wise (bottom)

CMS Calorimetric System

The Calorimetric System of CMS consists of the Electromagnetic Calorimeter (ECAL) Barrel (EB) and Endcap (EE) parts, Hadronic Calorimeter (HCAL) Barrel

(HB), Endcap (HE) and Outer (HO)[1] parts, and the Very-Forward Calorimeter (HF).

ECAL

The Electromagnetic Calorimeter [2] is a homogeneous calorimeter made of over 80,000 lead-tungstate ($PbWO_4$) crystals equipped with avalanche photo-diodes (APDs) for readout. The crystals in the barrel have a front face of $\sim 22x22mm^2$ and are 23 cm ($\sim$ 26 radiation lengths) long. Following the overall 18-fold ϕ-symmetry of the barrel part of CMS, the EB crystals are organized into 36 Super-Modules (18 in each positive and negative Z-direction) covering 20^o in ϕ-direction and pseudo-rapidity range of $|\eta| \lesssim 1.5$. Each ECAL crystal is read-out independently by two Avalanche Photo Diodes (APDs).

HCAL

The Hadronic Calorimeter [3] is a sampling calorimeter with $\sim 50mm$ thick copper absorber plates interleaved with $4mm$ thick scintillator sheets (barrel part). Again, following the overall 18-fold ϕ-symmetry of the barrel part of CMS, the HB is organized into 36 "wedges" (18 in each positive and negative Z-direction) covering 20^o in ϕ-direction and pseudo-rapidity range of $|\eta| \lesssim 1.5$. Scintillator tiles are optically grouped together in towers covering equal surface ($0.087x0.087$) in $\eta - \phi$ space, and are read-out together (single electronics channel per tower, as shown on Fig.2b) - top) by Hybrid Photo Diodes (HPDs).

Thickness of HB in the central region ($|\eta| = 0$) is $\sim 90cm$ (or $\sim$ 6 nuclear interaction lengths λ), which is somewhat thin. For that reason HB is complemented with scintillator tiles embedded in the first muon absorber layer just outside the magnet coil, thus forming the Outer Hadron Calorimeter (HO).

HF

The Very Forward Calorimeter (HF) is a Cherenkov quartz-fiber, steel absorber calorimeter, covering the very high pseudo-rapidity region ($3 < |\eta| < 5$) in CMS. Its design is driven by the requirements for extreme radiation hardness necessary in this part of the detector.

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[1] Not labeled in Fig.1, HO is situated in the immediate outside of the magnet coil, embedded in the first layer of muon absorber, and consists of Barrel part only

The 2004 Test-beam setup

The following elements of the calorimetric system of CMS were present in the 2004 test-beam:

- Two wedges of HB.
- One wedge of HE.
- A 7x7 matrix of prototype ECAL crystals, read-out by individual photo-multipliers.
- One wedge of HO.
- One wedge of HF.

All detector elements, except HF wedge, were mounted on a moving table (see Fig.2a)), allowing for beam particles to be sent to different (η,ϕ) sections of the calorimeter. The HF wedge was mounted on a separate table and was positioned in the beam independently downstream of the main calorimetric system.

The H2 beam-line of CERN's SPS accelerator was arranged as shown in Fig.3 to allow production of the following particle beam types:

- hadrons (mainly $\pi^{\pm}$) with momenta: $2-300 GeV/c$
- muons with momenta: $80, 150 GeV/c$
- electrons with momenta: $9-100 GeV/c$

The Very Low Energy ("VLE Setup") part of the beam-line was used to produce the beam particles below $10 GeV/c$. The following detectors were used for particle identification (PID) and beam cleanup:

- Three Wire Chambers: WC A,B,C - used for tagging of interactions in the beam-line;
- Two Cherenkov counters: CK2 - used for electron tagging, and CK3 used for pion/proton tagging;
- Three scintillators: V3, V6 and VM - used for muon tagging.

HB readout

By re-arranging the Optical Decoupling Units (ODUs) of the two HB wedges two different readout schemes were implemented: HB1 was read out tower-wise as usual (top of Fig.2b), while HB2 was read out layer-wise (bottom of Fig.2b) thus allowing for measurement of the longitudinal shower profiles in the calorimeter.

MONTE-CARLO SIMULATION

The complete TB2004 setup was simulated using the CMS software, which internally employs the Geant4 toolkit[4, 5]. A very detailed simulation geometry was used, as presented in Fig.4. The version of Geant4 used was 6.2_p02. The simulations were

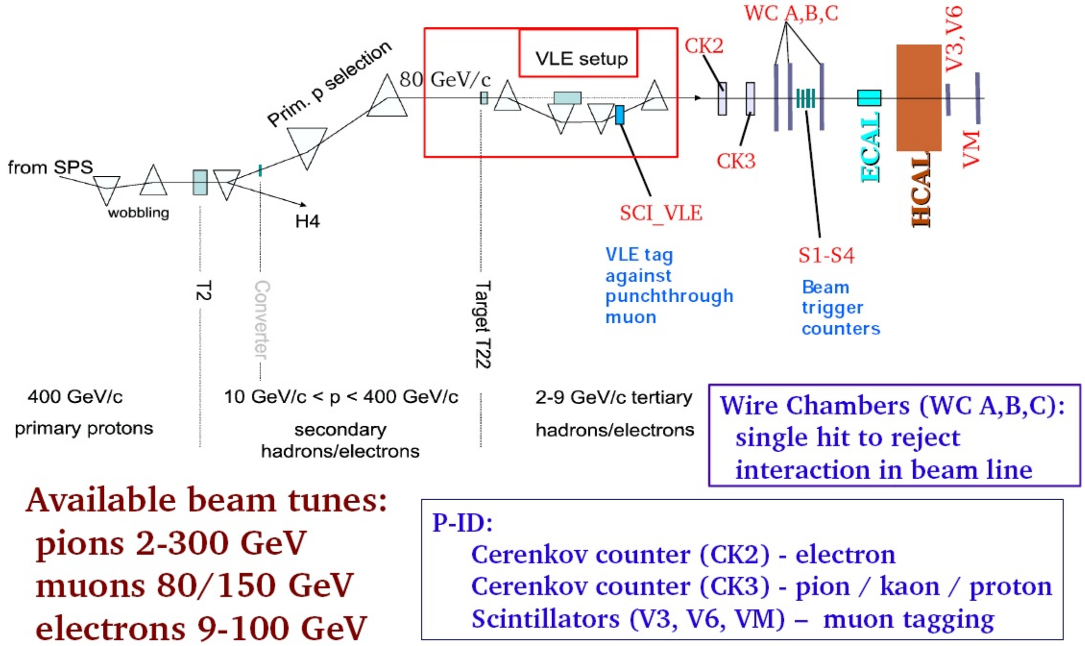

FIGURE 3. SPS's H2 beam-line. The VLE section is used for production/selection of very low beam energies (2 - 10 *GeV*)

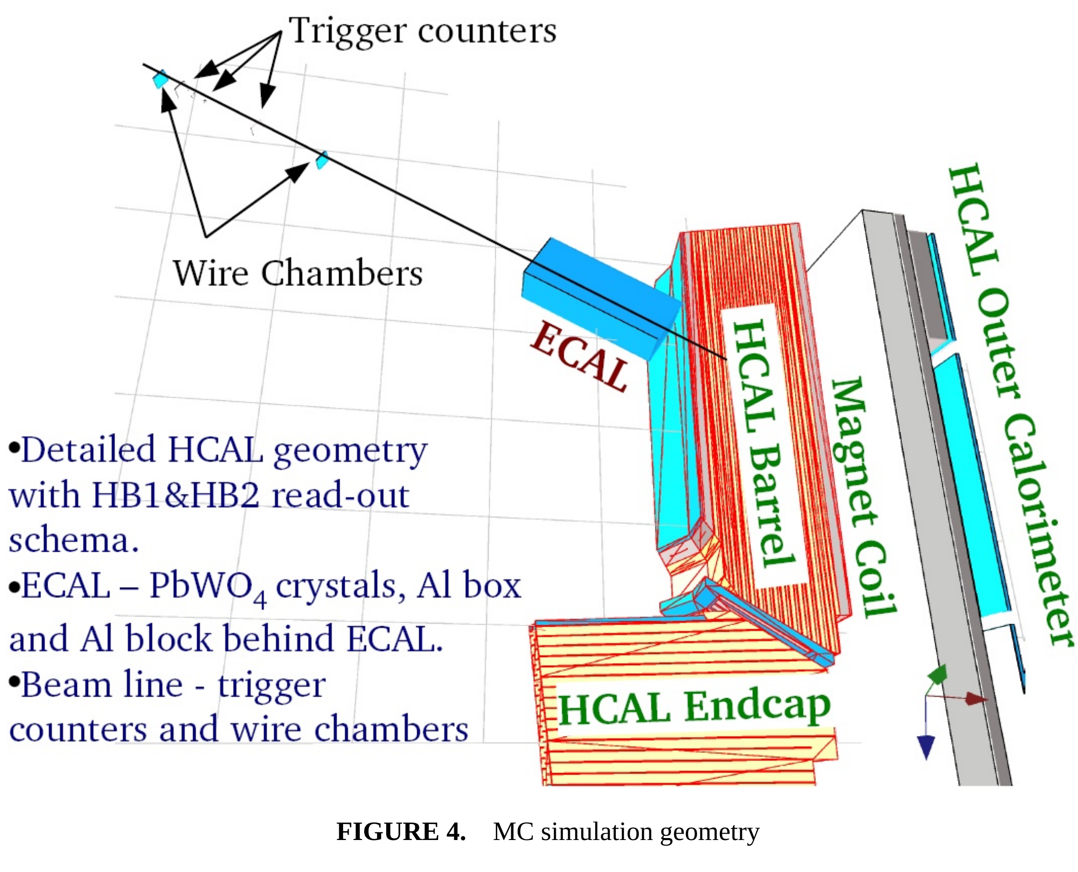

FIGURE 4. MC simulation geometry

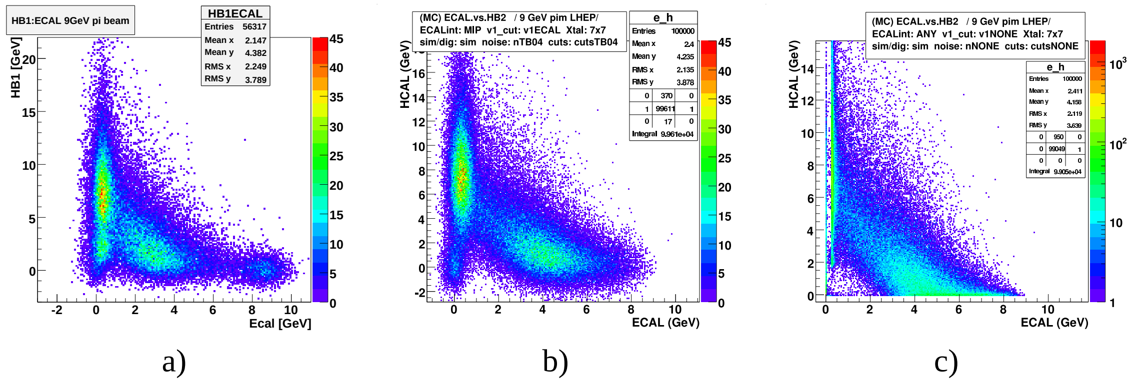

FIGURE 5. The "banana" plot - HCAL signal vs. ECAL signal - of a 9 GeV/c pion. a)Test-beam data; b) MC Simulation with included Gaussian noise; c) MC Simulation without noise.

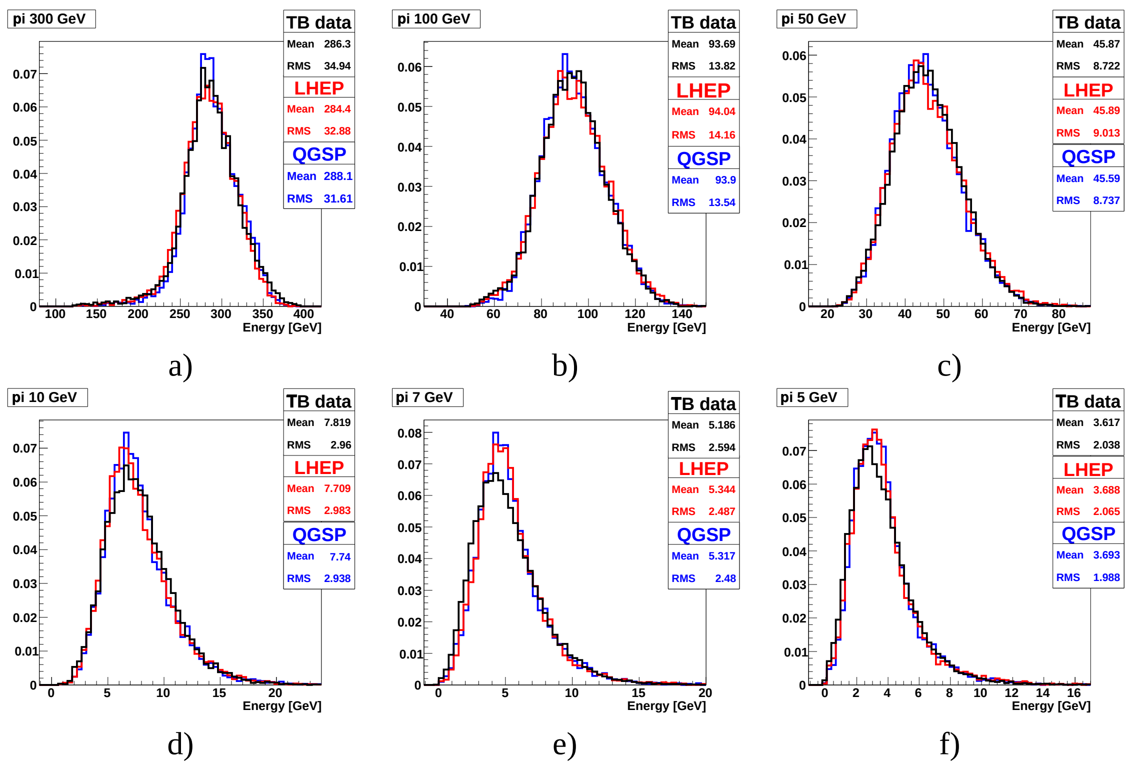

FIGURE 6. Comparison of detector response to pion beam of various momenta with the Monte-Carlo predictions obtained with two physics lists

repeated with all four physics lists (LHEP, QGSP, QGSC, FTFP) for High Energy Physics Calorimetry available in PACK 2.5[2].

Simulated detector response was studied at the simulated hit level - i.e. energy deposited in active materials. The digitization step was not simulated. Also, no detailed

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[2] `http://geant4.web.cern.ch/geant4/physics_lists/`

TABLE 1. TB2004 data sets

TB Data	Simulation
Very Low Energies (VLE)	
2,3,5,7,9 GeV mainly $\pi^{\pm}$ beam with/without ECAL HB1/HB2 Full particle identification	2,3,5,7,9 GeV $e^{\pm}$, $\pi^{\pm}$, p, $K^{\pm}$ beam with/without ECAL HB2
Medium Energies	
10,15,20 GeV $e^{\pm}$, $\pi^{\pm}$ beam with/without ECAL HB1/HB2 Partial particle identification	10,15,20 GeV $e^{\pm}$, $\pi^{\pm}$, p, $K^{\pm}$ beam with/without ECAL HB2
High Energies	
30,50,100,150,300 GeV $e^{\pm}$, $\pi^{\pm}$ beam with/without ECAL HB1/HB2	30,50,100,150,300 GeV $e^{\pm}$, $\pi^{\pm}$, p, $K^{\pm}$ beam with/without ECAL HB2

simulation of the detector noise was performed. Simple, gaussian-distributed noise with amplitudes matched to the ones observed in the real detectors was used where necessary.

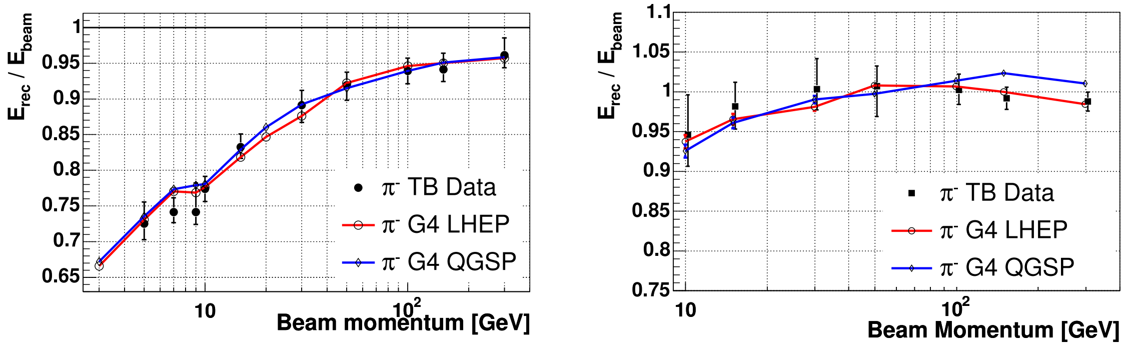
RESULTS

We consider here only the response of the ECAL and HCAL detectors to various beam particles. HO and HF detectors were not used in this study. On the Monte-Carlo side we have found that all three "calculated" (or "model-based") physics lists (QGSP, QGSC and FTFP) show similar results, so we only use QGSP as an example of the "calculated" physics lists, and we compare it to the "parametrized" physics list LHEP.

Detector response

Fig.5 shows the so-called "banana plot" - HCAL vs. ECAL response - of the combined system to a $9GeV/c$ pion beam. The left plot shows the response of the detectors measured in TB2004. Middle plot is the simulated response with included gaussian noise. Right plot shows the simulated response without noise. Several features of the TB2004 setup become evident from this comparison:

- There is electron contamination in the pion beam (the spot at $E_{ECAL} = 9$, $E_{HCAL} = 0$ in Fig.5a);
- Small fraction of the pions - perhaps due to scattering in the beam-line components - miss completely the ECAL crystals, leaving signal only in the HCAL;
- There are muons in the beam, leaving only a minimum-ionizing-particle signal in both calorimeters. These could be the result of pion decay in flight, or beam contamination (the spot at $E_{ECAL} = 0.3GeV$, $E_{HCAL} = 2GeV$ in Fig.5c).



a) b)

FIGURE 7. Linearity of pion response: a) Combined system ECAL + HCAL; b) HCAL alone.

These findings clearly indicate inefficiencies in the beam particle identification detectors and the muon vetoes. To eliminate the effect of these contaminations the following (geometrical) cuts were applied:

- Events in the vicinity of the ($E_{ECAL} = 0$, $E_{HCAL} = 0$) region were excluded from the analysis;
- Pion events with $E_{ECAL} > 0.8 \times E_{beam}$ were excluded from the analysis;
- the exact cut values were optimized for each beam type to maximize the cleaning efficiency;
- the same cuts were used both for TB data and MC simulation.

With these cuts applied, a reasonably good agreement (see Fig.6) was achieved between the reconstructed energy spectra of pions in wide momentum range. The cleaning process was not efficient in the lowest momentum range ($2,3 GeV/c$), so those points were excluded from the comparison.

Another important quantity - the linearity of response - also shows good agreement with the predictions obtained with both physics lists (Fig.7). The left plot shows the linearity of response for the whole system (ECAL+HCAL), while the right plot compares the linearity of response for the HCAL alone. This was accomplished by requiring only a MIP signal in ECAL and in the first readout layer (L0) of HCAL. In this second configuration (HCAL alone), the calorimeter is clearly too thin to completely contain the showers of high-energy pions, and a significant leakage is observed for energies above $50 GeV$. As we can see, the QGSP physics list does not reproduce this leakage very precisely, which could be an indication of differences in the predicted/simulated longitudinal shower profiles (see next section).

Longitudinal shower profiles

The only significant difference observed among the MC simulations performed with different physics lists (LHEP, QGSP, QGSC, FTFP) was the prediction of the longitudinal shower profiles. Fig.8 compares the longitudinal shower profiles for pions of

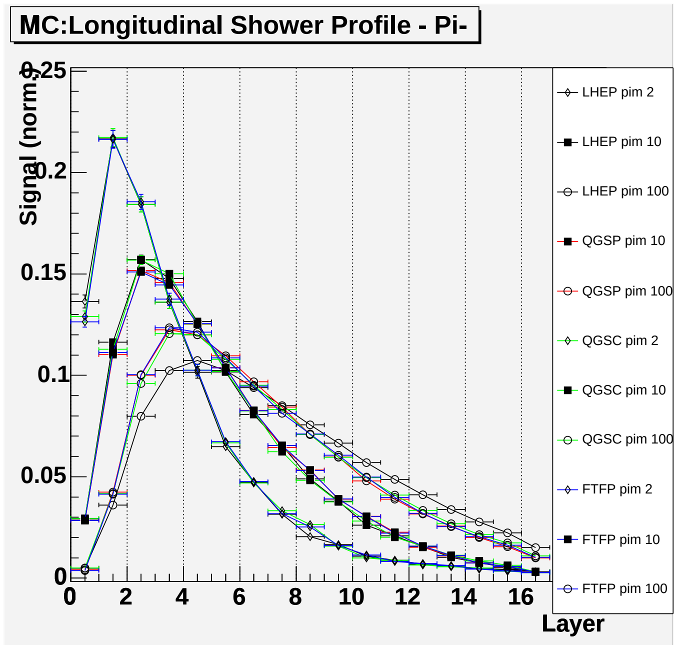
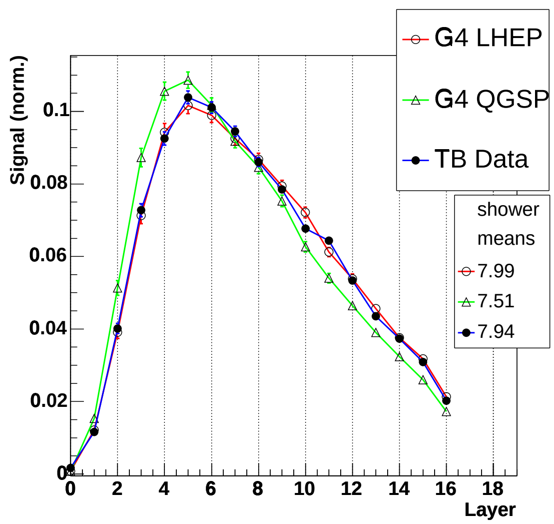


FIGURE 8. Longitudinal profiles of simulated pion showers. Three different energies and four Physics lists are shown.



b

FIGURE 9. Longitudinal profiles of 300*GeV* pion showers - MC simulation compared to Test Beam 2004 data

3 different energies (2,10,100 *GeV*) obtained with the different physics lists. Clearly, at high energies (100 *GeV*) the predictions of parametrized LHEP list start to differ from the predictions of the calculated (QGSP, QGSC, FTFP) lists. Comparison of these shower profiles with the one measured in TB2004 in Fig.9 indicates that the prediction of the LHEP physics list agrees better with the data. This result is in agreement with the

differences in the amounts of energy leakage seen in Fig.7.

CONCLUSION

The measured response of the combined ECAL+HCAL calorimetric system in Test-Beam 2004 agrees quite well with the Monte-Carlo simulations based on Geant4. The parametrized Physics List (LHEP) shows better agreement with data, while the model-based QGSP list seems to predict shorter showers than we measured.

REFERENCES

1. The CMS Collaboration, Technical Proposal, Tech. rep., CERN/LHCC 94-38 (1994).
2. The CMS Collaboration, CMS ECAL Technical Design Report, Tech. rep., CERN/LHCC 97-33 (1997).
3. The CMS Collaboration, The HCAL Technical Design Report, Tech. rep., CERN/LHCC 97-31 (1997).
4. J. Allison, et al., *IEEE Trans. Nucl. Sci.* **53**, 270 (2006).
5. S. Agostinelli, et al., *Nucl. Instrum. Meth.* **A506**, 250–303 (2003).