The Compact Muon Solenoid Experiment
Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

26 July 2010 (v2, 22 August 2010)

Measurement of the Muon Stopping Power in Lead Tungstate with the CMS detector

Federico De Guio for the CMS Collaboration

Abstract

A large sample of cosmic ray events collected by the CMS detector is exploited to measure the specific energy loss of muons in the lead tungstate (PbWO_4) of the electromagnetic calorimeter. The measurement spans a momentum range from 5 GeV/ c to 1 TeV/ c . The results are consistent with the expectations over the entire range. The calorimeter energy scale, set with 120 GeV/ c electrons, is validated down to the sub-GeV region using energy deposits, of order 100 MeV, associated with low-momentum muons. The muon critical energy in PbWO_4 is measured to be $160^{+5}_{-6} \pm 8$ GeV, in agreement with expectations.

Presented at *IPRD10: 12th Topical Seminar on Innovative Particle and Radiation Detectors*

Measurement of the Muon Stopping Power in Lead Tungstate with the Electromagnetic Calorimeter in CMS

Federico De Guio^a on behalf of the CMS Collaboration

^aUniversità di Milano Bicocca and INFN

A large sample of cosmic ray events collected by the CMS detector is exploited to measure the specific energy loss of muons in the lead tungstate (PbWO₄) of the electromagnetic calorimeter. The measurement spans a momentum range from 5 GeV/*c* to 1 TeV/*c*. The results are consistent with the expectations over the entire range. The calorimeter energy scale, set with 120 GeV/*c* electrons, is validated down to the sub-GeV region using energy deposits, of order 100 MeV, associated with low-momentum muons. The muon critical energy in PbWO₄ is measured to be $160^{+5}_{-6} \pm 8$ GeV, in agreement with expectations.

1. Introduction

The electromagnetic calorimeter (ECAL) of the Compact Muon Solenoid (CMS) experiment [1] has been designed with a stringent performance goal on energy resolution, driven by the capability to detect a Higgs boson decaying into two photons. While waiting to record events from beam collisions at the LHC, its outstanding characteristics have been exploited to measure the muon stopping power in lead tungstate (PbWO₄) for cosmic ray muon momenta between 5 and 1000 GeV/*c*. The stopping power for muons in the energy range considered can be conveniently written as

$$f(E) = \left\langle -\frac{dE}{dx} \right\rangle = a(E) + b(E)E \quad (1)$$

where E is the total muon energy, x is the thickness of the traversed material, commonly measured in mass per unit surface, $a(E)$ is the stopping power due to collisions with atomic electrons, and $b(E)$ is due to radiative processes: bremsstrahlung, direct pair production, and photonuclear interactions; $a(E)$ and $b(E)$ are slowly varying functions of E at energies where radiative contributions are important [11][9]. The lowest and highest momenta considered in the analysis reported here correspond to regions dominated by collision and radiative processes, respectively. Comparison of the experimental values

of the stopping power with predictions, extends the validity of the ECAL energy scale, set with 120 GeV/*c* electron beams [6], down to energy deposits below 1 GeV. Analysis of data in the full momentum range permits a comparison of collision losses with radiative losses, thus leading to the first experimental determination of muon critical energy.

2. Event measurement and selection

In order to perform muon stopping power measurement, the physical variables to be measured for each muon are the momentum, the path length in ECAL, and the energy lost in ECAL. The muon momentum is measured from the track fit performed in the inner tracking system [5]. The path length in ECAL is estimated by propagating the measured muon track inside the calorimeter taking into account bending due to the magnetic field and expected energy loss. The average path length in ECAL for the selected muon sample is 22.0 cm, with an rms spread of 2.6 cm. The energy deposited in ECAL by cosmic ray muons is measured by means of a dedicated clustering algorithm. The clusters are identified starting from a central crystal (seed) with an energy deposit of at least 139.5 MeV, or from the most energetic of a pair of adjacent crystals with at least 46.5 MeV each, the cluster energy is determined as the sum of all channels above

18.5 MeV belonging to a 5×5 matrix of crystals. The energy deposits in ECAL are associated with muon tracks according to a geometrical match between the track extrapolation to the calorimeter surface and the centre of gravity of the energy deposit. For the present analysis, the muon momentum has to be measured upstream of the energy release in the calorimeter. Thus only energy deposits in the bottom half of the ECAL barrel are used. For a complete discussion on the selection criteria, see [4].

3. Systematic corrections

3.1. Instrumental Effects

Online data reduction is based on zero suppression (ZS), that is a readout of channels above the ZS threshold (20 MeV), and on a full readout of selected regions (SR) of high interest, as identified by a Selective Readout Processor (SRP), based on the information of the Level-1 trigger system of ECAL [8]. When the condition for SR is met (170 MeV recorded in a trigger tower), a matrix of 3×3 trigger towers (centered around the tower with energy deposit above the SR threshold) is read out. Each trigger tower is comprised of 5×5 crystals. The ZS dominates at large angles while the condition for SR is met in the major part of cases when the muon direction is close to the crystal axis, so that a dependence of the raw dE/dx from the angle between the muon track and the axis of the hit crystal is observed. Corrections to take into account the different behavior at different angles have been extracted from data.

3.2. Containment corrections

The energy lost by the muon traversing a finite volume is not necessarily deposited within the same volume. In ECAL there is a net energy flow leaving the calorimeter from the rear crystals' face. Energy leakage and the effects of upstream and downstream materials are quantitatively different for collisions and radiative processes therefore losses and compensation for radiative and collision processes are treated separately. To estimate the difference between energy lost and energy deposited in ECAL, a model based on the Geant4 [7] simulation toolkit, with

a simplified description of the detector and materials surrounding it, was developed. Estimated corrections for energy containment in radiative processes have been derived in two extreme cases: with no material in front of ECAL and with the whole material budget of the tracker concentrated just in front of ECAL. In both cases the effects of the upper ECAL hemisphere, used as a veto in the analysis, were ignored. The mean value and half of the difference between the results of the two simulations are the estimate of the corrections for the energy containment in radiative processes and of the associated systematic error.

4. Experimental results and conclusions

The characteristics of radiative losses, which correspond to rare processes with high energy releases, generate probability distribution functions (pdf) of energy loss for single events with long tails at high energy. In this condition, convergence to a normal distribution for the average dE/dx of a sample of N events is slow. The skewness of the single event distribution increases with increasing muon momentum, owing to the increasing contribution of radiative losses with momentum. The number of events per bin in the selected data sample rapidly decreases with momentum for $p > 50$ GeV/c. It is thus expected that, due to the combined effect of increasing skewness of single event distribution and decreasing event statistics with increasing momentum, in the higher momentum bins the pdf of the sample mean of dE/dx cannot be approximated by a Gaussian. Moreover, when this condition occurs, sample mean and sample variance are highly correlated. It follows that the widely used "experimental error", namely the sample rms divided by the square root of the sample population, is not a good measure for the consistency of the sample mean with the expected value. Therefore the uncertainty of the result has been estimated by means of a numerical technique based on the simulation of the expected results with Geant4. For the high momentum bins, the increasing probability of large fluctuations in radiative energy losses, combined with the decreasing size of the event samples, cause the most probable values to

be systematically lower than the expectation values. The curve

$$(dE/dx)_{meas} = \alpha \left[\left(\frac{dE}{dx} \right)_{coll} + \beta \times \left(\frac{dE}{dx} \right)_{rad} \right] \quad (2)$$

where *coll* and *rad* label the predicted energy losses in PbWO₄ due to collisions with atomic electrons and radiative processes respectively [12], is fitted to experimental stopping power data using a binned maximum likelihood and the pdf described above. The parameters α and β account for the overall normalization of the energy scale and for the relative normalization of radiation and collision losses. With the adopted parameterization the β parameter, from which the critical energy is measured, is independent of the overall energy scale. The fit results is:

$$\alpha = 1.004^{+0.002}_{-0.003} (\text{stat.}) \pm 0.019 (\text{syst.}) \quad (3)$$

$$\beta = 1.07^{+0.05}_{-0.04} (\text{stat.}) \pm 0.6 (\text{syst.}) \quad (4)$$

Adding statistical and systematic contributions in quadrature, it may be concluded from the above results that the energy scale is consistent with expectations within a systematic uncertainty of 1.6%, with a 1.2% contribution from the uncertainty on the energy scale dependence on the angle and on the clustering, and a 1.0% contribution from uncertainty in containment corrections. This result is mainly determined by the precision of the measurements in the momentum region below 20 GeV/c, where radiation losses are marginal. Thus the energy scale set with 120 GeV/c electrons still holds in the sub-GeV region. This, assuming a linear response of the detector to the collected light, implies that the relative contribution to collected photons of Cherenkov light and scintillation are the same for 120 GeV/c electrons and for muons in the 5-20 GeV/c region, within the 1.6% precision of this measurement. From the fit results, a muon critical energy of $160^{+5}_{-6} (\text{stat.}) \pm 8 (\text{syst.})$ GeV is obtained, in agreement with the calculated value of 169.5 GeV for PbWO₄ [12]. The systematic uncertainty includes a contribution of 4.5 GeV from the uncertainty of the containment corrections, dominated by the limited knowledge of the

correction for radiation losses, and a contribution of 6 GeV due to the stability of the result against bias subtraction and event selection.

REFERENCES

1. CMS Collaboration 2008 The CMS experiment at the CERN LHC *JINST* **3** S08004
2. CMS Collaboration 2010 Commissioning of the CMS experiment and the cosmic run at four Tesla *JINST* **5** T03001
3. CMS Collaboration 2010 Performance and Operation of the CMS Crystal Electromagnetic Calorimeter *JINST* **5** T03010
4. CMS Collaboration 2010 Measurement of the Muon Stopping Power in Lead Tungstate *JINST* **5** P03007
5. CMS Collaboration 2010 Performance of CMS muon reconstruction in cosmic-ray events *JINST* **5** T03022
6. Adzic P et al. 2008 Intercalibration of the barrel electromagnetic calorimeter of the CMS experiment at start-up *JINST* **3** P10007
7. GEANT4 Collaboration, Agostinelli S et al. 2003 GEANT4: A simulation toolkit *Nucl. Instrum. Meth. A* **506** 250-303
8. Almeida N et al. Data filtering in the readout of the CMS electromagnetic calorimeter 2008 *JINST* **3** P02011
9. Groom Donald E, Mokhov Nikolai V and Striganov Sergei I 2001 Muon stopping power and range tables 10-MeV to 100-TeV *Atom. Data Nucl. Data Tabl.* **78** 183-356
10. Ivanov D, Kuraev E A, Schiller A and Serbo V G 1998 Production of e+ e- pairs to all orders in Z alpha for collisions of high-energy muons with heavy nuclei *Phys. Lett. B* **442** 453-8
11. Particle Data Group, Amsler C et al. 2008 Review of particle physics *Phys. Lett. B* **667** 1
12. Particle Data Group 2009 Atomic and Nuclear Properties of Materials *web pages at: <http://pdg.lbl.gov/2009/AtomicNuclearProperties>*