Nuclear Instruments and Methods in Physics Research A 729 (2013) 25–35

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Electromagnetic shower properties in a lead-scintillator sampling calorimeter

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ARTICLE INFO

Article history:
Received 20 November 2012
Received in revised form
27 May 2013
Accepted 30 May 2013
Available online 22 June 2013

Keywords:
Calorimeter simulation
Electromagnetic shower
Sampling calorimeter
Energy leakage

ABSTRACT

The Collider Detector at Fermilab (CDF) is a general-purpose experimental apparatus with an inner tracking detector for measuring charged particles, surrounded by a calorimeter for measurements of electromagnetic and hadronic showers. We describe a GEANT4 simulation and parameterization of the response of the CDF central electromagnetic calorimeter (CEM) to incident electrons and photons. The detector model consists of a detailed description of the CEM geometry and material in the direction of the incident particle's trajectory, and of the passive material between the tracker and the CEM. We use GEANT4 to calculate the distributions of: the energy that leaks from the back of the CEM, the energy fraction sampled by the scintillators, and the energy dependence of the response. We parameterize these distributions to accurately model electron and photon response and resolution in a custom simulation for the measurement of the *W* boson mass.

1. Introduction

The measurement of the *W* boson mass with the CDF detector [1] at the Fermilab Tevatron $p\bar{p}$ collider achieves a precision of 2 parts per 10,000 on the measured energy of electrons from *W* boson decays [2]. A key component of the energy calibration is a detailed simulation of the calorimeter response to incident electrons and photons. This simulation is based on parameterizations extracted from GEANT4 [3] predictions for the distributions relevant to the measurement. In this paper we describe the GEANT4 detector model and the parameterizations of calorimeter response and resolution.

The electron energy calibration [2] is performed in two steps. First, the calibrated track momentum (with a precision of 1 part per 10,000) is transferred to the measurement of calorimeter energy, using the distribution of the ratio of calorimeter energy to the track momentum (E/p) of electrons from the decays of *W* and *Z* bosons. In the second step, the *Z* boson mass (m_Z) is measured using electrons whose cluster energy has been calibrated with E/p. After confirming the consistency of the measured m_Z with the world average [4], the E/p-based calibration is combined with the m_Z-based calibration.

There are several regimes of particle type and energy relevant to this precise calorimeter calibration: the primary electron from the *W* boson decay, with incident energy in the ≈20–60 GeV range; radiated photons from the primary electron, with incident energies of ≈1 MeV to ≈10 GeV; and ≈0.5–10 GeV electrons from the conversion of photons[1] radiated by the primary electron. The CEM is a lead-scintillator sampling calorimeter. To simulate its response to incident electrons and photons of these energies, we parameterize the following quantities:

- the fraction of the incident particle's energy that leaks out the back of the CEM;
- the fraction of the deposited energy sampled by the scintillators;
- the sampling fluctuations in the scintillator energy fraction; and
- the loss of response due to absorption and back-scatter of low-energy particles.

In the following we describe the detailed detector geometry implemented in GEANT4 (Section 2); the fractional energy leakage for a given particle type and energy (Section 3); the sampling fraction and resolution of the calorimeter (Section 4); and the absorption of energy in the passive material that results in a non-linear calorimeter response (Section 5).

2. Detector model

The CDF detector [1,5–7] is shown in Fig. 1. The detector model implemented in the GEANT4 simulation includes the components

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[1] Tracks with $p_T < 500$ MeV curl up in the tracker's magnetic field and do not reach the calorimeter.

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http://dx.doi.org/10.1016/j.nima.2013.05.185

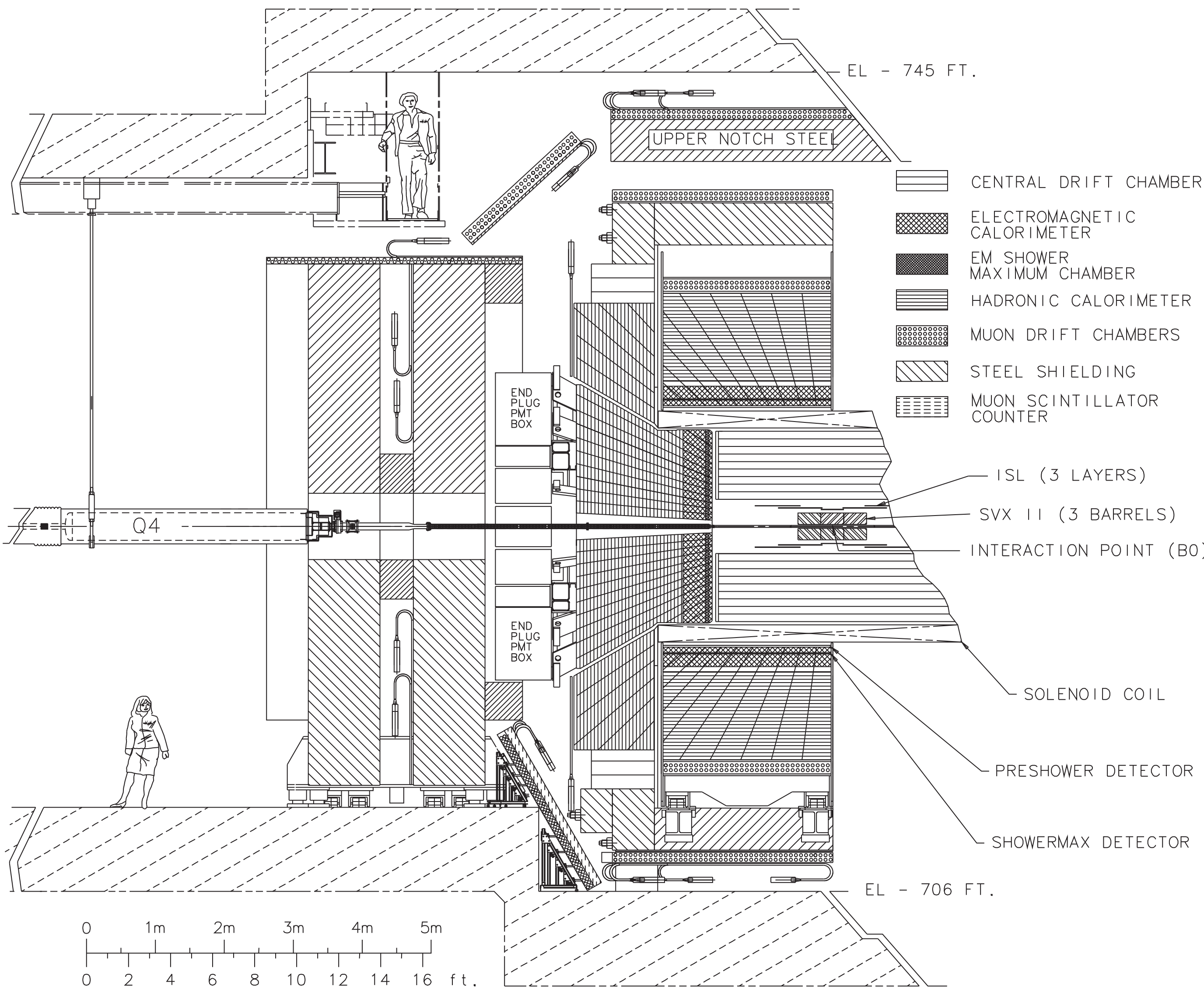

Fig. 1. A cut-away view of the CDF detector. We use a simplified GEANT4 model of the outer casing of the central drift chamber, the time-of-flight detector (not shown), the solenoid coil, the preshower detector, and the central electromagnetic calorimeter.

from the outer radius of the central tracking drift chamber [8] to the back end of the CEM calorimeter. These components are the outer aluminum casing of the tracker, the time-of-flight (TOF) system [9] attached to this casing, the solenoidal coil [10] that provides a nearly uniform 1.4 T magnetic field in the tracking volume, the central preshower system (CPR) [11] beyond the solenoid, and the CEM calorimeter (including longitudinal segmentation) [12].

The CEM calorimeter is divided into 0.1×0.15 η–ϕ [13] towers, shown in Fig. 2. The tower geometry depends on η, with towers numbered according to their distance in $|\eta|$ from $\eta = 0$. The longitudinal segmentation of Tower 0 is an alternating system of 31 scintillator sheets and 30 aluminum-clad lead sheets, with a plate of aluminum at the front end of the tower. Each lead sheet is 3.175 mm thick and the aluminum cladding is 380 μm thick on each side of the sheet. Each scintillator sheet is 5 mm thick. A thin (6 mm) aluminum casing contains a strip and wire chamber at the position of shower maximum (after six lead-scintillator sandwiches). Almost all the material between the tracking volume and the first scintillator – the outer casing of the tracker, the solenoid coil and the CEM front plate – is aluminum. The TOF and CPR are a combination of scintillator and aluminum. Table 1 shows the materials in the GEANT4 model with their thicknesses in units of mm (x) and radiation length ($x_0 \equiv x/X_0$).

We model the material between the tracking volume and the first CEM scintillator as an aluminum plate of 6.51 cm thickness plus an aluminum-clad lead sheet at the front of the active calorimeter volume. The additional lead sheet is included for simplicity: with this sheet the CEM volume is modelled as 31 alternating lead-scintillator layers. Combined, the 6.51 cm of aluminum and the single lead sheet reproduce the total radiation lengths upstream of the first scintillator layer.

The geometry of other towers is implemented according to Table 2. As $|\eta|$ increases, the number of lead sheets in a tower decreases, compensating for the increasing path length. This approximately maintains the same total number of radiation lengths traversed by a particle originating from the center of the detector. For each removed lead sheet, acrylic is used in its place and the subsequent scintillator sheet is blackened so that the sampling fraction is unaffected. In the GEANT4 model described here