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# Characterisation of different stages of hadronic showers using the CALICE Si-W ECAL physics prototype

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48 **Abstract**

49 A detailed investigation of hadronic interactions is performed using  $\pi^-$ -mesons with energies in the  
50 range 2–10 GeV incident on a high granularity silicon-tungsten electromagnetic calorimeter. The data  
51 were recorded at FNAL in 2008. The region in which the  $\pi^-$ -mesons interact with the detector mate-  
52 rial and the produced secondary particles are characterised using a novel track-finding algorithm that  
53 reconstructs tracks within hadronic showers in a calorimeter in the absence of a magnetic field. The  
54 principle of carrying out detector monitoring and calibration using secondary tracks is also demon-  
55 strated.

56 **Contents**

|    |  |           |
|----|--|-----------|
| 57 | <b>1 Introduction</b>  | <b>2</b>  |
| 58 | <b>2 The Si-W ECAL physics prototype</b>                           | <b>3</b>  |
| 59 | <b>3 Data and Monte Carlo samples</b>                              | <b>4</b>  |
| 60 | 3.1 Experimental setup at FNAL . . . . .                           | 4         |
| 61 | 3.2 Monte Carlo simulations . . . . .                              | 4         |
| 62 | 3.3 Event selection and preprocessing . . . . .                    | 5         |
| 63 | <b>4 The track-finding algorithm</b>                               | <b>6</b>  |
| 64 | 4.1 Identification and removal of the interaction region . . . . . | 6         |
| 65 | 4.2 Clusterisation of energy deposits . . . . .                    | 7         |
| 66 | 4.3 Formation of tracks . . . . .                                  | 8         |
| 67 | <b>5 Results</b>   | <b>9</b>  |
| 68 | 5.1 Energy fraction of the interaction region . . . . .            | 9         |
| 69 | 5.2 Lateral radius of interaction region . . . . .                 | 11        |
| 70 | 5.3 Number of clusters . . . . .                                   | 12        |
| 71 | 5.4 Number of tracks . . . . .                                     | 13        |
| 72 | 5.5 Number of hits per track . . . . .                             | 15        |
| 73 | 5.6 Angular distributions . . . . .                                | 16        |
| 74 | 5.7 Energy deposition by secondary tracks . . . . .                | 18        |
| 75 | <b>6 Summary and outlook</b>                                       | <b>20</b> |

76 **1. Introduction**

77 The design of particle detectors at future high-energy physics experiments and, in particular, at  
78 linear colliders is oriented towards the usage of Particle Flow Algorithms (PFA) for the event recon-  
79 struction. These algorithms aim to achieve good jet energy resolution by reconstructing individual  
80 particles and hence require high granularity calorimeters [1, 2, 3].

81 The primary objective of the CALICE (Calorimeter for the Linear Collider Experiment) collabo-  
 82 ration is the development, construction and testing of highly granular hadronic and electromagnetic  
 83 calorimeters for future particle physics experiments.

84 A detailed study of the calorimeter response to particle interactions is necessary to verify existing  
 85 Monte Carlo simulation models and to build reliable PFA. This implies the precise simulation and  
 86 reconstruction of the interaction of neutral and charged hadrons using the subsequent particle cascade.

87 This article presents a detailed study of  $\pi^-$ -meson interactions in the CALICE Silicon-Tungsten  
 88 Electromagnetic Calorimeter (Si-W ECAL) physics prototype [4]. The Si-W ECAL was tested at  
 89 Fermi National Accelerator Laboratory (FNAL) in 2008 using a beam of  $\pi^-$ -mesons in the energy  
 90 range from 2 to 10 GeV. The highly granular structure of the Si-W ECAL enables both a detailed  
 91 measurement of hadronic showers in terms of integral observables [5, 6] as well as deeper studies  
 92 of the interactions between hadrons and the absorber material, such as the characterisation of the  
 93 interaction region and the analysis of secondaries emerging from the interaction. The tracks produced  
 94 by these secondaries are reconstructed using a new simple track-finding algorithm. The resulting  
 95 observables are used to compare data with predictions from several GEANT4 simulation models [7, 8].  
 96 The analysis complements studies presented in [9] and [10] for tracking in CALICE prototypes of  
 97 hadronic calorimeters.

## 98 2. The Si-W ECAL physics prototype

99 The Si-W ECAL physics prototype has a sandwich-like structure comprising 30 layers of silicon as  
 100 the active material, alternating with tungsten as the absorber material. The active layers are made of  
 101 Si wafers segmented in  $1 \times 1 \text{ cm}^2$  pads. As shown in Fig. 1, each wafer consists of a square of  $6 \times 6$   
 102 pads and each layer is a matrix of  $3 \times 3$  of these wafers resulting in an active zone of  $18 \times 18 \text{ cm}^2$ .

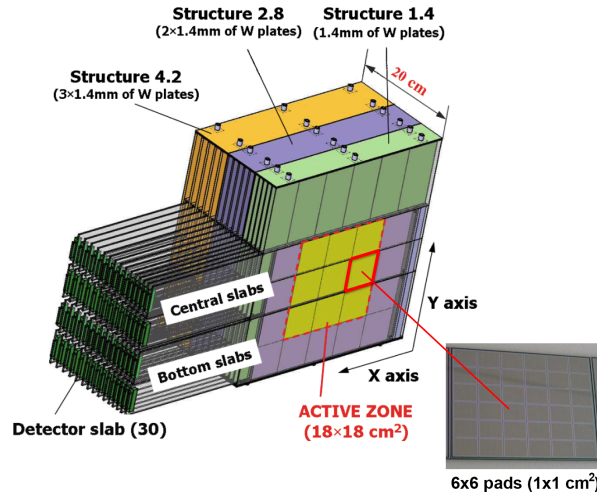


Figure 1: A schematic view of the Si-W ECAL physics prototype.

103 The Si-W ECAL is subdivided into three modules of ten layers. The tungsten depth per layer is  
 104 1.4 mm (0.4 radiation lengths,  $X_0$ ) in the first module, 2.8 mm in the second and 4.2 mm in the third.  
 105 The total thickness corresponds to  $24 X_0$  and about one nuclear interaction length  $\lambda_I$ . Therefore more  
 106 than half of the hadrons are expected to have a primary interaction within the detector volume. A more  
 107 detailed description of the prototype can be found in Ref. [4].

108 For the analysis presented in this article it is convenient to introduce a unit grid based on the Si-W

109 ECAL pad identifiers according to

$$\vec{x} = (x, y, z) = \begin{cases} x = 0.17 \\ y = 0.17 \\ z = 0.29, \end{cases} \quad (1)$$

110 where pad counting starts in the bottom right pad, see Fig. 1. Distances in this grid are measured in  
111 *grid units*, g.u.

### 112 3. Data and Monte Carlo samples

#### 113 3.1. Experimental setup at FNAL

114 The test beam measurements were carried out at the Fermilab Test Beam Facility<sup>7</sup>, FTBF, at FNAL  
115 in May and July 2008. A schematic overview of the beam line is given in Fig. 2. The Si-W ECAL was  
116 placed in front of two other CALICE physics prototypes, the analogue hadronic calorimeter (HCAL)  
117 [11] and a TailCatcher [12]. In both steel is used as absorber. Sensors are scintillator tiles (HCAL)  
118 or scintillator strips read out by silicon-photomultipliers. The beam-line also included wire chambers  
119 (WC1-3), drift chambers (DC1-4) and scintillator counters of different sizes, named T100(A,B), VETO,  
120 T20x20 and T10x10(A,B). The latter two cover an area of  $10 \times 10 \text{ cm}^2$  each and are used for triggering  
121 on beam particles analysed for this article. Finally, two Cherenkov detectors for particle identification  
122 are located upstream of the Wire Chamber 1.

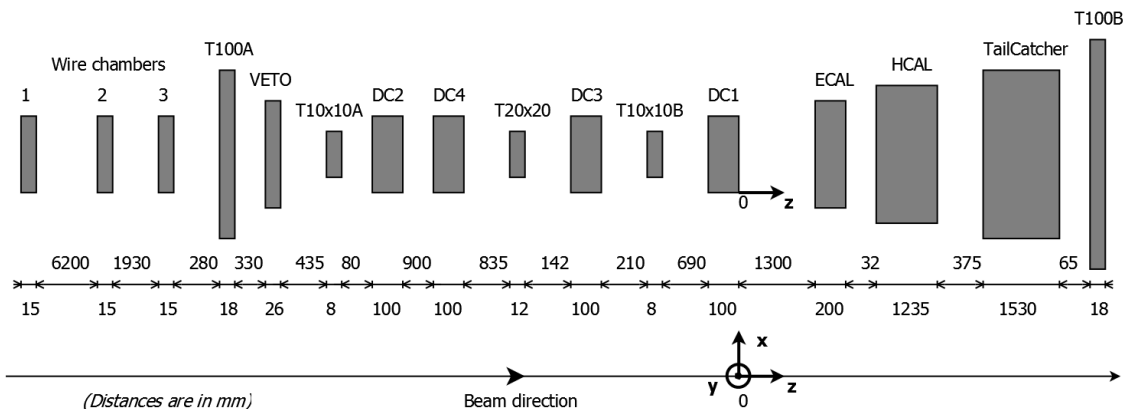


Figure 2: Plan view of the beam line at FNAL. Distances (not to scale) are in mm.

123 The chosen coordinate system is right-handed with the  $z$ -axis pointing along the beam direction  
124 and the  $y$ -axis being vertical. The data analysed in this article comprise runs with  $\pi^-$ -mesons with  
125 energies of 2, 4, 6, 8 and 10 GeV.

#### 126 3.2. Monte Carlo simulations

127 Monte Carlo simulations were carried out within the Mokka framework [13], which provides the  
128 geometry interface to GEANT4. There are several models of hadronic interactions available within  
129 GEANT4 that are combined into simulation models. Each hadronic interaction model has its own  
130 theoretical basis valid mainly in a specific energy range of hadrons. In this analysis, three simulation  
131 models contained in GEANT4 Version 10.1 are compared with the data:

- 132 • FTFP\_BERT uses the Bertini Cascade Model [14] and the Fritiof String Model [15, 16] where the  
133 first is used for hadron energies below and the second for hadron energies above 4.5 GeV;

<sup>7</sup>Fermilab Test Beam Facility web page: <http://www-ppd.fnal.gov/MTBF-w>

- QGSP\_BERT uses the Bertini Cascade Model at energies below, and the Fritiof String Model for energies above 9.9 GeV. The Fritiof String Model replaces the LHEP parametrisation that was employed until Version 9.6 of GEANT4;
- QBBC uses also the Bertini Cascade Model for energies below and the Fritiof String Model for energies above 9.9 GeV but interpolates in a larger transition region (for protons and neutrons below 1.5 GeV the Binary Cascade Model [17] is used).

The validity ranges of hadronic interaction models in the three simulation models are illustrated in Fig. 3. More information about these and other simulation models can be found in Ref. [18].

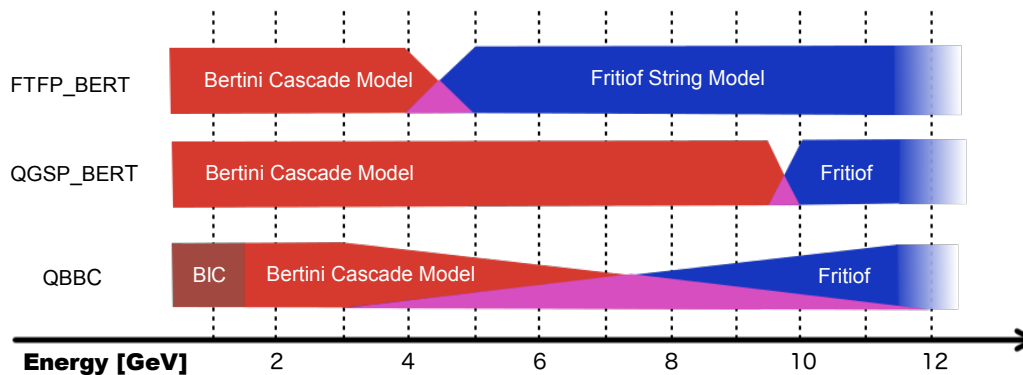


Figure 3: Illustration of the validity ranges of the three tested GEANT4 hadronic interaction models as contained in GEANT4 Version 10.1.

### 3.3. Event selection and preprocessing

The FNAL  $\pi^-$  test beam is contaminated with  $\mu^-$  and  $e^-$ , in particular at lower energies. At 2 GeV the beam contains about 5%  $\pi^-$ -mesons and 70% electrons. Events are triggered using the signals from the two scintillator counters T10x10A and T10x10B upstream of the Si-W ECAL and  $\pi^-$ -mesons are identified by using Cherenkov counters. The response of the Si-W ECAL to charged particles was calibrated with a 32 GeV  $\mu^-$  beam [19] and the deposited energy is converted into units of most probable energy depositions, called MIP hereafter, by particles with behaviour that is approximately minimally ionising. The deposited energy measured in a pad is called hit.

To select  $\pi^-$ -meson showers, data and simulation samples are required to satisfy similar criteria to those of Refs. [6, 20], as below:

- Selection criteria are applied to reject multi-particle events caused by beam impurities or products of decays or upstream interactions of beam particles;
- A lower threshold of 0.6 MIP is chosen to remove noise hits in the Si-W ECAL;
- A hit is classified as being isolated if all the 26 pads in the surrounding cube (in g.u.) have no signal above the noise threshold. The analysis presented in this article uses the non-isolated hits that remain after this removal. The term ‘hits’ will continue to be used to indicate only non-isolated hits in the following.
- A total of at least 25 hits in the Si-W ECAL is required to remove particles with large incident angle;

- 161 • For the event selection the hit coordinates  $x_{hit}$  and  $y_{hit}$  are defined in the coordinate frame  
 162 according to Fig. 2. The barycentres of the transverse coordinates  $\bar{x}_{hit}$  and  $\bar{y}_{hit}$  of the hits are  
 163 calculated as:

$$\bar{x}_{hit} = \frac{\sum_{hits} x_{hit} E_{hit}}{\sum_{hits} E_{hit}} \quad \text{and} \quad \bar{y}_{hit} = \frac{\sum_{hits} y_{hit} E_{hit}}{\sum_{hits} E_{hit}}, \quad (2)$$

164 where  $E_{hit}$  is the energy of a hit in MIP units, and the sums run over all hits in the calorimeter.  
 165 The event is accepted if  $-50 \text{ mm} < \bar{x}_{hit} < 50 \text{ mm}$  and  $-50 \text{ mm} < \bar{y}_{hit} < 50 \text{ mm}$  to reduce lateral  
 166 shower leakage;

- 167 • Initially, the interaction layer  $i$  is identified as the first of three consecutive layers for which

$$E_i > E_{cut}, E_{i+1} > E_{cut} \quad \text{and} \quad E_{i+2} > E_{cut}. \quad (3)$$

168 with  $E_i$  being the total energy of layer  $i$ ;

169 This simple condition is inefficient at low energies and is extended by the following relative energy  
 170 increase

$$\frac{E_i + E_{i+1}}{E_{i-1} + E_{i-2}} > F_{cut} \quad \text{and} \quad \frac{E_{i+1} + E_{i+2}}{E_{i-1} + E_{i-2}} > F_{cut}. \quad (4)$$

171 The variables  $E_{cut}$  and  $F_{cut}$  are free parameters with empirical values of eight MIP and six,  
 172 respectively. It is argued in [6] and references therein that these values optimise the selection  
 173 efficiency in the energy range relevant for the present study. The event is selected if  $5 < i < 15$  to  
 174 suppress electron contamination and to ensure secondaries that extend over several layers after  
 175 the interaction.

## 176 4. The track-finding algorithm

177 The track-finding algorithm reconstructs forward-scattered tracks from the interaction between the  
 178  $\pi^-$ -meson and the absorber material in the absence of a magnetic field.

179 The algorithm consists of three stages:

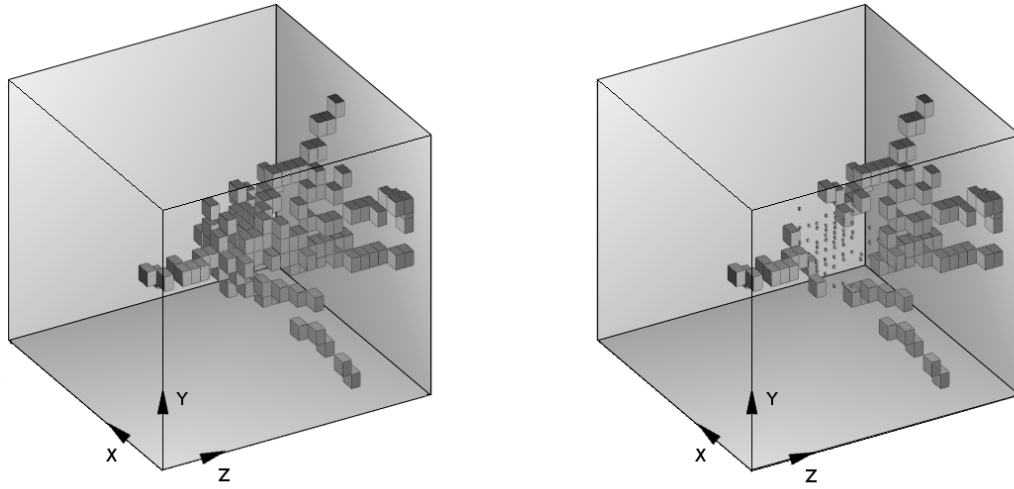
- 180 • identification and removal of interaction region;
- 181 • clusterisation of energy deposits;
- 182 • formation of track-like clusters;

183 The entire algorithm is carried out in the grid units introduced in Sec. 2.

### 184 4.1. Identification and removal of the interaction region

185 A typical inelastic hadronic interaction in the Si-W ECAL creates a shower with an interaction  
 186 region and tracks of long-lived particles emerging from it. The interaction region is created by particles  
 187 such as electrons, photons and low-momentum hadrons that have a short distance of flight in the  
 188 absorber material of the Si-W ECAL.

189 In the present analysis the interaction region is defined by all hits that have at least six neighbouring  
 190 pads with a signal above the noise threshold. For the minimal value of six pads a interaction region is  
 191 wrongly identified in only 1% of single muon events. Muon events are used to estimate the fraction of  
 192 events in which this procedure incorrectly identifies an interaction region. For the minimal value of six  
 193 (five) pads, an interaction region is found in 1% (10%) of muon events. Increasing the minimal value to  
 194 seven neighbouring pads with hits further reduces the fraction of events with a fake interaction region  
 195 but does not alter the results presented below in Sec. 5.



(a) Before removing the interaction region.

(b) After removing the interaction region.

Figure 4: Event display of a  $\pi^-$ -meson interaction with an energy of 10 GeV (a) before and (b) after removal of the interaction region. Smaller cubes are pads that are part of the interaction region and are not processed by the track-finding algorithm. In this event the hits in the first ten layers are classified as hits left by the incoming  $\pi^-$ -meson.

196 Figure 4a displays an event after applying noise and isolated hits filters and Fig. 4b is the same  
 197 event after removal of the interaction region, illustrating that the interaction region is the starting  
 198 point for secondary tracks.

199 *4.2. Clusterisation of energy deposits*

200 During the clusterisation step the energy deposits that are not assigned to the interaction region  
 201 are grouped into clusters according to topological criteria.

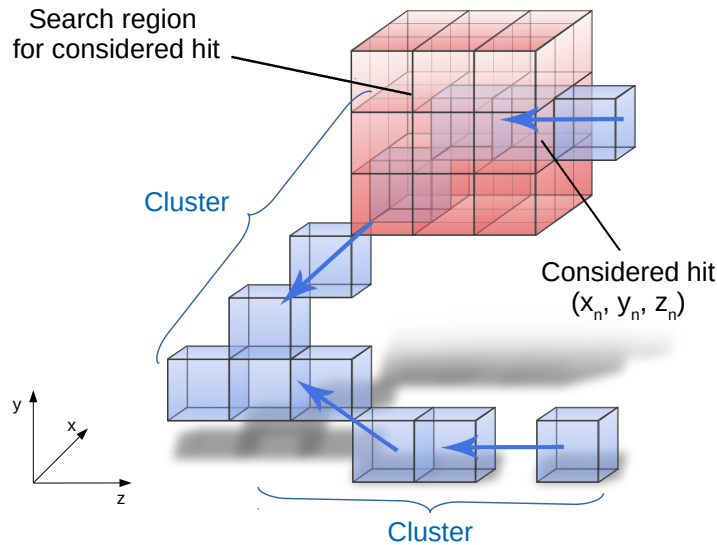


Figure 5: Illustration of the clusterisation step. The Si-W ECAL hits are represented by blue cubes, and the search region for adjacent hits is indicated by red cubes. The blue arrows point in the direction of the clusterisation flow.

202 The steps of the clusterisation algorithm are described below, with reference to Fig. 5.



- 203 1. The separation of tracks improves with increasing distance from the interaction layer. Therefore,  
 204 the search for hits to seed a cluster begins in the layers that have largest  $z$  and continues in the  
 205 direction of decreasing  $z$ . Typically, seeding hits are found in the last layer of the detector;  
 206 2. A hit can only be attributed to one cluster. This condition excludes double counting of hits. A  
 207 random choice of seeding hits shows that effects arising from ambiguities in the assignment of  
 208 hits to clusters such as the order in which clusters are created, are negligible;  
 209 3. For the clusterisation a nearest-neighbour clustering scheme is applied where for each newly  
 210 associated hit with coordinates  $(x_n, y_n, z_n)$ , the algorithm finds nearby hits with the following  
 211 conditions:
- 212 • a neighbour hit should have a  $z$  coordinate within  $[z_n - 2, z_n]$  g. u. ;
  - 213 • the transverse coordinates of neighbouring hits is searched within ranges  $[x_n - 1, x_n + 1]$   
 214 and  $[y_n - 1, y_n + 1]$ .

215 The search region for nearby hits is visualised in Fig. 5 as a ‘red cube’ with  $3 \times 3 \times 3$  pads;

- 216 4. For each newly associated hit the steps 2 and 3 are repeated until the process reaches the first  
 217 layer of the calorimeter or until no more neighbour hits are found.

218 The algorithm is motivated by a maximum correspondence between the number of clusters and the  
 219 number of detected tracks after classification and merging.

### 220 4.3. Formation of tracks

221 Secondary long-lived charged particles from hadronic interactions can leave straight, MIP-like tracks  
 222 in the detector. The goal of the classification of the clusters obtained in the previous step is thus to  
 223 select track-like clusters.

224 The classification algorithm executes the following steps:

- 225 1. Calculate the number of hits,  $N_{\text{hits}}$ , in a cluster and reject all clusters with only two hits as  
 226 residual noise clusters  
 227 2. Calculate the length  $l \in \mathbb{R}$  of the considered cluster as the maximal distance between any  
 228 pair of hits that are in the cluster. For example the lower cluster in Fig. 5 has a length of  
 229  $\sqrt{\Delta y_n^2 + \Delta z_n^2} = \sqrt{25 + 1} \approx 5.1$  g.u. ;  
 230 3. Reject a cluster with a length of less than  $l_{\text{cut}} = 2$  g.u.. This corresponds to the minimal length  
 231 of a track-like cluster with 3 hits;  
 232 4. Compute the following observable

$$\xi = \frac{l}{N_{\text{hits}} - 1} + \varepsilon N_{\text{hits}}, \quad (5)$$

233 as a measure for the eccentricity of the cluster. The first term of Eq. 5 is motivated by the linear  
 234 dependence of  $N_{\text{hits}} - 1$  on the cluster length  $l$ , illustrated in Fig. 6. The second term introduces  
 235 a free parameter  $\varepsilon$  as an ad hoc correction to increase the efficiency for selecting clusters that do  
 236 not match the nominal ‘pencil-like’ topology, as explained below. The value  $\varepsilon = 0.03$  was chosen  
 237 after visual inspection of a few tens of events for pion energies of 10 GeV in an event display.  
 238 The chosen value is a compromise between a too small value at which also muon tracks would  
 239 get assigned more than one track and too large values at which even for electrons the algorithm  
 240 would result in one single track. The choice made for 10 GeV is also adequate for the other  
 241 energies relevant for this analysis. For a detailed discussion see Refs. [21] and [22] ;

- 242 5. If  $\xi \geq 1$ , a cluster is considered as track-like. Otherwise, the cluster is classified as two inseparable  
 243 tracks.

244 Due to effects such as multiple scattering, residual detector-noise,  $\delta$ -rays or the residual arbitrariness  
 245 in the assignment of hits to clusters, the reconstructed tracks are in general not exactly pencil-like.  
 246 The correction term  $\varepsilon N_{\text{hits}}$  in the definition of  $\xi$  serves to keep a cluster as track-like even if it has  
 247 large  $N_{\text{hits}}$  and its form is not strictly pencil-shaped, i.e.  $l/(N_{\text{hits}} - 1) < 1$ .

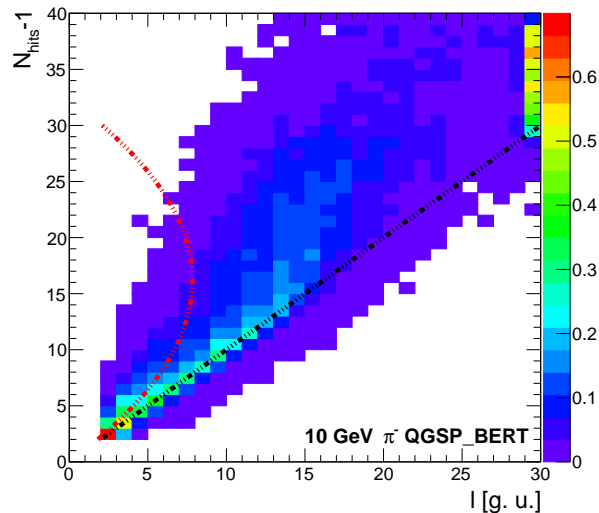


Figure 6: Correlation between  $N_{\text{hits}} - 1$  and cluster length  $l$  in g.u. for a sample of simulated pion interactions with an energy of 10 GeV using the QGSP\_BERT simulation model. Clusters inside the red parabola are rejected by means of Eq. 5. To guide the eye a black line for  $N_{\text{hits}} - 1 = l$  is also included in the figure.

248 A cluster is classified as being produced by the incoming  $\pi^-$ -meson if it starts in the first module  
 249 of the Si-W ECAL and if it has a small polar angle with respect to the  $z$ -axis. An example of a cluster  
 250 produced by an incoming  $\pi^-$ -meson is visible in Fig. 4b. Clusters assigned to the incoming  $\pi^-$ -meson  
 251 are discarded in the following analysis. The remaining track-like clusters are merged into tracks if the  
 252 relative angle  $\theta_c$  between these clusters fulfils the condition  $\sin \theta_c < 0.15$ , optimised using the polar  
 253 angle distribution of secondary particles in simulated  $\pi^-$ -meson interactions.

254 For a sample of single, isolated 6 GeV muons, the track-finding algorithm finds a single track with  
 255 a 99.7% efficiency.

## 256 5. Results

257 Observables characterising the interaction region and secondary particles are measured in data and  
 258 are compared with predictions of the three GEANT4 simulation models introduced in Sec. 3.2. The  
 259 average values of observables are also used to make quantitative comparisons. After pre-selection  
 260 the data have a residual contamination of 8.8% (1.5%) double  $\pi^-$ -meson events at 2 GeV (10 GeV)  
 261 beam energy [6]. Therefore, for comparison with data all simulation samples were produced with an  
 262 admixture of double  $\pi^-$  events. For average values of observables, correction factors are extracted  
 263 for each Monte Carlo sample by comparing the results of contaminated samples with those from pure  
 264 samples. To account for residual contamination, the averages of the data are multiplied by *final*  
 265 correction factors. This final correction factors are given by the arithmetic mean of correction factors  
 266 of the three considered simulation models. The final correction factors are between 0.99 and 1.01  
 267 and their uncertainties are much less than one percent. The total systematic error never exceeds two  
 268 percent and is dominated by two other sources of systematic uncertainties that have been studied.  
 269 These are the lowering of the MIP threshold from the nominal 0.6 to 0.4 and the uncertainty on the  
 270 absolute MIP energy scale [9] that has been varied by  $\pm 2\%$ .

### 271 5.1. Energy fraction of the interaction region

272 The first estimator to characterise the interaction of  $\pi^-$ -mesons with the absorber material is the  
 273 fraction

$$f_{\text{IR}} = \frac{E_{\text{IR}}}{E_{\text{tot}}} \quad (6)$$

274 where  $E_{\text{IR}}$  is the energy deposited in the interaction region and  $E_{\text{tot}}$  is the total energy deposited in  
 275 the Si-W ECAL .

276 Figure 7 compares the distribution of  $f_{\text{IR}}$  in data with the three simulation models. The lowest  
 277 bin of these histograms corresponds to the fraction of events for which no interaction region is found  
 278 by the algorithm. The rest of the distribution can be approximately described by a skewed normal  
 279 distribution. The mean value of  $f_{\text{IR}}$  is shifted towards larger values in data with respect to simulation.  
 280 Qualitatively, this observation suggests a different repartition of the deposited energy between the  
 281 dense interaction region and the sparser parts of the shower in data and the simulation models.

282 Figure 8 shows the average value of  $f_{\text{IR}}$ ,  $\langle f_{\text{IR}} \rangle$ , as a function of beam energy for beam energies  
 283 of 2, 4, 6, 8 and 10 GeV. Only events in which an interaction region has been detected are included  
 284 in  $\langle f_{\text{IR}} \rangle$ . An increase of  $\langle f_{\text{IR}} \rangle$  with increasing beam energy from 43% to around 64% is observed.  
 285 Qualitatively, this is expected as number of particles increases with increasing energy but also the  
 286 electromagnetic component of the hadronic shower becomes increasingly important for higher energies  
 287 of the interacting  $\pi^-$ -meson. All three simulation models underestimate the energy fraction by about  
 288 10–15% while the slope is reproduced to a much better level.

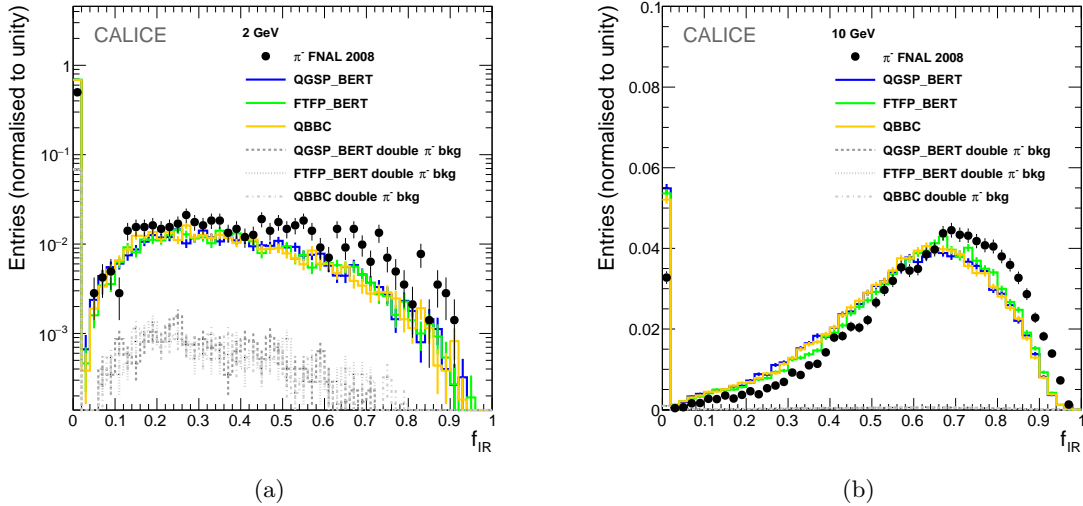


Figure 7: The  $f_{\text{IR}}$  distribution for energies of 2 GeV (a) and 10 GeV (b) of the beam energy as observed in data (points with error bars) and for the three simulation models, QGSP\_BERT, FTFP\_BERT and QBBC. The double  $\pi^-$ -meson background for each of the three models is also shown. The first bin contains events without a detected interaction region. All histograms are normalised to unit area. Error bars represent statistical uncertainties only.

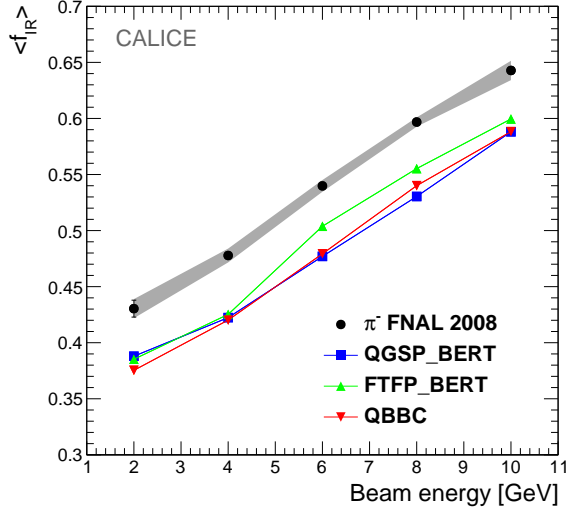


Figure 8: The average fraction  $\langle f_{\text{IR}} \rangle$  as a function of the beam energy for data (black points with grey shaded error band) and the three simulation models. Error bars represent statistical errors. The error band is the sum in quadrature of the systematic error and the statistical error. Only events for which an interaction region has been detected are included in  $\langle f_{\text{IR}} \rangle$ .

## 289 5.2. Lateral radius of interaction region

290 The lateral radius  $r_{\text{IR}}$  of the detected interaction region is a measure of the spatial extension of the  
 291 interaction region. It is defined as:

$$r_{\text{IR}} = \frac{1}{N_{\text{hits}}^{\text{IR}}} \sum_{\text{hit} \in \text{IR}} \sqrt{(\bar{x}_{\text{IR}} - x_{\text{hit}})^2 + (\bar{y}_{\text{IR}} - y_{\text{hit}})^2}, \quad (7)$$

292 where the sum runs over the hits in the interaction region, here labelled by IR, and  $N_{\text{hits}}^{\text{IR}}$  is the number  
 293 of hits in the interaction region. In Eq. 7  $\bar{x}_{\text{IR}}$  and  $\bar{y}_{\text{IR}}$  are the transverse coordinates of the barycentre  
 294 of the interaction region, which in analogy with Eq. 2, are defined as:

$$\bar{x}_{\text{IR}} = \frac{\sum_{\text{hit} \in \text{IR}} x_{\text{hit}} E_{\text{hit}}}{\sum_{\text{hit} \in \text{IR}} E_{\text{hit}}} \quad \text{and} \quad \bar{y}_{\text{IR}} = \frac{\sum_{\text{hit} \in \text{IR}} y_{\text{hit}} E_{\text{hit}}}{\sum_{\text{hit} \in \text{IR}} E_{\text{hit}}}. \quad (8)$$

295 Distributions of  $r_{\text{IR}}$  for data and the predictions of the three simulation models are displayed in  
 296 Fig. 9 for  $\pi^-$ -meson energies of 2 and 10 GeV. In both cases, the measured interaction region is wider  
 297 than the predictions by the simulation models. Figure 10 displays the dependence of the average  
 298  $r_{\text{IR}}$ ,  $\langle r_{\text{IR}} \rangle$ , on the beam energy for the data and the three simulation models. Again, only events in  
 299 which an interaction region has been detected are included in  $\langle r_{\text{IR}} \rangle$ . The lateral size of the interaction  
 300 region increases with increasing beam energy. This trend is the same for data and for the simulation  
 301 models. The interaction region measured in data is about 10% wider than those predicted by the three  
 302 simulation models, all of which yield similar distributions.

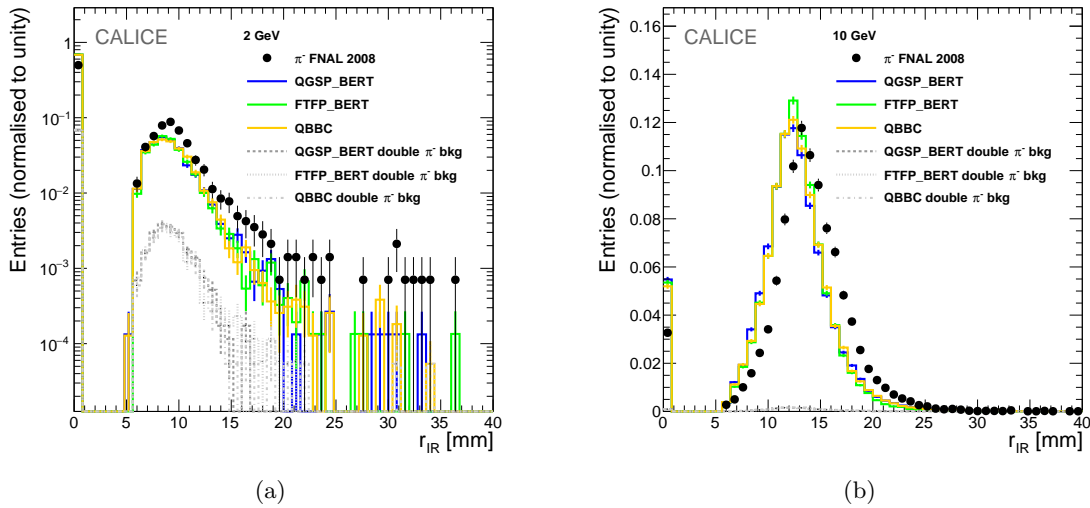


Figure 9: The  $r_{\text{IR}}$  distribution for energies of 2 GeV (a) and 10 GeV (b) of the beam energy. Other details follow those of Fig. 7.

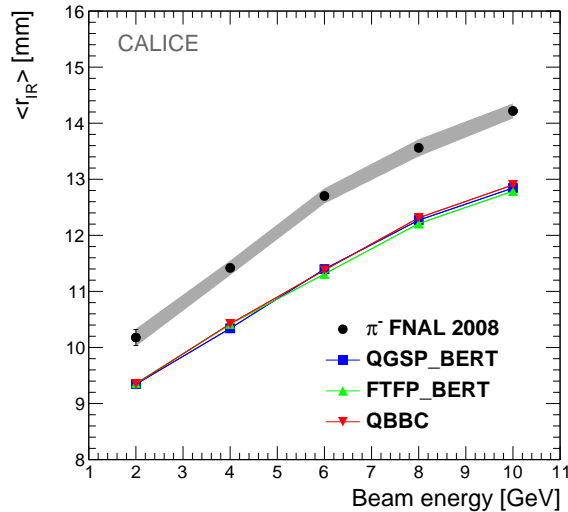


Figure 10: The average radius  $\langle r_{\text{IR}} \rangle$  as a function of the beam energy. Other details follow those of Fig. 8.

### 303 5.3. Number of clusters

304 The final tracks are composed from segments that are given by clusters, as described in Sec. 4.2.  
 305 This motivates studying the total number of clusters,  $N_{\text{clusters}}$ , reconstructed in each event by the  
 306 track-finding algorithm. This observable is independent of details of the track-finding algorithm since  
 307 it depends neither on the  $\varepsilon$  parameter value nor on other free parameters of the classification algorithm.  
 308 Note that in all following discussion, only events in which an interaction region has been detected are  
 309 considered. Figure 11 compares the distribution of  $N_{\text{clusters}}$  in data with the predictions of the three  
 310 GEANT4 simulation models for incoming  $\pi^-$ -mesons with energies of 2 and 10 GeV. The data are  
 311 described well by the simulation albeit being slightly shifted towards higher values.

312 Figure 12 shows the dependence of the average number of clusters,  $\langle N_{\text{clusters}} \rangle$ , on the beam energy  
 313 for data and the simulation models. The predictions of the models are systematically below data at all  
 314 energies. The largest deviation is about 7%. The agreement tends to improve with increasing beam  
 315 energy and is best at 10 GeV.

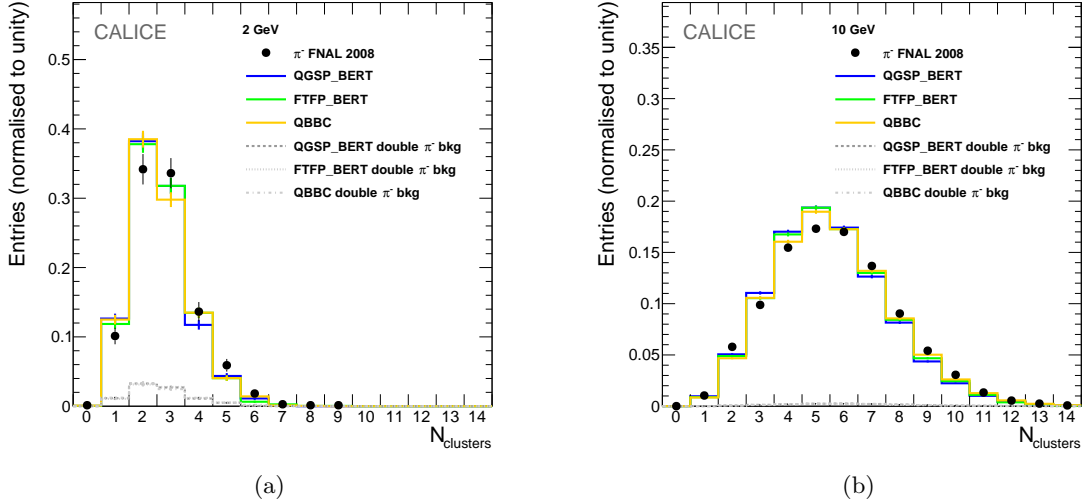


Figure 11: Number of clusters for energies of 2 GeV (a) and 10 GeV (b) of the beam energy. Only events for which an interaction region has been detected have been included. Other details follow those of Fig. 7.

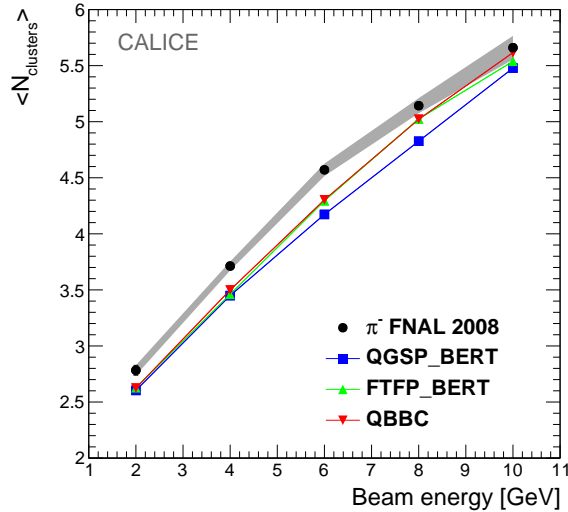


Figure 12: The average number of clusters  $\langle N_{\text{clusters}} \rangle$  as a function of the beam energy. Other details follow those of Fig. 8.

#### 316 5.4. Number of tracks

317 The  $N_{\text{tracks}}$  distributions are given in Fig. 13 for data and the three simulation models for energies  
 318 of 2 and 10 GeV of the incoming  $\pi^-$ -mesons, respectively. Data and simulation are in good agreement,  
 319 although at 10 GeV the simulation predicts a narrower spread in  $N_{\text{tracks}}$  than data.

320 Figure 14 shows the dependence of  $\langle N_{\text{tracks}} \rangle$  on the beam energy for data and the simulation models.  
 321 With increasing beam energy the centre-of-mass energy available for the  $\pi$ -tungsten scattering increases  
 322 with the square-root of the beam energy according to fixed target kinematics. It is therefore expected  
 323 that the number of outgoing tracks increases correspondingly. This is indeed observed in data and  
 324 simulation. The approximately linear increase at smallest energies flattens out towards higher beam  
 325 energies. The extension of the interaction zone also increases with energy, see for example Sec. 5.2.  
 326 This makes it more and more difficult to reconstruct clean tracks in the finite volume of the Si-W  
 327 ECAL. The simulation models are in agreement with the data at beam energies of 2 GeV and 10 GeV  
 328 and underestimate the number of secondary tracks by up to 7% at intervening energies.

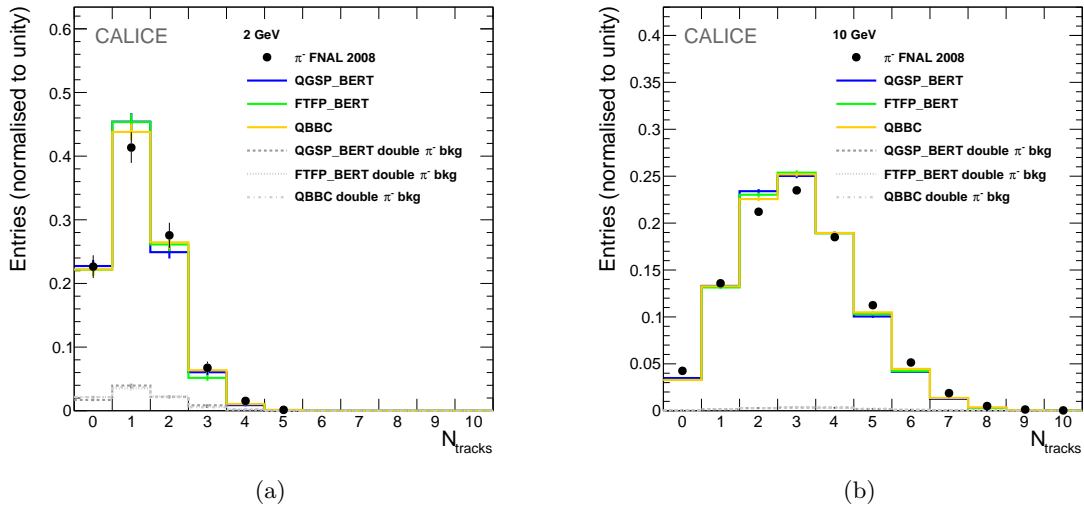


Figure 13: Number of secondary tracks for energies of 2 GeV (a) and 10 GeV (b) of the beam energy. Other details follow those of Fig. 11.

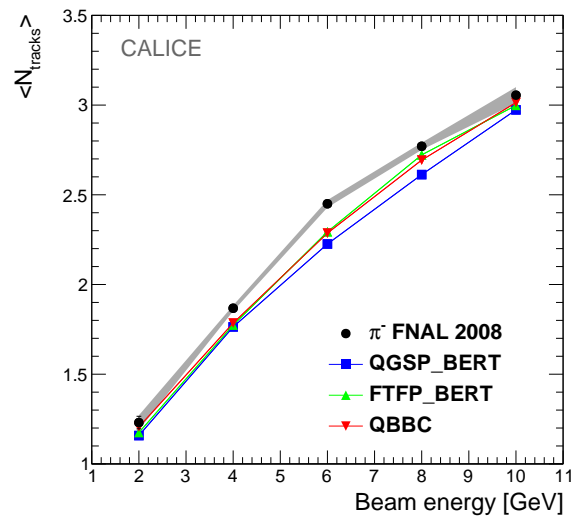


Figure 14: The average number of secondary tracks  $\langle N_{\text{tracks}} \rangle$  as a function of the beam energy. Other details follow those of Fig. 8.

329 5.5. Number of hits per track

330 The number of hits per track  $N_{\text{hits}}^t$  is an essential characteristic of the reconstructed tracks. The  
 331 histograms of  $N_{\text{hits}}^t$  for 2 and 10 GeV beam energy are shown in Fig. 15. The distributions obtained  
 332 for data and Monte Carlo are in good agreement with each other.

333 Figure 16 shows the dependence of  $\langle N_{\text{hits}}^t \rangle$  on the beam energy for data and the simulation models.  
 334 Data and simulation agree within 5%. For energies greater than 4 GeV all simulation models are,  
 335 however, systematically above the data. Note that the average number of hits slightly decreases with  
 336 increasing energy. The increasing size of the interaction zone limits the space available for track  
 337 reconstruction. This observation is, therefore, consistent with the flattening of the number of tracks  
 338 observed in Sec. 5.4.

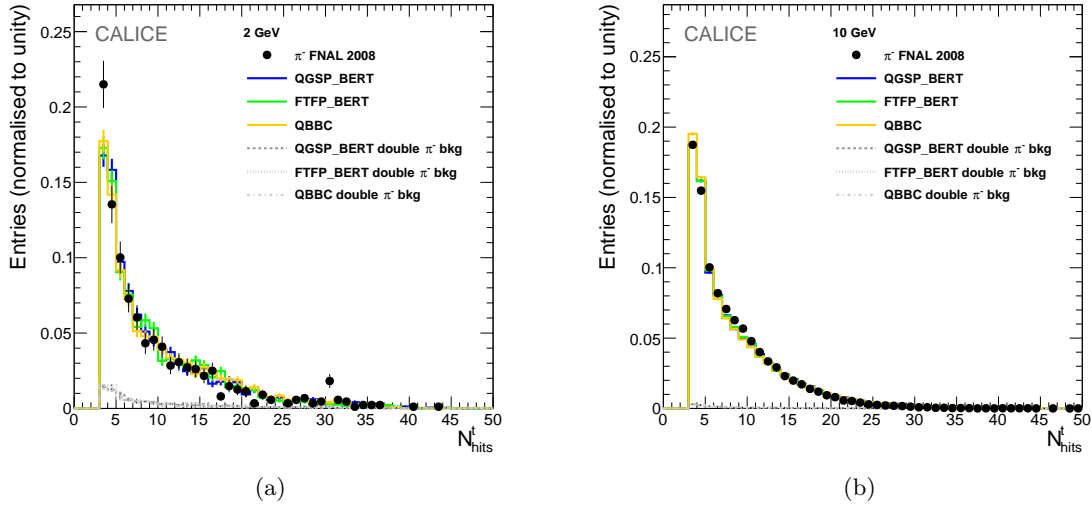


Figure 15: Number of hits per reconstructed track for energies of 2 GeV (a) and 10 GeV (b) of the beam energy. Other details follow those of Fig. 11.



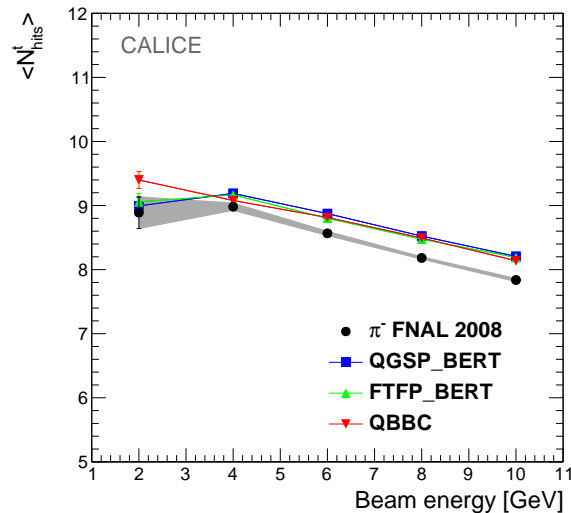


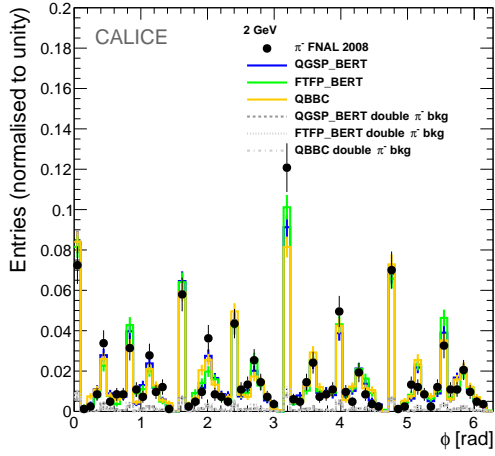
Figure 16: The average number of hits per reconstructed track  $\langle N_{\text{hits}}^t \rangle$  as a function of the beam energy. Other details follow those of Fig. 8.

### 339 5.6. Angular distributions

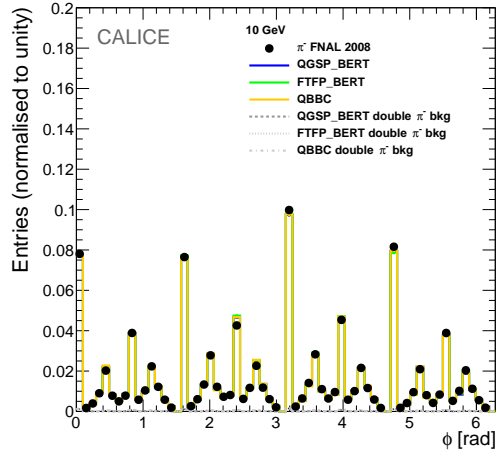
340 Due to the high granularity of the Si-W ECAL further tracking observables such as the polar  
 341 ( $\theta$ ) and azimuthal ( $\phi$ ) angles of secondary tracks become available. Both angles are measured in the  
 342 right-handed coordinate frame defined in Sec. 3.1 with  $\theta$  measured relative to the  $z$ -axis. The track  
 343 direction is calculated from the position of the first and the last hit of the track along the  $z$ -axis.

344 Figures 17 and 18 display histograms of the  $\phi$  and  $\theta$  angles, respectively, for 2 and 10 GeV data  
 345 together with corresponding corresponding results from simulation models. When corrected for the  
 346 staggering of the detector layers in  $x$  [4], the pad coordinates of the Si-W ECAL define a grid with  
 347 a step width of about 1 cm in the lateral direction. This leads to a discretisation of the measured  
 348 track direction. In particular, in the case of the azimuthal angle  $\phi$ , values that are a multiple of  $\pi/4$   
 349 are favoured. Beyond that the distribution in  $\phi$  is isotropic as expected. The bulk of the tracks are  
 350 scattered in polar angles  $\theta$  less than  $\pi/2$  as expected for a fixed target scattering. On the other hand  
 351 the polar angle spectrum develops a long tail created by backward scattered particles. The simulation  
 352 models reproduce the data adequately, largely within the experimental uncertainties.

353 The truncated mean of the  $\theta$  angle,  $\langle \theta \rangle$ , which can be interpreted as a measure of the collimation  
 354 of the secondary particles, is shown in Fig. 19 as a function of the beam energy. Here tracks with  
 355 polar angles smaller than  $\pi/2$  have been selected. The observable  $\langle \theta \rangle$  has only a weak dependence on  
 356 the beam energy but shows the tendency to decrease with increasing energy as expected due to the  
 357 increase of the boost transferred to the secondary particles. The simulation models reproduce the data  
 358 within a few percent, albeit the boost is less visible.

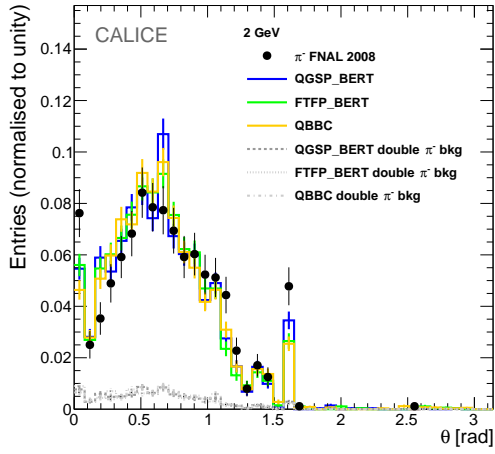


(a)

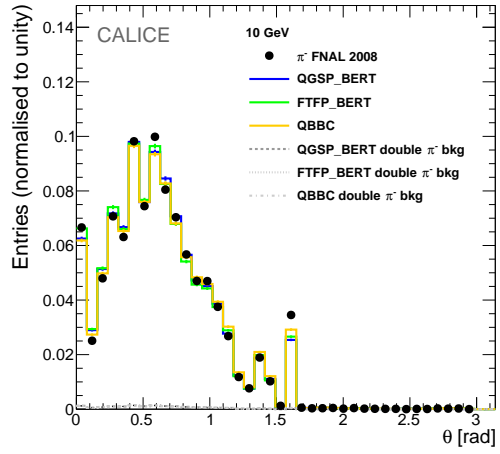


(b)

Figure 17: Comparison of the azimuthal angle  $\phi$  of secondary tracks for energies of 2 GeV (a) and 10 GeV (b) of the incoming  $\pi^-$ -mesons. Other details follow those of Fig. 11.



(a)



(b)

Figure 18: The polar angle  $\theta$  of secondary tracks for energies of 2 GeV (a) and 10 GeV (b) of the incoming  $\pi^-$ -mesons. Other details follow those of Fig. 11.

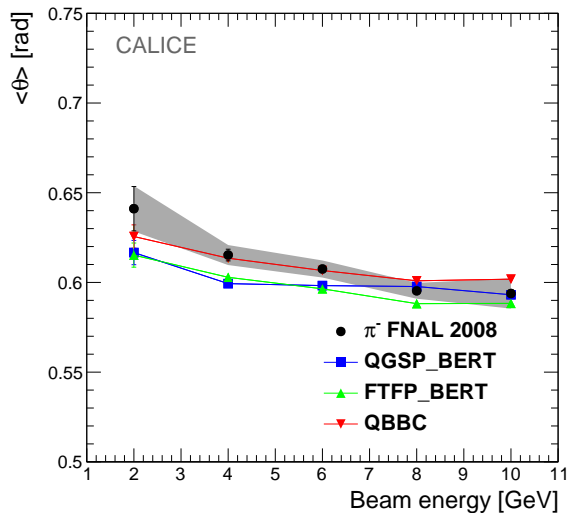


Figure 19: The truncated mean polar angle  $\langle\theta\rangle$  of secondary tracks as a function of the beam energy. Only tracks with polar angles less than  $\pi/2$  have been selected. Other details follow those of Fig. 8.

### 359 5.7. Energy deposition by secondary tracks

360 At energies relevant for this study, the secondaries that create sizeable tracks cross the detector  
 361 volume behaving in a similar manner to minimally ionising particles. This fact may be exploited as an  
 362 in situ calibration of the detector, or at least to monitor the response of individual detector regions.  
 363 For this specific study the selection criteria of events and tracks are modified as follows:

- 364 • events are required to have more than one track and an interaction region to suppress soft inelastic  
 365 scattering interactions at lower energies;
- 366 • reconstructed tracks must have a length  $l \geq 8$  g. u. and  $l/N_{\text{hits}} > 0.9$  g. u. to select long ‘pencil-like’  
 367 tracks;
- 368 • Reconstructed tracks must have a polar angle  $\theta < 0.3$  rad to reduce the angular dependence of  
 369 the energy deposits.

370 Figure 20 displays the energy deposition per hit by secondary tracks  $E_{\text{dep}}^t$  for beam energies of 2  
 371 and 10 GeV. Both distributions peak at around 1 MIP as expected for straight MIP-like tracks. The  
 372 overlaid fit is a Landau distribution convolved with a Gaussian resolution function, describing the data  
 373 well. The tighter selection criteria reduce considerably the event sample at 2 GeV. As a consequence,  
 374 the statistical uncertainty of the fit is large for the 2 GeV sample.

375 Figure 21 presents the dependence of the most probable value (MPV) of the energy deposition in  
 376 secondary tracks on beam energy. The MPV is about 1.05, which is compatible with the fact that the  
 377 selected tracks cross the detector pads at a small angle. It can be seen that the detector response is  
 378 both uniform within 1–2% for the analysed energy range in data and reproduced by the simulation  
 379 models within 1–2%.

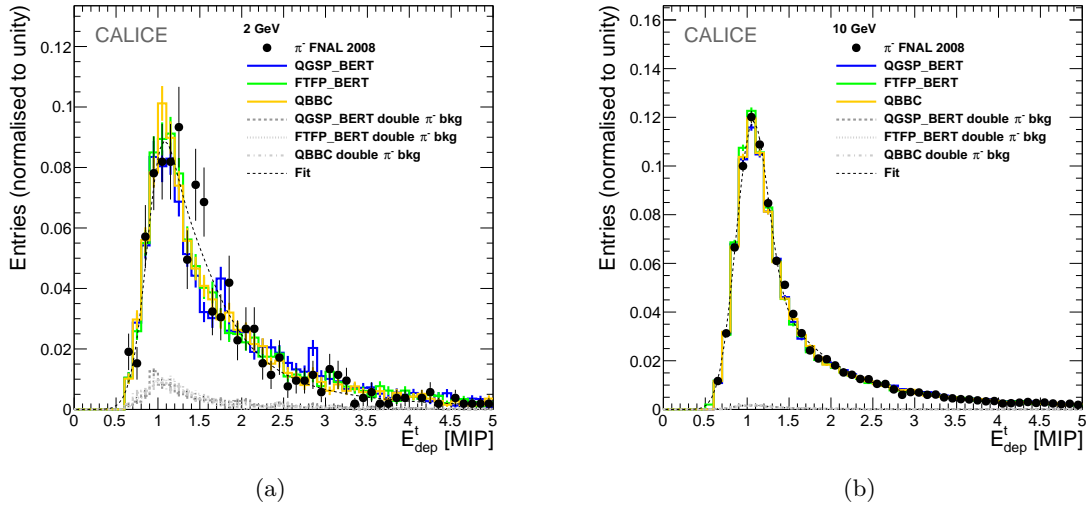


Figure 20: Energy deposition by secondary tracks observed in data (points with error bars) and for the three simulation models for beam energies of 2 GeV (a) and 10 GeV (b). The spectra are fit by the convolution of a Landau distribution with a Gaussian resolution function. The double  $\pi^-$ -meson background for the three models is shown by the grey dashed, dotted and dash-dotted histograms, respectively. All histograms are normalised to unity. Error bars represent statistical uncertainties only.

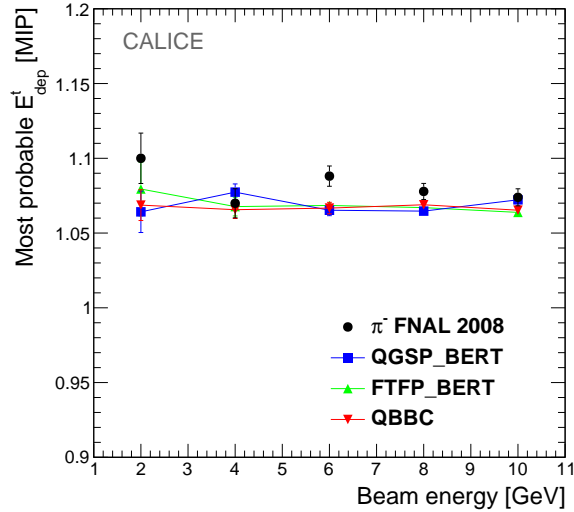


Figure 21: MPV of the Landau fit to the  $E_{\text{dep}}^t$  distributions of the 'pencil-like' secondary tracks as a function of the beam energy for  $\pi^-$  data (black points with error bars) in comparison to the three simulation models. Error bars represent the statistical fit uncertainty.

380 The algorithm has selected particles with approximately minimally ionising behaviour. The uniform  
 381 response supports the idea that the secondary tracks can be used for the in situ monitoring of the  
 382 calibration.

## 383 6. Summary and outlook

384 This study reveals the large potential of the CALICE Si-W ECAL physics prototype to obtain  
385 a detailed picture of the interactions of hadrons with matter. The article describes basic ideas and  
386 the application of a new simple track-finding algorithm for the Si-W ECAL. This algorithm allows  
387 for the reconstruction of tracks produced by secondary particles created in the interaction of hadrons  
388 with the absorber material, and hence to study the interaction region of hadron showers in the Si-W  
389 ECAL. The track-finding algorithm produces a new set of observables, based on reconstructed tracks  
390 of secondary particles and the interaction region of the hadronic cascades.

391 Data recorded in test beams at FNAL in 2008 using  $\pi^-$ -mesons with energies between 2 and  
392 10 GeV are compared with predictions from the simulation models QGSP\_BERT, FTFP\_BERT and QBBC  
393 as implemented in GEANT4 Version 10.1. The agreement between data and simulation varies with  
394 beam energy and the chosen physics observable. In most cases data and simulation models agree  
395 within 10% without revealing a clear preference for one of the chosen simulation models.

396 The largest discrepancy between data and the simulation models is observed for the deposited  
397 energy in and the radius of the interaction region. The measured energy deposition in the interaction  
398 region is up to 15% higher than predicted by the Monte Carlo simulation. The distributions of the  
399 number of secondary tracks and the number of hits per track for data are described well by the  
400 simulation models. The distribution of the polar angle of the reconstructed tracks in the simulation  
401 agrees with data within 3–4 % and the distribution of azimuthal angles is reproduced well by the  
402 simulation models in spite of the non-trivial detector geometry.

403 Future work should aim at transferring the insights about the interaction region and the secondaries  
404 emerging from it to the optimisation of Particle Flow Algorithms.

405 A tighter track selection leads to long tracks by particles that show approximately minimally  
406 ionising behaviour. The detector response determined using these tracks is stable to about 1–2% over  
407 the tested energy range and shows good agreement with simulation. This observation can be exploited  
408 as a starting point for a feasibility study of an in situ calibration (or at least a regular monitoring of  
409 the detector) by means of the selected tracks.

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