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

The CALICE Collaboration

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48 **Abstract**

49 A detailed investigation of hadronic interactions is performed using π^- -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 π^- -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.

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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 π^- -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 π^- -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 6×6
 102 pads and each layer is a matrix of 3×3 of these wafers resulting in an active zone of $18 \times 18 \text{ cm}^2$.

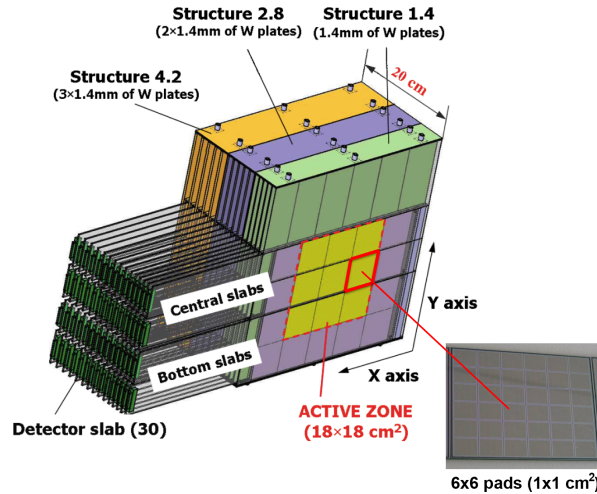


Figure 1: A schematic view of the Si-W ECAL physics prototype.

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 λ_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 Facility⁷, 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.

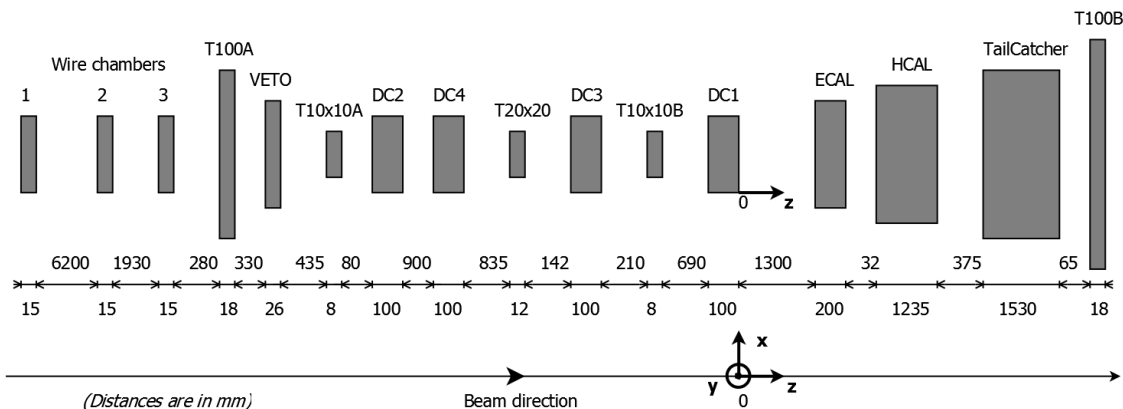


Figure 2: Plan view of the beam line at FNAL. Distances (not to scale) are in mm.

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 π^- -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;

⁷Fermilab 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].

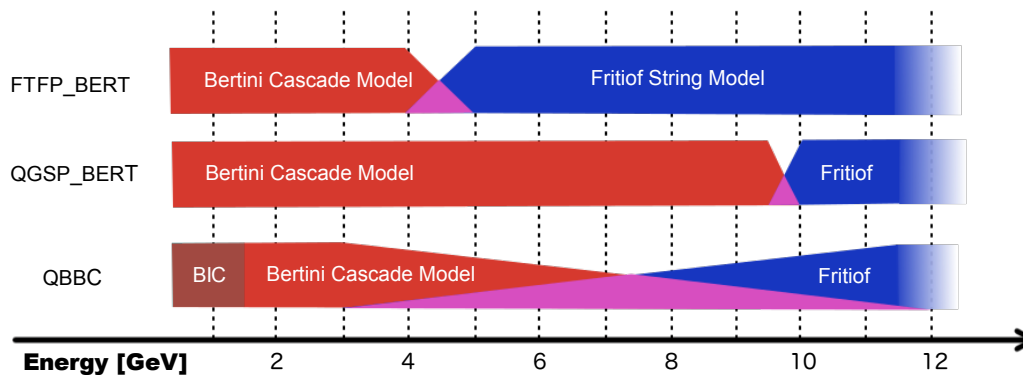


Figure 3: Illustration of the validity ranges of the three tested GEANT4 hadronic interaction models as contained in GEANT4 Version 10.1.

3.3. Event selection and preprocessing

The FNAL π^- test beam is contaminated with μ^- and e^- , in particular at lower energies. At 2 GeV the beam contains about 5% π^- -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 π^- -mesons are identified by using Cherenkov counters. The response of the Si-W ECAL to charged particles was calibrated with a 32 GeV μ^- 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 π^- -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 π^- -meson and the absorber material in the absence of a magnetic field.

179 The algorithm consists of three stages:

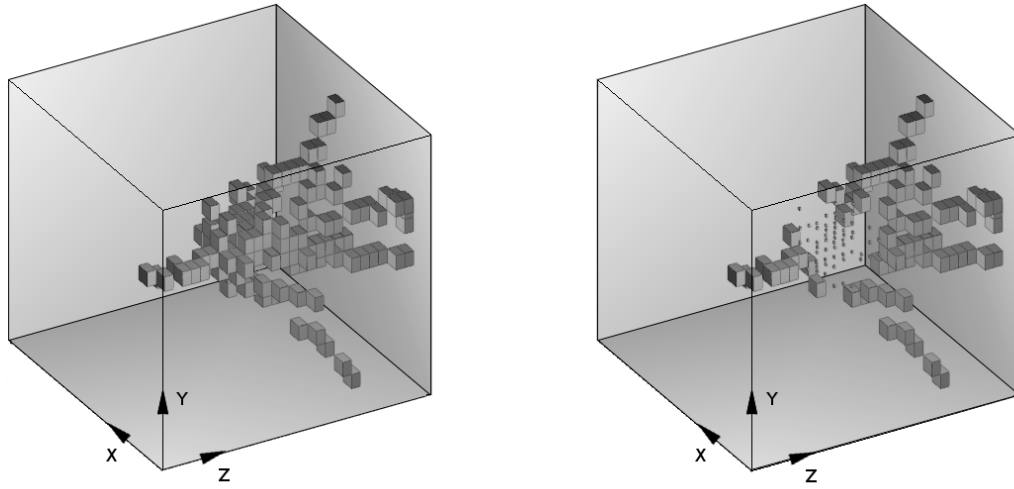
- 180 • identification and removal of interaction region;
- 181 • clusterisation of energy deposits;
- 182 • formation of track-like clusters;

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 π^- -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 π^- -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.

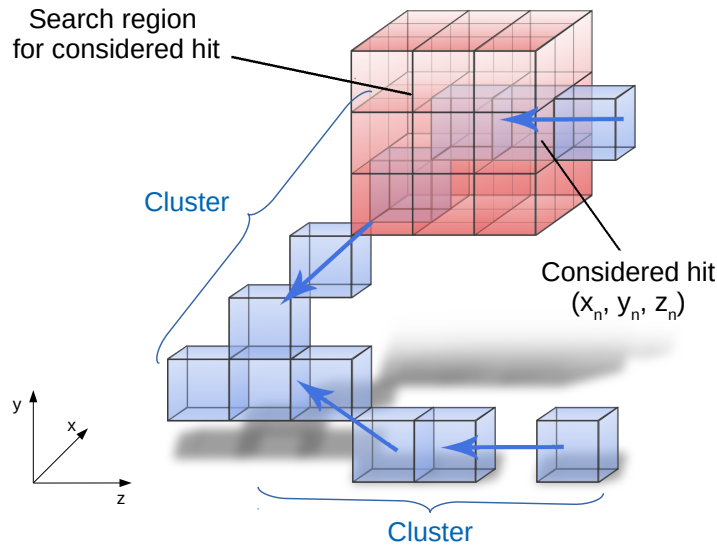


Figure 5: Illustration of the clusterisation step. The Si-W ECAL hits are represented by blue cubes, and the search region for adjacent hits is indicated by red cubes. The blue arrows point in the direction of the clusterisation flow.

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_{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 ε 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, δ -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 ξ serves to keep a cluster as track-like even if it has
 247 large N_{hits} and its form is not strictly pencil-shaped, i.e. $l/(N_{\text{hits}} - 1) < 1$.

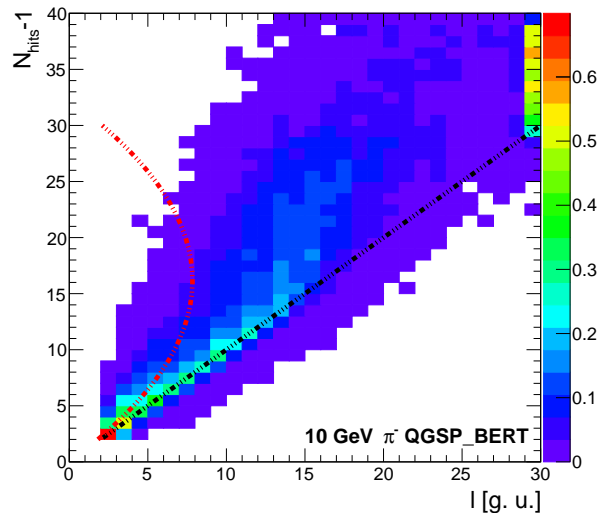


Figure 6: Correlation between $N_{\text{hits}} - 1$ and cluster length l in g.u. for a sample of simulated pion interactions with an energy of 10 GeV using the QGSP_BERT simulation model. Clusters inside the red parabola are rejected by means of Eq. 5. To guide the eye a black line for $N_{\text{hits}}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

248 A cluster is classified as being produced by the incoming π^- -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 π^- -meson is visible in Fig. 4b. Clusters assigned to the incoming π^- -meson
 251 are discarded in the following analysis. The remaining track-like clusters are merged into tracks if the
 252 relative angle θ_c between these clusters fulfils the condition $\sin \theta_c < 0.15$, optimised using the polar
 253 angle distribution of secondary particles in simulated π^- -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 π^- -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 π^- 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 π^- -mesons with the absorber material is the
 273 fraction

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

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

276 Figure 7 compares the distribution of f_{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_{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_{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 π^- -meson. All three simulation models underestimate the energy fraction by about
 288 10–15% while the slope is reproduced to a much better level.

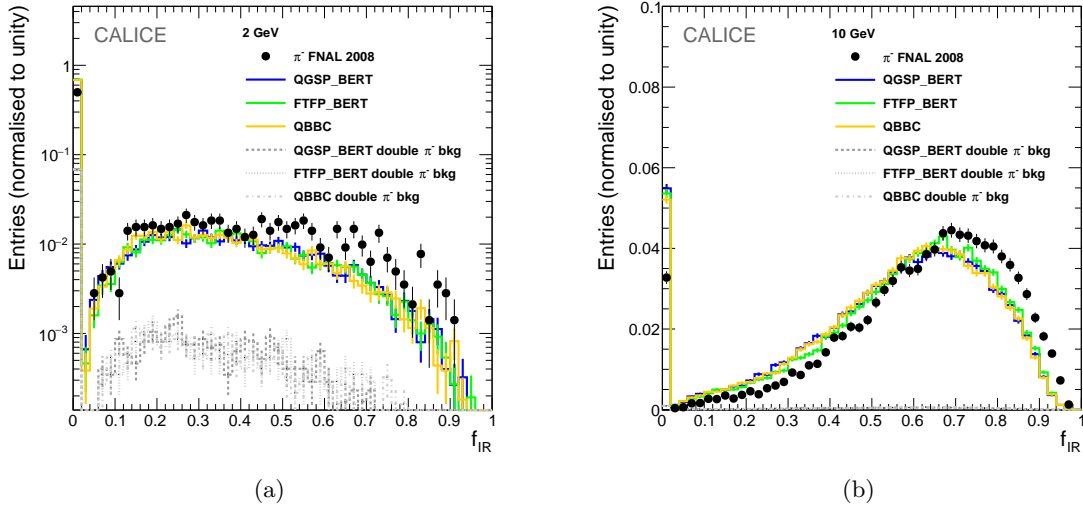


Figure 7: The f_{IR} distribution for energies of 2 GeV (a) and 10 GeV (b) of the beam energy as observed in data (points with error bars) and for the three simulation models, QGSP_BERT, FTFP_BERT and QBBC. The double π^- -meson background for each of the three models is also shown. The first bin contains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

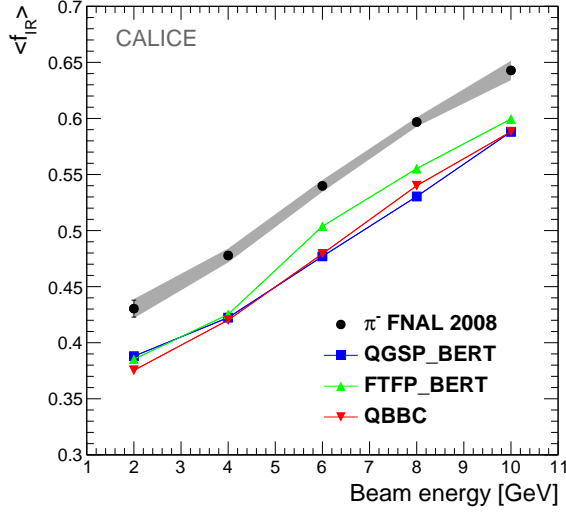


Figure 8: The average fraction $\langle f_{\text{IR}} \rangle$ as a function of the beam energy for data (black points with grey shaded error band) and the three simulation models. Error bars represent statistical errors. The error band is the sum in quadrature of the systematic error and the statistical 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_{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}_{IR} and \bar{y}_{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_{IR} for data and the predictions of the three simulation models are displayed in
 296 Fig. 9 for π^- -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_{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.

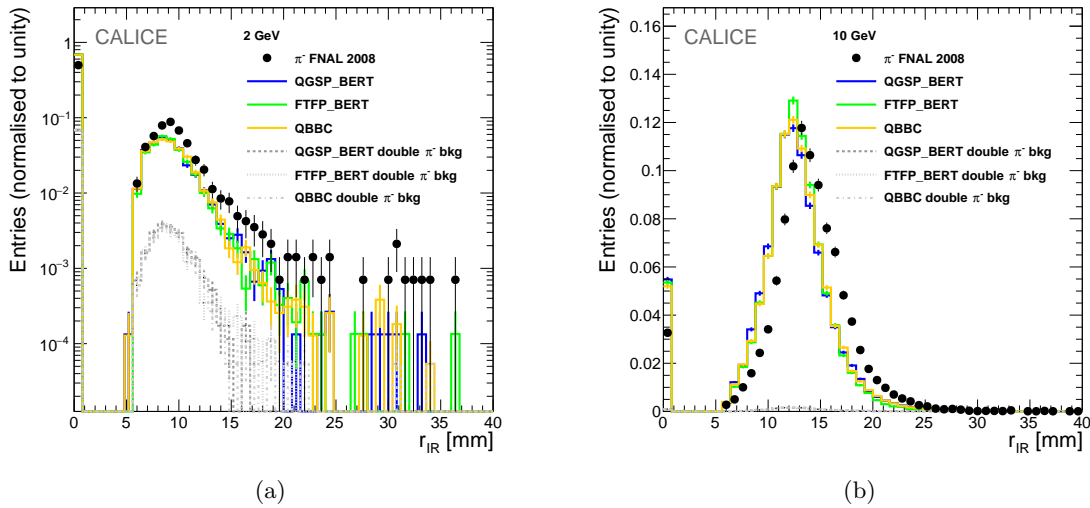


Figure 9: The r_{IR} distribution for energies of 2 GeV (a) and 10 GeV (b) of the beam energy. Other details follow those of Fig. 7.

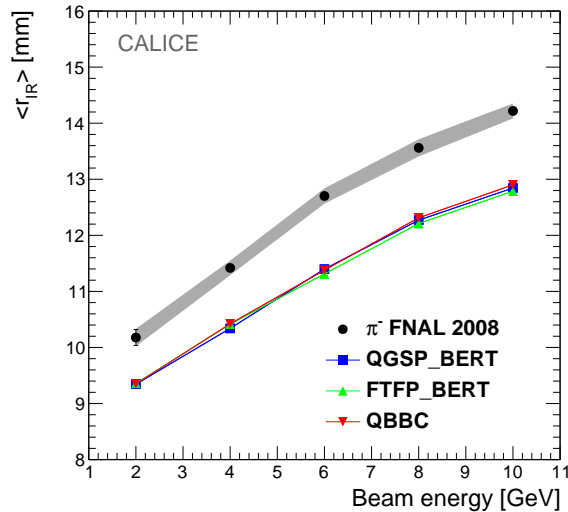


Figure 10: The average radius $\langle r_{\text{IR}} \rangle$ as a function of the beam energy. Other details follow those of Fig. 8.

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_{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 ε 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_{clusters} in data with the predictions of the three
 310 GEANT4 simulation models for incoming π^- -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.

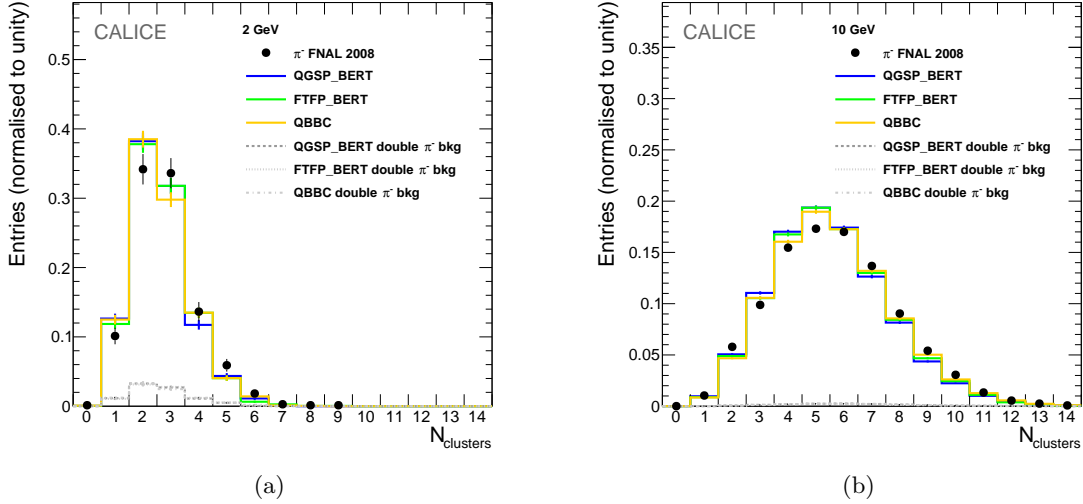


Figure 11: Number of clusters for energies of 2 GeV (a) and 10 GeV (b) of the beam energy. Only events for which an interaction region has been detected have been included. Other details follow those of Fig. 7.

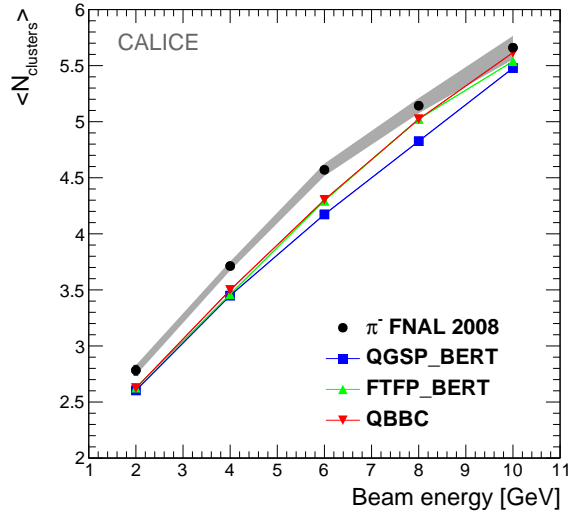


Figure 12: The average number of clusters $\langle N_{\text{clusters}} \rangle$ as a function of the beam energy. Other details follow those of Fig. 8.

316 5.4. Number of tracks

317 The N_{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 π^- -mesons, respectively. Data and simulation are in good agreement,
 319 although at 10 GeV the simulation predicts a narrower spread in N_{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 π -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.

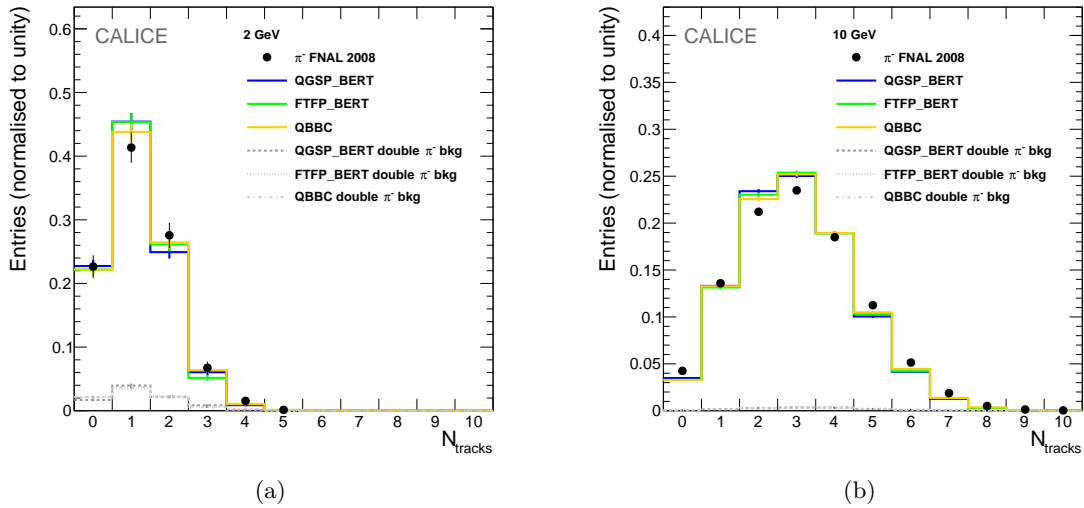


Figure 13: Number of secondary tracks for energies of 2 GeV (a) and 10 GeV (b) of the beam energy. Other details follow those of Fig. 11.

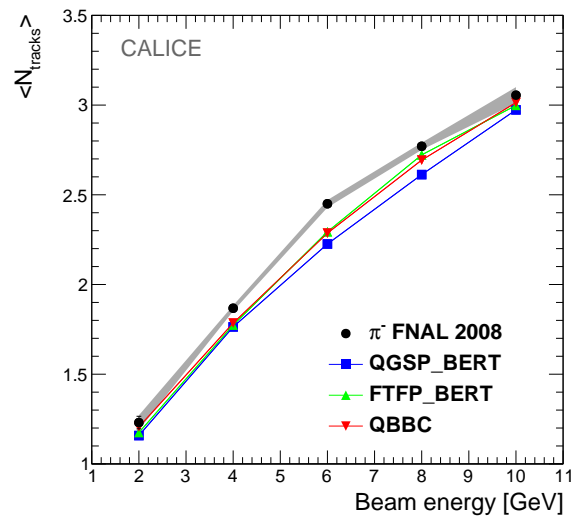


Figure 14: The average number of secondary tracks $\langle N_{\text{tracks}} \rangle$ as a function of the beam energy. Other details follow those of Fig. 8.

329 5.5. Number of hits per track

330 The number of hits per track N_{hits}^t is an essential characteristic of the reconstructed tracks. The
 331 histograms of N_{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.

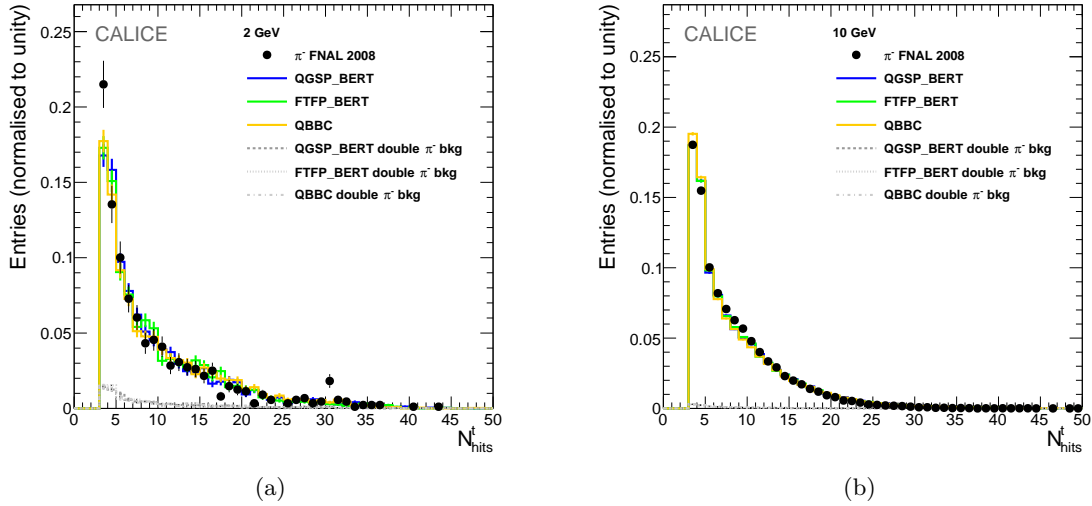


Figure 15: Number of hits per reconstructed track for energies of 2 GeV (a) and 10 GeV (b) of the beam energy. Other details follow those of Fig. 11.

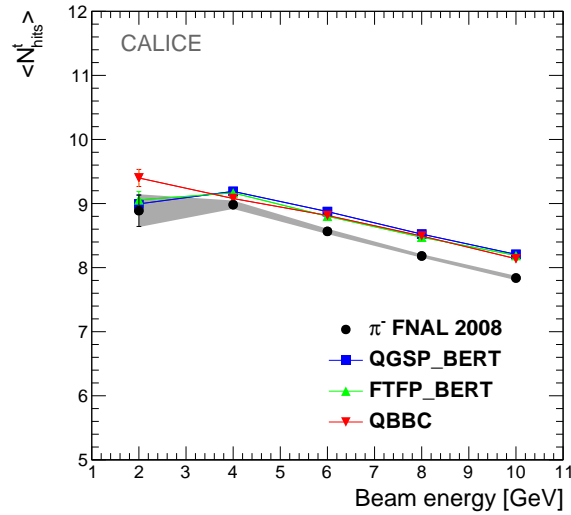


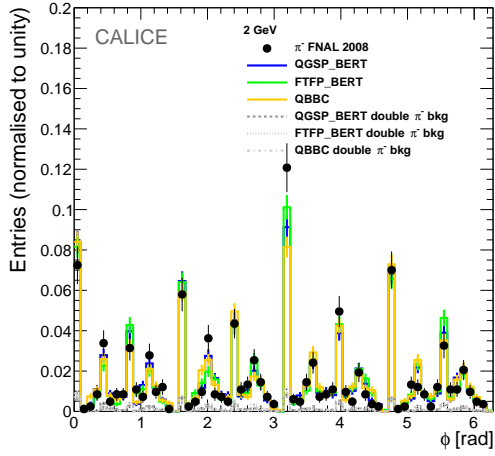
Figure 16: The average number of hits per reconstructed track $\langle N_{\text{hits}}^t \rangle$ as a function of the beam energy. Other details follow those of Fig. 8.

339 5.6. Angular distributions

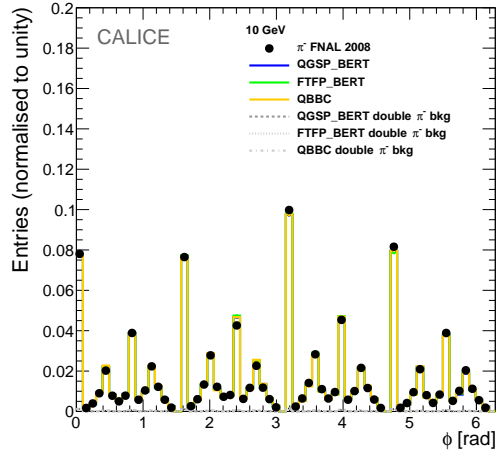
340 Due to the high granularity of the Si-W ECAL further tracking observables such as the polar
 341 (θ) and azimuthal (ϕ) angles of secondary tracks become available. Both angles are measured in the
 342 right-handed coordinate frame defined in Sec. 3.1 with θ measured relative to the z -axis. The track
 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 ϕ and θ 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 ϕ , values that are a multiple of $\pi/4$
 349 are favoured. Beyond that the distribution in ϕ is isotropic as expected. The bulk of the tracks are
 350 scattered in polar angles θ 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 θ 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.

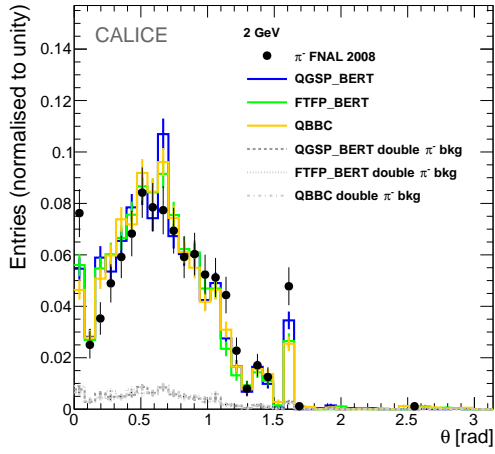


(a)

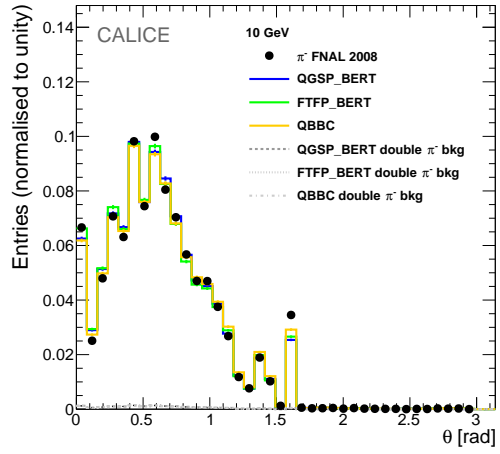


(b)

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



(a)



(b)

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

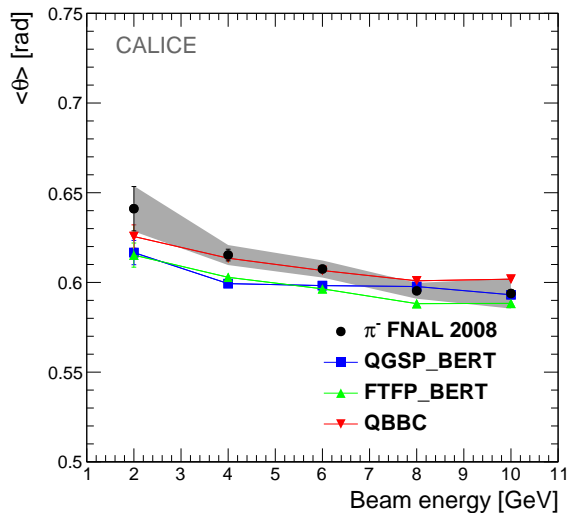


Figure 19: The truncated mean polar angle $\langle\theta\rangle$ of secondary tracks as a function of the beam energy. Only tracks with polar angles less than $\pi/2$ have been selected. Other details follow those of Fig. 8.

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_{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%.

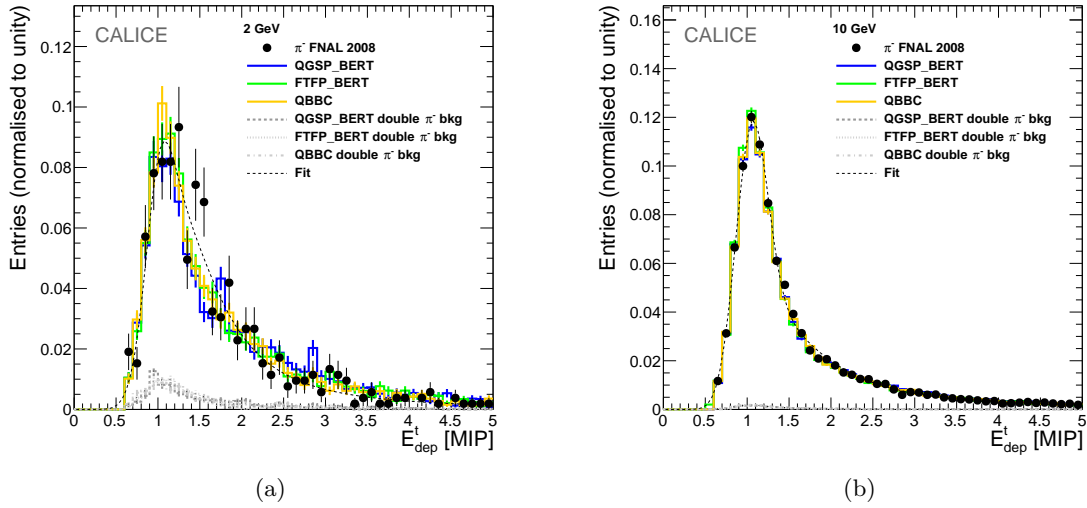


Figure 20: Energy deposition by secondary tracks observed in data (points with error bars) and for the three simulation models for beam energies of 2 GeV (a) and 10 GeV (b). The spectra are fit by the convolution of a Landau distribution with a Gaussian resolution function. The double π^- -meson background 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.

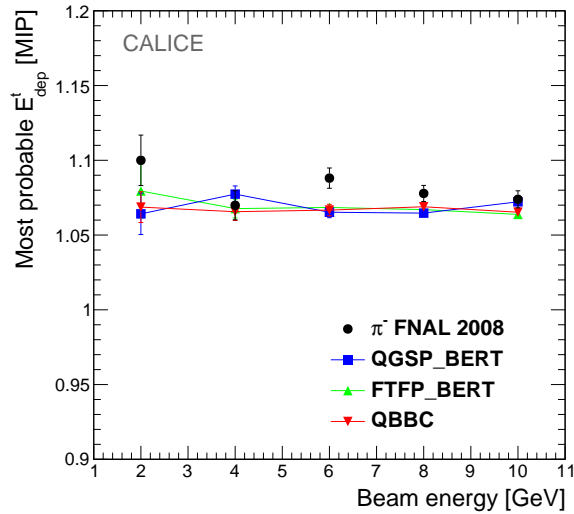


Figure 21: MPV of the Landau fit to the E_{dep}^t distributions of the 'pencil-like' secondary tracks as a function of the beam energy for π^- data (black points with error bars) in comparison to the three simulation tracks models. Error bars represent the statistical fit uncertainty.

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 π^- -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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