

Design of an Electromagnetic Calorimeter for use at a future e^+e^- Linear Collider

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Abstract

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Keywords: Particle flow calorimetry, ECAL, Linear Collider, CLIC

1. Introduction

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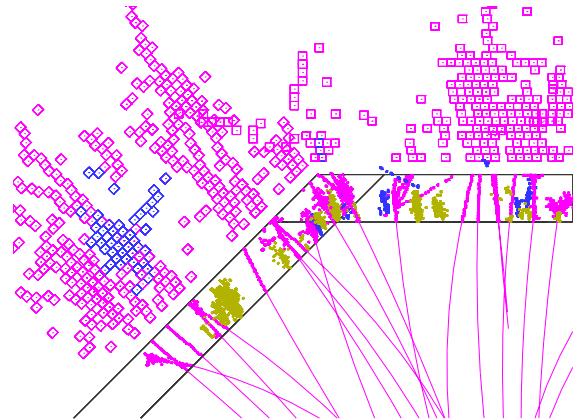


Figure 1

2. Implementation

2.1. Simulation

25 The simulation of detector model response to var-
26 ious physics events was performed using MOKKA.
27

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28 MOKKA uses Geant4 and the geometry information for
 29 a given detector model to produce detailed simulations
 30 of detector response for various ILC detector concepts.
 31 The flexibility in MOKKA allows various detector pa-
 32 rameters to be modified and so optimisation studies can
 33 be performed. In this study the optimisation was per-
 34 formed with respect to the ILD detector model.

35 2.2. Reconstruction

36 The reconstruction of physics events was performed
 37 using the MARLIN reconstruction framework, which
 38 allows for modular implementation of various c++ pro-
 39 grams each tasked with one aspect of the reconstruc-
 40 tion. While several programs are used in the full recon-
 41 struction it is important to highlight firstly to the pattern
 42 recognition implementation of particle flow calorime-
 43 try, which is done using PandoraPFA, and secondly the
 44 digitisation of calorimeter hits, implemented in the ILD-
 45 CaloDigi processor.

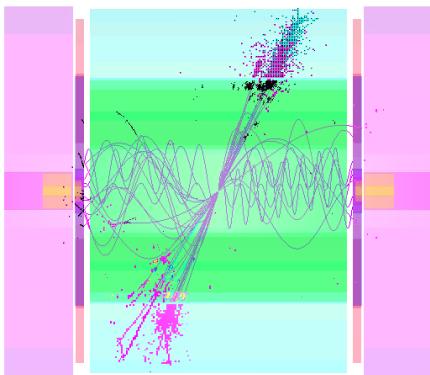


Figure 2: Typical topologies 250GeV jets simulated in the ILD detector model.

46 2.2.1. PandoraPFA

47 The PandoraPFA software package implements the
 48 pattern recognition side of particle flow calorimetry. It
 49 is essential that calorimeter hits are correctly assigned
 50 to charged particle tracks to avoid double counting of
 51 energy in the particle flow paradigm. This can be ex-
 52 tremely challenging given the complex topologies asso-
 53 ciated to particle showers at high energies such as those
 54 shown in figure 2.

55 Due to the varied nature of detector models be-
 56 ing simulated in these studies it is necessary to have
 57 reusable and flexible software that is isolated from the
 58 detector model. This is achieved using the Pandora
 59 Software Development Kit (PandoraSDK), which is an

60 independent framework for applying sophisticated topo-
 61 logical algorithms designed to perform the association
 62 of calorimeter hits to charged particle tracks. The al-
 63 gorithm logic applied in PandoraSDK is independent of
 64 detector model.

65 2.2.2. ILDCaloDigi

66 The ILDCaloDigi processor is designed to perform
 67 the digitisation of calorimeter hits for the ILD detector
 68 model. Digitisation of calorimeter hits is the process by
 69 which the energy deposits in the absorber (non-active)
 70 region of a calorimeter cell is estimated using the mea-
 71 sured value of the energy deposited in the active region
 72 of the cell. Accurate energy estimators for calorimeter
 73 cells is crucial for estimating detector performance and
 74 so calibration at this stage is essential for all simula-
 75 tions.

76 A number of realistic effects can be simulated using
 77 the ILDCaloDigi processor, the full details of which can
 78 be found here. For these studies electrical noise and a
 79 limited electronics read out range was simulated and the
 80 effect of timing cuts was analysed in detail.

81 2.3. Calibration

82 To ensure reliability in the conclusions drawn from
 83 these optimisation studies, it was necessary to calibrate
 84 the response of each detector model considered. This
 85 occurred in three stages, the full details of which can be
 86 found here.

87 Initially, the detector response to minimum ionising
 88 particles (MIPs) was determined by looking at the de-
 89 tector response to muons. This set the MIP scale in both
 90 the digitiser and inside PandoraPFA, which is needed as
 91 a reference energy unit for applying thresholds and cuts.

92 Secondly, the digitisation stage of the reconstruction
 93 was tuned for events of photons and long lived neutral
 94 kaons for events that were contained within the ECAL
 95 and HCAL respectively. This tuning was an iterative
 96 procedure where constants in the digitisation proces-
 97 sor, ILDCaloDigi, were varied and simulations repeated
 98 until the sum of calorimeter hit energies matched the
 99 Monte-Carlo energy of the photons and long lived neu-
 100 tral kaons being simulated.

101 Finally, the electromagnetic and hadronic energy
 102 scales within PandoraPFA must be correctly set. This
 103 is done by independently scaling the energy of parti-
 104 cle flow objects (PFOs), the output reconstructed parti-
 105 cles from PandoraPFA, for PFOs originating from elec-
 106 tron magnetic and hadronic showers separately. This is
 107 again done in an iterative procedure involving changing
 108 the inputs to PandoraPFA and repeating simulations un-
 109 til the PFO energy matches the Monte-Carlo energy for

110 the photons (electromagnetic showers) and long lived
 111 neutral kaons (hadronic showers) being simulated.

112 2.4. Parameterising Detector Performance

113 The primary figure of merit used in these optimisation
 114 studies is the jet energy resolution, as extensively
 115 described in (Pandora paper chapter 5). The jets used
 116 in these studies are from the decay of off-shell mass Z
 117 bosons decaying at rest into a pair of light quarks (u,d,s).
 118 Typically, such decays form mono-energetic jets back to
 119 back as can be seen in figure 2.

120 It is possible to decompose the jet energy resolution
 121 into various components by cheating various parts of the
 122 reconstruction as shown in figures 3 and 4. This pro-
 123 vides a wealth of information that can be used to distin-
 124 guish performance changes related to pattern recogni-
 125 tion from changes related to intrinsic energy resolution.

126 3. Jet Energy Resolution and Calibration

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149 4. ECAL Parameter Scan

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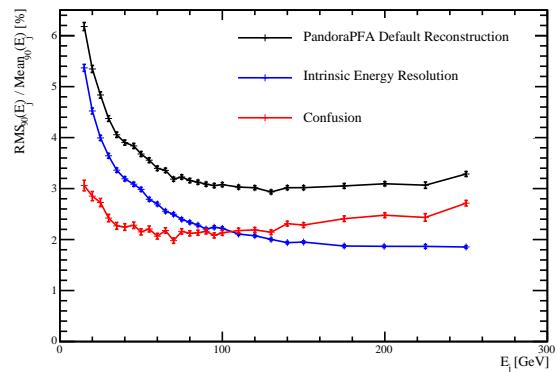


Figure 3: Jet energy resolution as a function of jet energy for the ILD detector model. The jet energy resolution has been decomposed into the intrinsic energy resolution and the confusion terms.

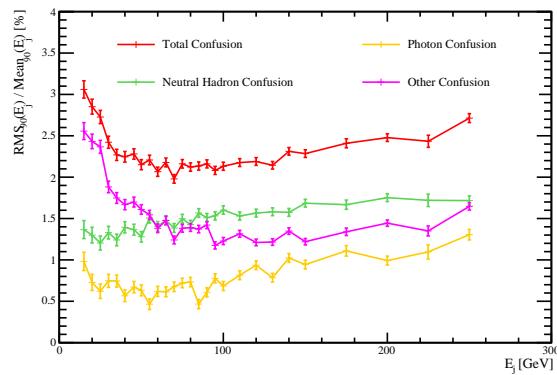


Figure 4: Confusion decomposed into various terms as a function of jet energy. Simulation was performed using the ILD detector model.

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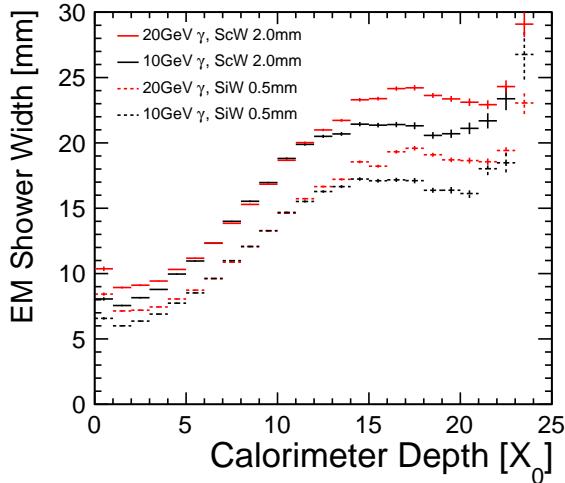
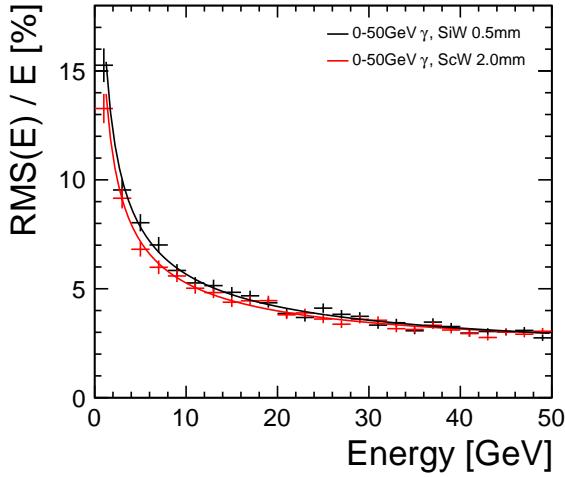


Figure 5

172 4.1. Transverse Granularity

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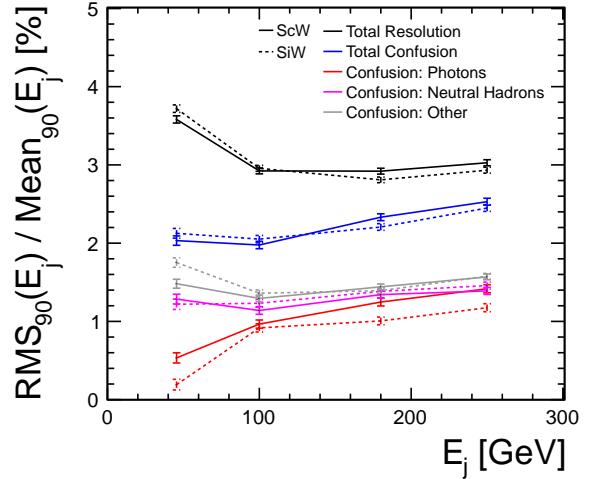


Figure 6

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195 4.2. Number of Layers

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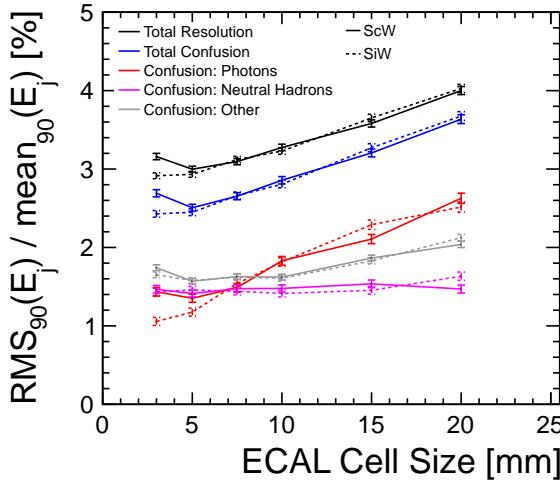
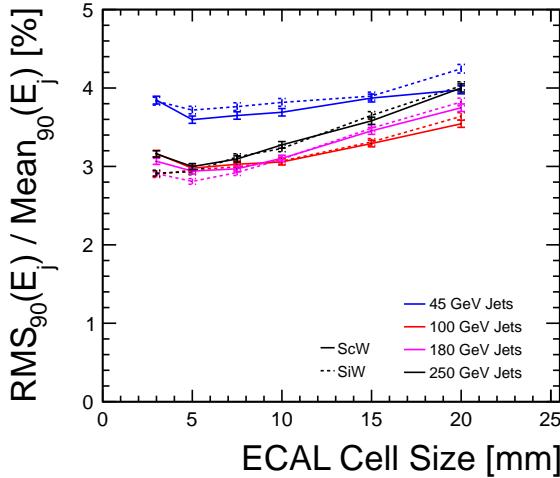


Figure 7

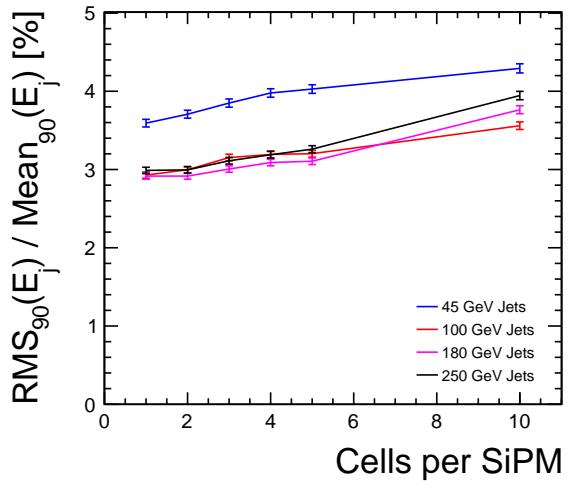
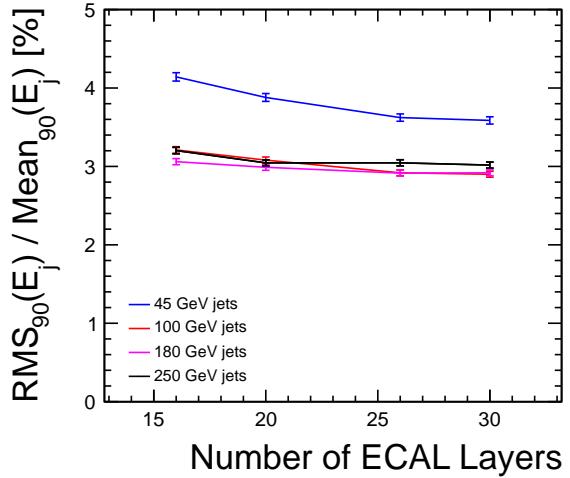


Figure 8

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218 5. HCAL Parameter Scan

219 ILD detector model used. Timing cuts used are 10ns
220 in HCAL and 20ns in ECal. No MaxHCALHitHadron-
221 icEnergy. Full calibration procedure applied for all
222 detector models. QGSP_BERT physics list used in
223 all cases except Fe and W comparison where both
224 QGSP_BERT and QGSP_BERT_HP used.

225 5.1. Fe/W HCAL Comparison

226 The feasible options for HCAL absorber material are
227 steel (Iron) and tungsten (WMod). The thicknesses of
228 the scintillator and absorber layers of the HCAL were
229 scaled to maintain the total number of nuclear interaction
230 lengths in the HCAL. The ratio of scintillator and
231 absorber thicknesses in the HCAL was held constant to
232 maintain the sampling fraction. Otherwise default ILD
233 DBD detector parameters were used.

234 Both the QGSP_BERT and QGSP_BERT_HP physics
235 lists were used in this analysis. The high precision neutron
236 package, included in QGSP_BERT_HP, offers more
237 realistic modelling of the transportation of neutrons below
238 20 MeV down to thermal energies. The compact

239 nature of the hadronic showers showering in tungsten
 240 was the primary reason for the inclusion of the high pre-
 241 cision neutron package in this analysis.

242 HCals using steel as an absorber material were found
 243 to outperform those using tungsten across the entire
 244 range of jet energies considered. This trend was found
 245 to be more prominent for high energy jets. No strong
 246 dependance on the choice of physics list was observed.

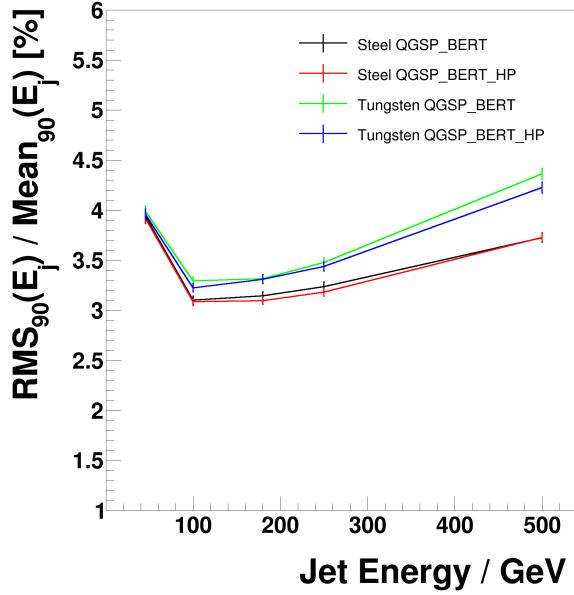


Figure 9: The jet energy resolution as a function of jet energy. Results are shown for detectors using both steel and tungsten HCal absorber materials and using both the QGSP_BERT and QGSP_BERT_HP physics lists.

247 5.2. Transverse Granularity

248 The transverse granularity of the HCal, the HCal cell
 249 size, was varied. Otherwise, default ILD DBD detector
 250 parameters were used in this analysis.

251 Figure 10 shows the jet energy resolution as a function
 252 of HCal cell size for various energy jets. It was
 253 found that smaller HCal cell sizes benefited the jet en-
 254 ergy resolution and that this trend became more promi-
 255 nent for higher energy jets. The jet energy resolution
 256 was decomposed into the confusion and intrinsic energy
 257 resolution terms. The results of this decomposition for
 258 the 250 GeV jets are shown in figure 10.

259 The intrinsic energy resolution was found to be in-
 260 variant under changes to HCal cell size. This indicates
 261 the performance trend observed for HCal cell size are
 262 dictated by the confusion term. This is expected as
 263 changes to HCal cell size will aid the association of

264 calorimeter cell clusters to charged particle tracks, but
 265 will not affect intrinsic energy resolution.

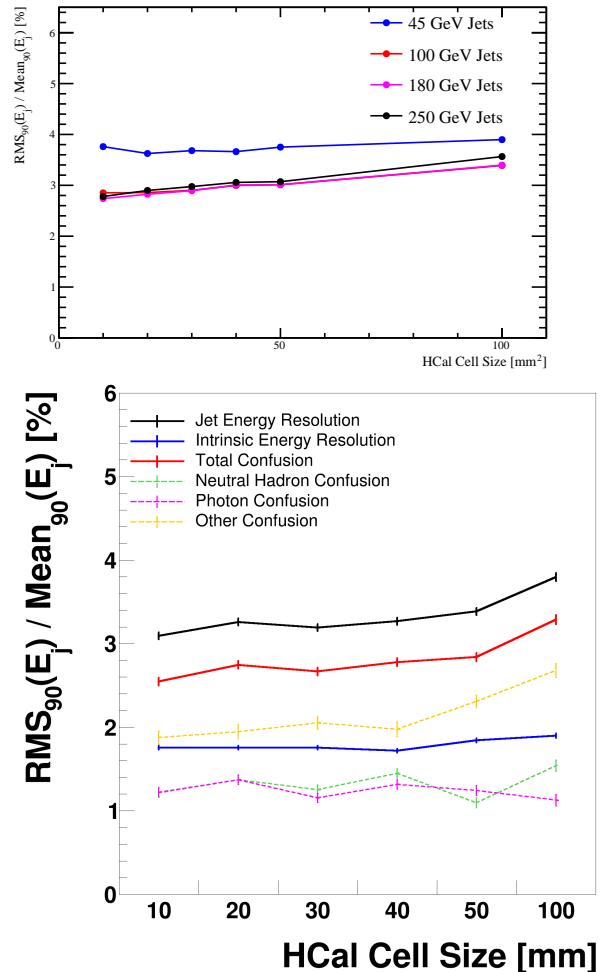


Figure 10: (top) The jet energy resolution as a function of HCal cell size. Results are shown for various jet energies ranging from 45 GeV to 500 GeV. (bottom) The jet energy resolution decomposition as a function of HCal cell size. The results shown are for a jet energy of 250 GeV.

266 5.3. Number of Layers

267 The number of layers in the HCal was varied. The
 268 scintillator and absorber thicknesses were scaled to
 269 maintain the total number of nuclear interaction lengths
 270 in the HCal. The ratio of scintillator and absorber thick-
 271 nesses was held constant to maintain the sampling fraction.
 272 Otherwise, default ILD DBD detector parameters
 273 were used in this analysis.

274 Figure 11 shows the jet energy resolution as a function
 275 of the number of layers in the HCal for various en-
 276 ergy jets. It was found that reducing the number of lay-
 277 ers in the HCal degrades the jet energy resolution and
 278 that this trend applies to all jet energies considered.

279 Insufficient sampling of particle showers in the HCal
 280 is likely to be the primary cause of the degradation at
 281 low numbers of layers in the HCal.

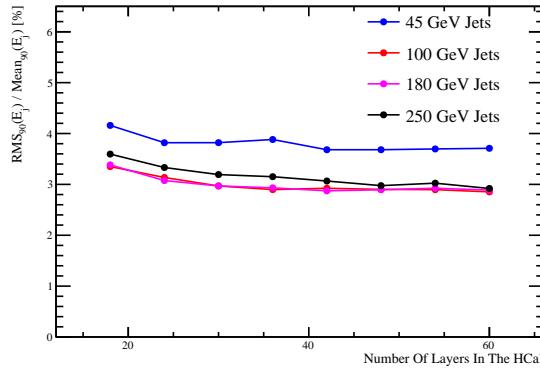


Figure 11: The jet energy resolution as a function of number of layers in the HCal. Results are shown for various jet energies ranging from 45 GeV to 500 GeV.

282 5.4. Depth

283 The total number of nuclear interaction lengths in the
 284 HCal was varied by changing both the absorber and
 285 scintillator thicknesses in the HCal. The ratio of ab-
 286 sorber to scintillator thicknesses in the HCal was held
 287 constant to maintain the sampling fraction. Otherwise,
 288 default ILD DBD detector parameters were used in this
 289 analysis.

290 Figure shows the jet energy resolution as a function
 291 of the total number of nuclear interaction lengths in the
 292 HCal. It was found that increasing the number of nu-
 293 clear interaction lengths in the HCal improved the jet
 294 energy resolution for high energy jets.

295 The number of nuclear interaction lengths in the HCal
 296 will determine the impact of leakage of energy out of
 297 the back of the calorimeters. Energy leaked from the
 298 back of the calorimeters will be measured in the muon
 299 chamber. The energy resolution in the muon chamber is
 300 significantly worse than in the calorimeters, therefore,
 301 leakage degrades the jet energy resolution. As jet en-
 302 ergy increases so does the fraction of the total energy
 303 leaking out of the back of the detector. Therefore, re-
 304 ducing leakage is more beneficial to higher energy jets,
 305 which is what is observed.

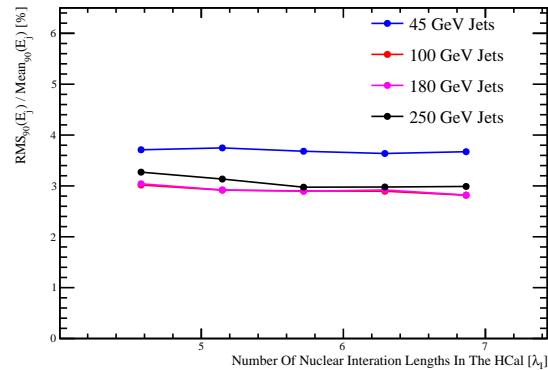


Figure 12: The jet energy resolution as a function of the total number of nuclear interaction lengths in the HCal. Results are shown for various jet energies ranging from 45 GeV to 500 GeV.

306 5.5. Sampling Fraction in HCal

307 Sampling fraction varied. Total number of nuclear
 308 interaction lengths in HCal held constant.

309 No picture needed in this section, all jet energy res-
 310 olutions are flat wrt sampling fraction except at 0.05
 311 (range considered 0.05 to 0.25 steps 0.05) where they
 312 start to deteriorate across all jet energies considered.

313 6. Global Parameter Scan

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 333 humanitatis per seacula quarta decima et quinta decima.
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336 **6.1. Inner Radius**

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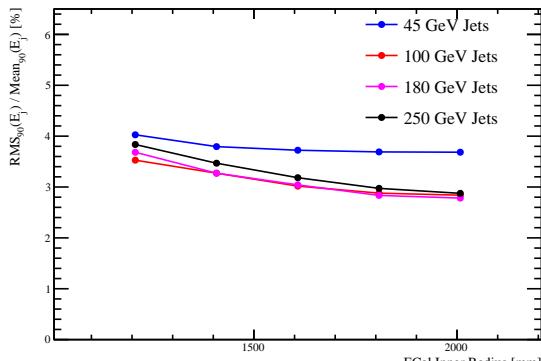


Figure 13: The jet energy resolution as a function of the outer TPC radius. The outer TPC radius can be interpreted as the inner ECal radius. Results are shown for various jet energies ranging from 45 GeV to 500 GeV.

359 **6.2. B-Field Strength**

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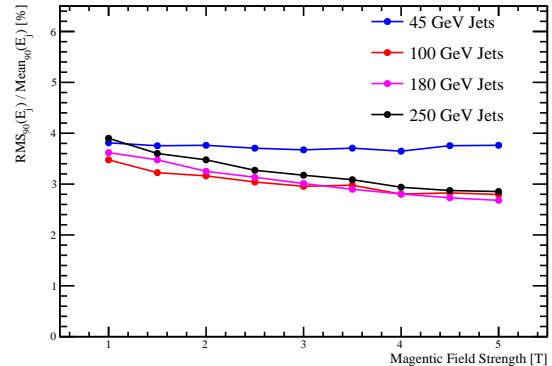


Figure 14: The jet energy resolution as a function of the magnetic field strength within the detector. Results are shown for various jet energies ranging from 45 GeV to 500 GeV.

392 **6.3. Scintillator Thickness**

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405 6.4. Parameterisation of Results

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428 7. Novel ECAL Models

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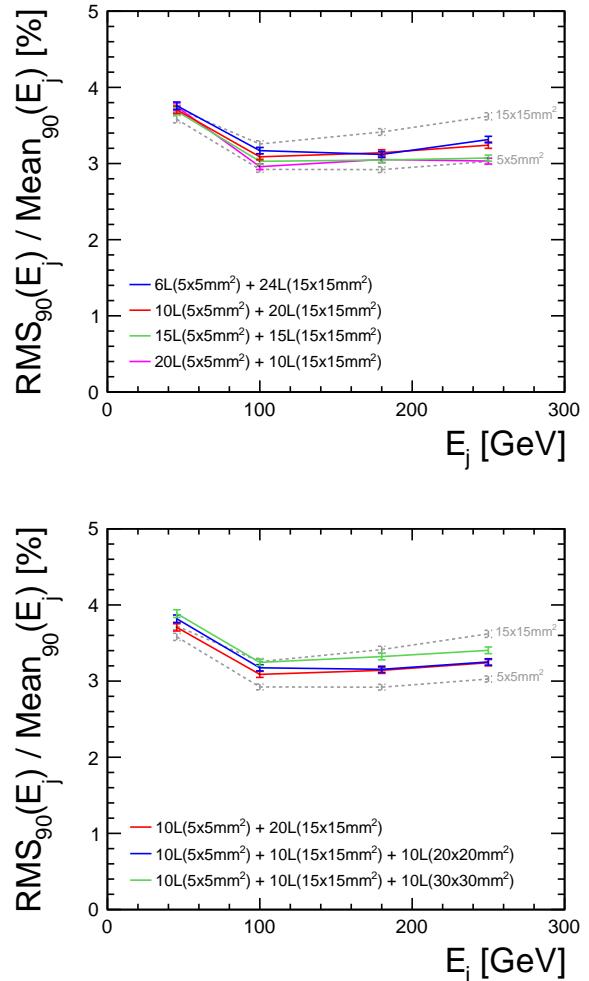


Figure 15

451 8. Performance for Higher Energy Jets

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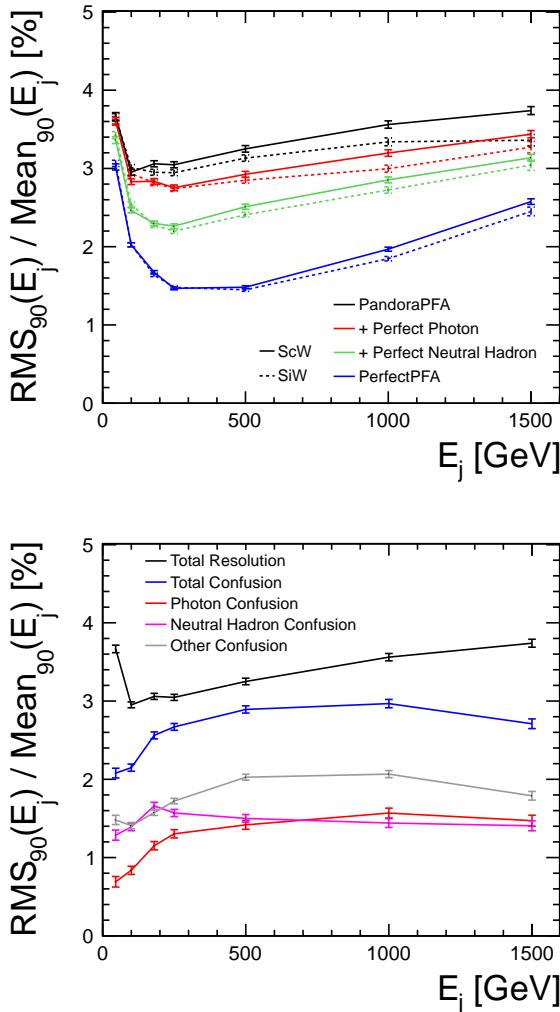


Figure 16

9. Summary

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Acknowledgements

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References