

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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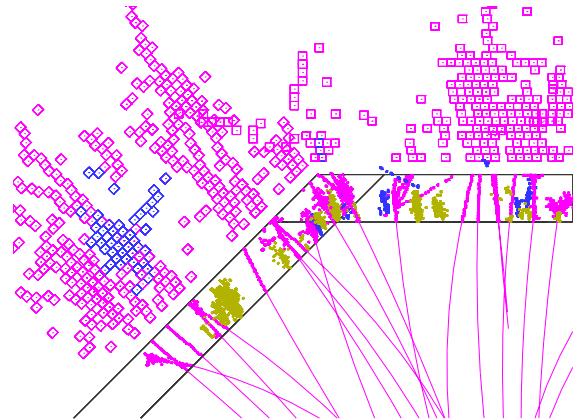


Figure 1

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.

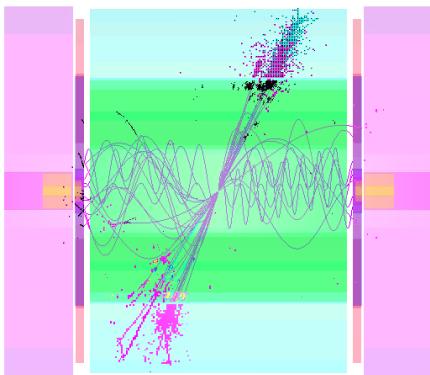


Figure 2: Typical topologies 250GeV jets simulated in the ILD detector model.

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. Default Detector Performance

127 In these studies the reference detector model will be
 128 the ILD detector model. In this model the ECal consists
 129 of a 30 layer, silicon-tungsten ECal with a square cell
 130 size of $5 \times 5\text{mm}^2$ containing ~ 24 radiation lengths (X_0)
 131 and ~ 1 nuclear interaction length (λ_I). The HCal con-
 132 sists of a 48 layer, scintillator-steel HCal with a square
 133 cell size of $30 \times 30\text{mm}^2$ containing $\sim 50X_0$ and $\sim 6\lambda_I$.

134 In order to have confidence in the conclusions drawn
 135 from detector model comparisons, a number of parame-
 136 ters used in the reconstruction should be specified. Both
 137 the timing cut placed on the simulation and the hadronic
 138 energy truncation applied to digitised HCal cells in Pan-
 139 doraPFA have a large impact on the detector per-
 140 formance. The details of their dependency of detector per-
 141 formance is described in sections 3.1 and 3.2.

142 For these studies the default jet energy resolutions are
 143 shown in table 1.

Jet Energy (GeV)	rms (GeV)	$\text{rms}_{90}(E_{jj})$ (GeV)	$\text{rms}_{90}(E_j) / E_j$ (%)
45.5	3.32	2.35	(3.68±0.05)
100	7.83	4.08	(2.90±0.04)
180	10.89	7.32	(2.89±0.04)
250	18.18	10.43	(2.98±0.04)

Table 1: Default ILD detector performance. A 100 ns timing cut was applied to this simulation and the hadronic energy truncation applied in PandoraPFA was 1 GeV.

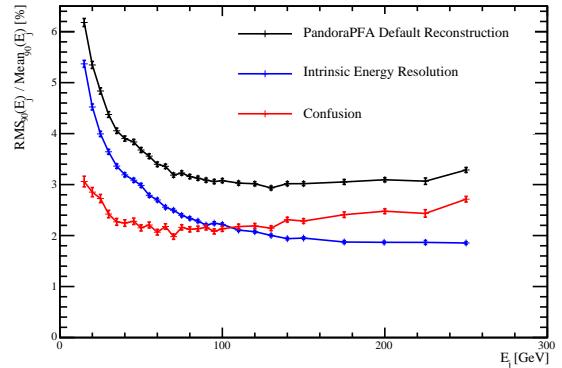


Figure 3: Jet energy resolution as a function of jet energy for the ILD detector model. The jet energy resolution has been decomposed into the intrinsic energy resolution and the confusion terms.

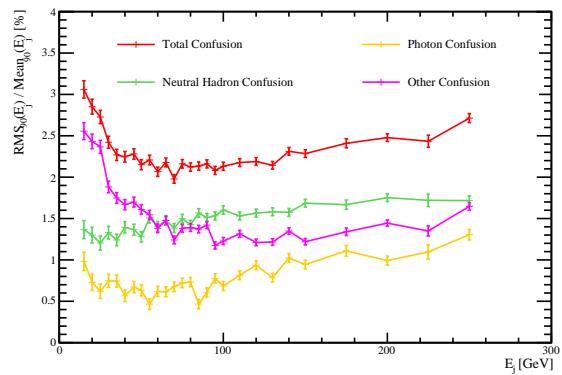


Figure 4: Confusion decomposed into various terms as a function of jet energy. Simulation was performed using the ILD detector model.

144 3.1. Timing Cuts

145 When considering calorimetry at a collider exper-
 146 iment, a balance has to be struck between allowing
 147 enough time for particle showers to develop and reading
 148 out signals, integrated over multiple collisions, at a suf-
 149 ficiently fast rate to prevent saturation. Therefore, hits
 150 in the calorimeter after a time of $O(100\text{ns})$ corrected
 151 for time of flight will not be used in the reconstruc-
 152 tion. The impact of this timing cut on the reconstruc-
 153 tion is shown in figure 5. In the following studies a timing cut
 154 of 100ns was applied to all simulations.

155 3.2. Hadronic Energy Truncation

156 In sampling calorimeters, it is possible to apply soft-
 157 ware compensation to improve the estimation of en-

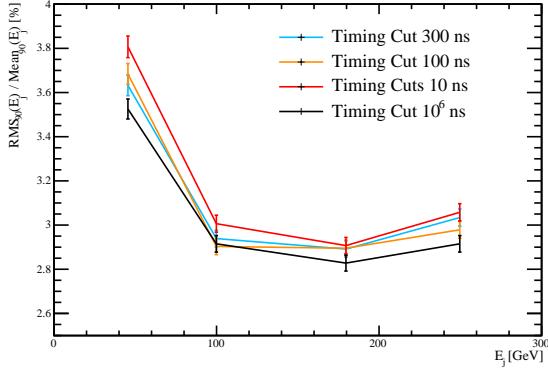


Figure 5: Jet energy resolution as a function of jet energy for the ILD detector model with various timings cuts applied to the reconstruction. The hadronic energy truncation applied to these simulations is 1 GeV.

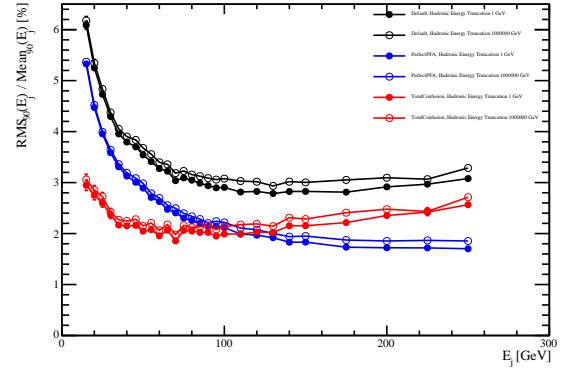


Figure 6: Jet energy resolution as a function of jet energy for the ILD detector model with various timing cuts applied to the reconstruction.

158 ergy deposited in the inactive medium of the calorimeters. A simplistic form of software compensation applied in PandoraPFA is truncation, on a per cell basis, 159 of the hadronic energy measured in the HCal. The effect of this software compensation is twofold, firstly, it 160 improves the energy estimators of the particle showers 161 in the calorimeters and, secondly, the improved energy 162 estimators make the pattern recognition logic more effective. Both of these effects can be seen clearly in figure 163 6, which shows an improvement in both the intrinsic 164 energy resolution of the detector and a reduction in 165 the pattern recognition confusion when a truncation of 166 1 GeV is applied to the default detector.

167 The truncation value applied in PandoraPFA strongly 168 determines the performance of the detector. The dependency of detector performance on the hadronic energy 169 truncation can be seen in figure 7. The optimal value of 170 the hadronic energy truncation varies both as a function 171 of jet energy and detector model. The value of the truncation 172 is optimised for each detector model considered 173 in the studies presented here, however, the truncation 174 applied is kept independent of the jet energy.

180 4. ECAL Parameter Scan

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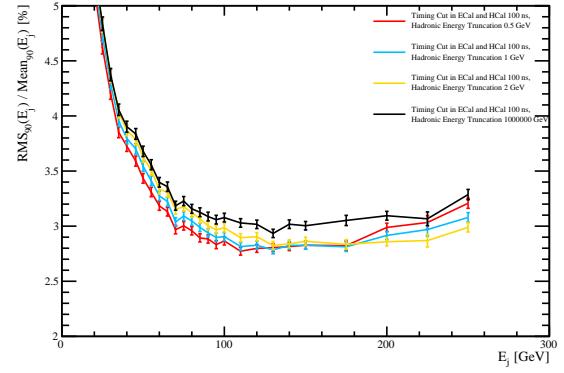


Figure 7: Jet energy resolution as a function of jet energy for the ILD detector model with various timing cuts applied to the reconstruction. The hadronic energy truncation applied to these simulations is 1 GeV.

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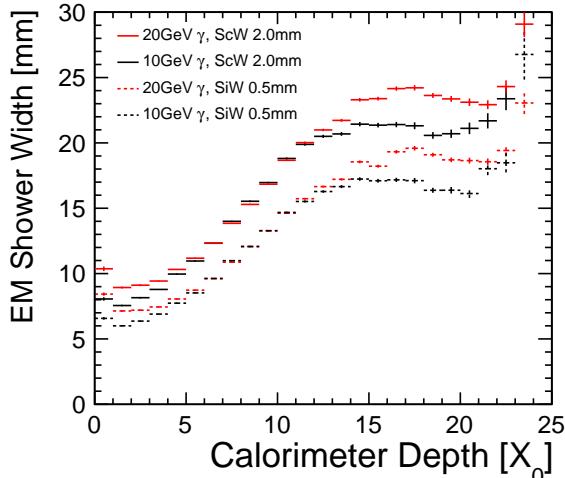
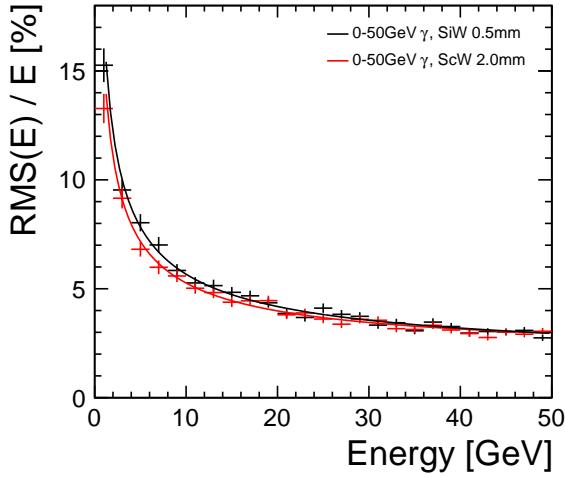


Figure 8

203 4.1. Transverse Granularity

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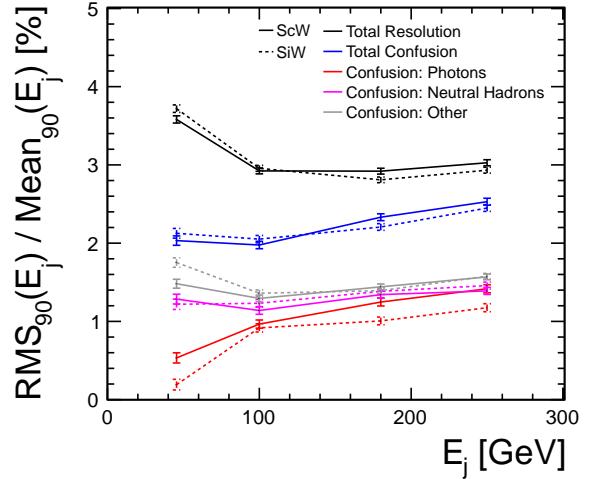


Figure 9

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226 4.2. Number of Layers

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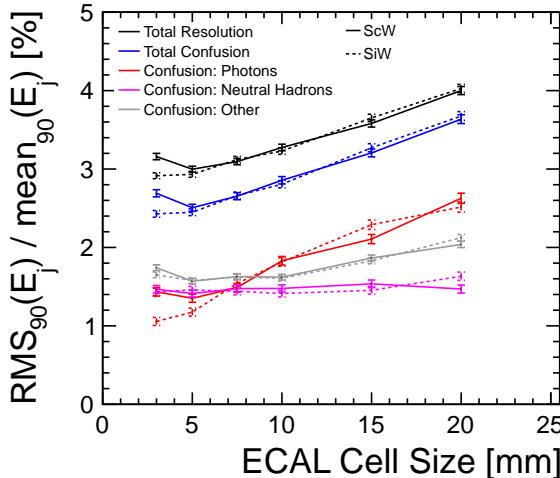
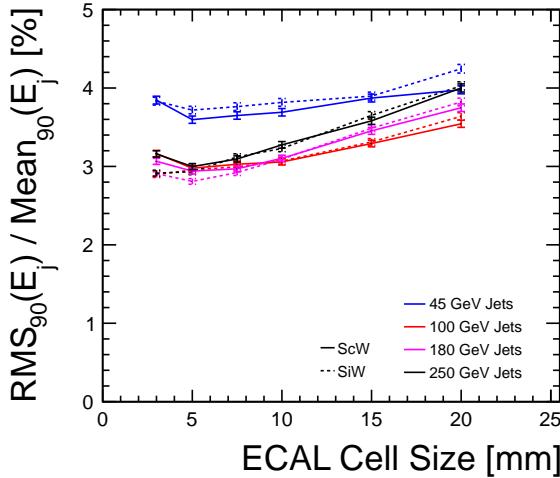


Figure 10

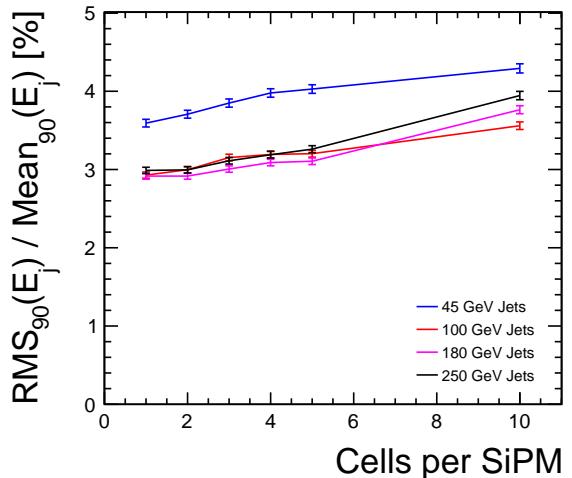
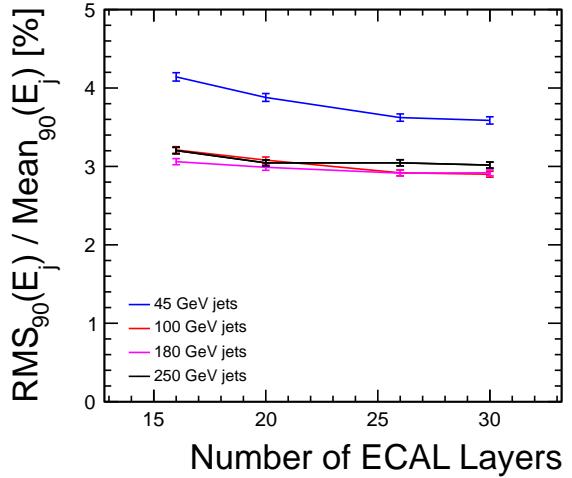


Figure 11

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248 fiant sollemnes in futurum.

249 5. HCAL Parameter Scan

250 ILD detector model used. Timing cuts used are 10ns
251 in HCAL and 20ns in ECal. No MaxHCALHitHadron-
252 icEnergy. Full calibration procedure applied for all
253 detector models. QGSP_BERT physics list used in
254 all cases except Fe and W comparison where both
255 QGSP_BERT and QGSP_BERT_HP used.

256 5.1. Fe/W HCAL Comparison

257 The feasible options for HCAL absorber material are
258 steel (Iron) and tungsten (WMod). The thicknesses of
259 the scintillator and absorber layers of the HCAL were
260 scaled to maintain the total number of nuclear interaction
261 lengths in the HCAL. The ratio of scintillator and
262 absorber thicknesses in the HCAL was held constant to
263 maintain the sampling fraction. Otherwise default ILD
264 DBD detector parameters were used.

265 Both the QGSP_BERT and QGSP_BERT_HP physics
266 lists were used in this analysis. The high precision neutron
267 package, included in QGSP_BERT_HP, offers more
268 realistic modelling of the transportation of neutrons below 20 MeV down to thermal energies. The compact

270 nature of the hadronic showers showering in tungsten
 271 was the primary reason for the inclusion of the high pre-
 272 cision neutron package in this analysis.

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

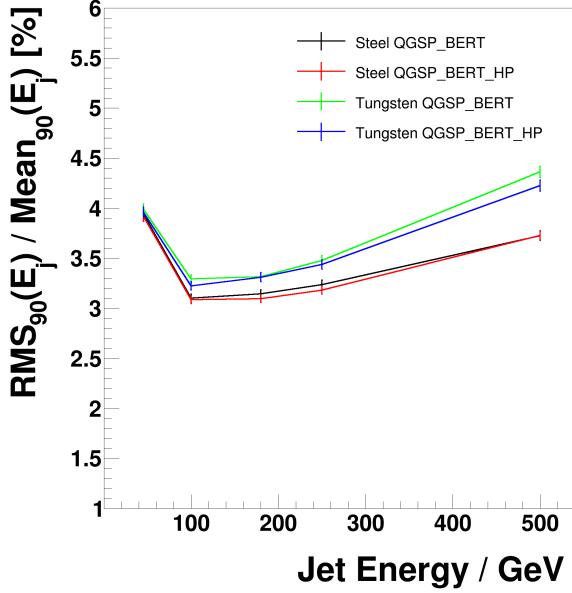


Figure 12: The jet energy resolution as a function of jet energy. Results are shown for detectors using both steel and tungsten HCal absorber materials and using both the QGSP_BERT and QGSP_BERT_HP physics lists.

278 5.2. Transverse Granularity

279 The transverse granularity of the HCal, the HCal cell
 280 size, was varied. Otherwise, default ILD DBD detector
 281 parameters were used in this analysis.

282 Figure 13 shows the jet energy resolution as a function
 283 of HCal cell size for various energy jets. It was
 284 found that smaller HCal cell sizes benefited the jet en-
 285 ergy resolution and that this trend became more promi-
 286 nent for higher energy jets. The jet energy resolution
 287 was decomposed into the confusion and intrinsic energy
 288 resolution terms. The results of this decomposition for
 289 the 250 GeV jets are shown in figure 13.

290 The intrinsic energy resolution was found to be in-
 291 variant under changes to HCal cell size. This indicates
 292 the performance trend observed for HCal cell size are
 293 dictated by the confusion term. This is expected as
 294 changes to HCal cell size will aid the association of

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

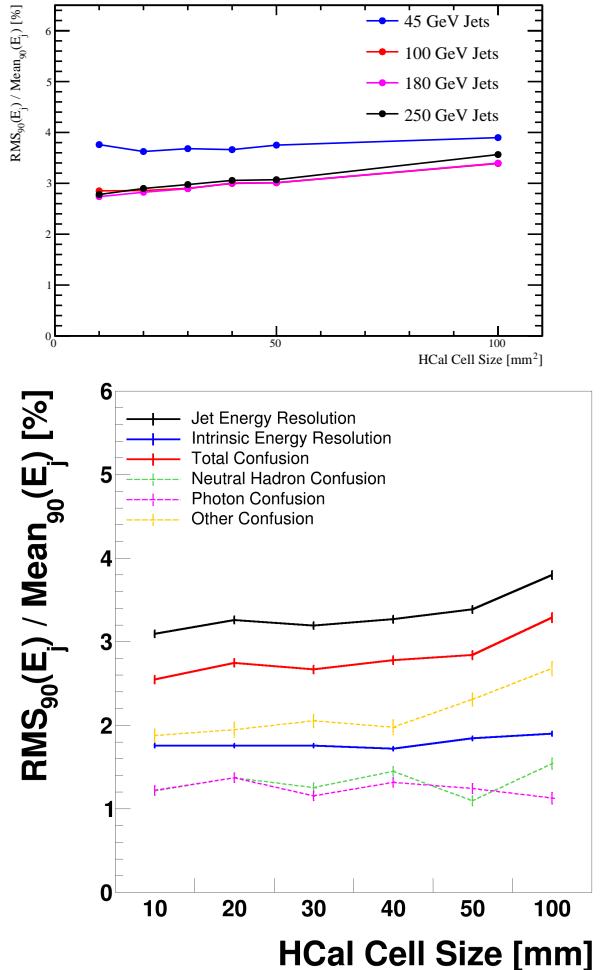


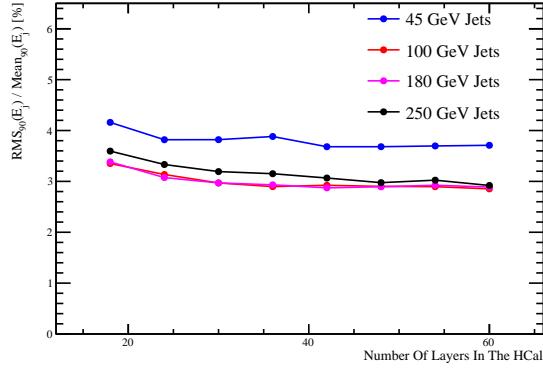
Figure 13: (top) The jet energy resolution as a function of HCal cell size. Results are shown for various jet energies ranging from 45 GeV to 500 GeV. (bottom) The jet energy resolution decomposition as a function of HCal cell size. The results shown are for a jet energy of 250 GeV.

297 5.3. Number of Layers

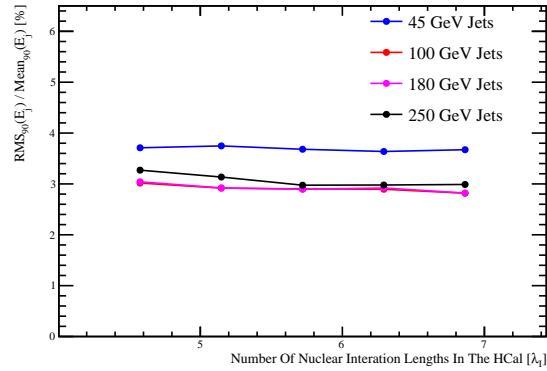
298 The number of layers in the HCal was varied. The
 299 scintillator and absorber thicknesses were scaled to
 300 maintain the total number of nuclear interaction lengths
 301 in the HCal. The ratio of scintillator and absorber thick-
 302 nesses was held constant to maintain the sampling fraction.
 303 Otherwise, default ILD DBD detector parameters
 304 were used in this analysis.

305 Figure 14 shows the jet energy resolution as a function
 306 of the number of layers in the HCal for various en-
 307 ergy jets. It was found that reducing the number of lay-
 308 ers in the HCal degrades the jet energy resolution and
 309 that this trend applies to all jet energies considered.

310 Insufficient sampling of particle showers in the HCal
 311 is likely to be the primary cause of the degradation at
 312 low numbers of layers in the HCal.



313 Figure 14: The jet energy resolution as a function of number of layers
 314 in the HCal. Results are shown for various jet energies ranging from
 315 45 GeV to 500 GeV.



316 Figure 15: The jet energy resolution as a function of the total num-
 317 ber of nuclear interaction lengths in the HCal. Results are shown for
 318 various jet energies ranging from 45 GeV to 500 GeV.

319 5.4. Depth

320 The total number of nuclear interaction lengths in the
 321 HCal was varied by changing both the absorber and
 322 scintillator thicknesses in the HCal. The ratio of ab-
 323 sorber to scintillator thicknesses in the HCal was held
 324 constant to maintain the sampling fraction. Otherwise,
 325 default ILD DBD detector parameters were used in this
 326 analysis.

327 Figure shows the jet energy resolution as a function
 328 of the total number of nuclear interaction lengths in the
 329 HCal. It was found that increasing the number of nu-
 330 clear interaction lengths in the HCal improved the jet
 331 energy resolution for high energy jets.

332 The number of nuclear interaction lengths in the HCal
 333 will determine the impact of leakage of energy out of
 334 the back of the calorimeters. Energy leaked from the
 335 back of the calorimeters will be measured in the muon
 336 chamber. The energy resolution in the muon chamber is
 337 significantly worse than in the calorimeters, therefore,
 338 leakage degrades the jet energy resolution. As jet en-
 339 ergy increases so does the fraction of the total energy
 340 leaking out of the back of the detector. Therefore, re-
 341 ducing leakage is more beneficial to higher energy jets,
 342 which is what is observed.

343 5.5. Sampling Fraction in HCal

344 Sampling fraction varied. Total number of nuclear
 345 interaction lengths in HCal held constant.

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

350 6. Global Parameter Scan

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 369 putamus parum claram, anteposuerit litterarum formas
 370 humanitatis per seacula quarta decima et quinta decima.
 371 Eodem modo typi, qui nunc nobis videntur parum clari,
 372 fiant sollemnes in futurum.

367 **6.1. Inner Radius**

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 387 humanitatis per seacula quarta decima et quinta decima.
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 389 fiant sollemnes in futurum.

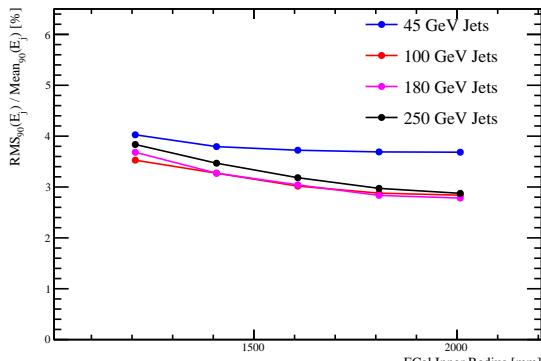


Figure 16: The jet energy resolution as a function of the outer TPC radius. The outer TPC radius can be interpreted as the inner ECal radius. Results are shown for various jet energies ranging from 45 GeV to 500 GeV.

390 **6.2. B-Field Strength**

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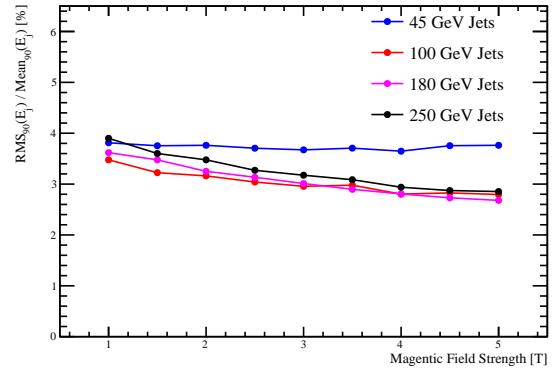


Figure 17: The jet energy resolution as a function of the magnetic field strength within the detector. Results are shown for various jet energies ranging from 45 GeV to 500 GeV.

413 **6.3. Scintillator Thickness**

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 433 humanitatis per seacula quarta decima et quinta decima.
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 435 fiant sollemnes in futurum.

436 *6.4. Parameterisation of Results*

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 456 humanitatis per seacula quarta decima et quinta decima.
 457 Eodem modo typi, qui nunc nobis videntur parum clari,
 458 fiant sollemnes in futurum.

459 **7. Novel ECAL Models**

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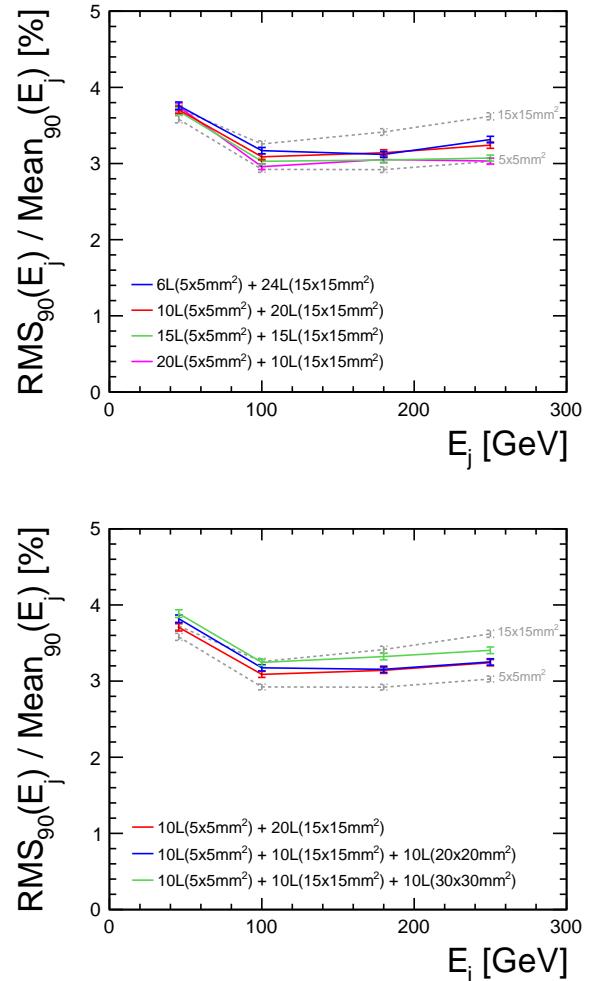


Figure 18

482 **8. Performance for Higher Energy Jets**

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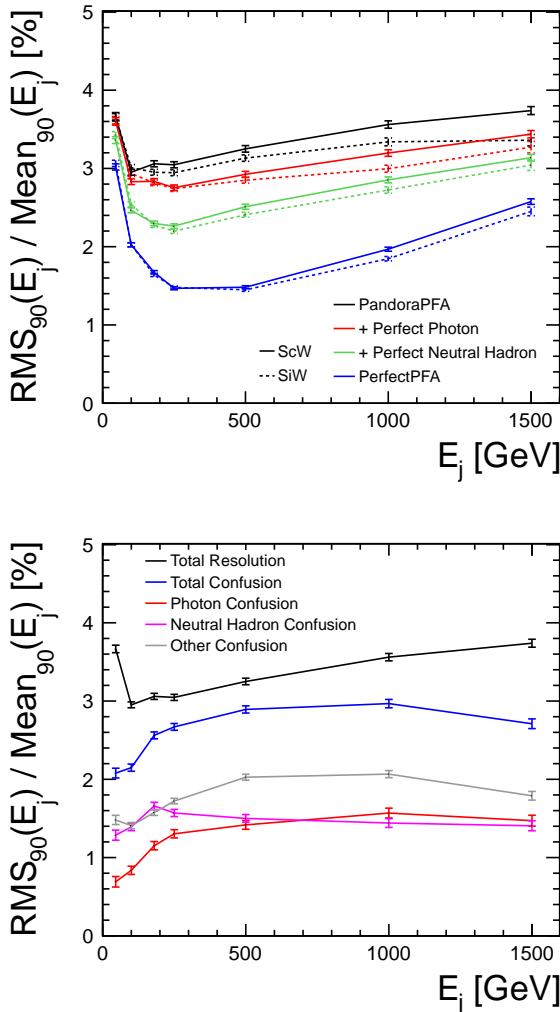


Figure 19

9. Summary

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Acknowledgements

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References