

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

J. S. Marshall^{a,*}

^aCavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

Abstract

Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed diam nonummy nibh euismod tincidunt ut laoreet dolore magna aliquam erat volutpat. Ut wisi enim ad minim veniam, quis nostrud exerci tation ullamcorper suscipit lobortis nisl ut aliquip ex ea commodo consequat. Duis autem vel eum iriure dolor in hendrerit in vulputate velit esse molestie consequat, vel illum dolore eu feugiat nulla facilisis at vero eros et accumsan et iusto odio dignissim qui blandit praesent luptatum zzril delenit augue duis dolore te feugait nulla facilisi. Nam liber tempor cum soluta nobis eleifend option congue nihil imperdiet doming id quod mazim placerat facer possim assum. Typi non habent claritatem insitam; est usus legentis in iis qui facit eorum claritatem. Investigationes demonstraverunt lectores legere me lius quod ii legunt saepius. Claritas est etiam processus dynamicus, qui sequitur mutationem consuetudium lectorum. Mirum est notare quam littera gothica, quam nunc putamus parum claram, anteposuerit litterarum formas humanitatis per seacula quarta decima et quinta decima. Eodem modo typi, qui nunc nobis videntur parum clari, fiant sollemnes in futurum.

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

1. Introduction

1 Lorem ipsum dolor sit amet, consectetur adipiscing
2 elit, sed diam nonummy nibh euismod tincidunt ut
3 laoreet dolore magna aliquam erat volutpat. Ut wisi
4 enim ad minim veniam, quis nostrud exerci tation
5 ullamcorper suscipit lobortis nisl ut aliquip ex ea
6 commodo consequat. Duis autem vel eum iriure dolor in
7 hendrerit in vulputate velit esse molestie consequat, vel
8 illum dolore eu feugiat nulla facilisis at vero eros et
9 accumsan et iusto odio dignissim qui blandit praesent
10 luptatum zzril delenit augue duis dolore te feugait nulla
11 facilisi. Nam liber tempor cum soluta nobis eleifend
12 option congue nihil imperdiet doming id quod mazim plac-
13 erat facer possim assum. Typi non habent claritatem
14 insitam; est usus legentis in iis qui facit eorum claritatem.
15 Investigationes demonstraverunt lectores legere me lius
16 quod ii legunt saepius. Claritas est etiam processus dy-
17 namicus, qui sequitur mutationem consuetudium lecto-
18 rum. Mirum est notare quam littera gothica, quam nunc
19 putamus parum claram, anteposuerit litterarum formas
20 humanitatis per seacula quarta decima et quinta decima.

22 Eodem modo typi, qui nunc nobis videntur parum clari,
23 fiant sollemnes in futurum.

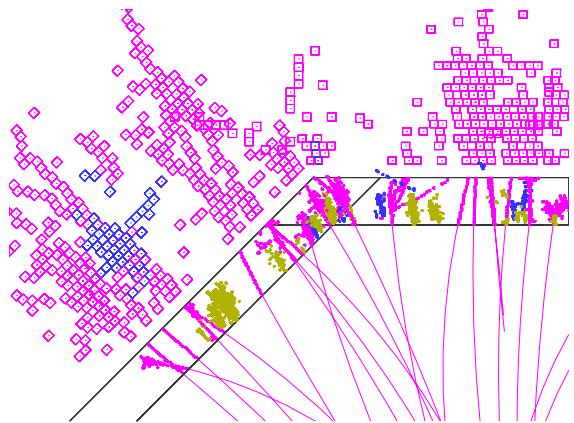


Figure 1

2. Implementation

2.1. Simulation

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

*Corresponding author
Email address: marshall@hep.phy.cam.ac.uk (J. S. Marshall)

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.

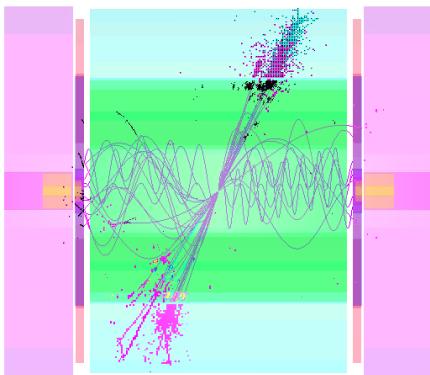


Figure 2: Typical topologies 250GeV jets simulated in the ILD detector model.

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. However, it is necessary to
 129 clarify both the timing cut placed on the simulation and
 130 the hadronic energy truncation applied in PandoraPFA
 131 to digitised calorimeter cells before accurate compari-
 132 sons between detector models can be made. Both of
 133 these reconstruction variables have a significant impact
 134 on detector performance, which is elaborated upon be-
 135 low.

136 3.1. Timing Cuts

137 The detector at a future linear collider will have tim-
 138 ing cuts applied of the order of tens of nano seconds.
 139 Timing cuts are necessary to prevent saturation of the
 140 detector model when reading out signals from the de-
 141 tector when integrating over multiple collisions. How-
 142 ever, a balance has to be struck between having large
 143 enough timing cuts to record all of the signal for a col-
 144 lision and not saturating the detector. Currently, tech-
 145 nology options for the read out electronics also apply
 146 a lower limit of approximately ten nano seconds to the
 147 timing cut window.

148 As it is clear that timing cuts will have to be applied
 149 the impact of the choice of timing cuts has been anal-
 150 ysed and results shown in figure 5.

151 3.2. Hadronic Energy Truncation

152 4. ECAL Parameter Scan

153 Lorem ipsum dolor sit amet, consectetur adipisci-
 154 ing elit, sed diam nonummy nibh euismod tincidunt ut

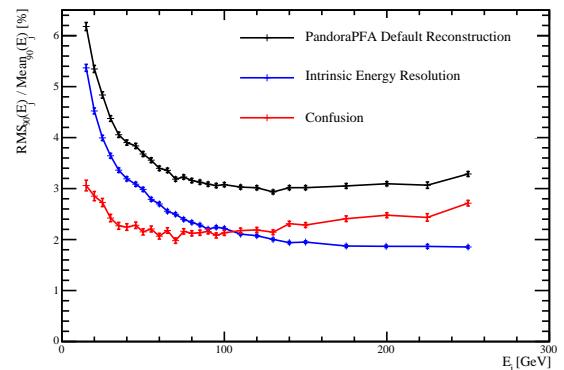


Figure 3: Jet energy resolution as a function of jet energy for the ILD detector model. The jet energy resolution has been decomposed into the intrinsic energy resolution and the confusion terms.

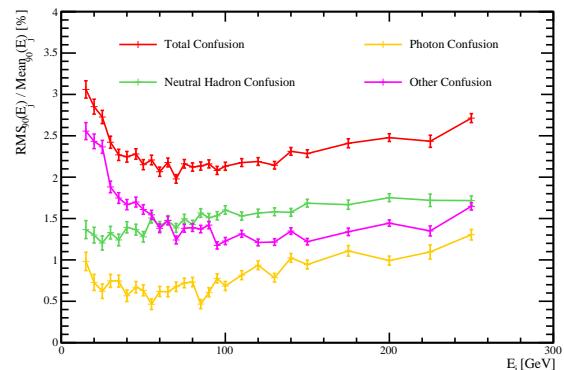


Figure 4: Confusion decomposed into various terms as a function of jet energy. Simulation was performed using the ILD detector model.

155 laoreet dolore magna aliquam erat volutpat. Ut wisi
 156 enim ad minim veniam, quis nostrud exerci tation ul-
 157 lamcorper suscipit lobortis nisl ut aliquip ex ea com-
 158 modo consequat. Duis autem vel eum iriure dolor in
 159 hendrerit in vulputate velit esse molestie consequat, vel
 160 illum dolore eu feugiat nulla facilisis at vero eros et ac-
 161 cumsan et iusto odio dignissim qui blandit praesent lup-
 162 tatum zzril delenit augue duis dolore te feugait nulla fa-
 163 cilisi. Nam liber tempor cum soluta nobis eleifend op-
 164 tion congue nihil imperdiet doming id quod mazim plac-
 165 erat facer possim assum. Typi non habent claritatem in-
 166 sitam; est usus legentis in iis qui facit eorum claritatem.
 167 Investigationes demonstraverunt lectores legere me lius
 168 quod ii legunt saepius. Claritas est etiam processus dy-
 169 namicus, qui sequitur mutationem consuetudium lecto-
 170 rum. Mirum est notare quam littera gothica, quam nunc

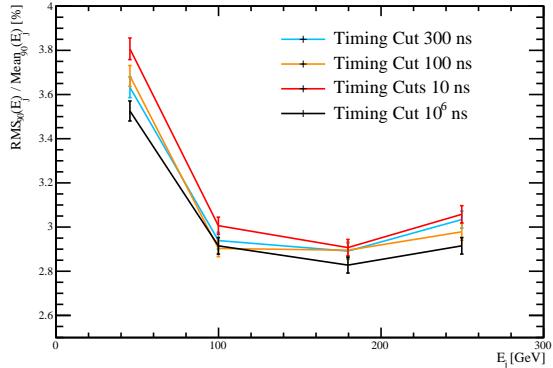


Figure 5: Jet energy resolution as a function of jet energy for the ILD detector model with various timings cuts applied to the reconstruction. The hadronic energy truncation applied to these simulations is 1 GeV.

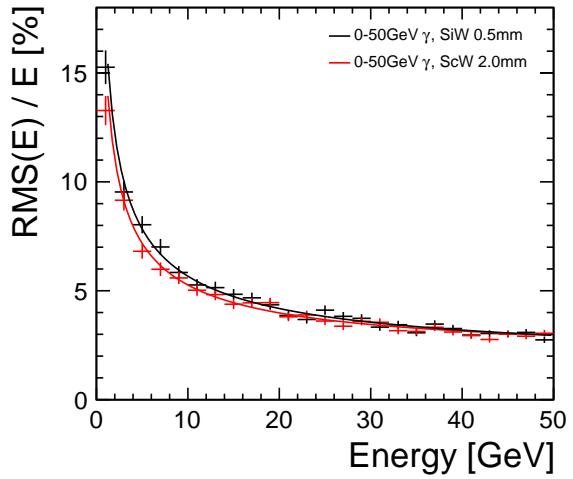


Figure 6

171 putamus parum claram, anteposuerit litterarum formas
 172 humanitatis per seacula quarta decima et quinta decima.
 173 Eodem modo typi, qui nunc nobis videntur parum clari,
 174 fiant sollemnes in futurum.

175 4.1. Transverse Granularity

176 Lorem ipsum dolor sit amet, consectetuer adipisc-
 177 ing elit, sed diam nonummy nibh euismod tincidunt ut
 178 laoreet dolore magna aliquam erat volutpat. Ut wisi
 179 enim ad minim veniam, quis nostrud exerci tation ul-
 180 lamcorper suscipit lobortis nisl ut aliquip ex ea com-
 181 modo consequat. Duis autem vel eum iriure dolor in
 182 hendrerit in vulputate velit esse molestie consequat, vel
 183 illum dolore eu feugiat nulla facilisis at vero eros et ac-
 184 cumsan et iusto odio dignissim qui blandit praesent lup-
 185 tatum zzril delenit augue duis dolore te feugait nulla fa-
 186 cilisi. Nam liber tempor cum soluta nobis eleifend op-
 187 tion congue nihil imperdiet doming id quod mazim plac-
 188 erat facer possim assum. Typi non habent claritatem in-
 189 sitam; est usus legentis in iis qui facit eorum claritatem.
 190 Investigationes demonstraverunt lectores legere me lius
 191 quod ii legunt saepius. Claritas est etiam processus dy-
 192 namicus, qui sequitur mutationem consuetudium lecto-
 193 rum. Mirum est notare quam littera gothica, quam nunc
 194 putamus parum claram, anteposuerit litterarum formas
 195 humanitatis per seacula quarta decima et quinta decima.
 196 Eodem modo typi, qui nunc nobis videntur parum clari,
 197 fiant sollemnes in futurum.

198 4.2. Number of Layers

199 Lorem ipsum dolor sit amet, consectetuer adipisc-
 200 ing elit, sed diam nonummy nibh euismod tincidunt ut

201 laoreet dolore magna aliquam erat volutpat. Ut wisi
 202 enim ad minim veniam, quis nostrud exerci tation ul-
 203 lamcorper suscipit lobortis nisl ut aliquip ex ea com-
 204 modo consequat. Duis autem vel eum iriure dolor in
 205 hendrerit in vulputate velit esse molestie consequat, vel
 206 illum dolore eu feugiat nulla facilisis at vero eros et ac-
 207 cumsan et iusto odio dignissim qui blandit praesent lup-
 208 tatum zzril delenit augue duis dolore te feugait nulla fa-
 209 cilisi. Nam liber tempor cum soluta nobis eleifend op-
 210 tion congue nihil imperdiet doming id quod mazim plac-
 211 erat facer possim assum. Typi non habent claritatem in-
 212 sitam; est usus legentis in iis qui facit eorum claritatem.
 213 Investigationes demonstraverunt lectores legere me lius
 214 quod ii legunt saepius. Claritas est etiam processus dy-

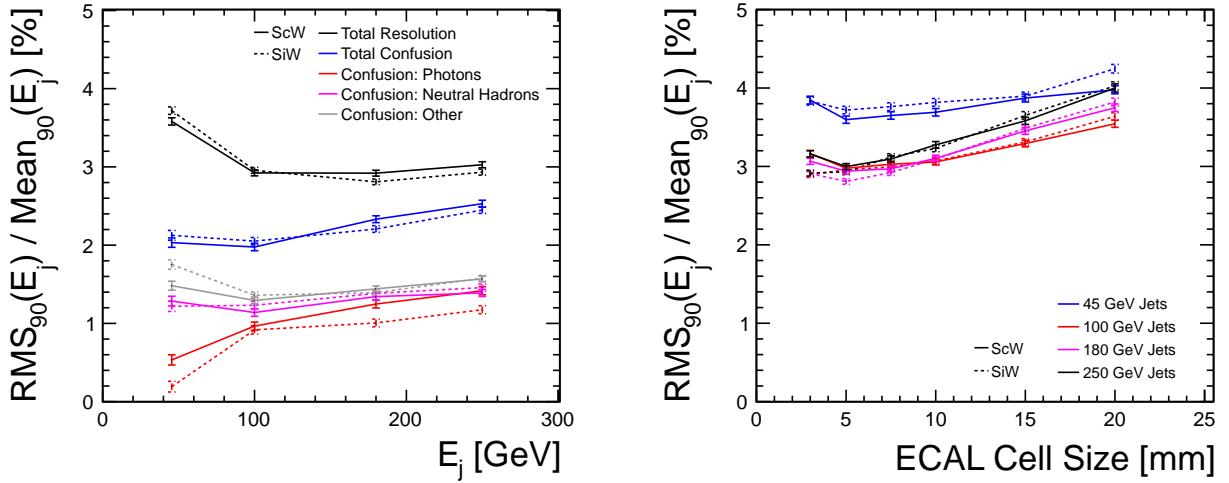


Figure 7

215 namicus, qui sequitur mutationem consuetudium lecto-
 216 rum. Mirum est notare quam littera gothica, quam nunc
 217 putamus parum claram, anteposuerit litterarum formas
 218 humanitatis per seacula quarta decima et quinta decima.
 219 Eodem modo typi, qui nunc nobis videntur parum clari,
 220 fiant sollemnes in futurum.

221 5. HCAL Parameter Scan

222 ILD detector model used. Timing cuts used are 10ns
 223 in HCal and 20ns in ECal. No MaxHCalHitHadronicEnergy.
 224 Full calibration procedure applied for all
 225 detector models. QGSP_BERT physics list used in
 226 all cases except Fe and W comparison where both
 227 QGSP_BERT and QGSP_BERT_HP used.

228 5.1. Fe/W HCAL Comparison

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

237 Both the QGSP_BERT and QGSP_BERT_HP physics
 238 lists were used in this analysis. The high precision neu-
 239 tron package, included in QGSP_BERT_HP, offers more
 240 realistic modelling of the transportation of neutrons be-
 241 low 20 MeV down to thermal energies. The compact

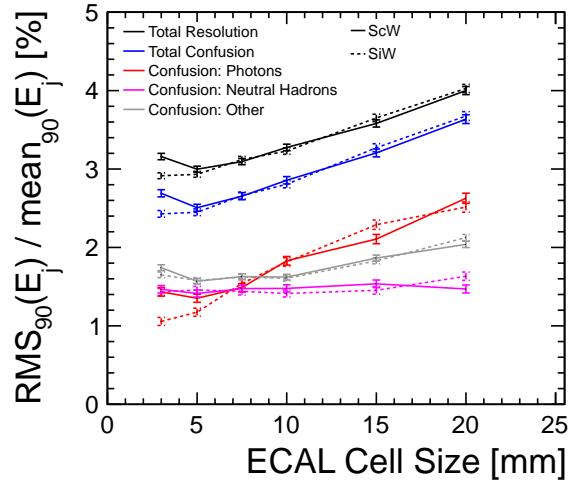


Figure 8

242 nature of the hadronic showers showering in tungsten
 243 was the primary reason for the inclusion of the high pre-
 244 cision neutron package in this analysis.

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

250 5.2. Transverse Granularity

251 The transverse granularity of the HCal, the HCal cell
 252 size, was varied. Otherwise, default ILD DBD detector
 253 parameters were used in this analysis.

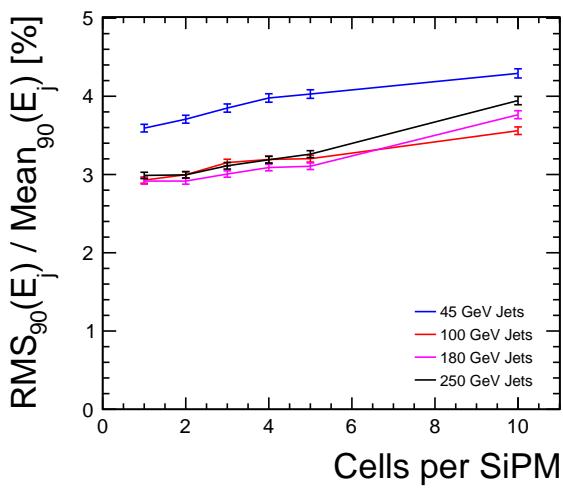
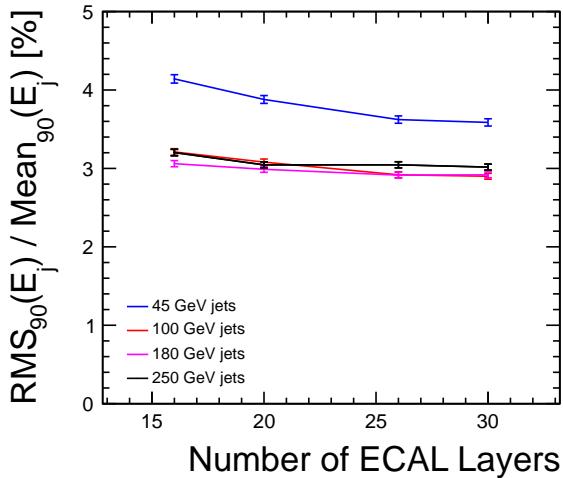
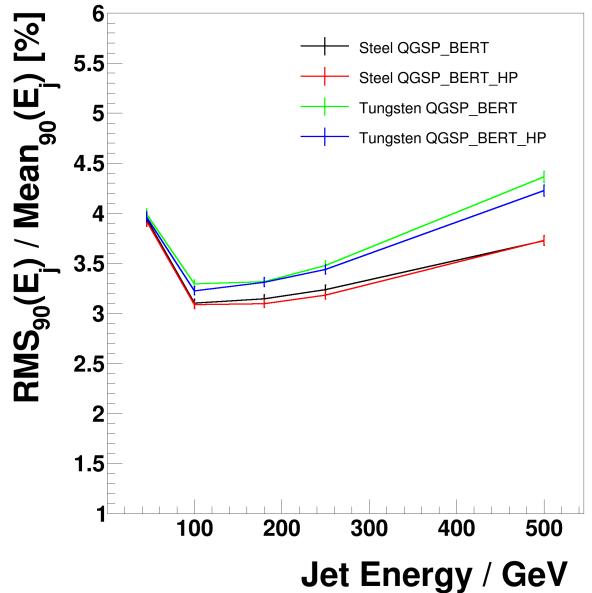


Figure 9

254 Figure 11 shows the jet energy resolution as a function
 255 of HCal cell size for various energy jets. It was
 256 found that smaller HCal cell sizes benefited the jet energy
 257 resolution and that this trend became more prominent
 258 for higher energy jets. The jet energy resolution
 259 was decomposed into the confusion and intrinsic energy
 260 resolution terms. The results of this decomposition for
 261 the 250 GeV jets are shown in figure 11.

262 The intrinsic energy resolution was found to be in-
 263 variant under changes to HCal cell size. This indicates
 264 the performance trend observed for HCal cell size are
 265 dictated by the confusion term. This is expected as
 266 changes to HCal cell size will aid the association of
 267 calorimeter cell clusters to charged particle tracks, but



268 Figure 10: The jet energy resolution as a function of jet energy.
 269 Results are shown for detectors using both steel and tungsten
 270 HCal absorber materials and using both the QGSP_BERT and
 271 QGSP_BERT_HP physics lists.

272 will not affect intrinsic energy resolution.

273 5.3. Number of Layers

274 The number of layers in the HCal was varied. The
 275 scintillator and absorber thicknesses were scaled to
 276 maintain the total number of nuclear interaction lengths
 277 in the HCal. The ratio of scintillator and absorber thick-
 278 nesses was held constant to maintain the sampling frac-
 279 tion. Otherwise, default ILD DBD detector parameters
 280 were used in this analysis.

281 Figure 12 shows the jet energy resolution as a function
 282 of the number of layers in the HCal for various en-
 283 ergy jets. It was found that reducing the number of lay-
 284 ers in the HCal degrades the jet energy resolution and
 285 that this trend applies to all jet energies considered.

286 Insufficient sampling of particle showers in the HCal
 287 is likely to be the primary cause of the degradation at
 288 low numbers of layers in the HCal.

289 5.4. Depth

290 The total number of nuclear interaction lengths in the
 291 HCal was varied by changing both the absorber and
 292 scintillator thicknesses in the HCal. The ratio of ab-
 293 sorber to scintillator thicknesses in the HCal was held
 294 constant to maintain the sampling fraction. Otherwise,

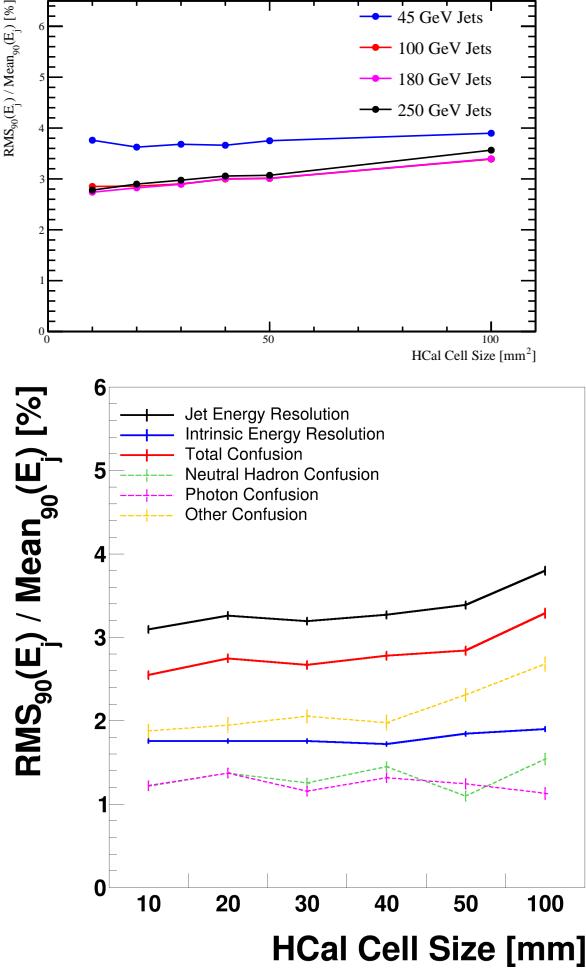


Figure 11: (top) The jet energy resolution as a function of HCal cell size. Results are shown for various jet energies ranging from 45 GeV to 500 GeV. (bottom) The jet energy resolution decomposition as a function of HCal cell size. The results shown are for a jet energy of 250 GeV.

291 default ILD DBD detector parameters were used in this
292 analysis.

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

298 The number of nuclear interaction lengths in the HCal
299 will determine the impact of leakage of energy out of
300 the back of the calorimeters. Energy leaked from the
301 back of the calorimeters will be measured in the muon
302 chamber. The energy resolution in the muon chamber is

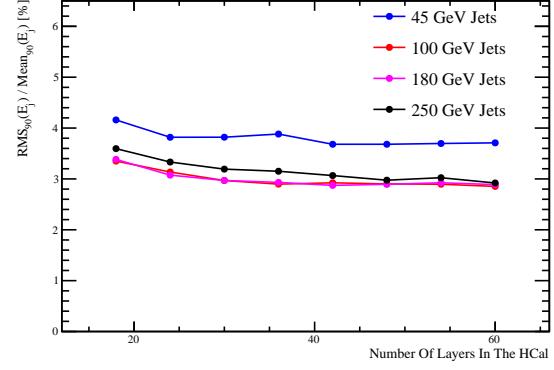


Figure 12: The jet energy resolution as a function of number of layers in the HCal. Results are shown for various jet energies ranging from 45 GeV to 500 GeV.

303 significantly worse than in the calorimeters, therefore,
304 leakage degrades the jet energy resolution. As jet en-
305 ergy increases so does the fraction of the total energy
306 leaking out of the back of the detector. Therefore,
307 reducing leakage is more beneficial to higher energy jets,
308 which is what is observed.

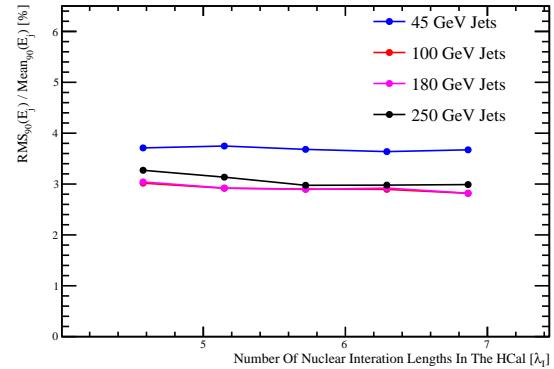


Figure 13: The jet energy resolution as a function of the total number of nuclear interaction lengths in the HCal. Results are shown for various jet energies ranging from 45 GeV to 500 GeV.

5.5. Sampling Fraction in HCal

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

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

316 **6. Global Parameter Scan**

317 Lorem ipsum dolor sit amet, consectetuer adipisc-
 318 ing elit, sed diam nonummy nibh euismod tincidunt ut
 319 laoreet dolore magna aliquam erat volutpat. Ut wisi
 320 enim ad minim veniam, quis nostrud exerci tation ul-
 321 lamcorper suscipit lobortis nisl ut aliquip ex ea com-
 322 modo consequat. Duis autem vel eum iriure dolor in
 323 henderit in vulputate velit esse molestie consequat, vel
 324 illum dolore eu feugiat nulla facilisis at vero eros et ac-
 325 cumsan et iusto odio dignissim qui blandit praesent lup-
 326 tatum zzril delenit augue duis dolore te feugait nulla fa-
 327 cilisi. Nam liber tempor cum soluta nobis eleifend op-
 328 tion congue nihil imperdiet doming id quod mazim plac-
 329 erat facer possim assum. Typi non habent claritatem in-
 330 sitam; est usus legentis in iis qui facit eorum claritatem.
 331 Investigationes demonstraverunt lectores legere me lius
 332 quod ii legunt saepius. Claritas est etiam processus dy-
 333 namicus, qui sequitur mutationem consuetudium lecto-
 334 rum. Mirum est notare quam littera gothica, quam nunc
 335 putamus parum claram, anteposuerit litterarum formas
 336 humanitatis per seacula quarta decima et quinta decima.
 337 Eodem modo typi, qui nunc nobis videntur parum clari,
 338 fiant sollemnes in futurum.

339 **6.1. Inner Radius**

340 Lorem ipsum dolor sit amet, consectetuer adipisc-
 341 ing elit, sed diam nonummy nibh euismod tincidunt ut
 342 laoreet dolore magna aliquam erat volutpat. Ut wisi
 343 enim ad minim veniam, quis nostrud exerci tation ul-
 344 lamcorper suscipit lobortis nisl ut aliquip ex ea com-
 345 modo consequat. Duis autem vel eum iriure dolor in
 346 henderit in vulputate velit esse molestie consequat, vel
 347 illum dolore eu feugiat nulla facilisis at vero eros et ac-
 348 cumsan et iusto odio dignissim qui blandit praesent lup-
 349 tatum zzril delenit augue duis dolore te feugait nulla fa-
 350 cilisi. Nam liber tempor cum soluta nobis eleifend op-
 351 tion congue nihil imperdiet doming id quod mazim plac-
 352 erat facer possim assum. Typi non habent claritatem in-
 353 sitam; est usus legentis in iis qui facit eorum claritatem.
 354 Investigationes demonstraverunt lectores legere me lius
 355 quod ii legunt saepius. Claritas est etiam processus dy-
 356 namicus, qui sequitur mutationem consuetudium lecto-
 357 rum. Mirum est notare quam littera gothica, quam nunc
 358 putamus parum claram, anteposuerit litterarum formas
 359 humanitatis per seacula quarta decima et quinta decima.
 360 Eodem modo typi, qui nunc nobis videntur parum clari,
 361 fiant sollemnes in futurum.

362 **6.2. B-Field Strength**

363 Lorem ipsum dolor sit amet, consectetuer adipisc-
 364 ing elit, sed diam nonummy nibh euismod tincidunt ut

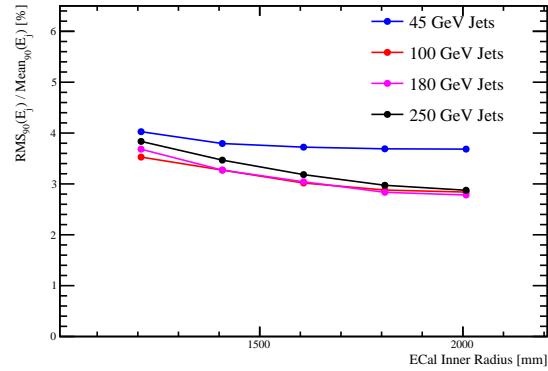


Figure 14: The jet energy resolution as a function of the outer TPC radius. The outer TPC radius can be interpreted as the inner ECal radius. Results are shown for various jet energies ranging from 45 GeV to 500 GeV.

365 laoreet dolore magna aliquam erat volutpat. Ut wisi
 366 enim ad minim veniam, quis nostrud exerci tation ul-
 367 lamcorper suscipit lobortis nisl ut aliquip ex ea com-
 368 modo consequat. Duis autem vel eum iriure dolor in
 369 henderit in vulputate velit esse molestie consequat, vel
 370 illum dolore eu feugiat nulla facilisis at vero eros et ac-
 371 cumsan et iusto odio dignissim qui blandit praesent lup-
 372 tatum zzril delenit augue duis dolore te feugait nulla fa-
 373 cilisi. Nam liber tempor cum soluta nobis eleifend op-
 374 tion congue nihil imperdiet doming id quod mazim plac-
 375 erat facer possim assum. Typi non habent claritatem in-
 376 sitam; est usus legentis in iis qui facit eorum claritatem.
 377 Investigationes demonstraverunt lectores legere me lius
 378 quod ii legunt saepius. Claritas est etiam processus dy-
 379 namicus, qui sequitur mutationem consuetudium lecto-
 380 rum. Mirum est notare quam littera gothica, quam nunc
 381 putamus parum claram, anteposuerit litterarum formas
 382 humanitatis per seacula quarta decima et quinta decima.
 383 Eodem modo typi, qui nunc nobis videntur parum clari,
 384 fiant sollemnes in futurum.

385 **6.3. Scintillator Thickness**

386 Lorem ipsum dolor sit amet, consectetuer adipisc-
 387 ing elit, sed diam nonummy nibh euismod tincidunt ut
 388 laoreet dolore magna aliquam erat volutpat. Ut wisi
 389 enim ad minim veniam, quis nostrud exerci tation ul-
 390 lamcorper suscipit lobortis nisl ut aliquip ex ea com-
 391 modo consequat. Duis autem vel eum iriure dolor in
 392 henderit in vulputate velit esse molestie consequat, vel
 393 illum dolore eu feugiat nulla facilisis at vero eros et ac-
 394 cumsan et iusto odio dignissim qui blandit praesent lup-
 395 tatum zzril delenit augue duis dolore te feugait nulla fa-

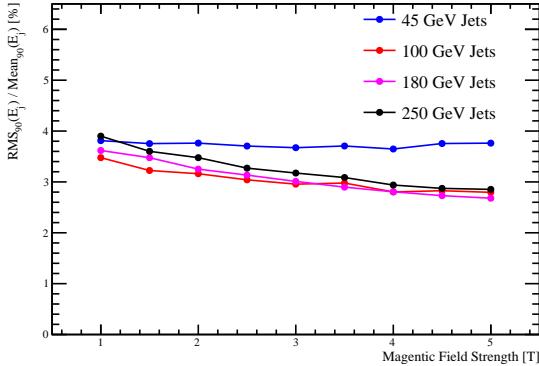


Figure 15: The jet energy resolution as a function of the magnetic field strength within the detector. Results are shown for various jet energies ranging from 45 GeV to 500 GeV.

cilisi. Nam liber tempor cum soluta nobis eleifend option congue nihil imperdierit doming id quod mazim plac erat facer possim assum. Typi non habent claritatem in sitam; est usus legentis in iis qui facit eorum claritatem. Investigationes demonstraverunt lectores legere me lius quod ii legunt saepius. Claritas est etiam processus dy namicus, qui sequitur mutationem consuetudium lecto rum. Mirum est notare quam littera gothica, quam nunc putamus parum claram, anteposuerit litterarum formas humanitatis per seacula quarta decima et quinta decima. Eodem modo typi, qui nunc nobis videntur parum clari, fiant sollemnes in futurum.

6.4. Parameterisation of Results

Lorem ipsum dolor sit amet, consectetuer adipisc ing elit, sed diam nonummy nibh euismod tincidunt ut laoreet dolore magna aliquam erat volutpat. Ut wisi enim ad minim veniam, quis nostrud exerci tation ullamcorper suscipit lobortis nisl ut aliquip ex ea com modo consequat. Duis autem vel eum iriure dolor in hendrerit in vulputate velit esse molestie consequat, vel illum dolore eu feugiat nulla facilisis at vero eros et accumsan et iusto odio dignissim qui blandit praesent luptatum zzril delenit augue duis dolore te feugait nulla facilisi. Nam liber tempor cum soluta nobis eleifend option congue nihil imperdierit doming id quod mazim plac erat facer possim assum. Typi non habent claritatem in sitam; est usus legentis in iis qui facit eorum claritatem. Investigationes demonstraverunt lectores legere me lius quod ii legunt saepius. Claritas est etiam processus dy namicus, qui sequitur mutationem consuetudium lecto rum. Mirum est notare quam littera gothica, quam nunc putamus parum claram, anteposuerit litterarum formas humanitatis per seacula quarta decima et quinta decima.

428 humanitatis per seacula quarta decima et quinta decima.
429 Eodem modo typi, qui nunc nobis videntur parum clari,
430 fiant sollemnes in futurum.

7. Novel ECAL Models

432 Lorem ipsum dolor sit amet, consectetuer adipisc ing elit, sed diam nonummy nibh euismod tincidunt ut
433 laoreet dolore magna aliquam erat volutpat. Ut wisi
434 enim ad minim veniam, quis nostrud exerci tation ul
435 lamcorper suscipit lobortis nisl ut aliquip ex ea com
436 modo consequat. Duis autem vel eum iriure dolor in
437 hendrerit in vulputate velit esse molestie consequat, vel
438 illum dolore eu feugiat nulla facilisis at vero eros et ac
439 cumsan et iusto odio dignissim qui blandit praesent lupt
440 atum zzril delenit augue duis dolore te feugait nulla fa
441 cilisi. Nam liber tempor cum soluta nobis eleifend op
442 tion congue nihil imperdierit doming id quod mazim plac
443 erat facer possim assum. Typi non habent claritatem in
444 sitam; est usus legentis in iis qui facit eorum claritatem.
445 Investigationes demonstraverunt lectores legere me lius
446 quod ii legunt saepius. Claritas est etiam processus dy
447 namicus, qui sequitur mutationem consuetudium lecto
448 rum. Mirum est notare quam littera gothica, quam nunc
449 putamus parum claram, anteposuerit litterarum formas
450 humanitatis per seacula quarta decima et quinta decima.
451 Eodem modo typi, qui nunc nobis videntur parum clari,
452 fiant sollemnes in futurum.

8. Performance for Higher Energy Jets

455 Lorem ipsum dolor sit amet, consectetuer adipisc ing elit, sed diam nonummy nibh euismod tincidunt ut
456 laoreet dolore magna aliquam erat volutpat. Ut wisi
457 enim ad minim veniam, quis nostrud exerci tation ul
458 lamcorper suscipit lobortis nisl ut aliquip ex ea com
459 modo consequat. Duis autem vel eum iriure dolor in
460 hendrerit in vulputate velit esse molestie consequat, vel
461 illum dolore eu feugiat nulla facilisis at vero eros et ac
462 cumsan et iusto odio dignissim qui blandit praesent lupt
463 atum zzril delenit augue duis dolore te feugait nulla fa
464 cilisi. Nam liber tempor cum soluta nobis eleifend op
465 tion congue nihil imperdierit doming id quod mazim plac
466 erat facer possim assum. Typi non habent claritatem in
467 sitam; est usus legentis in iis qui facit eorum claritatem.
468 Investigationes demonstraverunt lectores legere me lius
469 quod ii legunt saepius. Claritas est etiam processus dy
470 namicus, qui sequitur mutationem consuetudium lecto
471 rum. Mirum est notare quam littera gothica, quam nunc
472 putamus parum claram, anteposuerit litterarum formas
473 humanitatis per seacula quarta decima et quinta decima.

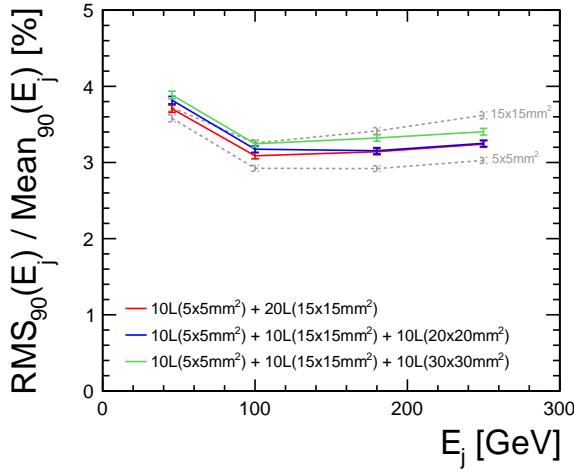
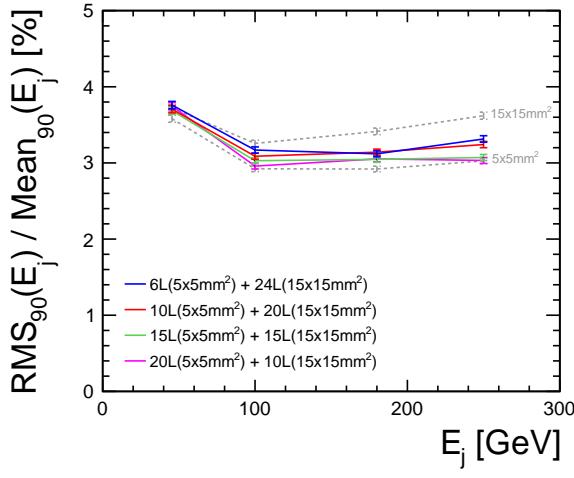


Figure 16

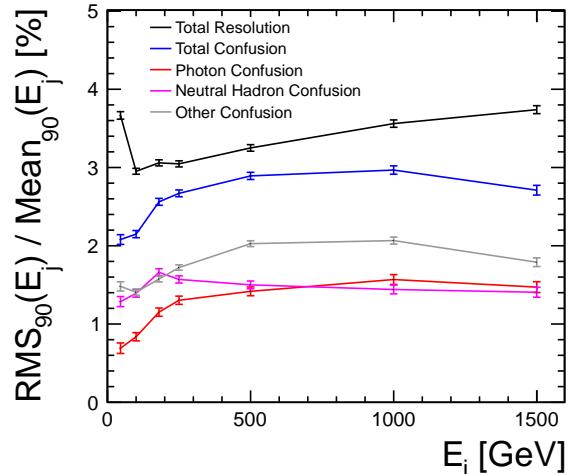
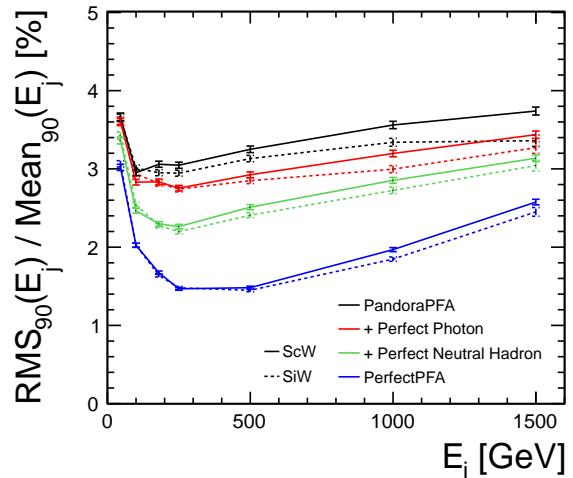


Figure 17

475 Eodem modo typi, qui nunc nobis videntur parum clari,
476 fiant sollemnes in futurum.

477 9. Summary

478 Lorem ipsum dolor sit amet, consectetur adipisci-
479 ing elit, sed diam nonummy nibh euismod tincidunt ut
480 laoreet dolore magna aliquam erat volutpat. Ut wisi
481 enim ad minim veniam, quis nostrud exerci tation ul-
482 lamcorper suscipit lobortis nisl ut aliquip ex ea com-
483 modo consequat. Duis autem vel eum iriure dolor in
484 hendrerit in vulputate velit esse molestie consequat, vel
485 illum dolore eu feugiat nulla facilisis at vero eros et ac-
486 cumsan et iusto odio dignissim qui blandit praesent lup-
487 tatum zzril delenit augue duis dolore te feugait nulla fa-

488 cilisi. Nam liber tempor cum soluta nobis eleifend op-
489 tion congue nihil imperdiet doming id quod mazim plac-
490 erat facer possim assum. Typi non habent claritatem in-
491 sitam; est usus legentis in iis qui facit eorum claritatem.
492 Investigationes demonstraverunt lectores legere me lius
493 quod ii legunt saepius. Claritas est etiam processus dy-
494 namicus, qui sequitur mutationem consuetudium lecto-
495 rum. Mirum est notare quam littera gothica, quam nunc
496 putamus parum claram, anteposuerit litterarum formas
497 humanitatis per seacula quarta decima et quinta decima.
498 Eodem modo typi, qui nunc nobis videntur parum clari,
499 fiant sollemnes in futurum.

500 **Acknowledgements**

501 Lorem ipsum dolor sit amet, consectetuer adipisc-
502 ing elit, sed diam nonummy nibh euismod tincidunt ut
503 laoreet dolore magna aliquam erat volutpat. Ut wisi
504 enim ad minim veniam, quis nostrud exerci tation ul-
505 lamcorper suscipit lobortis nisl ut aliquip ex ea com-
506 modo consequat. Duis autem vel eum iriure dolor in
507 hendrerit in vulputate velit esse molestie consequat, vel
508 illum dolore eu feugiat nulla facilisis at vero eros et ac-
509 cumsan et iusto odio dignissim qui blandit praesent lup-
510 tatum zzril delenit augue duis dolore te feugait nulla fa-
511 cilisi. Nam liber tempor cum soluta nobis eleifend op-
512 tion congue nihil imperdiet doming id quod mazim plac-
513 erat facer possim assum. Typi non habent claritatem in-
514 sitam; est usus legentis in iis qui facit eorum claritatem.
515 Investigationes demonstraverunt lectores legere me lius
516 quod ii legunt saepius. Claritas est etiam processus dy-
517 namicus, qui sequitur mutationem consuetudium lecto-
518 rum. Mirum est notare quam littera gothica, quam nunc
519 putamus parum claram, anteposuerit litterarum formas
520 humanitatis per seacula quarta decima et quinta decima.
521 Eodem modo typi, qui nunc nobis videntur parum clari,
522 fiant sollemnes in futurum.

523 **References**