

# LC HCAL Absorber and Active Media Comparisons using a Particle-Flow Algorithm

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We compared Stainless Steel (SS) to Tungsten (W) as absorber for the HCAL in simulation using single particles (pions) and a Particle-Flow Algorithm applied to  $e^+e^- \rightarrow Z \rightarrow q\bar{q}$  events. We then used the PFA to evaluate the performance characteristics of a LC HCAL using W absorber and comparing scintillator and RPC as active media. The W/Scintillator HCAL performs better than the SS/Scintillator version due to finer  $\lambda_1$  sampling and narrower showers in the dense absorber. The W/Scintillator HCAL performs better than the W/RPC HCAL except in the number of unused hits in the PFA. Since this represents the confusion term in the PFA response, additional tuning and optimization of a W/RPC HCAL might significantly improve this HCAL configuration.

## 1. INTRODUCTION

The detector for the  $e^+e^-$  linear collider will be required to make measurements of particle parameters to unprecedented precision. One of the most important requirements is that the hadronic decays of, i.e., vector bosons must be included in measurements of interactions involving these heavy particles. In order to distinguish a W- from a Z-boson, jet energy resolutions must be measured to  $\sim 30\%/\sqrt{E}$ , so that the hadronic decays (branching fraction  $\sim 70\%$ ) of these particles can be utilized. It is anticipated that the calorimeter (both ECAL and HCAL) information will be used in a Particle-Flow Algorithm along with tracking to achieve this precision. In addition, once a PFA is defined, it can be used to optimize the calorimeter since various calorimeter parameters will affect the results. In this report, both single particles and PFA results are used to investigate the effects of changing the absorber type and the active media type for the HCAL. The results show how a PFA can and will be used to optimize the HCAL design.

## 2. HCAL DETECTOR GEOMETRIES

The starting point for these studies was the SD detector geometry – version SDJan03 for the absorber studies and SDFeb05 for the active media studies. While there were some minor changes to other detector sub-components, the studies reported here are based on major changes to the HCAL only.

The HCAL for the original SDJan03 geometry is a 34 layer SS/Scintillator sandwich calorimeter. Each layer is composed of 2 cm SS absorber and 1 cm Scintillator. In terms of interaction length,  $\lambda_1$ , the HCAL is  $4 \lambda_1$  thick. The SS absorber thickness of 2 cm per layer corresponds to  $1 X_0$ . The HCAL radial extent from inner radius to outer radius is 102 cm.

The SDJan03 detector HCAL was modified to compare absorber types in the HCAL, motivated by: 1) curiosity about why the SDJan03 HCAL was less dense than its corresponding ECAL, 2) why the sampling in the HCAL was defined

in  $X_0$  instead of in  $\lambda_I$ , and 3) the desire to reduce the solenoidal magnetic field volume. A new version – SDAug04 was created by replacing the 34 layers of 2 cm thick SS absorber with 55 layers of 0.7 cm W absorber. The W absorber of thickness 0.7 cm corresponds to 2  $X_0$ , or 0.07  $\lambda_I$ . In the SDJan03 model, 2 cm SS corresponds to 1  $X_0$  or 0.12  $\lambda_I$ . The active media (1 cm thick Scintillator) was kept constant for both HCAL models and the total interaction length of 4  $\lambda_I$  was also kept the same. This resulted in a change in the radial extent of the HCAL from 102 cm with SS absorber to 94 cm with W absorber. If 0.5 cm thick scintillator is used as the active media for both HCAL versions, the radial extent is 85 cm for the SS absorber and 66 cm for the W – a savings of 19 cm (~20%) in this dimension. This represents a 40% reduction in the  $BR^2$  magnetic field figure of merit.

For studies of solid (scintillator) versus gas (RPC) active media, the version SDFeb05 in 2 variations was created. In both variations, the ECAL was identical – only the HCAL was modified. In each variation, the HCAL consisted of 55 layers of 0.7 cm W absorber and either 0.8 cm of scintillator or a 0.8 cm RPC gap in which the gas thickness was 1.2 mm.

### 3. COMPARISON OF TUNGSTEN/STAINLESS STEEL ABSORBERS FOR HCAL

First, single 5 GeV pions were analyzed in the combined ECAL/HCAL. The analog ECAL signal was added to the digital HCAL signal to obtain the total energy. The energy resolution for the W/Scintillator HCAL version was better by ~15% compared to the SS/Scintillator HCAL. Figure 1 illustrates this – more visible energy and increased number of hits in the W HCAL are consistent with the better energy resolution obtained with that model.

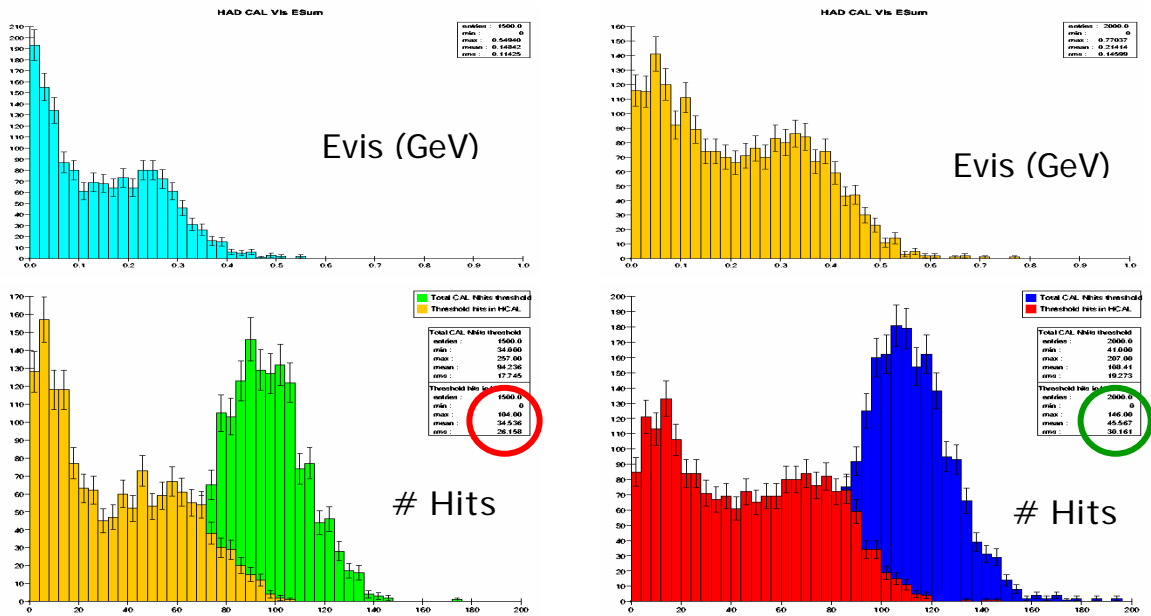


Figure 1: Visible energy and number of hits in SS HCAL (left) and W HCAL (right)

In addition to improved energy resolution in the W HCAL, the showers appear to be more compact – an advantage for PFA applications. The following plot shows the rms of the hit distributions versus a fixed cone size around the pion for both the SS and W HCAL versions – the showers in the W HCAL are ~10% more compact than in the SS version.

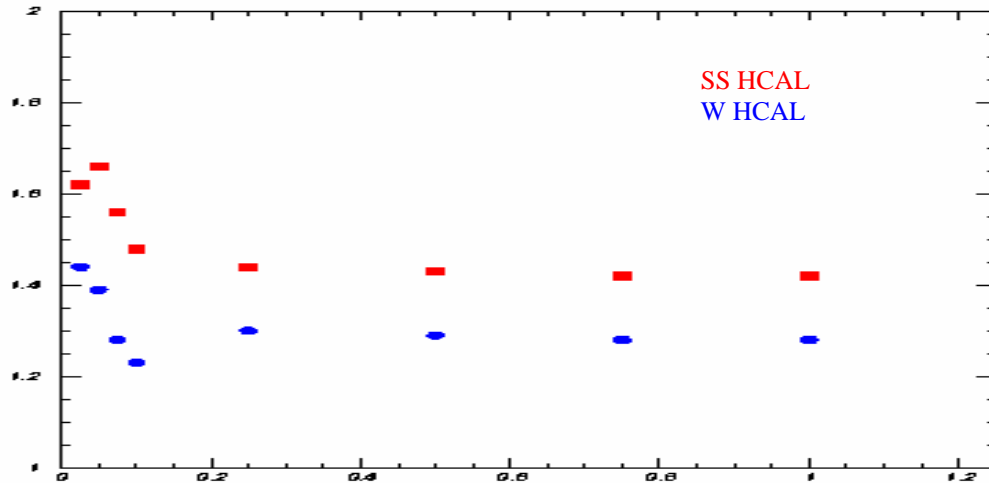


Figure 2: RMS of fixed cone size hit distributions vs cone size for SS HCAL (box) and W HCAL (oval)

Finally, the charged/neutral shower separation part of a PFA was applied to Z Pole events in the 2 HCAL versions. The results of true particle flow, in which perfect separation of fragmentation particles is achieved, show that the W HCAL version results in ~15% improvement in the total energy sum. Applying the real shower separation algorithm also yields a similar improvement in the results.

In summary, it appears that the relevant parameter for characterizing the energy resolution of hadrons is  $\lambda_1$ , not  $X_0$ . Finer  $\lambda_1$  sampling results in better energy resolution as expected. The W HCAL performs better than the SS HCAL in both resolution and PFA performance and, in addition, allows one to build a more compact detector, thus saving magnetic field volume. Even if the use of W increases the cost of the HCAL, the tradeoff in the smaller magnetic field volume might offset that cost, resulting in a cheaper overall detector.

#### 4. COMPARISON OF SCINTILLATOR/RPC ACTIVE MEDIA FOR HCAL

Since an HCAL with W absorber performs better than its SS counterpart, it is now used to compare the performance of two different active media types – a solid detector (scintillator) and a gaseous detector (RPC). For single pions, the scintillator HCAL in either analog or digital mode performs better than the RPC version in digital mode. The improvement in resolution is ~18% for the scintillator over the RPC version.

Next, the PFA is used to evaluate these options. This particular PFA begins with association of hits in the calorimeter to tracks of charged particles by iterating a cone around the particle trajectory and testing E/p after adding hits. For now, the true photon hits (from ECAL only) are removed from the analysis, so the PFA attempts to separate hits belonging to charged particle showers from those belonging to neutrals. Figure 3 shows the results of both the perfect PFA and the real charged/neutral separation algorithm in both HCAL versions.

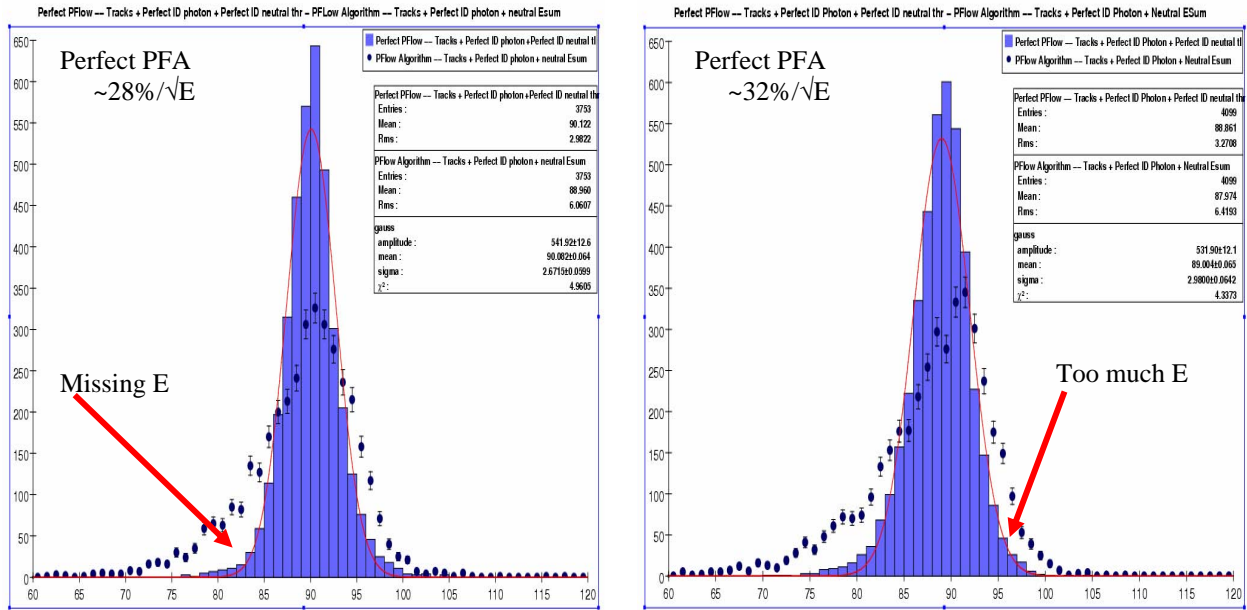


Figure 3. Results of PFA for W/Scintillator HCAL (left) and W/RPC HCAL (right)

The analysis of the perfect PFA results for these two options results in  $\sim 10\%$  improvement in energy sum resolution for the scintillator version over the RPC version. The same result for real charged/neutral separation is obtained by comparing the rms/mean for the two options using the real PFA. One indication of the quality of a PFA is the number of unassociated hits after the algorithm has been applied. Figure 4 shows the results for unused hits from the two options.

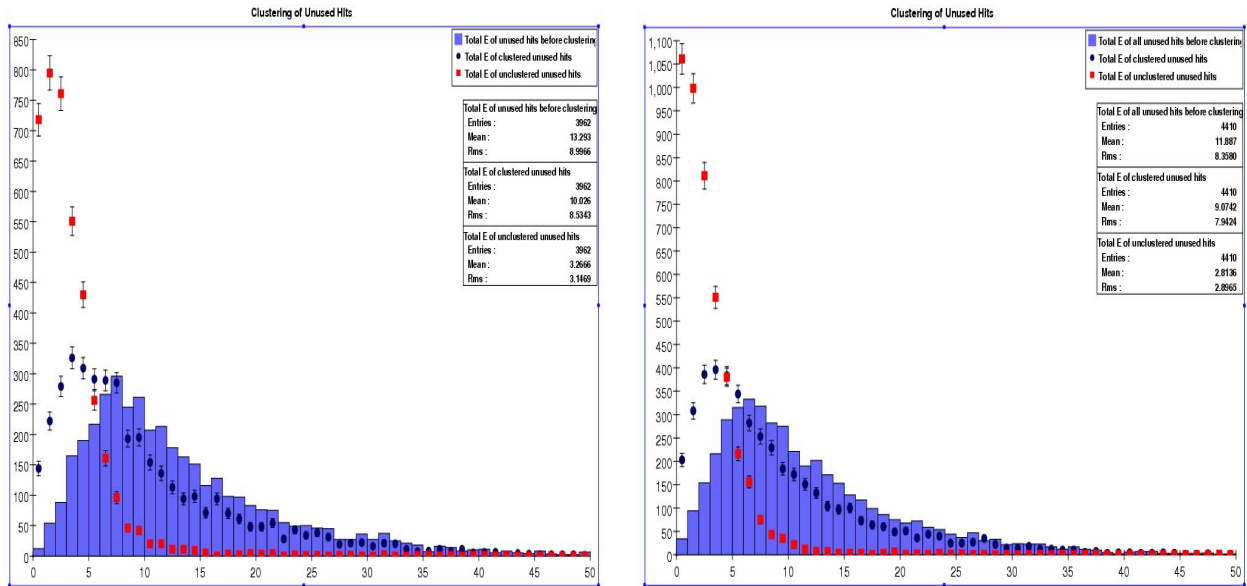


Figure 4. Unused hit distributions for Scintillator HCAL (left) and RPC HCAL (right). The large peak histogram in both plots represents the energy contained in unused and unclustered hits.

In this case, the RPC HCAL has an advantage in that less energy is leftover after the PFA has been applied. This means that it is easier to account for and separate the shower components for the case of the RPC HCAL. It may be possible to optimize this in further studies to improve the final result.

To summarize this section, the scintillator HCAL has better intrinsic resolution which translated into better perfect PFA resolution. However, the RPC HCAL resulted in fewer unassociated hits. Further studies may reveal that optimization of this feature of the RPC HCAL might result in big improvements in this option.

## 5. CONCLUSIONS

The absorber type studies indicate that a dense HCAL performs better in all ways than a less dense version. In comparing a W HCAL to a SS HCAL, it is clear that more  $\lambda_1$  is contained in the smaller volume of the W HCAL and, furthermore, the showers appear to be more compact in W than in SS. This means that PFA performance does not have to be sacrificed to gain in compactness of the detector and, therefore, in a smaller magnetic field volume. It also seems strange to build an HCAL that is less dense than the ECAL in front of it – for hadron showers that start in the W ECAL, as they propagate into the SS HCAL, they expand instead of contract making shower separation harder.

First indications of a comparison of active media show that better resolution for the neutral component resulting from application of a PFA is obtained with the scintillator HCAL. However, better charged/neutral separation might be obtainable with the RPC version. Optimization of the tradeoff between separation and neutral resolution might result in big improvements in the RPC HCAL.

In the detector models studied for this report, real PFA performance paralleled the perfect PFA calculation for the same model. This means that the perfect PFA calculation can be used to pre-evaluate detector models – showing the ultimate achievements for a particular detector configuration.