Summary of Calorimetry, Muon, and Other Detectors

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The present worldwide effort to develop calorimeters for a future linear collider detector is progressing rapidly. And there is much optimism that LC calorimeters, working together with the other detector sub-systems, will be significantly better than the LEP/SLC generation of detectors. Rather than making an attempt to provide a comprehensive summary of the many contributions to the busy calorimeter parallel sessions, I try to provide some context underlying the present efforts in this area, citing examples from the contributions.

1 Introduction

The calorimeter parallel sessions consisted of six sessions, including two joint sessions, one with the simulations group and one with the tracking group. There were 28 talks given. The main topic of 16 of these talks was detector R&D. Most of the talks involved simulation or detector R&D results related to the regional model detectors (see Table 1). The fact that there is substantial worldwide effort in detector R&D is significant. One could interpret this as an indication of broad agreement on calorimeter goals and the most promising techniques for achieving these goals.

Perhaps the most important goal, and the one most challenging to calorimeter designers, is the capability to measure electroweak processes which decay hadronically. In fact, multi-jet final states are common signatures of most new physics processes, many of which involve W and Z as intermediate states. Typical examples include the separation of the hadronic decays of WW from ZZ, or ZZ from ZH. Some important final states, such as HHZ to determine the Higgs self-coupling, have small cross sections and hence require the reconstruction of all final states, including those with 6 or more jets. Assuming that the detectors have this capability, the LC can provide these measurements. Excellent identification of specific hadronic final states and measurement of these states is a capability to examine new physics which is inherently limited at hadron colliders. Hence, there is strong motivation to provide this capability as a feature of LC detectors, independent of any specific prejudices we may have about the form of the new physics which underlies our LC observations.

The limitations to jet measurement at hadron colliders has been nicely described in a recent CMS study[1] which shows detector resolution to be a relatively minor contributor to the jet resolution relative to initial-state gluon radiation and underlying event effects. On the other hand, several studies[2] have examined what fundamentally limits LC jet resolution. They show that LC jet resolution will be primarily limited by detector resolution, not by QCD or other effects for which the experimenter has no control. (Nevertheless, it is still important to quantify QCD effects, which are likely to become more important for final states with many jets.) The limiting resolution, obtained by using the energy flow method and assuming perfect pattern recognition on events generated with QCD effects fully included, is $\approx 0.15/\sqrt{E_{\rm jet}}$ for 2-jet final states for the TESLA or SD detectors.

In addition to jet final states, the LC physics also requires that leptons are well measured. Tau identification and measurement becomes very important at the LC, and is mentioned below. SUSY final states require that the calorimeter coverage extend to small scattering angles, with no cracks, and places conditions on electron tagging at very small scatttering angles.

There is no clear physics case at the LC for excellent photon energy resolution, such as that for $H \to \gamma\gamma$ at the LHC, since the signal to background for such modes at the LC will be very good. On the other hand, some SUSY models predict secondary vertices where a photon is the only visible decay product. Thus, one would like to confidently identify photons which do not originate from the IP.

2 The Energy Flow Paradigm

As discussed above, excellent jet reconstruction and measurement is the outstanding challenge for LC calorimeters. Two basic facts drive the approach to this measurement. First, jets are composed primarily of charged particles. For example, for $ZZ \to$ jets the visible energy is 64% charged particles, 25% photons, and 11% neutral hadrons. (These numbers change very little for other hadronic final states.) Second, jet particles do not have large momenta, and the energy resolution for these charged particles is vastly better in the tracker than the calorimeter. Clearly, one would like to take full advantage of the tracker for jet physics. In fact, this idea has been in use in e^+e^- detectors for ages, in one way or another. It is sometimes called "energy flow," although there is much disagreement on the precise use of this term.

In the current LC studies, energy flow is used to describe a generic algorithm (EFA) in which energy depositions in the calorimeter are isolated and identified with parent particles in the categories photons, electrons, charged hadrons, neutral hadrons, and non-showering MIPs. Each charged particles is matched to its parent in the tracker so that the measured 4-vector is provided by the tracker and the corresponding energy in the calorimeter is identified so not to be used for other particles. Photon and neutral hadron 4-vectors must be provided solely by the calorimeter, of course, the latter representing a significant challenge.

Performance of EFA reconstruction requires a significant investment in full simulation and reconstruction algorithm development. The most sophisticated realizations of EFA to date[3,4] yield a jet energy resolution of $\approx 0.3/\sqrt{E_{\rm jet}}$. This is quite impressive relative to past experiments, for which $0.8/\sqrt{E_{\rm jet}}$ was about as good as one could expect. However, compared to the intrinsic LC limitations mentioned in the previous section, we see that there is still potentially a factor of two in resolution to be gained with detector and algorithm development.

2.1 Implications for the ECal

The primary role of the electromagnetic calorimeter (ECal) in EFA is to provide measurement of photons in jets. At the same time, one needs to accurately identify charged hadrons ($h^{\pm}$) and measure their trajectories accurately to allow matching to the tracker. Together, these two requirements call for a dense, highly segmented ECal. Photon-$h^{\pm}$ separation is provided in the overall detector configuration by BR^2 in the bend plane and R in the non-bend plane, where R in the outer tracker radius. And a small Molière radius (R_m) for the ECal is imperative. Studies show that typical minimum transverse photon-$h^{\pm}$ separation in jets is ≈ 1 cm. These requirements lead to designs such as the silicon-tungsten configurations of TESLA and SD, where $R_m = 0.9$ cm for tungsten is matched by transverse segmentation ~ 1 cm or better.

Longitudinal segmentation, with full read out, is also very important for providing MIP identification in the ECal (for matching with the tracker and HCal), shower shape discrimination, and photon vs hadron shower recognition. The relevance of this latter point is illustrated by the cartoon in Figure 1, wherein the energy deposited in the ECal by a hadron which begins to shower in the ECal cannot be determined without longitudinal segmentation.

A dense, highly segmented ECal provides other important assets. It is effectively an *imaging calorimeter*, so can be expected to provide crucial input wherever pattern recognition is helpful. As mentioned above, tau physics will likely be a key element for identifying and clarifying new physics. A dense, highly segmented ECal is clearly ideal for identifying taus and their decays. It also provides photon tracking, which opens the possibility to find photons not originating from the IP, potentially a critical signature for new physics. A study of this was presented at this meeting by Abe.[5] It might also be inter-

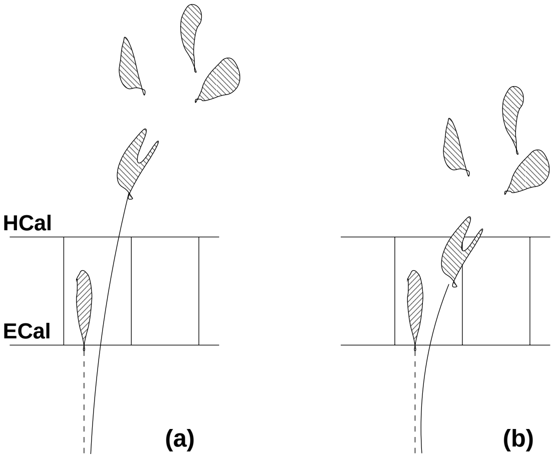

Figure 1: Illustration of the interaction of a π° and a π^{+} from a jet in a cartoon calorimeter. The π^{+} does not shower in the ECal in (a), but does in (b). The ECal has no longitudinal segmentation and the transverse segmentation is indicated.

esting to study how to combine photon reconstruction with charged particle information from the vertex detector to enhance flavor identification. Measuring positions and angles of Bhabha-scattered electrons will also be important as part of the program for determining the differential luminosity spectrum.[6,7] Finally, at very small angles, one would like to tag electrons from 2-photon events in order to distinguish these from SUSY signatures. Because of the huge background from the collective beam-beam interaction, this is a daunting task, but simulations[8] give one optimism.

2.2 Implications for the HCal

While hadronic showers are relatively large and diffuse, one still expects a highly segmented hadron calorimeter (HCal) to be very important for implementing the EFA, allowings MIPs to be tracked and providing good spatial resolution for pattern recognition. The measurement of neutral hadron energy is primarily rests with the HCal. And MIP tracking is also important for muon identification – one might imagine that a HCal with good imaging capability could provide muon identification by itself.

In the limit of a very highly segmented HCal, one might suppose that a simplified readout of only one bit per detector element is sufficient, and provides a way to simplify the readout and reduce cost. Several studies, starting with Videau[3] and discussed at this meeting by Magill,[9] have shown that for an HCal segmentation ~ 1 cm, the energy resolution for a one-bit readout is equivalent to a full analog readout. A HCal in this limit of small (~ 1 cm) segmentation and simplified (perhaps one bit) readout is called a digital HCal, or DHCal. This approach has received considerable attention since the 2000 LCWS, and as shown below, several groups are investigating this with both simulation studies and detector R&D. Simulations have not yet determined what segmentation is required for accurate jet reconstruction, or whether more than one bit would be useful.

The density of hits for a given hadron shower is an important consideration for DHCal design. Based on GEANT4 simulation, Videau[17] showed that a qualitative difference exists between the hit density for gas sampling versus scintillation sampling.

The other major approach bases the HCal sampling readout on scintillating tiles with full readout, where the transverse segmentation is in the approximate range 5 cm to 20 cm. In the case of the JLC and LD designs (see below), this is combined with a scintillating tile ECal to provide an integrated design with hardware compensation, whereas in the tile option for the TESLA HCal design, tiles are to be combined with the silicon-tungsten ECal.

3 The Regional Detector Models

Table 1 summarizes some of the major calorimeter parameters for current regional detector designs. It should be noted that in some cases these parameters are rapidly evolving, and are likely to soon be obsolete, if they are not already. The TESLA parameters are based on the TDR from 2001, except that the Shashlik ECal option is no longer included. The JLC parameters are based on the 3T design in the ACFA report.

4 Detector R&D

Given the limited space, I cannot begin to summarize the talks on detector R&D and detector design issues which were given at this meeting. A list of these talks is given in Table 2. Here, I simply mention a few relevant issues.

There are two overriding issues for silicon-tungsten ECal designs, cost of the silicon and how to deal with the channel count. A Moore's Law type analysis of silicon detector costs for HEP detectors would indicate costs of about \$2/cm^2 toward the end of the decade. Moreover, the ECal detectors would presumably be simpler, hence cheaper, than the strip detectors which are currently being costed for HEP applications. Bashindzhagyan discussed how the unit costs might be further reduced. So, for an ECal with total area $\sim 10^7$ cm^2, this does not seem at all unreasonable, given that this should be the dominant ECal cost. The SD design proposes an integrated electronics design, such that each wafer of detector pixels includes an integrated full readout chip, effectively reducing the external channel count by a factor $\approx 10^3$. The CALICE collaboration is also considering such an integration. Cooling becomes an important issue in such designs. Meanwhile the CALICE collaboration has made significant progress in developing detectors and readout for beam tests, which are planned to begin in 2004.

The JLC design, in which the baseline is a compensating Pb-scintillator structure, has now seen extensive test beam. The expected resolution and compensation have been demonstrated. More recently, significant effort has gone into improving the segmentation of the ECal using scintillating strips. The key issue here, common to all ECal scintillating designs, is how to attain fine longitudinal sampling, especially if compensation is required, while retaining sufficient light yield per sample; and how to achieve fine transverse segmentation given the light yield and cost of the readout. Matsunaga discussed some promising R&D using electron-bombarded CCDs to address the readout issue. Abe described a proposal by the Colorado group to effectively improve the granularity of tile ECal designs by offsetting successive layers in both transverse directions by a half unit. Initial simulations look promising. One motivation for the scintillator designs is to achieve a combined ECal and HCal which is hardware compensating. One might expect an improvement in neutral hadron energy response in this case, although one would have to weigh this against the difficulty in achieving fine segmentation, which to date has been dificult.

Checchia described a hybrid scintillator-silicon ECal. The motivation is that the silicon layers provide the required transverse segmentation, but by interleaving these layers at a frequency to be determined, the cost is reduced. A detector module was constructed and underwent a promising series of beam tests. What is required to make siginificant progress for the hybrid formulations are simulation studies which would indicate the tradeoff between cost and loss of pattern recognition capability. One nice feature of such a hybrid is the possibility of attaining better timing resolution than silicon alone, although a case for precise timing (< 1 ns) has not yet been established.

Significant progress has been made in recent years in the development of dense crystals, as presented in this meeting by Zhu.[14] Crystals of transverse size ~ 2 cm are possible with R_m of 2 cm in the best case (lead tungstate). However, the limitations in longitudinal segmentation for crystals are likely to represent an important limitation. Detailed simulations can help clarify this.

On the HCal development front, there are two main thrusts, as mentioned above: scintillating tiles and digital. For scintillating tiles, an impressive talk was given by Korbel on the R&D for the TESLA tile HCal. This group has made extensive studies of light output, fibers and fiber coupling to the tiles, and readout options, and is well on the way for beam test readiness starting in 2004. As discussed above, the JLC design also calls for a tile HCal, and indeed they have already provided test beam results, albeit with a configuration which may not be the final one.

For the digital HCal, the primary issue is what detector technology to use in the sampling gaps. The detectors must be easy to segment transversely, perhaps at the level of ≈ 1 cm pending definitive simulation results. And since there will be a huge number of channels, the detectors (and their readout) must be robust and inexpensive. The RPC option was discussed by Brient, which is being pursued both in Europe (IHEP) and N. America (ANL). Options to address the perceived RPC reliability issue include the use of glass RPCs, which are viable in the relatively low flux LC environment, and running the RPCs in avalanche mode rather than streamer mode. Martin discussed using scintillating tiles in a digital system and the R&D effort at NIU which has many elements in common with those of the TESLA and JLC tile efforts. Yu discussed a new idea to consider GEMs, long being considered for TPC readout, for the digital detector. In principle, triple GEMs could meet the requirements for the digital HCal, and an effort is underway to learn how to fabricate the GEMs.

5 Simulation Results

The boundary between the calorimeter and simulation groups is often fuzzy. Table 3 lists the talks which involved calorimeter-related simulation and reconstruction.

Evaluation of the EFA concept requires full, detailed simulations, and a collection of sensible algorithms. One lesson which has been learned many times in the last few years is that EFA will produce only modest improvement to jet resolution when applied to a calorimeter not optimized for EFA, or applied without careful attention to the pattern recognition algorithms.[12] At this meeting, we saw significant evidence that the development of reconstruction algorithms is rapidly approaching a state where reasonable evaluation of EFA is possible.

This was shown most dramatically in the talk by Brient on the REPLIC reconstruction package, which is being optimized for the TESLA design. These results were very nice indeed: Photons in jets are reconstructed with high efficiency, charged particles are matched to the tracker, and the remaining neutral hadron energy is identified, resulting in jet resolutions of $\approx 0.3/\sqrt{E_{\rm jet}}$, not only for 2-jet final states, but also for 4-jet final states. Magill and Graf discussed EFA implementations for the SD design which are similar to that of REPLIC, but with somewhat different ordering of the sequence of component algorithms. We note that to date, most researchers are using either the TESLA or SD designs for their EFA studies.

These developments are very promising, and we can expect to have some very useful exchanges of ideas and results over the next few years. In fact, Graf discussed ideas about how to effectively work together on simulations across the regions. It is clear that exchanging algorithms to be implemented on different detector designs is very difficult, since each tends to be optimized for a specific detector. However, there is no good reason not to use the same input/output formats to allow transparent exchange of data sets and results. In addition, it might be possible to eventually use a common executable for GEANT4.

6 Summary

I have tried to provide a superficial overview of progress in LC calorimeter development as reported at this meeting. This is a field which has seen a large growth in activity over the last two years, and for good reason – there are interesting ideas to pursue. And the calorimeter is seen to be key to the overall design of the LC detector. The energy flow paradigm remains the central idea which is guiding calorimeter design. We have seen at this meeting that simulation studies are reaching a threshold in sophistication and reliabilty which (1) allows validation of the basic EFA approach, and (2) will allow meaningful feedback to the detector designs.

Muon detectors were also included in our sessions. The only talk, given by Piccolo,[15] provided a nice summary of the worlwide efforts, to which the reader is referred.

Finally, for the first time in the LCWS series we had a discussion[16] of test beam availability and plans. With several groups already having performed significant beam tests, and others planning to test significant new detector modules starting in 2004, the worldwide availability of beams becomes a pressing issue. It is also perhaps the clearest reflection of the progress which has been made since the 2000 LCWS. In the opening talk, H. Videau[17] was asked to speak about how to test energy flow. From his talk and subsequent discussion it seems clear that one tests energy flow using detailed and realistic simulations (GEANT4) of the relevant physics final states. But the simulations themselves must be calibrated by the requirement that they reproduce the test beam data.

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Table 1: Parameters of the calorimeters for the main detector designs currently being studied with simulations. Note that many parameters, or even the detector concepts themselves, are likely to change. The labels T (tile) and D (digital) refer to two TESLA options.

	TESLA[3]	SD[10]	LD[10]	JLC[11]
Tracker type	TPC	Silicon	TPC	Jet-cell drift
ECal				
$R_{\rm min}$ barrel (m)	1.68	1.27	2.00	1.60
Type	Si pad/W	Si pad/W	scint tile/Pb	scint tile/Pb
Sampling	$30 \times 0.4X_0$ $+10 \times 1.2X_0$	$30 \times 0.71X_0$	$40 \times 0.71X_0$	$38 \times 0.71X_0$
Gaps,active(mm)	2.5 (0.5 Si)	2.5 (0.3 Si)	1 (scint)	1 (scint)
Long. readouts	40	30	10	3
Trans. seg. (cm)	≈ 1	0.5	5.2	4
Channels ($\times 10^3$)	32000	50000	135	5
$z_{\rm min}$ endcap (m)	2.8	1.7	3.0	1.9
HCal				
$R_{\rm min}$ (m) barrel	1.91	1.43	2.50	2.0
Type	T: sc. tile/steel D: digital/steel	digital	scint tile/Pb	scint tile/Pb
Sampling	$38 \times 0.12\lambda$ (B), $53 \times 0.12\lambda$ (EC)	$34 \times 0.12\lambda$	$120 \times 0.047\lambda$	$130 \times 0.047\lambda$
Gaps,active(mm)	T: 6.5 (5 scint) D: 6.5 (TBD)	1 (TBD)	2 (scint)	2 (scint)
Longitudinal readouts	T: 9(B), 12(EC) D: 38(B), 53(EC)	34	3	4
Transverse segment. (cm)	T: 5–25 D: 1	1	19	14
$\theta_{\rm min}$ endcap	5°	2°	2°	8°
Coil				
$R_{\rm min}$ (m)	3.0	2.5	3.7	3.7
B (T)	4	5	3	3
Comment	Shashlik ECal option in TDR discontinued		option: Si pad sh. max det	sc. strip (1cm) shower max det (2 layers)

Table 2: List of calorimeter detector R&D talks presented at this meeting.

Speaker	Topic
Brient, Manen, Vrba	Silicon-tungsten ECal, TESLA/CALICE design
Frey	Silicon-tungsten ECal, SD desgin
Bashindzhagyan	Silicon-tungsten ECal, new proposals
Y. Fujii	Lead-scintillator ECal and HCal, JLC design
Matsunaga	Fibers and strips for JLC ECal design and beam results
Abe	Offset scintillating tiles, LD ECal design
Checchia	Scintillator-silicon hybrid ECal design and beam results
Korbel	Tile scintillator HCal, TESLA/CALICE design
Brient	Digital HCal with RPC detectors, electronics
Martin	Digital HCal with scintillator detectors
Yu	Digital HCal with GEM detectors
Dauncey	Readout electronics for TESLA/CALICE beam tests
Lohmann	Very small-angle designs

Table 3: List of calorimeter-specific simulation talks presented at this meeting.

Speaker	Topic
Graf	Inter-regional cooperation, EFA ideas
Videau	The Mokka implementation of GEANT4
Martin	Software to augment geometries in GEANT4
Brient	REPLIC EFA package and results
Magill	EFA hadron reconstruction in digital HCal