STATUS REPORT

Investigation of ECAL Concepts Designed for Particle Flow

Personnel and Institution(s) requesting funding

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Collaborators

We have listed the names of various people with whom we have been in discussion with regarding participation in this and related projects.

Project Leader

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Project Overview

The project goal is to investigate electromagnetic calorimeter (ECAL) design concepts suited to the linear collider physics program. The principal physics design criteria for the ECAL are i) hermeticity ii) the precise measurement of jet energies using particle flow and iii) a design suited to a general purpose experiment. All these criteria are closely tied to the overall detector design concept with the work undertaken being very relevant to assessing the relative merits of the SiD, LDC and GLD approaches, and therefore this project is being coordinated with the detector design studies.

In the following sections we outline some of the reasons for highlighting these criteria and discuss their impact on the ECAL concept.

[Hermeticity] For e^+e^- center-of-mass energies beyond m_Z, physics processes with W's or Z's decaying in channels with 1 or 2 neutrinos occur frequently. Potential new physics such as supersymmetry leads to final states with characteristic missing transverse momentum. A principal detector goal is that events with significant missing transverse momentum should not be faked by Standard Model processes without neutrinos. It is of paramount concern that high transverse momentum particles, particularly photons, are detected with zero inefficiency. In the very forward region, (nearer the beam than the forward tracking), extremely efficient detection of electrons from two-photon processes is mandatory. It can also be necessary to detect muons and mips in such regions depending on the event topology.

The hermeticity requirements influence the ECAL design as follows: (i) need to avoid pointing cracks (ii) requirement to detect minimum ionizing particles (iii) elimination of "intruders" such as cosmics and halo muons (iv) reasonably uniform performance over the complete solid angle

[Particle Flow] In the particle flow method of jet energy measurement [1], the ECAL is used to measure the energy, polar angle and azimuth of photons in hadronic jets. A major requirement is to avoid double-counting of charged particles and photons in the visible energy measurement. This is most easily achieved by placing the ECAL at large radius.

The essential issue for the ECAL is measuring the 3-momenta of the photons over a dynamic range of between about 100 MeV and 500 GeV.

We have studied the intrinsic contribution to jet energy resolution arising from electromagnetic energy resolution [2] and we confirm that fractional energy resolution of $\approx 10\%/\sqrt{E}$ is necessary in order to not appreciably degrade the potential jet energy resolution of $18\%/\sqrt{E}$. For a realistic particle flow algorithm in a detector where the overall jet energy resolution attains $30\%/\sqrt{E}$, we expect this resolution would be dominated by confusion issues, and one could consider relaxing the electromagnetic energy resolution requirement substantially (perhaps by a factor of two) if jet energy resolution was the only physics concern (it isn't !).

The measurement of τ-lepton decays places severe constraints on the separation of charged hadrons from photons from π^0 decay. Kinematic reconstruction of events containing τ-leptons places rather stringent demands on the ECAL. (HCAL is relatively unimportant since neutrons are absent and K_L^0 are rare).

Another aspect of the calorimeter design which should not be overlooked is the detection and measurement of hadronic jets in the forward region where the charged particle tracking is likely to be compromised, specialized functions need to be accommodated (eg. Bhabha acolinearity measurement, luminosity measurement), and in general the environment is less conducive to full reconstruction (pile-up from $\gamma\gamma$ events).

[Design suited to general purpose e^+e^- experiment] Detection and precision measurements of electrons and photons is an essential element of an e^+e^- experiment. The measurement of Bhabha's and the $e^+e^- \to \gamma\gamma$ process are part of the basic program and are expected to play an important role in the measurement of absolute luminosity and the differential luminosity spectrum. Photons from initial and final-state radiation are often crucial aspects to doing some of the physics. With the prevalence of "radiative-return" events and events from two-photon interactions, the tagging of the initial-state photon or a scattered electron can be essential to physics analyses. $\ell\ell\gamma$ events will be a useful cross-check of the center-of-mass energy determination.

Given that we don't know what new physics will be explored at the linear collider, there is little strong guidance on the required energy resolution for the ECAL. One scenario which deserves more investigation, as it is one of the more compelling constraints on the ECAL energy resolution, is the measurement of the Higgs branching ratio to $\gamma\gamma$ presuming a Higgs mass of around 120 GeV. This was studied in [3]. The best measurement will come from the WW fusion channel ($e^+e^- \to \nu_e\overline{\nu_e}\gamma\gamma$) at the highest center-of-mass energy which has to compete against a large non-Higgs Standard Model background. This measurement would be complementary to LHC because together with other channels the BR could be measured directly. For similar reasons to LHC, the ECAL mass resolution directly influences the measurement precision. For this kind of application, the constant term in the energy resolution can be just as important as the stochastic term, and so an ECAL design which minimizes non-uniformities and can be easily calibrated is important.

Detector Design Considerations relevant to ECAL

The final detector designs will be heavily influenced by the choices made for the calorimetry. Some of the main design parameters which need to be considered are: the chosen B-field, the inner radius of the ECAL, the radius of the coil, and the aspect ratio (ie. the polar angle at which to change from a barrel to an endcap geometry).

Much of the current ECAL effort has been directed to applying the principles used very successfully in the limited solid angle LEP/SLC Silicon-Tungsten ECALs used for luminosity measurements to a full solid angle detector [4]. This approach is very attractive. Existing studies have characterized reasonably well the potential performance of the design studied for the TESLA TDR [5]. The main potential drawback is the cost, which may force the detector design to smaller radius, larger field and fewer sampling layers, as in the SiD approach.

To date, there has been relatively little work focussed on ECAL concepts which are well matched to the goals of particle flow at large radius, where with TPC tracking one can envisage comprehensive charged particle flow. Given that there are good reasons to believe that a larger detector has a better physics potential, [6], this should be seen as an area of critical need.

The University of Kansas group has been working on developing ECAL concepts which have the potential to be competitive with Si-W in properties where Si-W excels while substantially more cost effective and offering complementary capabilities in terms of energy resolution and timing resolution. A more cost effective solution would naturally lead to the possibility of building a much larger detector which would be the most effective way of ensuring particle separation for particle flow measurements. This would naturally fit well into the large and huge detector design studies.

We have been studying compact hybrid sampling ECAL structures with Tungsten absorber, with both silicon sampling gaps and scintillator sampling gaps. This approach promises the cost-effective use of silicon for shower pattern recognition and position measurement, while using cheaper scintillator layers as the main sampling medium. With this approach we have studied the simpler configurations of only Silicon sampling and only Scintillator sampling too. The current favored approach for the scintillator sampling is using scintillator-tiles with wavelength shifting (WLS) fiber readout to “on-tile” Silicon-Photomultiplier photo-detectors as employed in the CALICE MiniCAL [7]. The Silicon-PM has obvious advantages in terms of hermeticity, operation in B-field, and calibration (individual photo-electron peaks can be resolved). Features which need to be taken into account/mitigated are the noise and saturation characteristics.

We have been very encouraged by superb position resolution estimates for photons with Si-W sampling structures (300 μm for 1 GeV photons) assuming probably unrealistically small 1mm^2 pads [8] in a Si-W structure with a Moliere radius of 15 mm (see Figure 1). We are starting to envisage a new kind of particle-flow ECAL.

The essential issue about granularity is the separation of photons from charged tracks. This is best achieved by doing this separation at the longitudinal coordinate near which the photon converts. Our current ideas are to have a calorimeter which might consist of the following sections in depth :

- PAIRCAL: About 5 radiation lengths with Tungsten absorber and fine transverse granularity Silicon sampling layers (sampling at least every 0.5 radiation lengths). This device would pin-point the initial photon-conversion both in terms of transverse coordinate and longitudinal coordinate with very high efficiency. It may also be used to add some precise outer space points on high momentum tracks.
- SHOWERCAL: About 10 radiation lengths with Tungsten absorber and coarser transverse granularity Silicon sampling layers. The sampling would be at least every radiation length. More frequent sampling with some scintillator layers could be considered, but

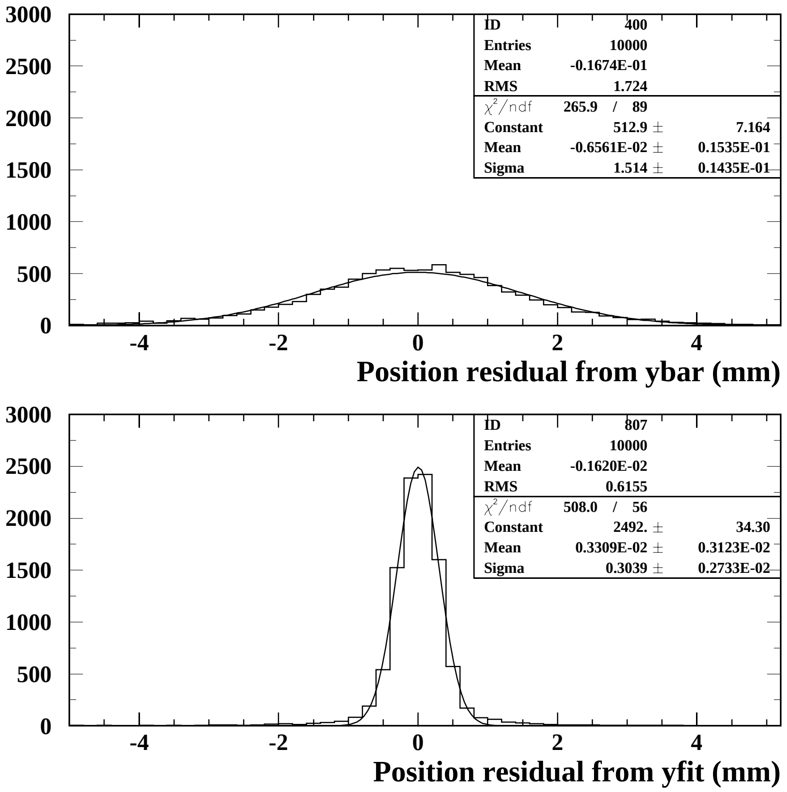

Figure 1: *Measured position resolution in one dimension for 1 GeV photons in a simulated Si-W calorimeter with 42 sampling layers (5/7 X_0 each) with 1mm^2 pads. Upper graph shows the results from the longitudinally integrated center-of-gravity of the shower with a resolution of 1.5 mm. The lower graph shows the results of a weighted "track-fit" to the first 12 layers, where layers close to the conversion point are given the most weight. A position resolution of 300 μm is achieved with 100% efficiency.*

would need to be rather compact longitudinally. This device would do the bulk of the energy measuring while retaining excellent pattern recognition abilities before and after the EM shower maximum.

- EM-TAILCAL: About 15 radiation lengths of cheaper technology ECAL still with sampling frequency of at least every radiation length. The absorber could be Tungsten or Lead. Lead would have the advantage of a better radiation length to interaction length ratio, and being cheaper. Longitudinal compactness requirements would be less severe. This portion should also provide functionality at least as good as the chosen HCAL technology, but needs to be analog.

This kind of arrangement is better suited to detector integration than the hybrid designs we had been exploring. Each potentially different technology has its own radial space. However, the radial subdivision may also entail new difficulties with calibration and pattern recognition which will need to be investigated/minimized.

Broader Impact

The project will support participation of undergraduates in research.

Our on-going work with setting up cosmic-ray test facilities will be done in such a way that we can use the apparatus as part of an open-day type demonstration in conjunction with a diffusion cloud-chamber we recently acquired. This apparatus will allow the general public to see and hear cosmic-ray muons.

We are interested in making movies which depict what happens in an e^+e^- interaction as the reaction products propagate through the detector and interact. The idea will be to capture images of a simulated event at appropriate time intervals after the interaction. Particularly relevant to this project, is to depict well the electromagnetic shower development.

Status Report

[Progress to Date]

We have made progress on many aspects of the project.

- We have studied the dependence of jet energy resolution on the intrinsic resolution of the tracker, the ECAL and the HCAL for all individual jet flavors. This study was carried out by Darius Gallagher (graduate student) under the supervision of Wilson. Initial results were reported at the Cornell, Summer 2003 meeting and are now written up in [2]
- Studies related to the importance of hermeticity in the detector design were described in the TESLA TDR by Wilson [9], and related results were reported in a plenary talk at the SLAC January 2004 ALCPG meeting [10]. Gallagher explored the ability to detect smuons in low visible energy scenarios where hermetic forward coverage is essential and the beam-hole caused by a large crossing-angle can be a hard limitation. Gallagher has now graduated with an M.Sc.
- Undergraduate student, Eric Benavidez, has been instrumental in developing our GEANT4 capabilities under the supervision of Wilson. We have developed simulations related to the following:

  optical tracking of photons in scintillator tiles

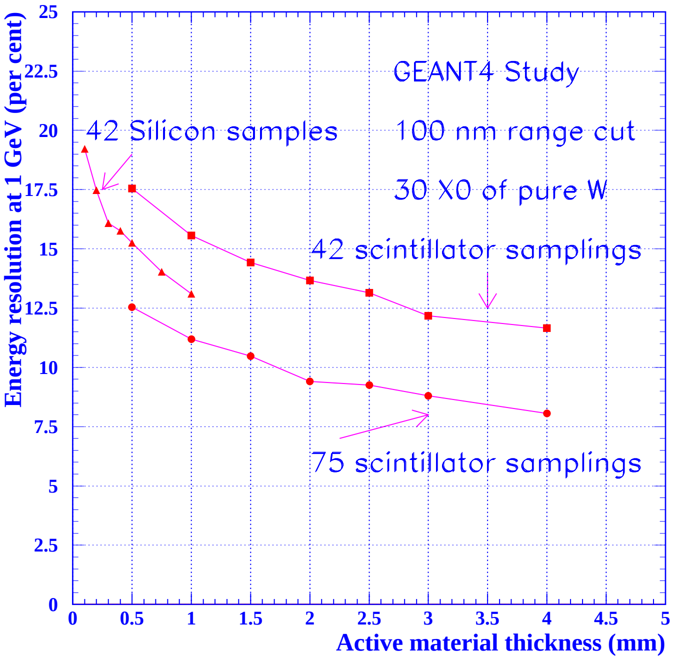

Figure 2: *Dependence of energy resolution for 1 GeV photons on sampling layer thickness for 3 different ECAL configurations. Each ECAL has 30 radiation lengths of Tungsten absorber (ie. 105 mm of W).*

simple sampling calorimeter test-beam geometries with arbitrary sampling media

pixelized sampling calorimeters. During 2005, we used the SLAC implementation of GEANT4 for cross-checks, and are working on maintaining and extending the functionality of these types of simulation with up to date GEANT4 releases. Michael Ambroselli (undergrad.) is working on this aspect at Univ. of Kansas.

- We have used these simulation tools to study several issues relevant to the ECAL design concept. These have been reported at the regular meetings both nationally and internationally [11]. Some of the main results are the following:

  Characterization of the energy resolution dependence on absorber and active material thicknesses. Studies have been done for Si-W, Scint-W and hybrids with W absorber and both Si and scintillator active layers. In particular we demonstrated that thicker Silicon layers which lead to a higher sampling fraction benefit the energy resolution. An example is shown in Figure 2.

  We have investigated the position resolution for photons as a function of the cell size. We have found, (as we expected), that cell sizes much smaller than the Moliere radius, do indeed lead to much better position resolution. Even with 1mm pads, we still found a resolution of pad-size/$\sqrt{12}$.

  Study of the correlation between the Silicon and scintillator response in hybrid structures. An anti-correlation of as much as 20% was observed which goes in the direction of improving the energy resolution compared to that which would be obtained with pure Si-W or pure Scint.-W. This observation offers the possibility that novel media may lead to larger (and more beneficial) anti-correlations.

  Study of some of the dynamic range issues associated with measuring beam energy electrons and photons at the highest center-of-mass energies.

  Observation that studies reported by other groups were using tracking cutoffs in the electromagnetic simulation which were affecting quantitatively their conclusions. This problem was reported in Summer 2003, and reiterated this summer [12], and the definitive time efficient fix from the GEANT4 electromagnetic processes team is expected this December.

- We have continued to develop our lab., centered around a VME based data acquisition system with multi-channel QDC's and TDC's for measurements with scintillator-based detectors. Undergraduates Eric Benavidez and Jonathan van Eenwyk worked together with Wilson on the commissioning of this system. Some of these developments are documented at [13]. We have been using this with a cosmic-ray trigger, as a set-up designed for testing scintillator-tile assemblies. We are currently using this with scintillator tiles from the OPAL experiment, described in [14]. We also have some internal conversion electron sources which are being used in this study. Graduate student, Treaster, started in late summer 2005, and is being trained in doing lab. measurements. During 2005, we have added considerable functionality:
  - Development of a motorized computer controlled X-Y stage for position scans (undergraduate project with Stephen Floor)
  - Development of LED driver circuit with precise pulse length adjustment (undergraduate project with Chris Partick in collaboration with John Ledford (EE).
  - Upgrading throughput of the VME data acquisition system by replacing parallel-port VME controller with fiber-optic link controller. (Wilson and van Eenwyk)

  - Commissioning of new VME scalers (van Eenwyk)
  - Development of optical bench type functionality with neutral-density filters and diaphragms for additional light intensity control.
  - Addition of new electronics modules including variable-gain amplifiers and variable-attenuation attenuators for amplitude measurement control
  - Addition of new 1.5 GHz bandwidth 4-channel oscilloscope.

- Participation in all three established detector concept groups (LDC, SiD, GLD).

- Wilson has written a summary of the main issues involved in evaluating the calorimetry performance of detector design concepts [15] particularly in light of particle flow. Many of the issues discussed are very relevant to this status report.

- Photon Reconstruction studies: Eric Benavidez worked in summer 2005 on clustering algorithm studies related to photon reconstruction under the supervision of Wilson and in collaboration with Norman Graf at SLAC. Eric was a recipient of a McNair Scholarship (funding from Dept. of Education). Eric studied the performance of different clustering algorithms, in particular nearest-neighbor and fixed-cone algorithms and these studies are documented [16]. Together with Wilson and Hensel, they started exploring the use of the H-matrix approach (developed by Graf) for photon identification. Initial studies used only the longitudinal energy deposition information. The H-matrix approach uses the inverse covariance matrix of the fractional energy depositions to form a chi-squared for the goodness-of-fit of the observed cluster to the average behavior of an ensemble of photons.

- Kinematic fits. Wilson has investigated the potential for improving the energy resolution of π^0's in hadronic jets by using 1-C kinematic fits of photon pairs to the π^0 mass. Studies [17, 18] indicate that there are excellent prospects for very significant improvements for detector designs similar to the current LDC and SiD concepts, where for typical π^0 energies in jets, the dominant contributions to the di-photon mass resolution come from the electromagnetic energy resolution rather than the opening angle measurement. Figure 3 illustrates the demonstrated improvement of around a factor of 2 in resolution for 5 GeV π^0's assuming rather typical photon resolution characteristics. This is a direct consequence of the extremely precise measurement of the photon-pair opening angle enabled by fine granularity ECAL cell sizes. This study suggests that ultra-fine ECAL granularity may have significant performance merits.

- Hensel and Wilson participated in the SLAC simulation workshop (March 2005) and the Snowmass workshop [18, 19].

- Electromagnetic showers in high B-fields. Wilson realized that there are potential disadvantages to very high B-fields in terms of photon reconstruction. The high B-field increases the effective transverse shower size for photons beyond that expected from just the Moliere radius, potentially diminishing the effectiveness of using high B-field and small Moliere radius to compensate for small ECAL radius. A secondary effect seen in studies of kinematic fits is a bias in the azimuth measurement of photons which may be attributable to the charge asymmetry of secondary electrons compared to secondary positrons in EM showers, an effect which will be exacerbated with high B-field.

- Initiated work on detector design model incorporating the PAIRCAL/SHOWERCAL/EM-TAILCAL ideas with Mark Thomson. Strawman detector design is implemented in the org.lcsim framework (frankyaug05) and events have been generated. Assistance from

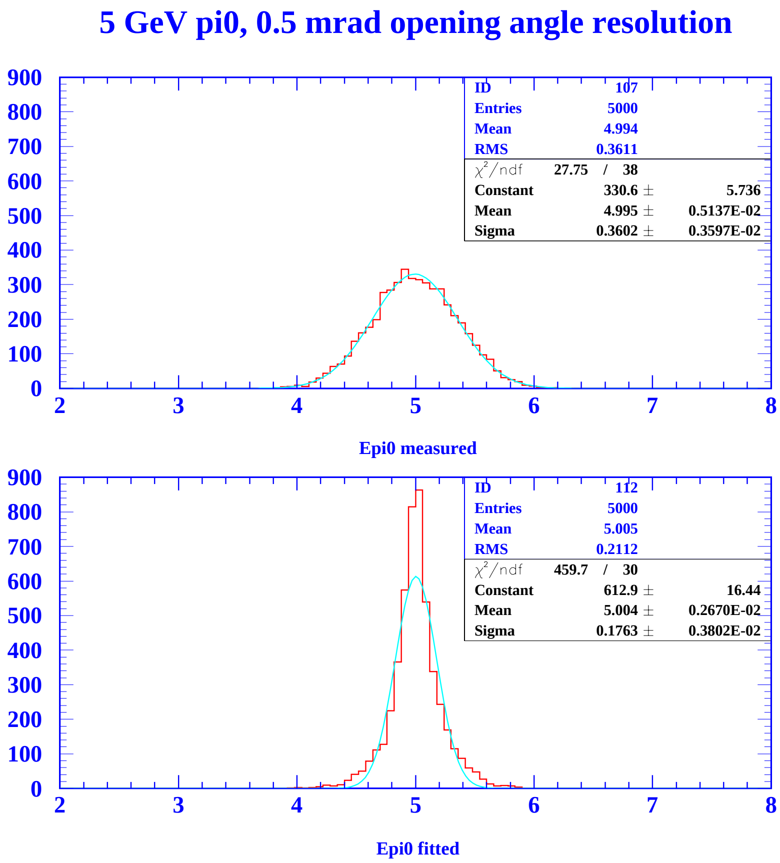

Figure 3: *Upper graph: Simulated measured energy resolution for 5 GeV π^0's assuming ECAL fractional energy resolution of 16%/$\sqrt{E}$. Lower graph: Energy resolution from kinematic fit for 5 GeV π^0's assuming opening angle resolution of 0.5 mrad. All decay angles are included.*

Norman Graf appreciated. The model has B-field of 3 T, and ECAL inner radius of 2.1m, and as implemented uses Tungsten as absorber throughout. The ECAL sections total 40 sampling layers and a total thickness of 20 X_0 with uniform 0.5 X_0 sampling per layer. The first 10 sampling layers (PAIRCAL) have Silicon pads with 320 micron thickness, and pad size of 2.5mm × 2.5 mm. The next 10 sampling layers (SHOWER-CAL) have Silicon pads with 320 micron thickness and pad size of 1 cm × 1 cm. The remaining 20 layers are 2 mm thick 2cm by 2cm scintillator tiles. This is followed by 50 layers of 2 mm thick 4cm by 4cm scintillator tiles. Dimensions were chosen to be technically feasible, and does not yet take advantage of potential new technologies like MAPS for the PAIRCAL.

- Particle Flow Algorithm Studies: We have contributed to the photon reconstruction effort which has been used in the org.lcsim based work, led by Norman Graf. Particularly in the context of investigating the particle flow performance of various detectors including issues like charged particle tracking in a TPC, and in contributing to studies for LDC, we felt it was necessary to develop some expertise with the MARLIN-based reconstruction code.
- Particle Flow Discussion: Led prioritization discussion at Snowmass of various detector issues related to particle flow and helped initiate relevant studies in collaboration with Mark Thomson, Felix Sefkow, Norman Graf, Steve Magill. Many of the main issues are starting to be studied rather seriously in several of the regions.
- We have been in communication with a number of potential collaborators, whom we are interested in collaborating with on this or related projects.

  M. Ronan, (LBL) : large detector concept
  R. Frey, D. Strom (Oregon) : Si-W
  J.C. Brient, (Ecole Polytechnique) : Si-W ECAL
  M. Thomson, D.R. Ward, (Cambridge), calorimeter reconstruction
  K. Kawagoe (Kobe), T. Takeshita (Shinshu), scintillating-tile ECAL
  B. Dolgoshein (MePHI), M. Danilov (ITEP), Silicon-PM
  V. Korbel, F. Sefkow (DESY), tile-HCAL applied to ECAL
  V. Zutshi (NIU)
  S. Kuhlmann, S Magill (Argonne)
  P. Checchia (Padova)
  D. Onoprienko, E. von Toerne, T. Bolton (Kansas State)
  P. Baringer, A. Bean, D. Besson (Kansas)
  N. Graf, A. Johnson, R. Cassell, J. McCormick (SLAC)
  F. Gaede, A. Raspereza (DESY)

FY2006 Project Activities and Deliverables

We will continue investigations of the performance characteristics of various ECAL concepts.

A particular priority will be to quantify the relative importance in realistic particle flow algorithms of charged-particle/photon separation compared to charged-particle/neutral hadron separation. This is critical for assessing the granularity requirements of the ECAL compared to the HCAL. This amounts to gaining a quantitative understanding of the various sources of “sigma confusion”.

We will extend the study of kinematic fits to π^0 candidates to assessing the performance gains expected of such kinematic fits in a hadronic jet environment. In hadronic jets, typically 92% of photons originate from π^0's but there are around 5 π^0's per jet. An important aspect will be to develop an appropriate algorithm for testing different ways to assign photons to π^0 candidates. This should be easier than one might naively think in that the symmetric decays have the biggest potential improvement, and if one starts from the most energetic photon, there will be relatively few potential partner photons giving a reasonable fit probability. We expect that the photonic energy contribution to the jet resolution will be improved substantially.

We will work on the photon reconstruction for particle flow algorithms. In calendar year 2006, we expect substantial contributions from Benavidez, Hensel, Treaster and Wilson. This activity should be beneficial to all ECAL concepts and detector design concepts. Deliverables will include characterization of the photon reconstruction performance. We are very keen to also investigate the quality of reconstruction of photons inside hadronic jets (ie. near interacting charged particles). A useful figure of merit, which factorizes out neutral hadron effects, is the reconstructed visible energy in hadronic Z decays where there are no neutral hadronically interacting particles, nor neutrinos. For these studies to have an impact on the global detector optimization in the context of particle flow, we plan to develop our ability to contribute to characterizing the overall detector performance using the state-of-the-art particle flow algorithms taking advantage of and contributing to software developments in all regions.

We will investigate calibration issues for longitudinally subdivided ECAL sections. This will involve sampling corrections as a function of shower depth/age, and will necessitate reconstruction of the photon conversion point shower by shower.

We plan to characterize the expected photon response over the full solid angle paying particular attention to the regions where hermeticity might be compromised.

We are very interested in getting involved in test-beam tests of particularly photon/charged-hadron separation, and anticipate participating in current Si-W projects.

FY 2007 Project Activities and Deliverables

This proposal is targeted at the development of an electromagnetic calorimeter design concept in a timely manner. However it is probable that many of the issues targeted in FY2006 will require further investigation in FY2007 or lead to other compelling related areas of investigation. We foresee future funding requests for the validation of design choices and construction and testing of a prototype once we have converged on an electromagnetic calorimeter design concept. The outlined budget for both fiscal years assumes little growth in budgets. If substantial growth were possible, the project would most benefit from additional funding which would permit dedicated work by a post-doc, or dedicated faculty work during the semester.

Budget justification: University of Kansas

The budget and scope we have outlined for this project is primarily for the design of a concept. In this respect a majority of the costs are associated with personnel (in the form of undergraduate and graduate research support), and the support for travel. The travel will be associated both with software development, particularly in collaboration with SLAC, and also work related to the detector design concept which will involve travel to discuss with collaborators both in Europe and Asia, and participation at future workshops.

The materials and supplies items are associated with fabrication of scintillating-tile assemblies and associated photo-detectors.

Two-year budget, in then-year K$

Institution: University of Kansas

Item	FY2006	FY2007	Total
Other Professionals	0	0	0
Graduate Students	0	0	0
Undergraduate Students	6	6	12
Total Salaries and Wages	6	6	12
Fringe Benefits	0	0	0
Total Salaries, Wages and Fringe Benefits	6	6	12
Equipment	0	0	0
Travel	10	10	20
Materials and Supplies	5	5	10
Other direct costs	0	0	0
Institution 2 subcontract	0	0	0
Total direct costs	21	21	42
Indirect costs(1)	9	9	18
Total direct and indirect costs	30	30	60

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