On Evaluating the Calorimetry Performance of Detector Design Concepts

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Aspects of how to evaluate the calorimetry performance in the detector design studies are discussed. After contributing to the benchmark discussion, we look in more detail at issues related to calorimetry performance, and propose studies to test single particle response and particle flow, and conclude with some comments on electromagnetic energy resolution requirements.

1. INTRODUCTION

A primary goal of the linear collider detector design studies, is to conceive mature general-purpose detector design concepts which are robust, affordable, and capable of proficiently investigating whatever physics the linear collider has in store for us.

I believe that the invitation to give a talk in this “Benchmarking” session was to help further develop the discussion regarding how best to proceed with detector performance evaluation and optimization. A similar discussion started in earnest at the LDC (Large Detector Concept) meeting at Ecole Polytechnique, Paris, in January 2005, attended by several participants at LCWS05. My brief at LCWS05 was to discuss “Benchmarks for Calorimetry”. Items related directly to evaluating calorimetry performance are discussed in Sections 2-5.

At the Paris meeting, and at LCWS05, it was clear that “benchmarks” or related measures of performance, mean very different things to different people. Two main philosophies emerged:

- “Physics-based”: Optimize the detector based on a small set of judiciously chosen physics benchmark reactions emphasizing final precision on physics quantities.
- “Detector-based”: Comprehensively evaluate detector performance using simple detector-level observables with full simulation.

In my judgement, the primary goal of conceiving mature general-purpose detector design concepts is best addressed by the latter detector-based approach. The physics-based approach also has some merit[1], but clearly, is not primarily designed to measure detector design. It is an approach which encapsulates the detector design parameters in specific physics-based metrics, which may or may not be useful in discriminating between different detector designs.

We also need to understand how to introduce “tension” and constrain the design of the different detector elements as a whole. Physics-based benchmarking (allied with cost!) is appealing from this point of view, but may quite easily end up driving particular detector design parameters which end up being insensitive to the *chosen* benchmarks into regions which are incompatible with the goals of a general-purpose detector.

1.1. Some arguments

Using “physics benchmarking” will often be based on physics that doesn’t exist, or may turn out to be unimportant.

My principal criticism is that if we end up comparing detector designs based on final physics reach in complex final states, the comparison is likely to highlight the smartness of the analyzer or the complexity of the analysis

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[1] When the primary focus of our efforts was the development of the physics case for the linear collider, it was clearly essential to focus on how well physics quantities could be measured.

rather than the performance of the detector. In addition, such studies may only be feasible at fast simulation level, thus not really being able to explore issues which impact on the actual detector technical design. I fail to see how such an exercise helps directly to evolve the design of each sub-detector system. A good example cited by Klaus Moenig in the discussion is the measurement of the top mass at the Tevatron with RunI data by CDF and D0. The two detectors are very different, but it is clear in doing such comparisons that the analysis method is as much what is being tested rather than the detector designs. Why not then just use the same analysis? The very nature of complementary detectors means that it is absurd to impose the same analysis technique on the two detector designs in order to have consistent comparisons.

Related to this, is a concern, that for consistency "physics benchmarking" needs to be asking questions like how well can the top mass be measured, rather than how well can it be measured just in the purely hadronic channel. These are interesting questions, but not that easily answered without considerable work, and still not that useful to the detector design studies. I can easily imagine that what turn out to be critical detector design parameter choices are not addressed at all by such studies. For example, a limiting systematic in the application of particle flow to jets may arise from the jet flavor, and the knowledge of the characteristics of $\pi^{\pm}$, $K^{\pm}$, p, n, K_L^0 interactions. A detector which is able to identify charged particles (eg. using dE/dx in a TPC), may have a distinct advantage in controlling such systematics.

Using "detector benchmarking" will make it easier to do clear comparisons of detector/accelerator performance and not physicist performance, and may lead to catching design errors in particular design concepts. It should also allow experimental physicists to make an informed choice on which detector to work on.

2. CALORIMETRY PERFORMANCE ISSUES

The following list represents a presumably incomplete list of important calorimetry-related performance issues.

- Hermeticity
- Calibratibility
- Alignability
- Jet Energy and Angular Resolution
- Electromagnetic Energy and Angular Resolution
- Hadronic Energy and Angular Resolution
- Transparency of Upstream Material
- Detection Thresholds
- Dynamic Range
- Noise
- Cross-talk
- Propensity for dead channels
- Tolerance to dead channels
- Luminosity, Energy, Polarization related measurements
- Electron reconstruction

The detector design ethos has been particle flow: the reconstruction particle by particle of hadronic jets. Many of these specific calorimetry issues, when folded with the overall detector goals, are expressed in terms of particle flow capability. This is quite a departure from the traditional design considerations for calorimetry, and some seemingly mandatory design criteria may be found to be less stringent in the context of a highly granular calorimeter.

3. EVALUATING CALORIMETRY PERFORMANCE

One of our main proposals at the Paris LDC workshop was to make sure that the detector studies did comprehensive single particle response studies. These are of general interest to all detectors, and in particular the calorimetry. The goals are to quantify measurement errors and acceptance for single particles. This is essential to understanding hermeticity, and should have a particular emphasis on transition regions (eg. barrel/endcap overlap) and the forward acceptance for electrons. These single particle samples can also be used to understand reconstruction efficiencies and mis-identification probabilities for isolated particles. It will be important to include buildable geometries and include realistic occupancy.

3.1. Comprehensive Single Particle Response Studies

All particle types should be studied over the full phase-space (ie. 4π sterad, and as a function of (momentum, $\cos\theta$, ϕ) and for both charges) Explicitly:

- Photons
- Prompt Leptons: $e^{\pm}$, $\mu^{\pm}$
- $\tau^{\pm}$, also separated into topologies
- Hadronic Charged Particles: $\pi^{\pm}$,$K^{\pm}$, p, $\overline{\mathrm{p}}$
- Di-photons: π^0
- V^0's: K_S^0, Λ^0 (include neutrals).
- Neutral hadrons: K_L^0, neutrons

3.2. Random Beam Crossing Simulation

One item that is essential for studying events with missing transverse momentum is an understanding of the noise rates in the detectors. This will also be a key factor in the data acquisition design. The noise rates have several contributions: accelerator-induced (eg. pairs, halo muons), physics-induced (eg. underlying gamma-gamma events and Bhabhas), detector noise, and cosmic-ray interactions, and of course also depend on integration times.

I think it would be worth evaluating whether a serious job of simulating all aspects of random beam crossings could be undertaken at this time. This has the potential of being a really important aspect for feedback between the detector designs and the accelerator design, and can crucially affect the ability to veto certain types of events without incurring large inefficiencies.

4. TESTING PARTICLE FLOW

One of the intrinsic problems with testing particle flow performance, is that one has to test not just the detector performance, but also the particle flow algorithm (PFA). PFAs are under development, and in principle they can very easily be quite dependent on the detector conceptual design. In this situation, we will be well advised to restrict to rather simple observables for eliciting comparisons among detectors.

4.1. Z → hadrons Response Studies

Having in hand comprehensive isolated single particle studies, the main job for evaluating particle flow is to understand how to reconstruct events with hadronic jets. The major issue is minimizing the "confusion term" [1], related to separating individual particles and avoiding double counting of energy deposits. The physics process that we believe is most relevant to measuring this is Z → hadrons. For simplicity, events should be generated at 91.2 GeV and arguably with no initial state radiation or beamstrahlung. Care should be taken to identify and/or remove events with neutrinos.

Why study events at $\sqrt{s} = 91.2$ GeV again? Well, almost every interesting physics process at the linear collider which has W or Z's in the decay chain is likely to be studied near its kinematic threshold where the W and/or Z is almost at rest. Why ignore ISR and beamstrahlung? These are complications which get in the way of understanding if different detector designs / PFAs have significantly different performance. For the reactions where the W or Z would be the result of a decay, the ISR and beamstrahlung calculations would be different anyway.

4.2. More difficult cases

In practice, the particle flow problem at the linear collider will be more difficult than that indicated by the single Z studies. There are two aspects to this: i) multi-jet events such as 4-jets (WW, ZH, ZZ), 6-jets eg. $\mathrm{t\overline{t}}$, ZHH etc where the number of particles increases dramatically and the probability of particles from different jets overlapping increases. ii) very dense jets which stress the ability to resolve separate particles, eg. highest energy $\mathrm{q\,\overline{q}}$ events, or $\tau^+\tau^-$.

A suggested course of action would be to use events with multiple Z's at 91 GeV overlapped, to study the dependence of particle flow performance on vector boson multiplicity, and to use the 2-fermion events with both quarks and taus to test the dense jet issues as a function of center-of-mass energy.

4.3. How should we test and develop particle flow ?

From the calorimetry viewpoint, there are several distinct parts to particle flow.

- Electron / photon separation
- Photon / charged-hadron separation
- Charged hadron / neutral-hadron separation
- Photon / neutral-hadron separation
- Photon / photon separation

Electron/photon separation should be relatively straightforward with a good tracker. Photon/neutral-hadron separation is not essential to particle flow per se in that there isn't a double-counting issue to resolve. However, recent studies indicating that mass constrained fits of di-photons to the π^0 mass have potential to improve the electromagnetic energy resolution of jets point to photon/neutral-hadron separation being at least of some importance. Likewise if this is indeed important, photon-photon separation is also worthwhile.

So the two main issues which are currently widely appreciated as the essence of the particle flow problem are the separation of the charged-hadrons measured in the tracker from i) the photons in the electromagnetic calorimeter and from ii) the neutral hadrons found in the electromagnetic and hadronic calorimeters. Ideally, we should factorize to some extent the problem, or at least understand the relative importance of these two contributions. One way to go about this would be to separate hadronic Z events into samples with and without neutral hadrons. Figure 1 shows the intrinsic contribution to the visible energy resolution from detector momentum and energy resolution for some particular resolution choices [2] for hadronic Z events. Most (87%) such events contain some neutral hadrons

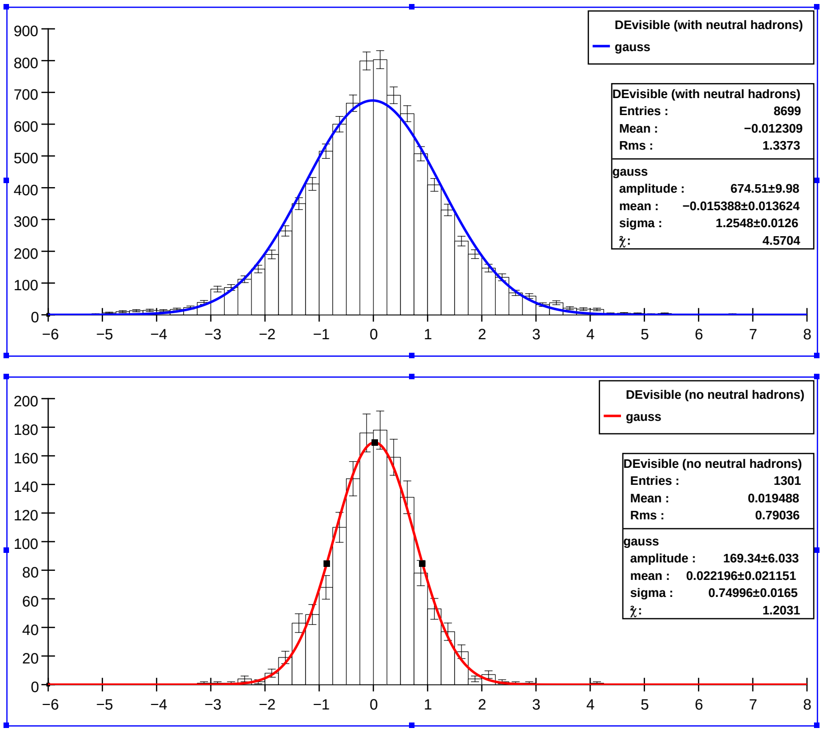

Figure 1: Visible energy residual (GeV) for hadronic Z events containing neutral hadrons (top) and for those containing *no* neutral hadrons (bottom).

(upper figure) leading to a resolution on the visible energy of 1.25 GeV, equivalent to $13\%/\sqrt{E}$. In these events we will have to deal with both issues, and the relative importance of the two different types on confusion term will be important to understand. The remaining small fraction (13%) of events with no neutral hadrons (lower figure) have a visible energy resolution of 0.75 GeV, equivalent to $8\%/\sqrt{E}$. For these events the real issue will just be charged-hadron/photon separation.

Perhaps the best way to study this problem would be to study the particle flow performance for different regions of the (track momentum fraction, photon energy fraction, neutral hadron energy fraction) Dalitz plot. Figure 2 shows such a plot with the charged particle energy vs photon energy in hadronic Z events. Energy conservation (neglecting neutrinos) requires the sum of the two variables plus the neutral hadron energy to sum to 91.2 GeV, so there is a kinematic limit on the diagonal. One sees that on average there is not much energy in neutral hadrons, but that there are long tails to large contributions. It will be interesting to explore whether the particle flow performance is most dependent on the region within the Dalitz plot, or is mostly influenced by effects like particle multiplicity.

5. INTRINSIC ELECTROMAGNETIC ENERGY RESOLUTION REQUIREMENTS

The documented physics case for e^+e^- collisions at the linear collider contains few strong explicit constraints on the electromagnetic energy resolution. However, the actual requirement, potentially is a large cost driver in probably the most expensive system (the ECAL). One process which might help place this in physics context is the measurement of WW fusion production of Higgs followed by decay to $\gamma\gamma$ at the highest energy. Without some “tension” like this in the detector optimization process from other physics requirements besides particle-flow, we could end up with something that doesn’t really match the goal of a general-purpose detector.

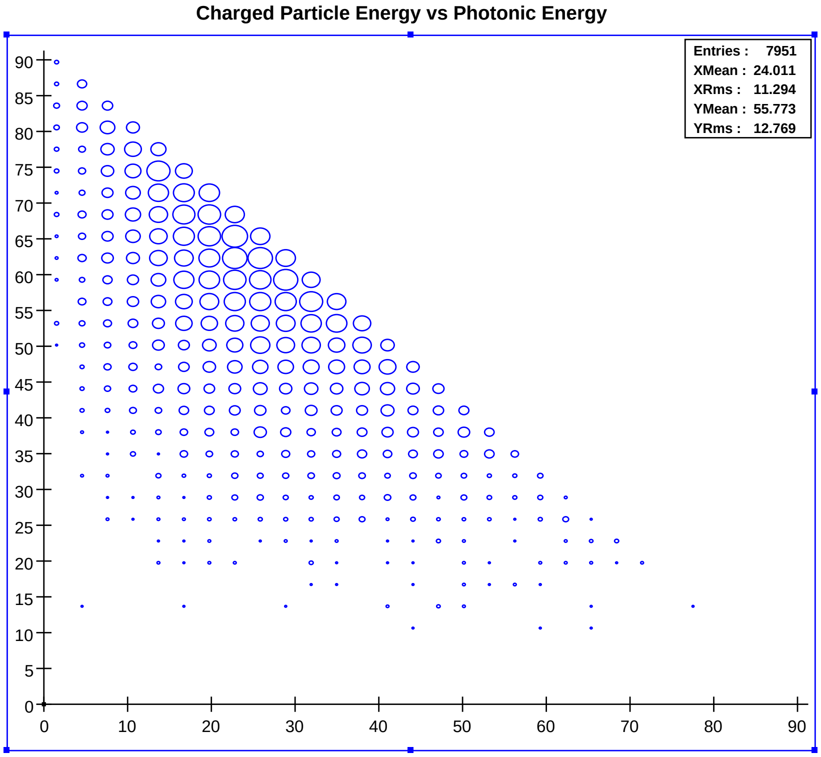

Figure 2: Total charged particle energy (GeV) vs total photon energy (GeV) for hadronic Z events with no neutrinos.

6. CONCLUSIONS

We can make efficient progress if we keep things simple and concentrate on doing detector physics and encouraging participation. For comparisons to happen, we need studies that are well enough defined and simple that they get accepted by the detector design groups, and continued progress is made on sharing 4-vectors, GEANT4 setups and reconstruction frameworks. The eventual utility greatly depends on the realism and accuracy of the detector simulations which hopefully will be addressed by the test-beam program in the near future.

Acknowledgments

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References

[1] D. Karlen in Proceedings of LCWS02, Jeju, Korea.
[2] The intrinsic fractional resolution assumptions used in this simulation for photons is $15\%/\sqrt{E} \oplus 1.5\%$, for neutral hadrons is $35\%/\sqrt{E} \oplus 3\%$, and for charged tracks it is $5 \times 10^{-5} p_T$. Units are in GeV.