1 What kind of demands does the precision physics program at future e+e- colliders place on the event (energy) reconstruction?

In contrast to hadron collisions, which produce a huge amount of QCD background reactions (producing jets) sometimes shadowing the processes of interest, lepton collisions provide a much cleaner environment for high energy physics. This promotes, among others, precision measurements of standard model gauge bosons (W, Z, Higgs). Since these bosons decay preferably into quark-antiquark pairs, the detector systems must be able to identify and measure the jets creates by this final state quarks. To separate the Jets from W and Z boson decays, which have a mass difference of $\sim$ 10GeV, and to get access to the coupling of the respective boson, the detector has to determine the jet energy with a precision of 3% to 4%.

2 What is the difference between classical jet energy measurement and the particle flow approach?

- **Classical:** The reconstructed jet energy is the sum of all energy depositions in the electromagnetic and hadronic calorimeter, within the jet volume determined by a jet clustering algorithm.
  Problem: $\sim$70% of the jet energy is deposited in the hadronic calorimeter, which offers the worst energy resolution.

- **Particle Flow:** Since $\sim$ 60% of the particles in a jet are charged, the energy measurement of these particles can be done with the tracking detector, potentially reaching an energy resolution in the sub percent region. About 20% of the jet energy is carried by photons, which are not detectable in the tracker because they are neutral. The photons are detected in the electromagnetic calorimeter. The remaining $\sim$10% of the jet energy, carried by neutral hadrons like neutrons or neutral kaons, are detected in the hadronic calorimeter. In contrast to the 70% of the jet energy measured in the worst subdetector, $\sim$ 90% of the jet energy is now measured in the subdetectors with good energy resolution. This intrinsically improves the jet energy resolution.

3 How does particle flow benefit from highly granular calorimeters?

In order to avoid double counting of particles, and thus double counting of energy, the tracks of the particles in the tracking detector have to be associated to the energy depositions in the calorimeters. With rising jet energies, the jets get narrower. Electrons, photons and hadrons entering the calorimeters typically produce particle showers which also grow longitudinally and transversally with rising energy. The calorimeters have to be able to separate these showers. This is achieved by subdividing their active area into smaller segments to record an image of the particle shower ('imaging calorimetry").Thus, the energy measurement transforms into a pattern recognition problem with rising jet energies.

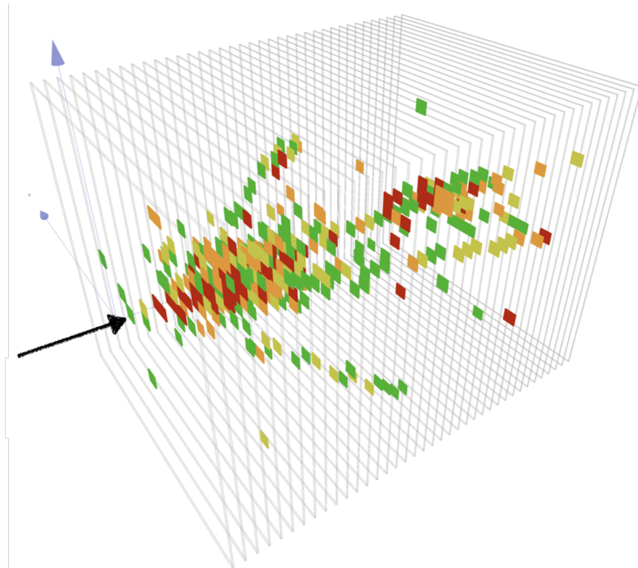

Figure 1: Event display of a 60GeV charged pion producing a particle shower in the CALICE Analoge Hadronic Calorimeter (AHCAL).

4 What is the preferred ordering of the detector components of a full collider detector system to fully exploit the particle flow approach (from the interaction point outwards)?

- Vertex detector
- Tracking detector
- Electromagnetic Calorimeter
- Hadronic Calorimeter
- Magnet
- Muon system

5 Why are software compensation techniques especially effective in combination with highly granular calorimeters, e.g. the CALICE AHCAL (Analoge Hadronic Calorimeter)?

A fundamental difference between electromagnetic (em) and hadronic showers is their energy density and particle multiplicity. Em showers are very dense, their evolution is governed by the ratiation length (see lecture), and their particle multiplicity is very high. Hadronic ones are typically rather sparse with a lower particle multiplicity. Since an inelastic hadronic interaction in the detector can produce neutral pions, which decay into two photons, hadronic showers can (and typically do) develop an electromagnetic component. This is seen in the red core region of the shower in figure 1. The fraction of the initial particle energy deposited in the electromagnetic component, fluctuates from event to event, depending on the number of neutral pions. This fluctuation leads to a deterioration of the energy resolution. Using highly granular calorimeters, one can identify the em component of the shower by looking at the energy density. A software compensation algorithm uses the energy density to apply weights to the measured energy, to correct for the difference in response to em and hadronic component of the shower. The potential improvement of these algorithms depends on the power of disentangling the em and hadronic component and thus on the granularity. Since increasing the granularity typically increases the complexity of the detector and thus the cost, the design of such a calorimeter is a demanding optimization process.