Integrated Calorimeter Design for Optimal Jet Energy Resolution

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- Motivation
- Physics Requirements -> Future Detectors
- Energy Flow Analyses
- Tracker Requirements for E-Flow
- E-Flow Implications for Calorimetry
- The Ultimate E-Flow HCAL?
- Conclusions

Motivation

Motivated by calorimeter studies at a 500 GeV e+e- LC (ECFA/DESY, American Linear Collider Working Group}

In production of W^+W^-, ZZ, Zh :

- **Need to identify W,Z in dijet decay mode ->**
  - **Requires ~few GeV mass resolution ->**
    - **~30%/√E jet energy resolution as well as good angular resolution**

How to design and build future calorimeters for optimal jet reconstruction/resolution?

Many other related talks here at Snowmass (WG E3) :

- H. Matsunaga
- G. Bower
- J.-C. Brient/H. Videau
- V. Korbel
- V. Morgunov
- R. Frey

→ **SG3 Detector R&D**
Monday, July 16

SG3 Detector R&D
Detector Overviews
Monday, July 9 →

- J. Brau
- T. Tauchi
- K. Moenig

Physics Requirements -> Future Detectors

Hermeticity

- SUSY, Extra Dimensions – missing E
- Forward detector coverage

Energy Flow Analyses

- New Physics Signal/Standard Model Backgrounds
- Increasing dependence on reconstruction of multi-jet final states
- *Optimal integrated detector design*

Track Momentum Resolution

- Resolution of di-leptons
- Large tracking volume/High B-field

Jet Flavor Tagging

- High tagging efficiencies for heavy quarks
- Multi-layered vertexing

Why Energy Flow Analysis is Needed

Physics Requirements

Multi-jet final states require separation of WW, ZZ, and Zh -> *<u>~few GeV mass resolution at 100 GeV</u>*

Missing energy -> *hermiticity*

Heavy q tags -> lepton ID + *jet reconstruction*

Process/Machine Requirements

Signal/BACKGROUNDS (both machine and process)

High B-fields -> 4 T, ~2 m R to ECAL -> ~1 GeV min charged particle momentum to get to calorimeter -> *need for excellent tracking*

⑤Incorporate E-Flow into Detector design

E-Flow Analysis Technique

Jets treated as a collection of objects, each having its own reconstruction method tuned for optimal jet energy resolution :

Charged hadrons, electrons, muons – high momentum resolution tracker

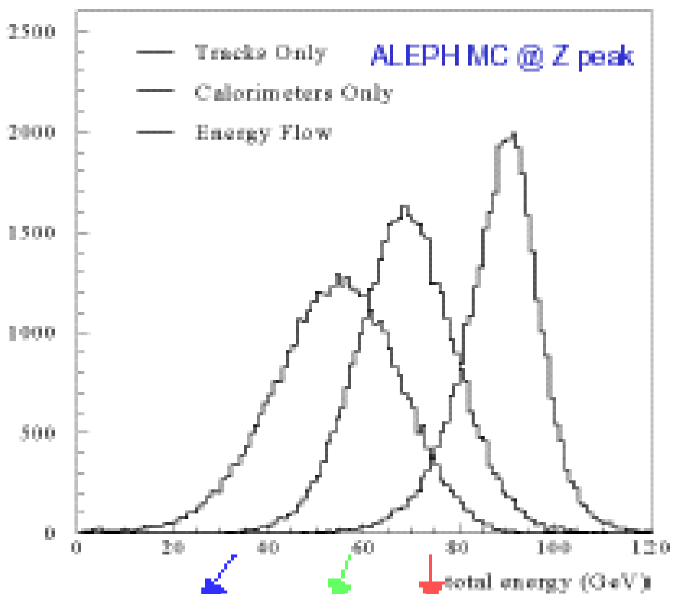
Photons – fine-grained electromagnetic calorimetry (ECAL)

Neutral hadrons – *optimized* hadronic calorimetry (HCAL)

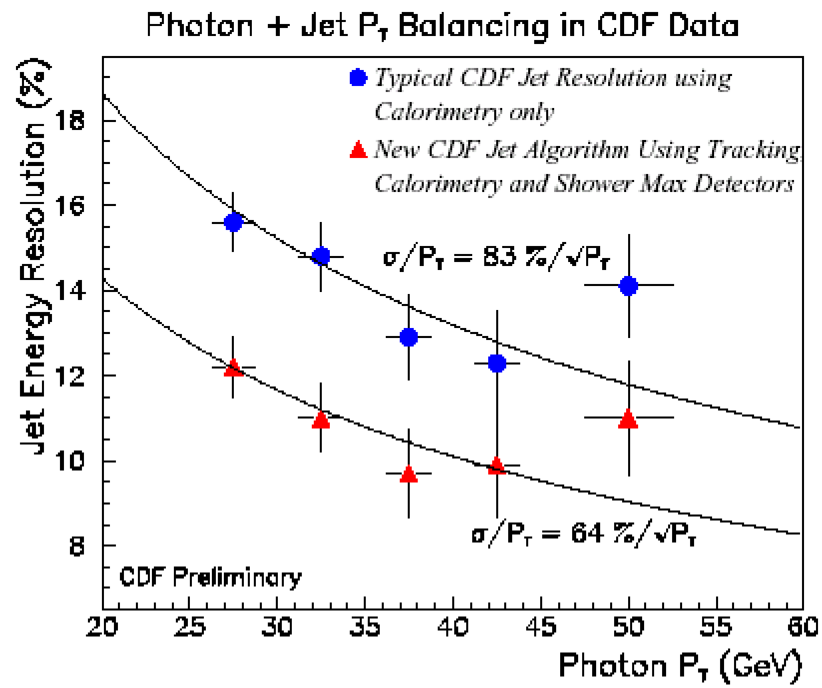
Depends on the ability of the calorimeter to separate energy deposits of charged hadrons from neutral hadrons

$$E_{jet} = \Sigma E_{photons} + \Sigma E_{tracks} + \Sigma E_{neut.\ hadrons}$$

Jet Energy Resolution Improvements from E-Flow?



.(E)/E =	0.22	0.13	0.07
.(.) =	1.6°	1.4°	0.9°



Angular granularity + particle ID capabilities

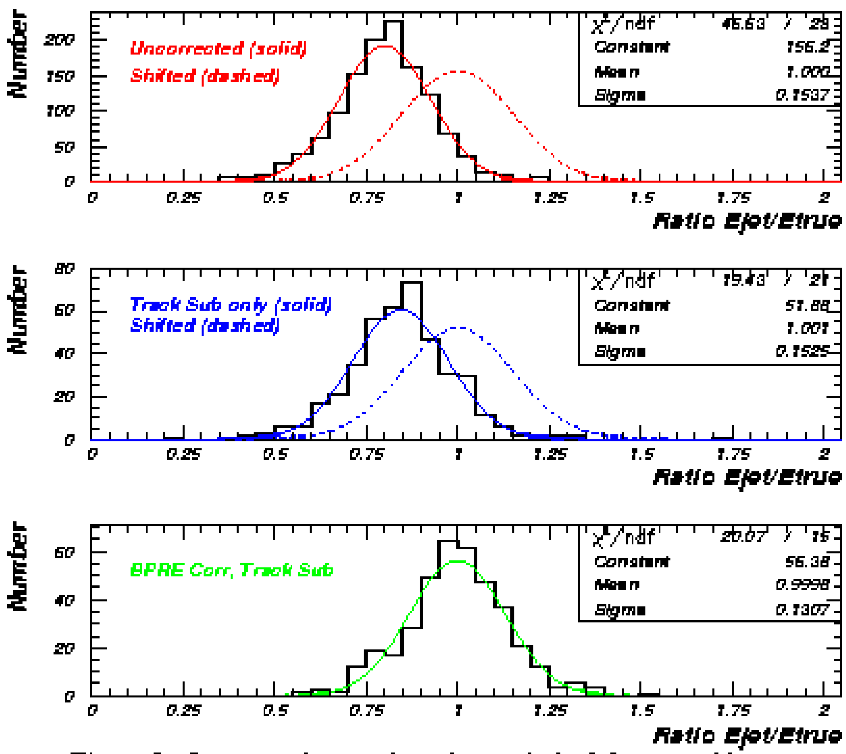
Good performance of E-flow algorithms

Improvements in jet energy resolutions at ALEPH and CDF with E-Flow

F. Ligabue, CALOR2000

More Improvements

A slightly different kind of E-Flow :



From ZEUS : optimize jet resolution by correcting electromagnetic energy deposits with a preshower signal

Track substitution for charged hadrons not so good – large (>20 x 20 cm) cells in HCAL -> poor separation of energy deposits from charged and neutral hadrons

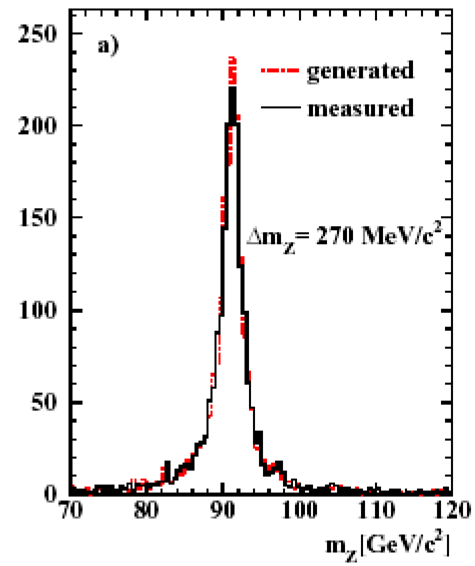
Tracking Requirements

Momentum resolution $\Delta(1/p) \sim 5 * 10^{-5}$ (GeV/c)$^{-1}$

Tag b- and c-jets with high efficiency

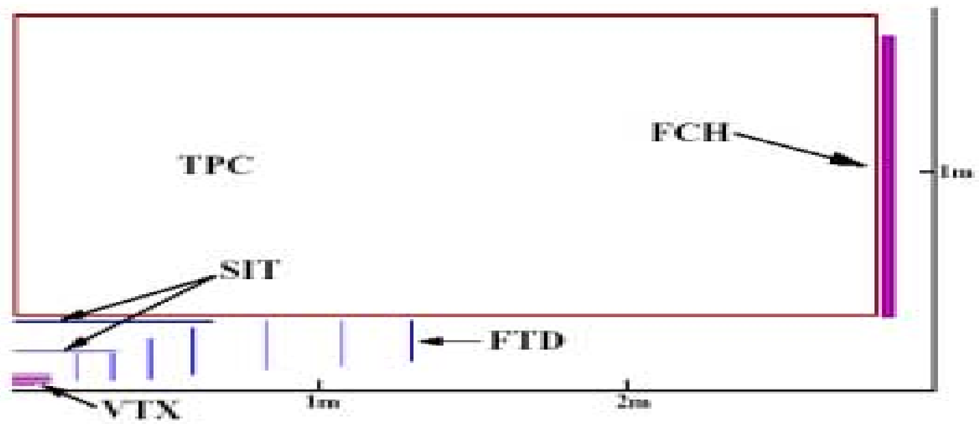
Good momentum resolution extending to the forward region

e+e- -> ZH -> l^+l^-H



Separation of dense tracks

Minimal material



TPC Advantages :

- **Large number of measurements along particle trajectory**
- **Measurement of 3-D spacepoints directly and dE/dx**
- **Well suited for high B-fields – no Lorentz angle**

E-Flow Implications for Calorimetry

Traditional Standards

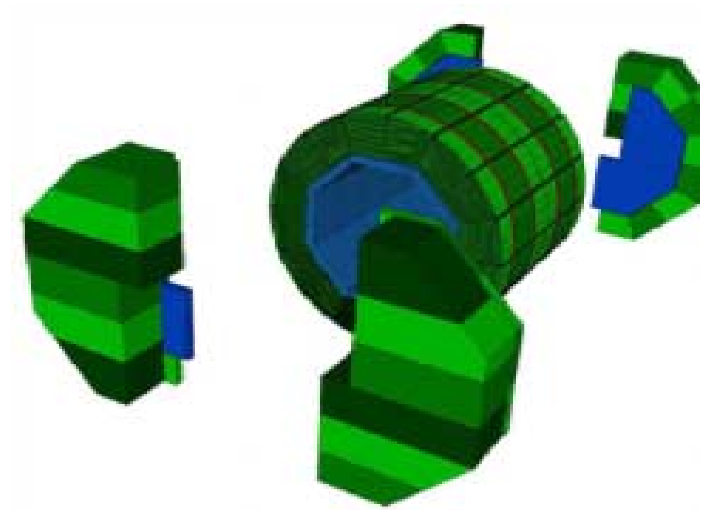
Hermeticity
Uniformity
Compensation
Single Particle E measurement
Outside “thin” magnet (~1 T)

Optimized for best single particle E resolution

E-Flow Modification

Hermeticity
Optimize ECAL/HCAL separately
Longitudinal Segmentation
Particle shower reconstruction
Inside “thick” coil (~4 T)

Optimized for best particle shower separation/reconstruction



ECAL Requirements

For electromagnetic showers in a dense calorimeter, the transverse size is small

-> small r_M (Moliere radius)

If the transverse segmentation is of size r_M, get optimal transverse separation of electromagnetic clusters.

If X_0/λ_I is small, then the longitudinal separation between starting points of electromagnetic and hadronic showers is large

-> good separation of showers in the longitudinal direction

$X_0 \propto A/Z^2$, $\lambda_I \propto A^{1/3}$, so $X_0/\lambda_I \propto A^{2/3}/Z^2$

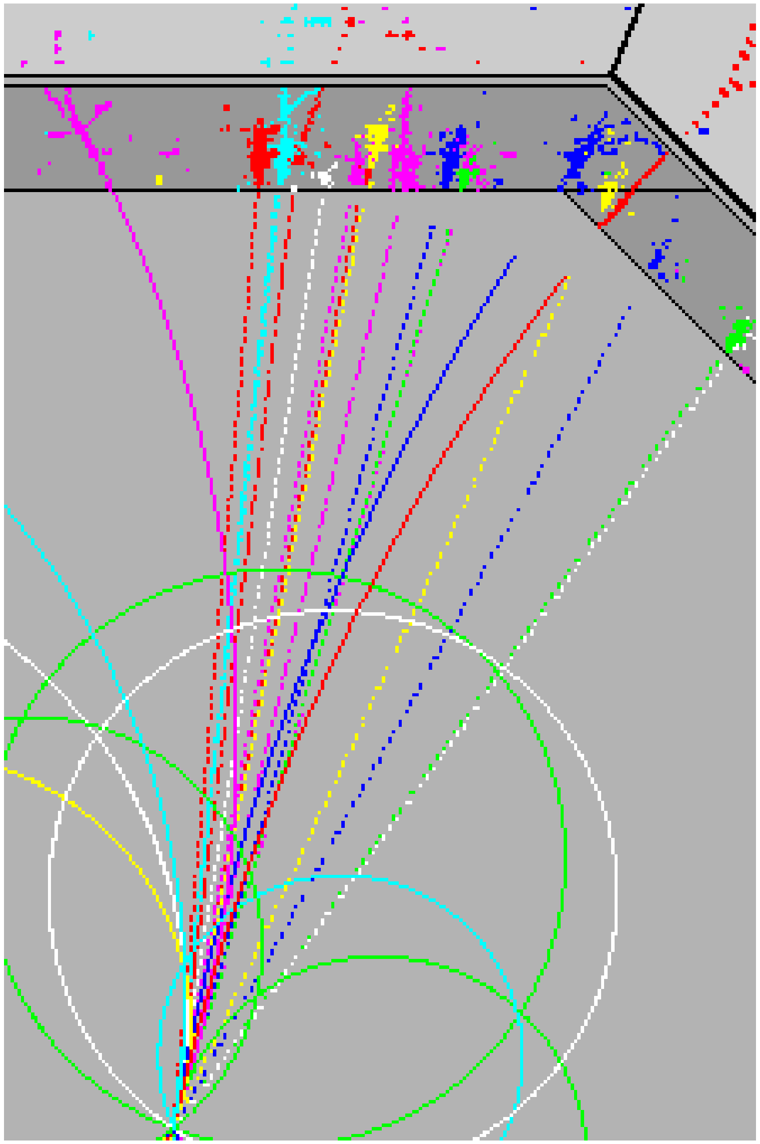
Some examples :

Material	Z	A	X_0/λ_I
Fe	26	56	0.0133
Cu	29	64	0.0106
W	74	184	0.0019
Pb	82	207	0.0029
U	92	238	0.0016

Optimal ECAL for E-Flow

A dense ECAL with high granularity (small transverse size cells) and with X_0/λ_I small is optimal for E-Flow.

-> good 3-D shower reconstruction.



TESLA/NLC SD solution -> Tungsten absorber/Silicon pad sandwich construction with 1 X 1 cm^2 transverse pad size.

Towards Optimization of HCAL

To optimize the HCAL for E-Flow requires :

full containment of hadronic showers.
good precision on energy measurement.
highly segmented in transverse and longitudinal directions in order to separate in 3-D close-by clusters in jets.

Requires integrated approach which includes other detector sub-components in the design phase and incorporating E-Flow algorithm.

Assume a tracking system optimized for, e.g., di-lepton measurements.
Assume an ECAL optimized for photon reconstruction.
Vary HCAL parameters, e.g., absorber material, thickness, size of readout cells in both transverse and longitudinal directions, to determine optimal performance in an E-Flow Algorithm.

What if ?

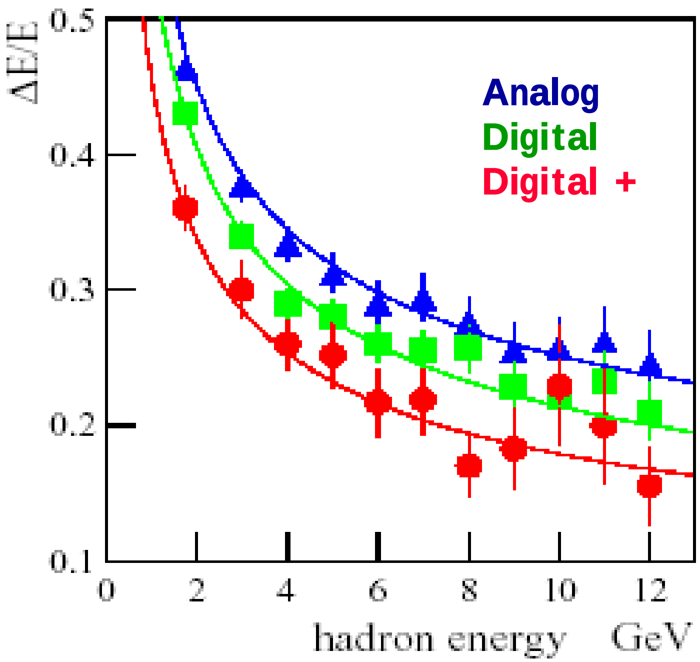
Digital Hadronic Calorimetry!?

What if the segmentation requirements of E-flow on the HCAL demand cell sizes of, say, < 3 cm on each side? Also, don't forget the shower containment and 3-D separation requirements.

Some questions :

If it's scintillator, can enough light be collected?
How many (tens of) <u>MILLION channels</u> is that?
Is there any way to afford a calorimeter like this?

Possible solution – make the cell sizes small, small enough so that each cell contains 1 mip from the hadronic shower – get the energy of the hadronic shower from the sum of the calibrated mip signals – don't need or get pulse height, just 1 mip or 0.



H. Videau, CALOR2000, LCWS2000

Conclusions

- Future calorimeters will be required to measure jet energies at unprecedented precisions.
- This will require an Energy Flow approach to jet reconstruction.
- E-Flow implies an integrated approach to calorimeter design, unlike traditional methods.
- Radical departures from current calorimetric methods may be needed -> Digital Hadronic Calorimetry.