Thoughts on the ILC Calorimetry?

Ignorant Non-believer Guide to the ILC Calorimetry

Adam Para, April 11, 2007

SiD Workshop, Fermilab

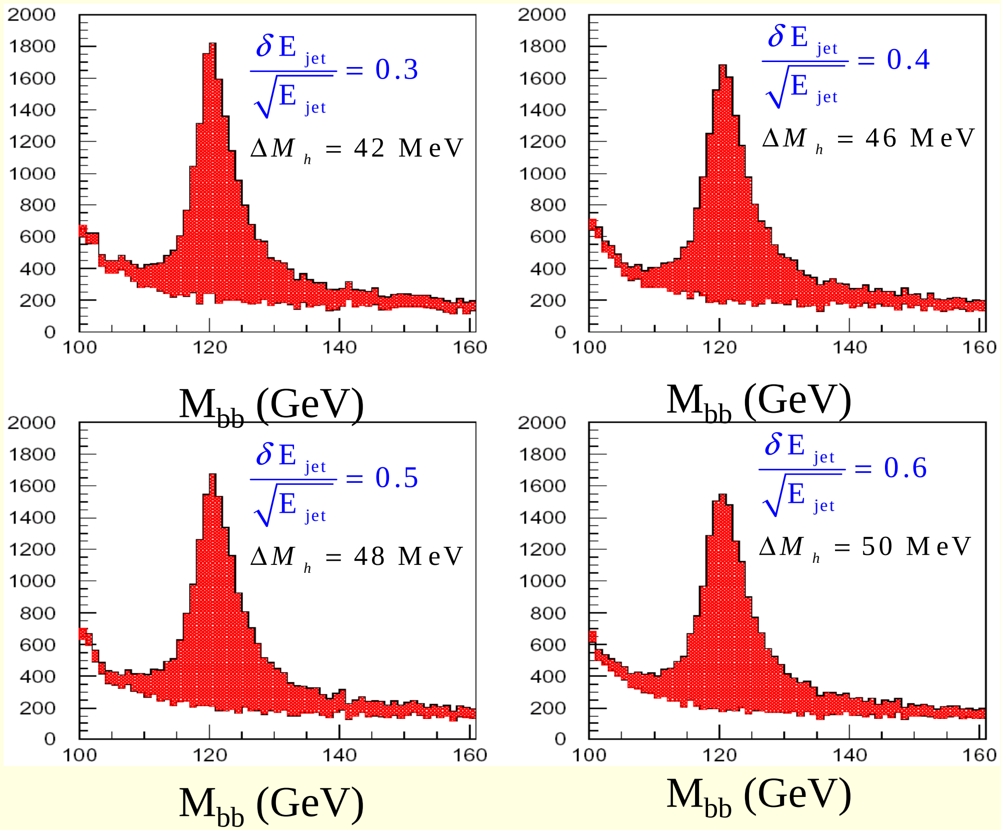
The ILC Calorimetry Mantra

- Multi (di-) jet spectroscopy, W/Z separation requires jet energy resolution of the order 30%/√E
- Such a resolution is beyond the reach of 'traditional' hadron calorimeters
- The only possible solution: PFA algorithm. Excellent jet energy resolution can be achieved by replacing calorimetric energy measurement of all charged hadrons by the momentum measured in the tracker.

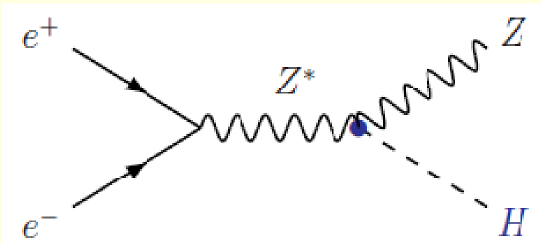
It is quite possible that some (or may be even all) of the above statements are true, but so far the proofs are far from convincing.

Examples of Physics-driven Requirements

- $e^+e^- \rightarrow \nu\nu$ WW/ZZ (strong interactions of IVB if no higgs)
- Self-coupling of higgs boson: ZHH
- These processes are potentially interesting at the upgraded ILC. These examples are not very convincing.
- Mass and total width of the higgs boson @ E=350 GeV



T.Barklow



$\Delta E/\sqrt{E} = 60\% \rightarrow 30\%$

equivalent to $1.4\times$ Lumi

Meaning of 30%/sqrt(E) Requirement

- The real ingredient of the simulation/analysis:

ΔE/E = 0.03 (0.02) for 100(200) GeV jets. It translates into 30%/sqrt(E) only if the usual constant terms in the resolution < 1%. [Remember: total absorption hadron calorimeter: ΔE/E=9%+11%/sqrt(E). Not a good calorimeter at all!]

- Gaussian line shape. The principal gain from the improved energy resolution is in the effective luminosity/number of multi-jet combinations. Significant (say 10%?) non-gaussian tails induce rapid degradation of the effective statistics. [For example, for 4-jet final state: $1.4*0.9^4=0.919$]
- Observation (at least in the higgs case): Gain(0.6 -> 0.4) = Gain(0.4 -> 0.3). The last bit is the most critical.

On the other hand: ILC experiments are to provide ultimate precision measurements. Aiming for very good energy resolution: small stochastic term (0.3?) and small constant term (<0.01) and a gaussian line shape (no tails!) sounds like a sensible goal.

High Precision Hadron Calorimetry

- The best hadron calorimeters built tend to be neutrino detectors. It is no accident:
  - no practical constraints of hermetic detectors,
  - 'infinite' dimensions (no coil in front to introduce fluctuations, no coil behind forcing small depth)
  - Uniform! Sampling calorimeters ←→ 'sampling fractions'. They heavily depend on the materials and thicknesses involved. Even for a given geometry they vary along the shower axis. Shower development fluctuations lead to a significant contribution to a resolution if different detector geometries (like EM and HAD, fine and coarse) are involved.

PFA: The Ultimate Calorimetry

- Observation: The best calorimeters proposed, built, over the past two decades (LEP, HERA, SSC, LHC) have poor jet energy resolution (60-80%/sqrt(E), large constant term. A major contribution to the jet energy resolution comes from the fluctuating electromagnetic component of a jet in the presence of difference of the detector response to charged and neutral pions
- Intriguing proposition: reduce the role of the hadron calorimeter to a minor one: measuring the neutron/K0 component of the jets only. Use tracker to measure charged hadrons, EM calorimeter to measure π^0's.
- This is a very attractive solution: it removes most of the conflicts between the jet measurement (a.k.a. hadron calorimeter) and other subsystems of the experiment
- It offers a possibility of very high jet energy resolution (~20%/sqrt(E))

The Challenges of the PFA Calorimeter

- New detector requirement: enable clean separation of energy deposits of different particles. Can it be done? What kind of calorimeter is necessary?
  - Electromagnetic calorimeter/granularity
  - Sampling of the hadron calorimeter
  - Active medium: gas/scintillator
  - Transverse segmentation
  - Digital or analog readout
  - Size (radius) of the calorimeter
  - Magnetic field
  - Does any of the above matter? How much?
- Specific answers to the above listed questions have major implications for the detector design and cost

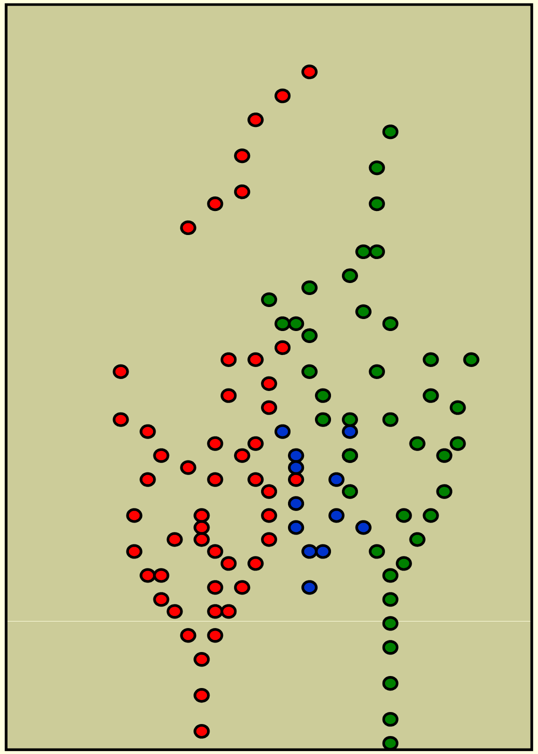
The PFA Challenges

- Tracking efficiency?

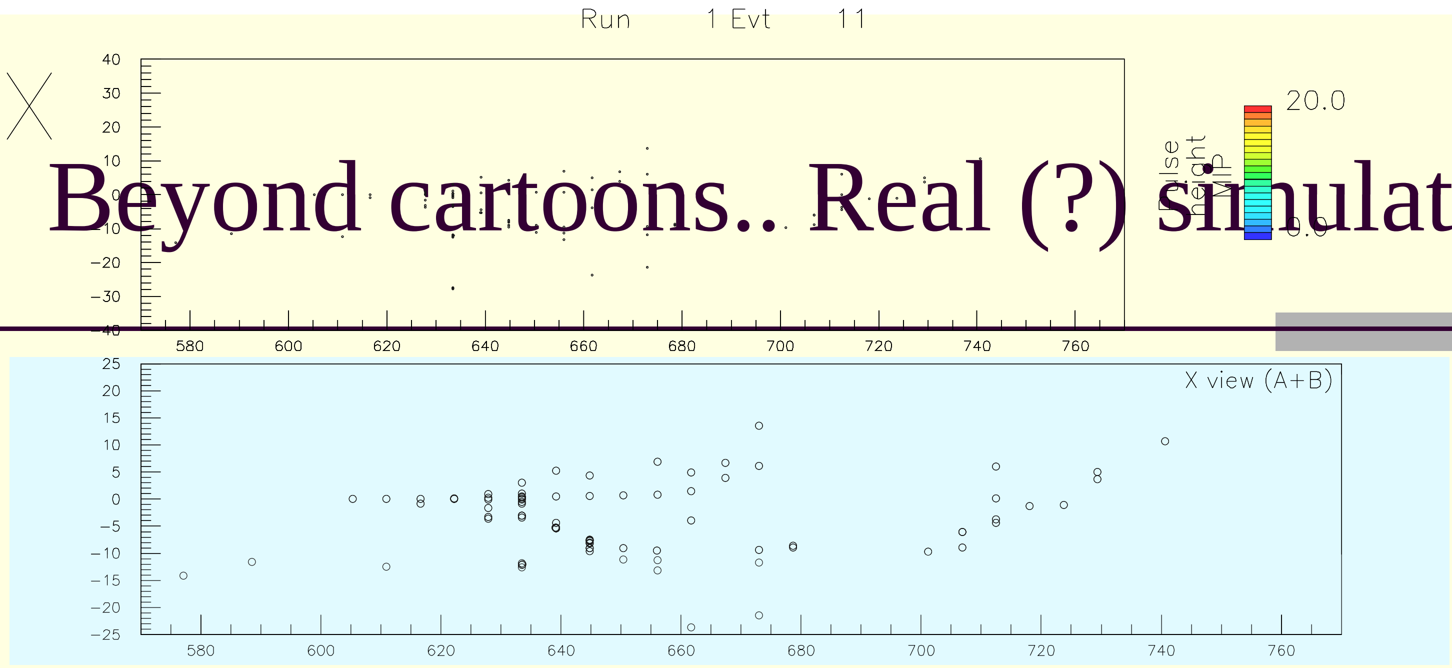
Not really. If some tracks are not reconstructed the corresponding energy will be measured with the resolution of the hadron calorimeter. Not a serious obstacle to reach the '30%' challenge if the tracking efficiency ≥90%

- Subtraction 'quality':
  - Some of the energy deposited by neutral hadrons can be mistakenly removed => reduce the jet energy
  - Some of the energy deposits of charged partcles may not be properly subtracted and identified as neutral particles. Double counting => increase the jet energy

Fluctuations of the above effects will likely dominate the energy resolution

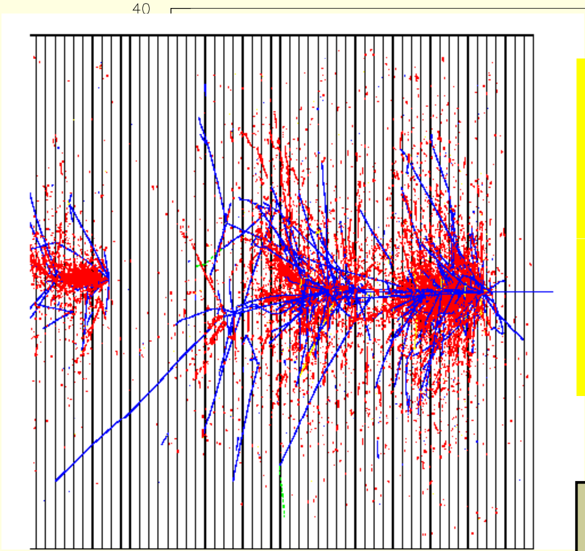


Beyond cartoons.. Real (?) simulation



10 GeV π-

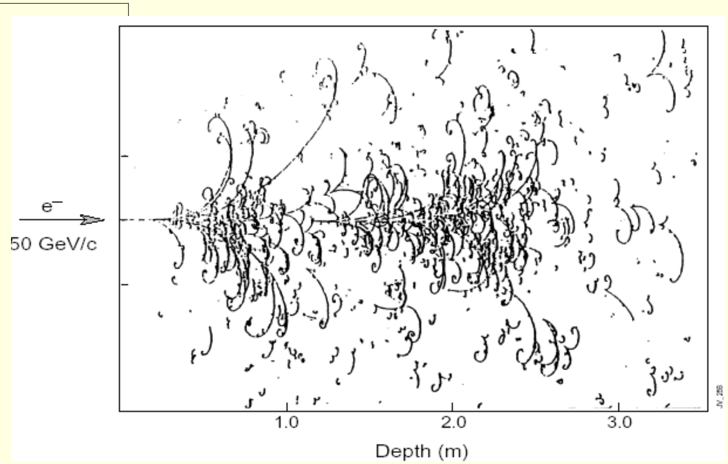
steel/PRC



150 GeV π-
in copper

IMHO: very fine transverse segmentation unlikely to help.

Timinig??



Bubble chambers: gammas point to the vertex. Neutral stars do not (missing neutrals). In heavy liquid BC the Fermi motion complicates pointing even futher.

Scaling of the Energy Resolution of the PFA Calorimetry

•Energy resolution typically evaluated at Z0 pole. Hard enough to achieve the target energy resolution, do the ‘easy’ case first.

•A lot of ingenuity devoted to the definition of the performance figure which meets the desired target. (Multi-component fits, ‘90%’ resolution..). Allowed/encouraged by the missing requirement on the line shape.

Usually dominant

$$\left(\frac{\Delta E}{E}\right)^2_{jet} = \left(\frac{\Delta p}{p}\right)^2_{charged} + \left(\frac{\Delta E}{E}\right)^2_{EM} + \left(\frac{\Delta E}{E}\right)^2_{neutrals} + \left(\frac{\Delta E}{E}\right)^2_{confusion}$$

~p, but very small

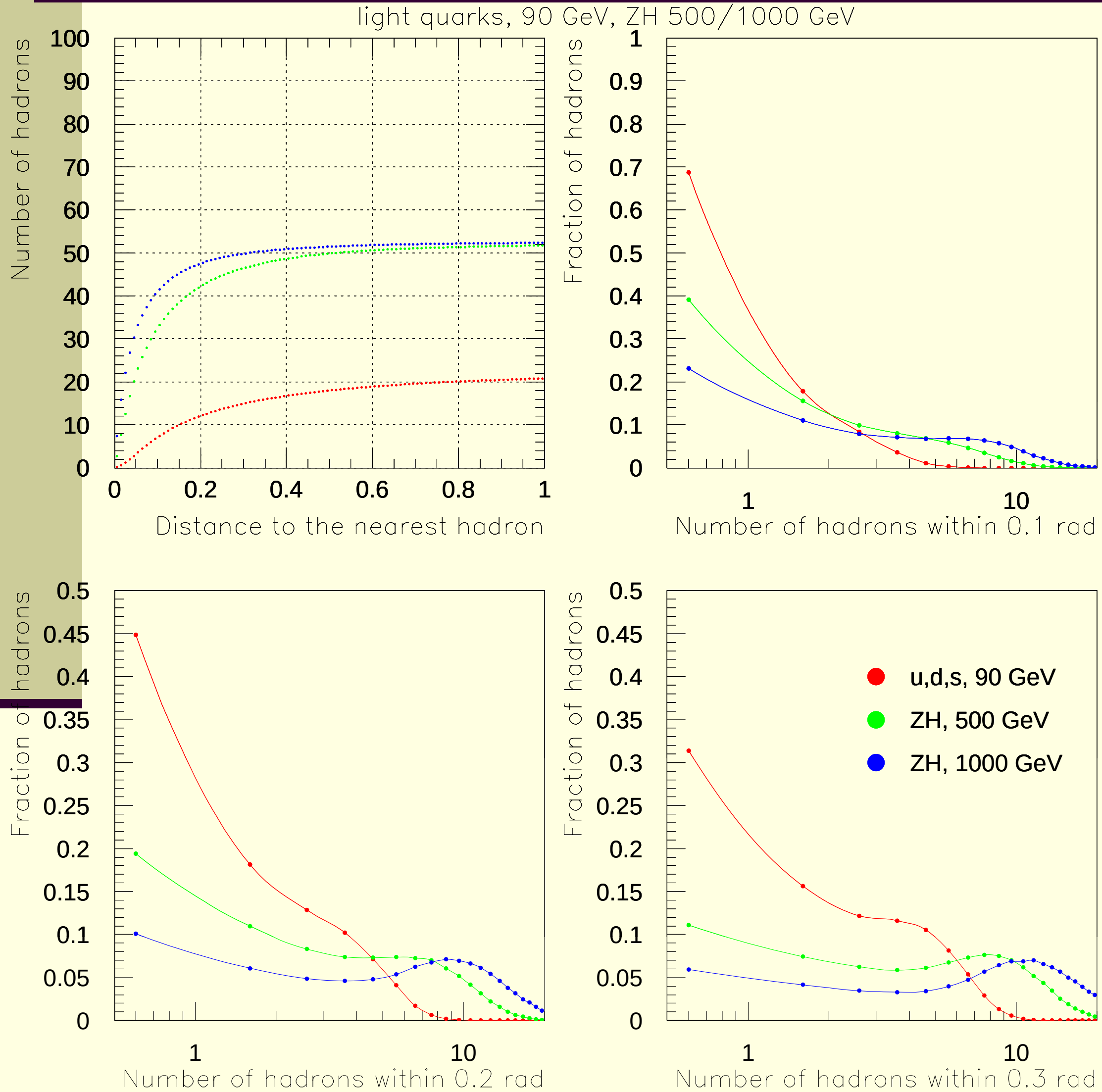
$\sim \frac{1}{\sqrt{E}}$

$\sim \frac{1}{\sqrt{E}}$

Can it possibly get smaller with energy ????

What is the energy dependence of the resulting energy resolution?? 1/√E ? Constant? √E ??

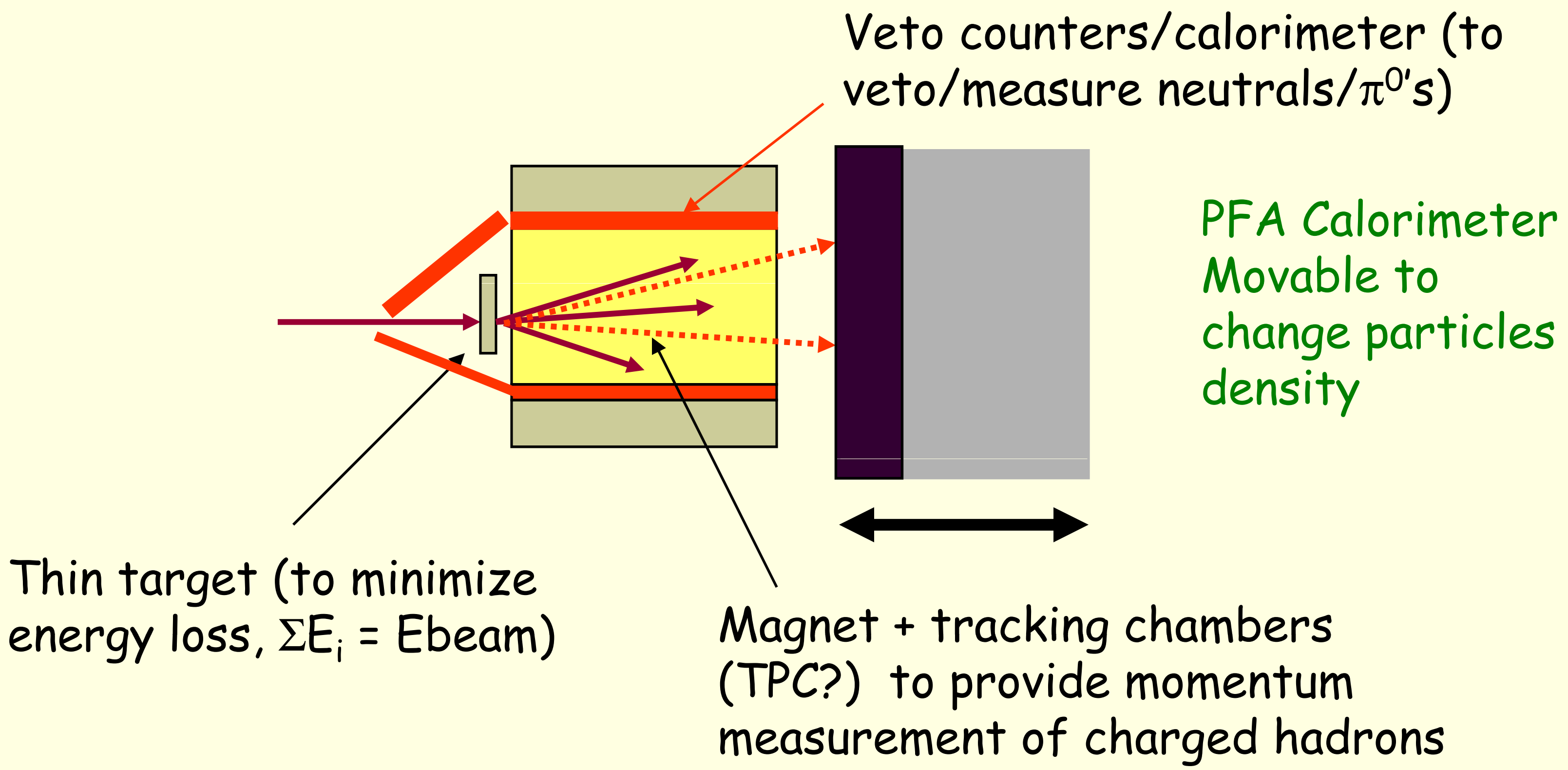
Uds at Z0 pole vs ZH at 500/1000 GeV?



- Event multiplicity higher by a factor ~3
- Number of isolated hadrons drops very significantly
- High probability, ~50%, of having several (>5) hadrons in a very tight cone of 0.1 rad
- Particle density/isolation changes significantly for ZH events between 500 and 1000 GeV, although the overall multiplicity the same (jet colimation?)

Experimental Demonstration of PFA ?

- Demonstrate that a given a collection of particles (a.k.a. jet) and given the momenta of charged particles one can measure the total jet energy with the claimed resolution

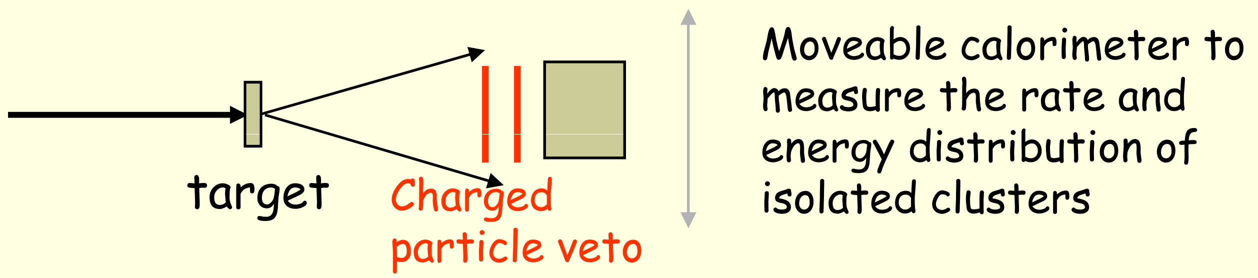


PFA (Jet) Test Beam?

- High energy beam 200? 300? GeV essential to demonstrate the robustness of the technique at high particles density. Perhaps can be traded for close proximity of the calorimeter to the target, provided the momentum resolution is maintained (silicon tracker?)
- Analysis magnet (not necessarily 5T)
- A tracking system (not necessarily the same design as the real experiment) with adequate $\Delta p/p$ resolution
- EM and hadron calorimeters with sufficient transverse extent (~ 3 x 3 m^3) to measure the energy of an ensemble of particles scattered over ~ a cone of 1-2 m opening and ensure the full coverage at all distances (narrow/wide jets)
- Add muon system/tail catcher if deemed necessary for the PFA
- A post-PFA application: a prototype for a vertical slice test of the entire detector ?
- Make no mistake: this is not a simple ‘test beam’. It is a complicated and resource consuming experiment. It would be wonderful to be able to prove the performance of PFA calorimeter in a simpler (and faster!) way..

Principal Uncertainties of the PFA?

- Not very well (not at all?) understood
- My guess: Neutral hadrons production modeling
- Very scarce experimental information. Need dedicated experiment?
- K^0 – MIPP/son of MIPP? Acceptance?
- Neutron/antineutron production by pion beams 1- 20 GeV:

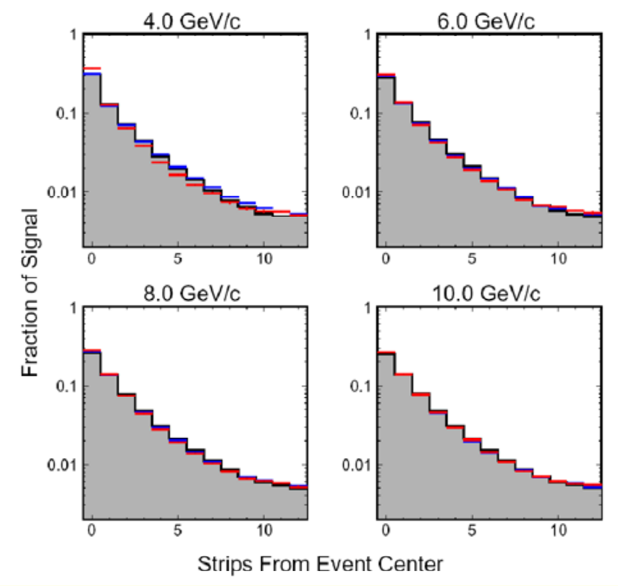


- Isolated neutrals only. Enough for validation?

Often Quoted Excuse: Quality of Monte Carlo Simulation

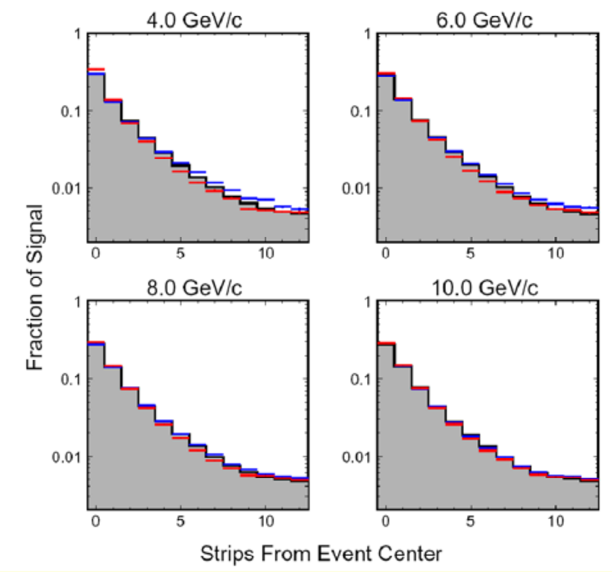
- PFA performance can be demonstrated and optimized with the help of simulated jets. No complicated (and expensive) experimental demonstration of PFA is necessary. However..
- At the moment there is a major uncertainty related to possible inadequacy of the hadron shower simulations, especially its transverse aspects as evidenced by huge variation of the transverse shower size between different simulation codes
- Experimental data from finely segmented calorimeters are necessary to tune/select the correct shower
- Once such data become available the simulated data will be sufficient for a convincing demonstration of the validity and performance of the PFA approach.

2 Cubic Meters of 2.5 cm Iron-scintillator Sandwich, 4 cm Transverse Segmentation (a.k.a. MINOS CalDet)



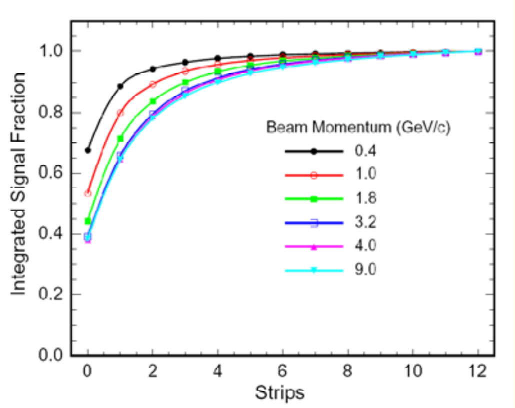
protons

pions



Red: Gheisha

Blue: GCALOR



This are just few examples, a lot more data exists in a form of plots and raw data/ntuples.

Can such data help to make a breakthrough in the PFA optimization?

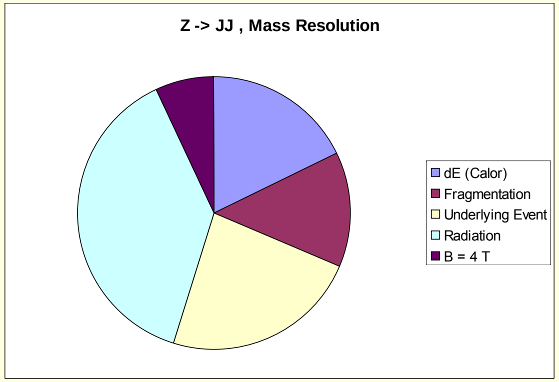
Calorimetry is a Science

- EM calorimetry: practical application of QED. Well understood 'forever' (in my lifetime).
- Hadron calorimetry:
  - Pre ~1985 'dark ages': trial and error. This includes LEP era. Technological aspects dominant: Hermeticity/segmentation with gas only.
  - ~1985: T. Gabriel/J. Brau, R. Wigmans enlightenment: nuclear break-up, neutrons, EM suppression. Compensation! High resolution hadron calorimeter can be designed and built
- SSC, LHC experiments have 'poor' hadron calorimeters. Why?

It is the choice and not limitation of technology.

In the hadron collider experiment the jet

Is a manifestation of the primary fundamental parton (quark/gluon) and the nature hadron collission environment limits the jet/dijet resolution.

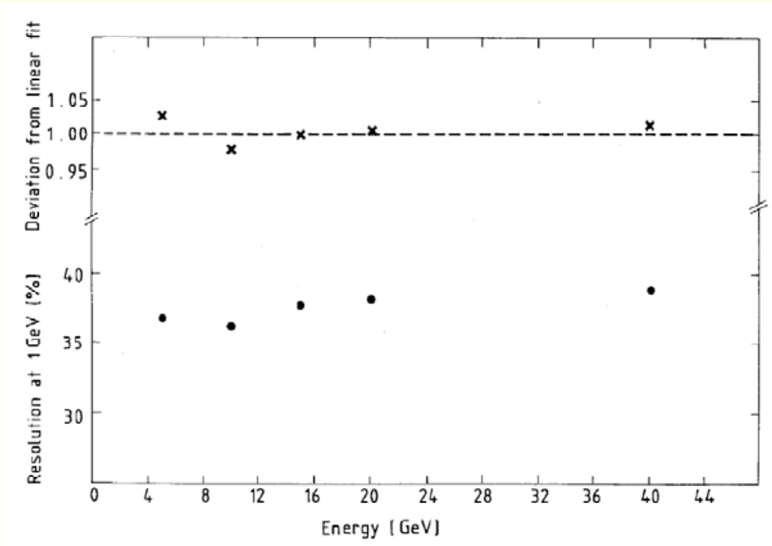


D. Green

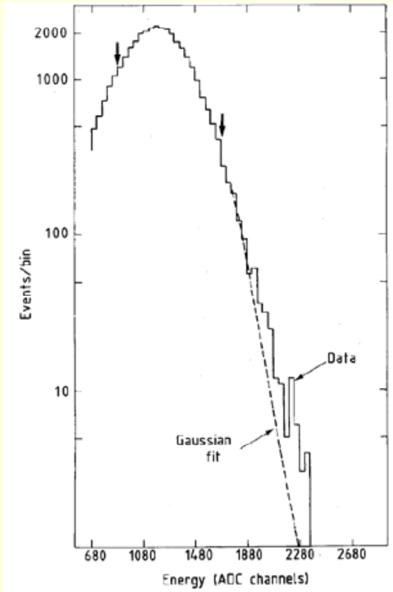
High Resolution Jet Calorimetry is Possible: Axial Field Spectrometer

ABSTRACT

We present results obtained with a uranium/copper scintillator fine-sampling calorimeter with wavelength shifter readout. Test beam measurements made with $e^{\pm}$, $\pi^{\pm}$ and protons in the momentum range 0.3 to 40 GeV/c are presented. The calorimeter achieves energy resolutions of $\sigma(E)/E = 0.36/\sqrt{E}$ and $0.16/\sqrt{E}$ for hadrons and electrons, respectively. The measured ratio of response for electrons to that for hadrons is 1.11, for energies of 2 GeV or more. The spatial resolution achieved for single particles at normal incidence is ∿ 1 cm for electromagnetic showers and ∿ 3 cm for hadronic showers. Operational experience over three years of running at the CERN ISR, including operation at very high luminosities (∿ 1.4×10^{32} $cm^{-2}s^{-1}$), is described.



- 36%/sqrt(E) for jets achieved in the final experiment
- No tails (high)
- Configuration yielding 33%/sqrt(E) tested

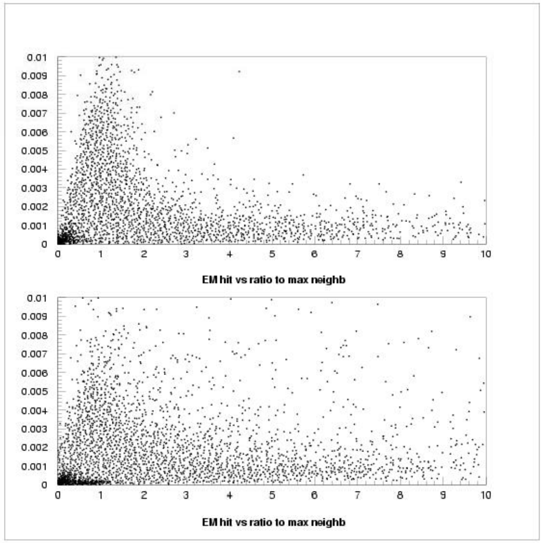


Improving AFS Resolution?

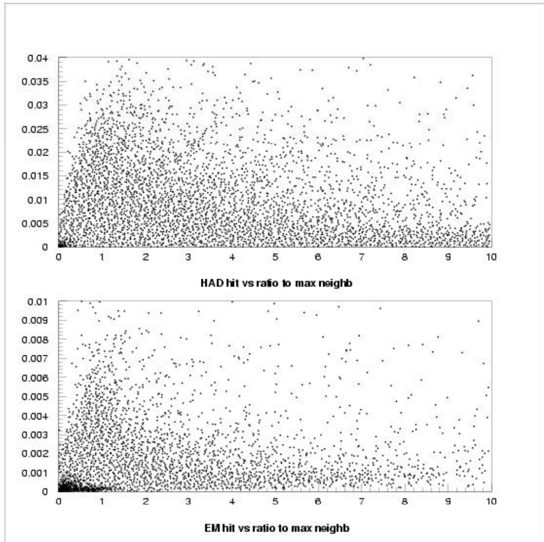
- AFS: Late 1970-ties. Waveshifter bars. Bulky and expensive electronics. 3072 PMT's and readout electronics channels. Crude transverse, no depth segmentation (beyond EM/HAD). Elementary volume read out ~ $2x10^4$ cm^3.
- Today: inexpensive electronics, fibers, inexpensive miniature photo-detectors. Readout of the ~100 cm^3 volume quite practical
- Homogeneous calorimeter? (the same sampling in the 'EM' and 'HAD' sections? Merge ECAL and HadCCAL into CAL)
- It is possible/practical to record the shower information with granularity over 100 times better than in the AFS case. This is a new era in hadron calorimetry. Is there a way to utilize this information to improve the resolution?

Using Fine Granularity to Improve Sampling Calorimetry

- Fundamental assumption of sampling calorimetry: the observed signal represents 1/SF energy deposition in the absorber
- Usually true. But in the hadron shower..(SiD calorimeter aug05)

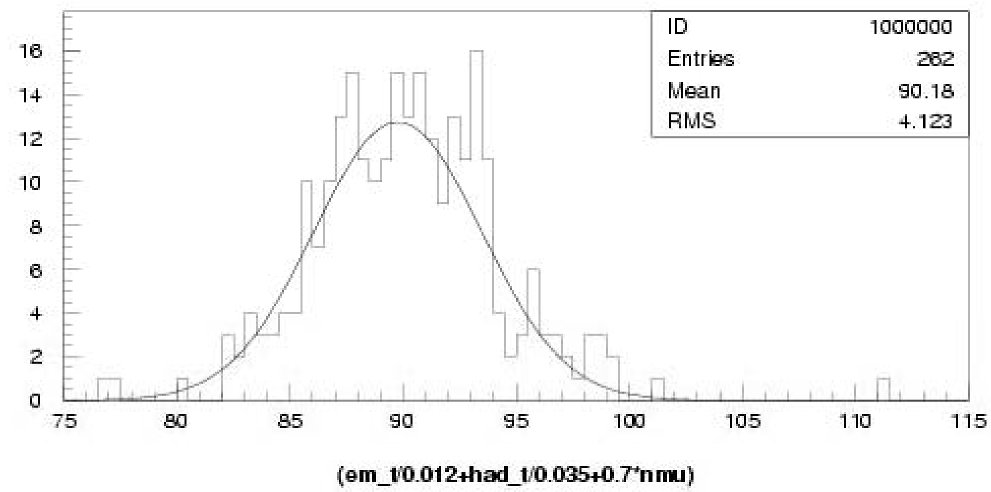


Isolated large energy depositions in hadronic showers. Slow protons? Heavy fragments?



Suppressing the Abnormal Energy Depositions

- σ/mean = 3.71%, ➔ "39%/sqrt(E)"
- This is just an illustration that high readout granularity provides new sources of information which can be used to improve the energy resolution. Such fluctuations always contribute to the hadron shower signals, but they were unnoticeable before.

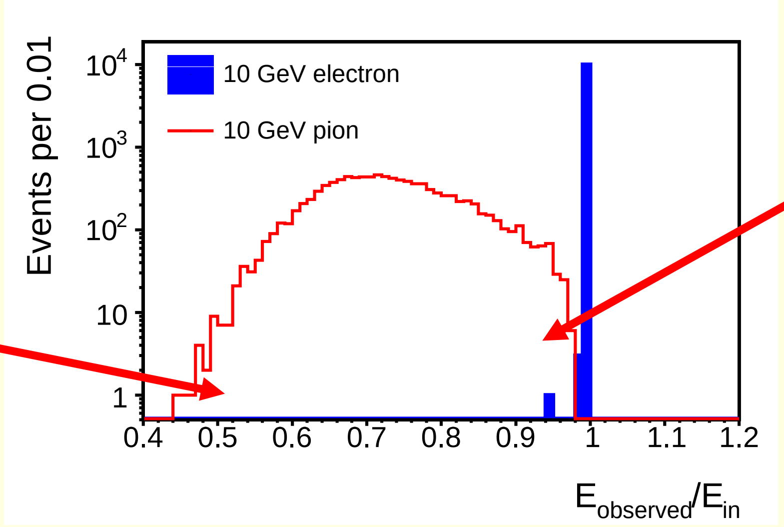


How About Compensating Calorimeters?

- Electrons/photons interact with atomic electrons. Total energy of the incoming particle is converted into detectable kinetic energy of electrons
- Hadrons interact with nuclei. They break nuclei and liberate nucleons/nuclear fragments. Even if the kinetic energy of the resulting nucleons is measured, the significant fraction of energy is lost to overcome the binding energy. Fluctuations of the number of broken nuclei dominates fluctuations of the observed energy

Large number of broken nuclei:

- large number of slow neutrons
- Small fraction of energy in a form of π^0's



Very few broken nuclei:

- Small number of slow neutrons
- Large fraction of energy in a form of π^o's

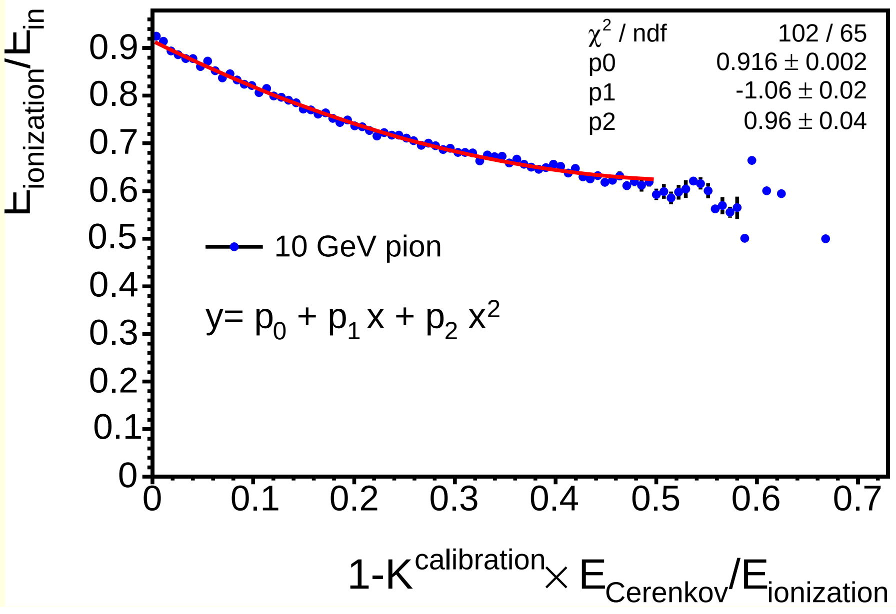
Path to High Precision Hadron Calorimetry: Compensate for the Nuclear Energy Losses

- Compensation principle: $E = E_{obs} + k^*N_{nucl}$
- Two possible estimators of N_{nucl}:
  - $N_{nucl} \sim N_{slow\ neutrons}$
  - $N_{nucl} \sim (1-E_{em}/E_{tot})$

Cherenkov-assisted hadron calorimetry: $E_{em}/E_{tot} \sim E_{Cherenkov}/E_{ionization}$

• 'EM' shower: relativistic electrons, relatively large amount of Cherenkov light

•'hadronic' shower – most of the particles below the Cherenkov threshold



Cherenkov-assisted Calorimetry at Work: Single Particle Case

- Use the $E_{Cherenkov}/E_{ionization}$ ratio to 'correct' the energy measurement

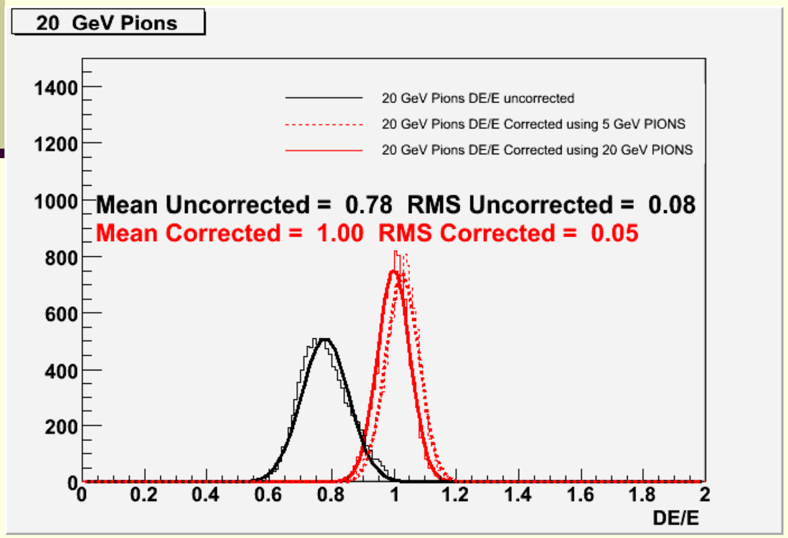
• Corrected pion shower energy = pion energy ("e/π"=1)

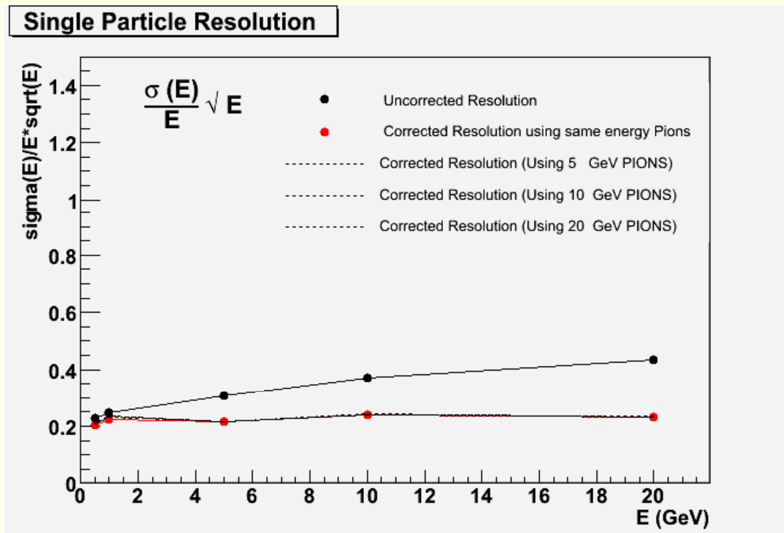
• Correction function independent of the actual shower energy

• Single particle energy resolution ΔE/E=0.25/√E

• Scales with energy like 1/√E (no 'constant term')

• Linear response





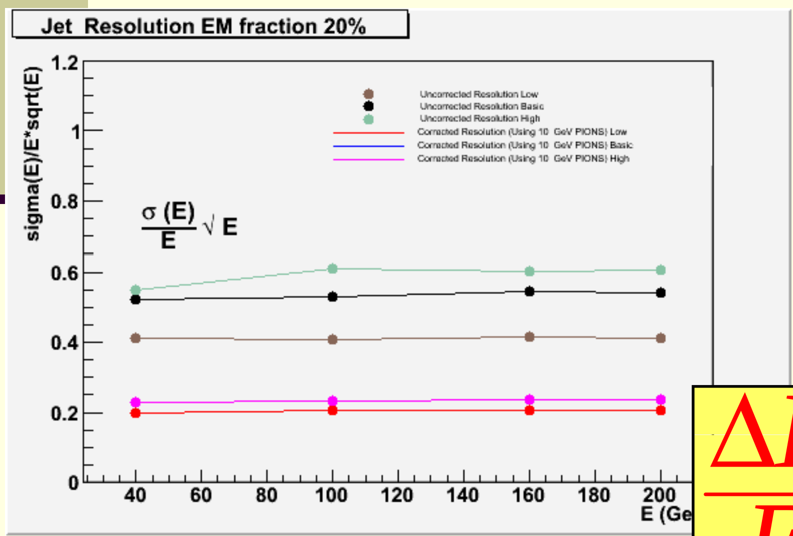
Measuring jets (== ensembles of particles)

Jet fragmentation (in)dependence

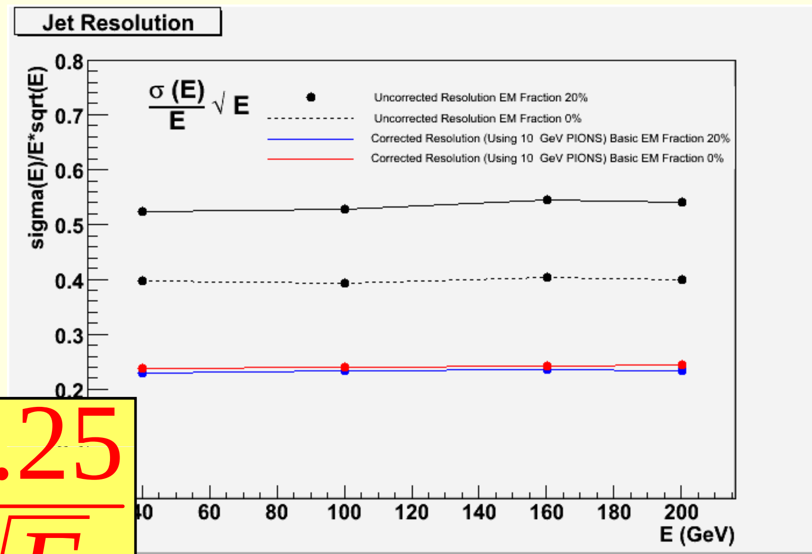
- Resolution of Cherenkov-corrected energy measurement is nearly independent of the jet fragmentation
- Resolution (and the response) of the uncorrected energy measurement dependent on the jet composition

Fluctuations of EM fraction of jets

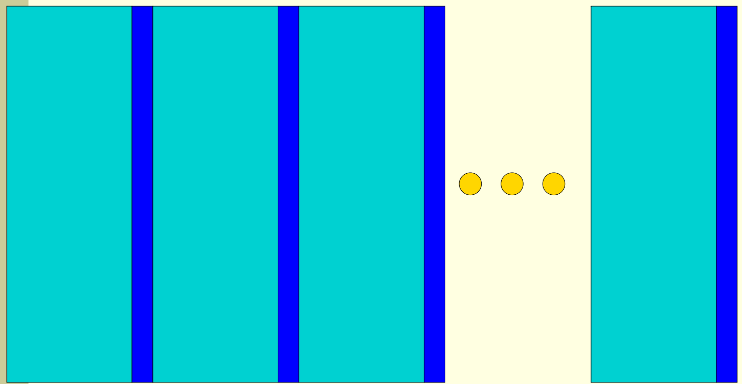
- Do not contribute to the jet energy resolution for Cherenkov-corrected measurement
- Dominate the jet energy resolution in the uncorrected case



$$\frac{\Delta E}{E} \leq \frac{0.25}{\sqrt{E}}$$



Practical Implementation of a Cherenkov-assisted Hadron Calorimeter



Alternating layers of:

- lead glass to read out Cherenkov light
- scintillator to measure (sampled) ionization energy loss

- Lead glass and scintillator light read out with WLS fiber. Enabling technology: silicon photodetector
- Longitudinal and transverse segmentation, as required by physics driven considerations, relatively easy
- Thin layer of structural material (steel?) may be necessary for support
- Ultimate hadron energy resolution likely dominated by sampling fluctuations (thickness of lead glass). Optimization in progress.

Advantages in Comparison with DREAM (Fiber Based Dual Readout)

- Very good energy resolution for electrons (using lead glass, nearly 100% sampling fraction), hence…
- Uniform calorimeter (the same structure for EM/Hadron section)
- Easy transverse and longitudinal segmentation
- High yield/detection efficiency of the Cherenkov photons

(Kind of) Conclusions

- Progress in technology (inexpensive large scale electronics, novel photodetectors,…) enables construction of highly granular calorimeters
- Fine granularity of calorimeters offers a completely new view of hadron (and electron!) showers. It may provide further insights into origin of shower fluctuations and/or offer ways to reduce the contribution of known fluctuations.
- ILC provides an opportunity to exploit our progress in understanding of hadron calorimetry. It is worthwhile to investigate the new sources of information to explore new techniques for high resolution calorimetry.
- While the PFA remains an extremely appealing and attractive avenue for the jet calorimetry, it may prove to have major performance limitations and higher energies. Therefore it is very important to explore possible alternative techniques.