High Resolution Jet Calorimetry: Total Absorption Homogeneous Calorimeter with Dual Readout

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Path to High Resolution Jet Calorimeter

- [Jet == collection of particles with composition, spatial and momentum distribution characteristic for QCD fragmentation process]

1. Response independent of the particle type (in particular $R(\pi^+)=R(\pi^0)=R(e)$)
2. Response linear with energy $R = AE$ (No offset!!)
3. Good energy resolution for hadrons. Adequate energy resolution for electrons taken for granted.

Why Hadron Calorimeters are so Poor?

Reminder: $(DE/E)_{EM}$ can be as good as 0.01 for total absorption calorimeters. What's wrong with hadrons?:

- A fluctuating fraction of the hadron energy is lost to overcome nuclear binding energy
- Hadron calorimeters are sampling calorimeters
  - Sampling fluctuations (fluctuation of the energy sharing between passive and active materials)
  - Sampling fraction depend on the particle type and momentum (good example: a 'neutrons problem' in iron-scintillator calorimeter. SF ~ 0.02 at high energy, SF = 1 for thermal neutrons)
- Inhomogeneous calorimeters (typically: EM + HAD)
- The net result: Response/True energy = F(particle type, E). Tolerable for single particle measurement, major contribution to energy resolution for jets (collection of particles).

Path to High Resolution Jet Calorimeter

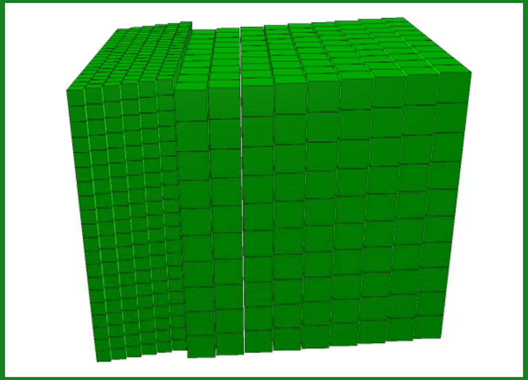
- Homogeneous Calorimeter (EM/Had combined). Need a calorimeter capable of performing required topological measurements for e/γ (position, direction, close showers separation)
- Total absorption calorimeter (SF = 1 for all particles and energies). This practically implies a light-collection based calorimeter.
- Correct (on the shower-by-shower basis) for the nuclear binding energy loses. This can be done, for example, by dual readout of scintillation and Cherenkov light signals.

High Resolution Jet Calorimeter?

- All the underlying principles are known/understood since a very long time (> 20 years). If it is so simple why we haven't built good hadron/jet calorimeters??
  - Low density scintillators ➔ huge detector size for total absorption
  - Bulky photodetectors ➔ cracks to bring the light out or further increase of the detector size
  - No photodetectors in the magnetic field
- Major advances in the detectors technology/enabling technologies:
  - High density scintillating crystals/glasses (λ~20 cm)
  - 'Silicon Photomultipliers' ~ robust compact, inexpensive

Conceptual Design of a High Resolution Calorimeter

- Six layers of 5 x 5 x 5 cm^3 crystals (a.k.a. EM section): 108,000 crystals
- three embedded silicon pixel layers (e/γ position, direction)
- 9 layers of 10 x 10 x 10 cm^3 crystals (a.k.a. hadronic section): 60,000 crystals
- 4(8?) photodetectors per crystal. Half of the photodectors are 5x5 mm and have a low pass edge optical filters (Cherenkov)
  - No visible dead space.
  - Signal routing avoiding projective cracks
  - Should not affect the energy resolution
  - 500,000(1,000,000?) photodetectors
- Total volume of crystals ~ 80-100 m^3.

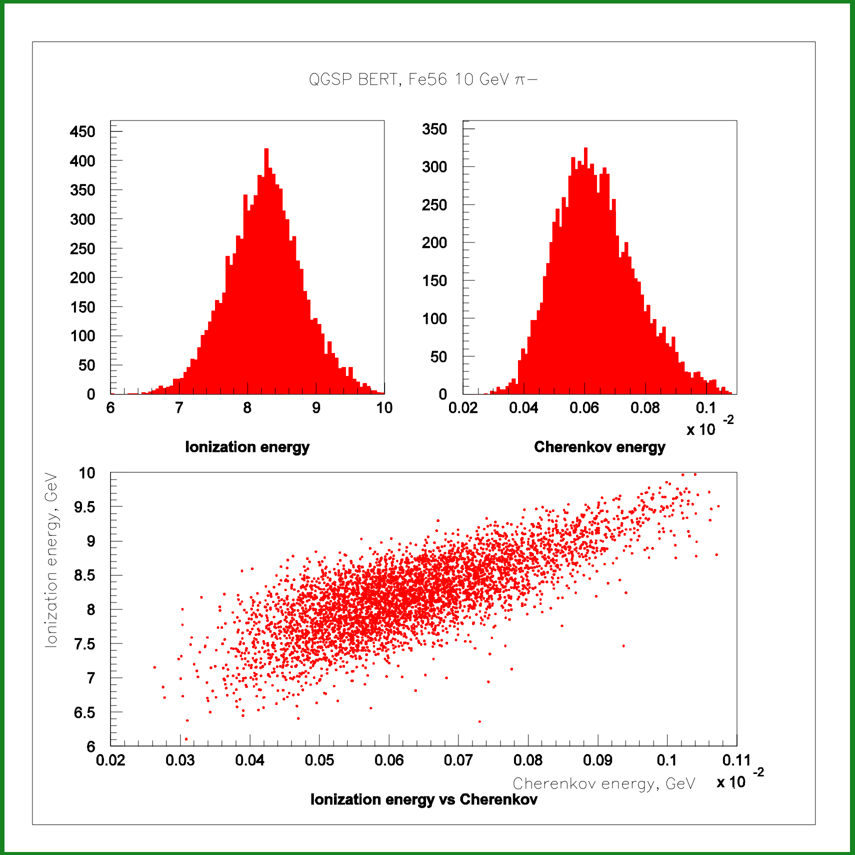


Vito Di Benedetto, Lecce, ILCRoot

Dual Readout Calorimeter Simulation and Analysis

- Optical calorimeter option in SLIC (Hans Wenzel)
- 1 x 1 x 3 m^3 volume subdivided into 1 cm^3 'crystals'
- Crystals composed of various materials (elements or isotopes) at fixed density of 8 g/cm^3
- Optical properties characterized by the refractive index n (relevant for Cherenkov)
- All scintillation (==ionization) and Cherenkov light summed up from the entire volume. Total information about an event reduced to two variables : S and C.
- Completely automatic reconstruction, no tuning/optimization. No use of the spatial distribution information (yet). Much room for the improvement.

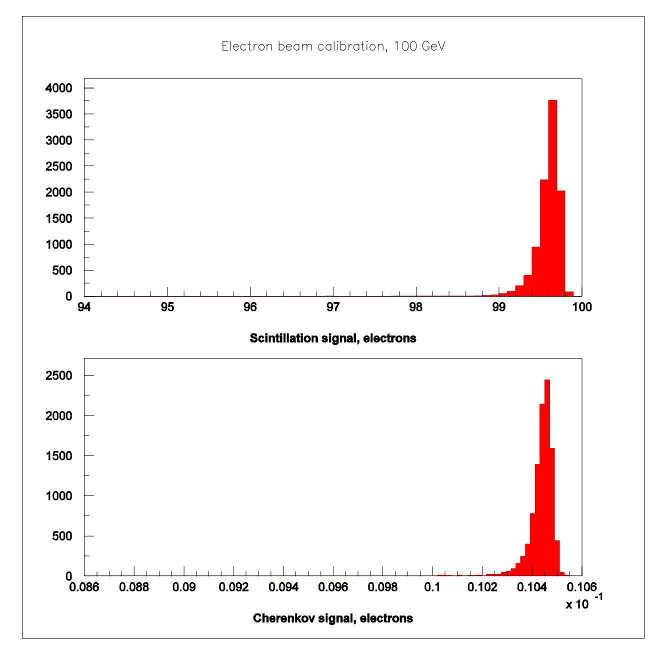
Dual Readout at Work: an Example



- Physics model: QGSP_BERT
- Material: Fe56, n=1.65 (i.e. scintillating, transparent material with the absorption, radiation length and the nuclear properties of Fe56)
- 10 GeV negative pion beam

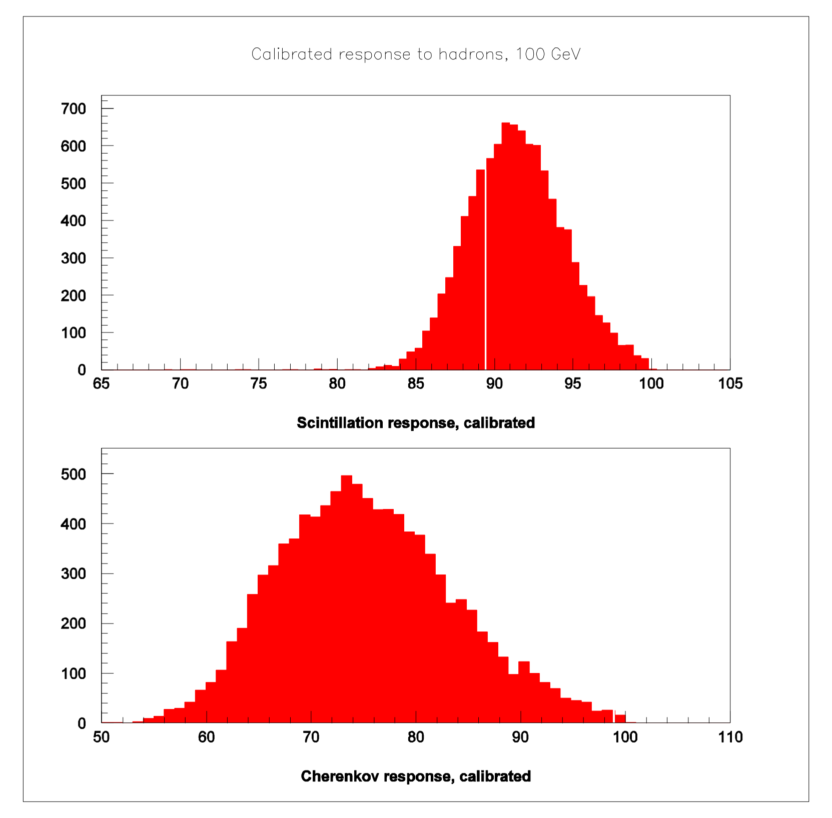
- *Only ~80% of energy observed through ionization*
- *Cherenkov fluctuations much larger than the ionization*
- *Clear correlation of the total observed ionization and Cherenkov light*
- *Using the C-S correlation the energy resolution will be limited by the width of the scatter plot only*

'Test beam' 100 GeV Step I: Electron Beam Calibration



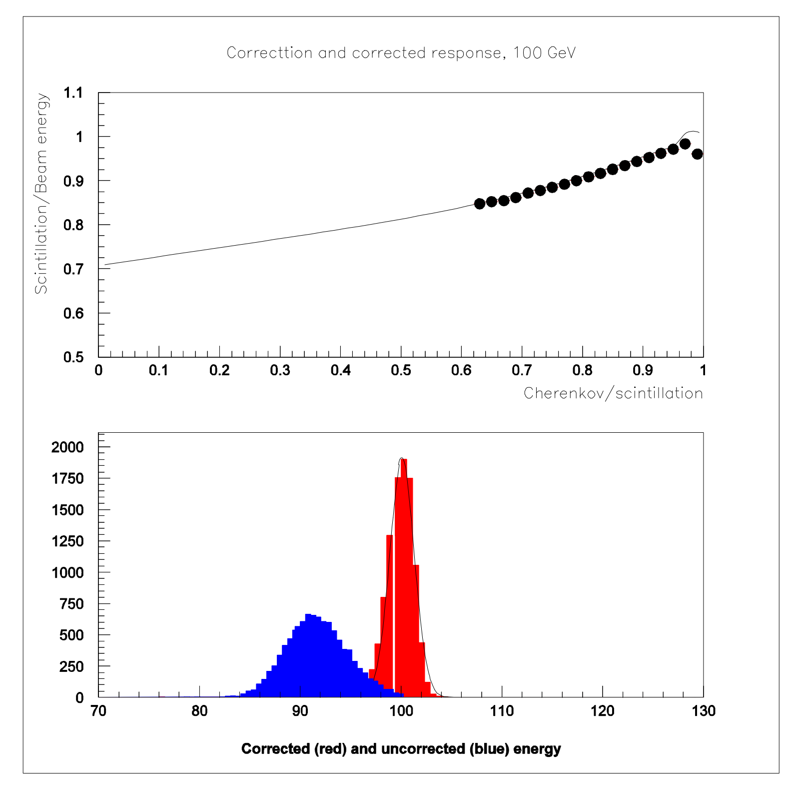
- Collect the scintillation and Cherenkov light measured in some arbitrary units.
- Define the mean values of the distributions to correspond to 100 GeV (calibration beam energy)
- A_{sc}=100/<Scintillation>
- A_{ch}=100/<Cherenkov>

'Test Beam' 100 GeV Step II: π- Beam



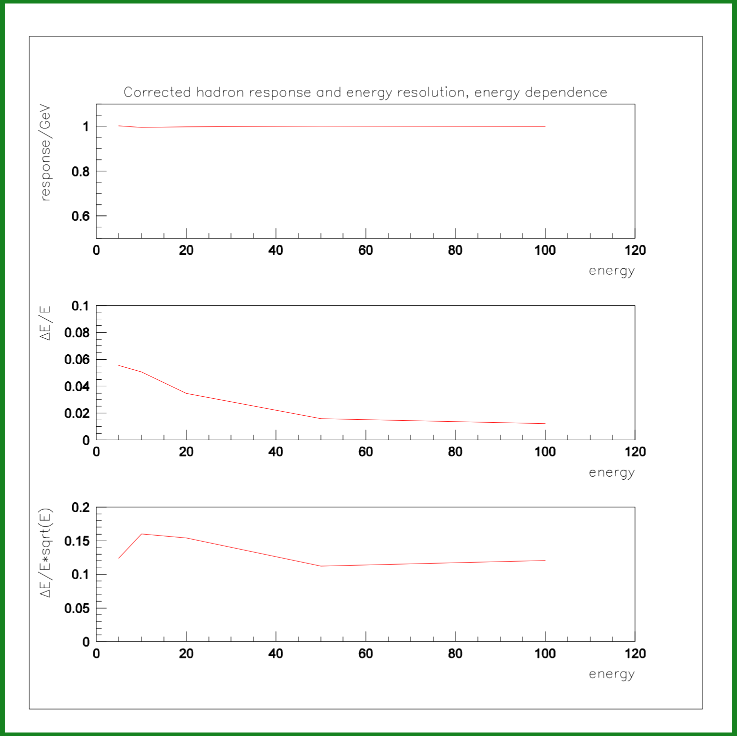
- Collect scintillation and Cherenkov light for 100 GeV negative pions entering the detector
- Use absolute calibration determined with electrons
  - $E_{sc} = A_{sc} * S$
  - $E_{ch} = A_{ch} * C$
- Notice (just observations, not used in the forthcoming):
  - $(\pi/e)_{sc} \approx 0.9$
  - $(\pi/e)_{ch} \approx 0.75$
  - Resolution much worse with Cherenkov

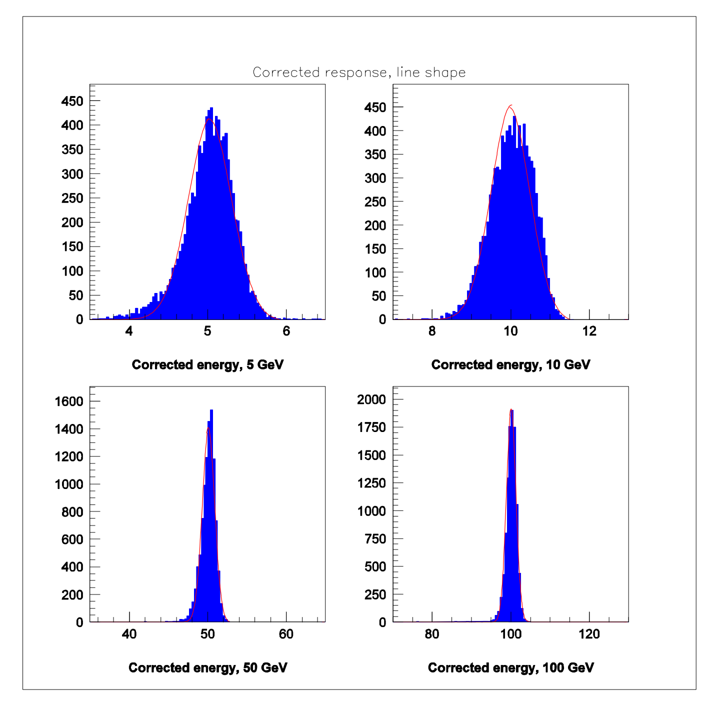
'Test Beam' 100 GeV Step III: Analysis



- Plot average S/E_{beam} as a function of C/S
- Fit some correction function F(C/S) (for example polynomial)
- Re-analyze the data:
  - $E = A_{sc} * S/F(C/S)$
- Observe:
  - Average corrected energy(red) ≈ Beam Energy (== π/e ≈ 1)
  - Significantly improved resolution
  - Analysis completely automated, no tuning or free parameters

Response and Resolution, Single Hadrons





After correction:

- good linearity of the corrected response
- good energy resolution ~ 0.12/√E
- no sign of a constant term up to 100 GeV
- Gaussian response function

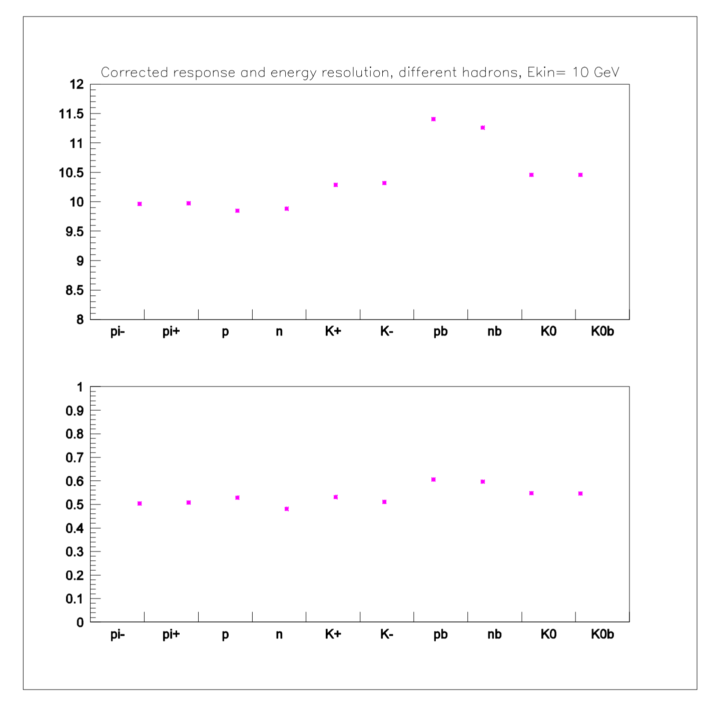
'Other particles'

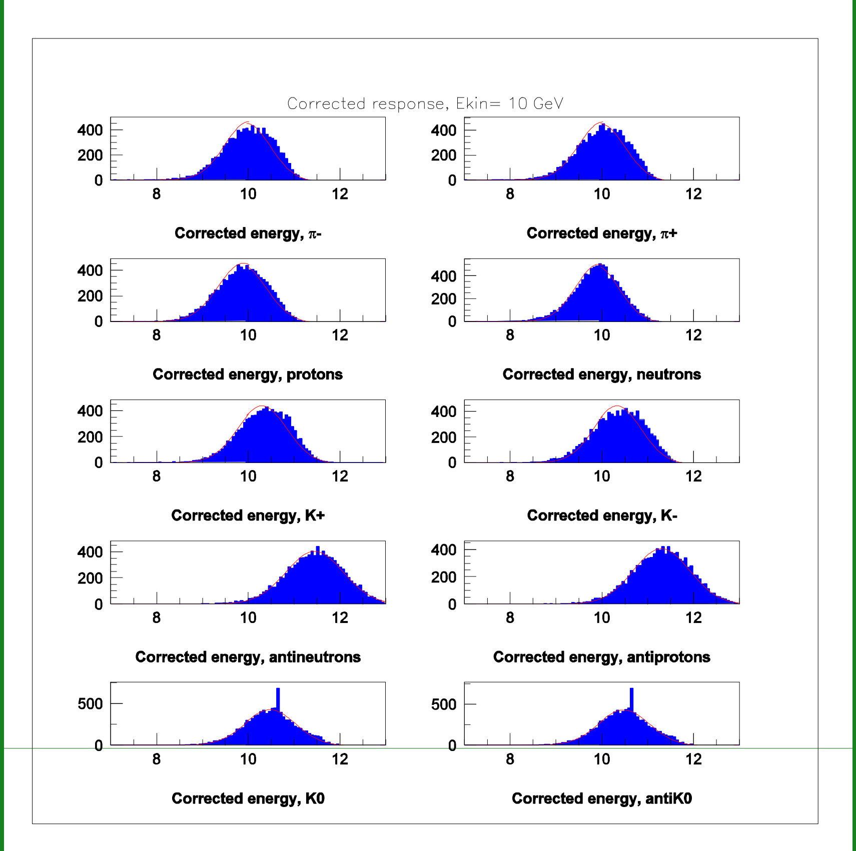
- We can calibrate the response of the detector to pions and protons (perhaps).
- Jets contain also neutrons and kaons. At high energies antiprotons and antineutrons are significant.
- We do not have neutrons/Ko/antineutrons test beams. K’s and antiprotons are scarce too.
- We may not have good particle ID inside jets, hence pion calibration will be used as a default.
- How does it affect the energy measurement??

Different Particles, Corrected Response (Using Pion-derived Correction)

- Proton/neutron response: -2%, ~OK
- K's: +0.5 GeV OK!
- Pbar, nbar: +1.5 GeV almost OK
- Resolution ~5% at 10 GeV for all the particles

Gaussian response functions for all particles





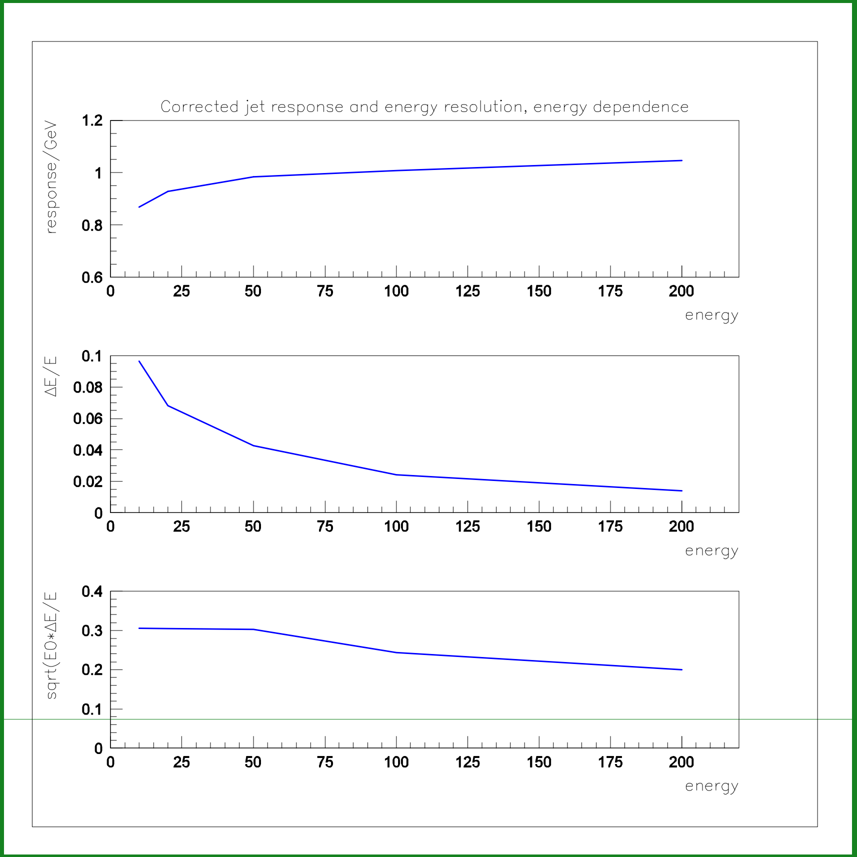
Jets!

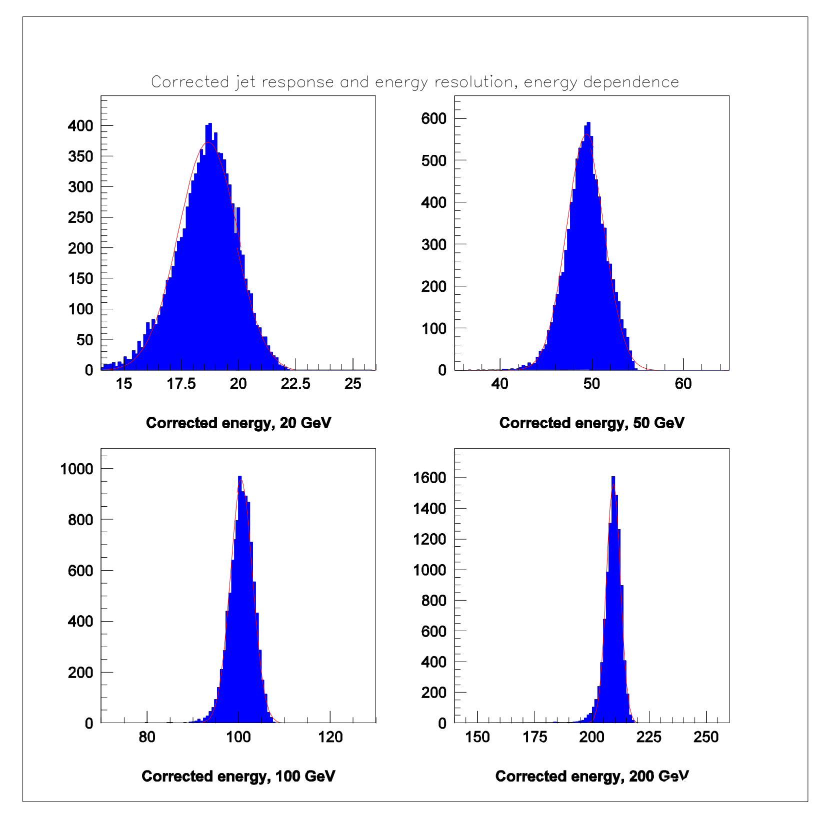
- Use Pythia e+e- → light quarks to create collections of particles with the composition and energy distributions characteristic of QCD jets (beware of the radiative return above Z0 peak)
- Edit the StdHEP list to send all jet particles along z-axis into the detector: S and C are the total amount of light collected from the jet
- Denote $E_{jet} = \sqrt{s}$
- Use (for example) 10 GeV 'pion test beam' correction function to correct (as a function of C/S) the scintillation signal
- This is a very crude algorithm. In a real detector the correction can be applied to localized clusters, using a 'local' C/S. Many other improvements come to mind too.. Under the investigation with a complete detector simulation (SLIC, ILCRoot).

Jets, Corrected Response

- Small non-linearity (~5%) for jets above 50 GeV
- Resolution improves like 1/√E (or better)
- ΔE/E ~ 0.22/√E

Gaussian response function. No tails!

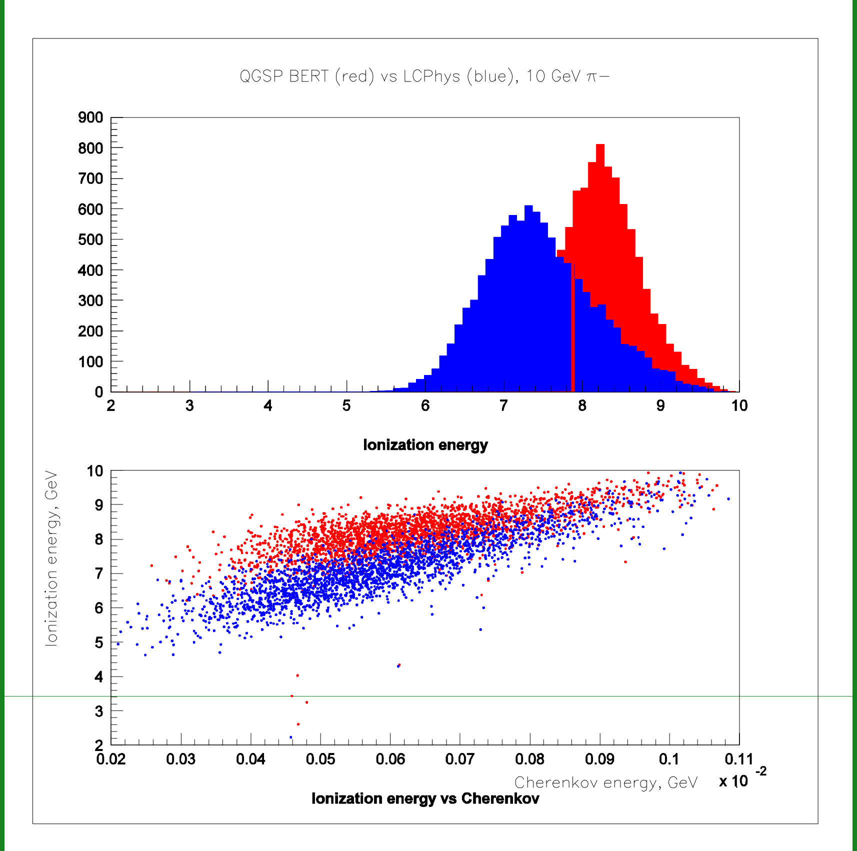




Jets, Summary

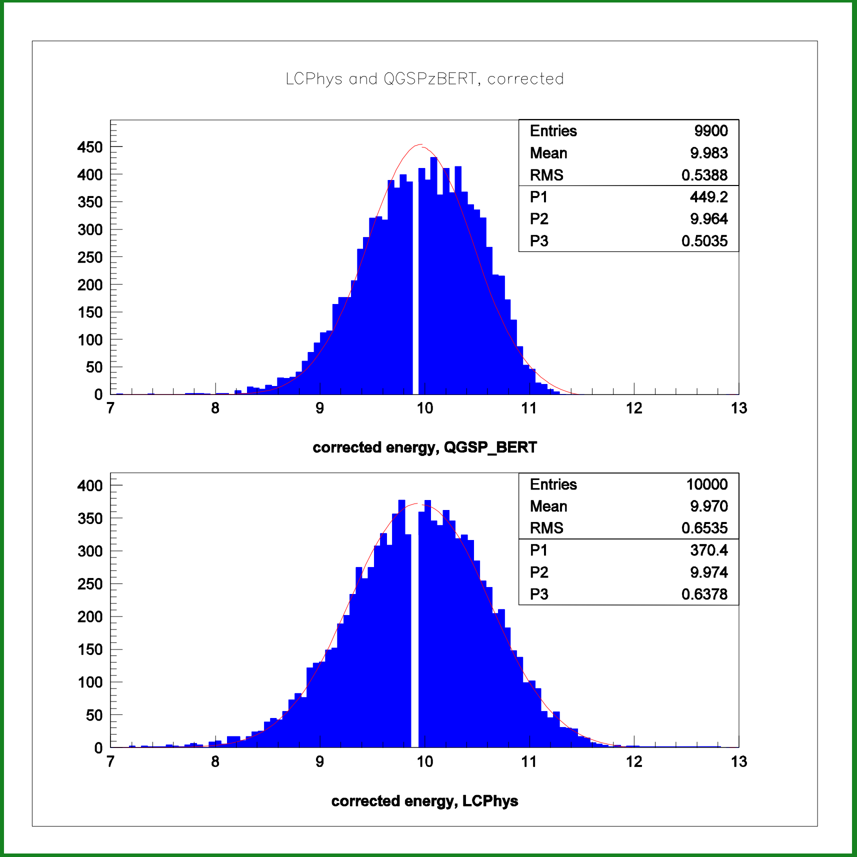
- Complete detector simulation
- Complete reconstruction (crude, veryfar from optimal)
- Gaussian response function, no tails
- Energy resolution (0.2-0.25)/√E
- No indication of a constant term in the energy resolution up to 200 GeV
- This is only Monte Carlo simulation! How trust-worthy is it??

Compare Different Monte Carlo Models



- Use two different physics lists: LCPhys and QGSP_BERT
- Most of the interactions with matter is the same, only hadron production modeling is different
- Surprisingly large difference between the overall response
- But.. Reconstruction/analysis does not use any input from the Monte Carlo,it derives everything from the test beam data (self-consistent set)
- Hence.. Treat one and the other simulated data set as a putative data and proceed with the calibration and reconstruction

Model Dependence of the Calorimeter Performance

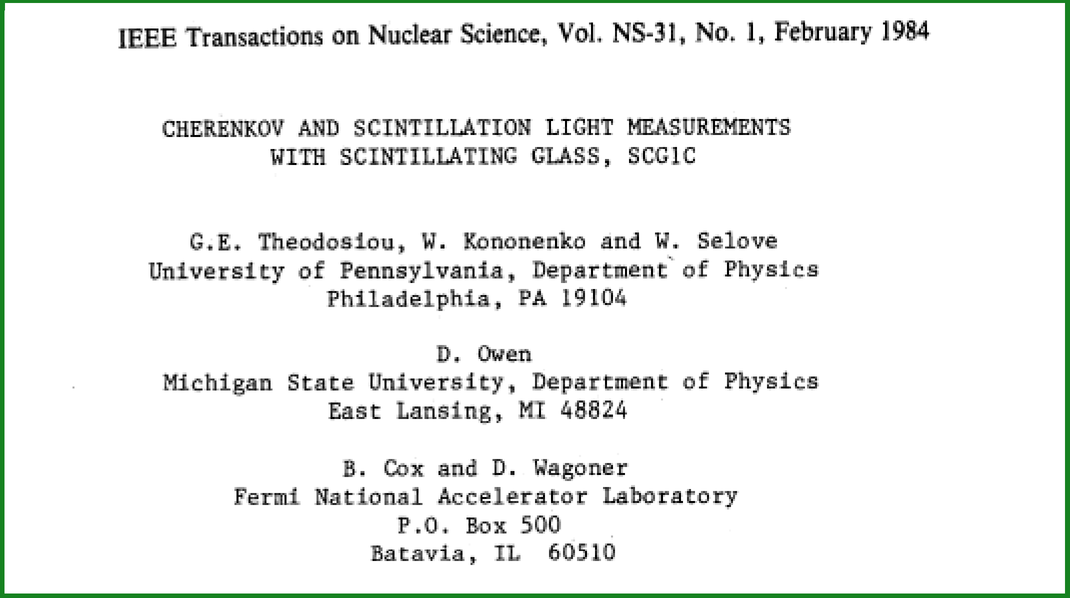


- Use 10 GeV data sets simulated with two different GEANT4 Physics lists
- Treat each set as a hypothetical 'data'. Derive self-consistent calibrations and corrections
- Correct the observed scintillation signal using the Cherenkov signal
- Overall response is stable to about ~1%
- Resolution vary by ~20% of itself (0.50 – 0.63 GeV@ 10 GeV, or (0.15-0.20)/√E)

Conclusion

- Very high resolution jest calorimeters with the energy resolution of the order of 20%/sqrt(E) appears quite feasible and attractive option, especially for a relatively compact detector.
- Performance of such a calorimeter is fairly well understood in terms of elementary physics and relatively independent on the simulation details
- Such a calorimeter requires development of new scintillating materials. They appear to be quite feasible and may be quite affordable, but this development representsts the primary challenge
- Development of these new materials may take several years, but it is probably well matched with any realistic timeline for the ILC experiments.

Nihil Novi



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CHERENKOV AND SCINTILLATION LIGHT MEASUREMENTS
WITH SCINTILLATING GLASS, SCG1C

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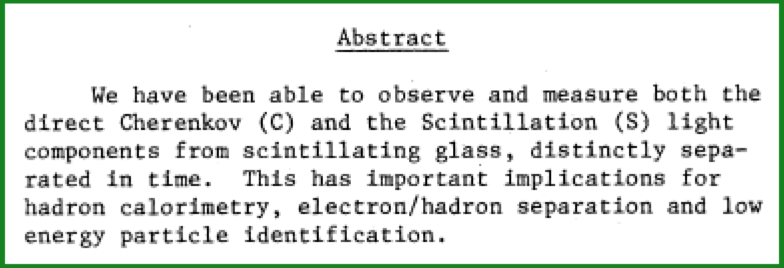

Abstract

We have been able to observe and measure both the direct Cherenkov (C) and the Scintillation (S) light components from scintillating glass, distinctly separated in time. This has important implications for hadron calorimetry, electron/hadron separation and low energy particle identification.