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HIGH RESOLUTION JET CALORIMETRY: TOTAL ABSORPTION HOMOGENEOUS CALORIMETER WITH DUAL READOUT

Summary

- Theoretical and experimental foundations of high resolution hadron calorimetry established more than 20 years ago
- Progress with development of dense scintillating materials and compact photodectors enables construction of hadron/jet calorimeters with energy resolution better than 20%/√E
- Past and present generations of experiments limited by physics and not the hadron calorimeter performance, experiments at the future lepton collider may be the first ones requiring high resolution hadron calorimetry
- Practical construction of very high resolution calorimetry is technically possible, but it requires further development of inexpensive scintillating crystals/glasses and economical large area photodetectors
- In any realistic detector the ultimate energy resolution is likely to be limited by the leakage fluctuations and calibration accuracy. At high energies it is the constant term, what counts!
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Why the Typical Hadron Calorimeters are so Poor?

- $(\Delta E/E)_{EM}$ can be as good as 0.01 for total absorption calorimeters. What's wrong with hadrons?:
- Typical 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: so called 'neutrons problem' is an artifact of sampling-scintillator calorimeter. SF ~ 0.02 at high energy, SF = 1 for thermal neutrons)
- A fluctuating fraction of the hadron energy is lost to overcome nuclear binding energy
- Inhomogeneous calorimeters (typically: EM + HAD with different responses)

From Single Hadrons to Jets

- [Jet == collection of particles with composition, spatial and momentum distribution characteristic for QCD fragmentation process].
- To achieve good energy resolution it is necessary to reduce the dependence of the calorimeter response on the jet fragmentation (particles composition and spectrum)

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

Path to High Resolution Jet Calorimeter

- Homogeneous Calorimeter (EM/Had combined).

- Total absorption calorimeter (No sampling fluctuations, 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.

- TAHCAL: Total Absorption Hadron Calorimeter

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
  - No physics-driven need (in hadron collider environment)
- Major advances in the detectors technology/enabling technologies:
  - High density scintillating crystals/glasses (λ~20 cm)
  - 'Silicon Photomultipliers' ~ robust, compact, inexpensive, functioning in magnetic field

TAHCAL Simulation and Analysis

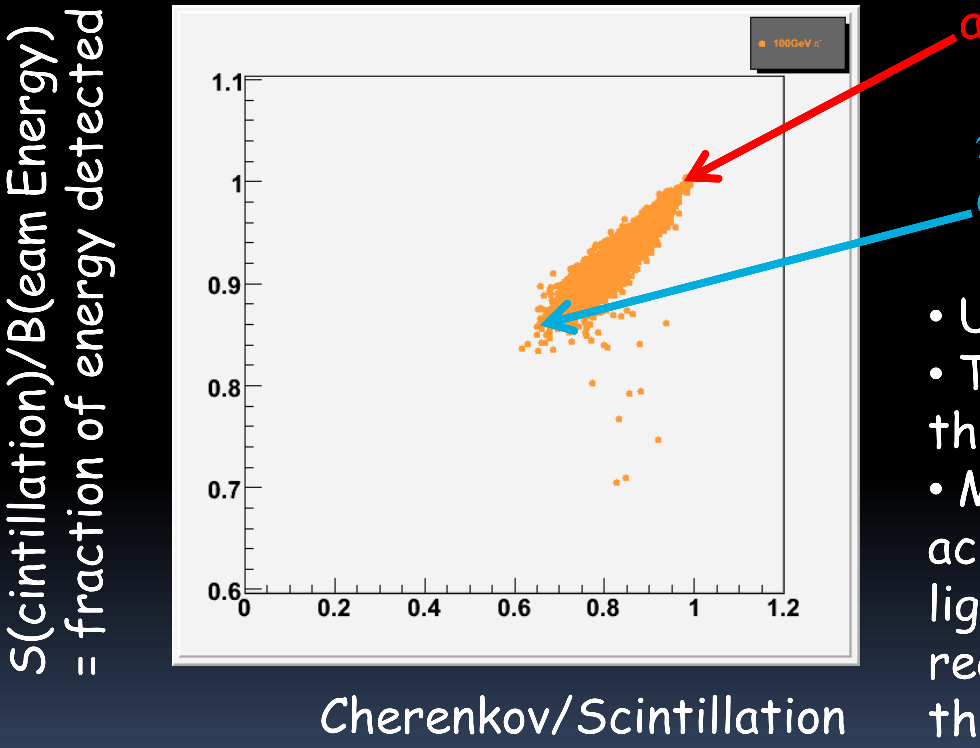
- Optical calorimeter option in SLIC (H. Wenzel, Fermilab)
  - "Test beam" calorimeter: 1 x 1 x 3 m^3 volume subdivided into 1 cm^3 'crystals'
  - SiD detector, version 1 ('thin')
- Crystals composed of various materials (elements or isotopes) at fixed density of 8 g/cm^3
- Optical properties characterized 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).
- "Test beam" analysis (K. Genser/Fermilab): physics principles, linearity and resolution
- "SiD" analysis (A. Driutti, G. Pauletta/Udine): containment, leakage fluctuations and their mitigation
- Very early stages, much room for refinements and improvements.

Physics Principles of High Resoluion, Total Absorption Calorimetry

- Total absorption: no sampling fluctuations and other sampling-related contributions. The dominant contribution to resolution: fluctuations of nuclear binding energy losses.

- Cherenkov-to-scintillation ratio a sensitive measure of the fraction of energy lost for binding energy:
    - Electromagnetic (π^0) showers do not break nuclei AND produce large amount of Cherenkov light (C/S~1)
    - Large 'missing' energy <-> large number of nuclei <-> small amount of energy in a form of EM showers <-> small C/S ratio
    - Low amount of 'missing' energy <-> small number of nuclei <-> large amount of energy in a form of EM showers <-> C/S ratio close to 1

Mechanics of Dual Readout Correction



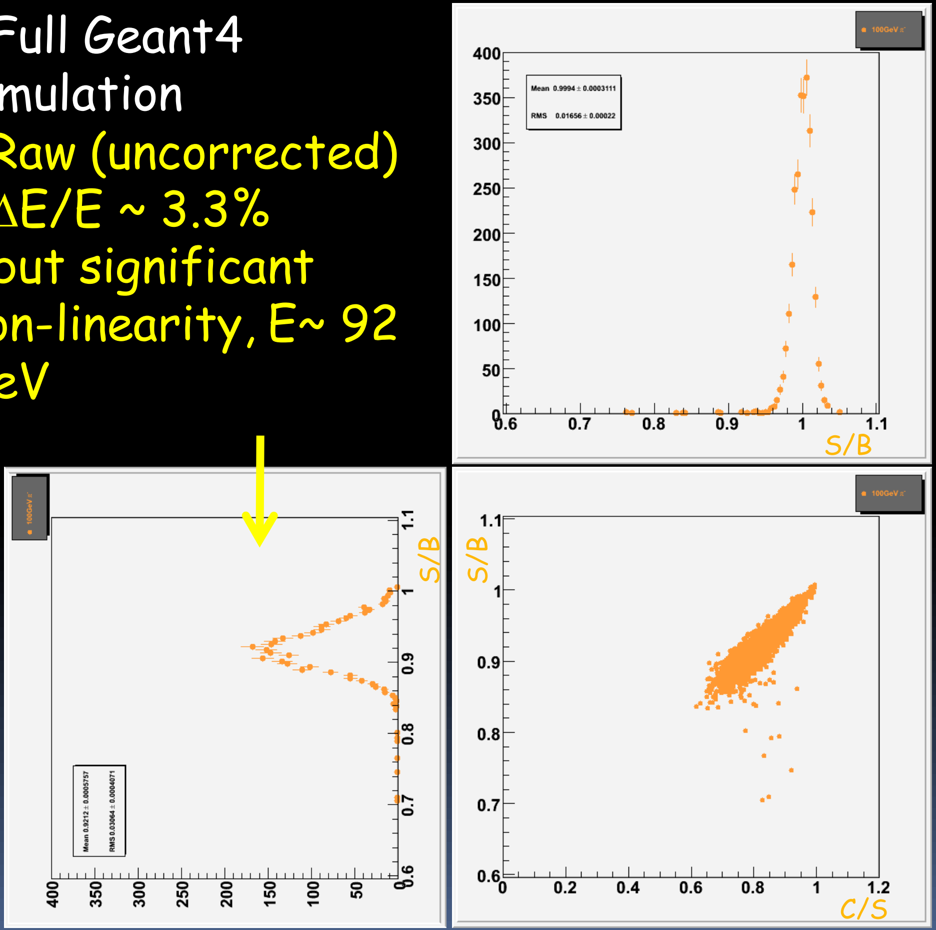
π^o-rich showers: almost all energy detected

π^o-poor showers: ~85% of the energy detected

- Use C/S to correct every shower
- The resulting resolution limited by the local width of the scatter plot
- Much better resolution can be achieved by using the C(herenkov) light rather than C/S, but it requires an *a priori* knowledge of the shower energy

TAHCAL at Work: Single Particle Measurement

- 100 GeV π^-
- Full Geant4 simulation
- Raw (uncorrected)
- $\Delta E/E \sim 3.3\%$
- but significant non-linearity, E~ 92 GeV



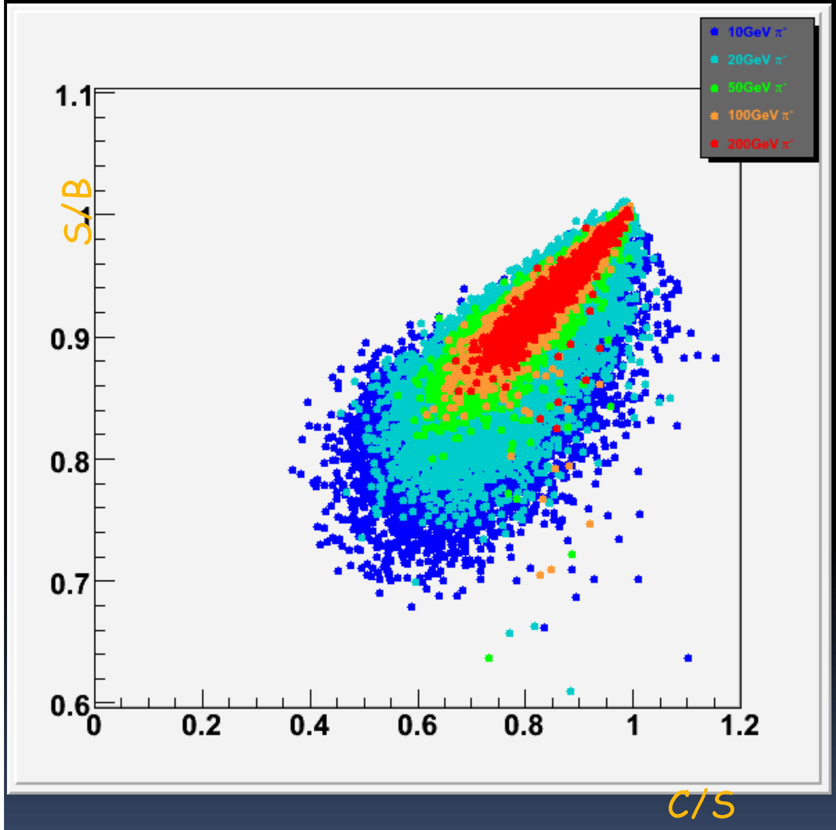
After dual readout correction, correction function (C/S) determined at the appropriate energy:

- Linear response: S/B=1 for all energies
- energy resolution scales as $\Delta E/E \sim \alpha/\sqrt{E}$ (no constant term)
- stochastic term $\alpha \sim 12\text{-}15\%$

From Single Particles to Jets

- Single particles provide an over-optimistic estimate of the calorimeter performance. Jets contain many particles of different kinds and various energies. And the jet fragmentation function fluctuates from jet-to-jet.
- In a segmented calorimeter jet energy measurement can be decomposed into several separated regions with the correction function optimized for the particles in this region
- The pessimistic limit of the detector performance can be evaluated by applying the average corretion function (derived from the global fit to data at different beam energies) to the total amount of scintillation and Cherenkov light measured for a jet.

Dual Readout Correction at Different Energies



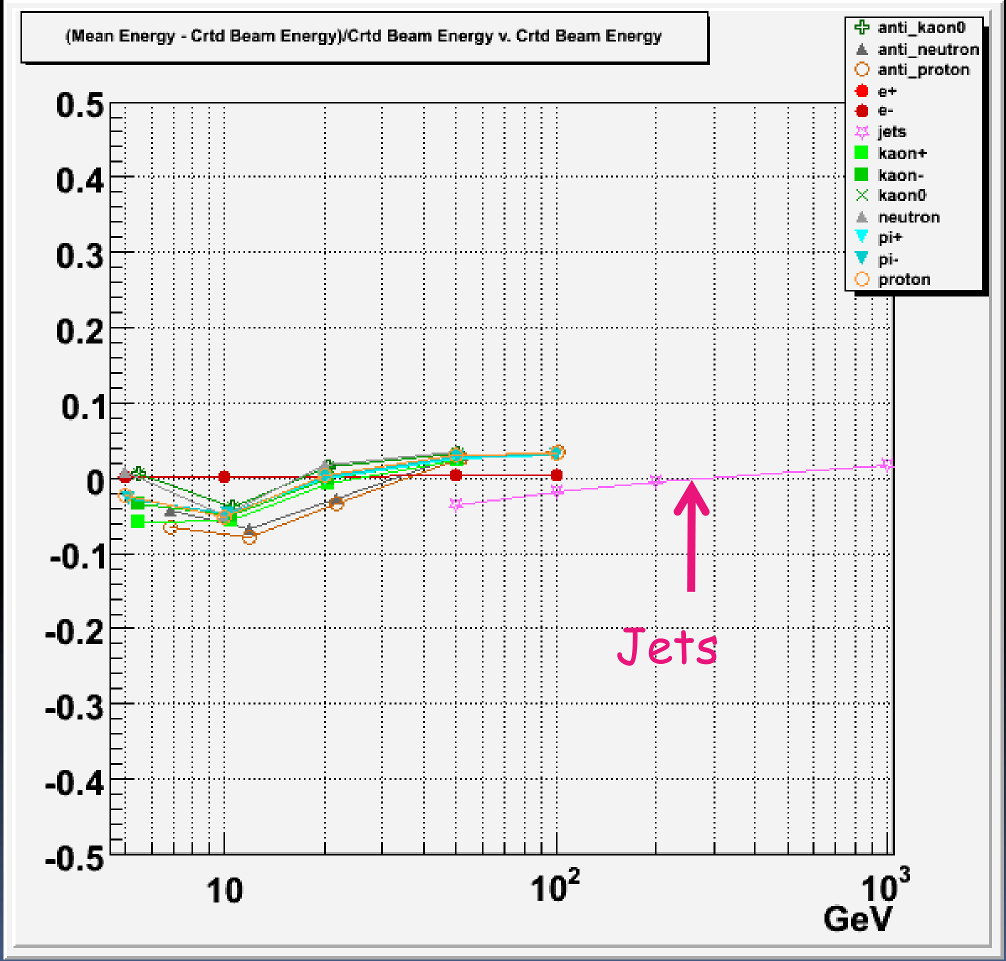
Correlation of the fraction of 'missing energy' and Cherenkov-to-scintillation ratio for showers of different energies: 10 – 200 GeV:

- High energy showers contain more EM energy (range of C/S confined to higher and higher values)

- Width of the correlation shrinks like ~1/√E (hence the ΔE/E~ 1/√E)

- Overall shape quite similar, but significant (compared to the width of the correlation) differences present. They will lead to:
  - non-optimal energy resolution
  - non-linearity of the response
  - contribution to the jet energy resolution

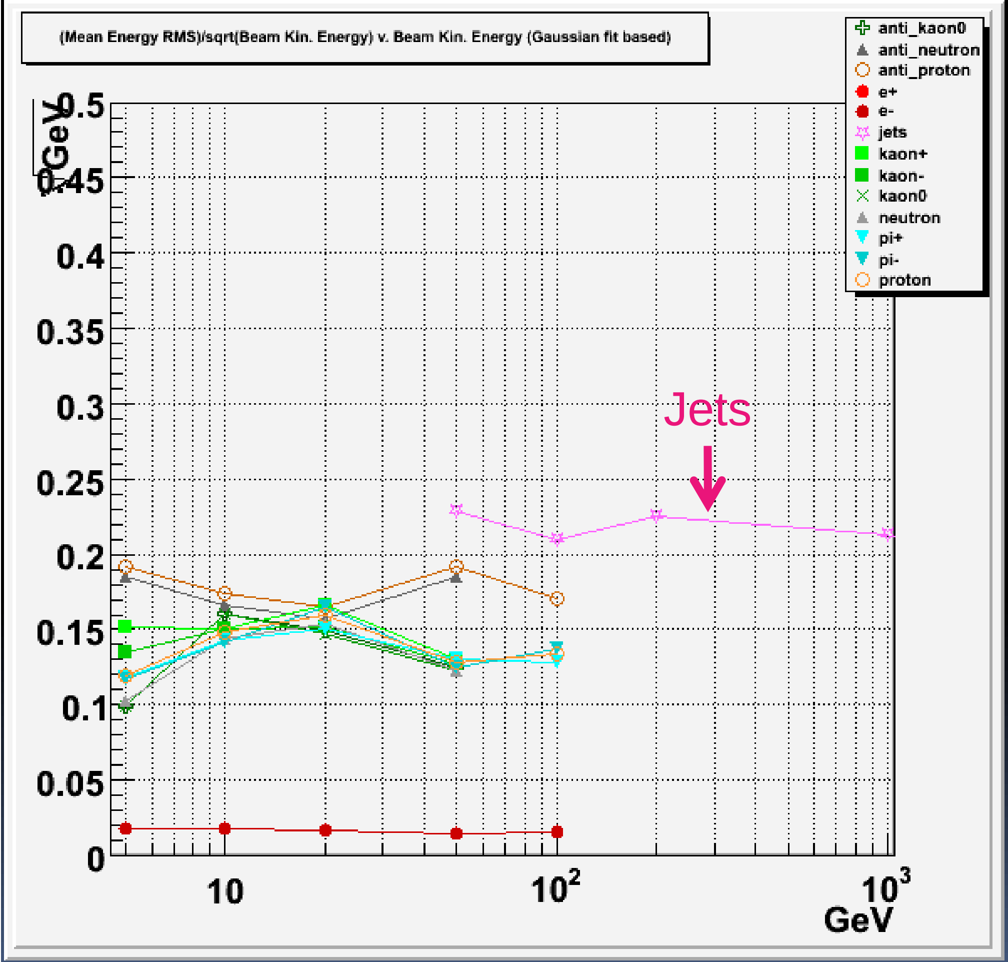
Response Linearity with Global Correction



Deviations from the linearity of the response (S-B)/B for different particles as a function of their energy:

- global correction mechanism induces some non-linearity of the response for single particles and for jets.
- For jets the induced non-linearity is of the order of 6% in the the energy range 50 – 1000 GeV
- This response non-linearity can be corrected, on average.
- Contribution of these non-linearites to the jet energy resolution cannot be, however, avoided

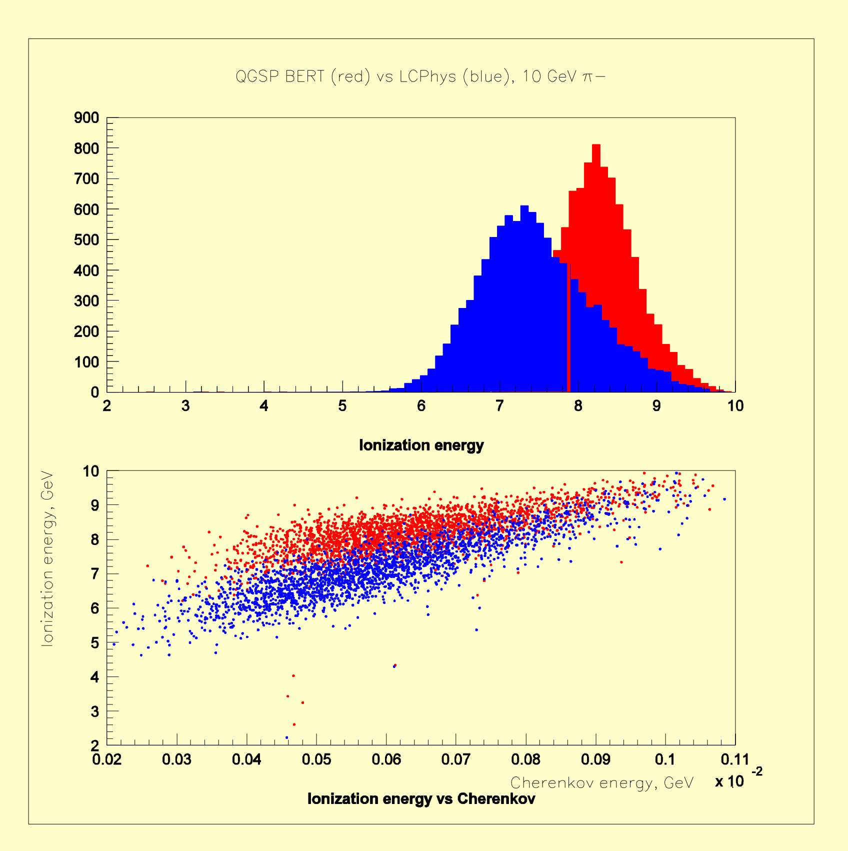
TAHCAL: The Energy Resolution with the Global Correction



With very crude reconstruction and non-optimal global correction function:

- energy resolution shows no constant term and scales ΔE/E~1/ √E
- stochastic term in the energy resolution is ~15% for single hadrons, 2% for electrons and ~22-23% for jets
- there are several obvious ways to improve the energy resolution. At least in the simulated calorimeter .
- But can we take the simulation seriously???

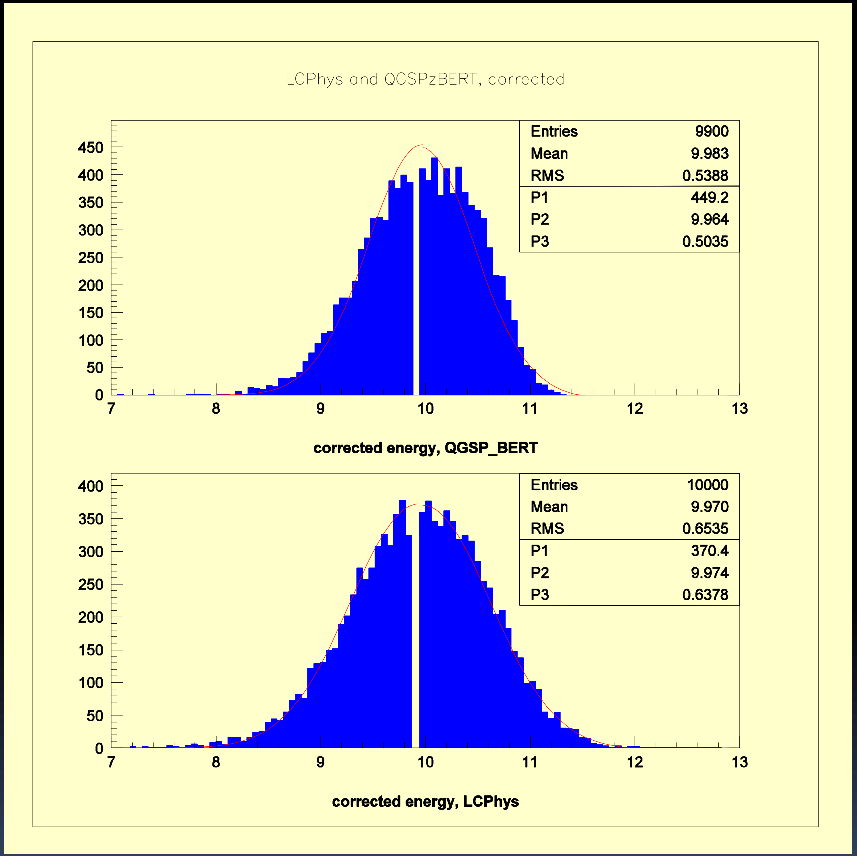
Compare Different Monte Carlo Models



- 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

Monte Carlo Dependence of the Calorimeter Response and Resolution



- 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)

OK.. Total absorption calorimeter may have very good jet energy resolution, but can one build one??

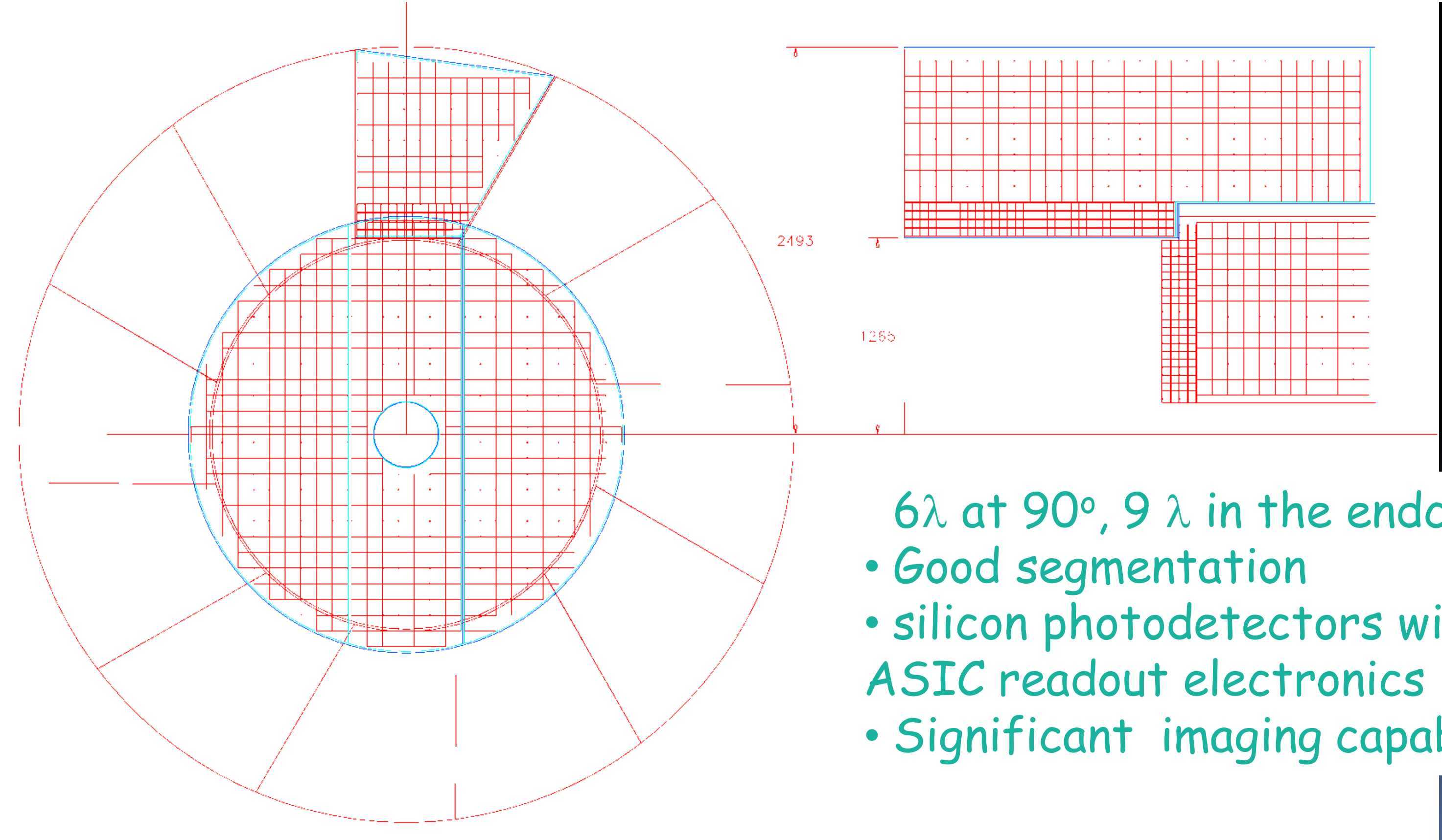
Conceptual Design of a TAHCAL

- Four layers of 5 x 5 x 5 cm^3 crystals (a.k.a. EM section): 72,000 crystals
- three embedded silicon pixel layers (e/γ position, direction)
- 10/16 (barrel/endcap) layers of 10 x 10 x 10 cm^3 crystals (a.k.a. hadronic section):70,000 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.
  - 6λ at 90^o, 9λ in the endcap region
  - 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.

TAHCAL in SiD: Initial Engineering

K. Krempetz, Fermilab:

… the crystal calorimeter could easily be incorporated in the SiD detector. The design that is presented has many engineering challenges which will need to be prototyped and tested before a final design could be made.



6λ at 90°, 9 λ in the endcap
- Good segmentation
- silicon photodetectors with ASIC readout electronics
- Significant imaging capabilities

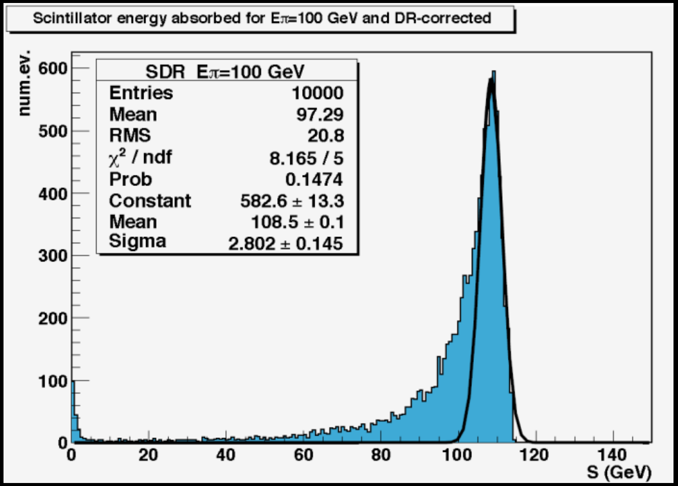
TAHCAL: Beyond the Simulation of the Ideal Detector

- TAHCAL offers an attractive perspective for a very high resolution jet calorimeter
- It could be constructed using the existing/nearly existing technologies, but it is not affordable
- The principal challenges on the road to the realistic detector:
  - Cost: crystals. Several of the existing crystals can be used. None of them is close to be affordable. Need a development of inexpensive crystals optimized for TAHCAL
  - Cost/performance: photodetectors. MPPC/SiPM must come through on their promises . Large(r) area detectors necessary (especially for Cherenkov readout).
  - Cost (of the entire detector): high energy resolution requires good containment. In a realistic case of space constrained by the superconducting coil the leakage fluctuations are likely to limit the energy resolution
  - Calibration: to achieve the energy resolution no segmentation is necessary. Several good physics and engineering reasons demand relative fine segmentation. Summing up the individual energy deposits requires 'good enough' relative calibration of the response. Calibration of readout of Cherenkov light is particularly challenging..

Leakage

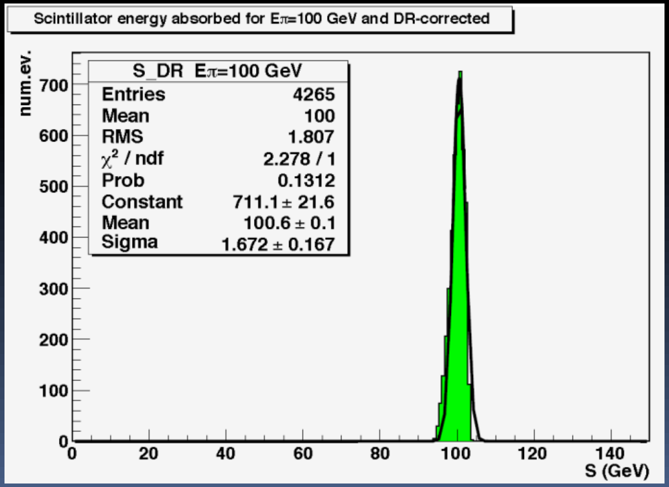
- A realistic detector design may provide some 120-150 cm of radial space for calorimeters (between the tracker at the coil).
- To minimize the leakage fluctuations it is important to maximize the average density of the calorimeter, including the readout. This is of particular importance in high resolution calorimeters.
- Heavy scintillating crystals and compact silicon photodetectors offer a possibility for the <u>average</u> interaction length of the order of 20-21 cm
- The leakage study (Udine):
  - 'thin' calorimeter (120 cm)
  - "worst case": single pions 100 GeV at 90°.
    [Note: This is not a 100 GeV jet! High energy single particles account for a relatively small fraction of high energy jet, but they maximize the leakage fluctuations.]

Leakage Studies: High Energy Single Particles

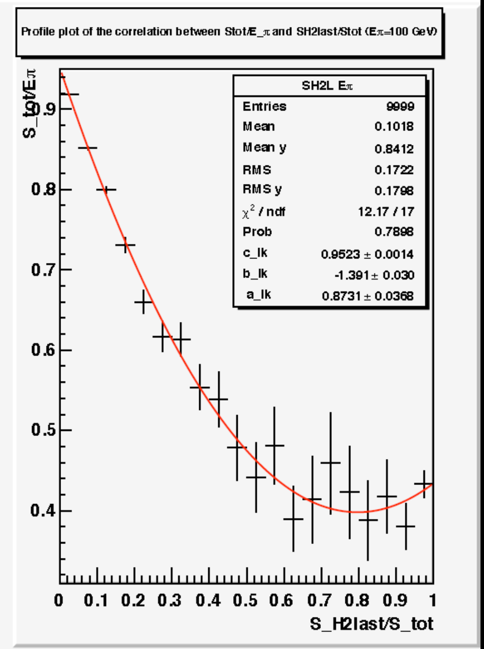


Corrected (or uncorrected) energy distribution shows major degradation of energy resolution: long tail towards low energies and a peak of punch-through pions. This is primarily caused by hadrons which interact deep inside the calorimeter, and see even smaller thickness of the detector.

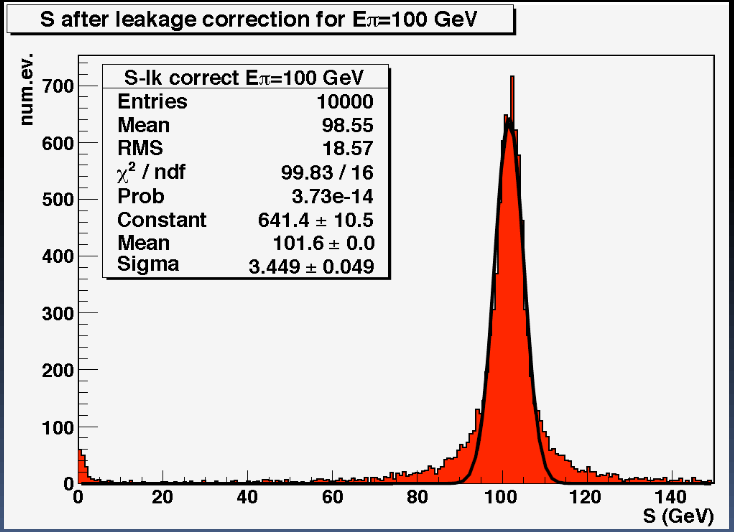
In a calorimeter with longitudinal segmentation the late showers can be recognized (for example by the energy deposition in the first of the last layers) and excluded from the analysis. Or they can be replaced by the measured momentum (PFA used in the right proportional may be beneficial).



Correcting for Leakage?



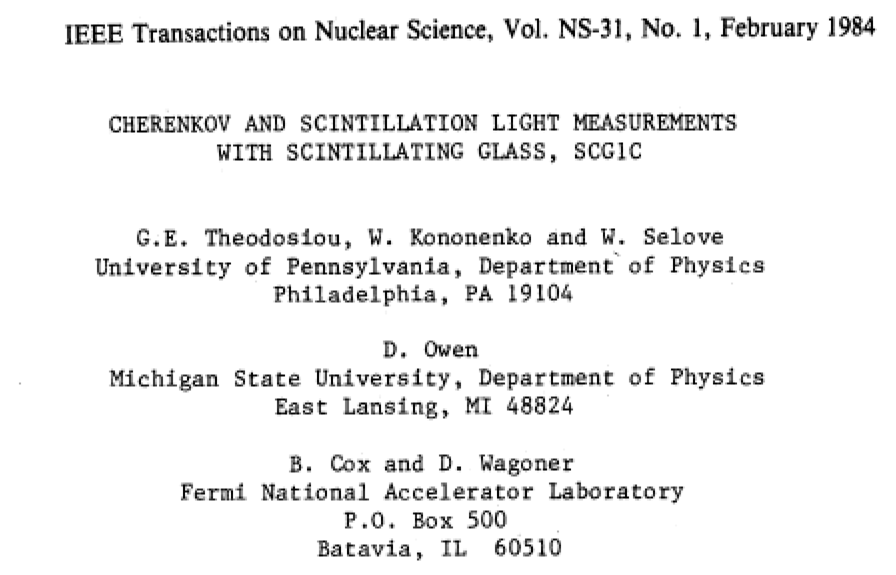
Longitudinal segmentation of a calorimeter provides information which can be used to identify and correct the leaking showers. For example (left): fraction of the observed energy of a shower correlates with the amount of the leaking energy



Using the information about the longitudinal shower development one can restore the symmetric form of the resolution function and improve the energy resolution.

Further improvement, especially for punching-through pions can be accomplished by using the information from the muon system (a.k.a. tail catcher).

Appendix: 25 Years of Dual Readout Calorimetry



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CHERENKOV AND SCINTILLATION LIGHT MEASUREMENTS WITH SCINTILLATING GLASS, SCG1C

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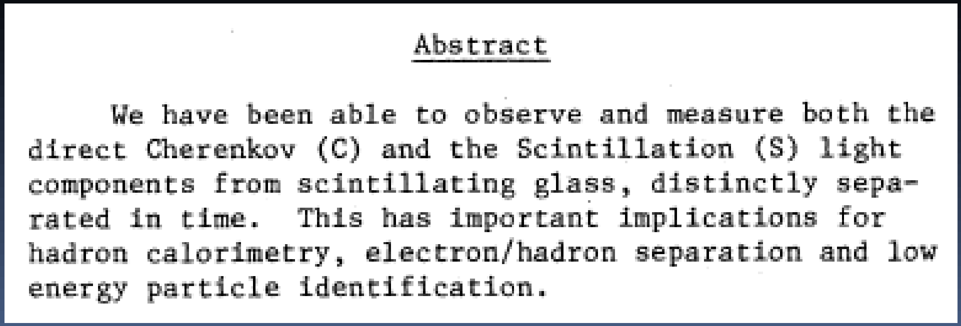

Abstract

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.

Summary

- Theoretical and experimental foundations of high resolution hadron calorimetry established more than 20 years ago
- Progress with development of dense scintillating materials and compact photodectors enables construction of hadron/jet calorimeters with energy resolution better than 20%/√E
- Past and present generations of experiments limited by physics and not the hadron calorimeter performance, experiments at the future lepton collider may be the first ones requiring high resolution hadron calorimetry
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