PPD Review,
Fermilab,
August 2, 2010

TOTAL ABSORPTION CALORIMETRY R&D

Purpose and the Organization

- Purpose:
  - Develop a strategy for a development of very high resolution hadron calorimetry
  - Identify the role of Fermilab, formulate a coherent program of R&D
  - Identify the resources required
- Organization:
  - Overview: prospects, roadmap (AP)
  - Simulation studies (HW)
  - Crystals and Photodetectors studies, prototypes (AP)
  - Readout electronics (PR)
  - New materials development (MD)

(Apparent Lack of?) Progress with Hadron Calorimeters

- More than 30 years ago: AFS hadron calorimeter 36%/sqrt(E)

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.

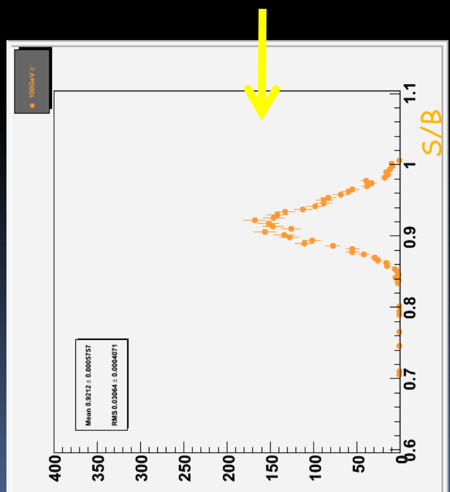
- Now: with great effort we can almost as well in R&D projects, much worse in real experiments
- Compare with the progress in other experimental techniques

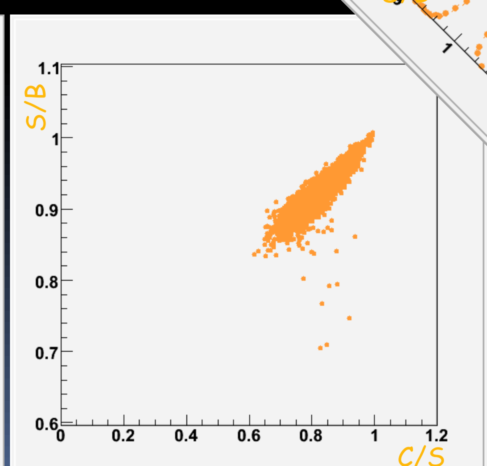
Huge Progress in Understanding Calorimetry and Physics of Hadronic Showers

- Nuclear effects induce dominating contribution to fluctuations of the observed signals
- Huge increase of the available computing power (GRID!) enables <u>calculations</u> of mind-boggling complexity
- But the complete and correct physics content must be provided
- Fundamental limitation of sampling calorimeters: 'sampling fraction depends on particle type and energy => hence they vary within the shower. This is in addition to unavoidable sampling fluctuations and this is the origin of a 'neutron problem'.
- Homogenous total absorption calorimetry (if practical and affordable) is an interesting candidate for super-high resolution calorimetry (both EM and hadron). Correlation of Cherenkov and scintillation signals can be used to correct for energy lost to nuclear binding and pions masses.

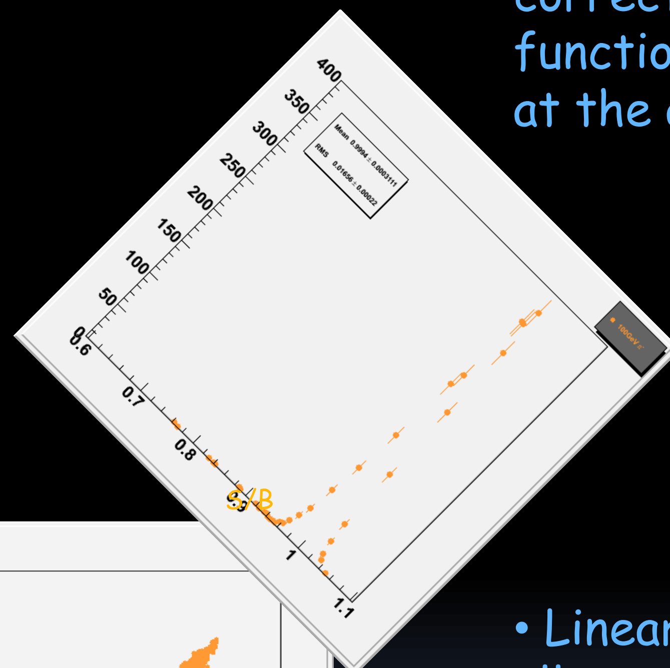
TAHCAL at Work: Single Particle Measurement

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



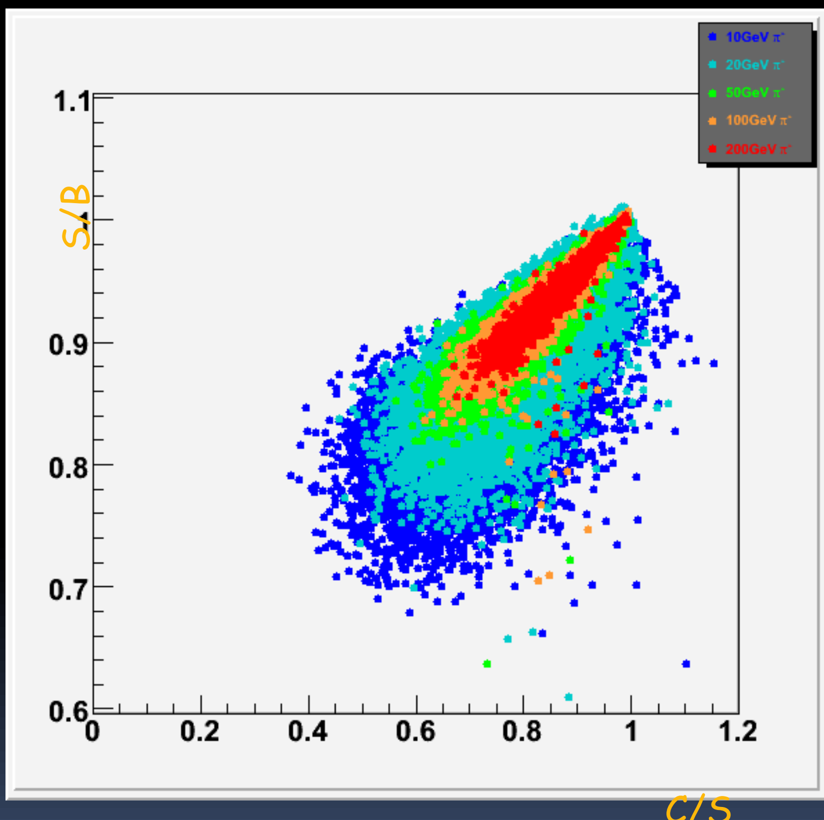


After dual readout correction, correction function (C/S) determined at the appropriate energy:



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

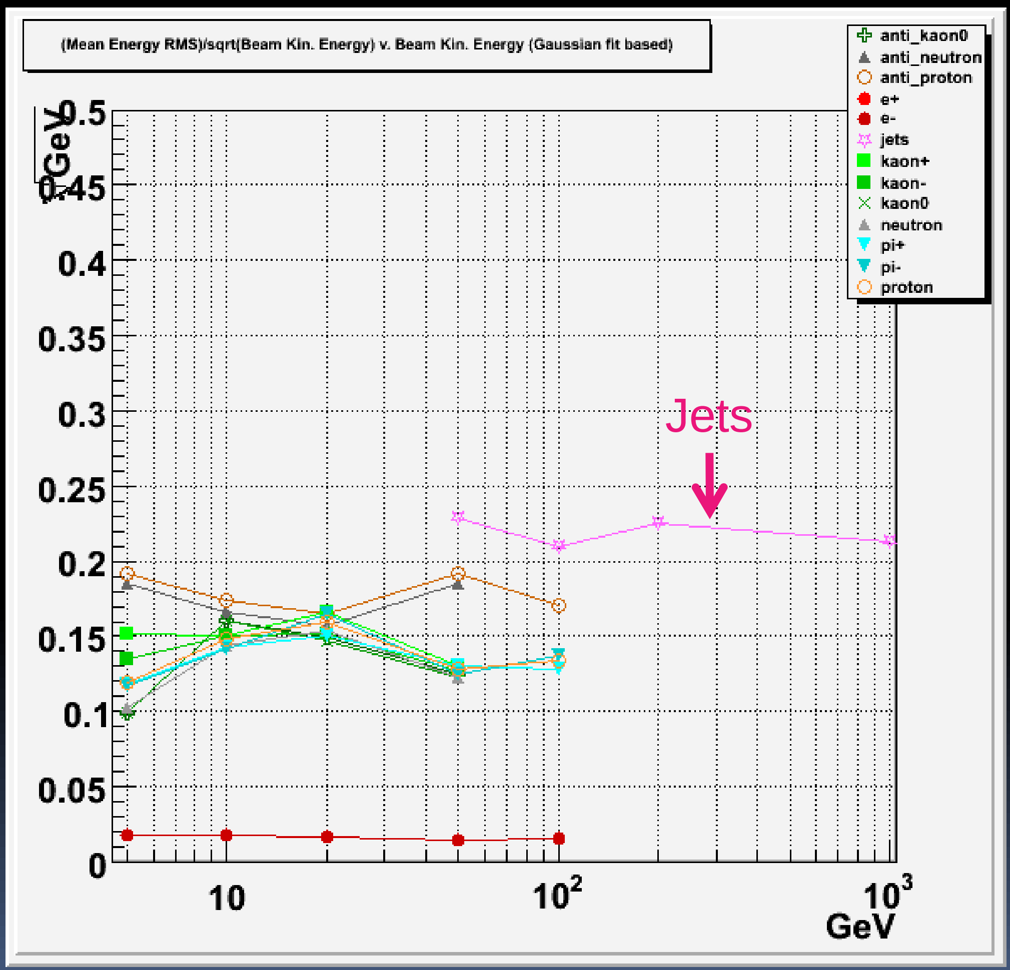
Dual Readout Correction at Different Energies



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

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 $\Delta E/E \sim 1/\sqrt{E}$
- stochastic term in the energy resolution is ~15% for single hadrons, 2% for electrons and ~22-23% for jets
- this performance is limited by the (known) shortcomings of the current simulation programs . One should expect significantly better energy resolution

Total Absorption Calorimeter in a Realistic Experiment

- Functional role:
  - Measure energy of electrons/photons
  - Reconstruct jets, measure invariant mass
  - Di-jet mass
  - Event Timing
  - Particle ID
  - Provide seed for trackers
  - Provide spatial (position/angle) measurement of neutrals
  - Separate close photons
  - Trigger   etc.. Etc..
- Geometry and granularity of the calorimeter requires careful optimization of the overall physics capabilities of the experiment. Crystals based calorimetry offers great degree of flexibility.

Separated Functions Calorimeter

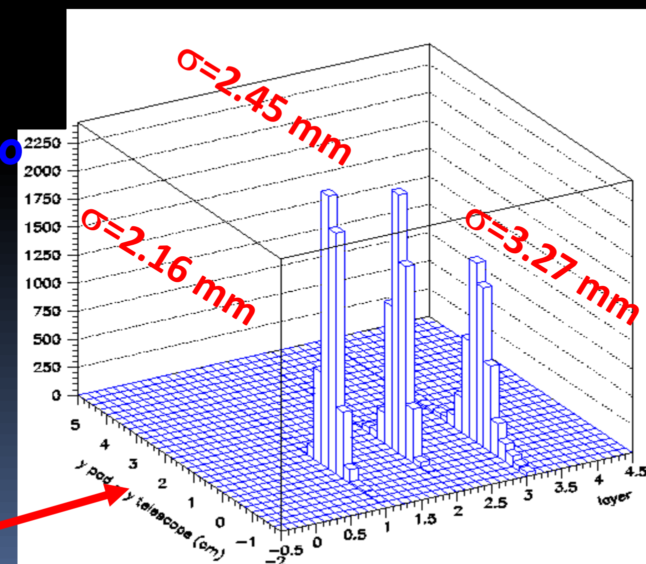
Calorimeters are expected to measure energies of particles/jets. But.. They are also expected to provide topological information: positions, directions, close showers separation. These additional requirements tend to complicate the detector design and compromise the energy

A possible solution: decouple the energy and topological measurements. Delegate the topological measurements to two-three layers of silicon pads. Negligible fraction of shower energy deposited in silicon should have no adverse effect on the overall energy resolution.

A possible alternative: a layer of imaging crystals made of crystalline fibers ? (P Lecoq)

- Such a concept has been put forward, and supported by INFN and DESY. Prototype has been constructed and tested in test beams at Frascatti and at CERN: LCCAL (P. Checchia, LCWS04)
- 3 layers of 0.9 x 0.9 cm silicon pads at 2, 6 and 12 X_0

30 GeV electrons



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Conceptual Design of a TAHCAL: an example for SiD

- Six 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.

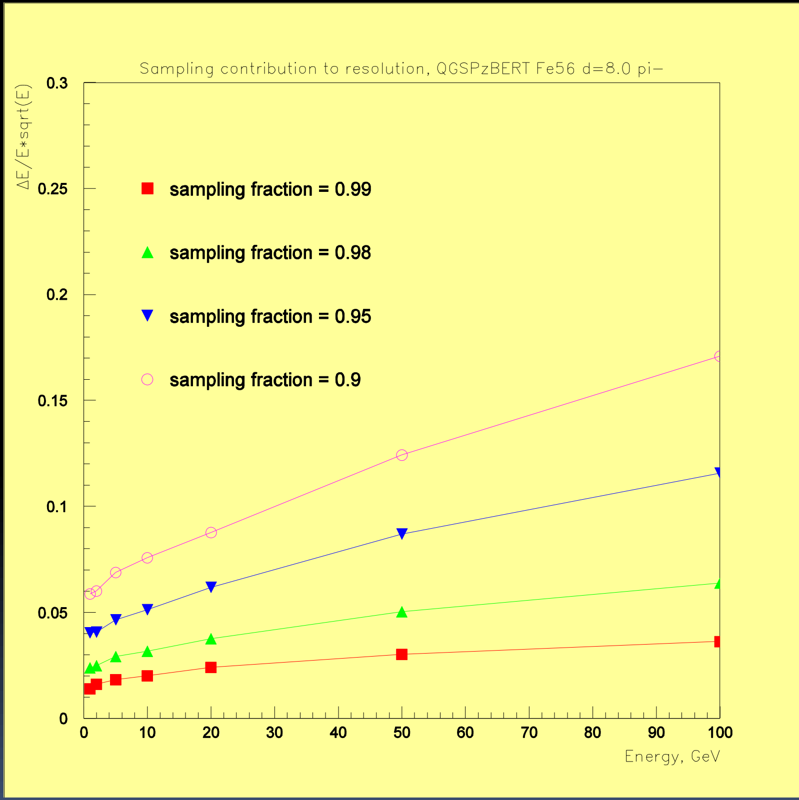
Practical Limitations: Dead Volumes

Any realistic calorimeter design will induce imperfections: support structures, cables, etc..

Impact of these imperfections on the calorimetric measurements can only be evaluated within a specific detector design, and this, in turn depends on specific crystals/glasses, photodetecotors, etc..

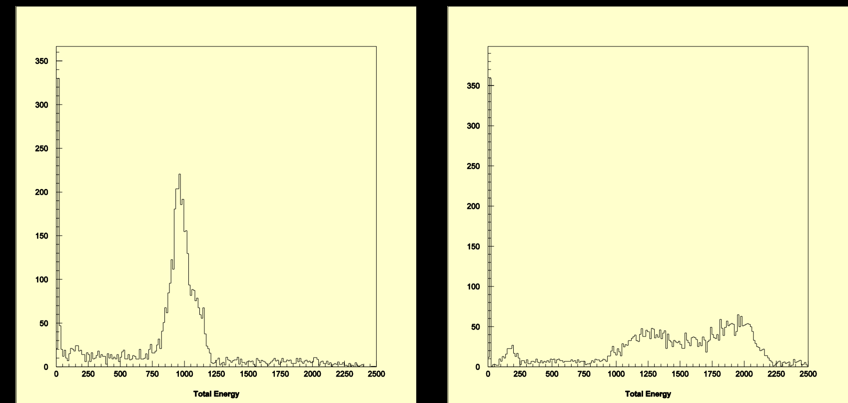
Sensitivity estimate: contribution to resolution as a fraction of energy lost in dead areas. Random distribution of dead volumes assumed.

Dead volumes absorbing up to 5% of the calorimeter volume induce negligible contribution to energy resolution

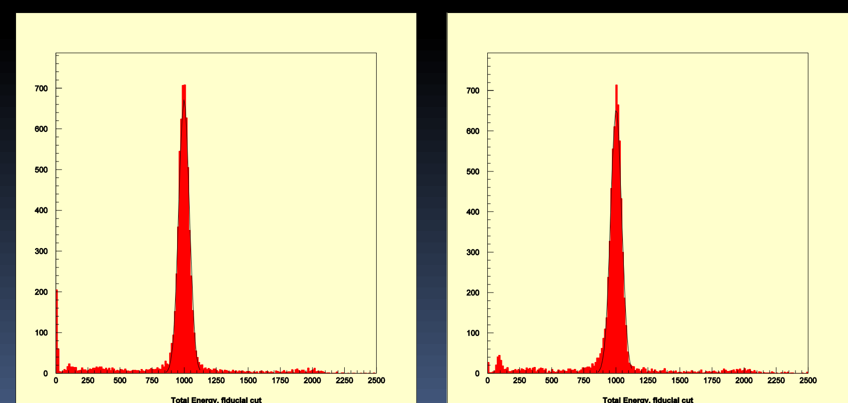


Practical Limitations: Calibration

- Segmented crystal calorimeter involves large number of independent detector volumes which need to be inter-calibrated
- This is always a pain, but at least straightforward in principle (T1004 test beam: upper row the response of collection of crystals before inter-calibration, bottom row – after inter-calibration)
- in-situ calibration (T-1004 test beam) yields ~ 4% resolution for 4 GeV electron beam (consistent with the beam energy spread)



Before calibration



After calibration

Practical Limitation: Light Yield

- To maintain the resolution at the level of ~ 10%/sqrt(E) one needs to detect ~ 200 photoelectrons/GeV in scintillation and ~ 1-2 photoelectrons/GeV in Cherenkov.
- It is sensible to have large contingency (it is very easy to loose light).. Sensible specs: 1000 photoelectrons in scintillation, 10 photoelectrons in Cherenkov.
- This is a complicated requirement involving the crystals, geometry and photodetectors (sizes, quantum efficiency, spectral response)
- Typical light yields for scintillating crystals : 100 – 50,000 photoelectrons per MeV
- Best light yield for Cherenkov: ~ 2 photons/MeV
- Maintaining the Cherenkov and scintillation light yield from a single volume is challenging.

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
- Longitudinal segmentation an important tool to detect and to minimize the impact of leakage on the energy resolution.
- Thorough studies in progress in Udine/Trieste

The Real Challenges

- Are there crystals suitable for scintillation/Cherenkov light separation? No. Nobody asked for slow, dim scintillator, short absorption length.
- Can such crystals be designed/produced? Yes. (crystal growers experts)
- Can such crystals be affordable (target price ~ $1/cc)? Perhaps. What drives the cost of crystals?
  - Energy cost for melting (➔ melting temperature)
  - Crucibles material wear
  - Raw materials (BGO)
- Do we need to insist on single crystals?? NO! High density scintillating glasses, metamaterials should be considered. Cost can be greatly reduced.
- SiPM's are probably adequate to detect scintillation, but they may be insufficient for Cherenkov. Development of large area compact photodetectors very important.

Roadmap (5 years scale)

- Demonstrate the excellent energy resolution of TAHCAL in a test beam (1.5-2 m^3, ~$10-12M)
  - Identify/develop photodetectors with adequate performance (especially for Cherenkov) component
  - Develop inexpensive optical materials suitable for dual readout calorimetry (may significantly reduce the cost)
  - Develop the front-end readout electronics for (~2000 channels) for the new photodetectors
  - Optimize the size/shape/geometry of the test module to minimize the cost but ensure adequate performance

Roadmap (2-3 years scale)

- Evaluate the uncertainties in the predicted energy resolution due to the accuracy of physics modeling
- Identify and quantify contributions of various systematic effects (like yield, imperfection of light separation, light collection, …)
- Provide experimental verification of modeling of the optical properties of the calorimeter.
- Provide experimental verification of modeling of hadronic showers (angular distribution of Cherenkov light inside the shower)
- Demonstrate the light yield and separation for scintillation and Cherenkov components using compact photodetectors
- Develop a calibration procedure for inter-calibration of the scintillation and Cherenkov light measurements.

Roadmap (2-3 year scale, II)

- Develop practical solution for reading out ~50-100 photodetectors (phototubes and SiPM's)
- Initiate R&D for development of readout system for ~1000 channels
- Characterize the properties of the SiPMs for a calorimetic application, develop a procedure for optimization of the operating point. Interact with the vendors to optimise the design of the SiPM's.
- Develop deeper understanding of scintillation light production in crystals by various particles at various energies
- Initiate and stimulate efforts to develop new inexpensive optical materials for hadron calorimetry

Broad Collaboration

- Scope of the medium and long term plans is very challenging. Need to engage large number of people/institutions in various areas. So far:
  - Prototypes construction/testing -Trieste, Udine, Iowa, Cyprus
  - Photodetectors study - LAL, Triumf, Cyprus, NIU, Udine
  - Optical modeling/experimental studies - NIU, Cyprus
  - New materials development – Caltech, SICCAS, LBL, Kharkov
  - Fundamental scintillation processes – Kharkov
- Initiated a series of workshops on 'Materials for Hadron Calorimetry', now a companion workshop to NSS IEEE
- Close collaboration with FACTOR (INFN)
- Collaboration within SUCCES (Ukraine, 7^{th} framework)