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SiD Workshop
Eugene, OR
November16, 2010

HIGH RESOLUTION HADRON CALORIMETRY

Why Hadron Calorimeters are so Poor?

- $(\Delta E/E)_{EM}$ can be as good as 0.01 for total absorption calorimeters . The best hadron calorimeters have $(\Delta E/E)$~50%/√E for single particles, 70%-100%/ √E for jets. What's wrong with hadrons???
- Hadron calorimeters used to be/are/will be (?) 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)
- A fluctuating fraction of the hadron energy is lost to overcome nuclear binding energy.
- Inhomogeneous calorimeters (typically: EM + HAD, with different responses)

Path to High Resolution Jet Calorimeter

- Homogeneous Calorimeter (EM/HAD combined. May have different granularity).
- 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 losses. This can be done, for example, by dual readout of scintillation and Cherenkov light signals.

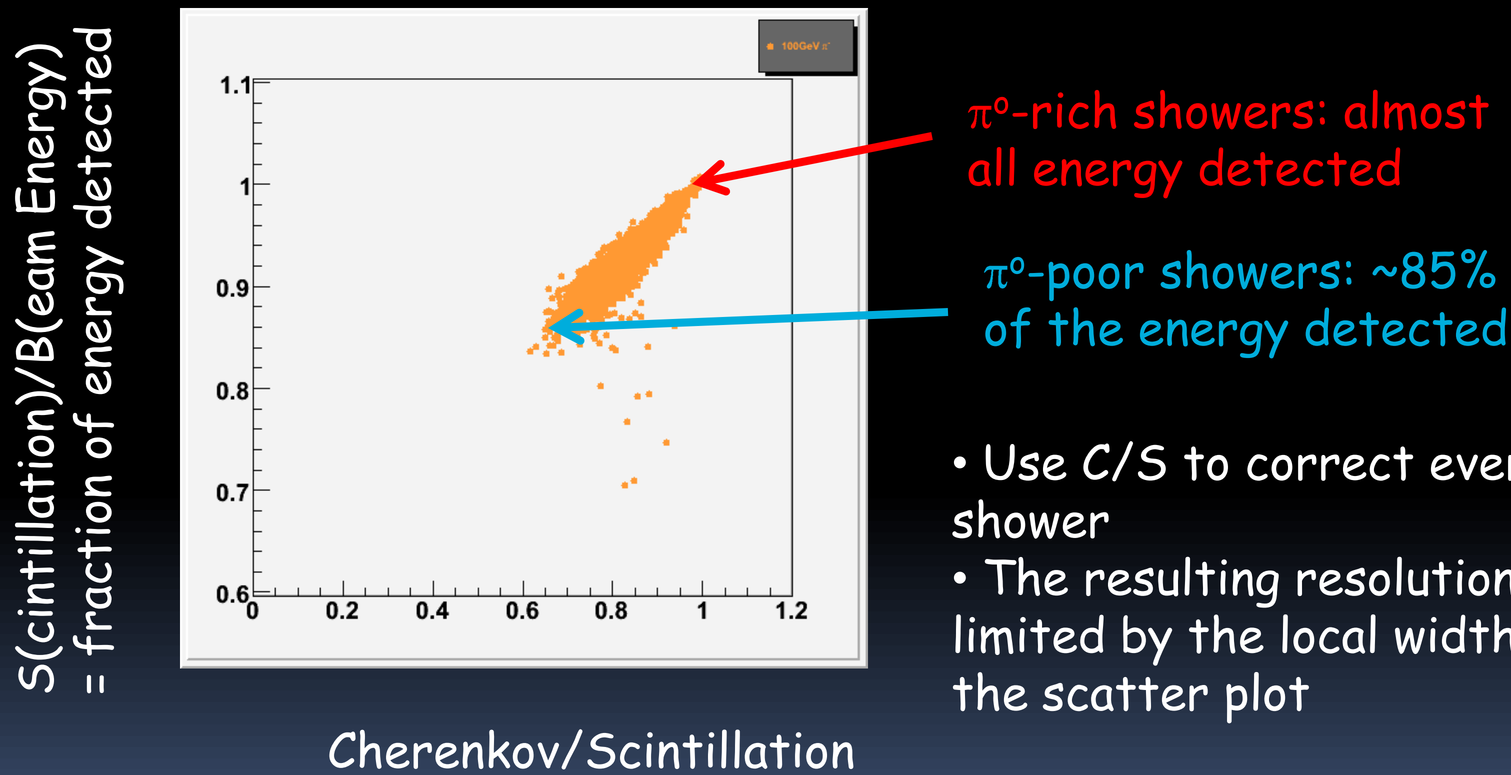
Key: Technological Advances

- 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 requirements (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

Physics Foundations of High Resolution, 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 broken nuclei <-> small amount of energy in a form of highly relativistic particles <-> 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



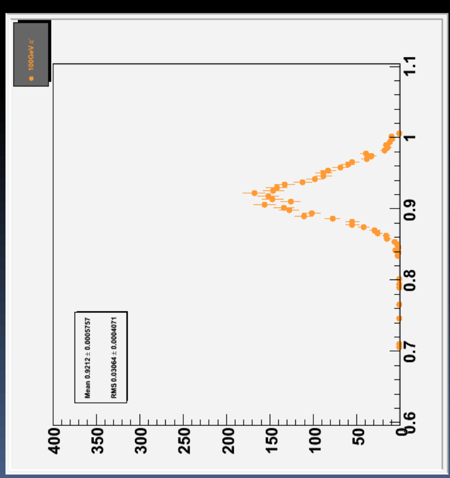
- Use C/S to correct every shower
- The resulting resolution limited by the local width of the scatter plot

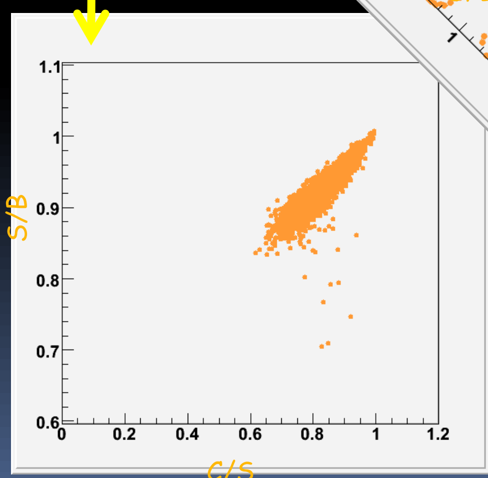
TAHCAL at Work: Single Particle Measurement

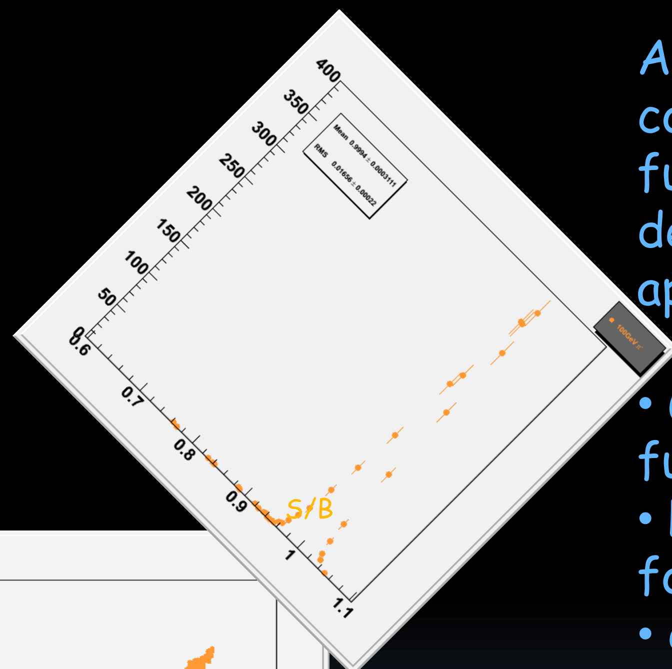
•100 GeV π-
• Full Geant4 simulation

• Raw (uncorrected) $\Delta E/E \sim 3.3\%$

•but significant non-linearity, E~ 92 GeV



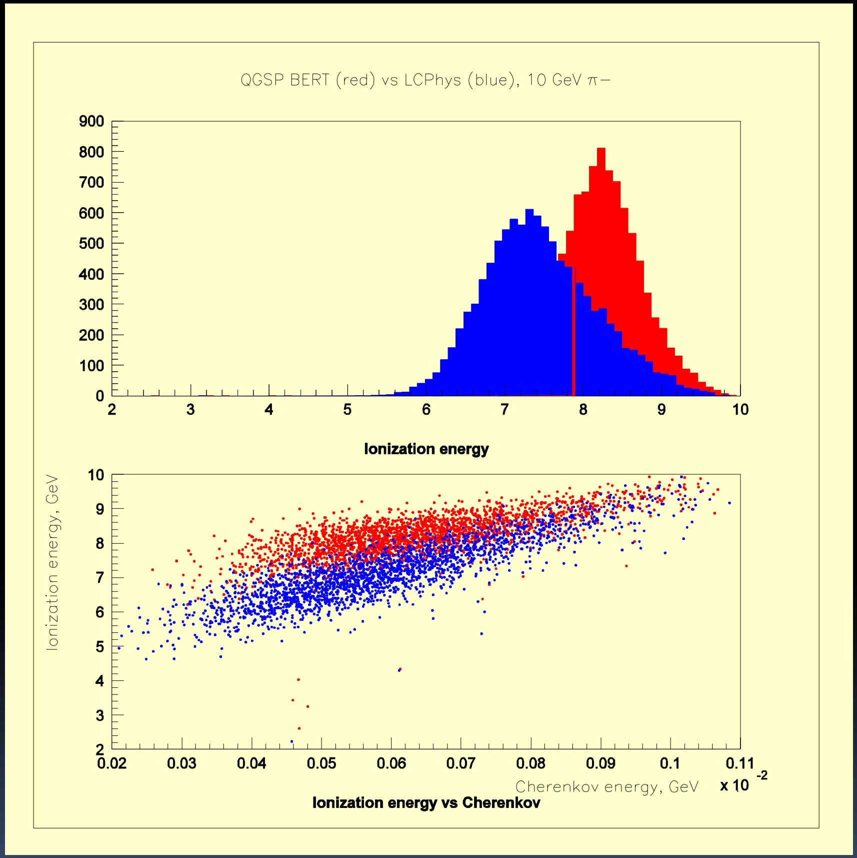




After dual readout correction, correction function (C/S) determined at the appropriate energy:

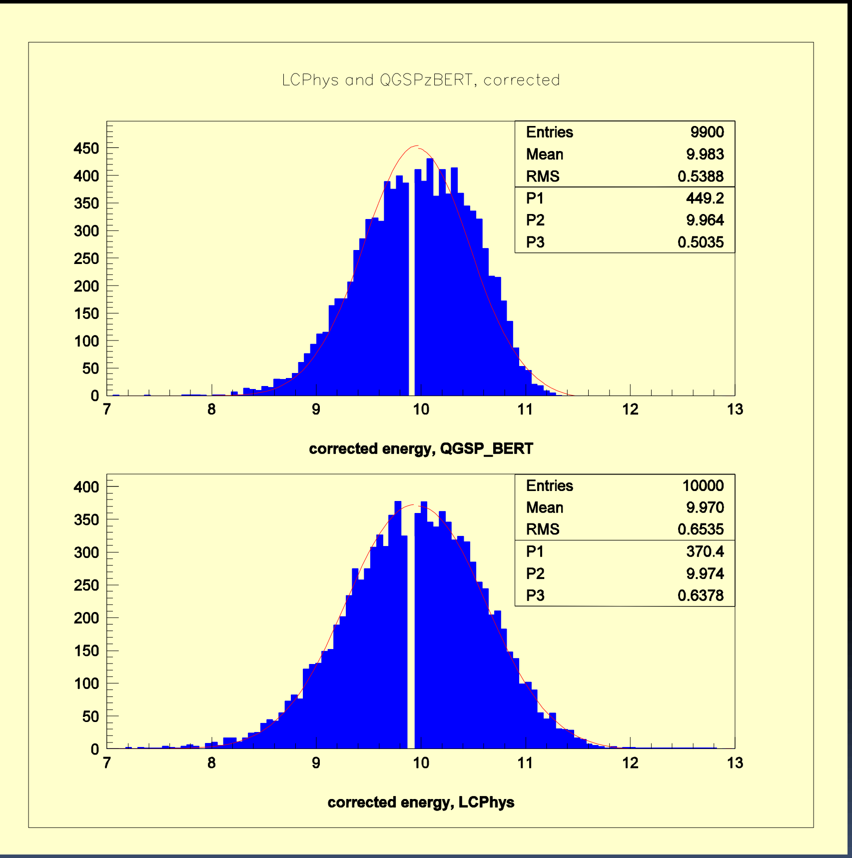
• Gaussian response function
• Linear response: S/B=1 for all energies
• energy resolution $\Delta E/E \sim \alpha/\sqrt{E}$ (no constant term)
• α~12-15% or $\Delta E/E$=1.2-1.5% at 100 GeV

Trust Monte Simulations ???



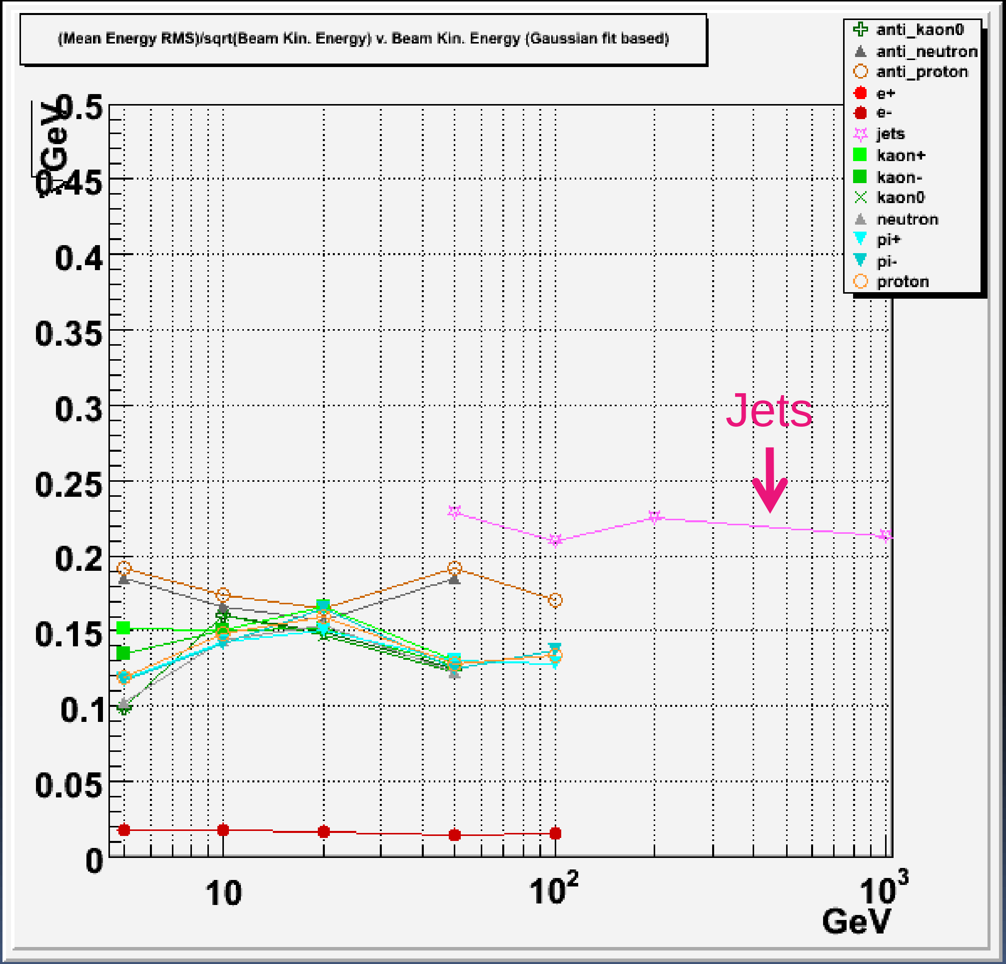
- Use two different physics lists: LCPhys and QGSP_BERT
- Most of the interactions with matter is the same, only hadron production modeling is different
- Surprisingly large difference between the overall response
- But.. Reconstruction/analysis does not use any input from the Monte Carlo,it derives everything from the test beam data (self-consistent set)
- Two components of simulations:
  - High energy physics (a.k.a. QCD). Porrly known, but irrelevant
  - Nuclear physics: of critical importance, but quite well known
- Deficiencies of GEANT limit the estimated energy resolution

Different Monte Carlo – Similar Energy 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%
- Simulated performance of the dual readout calorimeter is very insensitive to the 'QCD' part of the simulation

TAHCAL: The Jet Energy Resolution



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

• energy resolution shows no constant term and scales ΔE/E~1/ √E.. (This is a honest resolution)

• stochastic term in the energy resolution is ~15% for single hadrons, 2% for electrons and ~22-23% for jets

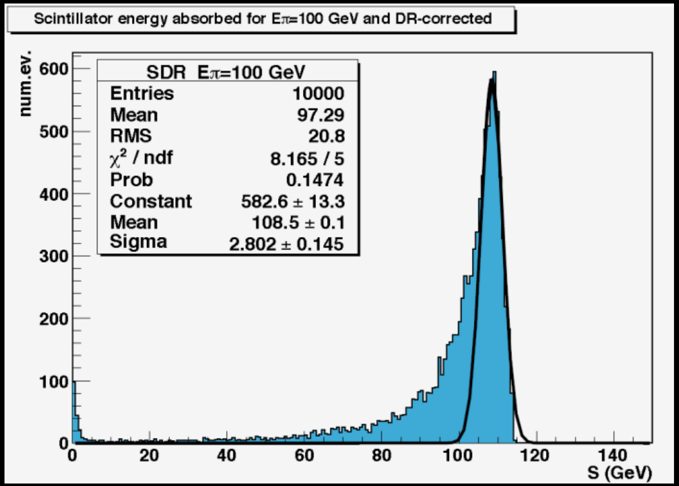
• gaussian response function, no long tails

• there are several obvious ways to improve the energy resolution. At least in the simulated calorimeter .

Leakage

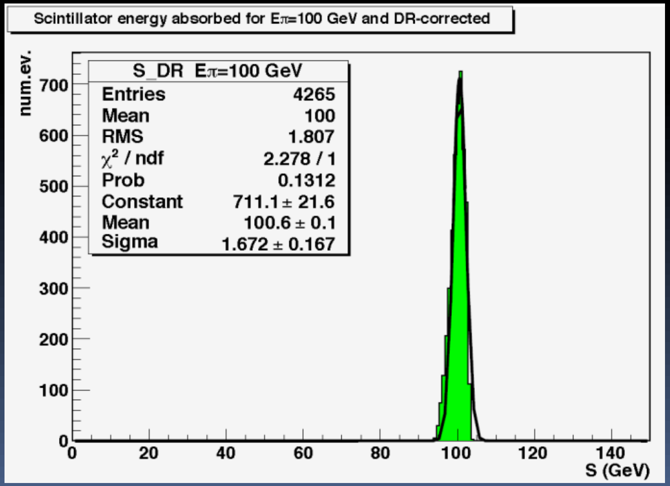
- A realistic detector design may provide some 120-150 cm of radial space for calorimeters . Leakage fluctuations may make the actual size of the stochastic term may be irrelevant
- To minimize the leakage fluctuations it is important to maximize the <u>average</u> density of the calorimeter, including the readout. This is of particular importance in high resolution calorimeters. It is highly desirable that the density is achieved with lowest possible Z materials
- 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^{o}.
  - [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

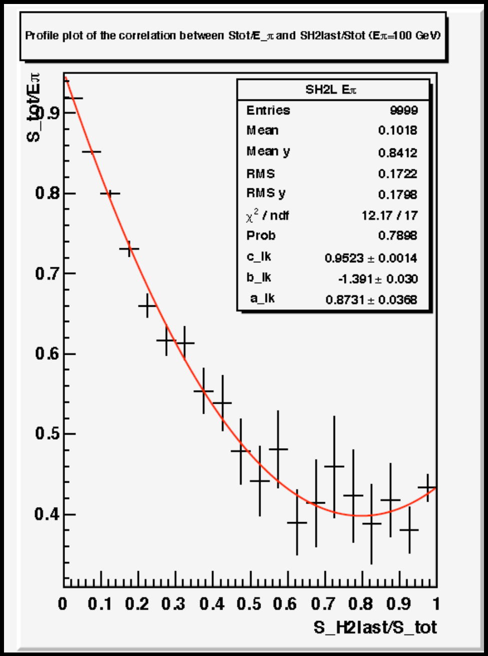


Corrected (or uncorrected) energy distribution shows major degradation of energy resolutions towards low energies and a peak of punch-through pions.
This is primarily caused by hadrons which interact deep inside the calorimeter, and see even smaller thickness of the detector.

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).

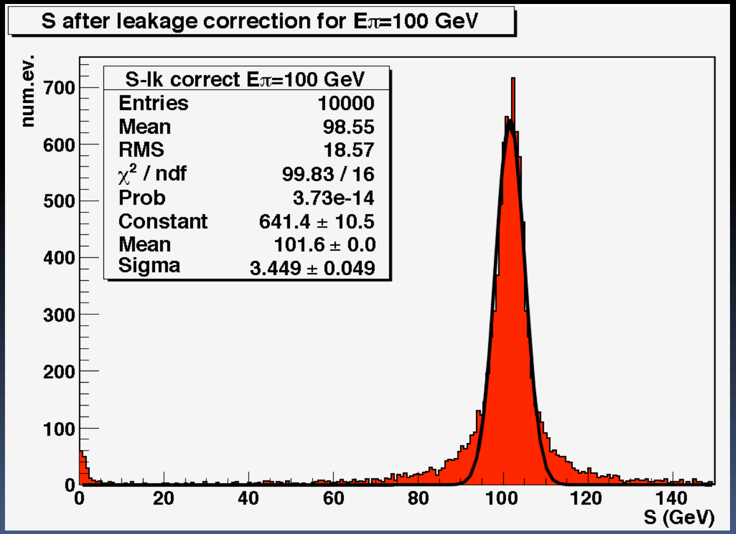


Correcting for Leakage?



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).



FAQ: Neutron (In)Sensitivity?

- A significant and fluctuating fraction of hadron shower energy is used up to liberate nucleons (mostly neutrons) from the target nuclei.
- Are inorganic scintillators 'sensitive' to neutrons?
- Total kinetic energy of the neutrons is a small fraction of the energy lost to overcome binding energy. It is a tiny fraction of the energy deposited in a calorimeter. The detection or not of the kinetic energy of neutrons does not significantly change the measured energy, in totally active calorimeter (as opposed to sampling calorimeters with very different response to neutrons and the showering particles – compensation)
- BTW.. What is the ultimate fate of these neutrons??? They will be re-captured ad they will re-emit the 'lost' energy in a form of nuclear EM cascades. A scintillation-only calorimeter with relatively short (microsecond) may be a very attractive possibility.

A Collection of 'Fun to Solve' Challenges (HEP physicists)

- Demonstrate separate detection of Cherenkov and scintillation light:
  - Done with phototubes, but for hadron calorimeter need a compact photodetector working in a strong magnetic field. APD? MPPC/SiPM? Novel, inexpensive MPC
  - Spectral matching of photodetectors
  - Getting the light out: photonic crystals? Light collectors?
  - Determine the light yield, collection uniformity, angular dependence
  - The bottom line: need to detect more than 200 photons/GeV from scintillation, more than 10 photons/Gev of Cherenkov. GeV! Not a typo!
- Invent a method of calibration of the scintillation and Cherenkov light collection channels
- Demonstrate the light yield, calibration in the test beam (small size prototype). Measure possible saturation effects.
- Demonstrate high resolution for hadrons with a test beam ptototype

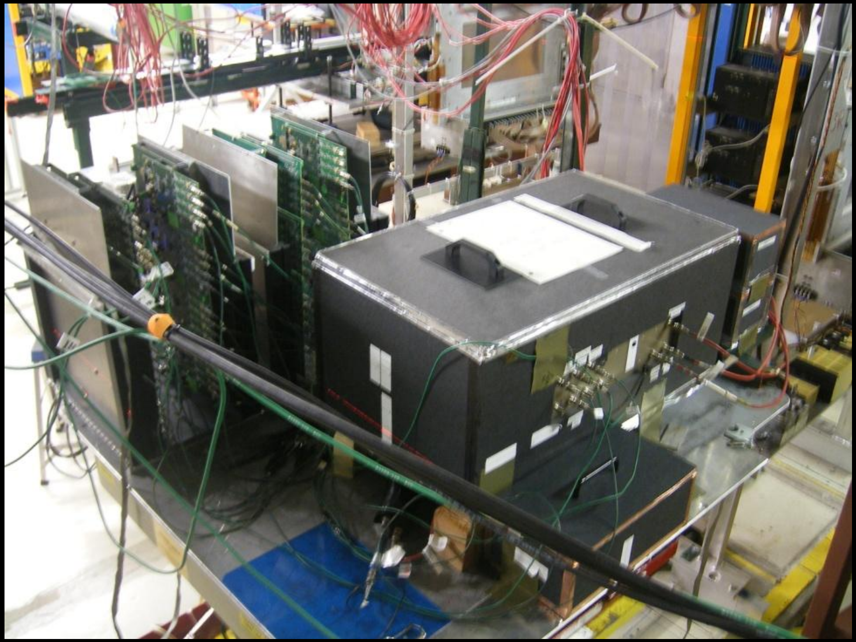
A "Real Challenge"

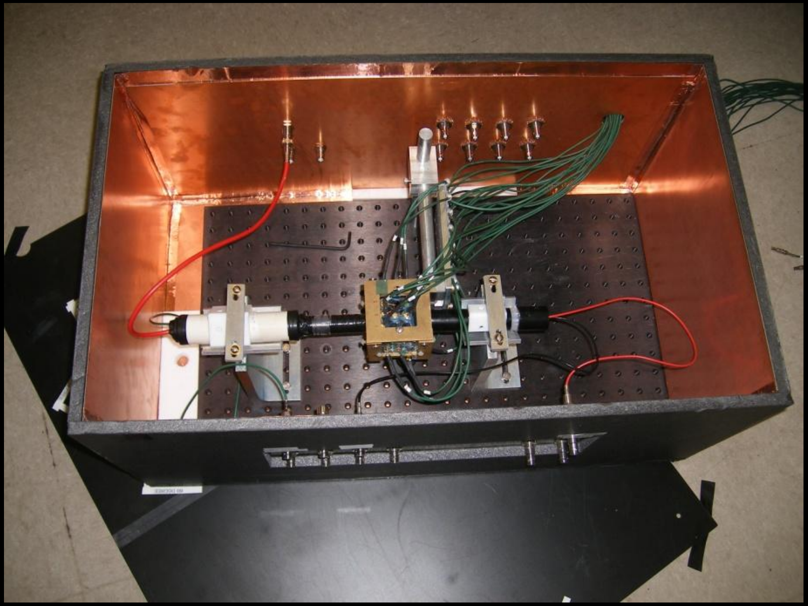
- All the previous problems can be addressed/solved with some of the existing crystals.
- A realistic detector for the future lepton collider is possible if new optical media (a.k.a. crystals) are developed
- The requirements:
  - Sintillation properties (decay time, spectrum) must allow separation of the scintillations and Cherenkov component. Very modest light yield: >200/GeV scintillation, >10/GeV Cherenkov detected. Combined requirement on crystals, photodetectors, geometry, system aspects.
  - Good transmission of the Cherenkov light
  - Inexpensive!! 50-100 m3 required ➔ cost (in large scale production) must not exceed ~2$/cc
  - Short interaction length 20-22 cm.
  - Mechanically stable
- NOT a requirement:
  - Speed of the response, absence of long components (1-10 μs fine, 1 ms too long)
  - Radiation resistance
  - Available immediately. 3-4 years will be fine, in time for the detector design

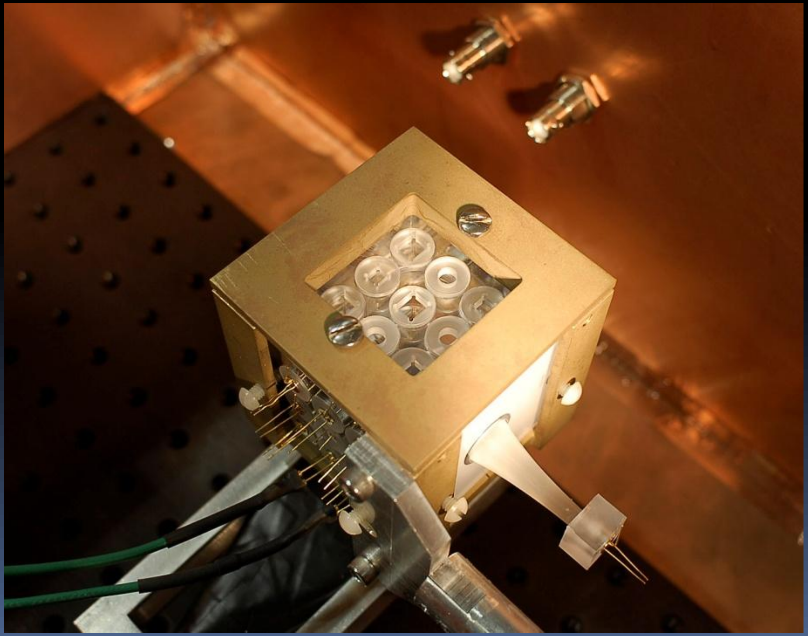
Testing Light Production and Collection in Test Beam

- One 5 x 5 x 5 cm3 BGO crystal. Provide information about scintillation and Cherenkov light yield as a function of the time, wavelength, position, photodetector type
  - All sides equipped with UV or visible filters.
  - Two sides viewed with PMTs (one through UV, one through vis filter)
  - Remaining four sides equipped wit 9 Hamamatsu SIPM each, located at different positions
  - 1 mm Hamamatsu MPPC;s with 25, 50 and 100 microns pixels

- Six BGO and six PbF2 crystals. All 5 cm length. 2 x 2 cm, 3 x 3 cm, 4 x 4 cm. 3 mm Hamamatsu MPPC's located in a center of the downstream face. Different wrapping (black paper/Tyvek), different surface finishes. To provide information about light collection for Cherenkov (PbF2), and scintillation as a function of crystal geometry and surface conditions



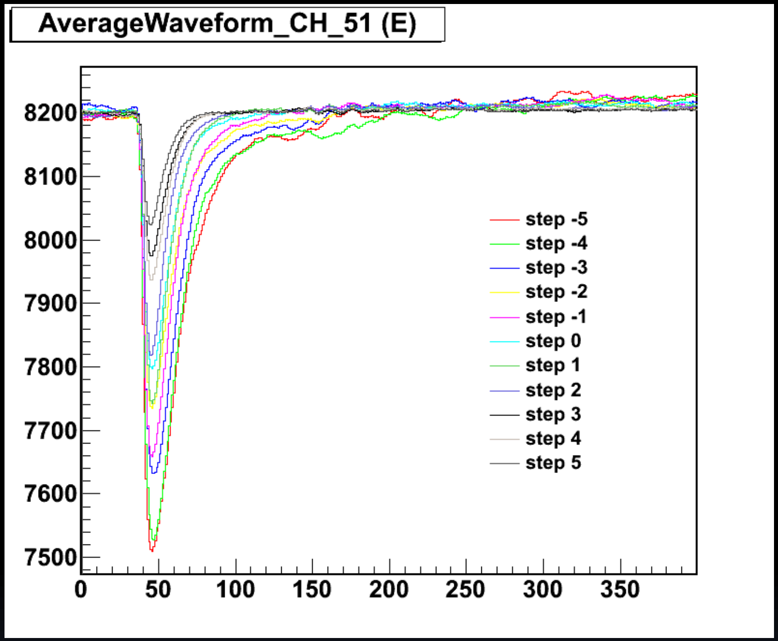




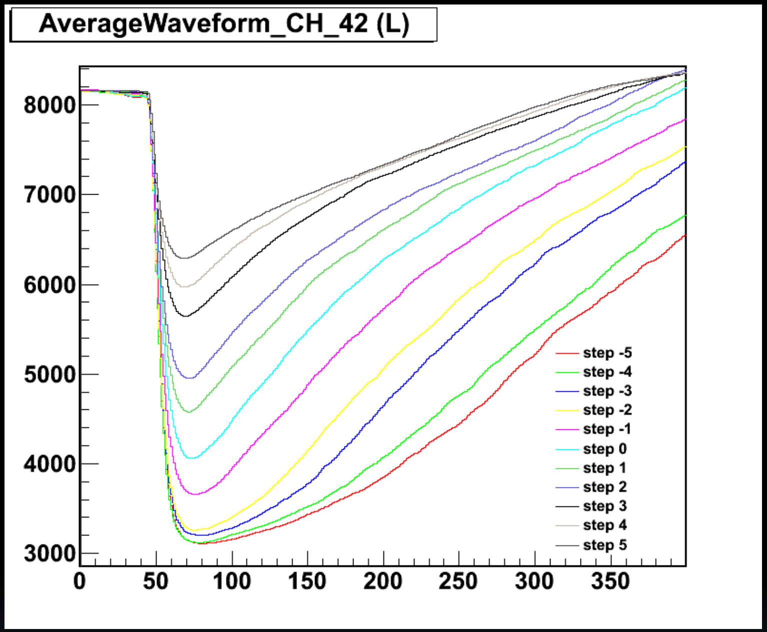
T1004 Test Beam Exposure (Fermilab)

- 120 Gev primary protons
- Run ended 80 hours ago
- Initial analysis by Burak Bilki (U. of Iowa)
- Will show only qualitative results, careful analysis necessary to draw quantitative conclusions

Cherenkov and Scintillation signals as a function of Bias Voltage

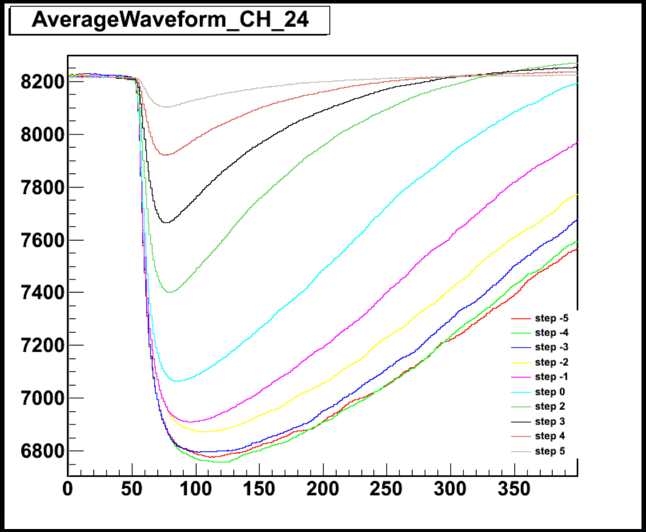


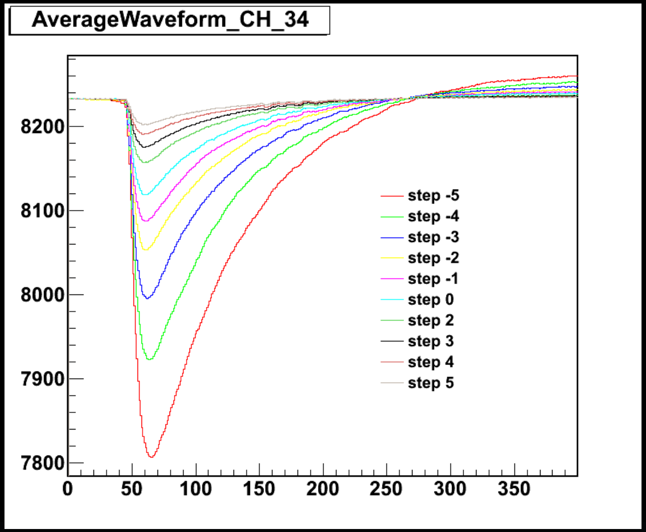
Average pulse from the PbF2 crystal (pure Cherenkov)



Average pulse from the BGO crystal (almost pure scintillation)

Dual Readout with SiPM (1 mm^2 detectors)





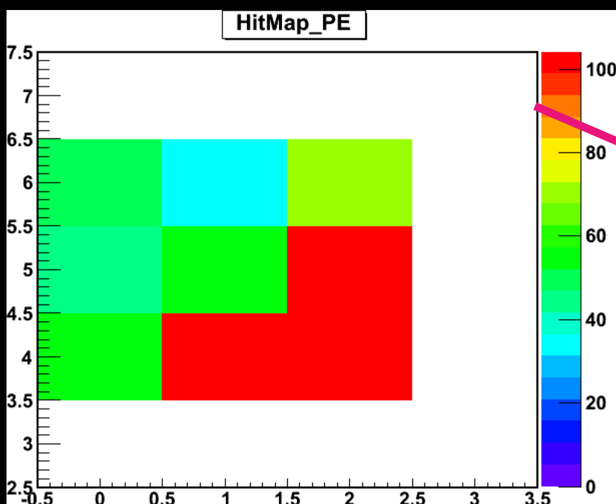
Signals from the same BGO crystal measured through a UV and Visible filter. Purity of the 'Cherenkov' signal needs to be studied.

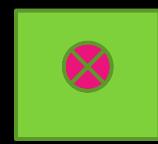
Single Crystals Signals

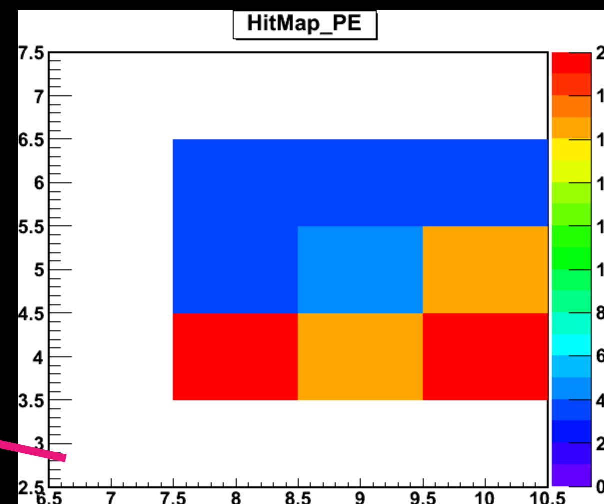
Visible filer

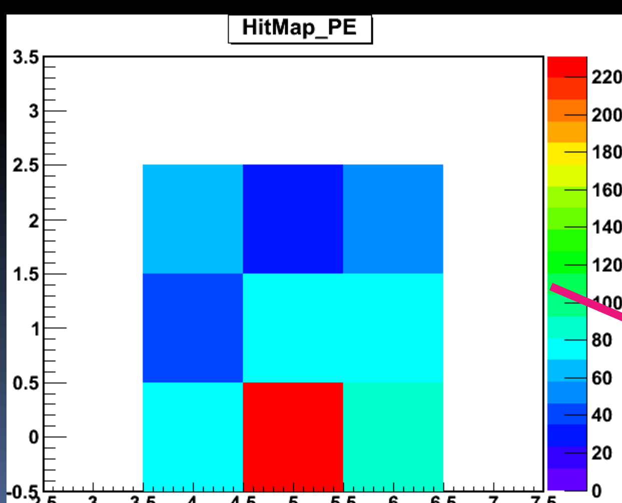
UV Filter

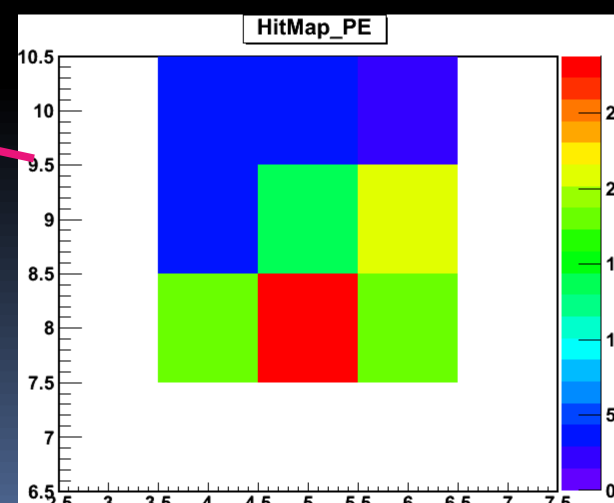
Numbers represent the average number of photons registered at a given location











Early Impressions from the Test Beam

- Cherenkov and Scintillation scignals observed with the SiPM's
- Filters do provide (at least some) separation of the two components
- A lot of data (positions, surfaces, optical couplings) to provide detailed tests of the simulation of light production and collection (both for Cherenkov and scintillation components)

HHCAL Workshops: Avenue to Initiate Development of New Materials

- Primary goal: develop better understanding of the issues, identify the principal problems, look for show-stoppers, intiate a brad R&D effort
- Broad based organizing committee with multidisciplinary representation
- First Workshop: Shanghai, February 2008
- Second Workshop: CALOR 2010, May 2010, Beijing
- Third Workshop: IEEE NSS Symposium, October 2010, Knoxville
- The future:
  - Companion workshops at IEEE NSS Symposia (October 2011 Valencia, Spain)
  - Dedicated sessions at various relevant conferences (SCINT-series, CALOR)
  - Ad-hoc topical workshops

Knoxville Workshop

- Prospects for High Resolution Hadron Calorimetry - Adam Para (Fermilab)
- Studies on Dual Readout Calorimetry with Meta-Crystals - Georgios Mavromanolakis (Conseil Europeen Recherche Nucl. (CERN))
- Degregation of resolution in a homogeneous dual readout hadronic calorimeter Don Groom (LBL)
- High-Throughput Synthesis and Measurement of Candidate Detector Materials for Homogeneous Hadronic Calorimeters - Steve Derenzo (LBL)
- Fluoride Glasses: State of Art and Prospects - Marcel Poulain (Rennes university)
- High Density Fluoride Glasses, Possible Candidates for Homogeneous Hadron Calorimetry - Ioan Dafinei (Dipartim.di Fisica G.Marconi RomeI)
- Prospects for Dense Glass Scintillators for Homogeneous Calorimeters -Peter Hobson (Detector Development Group)

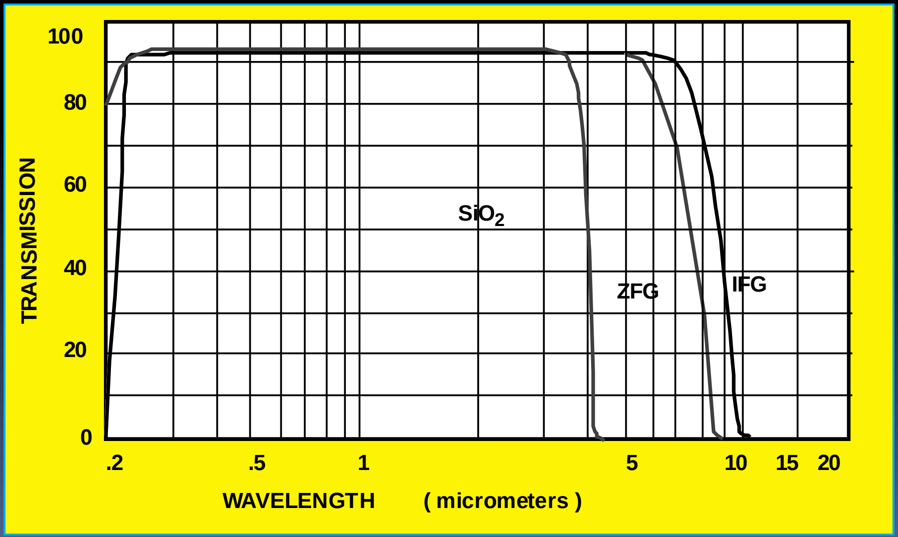
- Potential of Crystalline, Glass and Ceramic Scintillation Materials for Future Hadron Calorimetry - G Dosovitski (Moscow State University, Moscow)
- Study on Dense Scintillating Glasses -T Zhao (University of Washington)
- BSO-Based Crystal and Glass Scintillators for Homogeneous Hadronic Calorimeter -J. T. Zhao (Shanghai Institute of Ceramics, Shanghai, China)
- Development of RE-Doped Cubic PbF2 and PbClF Crystals for HHCAL G.H. Ren (R&D Center for crystals, Shanghai Institute of Ceramics, Shanghai, China)
- Transparent Ceramic Scintillators for Hadron Calorimetry - N Cherepy (Lawrence Livermore National Laboratory, Livermore, CA, USA
- The Development of Large-Area Flat-Panel Photodetectors with Correlated Space and Time Resolution - H. J. Frisch (1Enrico Fermi Institute,, University of Chicago

HHCAL Workshops: Impressions

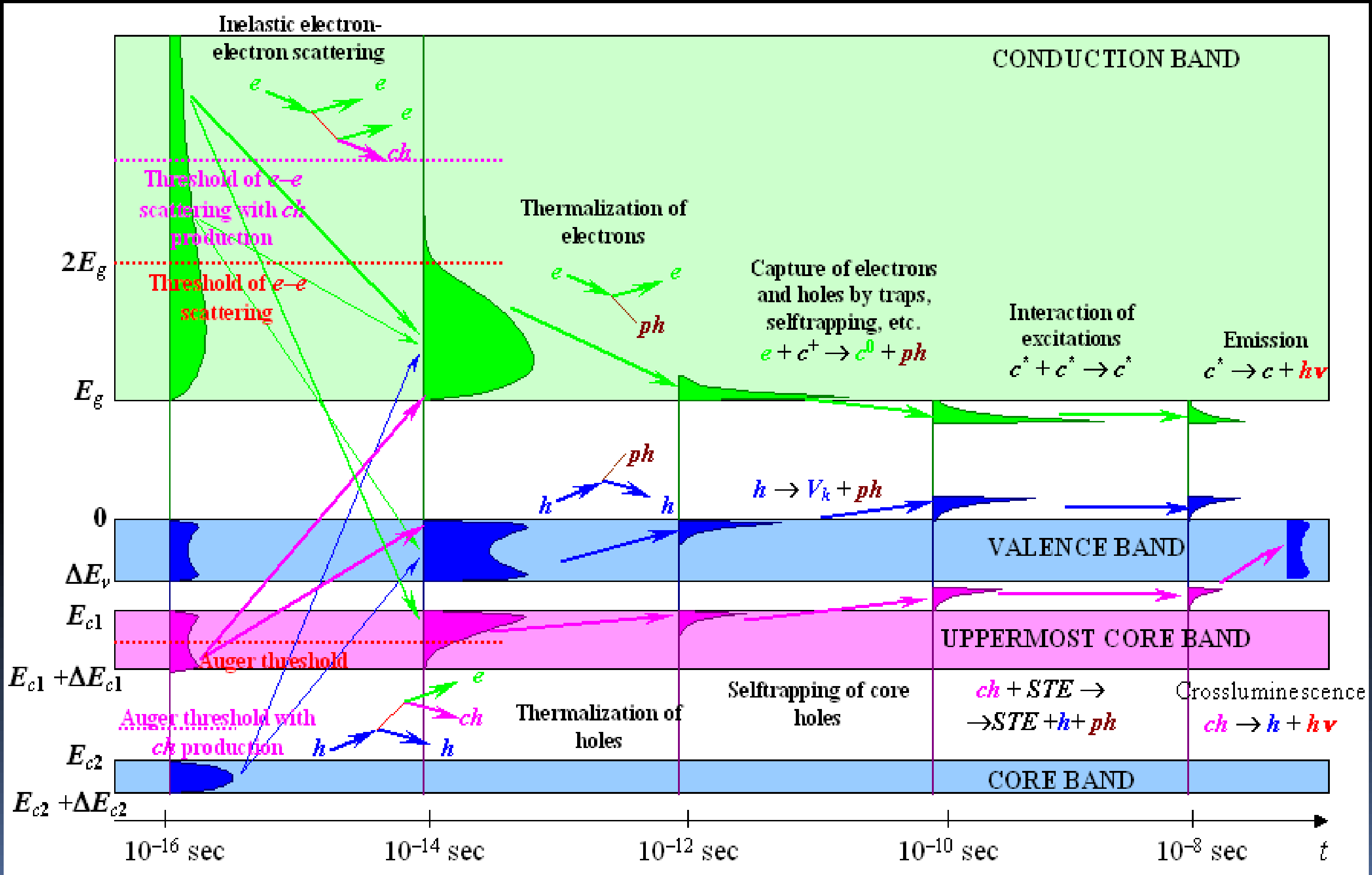
- Large body of experience with heavy glasses, crystals (legacy of SCC and early LHC work)
- Large body of interested parties
- Good understanding of underlying physics mechanisms and technical issues
- Prospects for inexpensive heavy optical materials quite real
- Photodetectors must be an integral part of the optimization







New Regime of Applications: New Insights?



New Insights?

- Bill Moses: By the standard of inorganic scintillators hadron calorimetry require non-scintillating scintillators..
- Alex Gektin: at the light yield required for hadron calorimetry even rock can be made to scintillate.
- Andrey Vasiliev: Every di-electric should produce light by intra-band radiative transitions . Such transitions correspond to energy differences ~1-2 eV, hence the produced light is somewhere in read. The light yield may be somewhere in the regime 10^{-4} – 10^{-5} of the traditional scintillation. Every Cherenkov radiator may be 'good enogh' scintillator for hadron calorimetry??

Summary

- Homogenous total absorption continues to be an attractive avenue for high precision hadron calorimetry
- Significant progress in the understanding of the underlying physics
- Experimental input/cross checks for the critical components of simulation is coming
- Dense scintillating materials offer an unique possibility for construction of very high energy resolution hadron calorimeters
- Development of new inexpensive crystals/glasses is of critical importance