Crystal Calorimetry with Dual Readout

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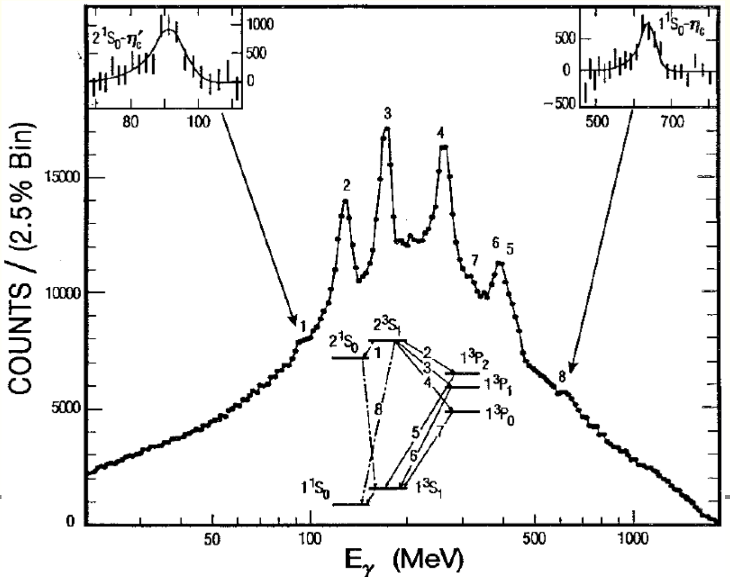
Hadron Calorimetry for the ILC

- What is the required energy resolution?
- What drives the requirement?
- What the requirement is really about?
  - Stochastic term
  - Constant term
  - High energy limit of the resolution
  - Single particle/jets
  - Line shape/non-gaussian tails
  - Jet reconstruction (in the magnetic field): energy-momentum four-vector. Energy, direction and mass
- Final judgment involves trade-offs with other aspects of the experiment and opinions may differ

Why is the Hadron Energy Resolution Important?

- Experiments at the ILC will try to elucidate the new physics hinted/discovered at the LHC
- It may be far more complicated and very different from what we think today
- Required machine energy may be higher than we think
- Resolution may be the key
- Spectrum of new particles may drive the requirements (separation of closely spaced states, for example)



A Quest for the High Resolution Calorimetry

- 'Experimental Physics' approach: try to construct the best affordable and realistic calorimeter within the constraints of the selected detector concept. It may depend on the concept!

Calorimetry 101 – part I

- Different types of calorimeters:
  - Total absorption: measure a signal proportional to the total energy deposition. Charge, Scintillation light
  - Sampling calorimeter: intersperse the active medium with the (heavy) absorber. Use the measured signal to 'represent' the energy deposited in the absorber (most of the energy to be measured)
  - Homogeneous (the entire volume has the same structure and materials)
  - Inhomogeneous (different materials, sampling frequencies, absorbers, active media)
- Resolution == fluctuations of the observed signals for the same incoming particle (and its energy)

Calorimetry: Total Absorption vs Sampling. A Puzzle

- Electromagnetic calorimeters:
  - Energy resolution: $\Delta E/E_{\text{total absorption}} \ll \Delta E/E_{\text{sampling}}$ (Sampling fluctuations dominate, $\Delta E/E \sim 10\text{-}15\%/\sqrt{E}$)
  - Energy resolution at high energies limited by non-uniformities ~0.5%
- Hadronic calorimeters:
  - Energy resolution: $\Delta E/E_{\text{total absorption}} > \Delta E/E_{\text{sampling}}$!!!
  - Energy resolution dominated by fluctuations of binding energy losses
  - $\Delta E/Ea_{\text{total absorption}} \sim 9\%$ (constant)
- *A puzzle*: how come that sampling calorimeters have better (usually) energy resolution? Solution: energy deposition by neutrons is treated 'incorrectly' and it (partly) compensates the binding energy losses. (Calorimetric version of Higgs mechanism)

Reasons For Not Building Total Absorption Hadron Calorimeters

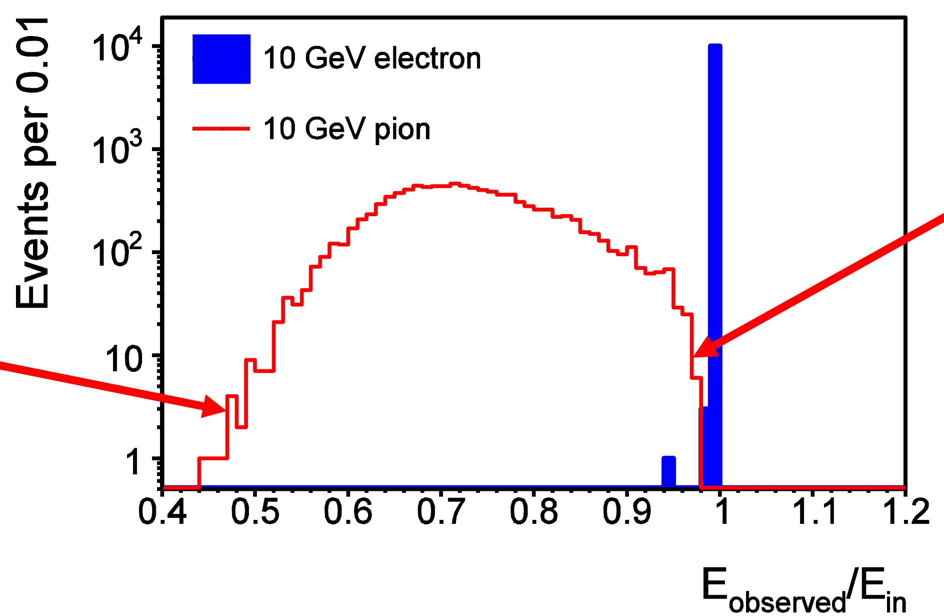
- Too big to be practical
- Hence too expensive
- Poor energy resolution
- Difficulty in light/signal collection/readout (especially in high magnetic field)

- These reasons are no longer valid thanks to a combination of technological breakthroughs (heavy scintillating crystals, silicon photodetectors) and progress in understanding of calorimetry (dual readout)

Total Absorption Calorimeter: A Primer

- 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
- Excellent energy resolution for electrons/photons
- Relatively poor energy resolution for hadrons (fluctuations constant with energy, $e/\pi > 1$)

Large number of broken nuclei ➔ large amount of missing energy
Small fraction of energy in form of π'^{o}



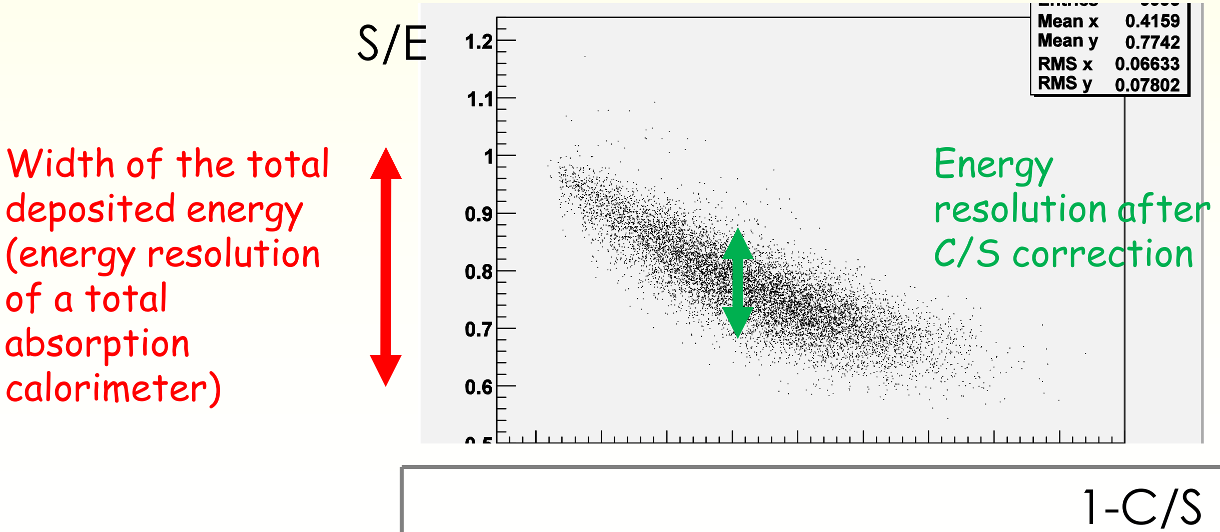
Small number of broken nuclei ➔ small amount of missing energy
Large fraction of energy in form of π'^{o}

Simulation of Total Absorption Calorimeter

- 'Infinite' uniform block of lead glass (used as a typical material composition and optical properties, like the refraction index n)
- Stand-alone GEANT4 (Hans Wenzel)
- Total ionization energy deposition summed up for all shower particles (S)
- Total Cherenkov photons energy summed up for all shower particles (C)
- Ignored:
  - scintillation mechanism, saturation, light propagation and correction
  - Cherenkov light absorption collection
  - Photodetectors

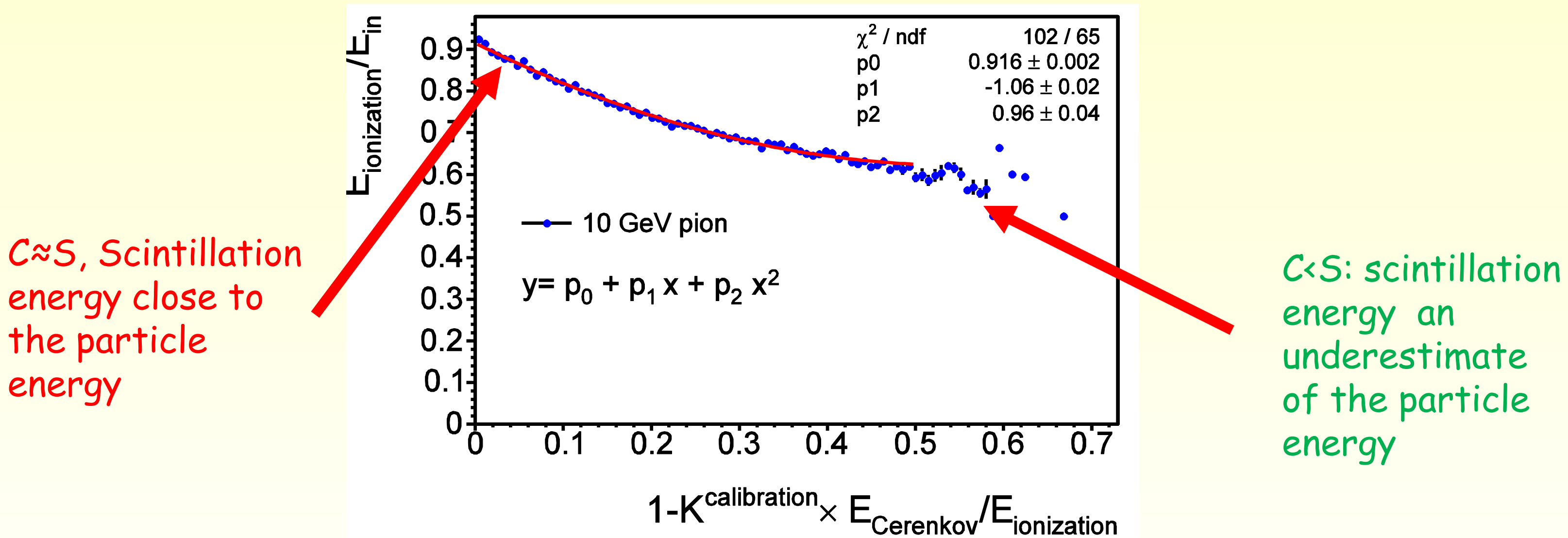
Ionization - Cherenkov (anti)Correlation

- Example: E=10 GeV pion showers in a very large block of a lead glass
- Let S = α*Ionization energy (assume that the scintillation is proportional to the total ionization energy deposition), α determined from electrons by requiring S = 10 GeV
- Let C = β*Cherenkov energy (β calibrated with electrons requiring C = 10 GeV)
- Dimensionless plot: fraction of missing energy as a function of C/S ratio
- Very little energy-dependent



Cherenkov/Scintillation Based Correction

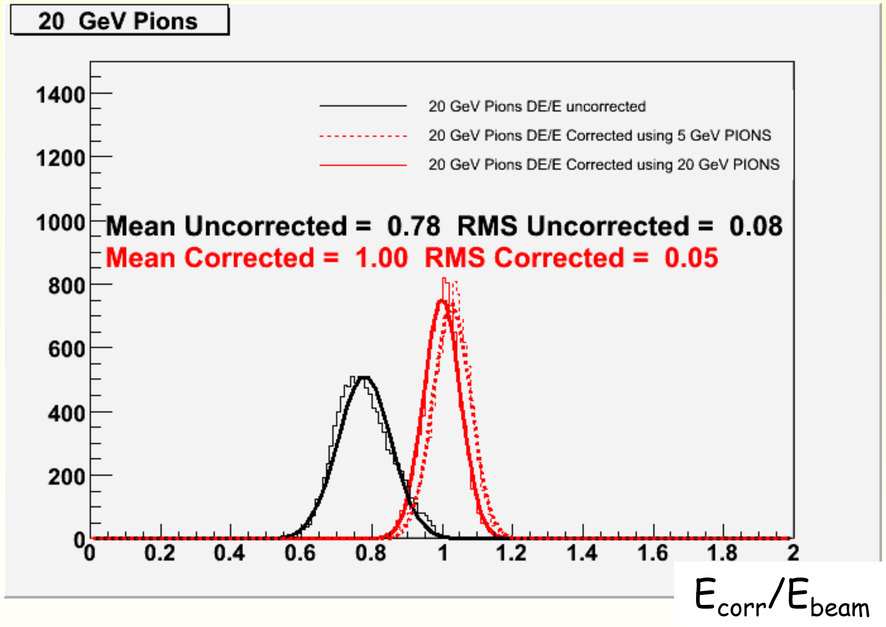
- Determine the Corr(C/S) by fitting the 'experimental' correlation.



- $E_{corr} = S/Corr(C/S)$
- Correction includes all contributions to missing energy (including Birks-like effects)
- Correction includes contribution of hadrons to Cherenkov light
- Correction function determined from the experiment: simulation independent (eventually)

Cherenkov-assisted Calorimetry at Work: Single Particle Response

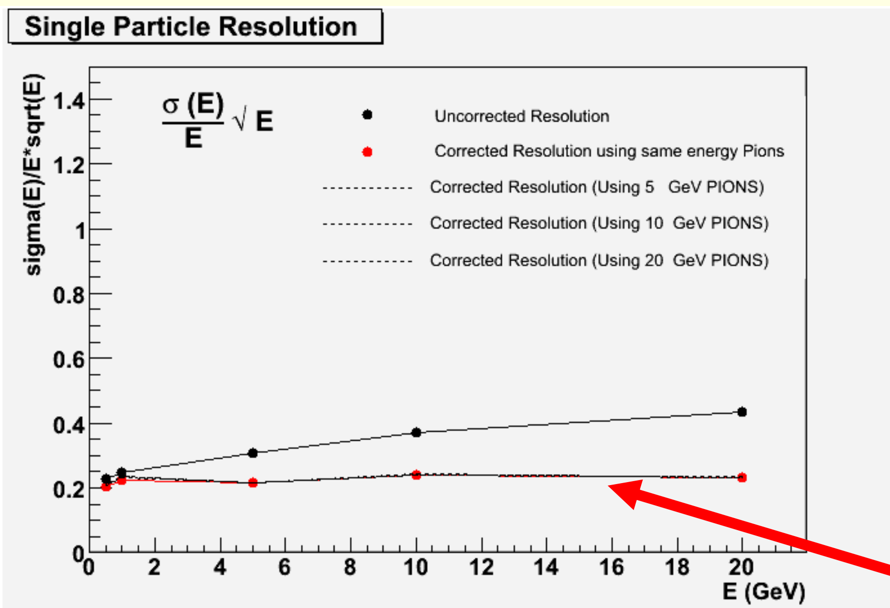
- Use the $E_{Cherenkov}/E_{ionization}$ ratio to 'correct' the energy measurement



- Corrected pion shower energy = pion energy ("e/π"=1)
- Linearity of response with the particle energy
- Gaussian response function (better than the uncorrected response)
- Correction function (almost) independent of the actual shower energy

Cherenkov-assisted Calorimetry at Work: Single Particle Energy Resolution

- Use the $E_{Cherenkov}/E_{ionization}$ ratio to 'correct' the energy measurement
- Use RMS of the corrected energy distribution (complete sample) as a measure of the resolution



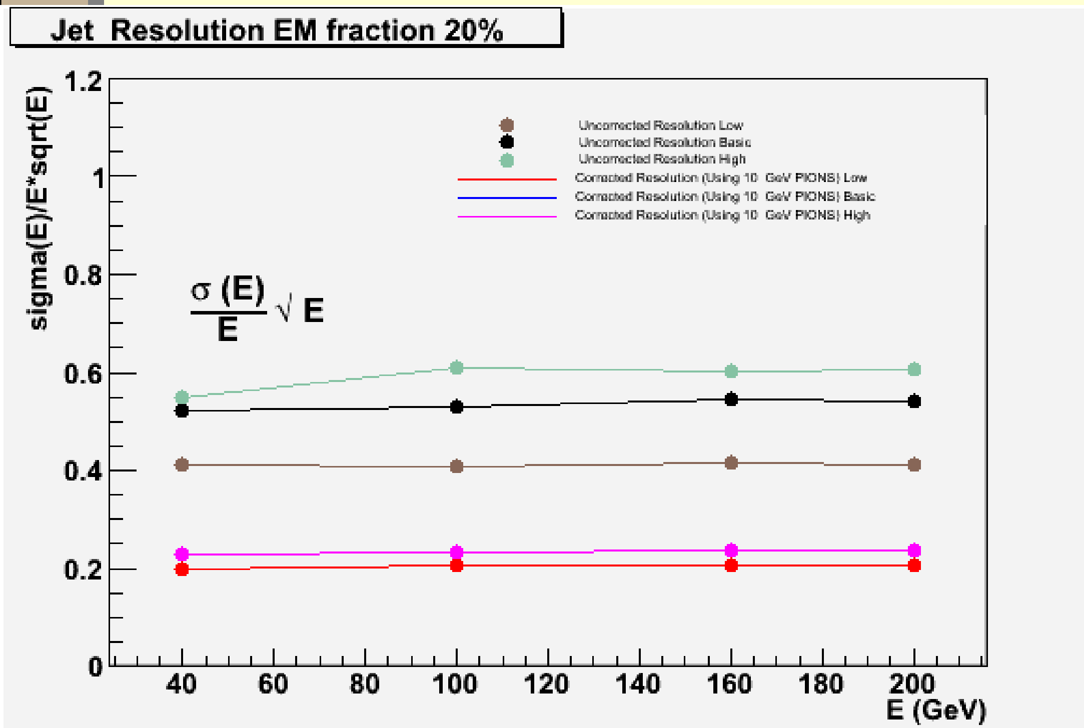
- Single charged hadron energy resolution $\Delta E/E=0.25/\sqrt{E}$
- Scales with energy like $1/\sqrt{E}$ (no 'constant term'), in contrast with the resolution of the uncorrected total absorption calorimeter
- Resolution independent of the energy at which the correction is determined

Three curves corresponding to three 'different' corrections

From Single Particles to Jets

- For now: Jet == a collection of particles with varying composition (particles type and spectrum)
- An experimental challenge (traditional calorimetry):
  - Measured jet energy and the resolution depends on the fragmentation function (fraction of π^0's and the spectrum/multiplicity of jet particles, dN/dz)
- Jet simulation: collection of single particles:
  - 'high' case : all particles 20 GeV
  - 'basic' case: 52% of 1 GeV, 21% of 5 GeV, 17% of 10 GeV, 10% of 20 GeV particles
  - 'low' case: all particles 5 GeV
  - Average fraction of π^0's = 0, 20% (with fluctuations)
- Global correction for the entire jet, based on summed ionization/Cherenkov energies of all particles
- Correction function derived for 10 GeV single particles used for the whole jet

Jet Energy Resolution: Fragmentation (In)Dependence

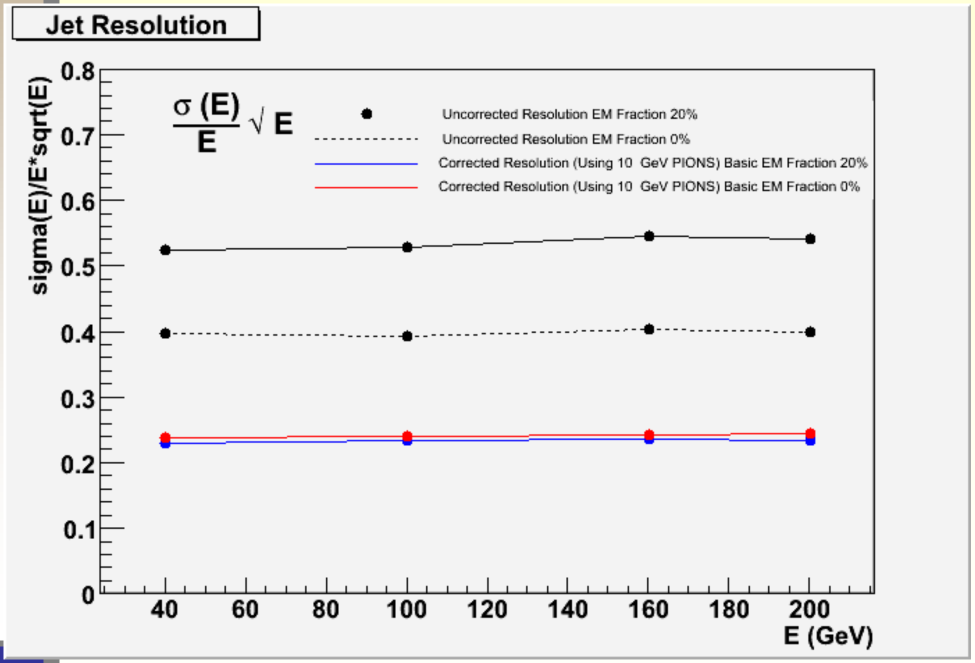


- Resolution of Cherenkov-corrected energy measurement is nearly independent of the jet fragmentation

- Resolution (and the response) of the uncorrected energy measurement dependent on the jet fragmentation

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

Jet Energy Resolution: Contribution of the Fluctuating EM Component



Fluctuations of the electromagnetic component of the jet:

Dominate (double!) the jet energy resolution in the uncorrected case

- Do not contribute to the jet energy resolution for Cherenkov-corrected measurement
- In fact the presence of the EM jet component slightly improves the jet energy resolution

Summary of the Simulation Studies

- It appears that the Cherenkov-derived correction to the observed scintillation signal is very robust and very powerful, even with very simple correction/analysis procedure
- It appears that linear response, with the gaussian lineshape and the energy resolution $\Delta E/E < 0.25/\sqrt{E}$ can be achieved for single particles and for collections of particles, independent of the composition of the collection.
- The correction principle can be easily understood in terms of relatively elementary physics arguments
- Limiting factors for the energy resolution of a dual readout calorimeter
  - Contribution of scintillation photon statistics
  - Cherenkov photon statistics
  - Efficiency and purity of separation of scintillation and Cherenkov light
  - Variation of ionization-to-light conversion (Birks law)
  - Response non-uniformities
  - Intercalibration

Possible Implementations of Dual Readout Calorimetry

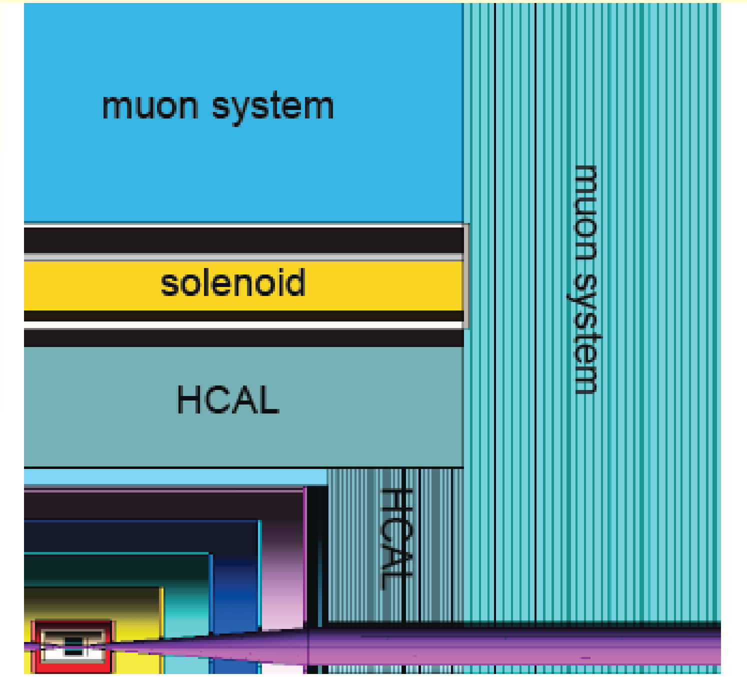
- Dual readout from a single homogeneous total absorption calorimeter (may be subdivided into voxels, if so desired)
- Planar sampling calorimeter with separate scintillation/Cherenkov readout
- Sampling calorimeter with scintillating/Cherenkov of fiber readout (DREAM)
- DREAM-like hadron calorimeter with crystal-like dual readout EM section
- The homogeneous dual readout option is the simplest conceptually, it is the easiest to understand and it probably offers the best resolution by eliminating the sampling fluctuations and the complications related to the particle and position dependence of the sampling fractions.

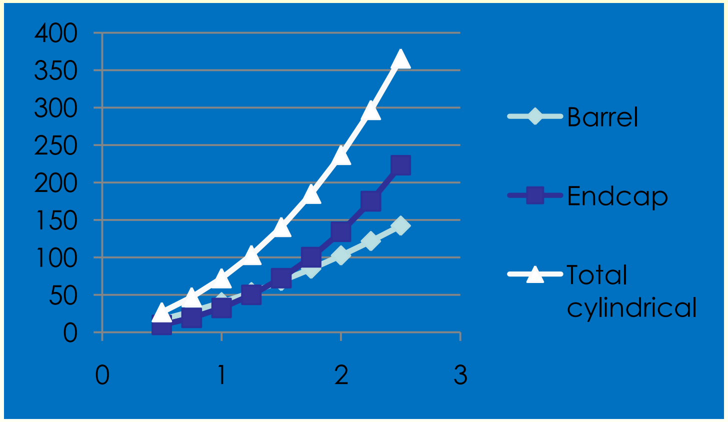
‘Crystals’

- Need dense medium which scintillates and is transparent to Cherenkov light. Scintillation light properties (wavelength, timing) must be such as to allow clean separation of the two light component. Will refer to this medium as ‘crystal’.
- Density realized with the lowest possible *A* materials to minimize the interaction length λ and the Moliere radius. $\lambda < 20$ cm desired
- Crystal must have adequate mechanical properties (Young’s modulus, Poisson ratio), it must be machine-able and easy to use/maintain (not hygroscopic, for example)
- Crystal must have the transmission edge at as low as possible wavelength (== desired gap between the valence and conduction bands > 5 eV or so)
- Must be affordable, when produced in kiloton-scale quantities. \$1/cc is a sensible target
- Must demonstrate experimentally the scintillation/Cherenkov light separation

Crystal Calorimetry for SiD? Take 1

- Fill the volume between the tracker and the coil with dual readout crystals. Rin = 1.27 m, Z = 1.8 m



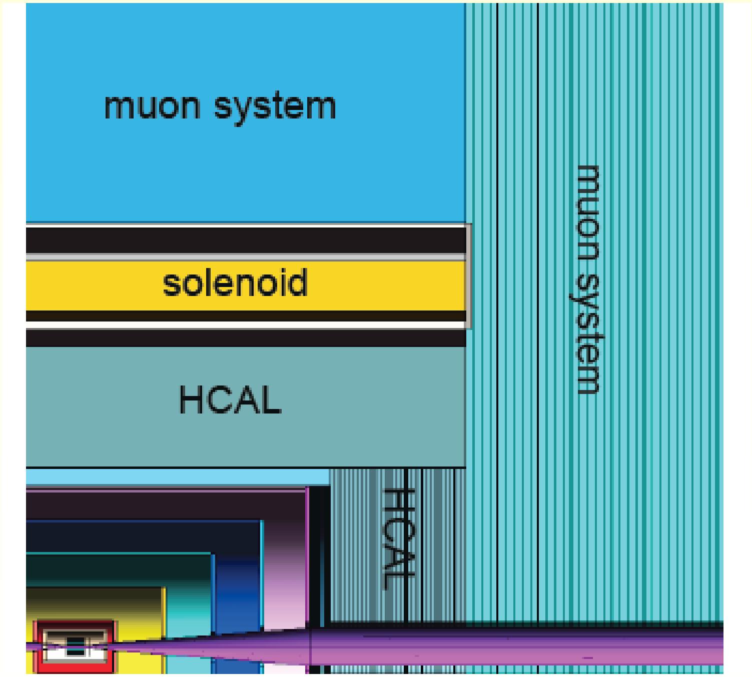


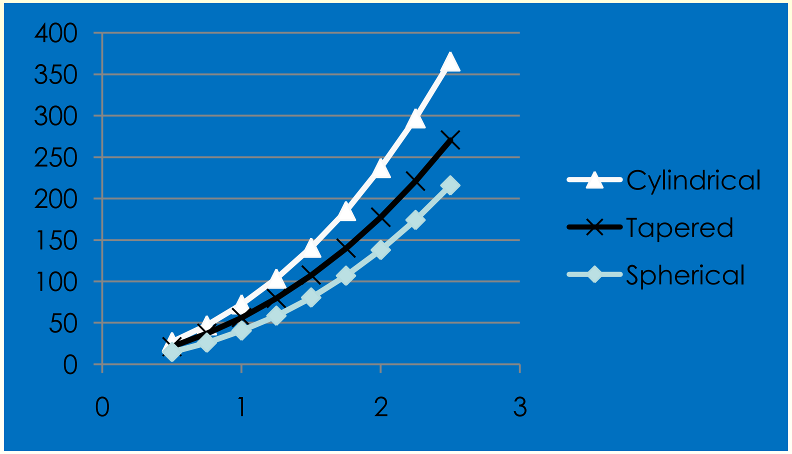
Total volume of a calorimeter as a function of its thickness

For a typical thickness of a calorimeter ~1.2 m one needs ~100 m^3 of crystals. 'Calibration' point: CMS ECAL total volume ~ 11 m^3.

Crystal Calorimetry for SiD? Take 2

- Fill the volume between the tracker and the coil with dual readout crystals? Calorimeter thickness will vary by a factor of 1.5 as a function of polar angle. Keep the thickness the same! Keep 6 λ.





Total volume of a tapered calorimeter as a function of its thickness

Total volume of 1.2 m thick tapered calorimeter ~ 75 m^3.
(Just an observation: for a spherical detector it would be 'only' 50 m^3.)

Pre-Conceptual Design: Calorimeter Segmentation

- For the energy measurement no segmentation is required. But it is allowed, as long as the separate volumes are properly inter-calibrated to provide the correct sum of the signals.
- Transverse and longitudinal segmentation will be necessary for a number of reasons:
  - Practical (construction, crystal availability and cost)
  - Physics requirements: particles (muons?) tracking through the calorimeter volume, photon identification, photon direction measurement, two/multiparticle spatial resolution
  - Light collection and readout
- The real detector design will require several iterations to identify and understand all trade-offs involved

Hadron vs EM calorimetry

- They are traditionally separate/different detectors.
- Differences in their response to hadrons usually precludes very good hadron energy resolution. This will be of particular concern when very high hadron resolution is to be achieved.
- Need to meet all the specifications of the ILC EM calorimeter at (the acceptable level) with the crystal calorimetry. Note: single depth EM crystal, CMS-like design, not likely to provide the desired two-particle resolution.
- Possible solution:
  - De-couple energy resolution function from the spatial measurement
  - longitudinal segmentation of the front section of the calorimeter
  - 2-3 layers of silicon pixel detectors (possibly with the pixel size better than the proposed SiW calorimeters) to provide very detailed spatial information

SiD Calorimeter Segmentation

- Version 1.00
- Four layers of 5 x 5 x 5 cm^3 crystals with three embedded silicon pixel layers (a.k.a. EM section): 72,000 crystals
- 10 layers of 10 x 10 x 10 cm^3 crystals (a.k.a. hadronic section): 66,000 crystals
- Reality check, sort of, CMS ECAL 80,000 crystals
- It is important to keep the channel count to a sensible minimum. Cross-calibration and monitoring will be a primary challenge
- A relatively small size of the SiD detector is an enabling factor here.
- Projective or cylindrical geometry? Needs careful optimization of performance vs engineering issues. (Cylindrical geometry avoids any projective cracks!)

Light Collection and Readout

- The enabling technology: silicon photomultipliers.
  - 4(8) photodetectors per crystal. The desired number of photodetectors depends on trade offs between the light collection efficiency and uniformity, detector reliability and cost
  - No visible dead space.
  - Signal routing avoiding projective cracks
  - Should not affect the energy resolution
  - 500,000(1,000,000) photodetectors
  - Note: CMS has 124,000 photodetectors (2 per crystal)
- Detector design philosophy: build in enough redundancy to avoid/minimize the need for repairs.

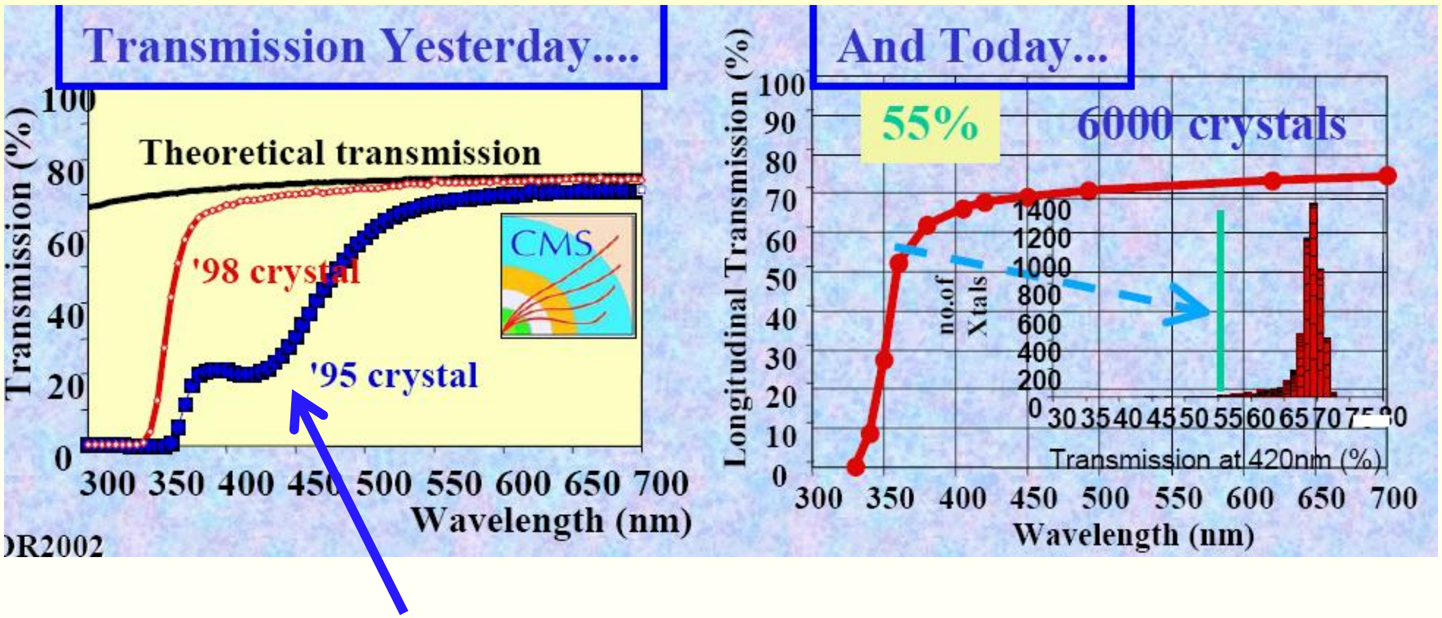
Comment on Light Yield: Scintillation

- Silicon photodetectors have tiny sizes. If we use them to collect light from a large volume (say 10x10x10 cm^3) – will there be a sufficient amount of light to maintain good energy resolution??
- Take the 'impossibly bad case': 1 mm^2 detector, light emitted isotropically, no light reflection/trapping in the volume → one detector sees 1/60,000 of light (1/15000 in the EM section)
- To maintain good (by hadronic standards) energy resolution one needs to detect more than 25 photons per GeV. Taking 25% as a realistic PDE we need 100 photons per GeV hitting the detector.
- The scintillator brightness requirements is, therefore,: $Y>6 \times 10^6$ photons per GeV, or 6,000 photons per MeV (with extraordinarily pessimistic assumptions)
- Reality check: PbW04 - 100 (fast), much more for doped crystals, CdWO4 –19,700, ZnWO4 – 22,000
- The scintillation light yield/collection not likely to be an issue. Uniformity of light collection is another matter, though.

Cherenkov Light Yield

- Observable light yield depends strongly on the short wavelength transmission of the material. Need large gap material.
- Primary light yield lower by a factor 50-100 than scintillation ➔ need much better light collection
- Crystal approach maximizes the light production, need additional factors in light collection:
  - Waveshifter fiber for light collection
  - Focusing mirror + lenses to collect light
  - Larger area of photodetectors

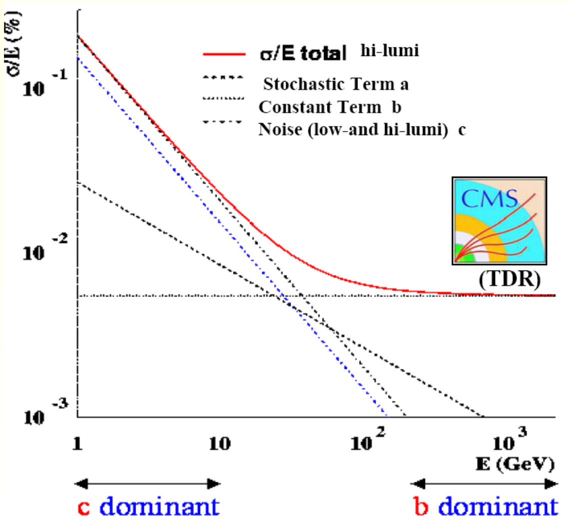
CMS Lead Tungstate: a Success Story

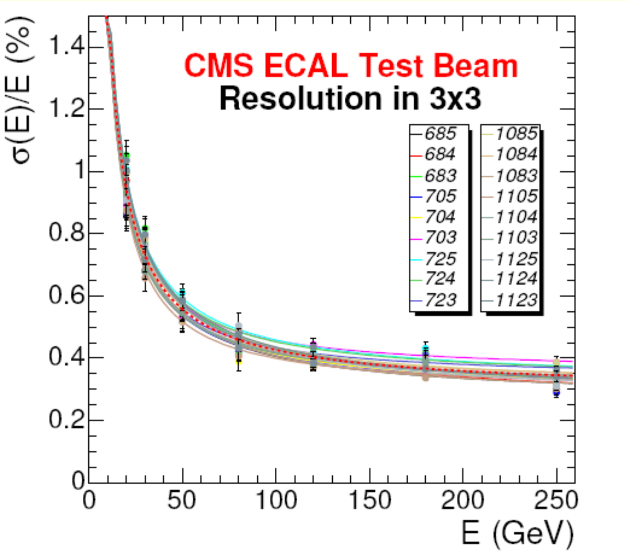


Impurities +
crystal imperfections

High Resolution: Limiting Factors

- Sobering lessons from high resolution crystal EM calorimeters: the stochastic term is not really important. The real life detector resolution is limited by noise and/or detector non-uniformities (constant term)
- Encouraging lesson: with enough care and attention the constant term can be kept below 0.4% even for very large systems, like CMS





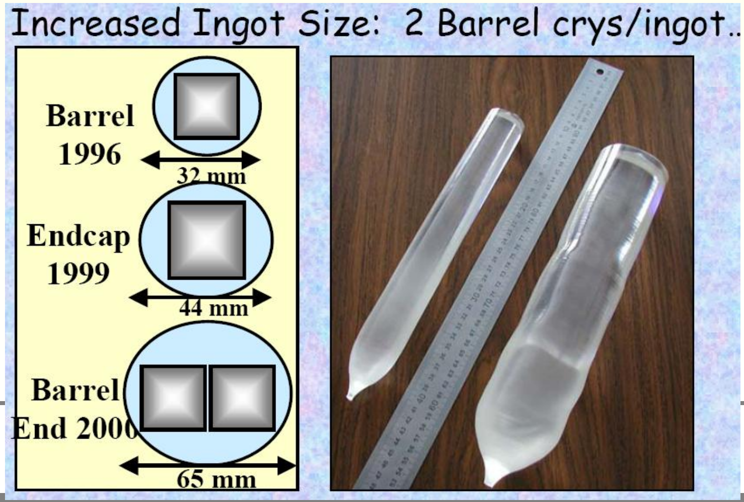
Crystal Hadron Calorimetry vs EM Crystal Calorimetry

- It was a major concerted effort to keep the constant term below 0.5% (crystal quality control, light collection, hermetic design, calibration and monitoring)
- But the goals were very ambitious: target energy resolution well below 1%!
- Why the hadron calorimetry should be significantly easier??:
  - Expectations are much lower. An ultimate resolution of the order of 1% would be terrific
  - Many problems are intrinsically much easier:
    - The signals are produced in much more distributed fashion. In the EM calorimetry case the signal sources are very compact, hence the uniformity is critical.
      - the uniformity requirement ought to be quite relaxed
      - The local hermeticity (mechanical tolerances) much relaxed
- Why hadron calorimetry can be more challenging?
  - Overall size a factor 5-10 larger
  - Hadronic shower containment/leakage

Path To the 'Right Crystal'?

- Do not try out re-invent the wheel
- Do not constrain ourselves to the current shopping list. It was produced to meet different specifications
- Engage (large) crystal-making industry. Make them understand our requirements and let them figure out what the best crystals could be
- Understand implications of various technological constraints and optimize the detector design accordingly (size? Shape? Uniformity?)
- Cost likely the primary concern

Example:
•Ingots are produced as cyliners
•Hexagonal cells can improve efficiency of crystal production
•Shorter crystals (less taper) can improve efficiency



Can we Afford the Crystal Solution?

- An excellent question. Can't answer not knowing the target crystal.
- Cost of crystal is driven by:
  - Cost of (high purity) raw materials (for some crystals, like BGO)
  - Energy costs (melting temperature a key characteristics)
  - Crucible material wear
  - Yield (QC, geometry)
- Given the required volume (~70 m^3) a good target price: <$1/cc
- Note: so far concentrated on single large crystals. From the calorimetry point of view a transparent (at short wavelength) scintillating material is required:
  - Novel materials (crystal fibers? P. Lecoq/CERN)
  - Scintillating glasses?

Possible Plan for the Near Future

- Identify and produce crystals optimized for dual readout (crystal industry)
- Develop a procedure for separation of Cherenkov and scintillation light. Demonstrate the separation in a test beam.
- Identify the requirements for the light collection efficiency and uniformity
- Study light collection and readout methods (wrappping, surface treatment, mirrors, lenses)
- Construct an EM-size test beam prototype with silicon pixel layers to evaluate the performance of the separated functions (energy – topological information) EM calorimeter
- (Eventually) construct the full size crystal hadron calorimeter and evaluate the energy resolution of the dual readout technique

Summary

- Progress in technology makes a dual readout total absorption hadron calorimeter feasible and affordable.
- Dual readout calorimeter offers a prospect for high resolution, gaussian response measurement of jet energy. The energy resolution of the order of 20%/√E and a constant term below 1% appears feasible.
- This is the only technique, so far, offering a chance for good energy resolution for high energy jets.