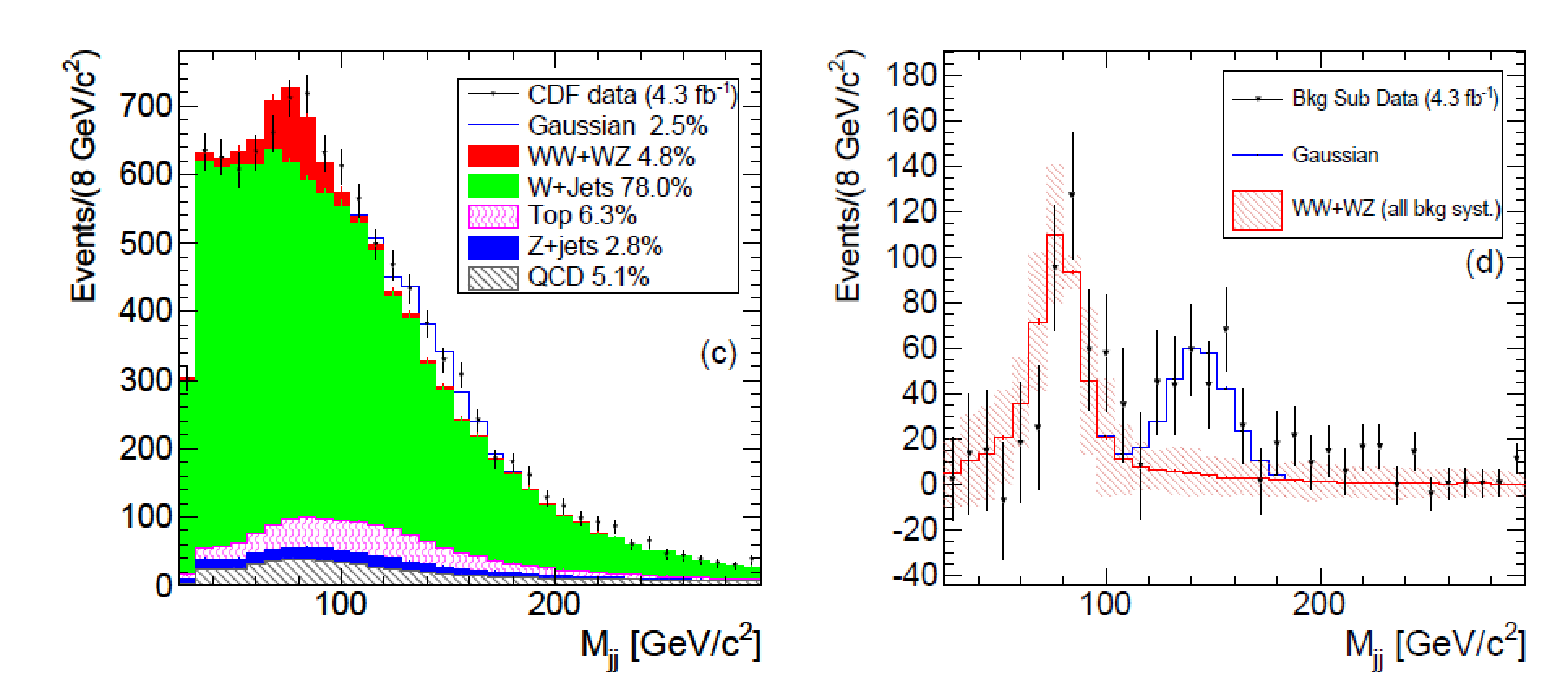
Fermilab Detector R&D Retreat
May 5, 2011
Adam Para, Fermilab

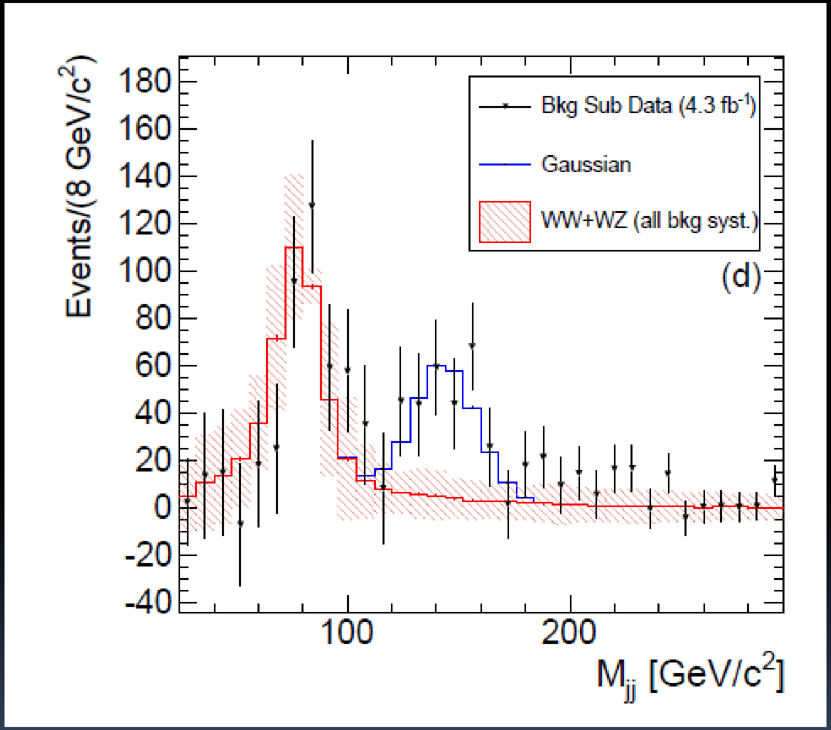
PROSPECTS FOR HIGH RESOLUTION HADRON CALORIMETRY

PART1: WHO CARES?

Imagine a Possible Outcome of an Experiment



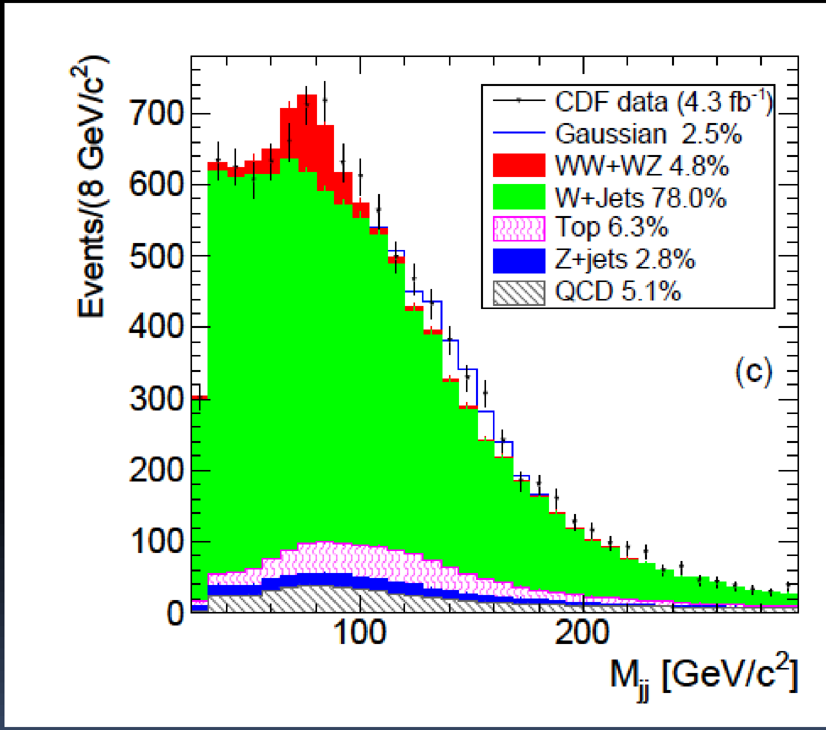
Jet Calorimetry: on the Importance of Resolution



If you had ΔM/M ~ 2-3%:

- WW vs WZ: more physics
- W vs Z convincing demonstration of the calibration and other systematics
- perhaps this other peak would be very narrow??

Jet Calorimetry: on the Importance of Linearity and Equal Response to All Particles (Democracy?)



A mysterious bump appears around ~160 GeV. It is on a falling edge, but above, the of W+jets background.

If you shift the background by one bin the effect is gone.

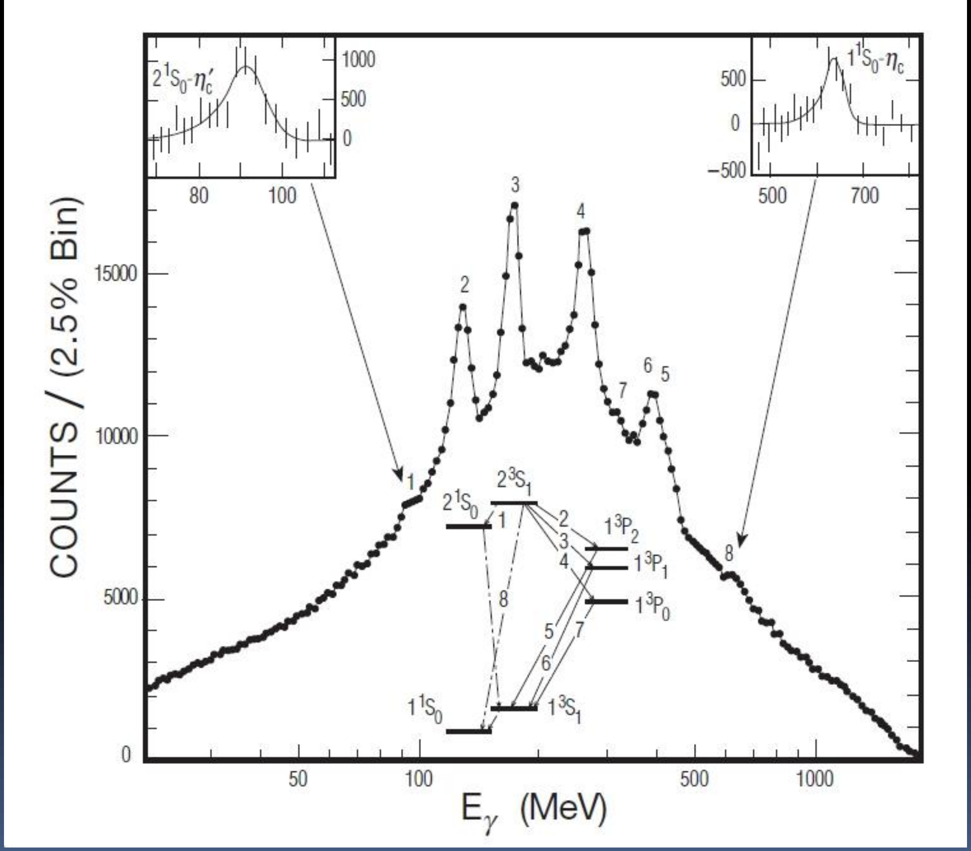
How well did you model jets fragmentation functions?

How do you know the correct fraction of quark vs gluon jets in your background?

…..

If your calorimeter was linear and had the same response to all particles such questions would not be even raised..

Historical Perspective: Calorimetry can be a Powerful Tool for Particles Spectroscopy



- 35 years ago two narrow states J/Ψ(3100) and Ψ'(3700) discovered. What were they???
- Radiative decays/Photon spectroscopy the key: these are the radial excitation of the ccbar states
- Excellent energy resolution of NaI crystals an enabling technology.
- <u>Note:</u> One particle Ψ'(3700) and precisely measured inclusive photon spectrum sufficient to uncover several intermediate states and prove their physics interpretation

Lessons

- When studying new phenomena an excellent resolution of a detector may be the critical enabling factor.
- It is difficult/impossible to know a priori how important the resolution will be (L3!)
- If you find out that you need a better resolution it is usually too late

PART 2: HIGH RESOLUTION HADRON CALORIMETRY

The case for new inorganic scintillators

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 $(\Delta E/E)\sim 50\%/\sqrt{E}$ for single particles, 70%-100%/ $\sqrt{E}$ for jets. What's wrong with hadrons???
- 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)
- 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.

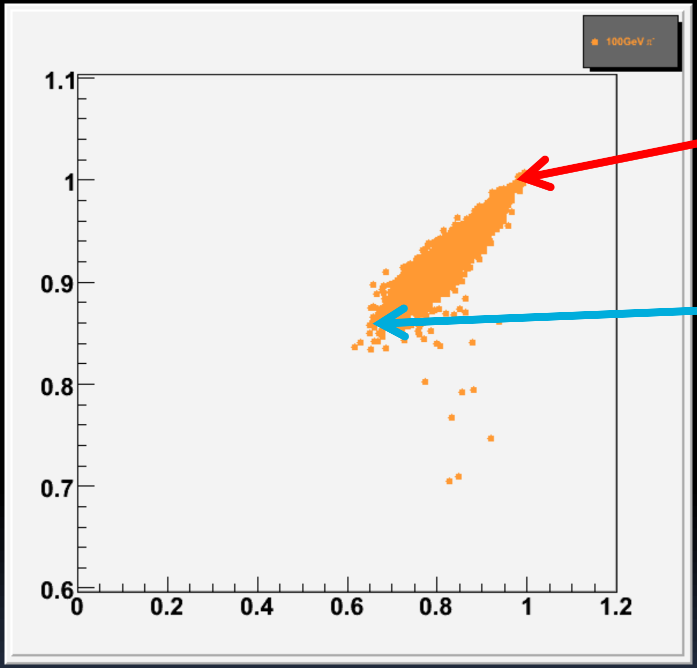
Key: Technological Advances

- 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 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 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



π^o-rich showers: almost all energy detected

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

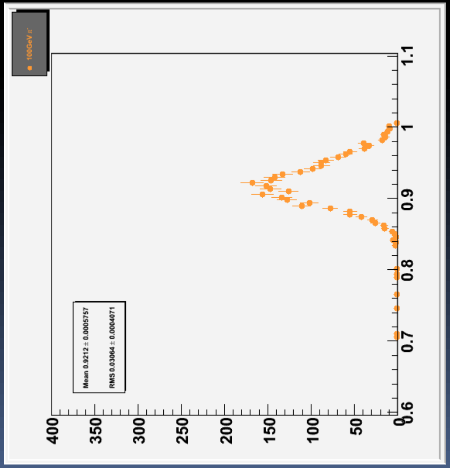
- Use C/S to correct every shower
- The resulting resolution limited by the local width of the scatter plot

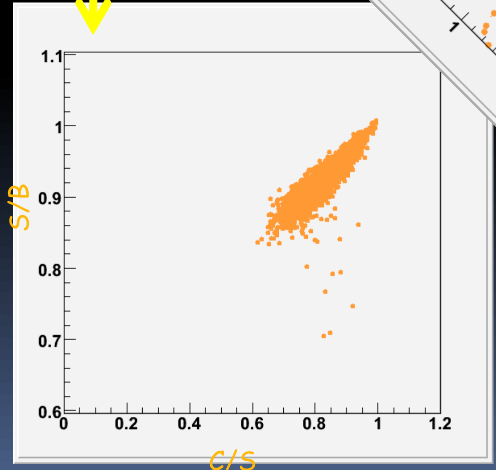
TAHCAL at Work: Single Particle Measurement

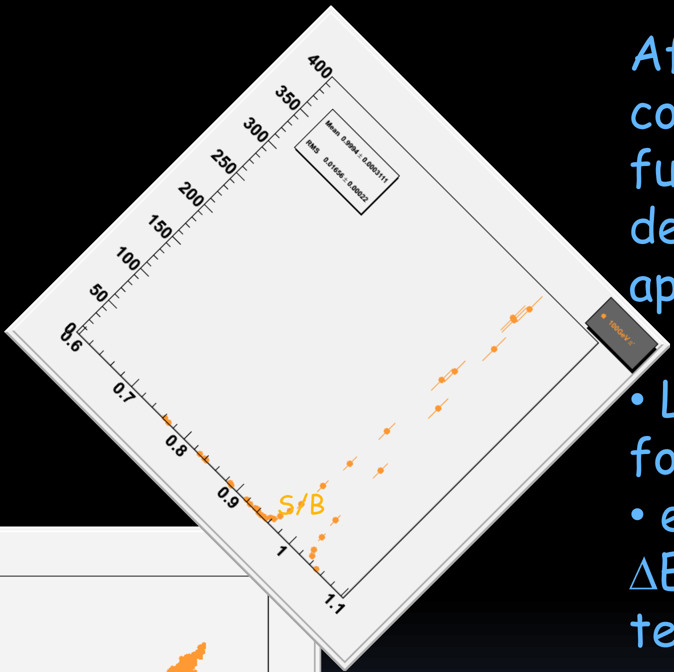
- 100 GeV π-
- Full Geant4 simulation

- Raw (uncorrected) ΔE/E ~ 3.3%

- but significant non-linearity, E~ 92 GeV



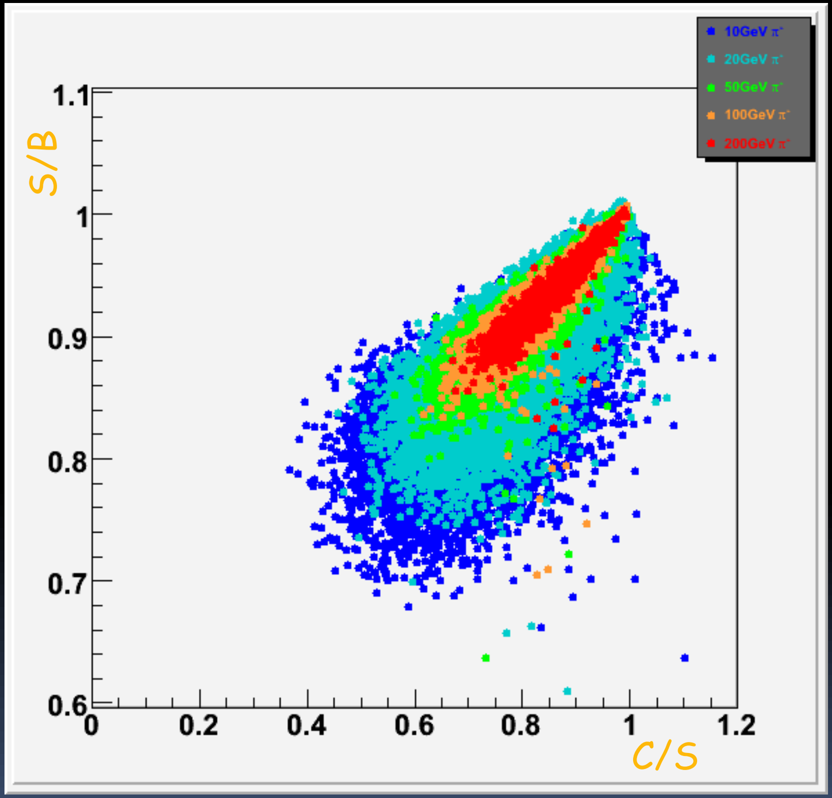




After dual readout correction, correction function (C/S) determined at the appropriate energy:

- Linear response: S/B=1 for all energies
- energy resolution ΔE/E~α/√E (no constant term)
- α~12-15% or ΔE/E=1.2-1.5% at 100 GeV

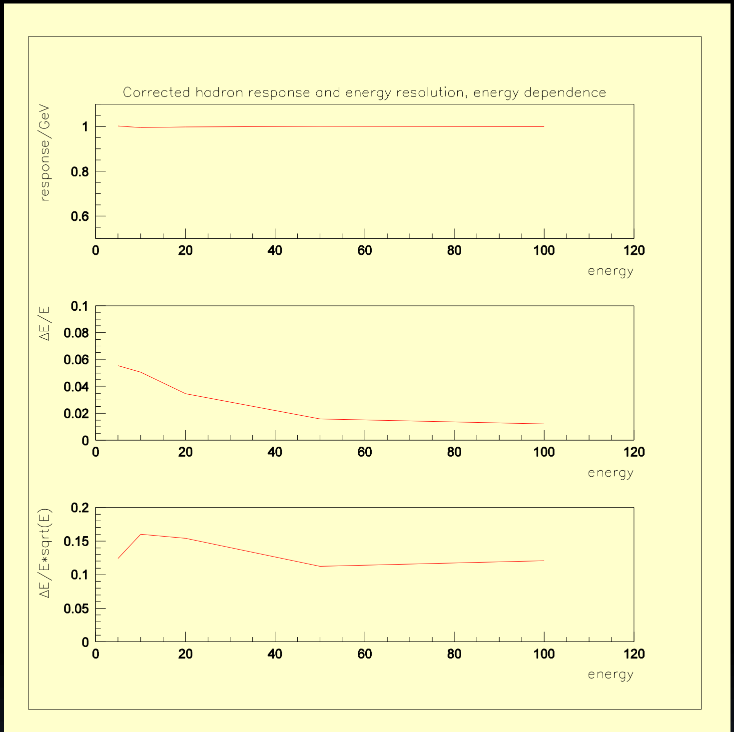
Dual Readout Correction at Different Energies

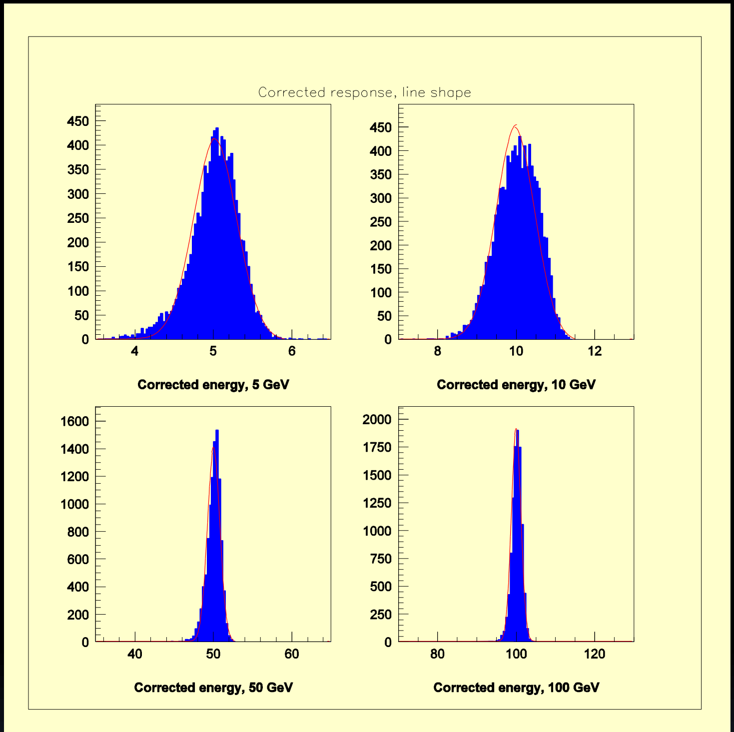


Correlation of the fraction of 'missing energy' and Cherenkov-to-scintillation ratio for showers of different energies: 10 – 200 GeV:

- high energy showers contain more EM energy (range of C/S confined to higher and higher values)
- overall shape quite similar, but significant differences present. They will lead to:
  - non-optimal energy resolution
  - non-linearity of the response
  - the latter will produce contribution to jet energy resolution

Response and Resolution, Corrected





After dual readout correction:
- good linearity of the corrected response
- good energy resolution ~ $0.12/\sqrt{E}$
- no sign of a constant term up to 100 GeV
- Gaussian response function

PART3: CAN THIS BE TRUE? IS THIS A PRACTICAL PROPOSITION FOR A HEP EXPERIMENT?

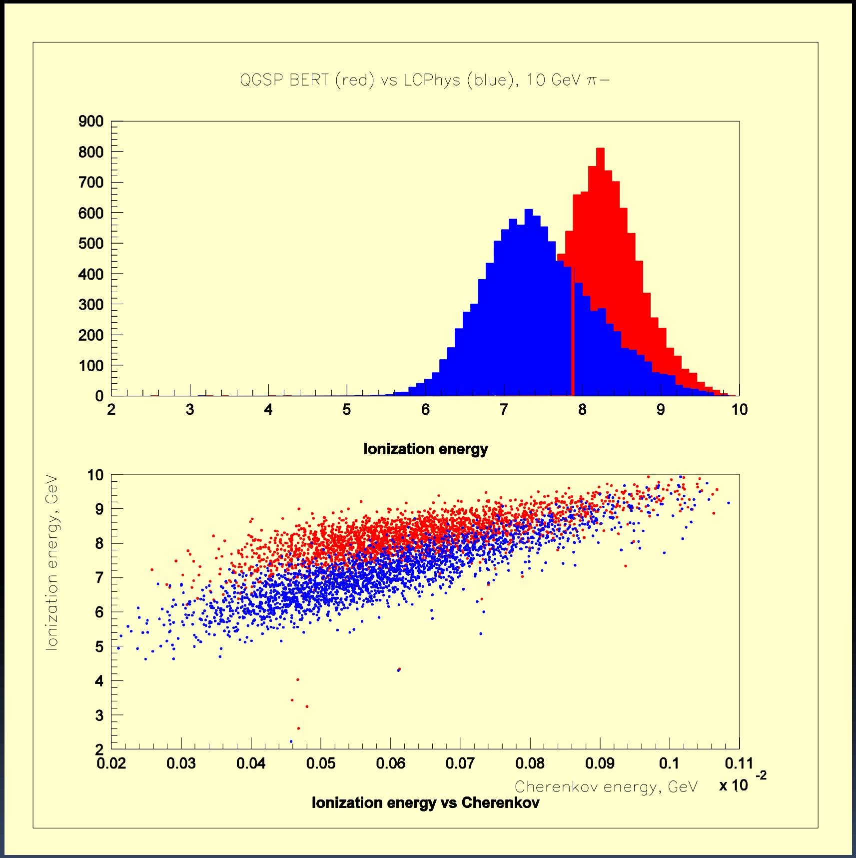
An Incomplete Collection of Challenges

- Understanding of physics principles and limitations to the energy resolution
- (in?)Adequacy of modeling of a development of hadron showers
- Modeling of light propagation and collection
- Getting the light out: photonic crystals? Light collectors?
- Collection of light in a hermetic detector
- Collection of Cherenkov light. Compact potodetectors. Spectral matching.
- Fluctuation of Cherenkov light due to the collection inefficiency
- Understanding of the role of neutrons

An Incomplete Collection of Challenges II

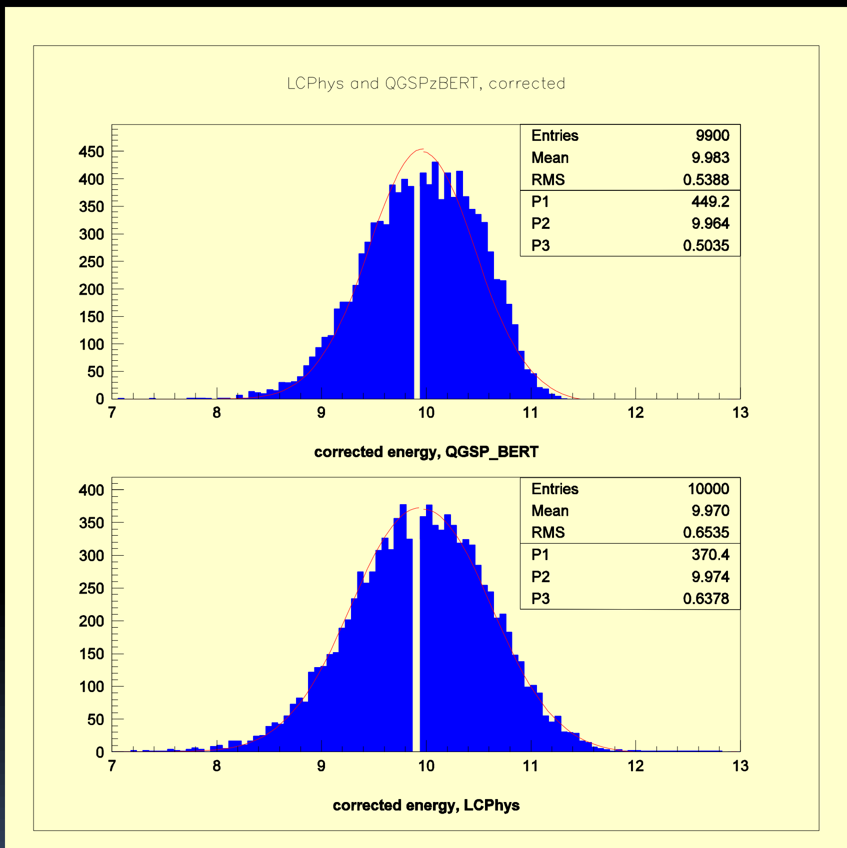
- Calibration scheme for segmented calorimeter (especially for Cherenkov readout)
- Separation of Cherenkov and scintillation light. Contribution to the energy resolution/linearity due to possible imperfection of light separation
- Potential non-linearity of response to non-relatiivistic particles
- Optimization of a realistic detector design

Can one Trust 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

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%
- 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??

PART4: DESPERATE NEED FOR NOVEL MATERIALS

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

Road to the New Crystals? Ignorant Physicist's Naïve Vision

- Review the existing data. Search the rejects of the searches for heavy, bright, fast radiation resistant scintillators.
- Systematic search for new heavy scintillating crystals with cheap raw materials and low melting temperature
- Try to find a way to make lead fluorite scintillate (without loosing the transparency for Cherenkov)
- Explore heavy scintillating ceramics (do not need much light)
- Explore new meta-materials. Scintillating nanomolecules for doping lead fluorite? Glasses?
- Heavy scintillating glasses?
- The HHCAL series of workshops

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

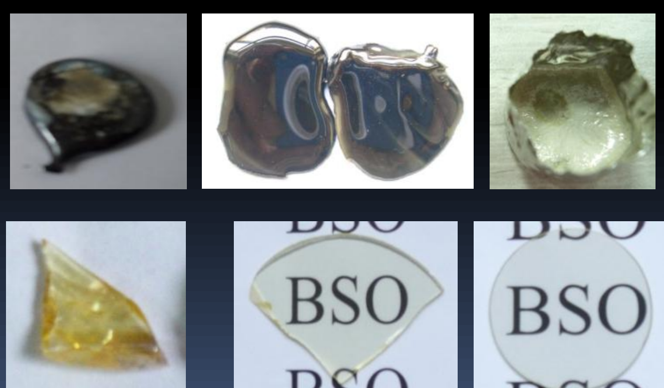
Knoxville Workshop

- 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 Insights?

- Bill Moses:

  By the standard of inorganic scintillators hadron calorimetry require non-scintillating scintillators..

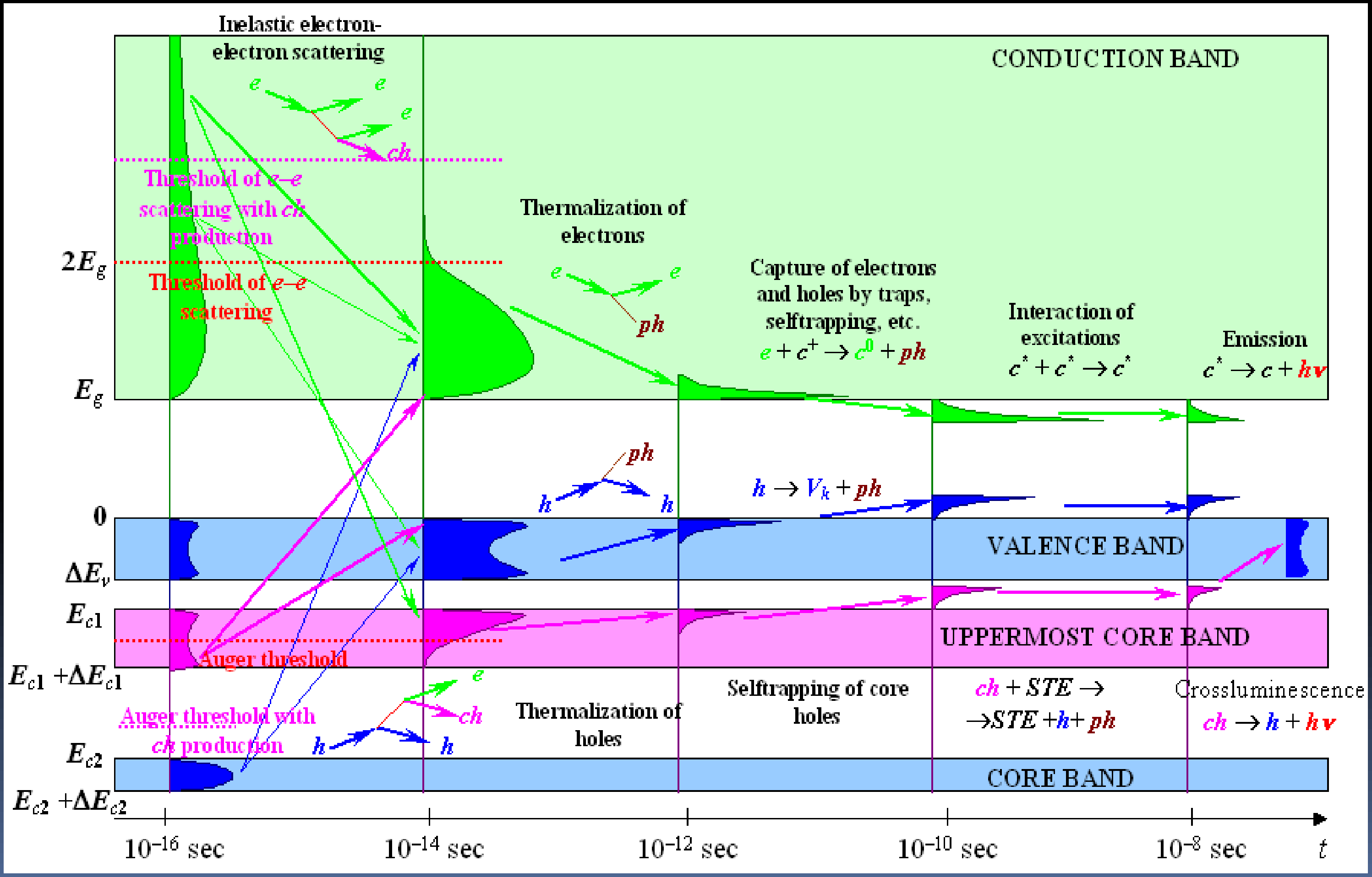
- Alex Gektin:

  at the light yield required for hadron calorimetry even rock can be made to scintillate.

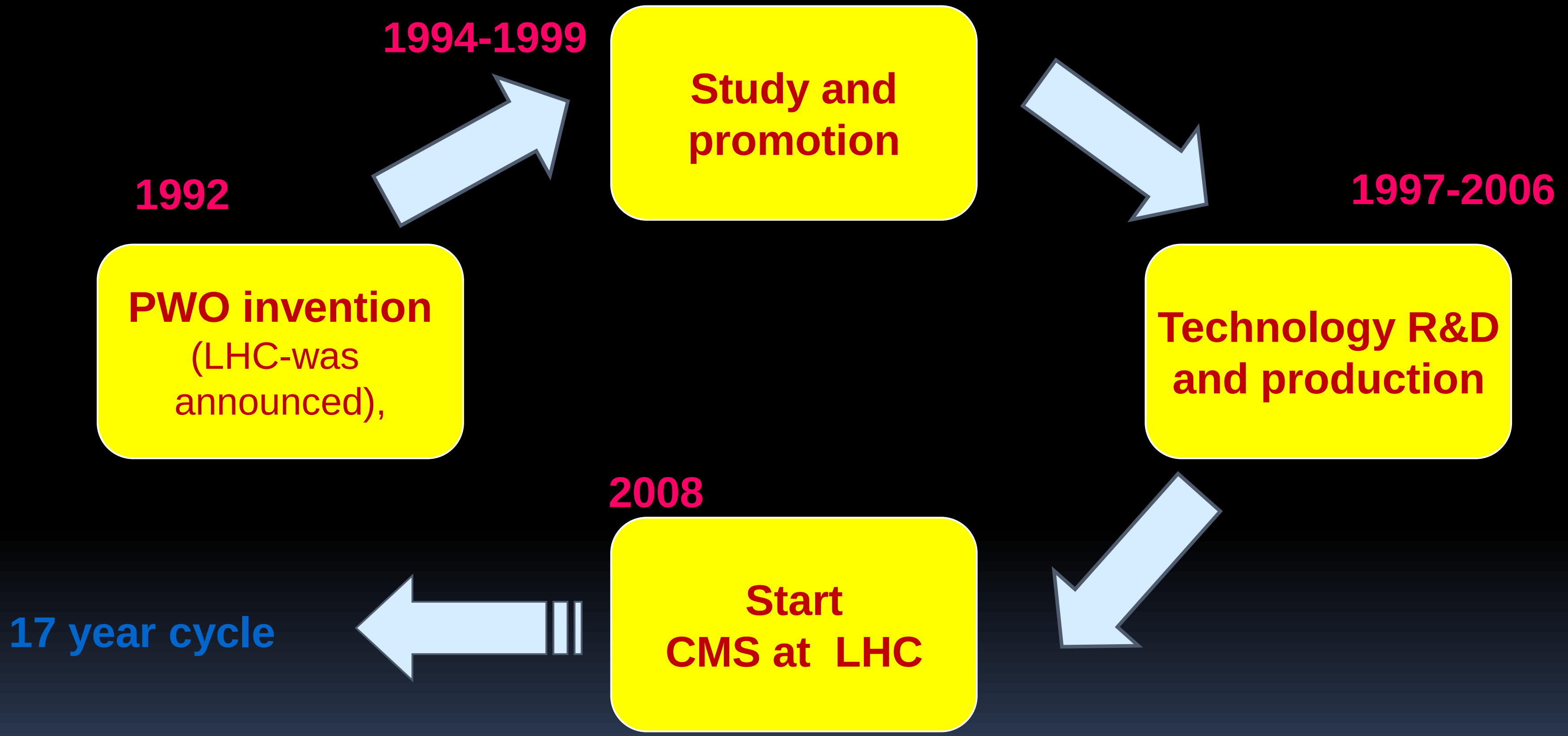
- Andrey Vasiliev:

  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 enough' scintillator for hadron calorimetry??

New Regime of Applications: New Insights?



$PbWO_4$ cycle. From invention to LHC use



Summary

- A lot of very interesting and challenging problems
- Must keep up with/stimulate technological progress (photodetectors, inorganic scintillators)
- A lot of physics insights necessary to establish the performance of the new calorimetric technique
- It may be of critical importance for the new lepton colliders