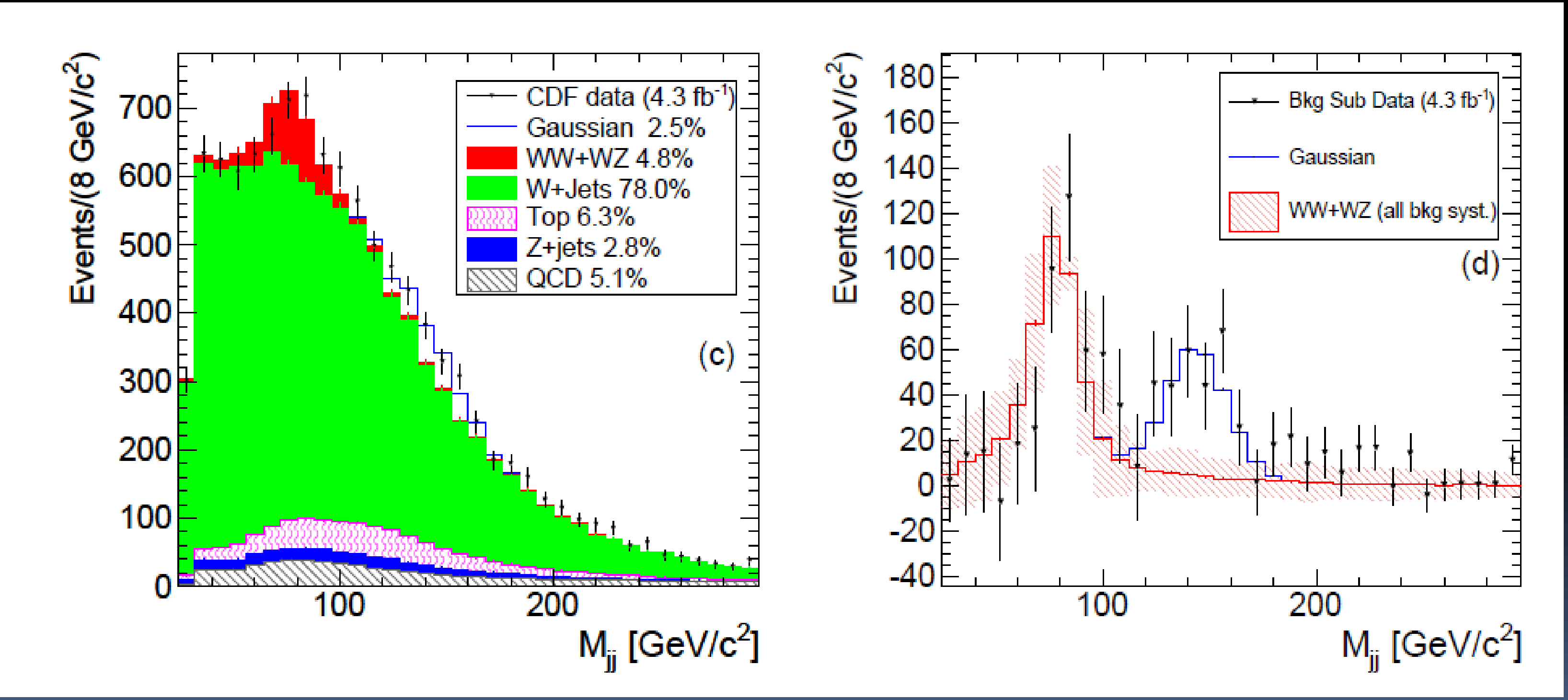
SOME ~~101~~ ~~1001~~ QUESTIONS ABOUT HIGH RESOLUTION HADRON CALORIMETRY

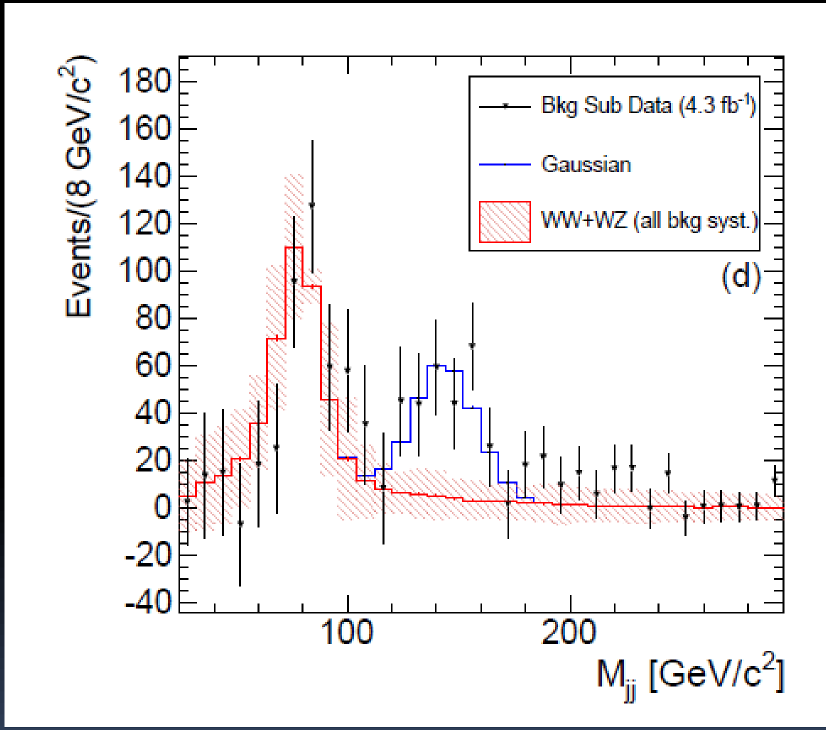
TIPP 2011, Chicago
June 9, 2011
Adam Para, Fermilab

PART1: WHO CARES?

Imagine a Possible Outcome of an Experiment: Mass of di-jets Rroduced in Association with W



Jet Calorimetry: is the Resolution Important?



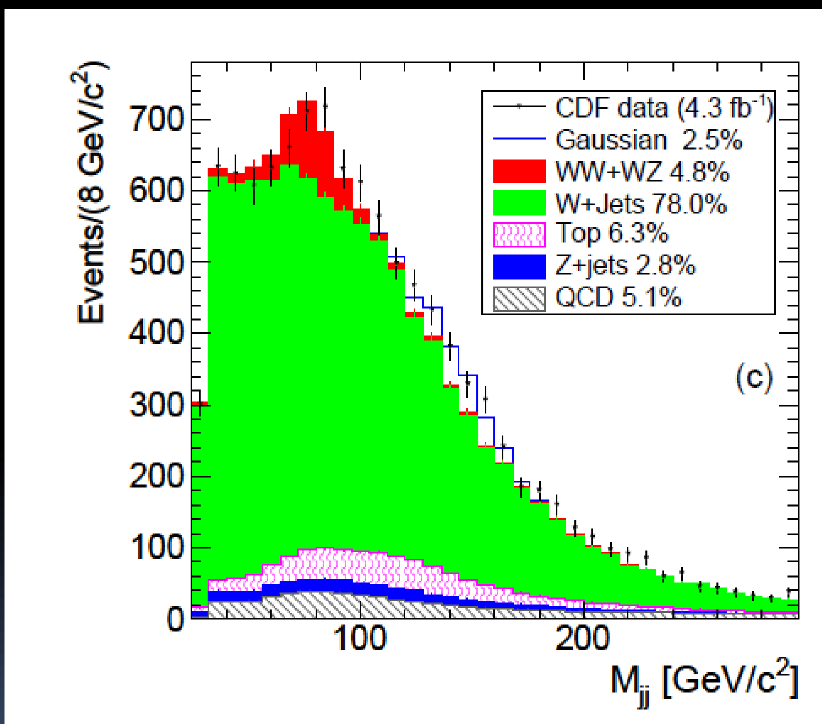
If you had $\Delta M/M$ ~ 2-3%:

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

Notice:

- CDF calorimeter cannot resolve W/Z mass peaks
- W/Z mass separation was not a design requirement for CDF
- W/Z were not even known to exist when CDF was being designed

Jet Calorimetry: is Linearity and Equality of Response to All Particles Important?

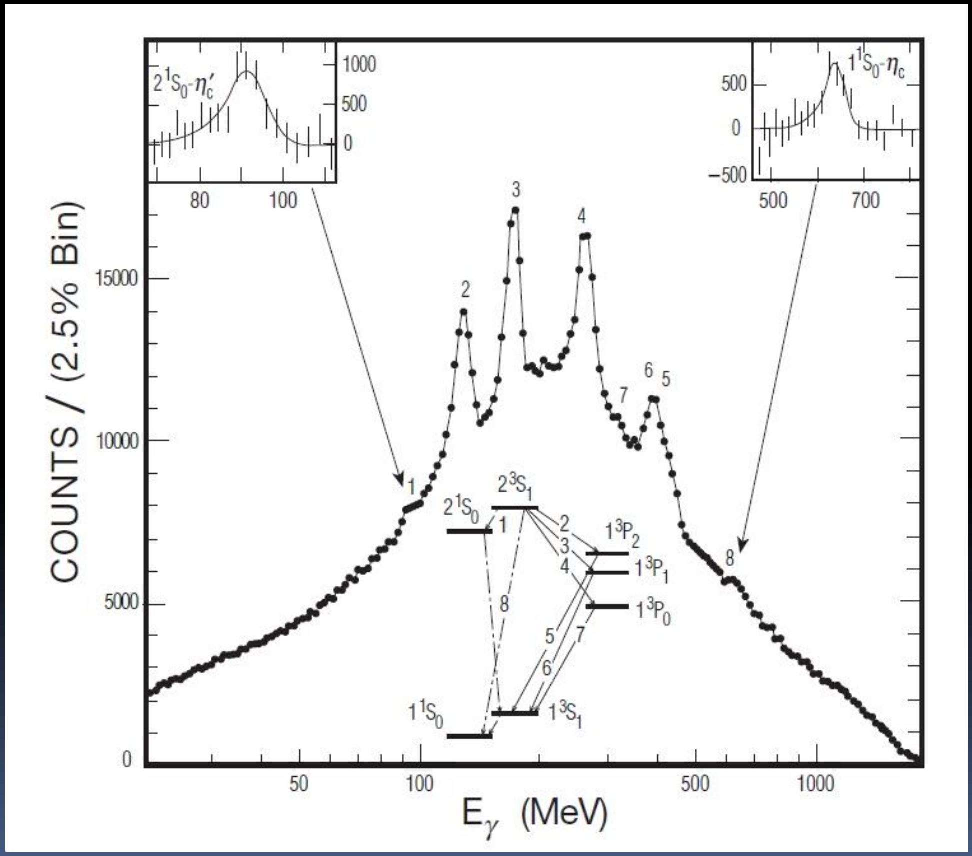


- A mysterious bump appears around ~160 GeV.
- It is on a falling edge, but above, the of W+jets background.
- If you shift the background by one bin the effect is gone.
- How well did you model jets fragmentation functions?
- How do you know the correct fraction of quark vs gluon jets in your background?

.....

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

Is Jet Spectroscopy of an Importance?



- 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.
- Note: One particle Ψ'(3700) and precisely measured inclusive photon spectrum sufficient to uncover several intermediate states and prove their physics interpretation

Any Lessons?

- CDF Calorimeter was designed over 30 years ago using the best available technology at that time. It works remarkably well even by today's standards (especially after the gas calorimeters were replaced by scintillators).
- It takes 20 years to construct an experiment and another 20 years to run it
- What energy resolution will YOU need to study leading edge physics in 2030? 2040?
- Beware of claims that X% is 'sufficient' for the future experiments exploring the unknown realms???

PART 2: HIGH RESOLUTION HADRON CALORIMETRY

Is it possible? What is 'high resolution'?

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 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 and to produce mass of secondary particles
- Inhomogeneous calorimeters (typically: EM + HAD, with different responses)

How to Achieve High Energy Resolution for Jets ?

- Identify and remove the dominant sources of the fluctuations of observed signals
- 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 and particles masses. This requires (at least one) additional measurement to provide the necessary information (Dual Readout). [or clever optimization of the sampling calorimeter composition: a.k.a. 'compensation', R. Wigmans]

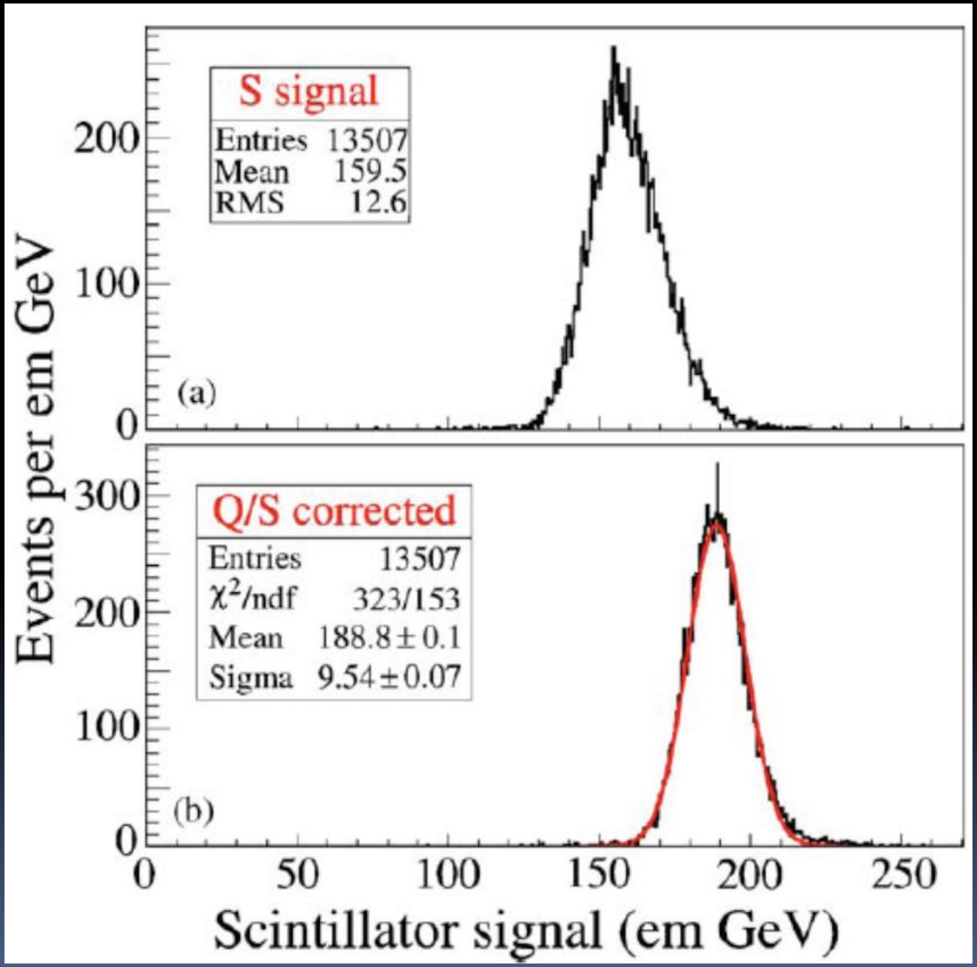
What are Physics Principles of High Resolution, Total Absorption Calorimetry?

- 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/kinematics:
  - 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

Can it be Done? In Principle? In Practice?

- 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

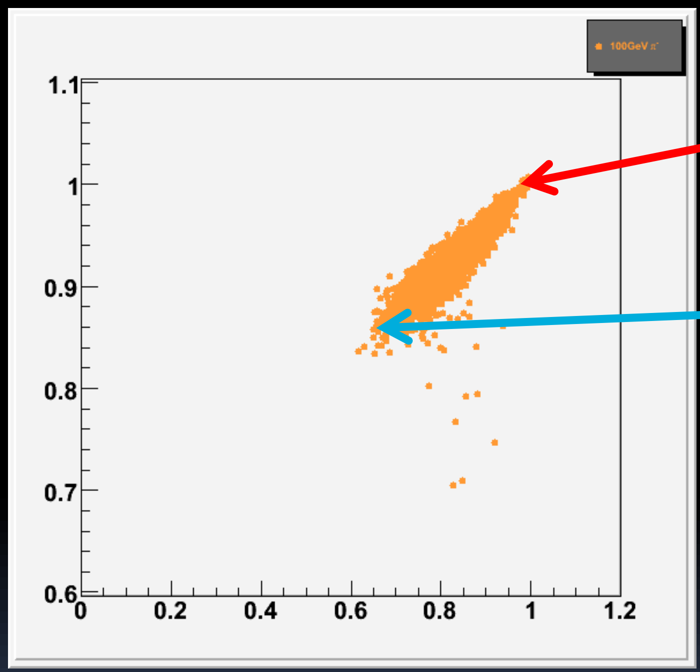
Does the Dual Readout Work in Practice?



- DREAM Collabration: Proof of principle. Yes, it does!
- Energy resolution improves markedly when the scintillation and Cherenkov signals are suitably combined
- The actual energy resolution limited by leakage fluctuations (very small test module)

Mechanics of Dual Readout Correction (Total Absorption Case)

S(cintillation)/B(eam Energy)
= fraction of energy detected



Cherenkov/Scintillation

π^o-rich showers: almost all energy detected

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

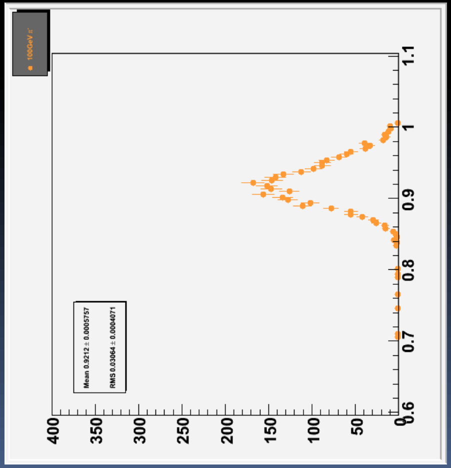
- Use C/S to correct every shower
- The resulting resolution limited by the local width of the scatter plot

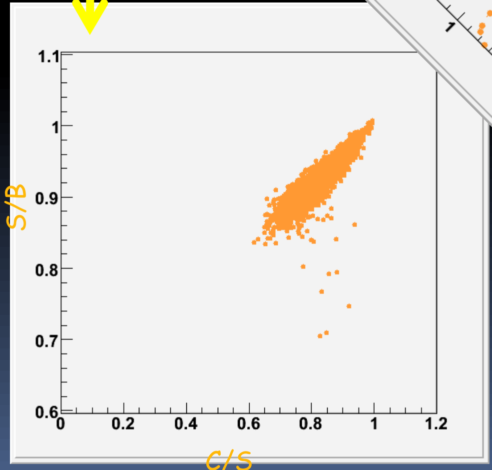
TAHCAL at Work: Single Particle Measurement

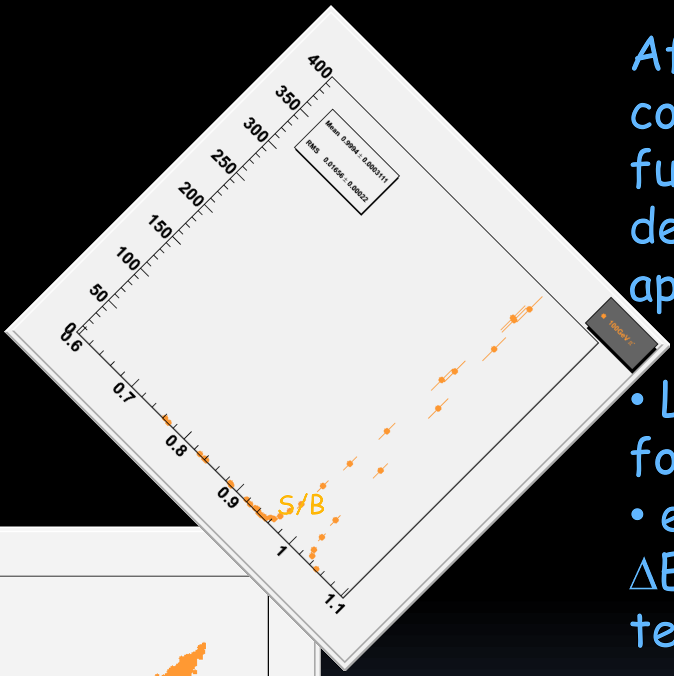
- 100 GeV π-
- Full Geant4 simulation

- Raw (uncorrected) ΔE/E ~ 3.3%

- but significant non-linearity, E~ 92 GeV



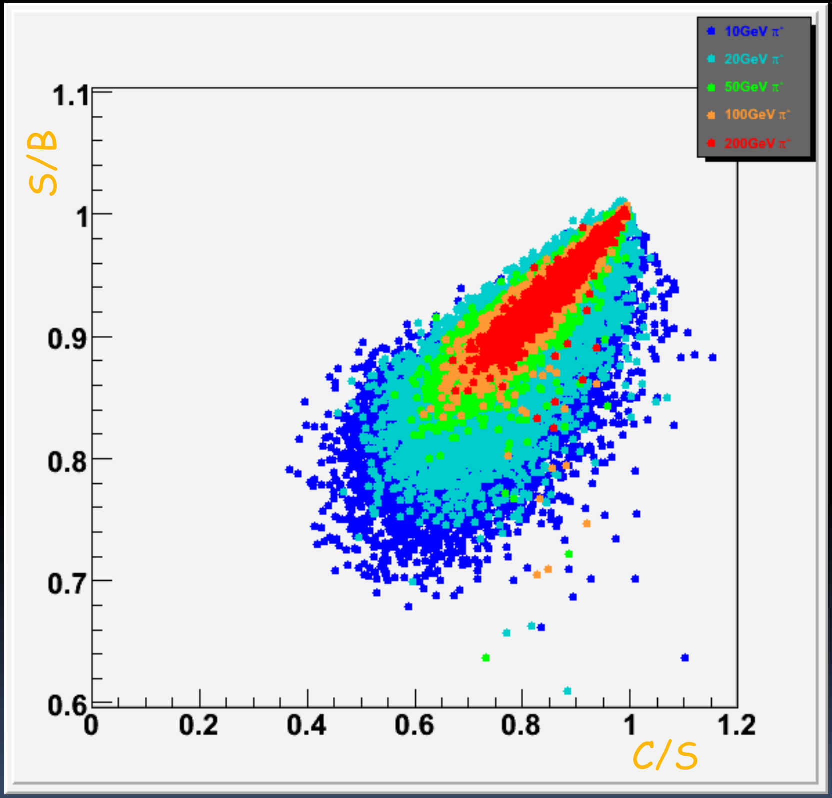




After dual readout correction, correction function (C/S) determined at the appropriate energy:

- 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

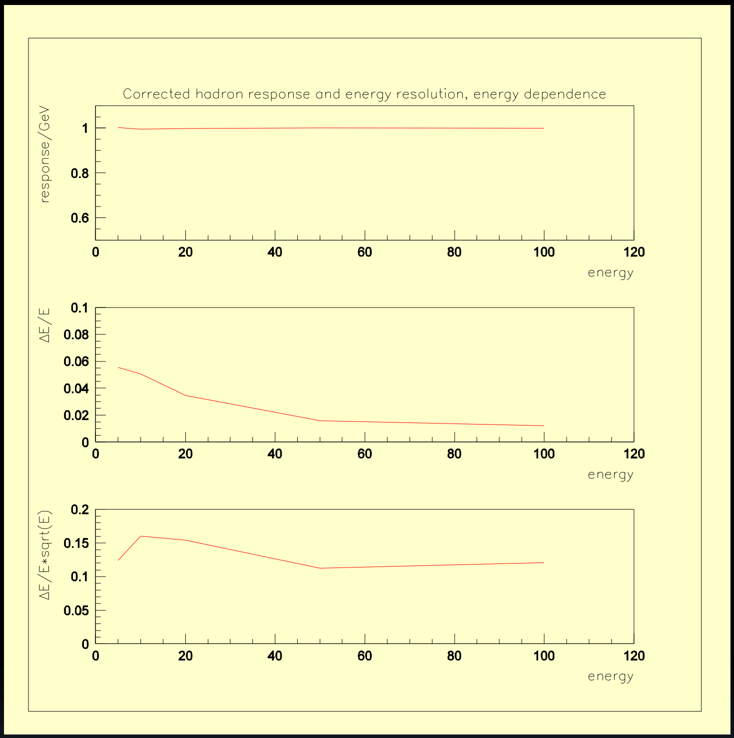
Does the Dual Readout Correction Depend on Energy

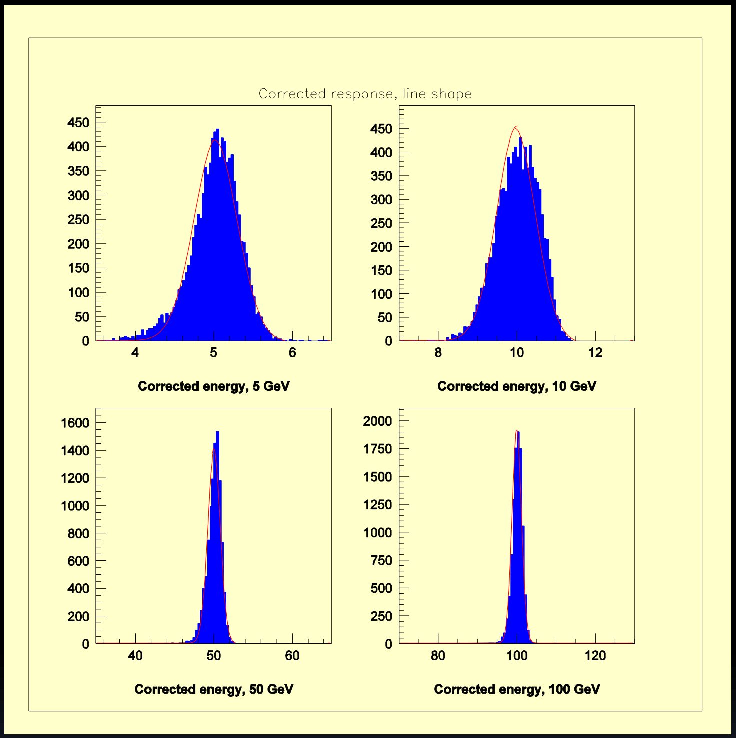


Correlation of the fraction of 'missing energy' and Cherenkov-to-scintillation ratio for showers of different energies: 10 – 200 GeV:

- 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.
- (Weak) Energy dependence can be implemented iteratively (0th order sufficient)
-

Response and Resolution, Corrected





After dual readout correction:

- good linearity of the corrected response
- good energy resolution ~ 0.12/√E
- no sign of a constant term up to 100 GeV
- Gaussian response function (no long tails)
- Calorimetric performance underestimated due to imperfections of simulation

Can one Build TAHCAL for a Collider Experiment? Like SiD?

- 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 3x3 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.

Can One Separate Scintillation and Cherenkov Signals from the Same Crystal?

IEEE Transactions on Nuclear Science, Vol. NS-31, No. 1, February 1984

CHERENKOV AND SCINTILLATION LIGHT MEASUREMENTS
WITH SCINTILLATING GLASS, SCG1C

G.E. Theodosiou, W. Kononenko and W. Selove
University of Pennsylvania, Department of Physics
Philadelphia, PA 19104

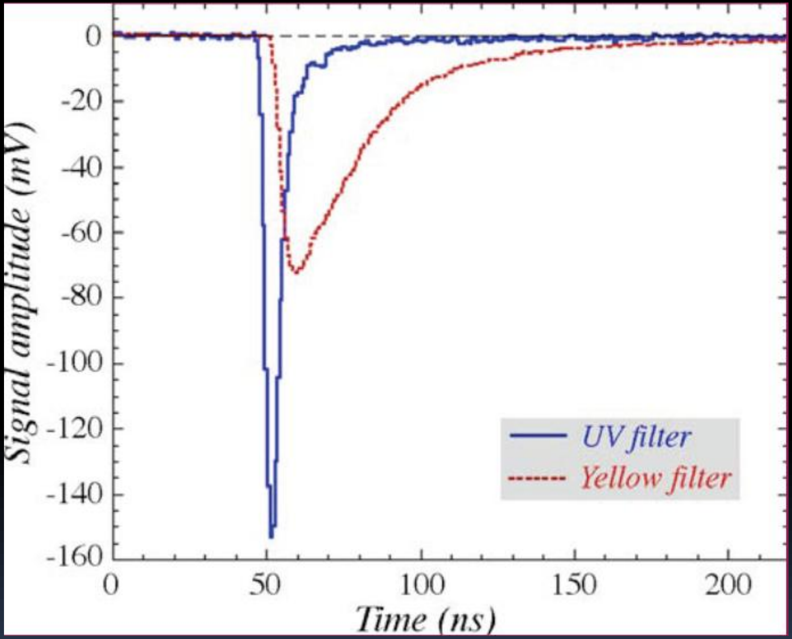
D. Owen
Michigan State University, Department of Physics
East Lansing, MI 48824

B. Cox and D. Wagoner
Fermi National Accelerator Laboratory
P.O. Box 500
Batavia, IL 60510

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.

By emission time



By emission time and wavelength/filters (DREAM)

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

An Incomplete Collection of Challenges

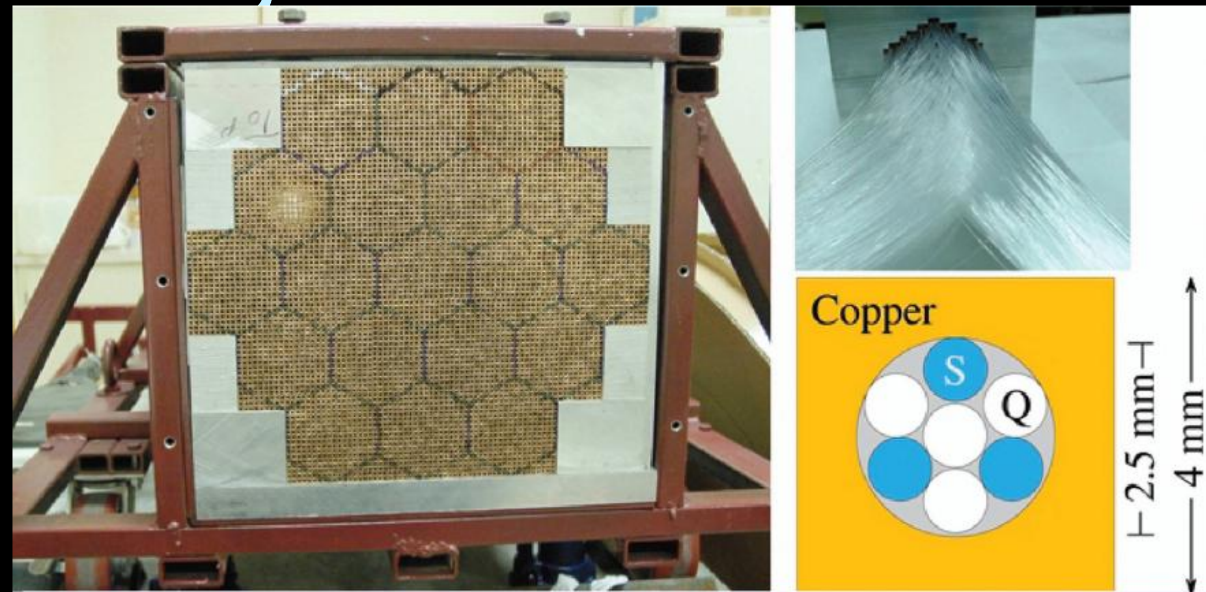
- Understanding of physics principles and limitations to the energy resolution
- (in?)Adequacy of modeling of a development of hadron showers
- Modeling of light propagation and collection
- Getting the light out: photonic crystals? Light collectors?
- Collection of light in a hermetic detector
- Collection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

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

- Availability and COST of suitable crystals

Alternative Designs?



Sampling calorimeter

- DREAM: Copper matrix with separate scintillation/Cherenkov/(neutron?) fibers.
- DREAM + Dual readout crystal EM calorimeter

The most mature design.

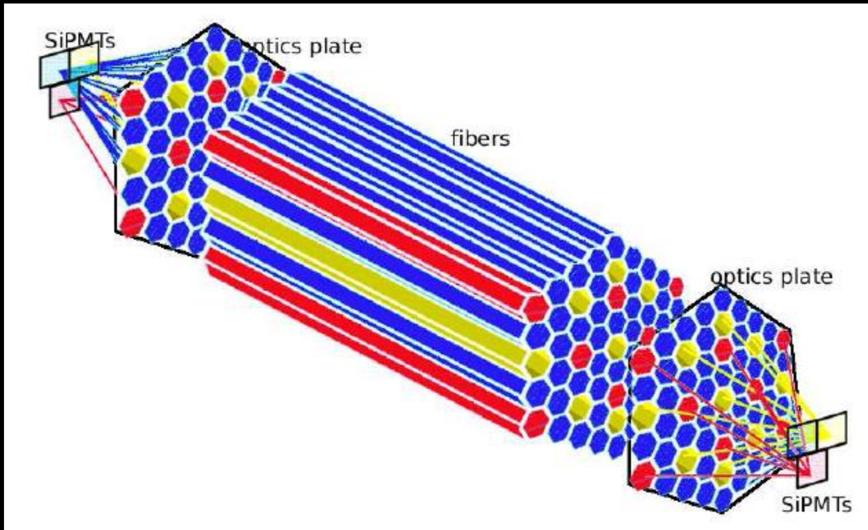
The only concept with relatively extensive test beam program up to date.

Extensive studies of crystal-based front-section.

Large number of published papers.

Alternative Designs?

Totally active designs (although effectively sampling calorimeters) : separate volumes with scintillation/Cherenkov readout



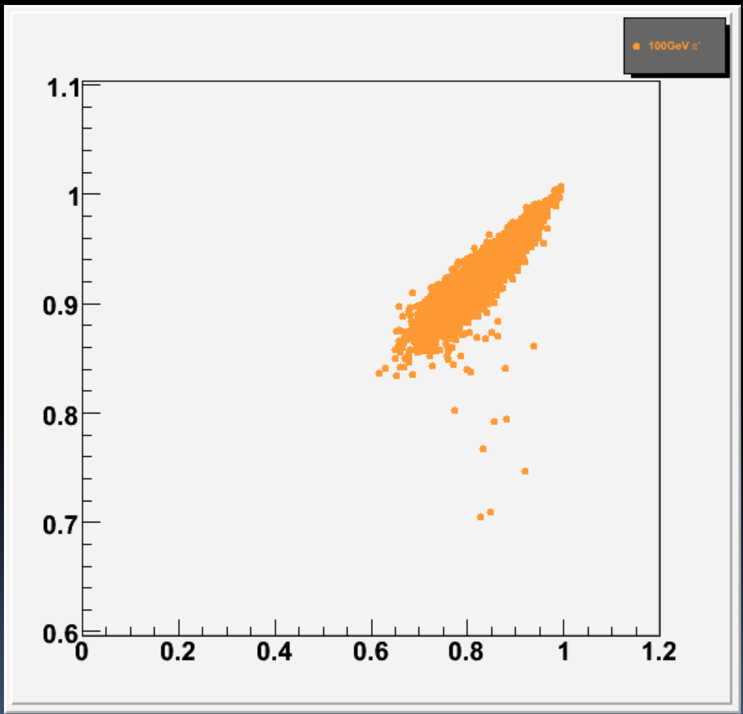
- Metacrystals (P. Lecoq, CERN)
- Lead-glass + scintillator plates (➔Takeshita)
- TWICE (INFN):
  - ADRIANO (➔Gatto) Lead glass + scintillating fibers
  - Scintillating glass (Udine/Trieste) total absorption, single readout

Beware: 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
- <u>Longitudinal segmentation</u> an important tool to detect and to minimize the impact of leakage on the energy resolution.

How to Implement a Dual Readout Correction?

Experimentally determined correlation



DREAM-way?

$$S = E\left[f_{em} + \frac{1}{(e/h)_S}(1 - f_{em})\right]$$

$$Q = E\left[f_{em} + \frac{1}{(e/h)_Q}(1 - f_{em})\right]$$

$e.g.$ If $e/h = 1.3\ (S),\ 4.7\ (Q)$

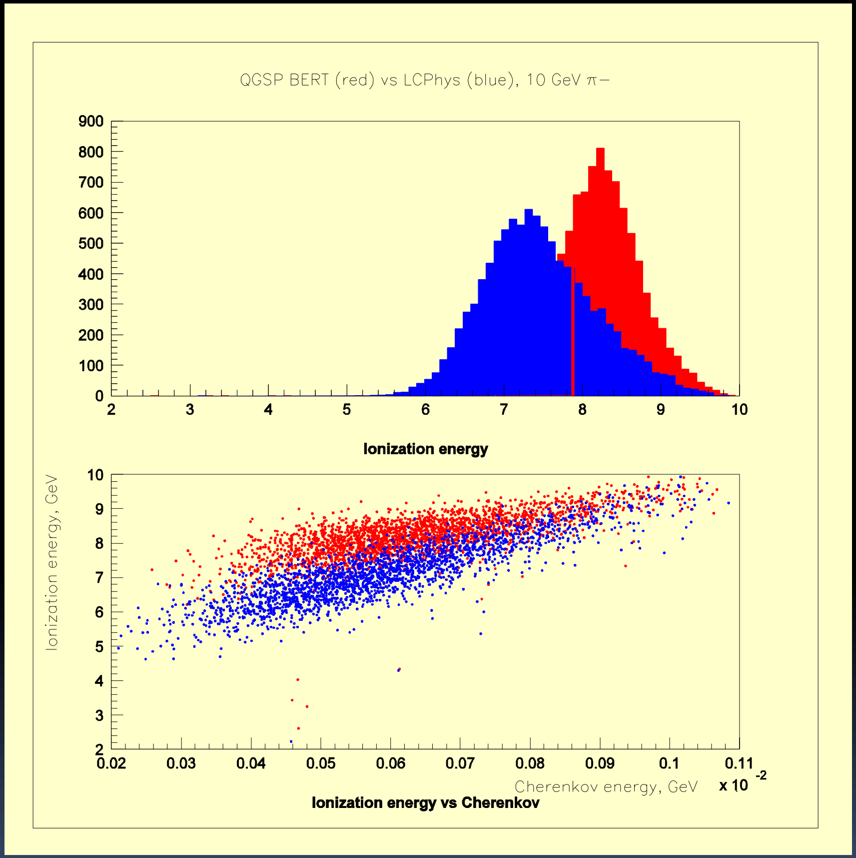
$$\frac{Q}{S} = \frac{f_{em} + 0.21\,(1 - f_{em})}{f_{em} + 0.77\,(1 - f_{em})}$$

$$E = \frac{S - \chi Q}{1 - \chi}$$

with $\chi = \dfrac{1 - (h/e)_S}{1 - (h/e)_Q} \sim 0.3$

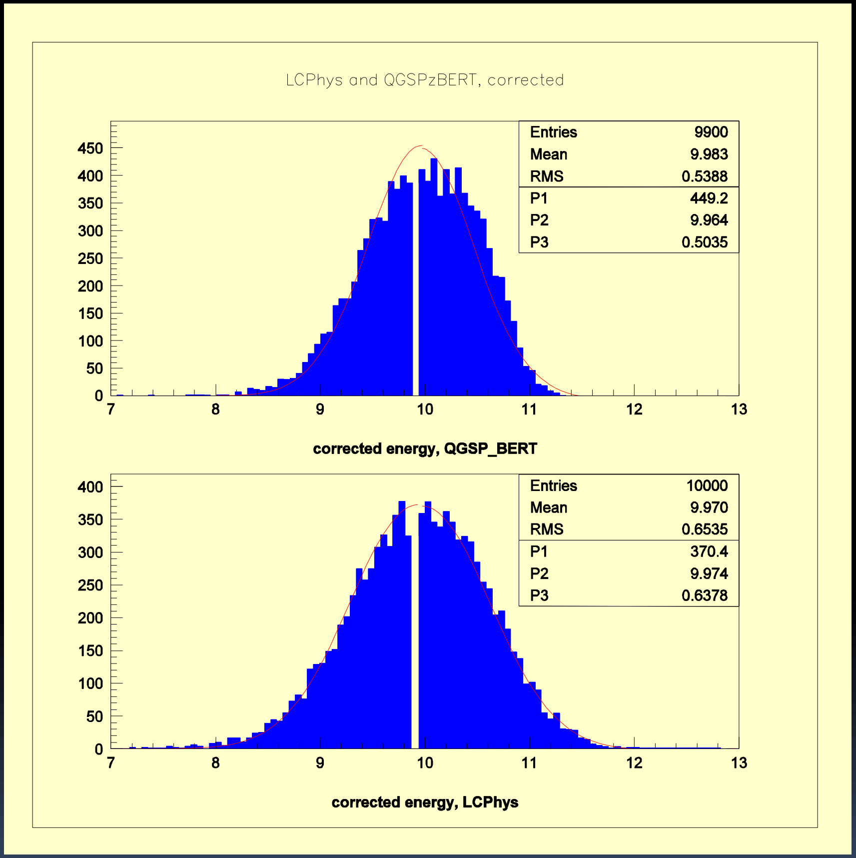
Approximate model, additional approximate parameters (e/h(S,Q)). Probably limits the achievable resolution, may depend on the design.

Monte Carlo Models? Trust and Verify



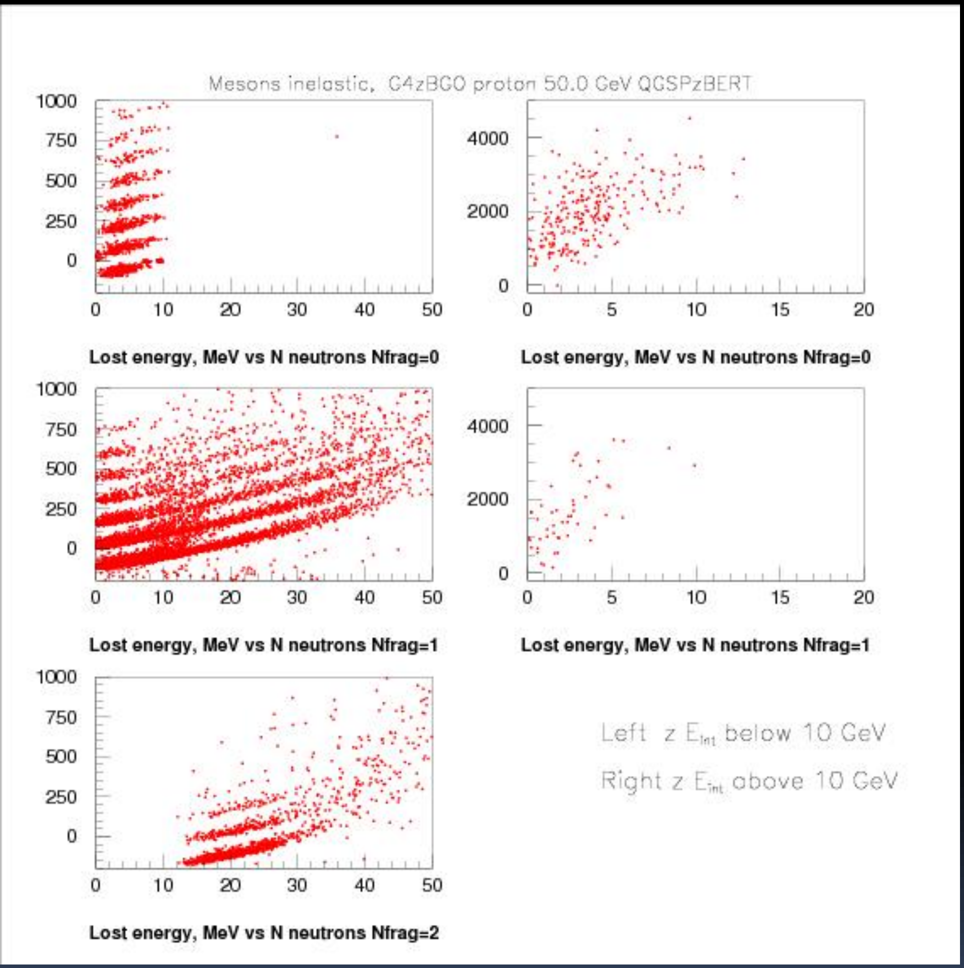
- Use two different physics lists: LCPhys and QGSP_BERT
- Most of the interactions with matter is the same, only hadron production modeling is different
- Surprisingly huge difference between the overall response. Possible reactions:
  - Simulations are known to be wrong, one more example
  - Make a test beam measurement to find which model, if any, is correct
  - Make your detector independent of Monte Carlo simulations
  - Really? Is our knowledge SO imperfect????

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)

Sanity Checks of Monte Carlos?



- Above 10 GeV: very large missing energy, not consistent with a small number of neutrons. Energy is not conserved
- Below 10 GeV:
  - no nuclear fragments:
    - missing energy increasing with number of neutrons
    - bands reflecting the number of mesons produced
  - one nuclear fragment:
    - large number of neutrons
    - missing energy increasing with number of neutrons
    - bands reflecting the number of mesons produced
  - two nuclear fragments:
    - as above, but somewhat less energy missing (fission!) , more neutrons

Most of the shower codes have obvious deficiencies degrading the predicted energy resolution

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
- Very active field of research. Many conceptual studies, several prototyping/test beam studies emerging to complement DREAM.
- Healthy interplay of physics (requirements), simulations, prototyping, technology (photodetectors), material science
- 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!
-