

HIGH RESOLUTION HADRON CALORIMETRY

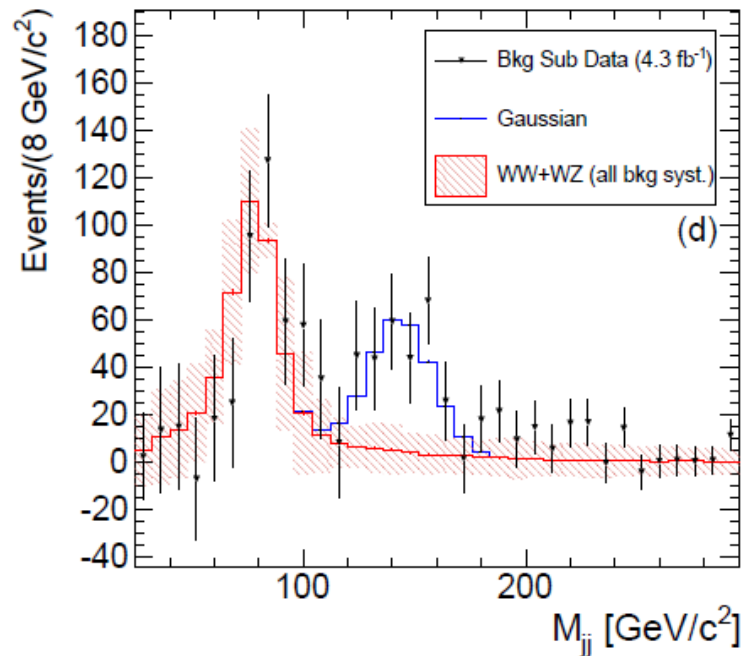
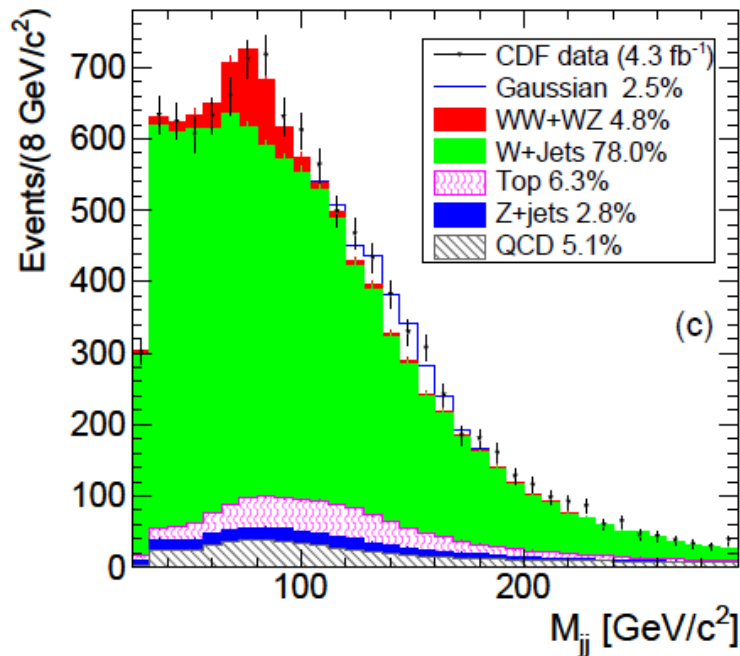
Adam Para, Fermilab

Tsinghua University

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PART 1: Why is Hadron Calorimetry Important? Interesting?

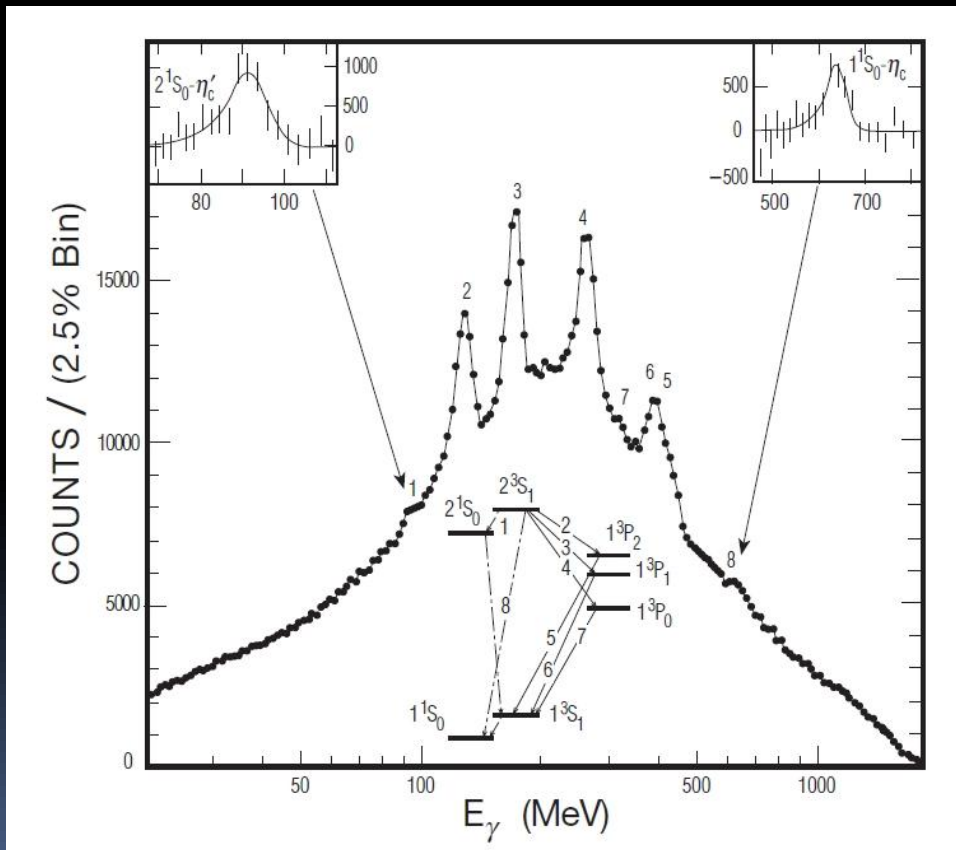
1.A Recent Past: Di-jet Mass Distribution in CDF



Notice:

- CDF calorimeter (late 70's) 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

Is Jet Spectroscopy of an Importance?



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

1.B Present: LHC Experiments

- Remarkably successful operation of the LHC accelerator enabling a first peek at the physics at Teraelectronvolt scale.
- Very impressive performance of the LHC experiments from the very beginning of the data taking run
- Where is the higgs boson?
- Are there new interactions, new families of heavy particles

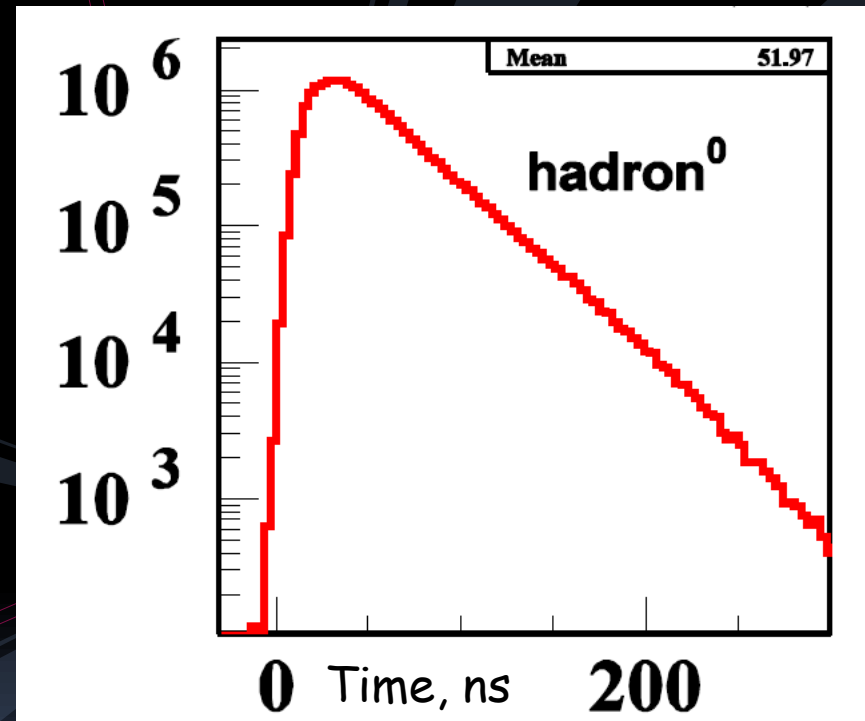
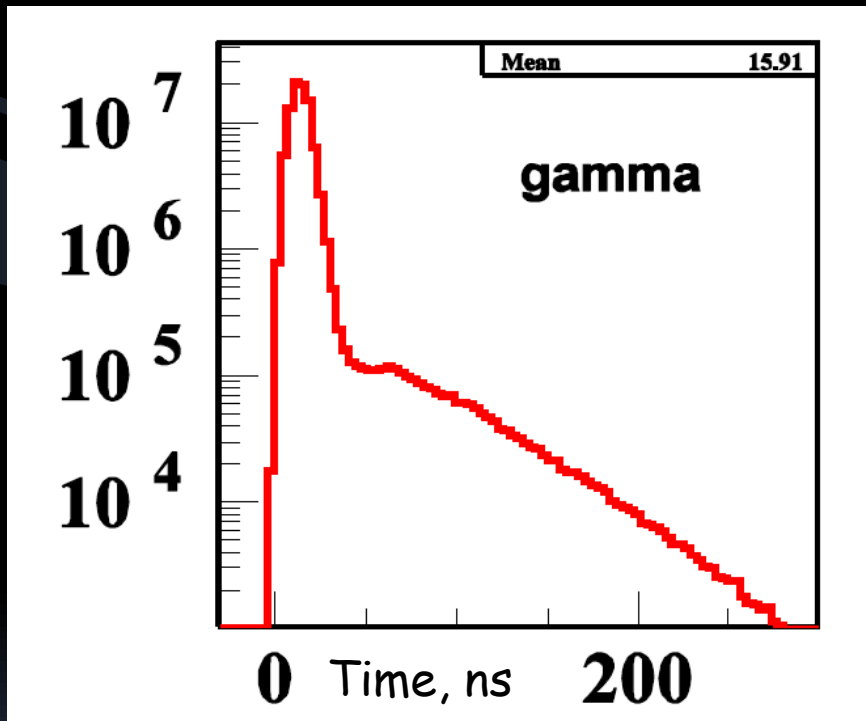
LHC Lessons so Far

- Higgs boson not found in the unexpected places
- If the higgs boson is as light as expected than the gamma-gamma decay channel is the most sensitive avenue: extreme importance of excellent energy resolution.
- New physics, if it exists, is likely to manifest itself at higher than hoped for energy scale. It may be that CLIC or a Muon Collider will be the next accelerator

1.C Likely Future (Not so Immediate)

- CLIC or a Muon Collider will be constructed to elucidate the physics discovered (hopefully) at the LHC
- New heavy particles with sequential decays by emission of jets and/or W/Z bosons are likely manifestation of new physics
- Very high resolution detectors, hadron calorimeters in particular, will be necessary to exploit fully the physics potential of these new machines.
- Experimental conditions at these new machines are likely to impose new requirements: very high granularity and timing resolution in addition to energy resolution.

Muon Decay Backgrounds at 1.5 TeV Muon Collider (per crossing)



164 TeV of photons
172 TeV of neutrons
92 TeV of muons (each sign)

Fast detectors with better than 10 nsec timing necessary to cope with the backgrounds

CLIC Timing Requirements

- Beam-beam crossing every 0.5 nsec
- Time stamping necessary to assign energy to the correct beam crossing

PART 2: HIGH RESOLUTION HADRON CALORIMETRY

Is it possible? The unique role
of 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 and to produce mass of secondary particles

Physics Principles of High Resolution, Total Absorption Calorimetry

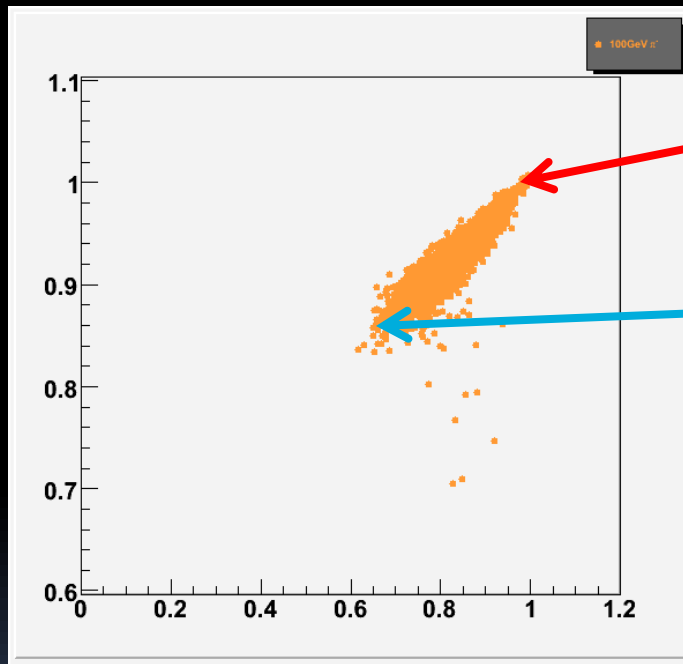
- Total absorption: no sampling fluctuations and other sampling-related contributions. The dominant contribution to resolution: fluctuations of nuclear binding energy losses.
- Cherenkov-to-scintillation ratio a sensitive measure of the fraction of energy lost for binding energy/kinematics:
 - Electromagnetic (π^0) showers do not break nuclei AND produce large amount of Cherenkov light ($C/S \sim 1$)
 - Large 'missing' energy \leftrightarrow large number of broken nuclei \leftrightarrow small amount of energy in a form of highly relativistic particles \leftrightarrow small C/S ratio
 - Low amount of 'missing' energy \leftrightarrow small number of nuclei \leftrightarrow large amount of energy in a form of EM showers \leftrightarrow C/S ratio close to 1
- Extra bonus: Cherenkov signal provides excellent timing

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 ($\lambda \sim 20$ cm)
 - 'Silicon Photomultipliers' ~ robust compact, inexpensive

Mechanics of Dual Readout Correction (Total Absorption Case)

$S(\text{cintillation})/B(\text{eam Energy})$
= fraction of energy detected



π^0 -rich showers: almost all energy detected

π^0 -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

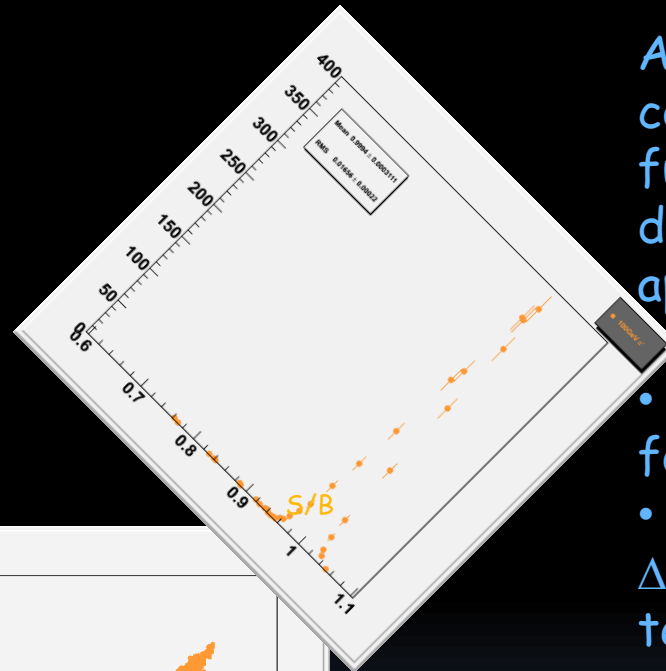
Cherenkov/Scintillation

TAHCAL at Work: Single Particle Measurement

- 100 GeV π^-
- Full Geant4 simulation

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

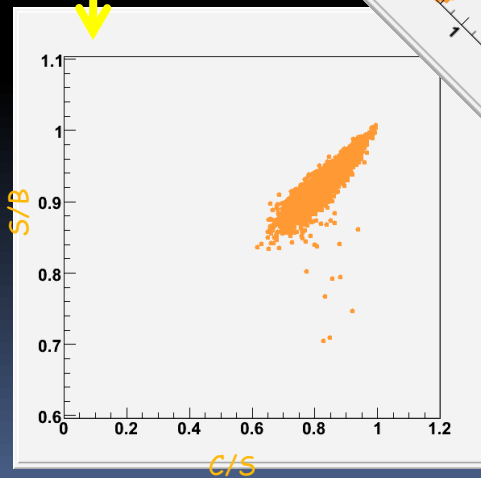
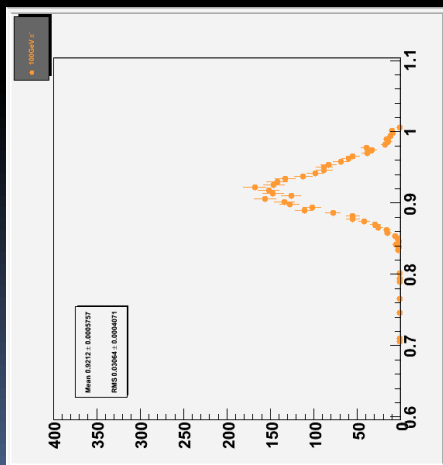
• but significant non-linearity, $E \sim 92$ GeV



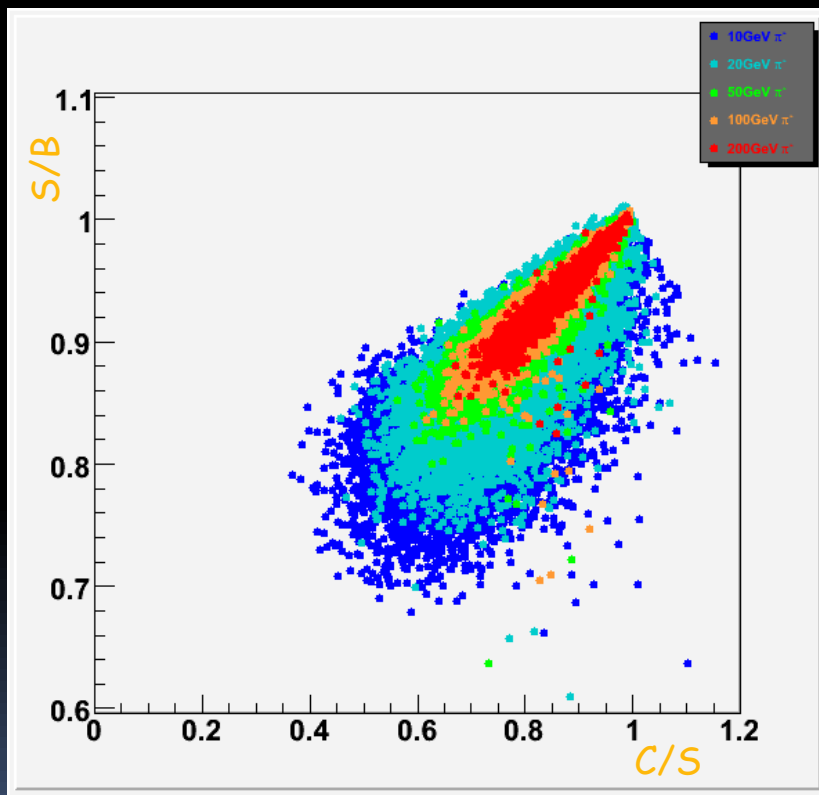
After dual readout correction, correction function (C/S) determined at the appropriate energy:

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

$\Delta E/E = 1.2-1.5\%$ at 100 GeV



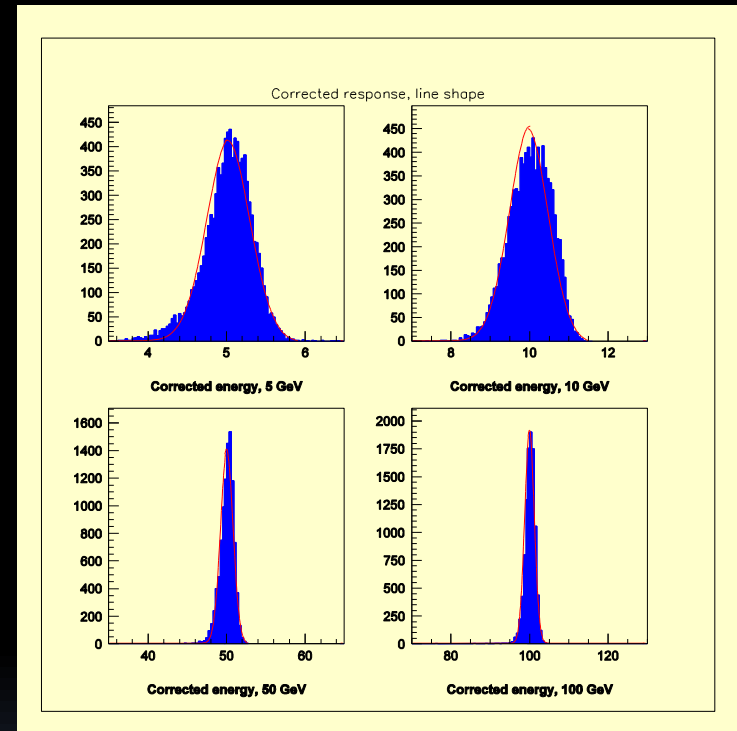
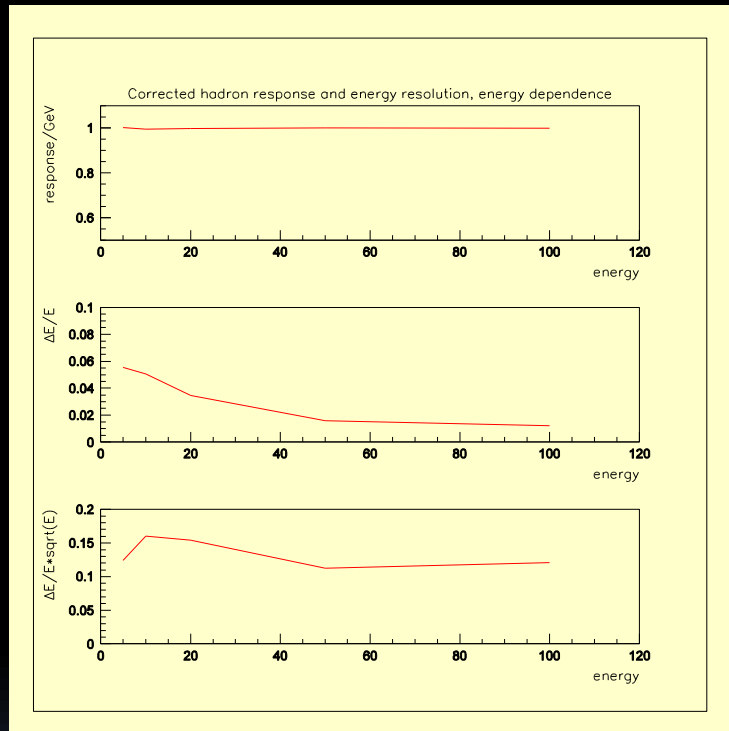
Does the Dual Readout Correction Depend on Energy



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 $\sim 0.12/\sqrt{E}$
- 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?

- Four layers of $5 \times 5 \times 5 \text{ cm}^3$ crystals (a.k.a. EM section): 72,000 crystals
- three embedded silicon pixel layers (e/γ position, direction)
- 10/16 (barrel/endcap) layers of $10 \times 10 \times 10 \text{ cm}^3$ crystals (a.k.a. hadronic section): 70,000 crystals
- 4(8?) photodetectors per crystal. Half of the photodetectors are $3 \times 3 \text{ mm}$ and have a low pass edge optical filters (Cherenkov)
 - No visible dead space.
 - 6λ at 90° , 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 $\sim 80\text{-}100 \text{ m}^3$.

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

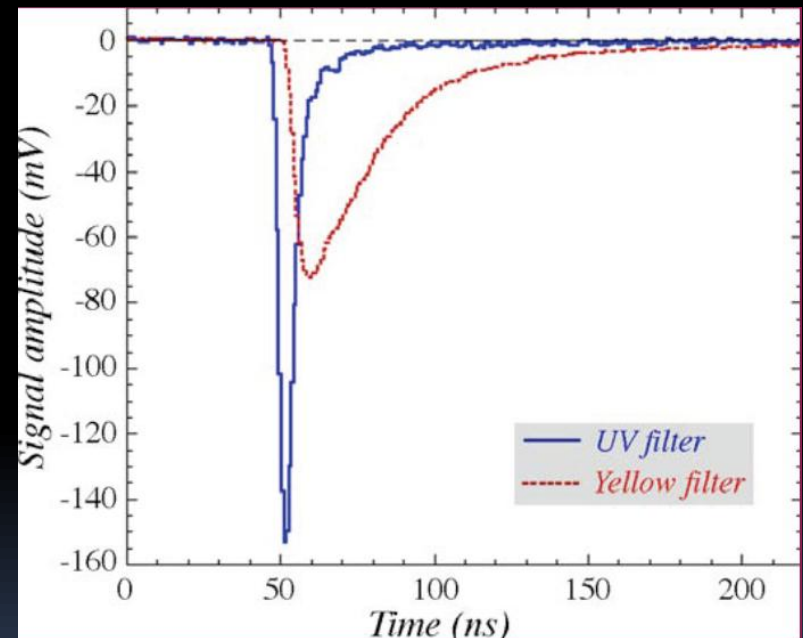
G.E. Theodosiou, W. Kononenko and W. Selove
University of Pennsylvania, Department of Physics
Philadelphia, PA 19104

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 and wavelength/filters (DREAM)

By emission time

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 photodetectors. 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-relativistic particles
- Optimization of a realistic detector design
- Availability and COST of suitable crystals

Potential Pitfalls

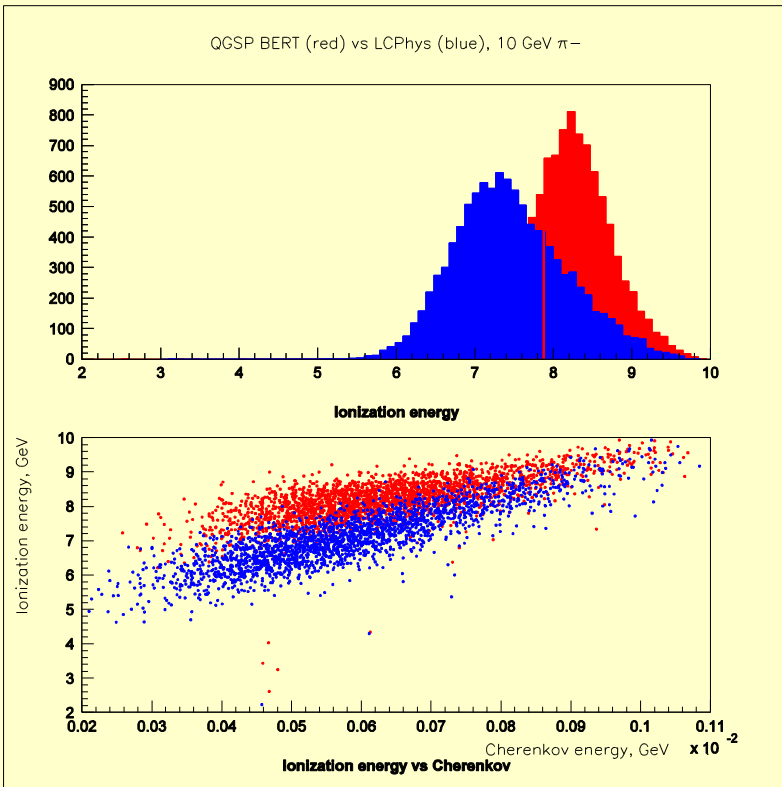
- Non-linearity of response for heavily ionizing particles
 - Hadron shower deposit a significant (and fluctuating) fraction of energy by heavy slow particles (protons, nuclear fragments)
 - If mechanism of the response non-linearity is the same as for electrons (Birks suppression) - no significant energy resolution degradation. But what if the suppression is much larger??
 - Need a dedicated measurement of the response of crystals to slow protons and light/heavy ions
 - May help with the theoretical understanding of non-proportionality
- 'Neutrons'. Popular misconception. Neutrons play a very important role in sampling hadron calorimetry with scinillator readout. They have negligible contribution to energy observed in total absorption calorimeters

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 average 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.

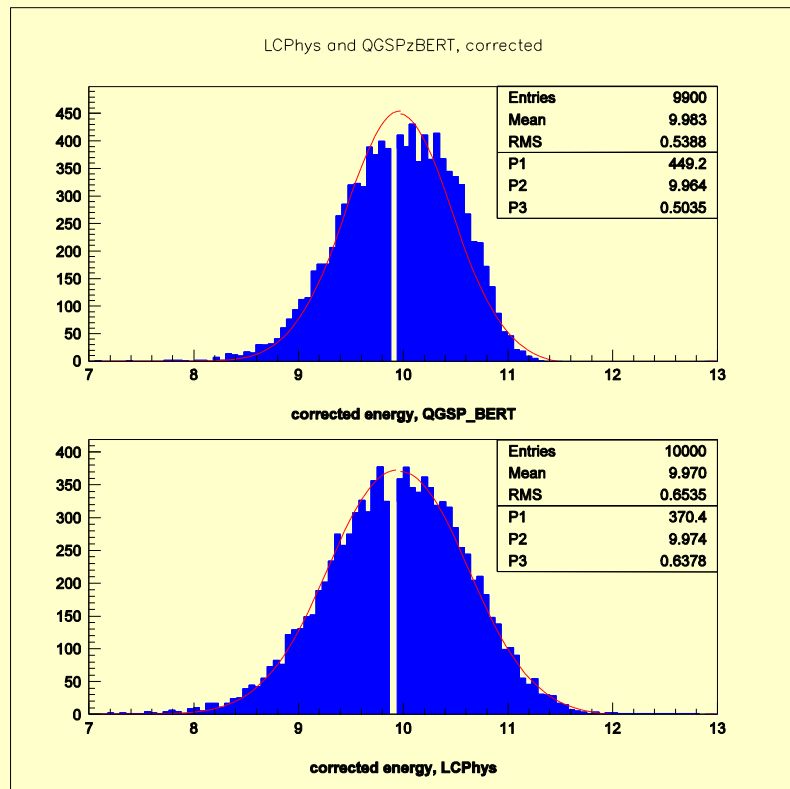
Monte Carlo Models? Trust and Verify

- 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:



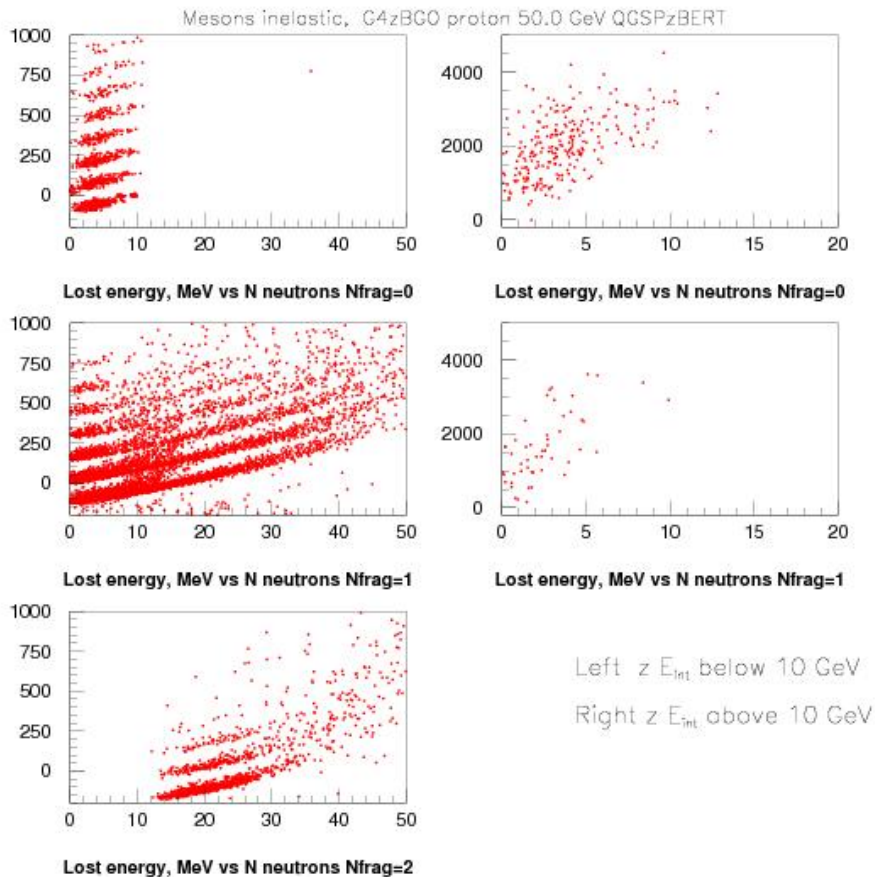
- Simulations are known to be wrong, one more example
- Make a test beam measurement to find which model, if any, is correct
- Make your detector independent of Monte Carlo simulations
- Really? Is our knowledge SO imperfect????

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 $(0.15-0.20)/\sqrt{E}$)

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

Inorganic Scintillators: the Critical Component

Inorganic scintillators can transform the hadron calorimetry into a precision technique. But we need your help to develop enabling crystals/glasses/ceramics. The requirements are quite different from 'typical', thus calling for dedicated R&D efforts.

- Inexpensive (\$1-2/cc)
- 'heavy' 7? 8? g/cc (more precisely: short nuclear interaction length, $\lambda \sim 20\text{cm}$)
- Allow detection/separation of scintillation and Cherenkov
 - Slow scintillation
 - Slow risetime scintillation
 - green-/red scintillation
 - Good transparency down to 300? 250? Nm
- NOT required:
 - high light yield (very high energies 100GeV measured)
 - High radiation resistance (low rate lepton machines)

Summary

- Future progress in understanding of fundamental structures and forces will require major improvements in hadron calorimetry.
- 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 ("Crystal Ball') with energy resolution better than $10\%/√E$
- Very active field of research. Many conceptual studies, several prototyping/test beam studies emerging
- Healthy interplay of physics (requirements), simulations, prototyping, technology (photodetectors), material science
- Great opportunity for major advances in the detectors and instrumentation.