HIGH RESOLUTION HADRON CALORIMETRY

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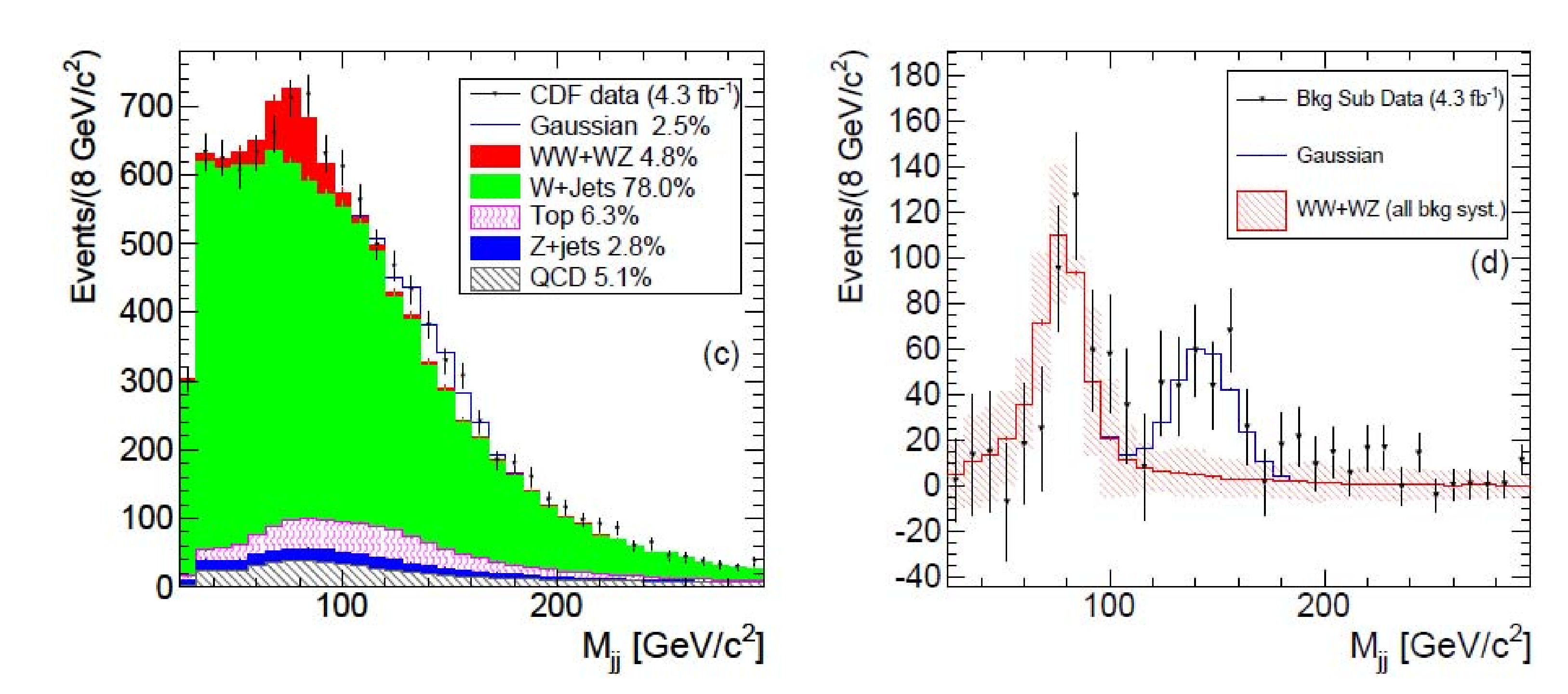
PART 1: Why is Hadron Calorimetry Important? Interesting?

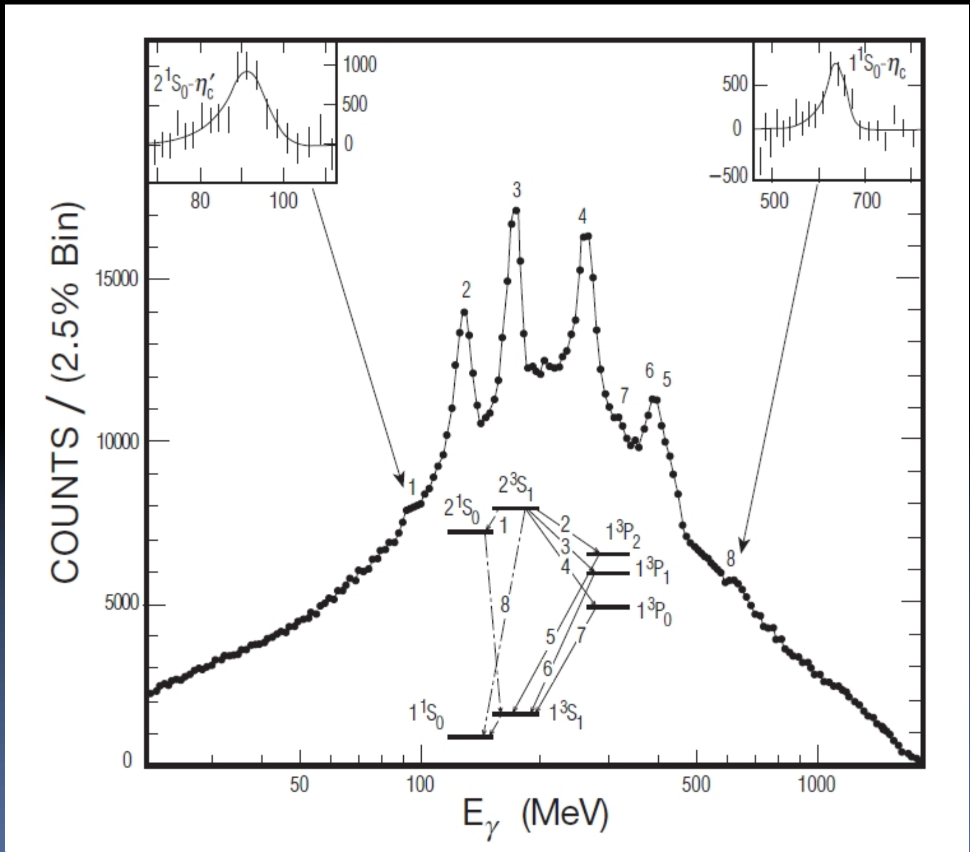
1.A Recent Past: Di-jet Mass Distribution in CDF



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/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

1.B Present: LHC Experiments

- Remarkably successful operation of the LHC accelerator enabling a first peek at the physics at Teraelctrovolt 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

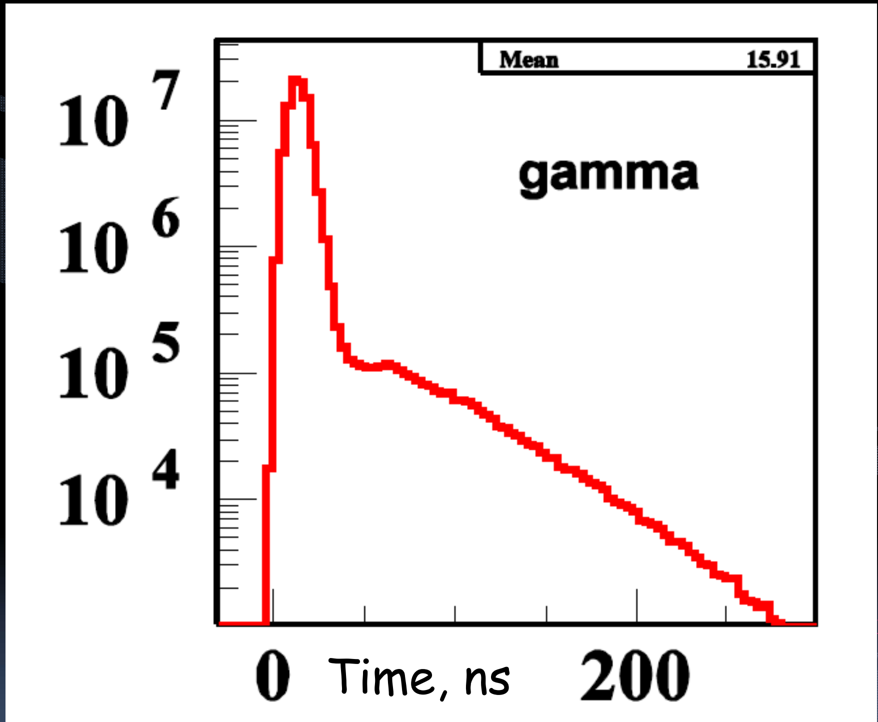
- Higgs boson not found in the unexpected places
- If the higgs boson is as light as expected than the gamma-gamma decay channel is the most sensitive avenue: extreme importance of excellent energy resolution.

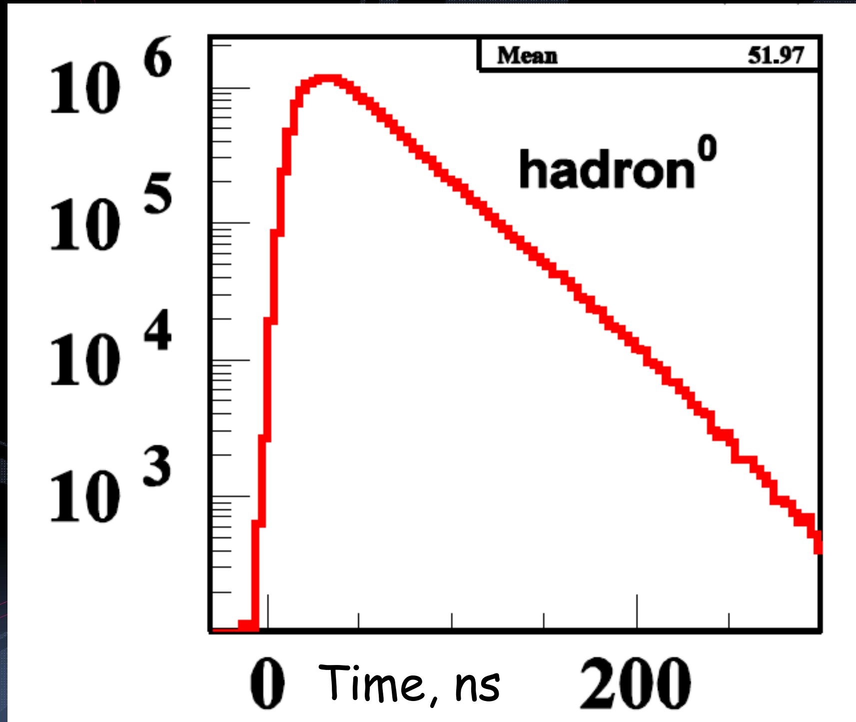
- New physics, if it exists, is likely to manifest itself at higher than hoped for energy scale. It may be that CLIC or a Muon Collider will be the next accelerator

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 $(\Delta E/E)$~50%/ √E for single particles, 70%-100%/ √E for jets. What's wrong with hadrons???
- Hadron calorimeters are <u>sampling</u> 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

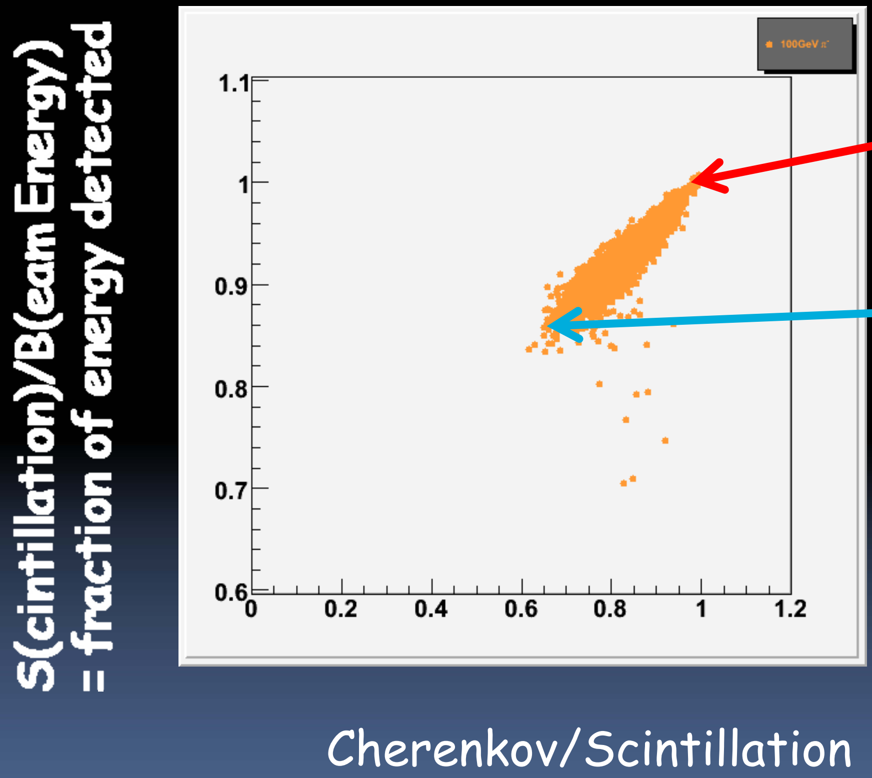
Physics Principles of High Resolution, Total Absorption Calorimetry

- 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~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
- Extra bonus: Cerenkov 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 (λ~20 cm)
  - 'Silicon Photomultipliers' ~ robust compact, inexpensive

Mechanics of Dual Readout Correction (Total Absorption Case)



π^o-rich showers: almost all energy detected

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

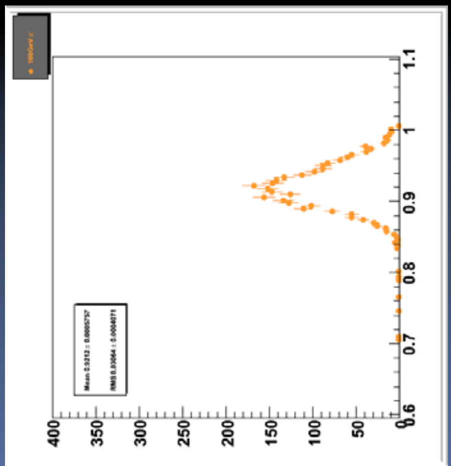
- Use C/S to correct every shower
- The resulting resolution limited by the local width of the scatter plot

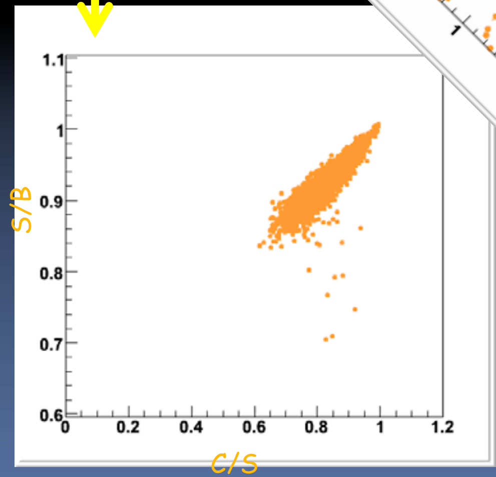
TAHCAL at Work: Single Particle Measurement

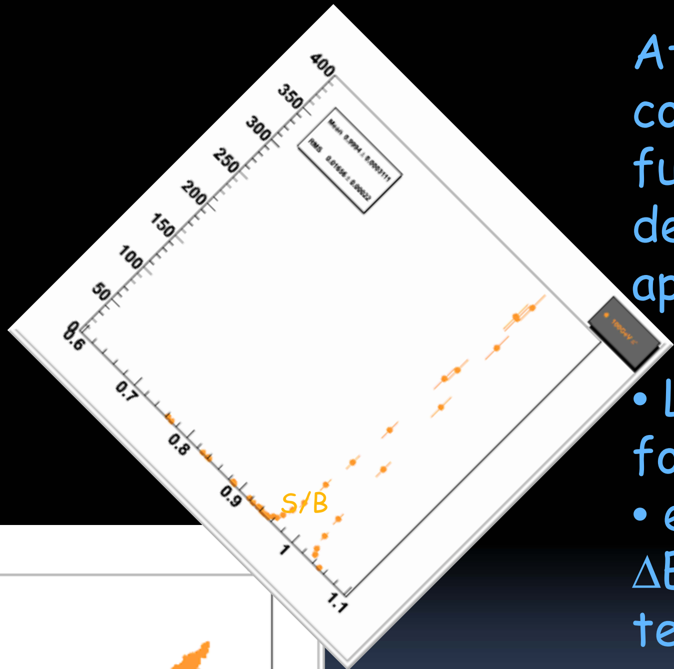
- 100 GeV π-
- Full Geant4 simulation

- Raw (uncorrected) ΔE/E ~ 3.3%

- but significant non-linearity, E~ 92 GeV



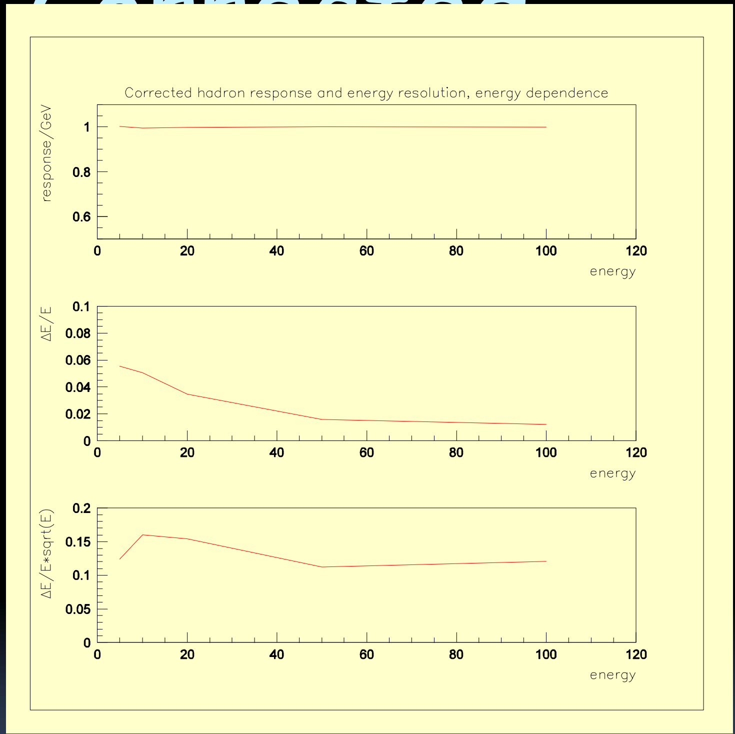


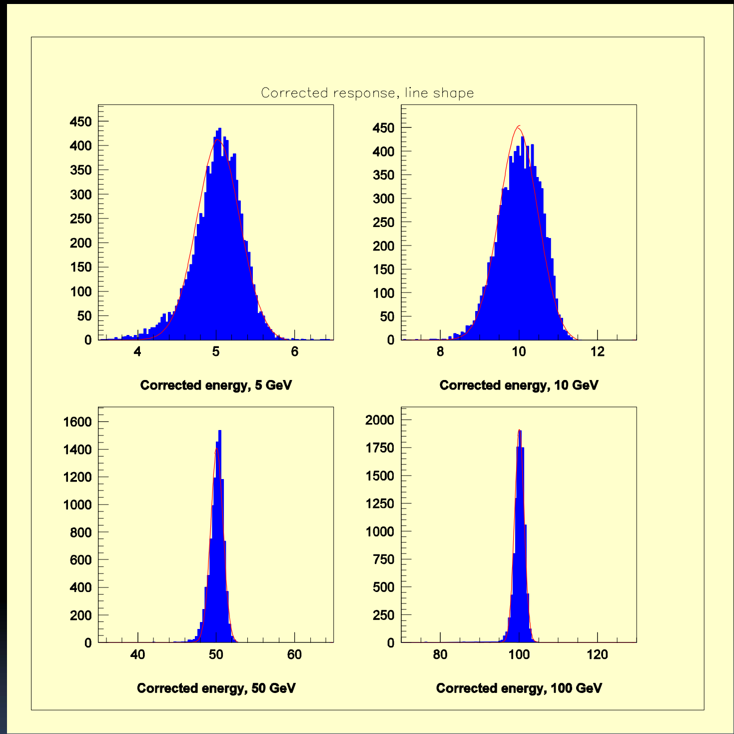


After dual readout correction, correction function (C/S) determined at the appropriate energy:

- 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

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 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

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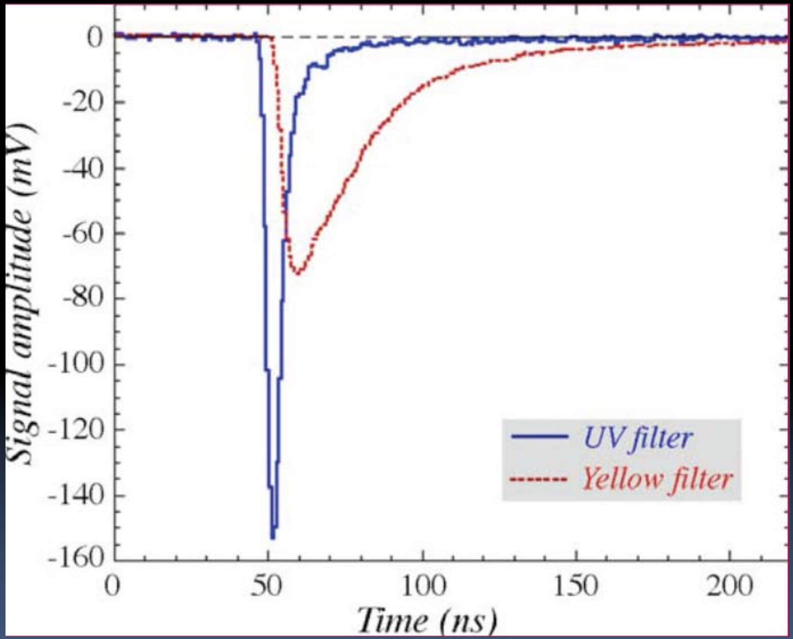
Abstract

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

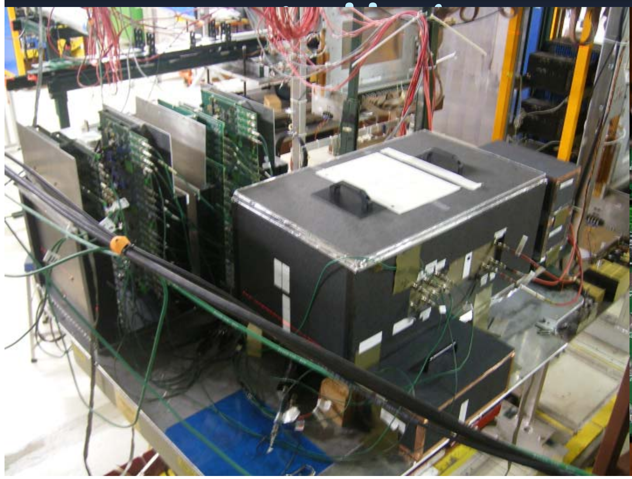


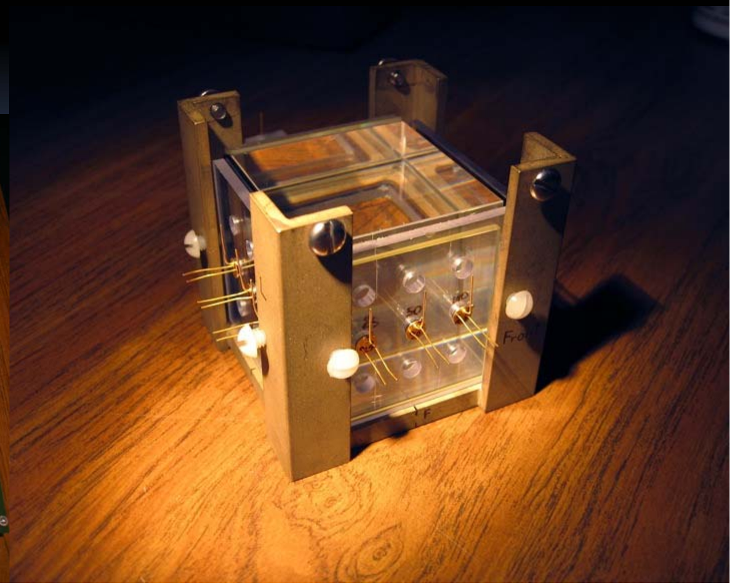
By emission time and wavelength/filters (DREAM)

PART3: HIGH RESOLUTION CALORIMETRY 'TO DO' LIST

Argonne-Caltech-Fermilab,

DOE supported,





Multi-prong Advances

- Understand physics principles, limitations, develop optimal design and analysis methods
- Test-beam studies of small prototypes (crystals + SiPM) IHEP test beam? Significant synergy with PET detectors !
- Compact photodetectors: characterization of SiPMs, novel compact photodetectors for Cherenkov (IHEP GPMT??), development of readout electronics for SiPM's
- Development of new scintillating crystals or glasses (SICCAS, Ningbo)
- Studies of non-linearity of response

An Incomplete Collection of Challenges (or Scientific and Technical Projects)

- 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

Study of Saturation Effects for Hadrons?

- Inorganic scintillators may offer an unique opportunity for very high resolution hadron calorimeters. A significant fraction of hadron shower energy is deposited by slow heavy particles (protons, alphas, nuclear fragments). Potential significant saturation effects may limit the attainable energy resolution.
- Crystals are playing an increasing role in beam monitoring for heavy ions experiments. Potential non-linearities of the response must be properly understood.
- Experimental data on saturation effects for hadrons may provide an important cross-check for the emerging understanding of the non-proportionality of the response

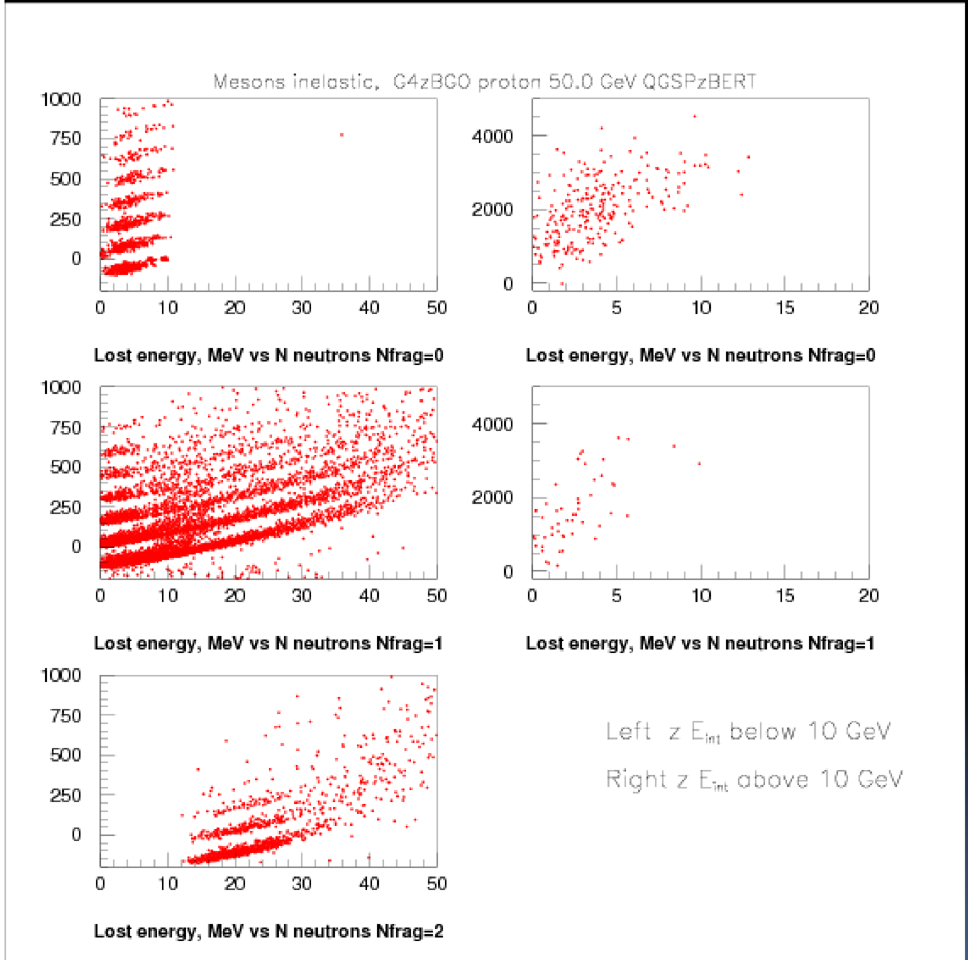
Proposition

- Let's provide experimental data on the response of inorganic scintillators to slow hadrons and nuclear fragments: measure S(cintillation)/E(nergy) ratio for different hadrons and nuclids as a function of their energy.
  - Is the response the function of the beta alone?
  - Is the moving charge the only effect?
  - Does the saturation depend on the mass of the particle?
  - How does it depend on the charge?
- The resulting parameterizations can be implemented in the proper simulation codes and/or used as the 'test cases' for various physics models.
- GSI Darmstadt, IHEP (electron/pion/proton) , Peking University/Lanzhou??

Monte Carlo Modeling Tool Kit

- Total absorption hadron calorimetry is a very sensitive test for (im)perfections of the Monte Carlo simulations
- Excellent tool for learning the simulation tools AND a surprising range of physics (high energy, nuclear, optics, material science) ←→ valuable educational tool for students
- Versatile tool for rapid evaluation of various detector concepts (LHC 420, CMS upgrades, g-2..)

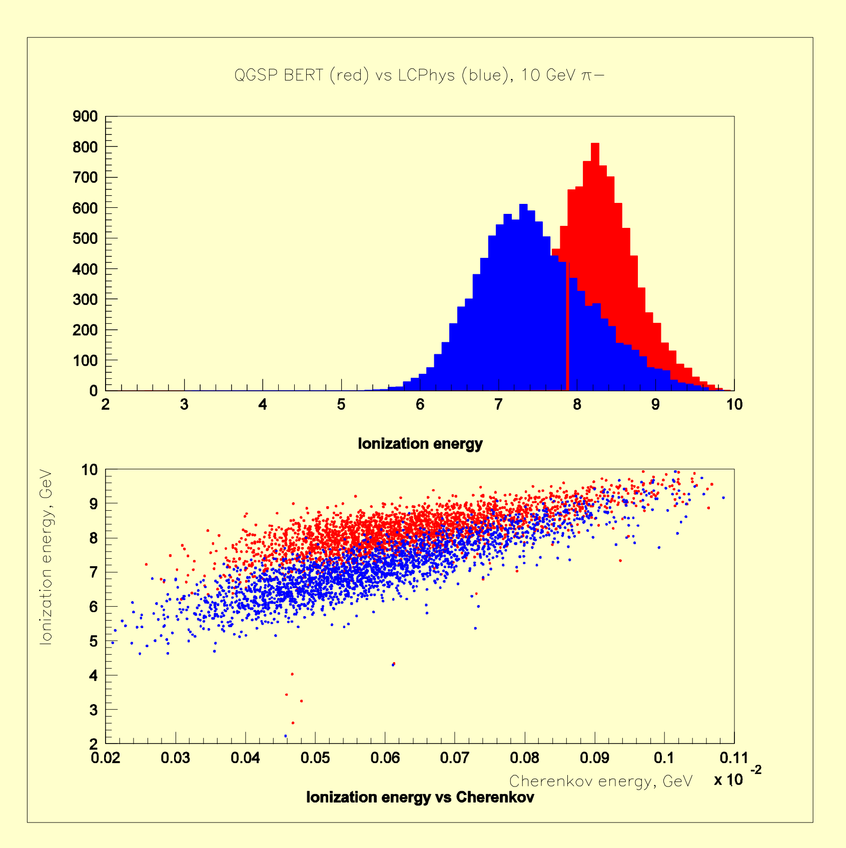
Sanity Checks of Monte Carlos?



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

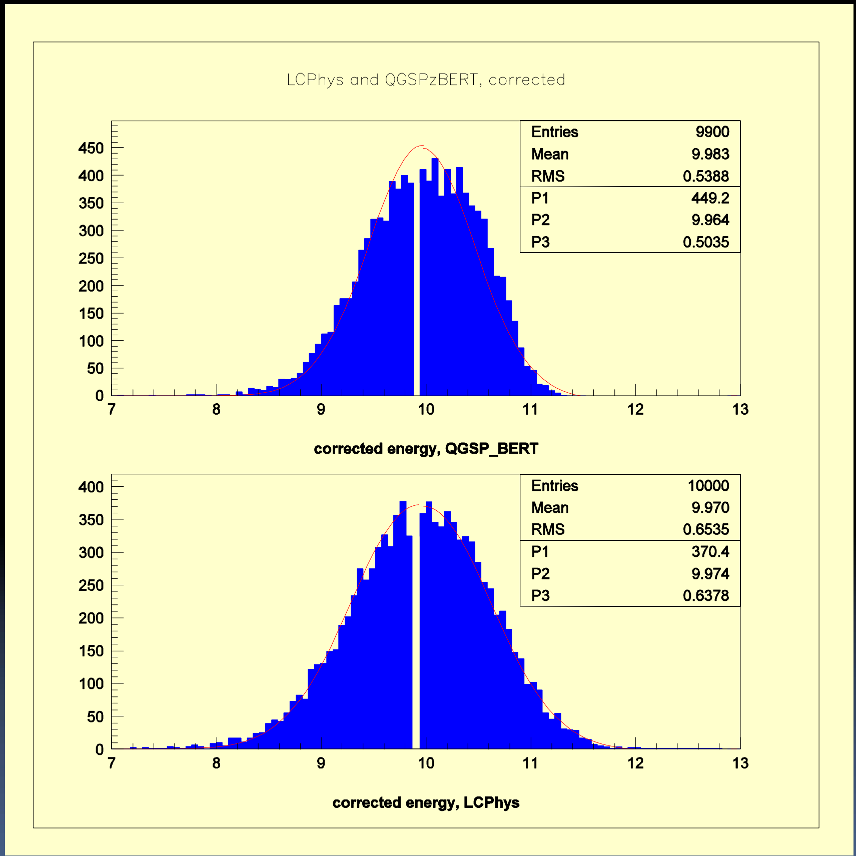
- Above 10 GeV: very large missing energy, not consistent with a small number of neutrons. Energy is not conserved
- Below 10 GeV:
  - no nuclear fragments:
    - missing energy increasing with number of neutrons
    - bands reflecting the number of mesons produced
  - one nuclear fragment:
    - large 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

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)

Inorganic Scintillators: the Critical Component

Inorganic scintillators can transform the hadron calorimetry into a precision technique. But we need 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, λ~20cm)

Initial R&D directions (SICCAS):

- Dope PbF2 with rare earth elements to make it scintillate
- Explore heavy scintillating glasses (BSO?)

Material Search

- Scintillators
  - Inorganic
    - Single Crystals
      - Halides
      - Oxides
    - Ceramics
    - Glasses
  - Organic
    - Plastics
    - Liquid Scintillators

A discipline in itself

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 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 and for fruitful collaborative efforts