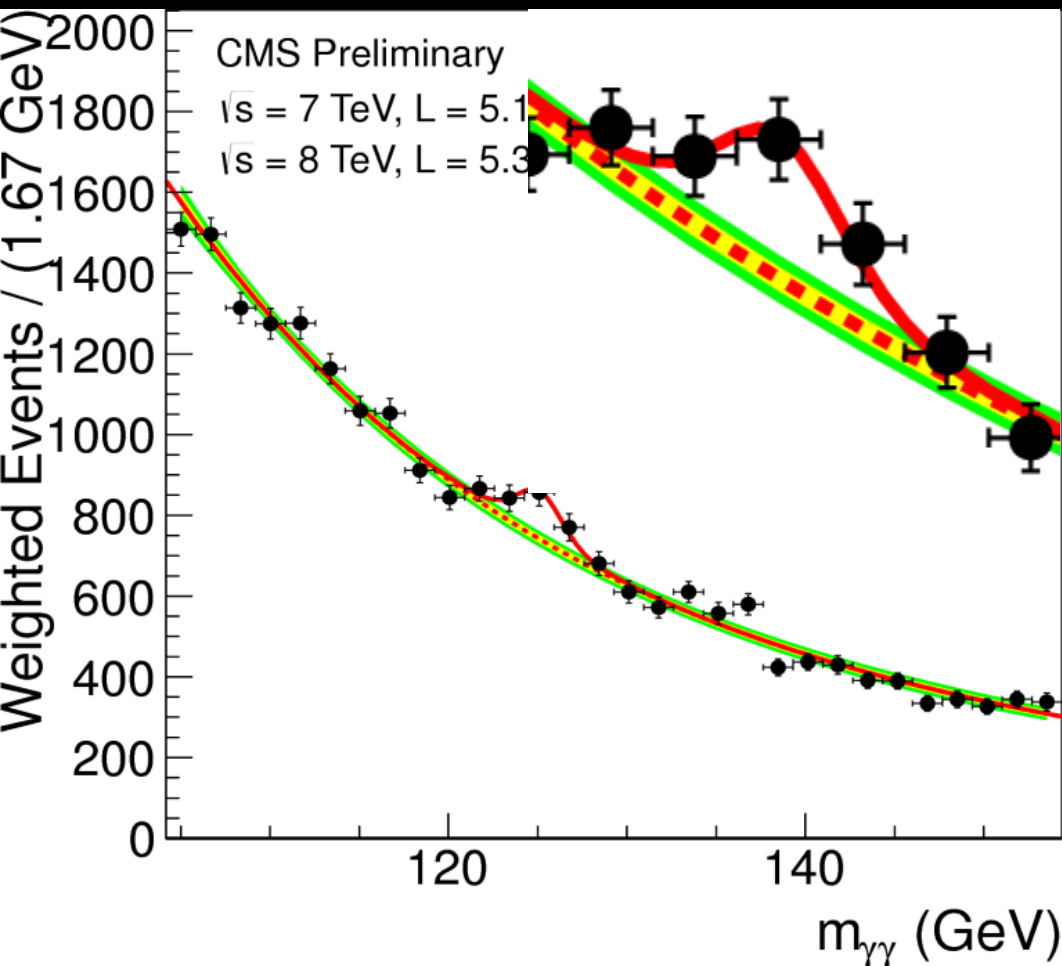# HIGH RESOLUTION HADRON CALORIMETRY

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# PART 1: How precise do you want to be? Why bother?

# 1.A Imagine a Narrow Resonance (for example around 125 GeV)



Its apparent width is determined by the energy resolution and if it is (as usual) produced on top of some background then signal-to-noise ratio critically depends on the mass/energy resolution.

$\Delta E/E \sim 1\%$ (@ 100 GeV)  is ~OK.
$\Delta E/E \sim 3\%$ (@ 100 GeV)  you are out of luck.

Requirements depend on the actual level of backgrounds but calorimetry with
$\Delta E/E \sim 10\%/sqrt(E)$ would be a huge asset for future precision studies.

# 1.B Jet Spectroscopy in Two-body Decays
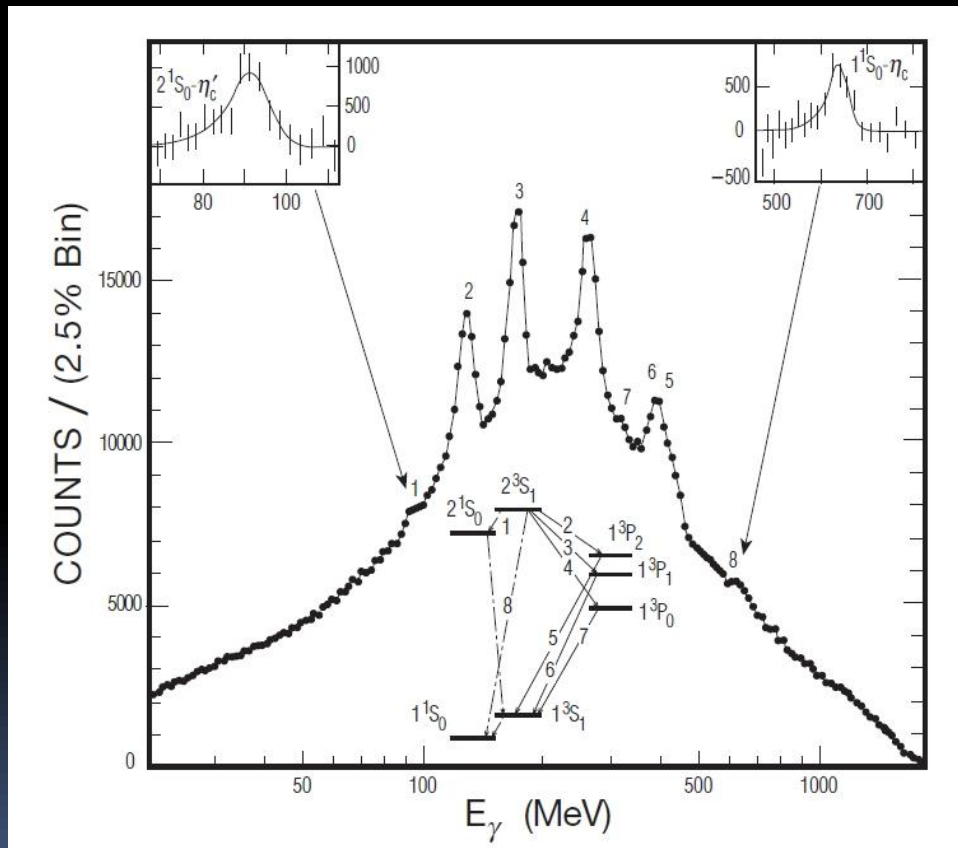


- ~40 years ago two narrow states J/Ψ(3100) and Ψ'(3700) were discovered. What were they???
- Radiative decays/Photon spectroscopy the key: these are the radial excitation of the ccbar states
- Excellent energy resolution of NaI crystals an enabling technology.
- <u>Note:</u> One particle Ψ'(3700) and precisely measured inclusive photon spectrum sufficient to uncover several intermediate states and prove their physics interpretation

# 1.C Likely Future?

- A Higgs Factory or ILC or CLIC or a Muon Collider will be constructed to elucidate the physics discovered at the LHC

- New heavy particles with sequential decays by emission of jets and/or W/Z bosons are likely manifestation of new physics (beyond Higgs)

- 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 time resolution in addition to energy resolution.

# 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 <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 ($\pi^0$) 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

- <u>Extra bonus</u>: 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 ($\lambda$~20 cm)
  - 'Silicon Photomultipliers' ~ robust compact, inexpensive

# Mechanics of Dual Readout Correction (Total Absorption Case)

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

100GeV π⁻

Cherenkov/Scintillation
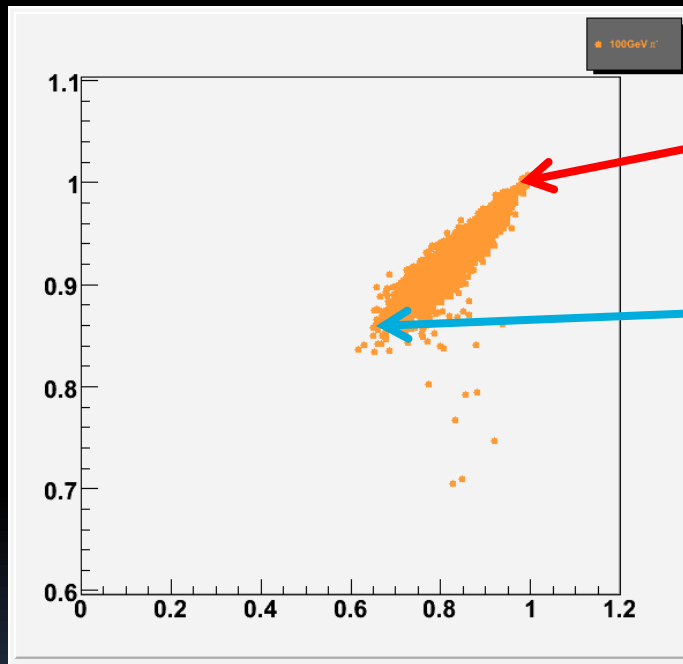
$\pi^0$-rich showers: almost all energy detected

$\pi^0$-poor showers: ~85% of the energy detected

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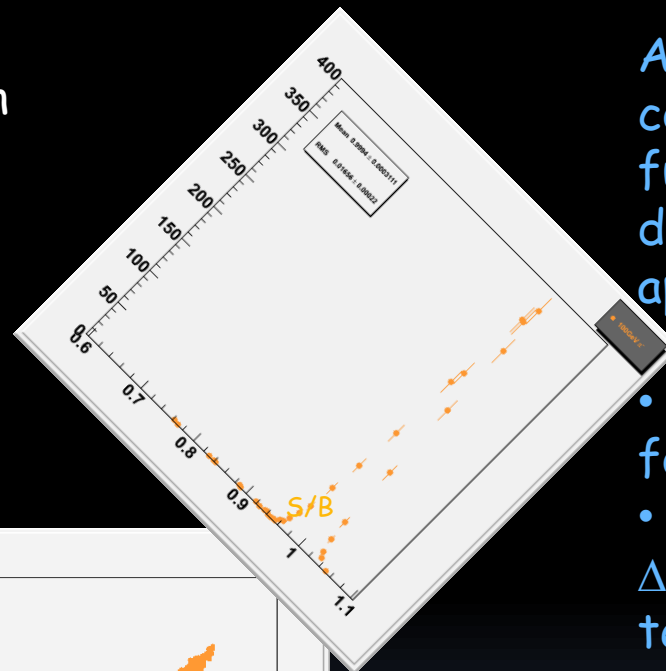• The resulting resolution limited by the local width of the scatter plot

# TAHCAL at Work: Single Particle Measurement

- 100 GeV $\pi-$
- Full Geant4 simulation

- **Raw (uncorrected) $\Delta E/E \sim 3.3\%$**
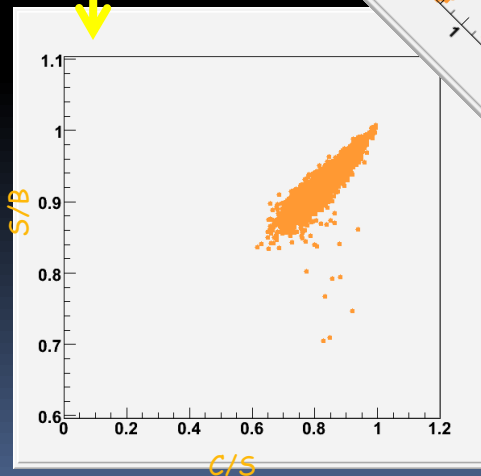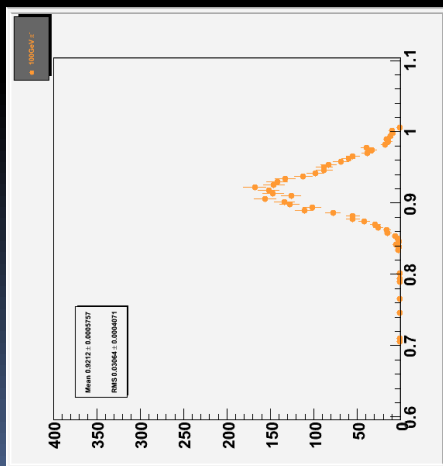
- but significant non-linearity, E~ 92 GeV

After dual readout correction, correction function (C/S) determined at the appropriate energy:
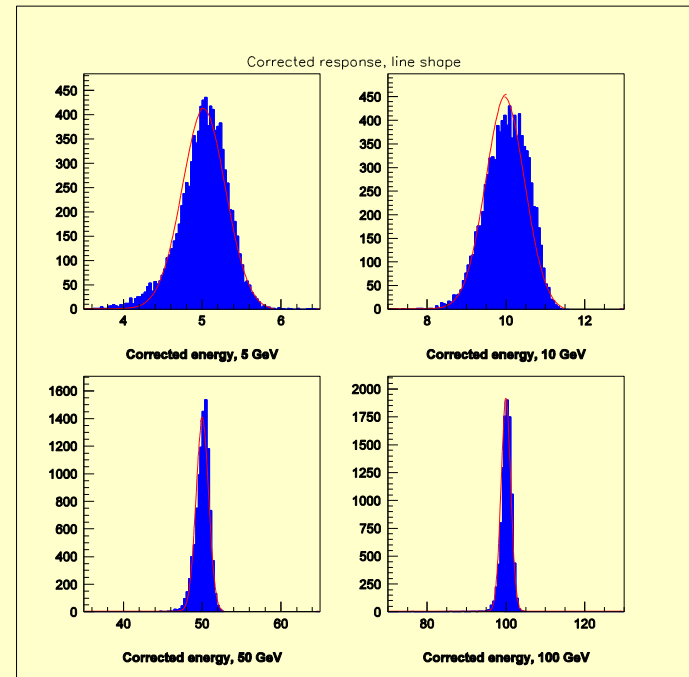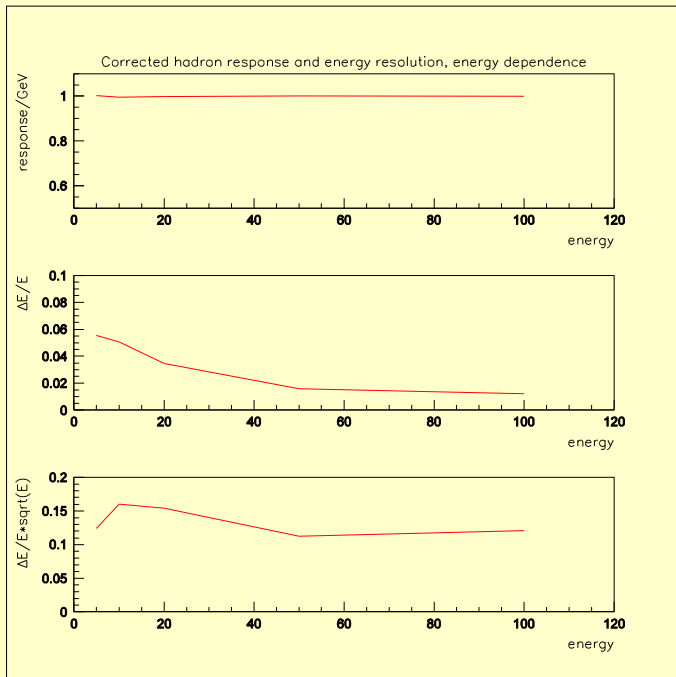
- Linear response: S/B=1 for all energies
- energy resolution $\Delta E/E \sim \alpha/\sqrt{E}$ (no constant term)
- $\alpha \sim 12\text{-}15\%$ or

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

NOTICE: an impossible (abandoned) dream of PFA: $\Delta E/E = 30\%/\sqrt{E}$

# Response and Resolution, Corrected



Corrected hadron response and energy resolution, energy dependence



Corrected response, line shape

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 <u>underestimated</u> due to imperfections of simulation

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

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.
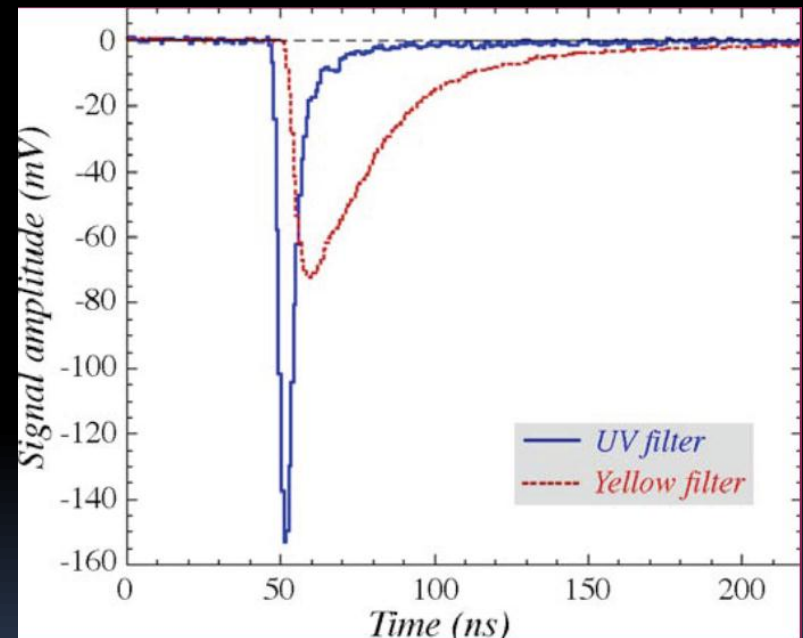
By emission time

By emission time and wavelength/filters (DREAM)

# PART3: 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

# Potential Pitfalls

- YES! 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
- NO! '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 and they play no role in the dual readout correction scheme.

# 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/cramics . 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, $\lambda$~20cm)

- 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 messured)
  - 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), <u>material science</u>

- Great opportunity for major advances in the detectors and instrumentation.

# BACKUP SLIDES

# Monte Carlo Models? Trust and Verify



QGSP BERT (red) vs LCPhys (blue), 10 GeV $\pi-$

Ionization energy

Ionization energy vs Cherenkov

- 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
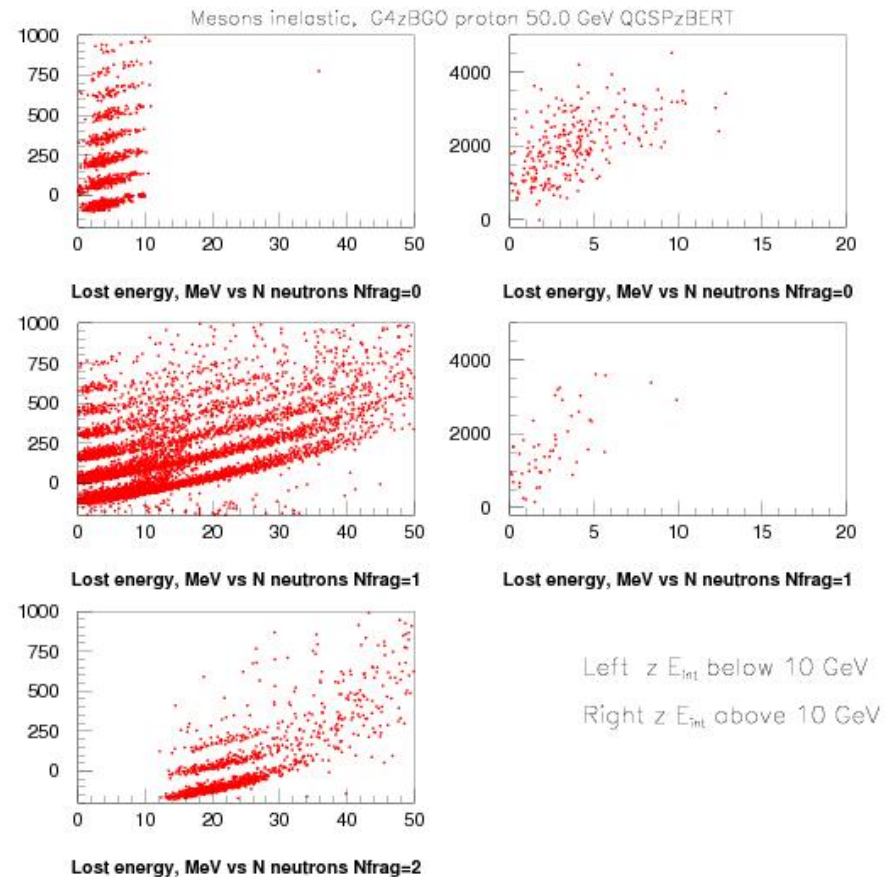  - Really? Is our knowledge SO imperfect????
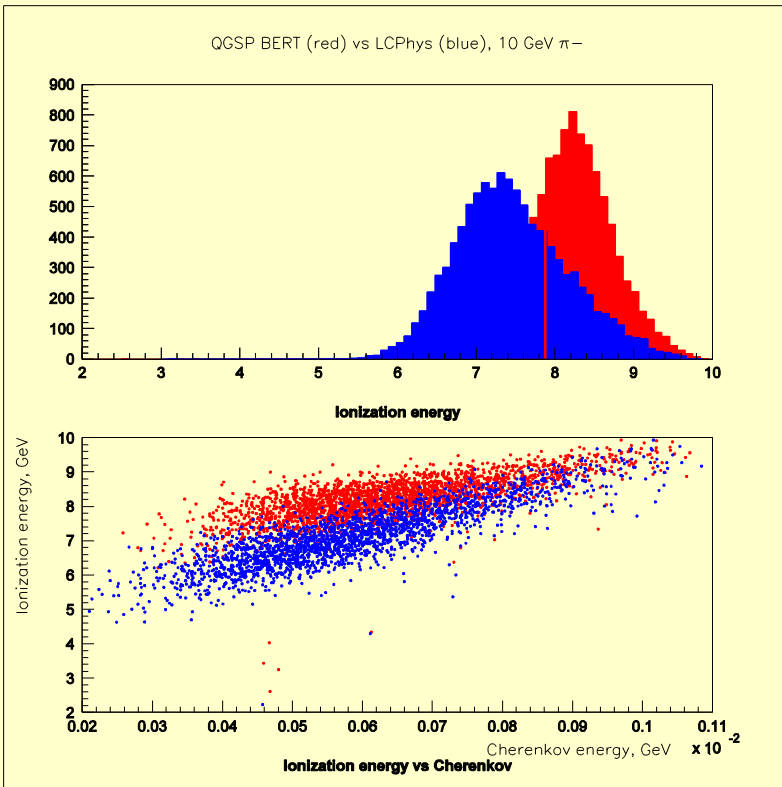
# Different Monte Carlo – Similar Energy Resolution
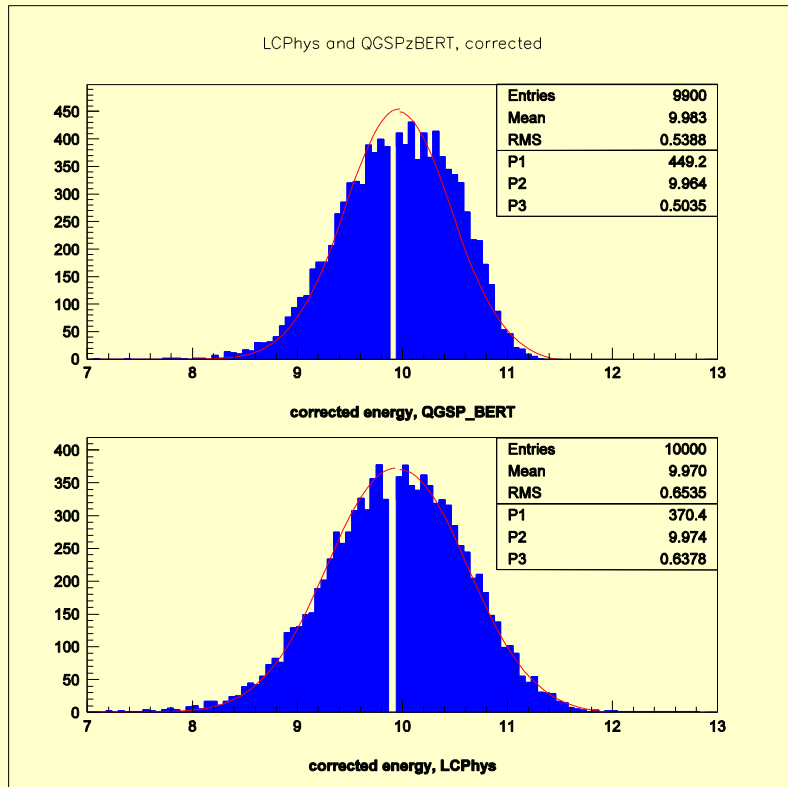


- Use 10 GeV data sets simulated with two different GEANT4 Physics lists
- Treat each set as a hypothetical 'data'. Derive self-consistent calibrations and corrections
- Correct the observed scintillation signal using the Cherenkov signal
- Overall response is stable to about ~1%
- Resolution vary by ~20% of itself (0.50 – 0.63 GeV@ 10 GeV, or (0.15-0.20)/√E)

# Sanity Checks of Monte Carlos?



Mesons inelastic, G4zBGO proton 50.0 GeV QGSPzBERT

Lost energy, MeV vs N neutrons Nfrag=0

Lost energy, MeV vs N neutrons Nfrag=0

Lost energy, MeV vs N neutrons Nfrag=1

Lost energy, MeV vs N neutrons Nfrag=1

Left z $E_{int}$ below 10 GeV

Right z $E_{int}$ above 10 GeV

Lost energy, MeV vs N neutrons Nfrag=2

**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

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# Does the Dual Readout Correction Depend on Energy?
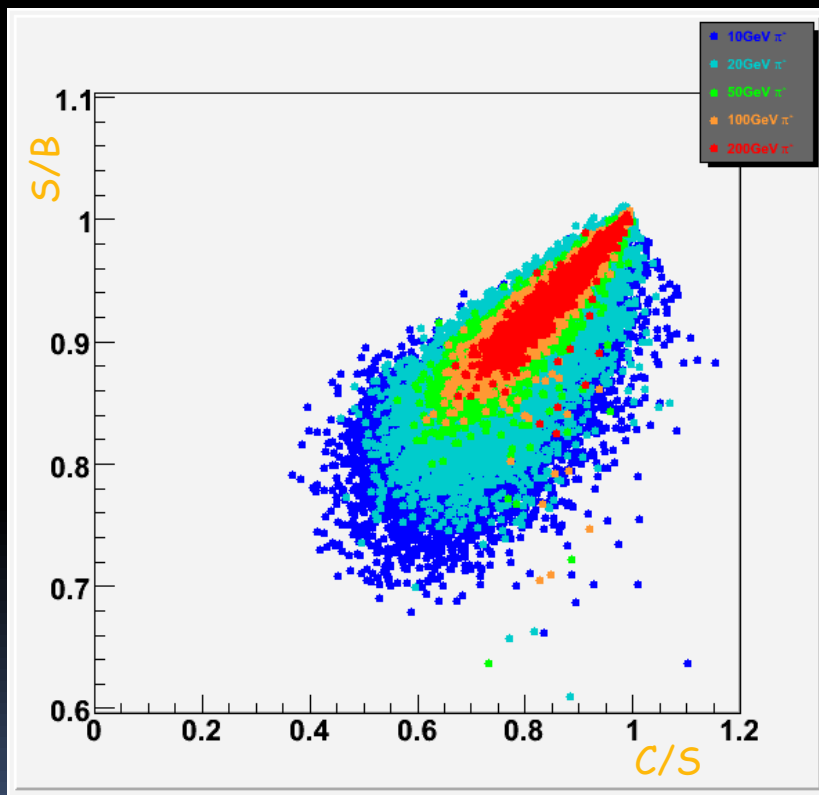


Correlation of the fraction of 'missing energy' and Cherenkov-to-scintillation ratio for showers of different energies: 10 – 200 GeV:
• high energy showers contain more EM energy (range of C/S confined to higher and higher values)
• overall shape quite similar, but significant differences present.
• (Weak) Energy dependence can be implemented iteratively (0th order sufficient)