High Resolution Jet Calorimetry
or
Total Absorption Homogeneous Calorimeter for SiD

Adam Para, Fermilab

SiD Workshop, Boulder, CO

September 18, 2008

SiD Detector

- Compact
- High resolution, robust tracking
- Good muon detection
- "Good enough" calorimetry

- Good enough??? How do we know what the ILC physics will be?? Even today: Chargino $dM/M \sim (dE/E)_{jet}$.
- Reasonable cost-performance compromise ??? Maybe, but within some arbitrarily imposed set of constraints (like PFA).

- Why not a Super Hadron Calorimeter (SHC=PFA++), taking advantage of a compact (➔ relatively small volume) detector design.

Why Hadron Calorimeters are so Poor?

Reminder: $(dE/E)_{EM}$ can be as good as 0.01 for total absorption calorimeters. What's wrong with hadrons?:

- A fluctuating fraction of the hadron energy is lost to overcome nuclear binding energy
- 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)
- Inhomogeneous calorimeters (typically: EM + HAD)
- The net result: Response/True energy = F(particle type, E). Tolerable for single particle measurement, major contribution to energy resolution for jets (collection of particles).

Path to High Resolution Jet Calorimeter

- Homogeneous Calorimeter (EM/Had combined). Need a calorimeter capable of performing required topological measurements for e/γ (position, direction, close showers separation)
- Total absorption calorimeter (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 loses. This can be done, for example, by dual readout of scintillation and Cherenkov light signals.

High Resolution Jet Calorimeter?

- 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
- Major advances in the detectors technology/enabling technologies:
  - High density scintillating crystals/glasses (λ~20 cm)
  - 'Silicon Photomultipliers' ~ robust, inexpensive

Conceptual Design of a High Resolution Calorimeter

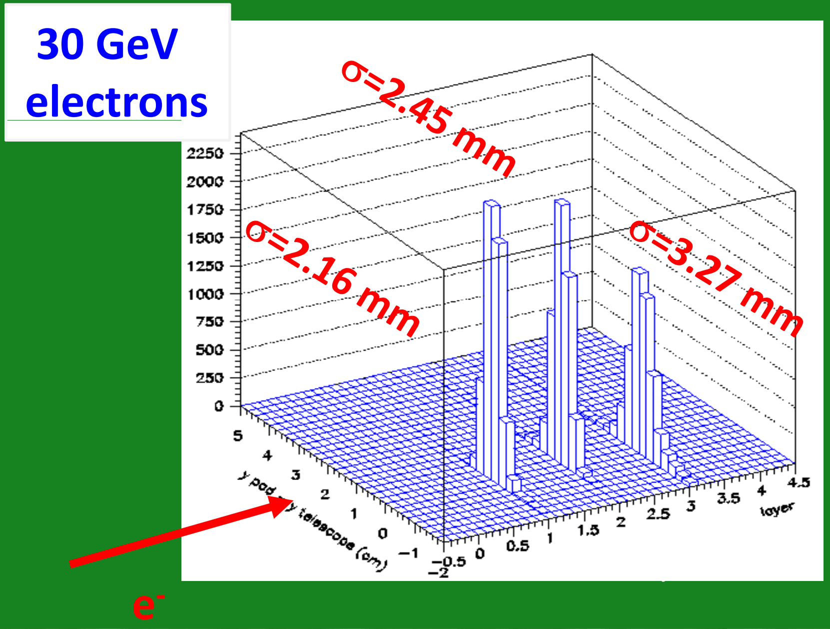
- Six layers of 5 x 5 x 5 cm^3 crystals (a.k.a. EM section): 108,000 crystals
- three embedded silicon pixel layers (e/γ position, direction)
- 9 layers of 10 x 10 x 10 cm^3 crystals (a.k.a. hadronic section): 60,000 crystals
- 4(8?) photodetectors per crystal. Half of the photodectors are 5x5 mm and have a low pass edge optical filters (Cherenkov)
  - No visible dead space.
  - 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.

Separated Functions Calorimeter

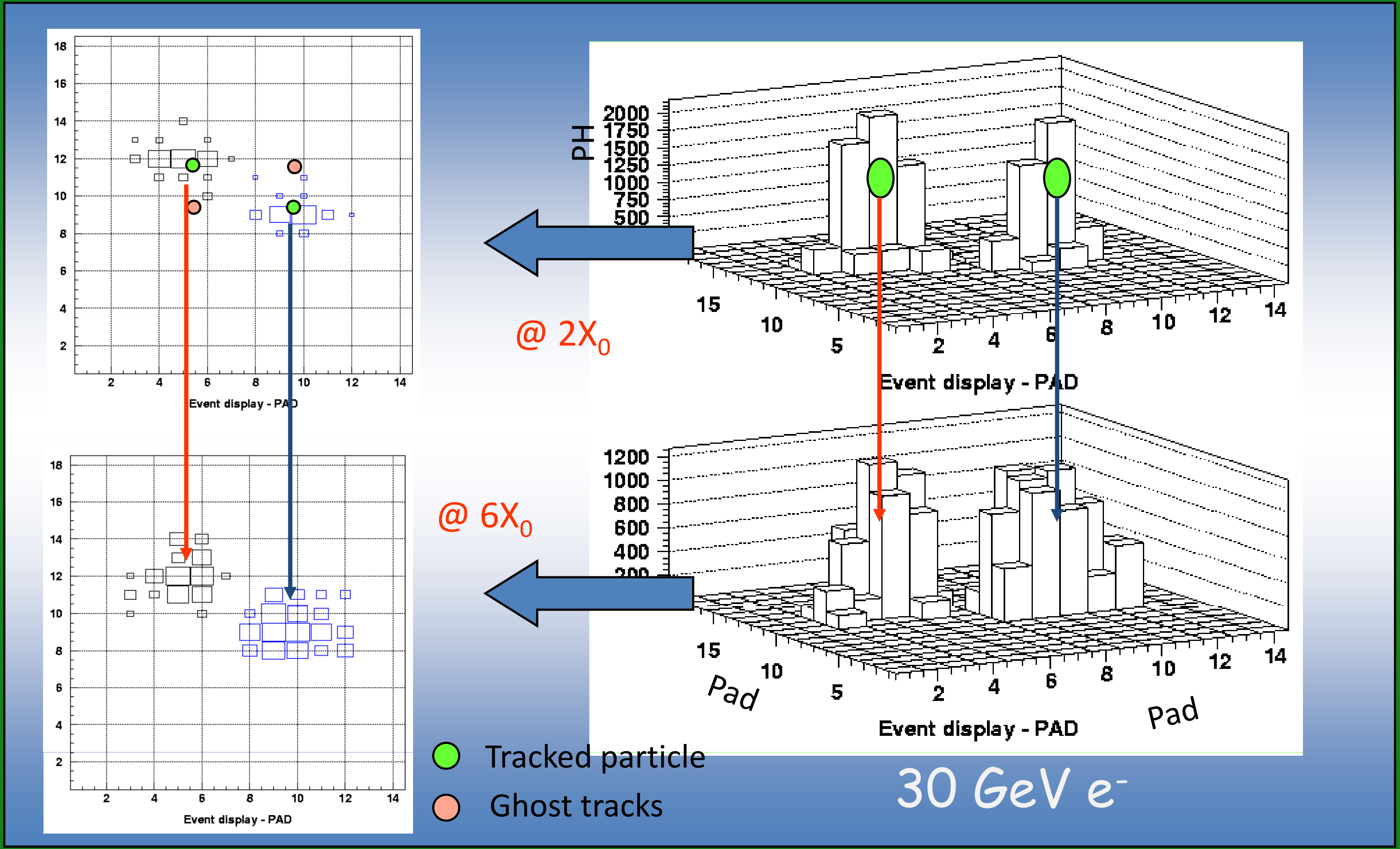
Calorimeters are expected to measure energies of particles/jets. But.. They are also expected to provide topological information: positions, directions, close showers separation. These additional requirements tend to complicate the detector design and compromise the energy measurement.

A possible solution: decouple the energy and topological measurements. Delegate the topological measurements to two-three layers of silicon pads. Negligible fraction of shower energy deposited in silicon should have no adverse effect on the overall energy resolution.

- Such a concept has been put forward, and supported by INFN and DESY. Prototype has been constructed and tested in test beams at Frascatti and at CERN: LCCAL (P. Checchia, LCWS04)
- 3 layers of 0.9 x 0.9 cm silicon pads at 2, 6 and 12 X_0



LCCAL: Two Particle Separation Example



@ $2X_0$

@ $6X_0$

🟢 Tracked particle

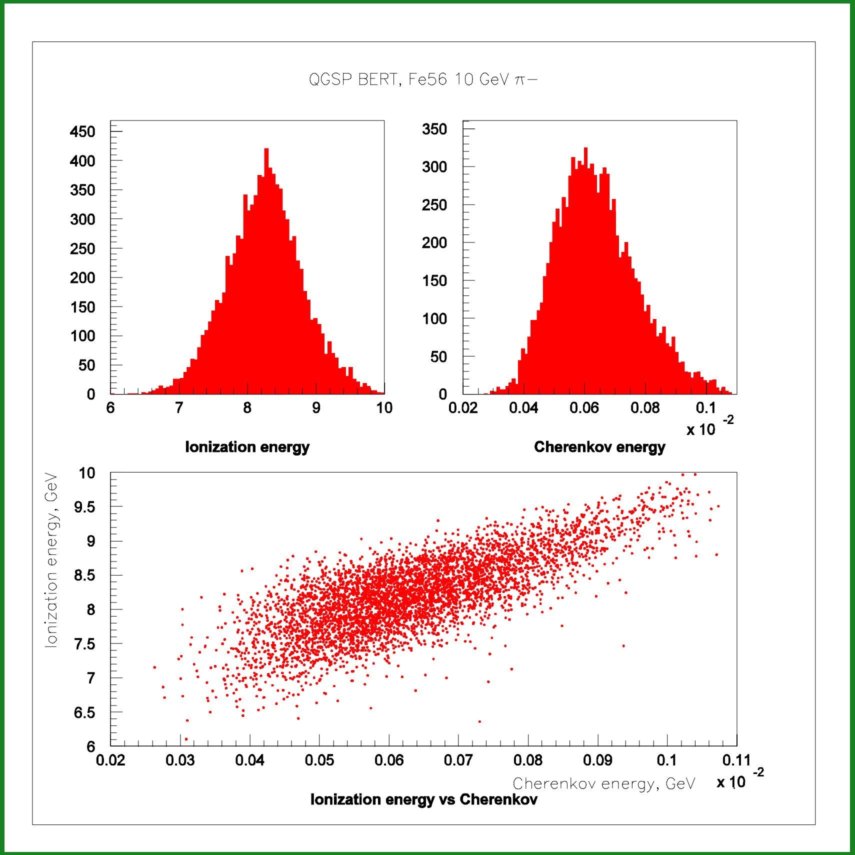
🟠 Ghost tracks

30 GeV e^-

Dual Readout Calorimeter Simulation and Analysis

- Optical calorimeter option in SLIC (Hans Wenzel)
- 1 x 1 x 3 m^3 volume subdivided into 1 cm^3 'crystals'
- Crystals composed of various materials (elements or isotopes) at fixed density of 8 g/cm^3
- Optical properties characterized by the refractive index n (relevant for Cherenkov)
- All scintillation (==ionization) and Cherenkov light summed up from the entire volume. Total information about an event reduced to two variables : S and C.
- Completely automatic reconstruction, no tuning/optimization. No use of the spatial distribution information (yet). Much room for the improvement.

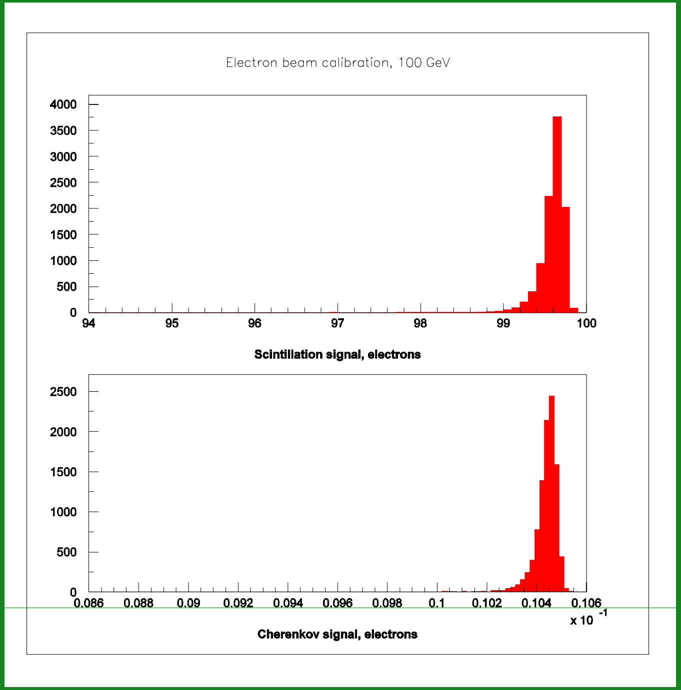
Dual Readout at Work: an Example



- Physics model: QGSP_BERT
- Material: Fe56, n=1.65 (i.e. scintillating, transparent material with the absorption, radiation length and the nuclear properties of Fe56)
- 10 GeV negative pion beam

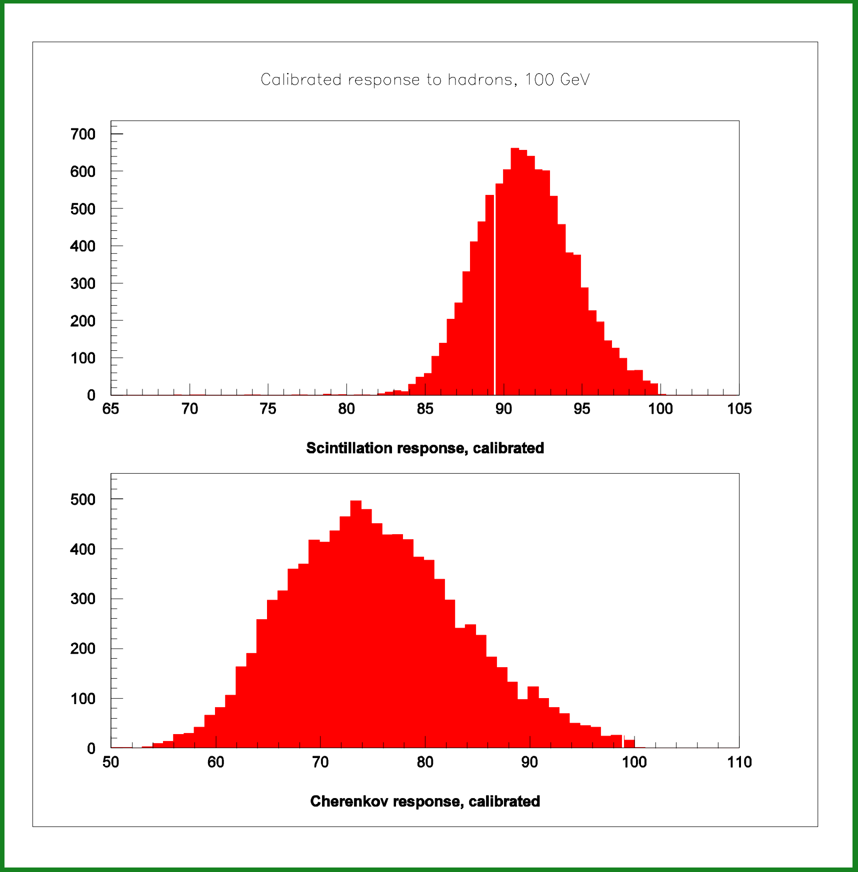
- Only ~80% of energy observed through ionization
- Cherenkov fluctuations much larger than the ionization
- Clear correlation of the total observed ionization and Cherenkov light
- Using the C-S correlation the energy resolution will be limited by the width of the scatter plot only

'Test beam' 100 GeV Step I: Electron Beam Calibration



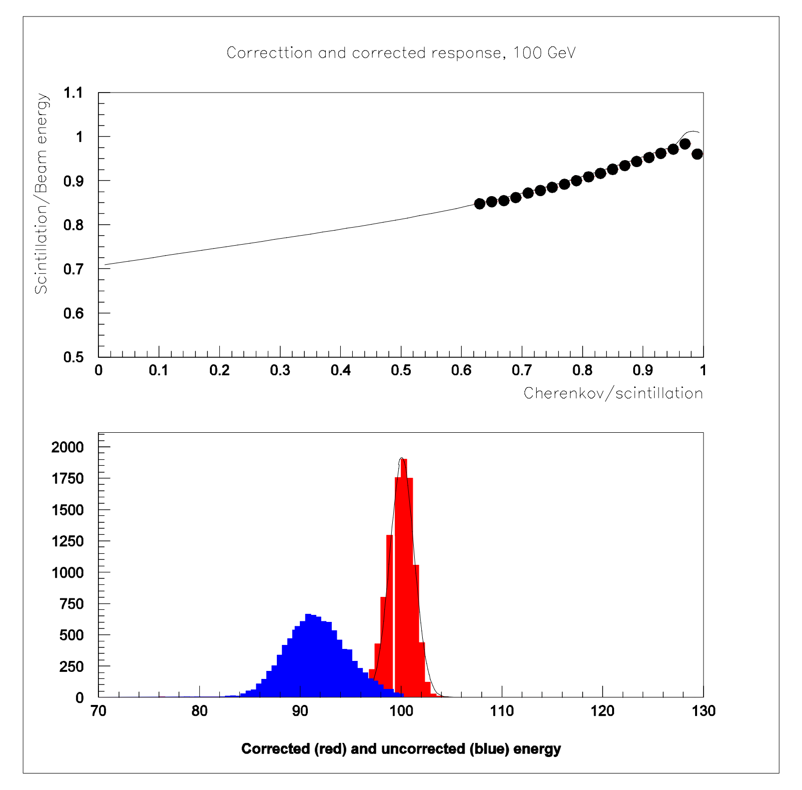
- Collect the scintillation and Cherenkov light measured in some arbitrary units.
- Define the mean values of the distributions to correspond to 100 GeV (calibration beam energy)
- A_{sc}=100/<Scintillation>
- A_{ch}=100/<Cherenkov>

'Test Beam' 100 GeV Step II: π- Beam



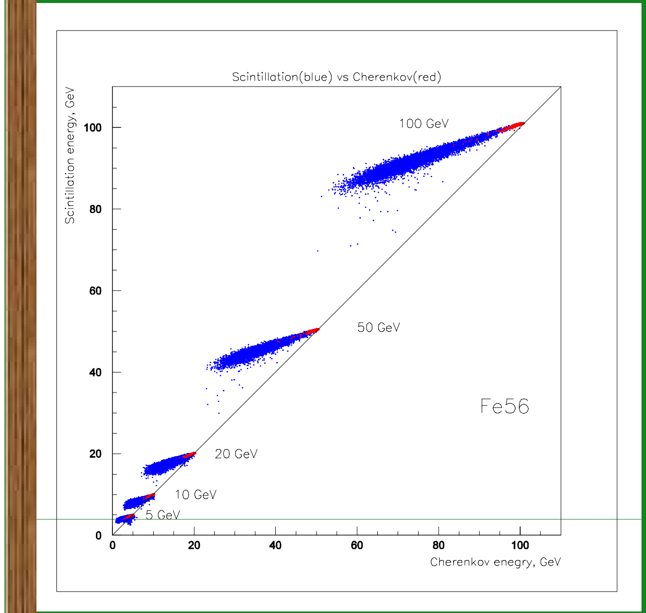
- Collect scintillation and Cherenkov light for 100 GeV negative pions entering the detector
- Use absolute calibration determined with electrons
    - $E_{sc} = A_{sc} * S$
    - $E_{ch} = A_{ch} * C$
- Notice (just observations, not used in the forthcoming):
    - $(\pi/e)_{sc} \approx 0.9$
    - $(\pi/e)_{ch} \approx 0.75$
    - Resolution much worse with Cherenkov

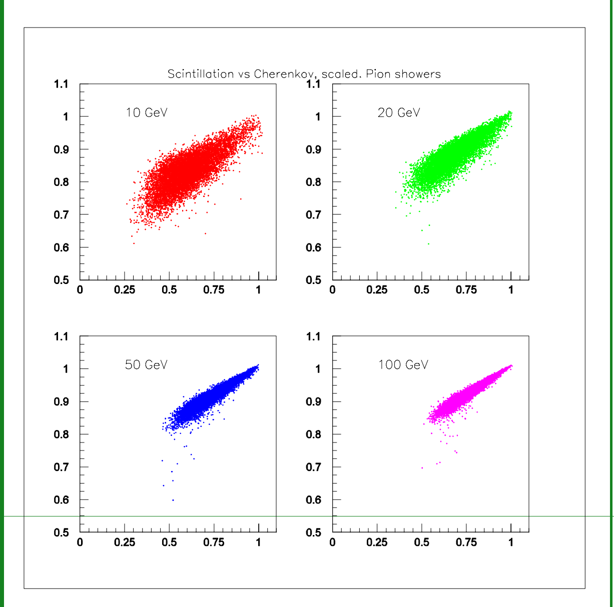
'Test Beam' 100 GeV Step III: Analysis

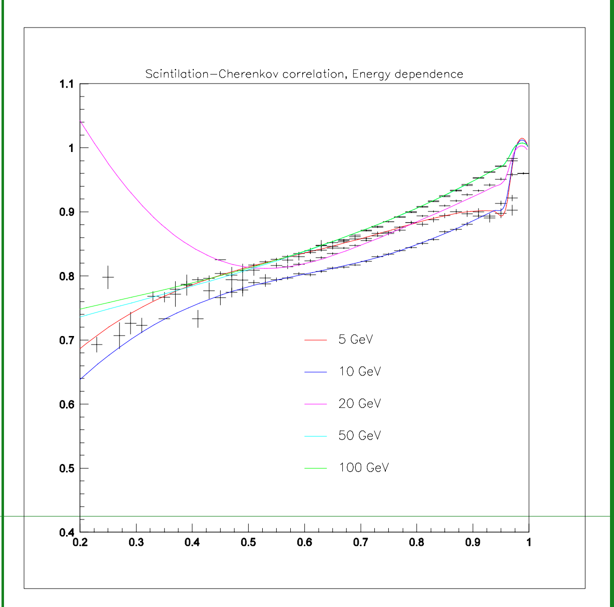


- Plot average S/E_{beam} as a function of C/S
- Fit some correction function F(C/S) (for example polynomial)
- Re-analyze the data:
  - $E = A_{sc} * S/F(C/S)$
- Observe:
  - Average corrected energy(red) ≈ Beam Energy (== $\pi/e \approx 1$)
  - Significantly improved resolution
  - Analysis completely automated, no tuning or free parameters

Scintillation vs Cherenkov Correlation: Energy Dependence

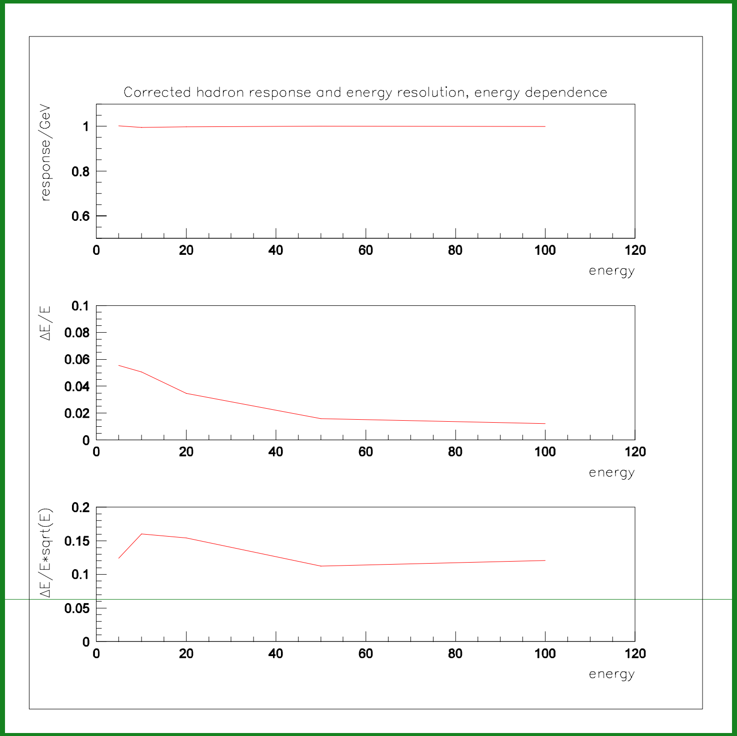


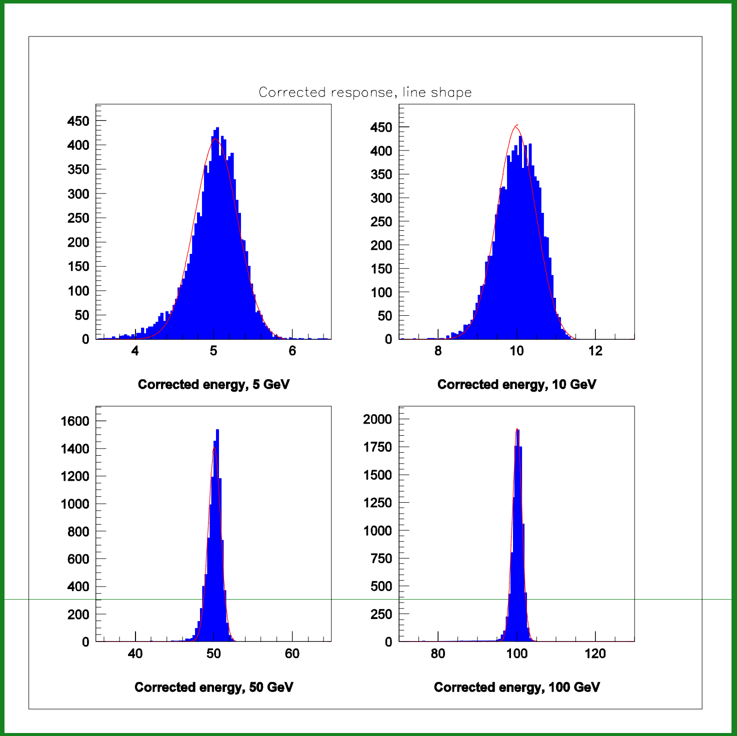




- Cherenkov response linear
- Relative amount of Cherenkov light increasing with E (more π^0's)
- Scintillation vs. Cherenkov correlation improving with E
- Slope of the correlation similar, but level increasing with E

Response and Resolution, Single Hadrons





After 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

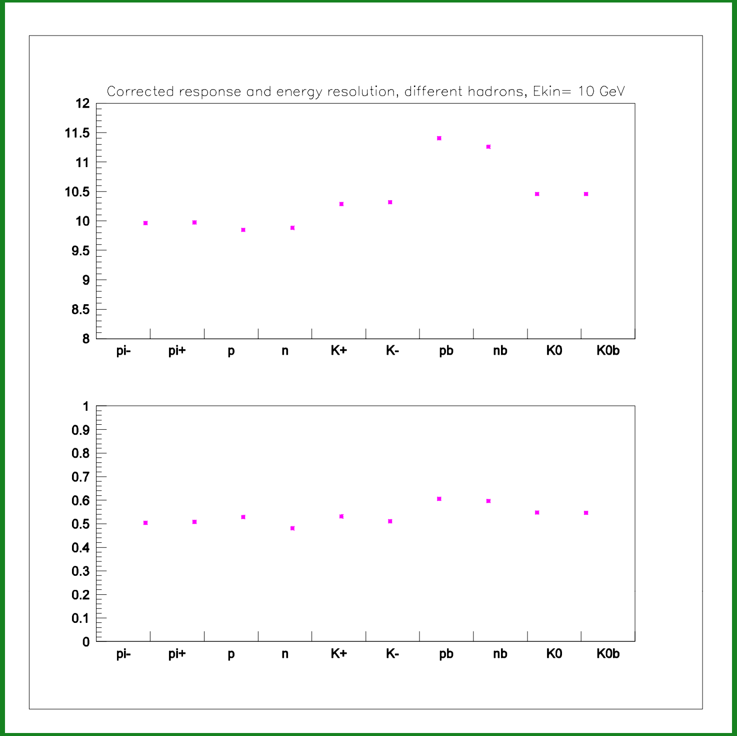
'Other particles'

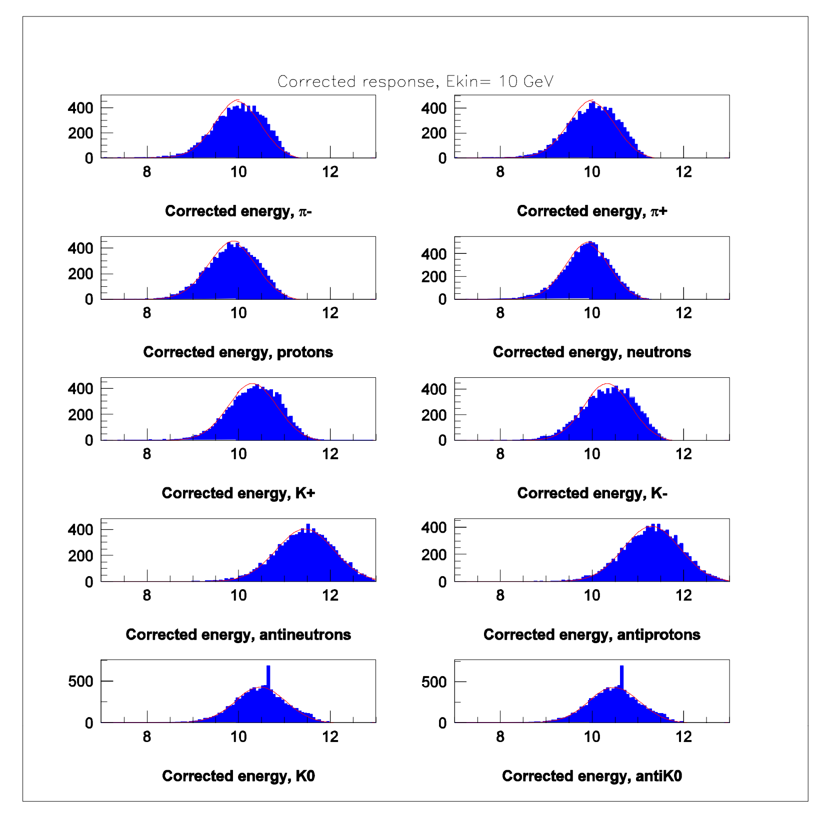
- We can calibrate the response of the detector to pions and protons (perhaps).
- Jets contain also neutrons and kaons. At high energies antiprotons and antineutrons are significant.
- We do not have neutrons/Ko/antineutrons test beams. K's and antiprotons are scarce too.
- We may not have good particle ID inside jets, hence pion calibration will be used as a default.
- How does it affect the energy measurement??

Different Particles, Corrected Response (Using Pion-derived Correction)

- Proton/neutron response: -2%, ~OK
- K's: +0.5 GeV OK!
- Pbar, nbar: +1.5 GeV almost OK
- Resolution ~5% at 10 GeV for all the particles

Gaussian response functions for all particles





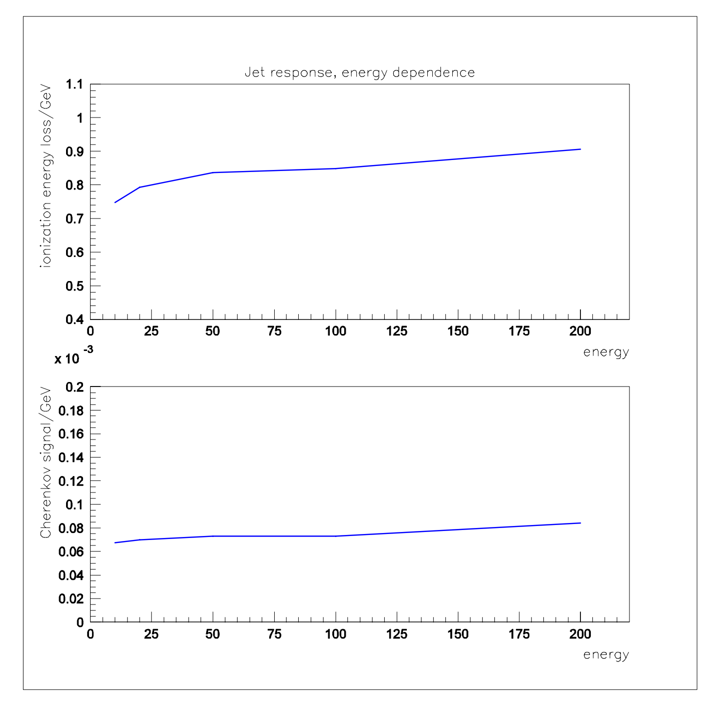
Jets!

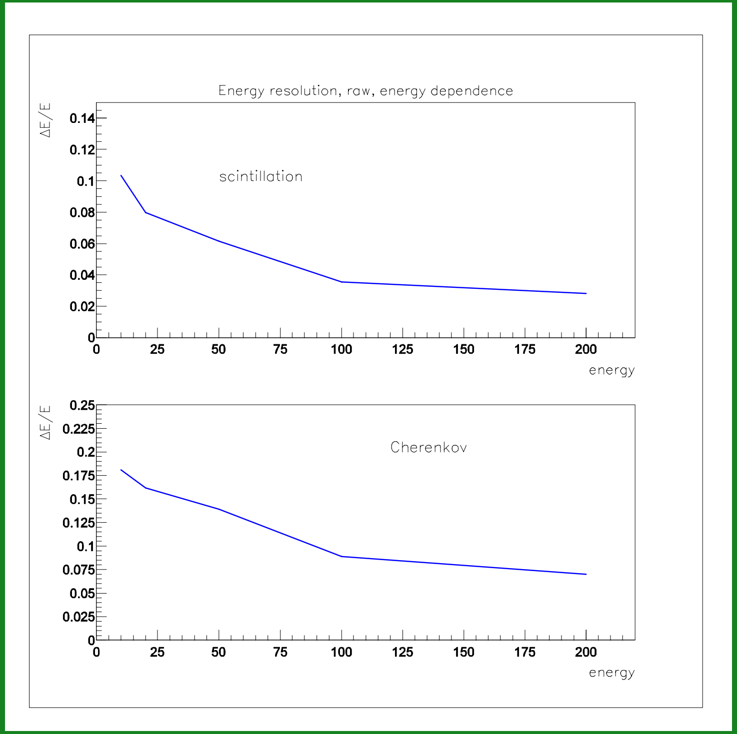
- Use Pythia e+e- → light quarks to create collections of particles with the composition and energy distributions characteristic of QCD jets (beware of the radiative return above Z0 peak)
- Edit the StdHEP list to send all jet particles along z-axis into the detector: S and C are the total amount of light collected from the jet
- Denote $E_{jet} = \sqrt{s}$
- Use (for example) 10 GeV 'pion test beam' correction function to correct (as a function of C/S) the scintillation signal
- This is a very crude algorithm. In a real detector the correction can be applied to localized clusters, using a 'local' C/S. Many other improvements come to mind too.. Will investigate once the complete detector simulation is available.

Jets Response and Resolution, Raw

- Response is somewhat non-linear.
- Jet energy underestimated by ~10-20%.
- Can be calibrated using the data (W/Z), probably

Constant term ~3.5% in energy resolution

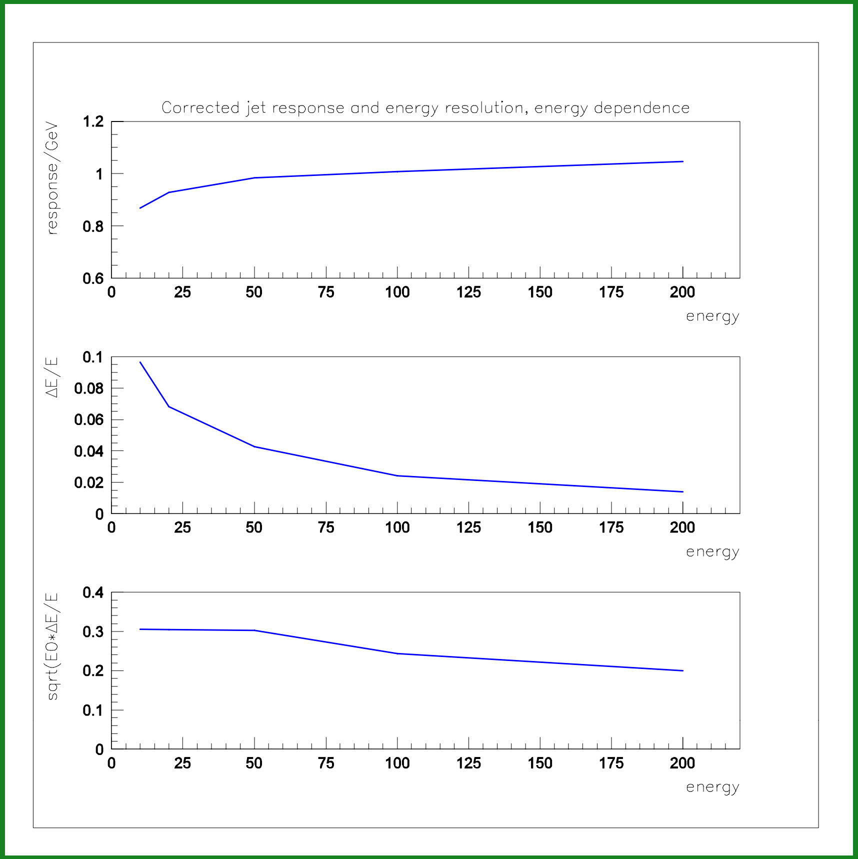


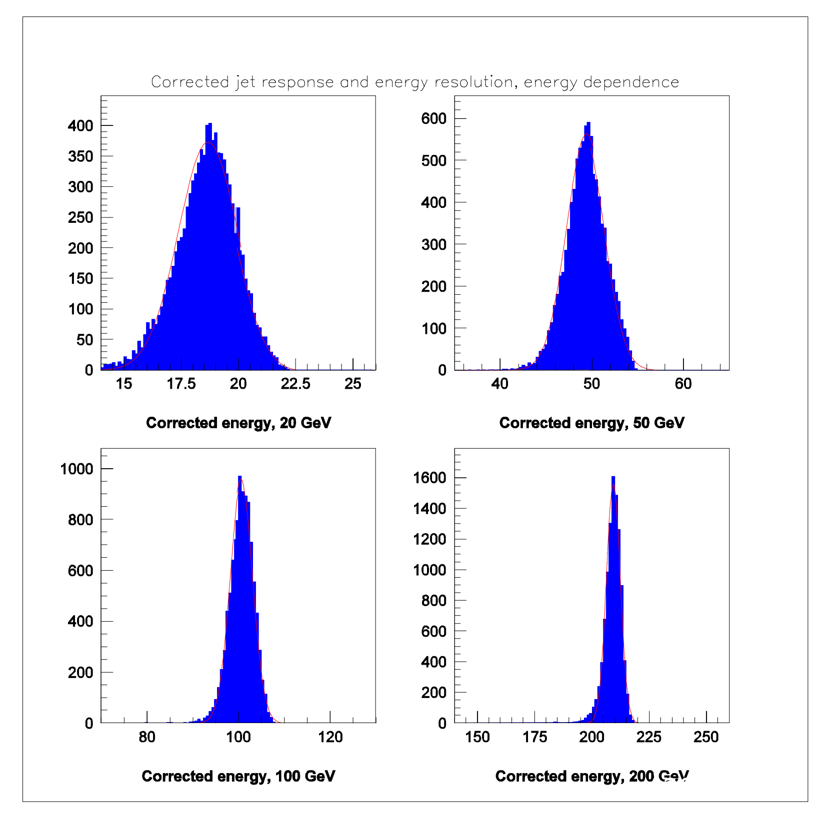


Jets, Corrected Response

- Small non-linearity (~5%) for jets above 50 GeV
- Resolution improves like 1/√E (or better)
- ΔE/E ~ 0.22/√E

Gaussian response function.
No tails!

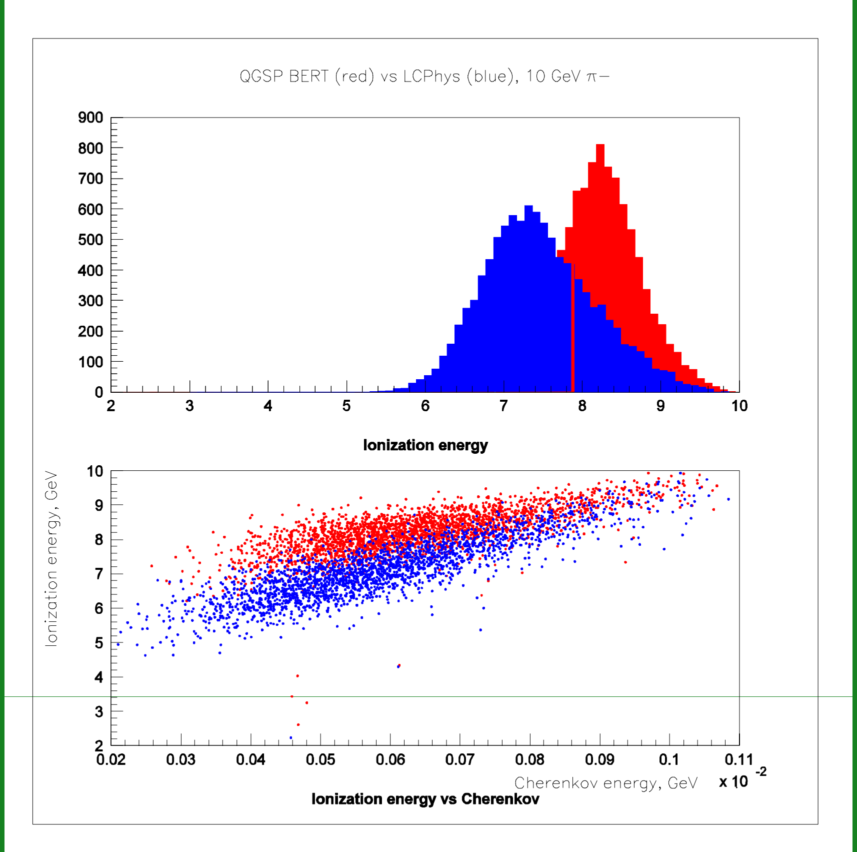




Jets, Summary

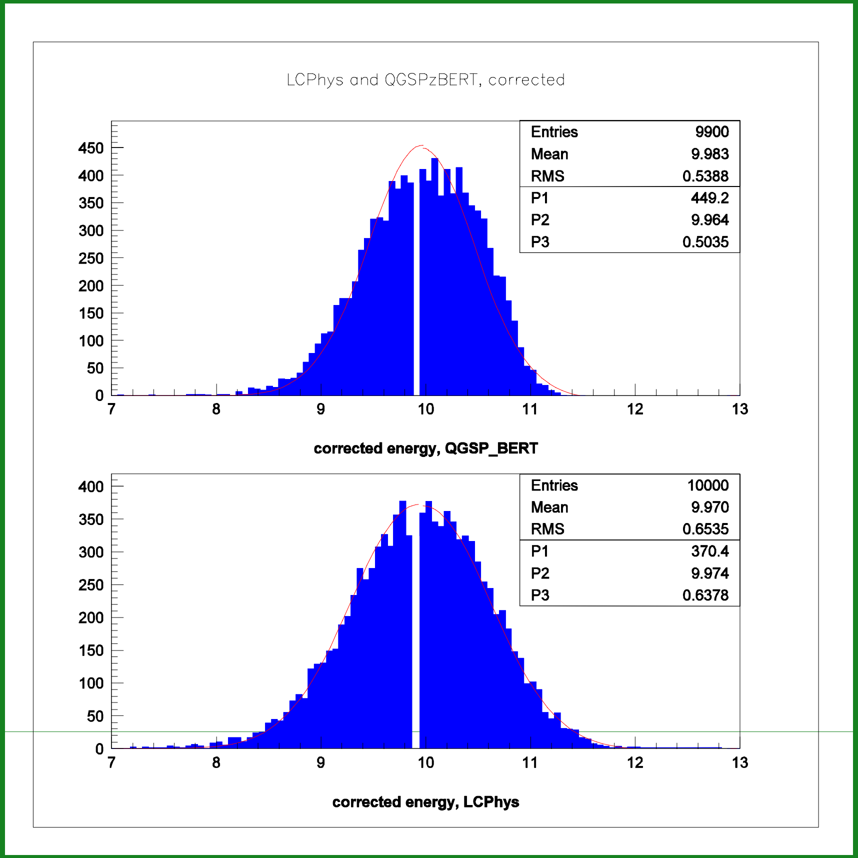
- Complete detector simulation
- Complete reconstruction (crude, far from optimal)
- Gaussian response function, no tails
- Energy resolution (0.2-0.25)/√E
- No indication of a constant term in the energy resolution up to 200 GeV
- Several improvements expected, once a complete detector simulation available
- This is only Monte Carlo simulation! How trust-worthy is it??

Compare Different Monte Carlo Models



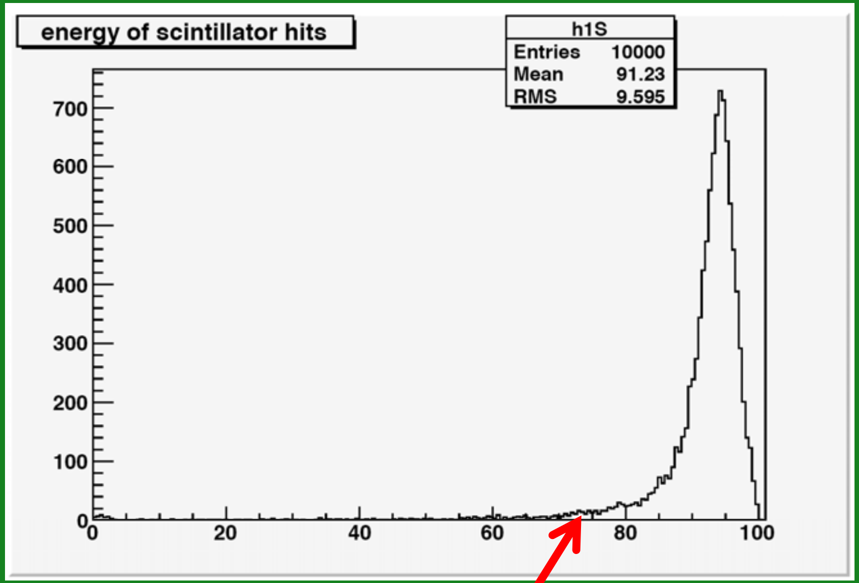
- Use two different physics lists: LCPhys and QGSP_BERT
- Most of the interactions with matter is the same, only hadron production modeling is different
- Surprisingly large difference between the overall response
- But.. Reconstruction/analysis does not use any input from the Monte Carlo,it derives 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

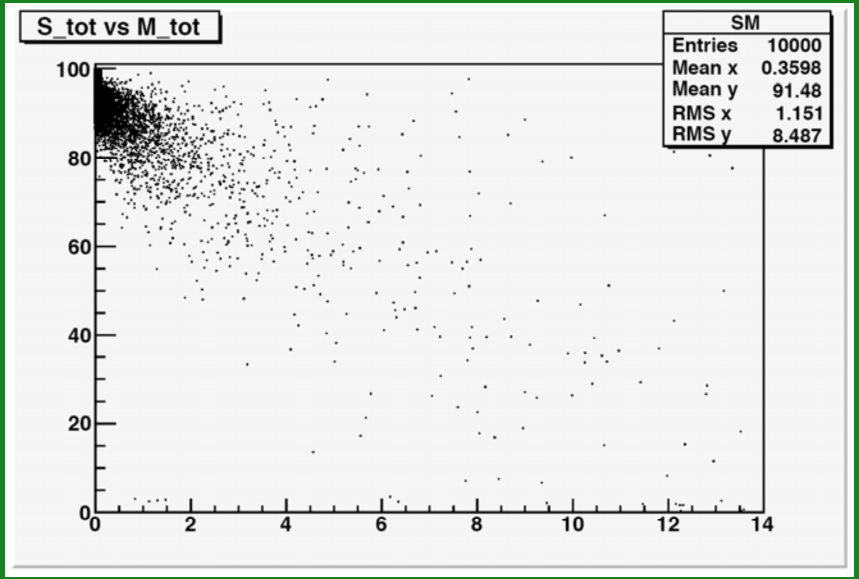
Model Dependence of the Calorimeter Performance



- 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)

SiD Geometry, 100 GeV Single Pions: Look for Punch Through/Leakage





Low(er) energy tail == late showers escaping the calorimeter

Muon system == tail catcher
(Anti-)Correlation of the calorimetric energy and energy observed in a muon system

On-going Studies

- Dependence on the nuclear modeling (use different A absorbers)
- Performance (response and resolution) as a function of the thickness of the calorimeter (containment)
- Performance as a function of the integration time
- Importance/requirements for cross-calibration
- Light collection/separation
- SiPM's characterization as possible photodetectors
- Fluctuations of light yield (especially Cherenkov) contribution
- Di-jet mass resolution:
  - Calorimeter granularity
  - Magnetic field contribution
  - ………
- H. Wenzel, D. Crowe (Fermilab), S. Cole, J. Hill (NIU), Tianchi Zhao, Washington, A. Driutti, G. Pauletta (Udine)

Reality Check?

- It is very likely that the simulation studies will continue to show that a total absorption calorimeter with dual readout can provide a high resolution jet calorimeter. They will never prove that you can built one, though.
- Practical issues:
  - Separation of Cherenkov and scintillation light (time and wavelength) ←→ new crystals design (not too bright, slow scintillation, low cut-off for short wavelength light)
  - <u>Affordable</u>, mass produced crystals (industry)
  - Robust, affordable photodetectors
  - Engineering design of a hermetic, yet buildable and self-supporting detector

'Crystals' Q&A

- Are there crystals suitable for scintillation/Cherenkov light separation? No. Nobody asked for slow, dim scintillator, short absorption length.
- Can such crystals be designed/produced? Yes. (Alain Iltis, St. Gobain)
- Can such crystals be affordable (target price ~ $1/cc)? Probably. What drives the cost of crystals?
  - Energy cost for melting (➔ melting temperature)
  - Crucibles material wear
  - Raw materials (BGO)
- Do we need to insist on single crystals?? NO! High density polycrystalline scintillating materials have been produced. Cost can be greatly reduced.

Performance Risk ?

- Dual readout offers path to very good energy resolution. What happens if there is heretofore unknown flaw, or if the separation of Cherenkov/scintillation light will not be practically possible or affordable? Jet energy resolution of a total absorption calorimeter with scintillation only readout is ~ 3.5%.
- If this is deemed 'good enough' than a much cheaper calorimeter can be also contemplated using heavy scintillating glasses. (R&D program initiated at Ningbo University)

Conclusion

- Very high resolution jest calorimeters with the energy resolution of the order of 20%/sqrt(E) appears quite feasible and attractive option for a relatively compact detector, like SiD.
- Such a calorimeter requires development of new scintillating materials. They appear to be quite feasible and may be quite affordable.
- Development of these new materials may take several years, but it is probably well matched with any realistic timeline for the ILC experiments.
- A scintillation-only total absorption calorimeter is an intriguing opition too. It is inferior to the dual readout one, but it may be an attractive cost-performance compromise.