High Resolution Jet Calorimetry
or
Total Absorption Homogeneous Hadron Calorimeter

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Statement of a Problem

Design the best calorimeter to measure jet energy, where 'jet' == a collection of particles with a composition and a momentum distribution characteristic of QCD fragmentation

Will ignore (for now):

- How good energy resolution is 'good enough' ?
- Jet finding algorithm
- Jet energy vs. underlying parton energy
- Jet mass measurement
- Jet direction measurement
- Magnetic field spreading the particles

Important for di-jet mass resolution.. Coming…

Detector Under Study

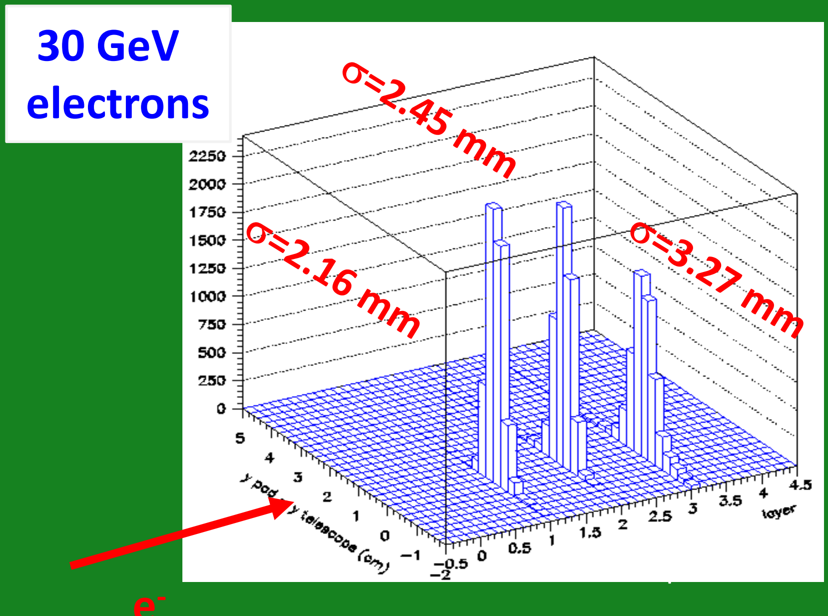
- Fully active, total absorption calorimeter with scintillation and Cherenkov light collection (separated)
- Full simulation using GEANT4/SLIC suite. Optical calorimeter option (Hans Wenzel)
- 'Test beam' geometry: 1 x 1 x 3 m^3, sub-divided into 1 cm^3 cubes
- Full albeit very simple reconstruction. Completely automatic with no tuning/adjustable parameters.
- Caveats:
  - All Cherenkov light collected
  - Scintillation light assumed proportional to the total ionization energy loss (no Birks saturation)

Separated Functions Calorimeter

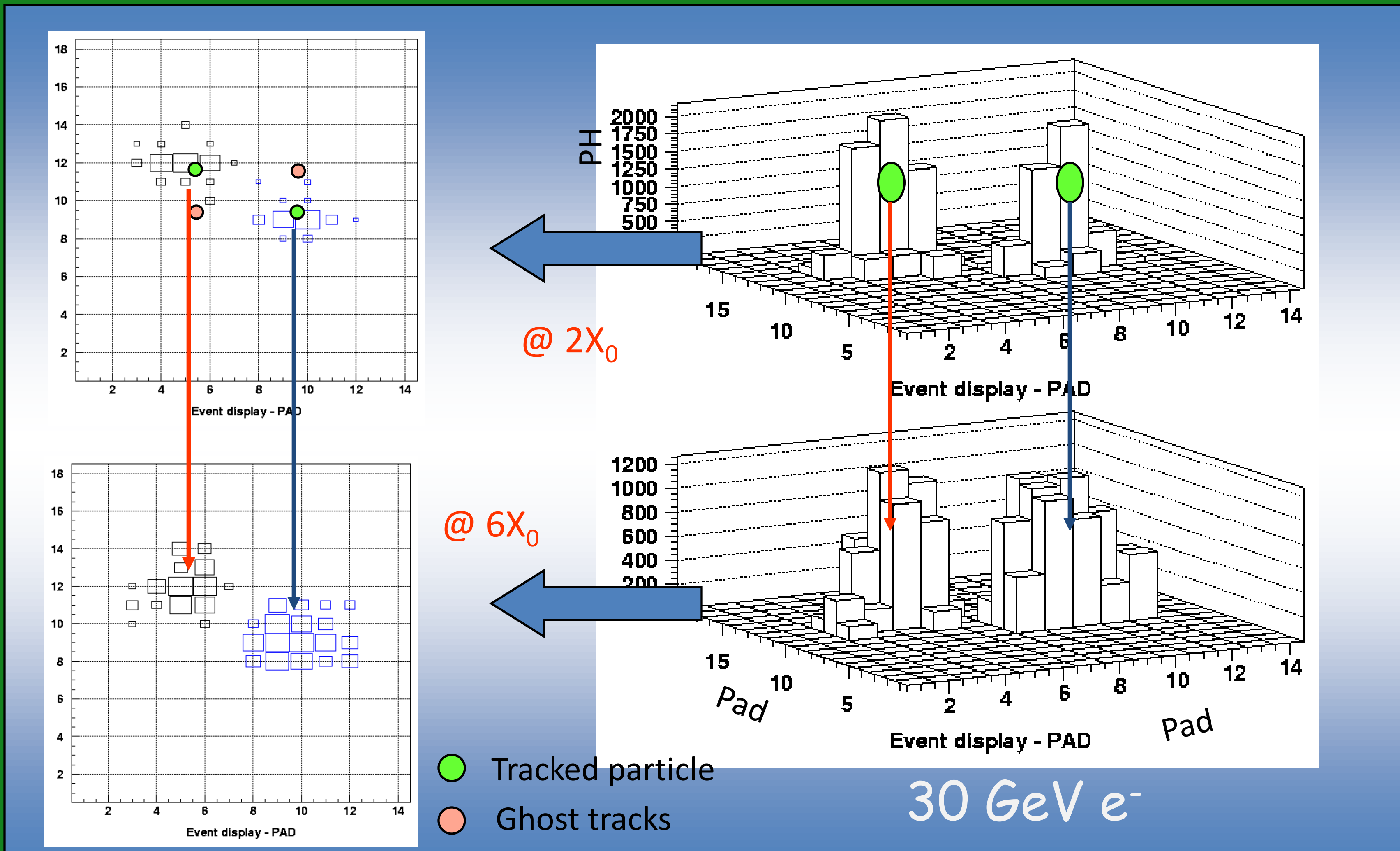
Calorimeters are expected to measure energies of particles/jets. But.. They are also expected to provide topological information: positions, directions, close showers separation. These additional requirements tend to complicate the detector design and compromise the energy measurement.

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



Studies Presented (Progress Report)

- Physics principles and performance of the dual readout calorimeter
- Single particle response linearity and energy resolution as a function of particle energy
- Dependence on the detector material (nuclear interactions)
- Dependence on the optical properties of the detecting medium
- Response and energy resolution for different hadrons
- Response and energy resolution for jets
- Comparison of different detector simulation codes
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Forthcoming studies

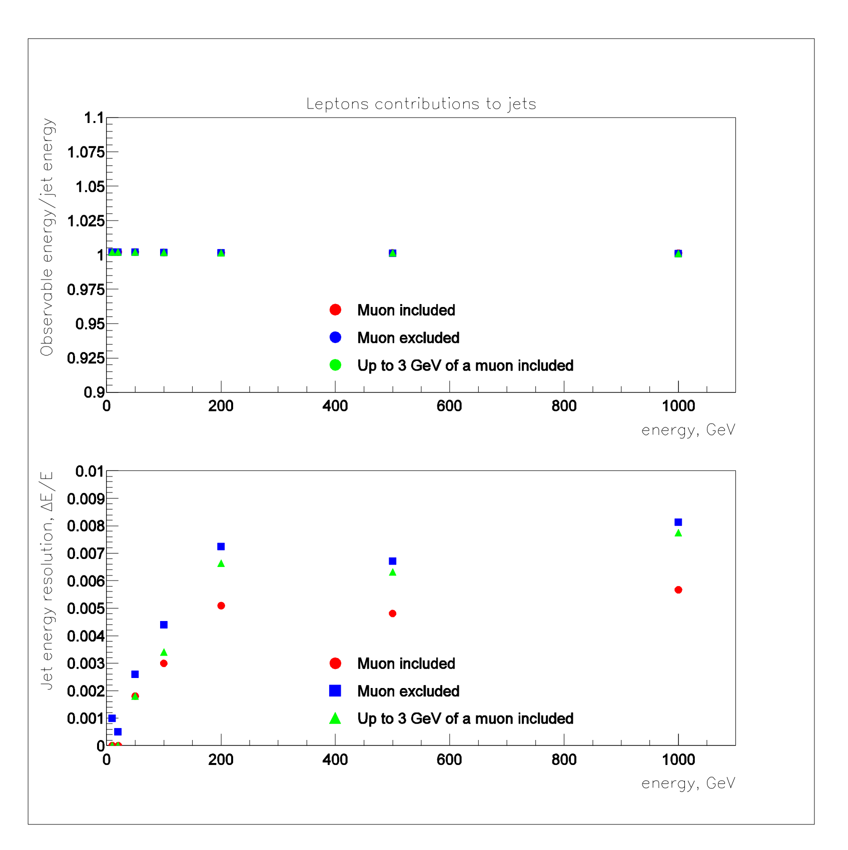
- Light (scintillation and Cherenkov) propagation collection (Hans Wenzel (Fermilab), Stephen Cole (NIU))
  - Contribution of photo-statistics (Cherenkov!)
  - Contribution of light collection non-uniformities
- Implementation into SiD detector (Hans Wenzel (Fermilab), Daniel Crow (Summer Student), Anna Driutti (Udine))
  - Jet mass and direction
  - Jet finding
  - Magnetic field effects
  - Cracks and dead spaces

Jet Energy: A Toy Model

$$E_{jet} = \sum_{electrons,\pi^o} E\left(1 + \frac{\alpha_{EM}}{\sqrt{E}}\right) + \sum_{hadrons} \begin{pmatrix} \beta \\ f(E) \end{pmatrix} E\left(1 + \frac{\alpha_{Had}}{\sqrt{E}}\right) + \sum_{muons} \begin{pmatrix} E \\ 3\ Gev \end{pmatrix}$$

- Jet = {charged pions, π^o's, protons, neutrons, charged/neutral K's, electrons, muons, neutrinos}
- Electrons (and photons from π^o decays) have a linear response and have energy described by a stochastic term α_{EM}
- Hadrons have energy resolution described by a stochastic term α_{Had}. Their response is suppressed (relative to electrons) by a constant factor β, or by a non-linearity function f(E)
- Muons are measured well by tracker, or they deposit up to 3 GeV in a calorimeter (if not recognized as muons)
- Neutrinos are lost
- Constant terms in the energy resolution are ignored as particles in the jets have rather low energies.
- Jets are modeled using Pyhtia, e+e- → q qbar

Leptons and Jet Energy/Resolution



- Heavy quarks are produced in the jet fragmentation. Semileptonic decays produce neutrinos, muons and electrons.
- Electrons are measured well by EM calorimeter.
- Identified muons can be included properly.
- Non-identified muons deposit up to ~ 3 GeV in the calorimeter.
- Lepton content of jet does not affect the jet energy calibration.
- Fluctuations of the neutrino content contributes 0.5% to the jet energy resolution for jets above 200 GeV.
- In the absence of muon identification this constant term rises to 0.7-0.8%
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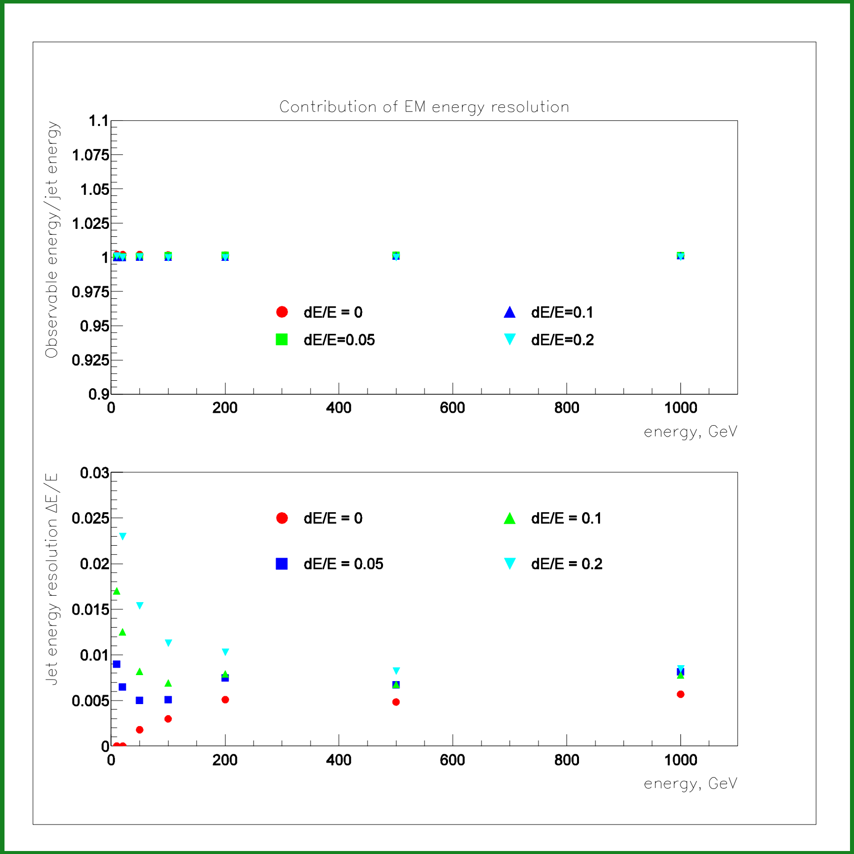
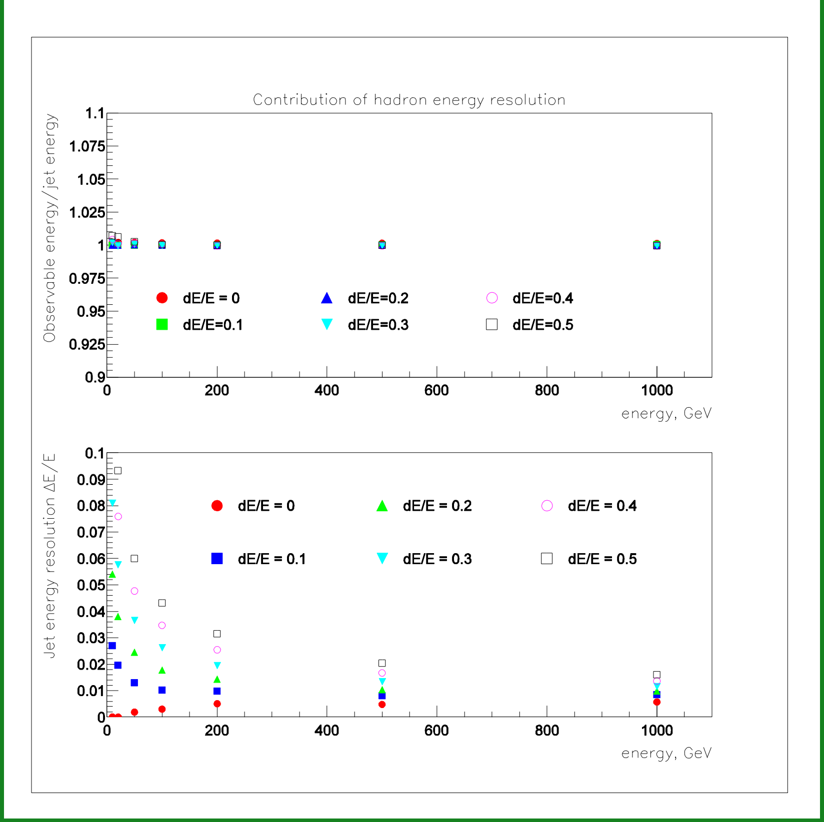
Jet Measurements and EM Energy Resolution



- Assume that the EM component of the jet is measured with the resolution $\alpha_{EM}/\sqrt{E}$, with α=0, 0.05,0.1 and 0.2.
- Neutrino contribution is included

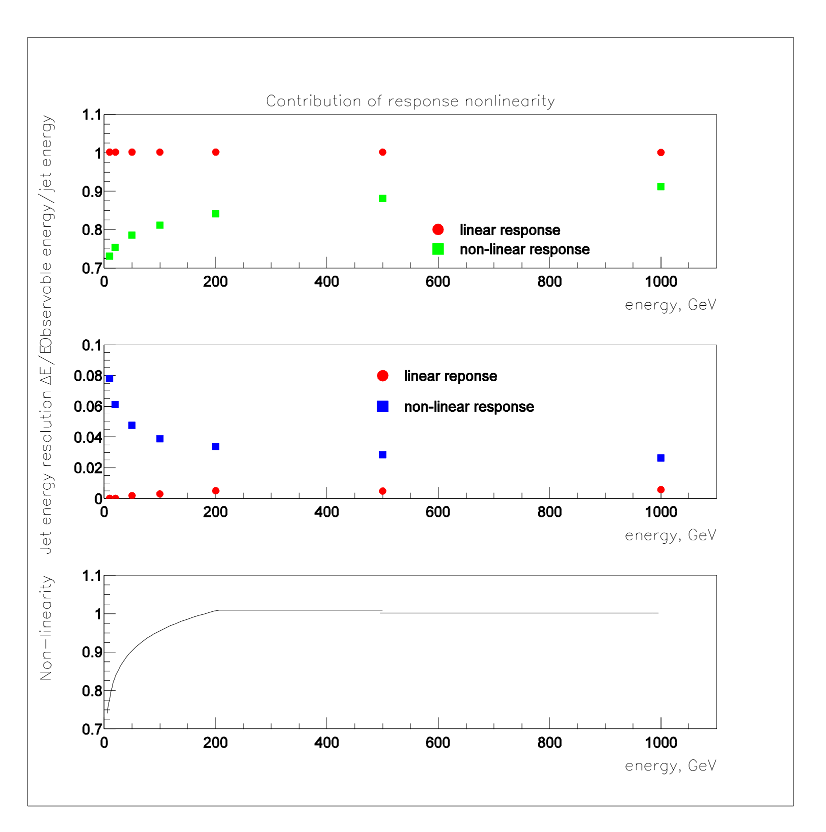
- Electromagnetic energy resolution does not have any impact on the jet energy calibration
- Contribution of the EM energy resolution to the jet energy resolution is very small and significantly exceeds the irreducible neutrino contribution only at low energies, E<100 GeV

Jet Measurement and Hadron Energy Resolution



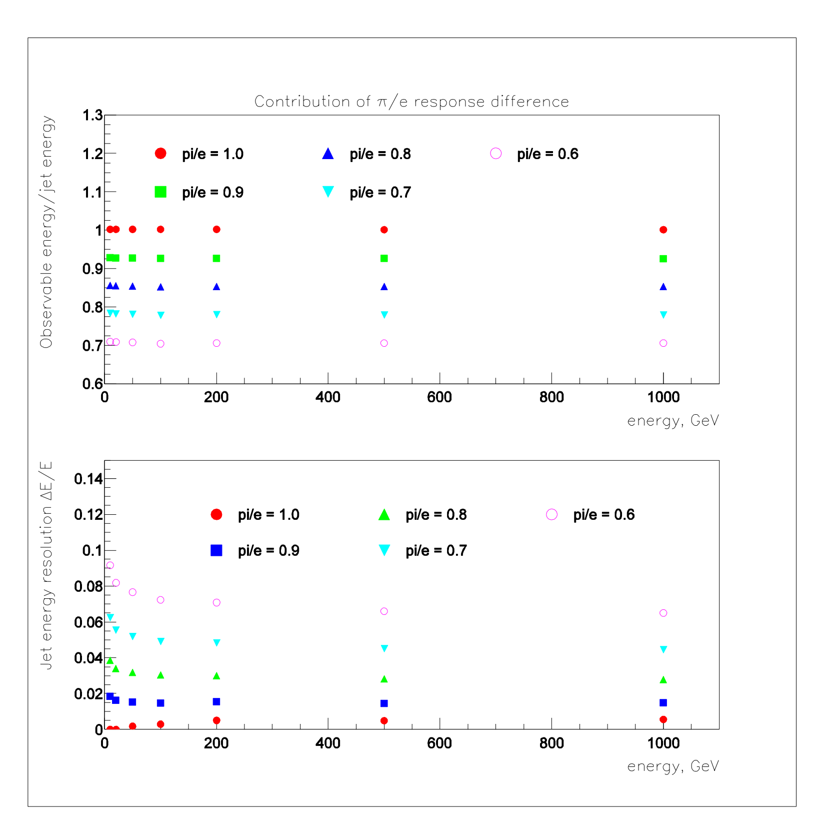
- Assume that the hadron energy is measured with the (Gaussian) resolution $\alpha_{Had}/\sqrt{E}$, with α=0, 0.1, 0.2,0.3 0.4 and 0.5
- Jet energy resolution is ~proportional to the hadron energy resolution

Non-linearity of the Hadron Response and Jet Measurement



- Assume that a response to electrons is linear
- Assume that π/e response ratio rises from 0.7 to 1 between 1 and 200 GeV
- Jet energy measurement is non-linear
- For 1000 GeV jets the observed energy is only 90% of the true energy
- Contribution to the jet energy resolution ranges from 6-8% at low energies to ~3% constant term at high energies

π/e Response Ratio and Jet Energy Measurement



- Assume that the response of a calorimeter to hadrons is reduced by a factor $\beta = 0.9, 0.8, 0.7, 0.6$ (energy independent) with respect to the response to electrons. The overall jet energy will be underestimated, whereas the fluctuations of the π^0 content of jets will lead to the worsening of the jet energy resolution.
- *Jet energy scale is reduced by an overall factor ~0.8*(1-β)*
- *Jet energy resolution is limited by a constant term ~0.15*(1-β)*

Contributions to Jet Energy Resolution

	50 GeV	100 GeV	200 GeV	500 GeV
Neutrinos	.002	.003	.007	.006
α_{had} = 0.1	.013	.010	.009	.008
α_{had} = 0.3	.037	.026	.020	.013
α_{had} = 0.5	.060	.043	.032	.020
α_{EM} = 0.1	.008	.007	.008	.007
α_{EM} = 0.2	.015	.011	.010	.008
Non-linearity	.048	.039	.034	.028
β = 0.9	.015	.014	.015	.014
β = 0.8	.032	.030	.030	.028
β = 0.7	.052	.049	.048	.045

Dominant contributions (in excess of 2%) are:

- Stochastic term in hadron energy resolution $\alpha>0.3$
- Non-linearity of the response to hadrons
- Difference in the response to electrons and hadrons, $\beta>0.9$
- The latter two dominate at very high energies (constant term)

Simulation or Test Beam Studies?

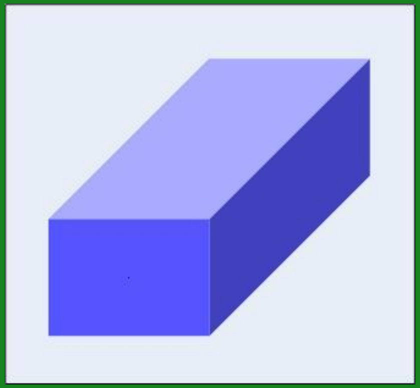
Test Beam

- Test beam is the ultimate test. Simulations cannot be trusted.
- But test beam study of a hadron calorimeter is a large and expensive experiment.
- Limited selection of beam particles and energies. No jets!
- Very limited of possible detector designs, materials and geometries can be tested.

Simulation

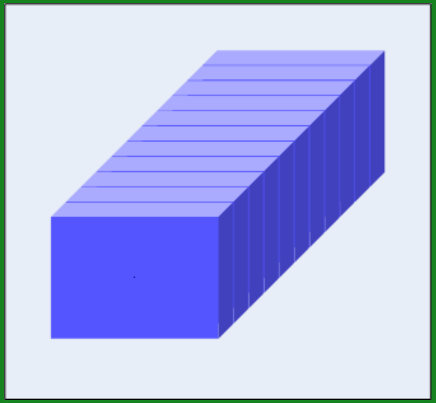
- Relatively easy to model different detector designs, geometries, materials.
- Necessary first step to design/optimize the test beam prototype.
- Good tool to explore underlying physics mechanisms (can simulate materials difficult or impossible to construct).

Simulating the Response of the Calorimeter. Case I: Total Absorption



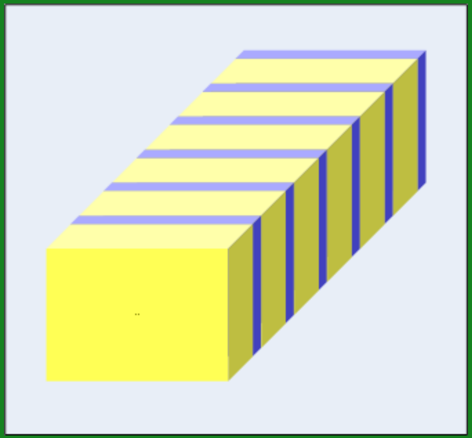
- Total kinetic energy deposited in the detector is detected.
- $E_{obs} = E - E_{leakage} - E_{potential}$
- Example of $E_{potential}$: binding energy of nucleons
- This is the simplest case. It does not depend on the details of the interactions, apart from the nuclear breakup modeling. (Ignoring saturation effects for slow nuclear fragments)
- For example: for electrons $E_{obs} = E$ (modulo small leakage correction). Another (academic) example: liquid hydrogen total absorption hadron calorimeter: $E_{obs} = E$ independent on the model of hadronic interactions.

Simulating the Response of the Calorimeter. Case II: Sampling, Homogeneous



- Somewhat academic example: Calorimeter built out of separate volumes (plates). Only signals from a small fraction f of the volumes is collected (if, for example readout electronics is not affordable)
- As the total absorption case, except that E_{obs} = $E_{detected}$/Sampling_Fraction
- Additional fluctuations (sampling)
- Sampling_Fraction = 1/f (for vary large sampling frequency). But it depends on the shower profile d^2E/dz.
- For realistic detectors Sampling_Fractions depends on particle energy ➔ response non-linearity
- Sampling_Fraction depend on the particle types
- Simulation of the response depends on the modeling of the interactions

Simulating the Response of the Calorimeter. Case III: Sampling, Inhomogeneous

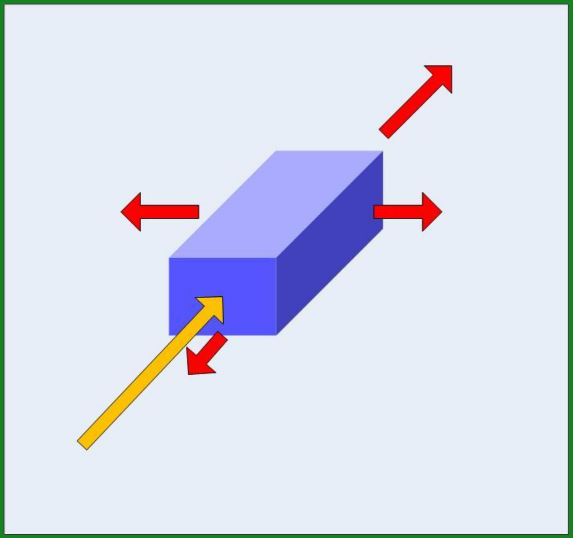


- A typical sampling calorimeter: Dense absorber and relatively light detecting medium.
- As in the case II, $E_{obs} = E_{detected}/Sampling\_Fraction$
- Sampling fractions saga: due to differences in the radiation/interaction length and the dE/dx the sampling fractions depend very much on the particle type and energy.
- Extreme case: slow neutrons and scintillator-based calorimeter: sampling_fraction = 1 independent of the absorber thickness.
- Simulation strongly depends on the details of modeling of the interactions and transport through the material.

Detector Simulation Codes

- MARS15
  - Inclusive distributions: Cascade-Exciton Model + inclusive hadron production parameterization
  - Event generator: LAQGSM2007 Quark-Gluon String model
- GEANT 4: event generator
  - LCPhys
  - QGSP_BERT
- These codes (as do others) encapsulate all of our knowledge and understanding of particles interactions and propagation in matter. Differences between them reflect our level of knowledge.

Leakage Studies (MARS)



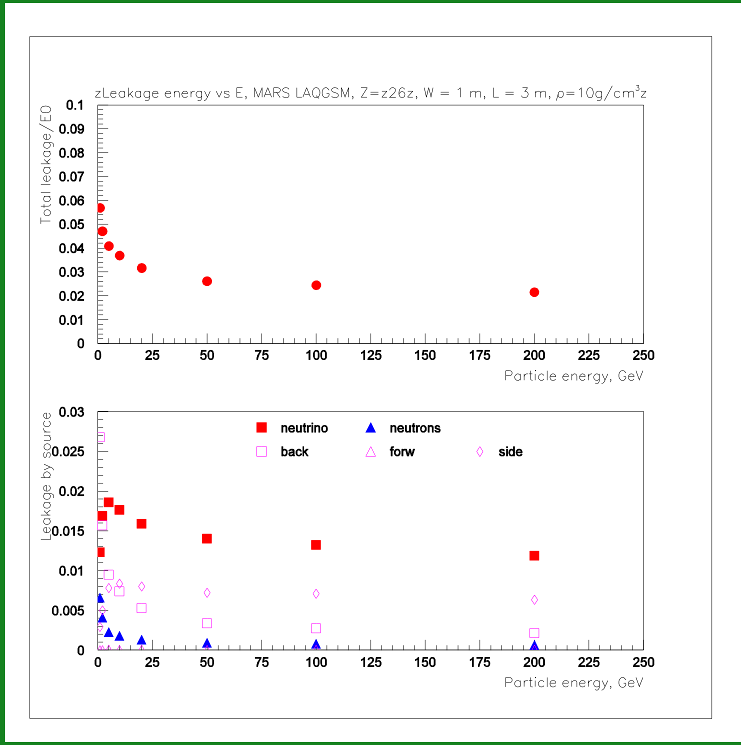
Detector: 1 x 1 x 3 m^3, density 10g/cm^3, different nuclear composition (at fixed density. Test of underlying physics models)

Not all of the energy of the incoming particle is deposited inside the detector. Leakage is composed of:

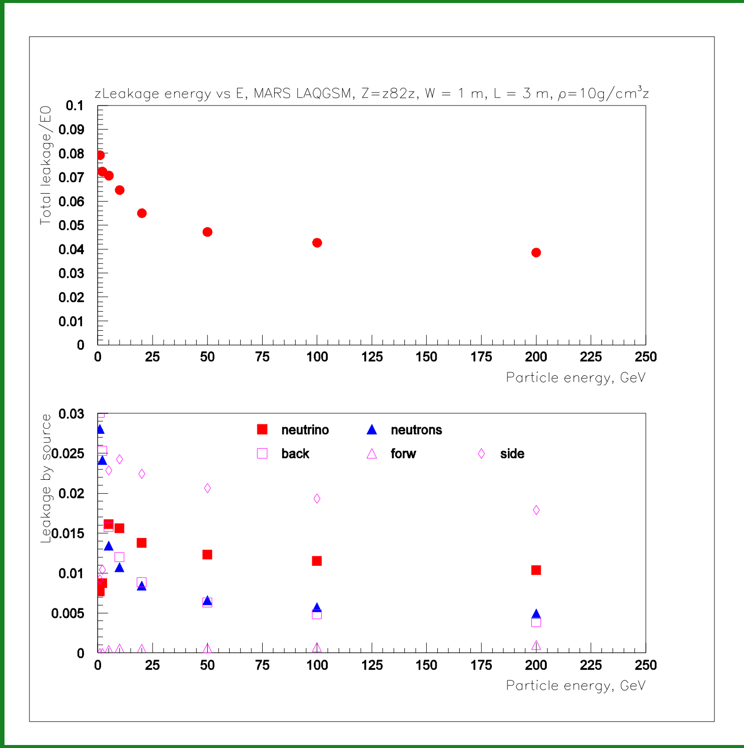
- Escaping muons and neutrinos (from π/K decays)
- Escaping neutrons
- Charged hadrons
  - Backscattered
  - Side leakage
  - Punch through

Leakage Composition

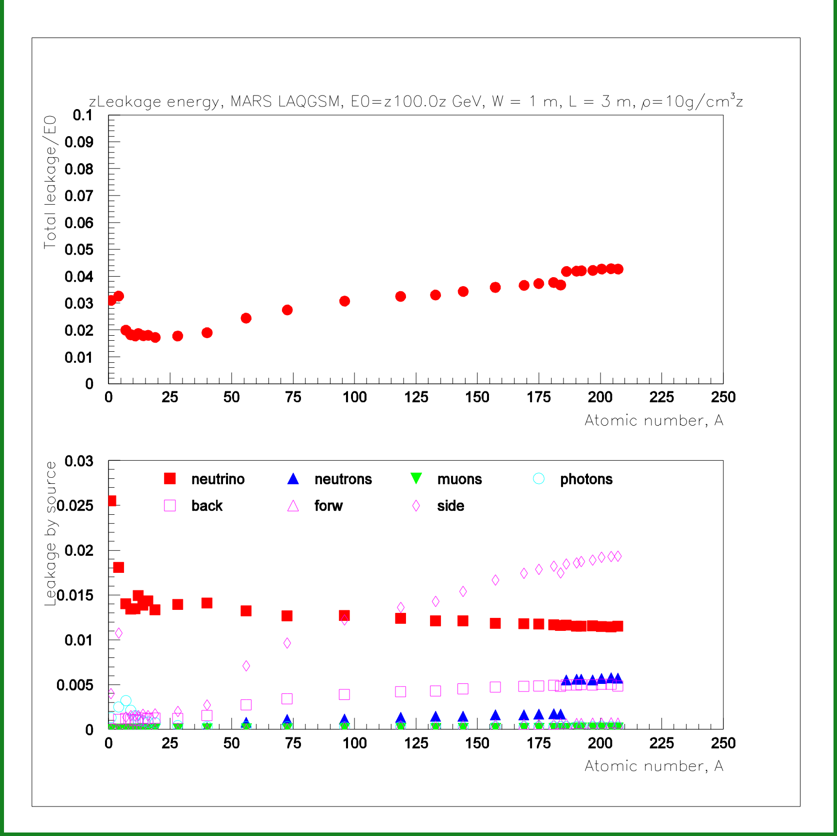
Moderate Z (iron): ~2% (high energy)
Mostly neutrinos, some hadrons (side)



Heavy materials (lead): ~4% (high energy)
Mostly hadrons (side)> neutrinos > some neutrons and back-scattered hadrons)

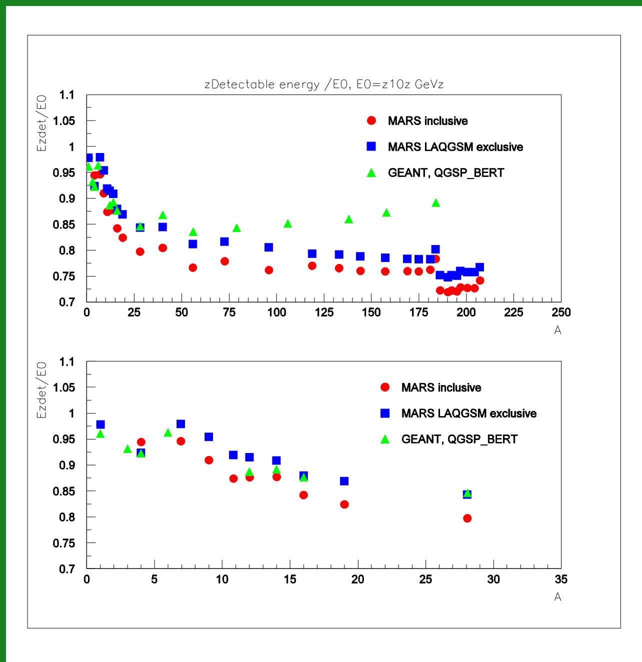


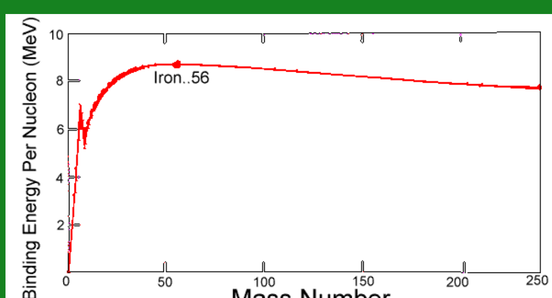
Leakage Dependence on Absorber Material (100 GeV π-)



- (At fixed density) Leakage increases with *A*, as a result of decreasing interaction length
- At low *A* the neutrinos dominate
- At high *A* side leakage of hadrons dominates, some backscattering
- Different modeling of neutron transport/interactions as a function of *A*
- Very little energy leaking as photons, muons or neutrinos

Modeling Nucler Binding Energy Loss (10GeV pion beam)





- Fraction of the beam energy deposited as an ionization.
- Amount of energy lost in breaking nuclei is a function of the average number broken nuclei, number of liberated nucleons and the nucleon binding energy.
- Light absorbers (A<20): nuclear effects consume 5-10% of the hadron energy, decent agreement between MARS and GEANT
- Heavy absorbers: disagreement between MARS and GEANT increasing with A.
- GEANT simulation resembles the nuclear binding energy curve. Good sign! Use GEANT for the further studies.
- On average: ~ 15% of a hadron kinetic energy transformed into un-detectable forms of energy.
- Caveat: This is for a long integration time and in a very large detector.

Total Absorption Hadron Calorimeter

- Need to collect signals proportional to the total ionization energy loss: ionization electrons or scintillation light
- Need to collect signals from a very large volume filled with a dense material ➔ scintillation
- Enabling technologies:
  - Heavy (ρ>6 g/cm^3) scintillating crystals and glasses (➔realistic dimensions of a calorimeter)
  - Compact photodetectors operating in a magnetic field (➔ efficient light collection in a hermetic 4π detector)

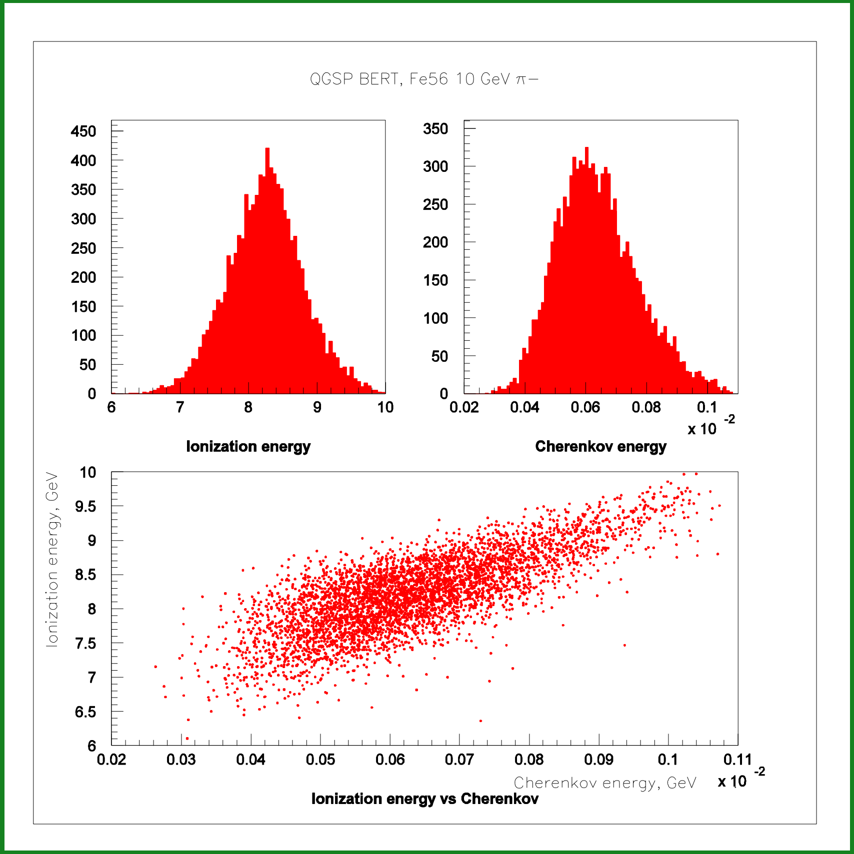
Principle of Dual Readout Calorimetry

- Hadron energy resolution is dominated by fluctuations in the fraction of the shower energy converted into unobservable potential energy (energy needed to extract nucleons from the nuclear potential well). An event-by-event correction for this effect is necessary to recover good energy resolution.
- Principles:
  - Nuclear binding energy loss is anti-correlated with the fraction of hadron shower deposited in a form of EM showers
  - EM showers consist of relativistic electrons, whereas most of particles in a 'hadron' component of a shower have $\beta<1$
  - Hence there should be anti-correlation on the event-by-event basis between the nuclear binding energy loss and the relative amount of Cherenkov radiation (Paul Mockett, 1984).

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.
- Calibration run: use electrons (10 GeV, for example) to determine the absolute calibration factors:
  - $E = A_{sc}*S = A_{ch}*C$
- Use 'test beam' of to determine the correction function F (the average fraction of missing energy) as a function of C/S (7^{th} order polynomial)
- Apply this correction to the total amount of the scintillation light in an event to be 'measured'
  - $E=A_{sc}*S/F(C/S)$
- Completely automatic reconstruction, no tuning/optimization. No use of the spatial distribution information (yet). Much room for the improvement.

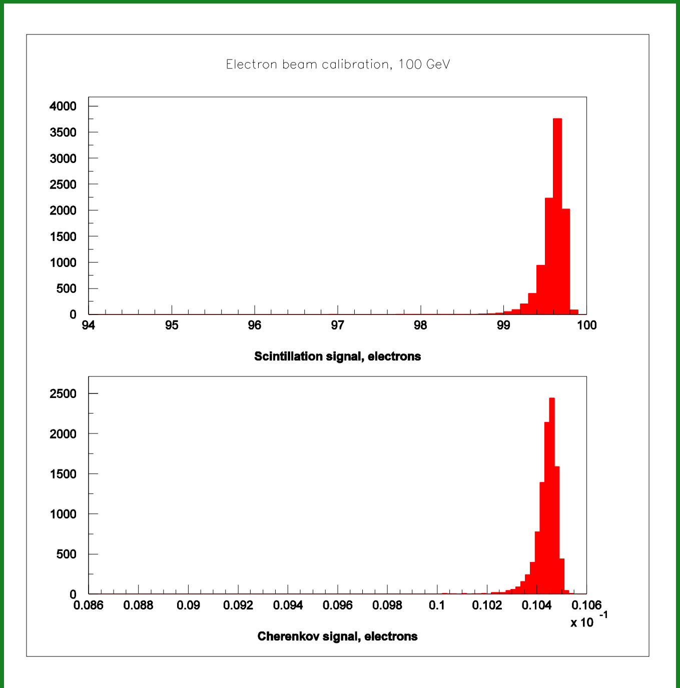
Dual Readout at Work: an Example



- 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

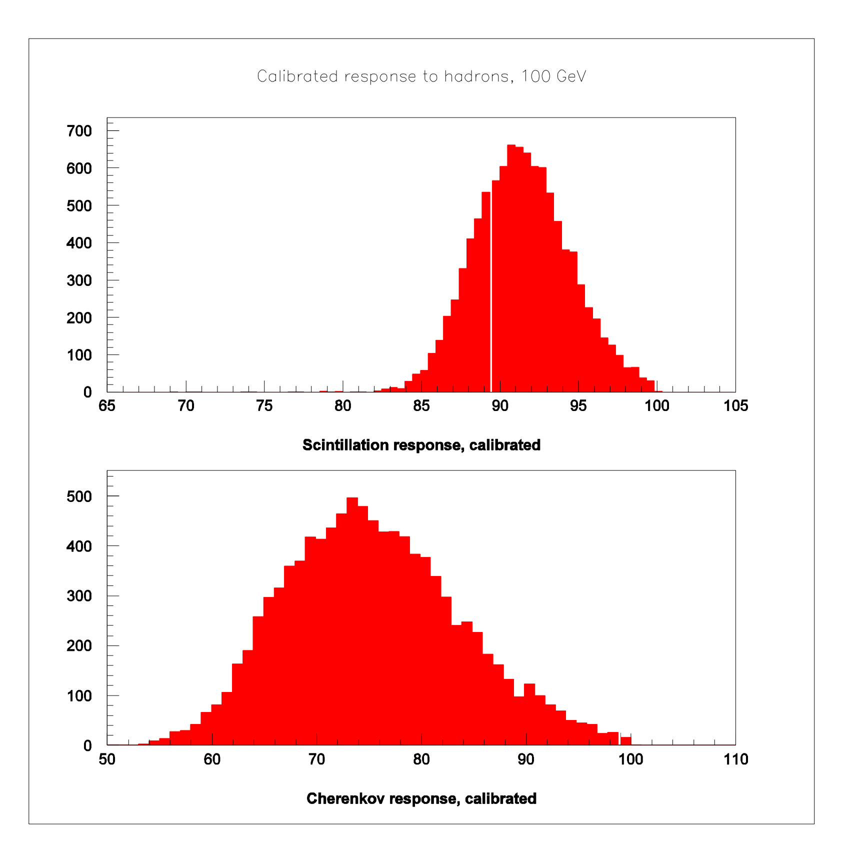
- Only ~80% of energy observed through ionization
- Cherenkov fluctuations much larger than the ionization
- Clear correlation of the total observed ionization and Cherenkov light
- Using the C-S correlation the energy resolution will be limited by the width of the scatter plot only

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



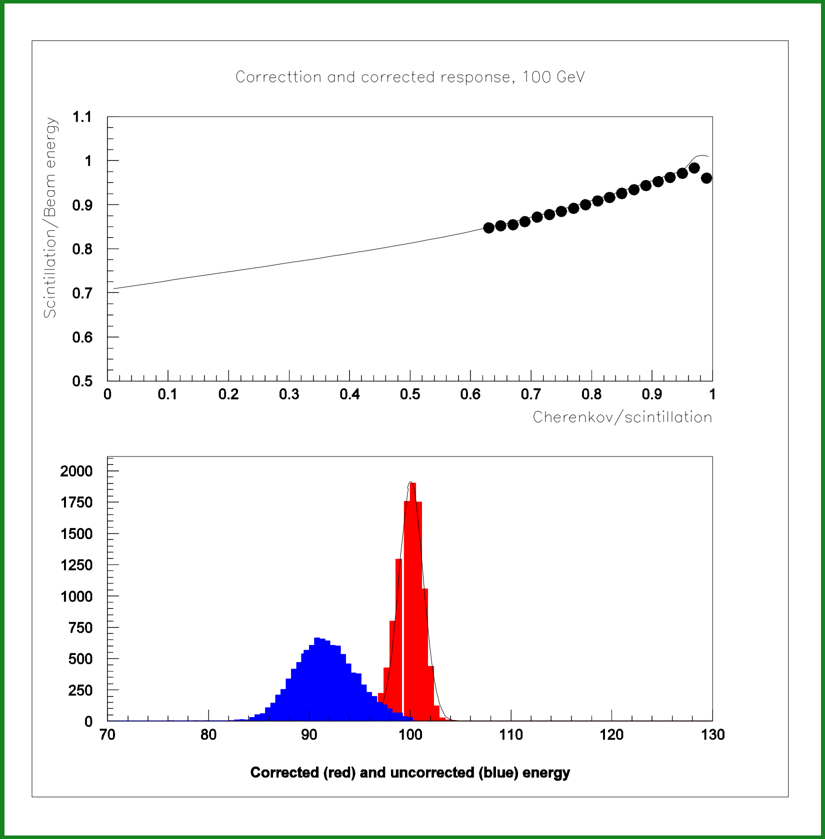
- Collect the scintillation and Cherenkov light measured in some arbitrary units.
- Define the mean values of the distributions to correspond to 100 GeV (calibration beam energy)
- A_{sc}=<Scintillation>/100
- A_{ch}=<Cherenkov>/100

'Test Beam' 100 GeV Step II: π- Beam



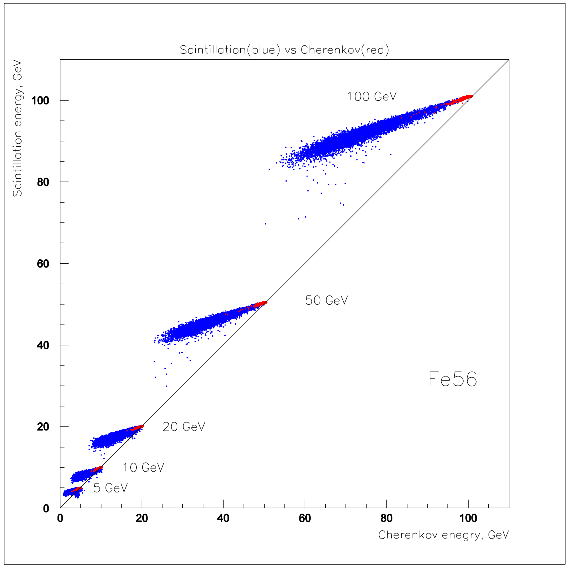
- Collect scintillation and Cherenkov light for 100 GeV negative pions entering the detector
- Use absolute calibration determined with electrons
  - $E_{sc} = A_{sc} * S$
  - $E_{ch} = A_{ch} * C$
- Notice (just observations, not used in the forthcoming):
  - $(\pi/e)_{sc} \approx 0.9$
  - $(\pi/e)_{ch}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

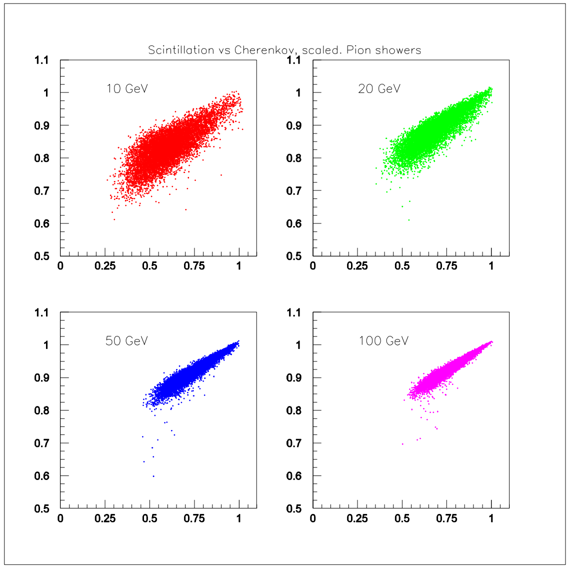
'Test Beam' 100 GeV Step III: Analysis

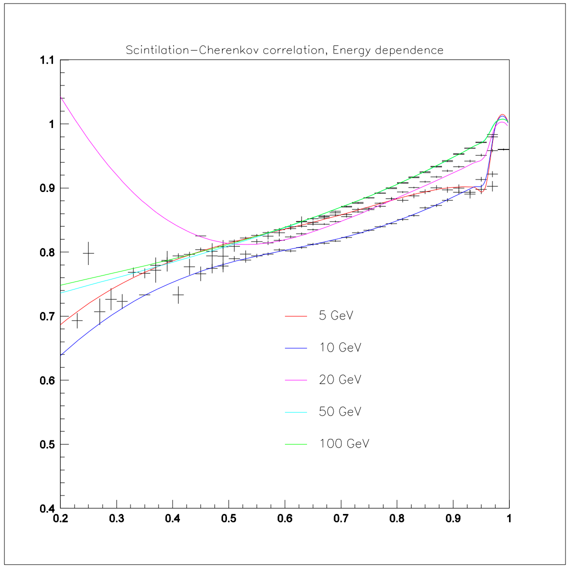


- Plot average S/E_{beam} as a function of C/S
- Fit some correction function F(C/S) (for example polynomial)
- Re-analyze the data:
  – $E = A_{sc}*S/F(C/S)$
- Observe:
  – Average corrected energy(red) ≈ Beam Energy (== π/e ≈ 1)
  – Significantly improved resolution
  – Analysis completely automated,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

Scintillation vs Cherenkov Correlation: Energy Dependence



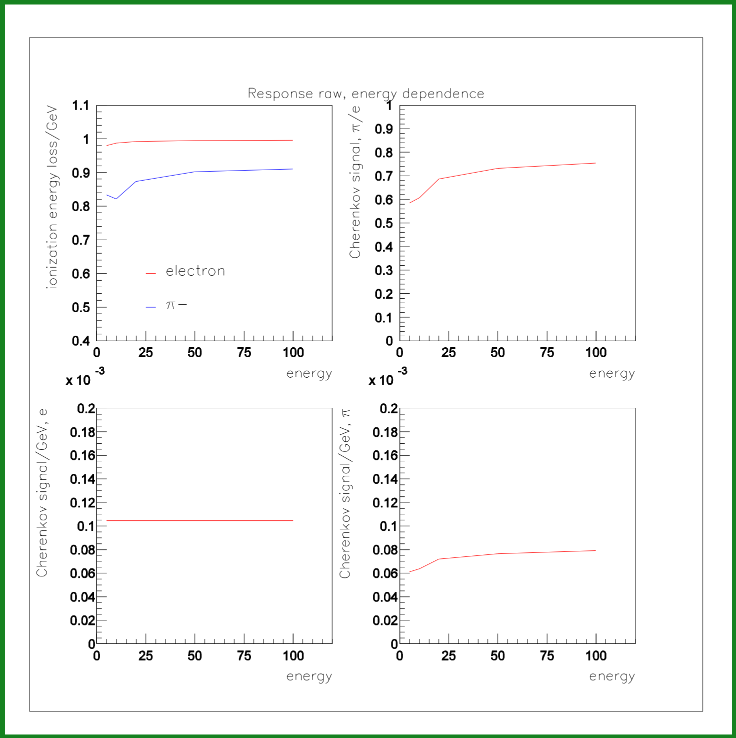




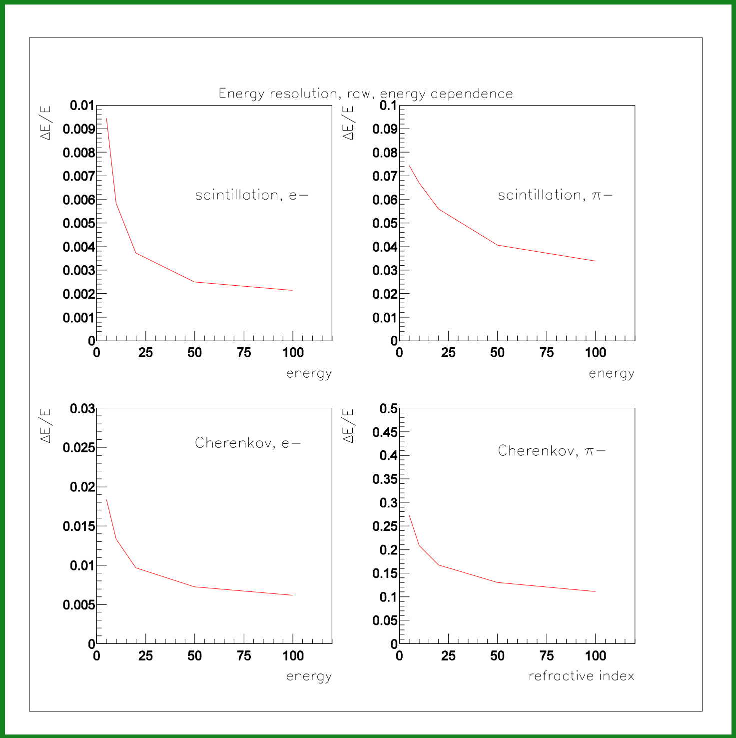
- Cherenkov response linear
- Relative amount of Cherenkov light increasing with E (more π^0's)
- Scintillation vs. Cherenkov correlation improving with E
- Slope of the correlation similar, but level increasing with E

Raw Response and Resolution, Energy Dependence

Response: Scintillation and Cherenkov

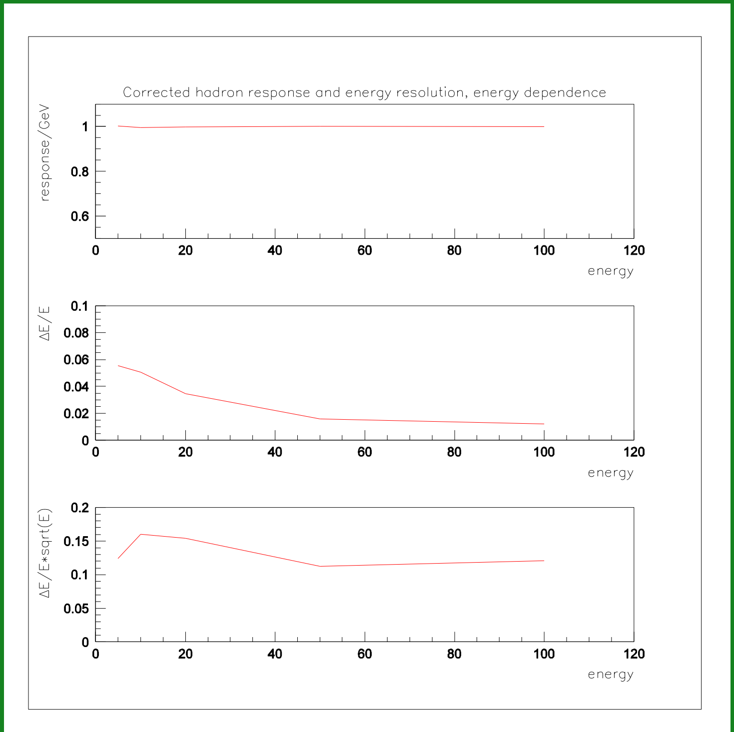


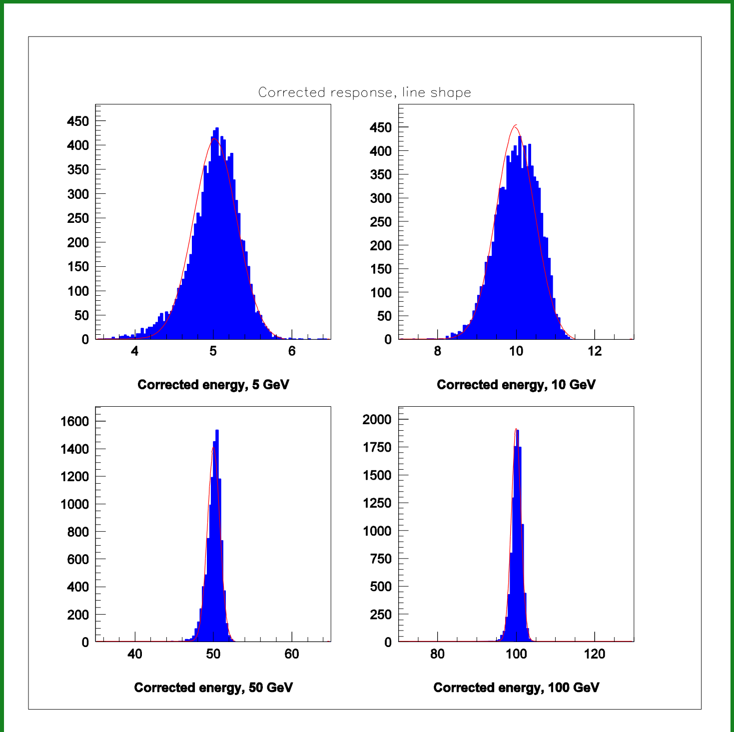
Resolution: Scintillation and Cherenkov



- Response: electrons linear, pions non-linear (both scintillation and Cherenkov)
- Resolution: very good for electrons, ~3% constant term for pions (scintillation), poor for pions measured with Cherenkov

Response and Resolution, Corrected



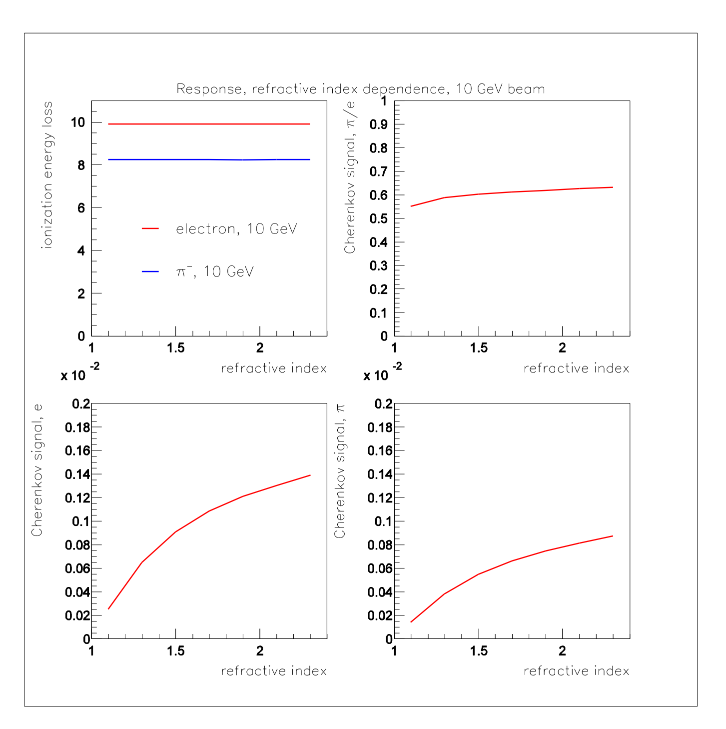


After correction:

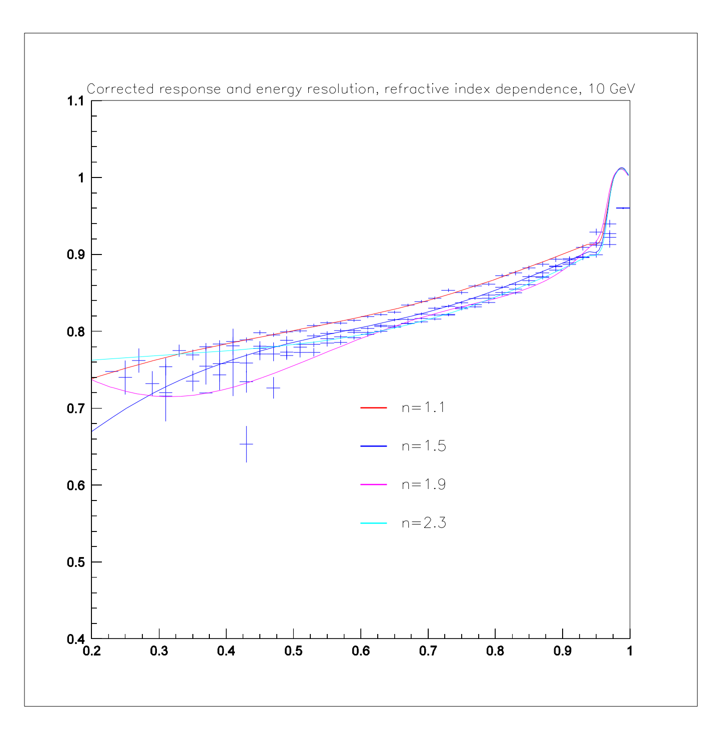
- good linearity of the corrected response
- good energy resolution ~ $0.12/\sqrt{E}$
- no sign of a constant term up to 100 GeV
- Gaussian response function

Index of Refraction? (from n=1.1 to n=2.3)

Amount of Cherenkov light



Scintillation-Cherenkov correlation



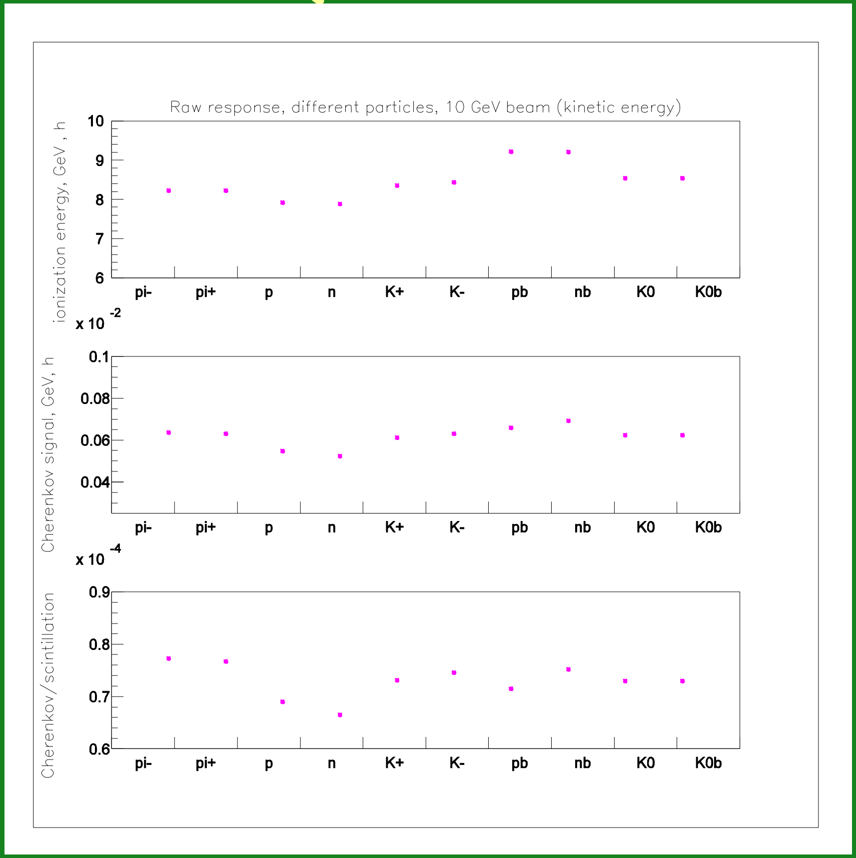
- Amount of Cherenkov light increases with n
- Increase faster for pions than for e

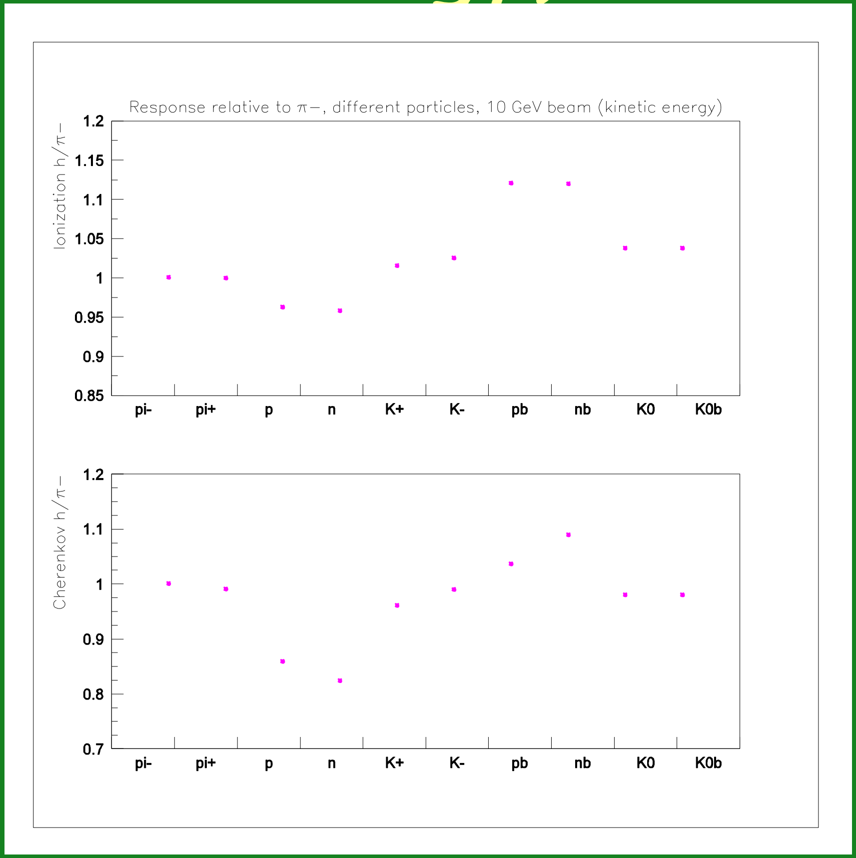
- Very similar for a wide range of n
- The corrected response and resolution independent of n

'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??

Raw Response to Different Particles (10 GeV of Kinetic Energy)

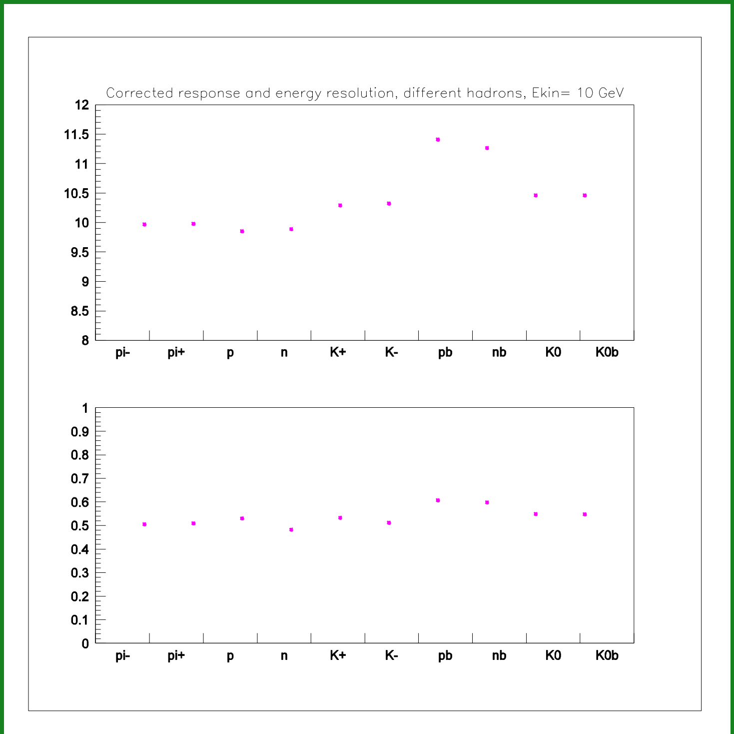




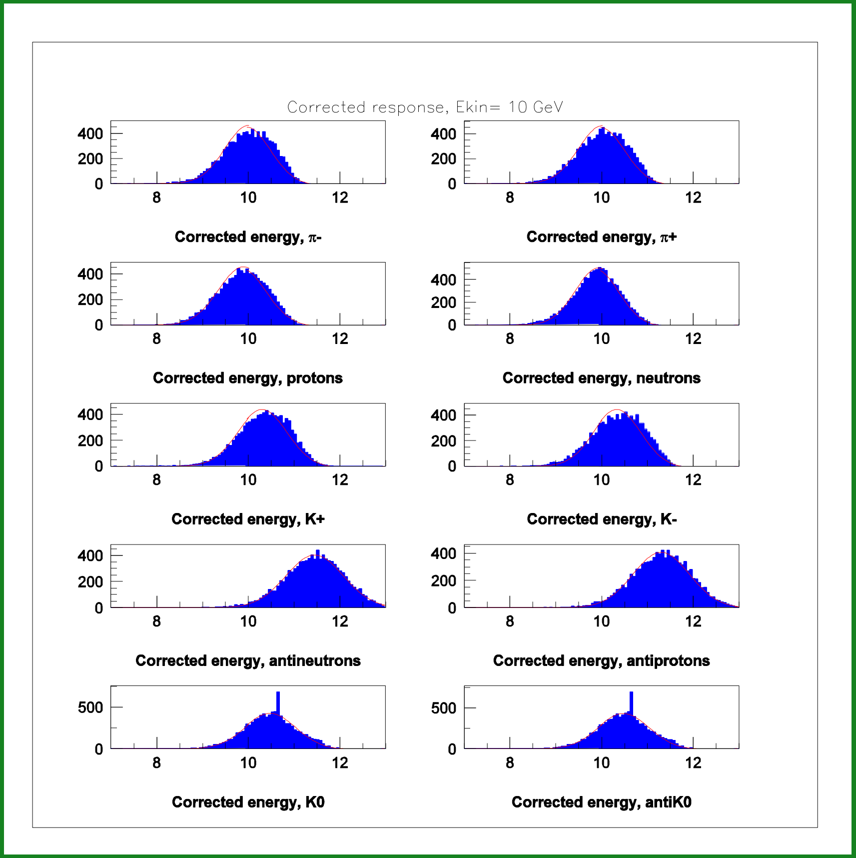
Scintillation, Cherenkov responses, Cherenkov/scintillation response ratio different for different particles.

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



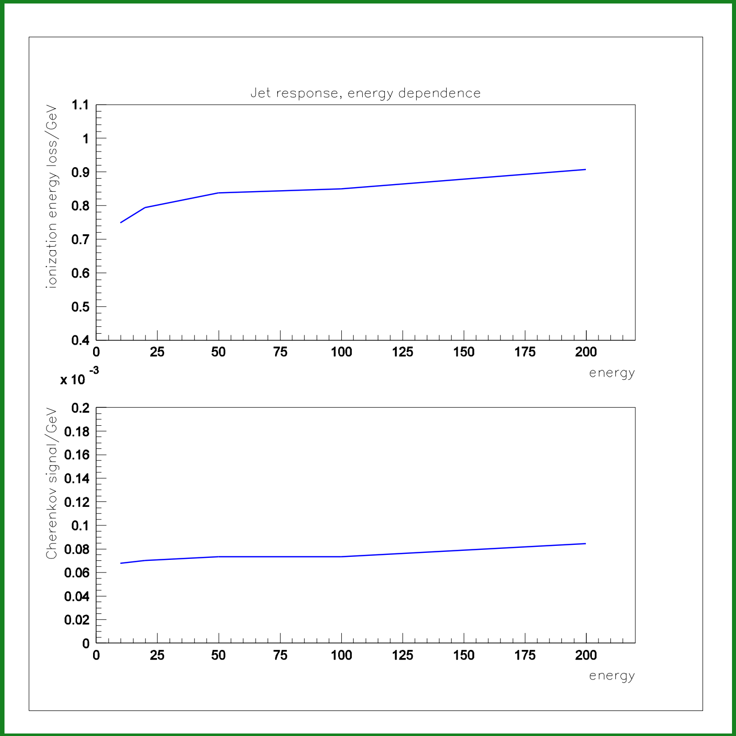
Jets!

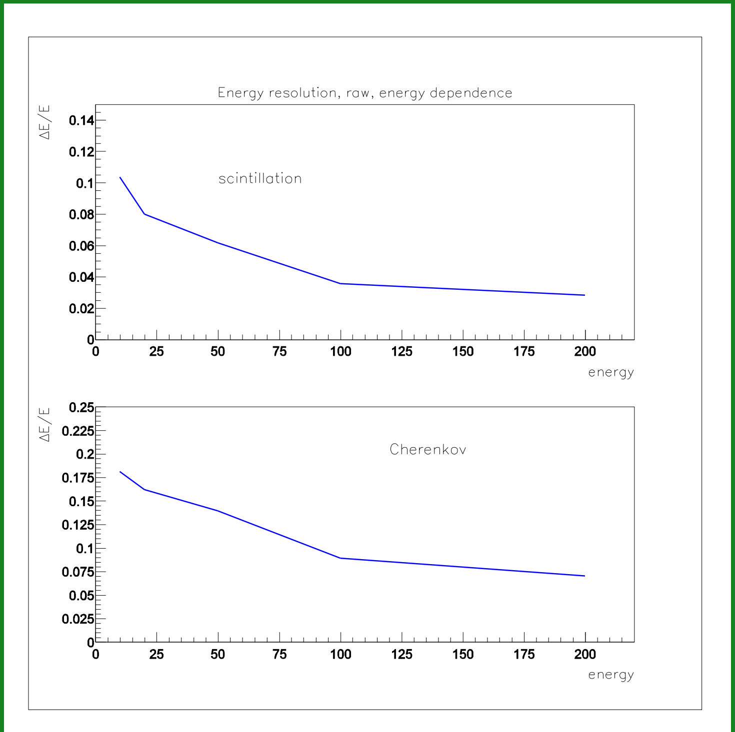
- Use Pythia e+e- → light quarks to create collections of particles with the composition and energy distributions characteristic of QCD jets (beware of the radiative return above Z0 peak)
- Edit the StdHEP list to send all jet particles along z-axis into the detector: S and C are the total amount of 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

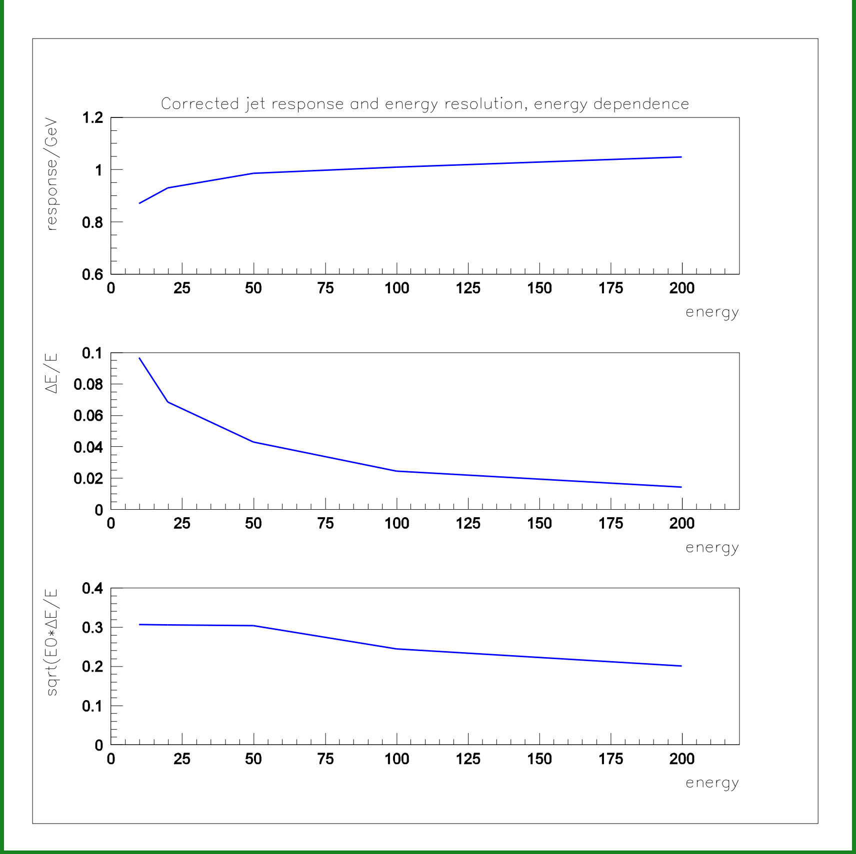


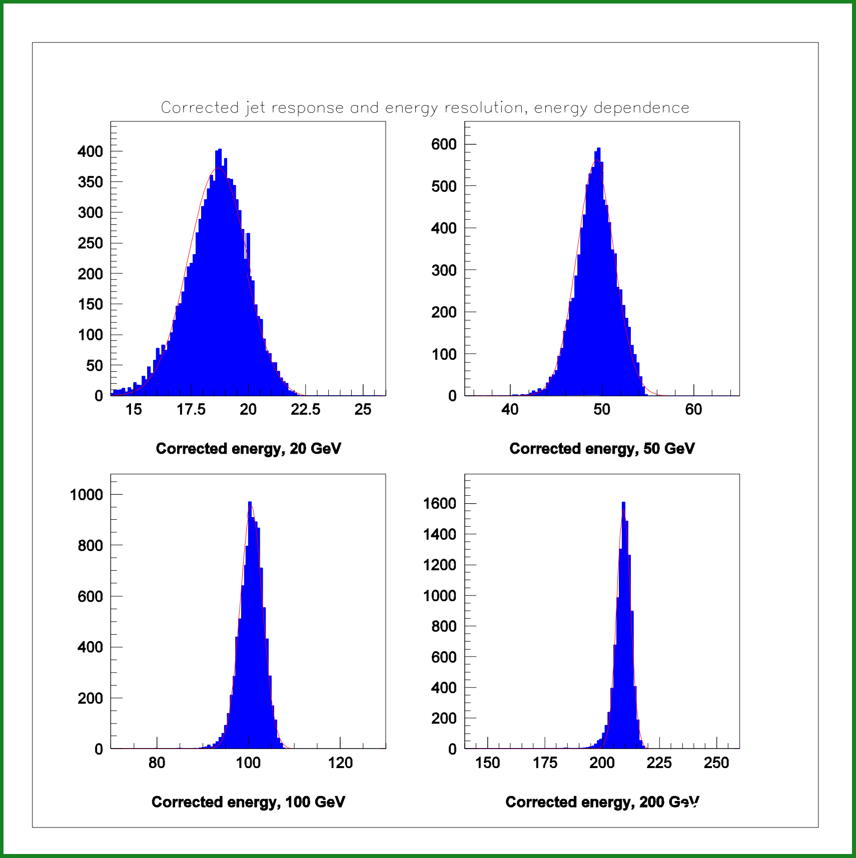


Jets, Corrected Response

- 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!

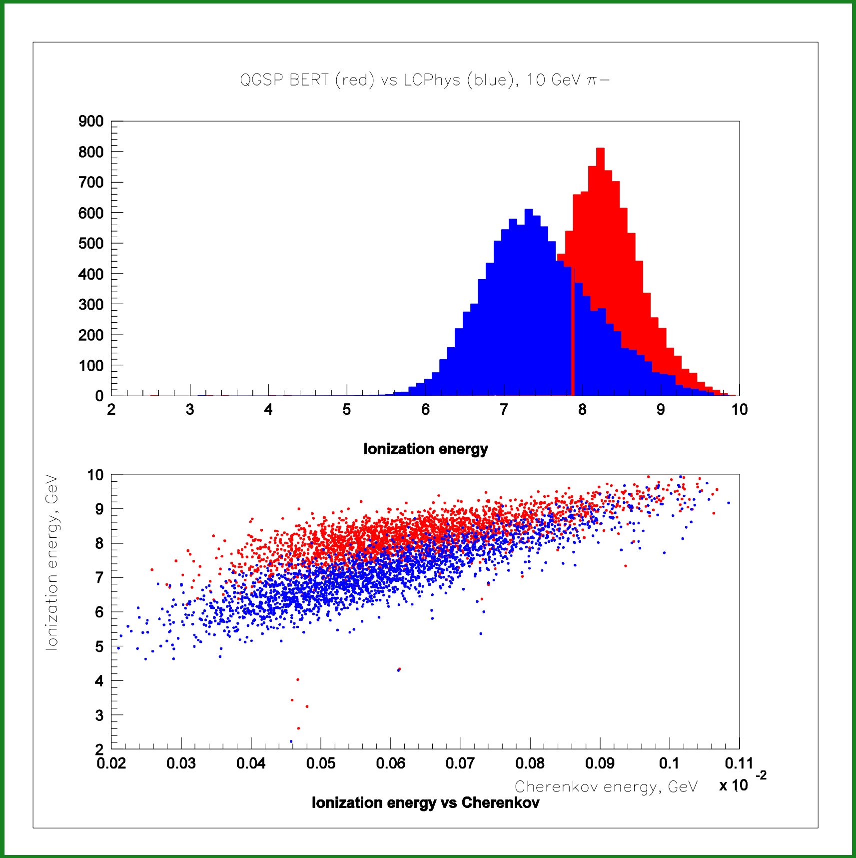




Jets, Summary

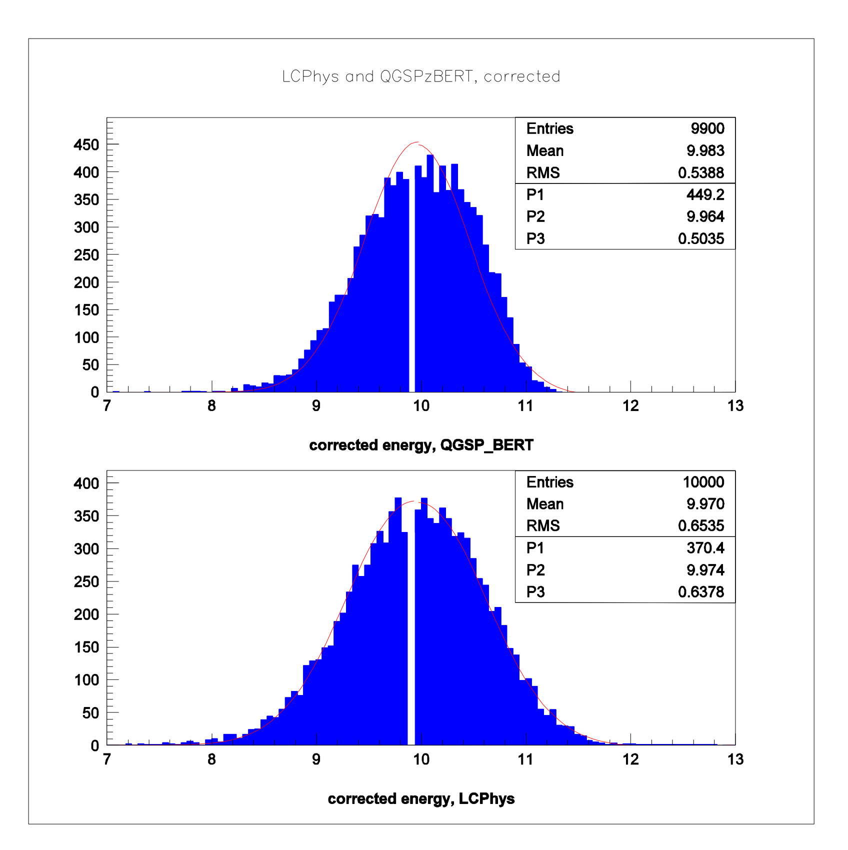
- Complete detector simulation
- Complete reconstruction (crude, far from optimal)
- Absolute response good to ~5%, small non-linearity (~5%) for jets above 50 GeV
- Gaussian response function, no tails
- Energy resolution $(0.2\text{-}0.25)/\sqrt{E}$
- No indication of a constant term in the energy 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)

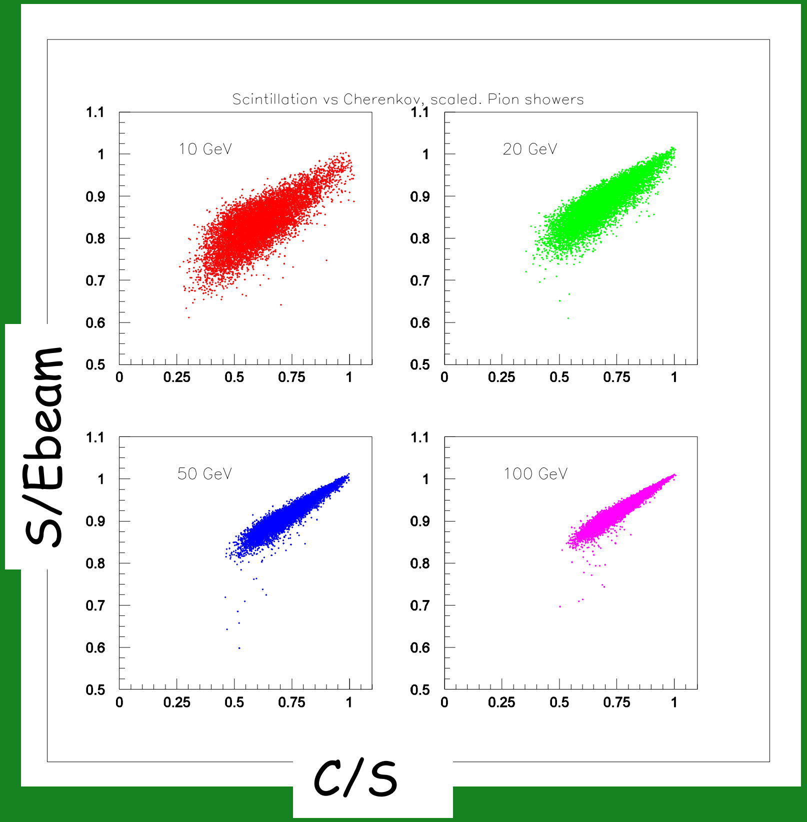
More Studies

Even using the test beam detector geometry there are many further studies which can be performed (ongoing):

- Dependence on the nuclear modeling (use different A absorbers)
- Performance (response and resolution) as a function of the thickness of the calorimeter
- Performance as a function of the integration time
- Importance/requirements for cross-calibration
- Fluctuations of light yield (especially Cherenkov) contribution
- …..

But the real fun (a.k.a. challenge) will start with a complete detector simulation..

Dual Readout Calorimetry Physics 101
Why it Works so Well?
Why is it Independent on Simulations?



- Principal tool: Scintillation-Cherenkov correlation
- For EM rich showers: S=C and S = Ebeam (1,1 is fixed and the fluctuations are small)
- Purely 'hadronic' component of a shower: less Cherenkov and lost energy (nuclear breakup). Whatever the correlation shape is – fit it.
- How 'low' does it go? Determine from test beam data ➔ $\pi/e=1$, linearity of the response.
- Resolution dependent on the width of the correlation. Lost energy comes in '9 MeV' chunks. Large missing energy – lots of chunks ➔ small fluctuations (Central Limit Theorem)
- Performance understandable from simple principles, like energy conservation.

Conclusion

- Homogeneous total absorption calorimeter represents a very attractive possibility for colliding beam detectors (and fixed target too)
- Especially when both the scintillation and the Cherenkov signals are collected separately
- Such a detector may offer a resolution for single hadrons and for jets better than $0.2/\sqrt{E}$
- And Gaussian response function with no tails
- No show-stoppers (so far..)