4th Concept
Dual Readout Calorimeter

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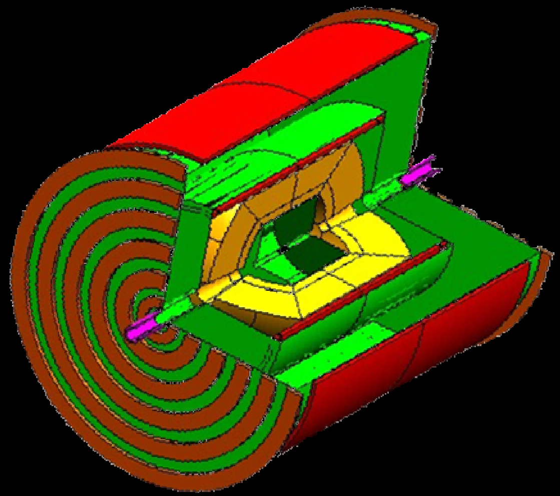
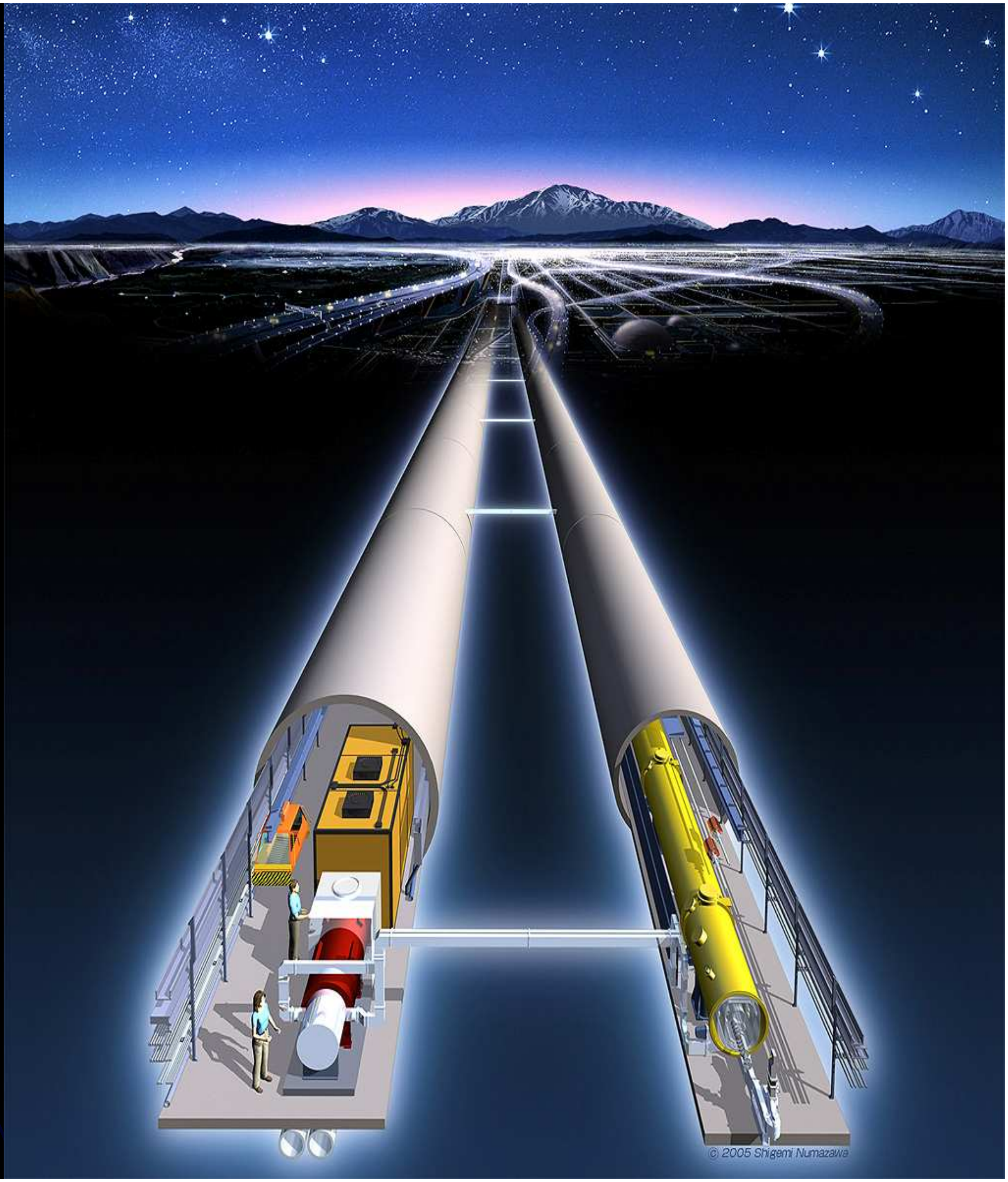


ILC

- electron-positron collider ;
- ILC's design consist of two facing linear accelerators, each 20 kilometers long;
- c.m. energy 0.5 - 1 TeV ;
- ILC target luminosity :

  500 fb-1 in 4 years

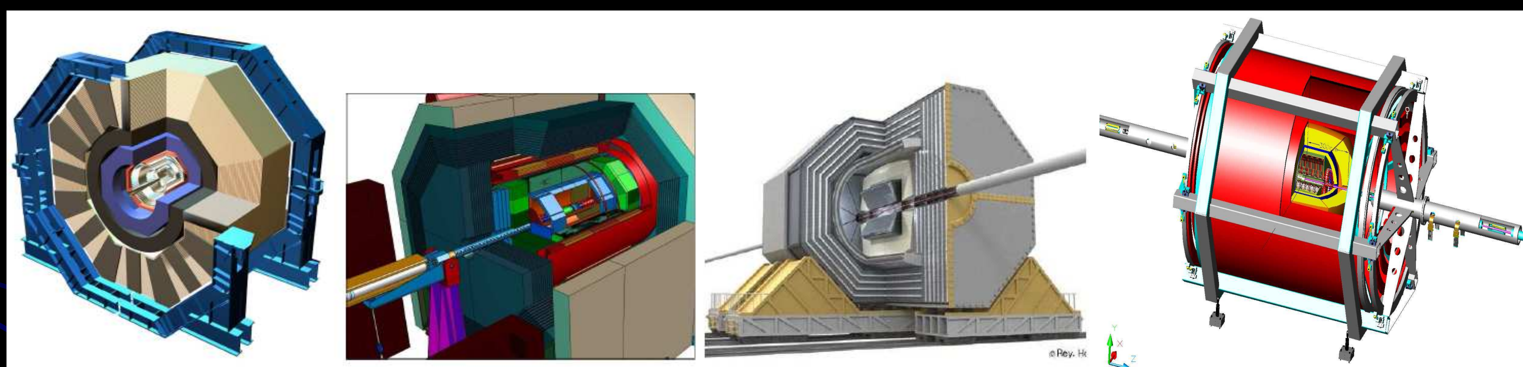


Requirements for ILC Detectors

- Physics goal of ILC
  - Wide variety of processes
  - Energy range: $M_z < E_{CM} < 1$ TeV
- Basic requirements
  - Reconstruct events at fundamental particle (quark, lepton, gauge bosons) level
  - Efficient identification and precise 4-momentum measurement of these fundamental particles
- ILC detectors should have performances of
  - Good jet energy resolution to separate W and Z
  - Efficient jet-flavor identification capability
  - Excellent charged-particle momentum resolution
  - Hermetic coverage to veto 2-photon background

Detector Design Study

- Detector Design Study
  - Conceptual design study of detector systems
  - 4 major concepts: 3 with PFA + 1 with Compensation Calorimetry



- Sub-detector R&D
  - More than 80 groups in the world (about 1000 physicist)
  - Usually related with several detector concepts

  ➔ Horizontal collaboration

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Performance Goal

- Jet energy resolution

$$\sigma(E_j)/E_j = 30\%/\sqrt{E_j}\ (\mathrm{GeV})$$

➔ 1/2 w.r.t. LHC

- Impact parameter resolution for flavor tag

$$\sigma_{IP} = 5 \oplus 10/\,p\beta\sin^{3/2}\theta\ (\mu\mathrm{m})$$

➔ 1/2 resolution term, 1/7 M.S. term w.r.t. LHC

- Transverse momentum resolution for charged particles

$$\sigma(p_t)/\,p_t^{\,2} = 5\times10^{-5}\ (\mathrm{GeV/c})^{-1}$$

➔ 1/10 momentum resolution w.r.t. LHC

- Hermeticity

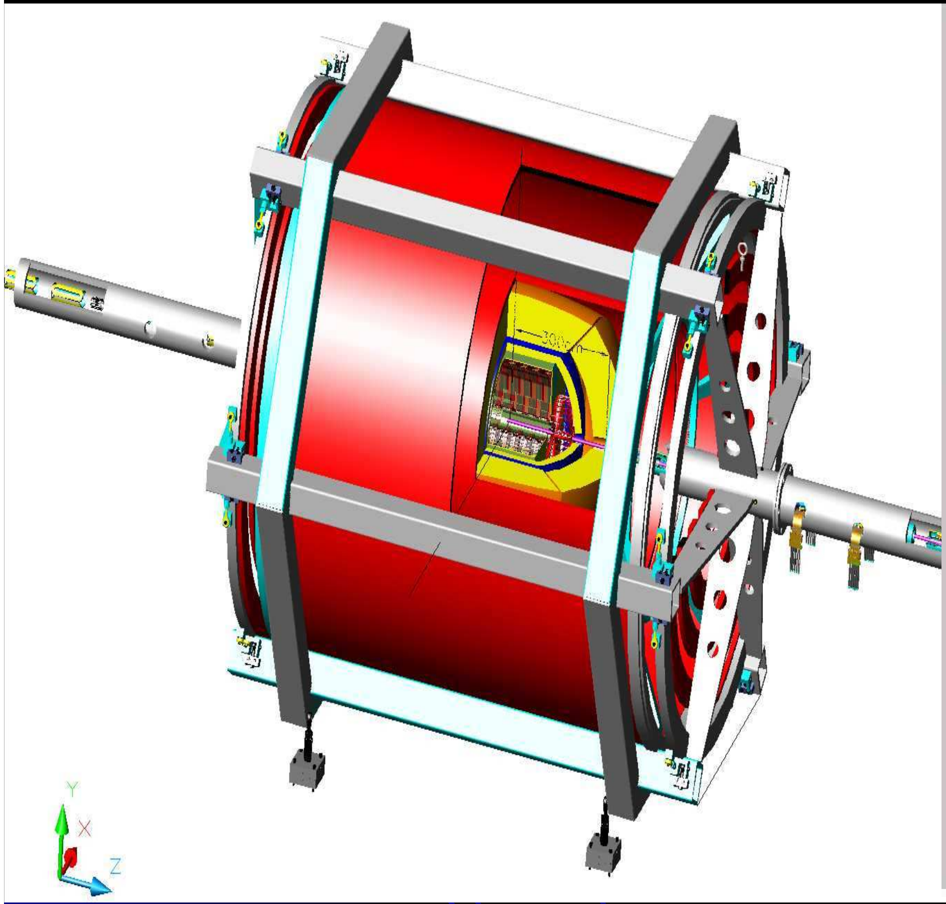
$$\theta_{\min} = 5\ \mathrm{mrad}$$

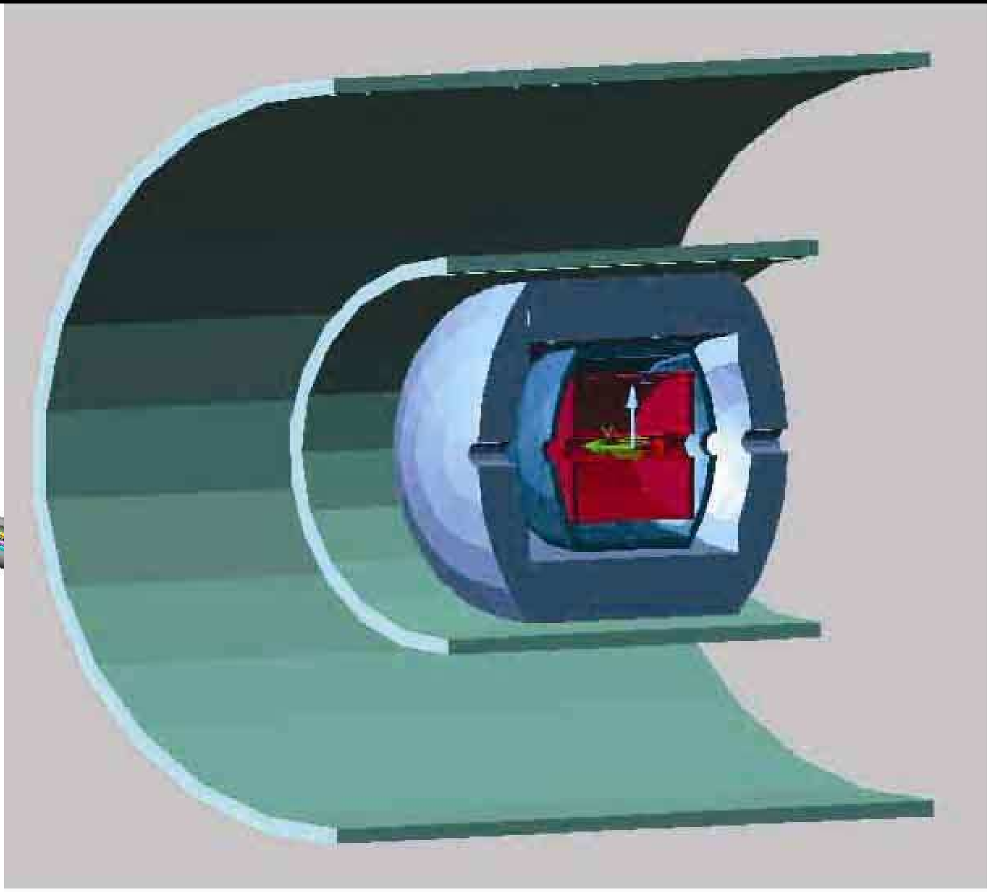
Fourth Concept Detector (“4th”)

Basic conceptual design: 4 subsystems

- Vertex Detector 20-micron pixels (SiD design)
- Time Projection Chamber (like LDC or GLD)
  - Drift Chamber as alternative to overcome known limitations of the TPC technology
- Double-readout fiber calorimeter: scintillation/Čerenkov
- Muon dual-solenoid spectrometer

4th Concept Detector





Calorimetry at ILC

Most of the important physics processes to be studied in the ILC experiment have multi-jets in the final state

Jet energy resolution is the key in the ILC physics

Jets at ILC experiments contain:

- Charged particles (~60%) measured by Tracker
- Photons (~30%) by ECAL
- Neutral hadrons (~10%) by ECAL + HCAL

The world-wide consensus of the performance goal for the jet energy resolution is $\sigma_E / E = 30\% / \sqrt{E(\mathrm{GeV})}$

Hadron Calorimeters

- Detectors measuring properties of particles by total absorption (calorimeters) crucial in HEP experiments
- Detection of em interacting particles performed with high precision
- NOT TRUE for particles subject to strong interaction, due primarily:
  1. Tipically, larger signal per unit E_{dep} for em shower component ($\pi^0 \rightarrow \gamma\gamma$) than for non em component (i.e. e/h >1)
  2. Fluctuations in the energy sharing between these 2 components large and non-Poissonian.

Problems in Hadron Calorimeters

- Hadronic response function non-Gaussian
- Hadronic signals non-linear
- Poor hadronic energy resolution and not scaling as $E^{-1\backslash 2}$

LESSONS FROM 25 YEARS OF R&D

Energy resolution determined by fluctuations

The “key” for the solution

To improve hadronic calorimeter performance

→ *reduce/eliminate the (effects of) fluctuations that dominate the performance*

1. Fluctuations in the em shower fraction, f_{em}
2. Fluctuations in visible energy (nuclear binding energy losses)

Solutions to f_{em} *fluctuations*

Several ways to deal with problem 1:

- *Compensating calorimeter* (design to have e/h=1) → fluctuations in f_{em} eliminated by *design*
- *Off-line compensation* (signals from different longitudinal sections weighetd)
- *Measurements of f_{em} event by event* (through spatial profile of developing shower)

Solutions in ILC community

1. *Particle Flow Analysis* (PFA)

   calorimeter information combined with measurements from tracking system

   GLD

   LDC

   SiD

2. Dual Readout Calorimeter

   measurement of f_{em} value event by event by comparing two different signals from scintillation light and Čerenkov light in the same device

   4^{th}

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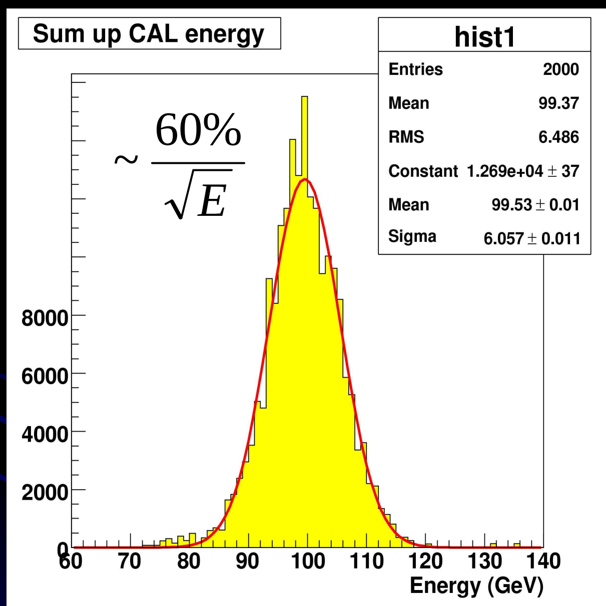
PFA Calorimetry

- PFA (Particle Flow Analysis) is thought to be a way to get best jet-energy resolution
- Measure energy of each particle separately
  - Charged particle : by tracker
  - Gamma : by EM Calorimeter
  - Neutral hadron : by EM and Hadron Calorimeter
- Overlap of charged cluster and neutral cluster in the calorimeter affects the jet-energy resolution
- Cluster separation in the calorimeter is important
  - Large Radius (R)
  - Strong B-field
  - Fine 3-D granularity (σ)
  - Small Moliere length (R_M)
  - Algorithm
- Often quoted figure of merit :

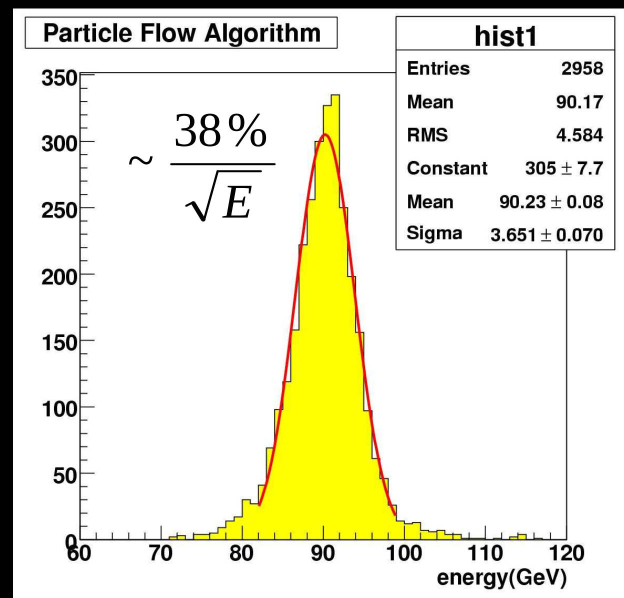
$$\frac{BR^2}{\sqrt{{R_M}^2 + \sigma^2}}$$

PFA Simulation Study at ILC

Z → qq @ 91.18GeV



CAL energy sum



PFA

Unfortunately, the stochastic term increases with energy

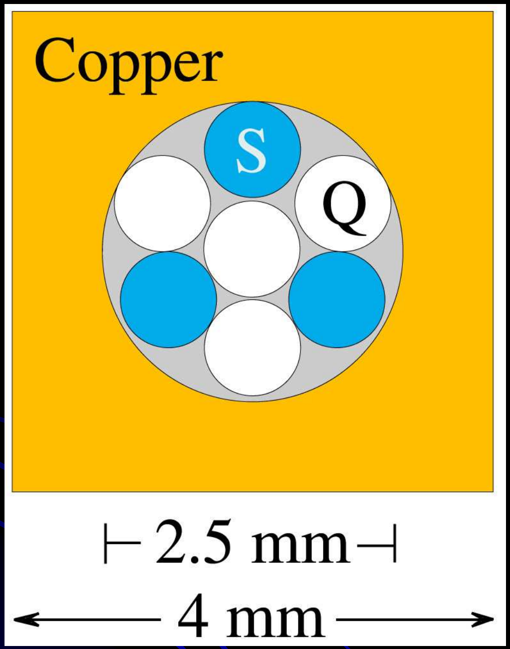
Dual (Triple) Readout Calorimetry

Dual-Readout: Measure every shower twice – in Scintillation light and in Cerenkov light.

- Spatial fluctuations are huge $\sim\lambda_{int}$ with high density EM deposits: fine spatial sampling with scintillating fibers every 2mm
- EM fraction fluctuations are huge, 5→95% of total shower energy: insert clear fibers generating Cerenkov light by electrons above E_{th} = 0.25 MeV measuring nearly exclusively the EM component of the shower (mostly from $\pi^0 \rightarrow \gamma\gamma$)
- Binding energy (BE) losses from nuclear break-up: measure MeV neutron component of shower.

Dual READout Module (DREAM)

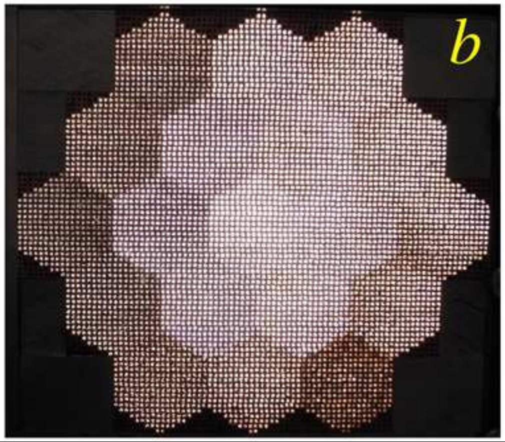
http://www.phys.ttu.edu/dream/



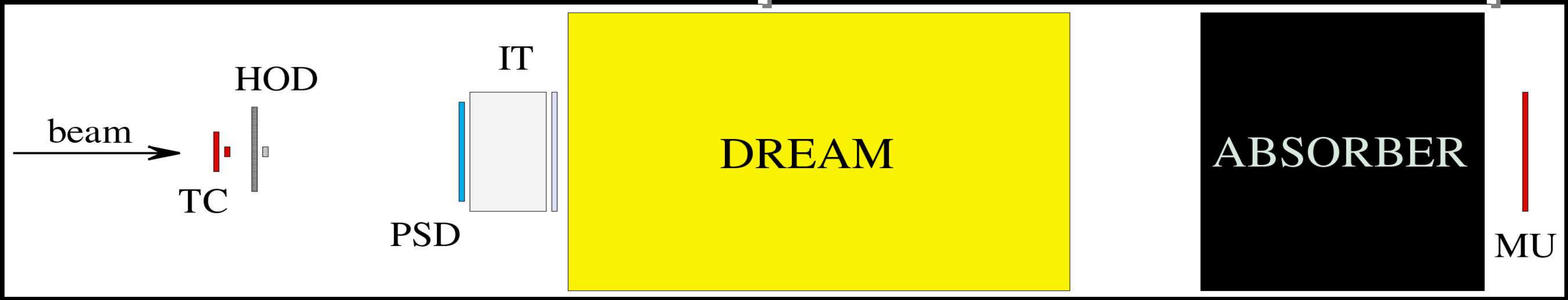
Unit cell

Back end of 2-meter deep module

Physical channel structure



Test Beam: Experimental setup



- **H4 beam line of the Super Proton Synchrotron at CERN**
- **TC : Trigger Counters**

  two scintillation counters (4 x 4 cm^2 each)

  coincidence of 2 counters provide main trigger signals
- **HOD : Hodoscopes**

  consist of ribbons of scintillating fibers oriented horizontally or vertically.

  provide x, y coordinate of beam spots(impact point on the detector).
- **MU : Muon detector**

  30 x 30 cm^2 scintillation counter behind 8 $\mathbf{l_{int}}$ absorber.

  to reject muon contaminated events.
- **PSD : Preshower detector**

  5mm thick (1 X_0) lead absorber with scintillation counter

  used to eliminate beam contamination.
- **IT : Interaction target counter**

Results

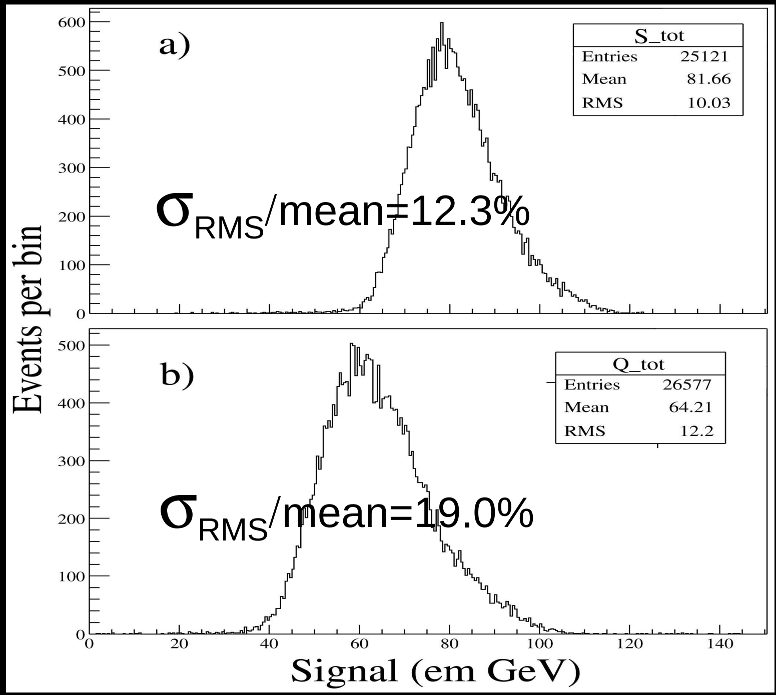
a), b) energy distributions from scintillating and Cerenkov fibers for 100GeV single π^-

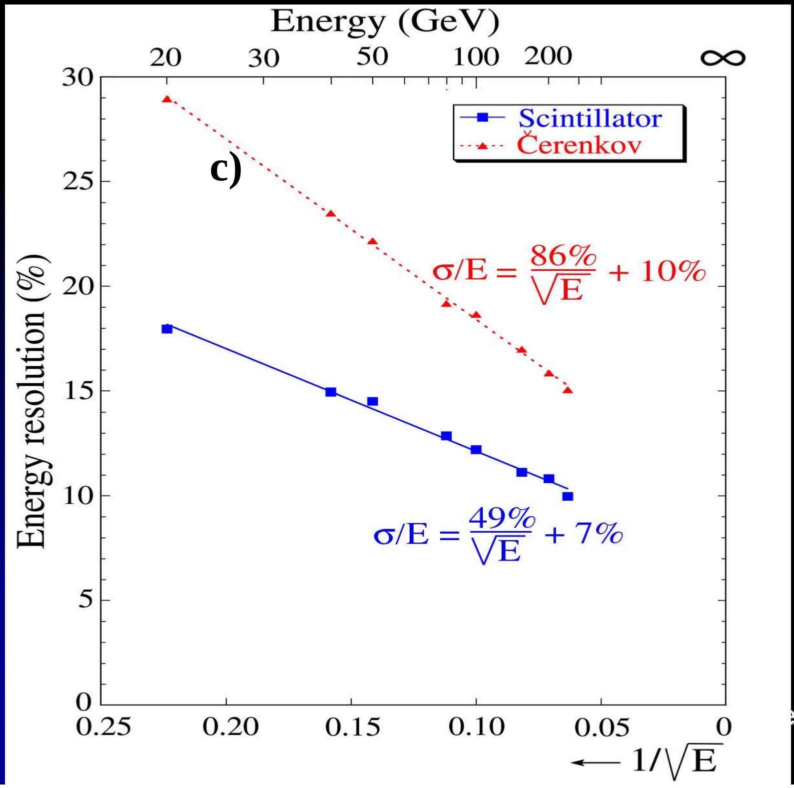
asymmetric, broad, smaller signal than e

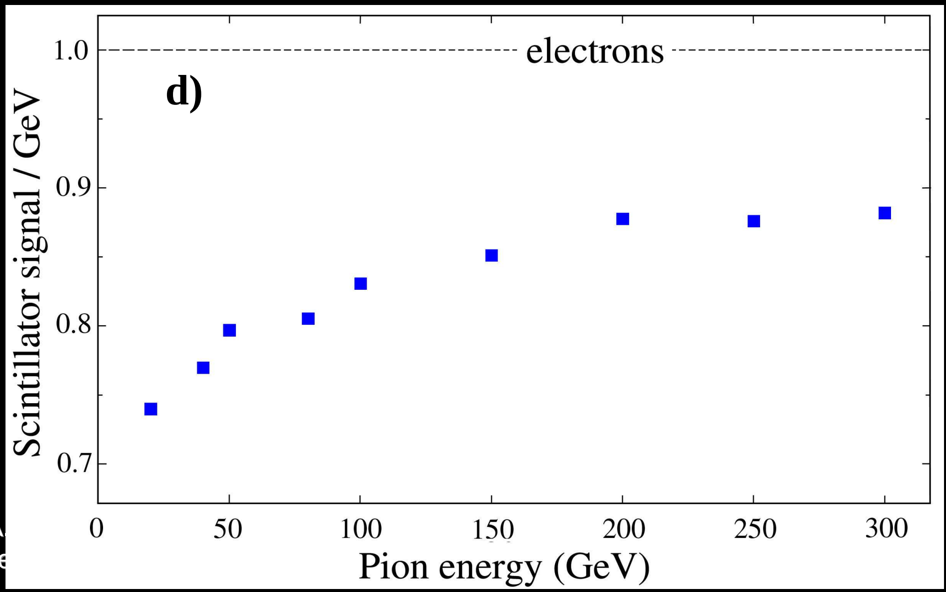
➡ typical features of non-comp calorimeter

c) energy resolution(%) vs beam energy

d) Scintillation signal response







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The C/S method

- Hadronic calorimeter response (C,S) can be expressed with f_{em} and *e/h*

$$R(f_{em}) = f_{em} + \frac{1}{e/h}\left(1 - f_{em}\right)$$

- e/h depends on: active & passive calorimeter media and sampling fraction

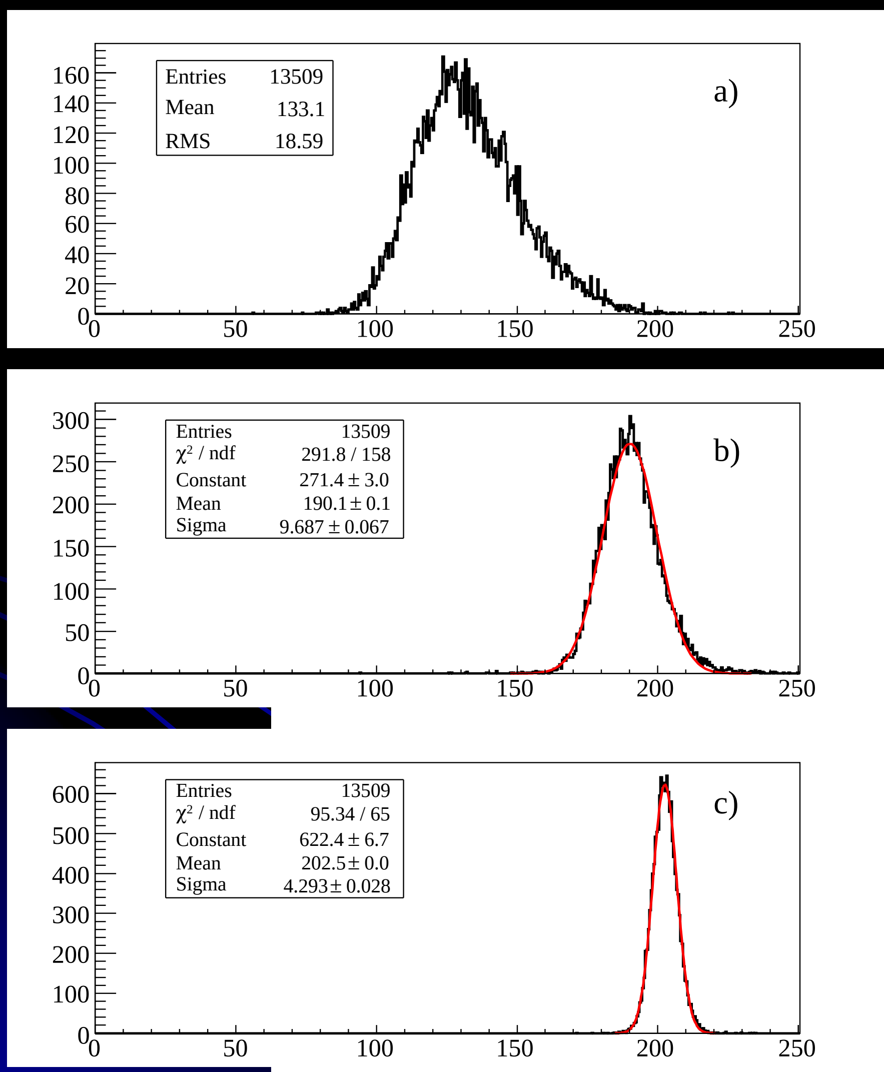
  $(e/h)_C = \eta_C \sim 5$ for copper/quartz fiber

  $(e/h)_S = \eta_S \sim 1.4$ for copper/plastic-scintillator

- Asymmetry, non-gaussian & non-linear response are due to fem fluctuation..
- Measurement f_{em} event by event is the key to improve hadronic calorimeter response

$$\frac{C}{S} = \frac{f_{em} + 0.20\left(1 - f_{em}\right)}{f_{em} + 0.71\left(1 - f_{em}\right)}$$

DREAM data 200 GeV π^-: Energy response



Scintillating fibers

Scint + Cerenkov

$f_{EM} \propto (C/E_{shower} - 1/\eta_C)$

(4% leakage fluctuations)

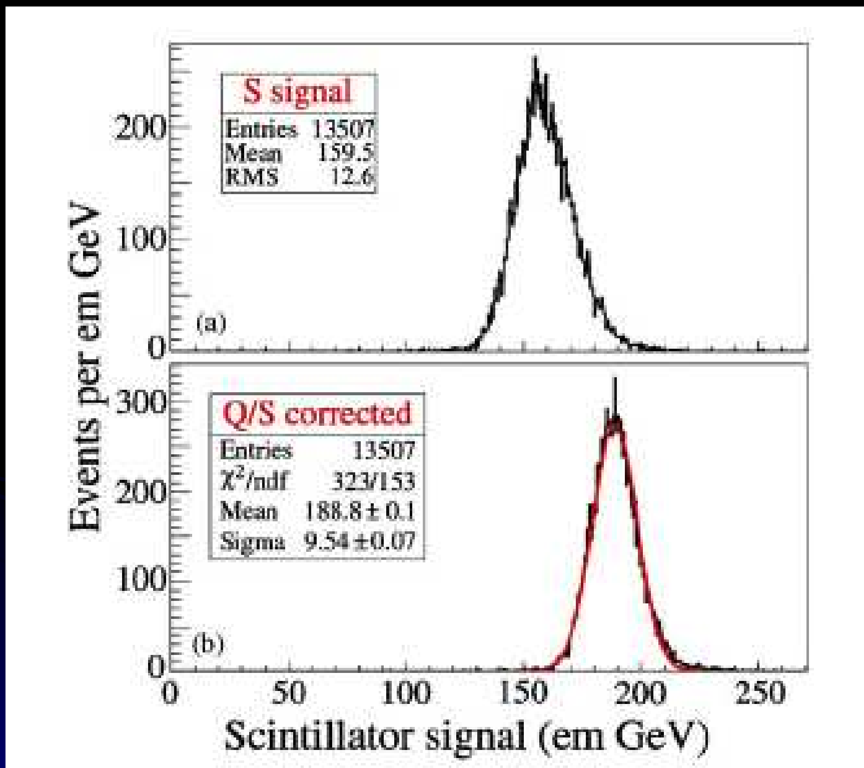
Scint + Cerenkov

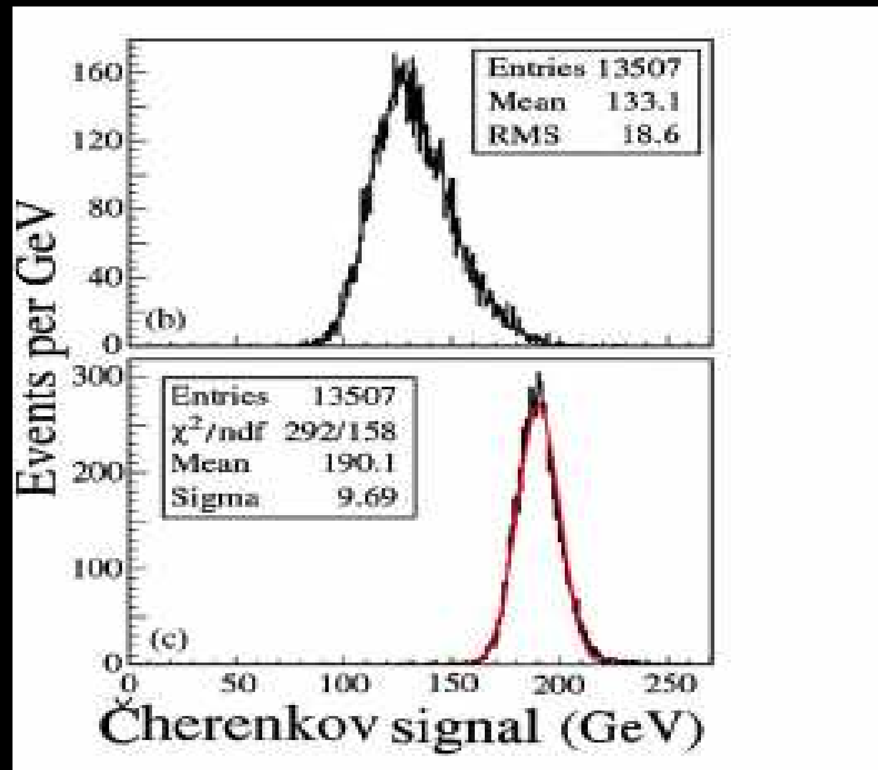
$f_{EM} \propto (C/E_{beam} - 1/\eta_C)$

(suppresses leakage)

Data NIM A537 (2005) 537.

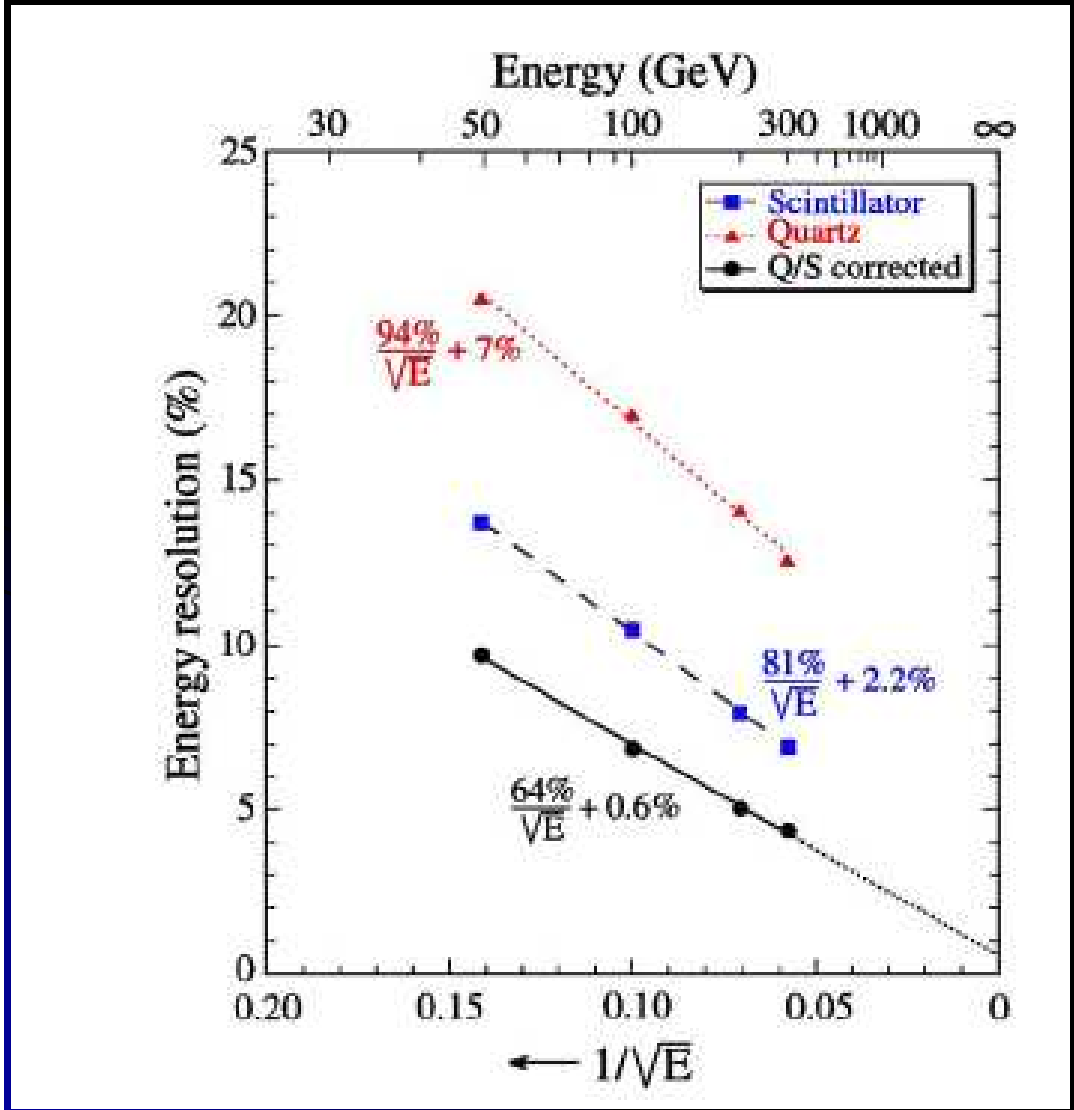
Correcting the Shower Components





- High multiplicity jets

Corrected Calorimeter Response

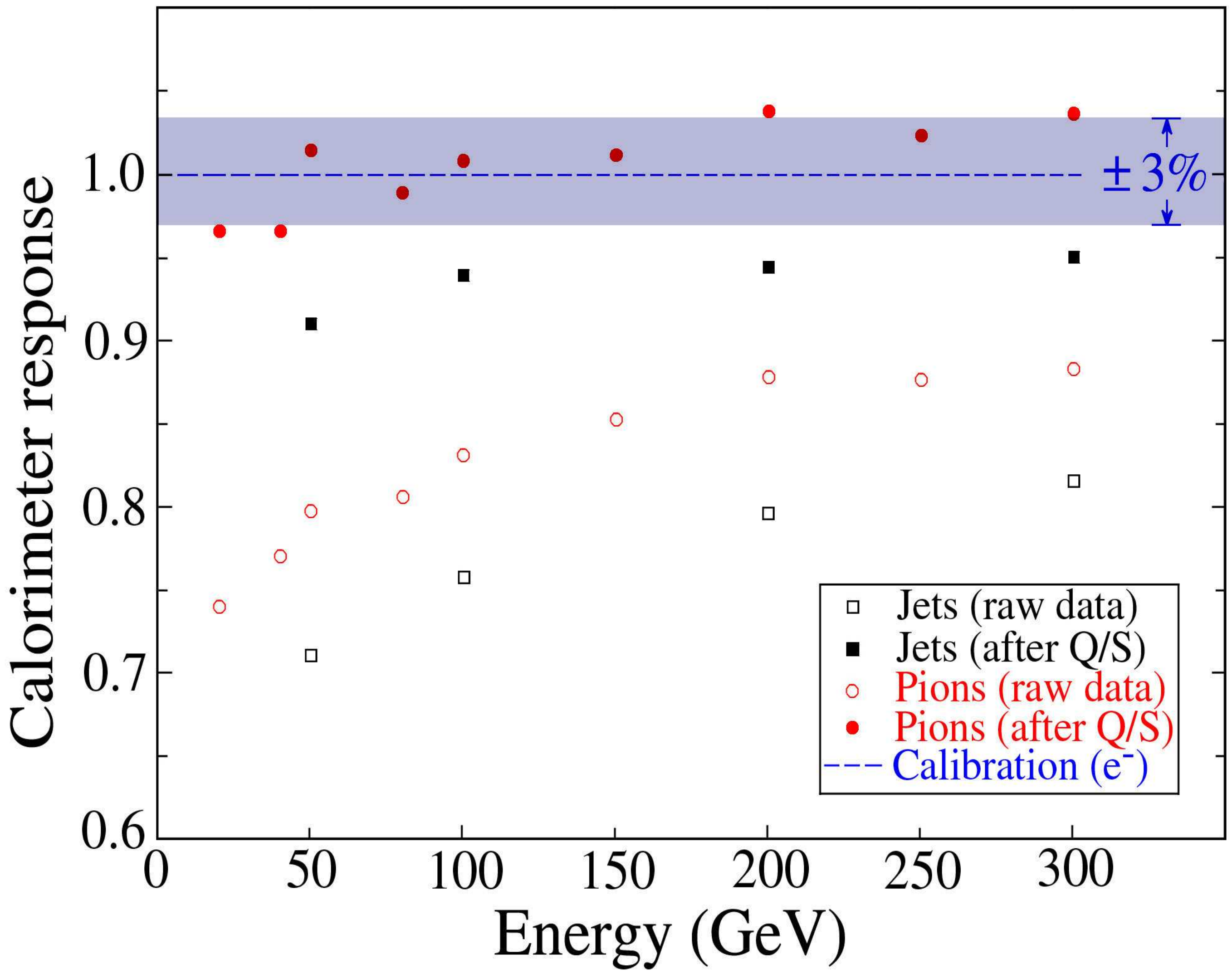


$$E_{HCAL} = \frac{\eta_S \cdot E_S \cdot (\eta_C - 1) - \eta_C \cdot E_C \cdot (\eta_S - 1)}{\eta_C - \eta_S}$$

- High multiplicity jets

DREAM calibrated with 40 GeV e^- into center of each tower

recover linear hadronic response up to 300 GeV for π^- and "jets"



Hadronic linearity may be the most important achievement of dual-readout calorimetry.

From DREAM to the 4th Concept HCAL

DREAM module

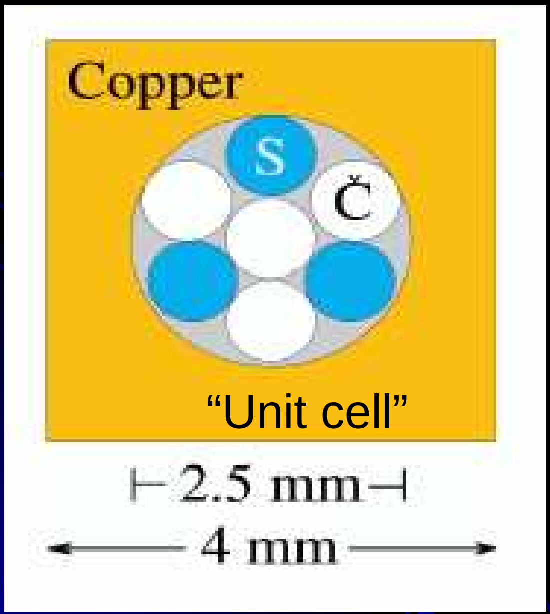
3 scintillating fibers

4 Cerenkov fibers

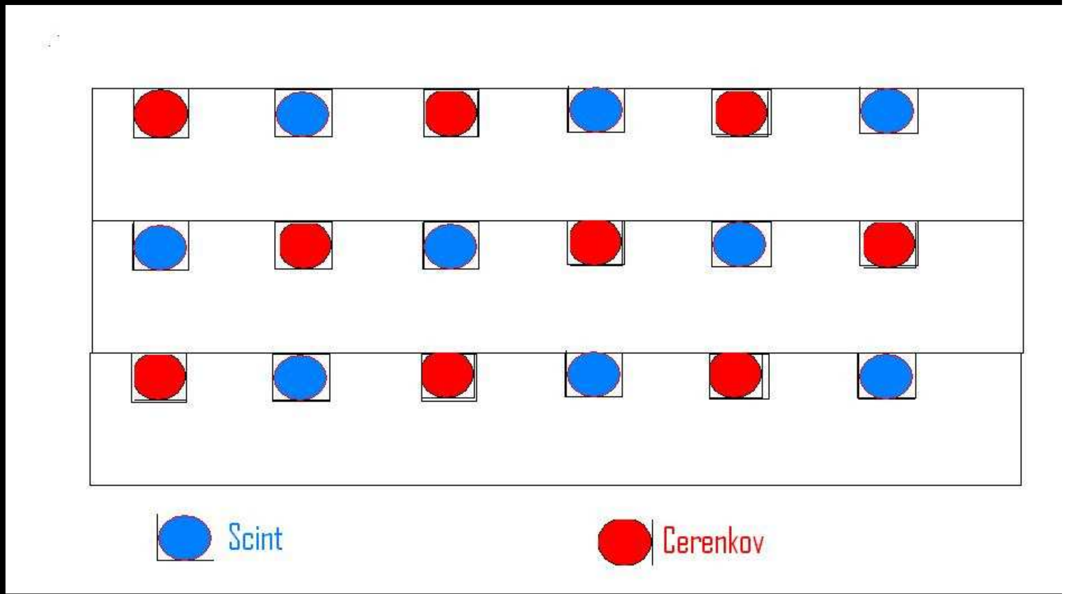
→

ILC-type module

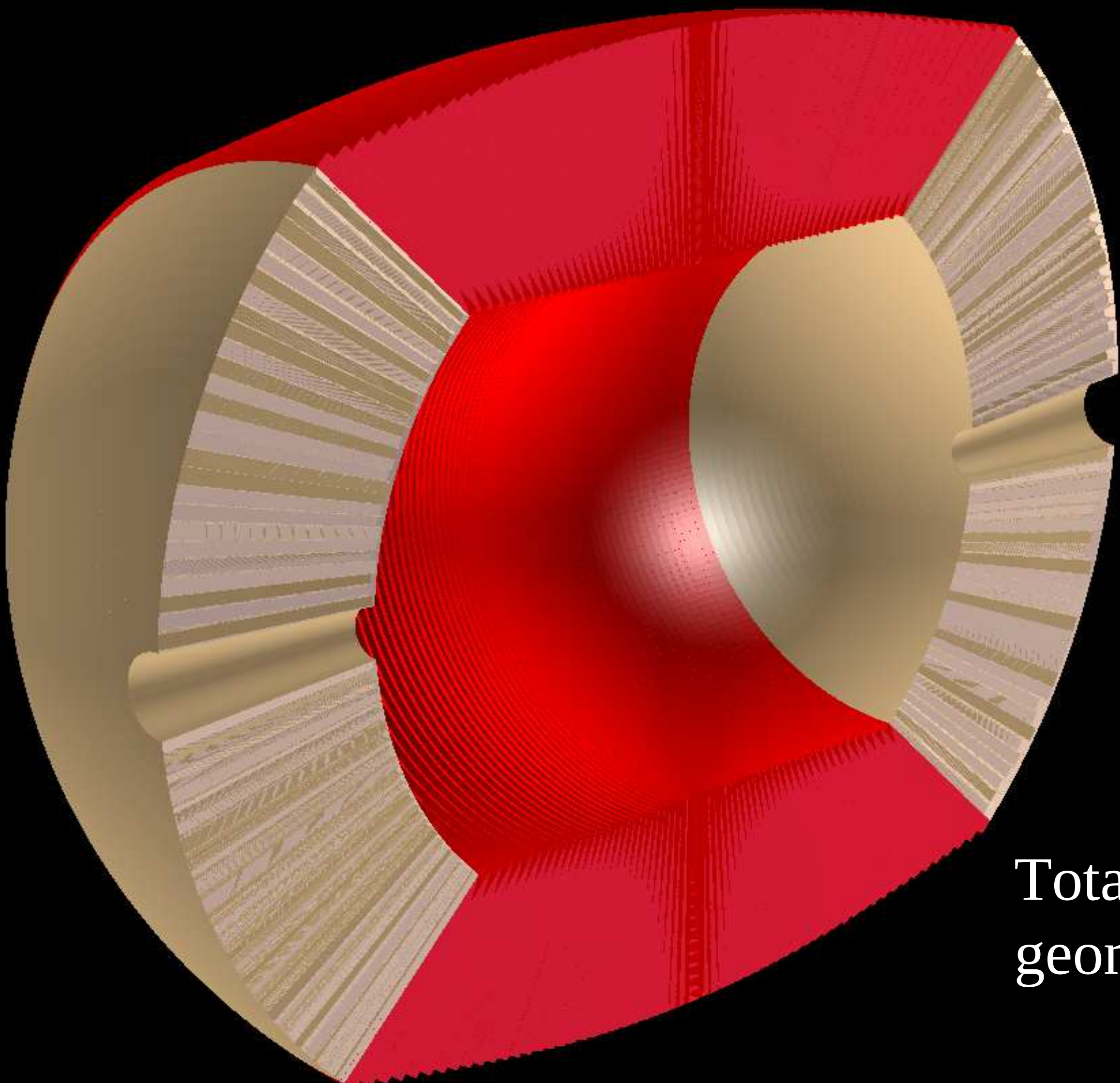
2mm W or brass plates; fibers every 2 mm



→



The 4th Concept Calorimeter in Ilcroot

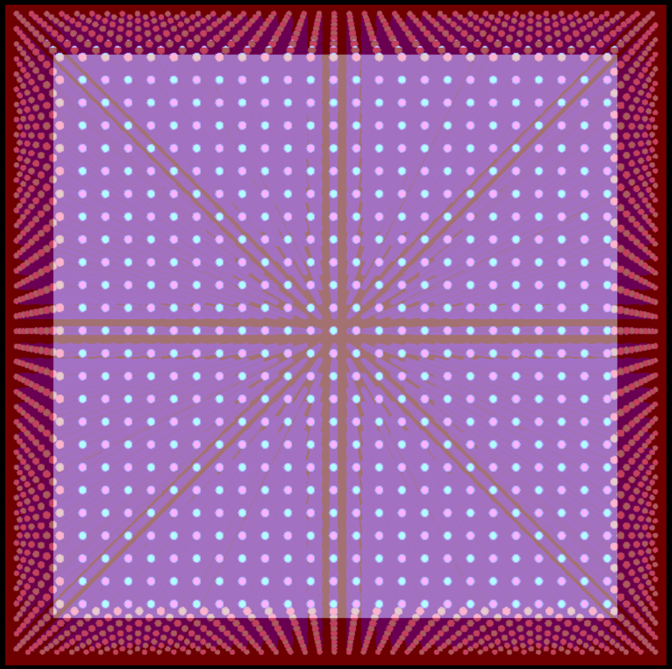


Totally projective geometry

4th Concept Simulation

- Cu + scintillating fibers + Ĉerenkov fibers
- ~ 10 λ_{int} depth
- Fully projective geometry
- ~1.5° aperture angle
- Azimuth coverage down to 3.4°
- Barrel: 13924 cells
- Endcaps: 3164 cells

Hadronic Calorimeter Cells



Bottom view of single cell

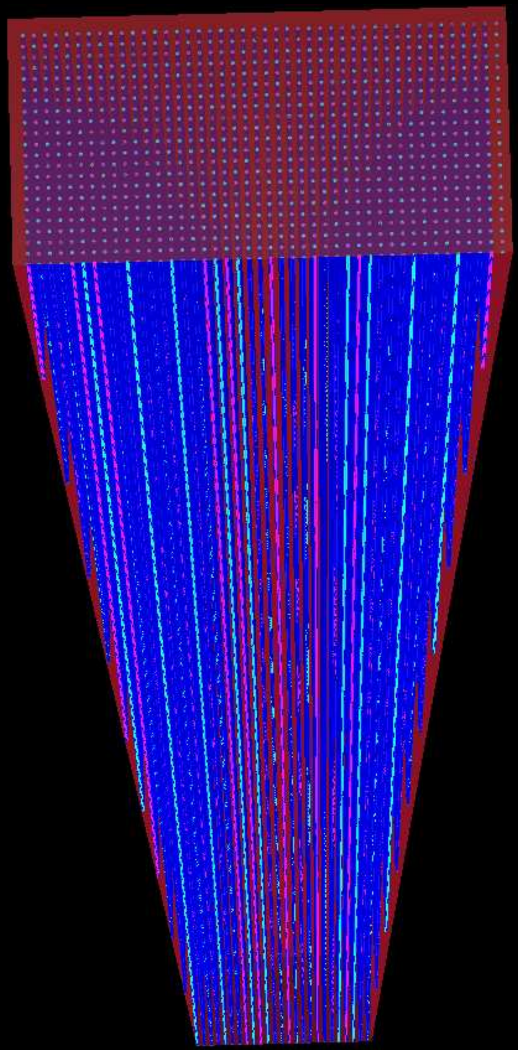
Bottom cell size: ~2 cm

Top cell size: ~ 4 cm

- Number of fibers inside each cell: 1980
  equally subdivided between Scintillating and Cerenkov
  Fiber stepping ~2 mm

Prospective view of clipped cell

Cell length: 150 cm (but DoD has 100cm)



Simulation/Reconstruction Steps

MC Simulation ⇒ Energy Deposits in Detector

↓

Digitization ⇒ Detector response combined

↓

Pattern Recognition ⇒ Recpoints

↓

Track Finding ⇒ Tracks

↓

Track Fitting ⇒ Track Parameters

Simulation

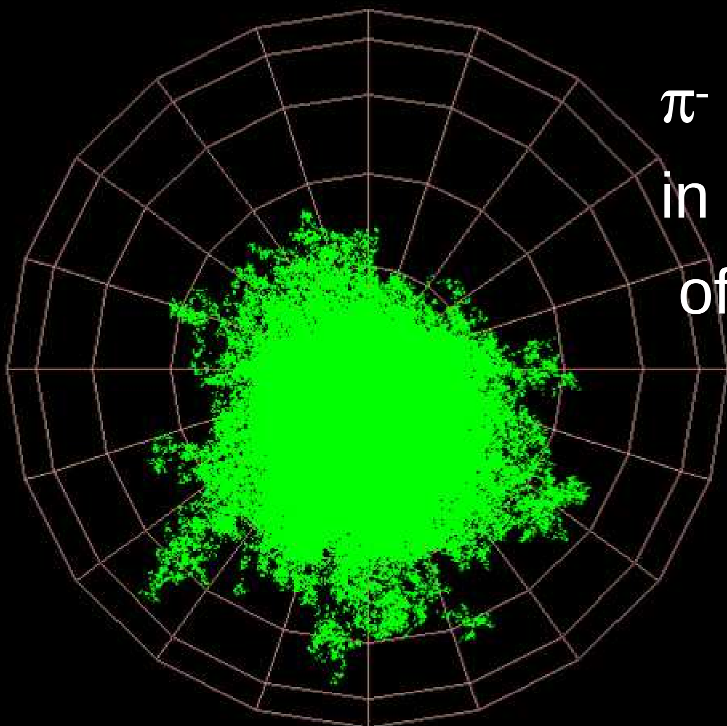
Light production in the fibers simulated through 2 separate steps:

1. Energy deposition (hits) in active materials calculated by the tracking algorithm of the MC
2. Conversion of the energy into the number of S and C photons by specific routins taking account several factors: energy of the particle, angle between the particle and the fiber, etc. Poisson uncertaintity introduced in the number of photon produced

Simulation

- Response function of the electronics not yet simulated (digits)
- Random noise generated to test the ability of reconstruction algorithm to reject such spurious “hits”

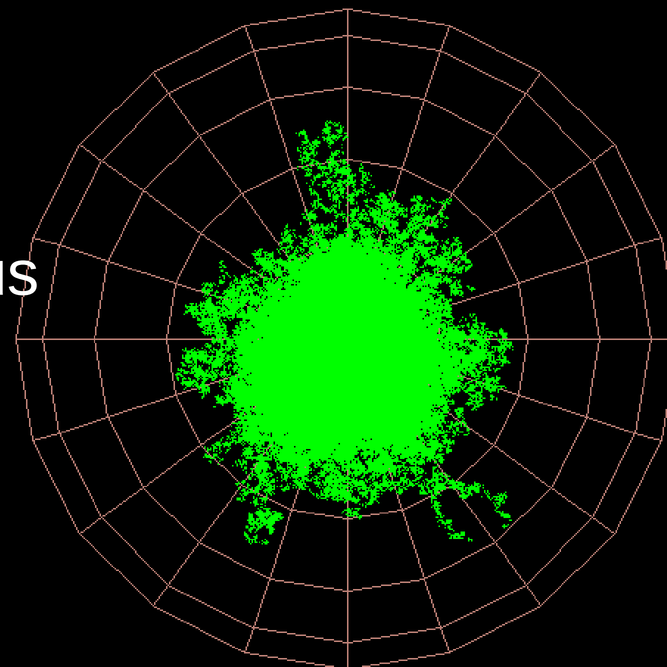
Fluka vs G3/G4



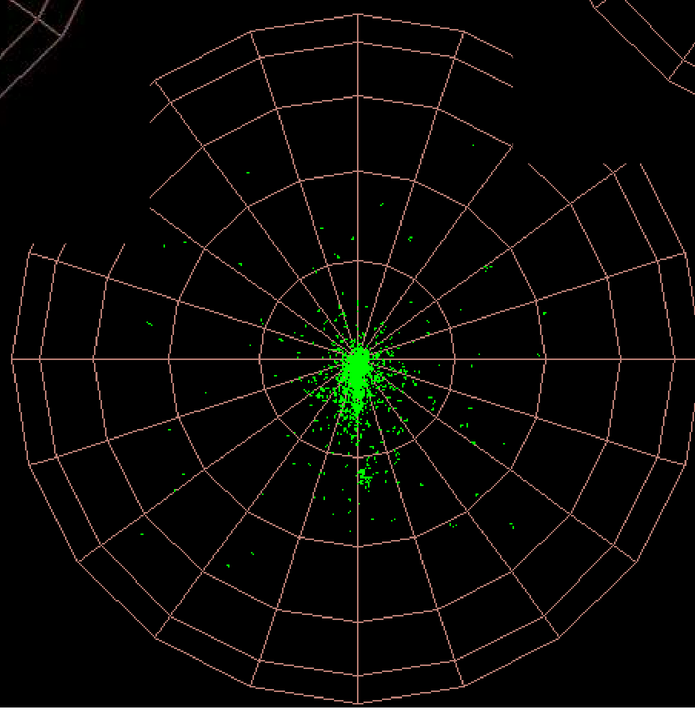
π^- at 50 GeV

in Pb sphere

of 500 cm radius



Geant3



Fluka

Geant4

Fluka vs G3/G4

Geant3	46.541 GeV
Fluka	48.074 GeV
Geant4 QGSP_BER	45.024 GeV
Geant4 QGSP_BER_HP	47.791 GeV

Reconstruction

- Clusterization (↔ pattern recognition)

  cluster = collection of nearby “digits”
  - Build Clusters from cells distant no more than two towers away
  - Unfold overlapping clusters through a Minuit fit to cluster shape

- Reconstructed energy E adding separately E_S and E_C of all the cells belonging to the reconstructed cluster

Calibration

Energy of HCAL calibrated in 2 steps:

1. Calibrate the signals from S and C fibers

   used single 40 GeV e^- (to get η_C and η_S)

2. Keep hadronic shower energy indipendent from f_{em}

   used single 40 GeV π^-

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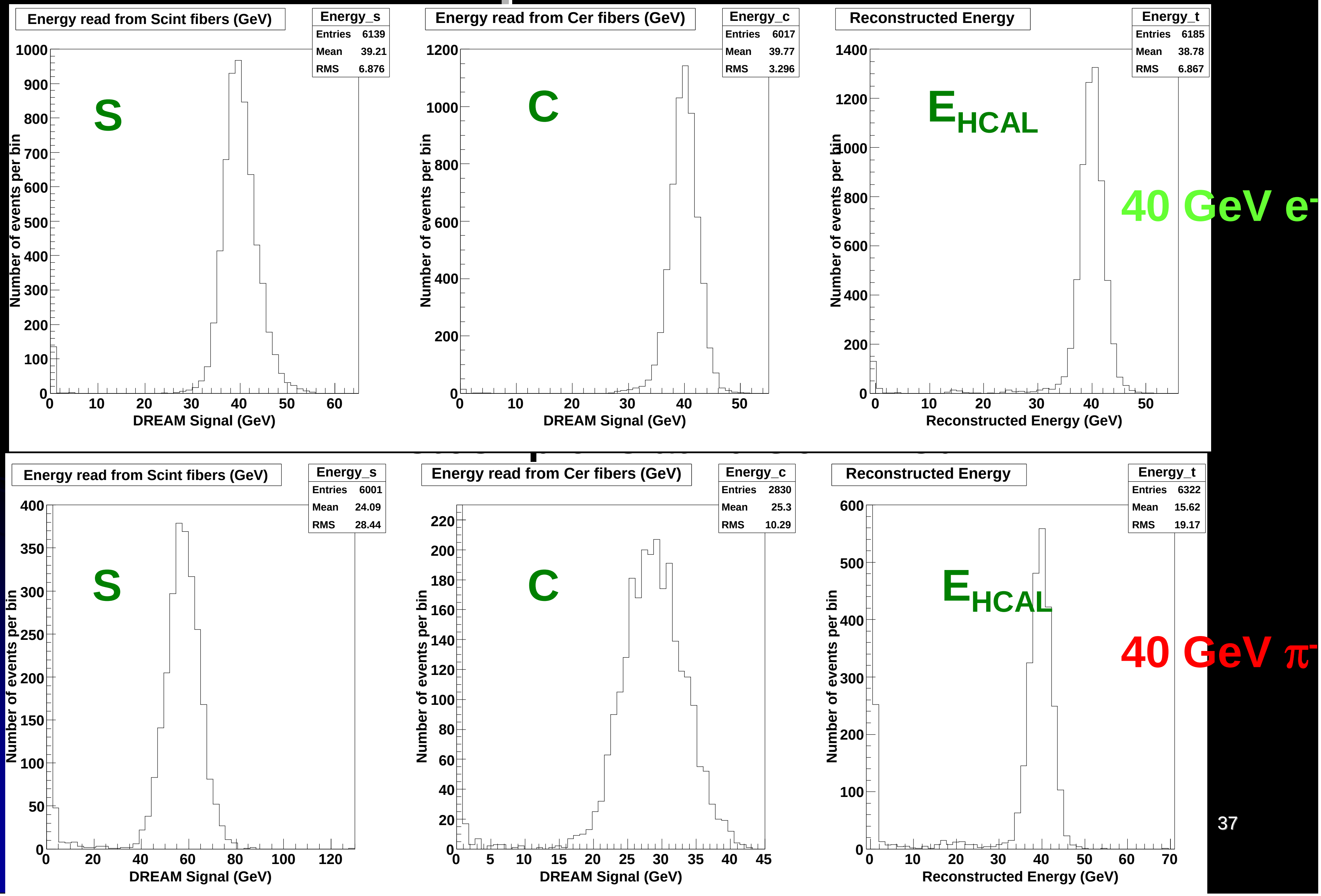
Reconstructed energy

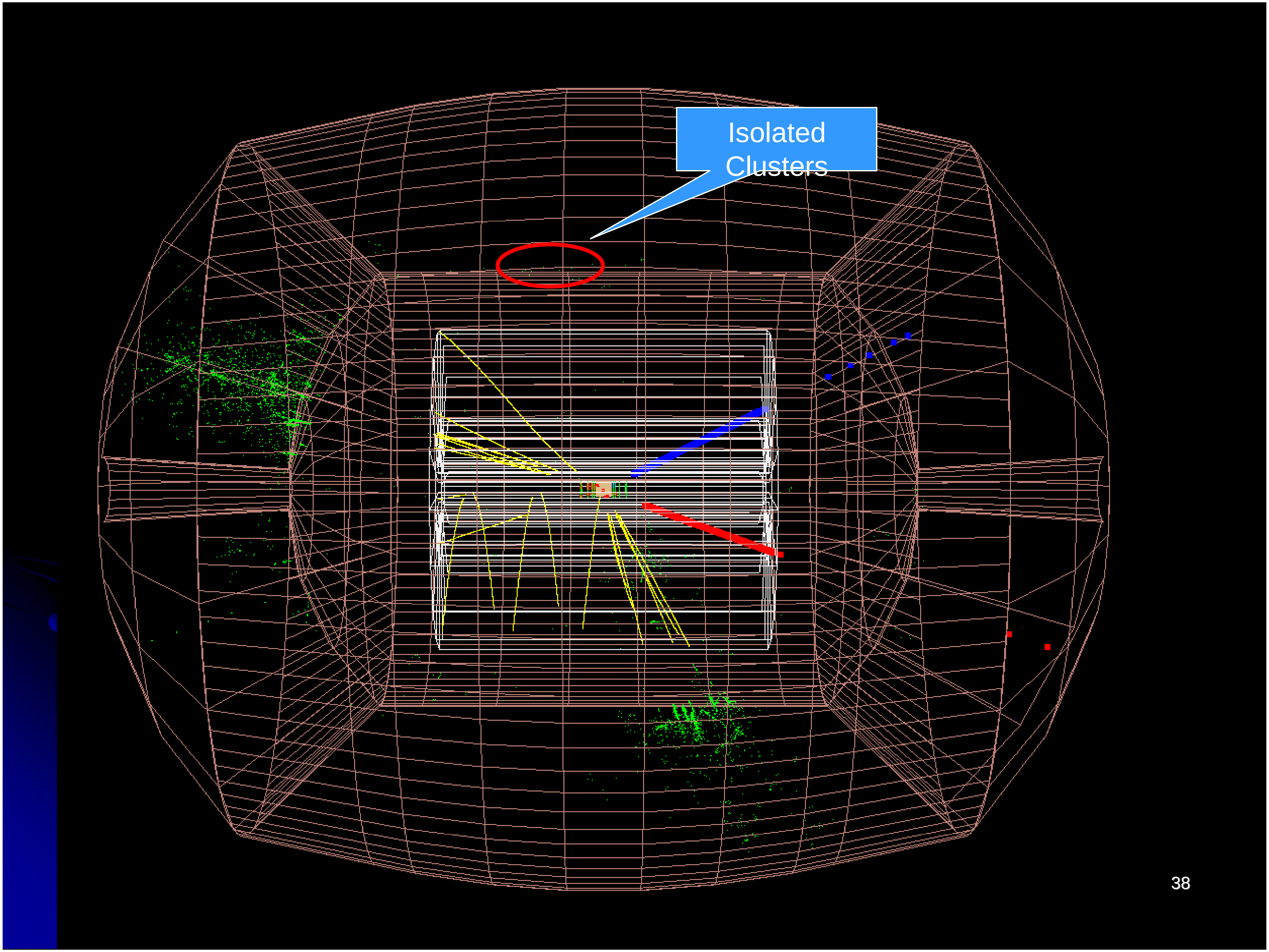
Once HCAL calibrated, calorimeter energy:

$$E_{HCAL} = \frac{\eta_S \cdot E_S \cdot (\eta_C - 1) - \eta_C \cdot E_C \cdot (\eta_s - 1)}{\eta_C - \eta_S}$$

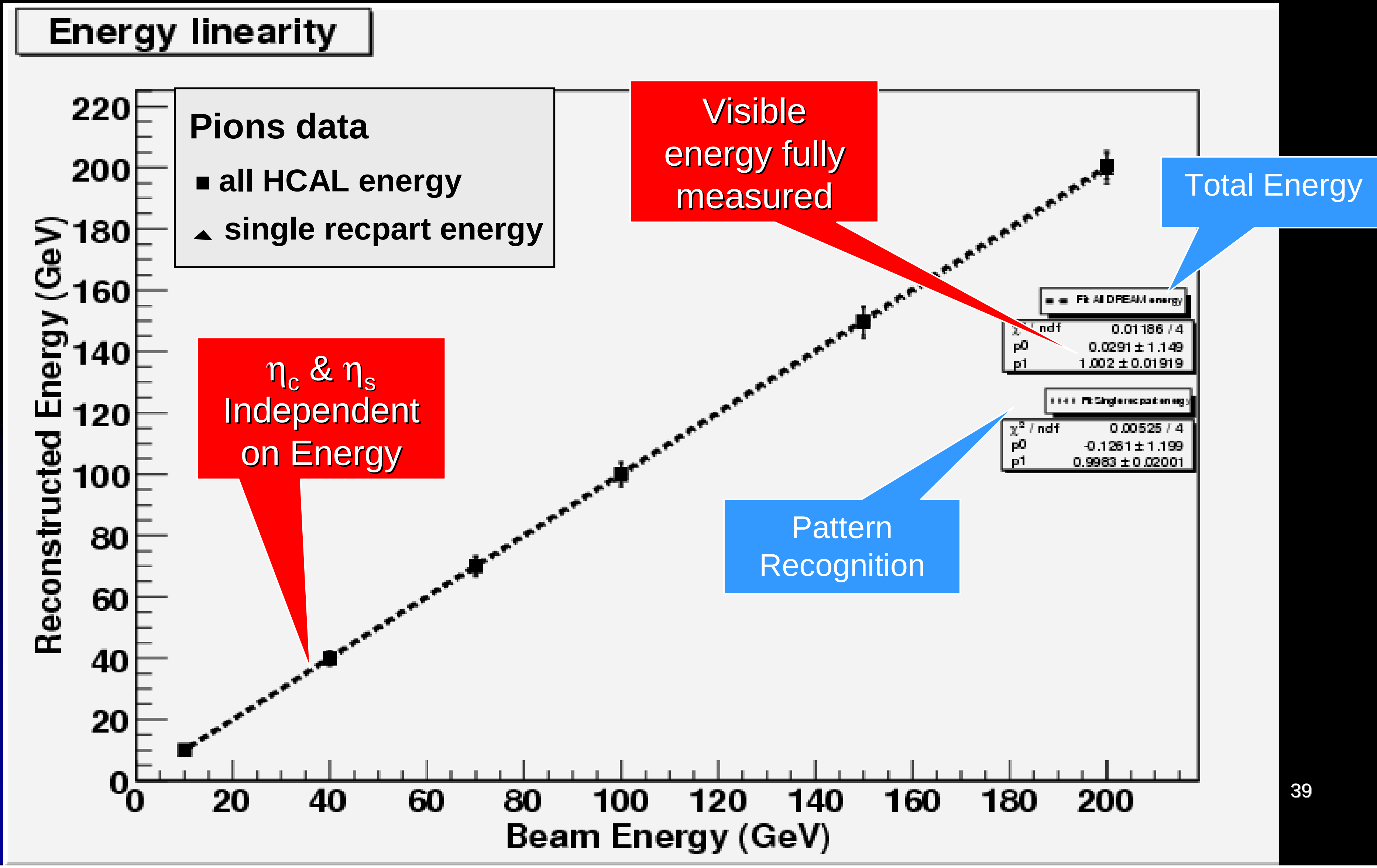
$$\eta_c = \left(\frac{e}{h}\right)_C \qquad \eta_S = \left(\frac{e}{h}\right)_S$$

4th Concept Resolution Plots

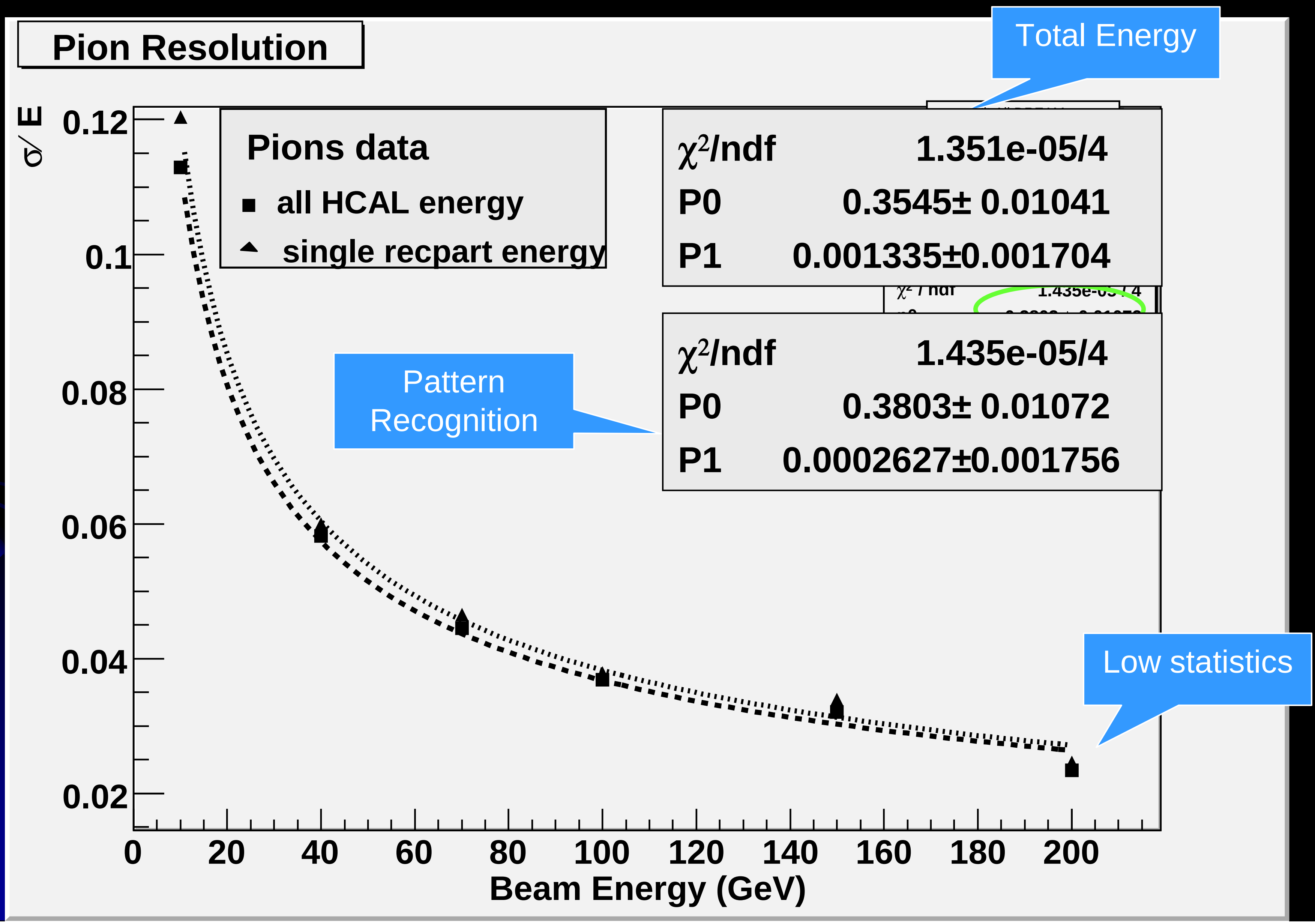



Isolated
Clusters

Reconstructed vs Beam Energy

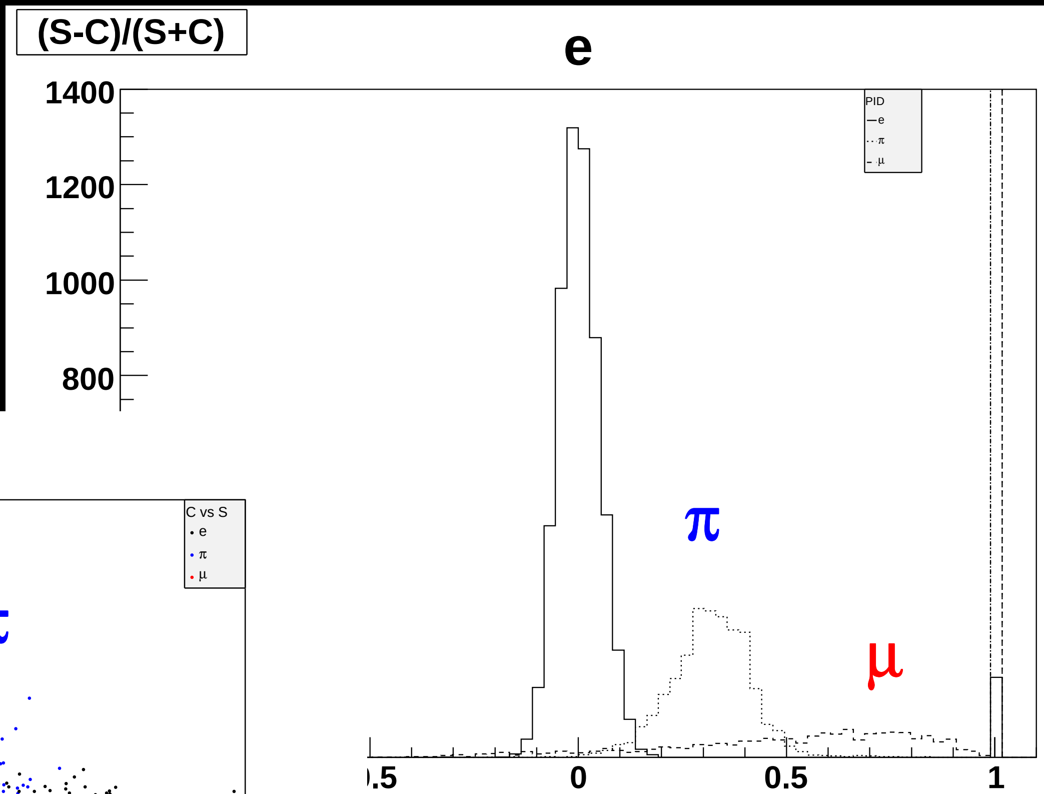


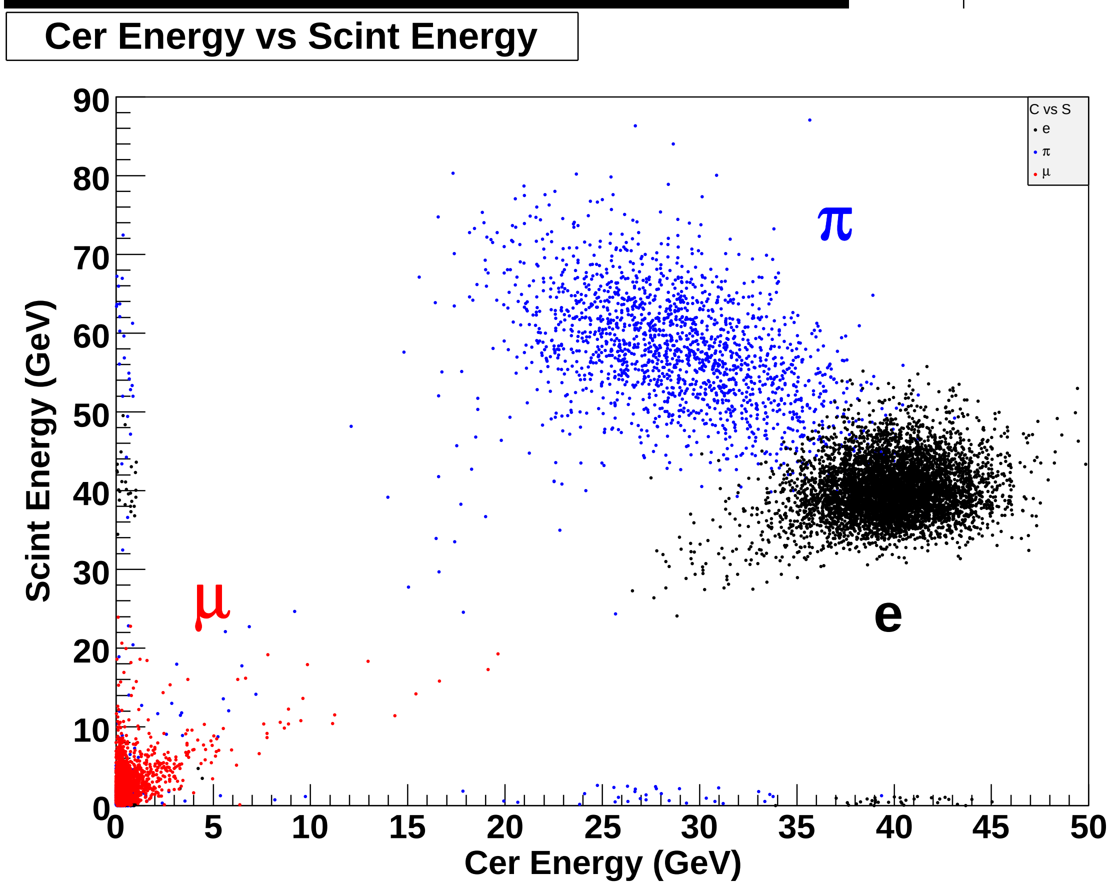
Resolution for hadrons



Particle Identification

- 40 GeV particles



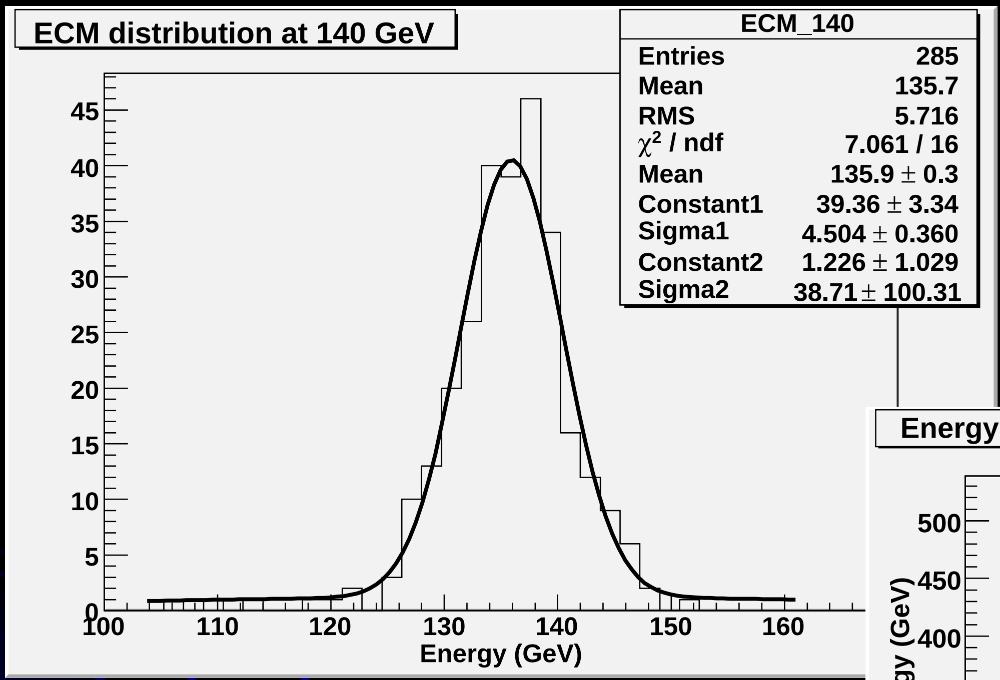


Jets Studies

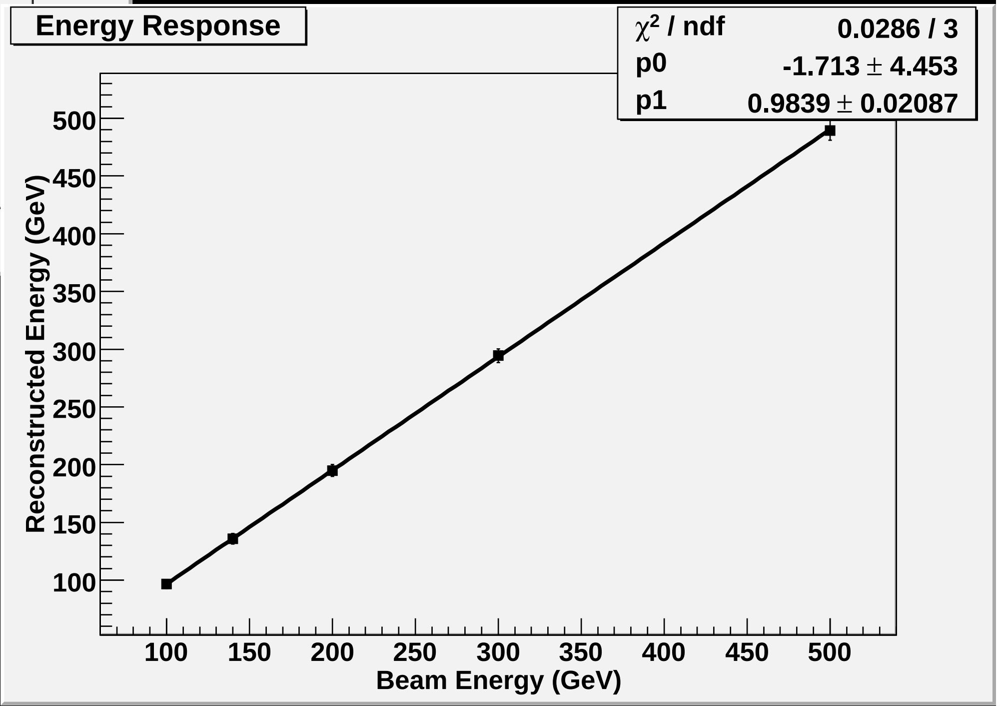
The Jet Finder Algorithm

- Look for the jet axis using a Durham algorithm
  - Charged tracks
  - Calorimeter cells
  - Calorimeter Clusters
- Jet core
  - Open a cone increasingly bigger around the jet axis (< 60°)
  - Run a Durham j.f. on the cells of the calorimeter inside the cone
- Jet outliers
  - Check leftover/isolated calo cluster/cells for match with a track from TPC+VXD
  - Add calorimetric or track momentum
  - Add low P_t tracks not reaching the calorimeter
- Muons
  - Add tracks reconstructed in the MUD

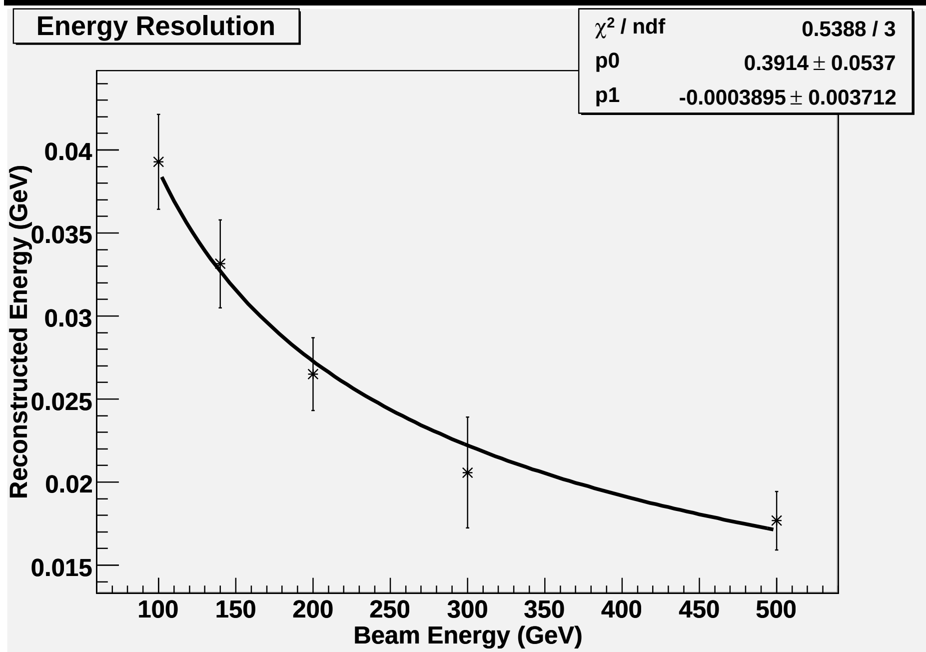
Total Energy Plots



- $e^+ e^-$ -> q qbar (uds)
- No jet finder
- Energy calibration with no material in front

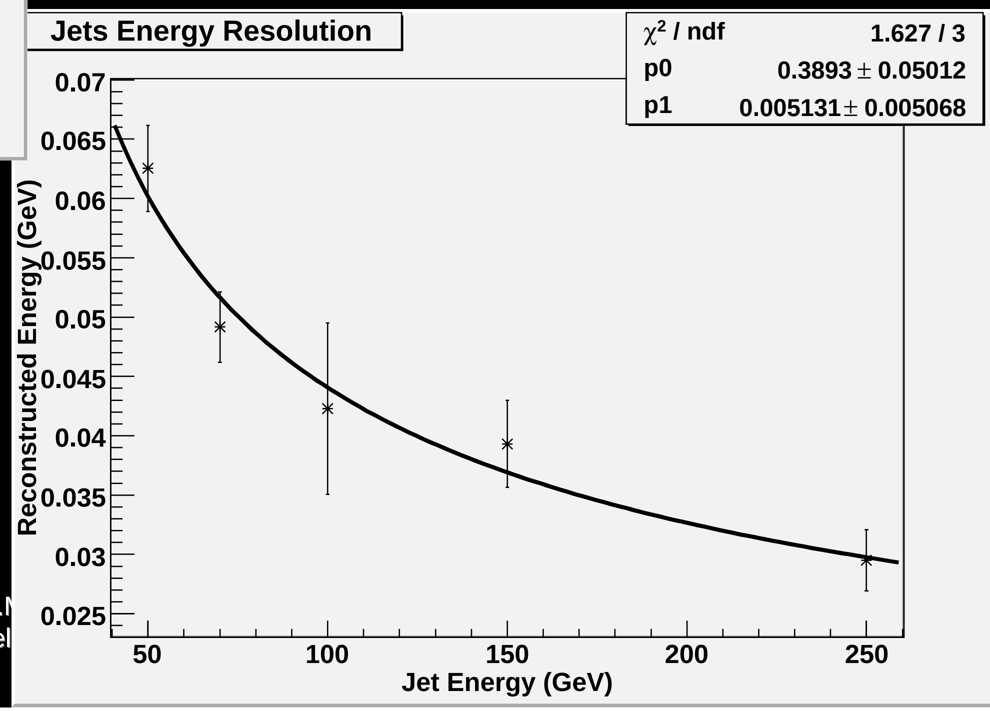


Energy Resolution



- Single jet (jet finding included)

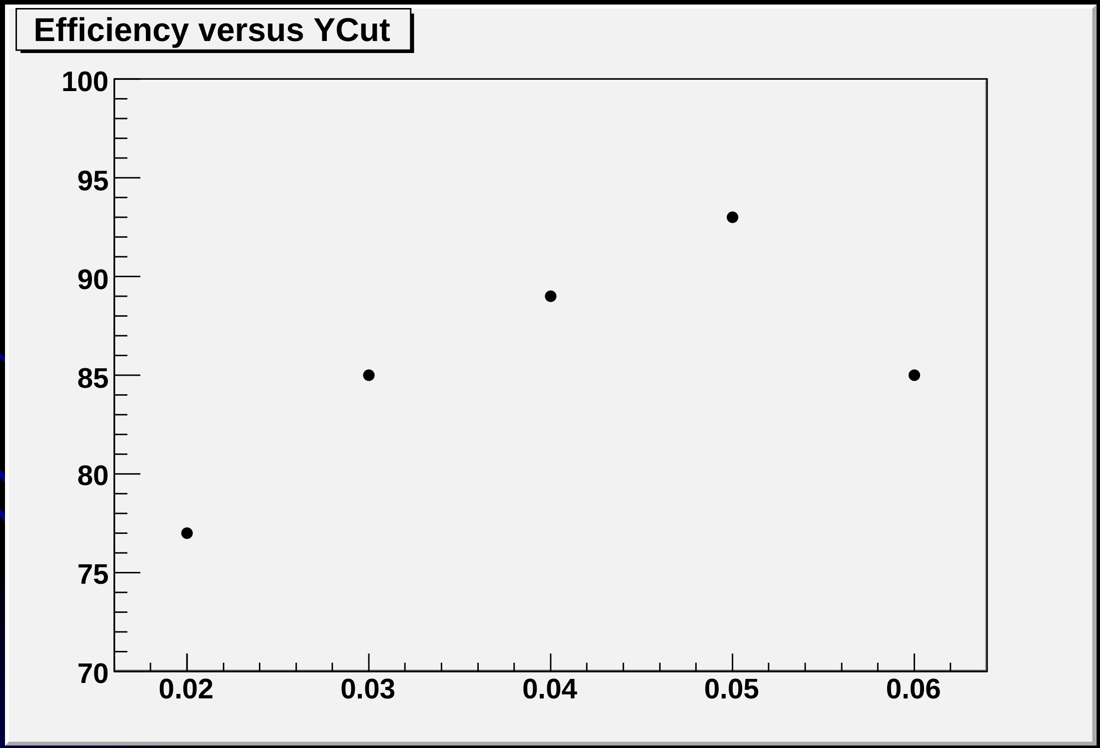
- Total ECM (no jet finding)



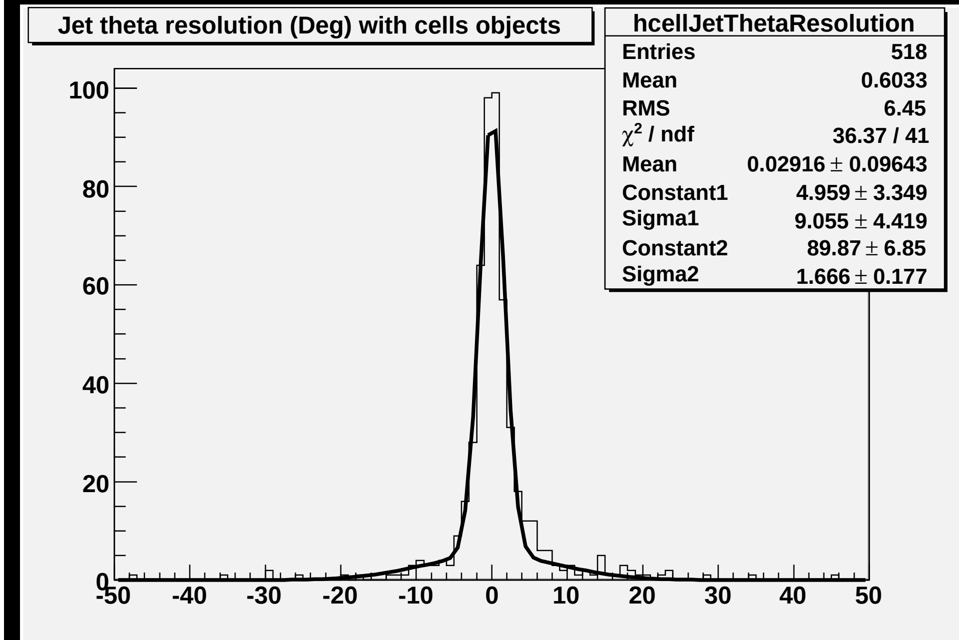
Physics Studies

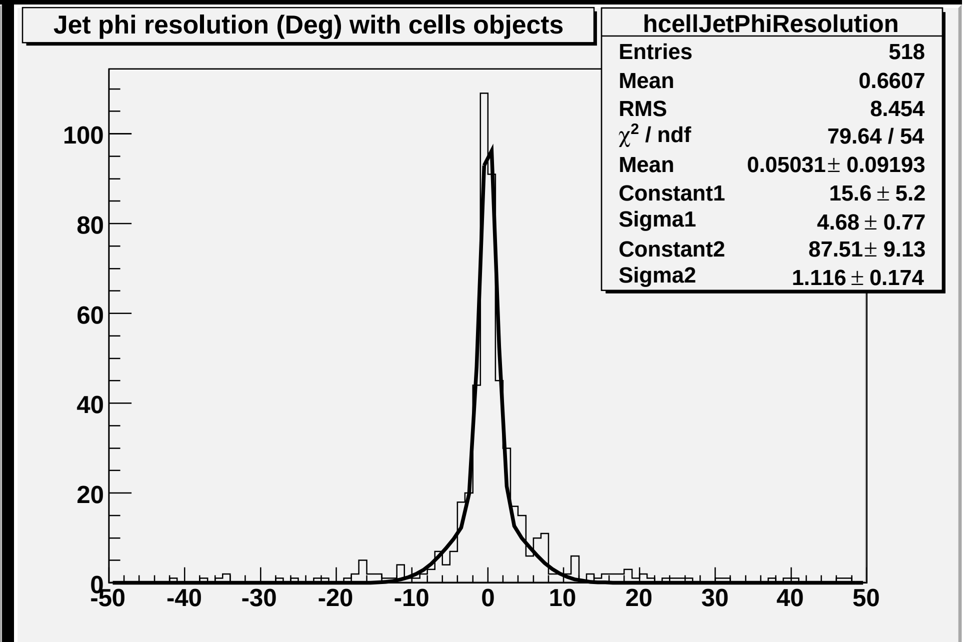
$e^+e^- \rightarrow Z^oH^o \rightarrow \nu\underline{\nu}\, c\underline{c}$

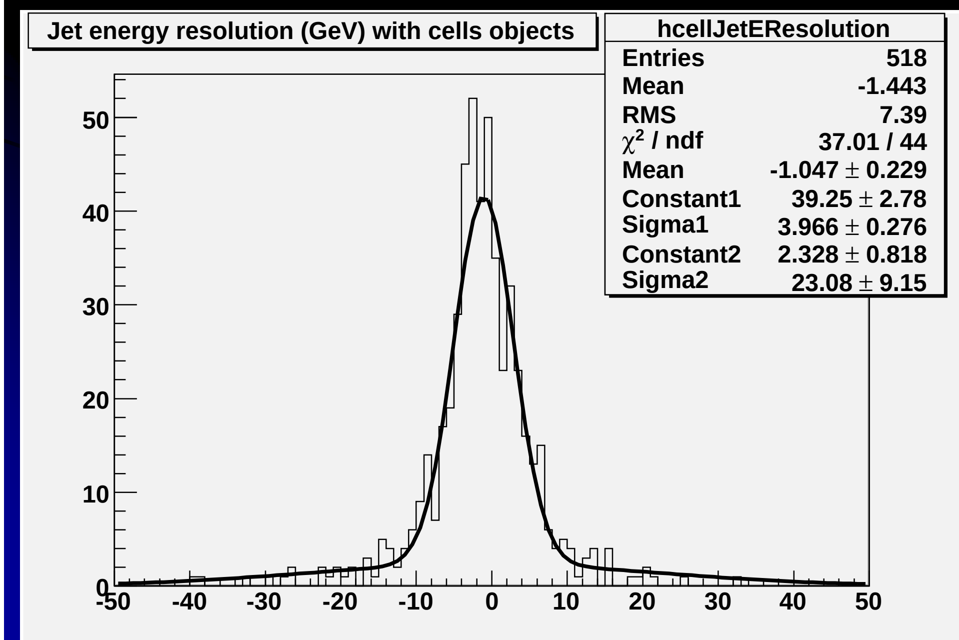
- Pandora-Pythia (E_{cm}=350 GeV, M_H=140 GeV) + Fluka
- No MUD (use MC truth)
- Cut recoil mass 20 GeV around Z^o mass
- Maximize j.f. efficiency through y_t cut (ε_{ff}=97%)



Jet Finder Performance

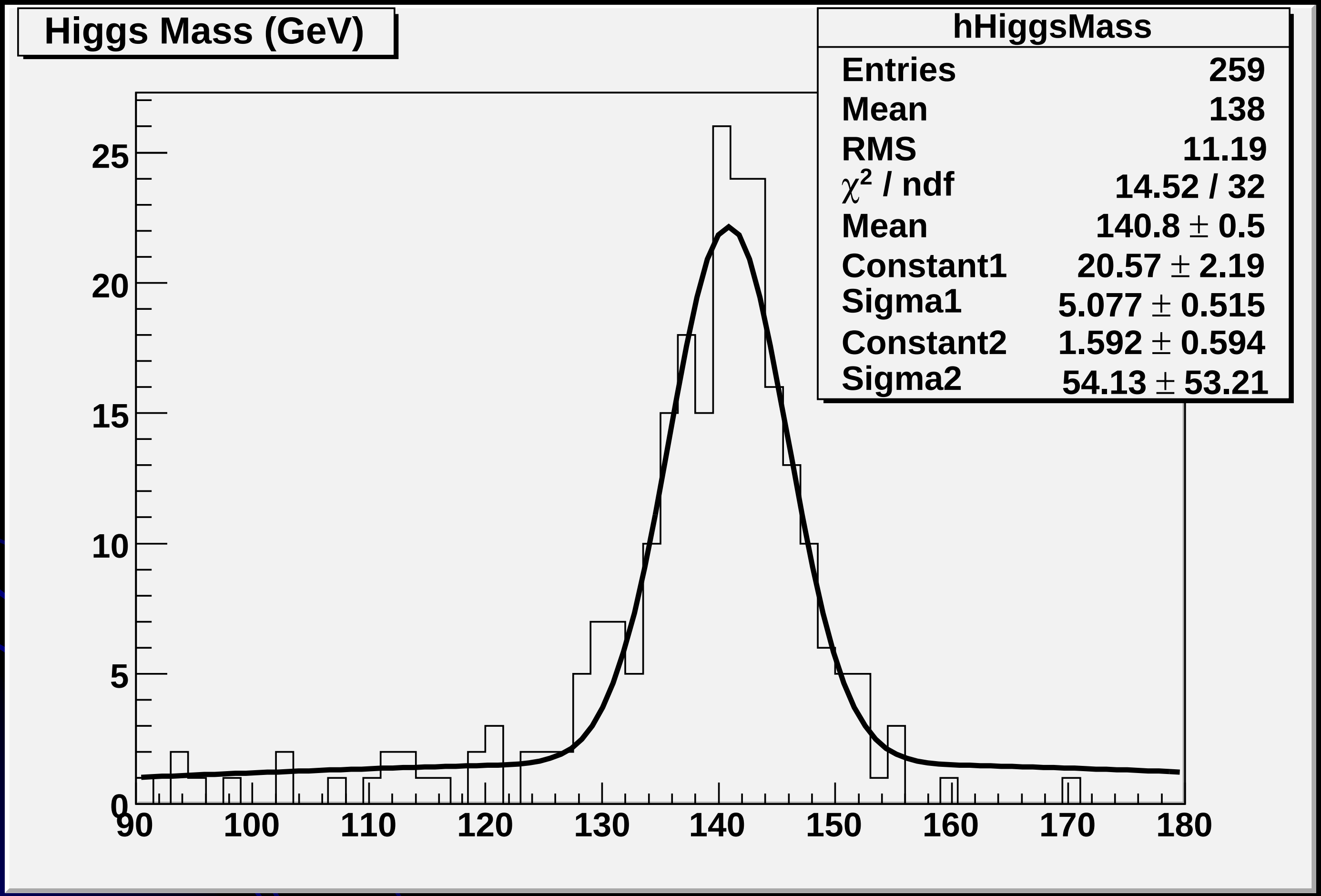






- Angular resolution < 2°
- Energy resolution = 4 GeV

Jet-Jet Mass Plot



Conclusions

- The 4th Concept has chosen a Calorimeter with Dual Readout
- The technology has been proved at a test beam, but never in a real experiment
- Performance of Calorimeter is expected to be extremely good:

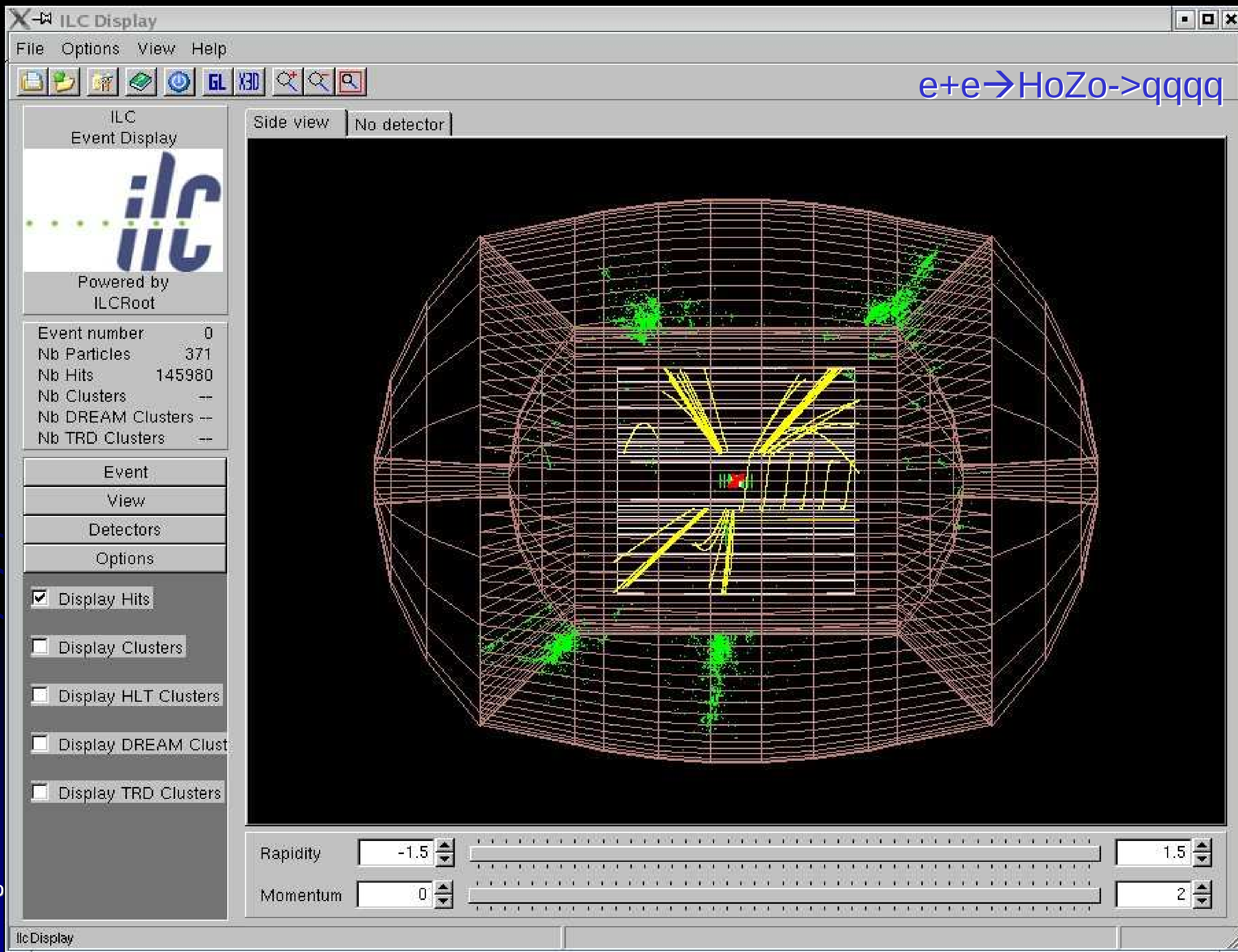
$$\sigma_E/E = 36\%/\sqrt{E} \text{ (single particles)}$$

$$\sigma_E/E = 39\%/\sqrt{E} \text{ (jets)}$$

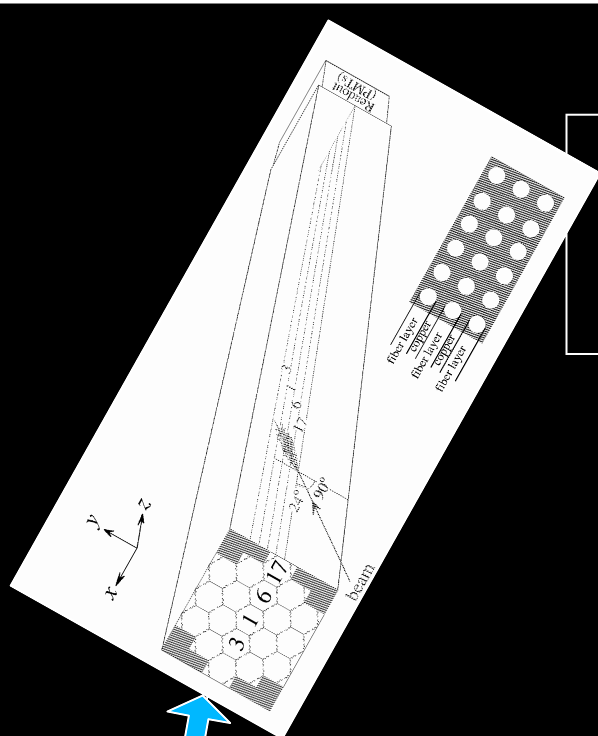
- An EMCAL design with Dual Readout crystal technology is under way

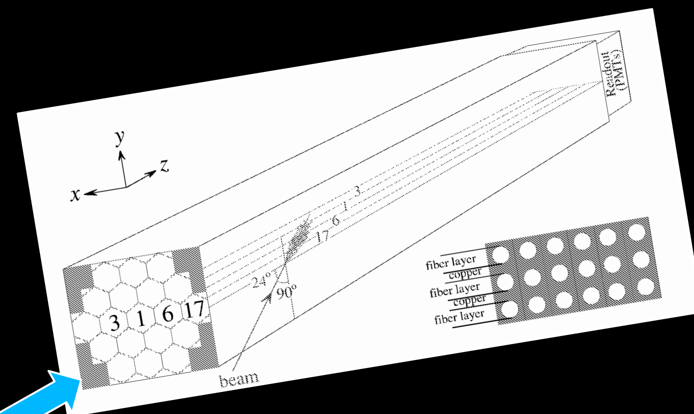
Backup slides

Present Status: VXD+TPC+DREAM



W decay to DREAM “jets”



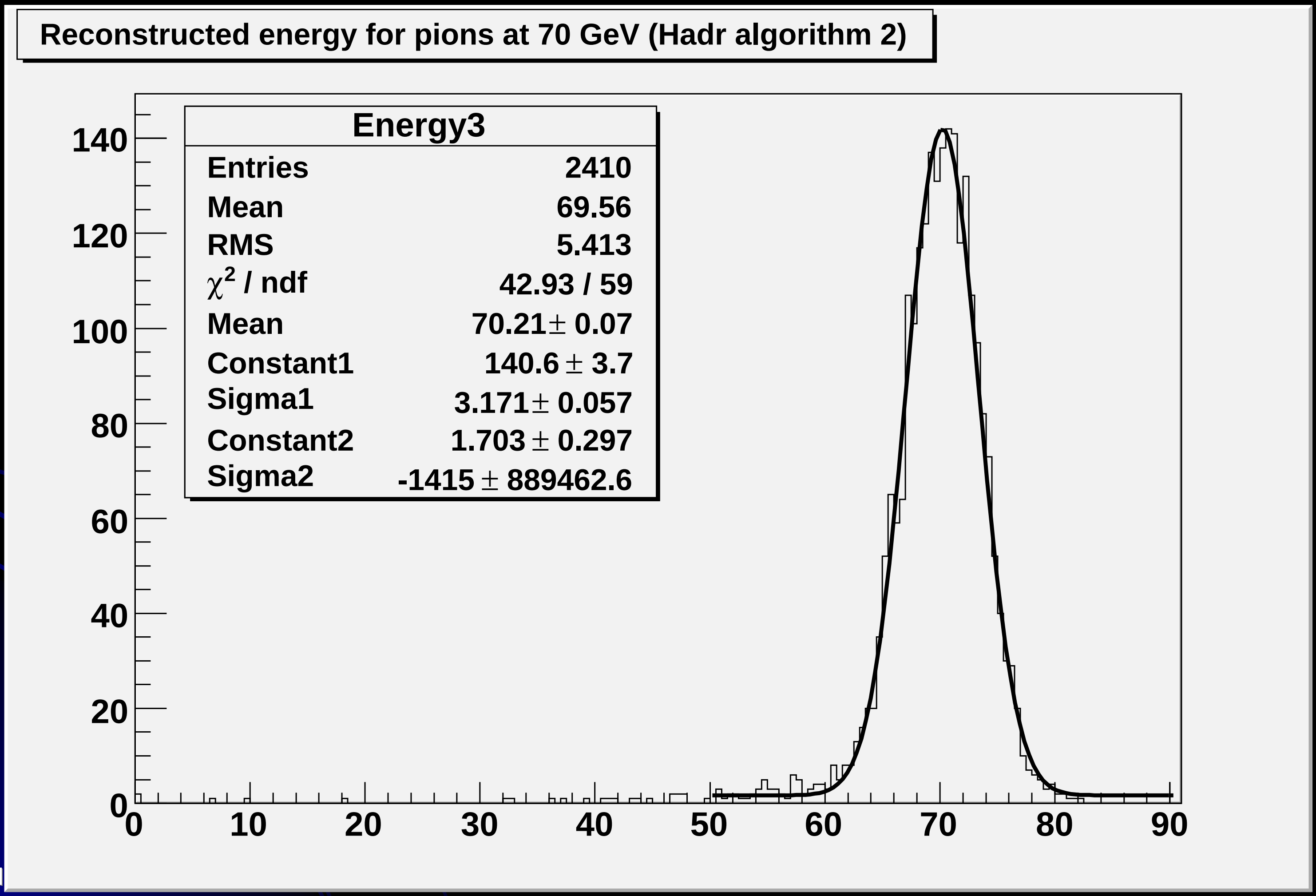


α

$M_W^2 = 2E_1E_2(1 - \cos\alpha)$

M_W

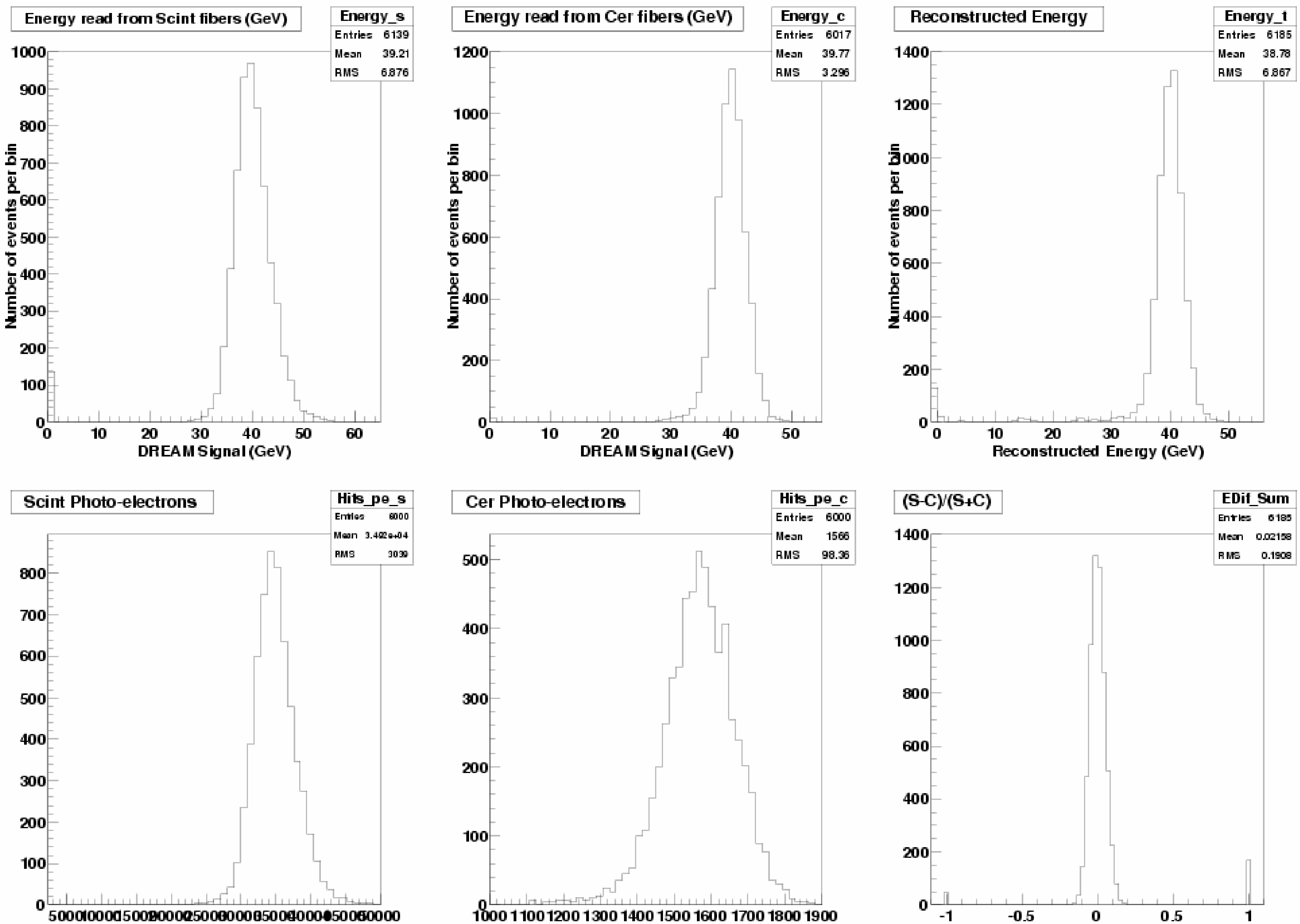
Dream Performance (pions)



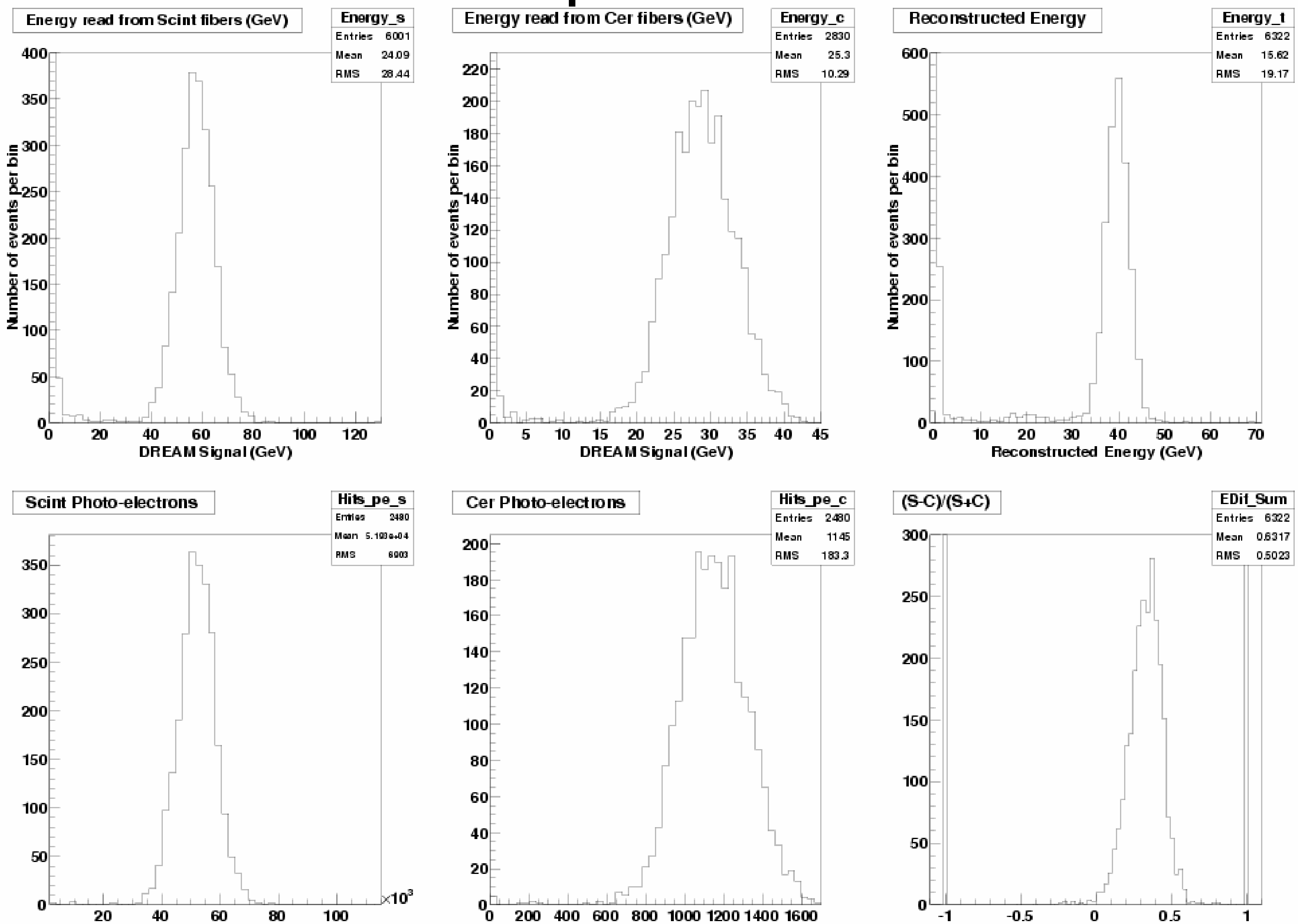
Results from DREAM simulation (V. Di Benedetto)

- Scintillation and Cerenkov processes well simulated
- Easily switch from Cu to W (however, need to change calibration values of η_S and η_C)
- Pattern recognition in place (nearby cells).
- Hadronic showers appear to reproduce the compensation effect seen in the test module (Fluka)
- PiD ($e/\pi/\mu$) results are very promising

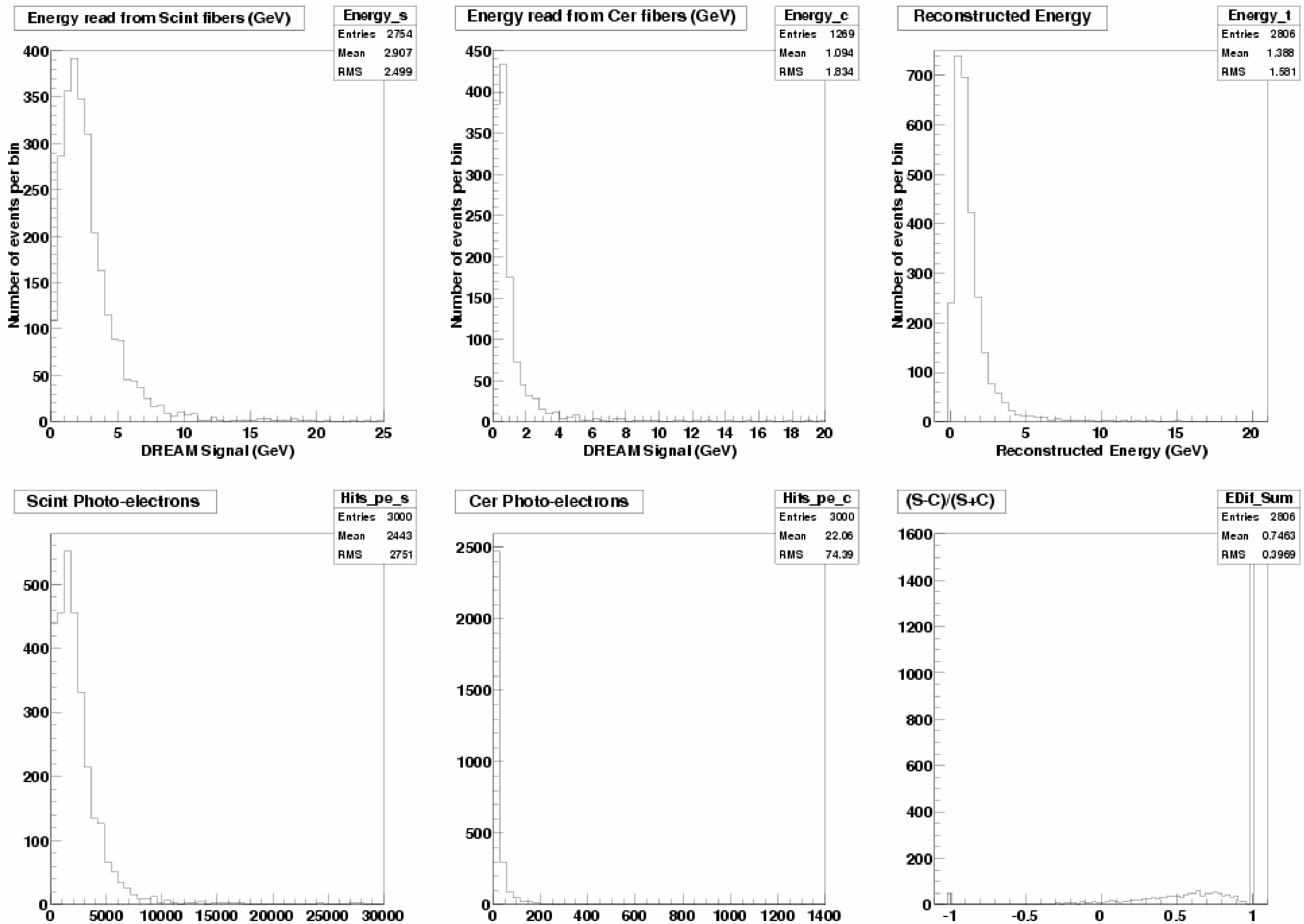
Histos electrons at 40 GeV in Cu

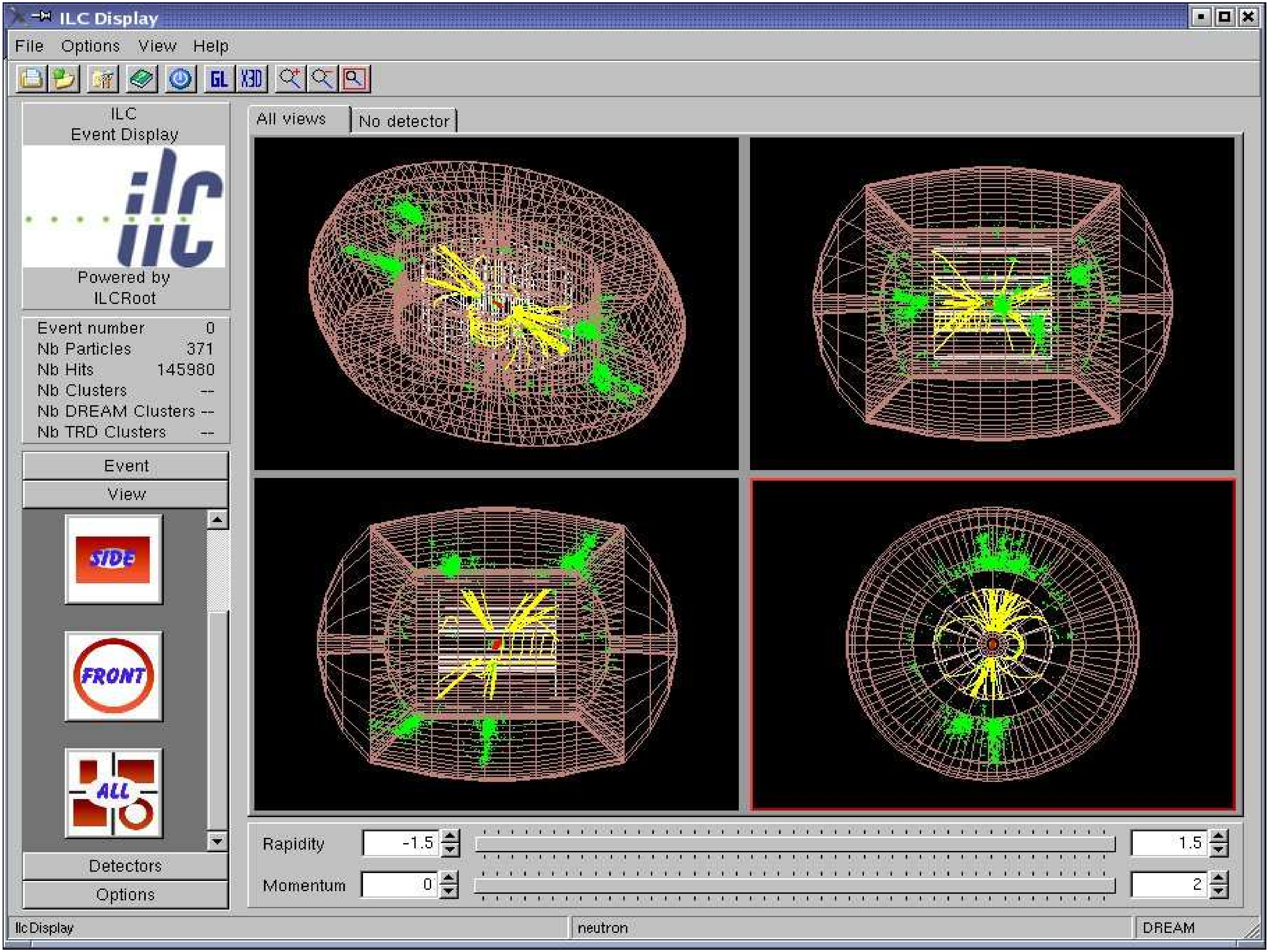


Histos pions at 40 GeV in Cu

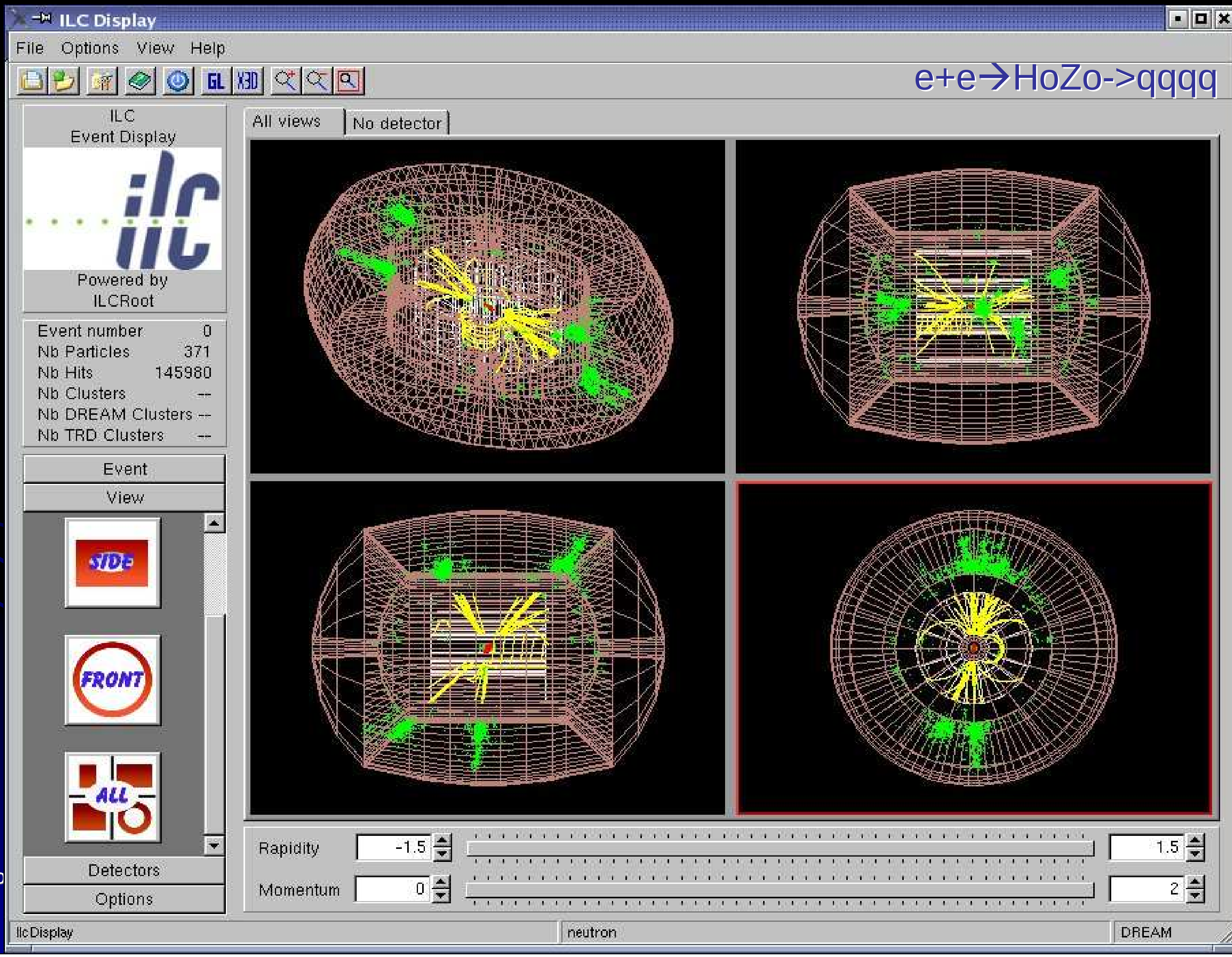


Histos muons at 100 GeV in Cu



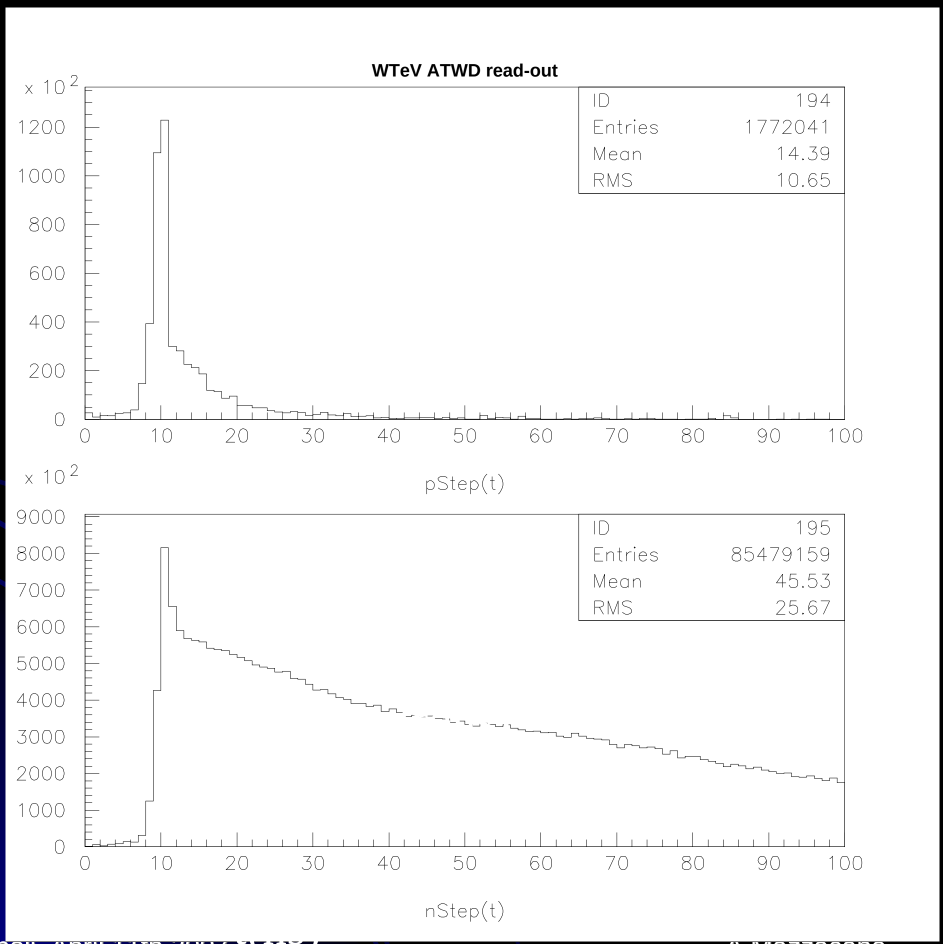

ILC Display
File Options View Help
GL X3D
ILC
Event Display
Powered by
ILCRoot
Event number 0
Nb Particles 371
Nb Hits 145980
Nb Clusters --
Nb DREAM Clusters --
Nb TRD Clusters --
Event
View
SIDE
FRONT
ALL
Detectors
Options
All views
No detector
Rapidity
-1.5
1.5
Momentum
0
2
IlcDisplay
neutron
DREAM

Present Status: VXD+TPC+DREAM



(1) Measure MeV neutrons (binding energy losses) by time.

Pathlength (cm)



Velocity of MeV neutrons is ~ 0.05 c

(1) Scintillation light from np→np scatters comes late; and,

(2) neutrons fill a larger volume

(2) Measure MeV neutrons (binding energy losses) by separate hydrogenous fiber

- A hydrogenous scintillating fiber measures proton ionization from np→np scatters;
- A second scintillating non-hydrogenous fiber measures all charged particles, but except protons from np scatters;
- This method has the weakness that the neutron component is the difference of two signals.

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(3) Measure MeV neutrons (binding energy losses) with a neutron-sensitive fiber

- Lithium-loaded or Boron-loaded fiber (Pacific Northwest Laboratory has done a lot of work on these)
- Some of these materials are difficult liquids
- Nuclear processes may be slow compared to 300 ns.
- But, most direct method we know about.

(4) Measure MeV neutrons (binding energy losses) using different Birk's constants

- Birk's constant parameterizes the reduction in detectable ionization from heavily ionizing particles (essentially due to recombination)
- Use two scintillating fibers with widely different Birk's constants.
- Two problems: (i) hard to get a big difference, and (ii) neutron content depends on the difference of two signals

The Ultimate Calorimetry: Triple fiber and dual crystal

Triple fiber: measure every shower three different ways: "3-in-1 calorimeter"

- Spatial fluctuations are huge ~λ_{int} with high density EM deposits: fine spatial sampling with scintillating fibers every 2mm
- EM fraction fluctuations are huge, 5→95% of total shower energy: insert clear fibers generating Cerenkov light by electrons above E_{th} = 0.25 MeV measuring nearly exclusively the EM component of the shower (mostly from $\pi^0 \rightarrow \gamma\gamma$)
- Binding energy (BE) losses from nuclear break-up: measure MeV neutron component of shower.

Dual-readout crystal EM section

(in front of triple-readout module)

- Half of all hadrons interact in the “EM section” … so it has to be a “hadronic section” also to preserve excellent hadronic energy resolution.
- Dual-readout of light in same medium: idea tested at CERN (2004) “Separation of Scintillation and Cerenkov Light in an Optical Calorimeter”, NIM **A550** (2005) 185.
- Use multiple MPCs (probably four, two on each end of crystal), with filters.
- Physics gain: excellent EM energy resolution (statistical term very small), excellent spatial resolution with small transverse crystal size. (This is what CMS needs …)

Calorimeter: triple-readout fibers + dual-readout crystals in front

Particle Flow Algorithm

Flow of PFA

1. Photon Finding
2. Charged Hadron Finding
3. Neutral Hadron Finding
4. Satellite Hits Finding

*Satellite hits = calorimeter hit cell which does not belong to a cluster core

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Dual-Readout: Measure every shower twice - in Scintillation light and in Cerenkov light.

$(e/h)_C = \eta_C \sim 5 \qquad (e/h)_S = \eta_S \sim 1.4$

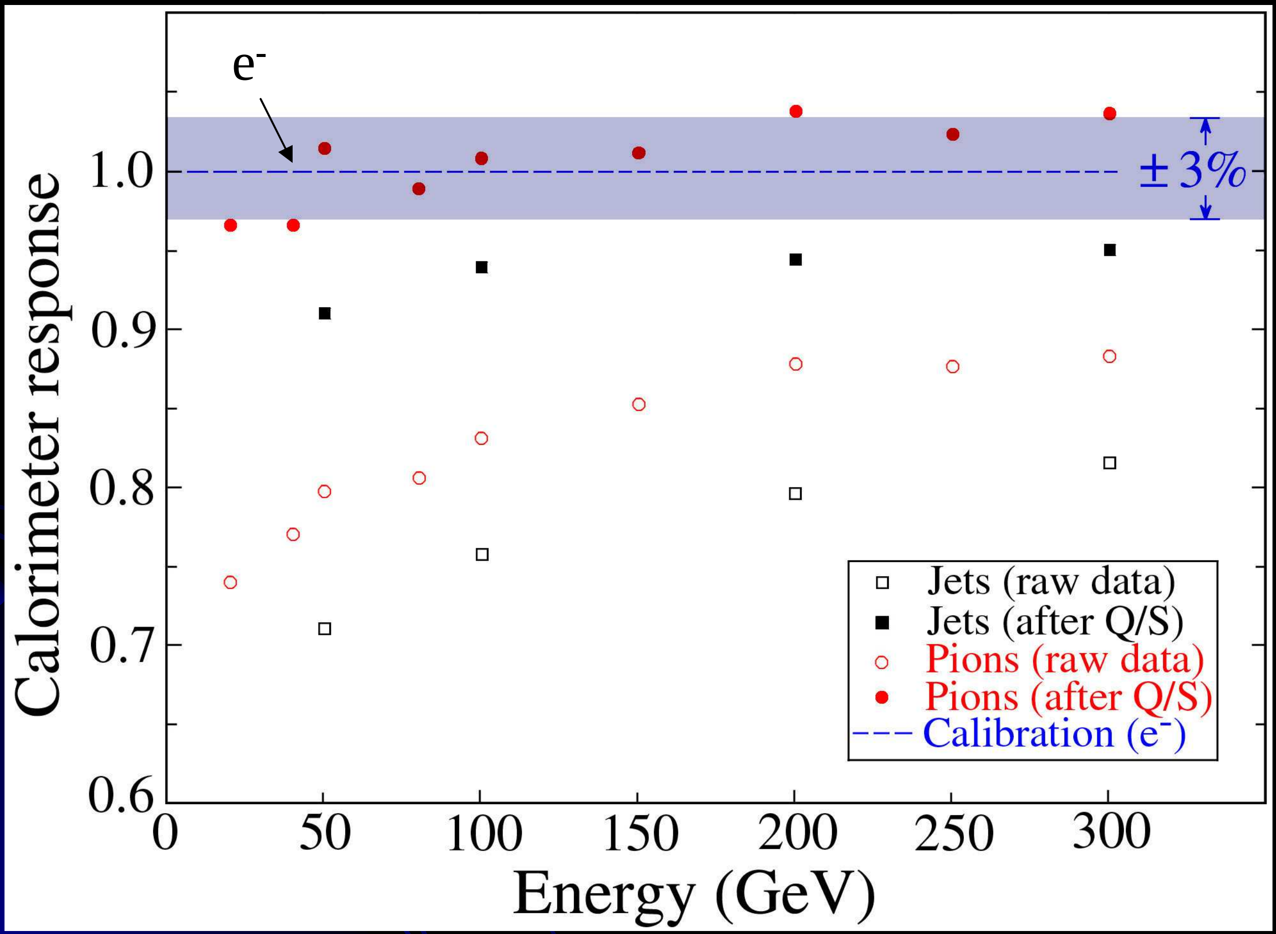
$C = [\, f_{EM} + (1 - f_{EM}) / \eta_C \,]\; E$

$S = [\, f_{EM} + (1 - f_{EM}) / \eta_S \,]\; E$

➡ $C / E = 1 / \eta_C + f_{EM} (1 - 1/\eta_C)$

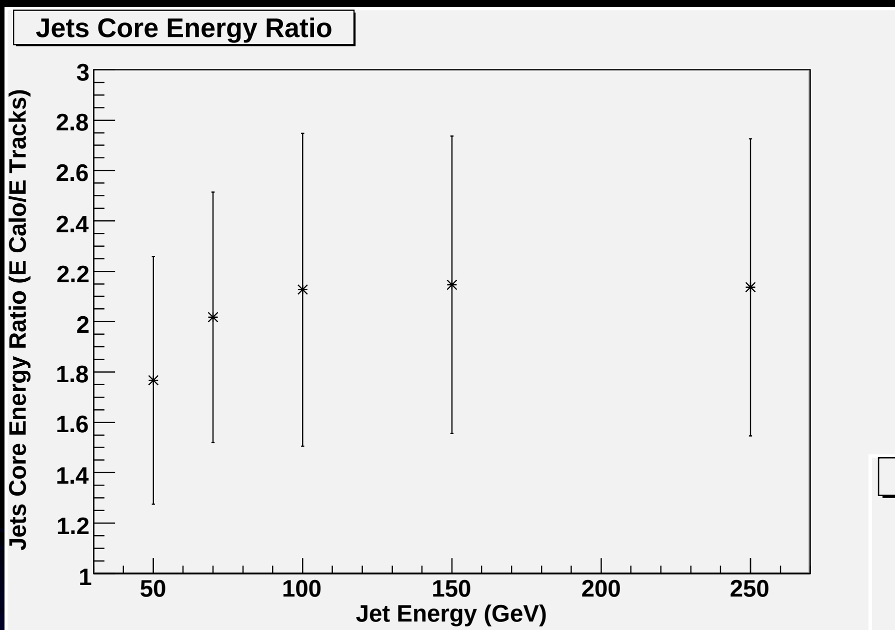
Data NIM A537 (2005) 537.

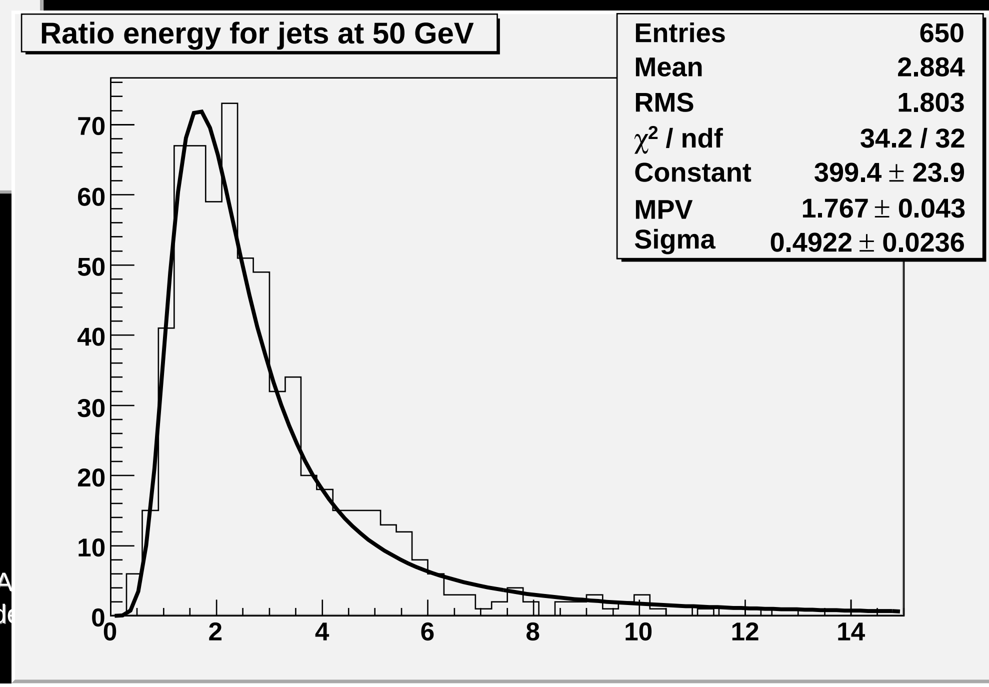
More important than good Gaussian response: DREAM module calibrated with 40 GeV e⁻ into the centers of each tower responds linearly to π⁻ and "jets" from 20 to 300 GeV.



Hadronic linearity may be the most important achievement of dual-readout calorimetry.

Calorimeric/charged contribution





Jet Outliers Charged Contribution