Jet Reconstruction and Resolutions

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ILC Experiment

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

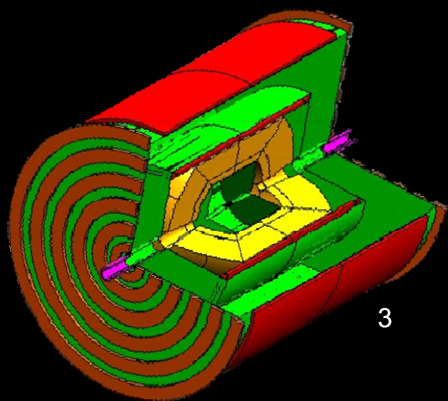
The world-wide consensus of the performance goal for the jet energy resolution is $\sigma_E / E = 30\% / \sqrt{E(\mathrm{GeV})}$

Fourth Concept Detector ("4th")

Basic conceptual design: 4 subsystems

- Vertex Detector 20-micron pixels (SiD design)
- Time Projection Chamber or
- CluCou Drift Chamber see F. Grancagnolo's talk on Drift Chamber
- Double-readout ecal
- Double-readout fiber hcal: scintillation/Čerenkov
- Muon dual-solenoid spectrometer

see C. Gatto's talk on calorimetry



Simulation Reconstruction and Analysis in IlcRoot Framework

- CERN architecture (based on Alice's Aliroot)
- Uses ROOT as infrastructure
  - All ROOT tools are available (I/O, graphics, PROOF, data structure, etc)
  - Extremely large community of users/developers
- Six MDC have proven robustness, reliability and portability
- Single framework, from generation to reconstruction through simulation. Don't forget analysis!!!
- Available at Fermilab

Simulation/Reconstruction Steps

MC Simulation ⇒ Energy Deposits in Detector

↓

Digitization ⇒ Detector response combined

↓

Pattern Recognition ⇒ Recpoints

↓

Track Finding ⇒ Tracks

↓

Track Fitting ⇒ Track Parameters

Simulation

- Event generators: Pandora-Pythia (moving to Sherpa)
- Full simulation is in place HCAL and ECAL (no gaussian smearing nor perfect pattern recognition)
- Hits using Fluka MC (for calorimeter studies)
- Cerenkov and Scintillation photon production and propagation in the fibers fully simulated. Poisson uncertaintity introduced in the number of photon produced
- Full SDigits + Digits + Pattern Recognition chain implemented (VXD, ECAL and HCAL)
- PID implemented for ECAL and HCAL only

Reconstruction

- Reconstruct tracks from the tracking devices (Kalman Filter)
- Build Clusters from cells distant no more than two towers away
- Unfold overlapping clusters through a Minuit fit to cluster shape (in progress)
- Calibration of HCAL

Calibration

Energy of HCAL calibrated in 2 steps:

1. Calibrate with single 40 GeV e^-

→ raw E_C and E_S

2. Calibrate with single 40 GeV π^-

→ η_C and η_S

Reconstructed energy

Once HCAL calibrated, calorimeter energy:

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

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

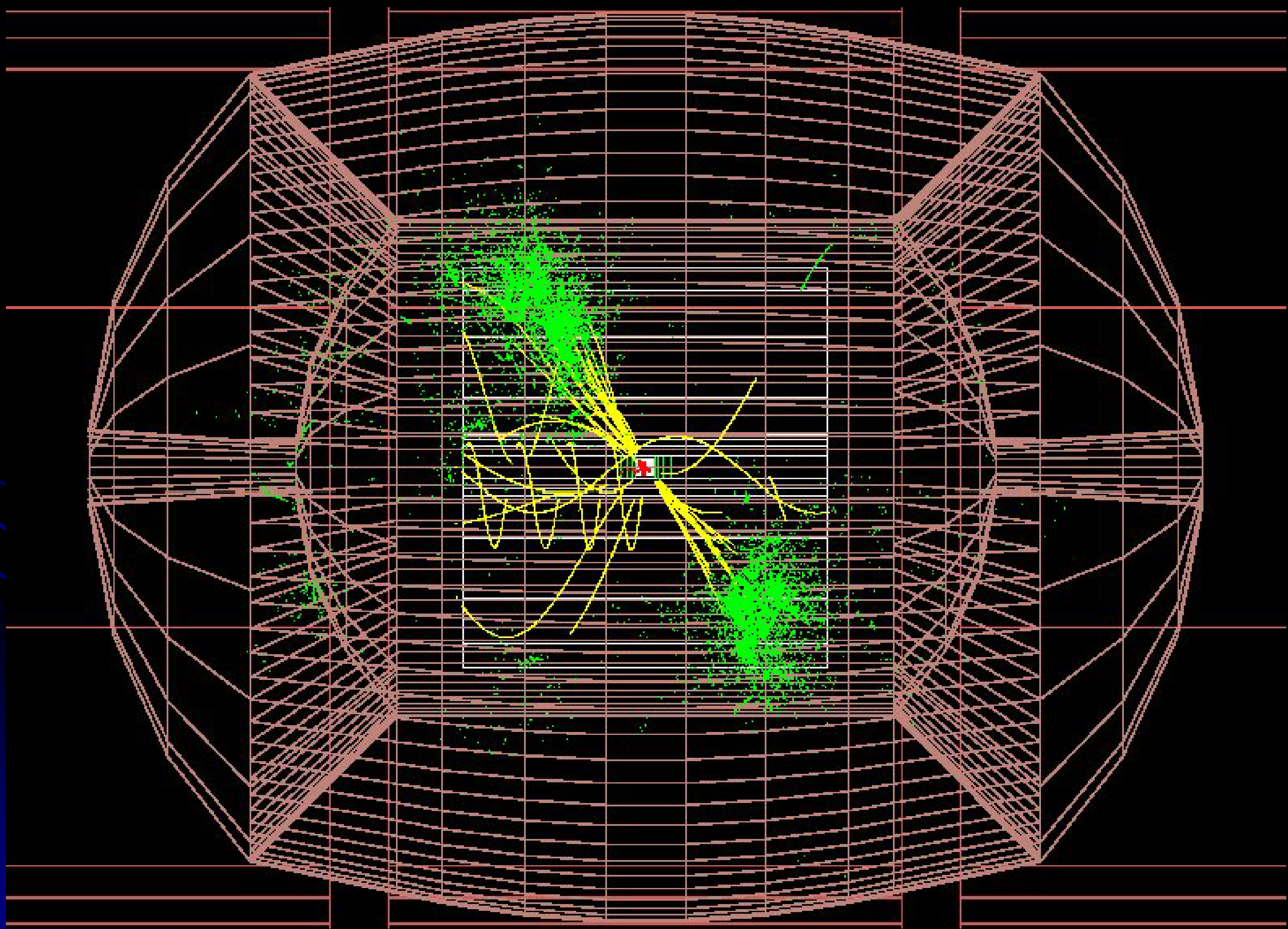
Jets Studies

Jets Performance Studies

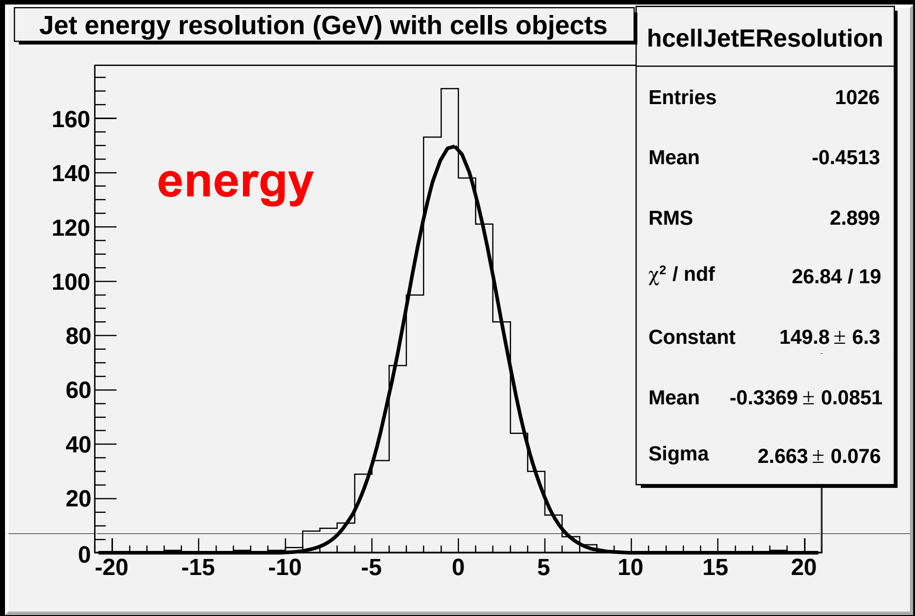
- e^+e^- –> qq generated in E_{cm} = (60, 100, 140, 200, 300, 500) GeV
- Jets reconstructed with Durham algorithm over calorimeter cells
- HCAL Resolutions and Responses from:
  - jet reconstructed energy (30, 50, 70, 100, 150, 250) GeV

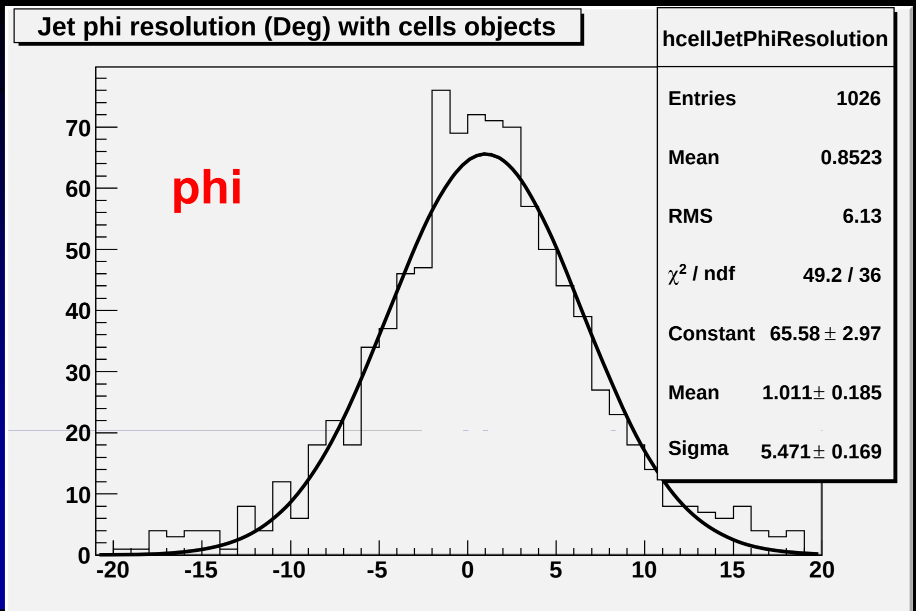
very **preliminary strategy**

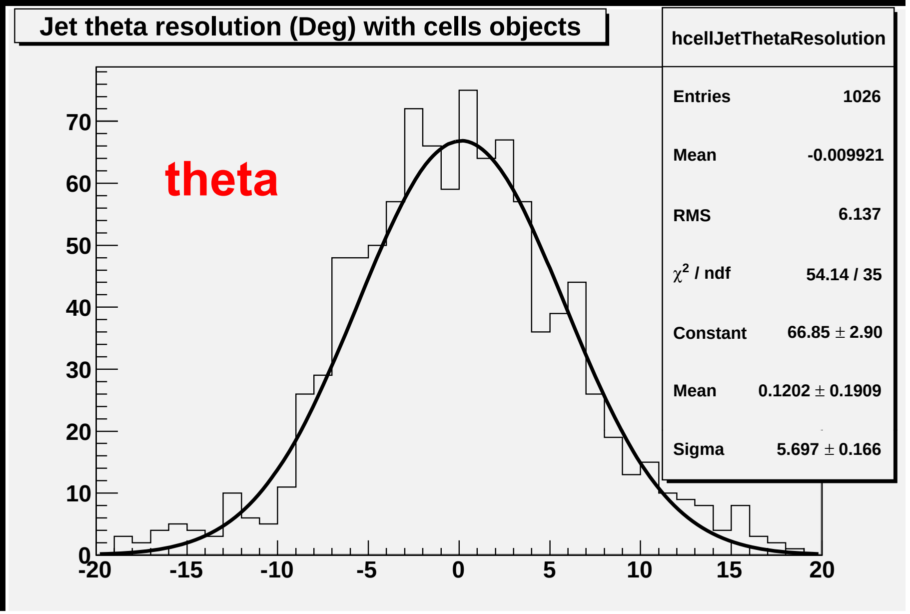
500 GeV dijets events



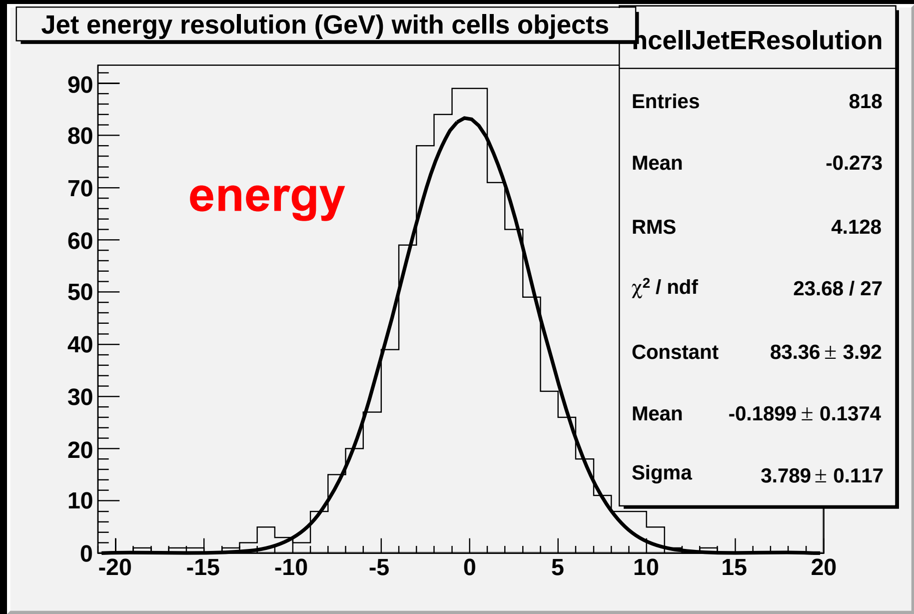
30 GeV Jet Resolutions

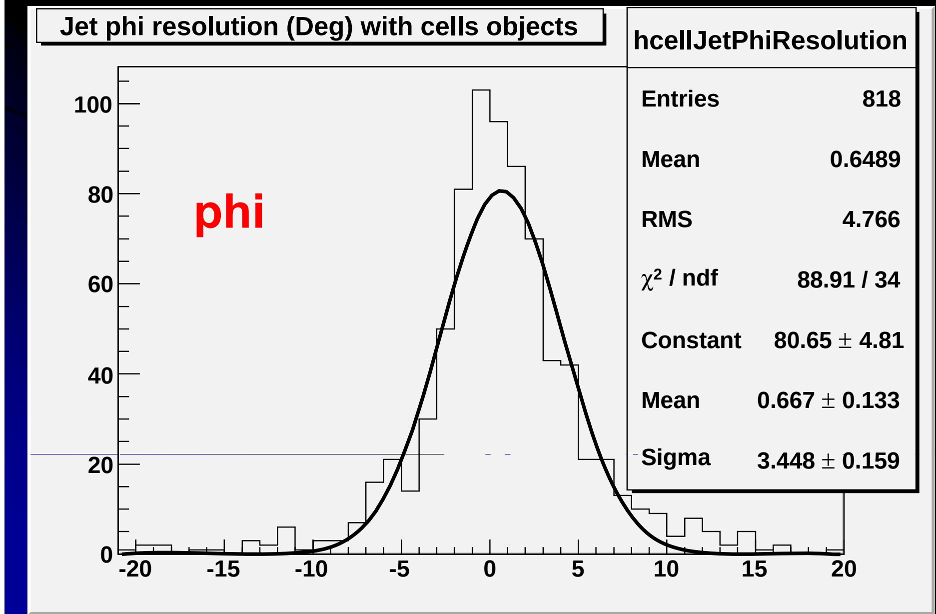


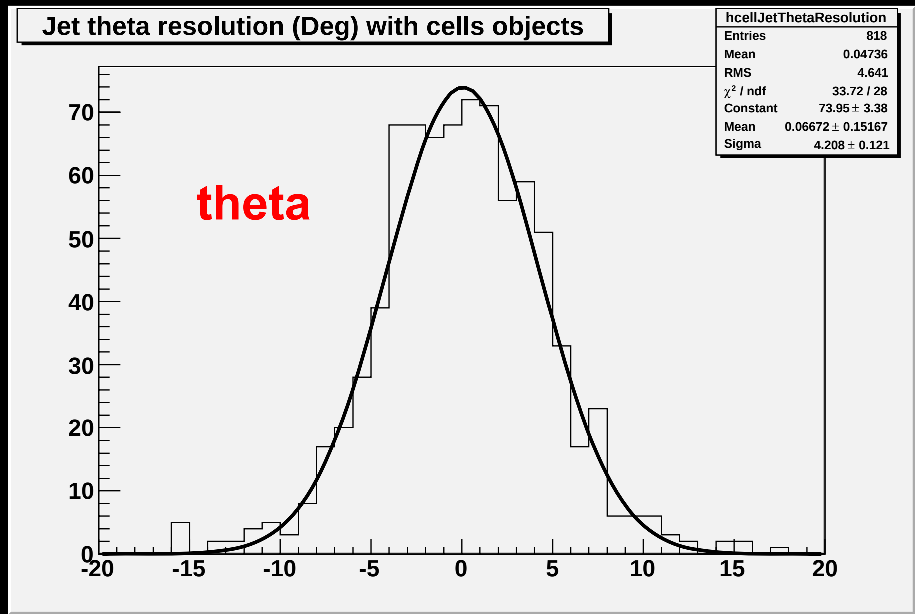




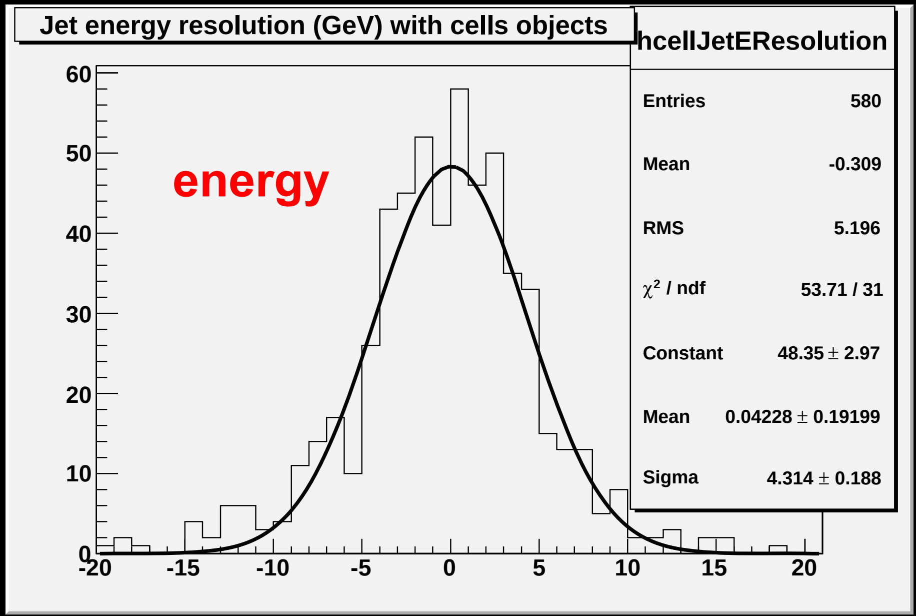
50 GeV Jet Resolutions

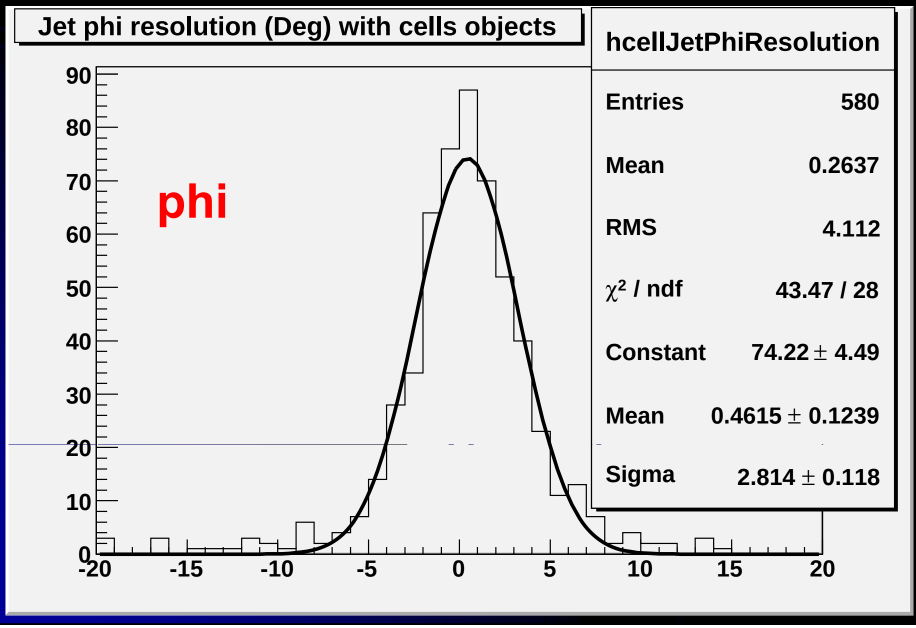


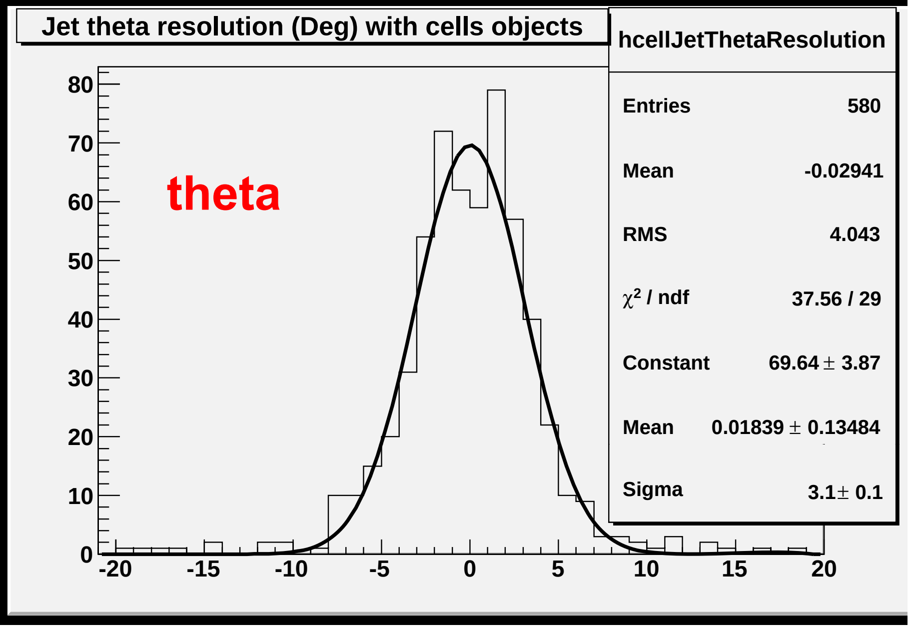




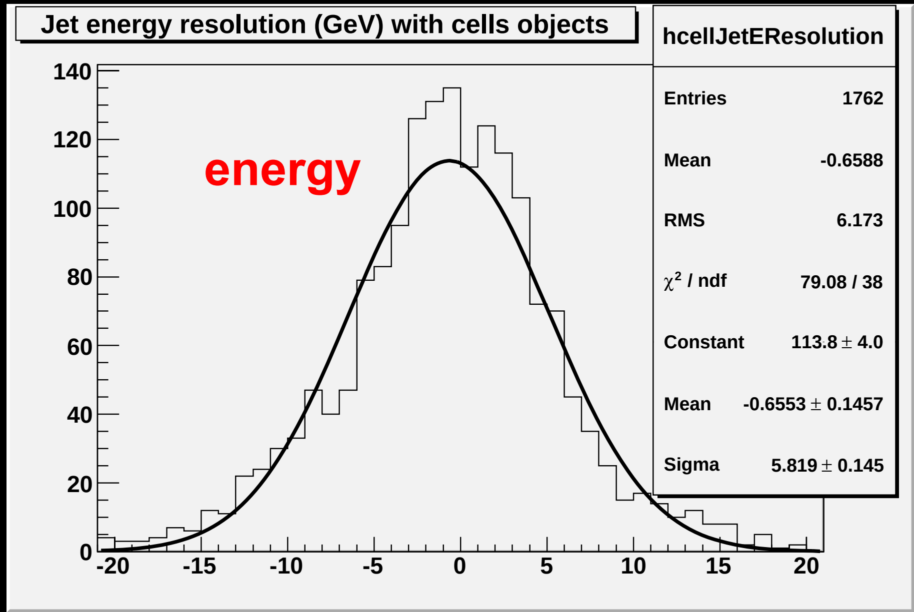
70 GeV Jet Resolutions

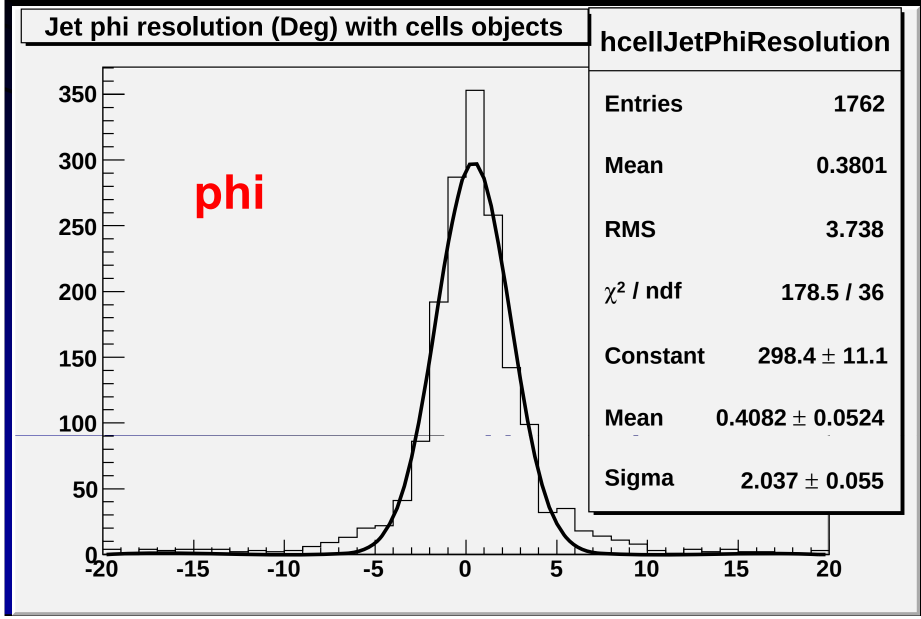


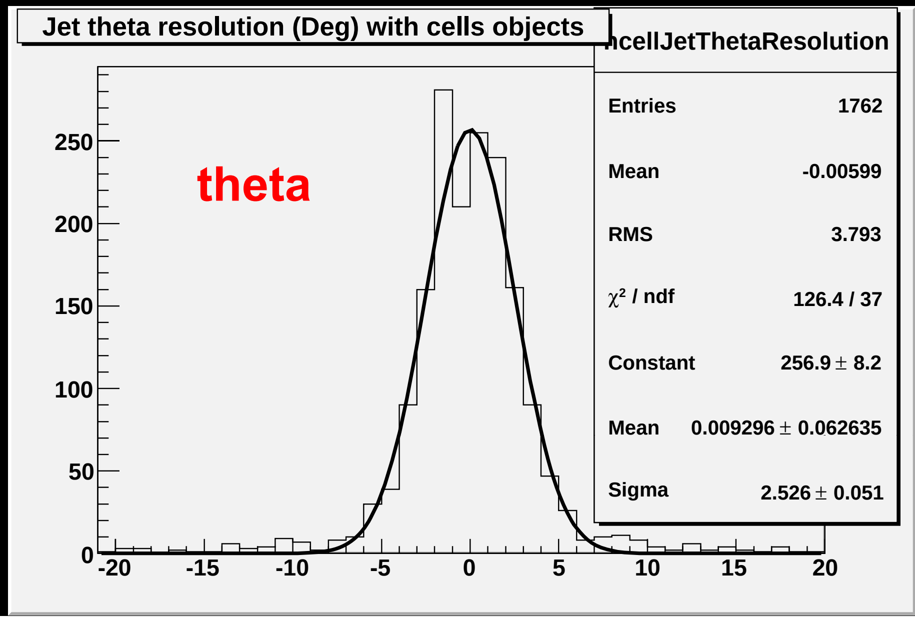




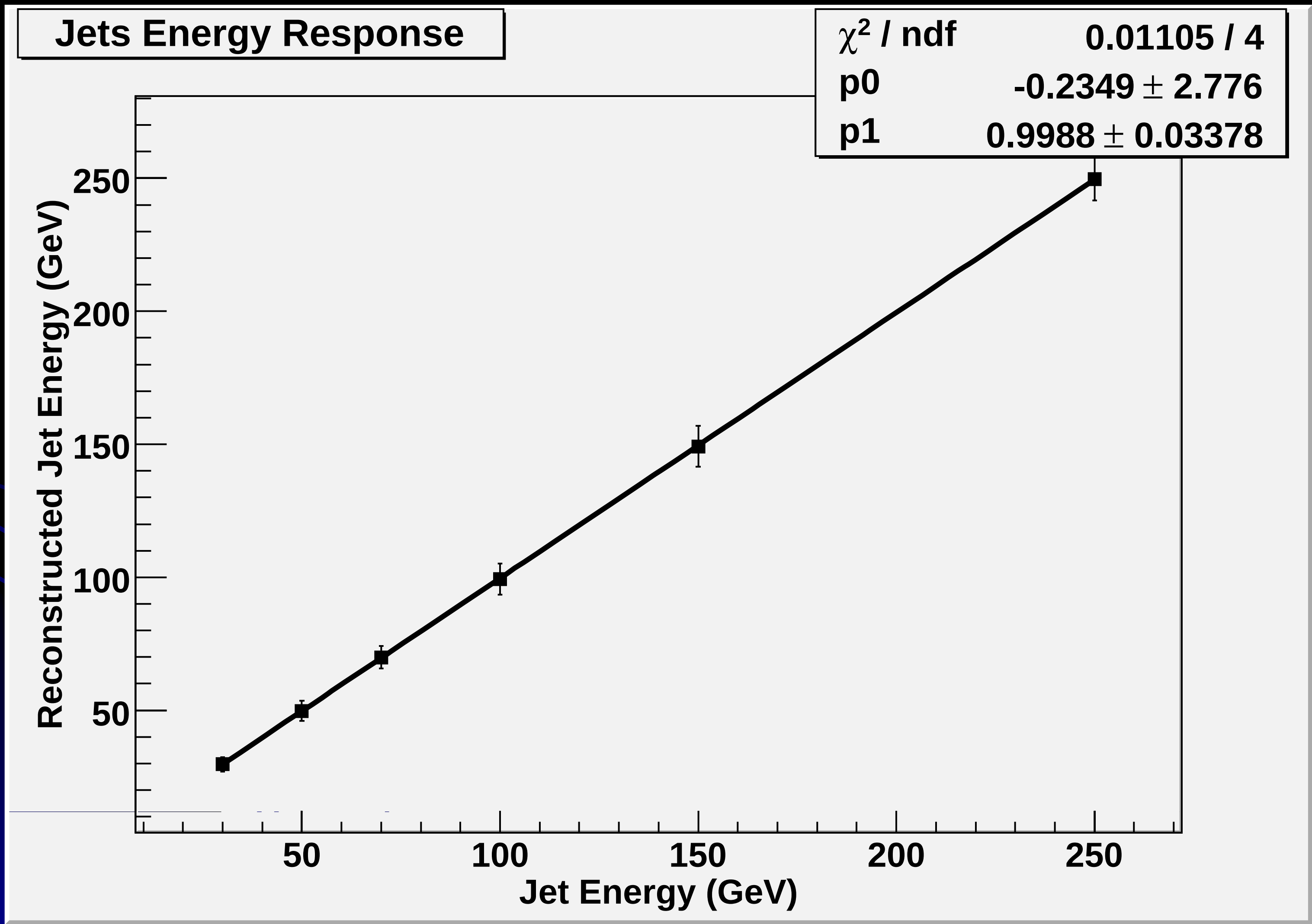
100 GeV Jet Resolutions



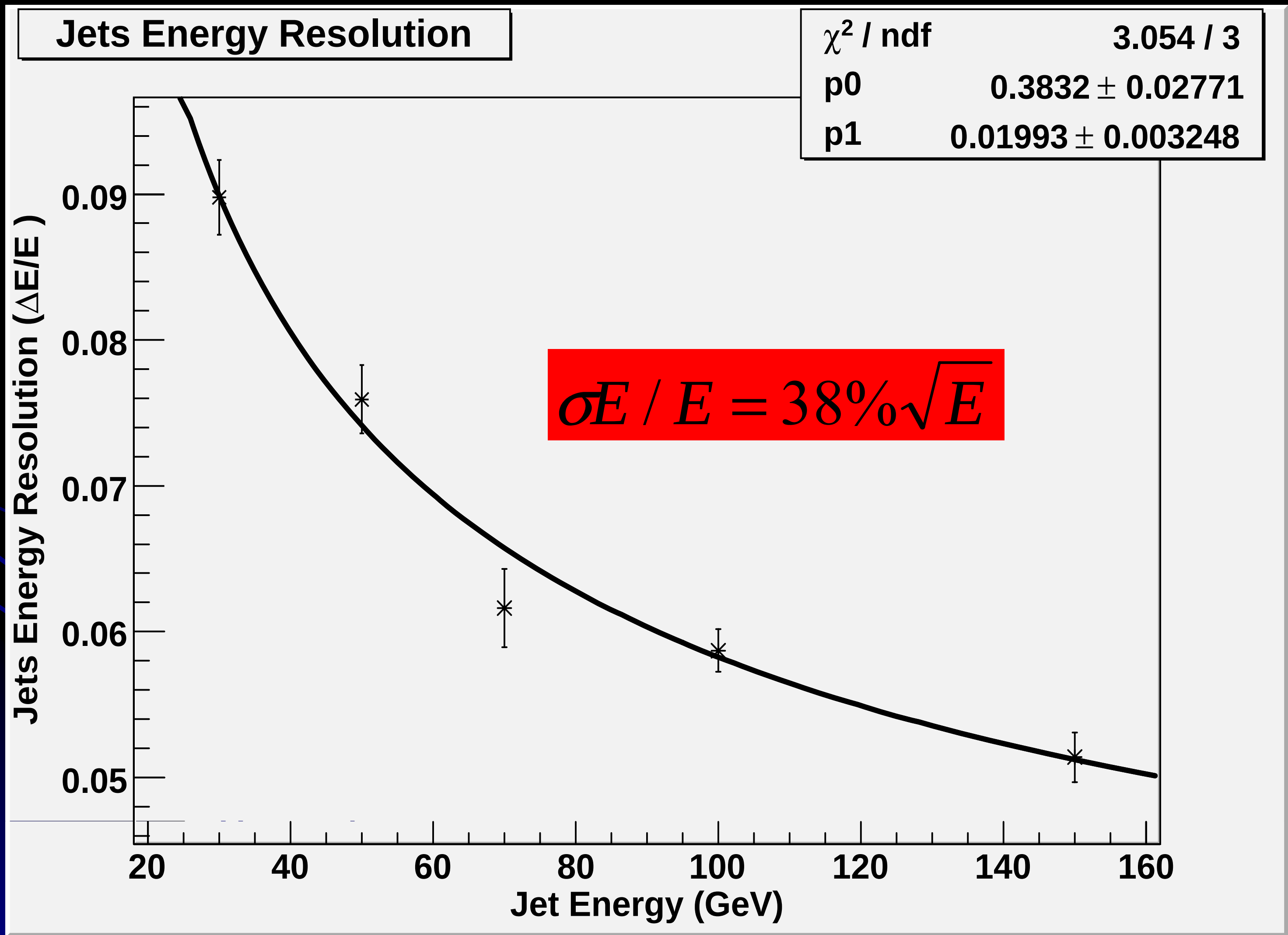




Jet Energy Response



Jet Energy Resolution



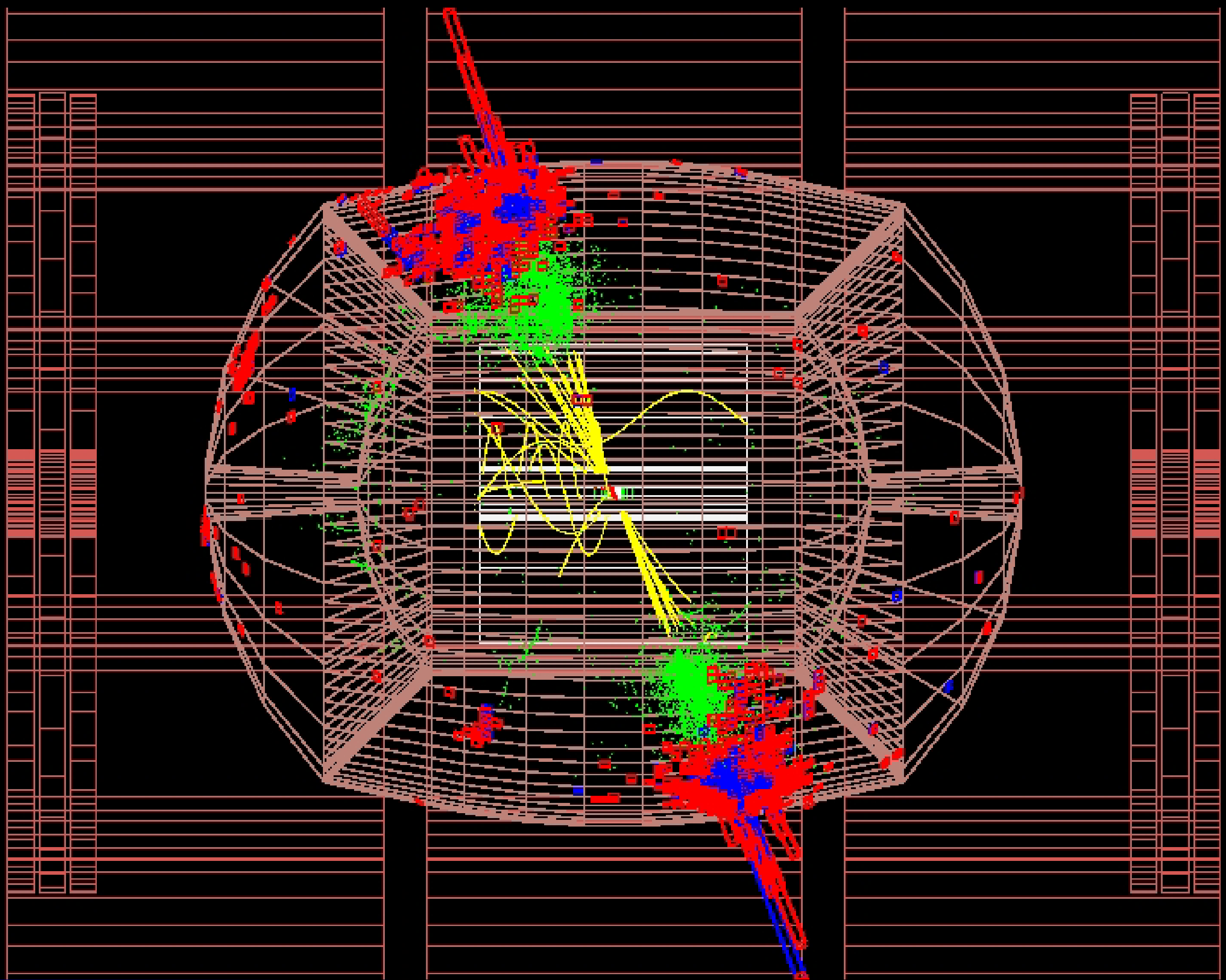
Need to improve jet reconstruction strategy

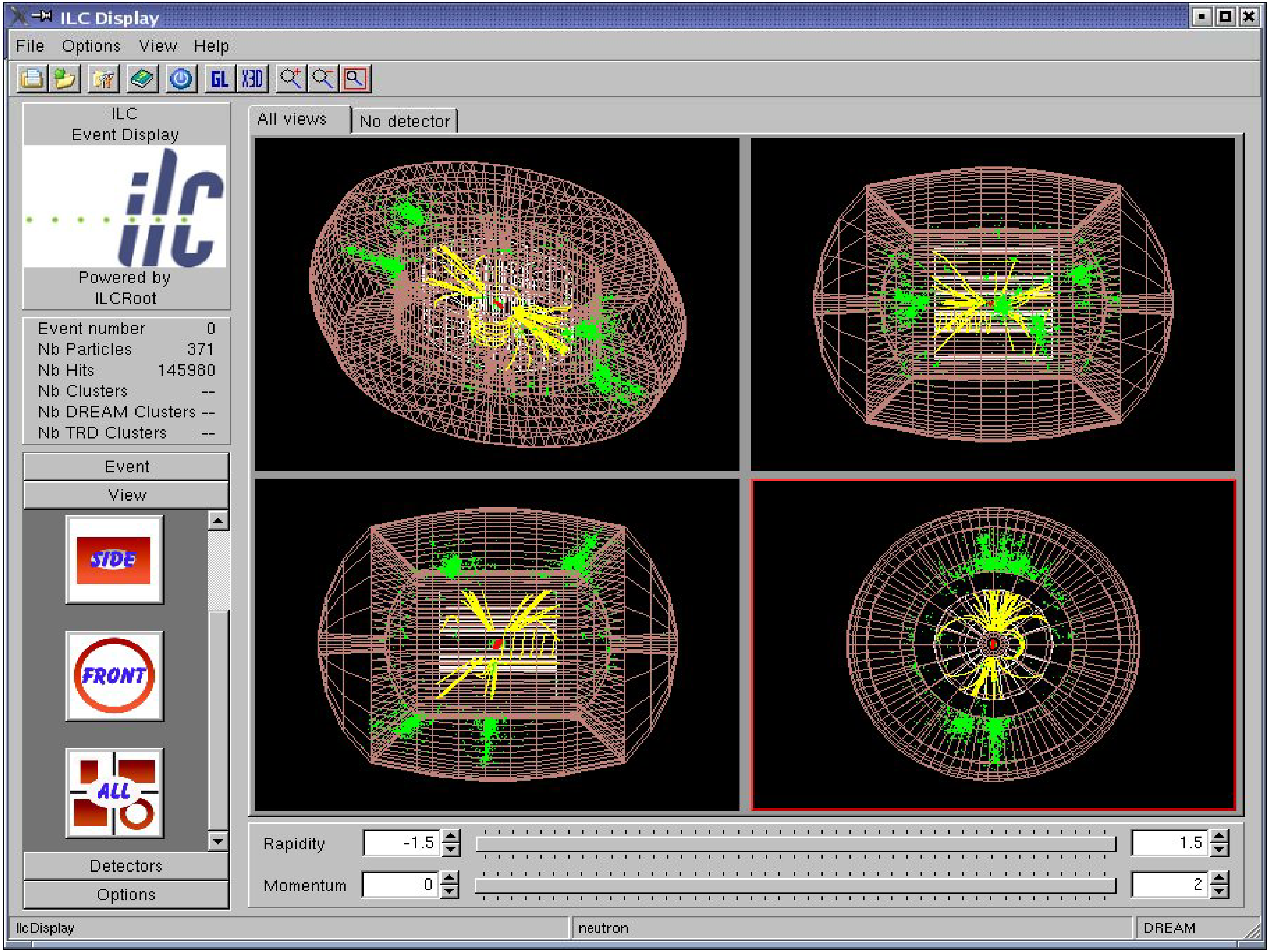
- Energy resolution with simple kt algorithm on calorimeter cells not satisfactory:

- Wrong direction for tracks bending in the central tracker

- Left muon particles leaving the calorimeter and dead tracks in the central tracker

500 GeV dijets events




ILC Display
File
Options
View
Help
GL
X3D
All views
No detector
ILC
Event Display
Powered by
ILCRoot
Event number 0
Nb Particles 371
Nb Hits 145980
Nb Clusters --
Nb DREAM Clusters --
Nb TRD Clusters --
Event
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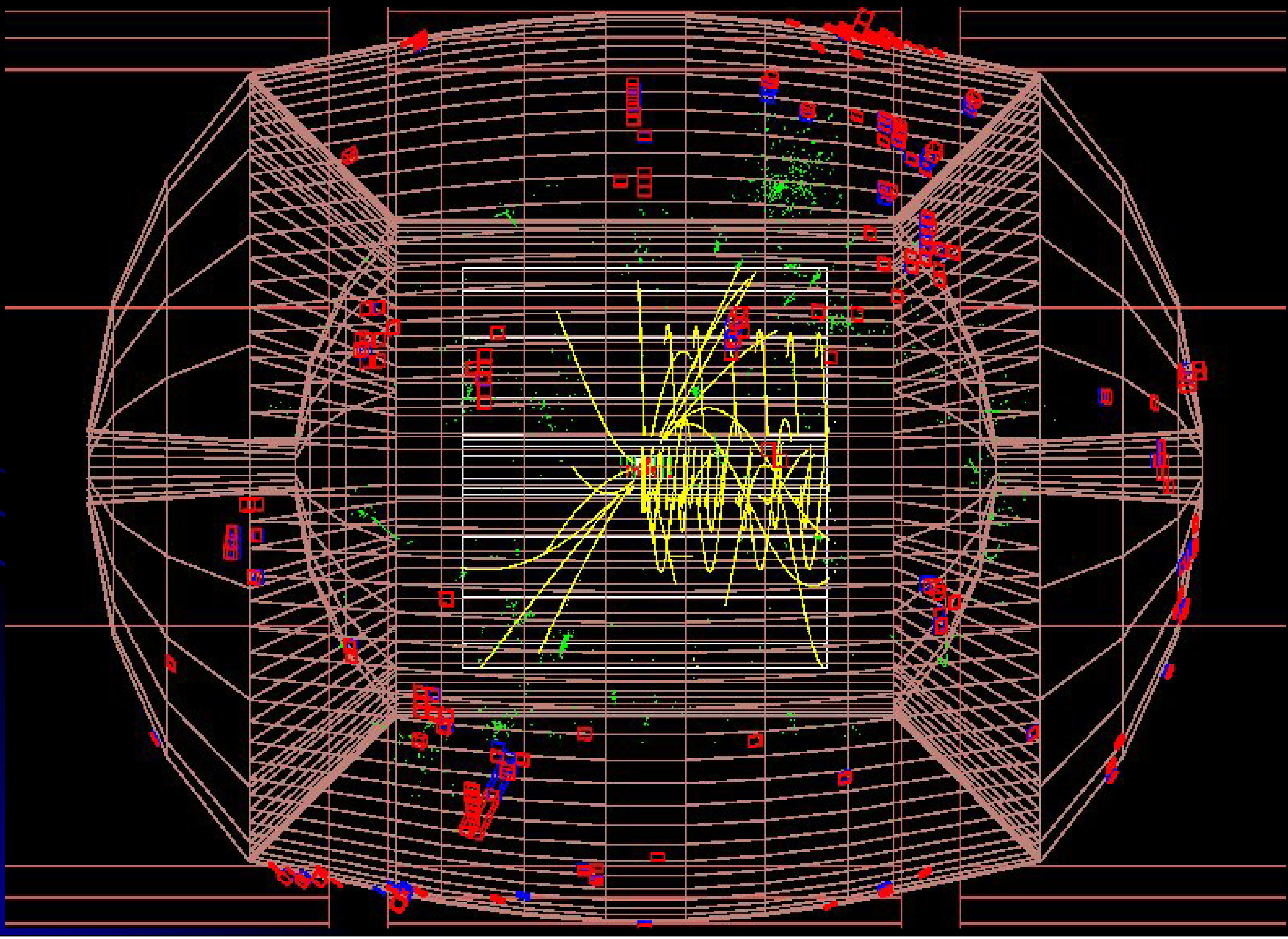
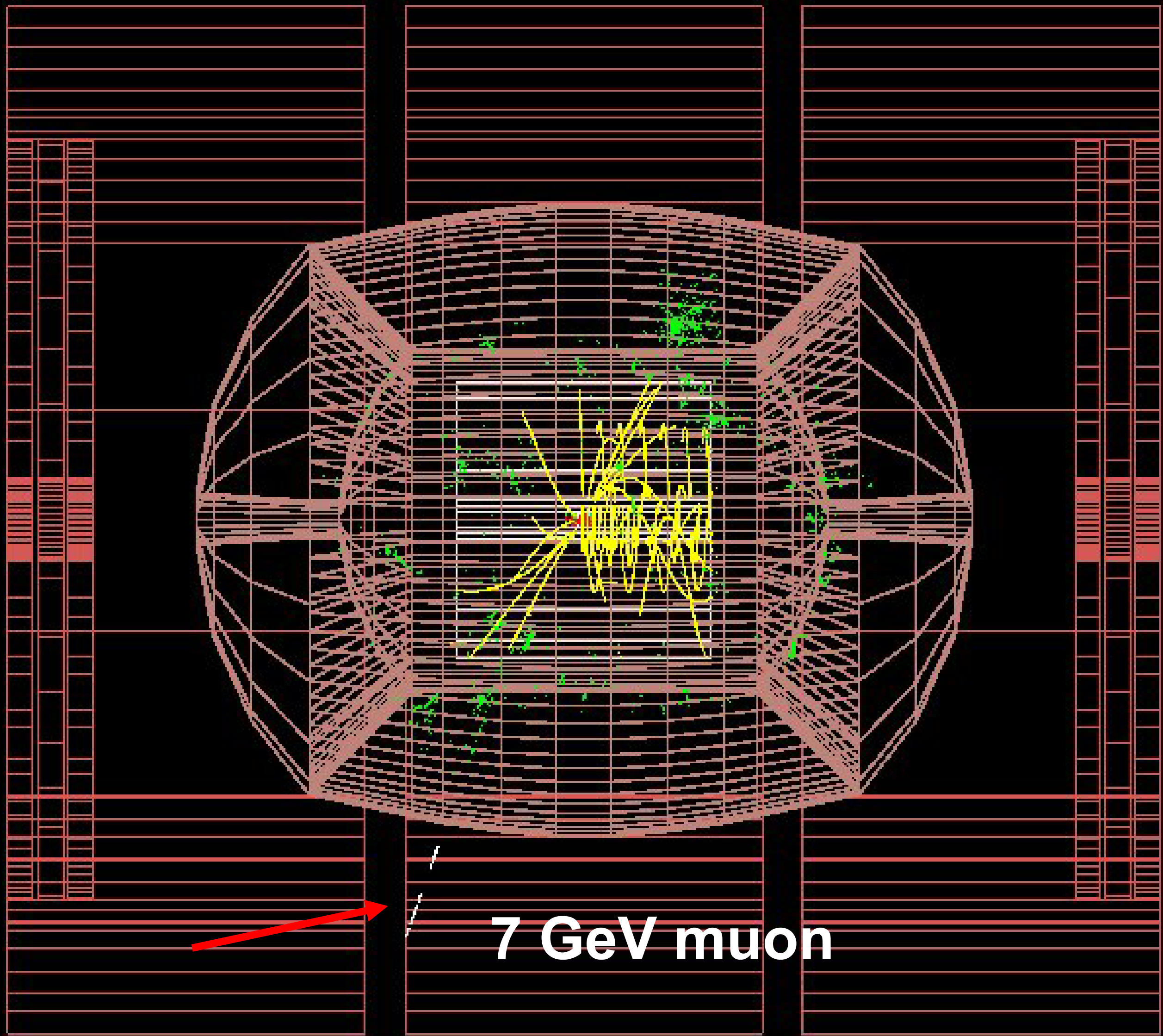
neutron
DREAM

60 GeV dijets events



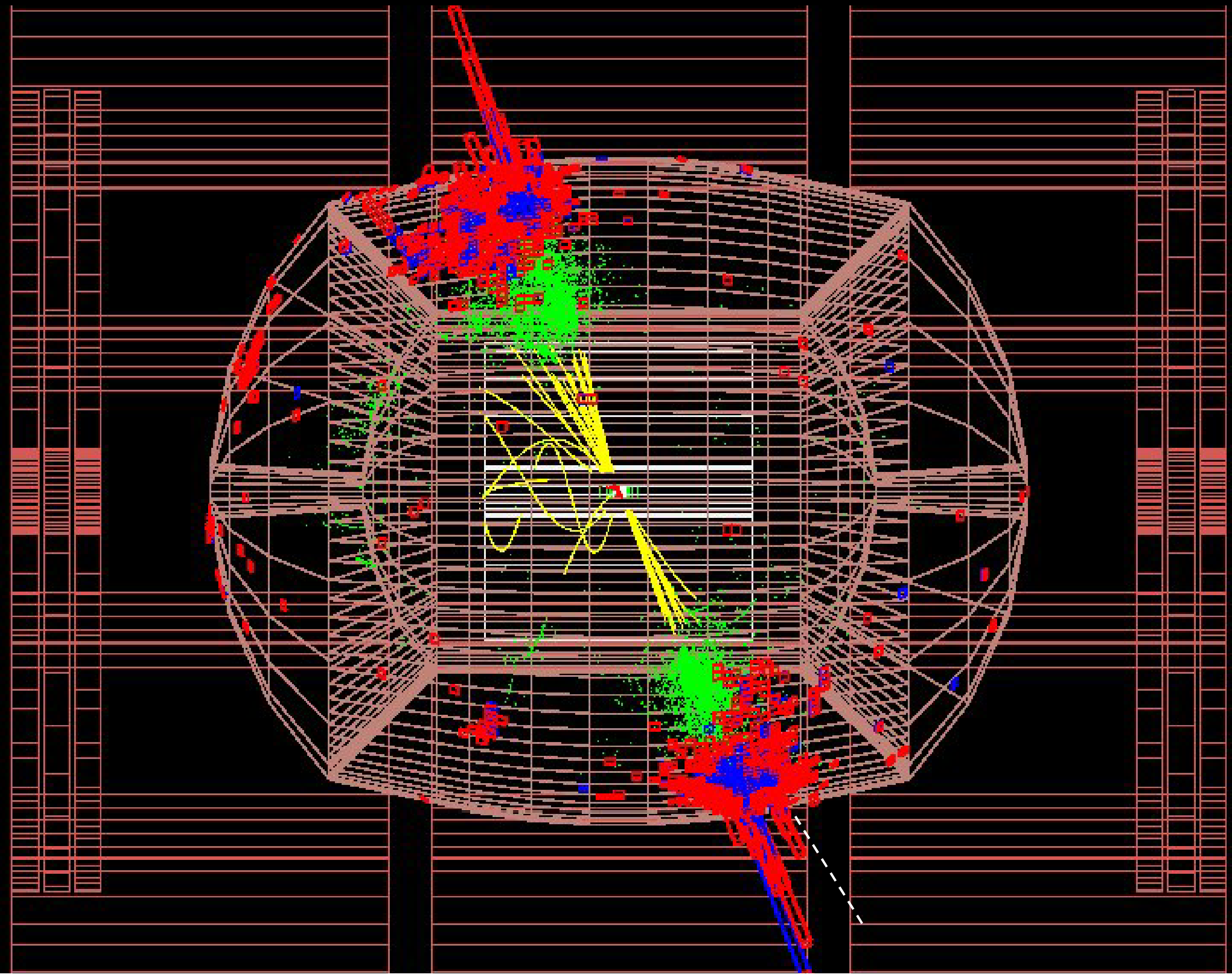
60 GeV dijets events



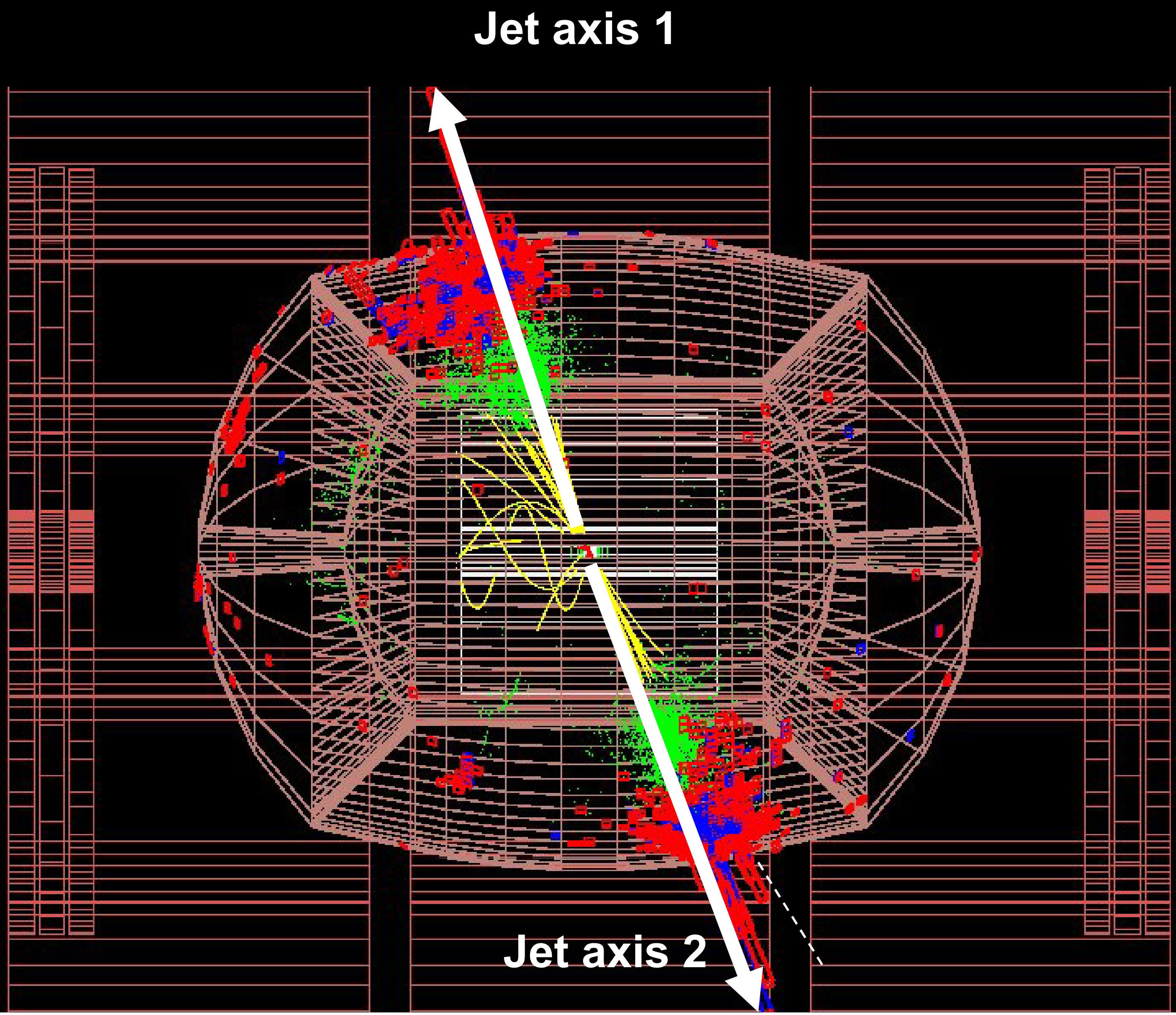
A different strategy

- Look for the jet axis using the Durham algorithm
  - Charged tracks
  - Calorimeter cells
- Jet core
  - Open a cone increasingly bigger around the jet axis (< 60°)
  - Add cells in the cones
- Jet outliers
  - Check leftover/isolated calo cluster for match with a track from TPC+VXD
  - Add isolated tracks and isolated neutral clusters
  - Add low P_t tracks not reaching the calorimeter
- Muons
  - Add tracks reconstructed in the MUD
- V0's, kinks

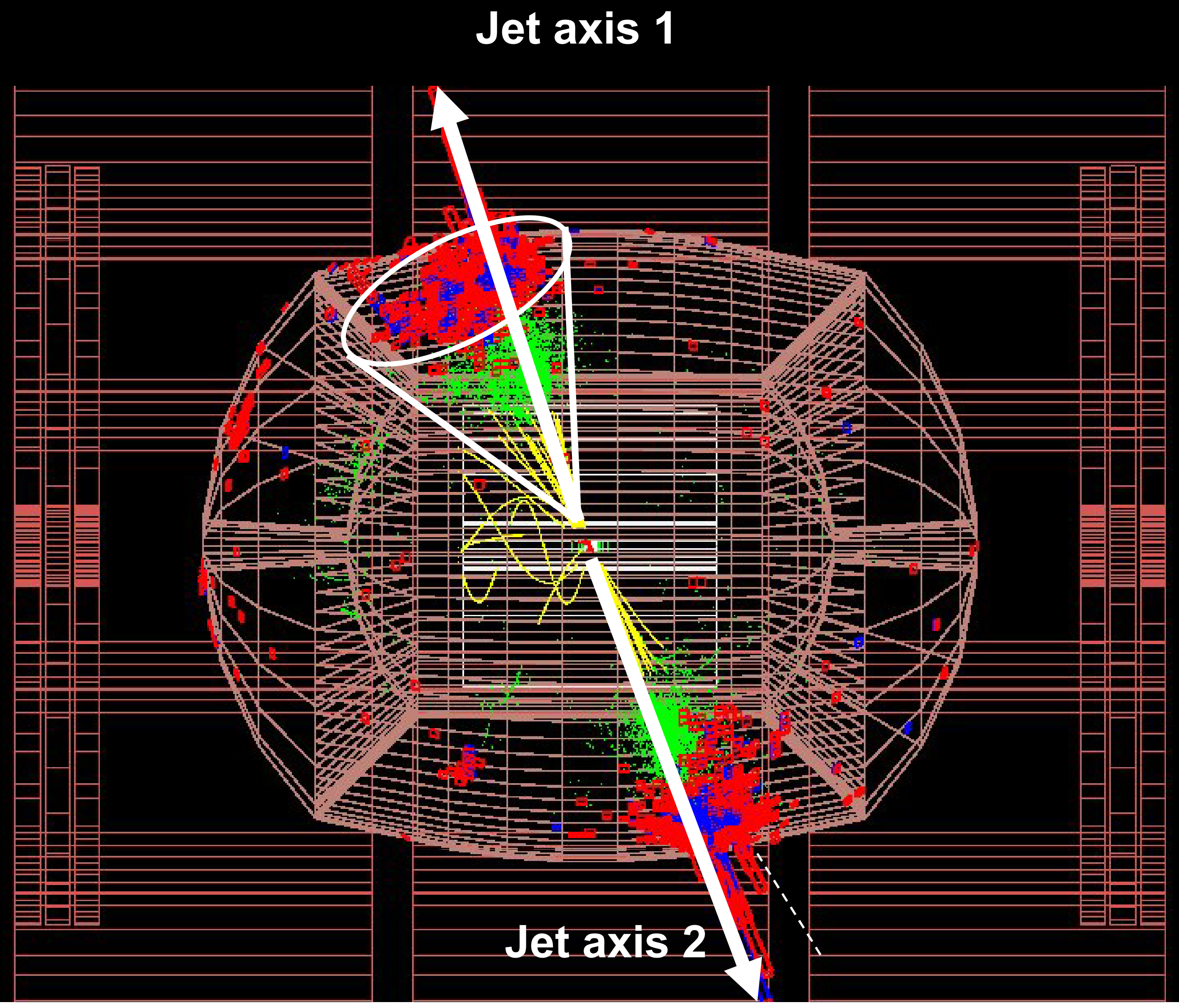
Jet Reconstruction Strategy



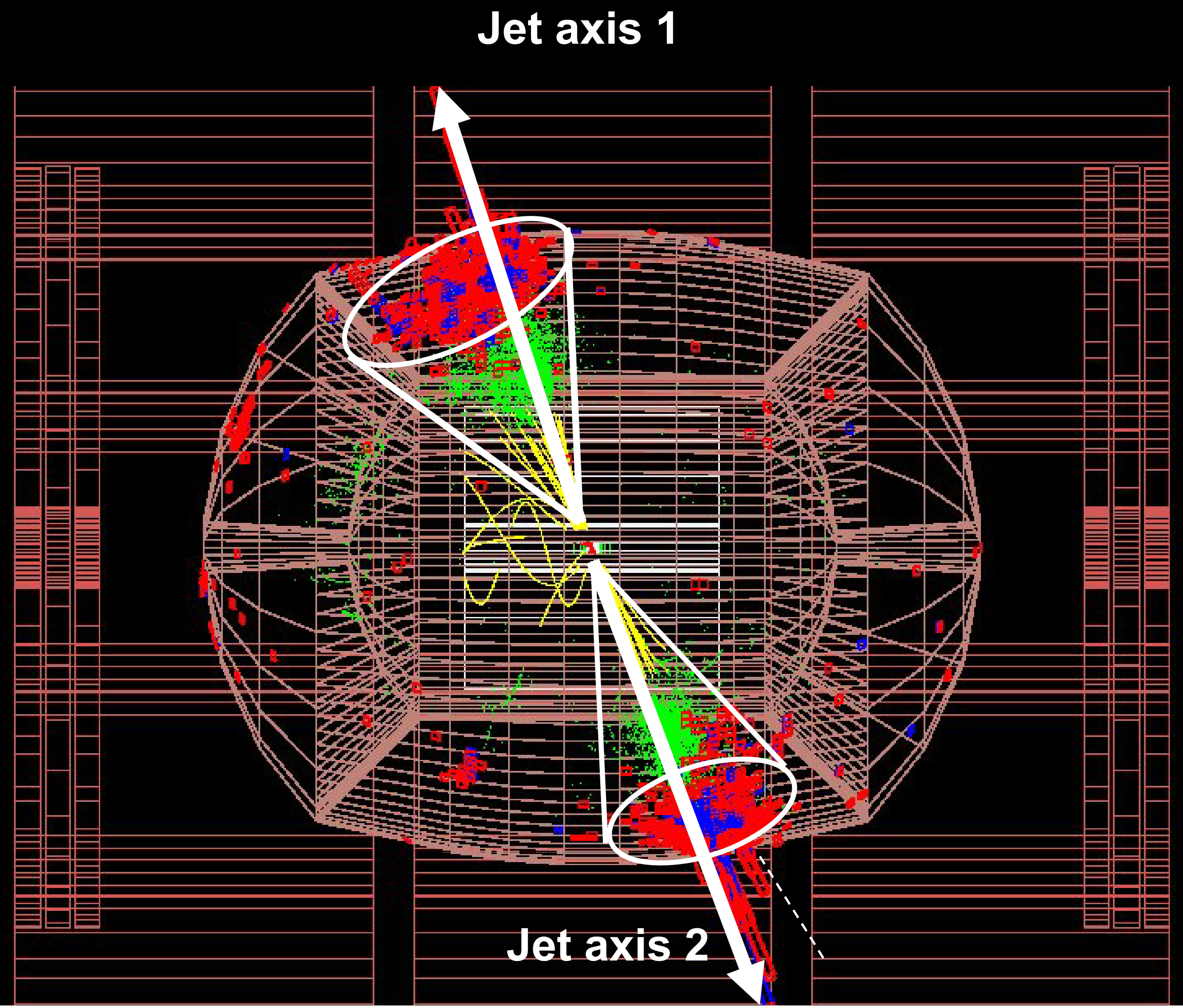
Jet Reconstruction Strategy



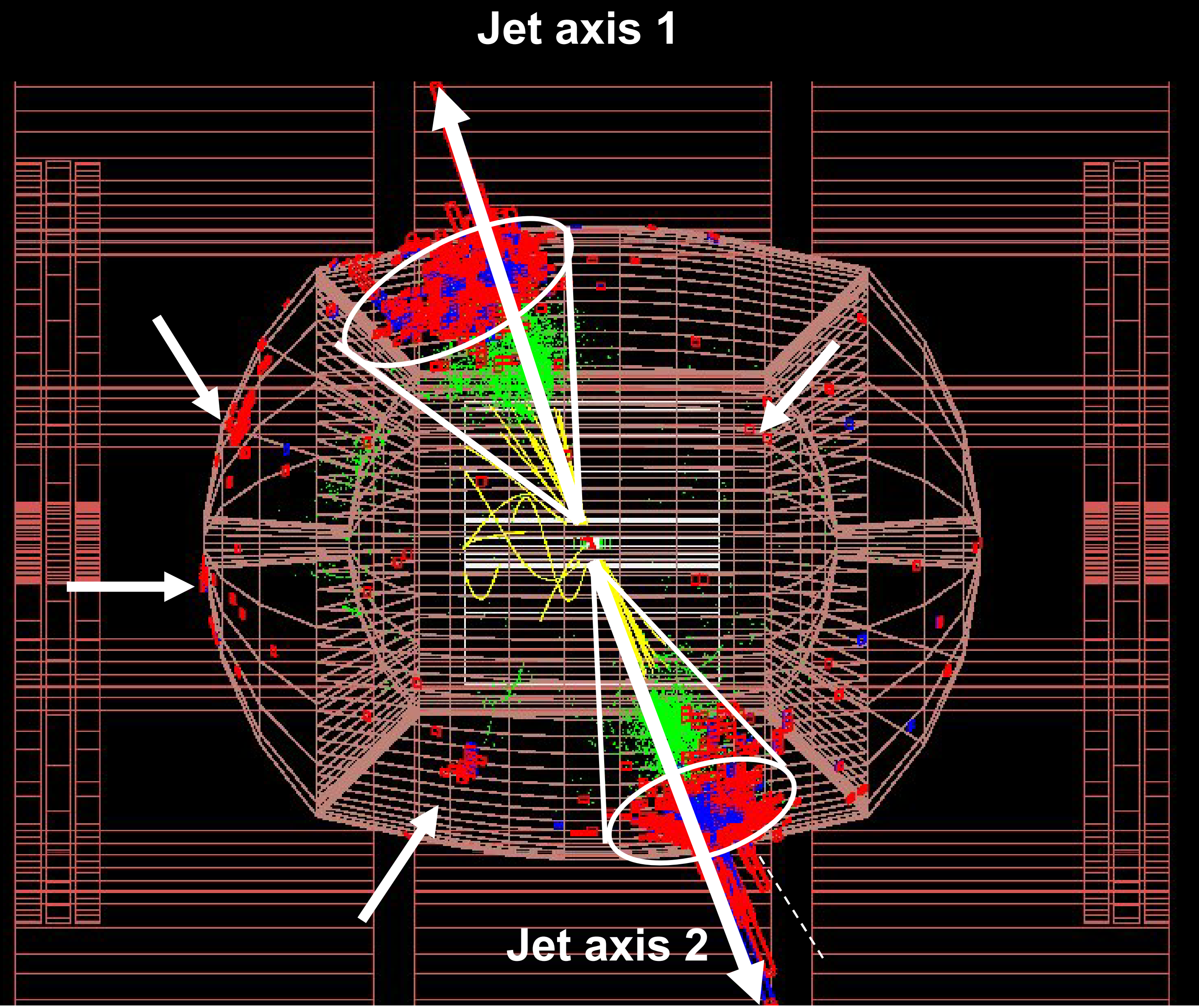
Jet Reconstruction Strategy



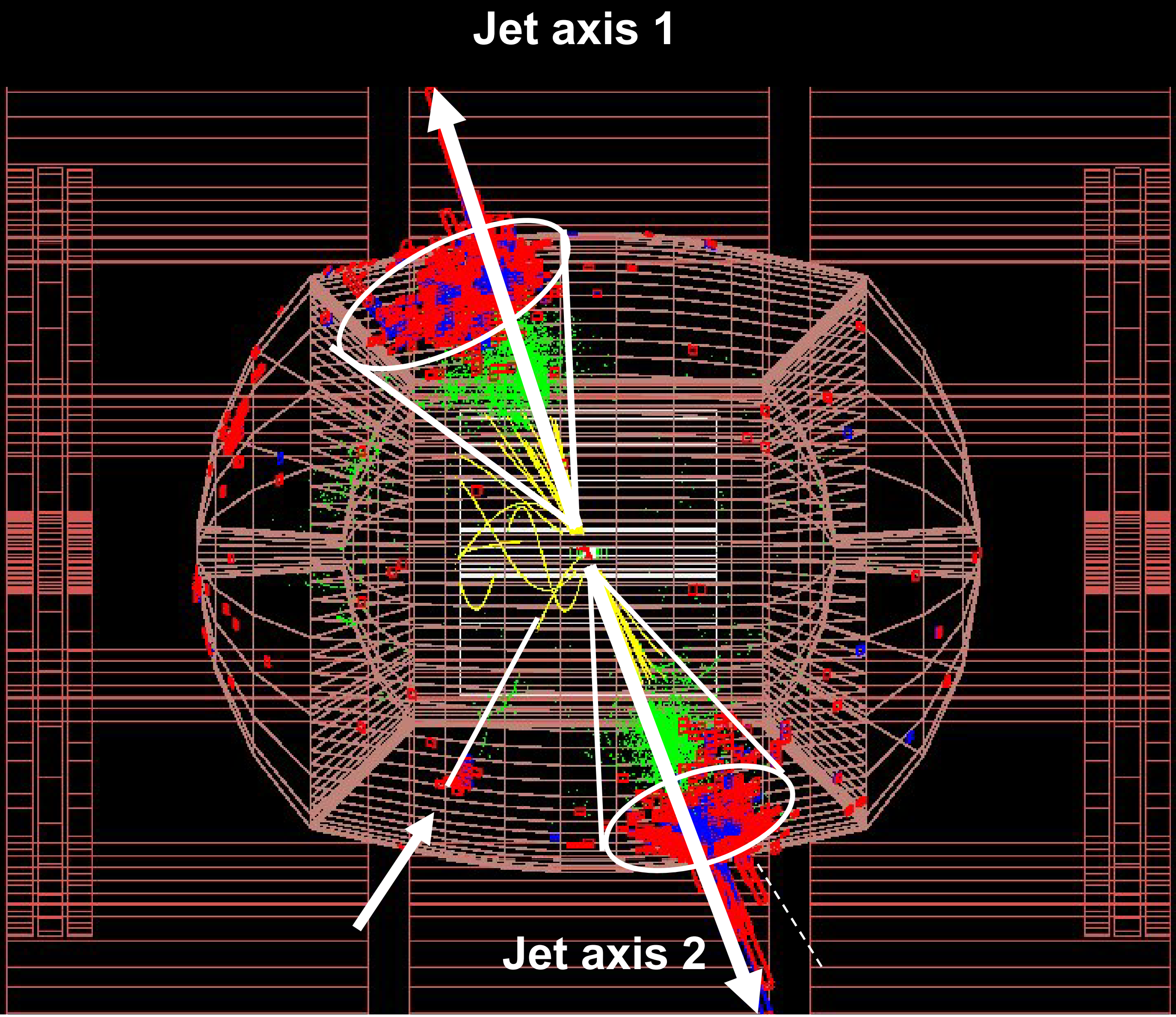
Jet Reconstruction Strategy



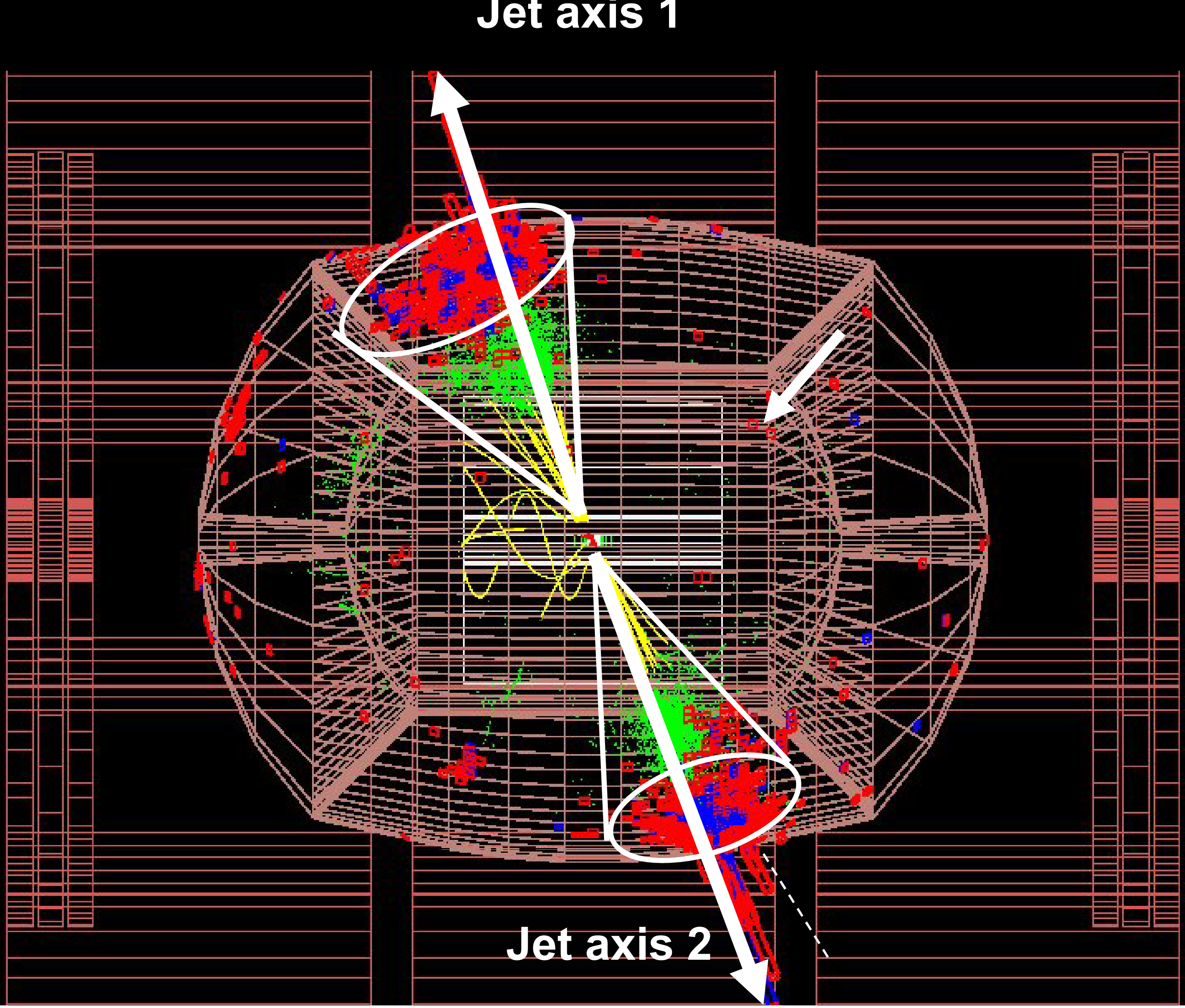
Jet Reconstruction Strategy



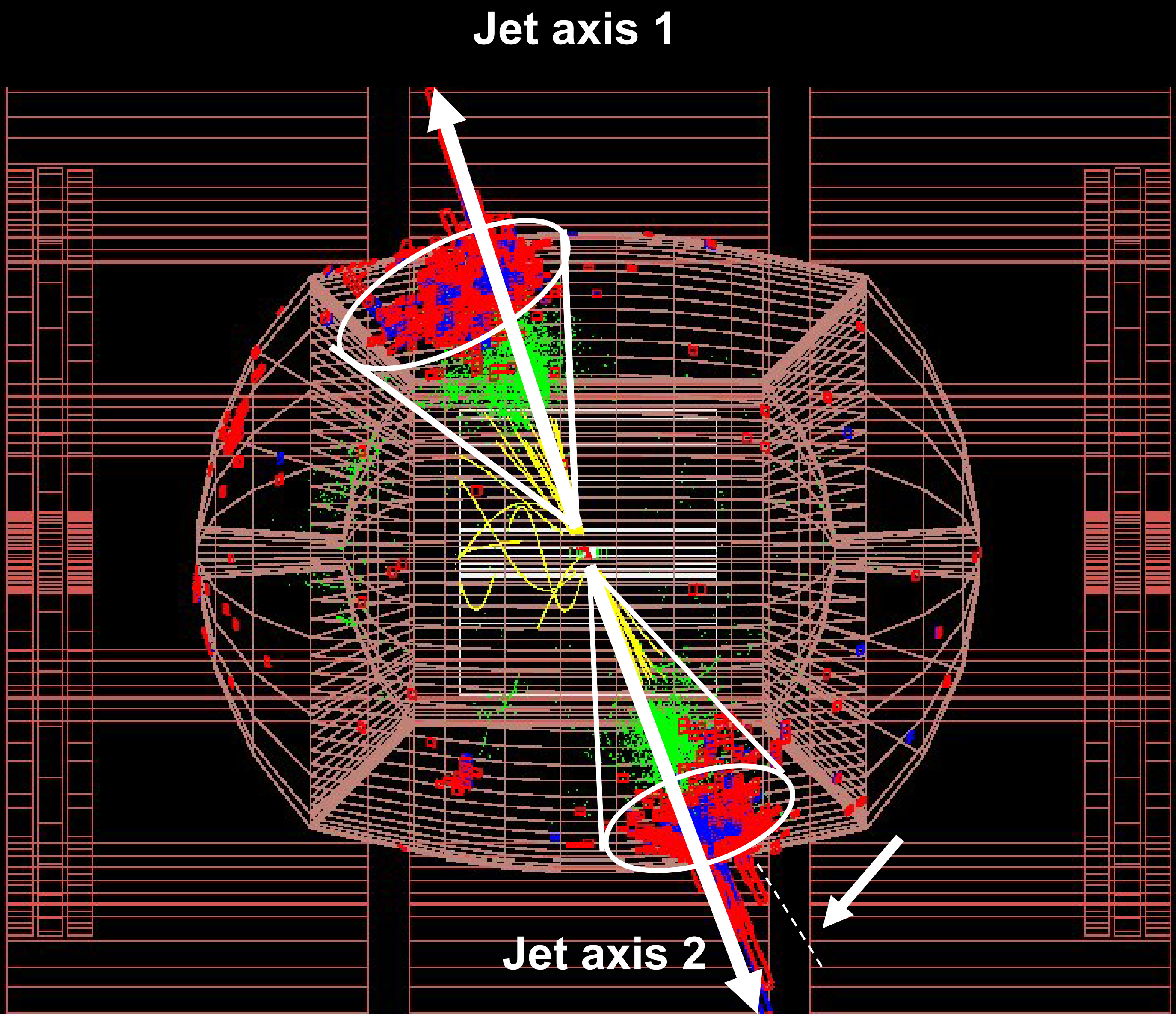
Jet Reconstruction Strategy



Jet Reconstruction Strategy



Jet Reconstruction Strategy



Work in progress

Conclusions

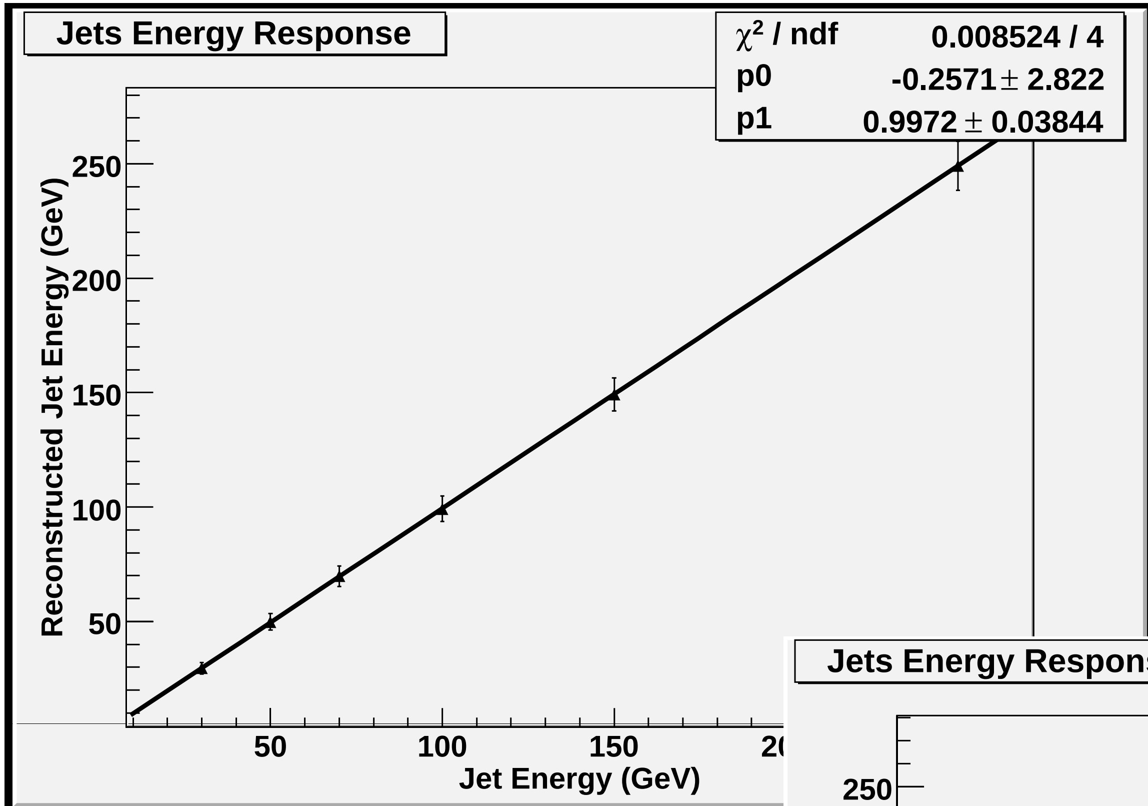
- The 4th Concept has chosen a Calorimeter with Dual Readout
- The technology has been proved at a test beam, but never in a real experiment
- Performance of Calorimeter extremely good:

$\sigma_E/E = 34\%/\sqrt{E}$ (single particles)

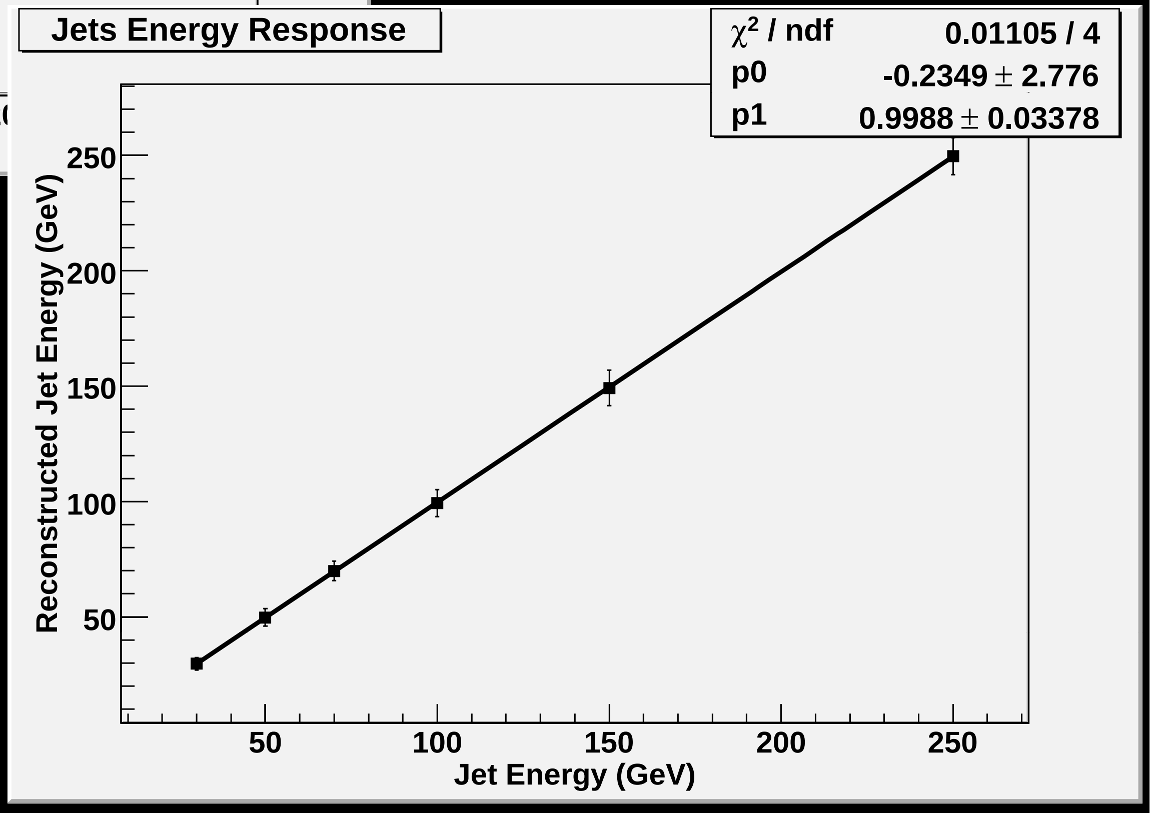
$\sigma_E/E = 38\%/\sqrt{E}$ (jets)

- There is room to improve these resolutions
- Dual Readout crystal EMCAL studies are under way

Backup slides

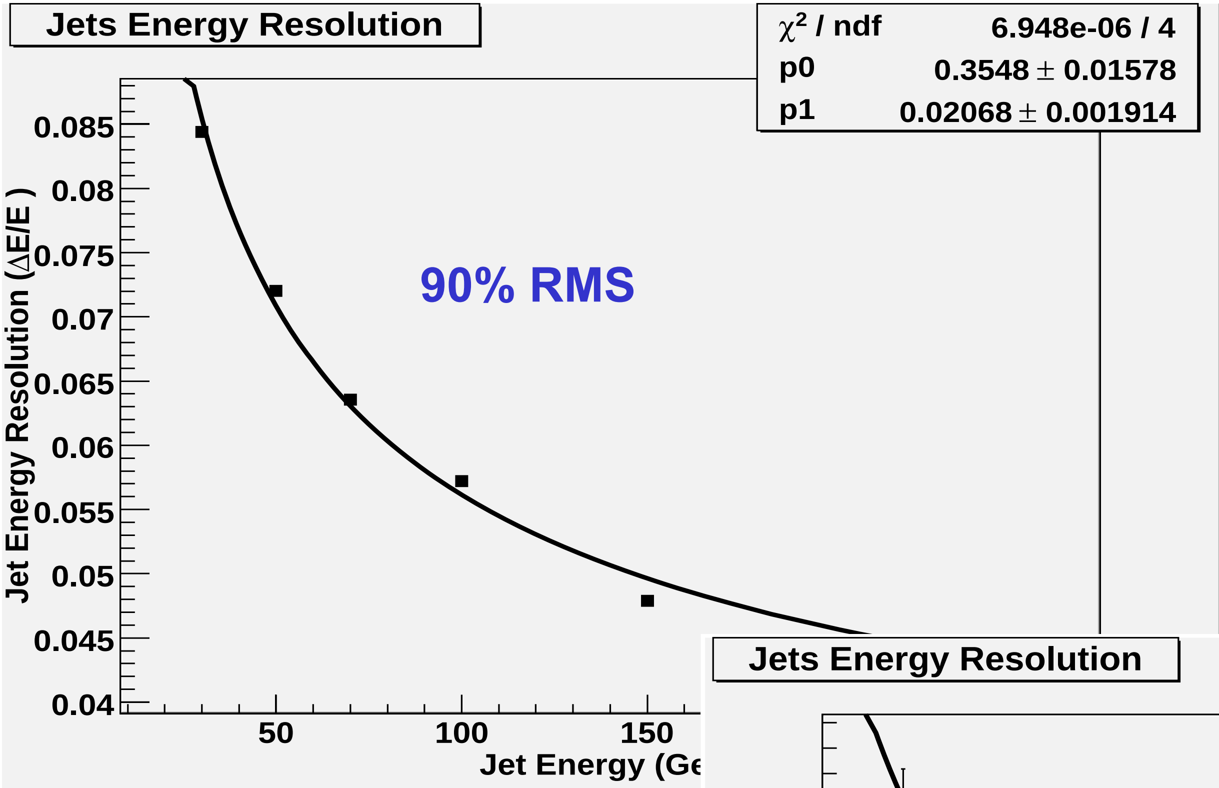


HCAL response with single jet

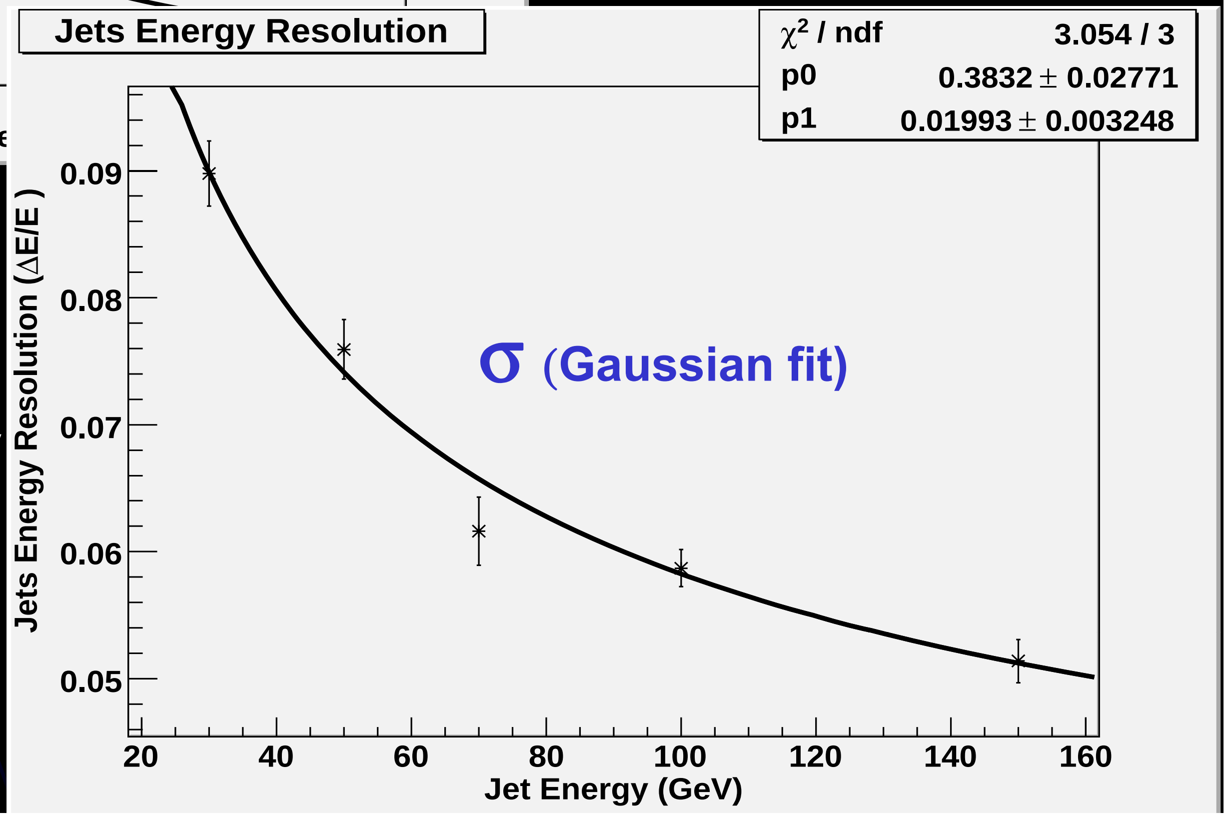


Jet reconstructed energy in HCAL

HCAL resolution with single jet



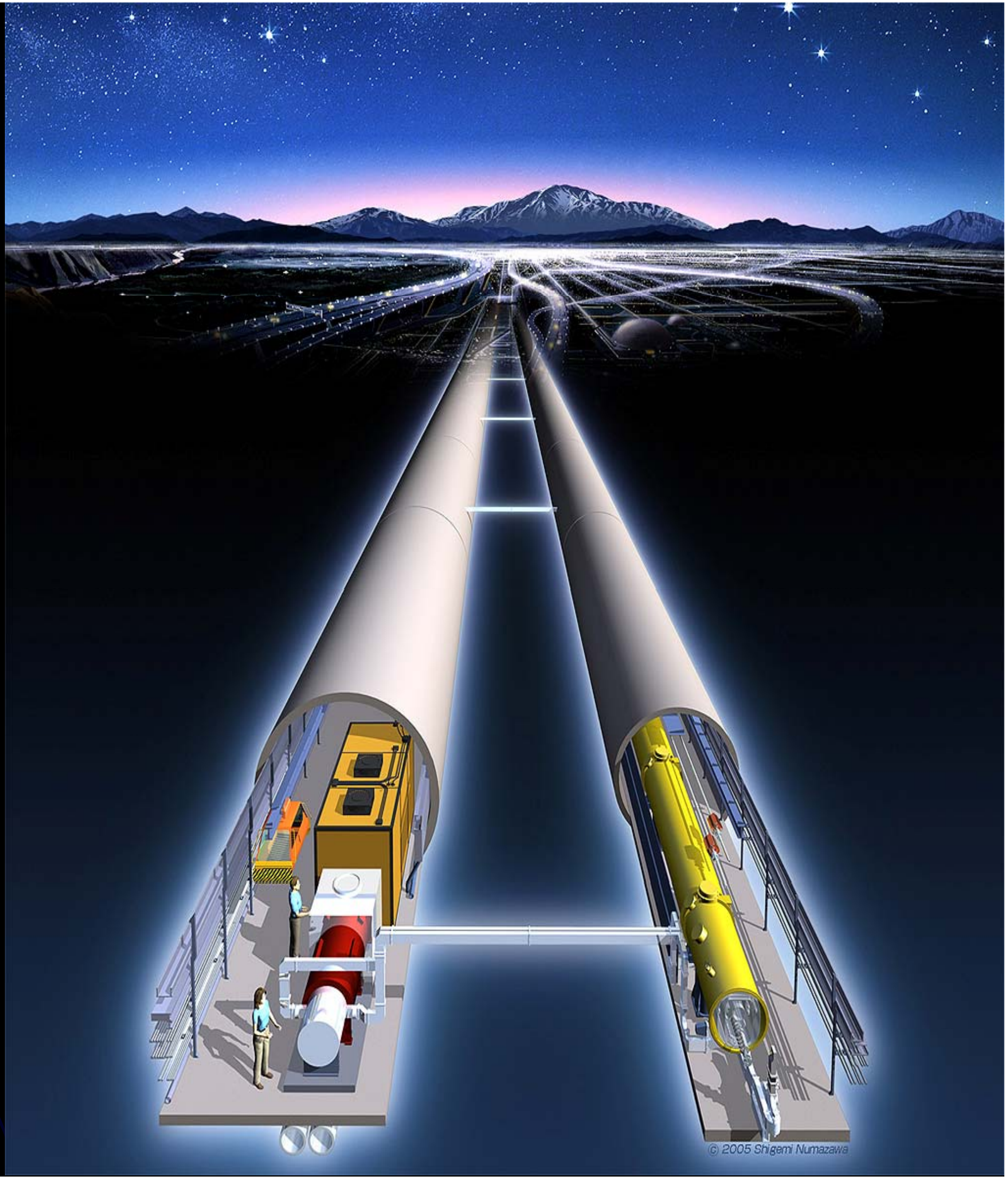
Jet reconstructed energy in HCAL



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

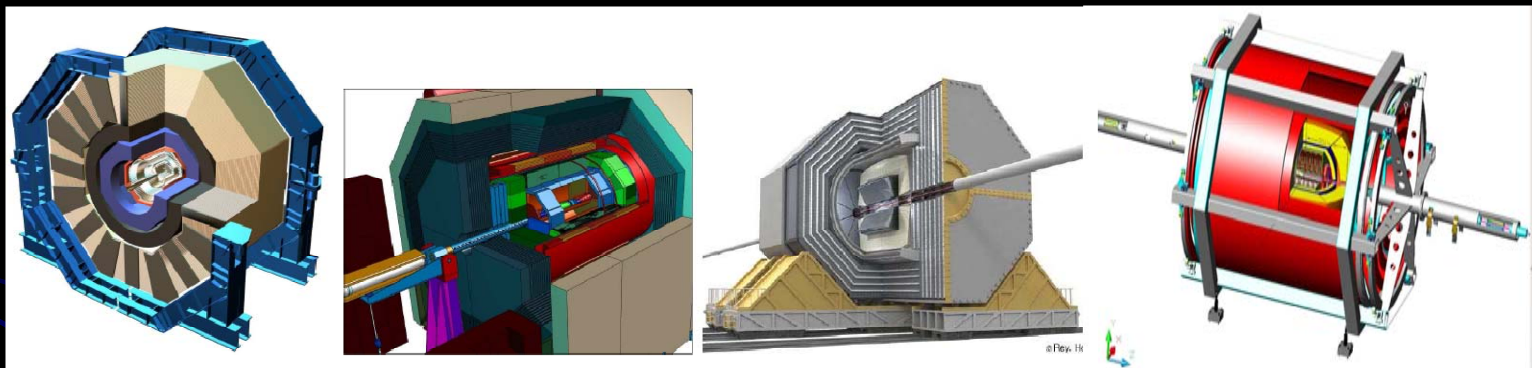


Requirements for ILC Detectors

- 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

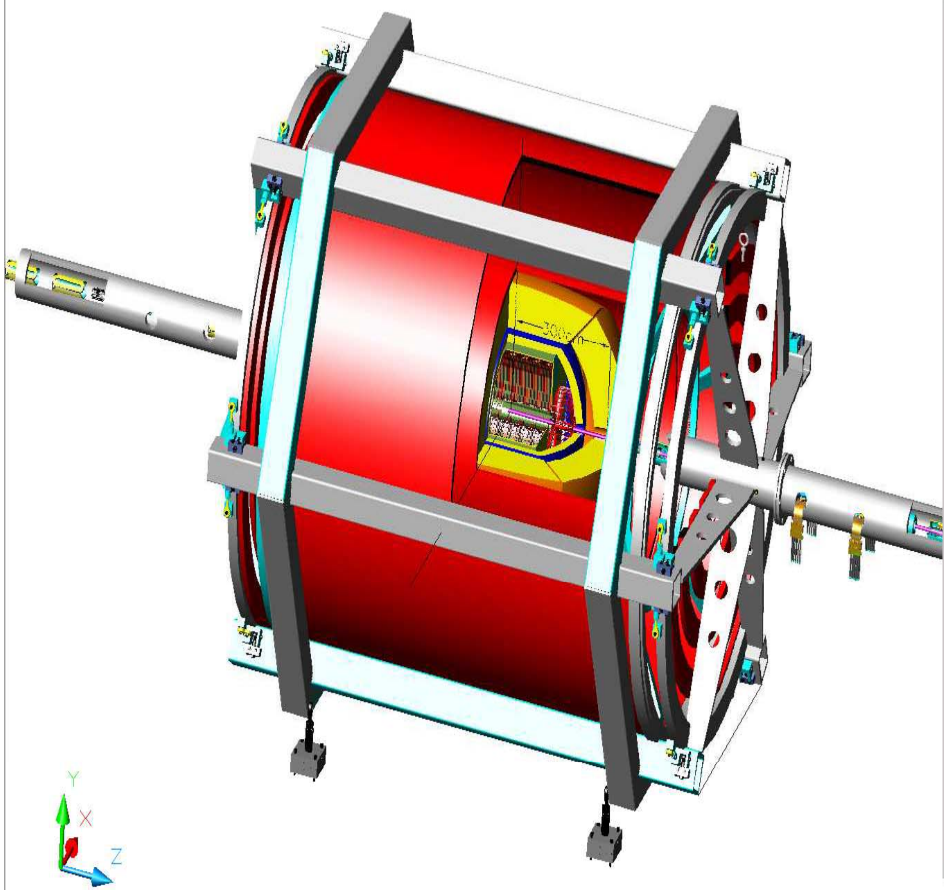
- Detector Design Study
  - Conceptual design study of detector systems
  - 4 major concepts: 3 with PFA + 1 with Compensation Calorimetry

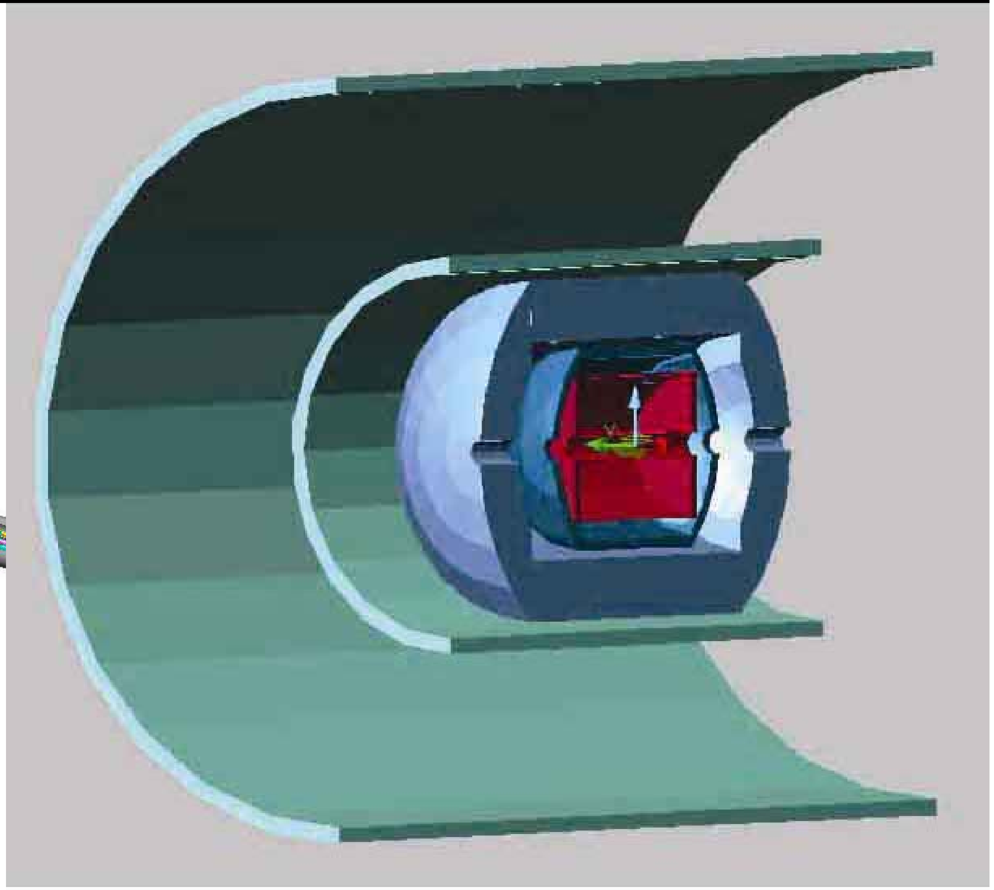


- Sub-detector R&D
  - More than 80 groups in the world (about 1000 physicist)
  - Usually related with several detector concepts

    ➔ Horizontal collaboration

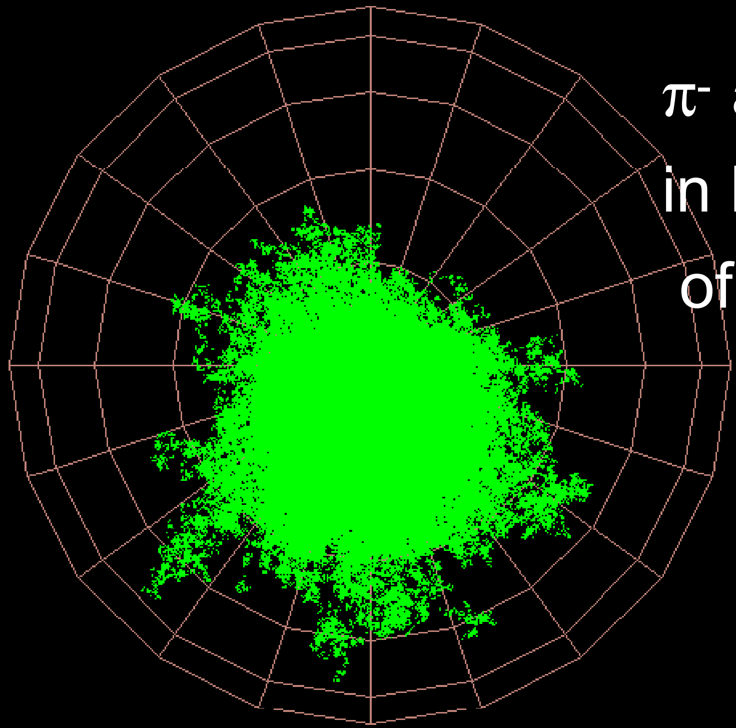
4th Concept Detector

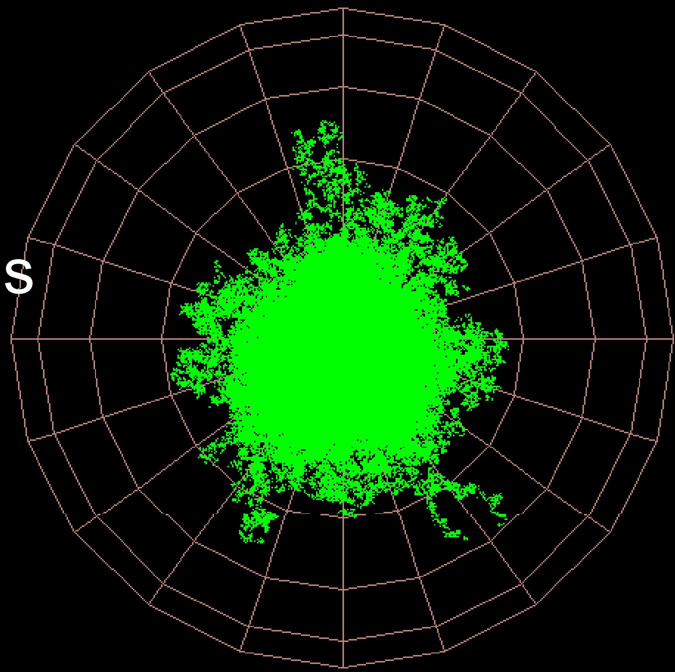




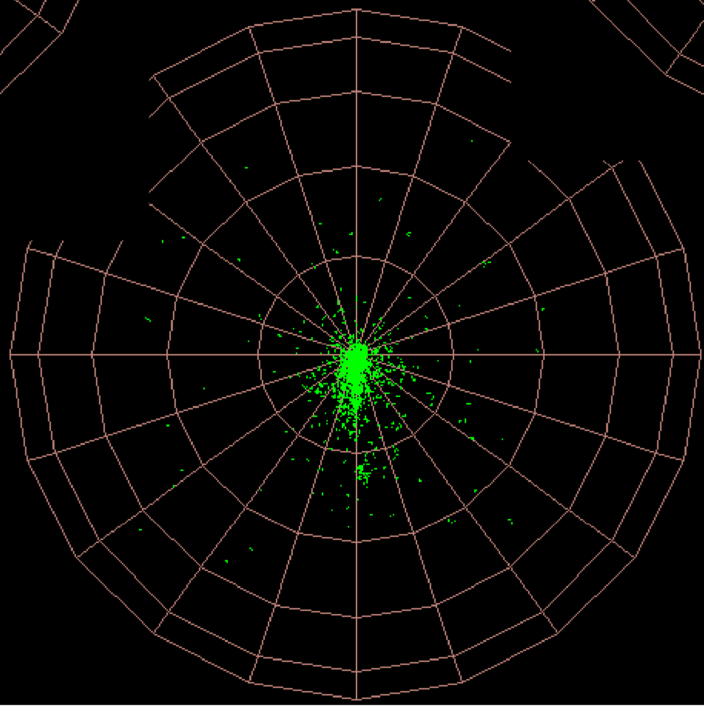
Fluka vs G3/G4

π^- at 50 GeV
in Pb sphere
of 500 cm radius





Geant3



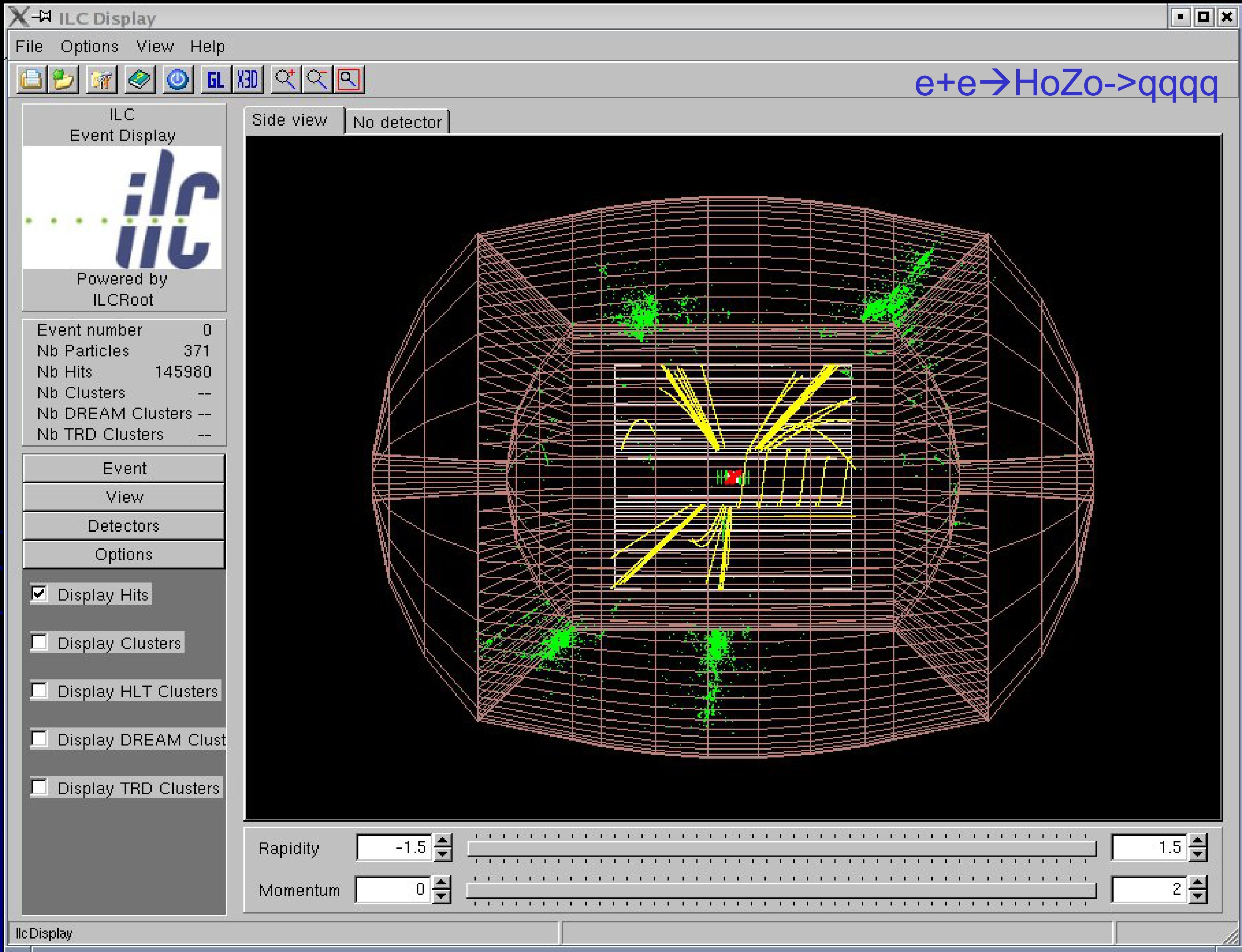
Fluka

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

Present Status: VXD+TPC+DREAM



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.

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

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

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 Ĉerenkov light in the same device

   4th

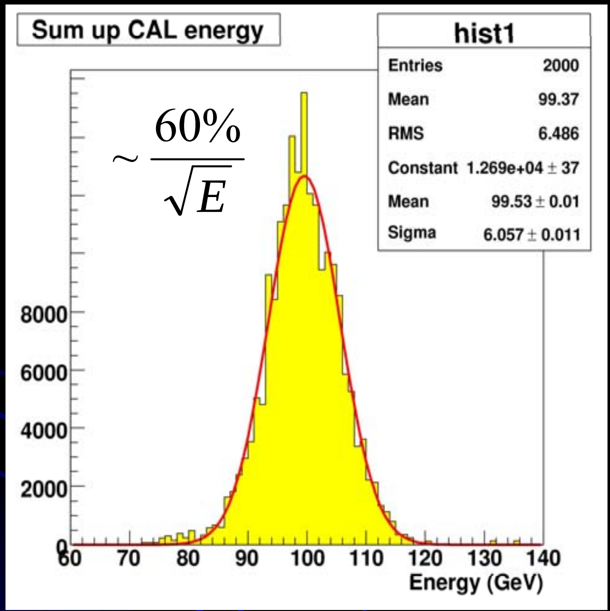
PFA Calorimetry

- 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 :

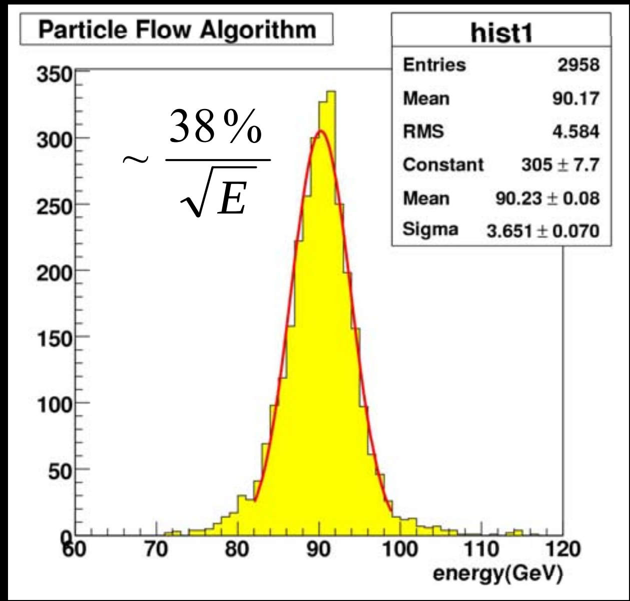
$$\frac{BR^2}{\sqrt{R_M{}^2 + \sigma^2}}$$

PFA Simulation Study at ILC

$Z \rightarrow qq$ @ 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 ~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.

The C/S method

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

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

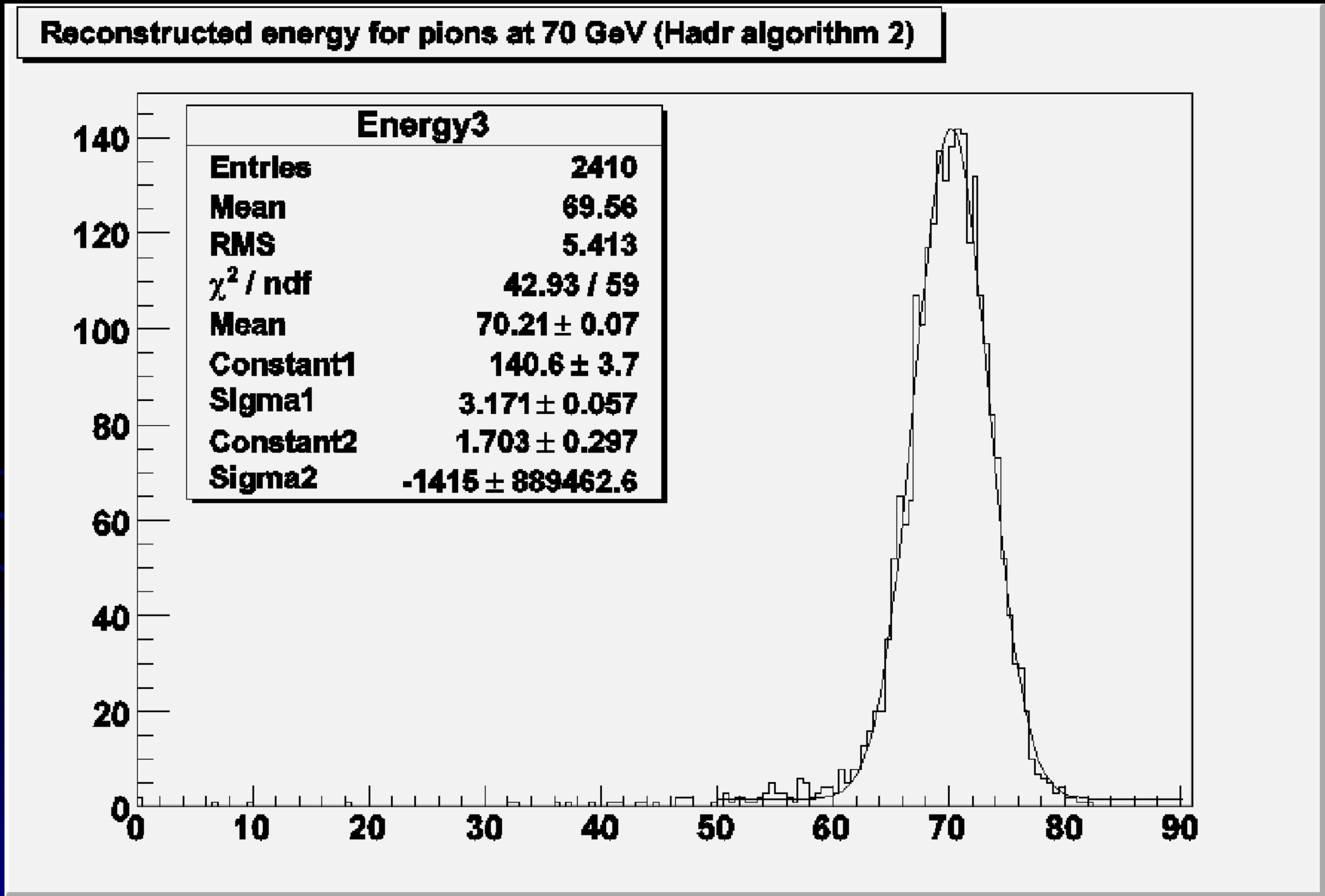
- **e/h depends on: active & passive calorimeter media and sampling fraction**

  $(e/h)_C = \eta_C \sim 5$ 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**

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

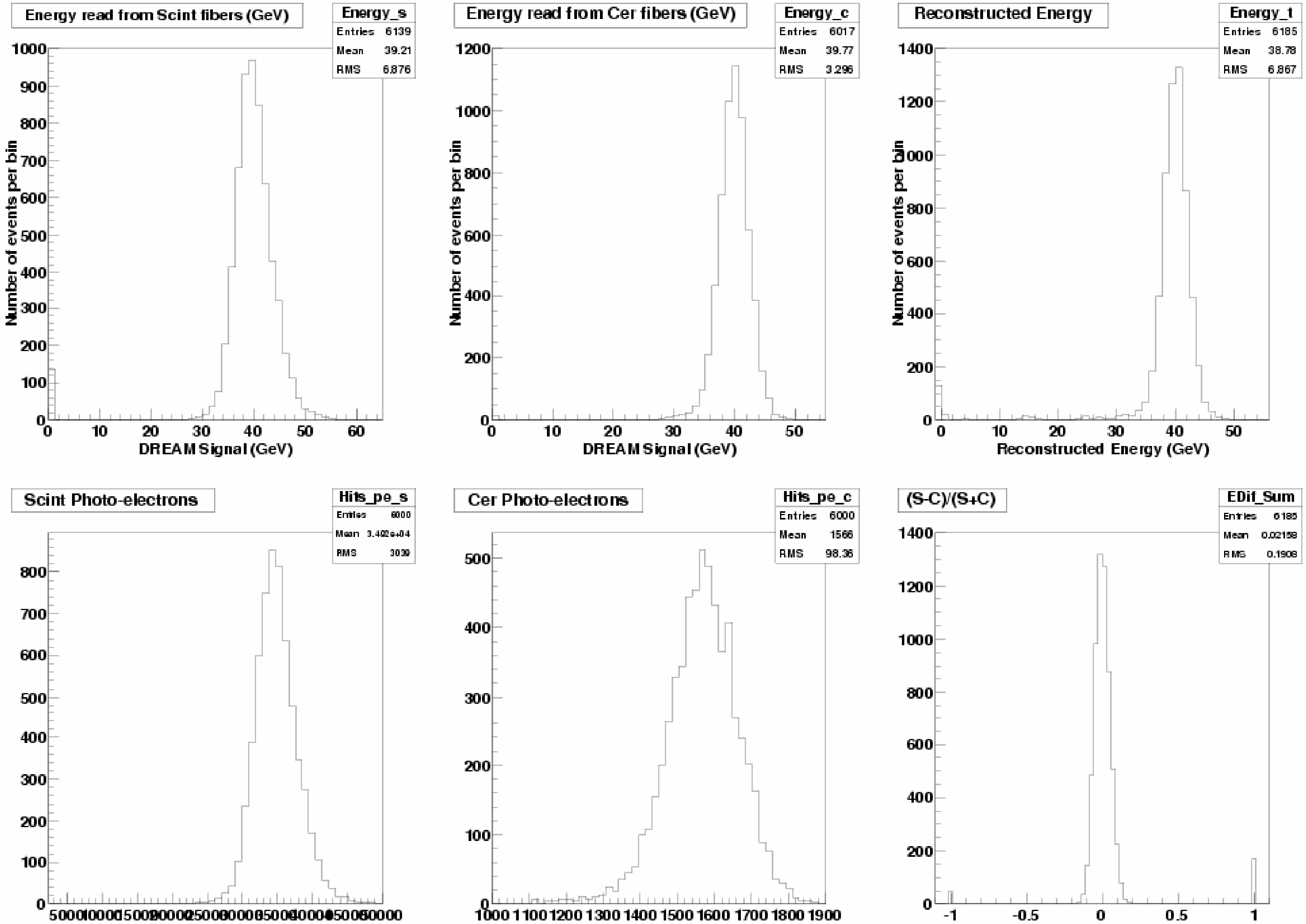
Dream Performance (pions)



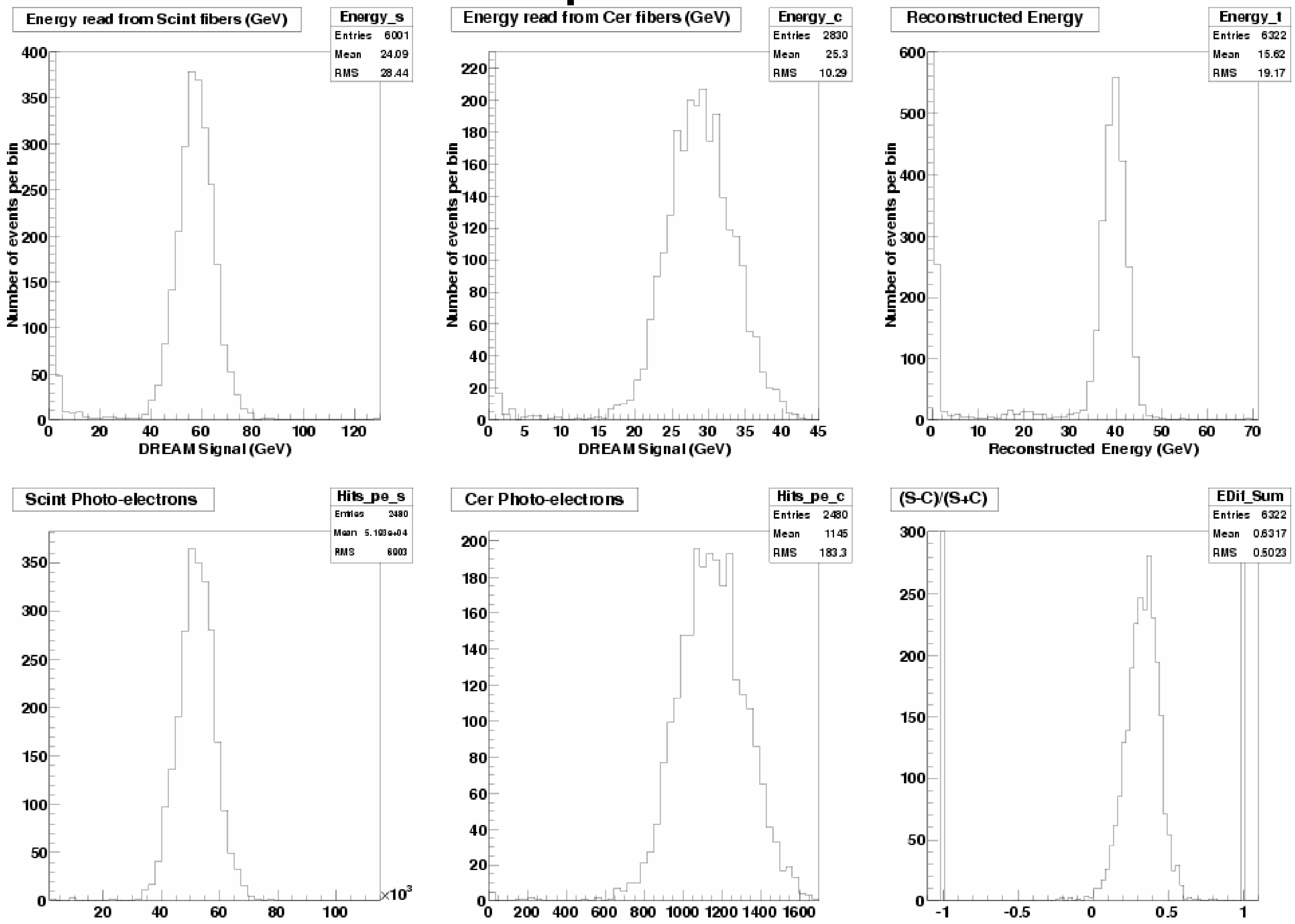
Results from DREAM simulation
(V. Di Benedetto)

- 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

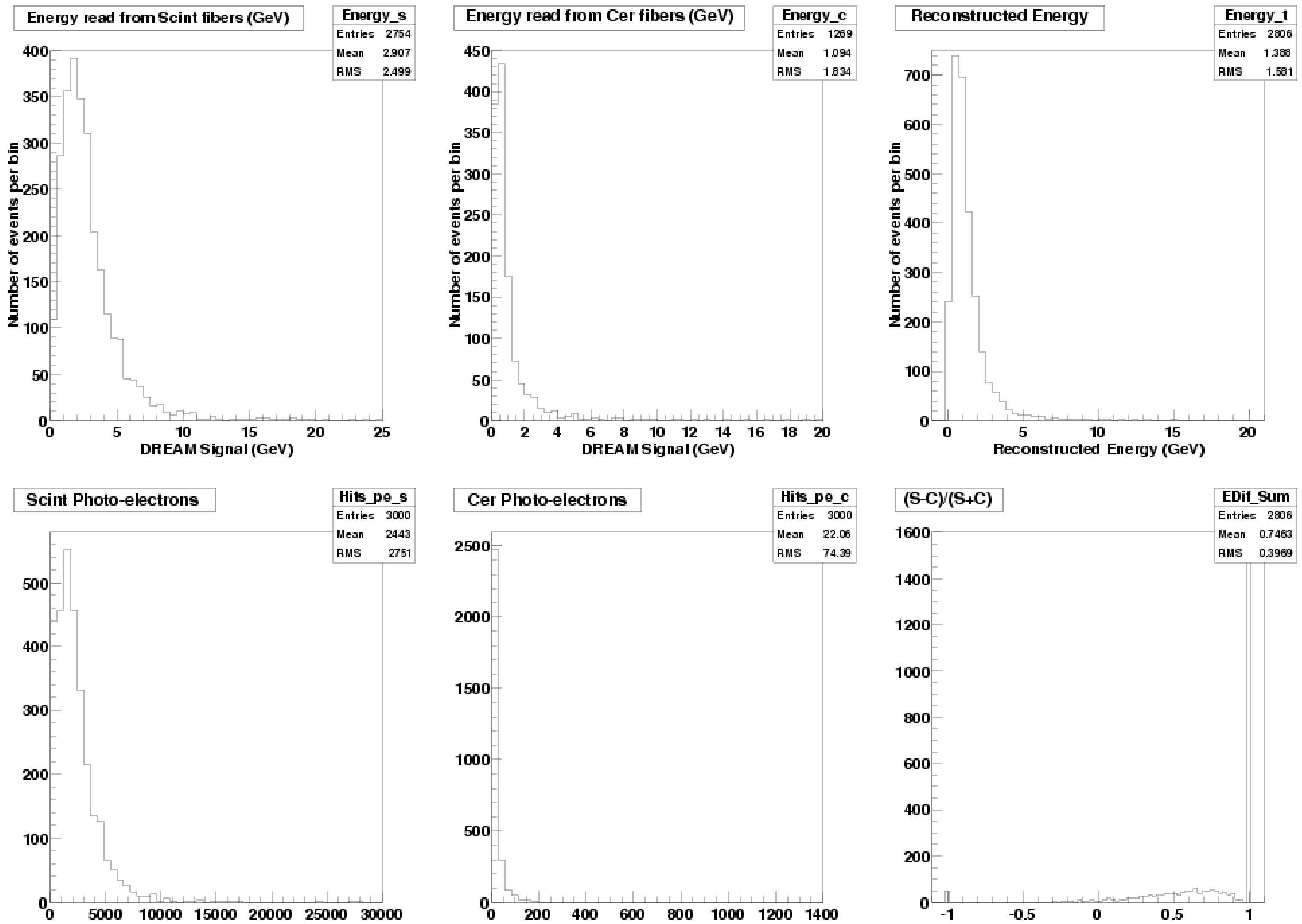
Histos electrons at 40 GeV in Cu

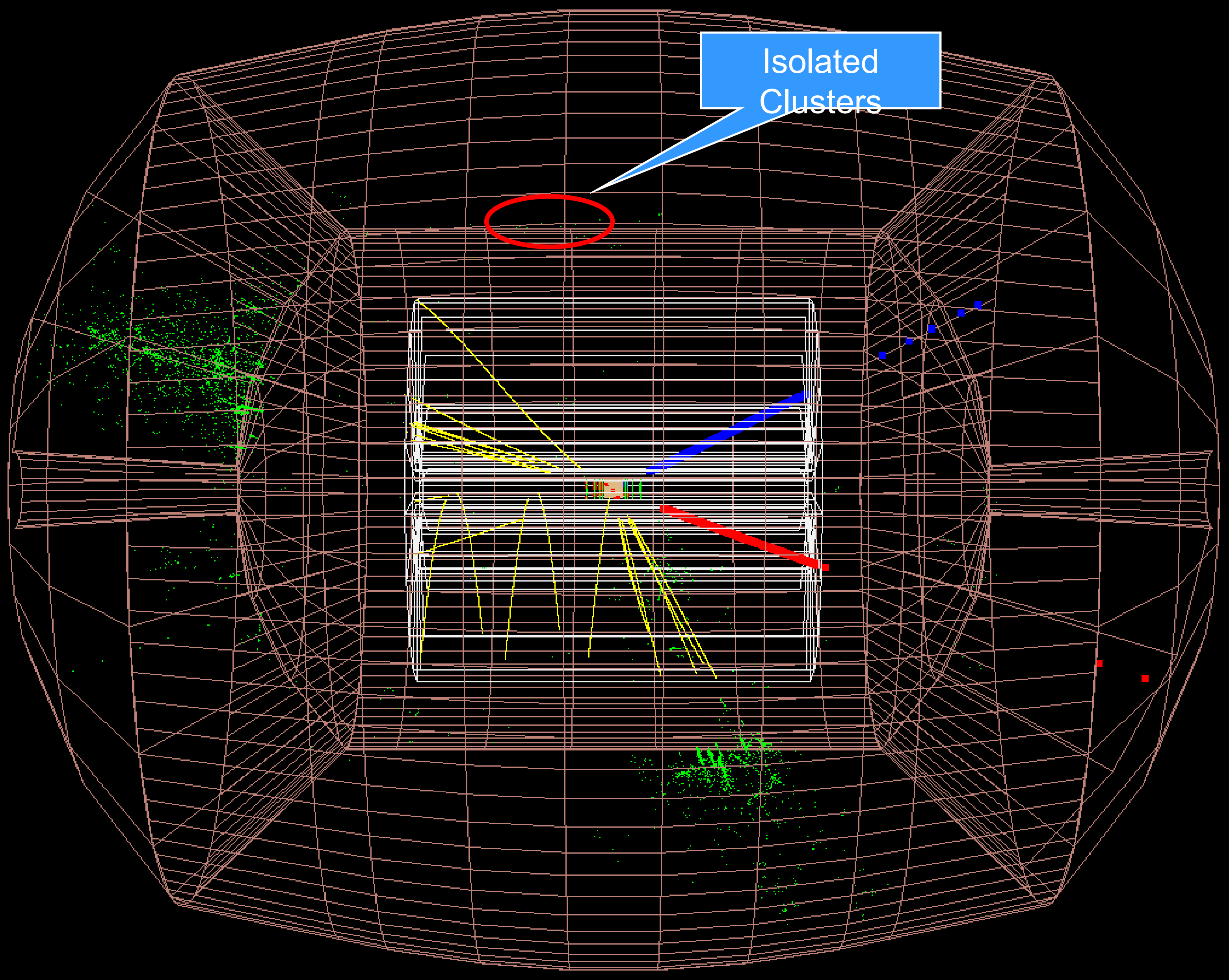


Histos pions at 40 GeV in Cu

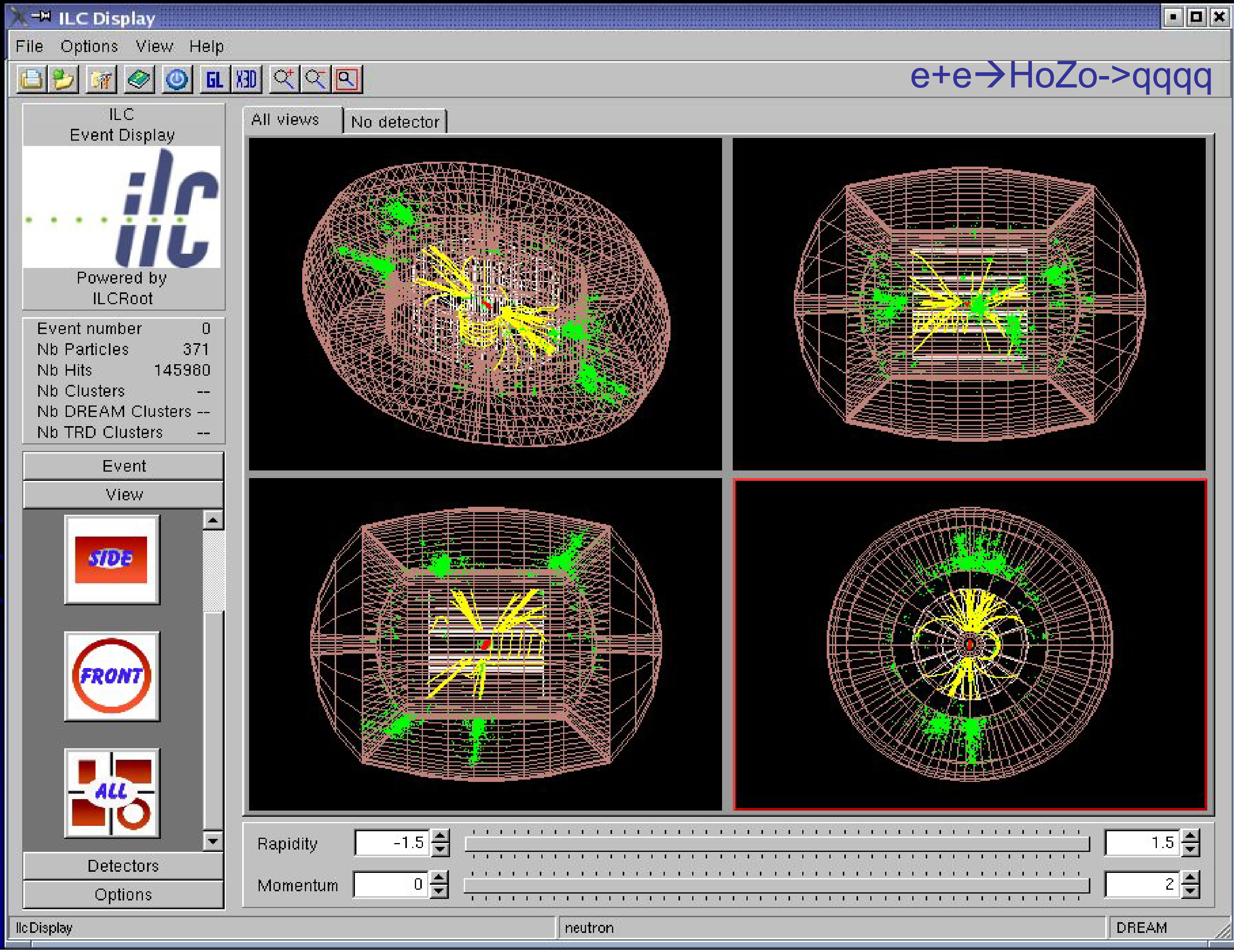


Histos muons at 100 GeV in Cu



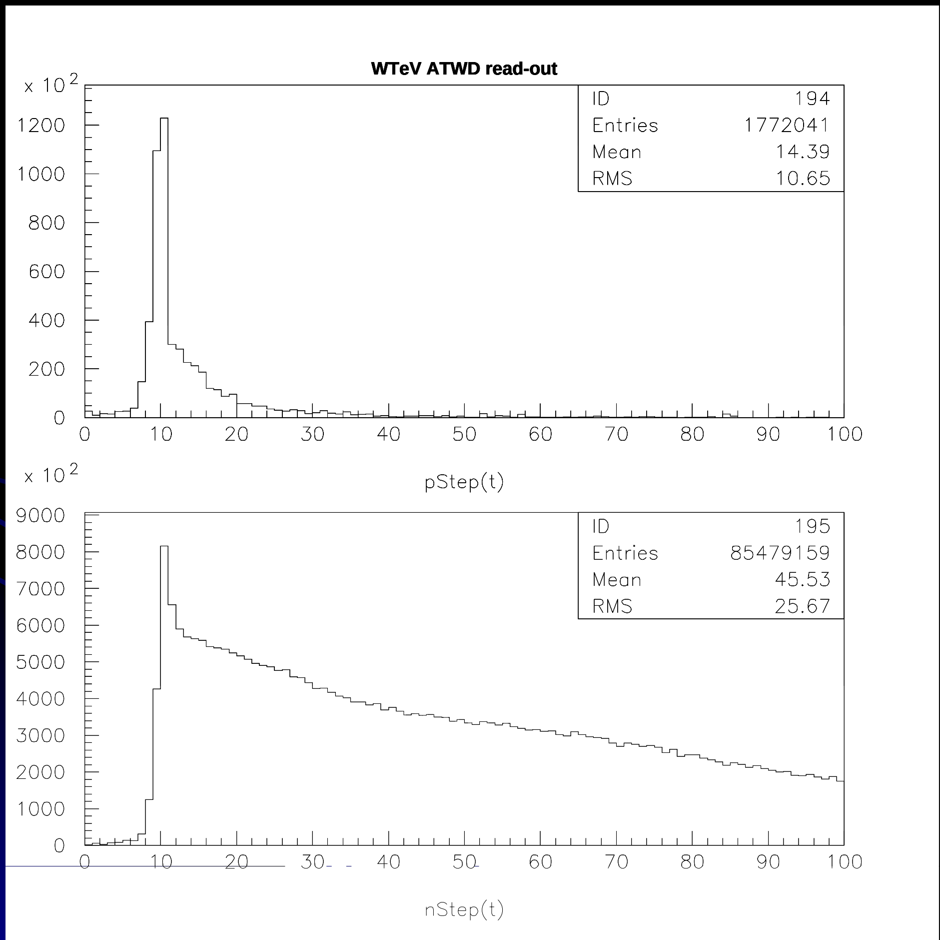

Isolated Clusters

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
- Th
  the d

(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 …)

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

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

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

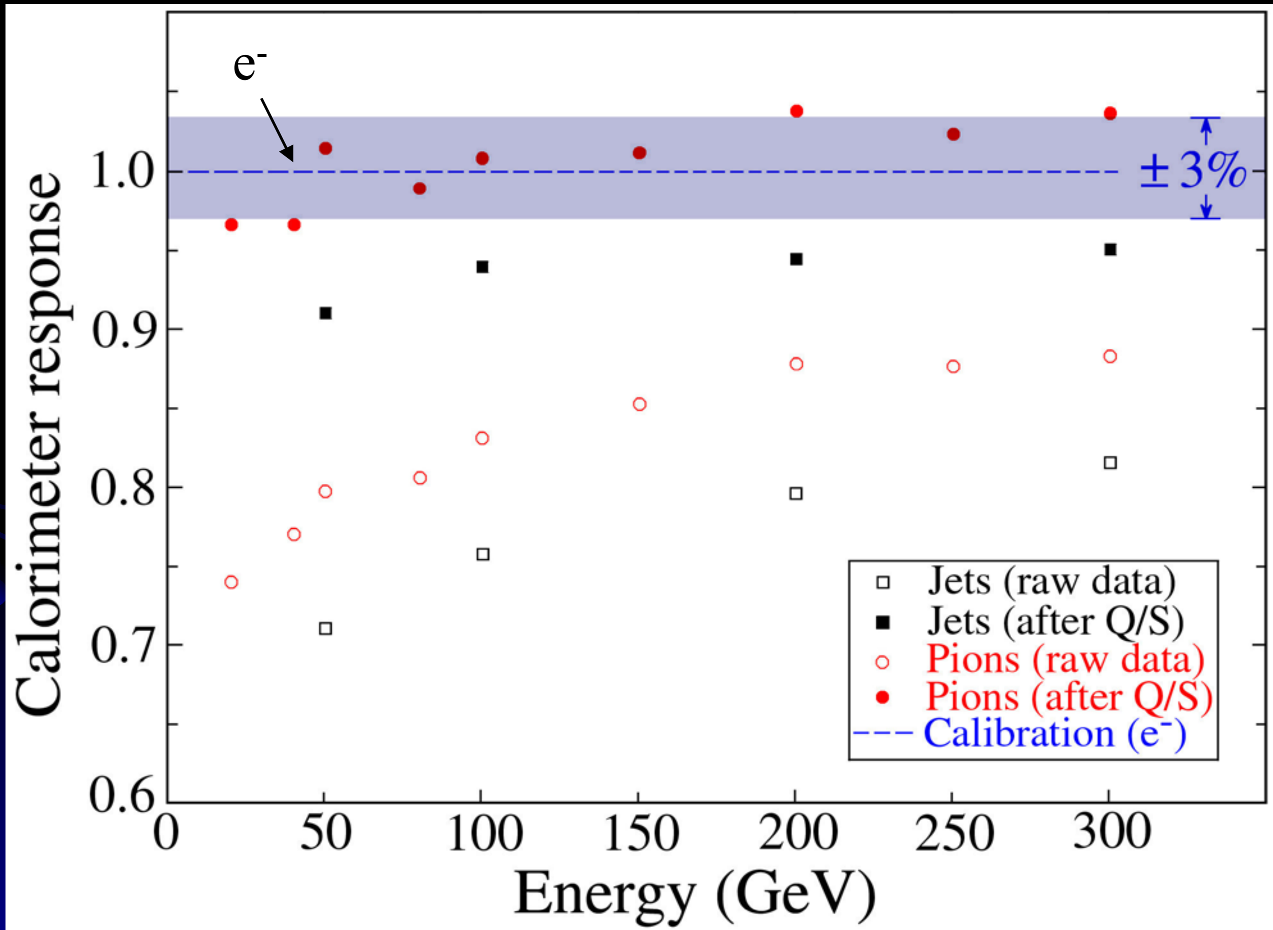
$$C = [\, f_{EM} + (1 - f_{EM}) / \eta_C \,]\; E$$

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

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

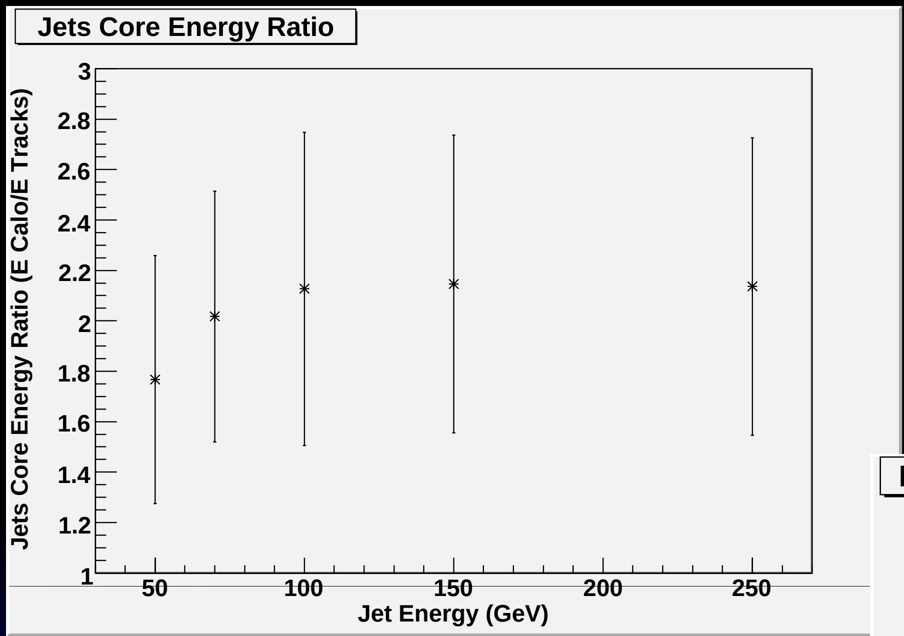
Data NIM A537 (2005) 537.

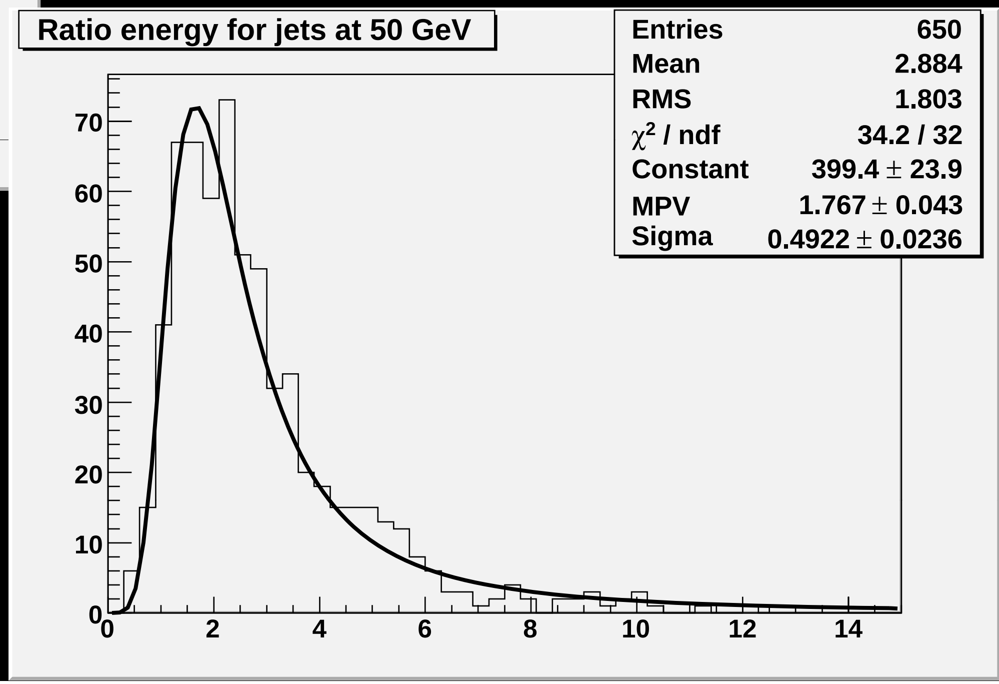
More important than good Gaussian response: DREAM module calibrated with 40 GeV e^- into the centers of each tower responds linearly to π^- and "jets" from 20 to 300 GeV.



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

Calorimeric/charged contribution





Jet Outliers Charged Contribution