Jet Reconstruction and Resolutions for Dual Readout Calorimetry

ILC ALPCG

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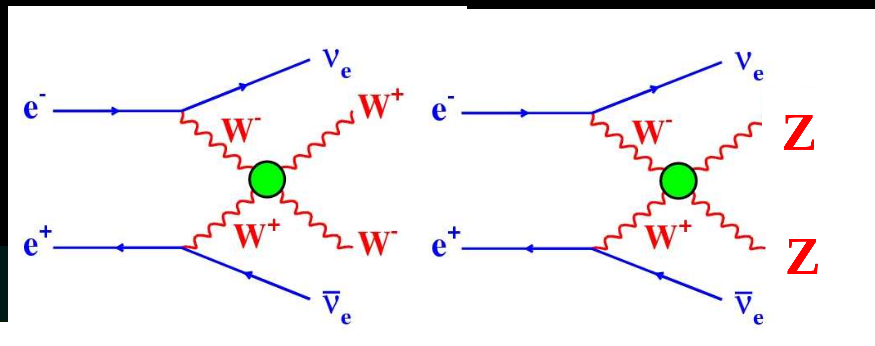
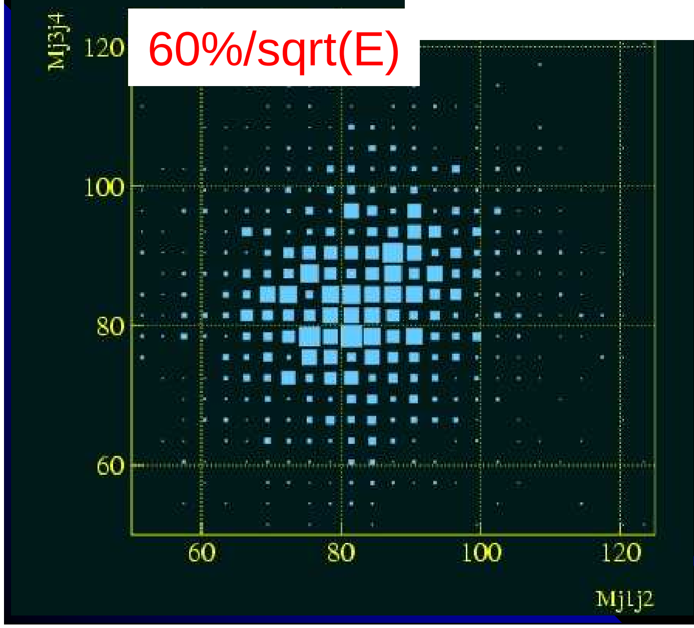
FNAL, September 13th 2007

Physics: Jets

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





Distinguish WW from ZZ, using M_{jj}

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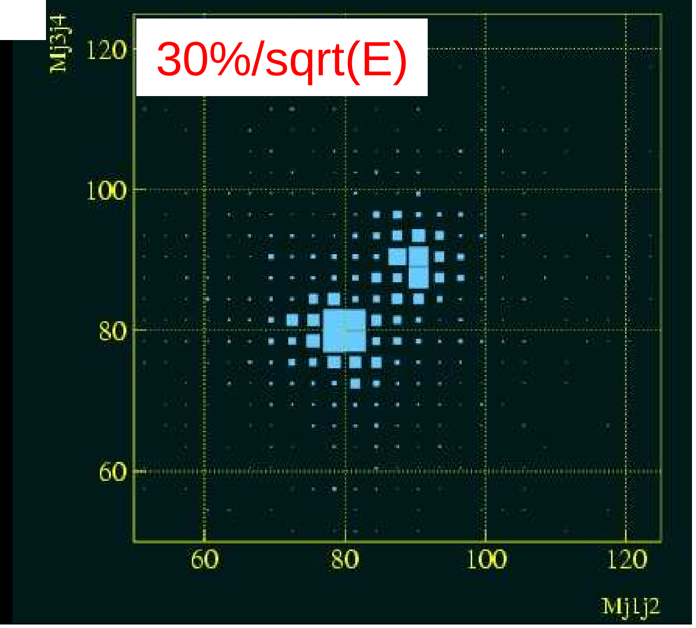

Jets at ILC Experiment

- Charged particles (~60%)
- Photons (~30%)
- Neutral hadrons (~10%)

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

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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

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

GLD

LDC

SiD

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 :

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

Dual 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

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

$$R_S \equiv S/E$$

$$R_C \equiv C/E$$

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

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

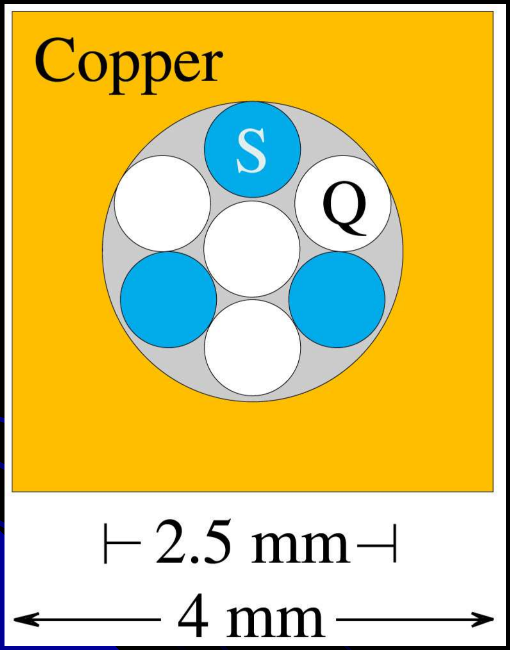
$(e/h)_S \equiv \eta_S \sim 1.4$ for copper/plastic-scintillator

- measurement of f_{em} value event by event from *C* and *S* signals

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

Dual REAdout Module (DREAM)

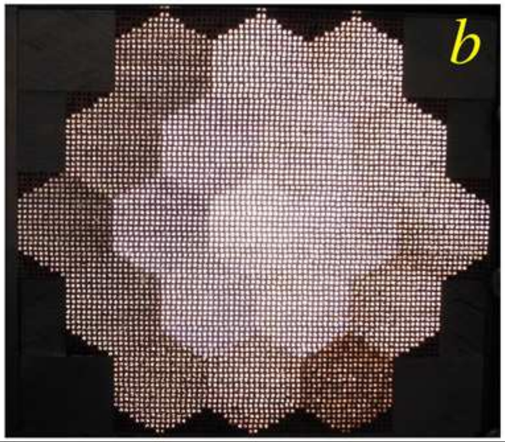
http://www.phys.ttu.edu/dream/



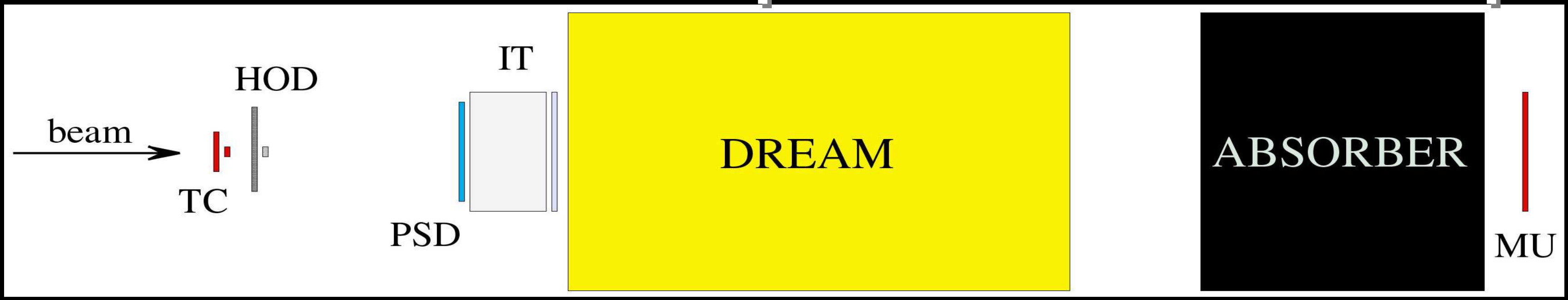
Unit cell

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**

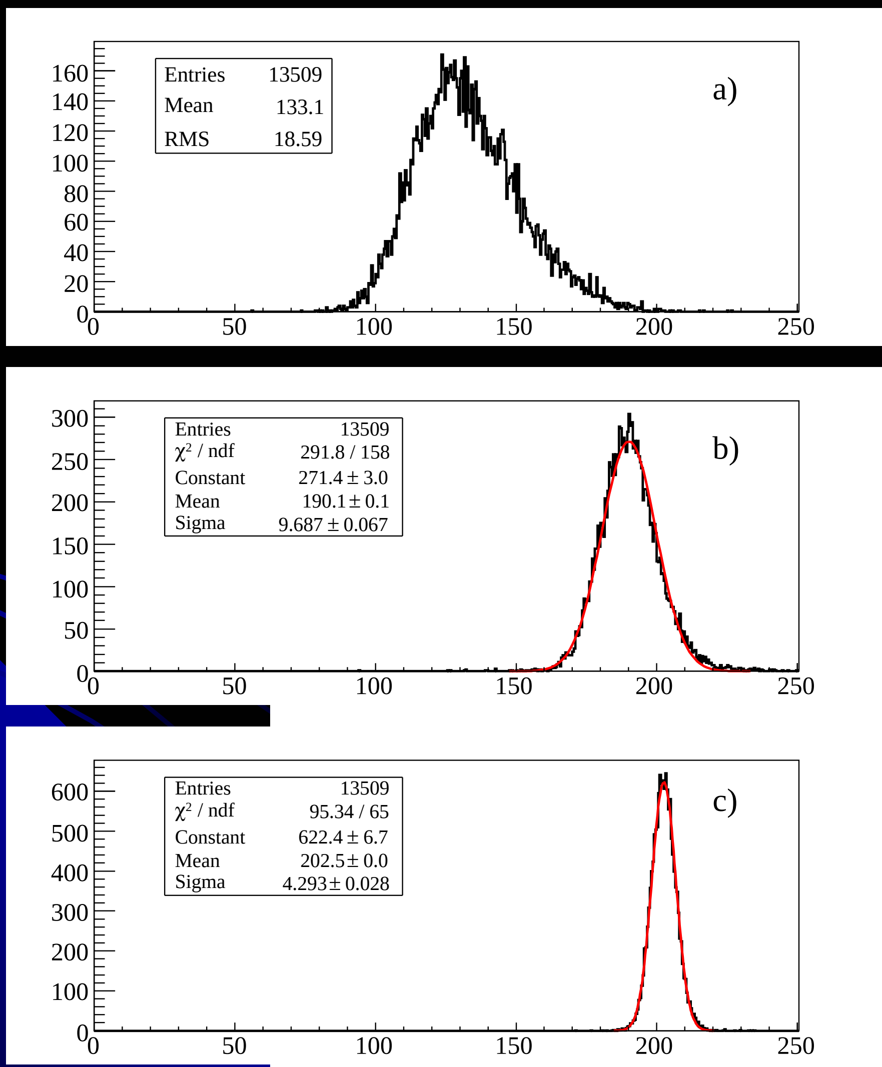
  30 x 30 cm^2 scintillation counter behind 8 $\mathbf{l}_{\mathbf{int}}$ absorber.

  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**

DREAM data 200 GeV π^-: Energy response



Scintillating fibers

typical features of non-compensating calorimeter

Scint + Cerenkov

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

(4% leakage fluctuations)

Scint + Cerenkov

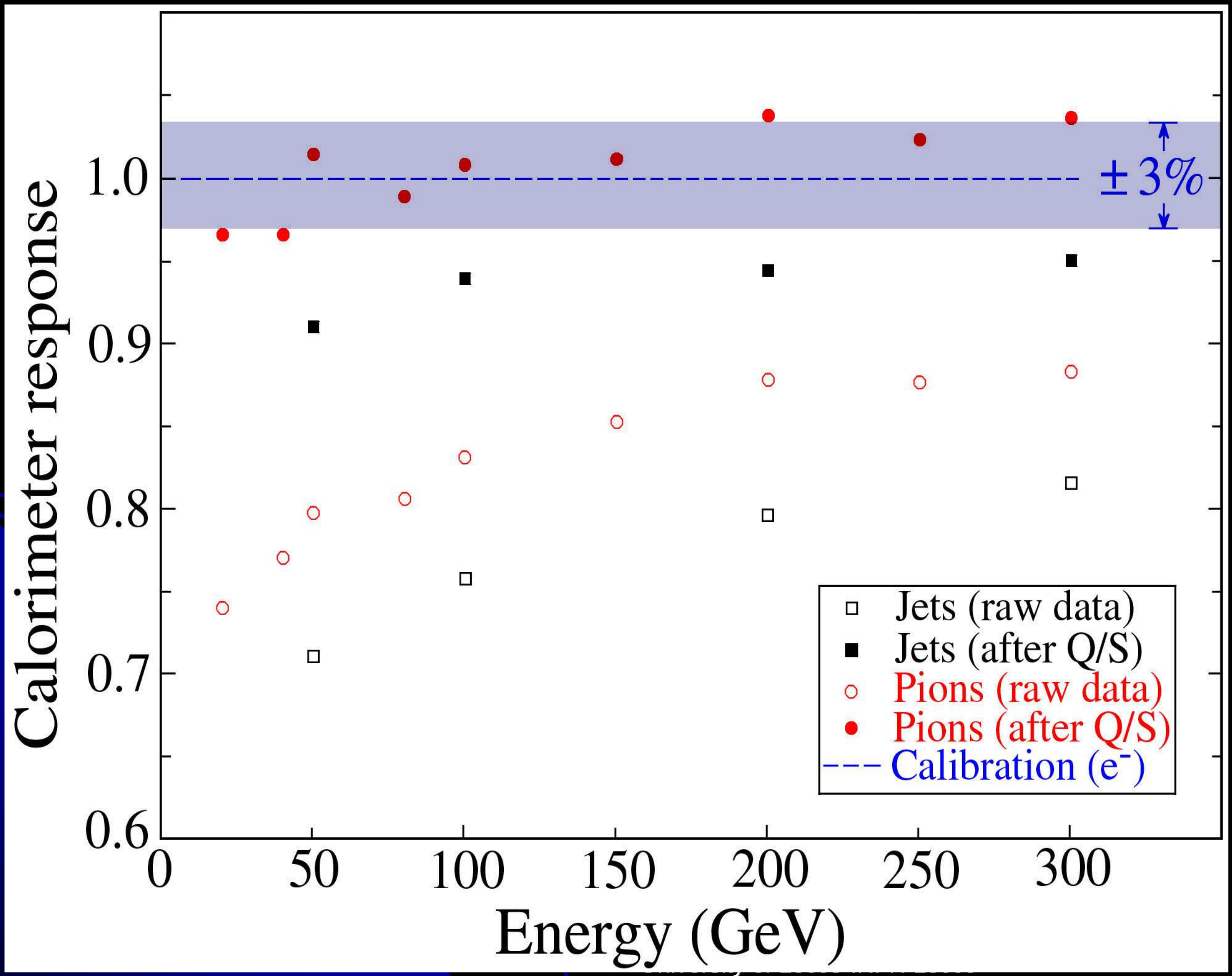
$f_{EM} \propto (C/E_{beam} - 1/\eta_C)$

(suppresses leakage)

Data NIM A537 (2005) 537.

DREAM calibrated with 40 GeV e⁻ into center of each tower

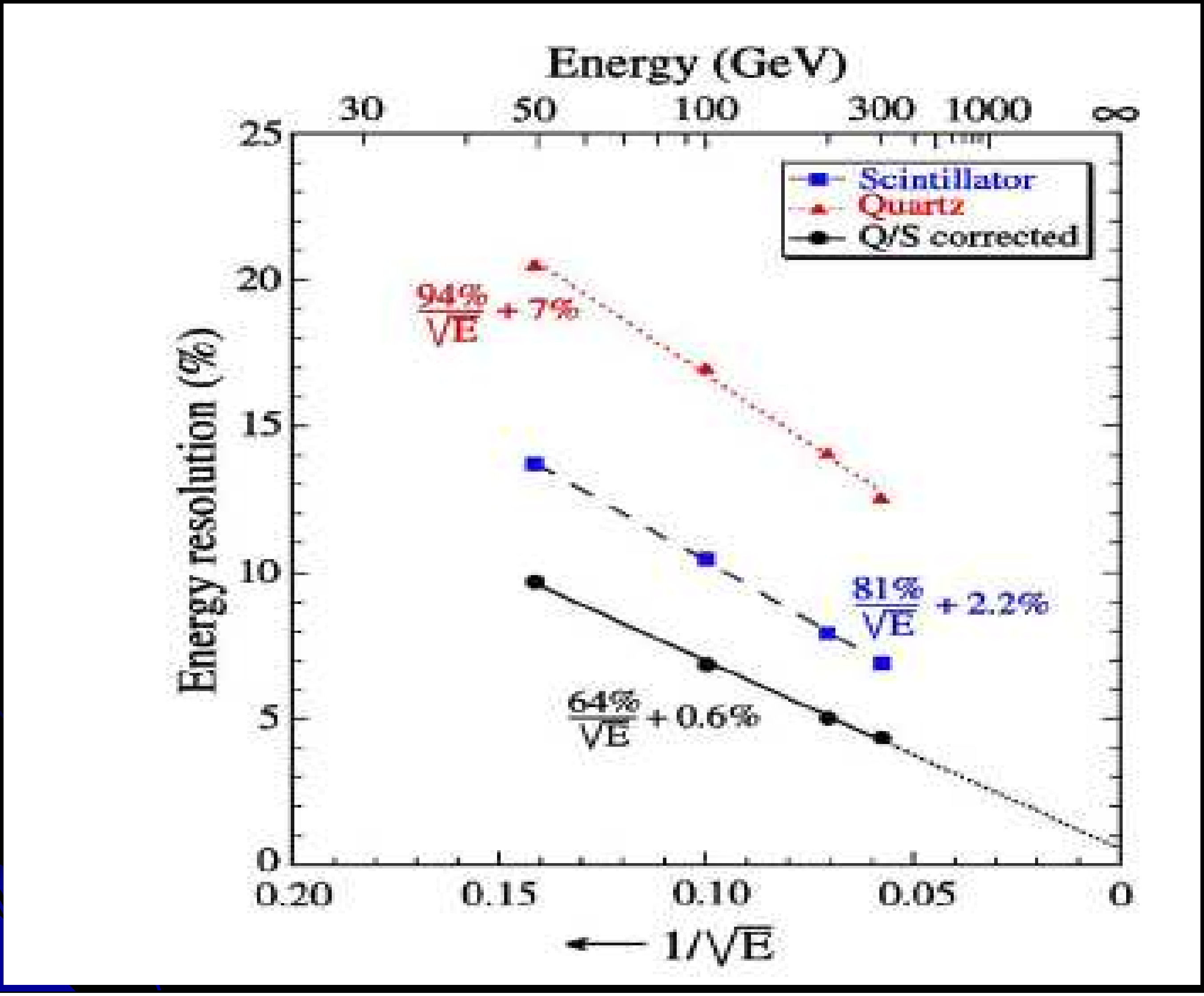
recover linear hadronic response up to 300 GeV for π^- and "jets"



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

$Q/S \equiv C/S$

Calorimeter Resolution



From DREAM to the 4th Concept HCAL

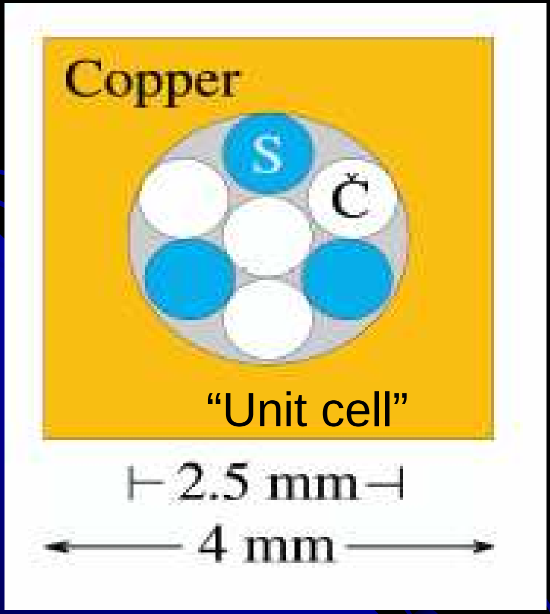
DREAM module

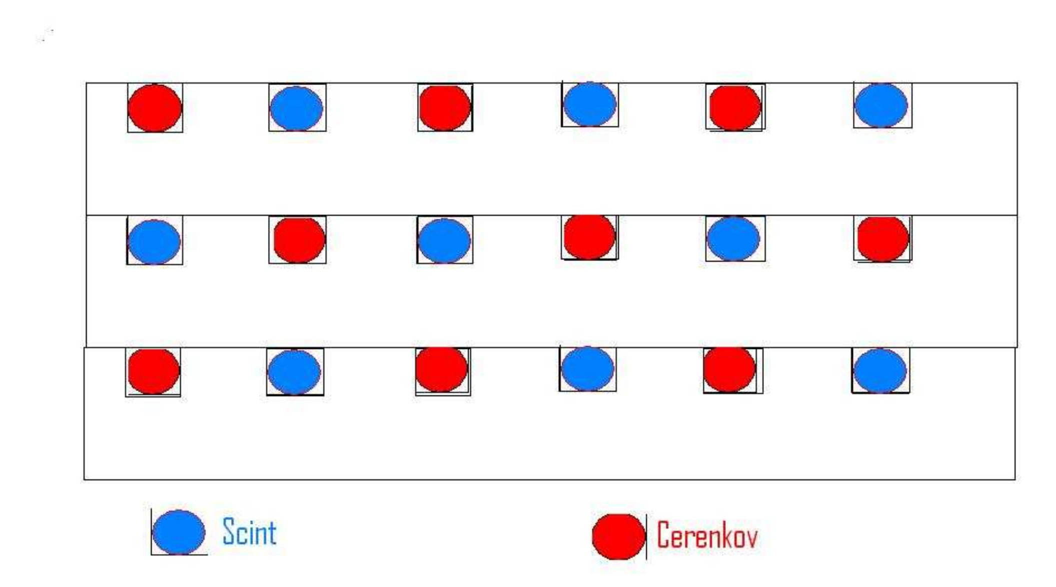
3 scintillating fibers

4 Cerenkov fibers

ILC-type module

2mm W or brass plates;
fibers every 2 mm



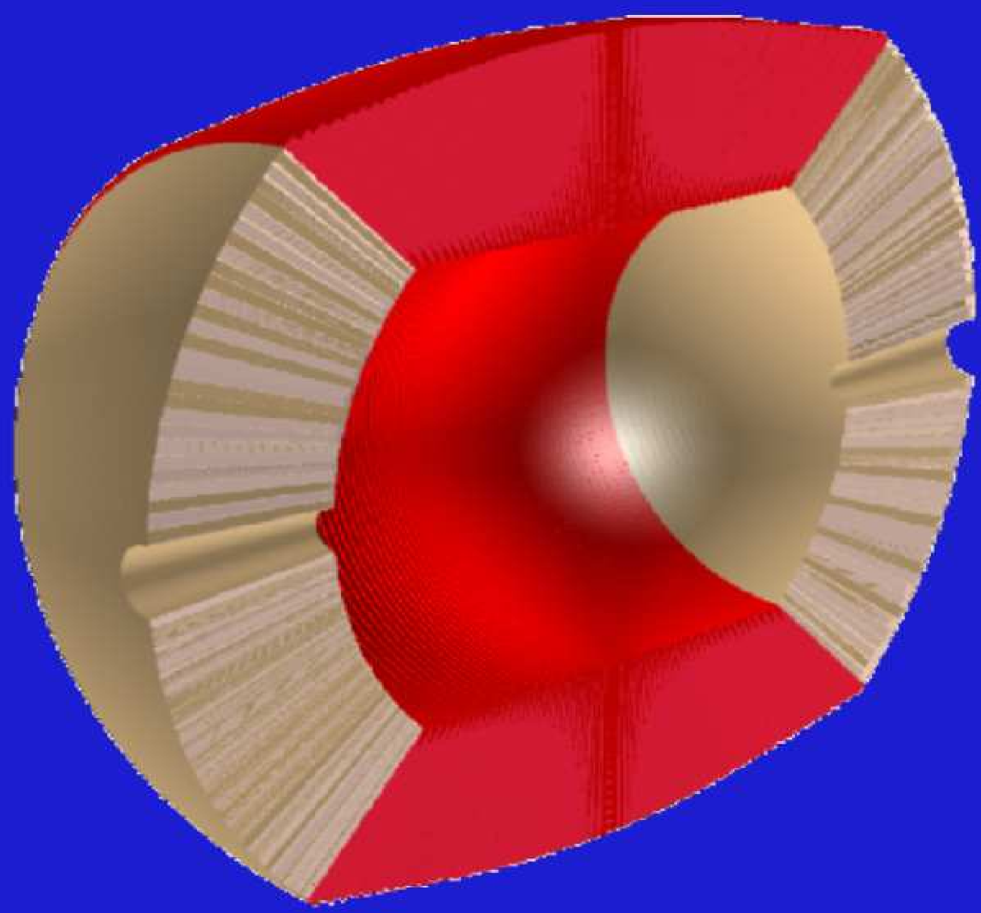


The 4th Concept Hadronic Calorimeter (first version*)

- Cu + scintillating fibers + Ĉerenkov fibers
- ~1.5° aperture angle
- ~ 10 λ_{int} depth
- Azimuth coverage

  down to 3.8°
- Barrel: 13924 cells
- Endcaps: 3164 cells

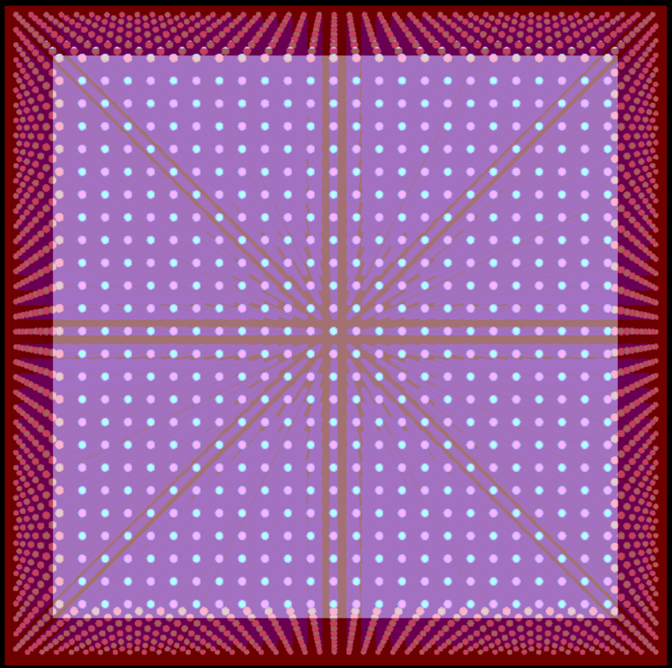
*In the present studies



Fully projective geometry

Hadronic Calorimeter Cells

Bottom view of single cell



Prospective view of clipped cell

3 μm radius

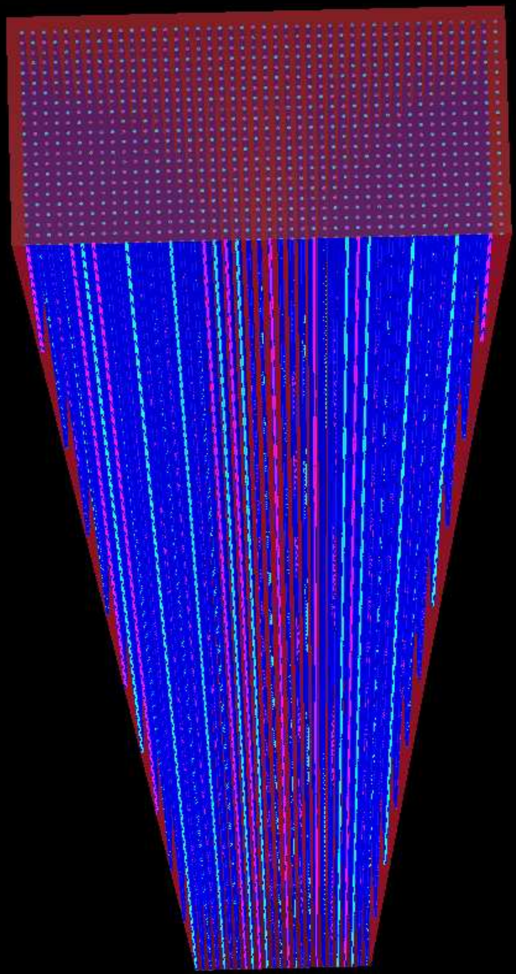
Plastic/Quartz fibers

Aperture Number=0.50

(C fibers)

Cell length: 150 cm

Top cell size:~ 8.8 × 8.8 cm^2



Bottom cell size: ~ 4.8 × 4.8 cm^2

Number of fibers inside each cell: 1980

equally subdivided between Scintillating and Cerenkov

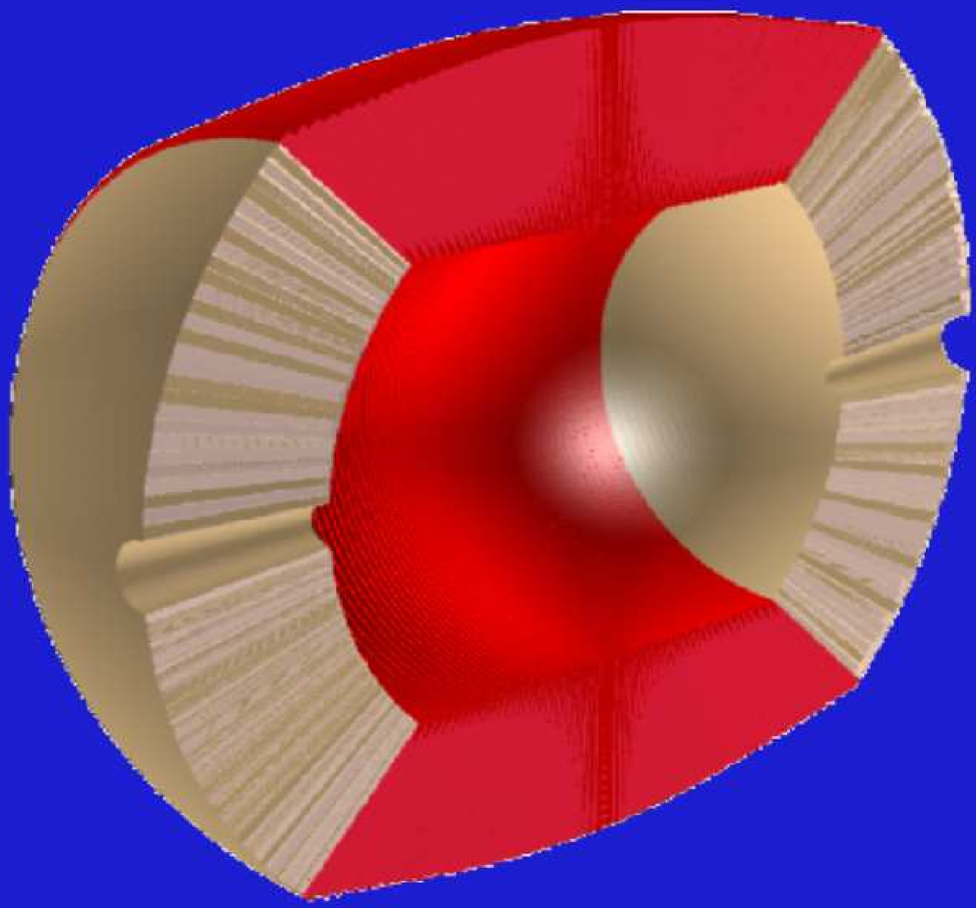
Fiber stepping ~2 mm

The 4th Concept Hadronic Calorimeter (second version*)

- Cu + scintillating fibers + Ĉerenkov fibers
- ~1.4° aperture angle
- Azimuth coverage down to 7°
- Barrel: 16384 cells
- Endcaps: 6084 cells

Changes from previos version red color

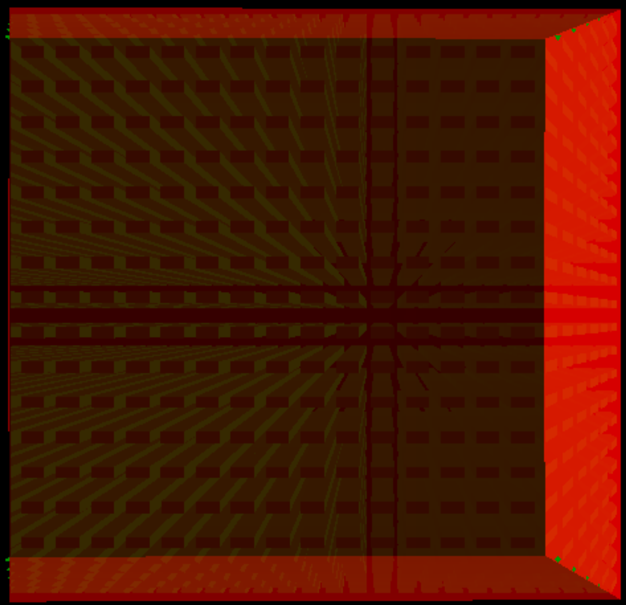
*Uder development



Fully projective geometry

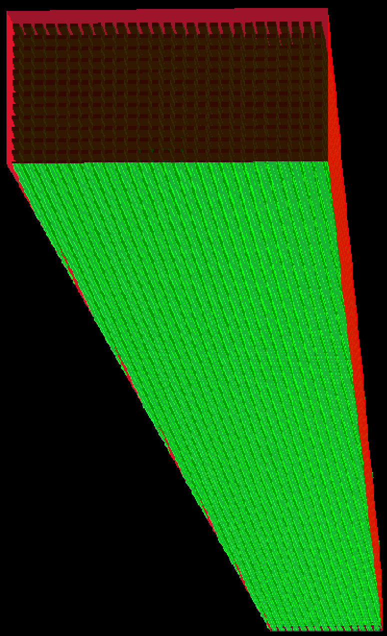
New Hadronic Calorimeter Cells

Bottom view of single cell



Prospective view of clipped cell

Top cell size:~ 8.1 × 8.1 cm^2



Square 1×1 mm^2

Plastic fibers

Aperture Number=0.73

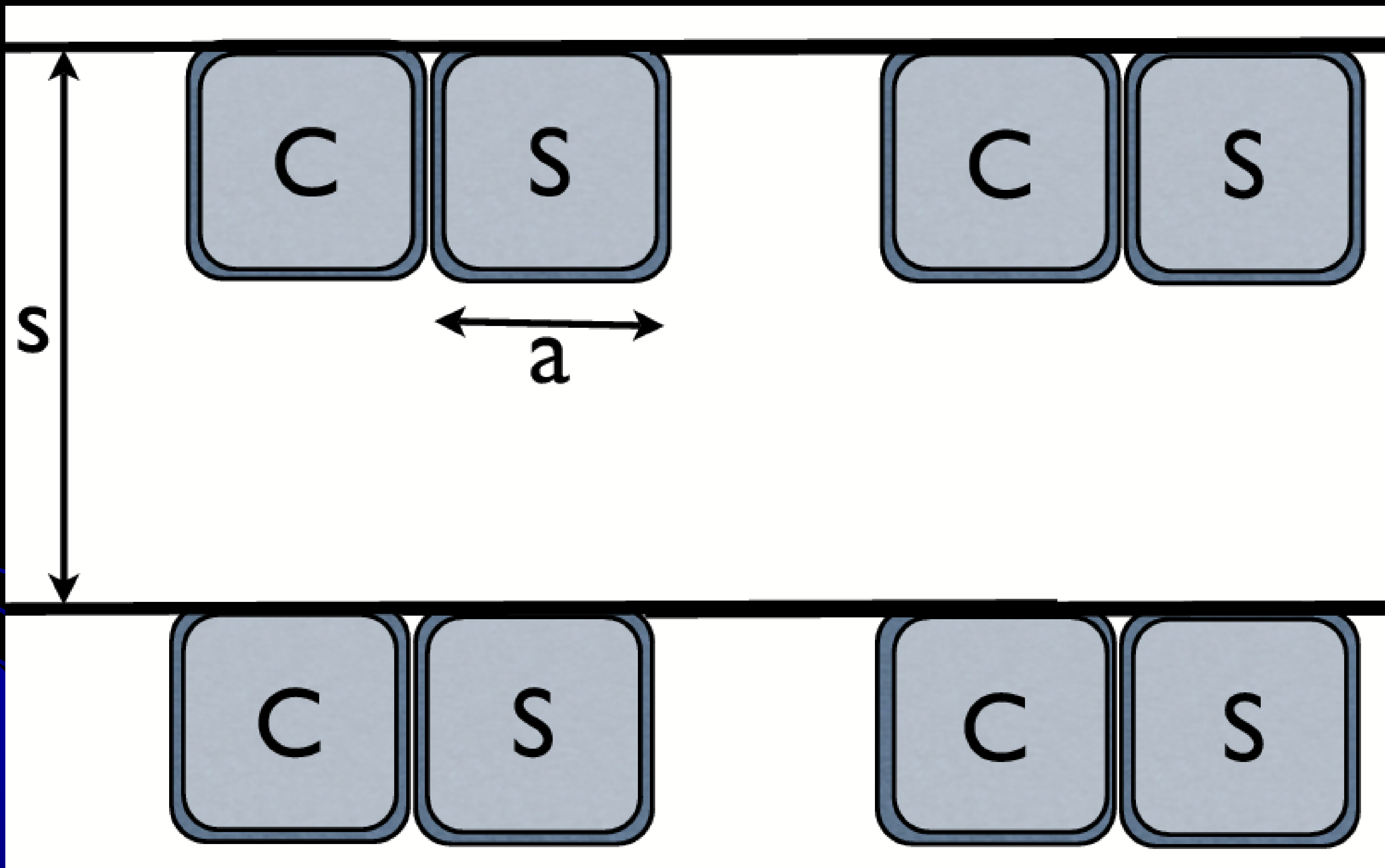
Cell length: 150 cm

Number of fibers inside each cell:~1480

equally subdivided between Scintillating and Cerenkov

Fiber stepping ~3 mm

Bottom cell size: ~ 4.4 × 4.4 cm^2


C
S
C
S
s
a
C
S
C
S

Simulation Details (1)

Light production in the fibers simulated through 2 separate steps:

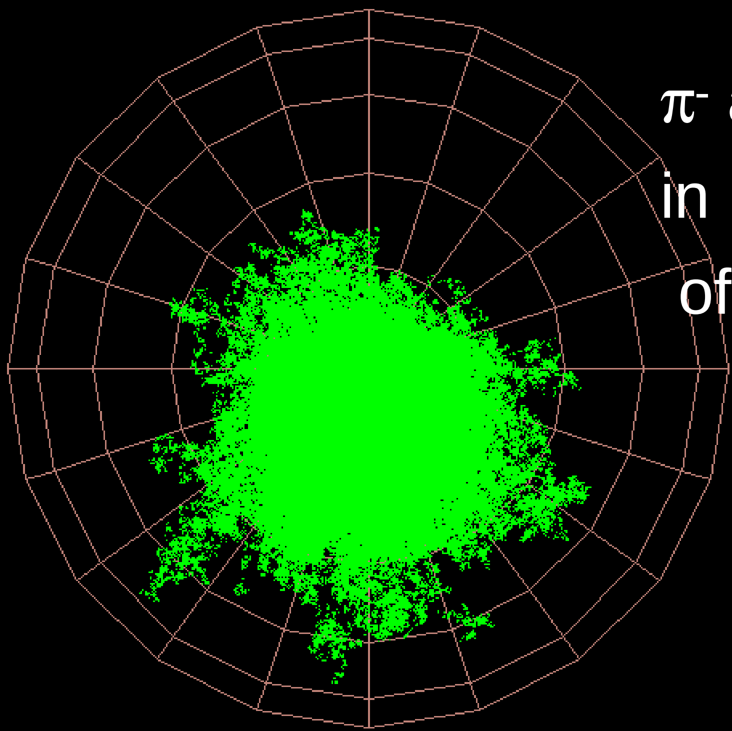
1. Energy deposition (hits) in active materials calculated by the tracking algorithm of the MC
2. Conversion of the energy into the number of S and C photone- by specific routins taking account several factors: energy of the particle, angle between the particle and the fiber, etc. Poisson uncertaintity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

Simulation Details (2)

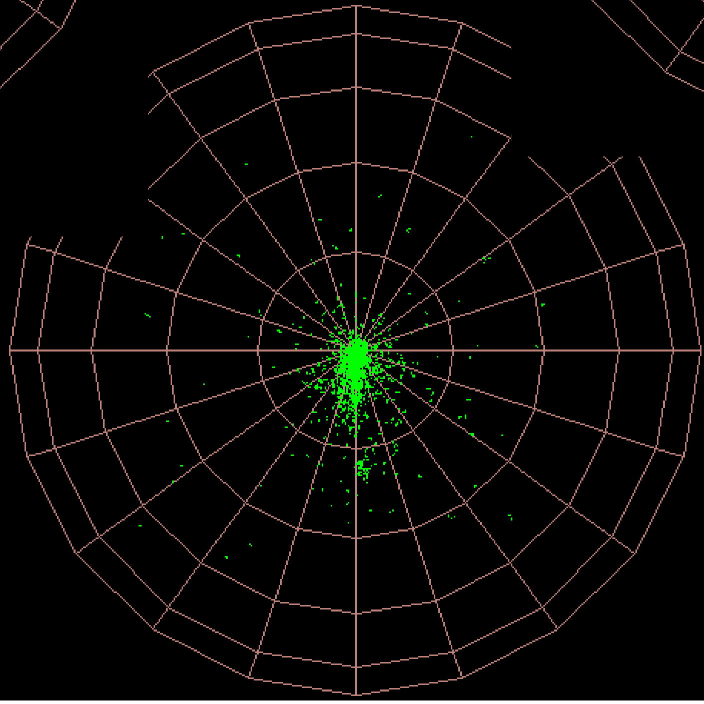
- Response function of the electronics not yet completely simulated (digits)
- Random noise generated to test the ability of reconstruction algorithm to reject such spurious “hits”

Fluka vs G3/G4

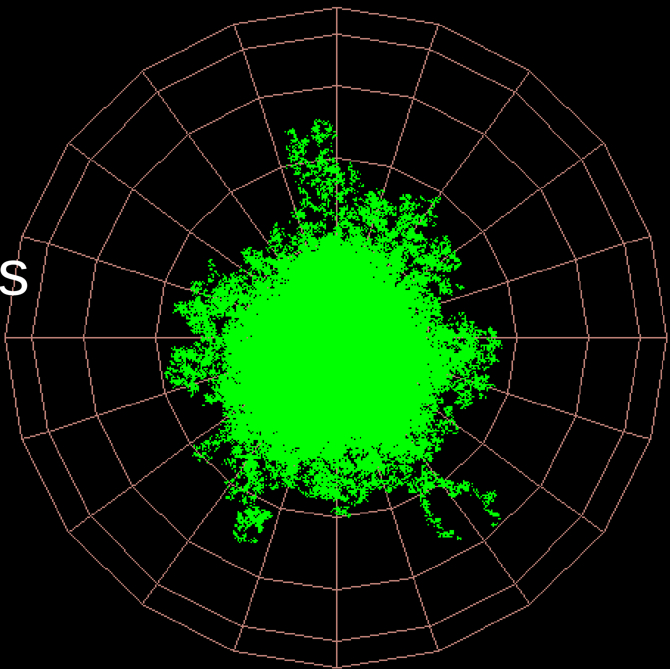
π^- at 50 GeV
in Pb sphere
of 500 cm radius



Fluka



Geant3



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 Details

- 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 with single 40 GeV e^-

→ raw E_C and E_S

2. Calibrate with single 40 GeV π^-

→ η_C and η_S

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Reconstructed energy

Once HCAL calibrated, calorimeter energy:

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

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

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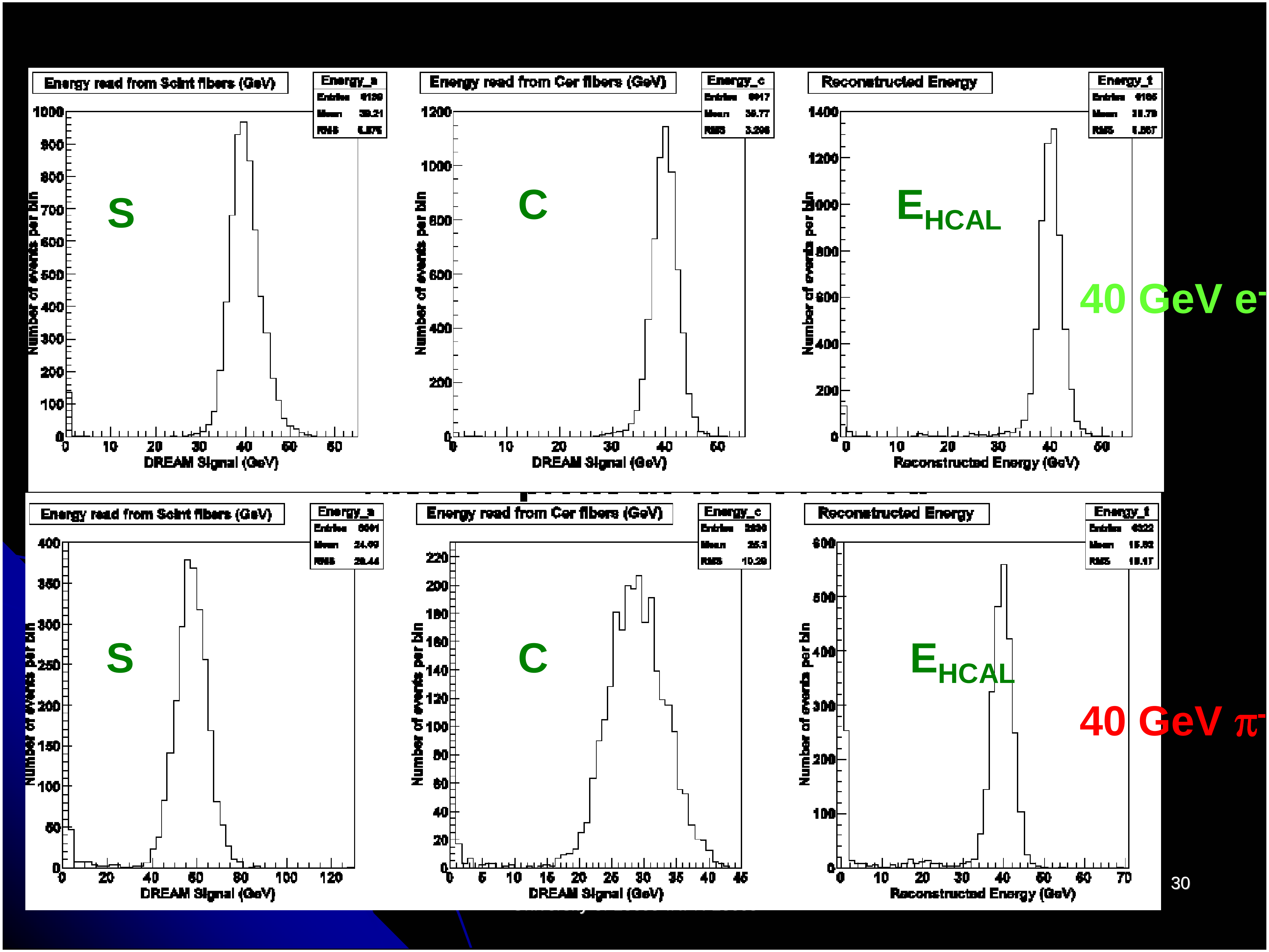
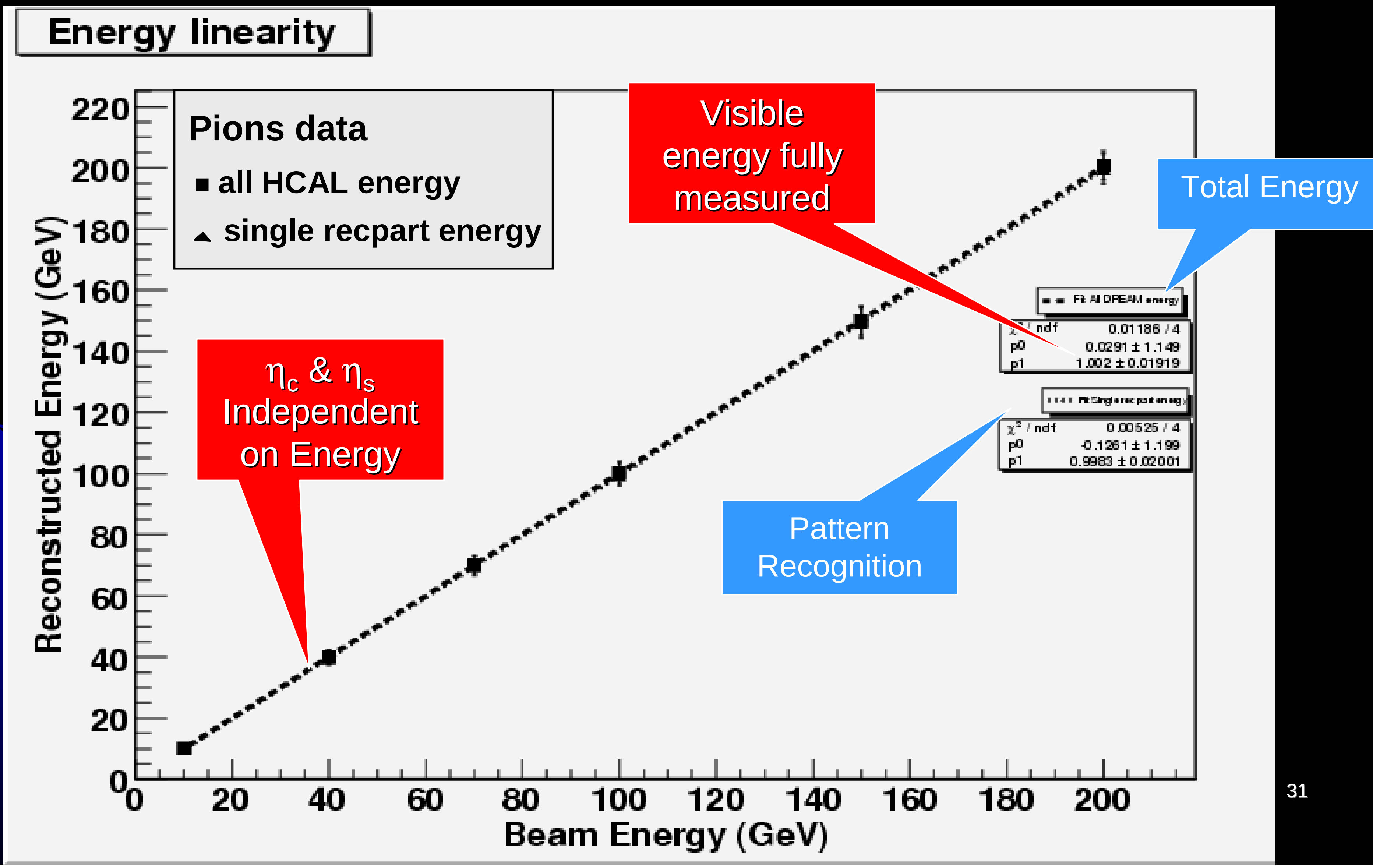
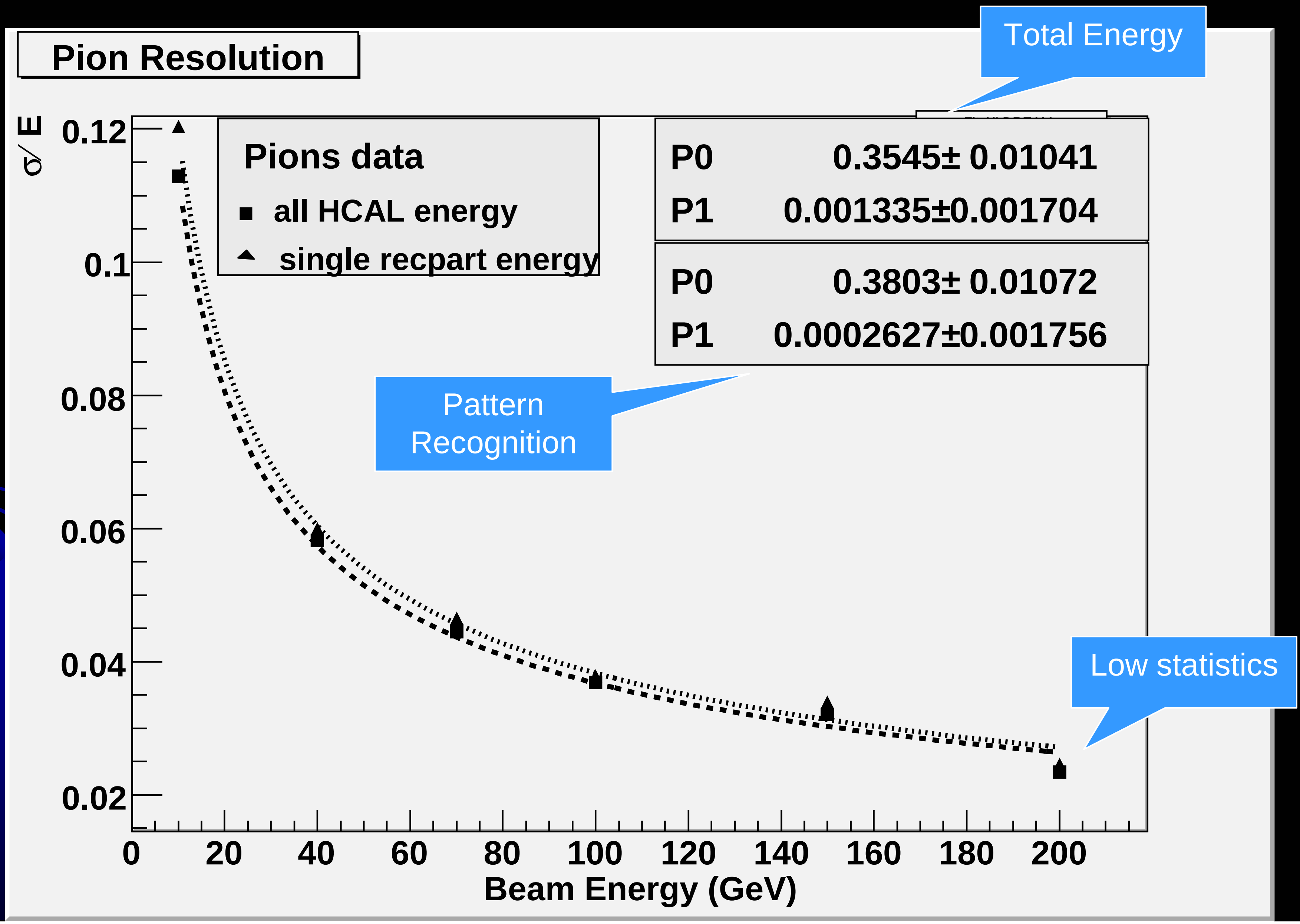

Energy read from Scint fibers (GeV)
Energy read from Cer fibers (GeV)
Reconstructed Energy
Energy_s
Energy_c
Energy_t
Entries
Mean
RMS
Number of events per bin
DREAM Signal (GeV)
Reconstructed Energy (GeV)
S
C
E_HCAL
40 GeV e-
40 GeV π-

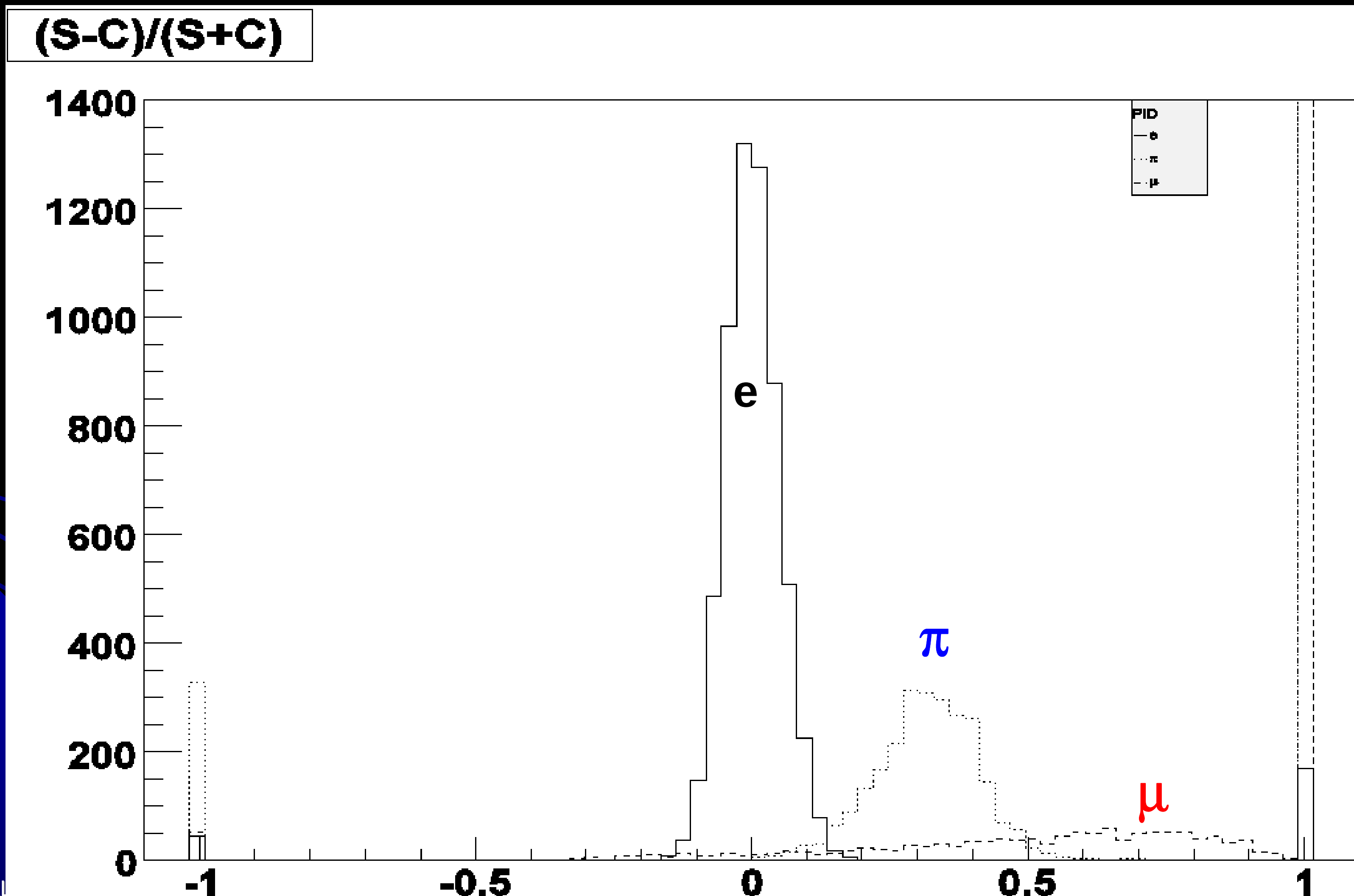
Reconstructed vs Beam Energy



Resolution for hadrons



Pid identification



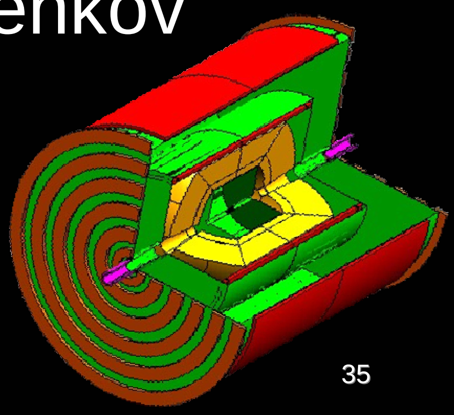
Jets Studies

- Detectors design of the 4th Concept
- Simulation, Reconstruction and Analysis in IlcRoot framework
- Data production on the GRID at FNAL and ilcsim and the farm in Lecce

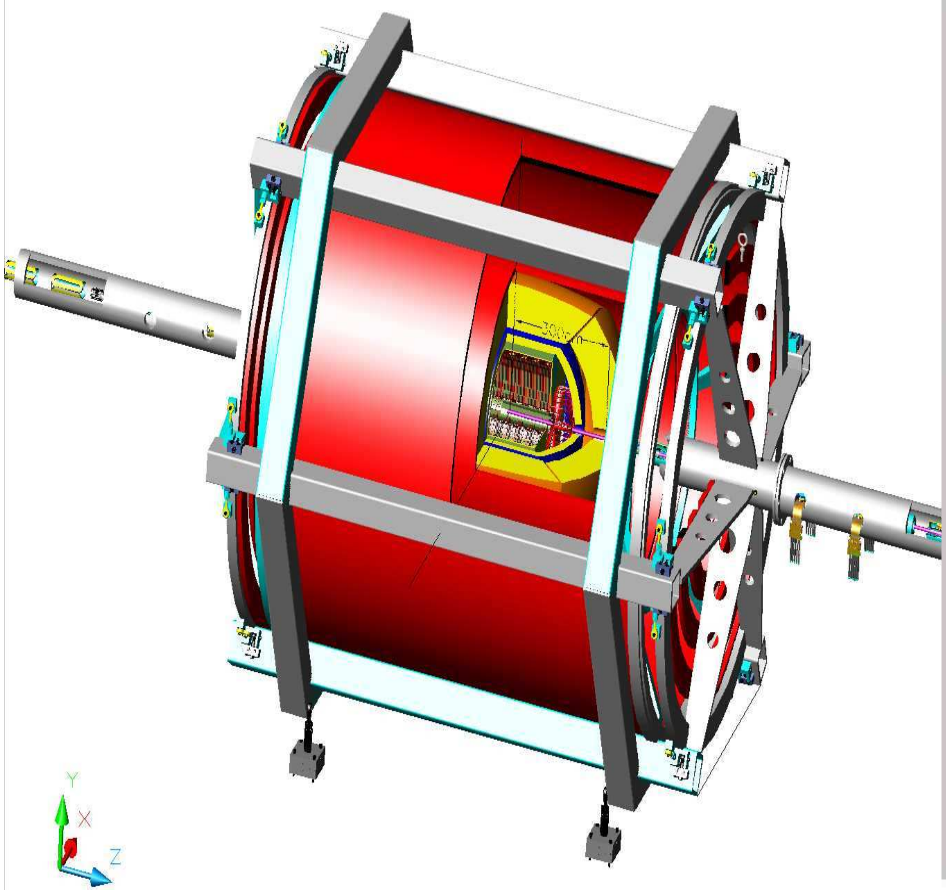
Fourth Concept Detector (“4th”)

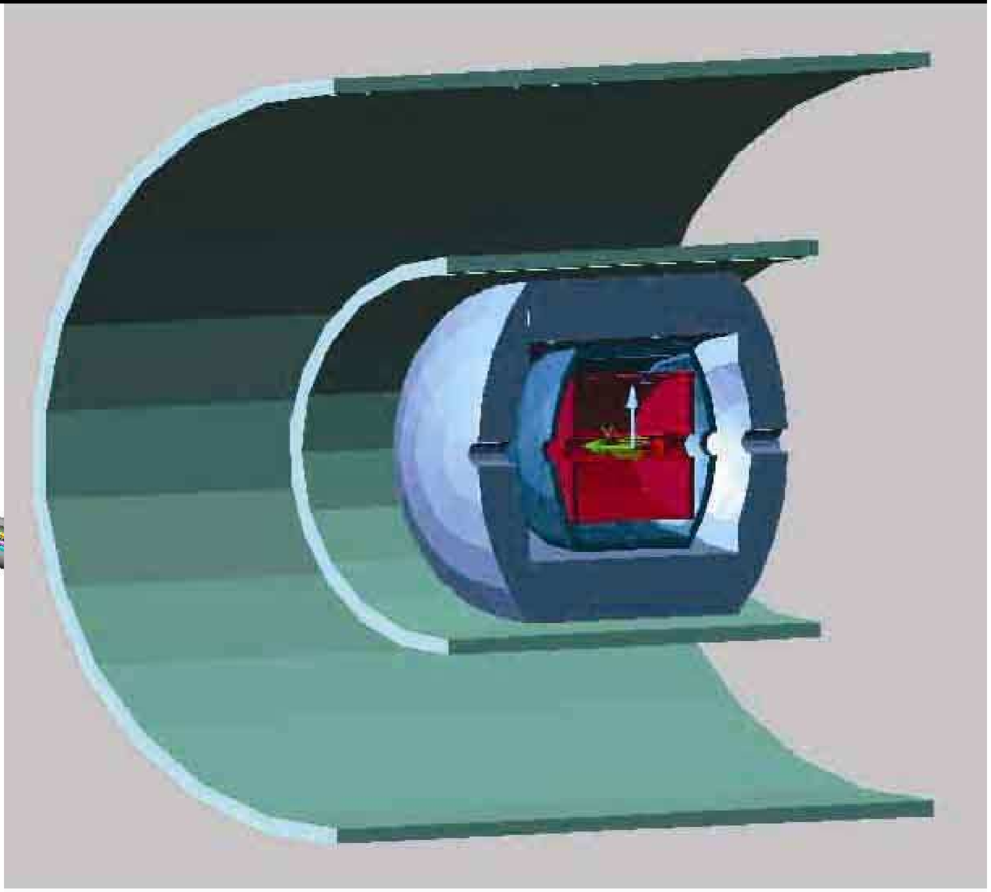
Basic conceptual design: 4 subsystems

- Vertex Detector 20-micron pixels (SiD design)
- Central tracker under evaluation
  (TPC for the present studies)
- Dual-readout ECAL (not present in these studies)
- Dual-readout fiber HCAL: scintillation/Čerenkov
- Muon dual-solenoid spectrometer



Detector layout





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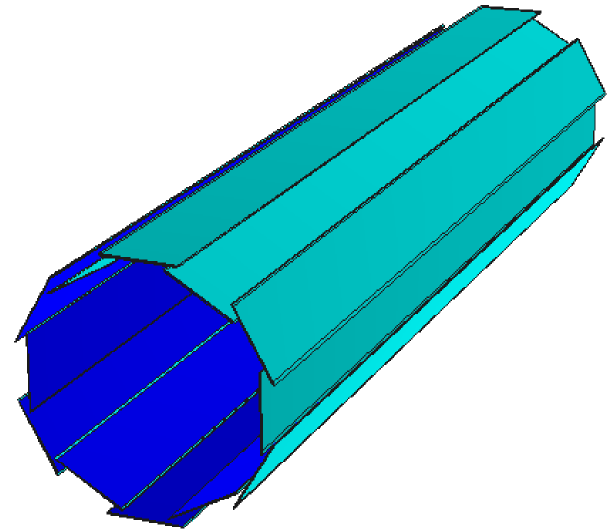
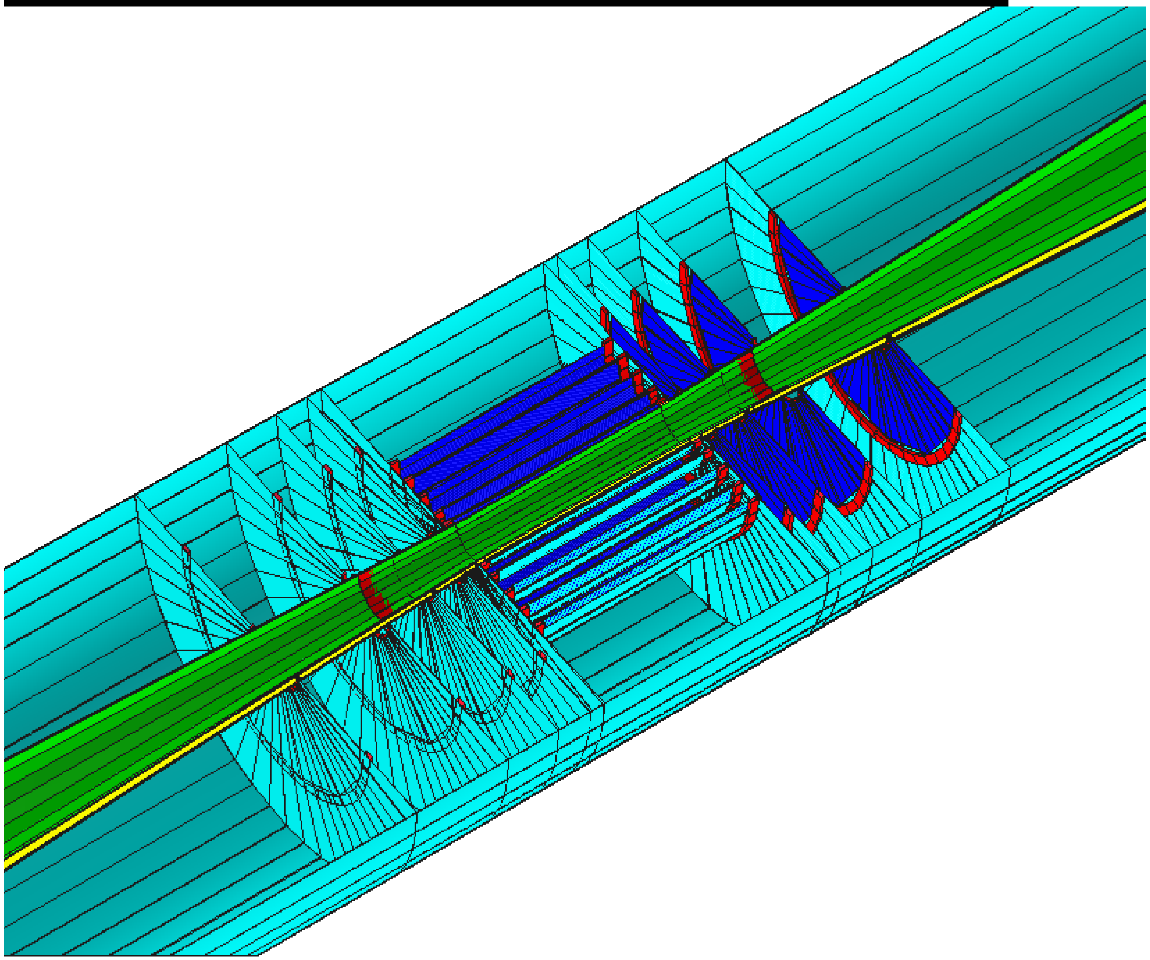
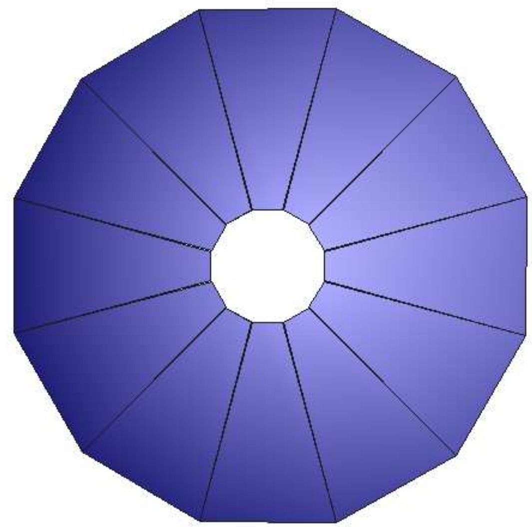
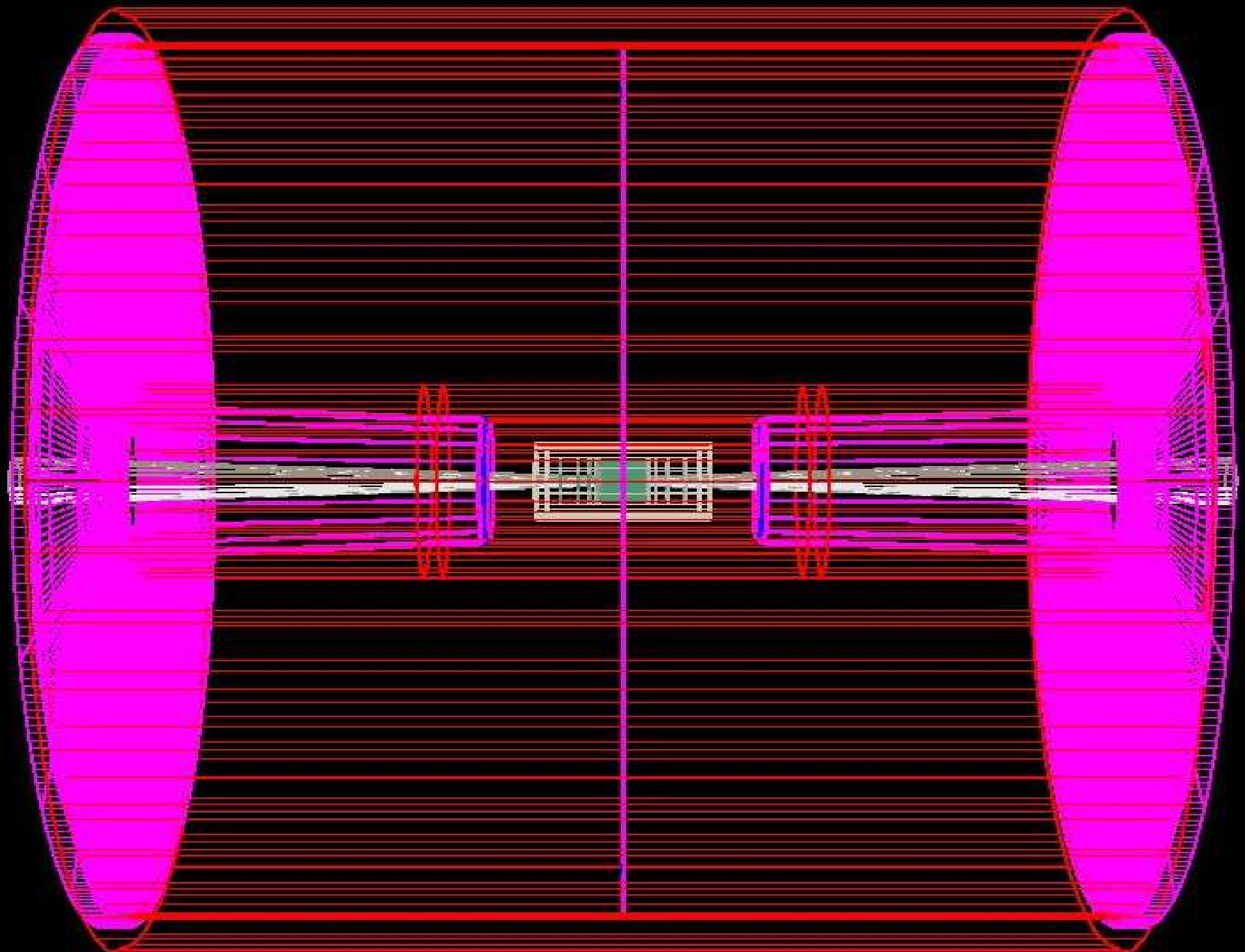
SiD/4th VXD







TPC

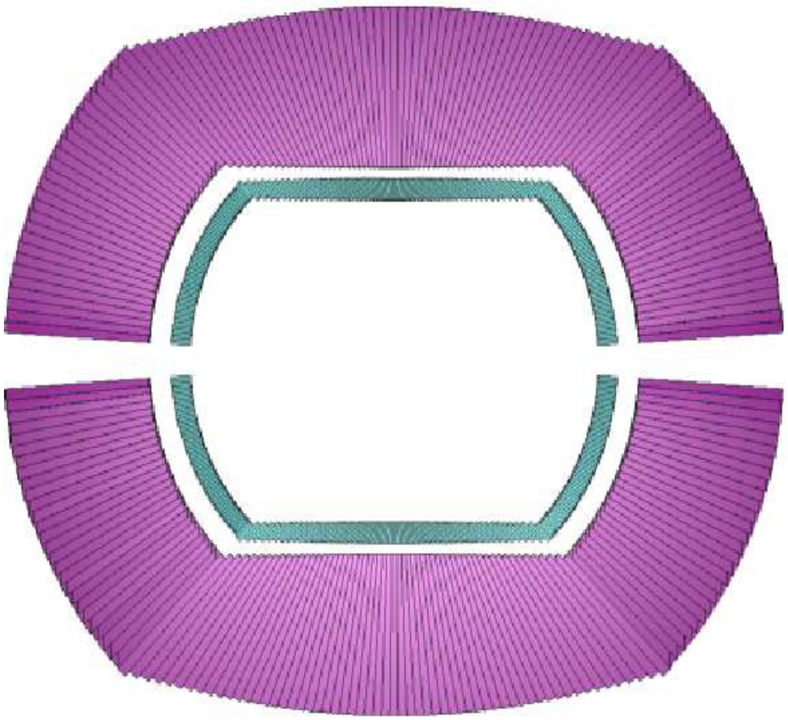


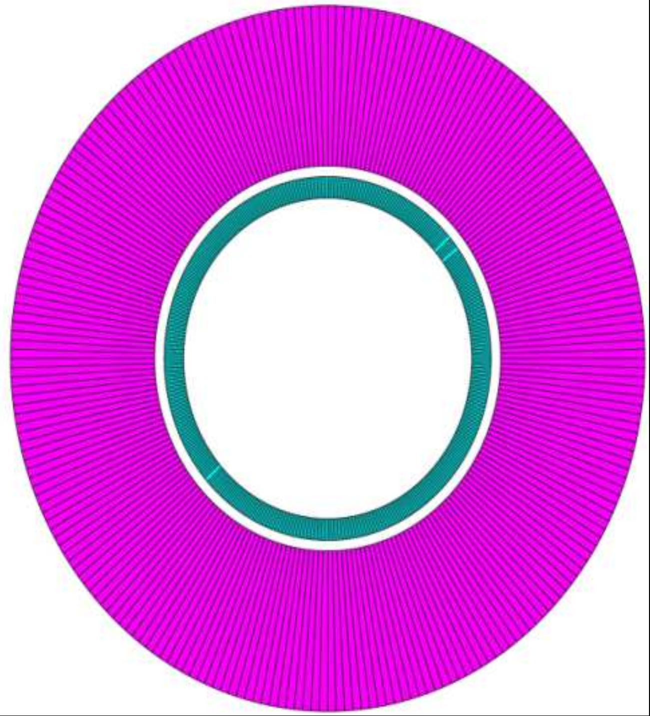
Simulation Details

- Gas: Ar-CF4: 97-3
- Alice's vessel scaled down
  - Inner Radius: 0.20 m
    Outer Radius: 1.50 m
    Half Length : 1.50 m
  - Active readout region: 25 cm – 137cm (145 cm for DCR)

- All passive material included in geometry
  - Cage
  - Endcaps
  - Electronics and cables
  - Services
  - Support

- Readout
  - Pad Inner: Width 0.23 cm Length 0.42 cm
    Pad Outer1: Width 0.34 cm Length 0.57 cm
    Pad Outer2: Width 0.34 cm Length 0.85 cm
  - 5 MuMega rows
  - 512 pixels with 55 μm x 55 μm
  - Cluster statistics included (30/cm)
  - ε = 90%/electron

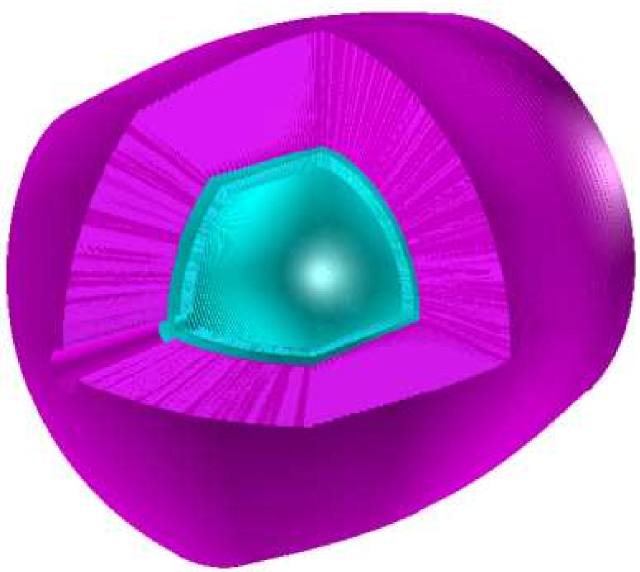


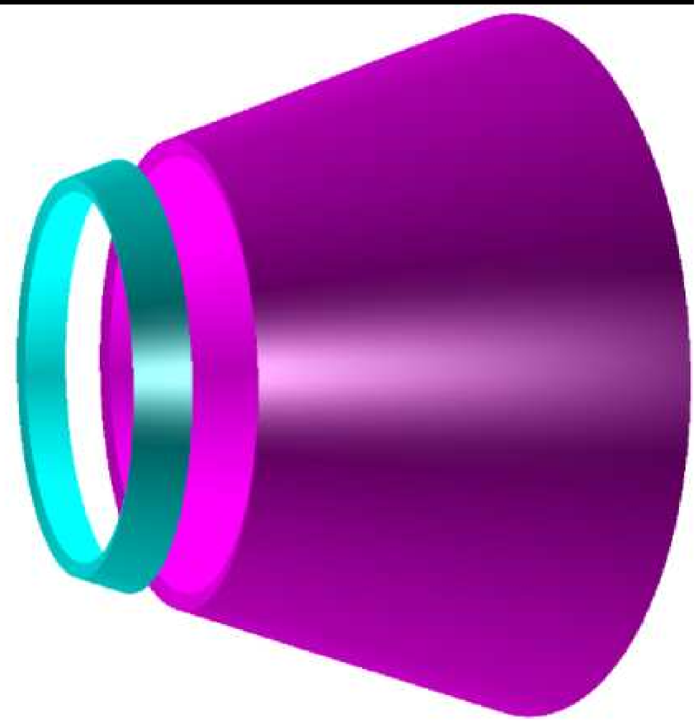


ECAL

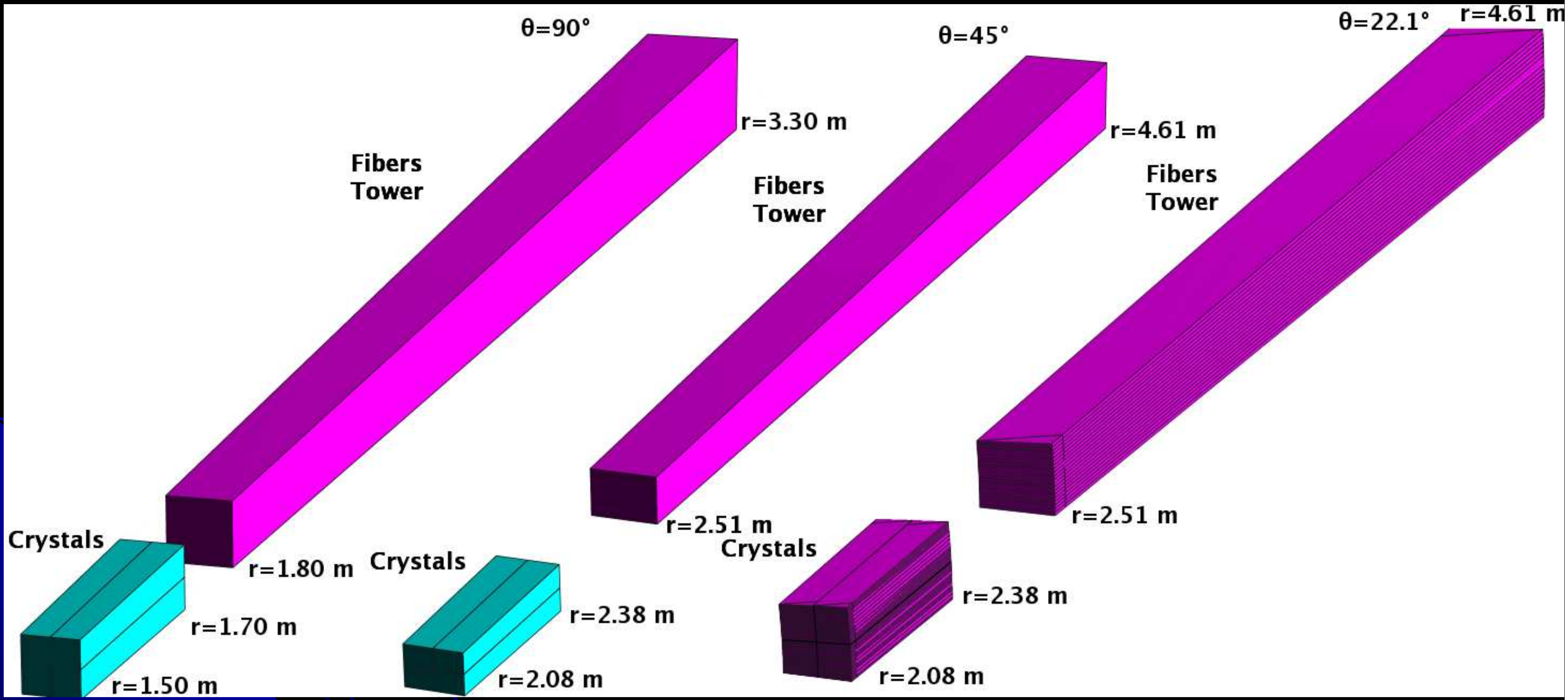
+

HCAL





ECAL+HCAL Cells (first version)



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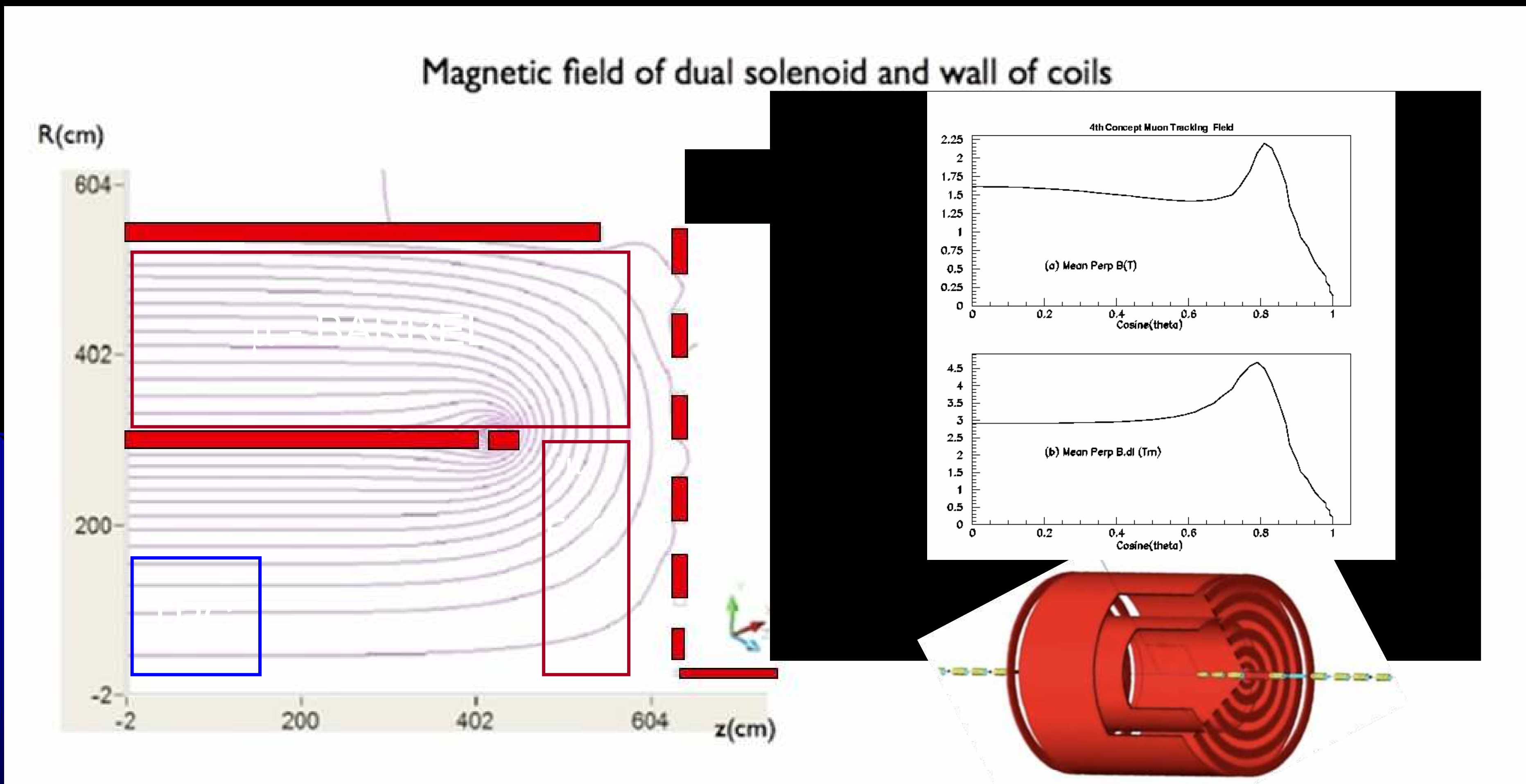
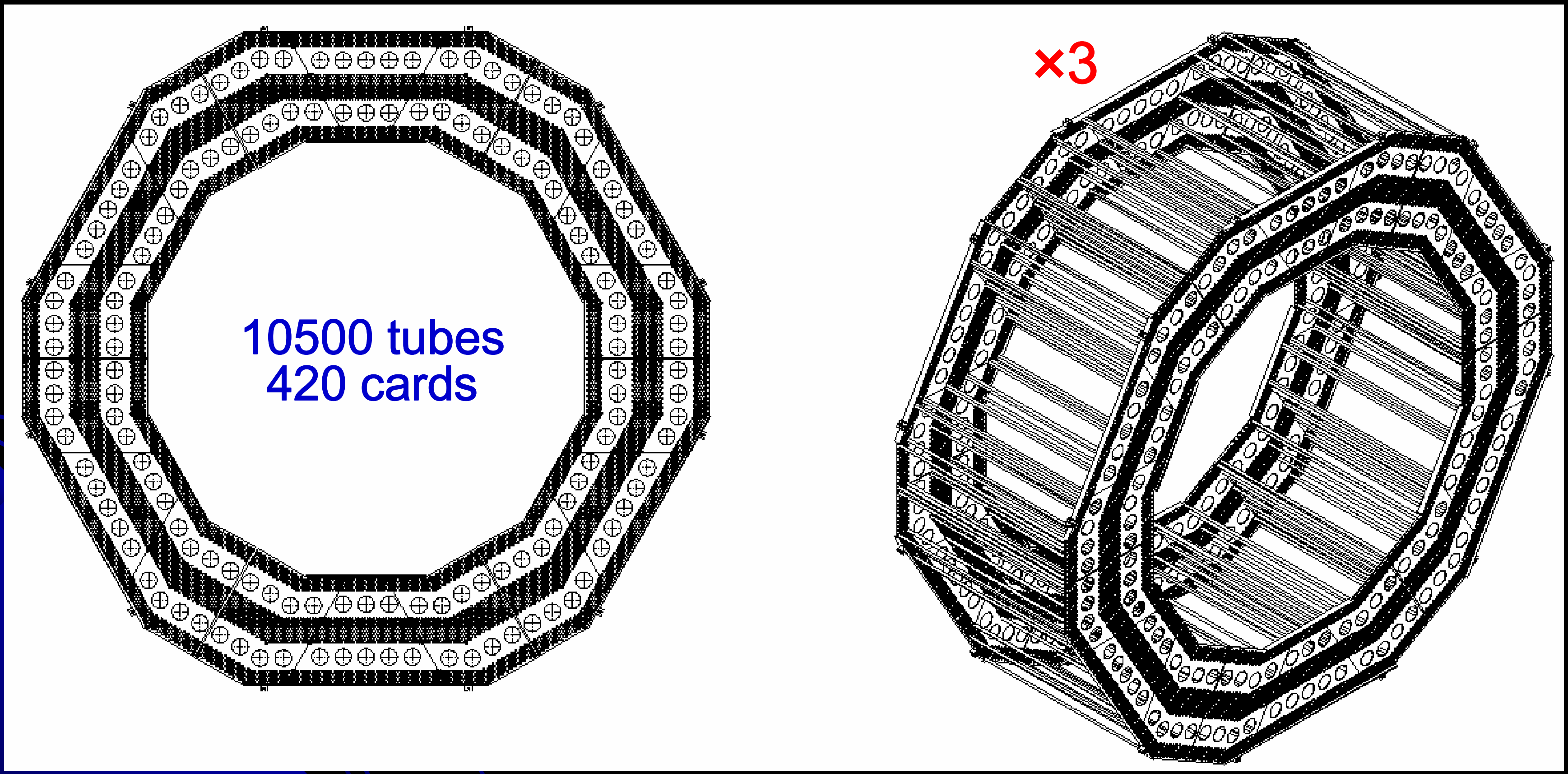
ECAL Layout

- 25 cm PbF_2 with PbF2 0.15% Gd doping
- ~ 1.25 λ
- ~ 27.7 X/X_o
- Fully projective geometry
- ~1.5° aperture angle
- Azimuth coverage down to 3.4°
- Barrel: 55696 cells (944slices containing 236 cells)
- Endcaps: 12656 cells arranged in 108 rings

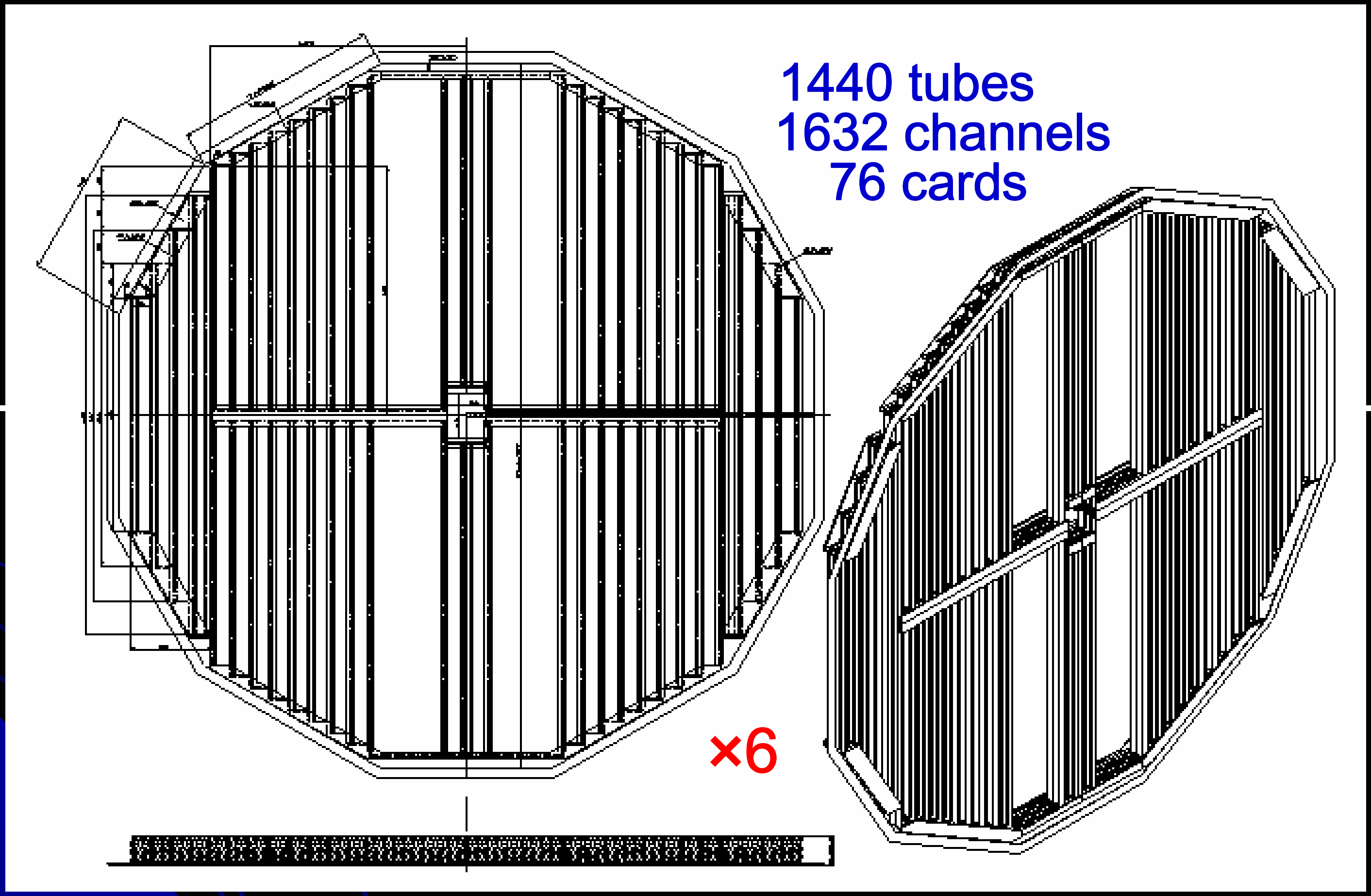
Dual Solenoid B-field



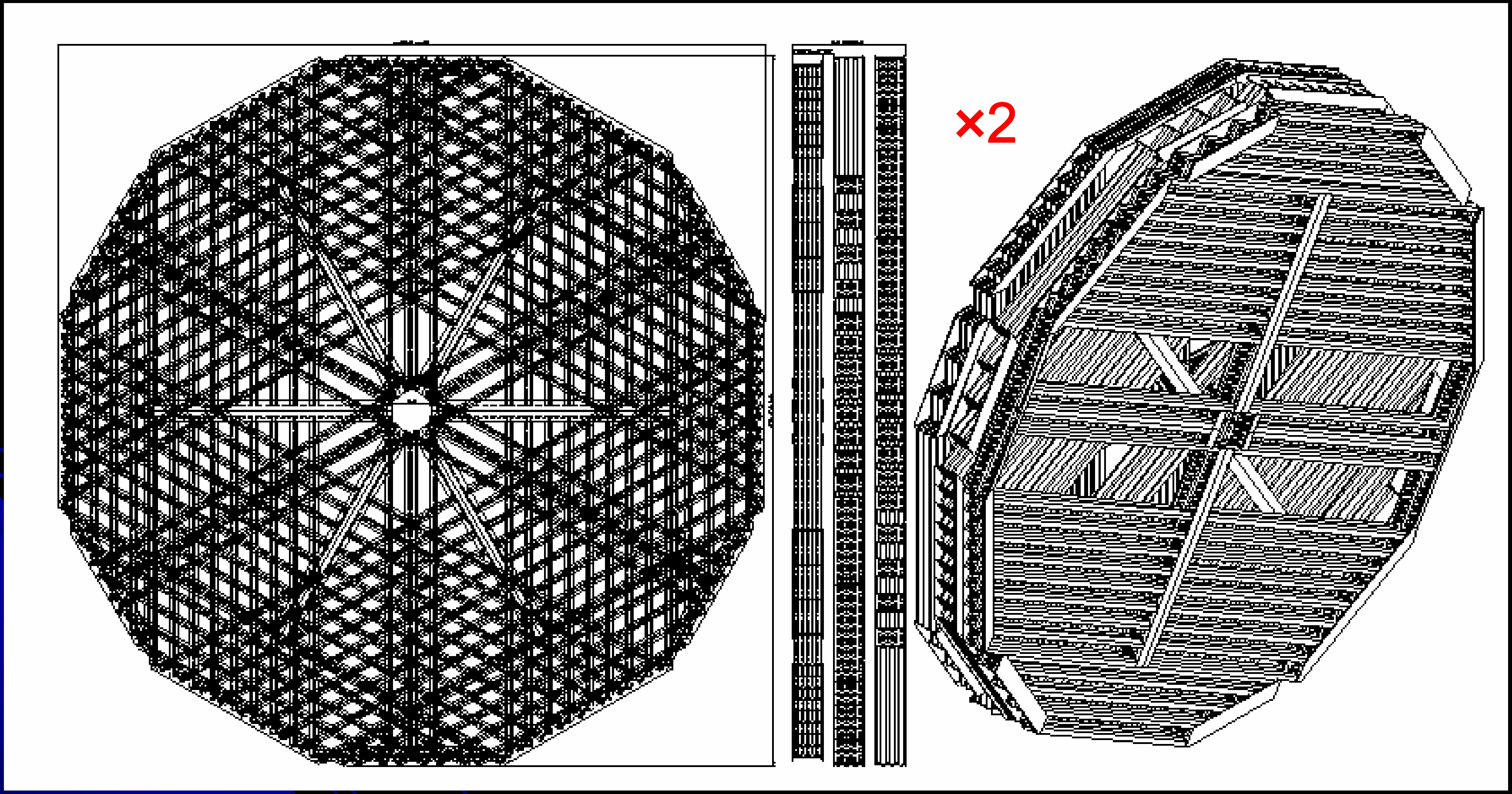
MUD Barrel



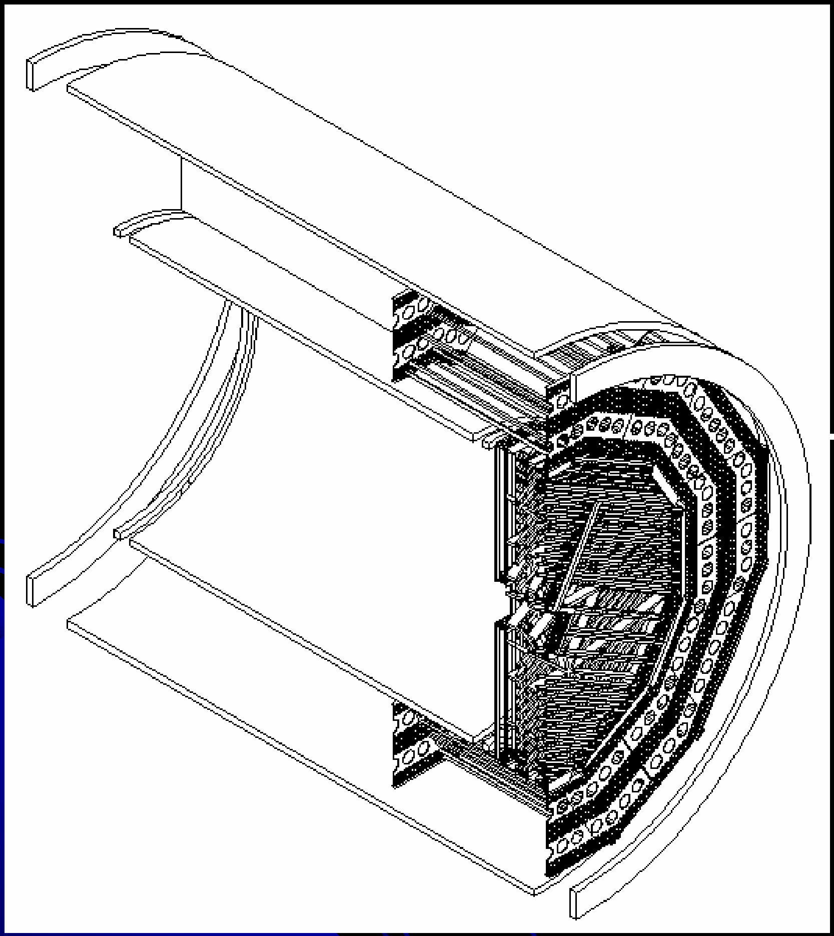
MUD Endcaps



MUD Endcap



Channel Count



Barrel:
- 31500 tubes
- 21000 channels
- 840 cards

End caps:
- 8640 tubes
- 9792 channels
- 456 cards

Total:
- 40140 tubes
- 30792 channels
- 1296 cards

IlcRoot Framework

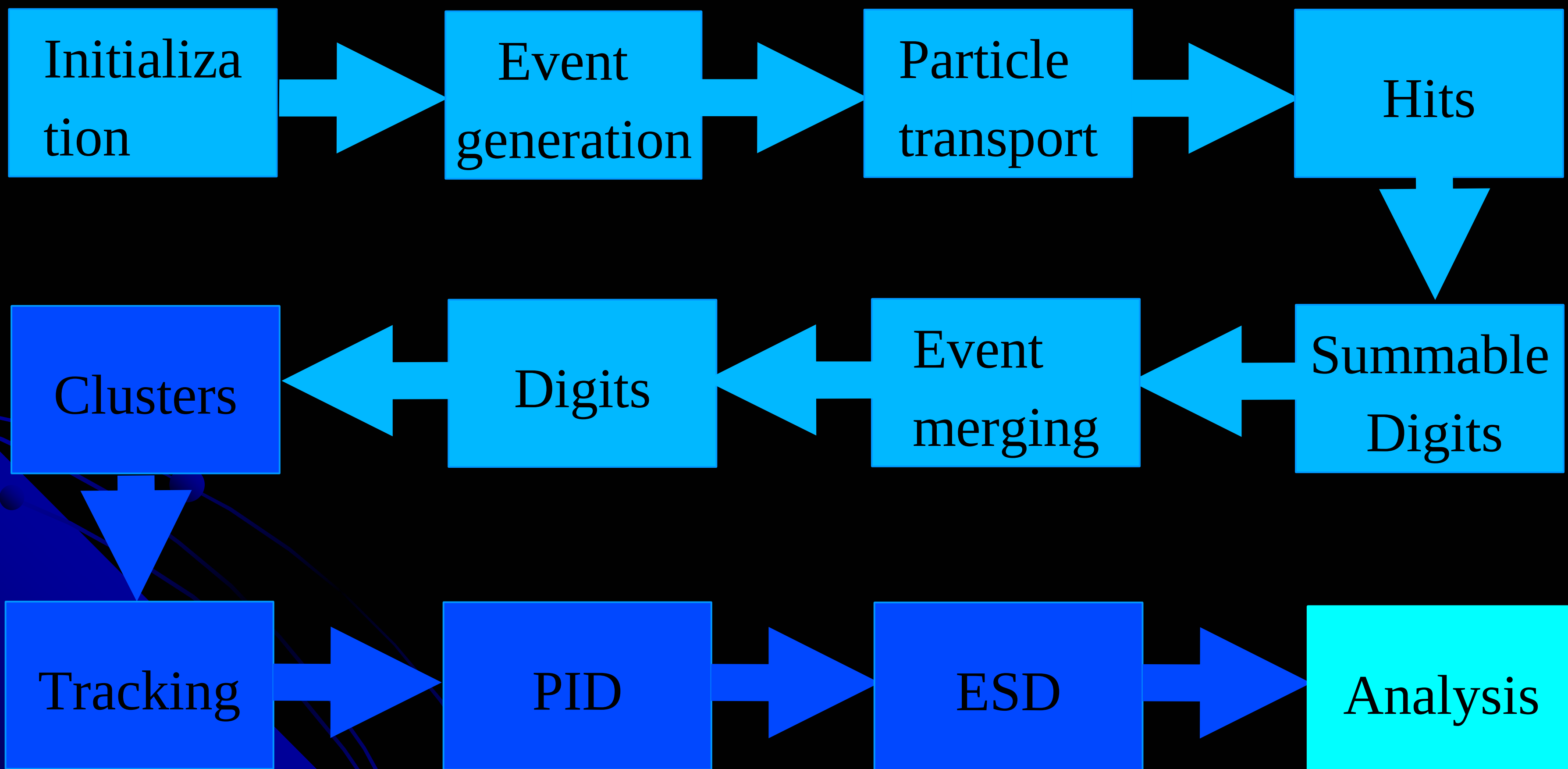
- CERN architecture (based on Aliroot)
- Uses ROOT as infrastructure
  - All ROOT tools are available (I/O, graphics, PROOF, data structure, etc)
  - Extremely large community of users/developers
- Six MDC have proven robustness, reliability and portability
- Single framework, from generation to reconstruction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

cvs -d :pserver:anonymous@cdcvs.fnal.gov:/cvs/ilcroot co

For the installation, see:

http://www.fisica.unile.it/~danieleb/IlcRoot

ILCRoot flow control



Data Simulation

- Pandora-Pythia to generate

  $e^+e^- \rightarrow qq(q=uds)@60,100,140,200,300,500GeV$

- Fluka MC to track particles in the detectors

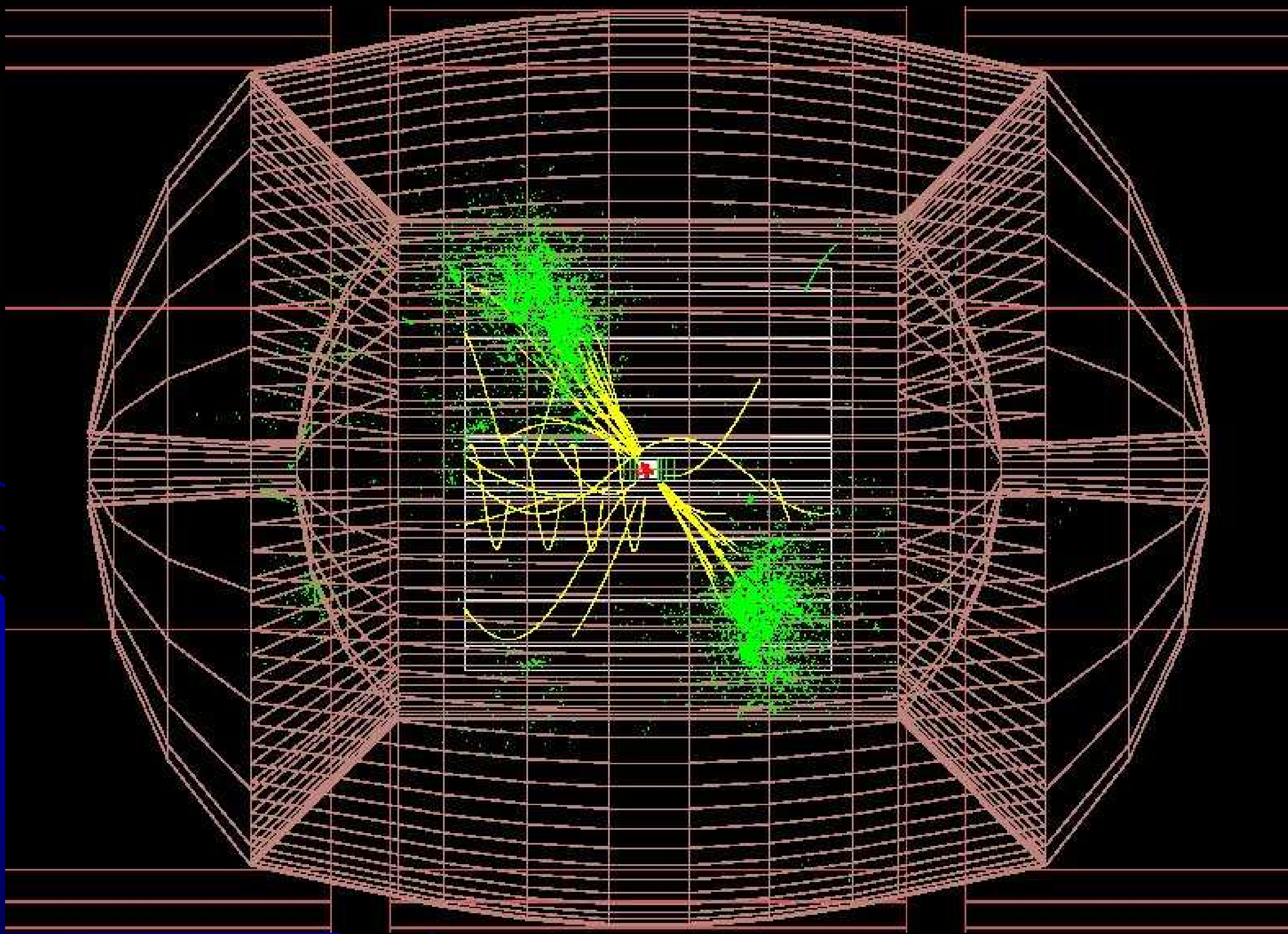
- Full simulation for VXD and HCAL

- Fast recpoints for TPC and MUD (gaussian smearing of hits)

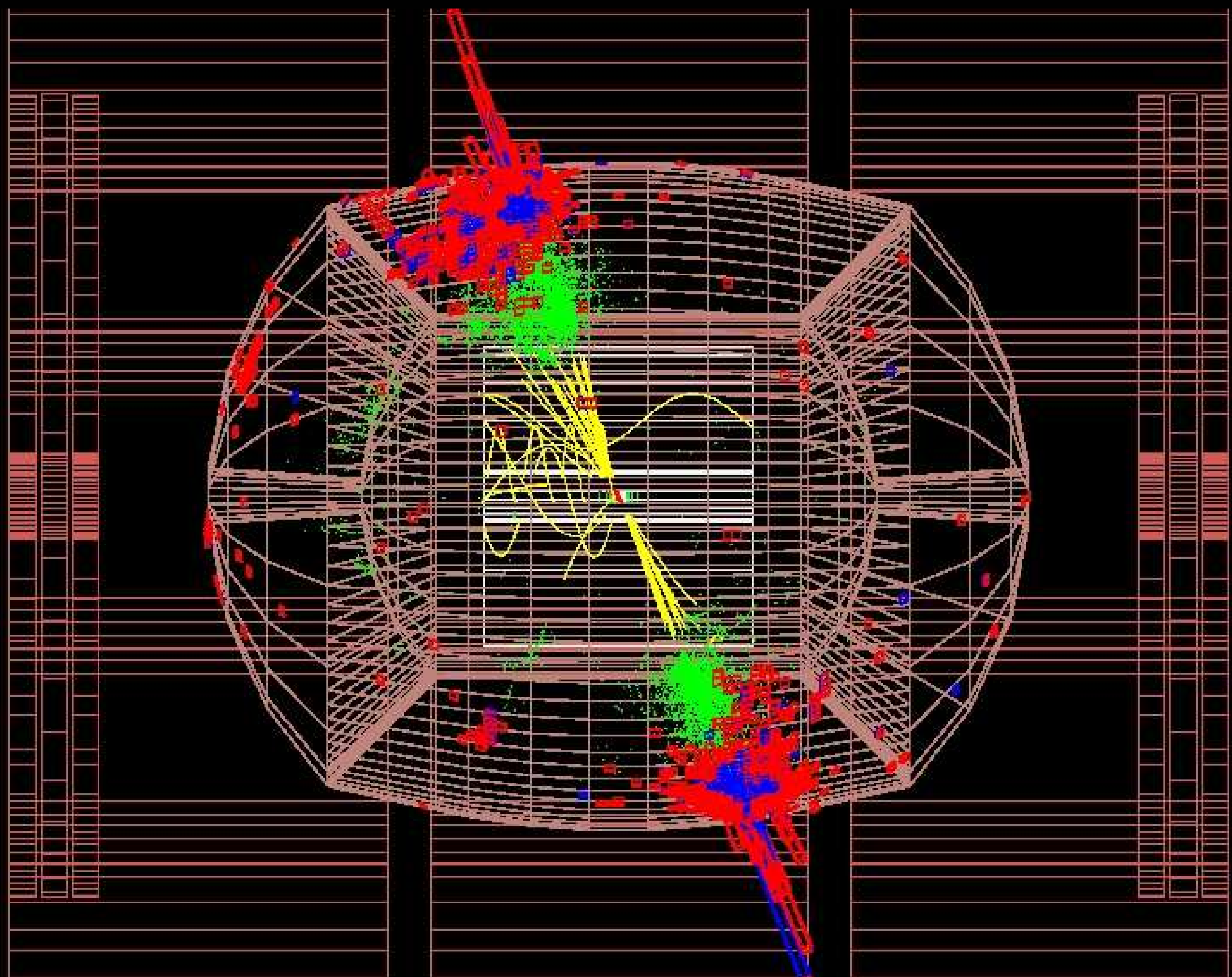
Reconstruction

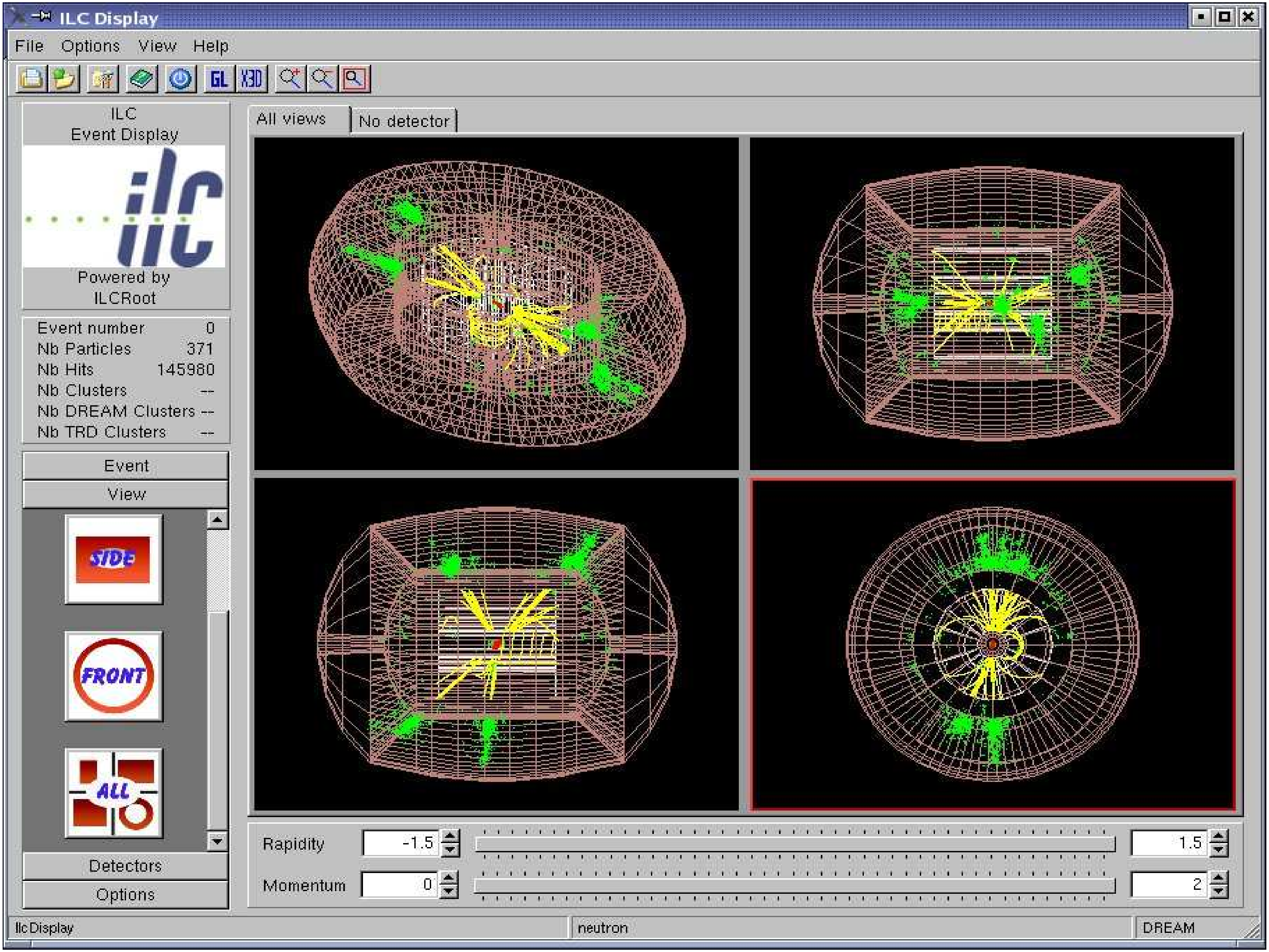
- Reconstruct tracks from the tracking devices (Kalman Filter)
- Build Clusters from cells distant no more than two towers away
- Unfold overlapping clusters through a Minuit fit to cluster shape (still in progress)
- Calibration of HCAL

500 GeV di-jets events



500 GeV dijets events




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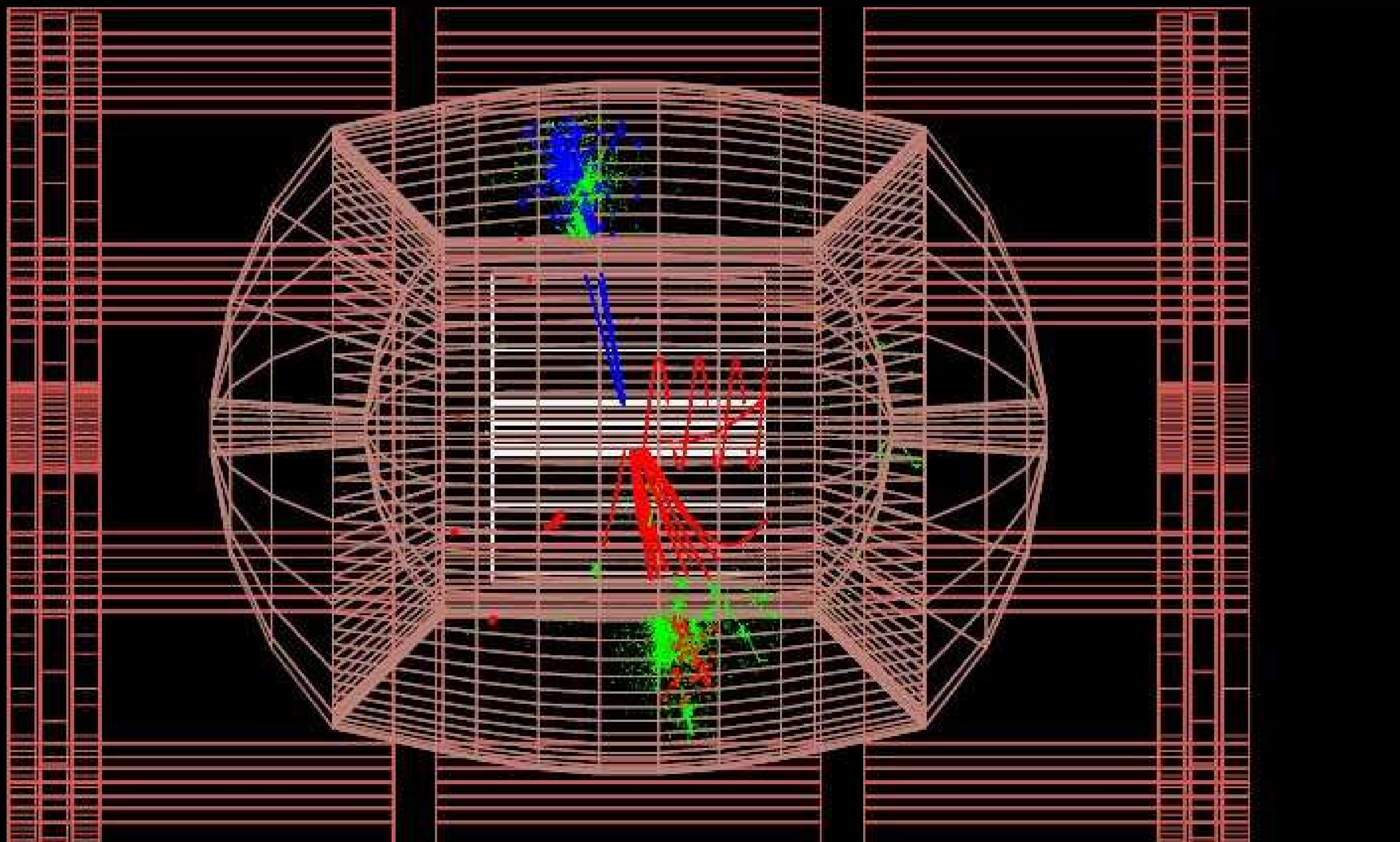
ALL
Detectors
Options
All views
No detector
Rapidity
-1.5
1.5
Momentum
0
2
IlcDisplay
neutron
DREAM

Jets Performance Studies

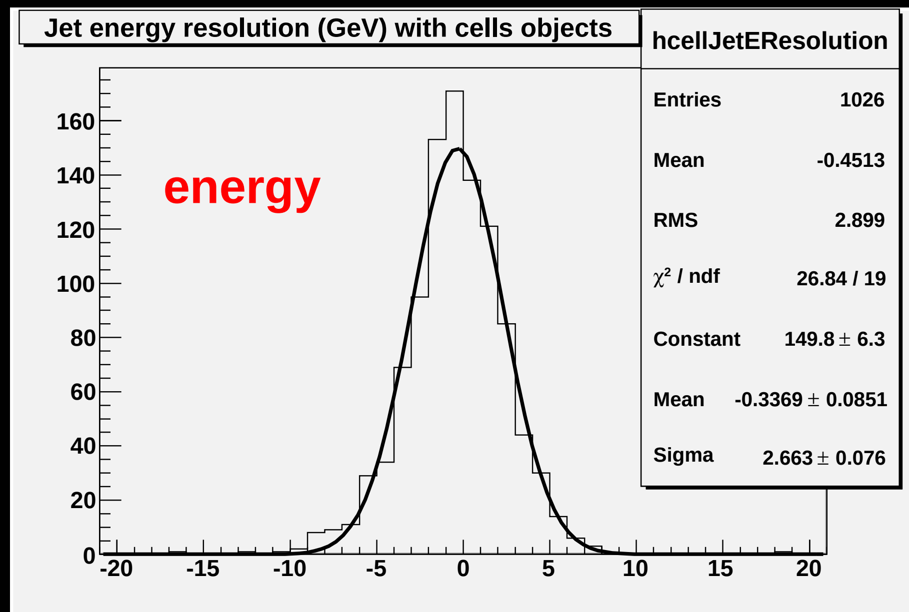
Jets reconstructed with Durham algorithm over calorimeter cells

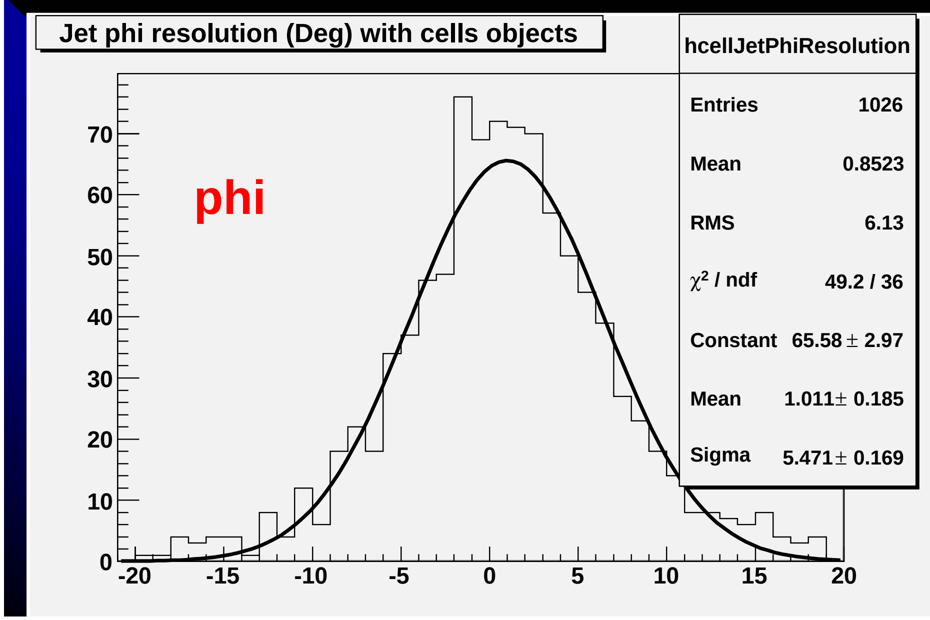
very **preliminary strategy**

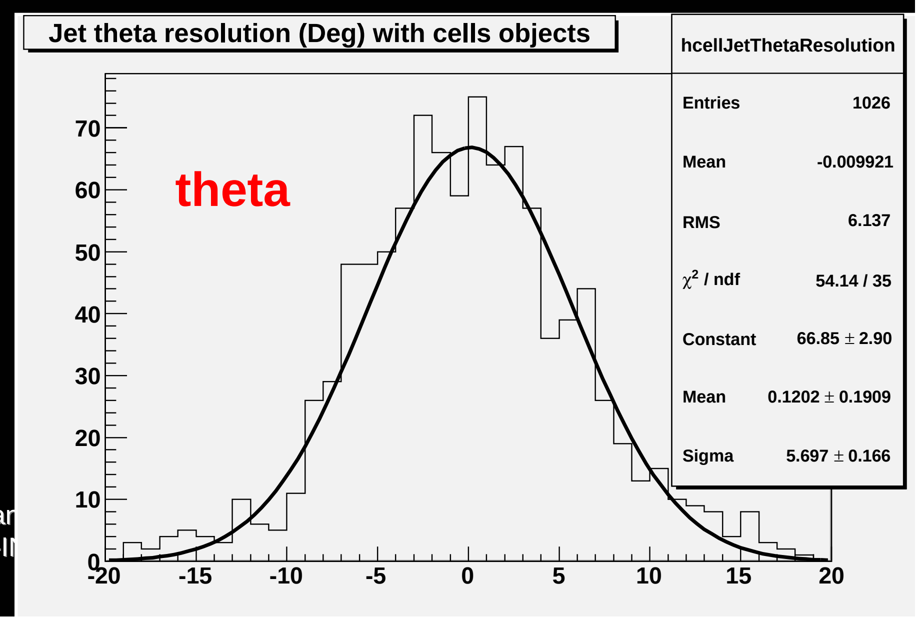
Di-jet event @ 200 GeV



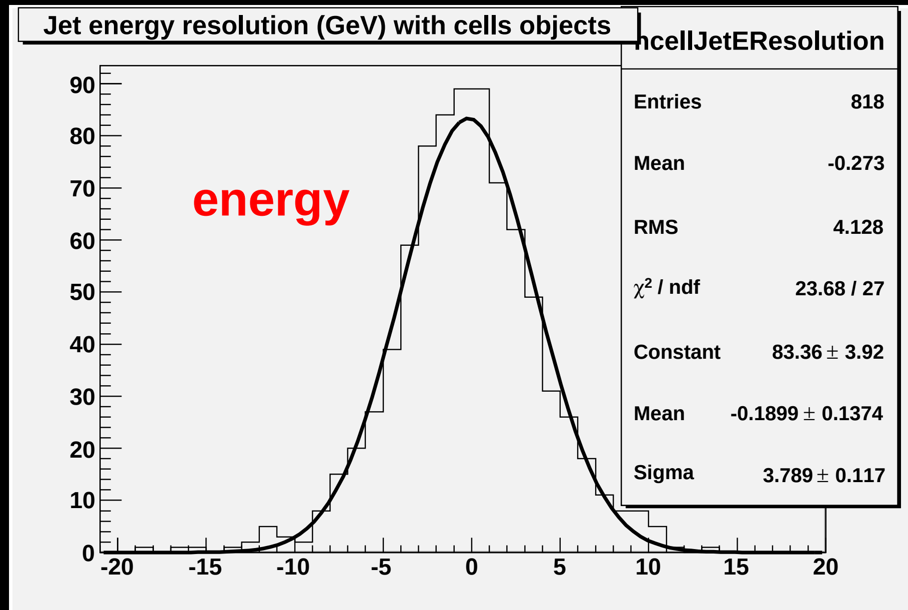
30 GeV Jet Resolutions

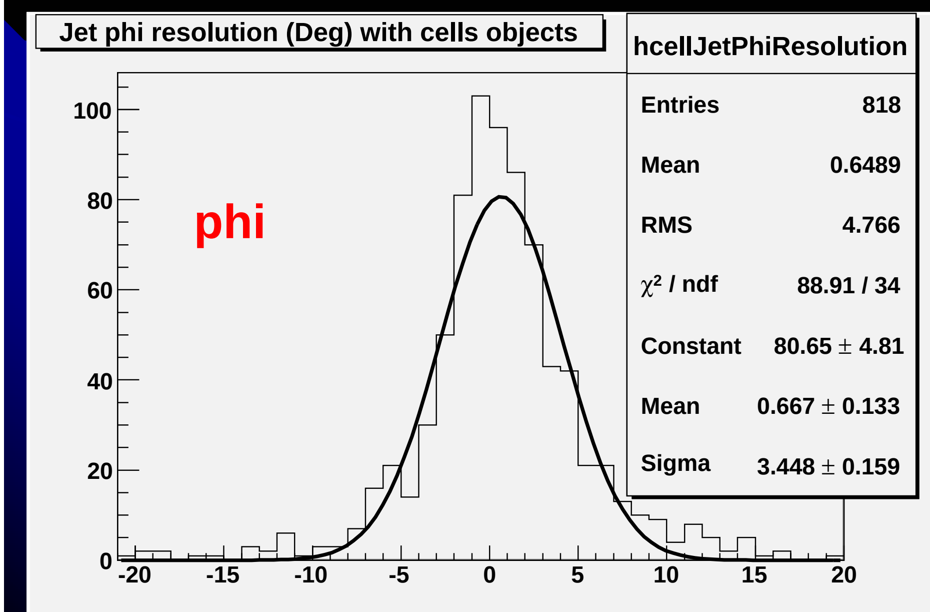


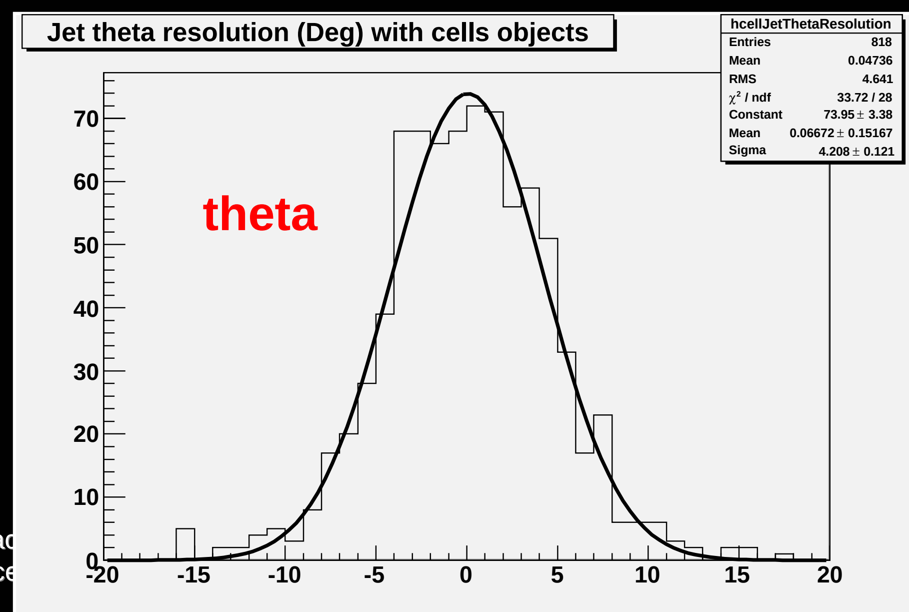




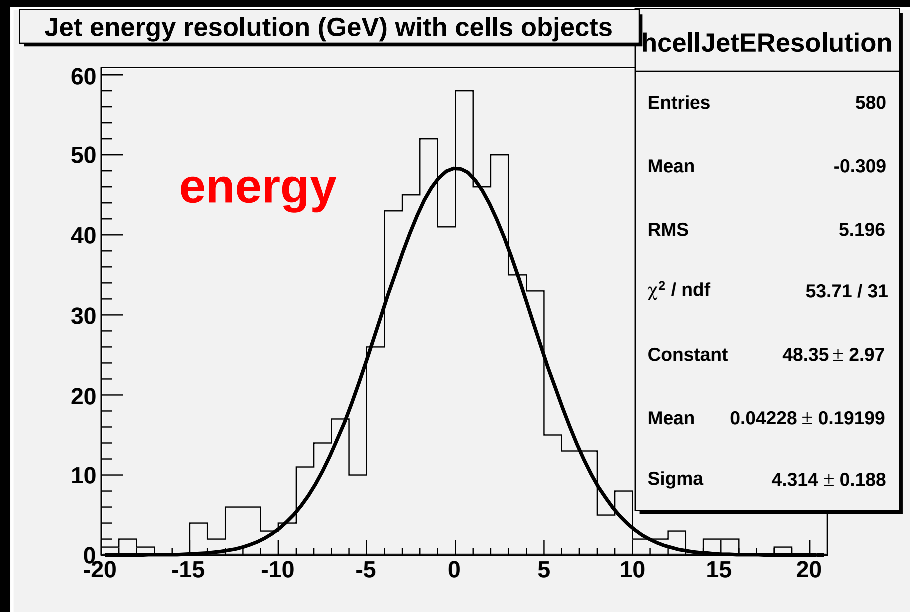
50 GeV Jet Resolutions

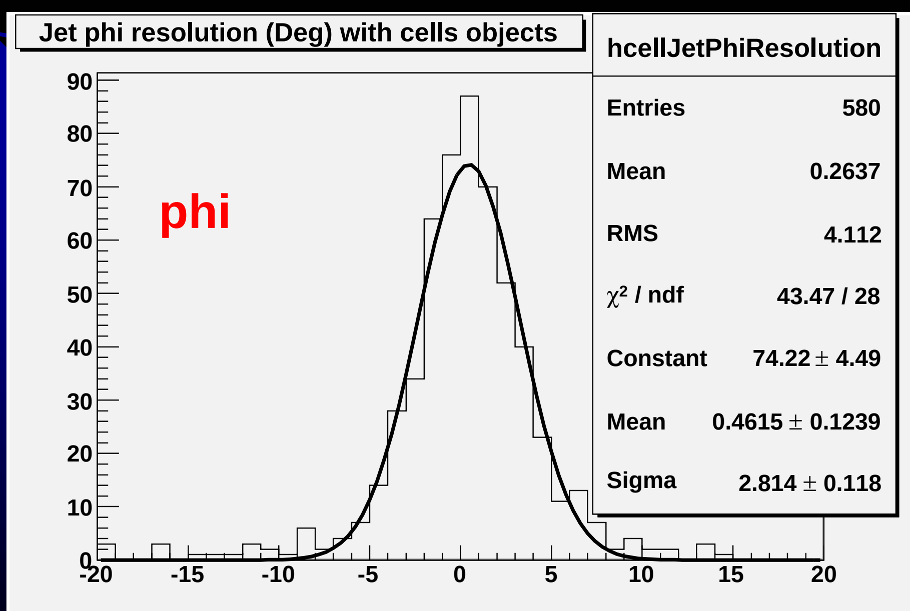


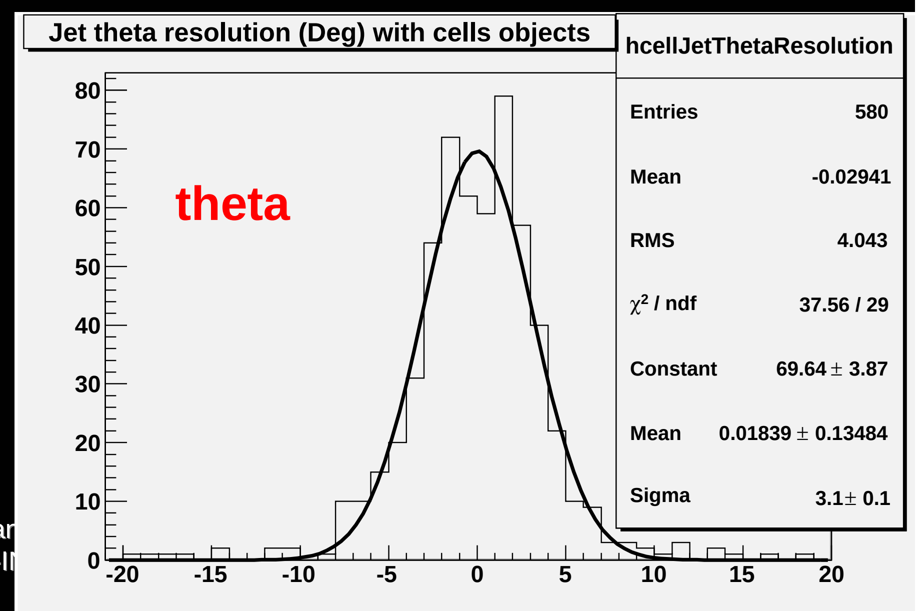




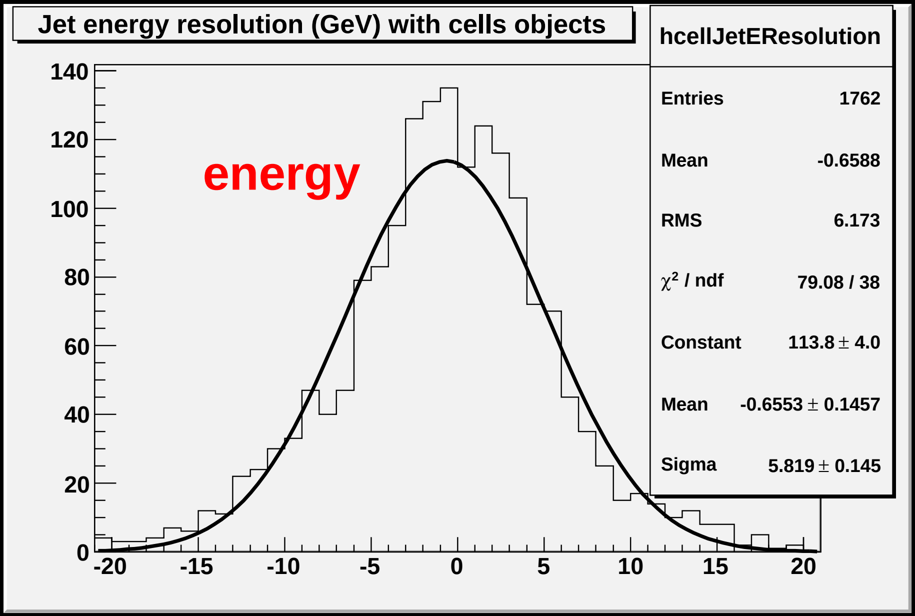
70 GeV Jet Resolutions

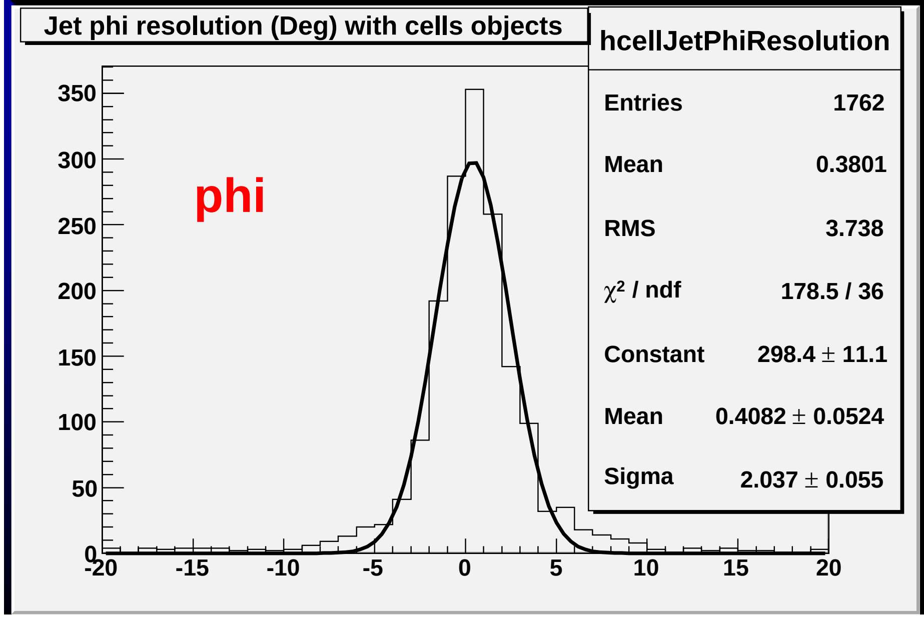


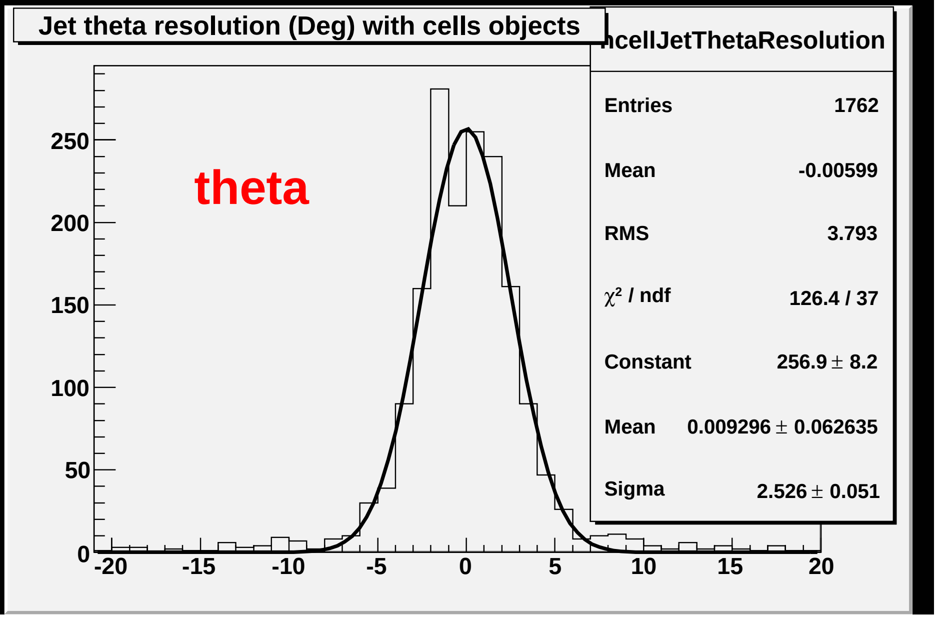




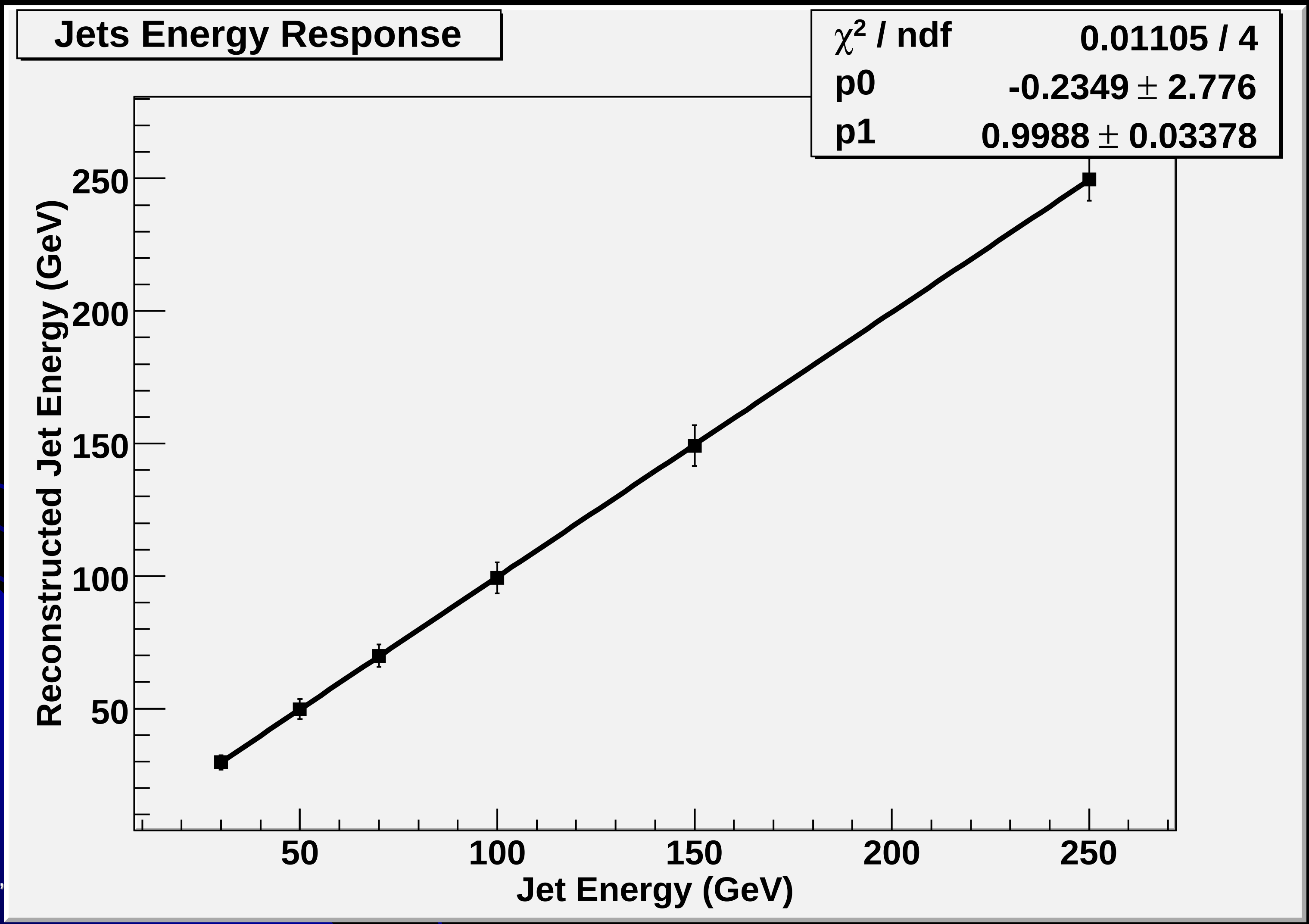
100 GeV Jet Resolutions



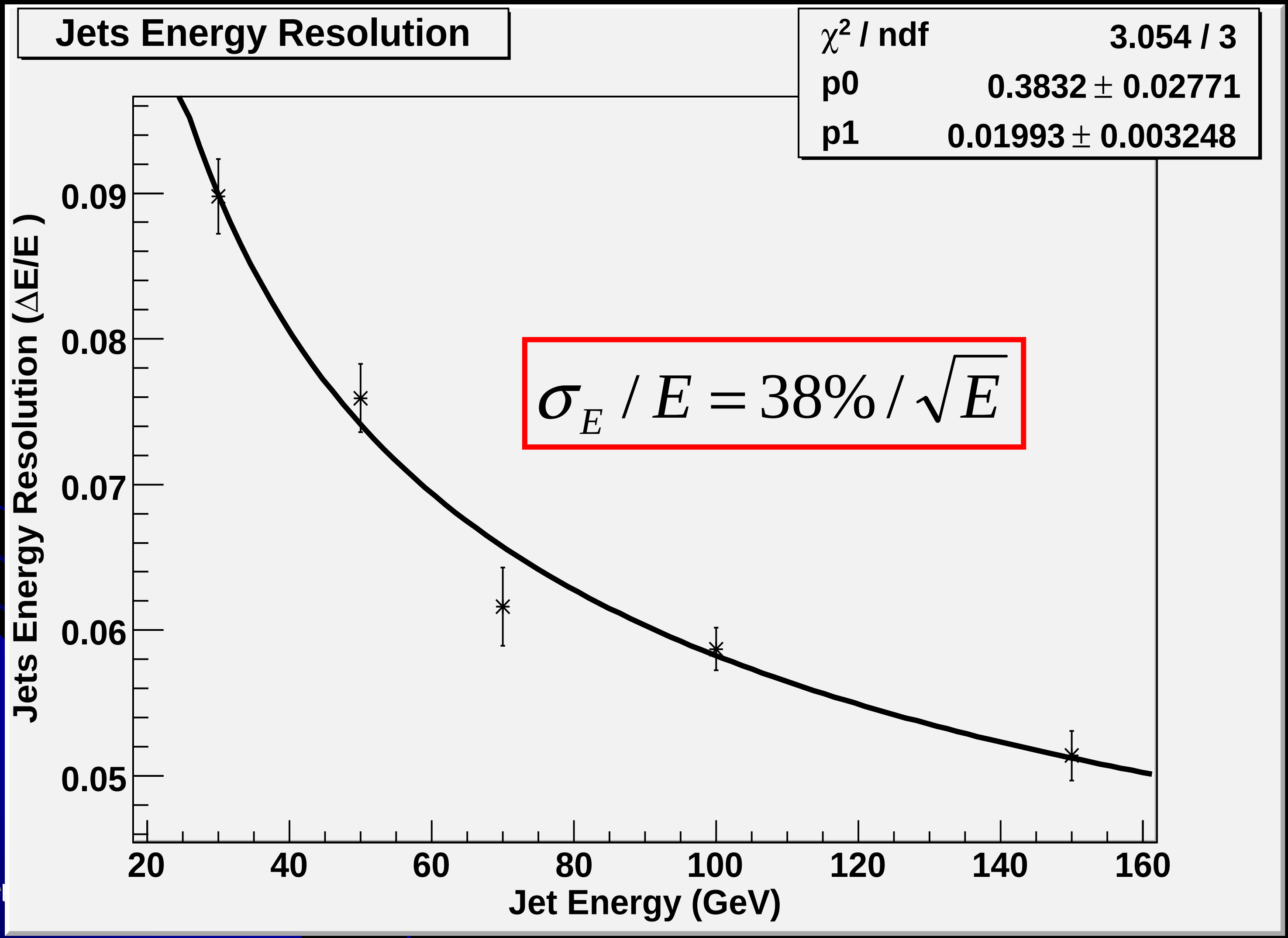




Jet Energy Response



Jet Energy Resolution



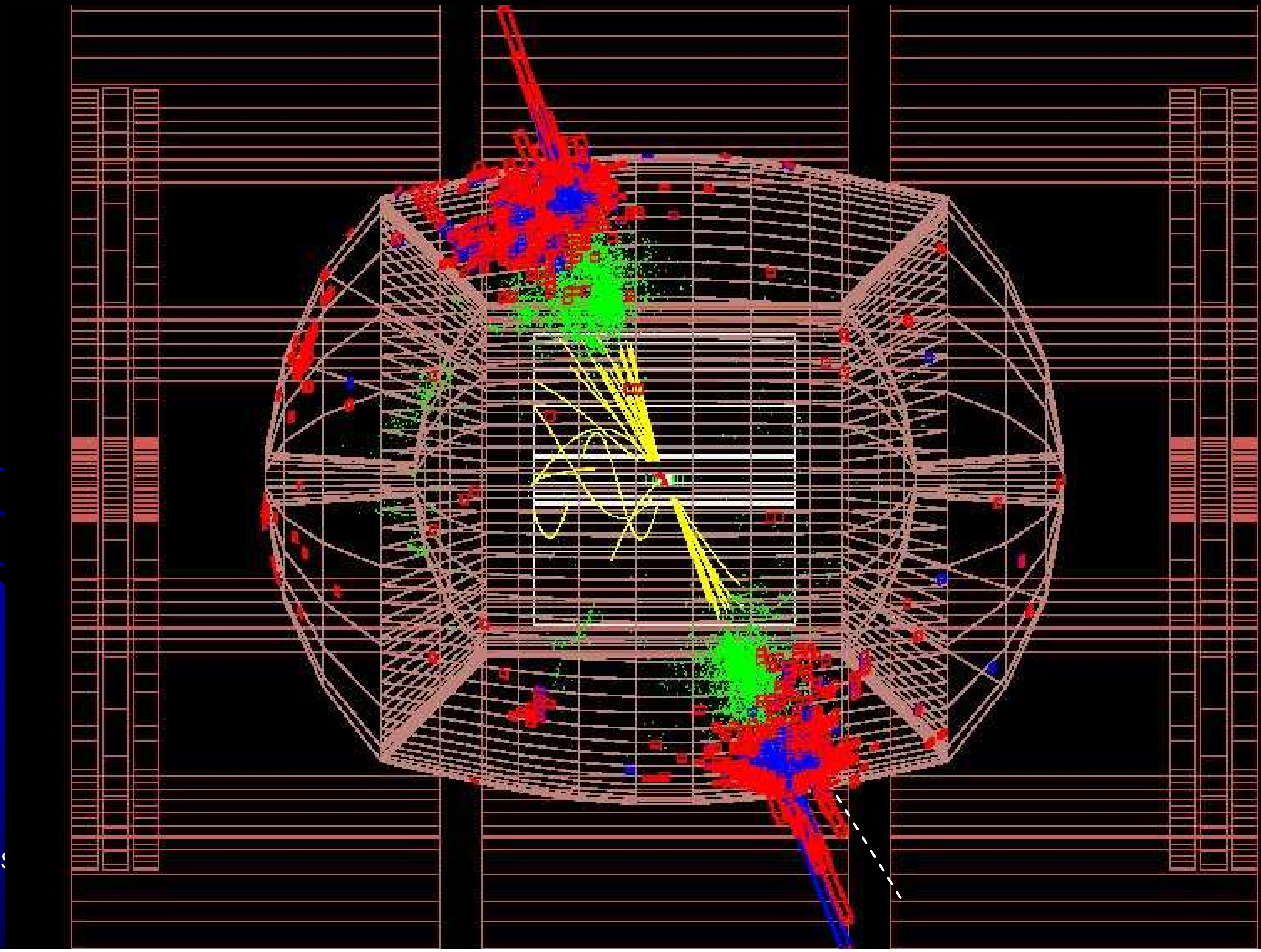
Jet reconstruction strategy

- Jet reconstruction with simple cluster algorithm not satisfactory
- Wrong direction for tracks bending in the central tracker
- Left muon particles leaving the calorimeter and dead tracks in the central tracker

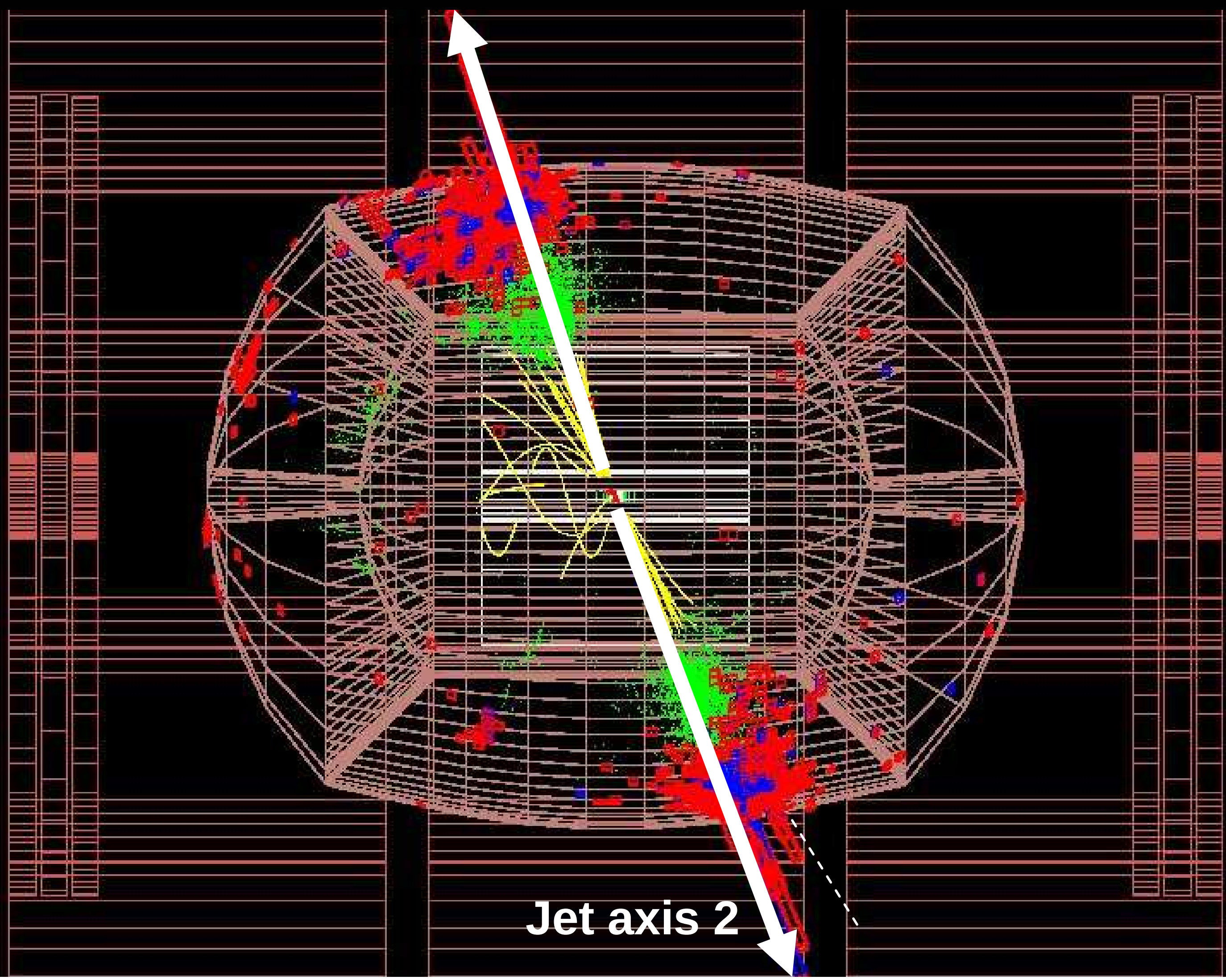
A different strategy

- 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

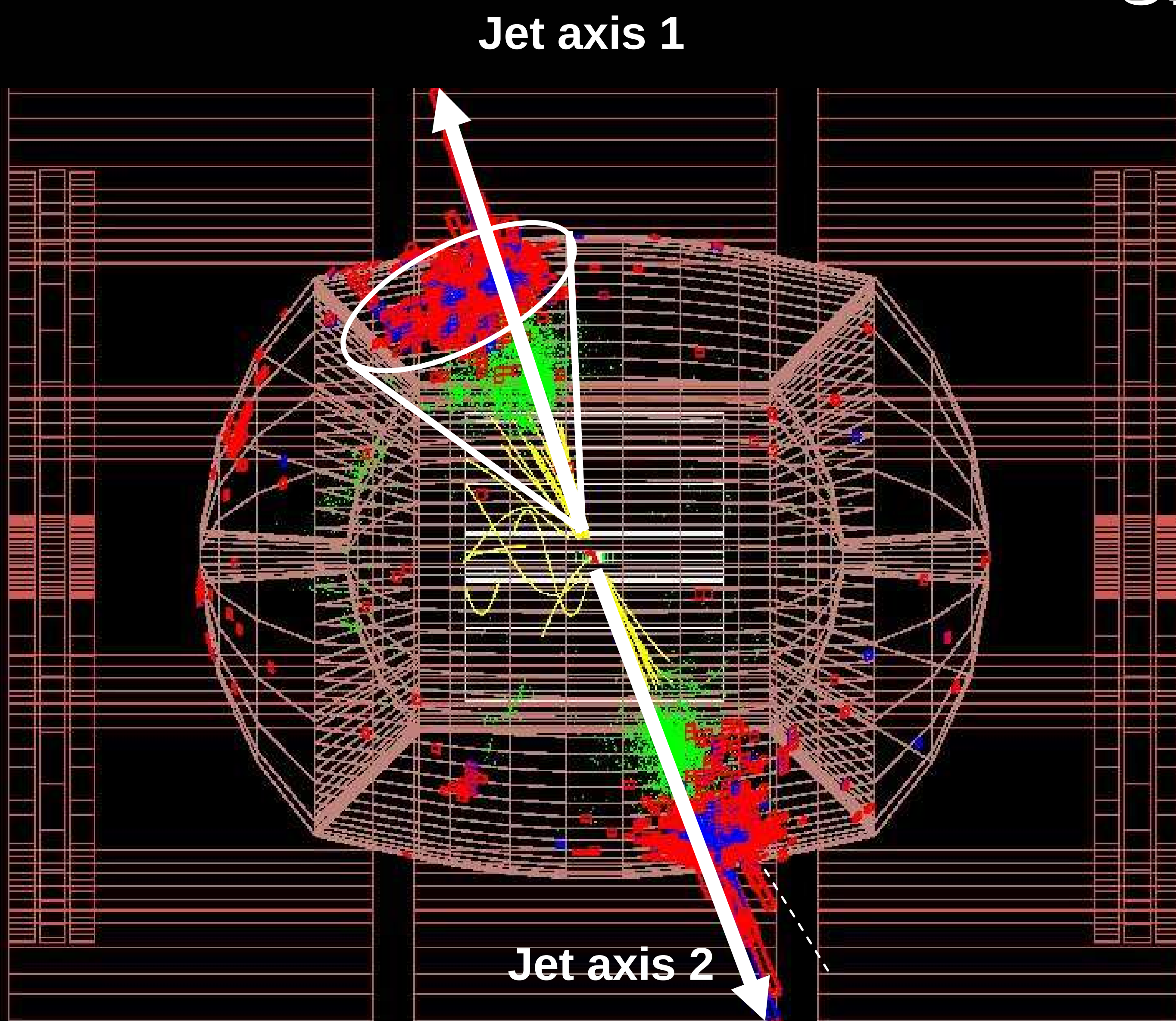
Jet Reconstruction Strategy



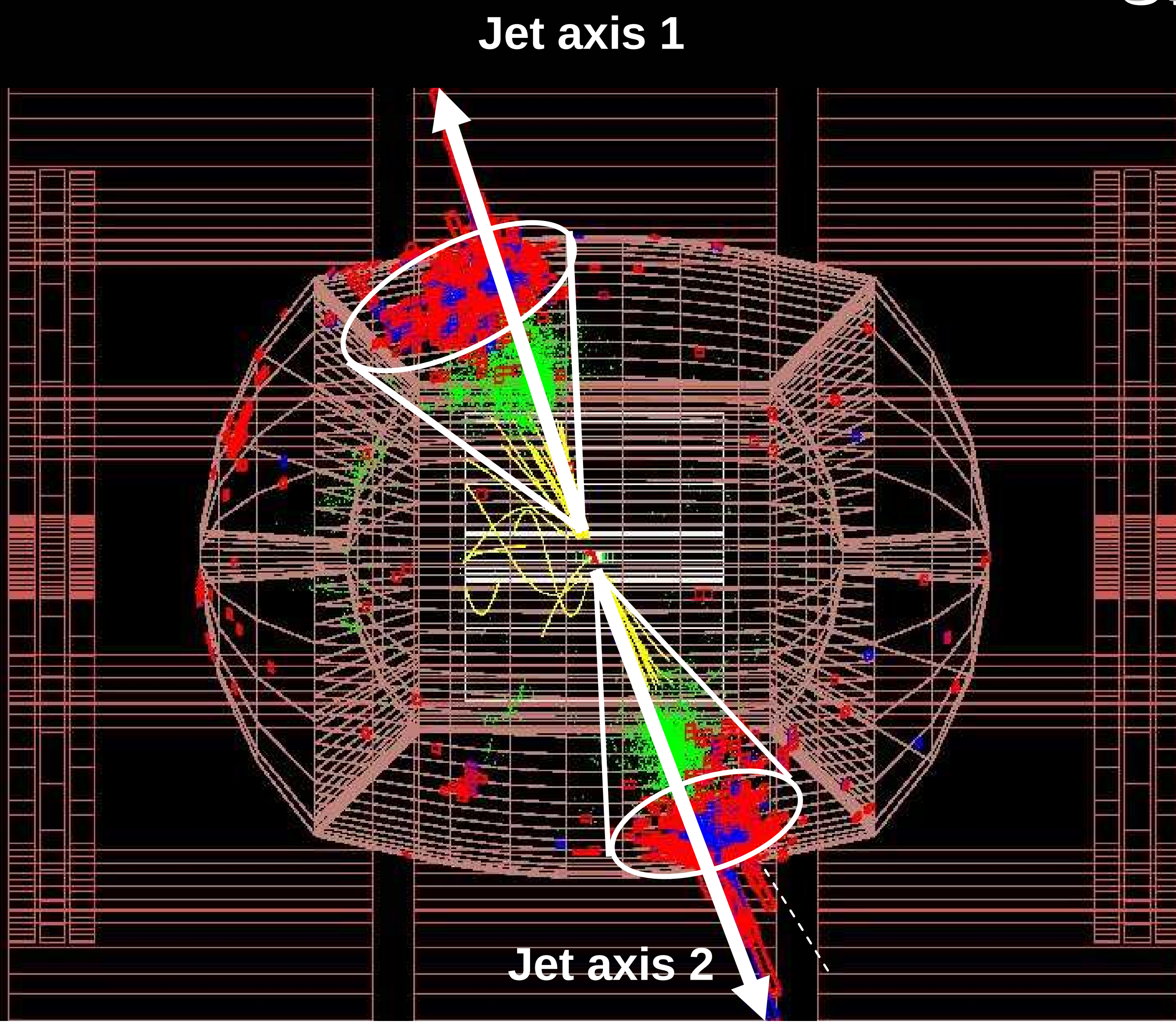
Jet Reconstruction Strategy



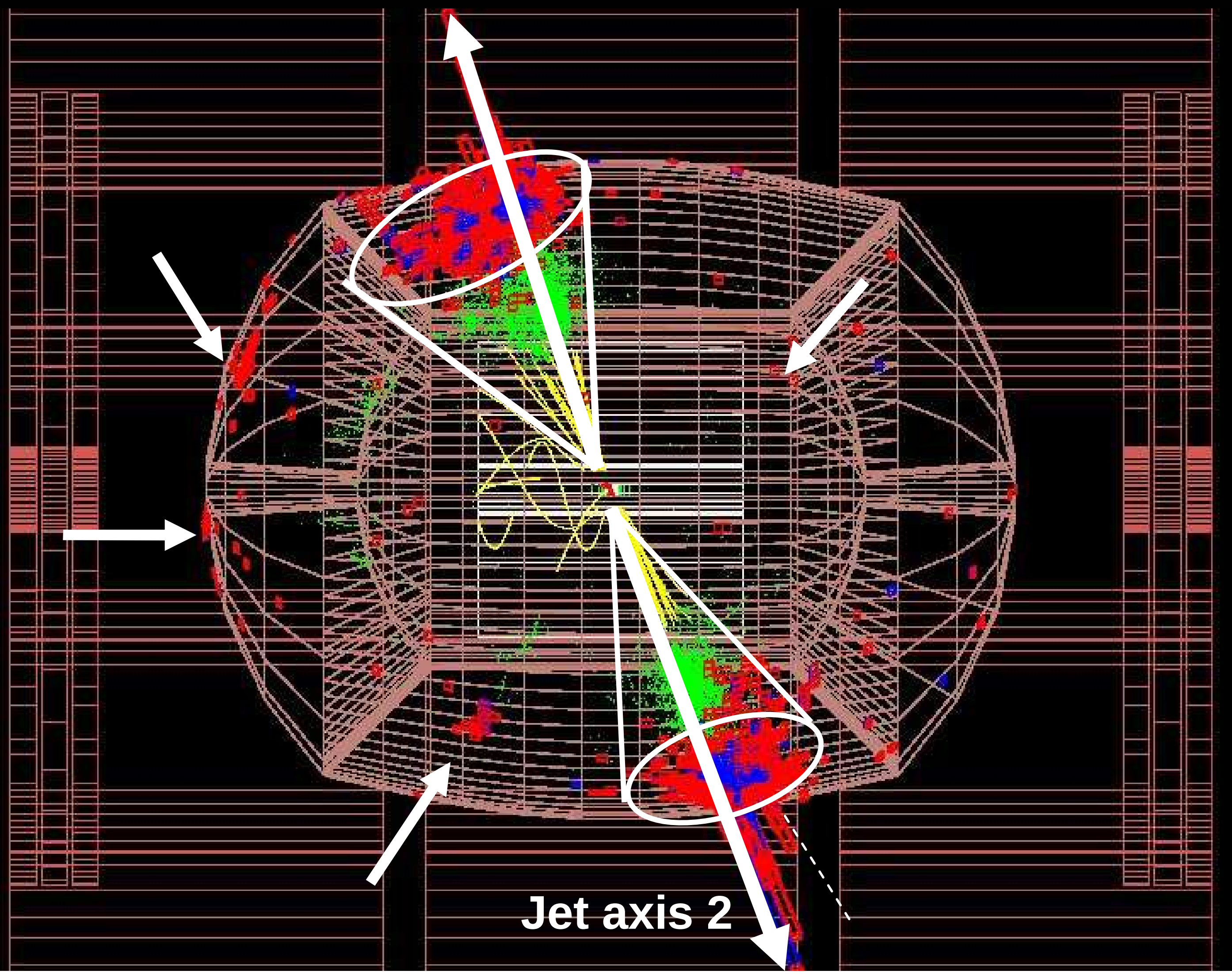
Jet Reconstruction Strategy



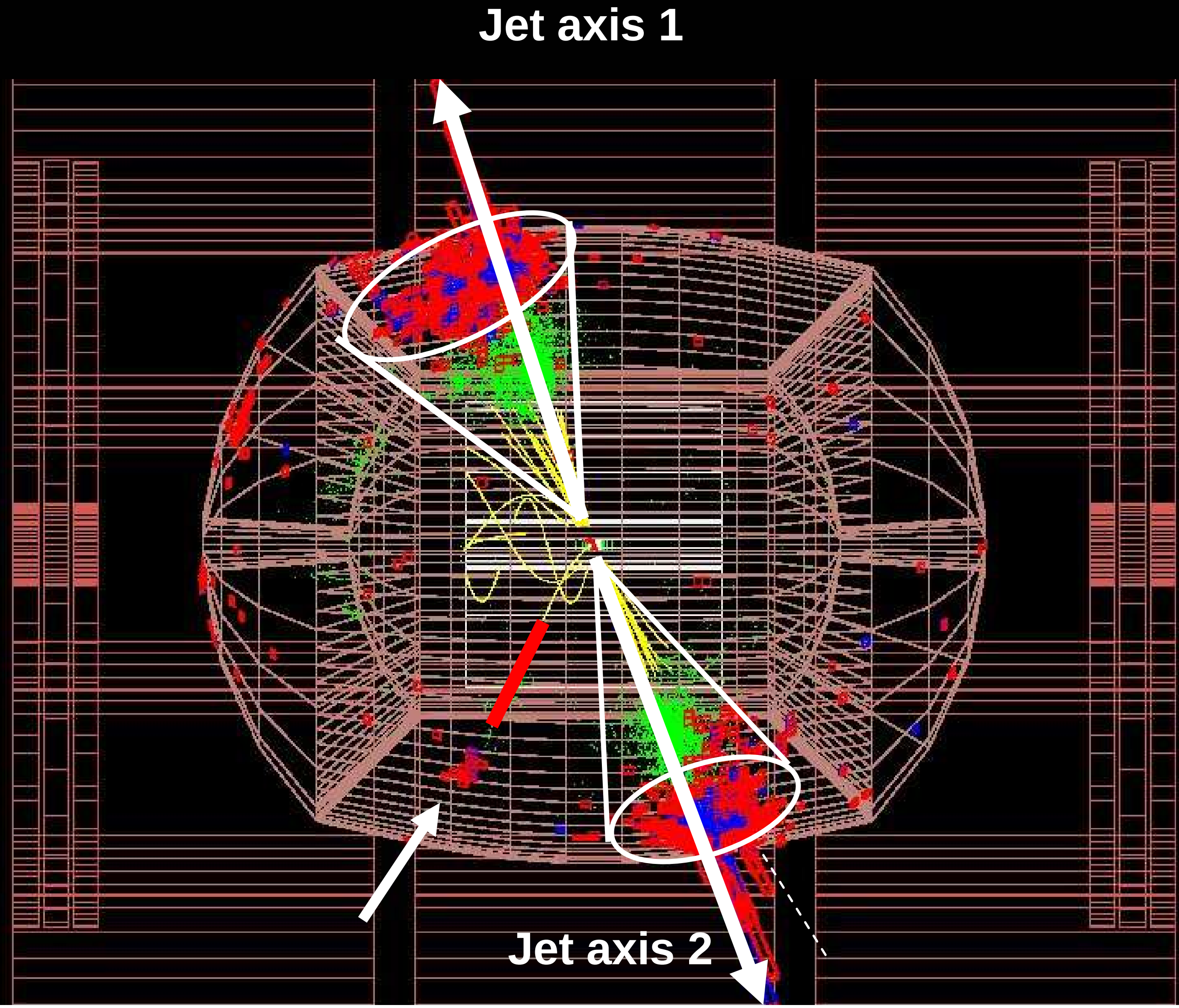
Jet Reconstruction Strategy



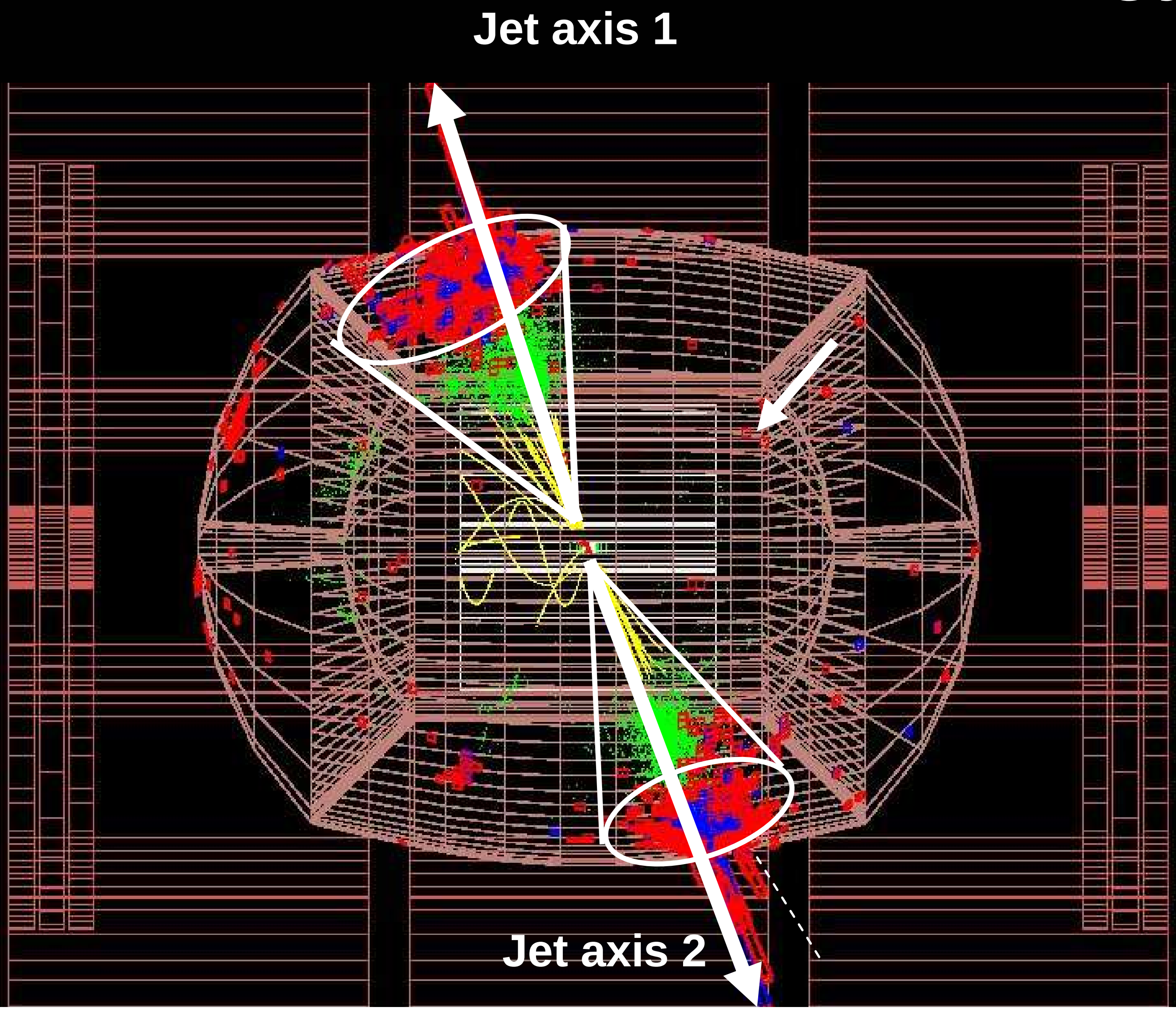
Jet Reconstruction Strategy



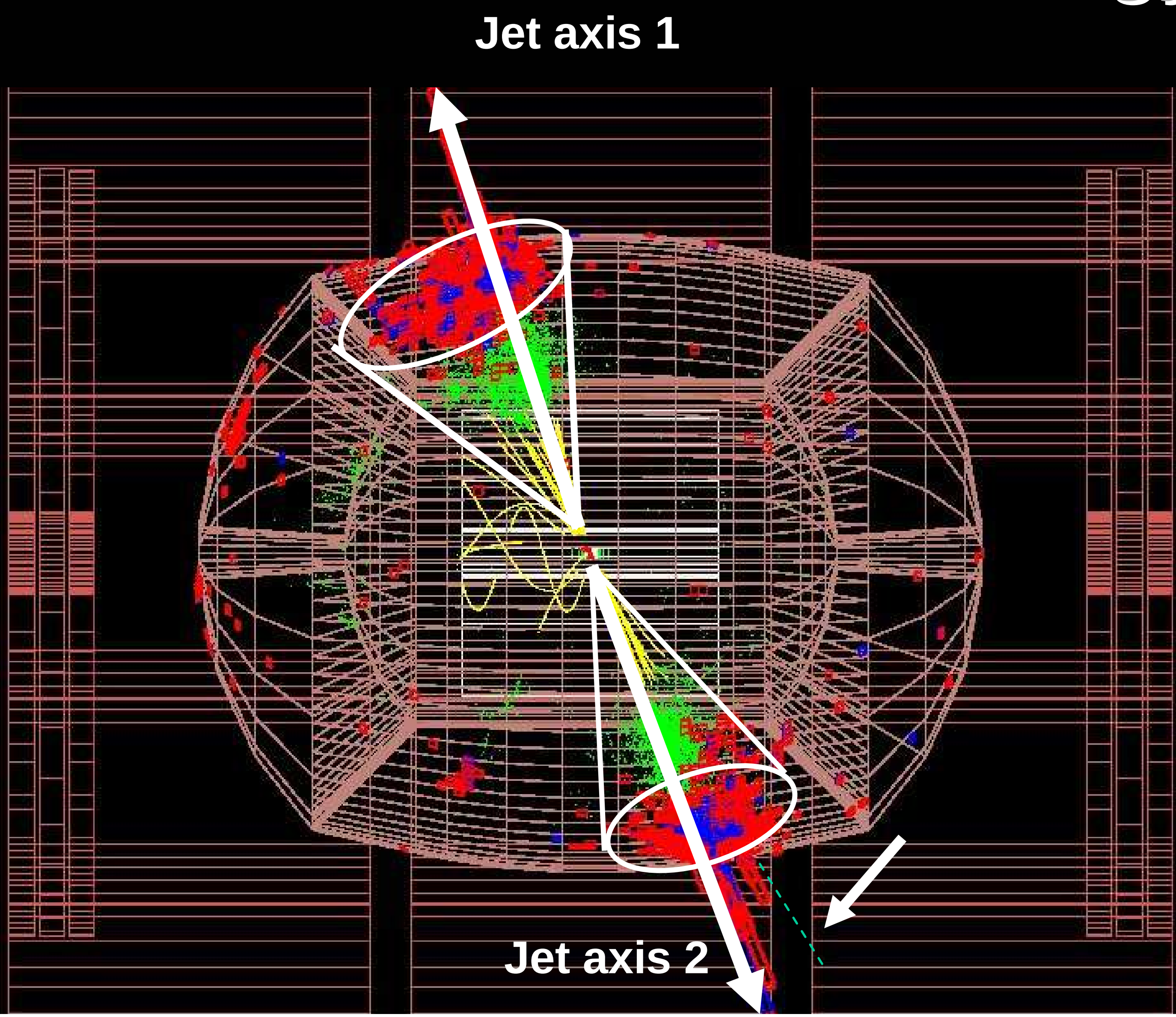
Jet Reconstruction Strategy



Jet Reconstruction Strategy



Jet Reconstruction Strategy



Summary

- 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) (30 GeV ÷250 GeV)
- There is room to improve these resolutions
- No new results with this strategy because of lack of statistic

  (data production stopped to introduce changes in the detectors geometry and algorithms)

Future Projects

- Sherpa and Whizard as event generators
- New HCAL geometry
- Dual-readout ECAL (see F.Grancagnolo's talk at
- CluCou Drift Chamber (see ILCWS 2007/ILC Workshop)
- SiD central tracker (*see C.Gatto's talk next week*)
- Tune jet algorithm
- New jet reconstruction strategy?

Backup slides

ECAL Performance Studies

- Assume 10% QA and PbF_2 doped with 0.15% Gd
  - Scintillation pe yield: 4.5 pe/MeV
  - Cerenkov pe yield: 1.5 pe/MeV
- Just started to produce events
- Priority given to $\tau^{\pm} \to \pi^{\pm}\gamma\gamma$ studies
- Preliminary resolution numbers available

ILC

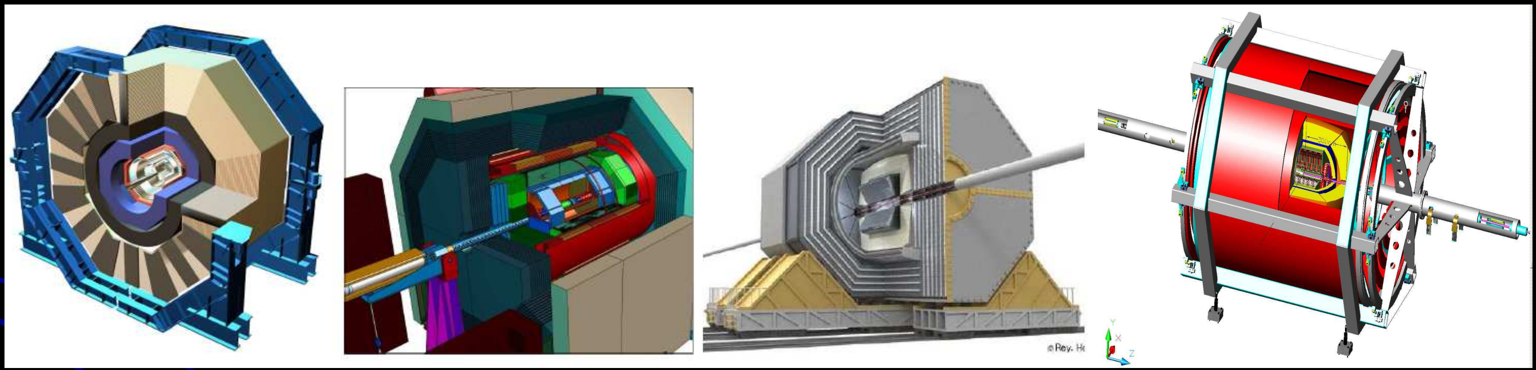
- electron-positron collider ;
- ILC's design consist of two facing linear accelerators, each 20 kilometers long;
- c.m. energy 0.5 - 1 TeV ;
- ILC target luminosity : 500 fb-1 in 4 years

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

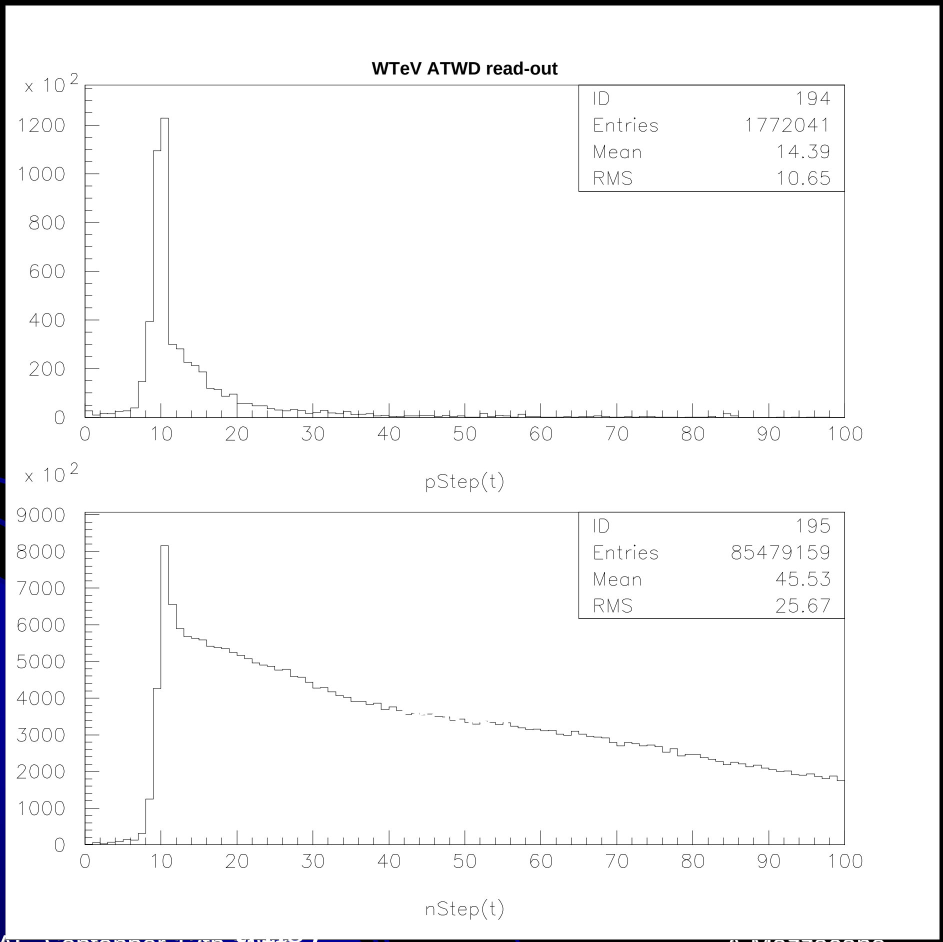


- Sub-detector R&D
  - More than 80 groups in the world (about 1000 physicist)
  - Usually related with several detector concepts

  ➔ Horizontal collaboration

(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.

(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 $\sim\lambda_{int}$ 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 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

Tracking Algorithm

- Primary TPC seeding: looks for track with hits 20 pads apart + beam constraint
- Secondary TPC seeding: looks for tracks with hits in layer 1, 4 and 7 (no beam constraint)
- **Parallel Kalman Filter** then initiated:
  - 1st step: start from TPC fit + prolongation to VXD (add clusters there)
  - 2st step: start from VXD, refit trough TPC + prolongation to MUD
  - 3st step: start from MUD and refit inword with TPC + VXD
- Final step: isolated tracks in VXD and in MUD
- Kinks and V0 fitted during the Kalman filtering
- All passive materials taken into account for MS and dEdx corrections