Digital Calorimetry and Particle Flow Algorithms

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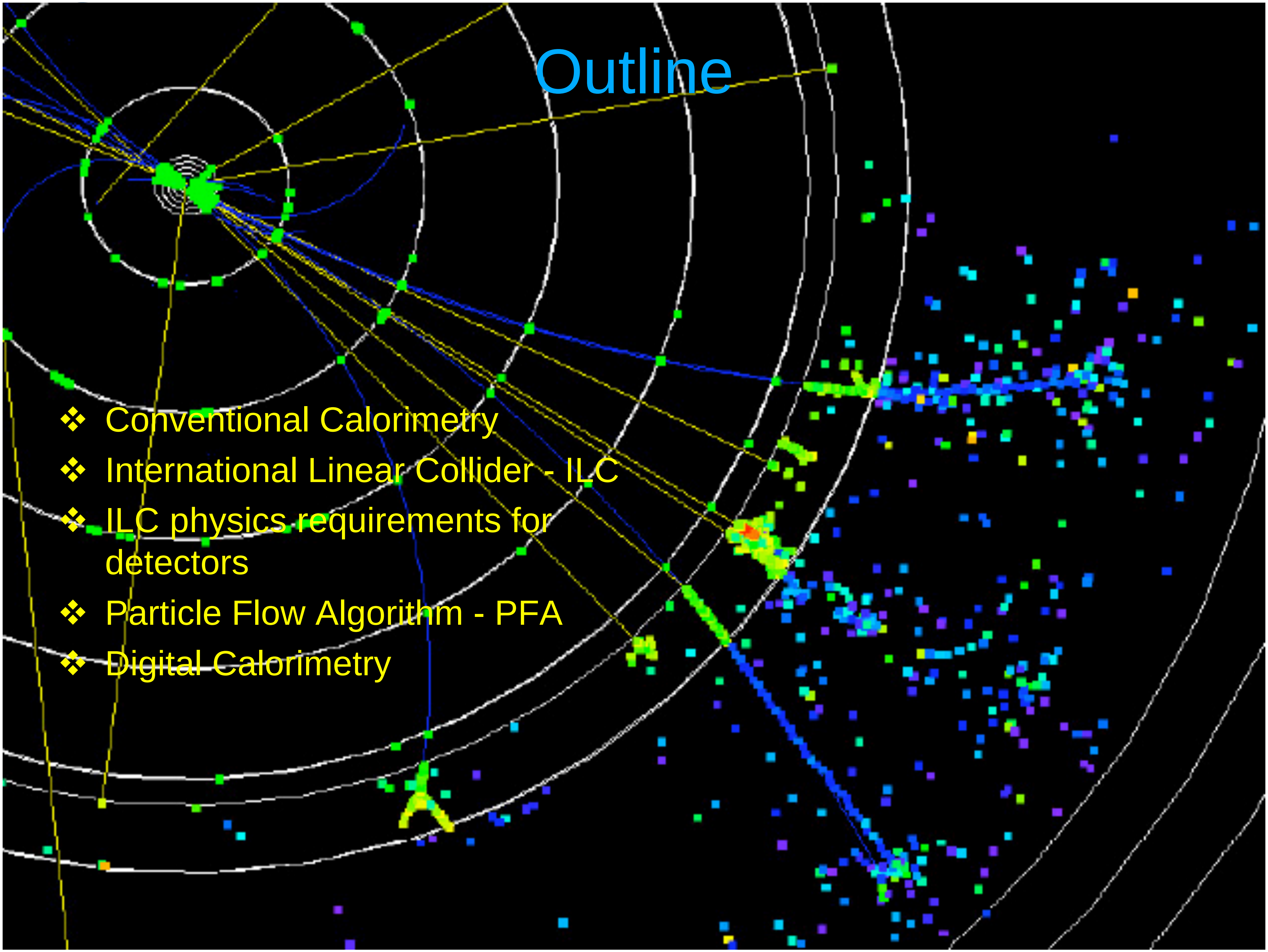
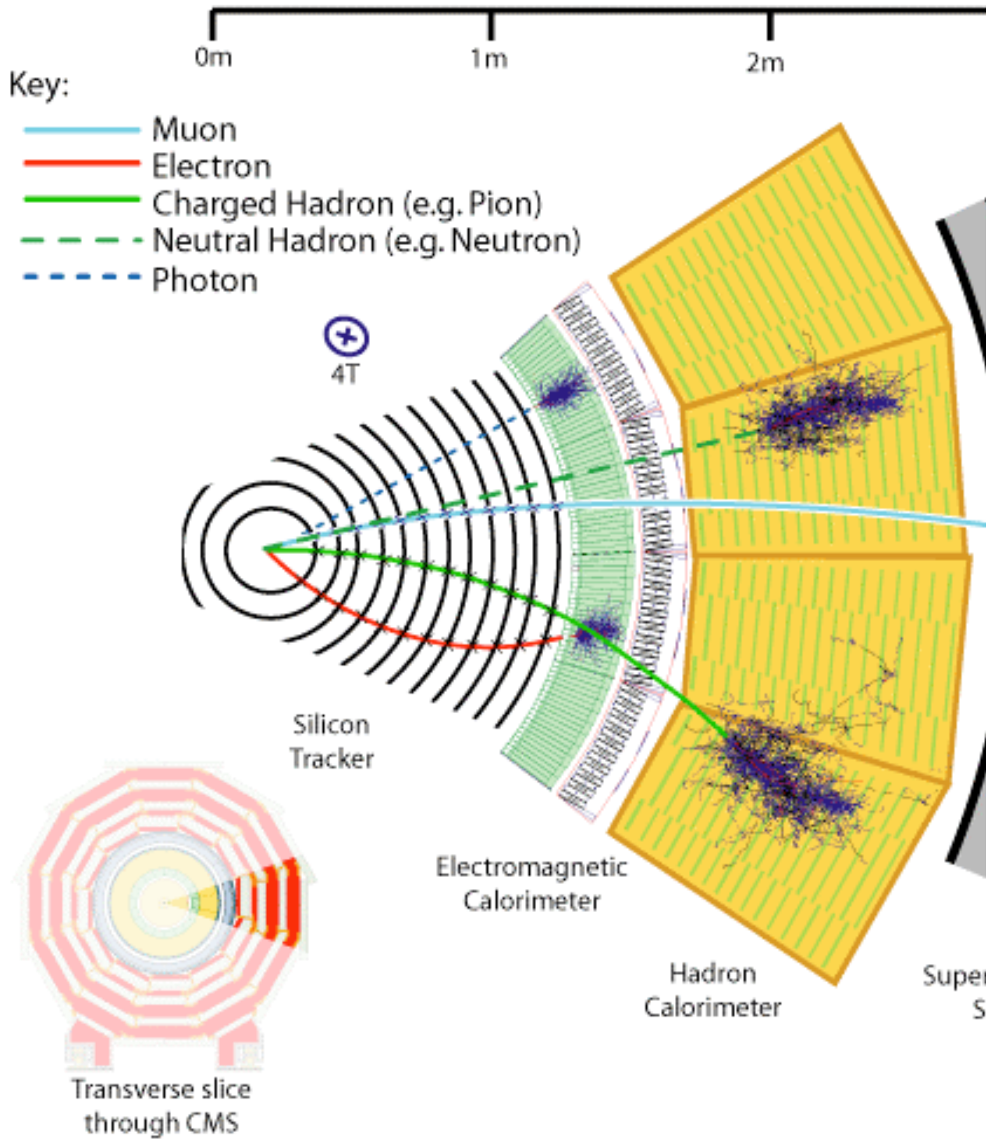
Outline



- Conventional Calorimetry
- International Linear Collider - ILC
- ILC physics requirements for detectors
- Particle Flow Algorithm - PFA
- Digital Calorimetry

What is a Calorimeter?

- Device to measure the energy of particles by total absorption
- Electromagnetic - ECAL
  - Measure EM objects - electrons, positrons, photons
- Hadron - HCAL
  - Measure hadrons - π, K, p, n, …
- To understand how calorimeters work, need to understand particle interactions with matter
  - See talk by Bernd Surrow, NEPPSR V, 2006
  - Particle Data Group



Conventional Calorimeters

- Homogeneous
  - Inorganic, high-Z, scintillating crystals - BGO, CsI, NaI,…
  - Cherenkov radiators - lead glass,…
  - Ionizing noble liquids

- Sampling
  - Sandwich of absorber and active medium
  - Absorbers - steel, uranium, copper,…
  - Active medium - scintillator, ionizing noble liquid, gas-filled detector, semiconductor

Energy Resolution

$$\frac{\sigma(E)}{E} = \frac{S}{\sqrt{E}} \oplus C \oplus \frac{N}{E}$$

- Stochastic term
  - Statistics-related fluctuations: shower fluctuations, PE statistics, dead material in front of the calorimeter, sampling fluctuations
- Constant term
  - Detector non-uniformity and calibration uncertainties
- Noise term
  - Electronic noise

EM Resolution of Real Detectors

Table 28.7: Resolution of typical electromagnetic calorimeters. E is in GeV.

Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/\mathrm{E}^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	16–$18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
Lead glass (OPAL)	$20.5X_0$	$5\%/\sqrt{E}$	1990
Liquid Kr (NA48)	$27X_0$	$3.2\%/\sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998
Scintillator/depleted U (ZEUS)	20–$30X_0$	$18\%/\sqrt{E}$	1988
Scintillator/Pb (CDF)	$18X_0$	$13.5\%/\sqrt{E}$	1988
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/\sqrt{E} \oplus 0.6\%$	1995
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\%/\sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988
Liquid Ar/Pb (SLD)	$21X_0$	$8\%/\sqrt{E}$	1993
Liquid Ar/Pb (H1)	20–$30X_0$	$12\%/\sqrt{E} \oplus 1\%$	1998
Liquid Ar/depl. U (DØ)	$20.5X_0$	$16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

S ~ few %

S ~ 10%

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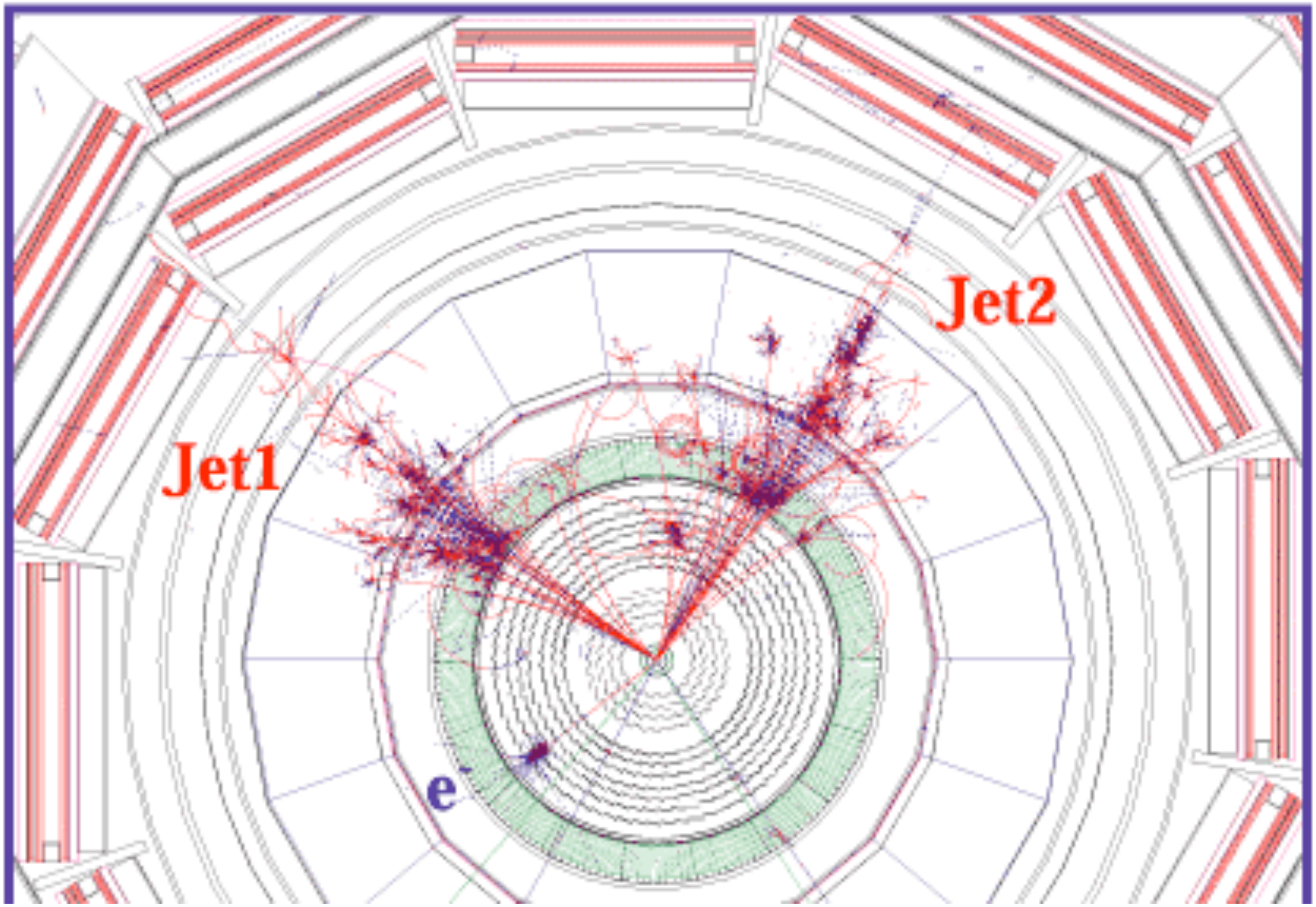
Want E(q,g,…) ⇒ Measure Jets



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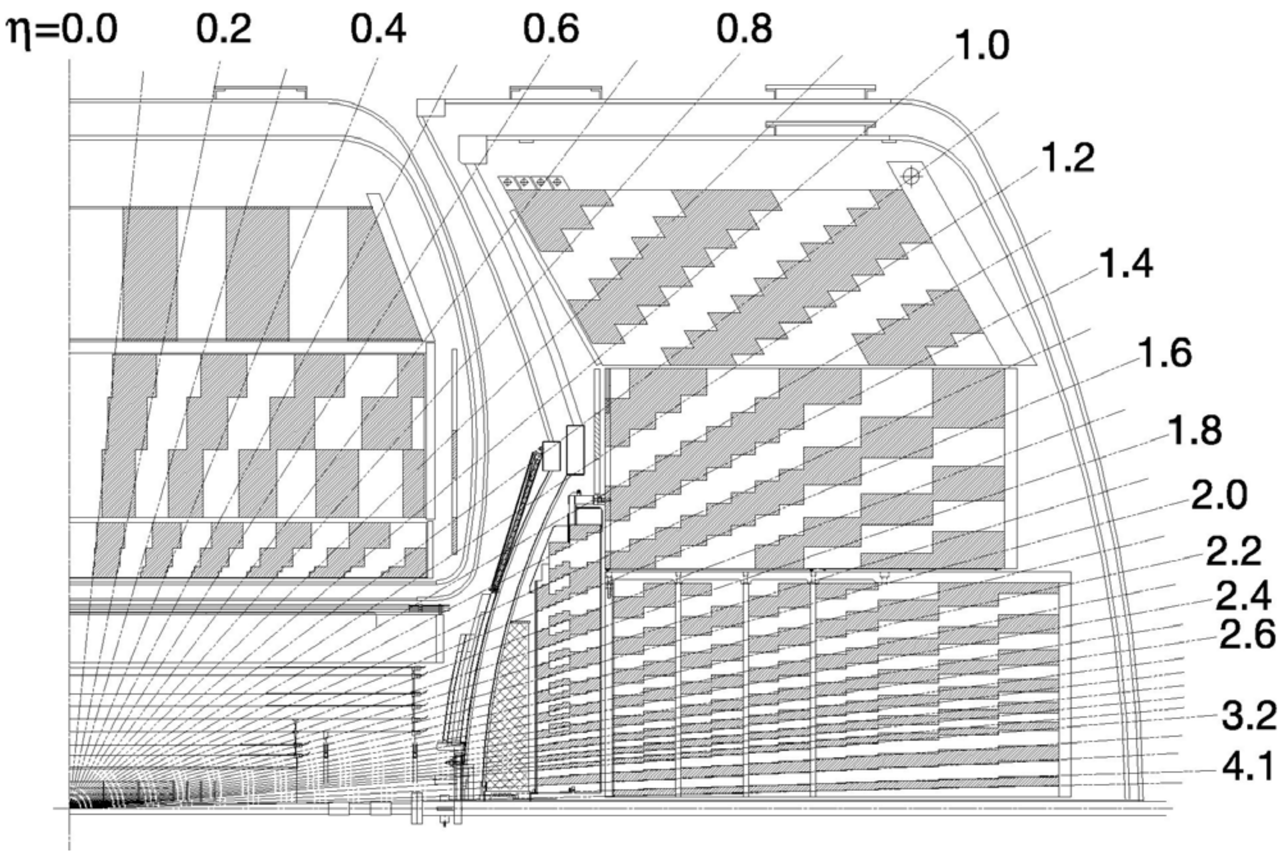
Calorimeter Segmentation



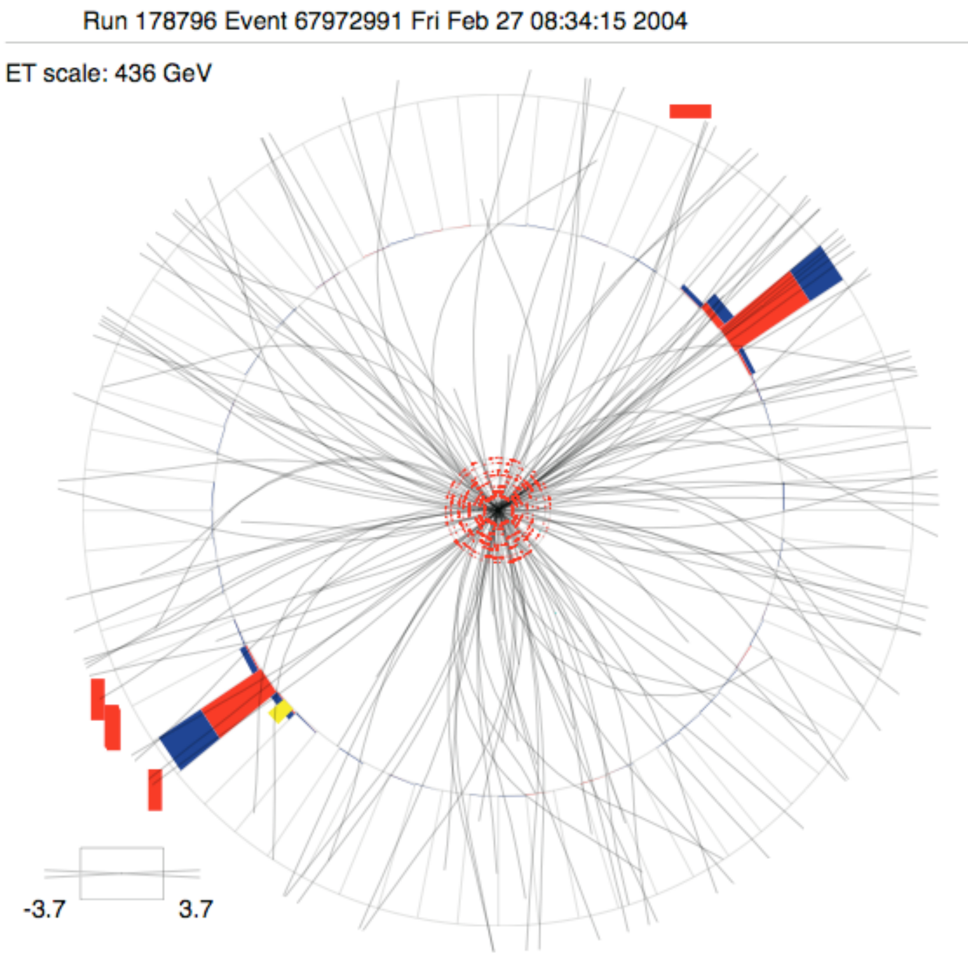
DØ calorimeter

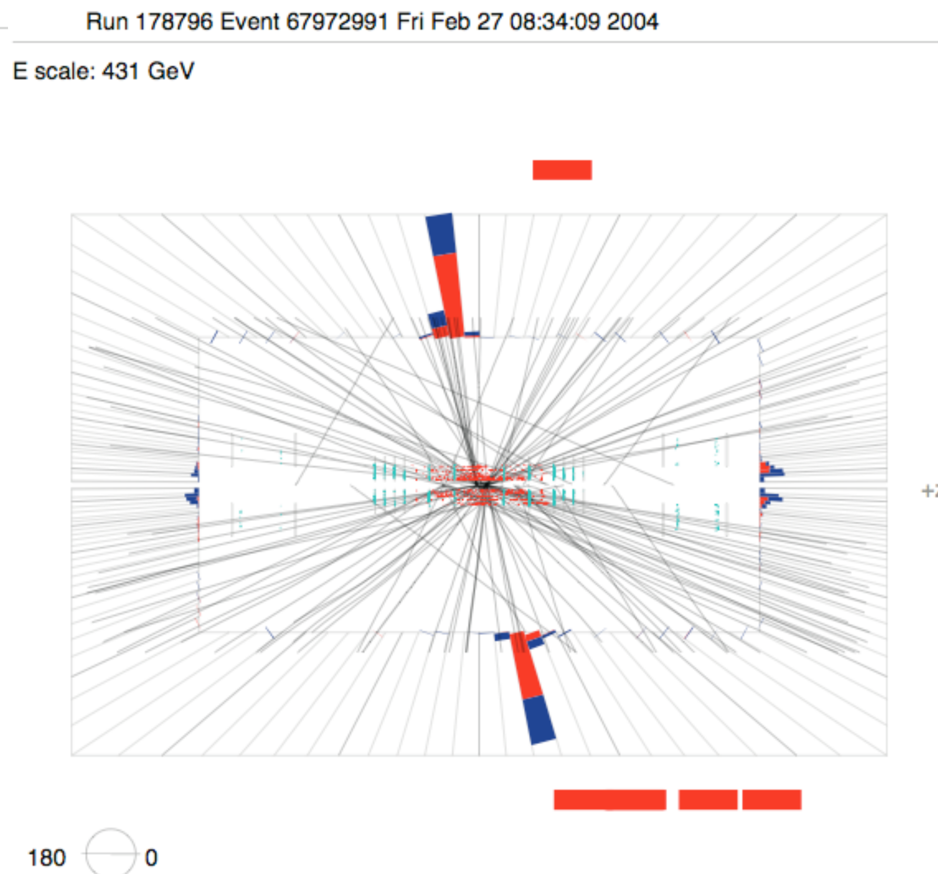
Uranium - liquid Argon sampling calorimeter

segmentation: $\Delta\eta \times \Delta\phi \sim 0.1 \times 0.1 \Rightarrow$ ~50k channels

~12 bit charge measurement

"Typical" 2-jet Event



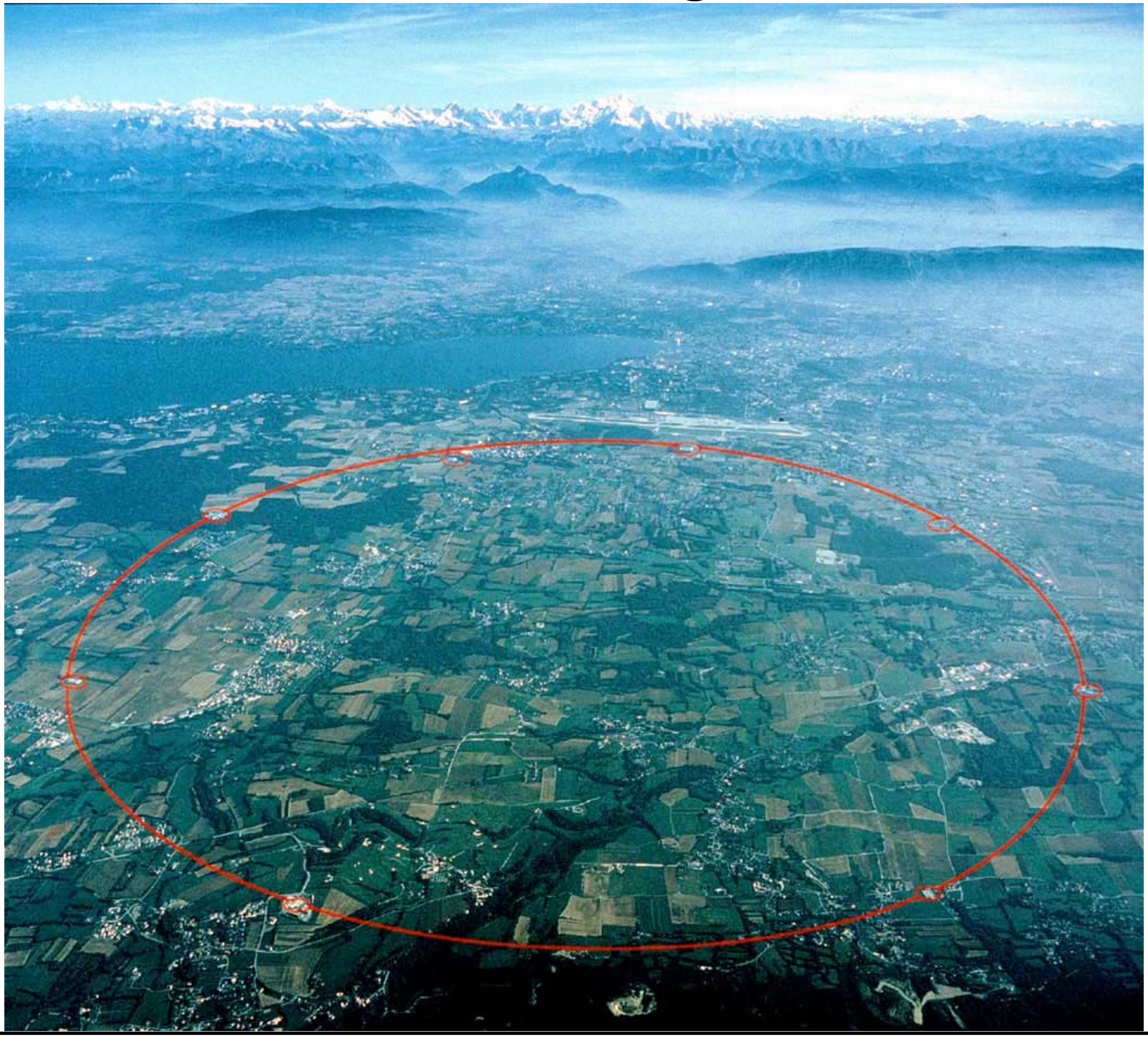


Jet Energy Resolution for Real Detectors

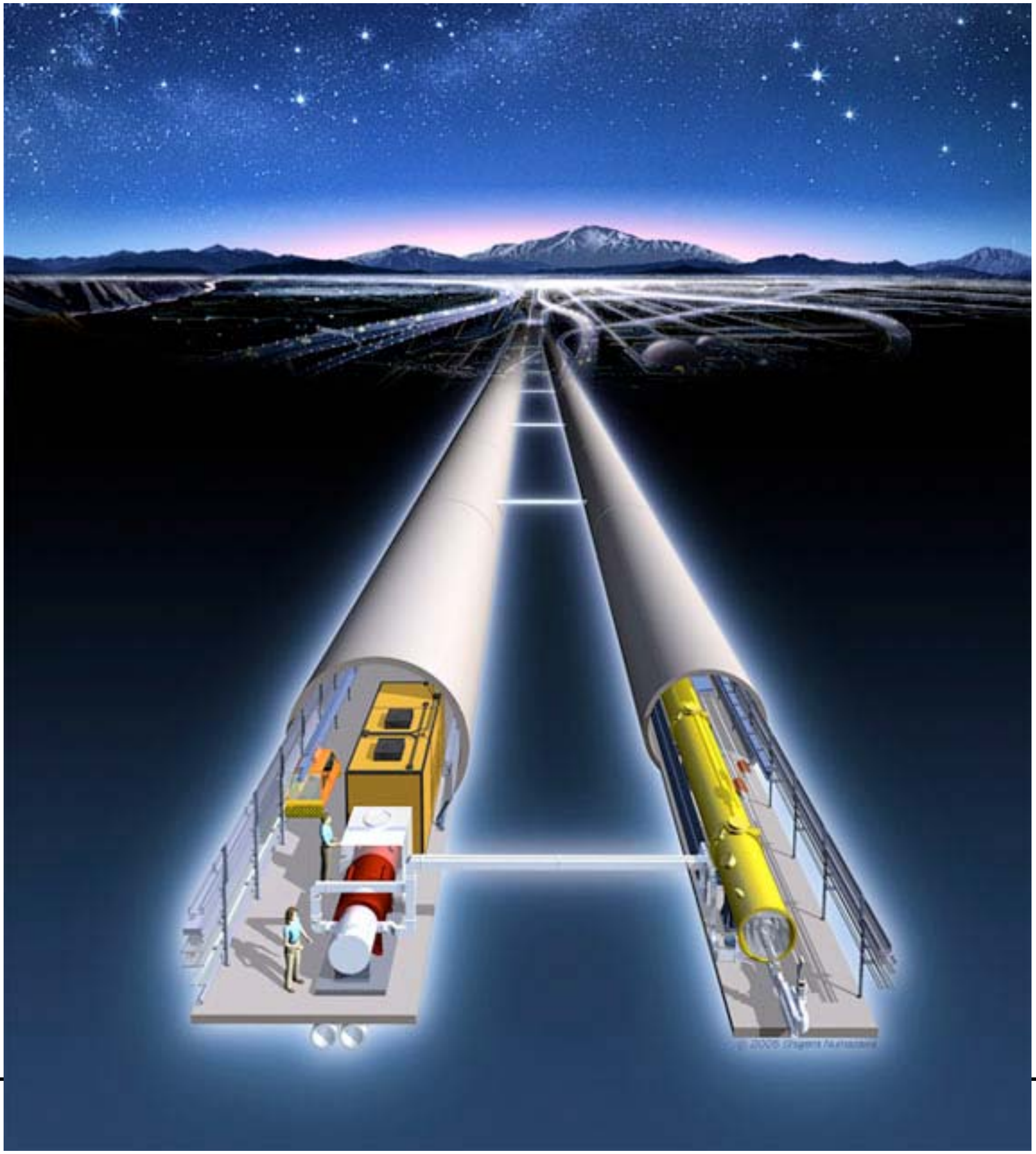
$$\sigma(E) \approx \alpha\sqrt{E(\mathrm{GeV})}$$

No nice table here but a typical range
for recent collider detectors is α = (60-80)%

LHC - The Next Big Accelerator

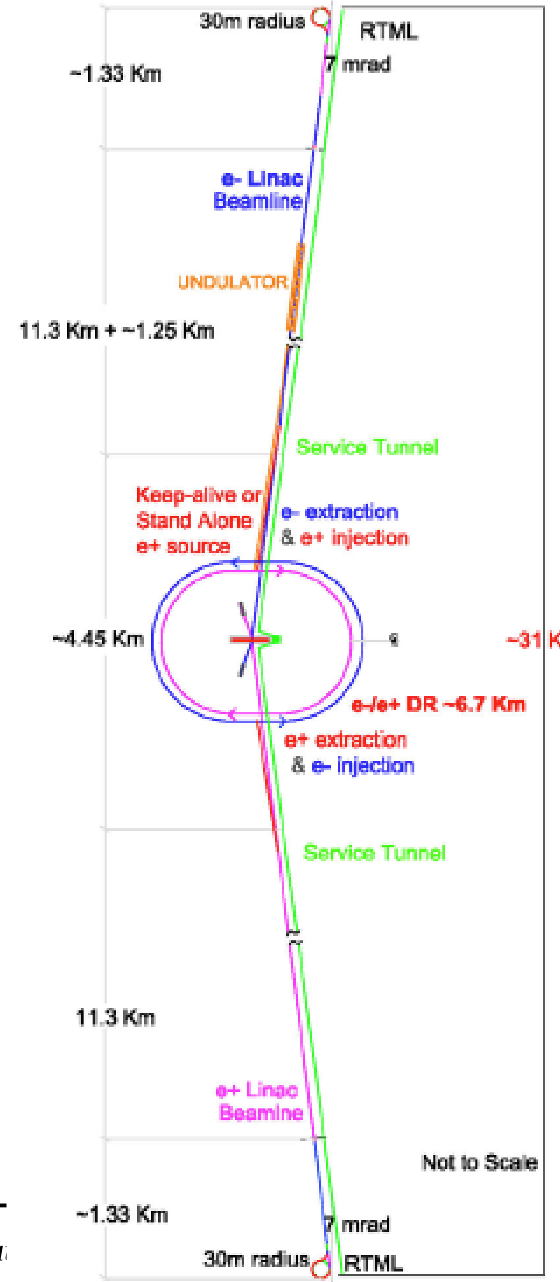


ILC - The Next *Next* Big Accelerator



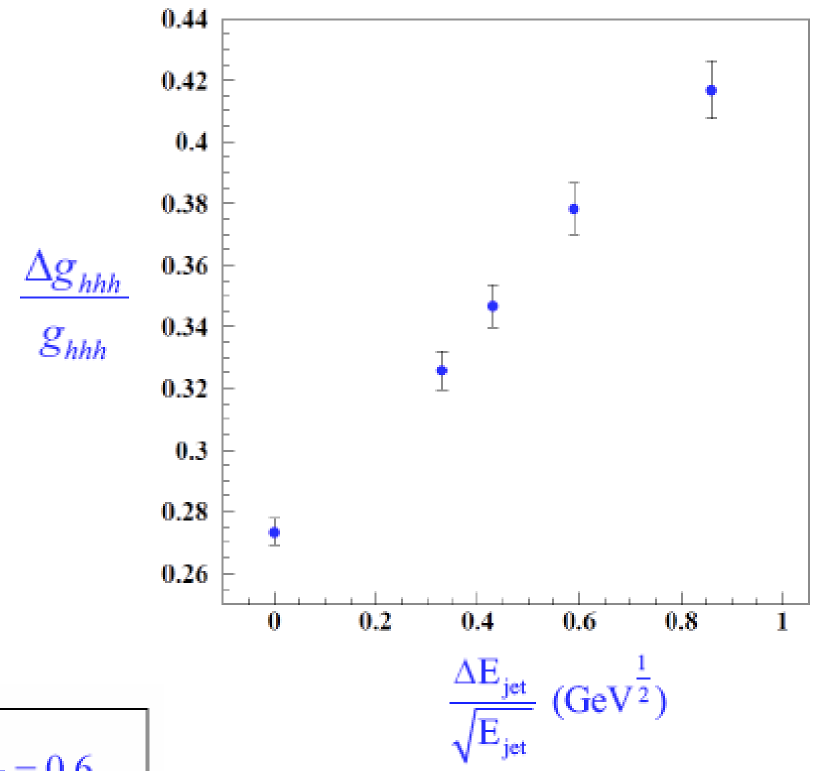
ILC - International Linear Collider

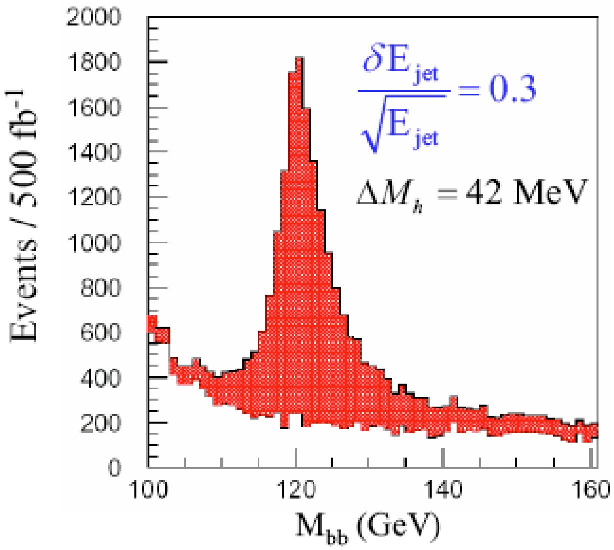
- e^+e^- collisions at 200-500 GeV
  - E_{CM} tunable with 0.1% stability and precision
  - Upgrade to 1 TeV
- Peak luminosity 2×10^{34} $cm^{-2}s^{-1}$
  - $\int Ldt = 500\ fb^{-1}$ in 4 years
- Polarized beams allow control of initial state angular momentum
  - Electron polarization at least 80%, positrons 30→60%
- Complementary to LHC
  - LHC: run first, higher energy, broadband q, qbar, g beams
  - ILC: 2nd view with high precision, E_{CM} fixed, initial state well defined
- When, if ever, will ILC be built?
  - Where would it be built?
    - How much will it cost?
      - These are very good questions…

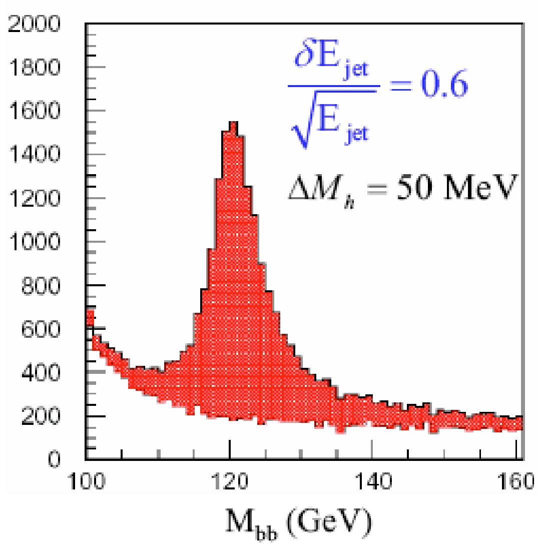


ILC Physics Drives Jet Resolution

- Many of the important ILC physics topics involve multi-jet final states
- Higgs self-coupling λ_{hhh}
  - $e^+e^- \rightarrow ZHH \rightarrow qqbbbb$
  - Test of the Higgs mechanism
- Higgs mass in 4-jet channel
  - $e^+e^- \rightarrow ZH \rightarrow qqbb$



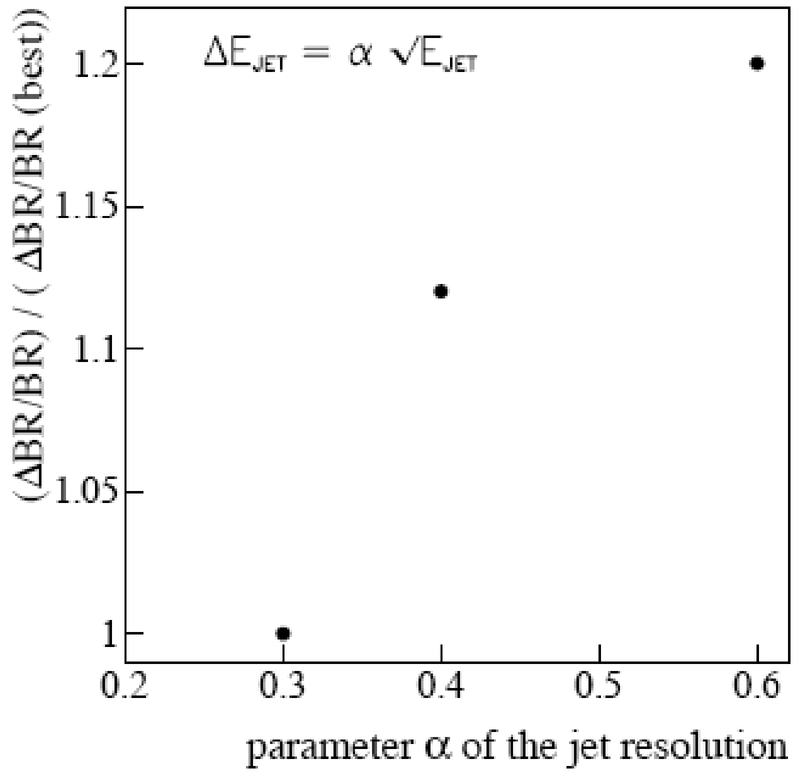




α = 60% → 30%
⇒ 40% luminosity gain

ILC Physics Drives Jet Resolution

- H → WW* branching fraction
  - $e^+e^- \to ZH \to ZWW^* \to qqql\nu$
  - Distinguish hadronic W and Z decays
- Cross section for $e^+e^- \to \nu\nu WW$
  - Probe strong WW scattering in a Higgs-less world
  - Distinguish hadronic W and Z decays



α = 60% → 30%
⇒ 40% luminosity gain

Estimate of Performance Needed for ILC

Separate $H \to WW$ and $H \to ZZ$

- Jet energy resolution

$$\sigma(E) \approx \alpha \sqrt{E(\mathrm{GeV})}$$

- Dijet mass resolution

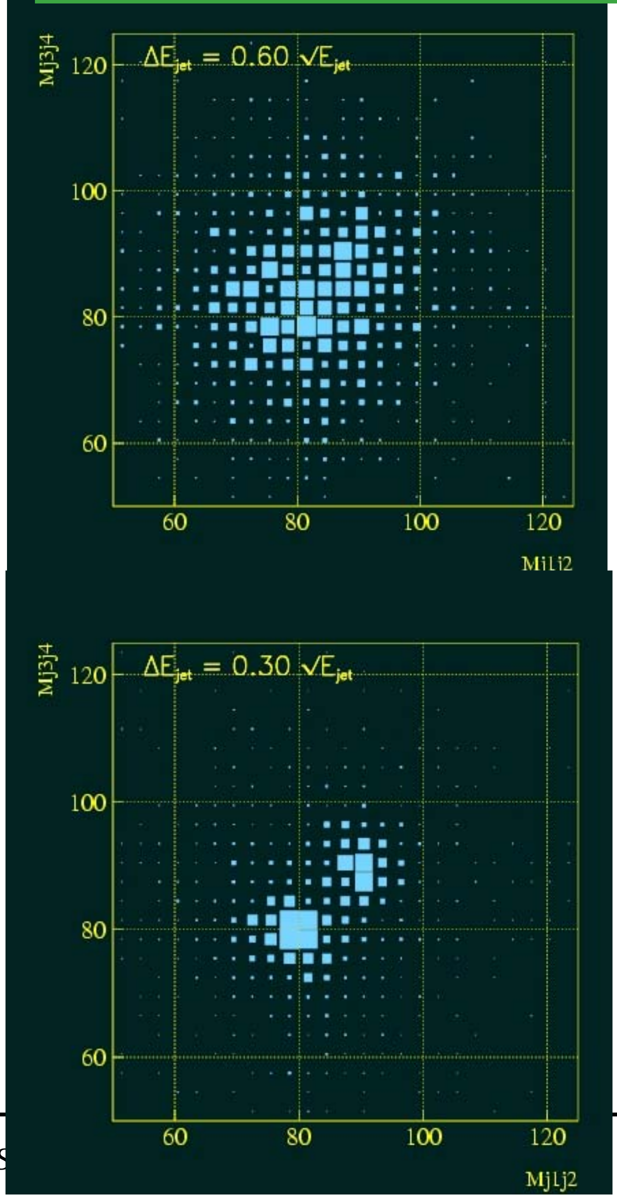
$$\sigma(M)/M \approx \alpha / \sqrt{E_{jj}}$$

  where E_{jj} is the energy of the dijet system

- Goal: σ(M) for W→qq and Z→qq ~ W or Z natural widths ⇒ σ(M) ~ 2 GeV
- At ILC, E_{jj} ~ 150 GeV so we need

$$\sigma(E) \approx 30\% \sqrt{E(\mathrm{GeV})}$$

- About factor of 2 better than achieved to date!

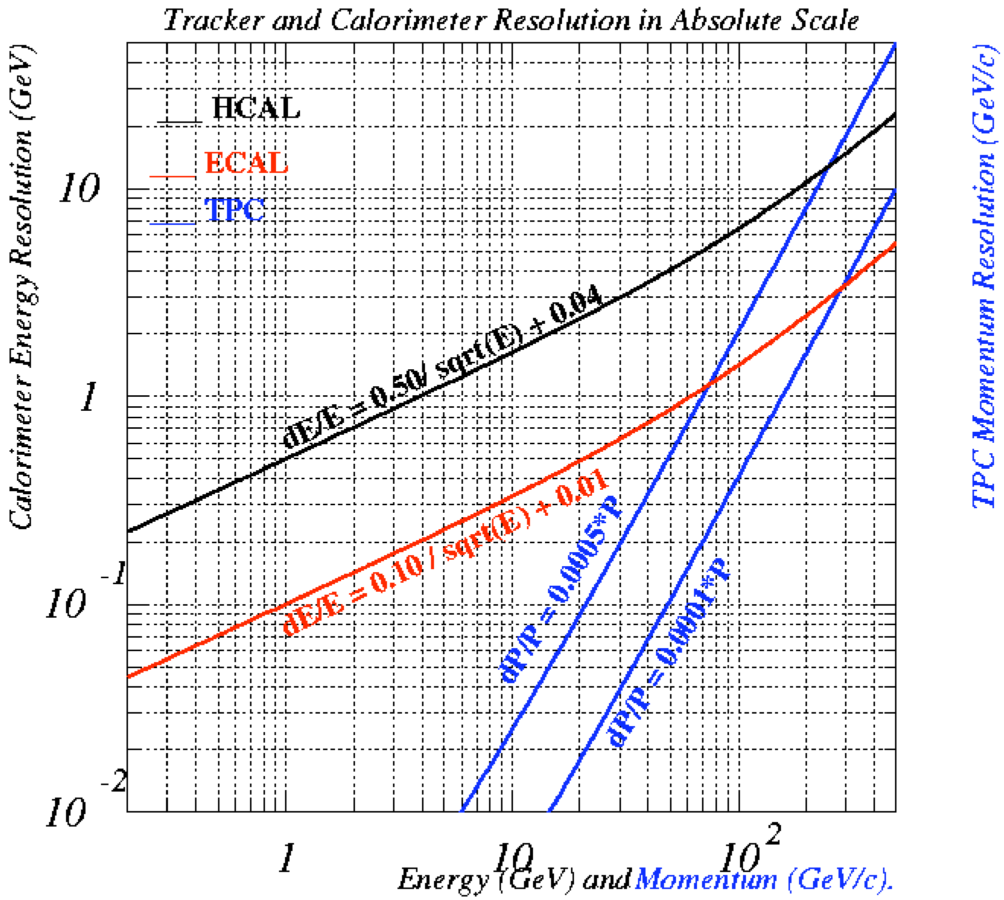


$$\sigma(E) = 60\% \sqrt{E}$$

$$\sigma(E) = 30\% \sqrt{E}$$

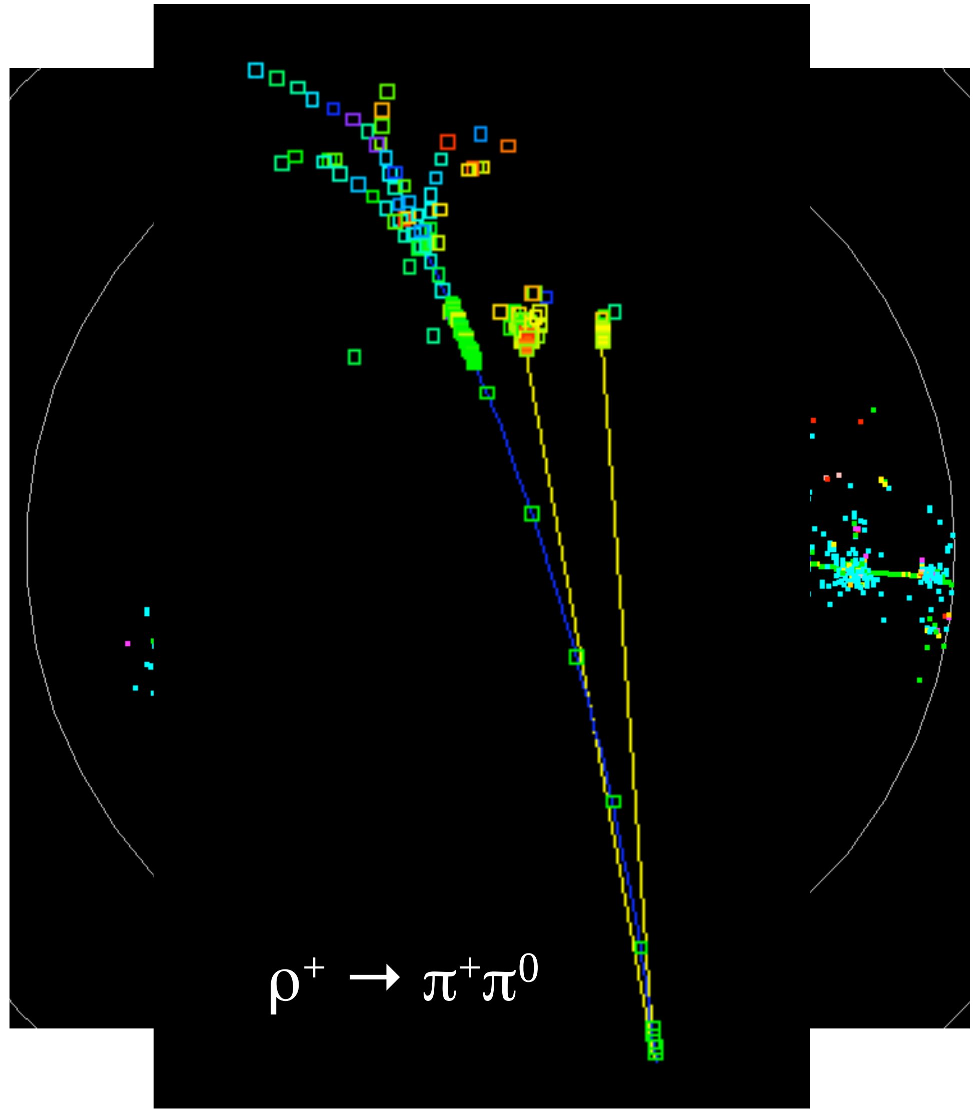
Particle Flow Algorithm

- Basic idea - use entire detector to measure jet energy
  - Must be an integral part of detector design
- Reconstruct all visible particles in the event
  - Measure charged particles' momenta in tracker (~60% E)
  - Measure photons in the ECAL (~30% E)
  - Measure neutral hadrons in HCAL (~10% E)
- Works best when energies of particles in jets < ~100 GeV



PFA and Digital Calorimetry

- Crucial ingredients
  - Correctly assign hits in calorimeter to charged particles
  - Separate showers produced by charged and neutral particles
- Need essentially an imaging device
  - Requires fine segmentation ~ 1x1 cm^2 in the transverse direction plus ~40 layers $\Rightarrow$ ~5x10^7 channels!
- Analog - low channel-count and O(10-bit) measurement/channel ➞ Digital - high channel-count and 1-bit measurement/channel



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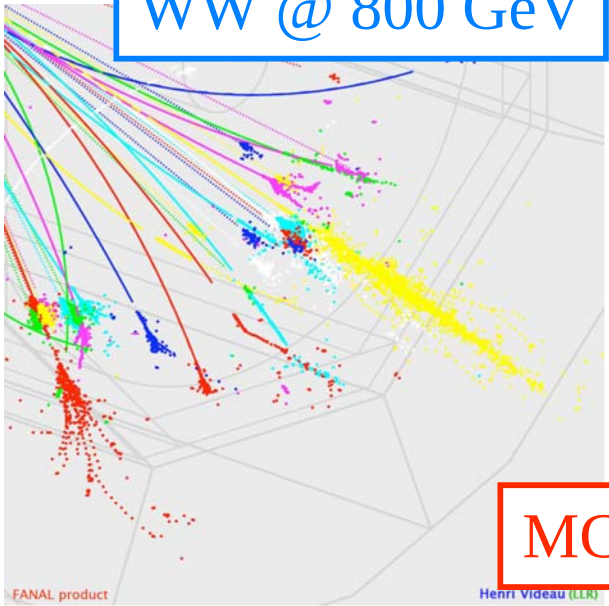
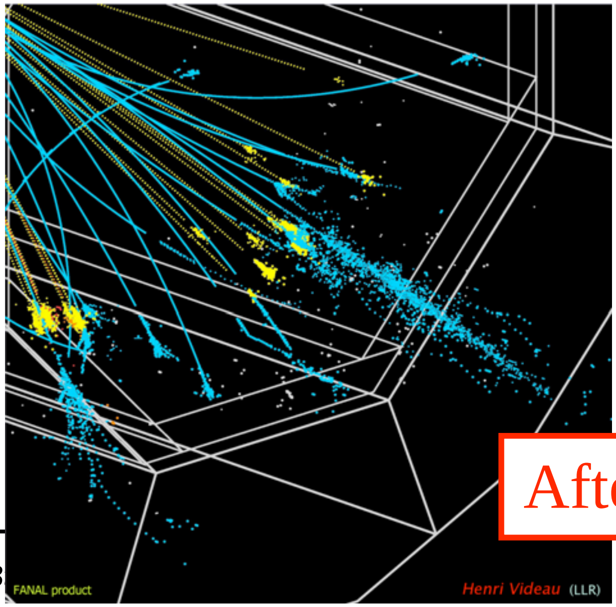
PFA: General Strategy

- Output is a list of reconstructed particles: "Particle Flow Objects" (PFOs)
  - Algorithms differ in detail but general strategy is same
- Reconstruct all charged particles
  - Careful to identify neutral particles that decay, e.g. $K^0 \rightarrow \pi^+\pi^-$, photon conversions, kinks, etc.
  - Pattern recognition in ECAL&HCAL
    - Associate charged particles with calorimeter clusters
    - Separate from nearby clusters
  - Charged particle PFO = track + cluster
  - If particle ID info available, assign mass to PFO
- Unassociated calorimeter clusters are neutral PFOs
  - Either photons or neutral hadrons, assignment based purely on calorimeter info

WW @ 800 GeV



MC Truth



After PFA

PFA Jet Energy Resolution

- Factors affecting the resolution
  - Resolution of subdetector systems: tracker and calorimeters
  - Unmeasured energy
    - Finite detector acceptance
    - Neutrinos - b and c quark jets
  - Clustering algorithms

$$\sigma^2(E_{jet}) = \sigma^2(X^{\pm}) + \sigma^2(\gamma) + \sigma^2(h^0) + \sigma^2(miss) + \sigma^2(conf)$$

Tracker

Photons

Neutral hadrons

Unobserved particles

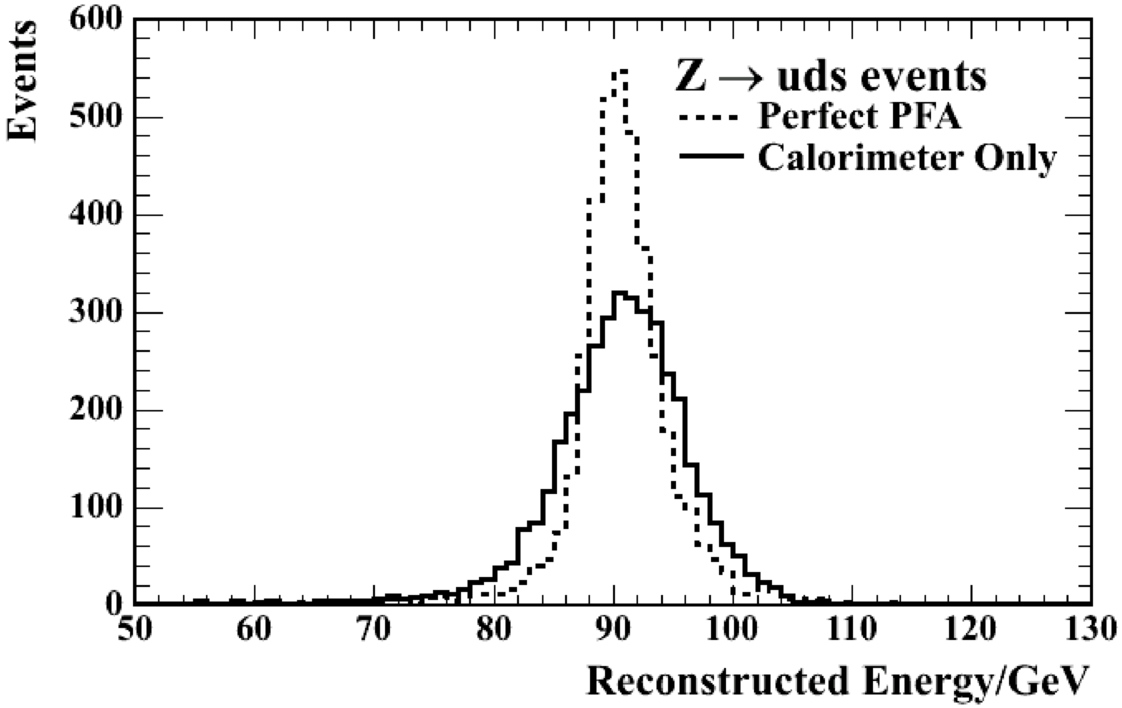
Confusion Term

Perfect PFA Performance

- Run “perfect” PFA where all factors except confusion term are included
  - Neutrinos
  - Acceptance to 5^0 of beampipe
  - ECAL and HCAL resolutions
  - Wrong mass assignment, e.g. pion for a proton
- Jet energy resolution ~ 25%/sqrt(E)

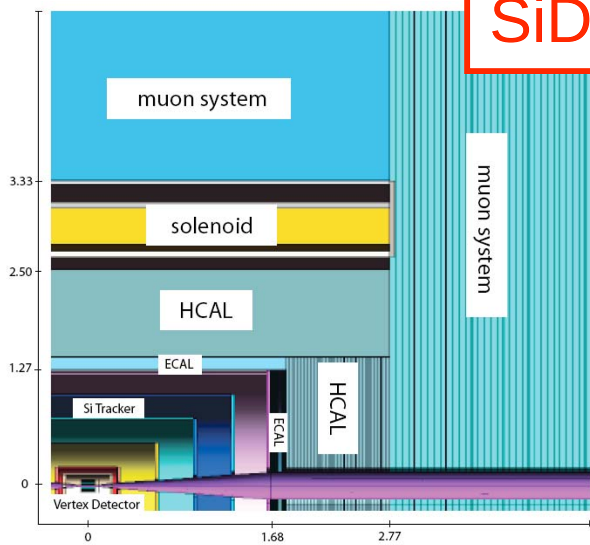
	$e^+e^- \to Z \to qq$ (91.2 GeV)	$e^+e^- \to tt$ (500 GeV)
σ_ν / GeV	0.84	1.36
σ_{FWD} /GeV	1.55	2.68
σ_{HCAL}/GeV	1.40	3.93
σ_{ECAL}/GeV	0.57	1.40
σ_{MASS}/GeV	0.61	1.32
σ_{TOTAL}/GeV	2.40	5.31
$\sigma_{TOTAL}/\sqrt{E}$(GeV)	25.1 %	23.7 %

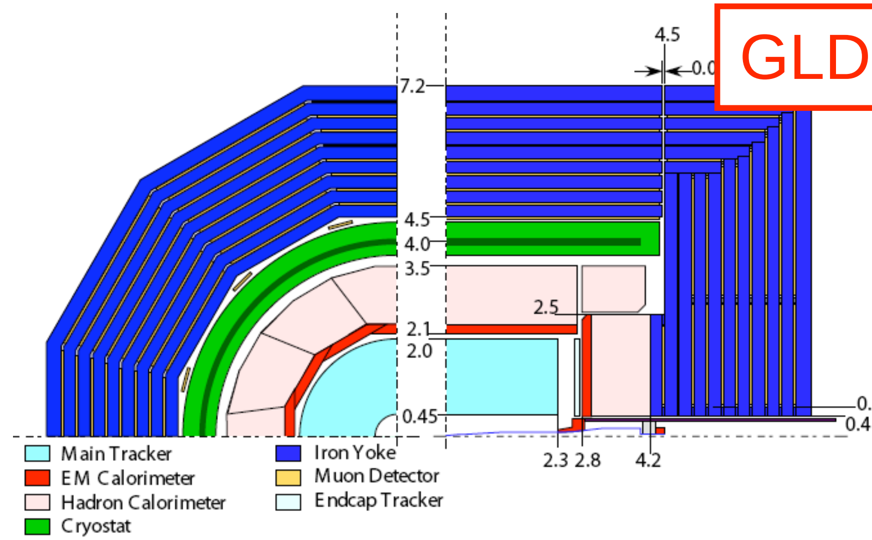
Perfect PFA Performance

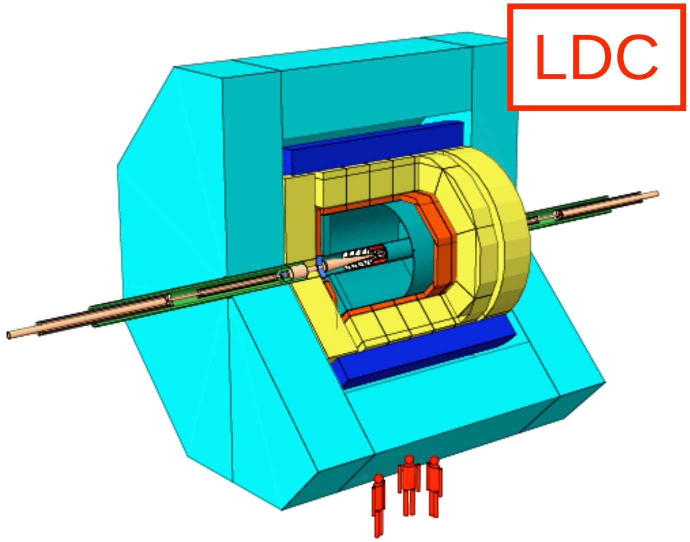


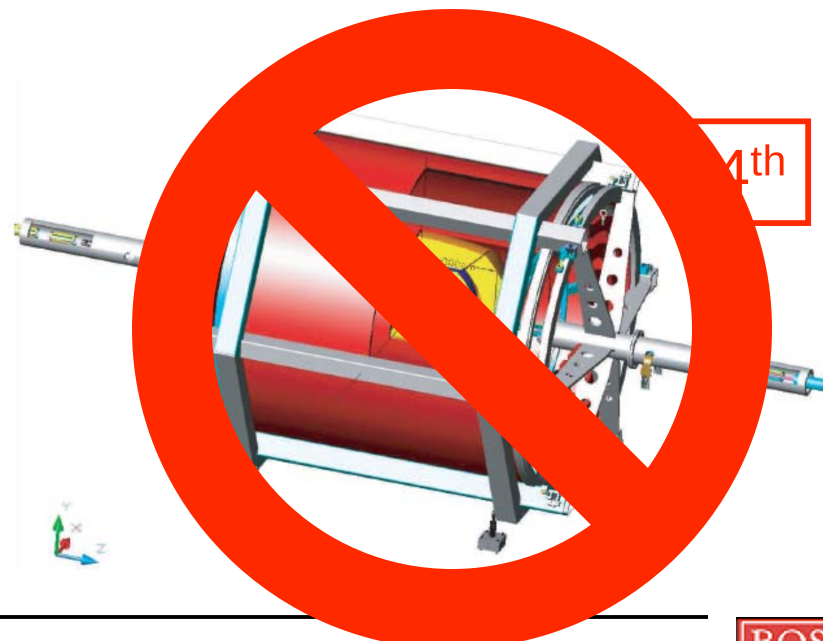
Better than a factor of 2 improvement over calorimeter only measurement!

ILC Detector Concepts

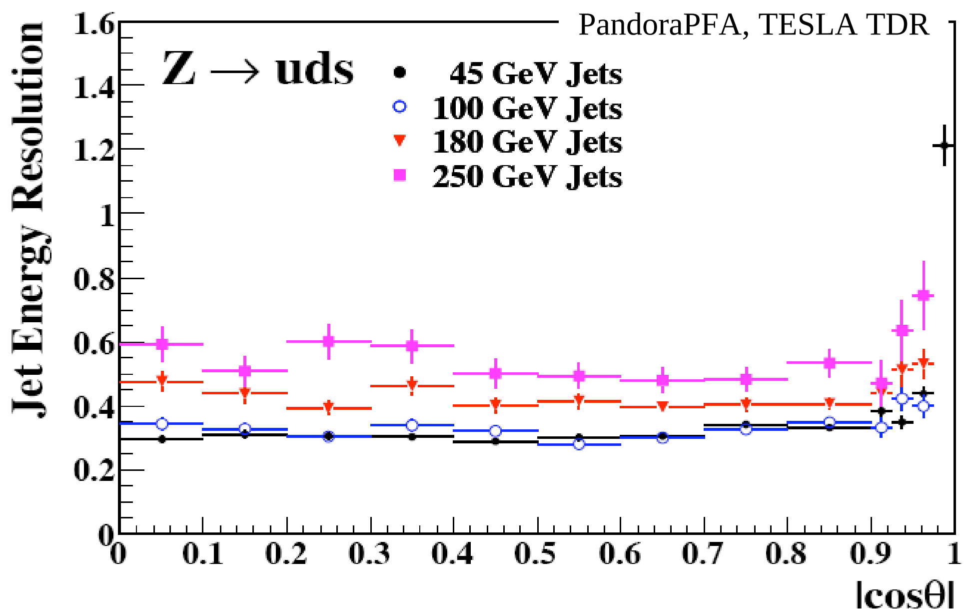


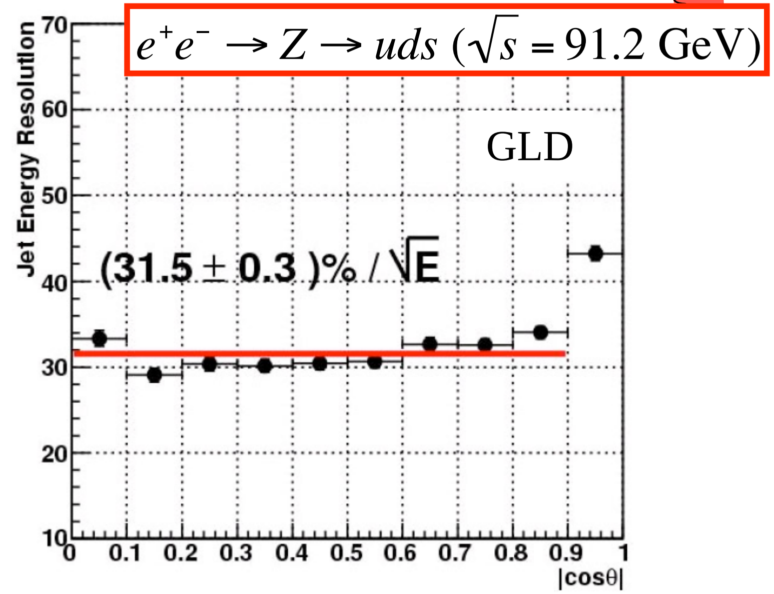


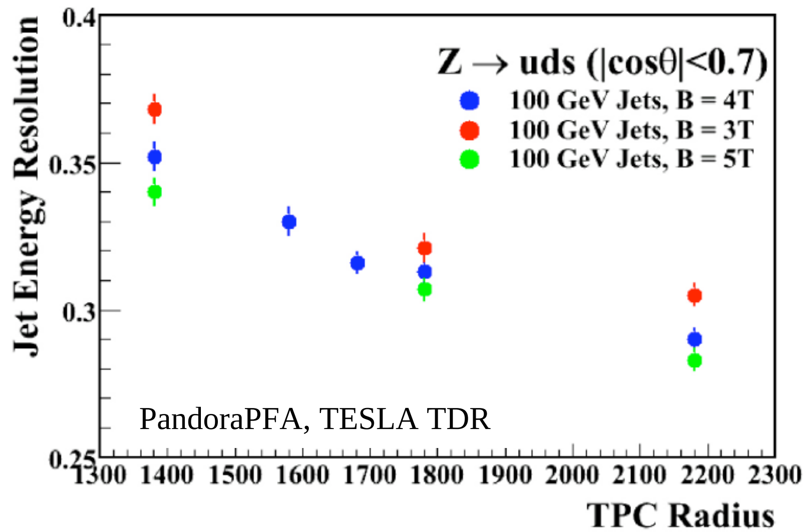




PFA Results From Detector Concepts







σ(E) improves with larger R and B

What could possibly go wrong?

- Monte Carlo is not real life!
- Models of showers need to be tuned to data
- Data with sufficient detail does not exist
- Motivates a program of R&D

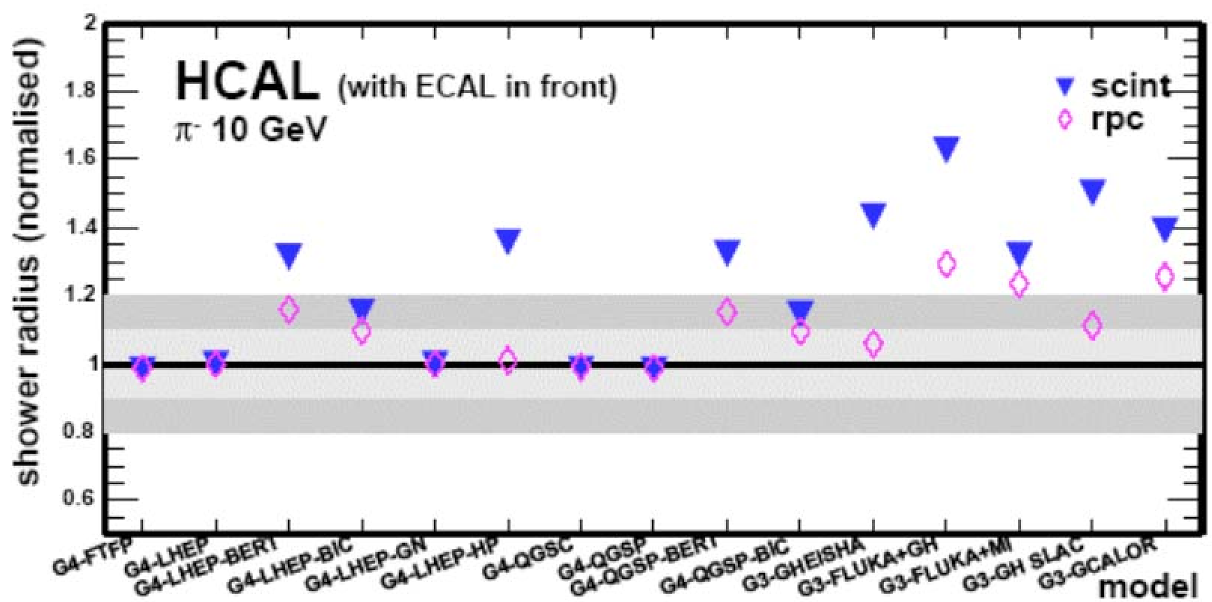
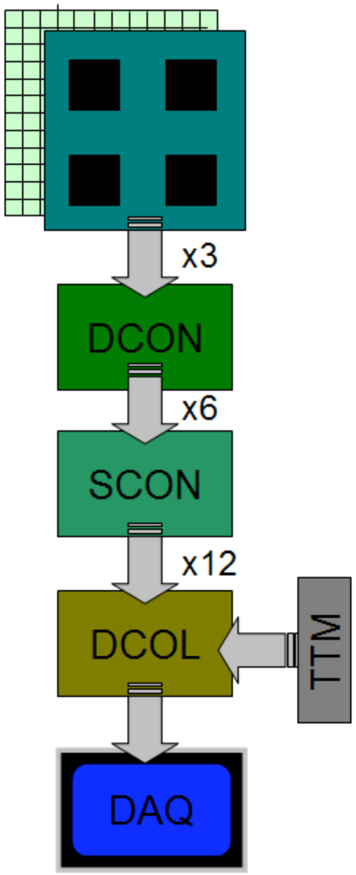


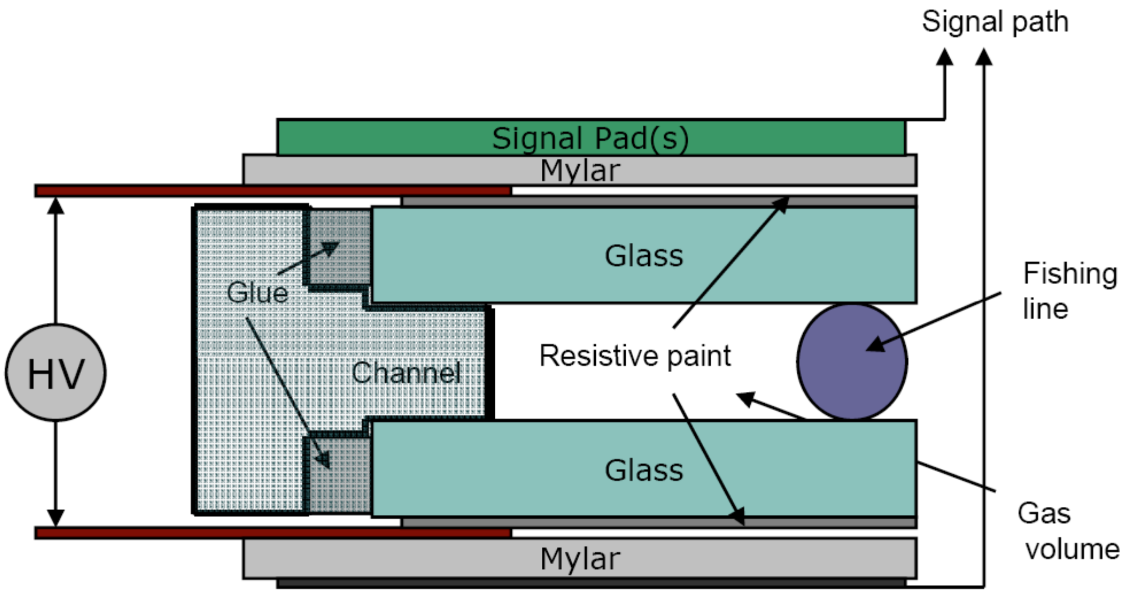
Figure 1.1 Comparison of the shower radius in a hadron calorimeter as predicted with fifteen different MC models of hadronic showers normalized to the result with G4-FTFP.

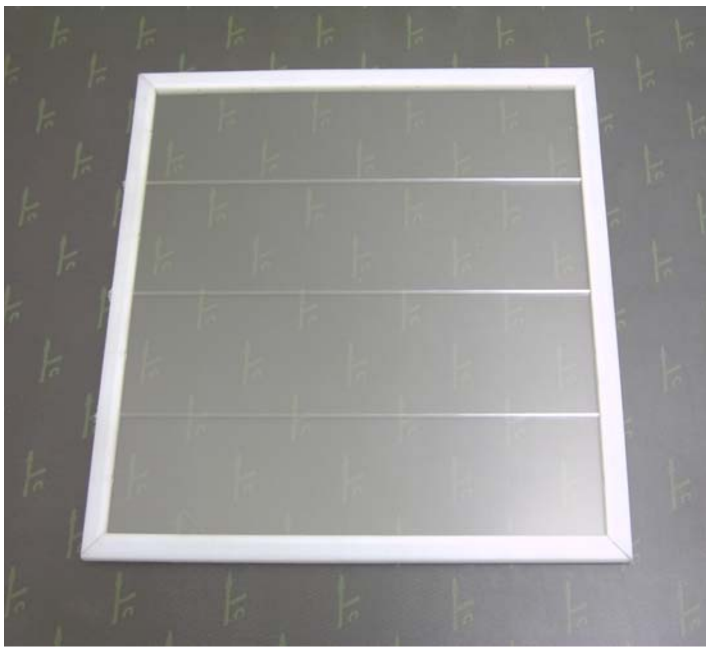
Digital HCAL R&D

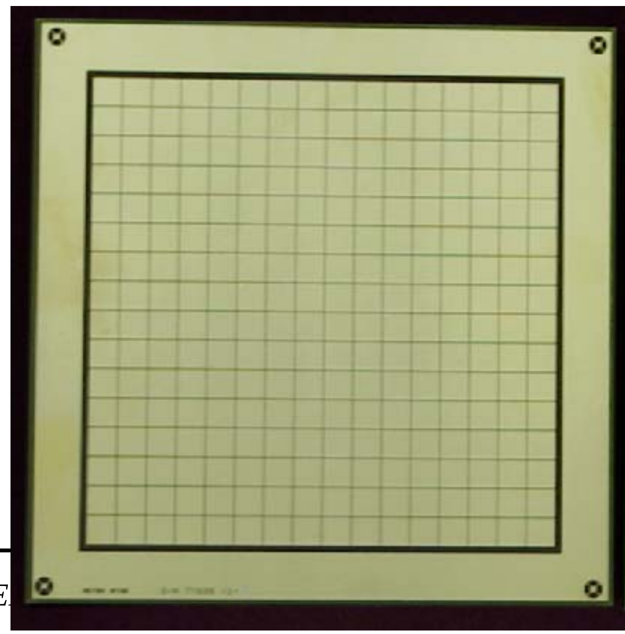
- CALICE Collaboration leads R&D
- Goal: test a physics prototype to validate/calibrate PFAs
  - "The 1 m^3" - big enough to contain a shower
  - 40 layers: 2 cm steel and an active element per layer
  - 1 x 1 cm^2 pads with digital (single-bit) readout
- The prototype has ~400,000 channels!
- Active elements considered
  - Resistive Plate Chambers (RPCs)
  - Gas Electron Multipliers (GEMs)
  - MicroMegas
  - Scintillator
- Current Status: Vertical Slice Test
  - Argonne, BU, UC, FNAL, Iowa, UTA
  - Test at least one of everything in the detector and readout chain
  - 8-10 layers, ~2000 channels
  - RPCs are active medium

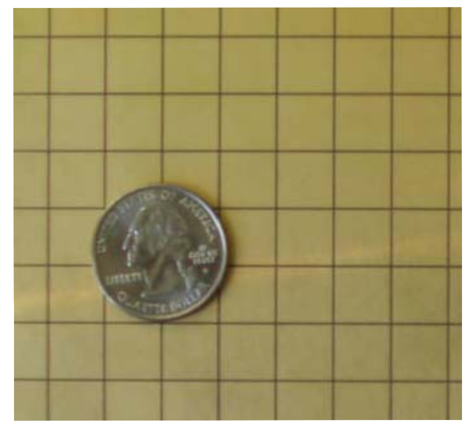


Digital HCAL R&D: RPCs



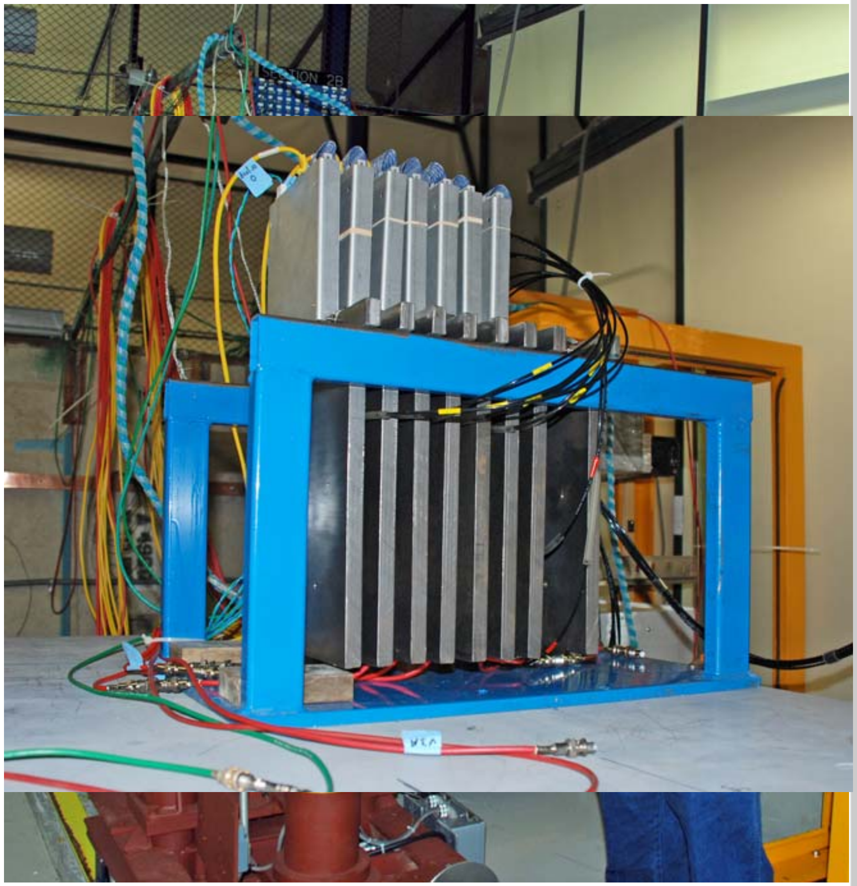


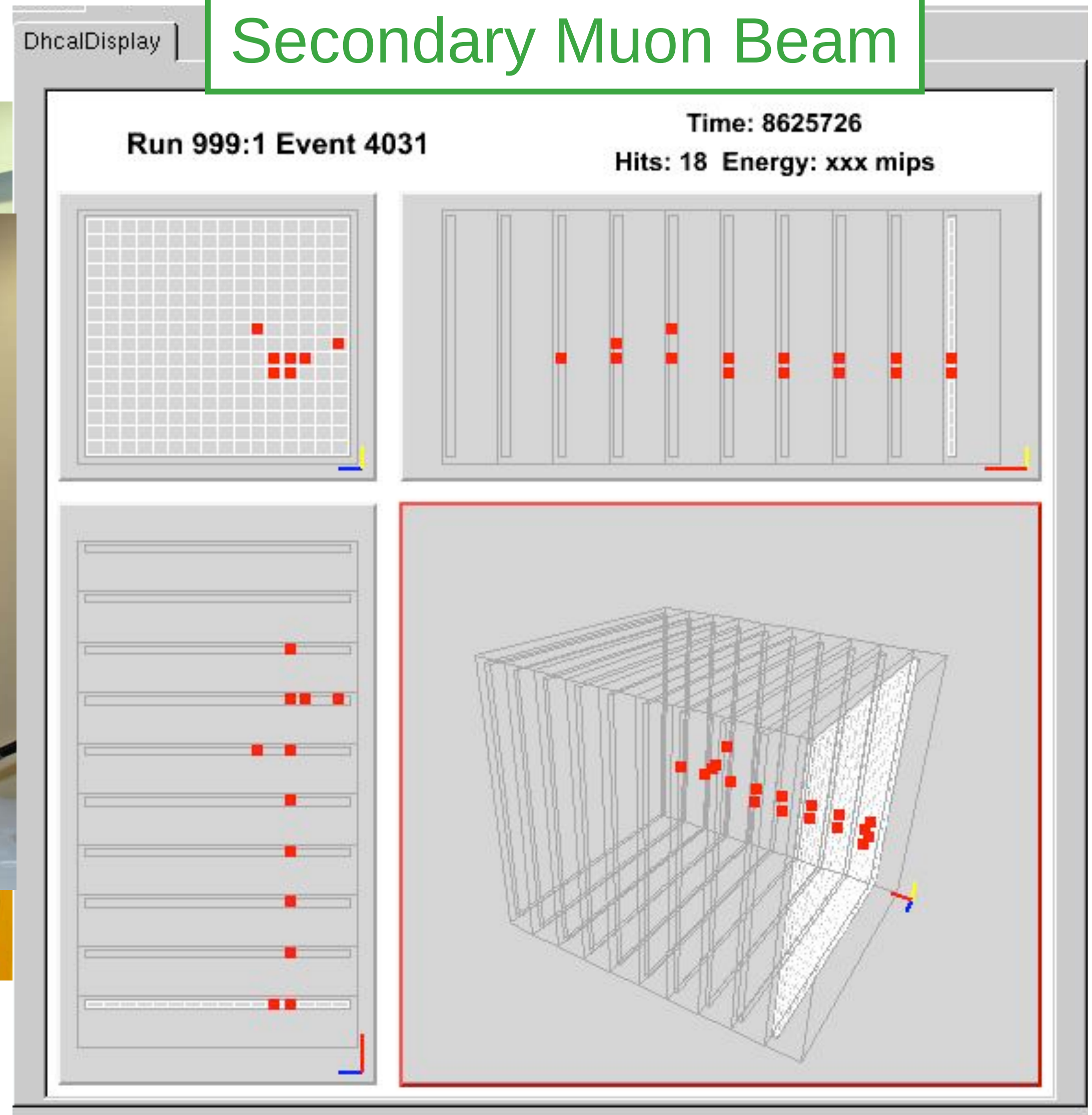




Vertical Slice Beam Test at FNAL

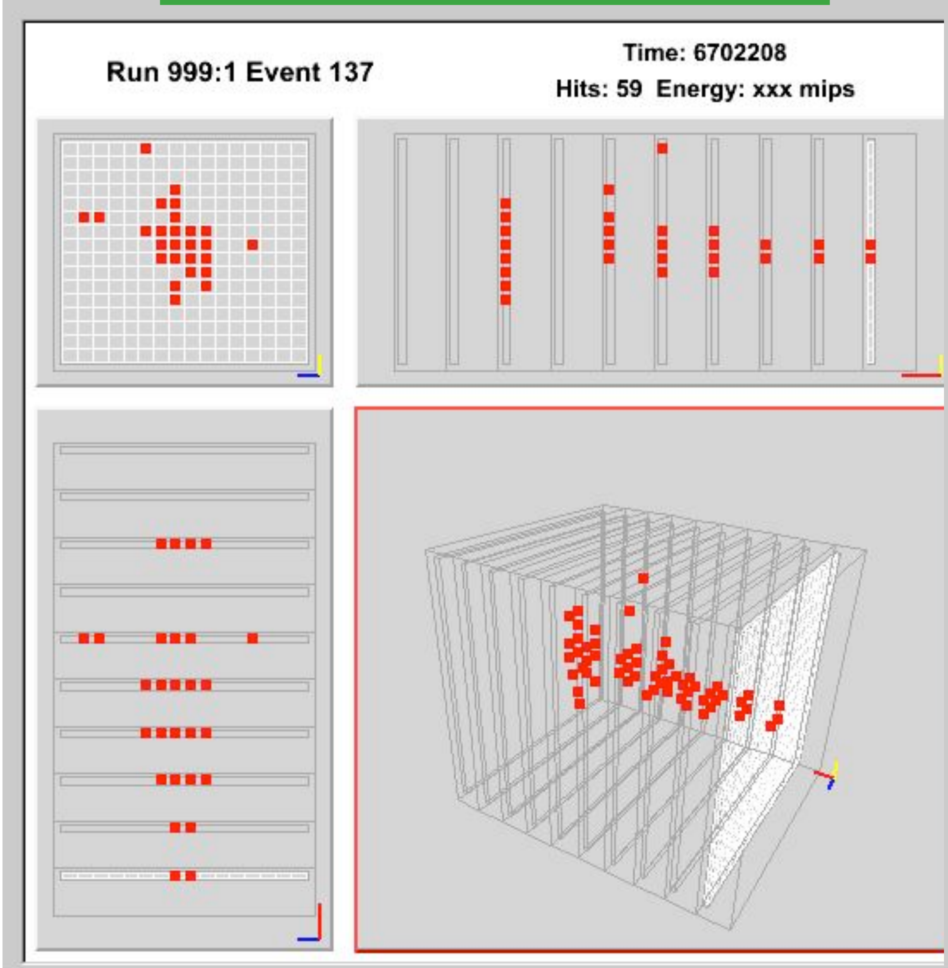
Secondary Muon Beam



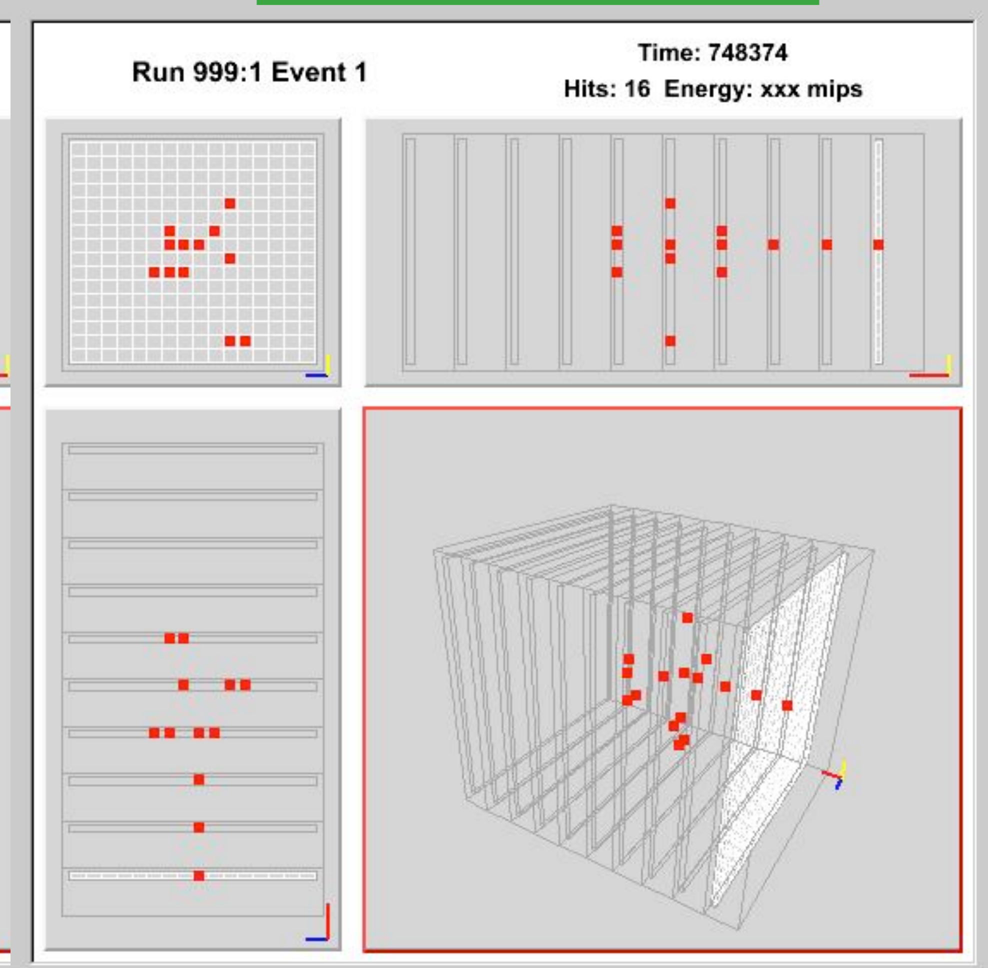


Vertical Slice Beam Test at FNAL

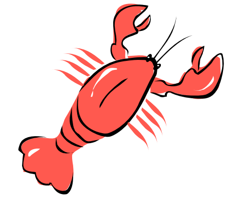
8 GeV Electron Beam



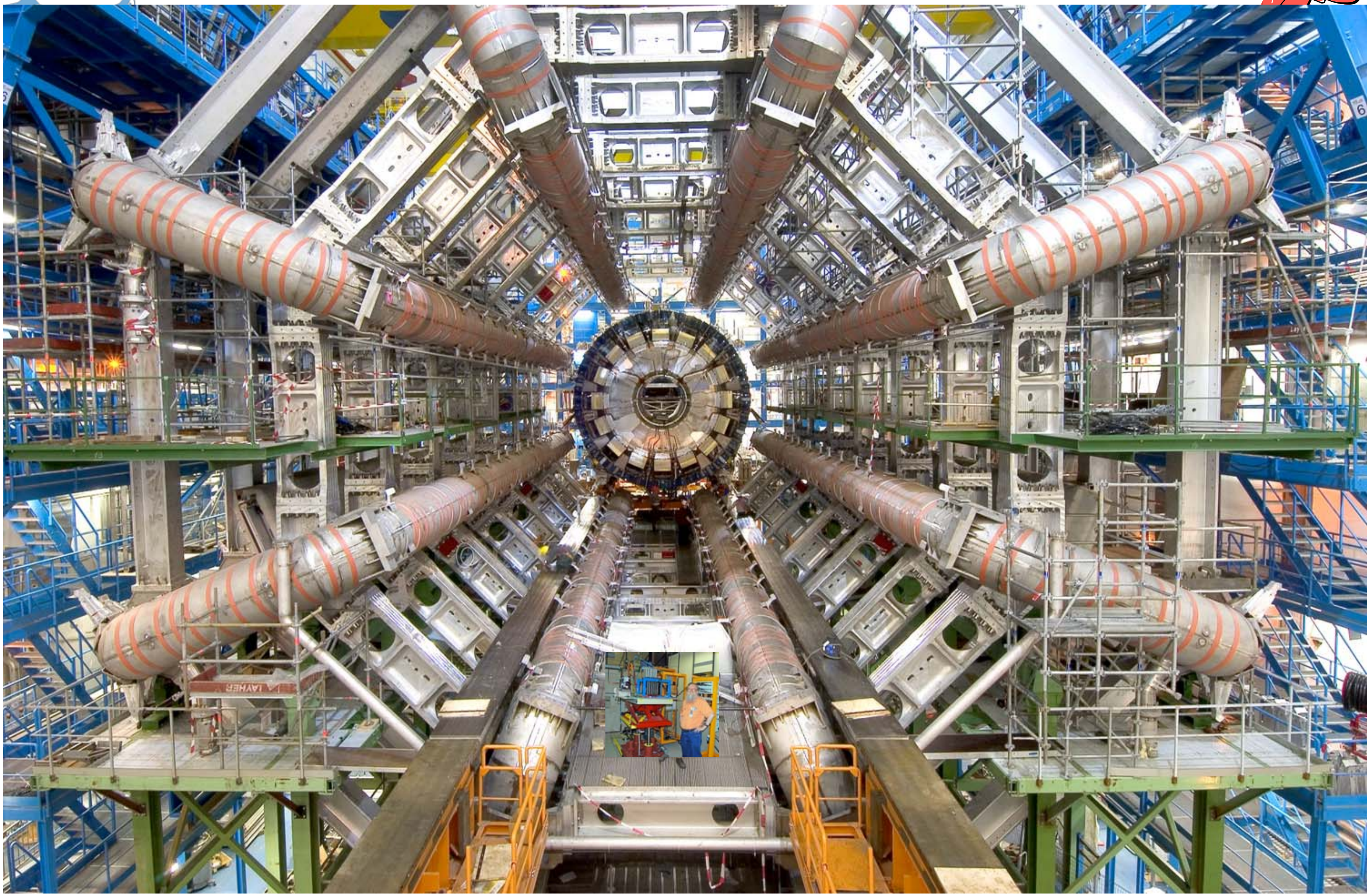
8 GeV Pion Beam



Summary



- To meet the needs of the physics program, detectors at the ILC must achieve unprecedented jet energy resolution
- The most promising strategy is the Particle Flow Algorithm
- Requires a detector whose tracker, ECAL, and HCAL work in concert to measure jet energy
- Calorimeter must be an imaging device
  $\Rightarrow$ 50 megachannels $\Rightarrow$ digital readout
- Monte Carlo studies show that a digital HCAL will meet the performance goals
- Prototype R&D and test beam measurements are underway to demonstrate the PFA concept works in the real world


LAYHER

References

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- Particle Data Group: http://pdg.lbl.gov/
- Linear Collider Workshop 2007, http://lcws07.desy.de/
- CALICE Homepage: http://polywww.in2p3.fr/activites/physique/flc/calice.html
- ILC Reference Design Report, 2007 http://www.linearcollider.org/

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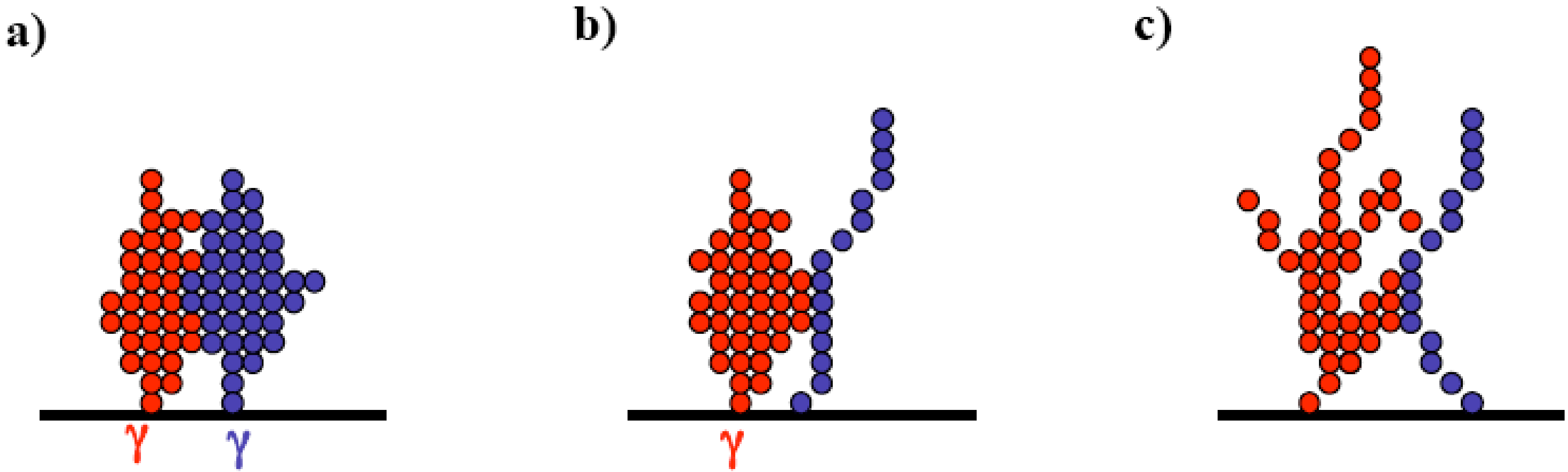
Extra Stuff

Cluster Splitting & Merging



2 photons

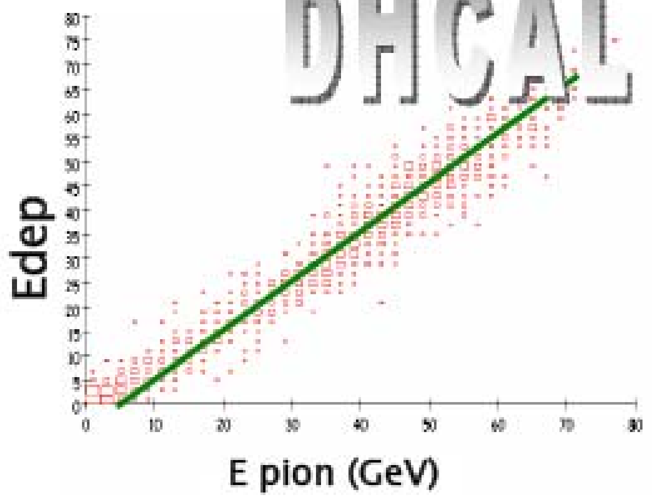
1 photon

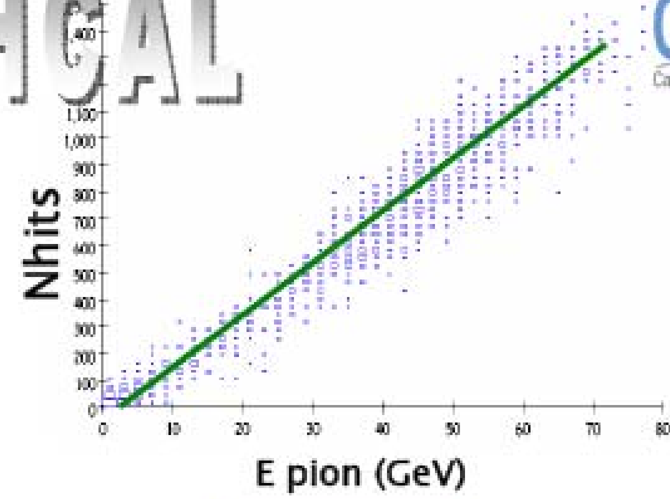
0 photons

PandoraPFA

Jean-Claude Brient

DHCAL vs AHCAL

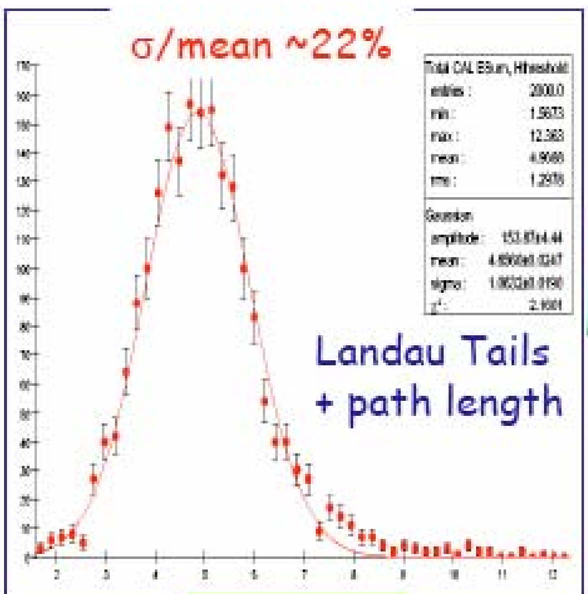




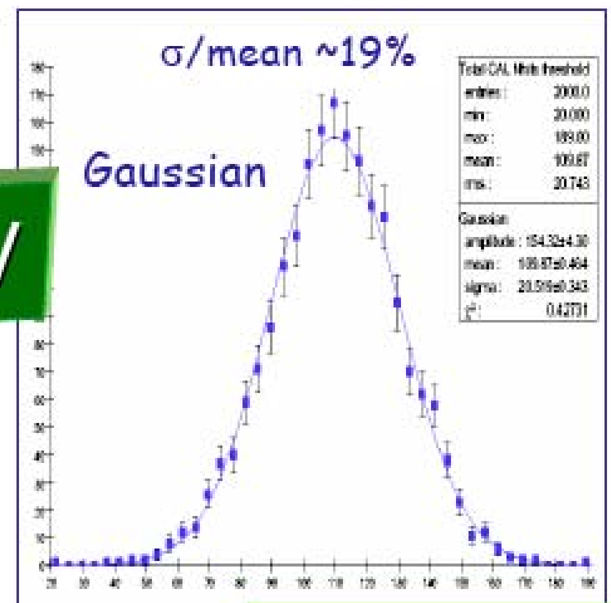
Analog

Digital

π^+ 5GeV

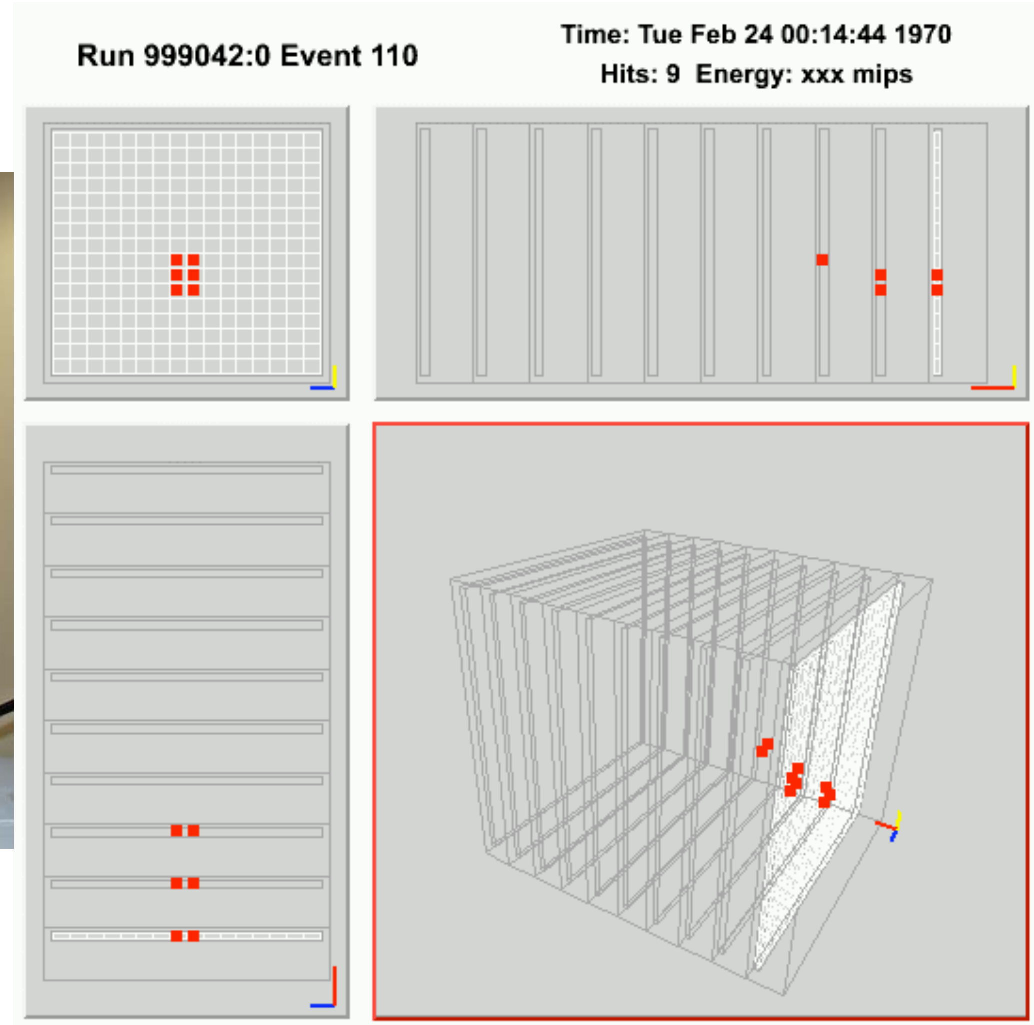


E (GeV)

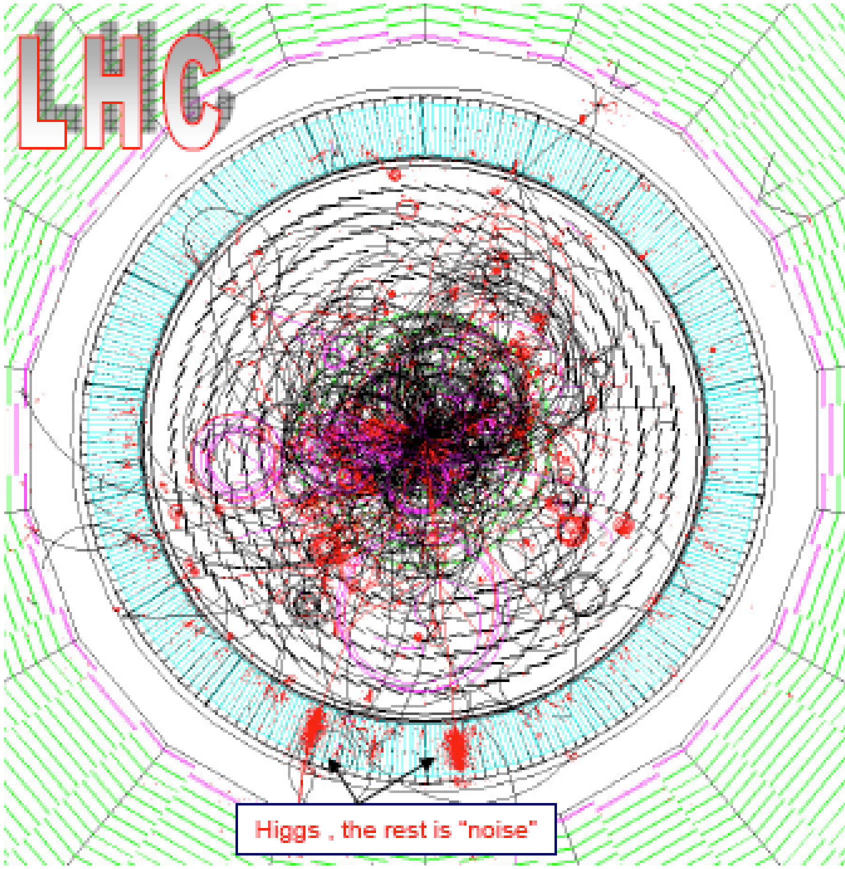


Number of Hits

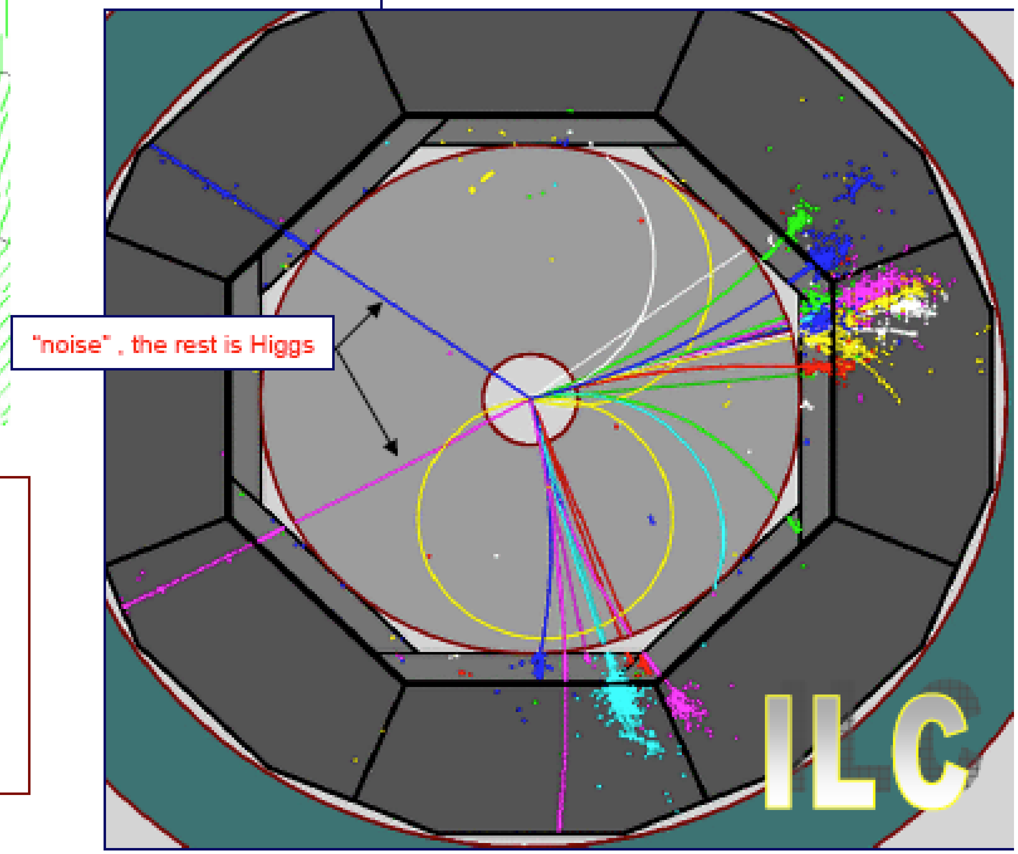
Cosmic Ray Events



One Higgs event



After removing the 2 muons,
All the rest of the event is
Coming from the Higgs decay

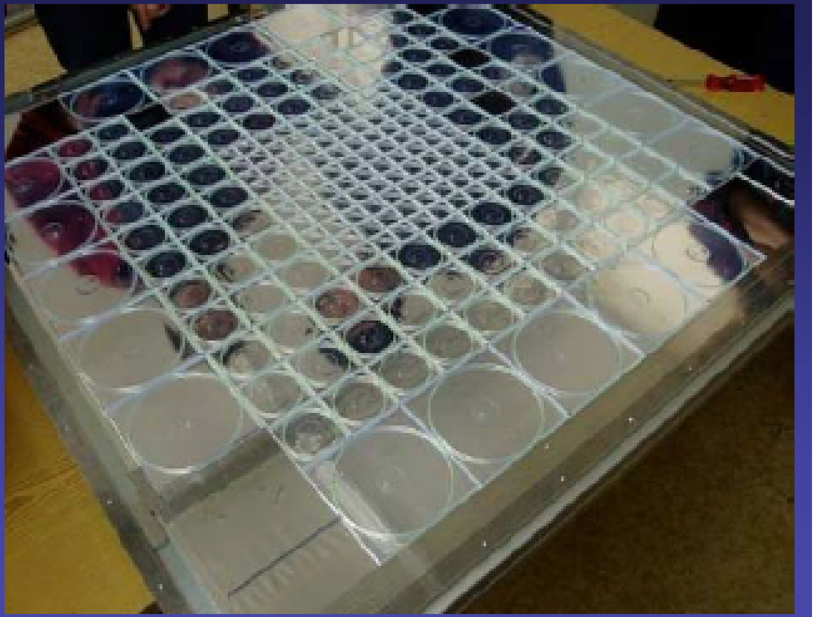


LHC will discover
(open the doors)

ILC will probe the underlying theory (turn on the light)

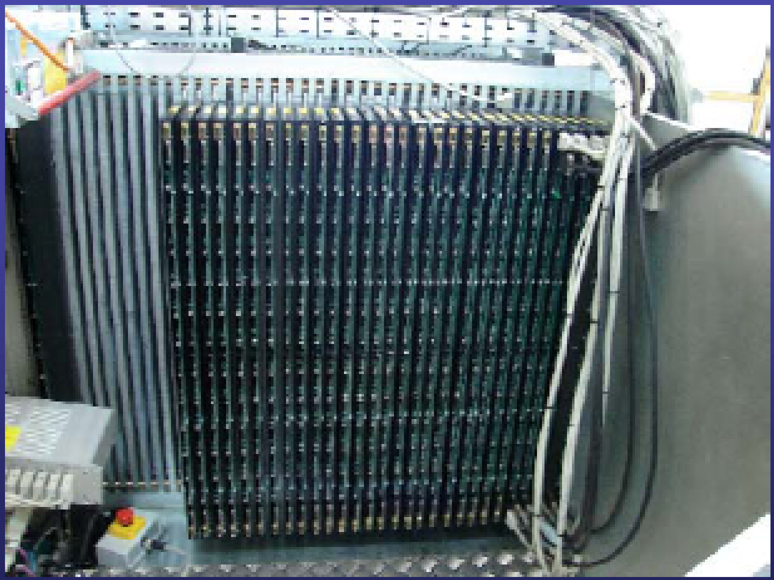
Scintillator HCAL

First calorimeter to use SiPMs



Physics prototype

38 steel plates with a thickness of 1 X_0 each
Scintillator pads of 3 x 3 → 12 x 12 cm^2
→ ~8,000 readout channels



Electronic readout

Silicon Photomultipliers (SiPMs)
Digitization with VME-based system (off detector)

Tests at DESY/CERN in 2006

23/38 readout planes
Electrons 1 – 45 GeV
Pions 6 – 50 GeV