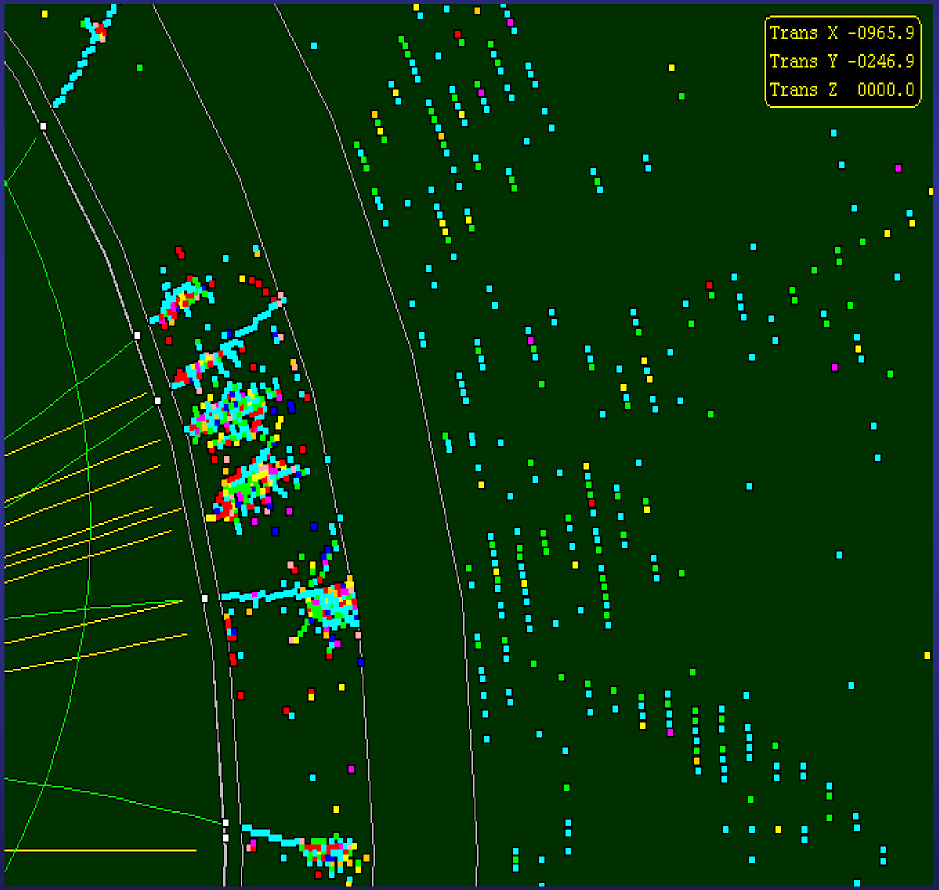
Particle Flow Algorithms



José Repond
Argonne National Laboratory

Snowmass Workshop, August 14 – 27, 2005

Historical milestones for particle physics

Based on K.Pretzl's CALOR'02 review talk

1930 First calorimetric measurement

Mean energy of continuous β spectrum from ^{210}Bi
L. Meitner and W. Orthmann Zeitschrift für Physik 60 (1930) 143

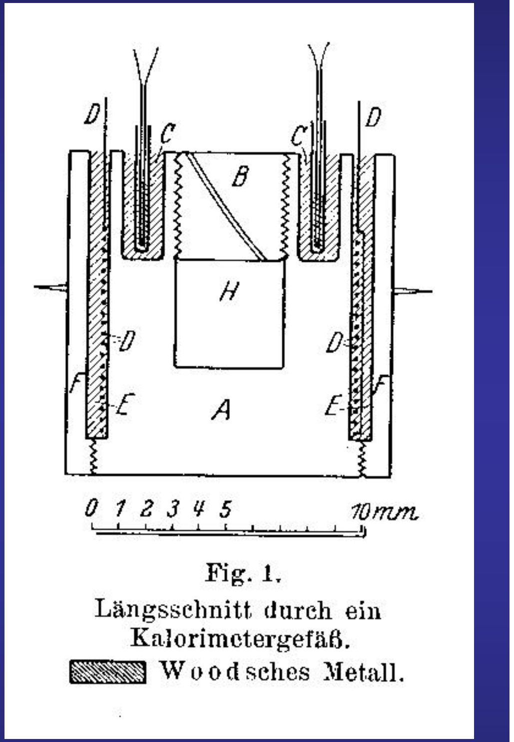
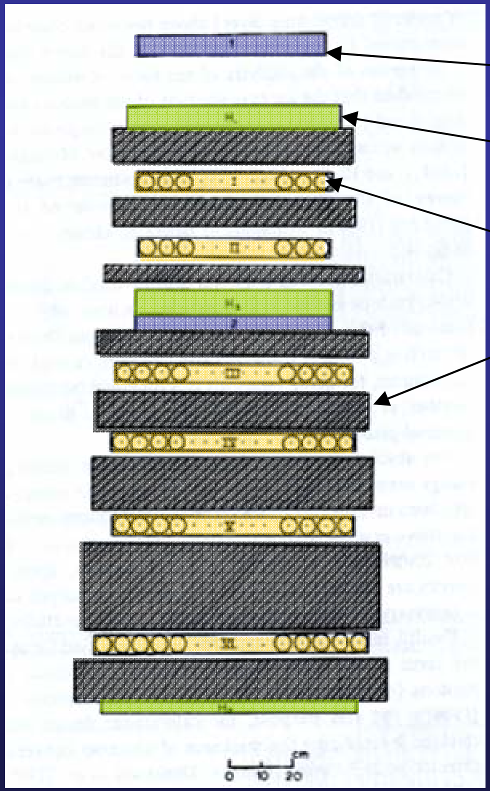


Fig. 1.
Längsschnitt durch ein Kalorimetergefäß.
▨ Woodsches Metall.



Telescope counters

Hodoscopes

Ionization chambers

Absorber (Iron)

1954 First sandwich calorimeter

Measure cosmic rays with E > 10^{14} eV
N.L. Grigorov et al. Zh.Exsp.Teor.Fiz. 34(1954) 506

1968 First total absorption calorimeter

Using large NaI(Tl) or CsI Crystals for π^0 spectroscopy
E.B.Hughes et al., IEEE:NS 17 (1970) 14

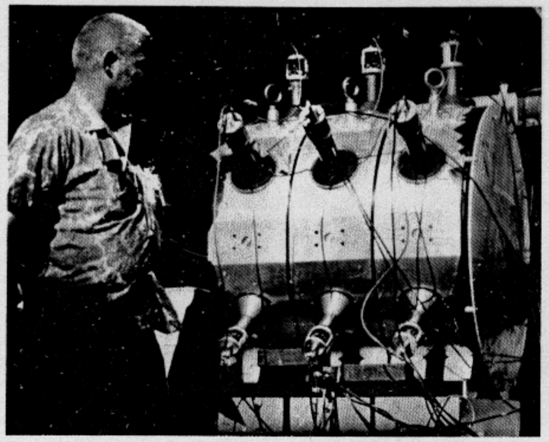
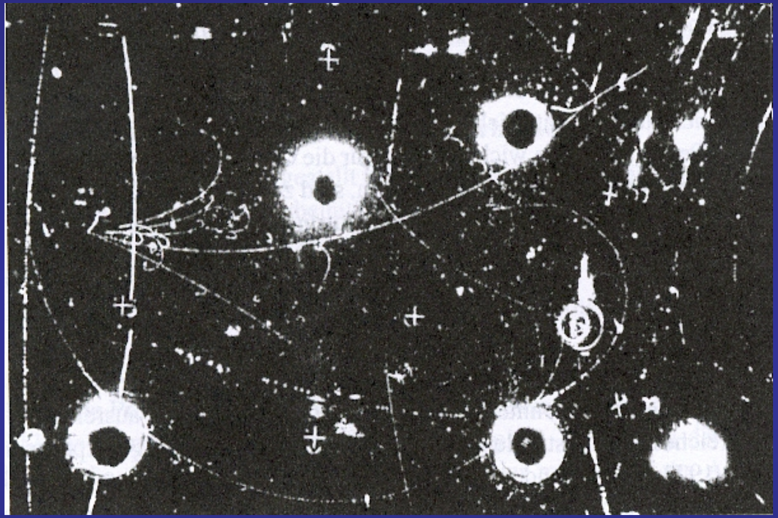


Fig. 4. A photograph of a NaI(Tℓ) spectrometer consisting of three 10" × 30" diameter assemblies.

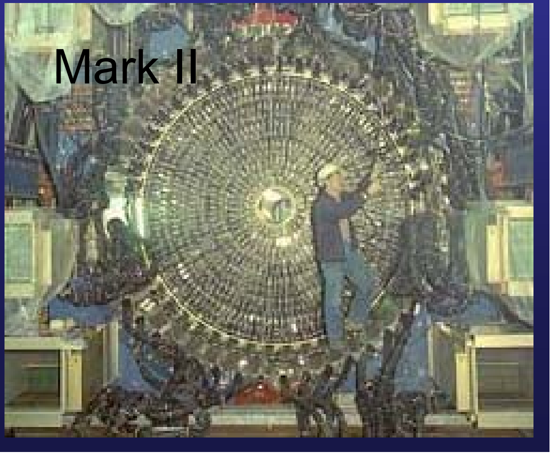


First hadron calorimeter ~1970

GARGAMELLE (bubble chamber) at CERN with $5\ \lambda_I$
Discovery of neutral currents

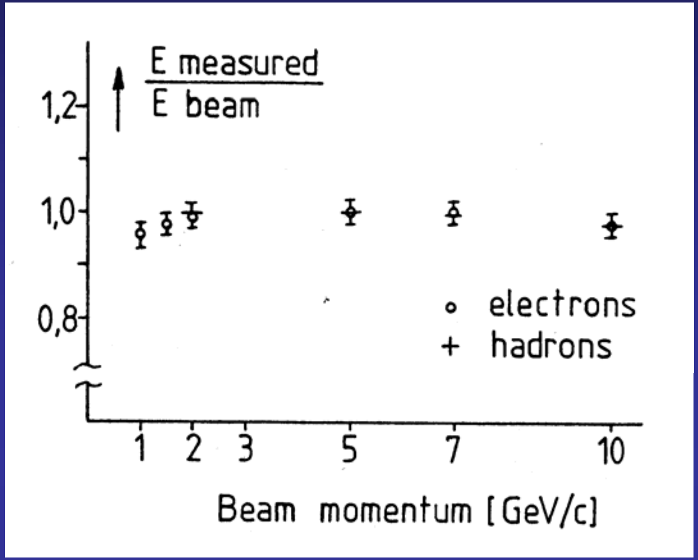
1980's First 4π calorimeters at colliders

SPEAR, PETRA, PEP, SppS…



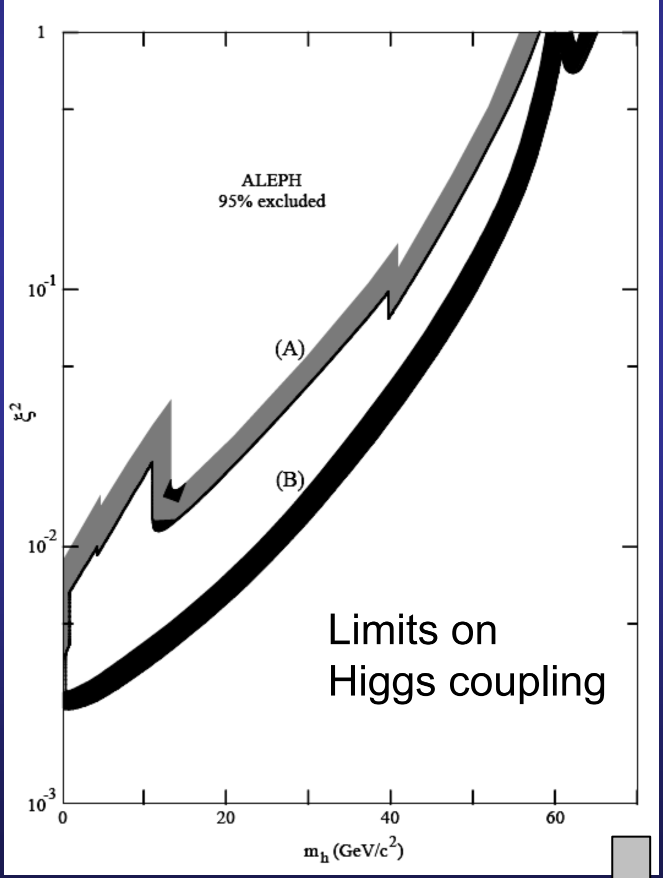
1982 First compensating calorimeter with e/h ~ 1

Axial field spectrometer at the ISR
H.Gordon et al., NIM 196 (1982) 303



First application of 1990 Energy Flow Algorithms

ALEPH detector searching for Higgs



Limits on
Higgs coupling

Now: **Particle Flow Algorithms**

Measuring WW and Z^0Z^0

Many final states involve WW or ZZ pairs

$e^+e^- \rightarrow WW\nu\bar{\nu}$ or $e^+e^- \rightarrow ZZ\nu\bar{\nu}$

Hadronic decay of W or Z

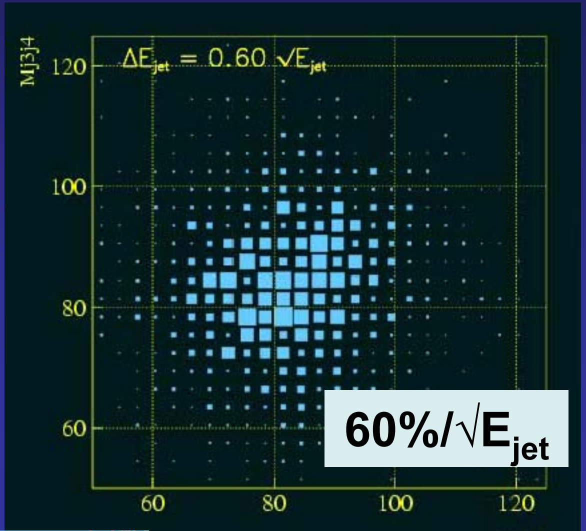
Branching ratio ~ 70%
Results in two hadronic jets

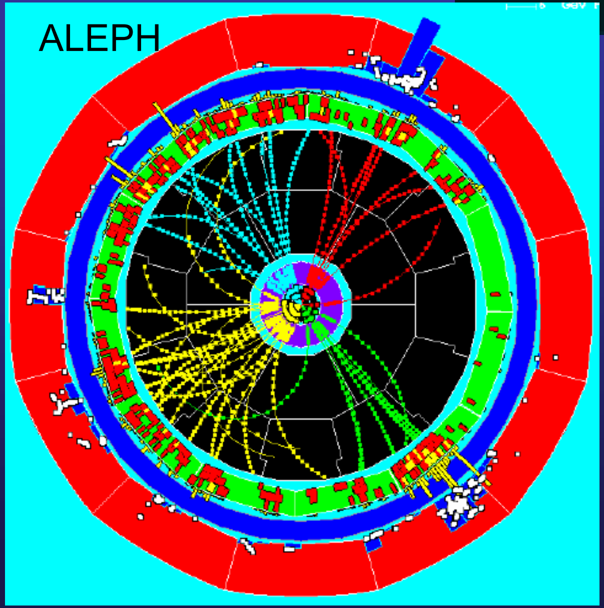
Requires excellent

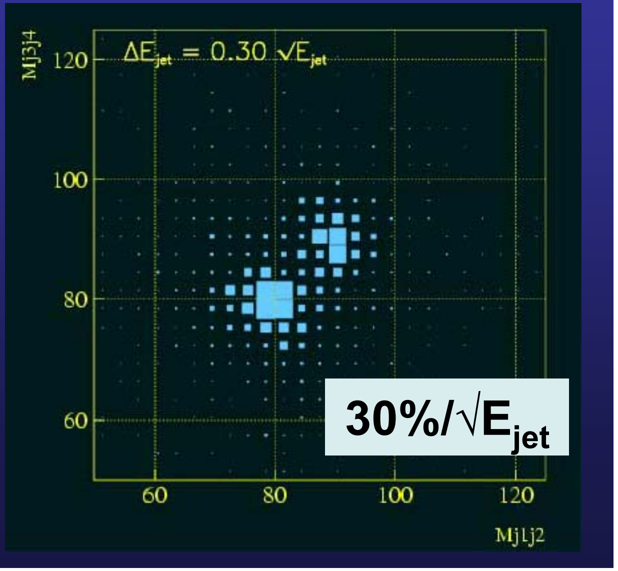
Jet Energy Resolution

to resolve

$\Delta m_{Z\text{-}W} = 9.76$ GeV



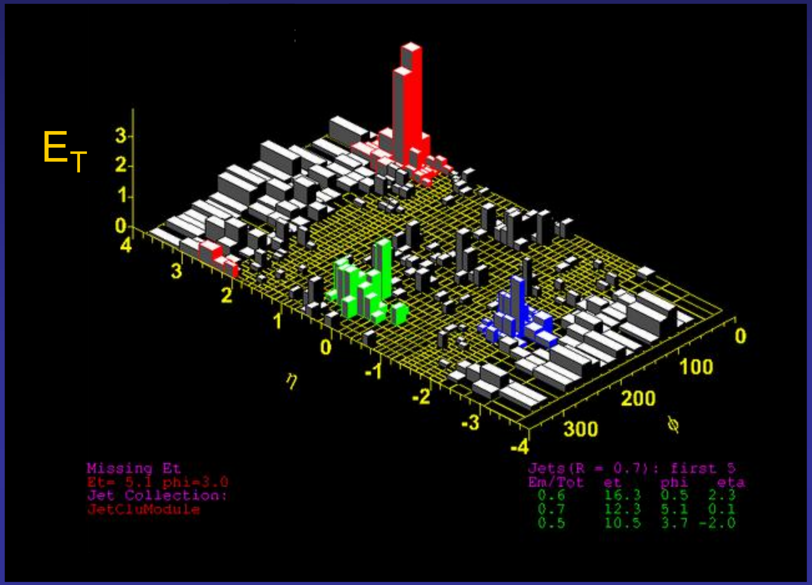




Traditional Jet Measurement

Uses calorimeter alone

→ Example of CDF live event



```
Missing Et
Et= 5.1 phi=3.0
Jet Collection:
JetCluModule
```

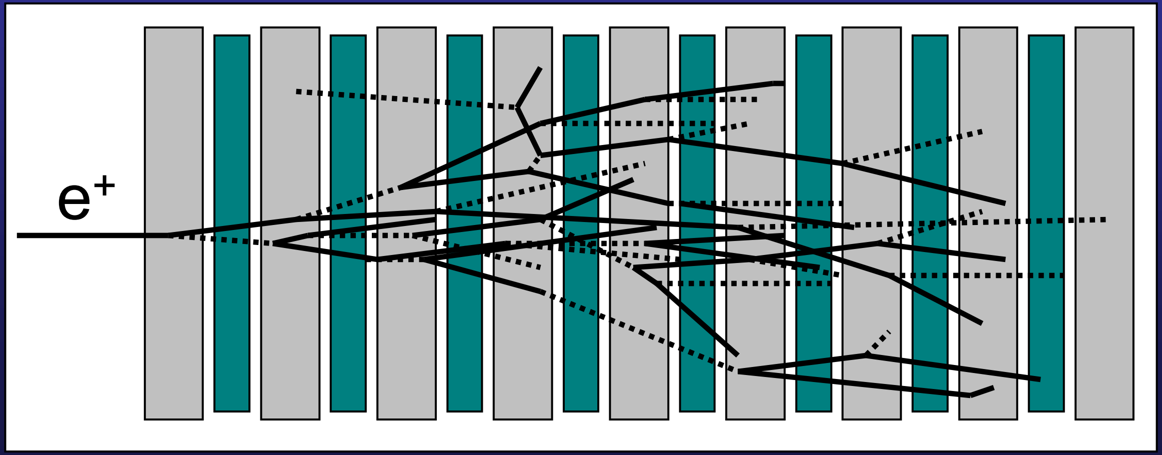
```
Jets(R = 0.7): first 5
Em/Tot  et    phi   eta
 0.6    16.3  0.5   2.3
 0.7    12.3  5.1   0.1
 0.5    10.5  3.7  -2.0
```

Sandwich design

Used by most calorimeters at colliders

→ Alternating layers of

Absorber plates to incite shower and
Active medium (detector) counting charged particles traversing it



$$E_{e^+} \propto \sum N_i$$

Traditional jet measurement

Calorimeter measures photons and hadrons in jet

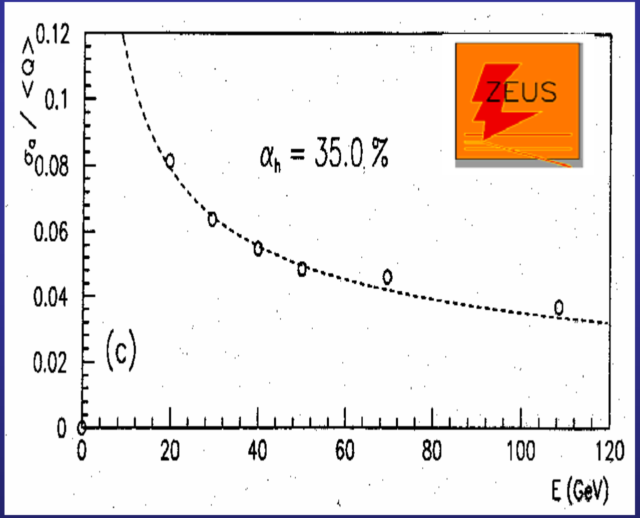
Typically with different response: $e/h \neq 1$
Leads to poor jet energy resolution of > $100\%/\sqrt{E_{jet}}$

ZEUS tuned

Scintillator and Uranium thickness to achieve $e/h \sim 1$

→ **Best single hadron energy resolution ever**

$35\%/\sqrt{E}$ ⇨ $50\%/\sqrt{E}$ Jet Energy Resolution



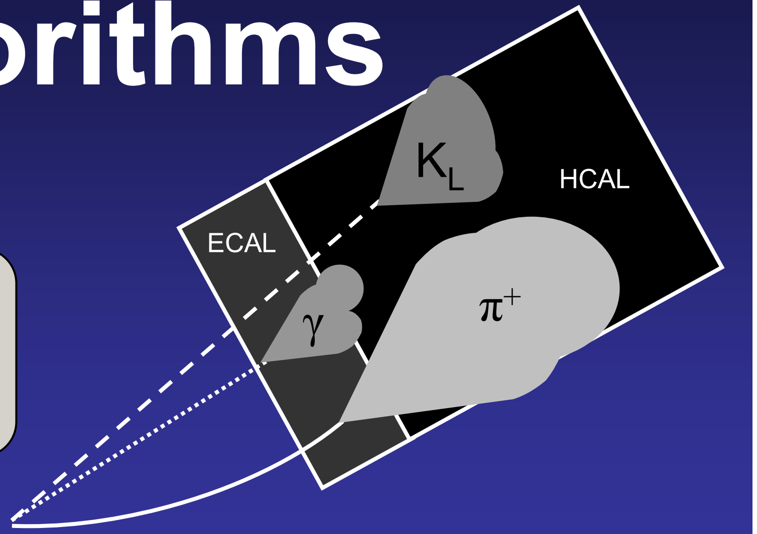
At the Linear Collider

Goal of **$\sigma/E_{jet} = 30\%/\sqrt{E_{jet}}$**

New approach

Need new approach

Particle Flow Algorithms



The idea…

Charged particles
Neutral particles
} measured with the {
Tracker
Calorimeter

Particles in jets	**Fraction of energy**	**Measured with**	**Resolution** [σ^2]
Charged	65 %	Tracker	Negligible
Photons	25 %	ECAL with 15%/√E	$0.07^2 E_{jet}$
Neutral Hadrons	10 %	ECAL + HCAL with 50%/√E	$0.16^2 E_{jet}$
Confusion	Required for 30%/√E		**$\leq 0.24^2 E_{jet}$**

} 18%/√E

Requirements on detector

→ Need excellent tracker and high B – field
→ Large R_l of calorimeter
→ Calorimeter inside coil
→ Calorimeter with extremely fine segmentation

} **Figure of merit BR_l^2**

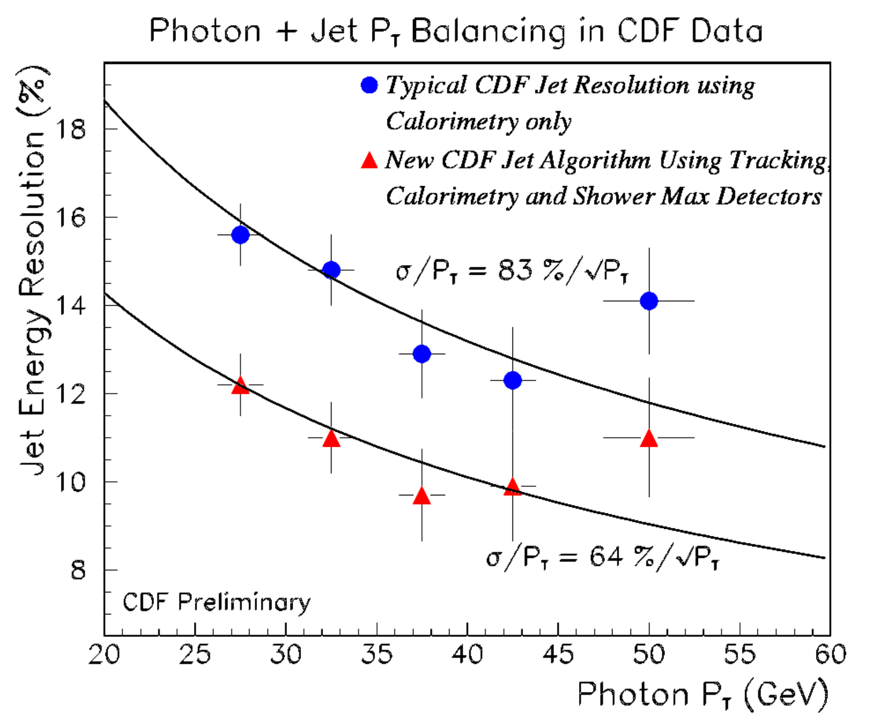
Do they work?

Applied to existing detectors

ALEPH, CDF, ZEUS…

→ **Significantly improved resolution**

YES! **But that is not the issue…**



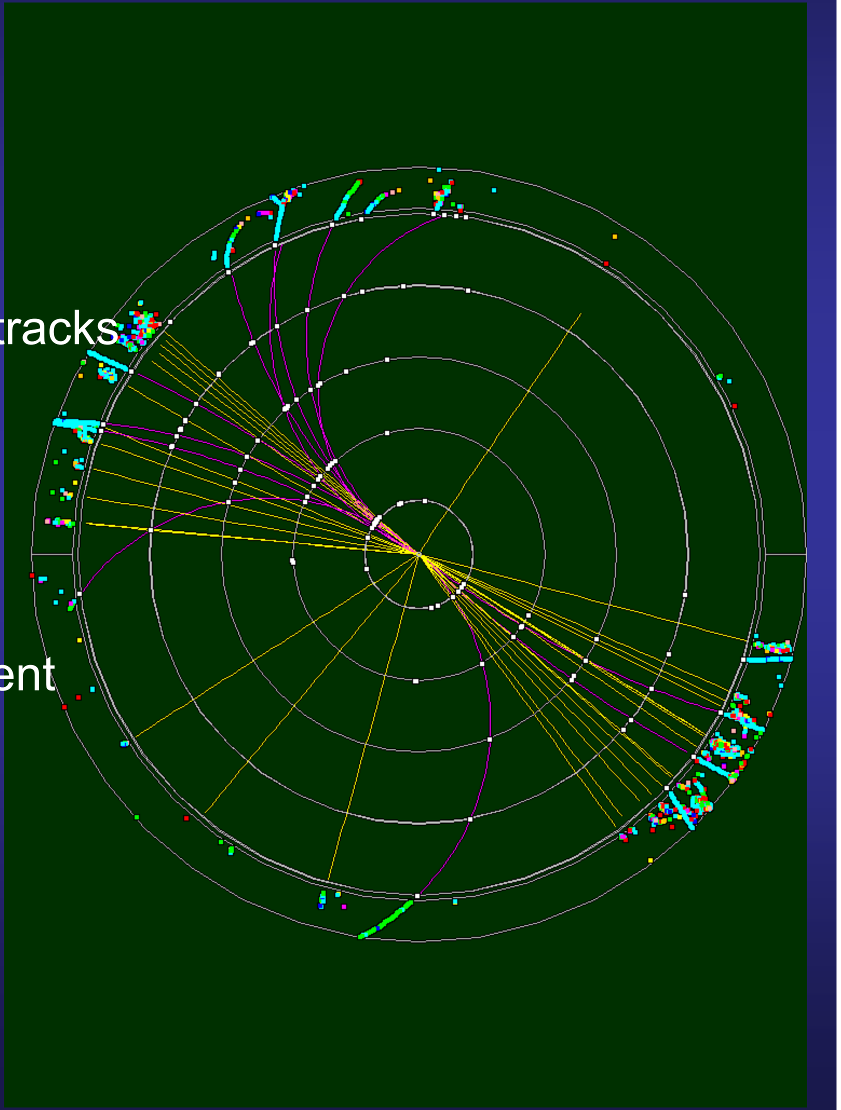
Goal for the Linear Collider Detector

Design a detector optimized for the application of PFAs

Huge simulation effort underway

→ England, France, Germany, Argonne, Iowa, Kansas, NIU, SLAC…

Ingredients of PFAs



I Clustering of calorimeter hits

II Matching of clusters with charged tracks

III Photon finder

IV Neutral hadron energy measurement

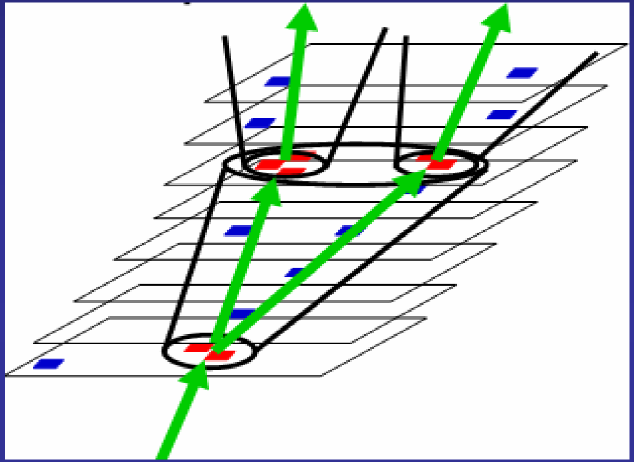
V Special tasks

Most important subtask of PFAs…

Clustering of calorimeter hits

Tubes (Kuhlmann, Magill)

Adding hits in cones originating at high density points
Tuned cone size



Cone algorithm (Yu)

Using maximum density cells as centroids
Add hits (energy) in cones

Layer – by – layer (Ainsley)

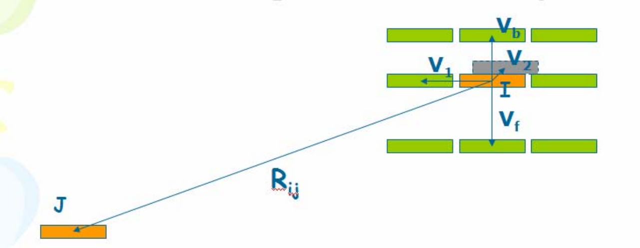
Minimizing distance between hits in adjacent layers
Tracking algorithm

Directed tree (NIU)

Calculate density differences for pairs of cells
Use maximum density difference to either start new cluster or merge cells

Density weighted (Xia)

Defined geometry independent density function
Seeds are cells with highest density
Cluster hits with densities above a given cut



$$D_{ij} = e^{-(|(\hat{V}_1,R_{ij})|/|V_1|)} \times e^{-(|(\hat{V}_2,R_{ij})|/|V_2|)} e^{-((\hat{V}_3,R_{ij})/|V_3|)}$$

With $V_3 = V_f$ (if $(V_f,R_{ij}) > 0$) or V_b (if $(V_b,R_{ij}) > 0$)

….more

Clustering of calorimeter hits

Criteria for performance

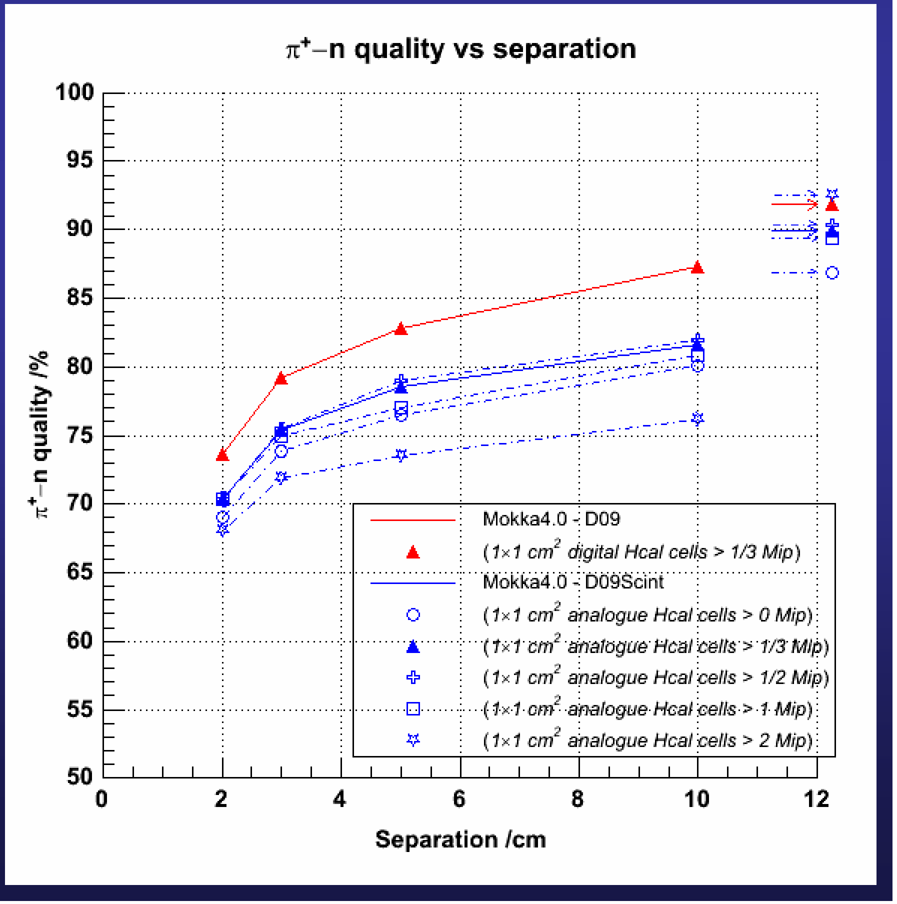
Efficiency (find all hits belonging to a given particle)
Purity (reject hits not associated with a given particle)

Example from Ainsley

5 GeV (π^+n) event at a distance of 5 cm

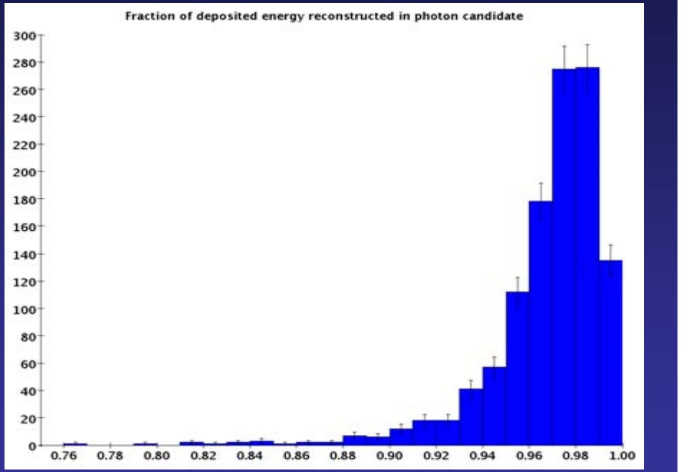
Distribution of event energy [%]	True cluster ID	
Reconstructed cluster ID	7.4	40.1
	46.3	6.1

Quality = Fraction of event energy that maps in a 1:1 ratio between true and reconstructed clusters

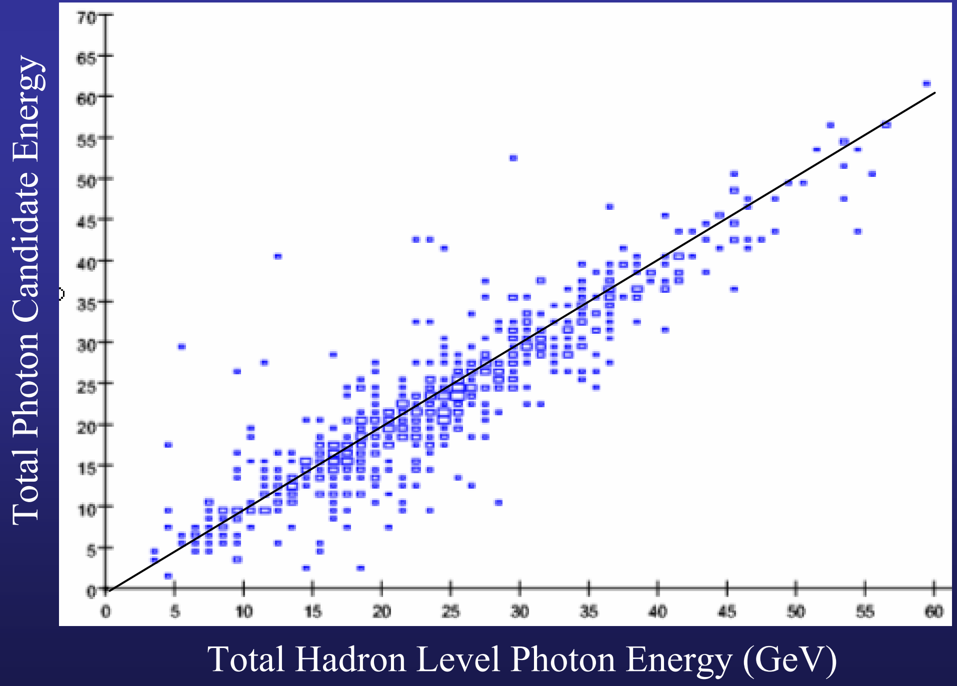


Photon finders

Using Minimum Spanning Tree clustering (Iowa)



Evaluation of	Number of hits in cluster Distance to closest MIP track Eigenvalue of energy tensors
Performance	99% γ efficiency with 5% π^+ contamination Good energy reconstruction



Using HMatrix (Graf, Wilson)

Using Cones (Kuhlmann, Magill)

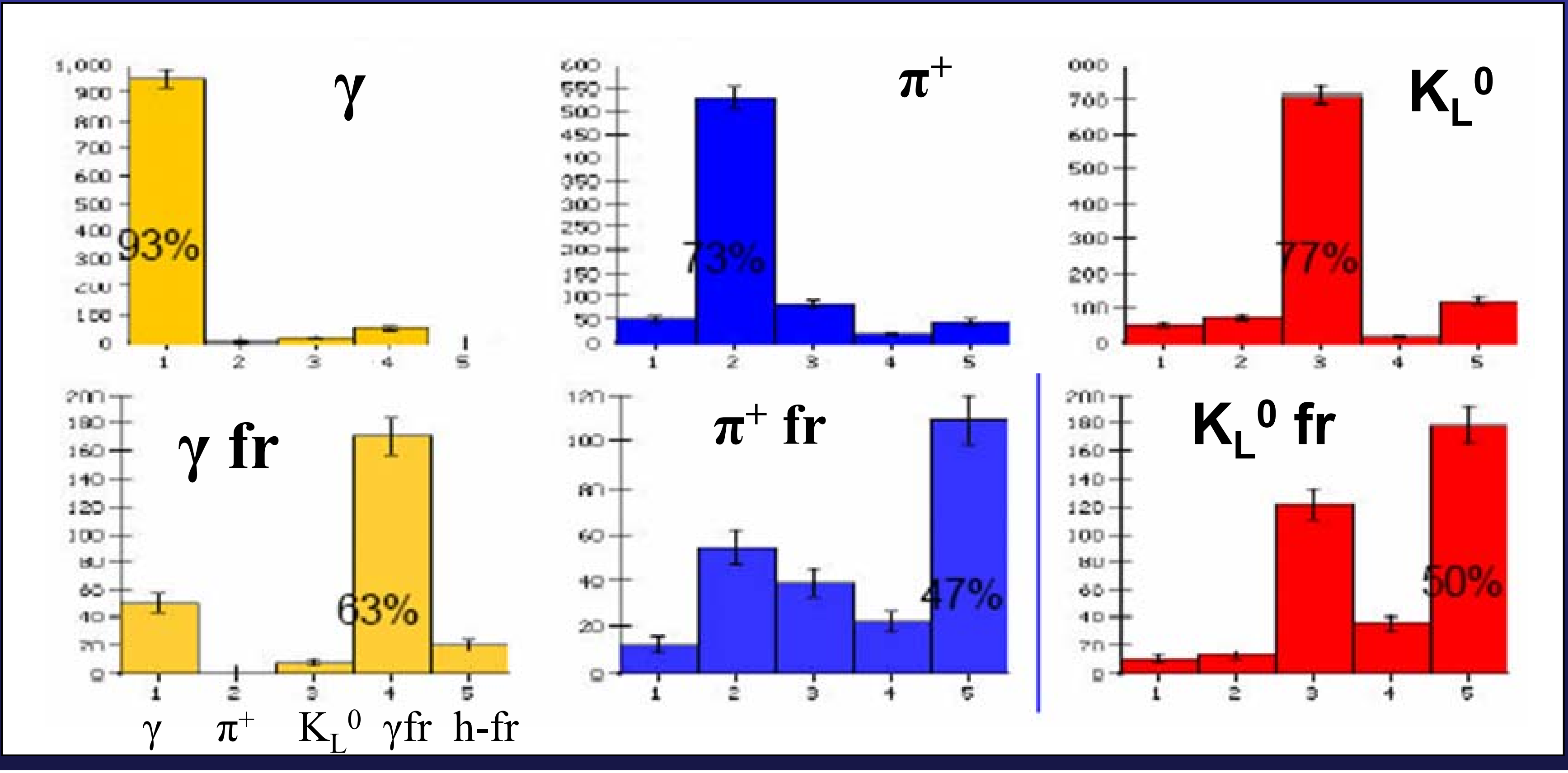
Cuts on	Distance to charged tracks Location of shower maximum

Example using Neural Nets (Bower, Cassell)

Calculates energy tensor of clusters
Neural net separates into

- EM clusters
- Neutral hadronic
- Charged hadronic
- EM fragment
- Hadronic fragment

Putting it all together



First Results

Applied to $e^+e^- \rightarrow Z^0 \rightarrow q\,\bar{q}$ events

Two Gaussian fit

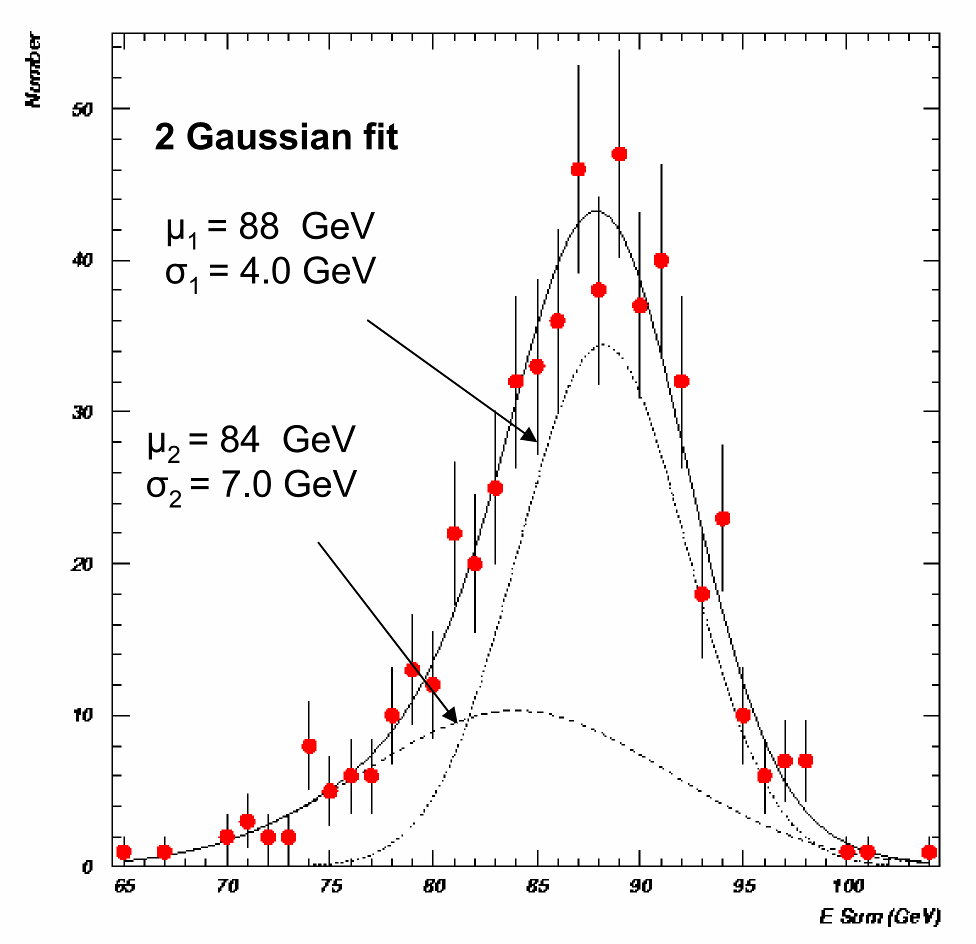
Jet Energy Resolution still factor 2 from goal

Future improvements to

- Tube algorithm
- Photon finding
- Neutral hadron energy measurement

Lots of effort needed!!!

(before being useful for detector design)



Calorimeter Developments

Requirements for the LCD

- Highly segmented readout

  Layer – by – layer longitudinally
  $\mathcal{O}$(1 cm²) laterally

- Compact design

  Short radiation length X_0 for ECAL
  Short interaction length λ_I for HCAL
  Minimal Molière radius R_M

Molière Radius

Definition $R_M = X_0 E_S / E_C$

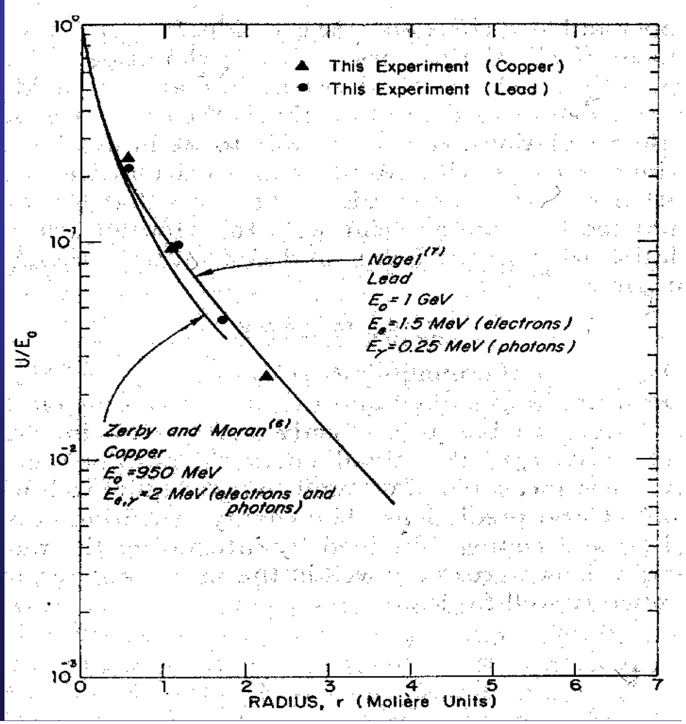
with X_0 … Radiation length

Electron looses all but 1/e of its energy by Bremsstrahlung
Scale for longitudinal development of EM showers

E_S … Scaled energy = 21 MeV
E_C … Critical energy

Energy where shower development dies

Meaning 90% of energy contained in cylinder with R = R_M



Concept of the SiD Calorimeter

1) **Located inside the coil**

2) **Finest readout segmentation possible**

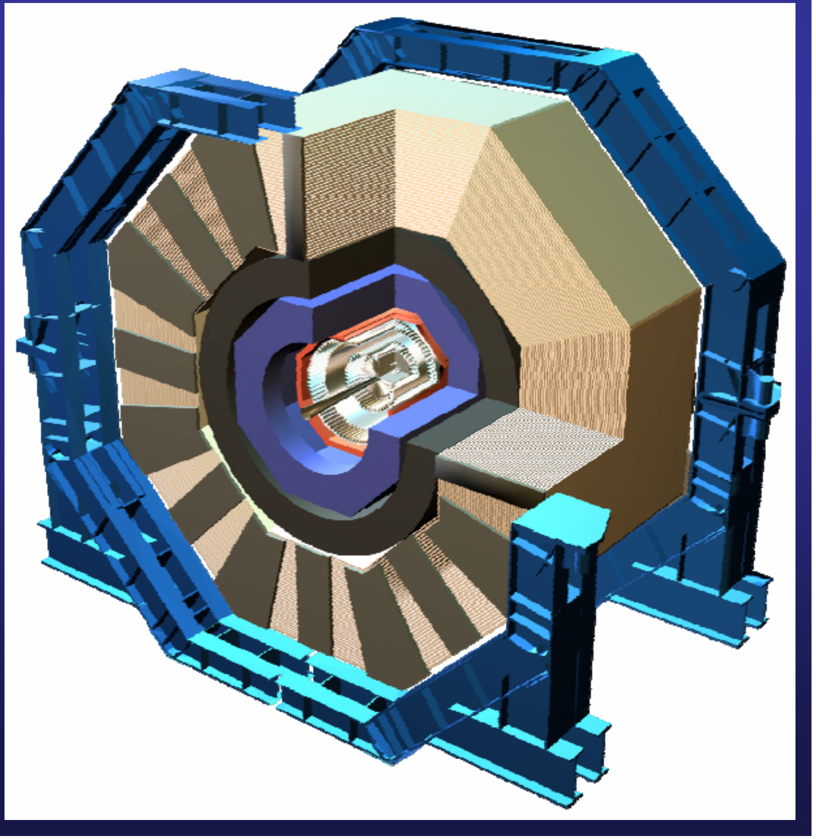
In ECAL of order 0.2 cm^2
In HCAL of order 1.0 x 1.0 cm^2 } laterally
Layer – by – layer longitudinally

3) **Thinnest possible active detectors**

Minimize $R_{Moliere,}$ and cost
In ECAL of order 1 – 2 mm
In HCAL of order 5 – 10 mm

4) **Absorber**

Tungsten in ECAL ($R_{Moliere}$ ~ 9 mm)
Steel (default) or Tungsten in HCAL



Technical Realization: ECAL

Ray's preferred structure

$20 \times 5/7\ X_0 + 10 \times 10/7\ X_0$
corresponding to $29\ X_0$

Silicon – Tungsten Sandwich

30 x	Tungsten	0.250 cm	corresponds to $5/7\ X_0$
	G10	0.068 cm	
	Silicon	0.032 cm	
	Air	0.025 cm	
		0.375 cm	

→ $R_{Moliere} \sim 14$ mm

Overall thickness

$\sim 22\ X_0$ or $\sim 0.8\ \lambda_I$

Barrel

$R_I = 127$ cm → $R_O = 138.25$ cm
$-179.5\text{ cm} < z < +179.5\text{ cm}$

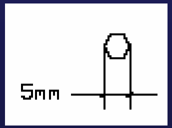
Endcaps

$z_I = 168$ cm → $z_O = 179.25$ cm
$20\text{ cm} < R < 125\text{ cm}$

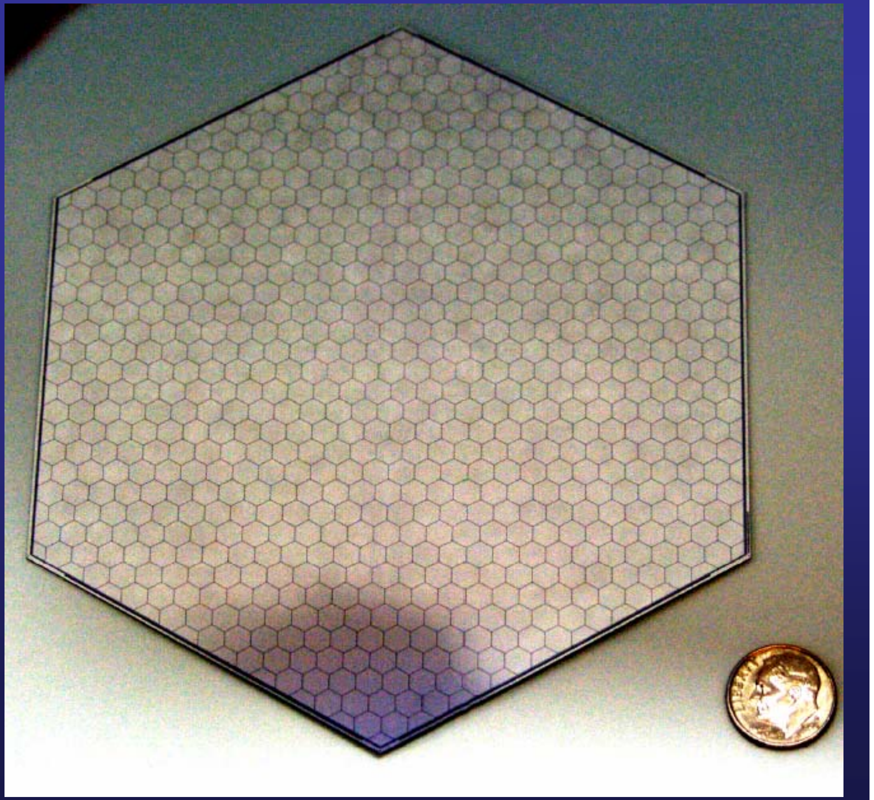
Readout segmentation

$\sim 0.16\text{ cm}^2$

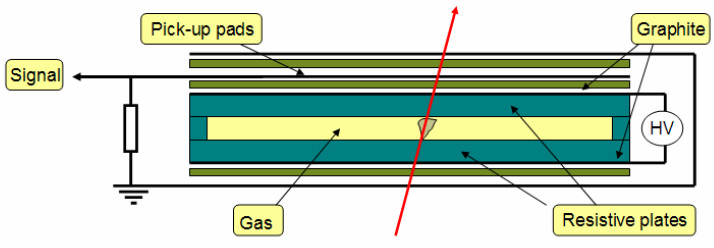
Single electron resolution



$\sim 16\%/\sqrt{E}$



Technical Realization: HCAL



RPC – Steel Sandwich

34 x	Steel	2.00 cm	corresponds to 1.1 X_0
	G10	0.30 cm	
	Pyrex Glass	0.11 cm	
	RPC gas	0.12 cm	
	Pyrex Glass	0.11 cm	
	Air	0.16 cm	
		2.80 cm	

Overall thickness

~ 45 X_0 or ~ 4.1 λ_I

Barrel

R_I = 138.5 cm → R_O = 233.7 cm
-277 cm < z < +277 cm

Endcaps

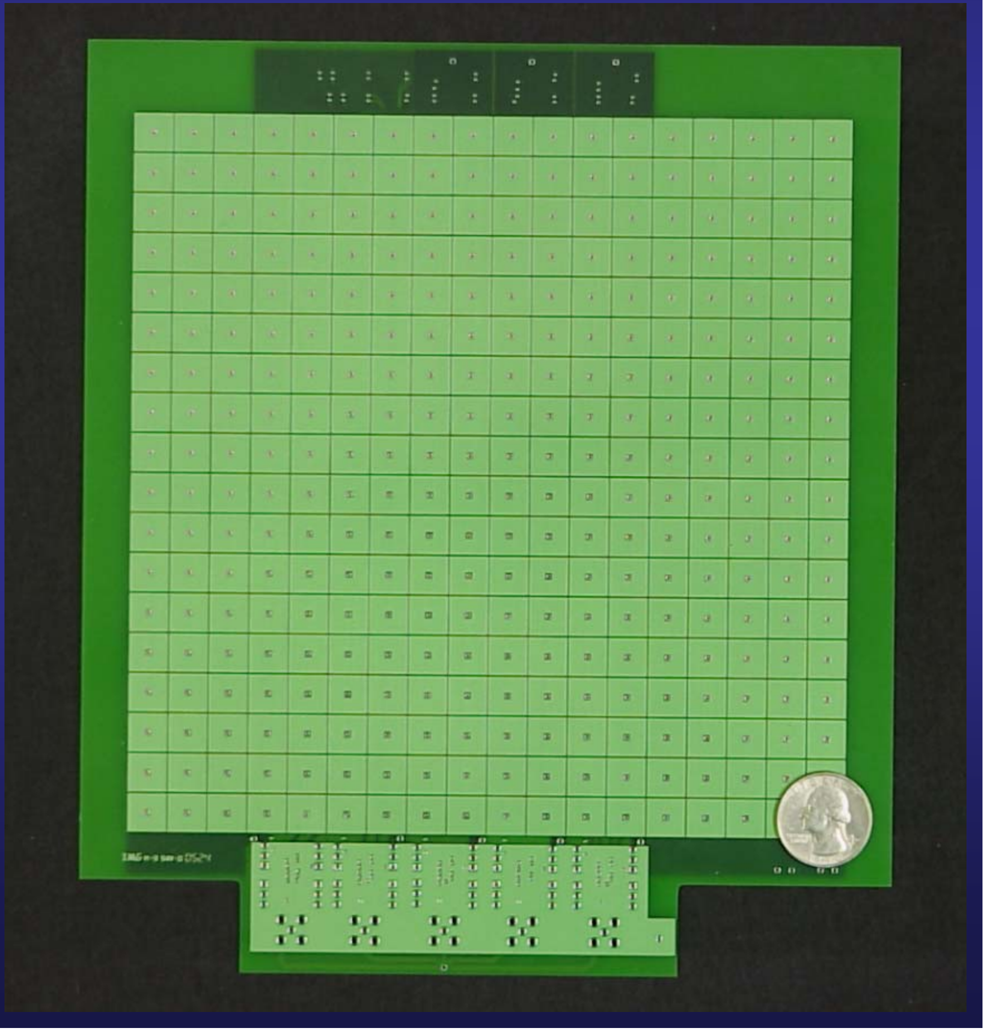
z_I = 179.5 cm → z_O = 274.7 cm
20 cm < R < 138.25 cm

Readout segmentation

1.0 x 1.0 cm^2 …is this the default now?

Single π^+ resolution

55 – 65 %/√E



Choices for HCAL active media

	Scintillator	GEMs	RPCs
Technology	Proven (SiPM?)	Relatively new	Relatively old
Electronic readout	Analog (multi-bit) or Semi-digital (few-bit)	Digital (single-bit)	Digital (single-bit)
Thickness (total)	~ 8mm	~8 mm	~ 8 mm
Segmentation	3 x 3 cm^2	1 x 1 cm^2	1 x 1 cm^2
Pad multiplicity for MIPs	Small cross talk	Measured at 1.27	Measured at 1.6
Sensitivity to neutrons (low energy)	Yes	Negligible	Negligible
Recharging time	Fast	Fast?	Slow (20 ms/cm^2)
Reliability	Proven	Sensitive	Proven (glass)
Calibration	Challenge	Depends on efficiency	Not a concern (high efficiency)
Assembly	Labor intensive	Relatively straight forward	Simple
Cost	Not cheap (SiPM?)	Expensive foils	Cheap

?

Fine Tuning of the Calorimeter Design

Many design parameters to adjust

Overall	Inner radius of calorimeter
	Outer radius of calorimeter
	Transition from barrel to endcaps
	Transition from endcaps to very forward calorimeters
ECAL	Absorber thickness (uniform, varying with depth)
	Number of layers
	Segmentation of readout
HCAL	Absorber choice → Tungsten (2 X_0) versus steel (1 X_0)
	Number of layers
	Active medium (RPC, GEM, Scintillator)
	Segmentation of readout
	Resolution of readout (number of bits)
Tail catcher	Needed?
	Same technology as HCAL

Need reasonably well performing PFA to evaluate different designs

Reasonably well performing PFA

Jet energy resolution of 40%/√E or better

Test with $e^+e^- \rightarrow W^+W^-$ at $\sqrt{s} = 500$ GeV
Reconstruct W mass with $\Gamma \leq 4$ GeV

Allowed tricks (at the moment)

Use of MC truth for track parameters
Cut on event axis to be within 55 degrees of normal
Eliminate events with significant energy in neutrinos
Use of code by other developers

Reward for 1st person/group to achieve goal

Several bottles of champagne (John, José, Harry)

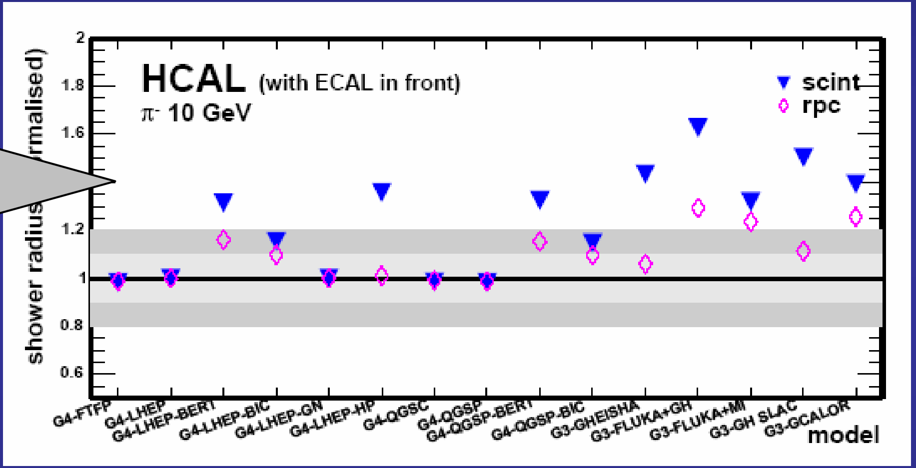
Problem I: Can we trust GEANT4?

Tuning of detector relies on

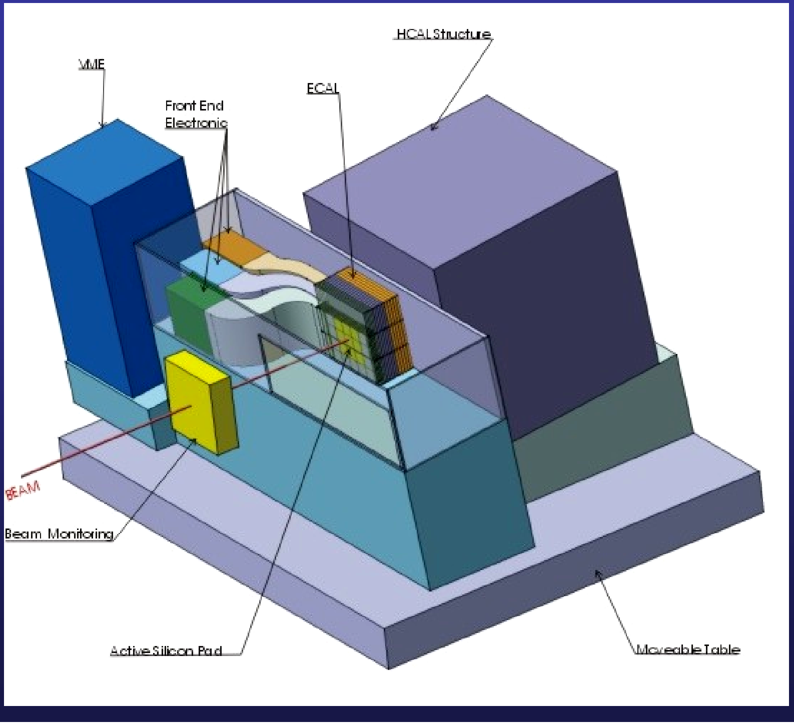
PFAs and a
Realistic simulation of hadronic showers

Comparison of various models

Differences up to 60%



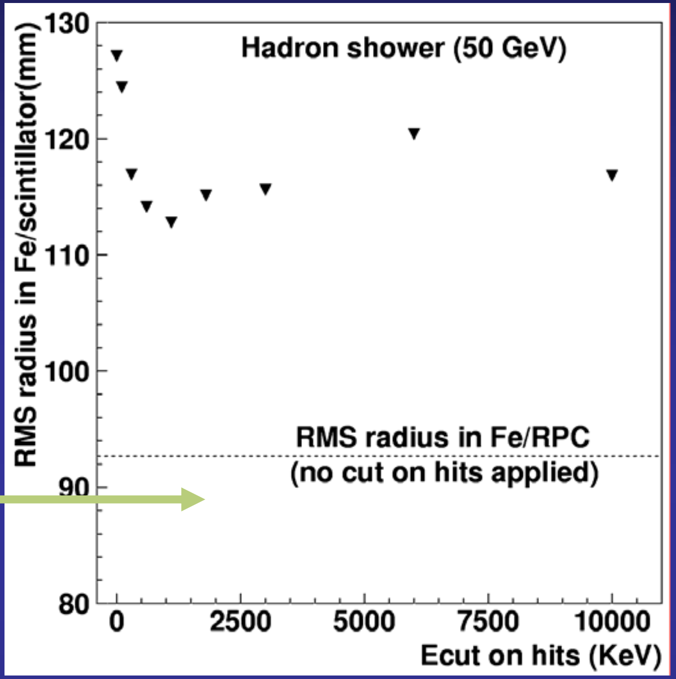
Plot by G Mavromanolakis



Measurements with fine granularity
prototype calorimeters absolutely
mandatory

Problem II: Sensitivity to slow neutrons?

	Scintillator	**RPC Gas**
Molecule	$C_6H_5CH=CH_2$	$C_2H_2F_4$
Density	1.032 g /cm^3	4.3 x 10^{-3} g/cm^3
Thickness	5 mm	1.2 mm
Sensitivity to slow neutrons	small	negligible
Hadronic shower radius	**larger**	smaller
Single particle resolution	better	**worse**



K_L^0

Momentum [GeV/c]	5	10	20
$\sigma = x\sqrt{E}$ Scintillator		(54.2)	(55.5)
$\sigma = x\sqrt{E}$ RPC	0.57	0.66	0.64

Neutron

Momentum [GeV/c]	5	10	20
$\sigma = x\sqrt{E}$ Scintillator		(54.2)	(55.5)
$\sigma = x\sqrt{E}$ RPC	0.78	0.80	0.74

Different shower models in G4?

Tradeoff

More studies needed…

Summary

PFAs are needed to improve jet resolution beyond $\sim 50\%/\sqrt{E}$

PFAs have been applied to existing detectors and work

LC detectors being designed with application of PFA in mind

Calorimeters with extremely fine segmentation
shortest possible Moliere Radius
Technical solutions being developed

Detailed measurements of hadronic showers absolutely needed

Prototype ECALs with 0.2 cm^2 – 1.0 cm^2 pixels
HCALs with 1.0 cm^2 – 3.0 cm^2 readout pads

Funding badly needed