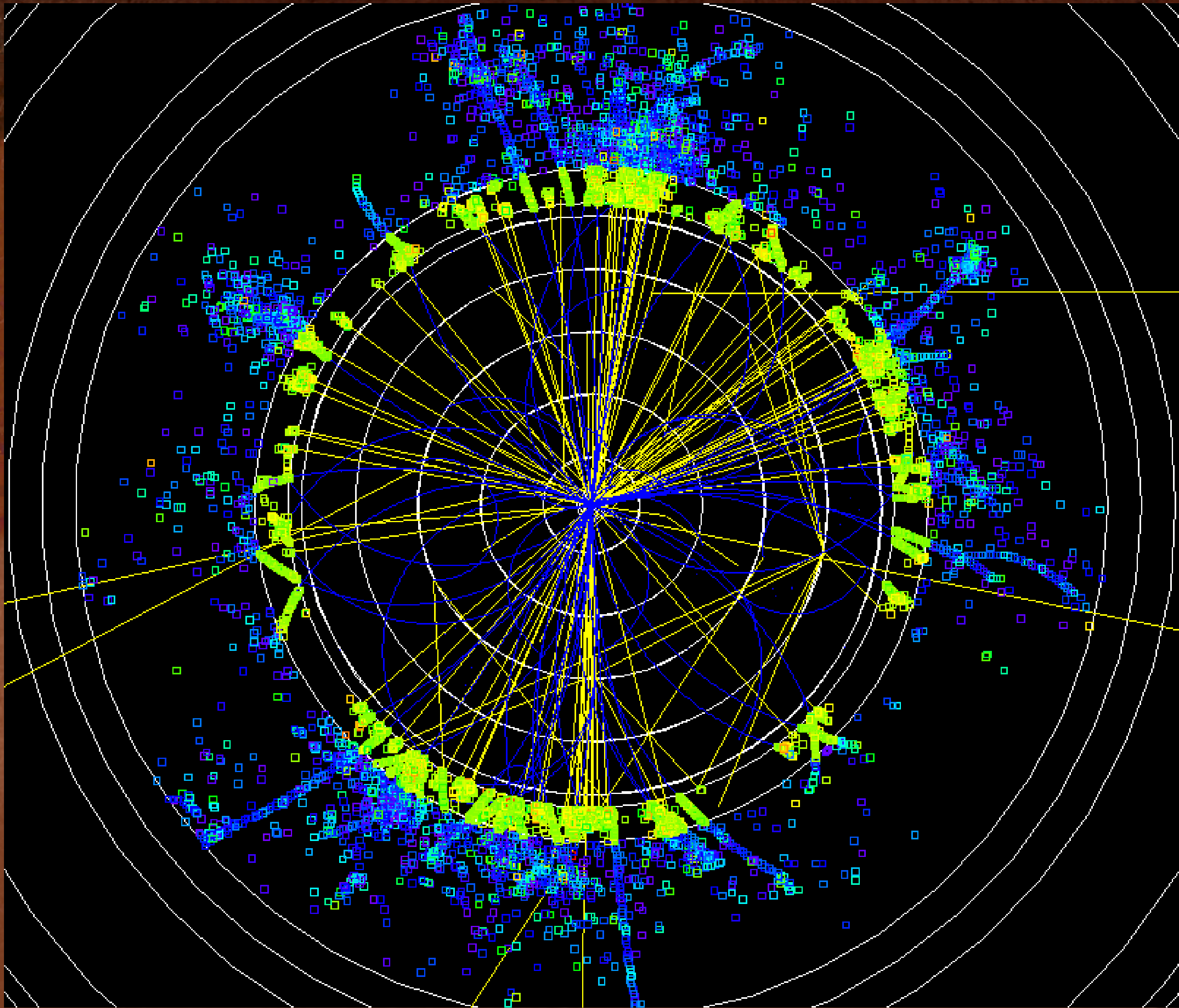
Particle Flow Review

- Particle Flow for the ILC
- (Jet) Energy Resolution Goal
- PFA Confusion Contribution
- Detector Optimization with PFAs
- Future Developments

Stephen Magill
Argonne National Laboratory

e^+e^- -> ttbar -> 6 jets @500 GeV CM

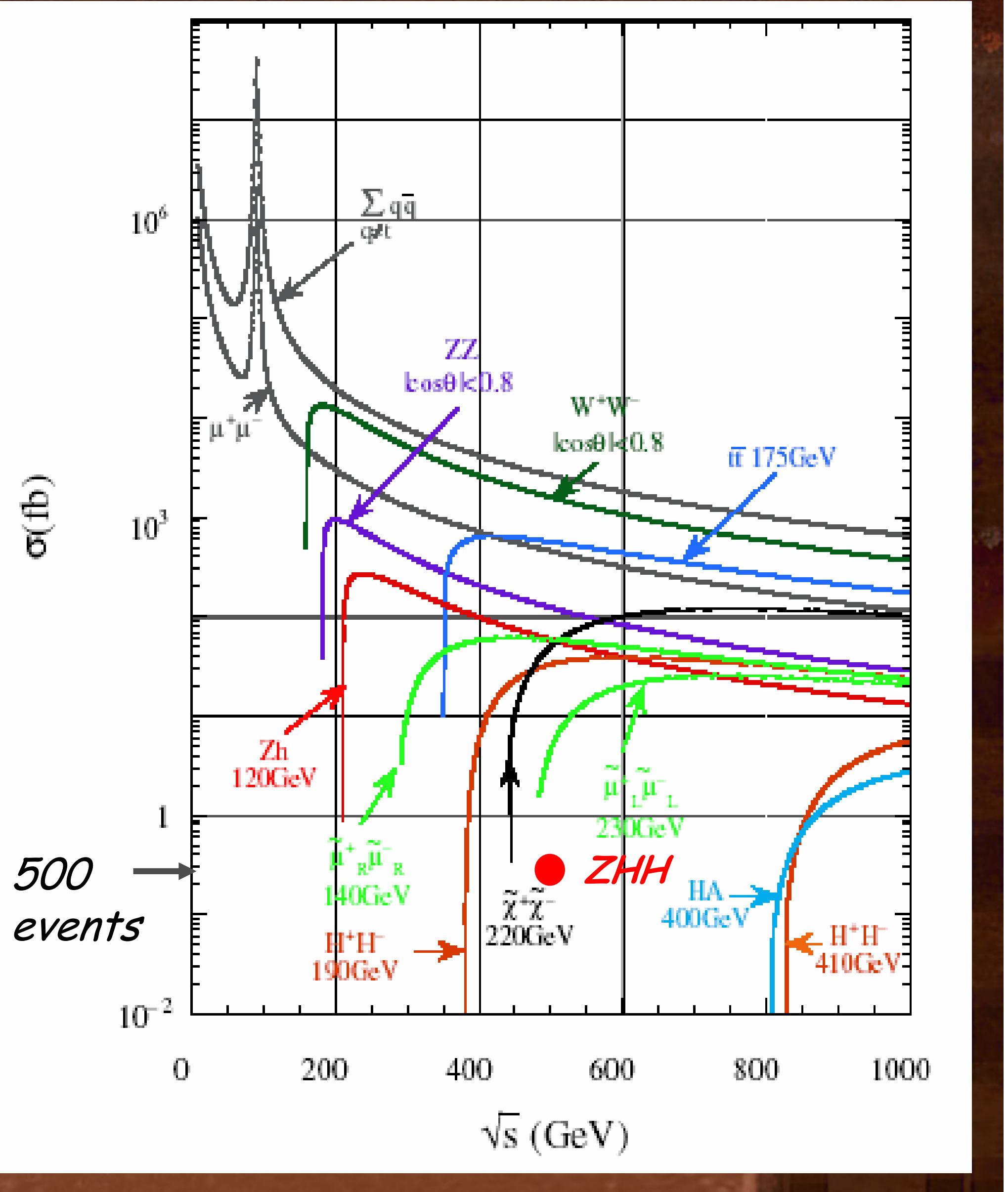


Precision Physics at the ILC

- e^+e^- : clean but sometimes complex events
- often statistics limited
- final states with heavy bosons **W, Z, H**

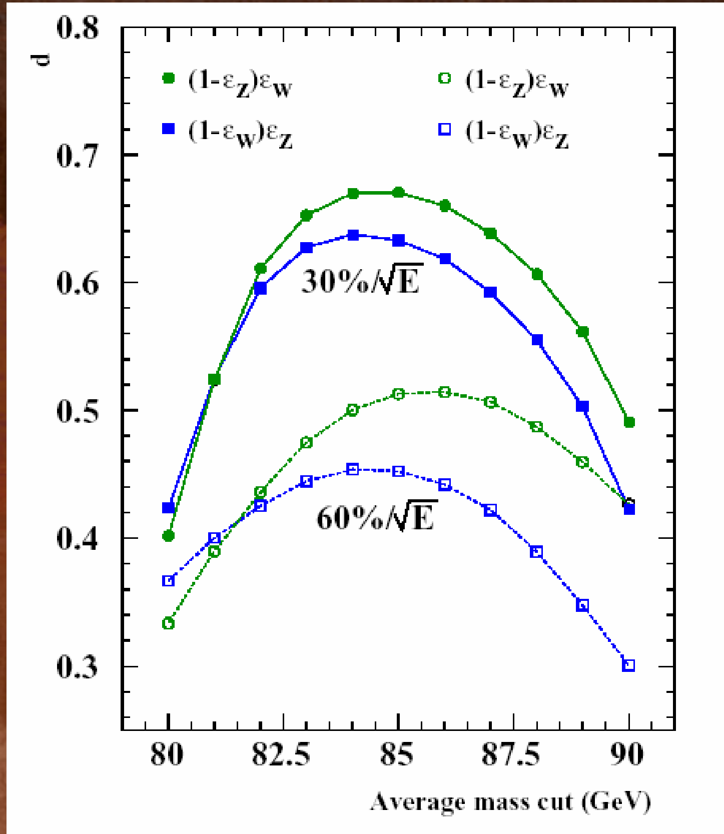
- can't ignore hadronic decay modes (80% BR) -> **multi-jet events**

- in general no kinematic fits

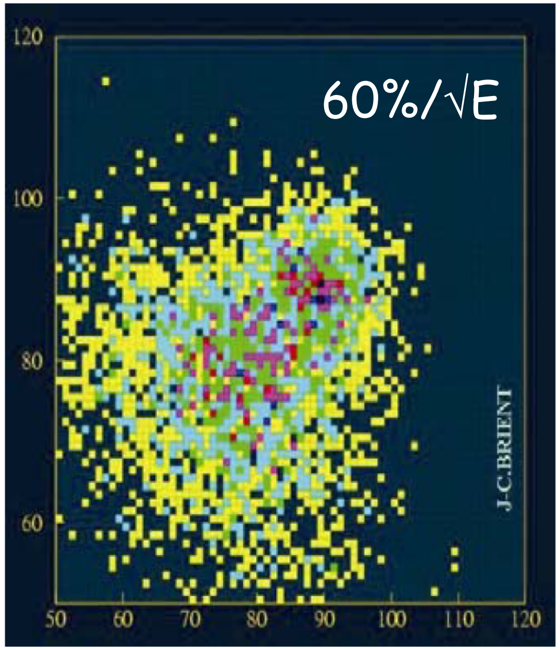


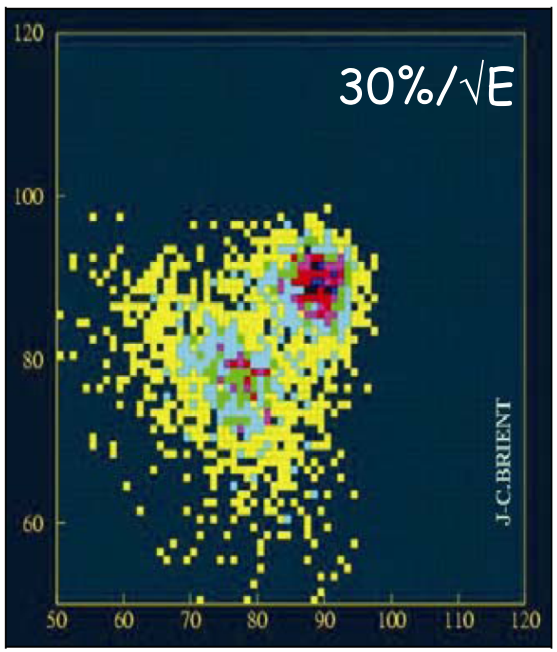
W, Z separation

- Want $m_Z - m_W = 3\sigma$
  -> **jet energy resolution** of 30%/√ E
- Better resolution is worth almost a factor 2 of luminosity – or running cost



Dijet masses in WW and ZZ events





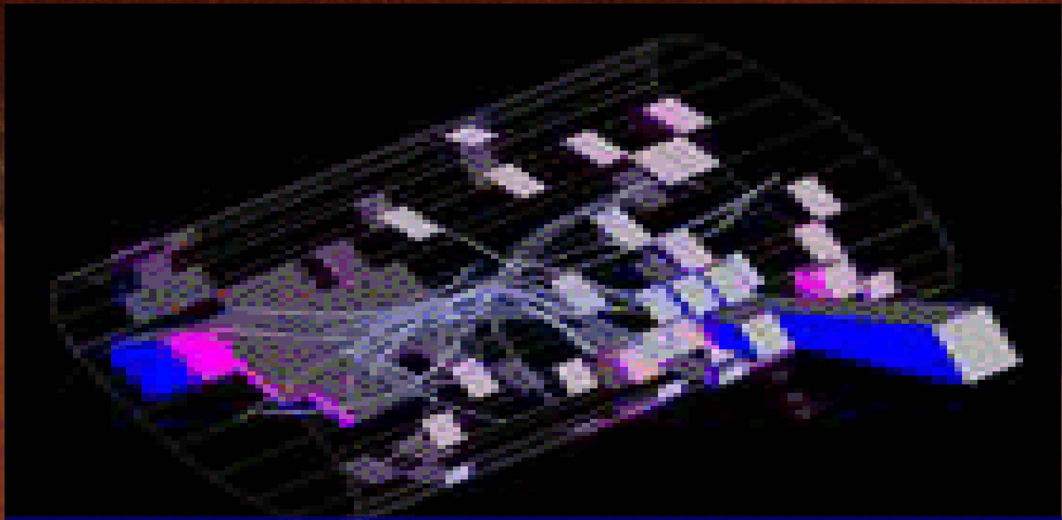
Dilution factor vs cut:
integrated luminosity equivalent

The Particle Flow Approach

PFA Goal : *1 to 1 correspondence between measured detector objects and particle 4-vectors -> best jet (parton) reconstruction (energy and momentum of parton)*

-> combines tracking and 3-D imaging calorimetry :

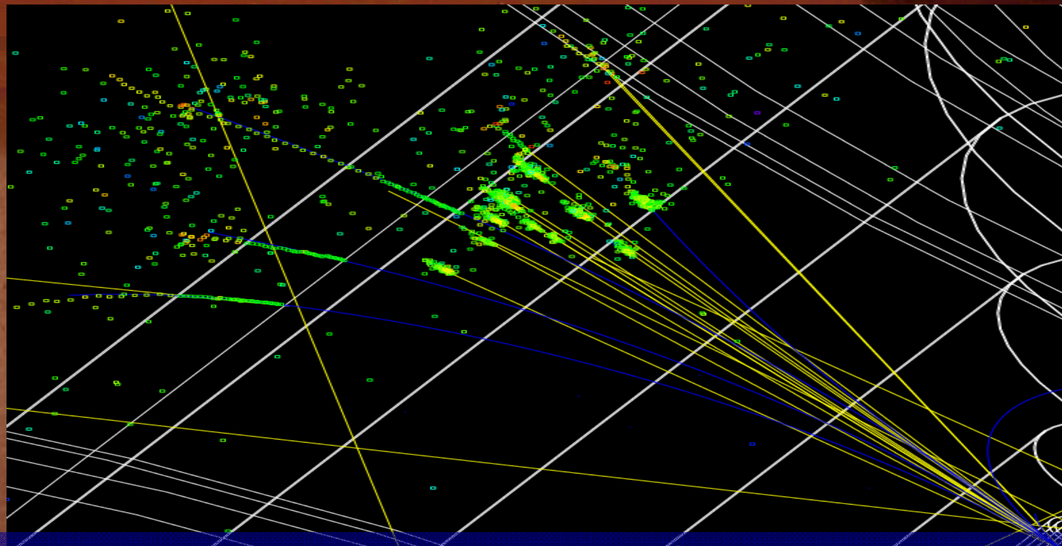
- good tracking for charged particles (~60% of jet E)
  -> σ_p (tracking) <<< σ_E for photons or hadrons in CAL
- good EM Calorimetry for photon measurement (~25% of jet E)
  -> σ_E for photons < σ_E for neutral hadrons
  -> dense absorber for optimal longitudinal separation of photon/hadron showers
- good separation of neutral and charged showers in E/HCAL
  -> CAL objects == particles
  -> 1 particle : 1 object -> small CAL cells
- adequate E resolution for neutrals in HCAL (~10% of jet E)
  -> σ_E < minimum mass difference, e.g. $M_Z - M_W$
  -> still largest contribution to jet E resolution



Dijet event in CDF Detector

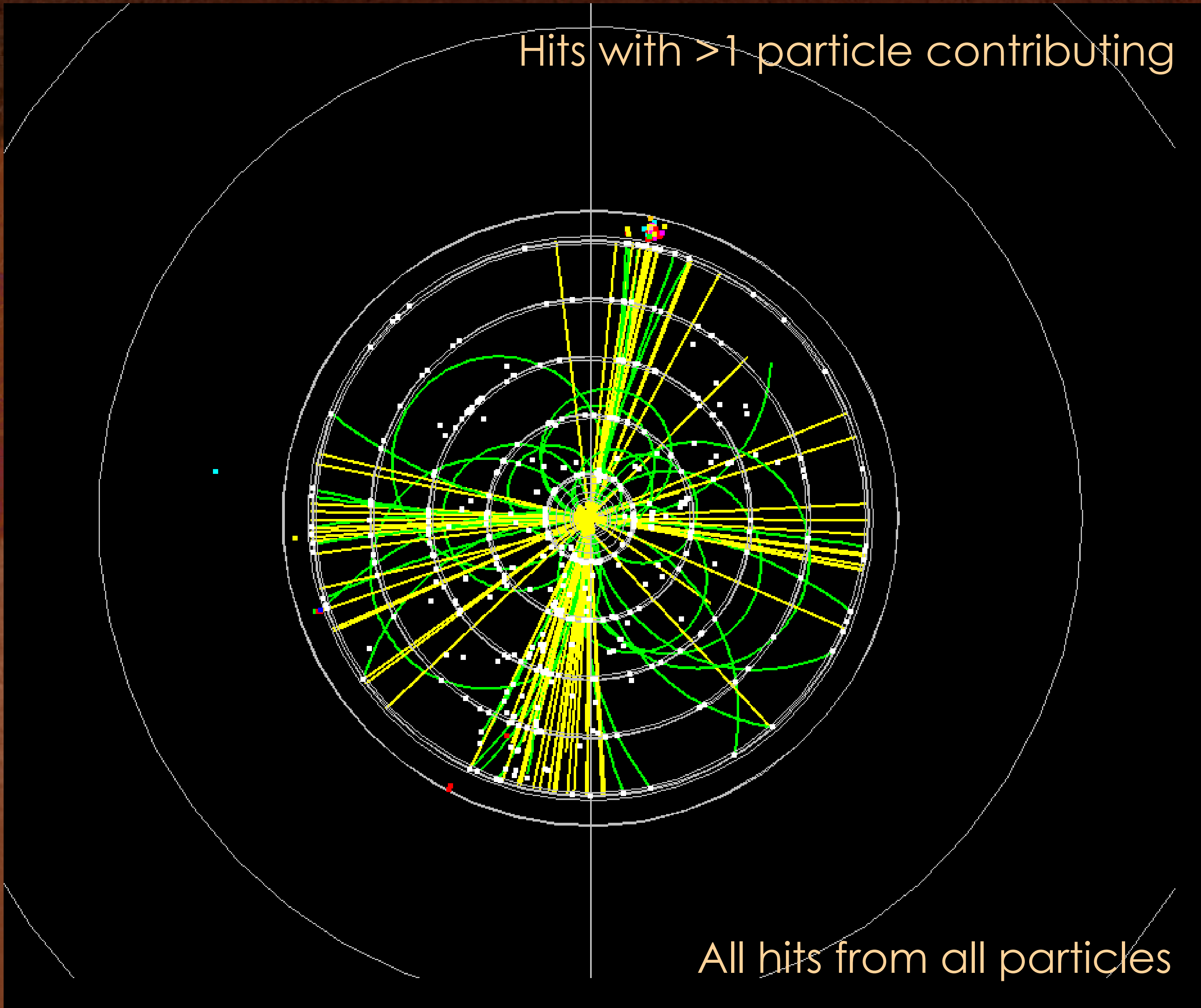
ppbar -> qqbar -> hadrons + photons -> large calorimeter cells
traditional jet measurement

One jet in Z -> qqbar event in a LC Detector



Z -> qqbar -> hadrons + photons = small 3D cal cells
PFA jet measurement

Occupancy Event Display



Jet E Resolution - Particle Flow Approach

- Jet energy resolution
  $\sigma^2(E_{jet}) = \sigma^2(ch.) + \sigma^2(\gamma) + \sigma^2(h^0) + \sigma^2(conf.)$
- Excellent tracker :
  $\sigma^2(ch.) \ll \sigma^2(\gamma) + \sigma^2(h^0) + \sigma^2(conf.)$
- Perfect PFA : $\sigma^2(conf.) = 0$
- $\sigma^2(E_{jet}) = A_\gamma^2 E_\gamma + A_h^2 E_{h0} = w_\gamma A_\gamma^2 E_{jet} + w_{h0} A_h^2 E_{jet}$
  $\sigma(E_{\gamma,h})/E_{\gamma,h} = A_{\gamma,h}/\sqrt{E_{\gamma,h}}$

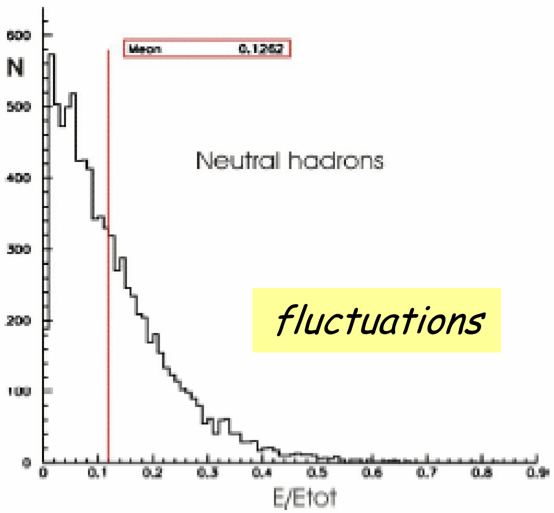
Typically $w_\gamma = 25\%$; $w_{h0} = 13\%$

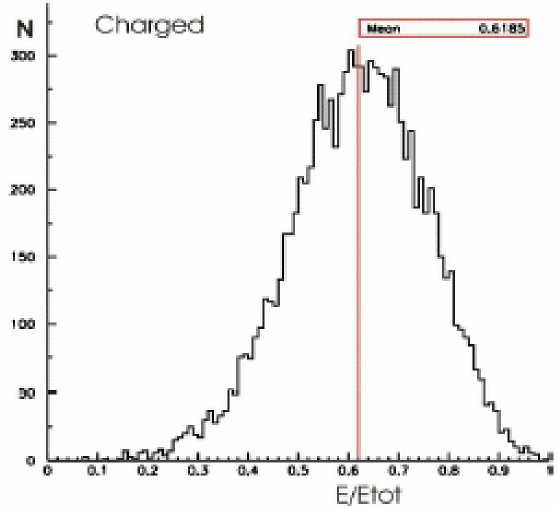
$A_\gamma = 11\%$; $A_{h0} = 34\%$

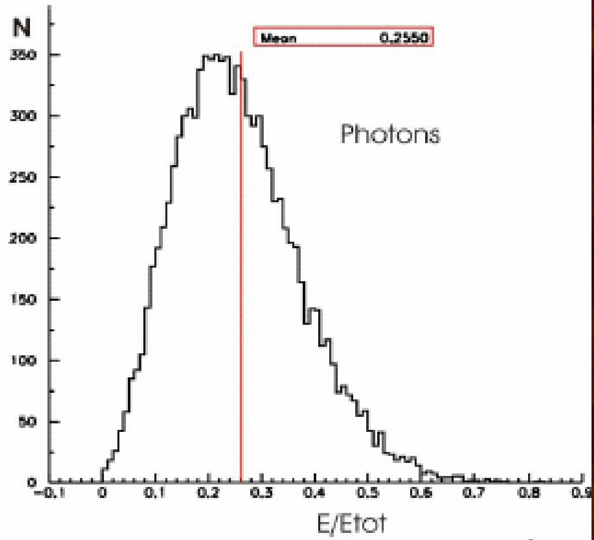
$\Rightarrow \sigma(E_{jet})/E_{jet} = 12\%/\sqrt{E_{jet}}$

$A_\gamma = 11\%$; $A_{h0} = 50\%$

$\Rightarrow \sigma(E_{jet})/E_{jet} = 17\%/\sqrt{E_{jet}}$







Confusion term breakdown ->

Jet E Resolution – Confusion Term

Example PFA Construction – mips, photons, charged hadrons, neutral hadrons

	mips	photons	Ch. hadrons	Neu. hadrons
mips	σ_{mip}	$\sigma_{mip\gamma}$	σ_{mipch}	σ_{mipnh}
photons	$\sigma_{\gamma mip}$	σ_{γ}	$\sigma_{\gamma ch}$	$\sigma_{\gamma nh}$
Ch. hadrons	σ_{chmip}	$\sigma_{ch\gamma}$	σ_{ch}	σ_{chnh}
Neu. hadrons	σ_{nhmip}	$\sigma_{nh\gamma}$	σ_{nhch}	σ_{nh}

-> Replace mips, charged hadron showers with tracks

-> mip γ, neutral hadron confusion small

So, $\sigma_E^2 = \sigma_\gamma^2 + \sigma_{nh}^2 + \sigma_{conf}^2$

where $\sigma_{conf}^2 = \sigma_{chnh}^2 + \sigma_{\gamma ch}^2 + \sigma_{\gamma nh}^2$ (6 terms)

PFAs and Detector Design

PFA key to success -> complete separation of charged and neutral hadron showers

-> hadron showers *NOT* well described analytically, fluctuations dominate # of hits, distribution (shape)
-> average approach -> E resolutions dominated by fluctuations
-> shower reconstruction algorithms -> sensitive to fluctuations on a shower-by-shower basis

-> PFA approach for better E resolution

Calorimeter designed for optimal 3-D hadron shower reconstruction :

-> granularity << shower transverse size
-> segmentation << shower longitudinal size
-> dependence on inner R, B-field, etc.

using PFA approach to test variations

PFA + Full Simulations -> ILC detector design

- unique approach to calorimeter design
- needs good simulation of the entire ILC detector
- requires flexible simulation package -> fast variation of parameters
- huge reliance on correct! simulation of hadron showers

-> importance of timely test beam results!

Approaches to PFA Development *

Calorimeter Cluster-based Algorithms

-> start with calorimeter cell clustering ~ particle showers

Cluster ID by Neural Net

Many variables used to determine particle origin of cluster including tracking input

Weighted Calorimeter Clusters

Density or energy weights used to link calorimeter cells

Tracks matched to clusters – use track p

Sub-cluster ID

Separately cluster EM, mip, and hadronic parts of a particle shower

"perfect" compensation?

Track Extrapolation/Shower Association Algorithms

-> start with tracks (60% of jet energy from charged particles

Mip stubs, track extrapolation with E loss

Calorimeter cell or cluster association to extrapolated track with various algorithms

Leftover cells (clusters) are photons (ECAL), neutral hadrons

* Don't miss Cal/Sim session Friday before lunch!

Particle-Flow Algorithm Approaches

Calorimeter Cluster-based Algorithms

-> start with calorimeter cell clustering ~ particle showers

Cluster ID by Neural Net

- Many variables used to determine particle origin of cluster including tracking input

Weighted Calorimeter Clusters

- Density or energy weights used to link calorimeter cells
- Tracks matched to clusters – use track p

Sub-cluster ID

- Separately cluster EM, mip, and hadronic parts of a particle shower
- "perfect" compensation
- "pixel" calorimeter
- No tracking needed?!

Track Extrapolation/Shower Association Algorithms

- Mip stubs, track extrapolation with E loss
- No calorimeter clustering needed – cell-by-cell association to extrapolated track with various algorithms
- Leftover cells are photons (ECAL), neutral hadrons

Why Z Pole Analysis?

- Generate Z→ qq events at 91GeV.
- Simple events, easy to analyze.
- Can compare analysis results with SLC/LEP.
- Can easily sum up event energy in ZPole events.
  - Width of resulting distribution is direct measure of resolution, since events generated at 91GeV.
- Without uncertainty of jet algorithm effects, can test PFA performance
- Run jet-finder on Reconstructed Particle four vectors, calculate dijet invariant mass.

We are basically here, we are just beginning to understand some very basic performance characteristics of Particle Flow

-> we are ready to tackle the multi-jet events and higher energy jets at 500 GeV

❶ PandoraPFA : brief overview

- ★ ECAL/HCAL reconstruction and PFA performed in a single algorithm
- ★ Keep things fairly generic algorithm
  - ★ applicable to multiple detector concepts
- ★ Use tracking information to help ECAL/HCAL clustering

Five Main Stages:

i. Loose clustering in ECAL and HCAL
ii. Topological linking of clearly associated clusters
iii. Courser grouping of clusters
iv. Statistical reclustering
v. Formation of final Particle Flow Objects (reconstructed particles)

Mark Thomson, Univ of Cambridge
-> Marlin Reconstruction package (C++ based)
-> primarily LDC + variants

❸ Current Performance (as of 15/6/06)

Example Reconstruction

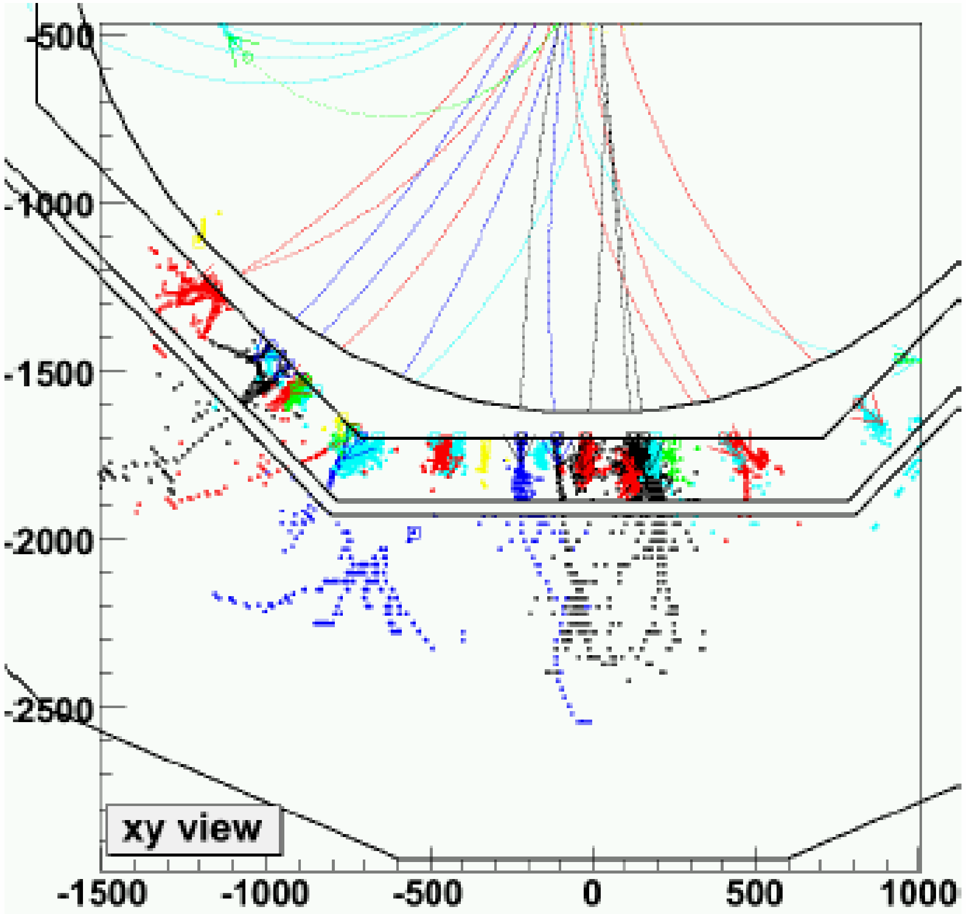
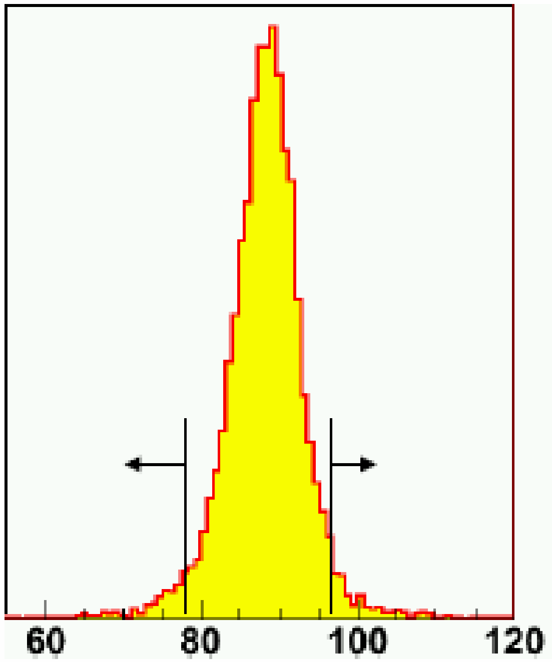
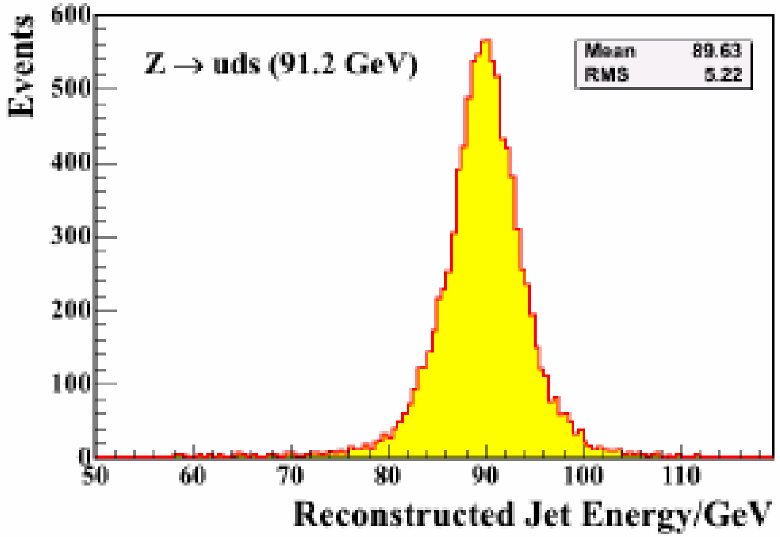


Figure of Merit:



- ★Find smallest region containing 90 % of events
- ★Determine rms in this region

PFA Results (Z →uds)

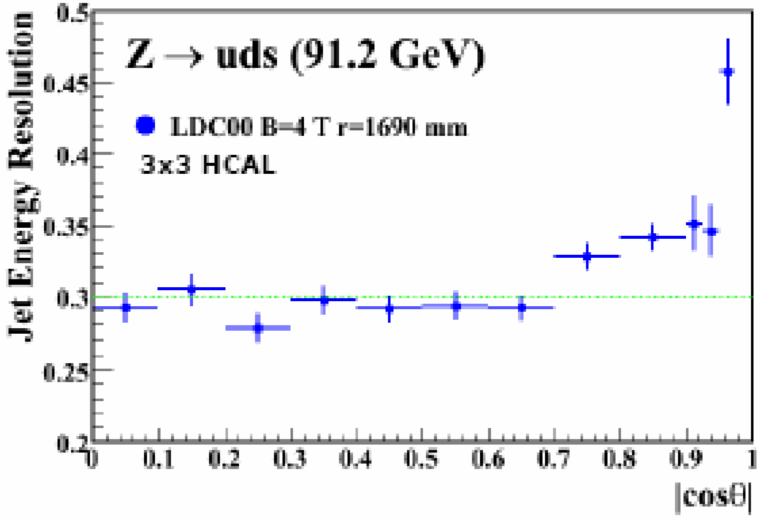


LDC00

|cosθ|	$\sigma_E/E = \alpha\sqrt{(E/GeV)}$
all	33.4±0.3%
<0.9	30.5±0.3 %
<0.7	29.2±0.4 %

ILC GOAL OF 30 % ACHIEVED !

- ★ BUT only for Z at 91.2 GeV
- ★ In barrel essentially "perfect"
- ★ Endcap issues



Track-first Extrapolation PFA

1st step – Track-linked mip segments (ANL)

-> find mip hits on extrapolated tracks, determine layer of first interaction based solely on cell hit density (no clustering of hits, no energy measurement)

2nd step - Photon Finder (SLAC, Kansas)

-> use analytic longitudinal H-matrix fit to layer E profile with ECAL clusters as input (any cluster algorithm)

3rd step – Track-linked EM and HAD clusters (ANL, SLAC)

-> substitute for Cal objects (mips + ECAL shower clusters + HCAL shower clusters), reconstruct linked mip segments + clusters loose NN clusterer) iterated in E/p

-> Analog or digital techniques in HCAL

4th step – Neutral Finder algorithm (SLAC, ANL)

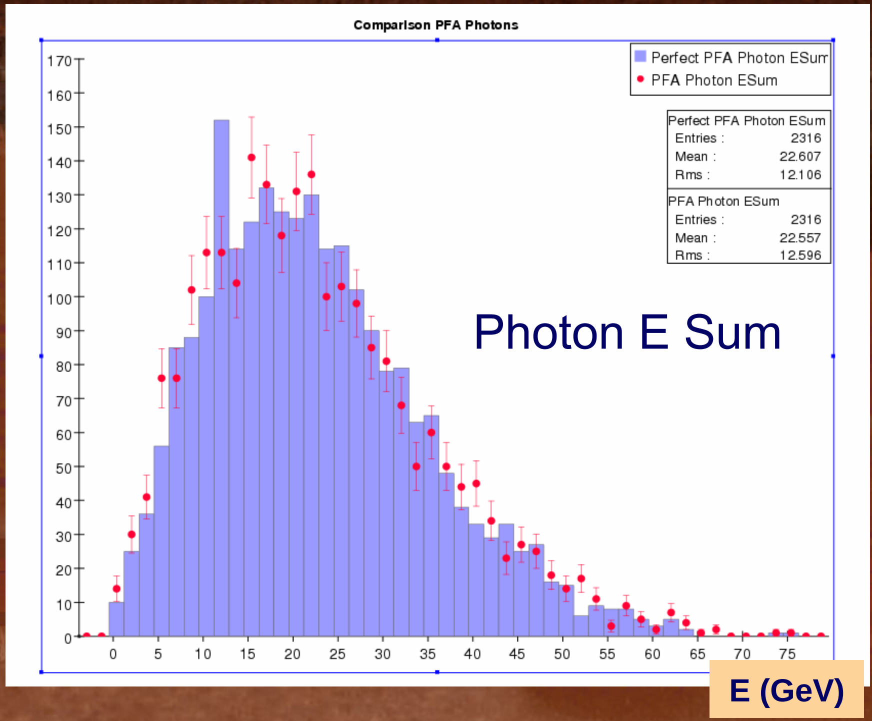
-> cluster (tighter NN clusterer) remaining CAL cells, merge, cut fragments

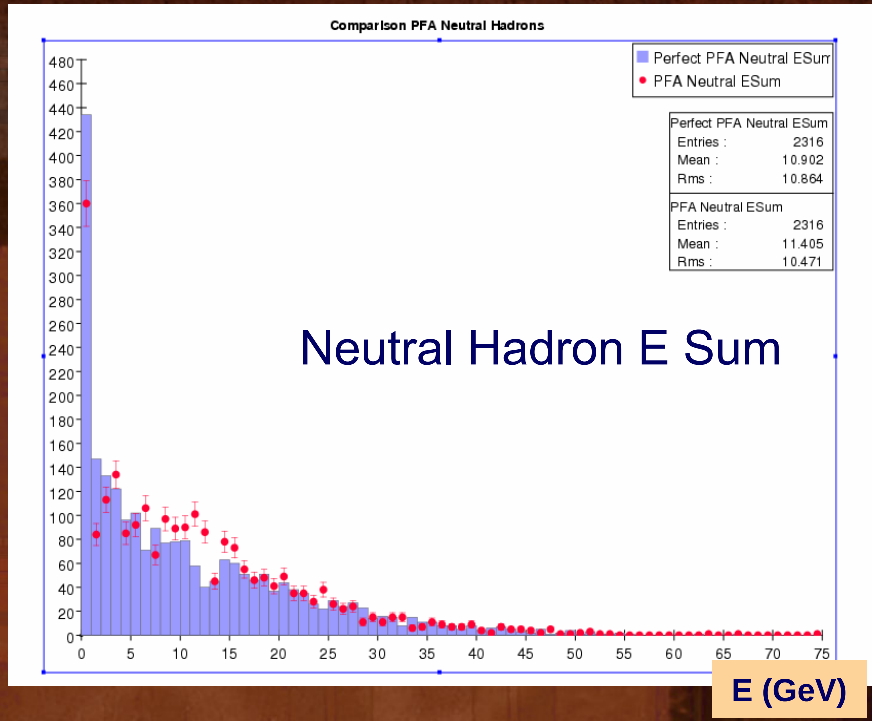
ANL, SLAC, Kansas

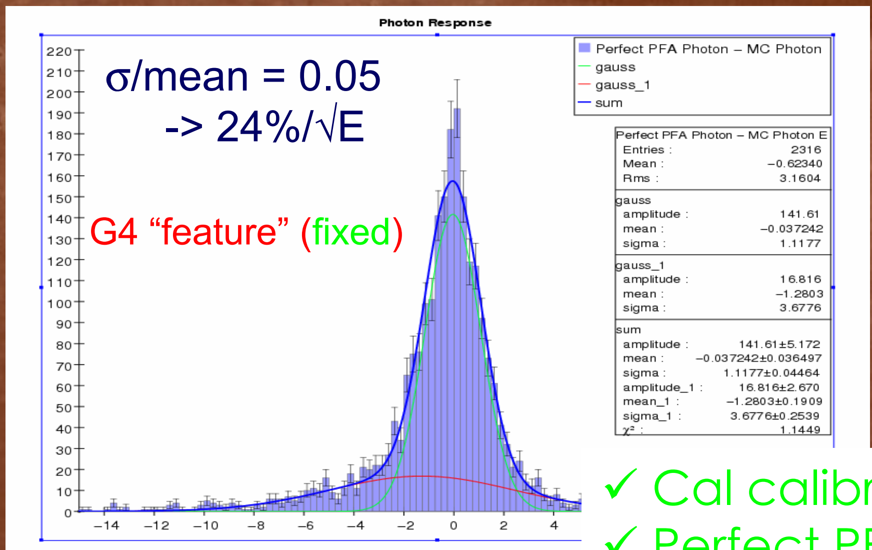
-> org.lcsim reconstruction, JAS3 analysis (Java)

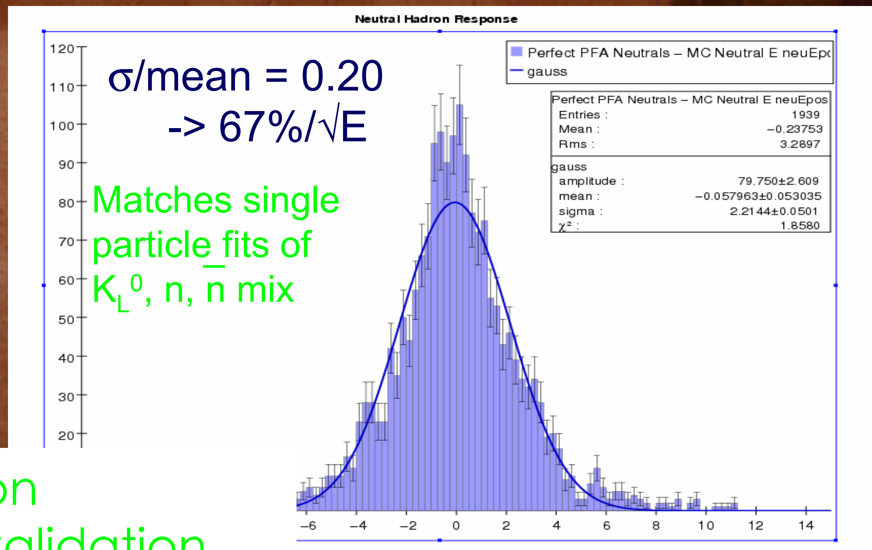
-> primarily SiD and variants

PFA Module Comparisons



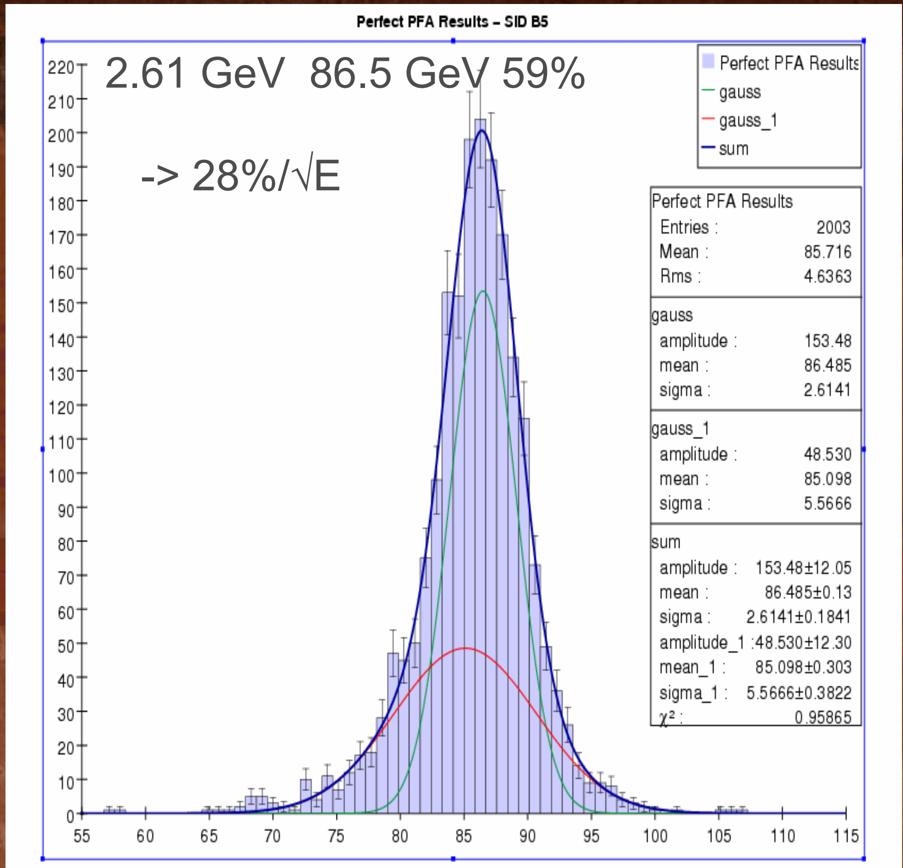


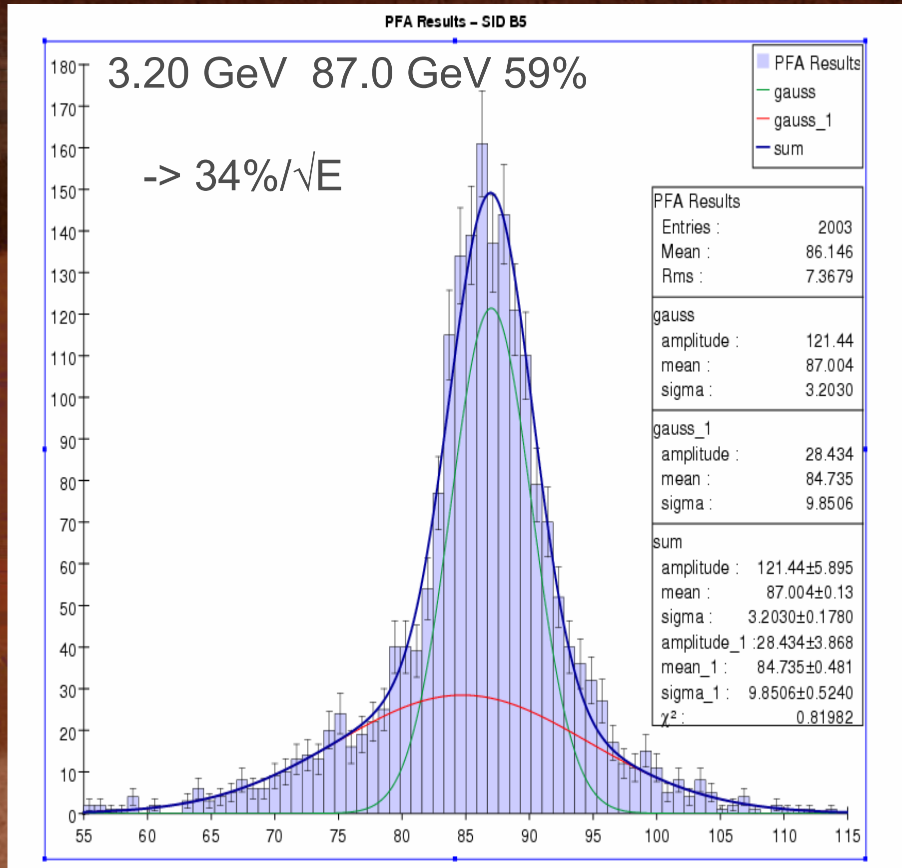




- ✓ Cal calibration
- ✓ Perfect PFA validation

PFA Results





SiD Detector Model
Si Strip Tracker
W/Si ECAL, IR = 125 cm
4mm X 4mm cells
SS/RPC Digital HCAL
1cm X 1cm cells
5 T B field (CAL inside)

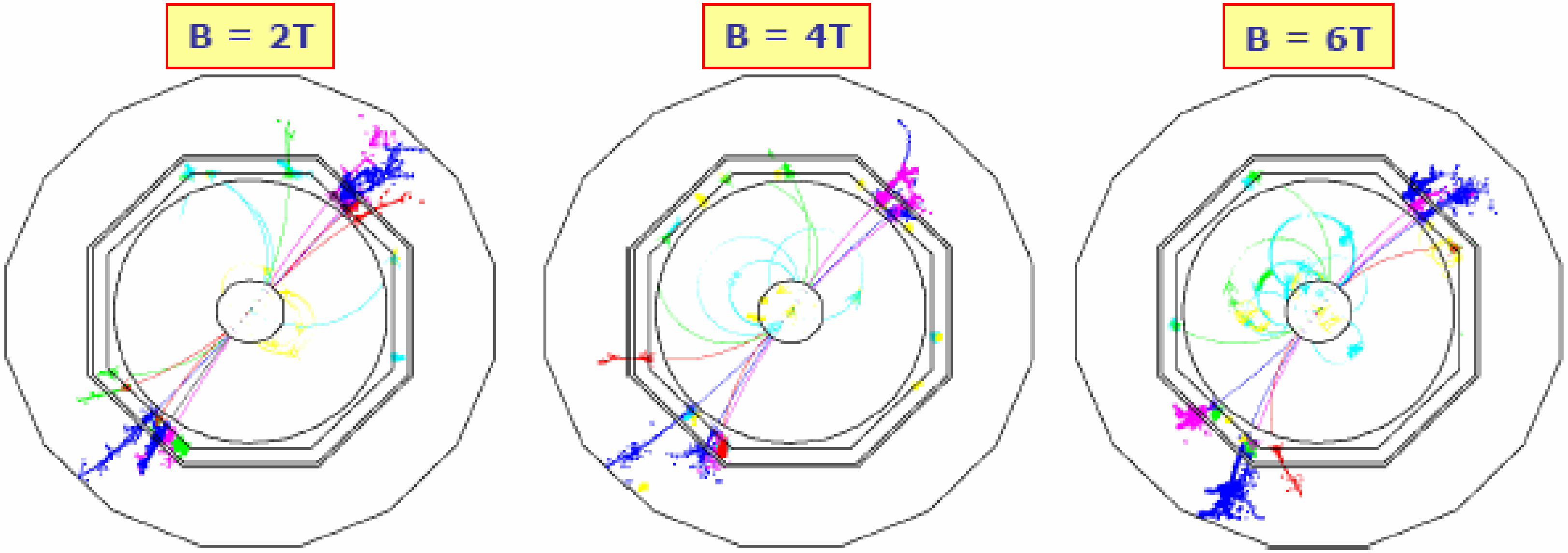
Average confusion contribution = 1.9 GeV < neutral hadron resolution contribution of 2.2 GeV

-> PFA goal!*

* other 40% of events!

e.g. B-Field

LDC00 Detector (≈ TESLA TDR) – same event different B



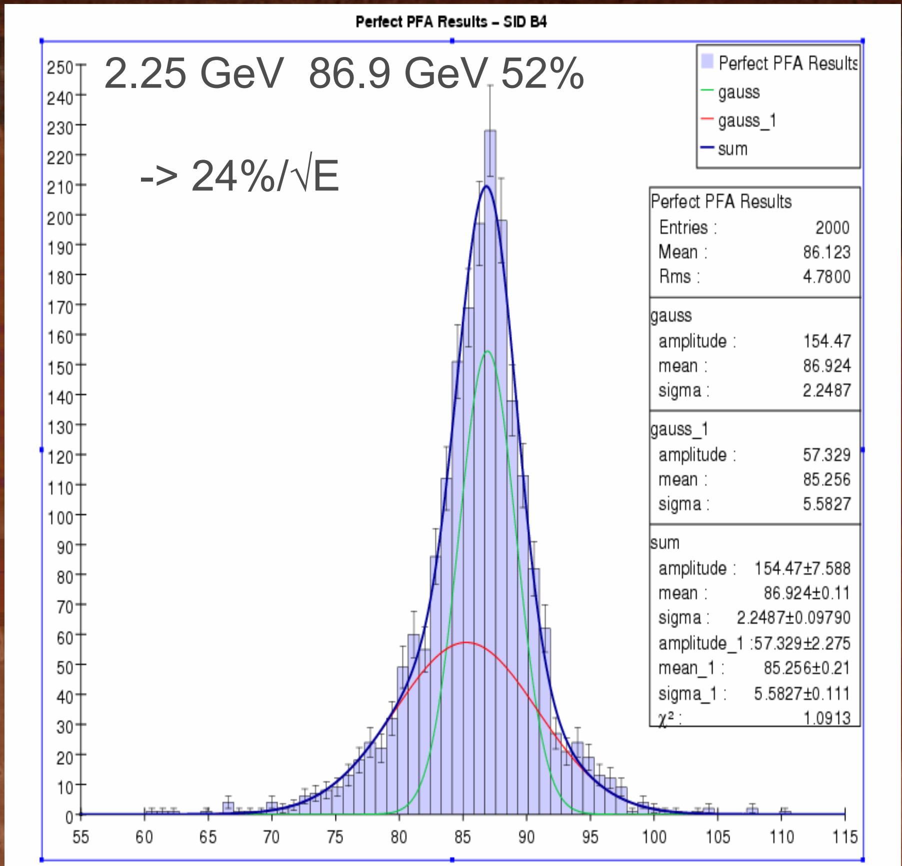
B-Field	$\sigma_E/E = \alpha\sqrt{(E/GeV)}$	
	All angles	|cosθ|<0.7
2 Tesla	34.1±0.3%	30.8±0.4 %
4 Tesla	33.4±0.3 %	29.2±0.4 %
6 Tesla	34.4±0.3 %	29.7±0.4 %

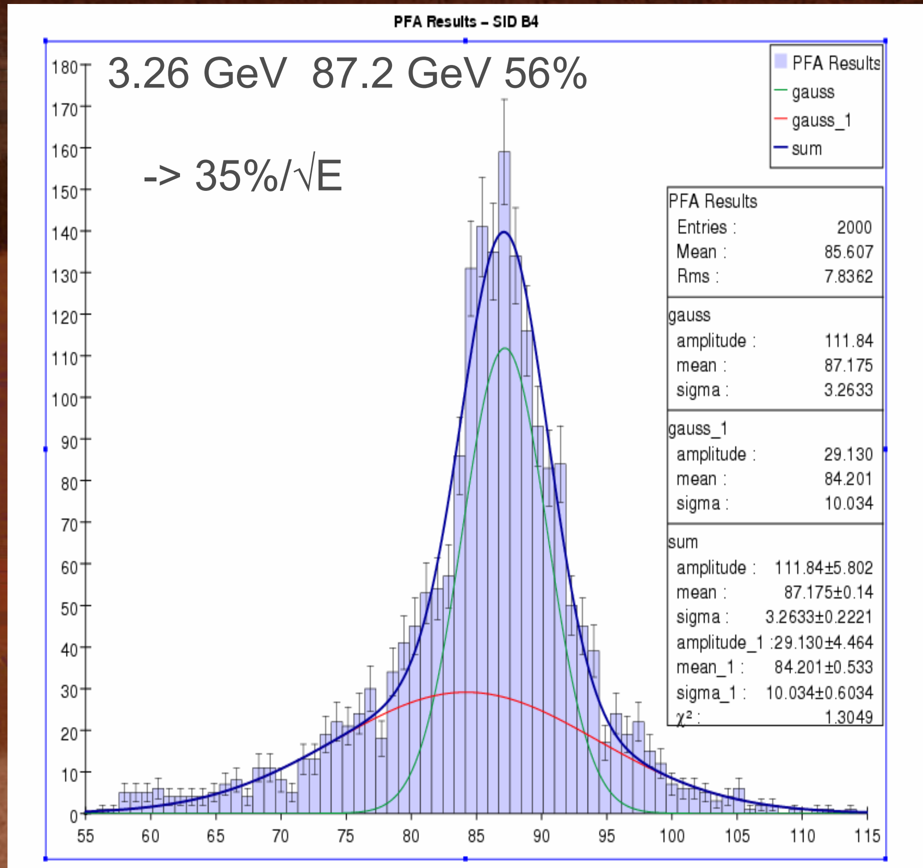
Only weak B-field dependence

★ BUT still Z at 91.2 GeV

Detector Comparisons with PFAs

Vary B-field



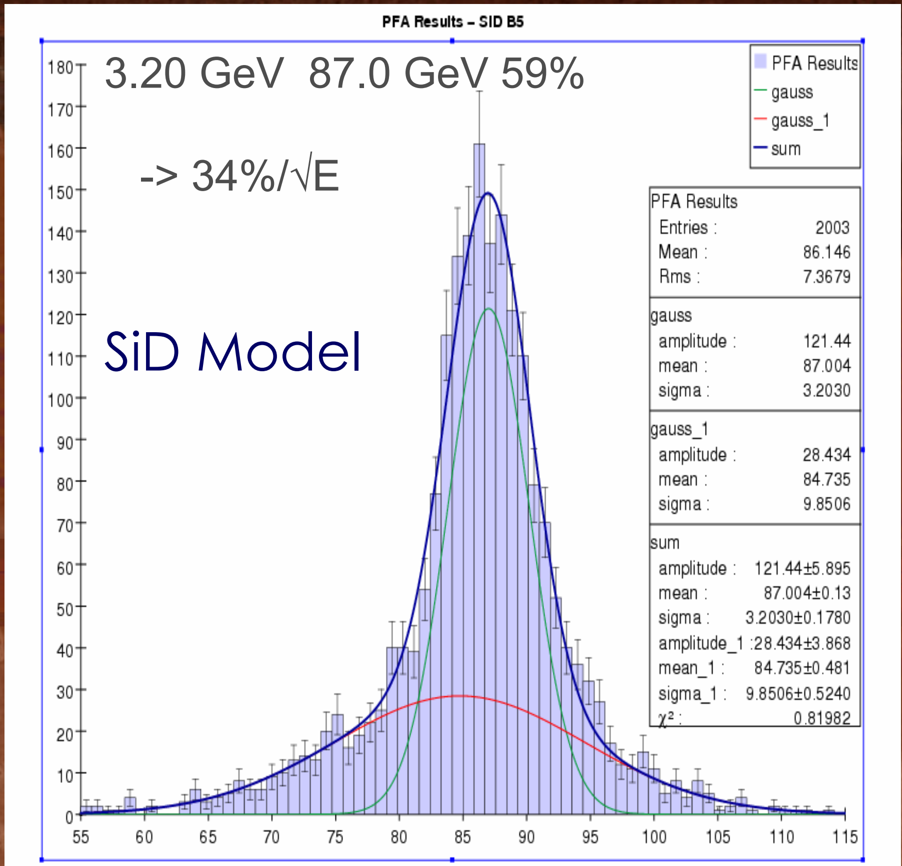


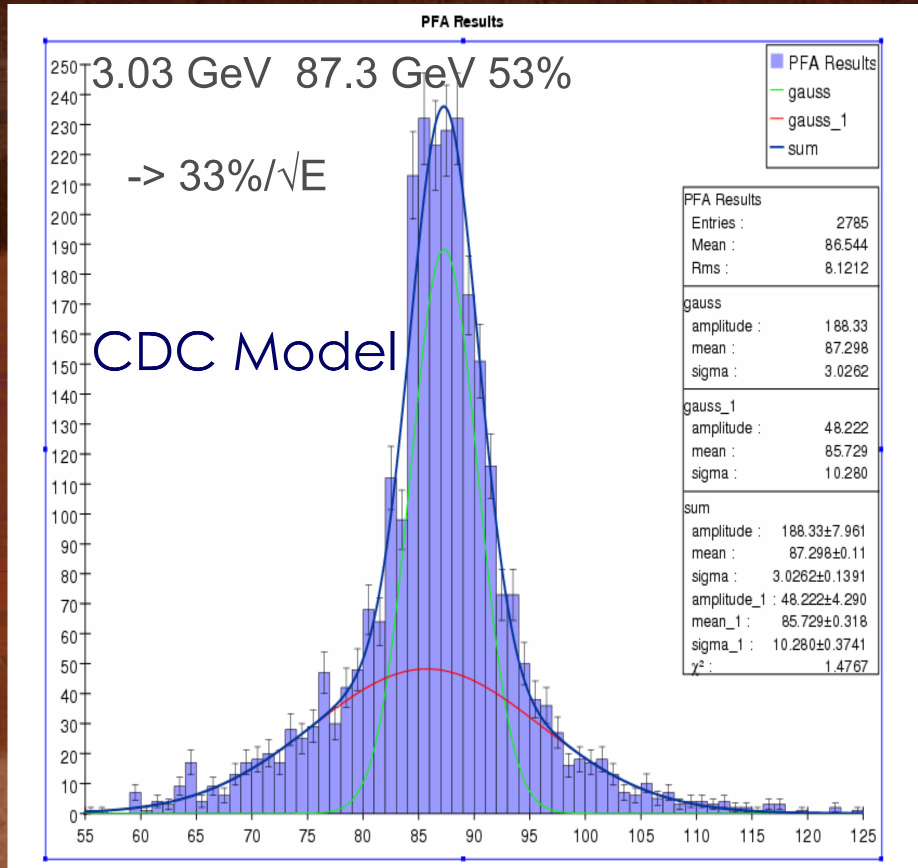
SiD SS/RPC - 5 T field
Perfect PFA σ = 2.6 GeV
PFA σ = 3.2 GeV
Average confusion = 1.9 GeV

SiD SS/RPC - 4 T field
Perfect PFA σ = 2.3 GeV
PFA σ = 3.3 GeV
Average confusion = 2.4 GeV

-> Better performance in larger B-field

Detector Optimized for PFA?





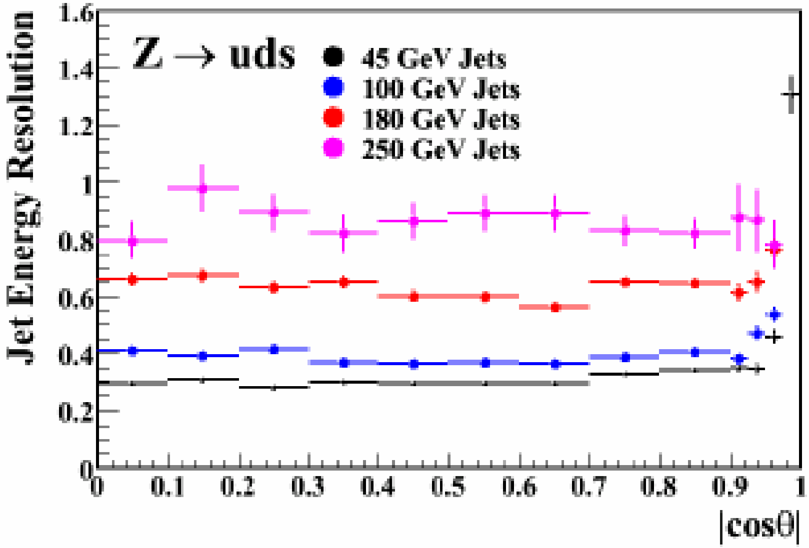
SiD -> CDC 150

- ECAL IR increased from 125 cm to 150 cm
- 6 layers of Si Strip tracking
- HCAL reduced by 22 cm (SS/RPC -> W/Scintillator)
- Magnet IR only 1 inch bigger!
- Improved PFA performance w/o increasing magnet bore

Jet Energy Dependence

- ★ Look at Z→uds at $\sqrt{s}$ > 91.2 GeV
- ★ LDC00 detector model

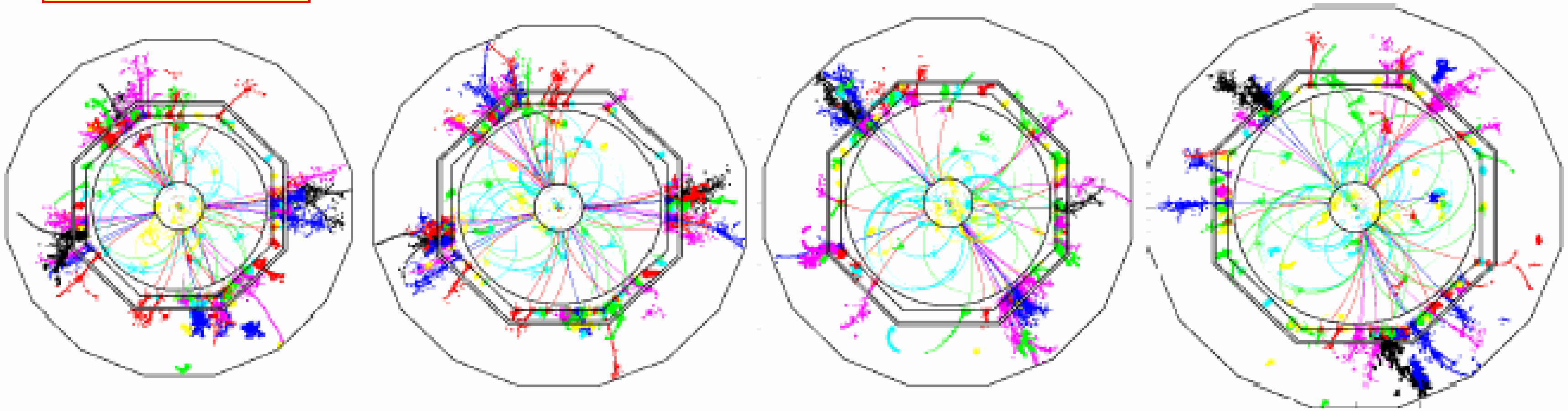
E_{JET}	$\sigma_E/E = \alpha\sqrt{(E/GeV)}$	
	All angles	|cosθ|<0.7
45 GeV	33.4±0.3%	29.2±0.4 %
100 GeV	42.0±0.3 %	38.4±0.5 %
180 GeV	71.7±0.3 %	63.8±0.4 %
250 GeV	90.7±2.0 %	87.2±2.5 %



- ★ Rapid degradation of performance with increasing jet energy
- ★ However, for 100 GeV jets not bad
- ★ At ILC typically interested in 6 fermion final states
- ★ Current performance probably OK for physics studies at $\sqrt{s}$ =500 GeV
- ★ Probably not yet good enough for $\sqrt{s}$ = 1 TeV

$e^+e^- \to tt \to 6$ jets at $\sqrt{s}=500$ GeV

r_{TPC} = 1380 mm | r_{TPC} = 1580 mm | r_{TPC} = 1690 mm | r_{TPC} = 1890 mm

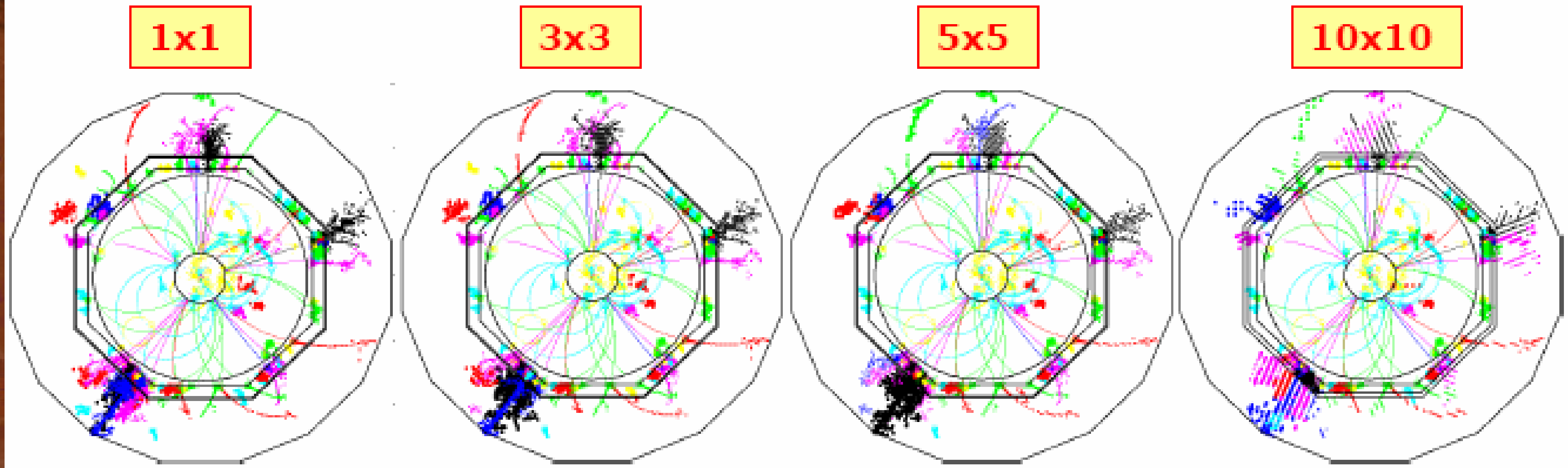


★compare raw resolutions; + add in ν; + add energy lost in forward region

Detector Model	$\sigma_E/E = \alpha\sqrt{(E/\mathrm{GeV})}$		
	E_{RECO}	$+ E_\nu$	$+E_{FWD}$
LDC01Sc r_{tpc} = 1380mm	89 ± 2 %	61 ± 1 %	56 ± 1 %
LDC01Sc r_{tpc} = 1580mm	83 ± 2 %	56 ± 1 %	52 ± 1 %
LDC00Sc r_{tpc} = 1690mm	76 ± 2 %	48 ± 1 %	45 ± 1 %
LDC00Sc r_{tpc} = 1890mm	75 ± 2 %	46 ± 1 %	42 ± 1 %

- ★ Fairly strong dependence of performance on Radius
- ★ Discontinuity in going from LDC00 → LDC01 (alg. tuned on LDC00)
- ★ "$+E_{FWD}$" : imperfect accounting of lost energy in FWD region

HCAL Granularity



Detector Model	$\sigma_{E_{vis}}/E = \alpha\sqrt{(E/GeV)}$		
	Z @91 GeV	tt@500 GeV	Z@500GeV
LDC00Sc 1cm x 1cm	31.4 ± 0.3 %	42 ± 1 %	81 ± 2 %
LDC00Sc 3cm x 3cm	30.6 ± 0.3 %	45 ± 1 %	88 ± 2 %
LDC00Sc 5cm x 5cm	31.3 ± 0.3 %	48 ± 1 %	94 ± 2 %
LDC00Sc 10cm x 10cm	33.7 ± 0.3 %	56 ± 1 %	114 ± 2 %

- ★ 10x10 too coarse (can be seen clearly from display)
- ★ Finer granularity helps somewhat at higher energies – why ?

Summary – where we go from here

At ZPole :

- *Have achieved desired jet energy resolution of 30%/√E*
- *Have achieved $\sigma_{confusion} < \sigma_{neutral\ hadron}$ in PFA energy sum*

Have developed huge collection of tools necessary for both PFA development and detector optimization :

- Flexible, fast full simulation packages
- Full reconstruction capabilities
- Calorimeter calibration procedures
- Standardized algorithm comparison tools
- Modular, standardized PFA Template

Next Steps :

- Move from energy sums to dijet mass – PFA jet reconstruction
- Move to physics events at 500 GeV CM
- Use PFAs for detector optimization at 500 GeV