Particle Flow Calorimetry

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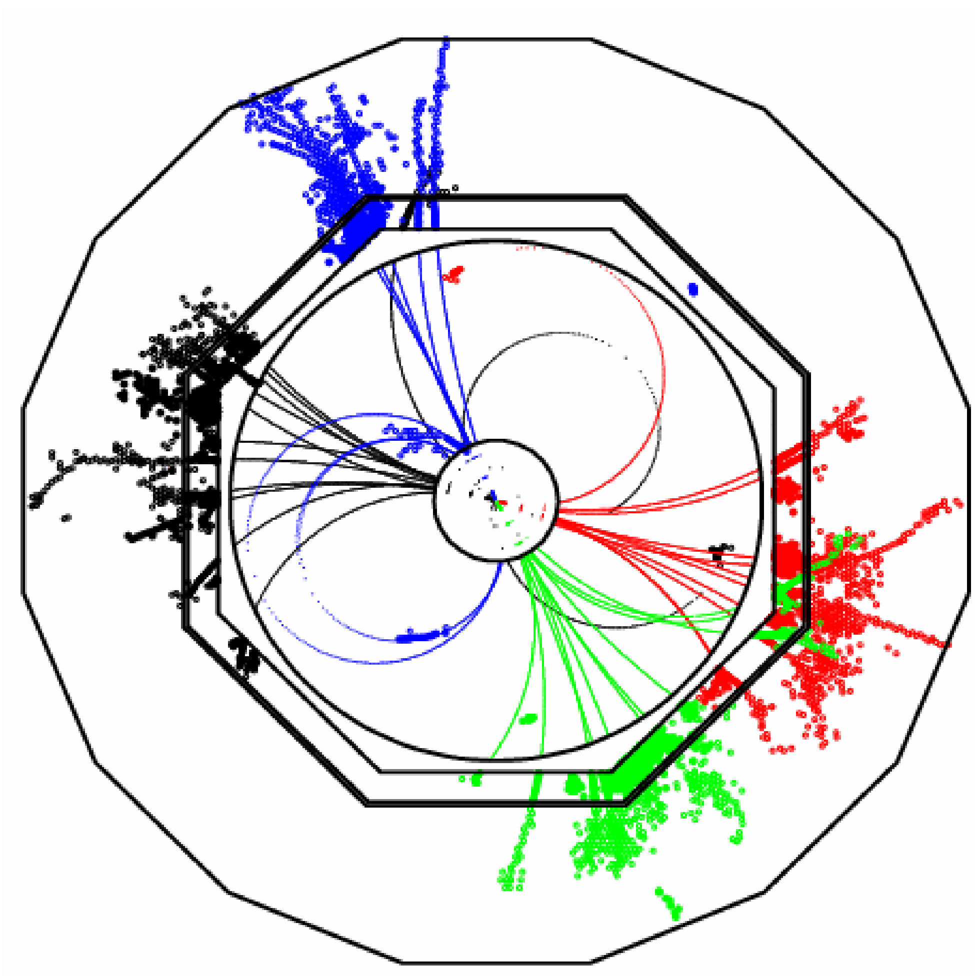


This Talk:

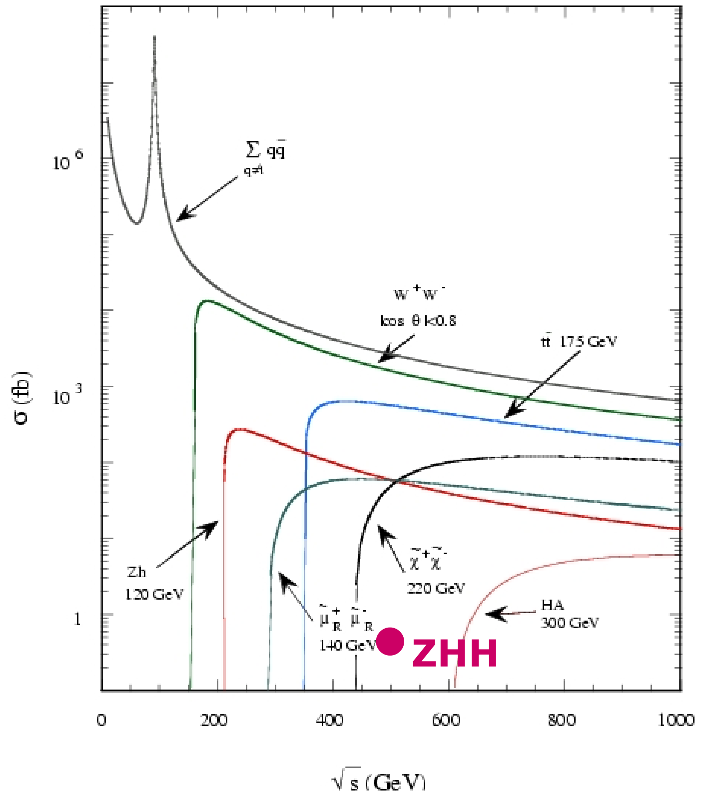
➊ ILC Physics ↔Calorimetry
➋ Jet Energy Resolution
➌ Particle Flow Calorimetry
➍ Algorithms
➎ Summary

❶ ILC Physics ↔ Calorimetry

ILC PHYSICS:

Precision Studies/Measurements

- ★ Higgs sector
- ★ SUSY particle spectrum (if there)
- ★ SM particles (e.g. W-boson, top)
- ★ and much more...



Physics characterised by:

- ★ High Multiplicity final states
  often 6/8 jets
- ★ Small cross-sections
  e.g. $\sigma(e^+e^- \rightarrow ZHH) = 0.3$ fb

> ✸ **Require High Luminosity – i.e. the ILC**
> ✸ **Detector optimized for precision measurements in difficult multi-jet environment**

LEP vs. ILC

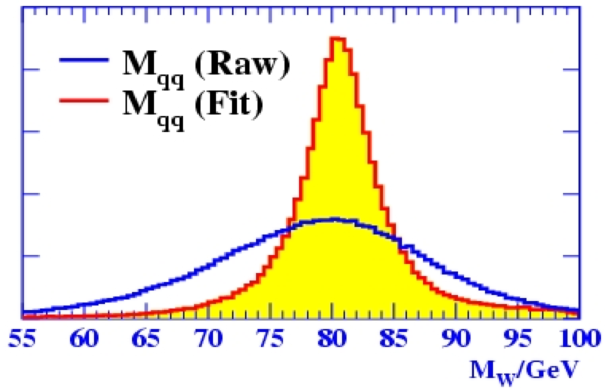
At LEP:

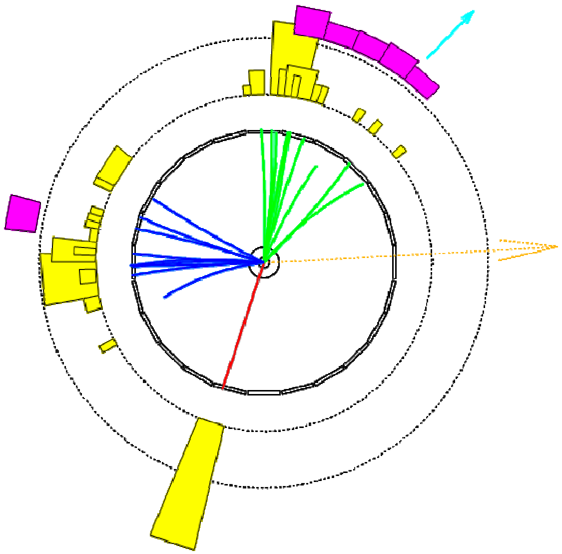
- ★ Signal dominates: $e^+e^- \to Z$ and $e^+e^- \to W^+W^-$
  backgrounds not too problematic
- ★ Even for W mass measurement, jet energy resolution not too important

Kinematic Fits

$$\sum E_i = \sqrt{s}$$

$$\sum \vec{p}_i = 0$$





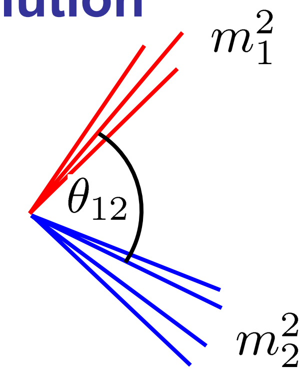
At the ILC:

- ★ Backgrounds dominate interesting physics
- ★ Kinematic fitting much less useful: Beamsstrahlung + many final states with > 1 neutrino

> ✸ Physics performance depends critically on the detector performance (not true at LEP)
> ✸ Places stringent requirements on the ILC detector

❷ Required Jet Energy Resolution

★Aim for jet energy resolution giving di-jet mass resolution similar to Gauge boson widths



★For a pair of jets have:

$$m^2 = m_1^2 + m_2^2 + 2E_1E_2(1 - \beta_1\beta_2\cos\theta_{12})$$

★For di-jet mass resolution of order $\Gamma_{W/Z}$

$$\frac{\sigma_m}{m} \approx \frac{2.5}{91.2} \approx \frac{2.1}{80.3} \approx 0.027$$

⇨ $\sigma_E/E < 3.8\%$

+ term due to θ_{12} uncertainty

★**Assuming** a single jet energy resolution of normal form

$$\sigma_E/E = \alpha(E)/\sqrt{E(\text{GeV})}$$

⇨ $\sigma_m/m \approx \alpha(E_j)/\sqrt{E_{jj}(\text{GeV})}$

⇨ $\alpha(E_j) < 0.027\sqrt{E_{jj}(\text{GeV})}$

E_{jj}/GeV	$\alpha(E_j)$
100	< 27 %
200	< 38 %

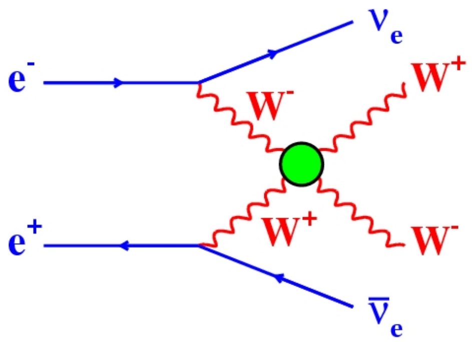
★ Typical di-jet energies at ILC (100-300 GeV) suggests jet energy resolution goal of $\sigma_E/E < 0.30/\sqrt{E(\text{GeV})}$

Jet Energy Resolution : LEP vs. ILC

Best at LEP (ALEPH):
$\sigma_E/E = 0.6(1+|\cos\theta_{Jet}|)/\sqrt{E(\mathrm{GeV})}$

ILC GOAL:
$\sigma_E/E = 0.3/\sqrt{E(\mathrm{GeV})}$

★ **Jet energy resolution directly impacts physics sensitivity**

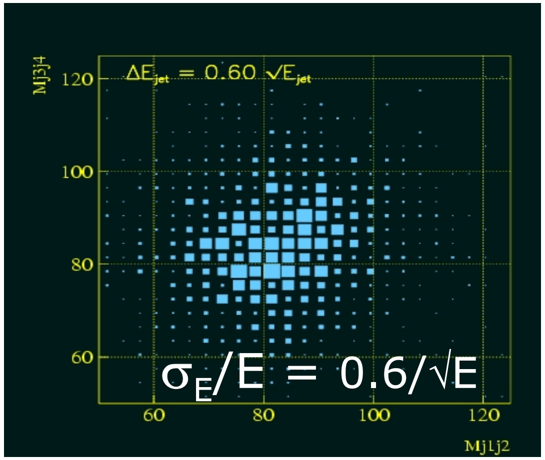


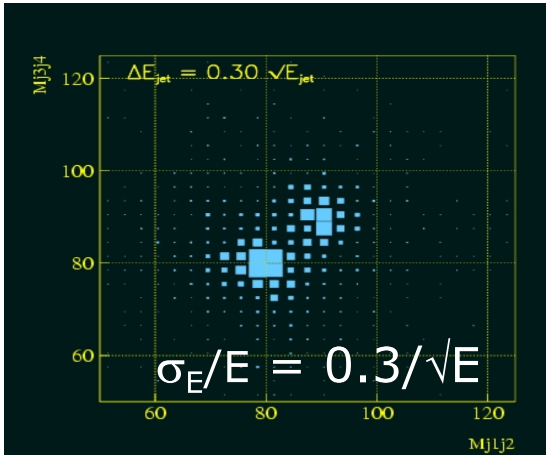
Often-quoted Example:

If the Higgs mechanism is not responsible for EWSB then QGC processes important

$e^+e^- \to \nu\nu WW \to \nu\nu qqqq$, $e^+e^- \to \nu\nu ZZ \to \nu\nu qqqq$

Reconstruction of two di-jet masses allows discrimination of WW and ZZ final states





★ **EQUALLY applicable to any final states where want to separate $W \to qq$ and $Z \to qq$!**

★ Want $\sigma_E/E < 0.30/\sqrt{E(\mathrm{GeV})}$

or more correctly $\sigma_E/E < 3.8\%$

★ Very hard (may not be possible) to achieve this with a traditional approach to calorimetry

Limited by typical HCAL resolution of > 50%/√E(GeV)

⇒ a new approach to calorimetry

❸ Introduction to Particle Flow

- In a typical jet :
  - 60 % of jet energy in charged hadrons
  - 30 % in photons (mainly from $\pi^0 \rightarrow \gamma\gamma$)
  - 10 % in neutral hadrons
- Traditional calorimetric approach:
  - Measure all components of jet energy in ECAL/HCAL !
- Particle Flow Calorimetry paradigm:
  - charged particles measured in tracker (essentially perfectly)
  - Photons in ECAL (<20%/ √E(GeV))
  - Neutral hadrons in HCAL (+ECAL) (~60%/ √E(GeV))

Only 10 % of jet energy measured in "poor resolution" HCAL

- What is important in particle flow calorimetry ?
  - NOT: Calorimetric performance
  - Confusions Rules : particle flow lives and dies on ability to correctly separate energy deposits from different particles

PFA : Basic issues

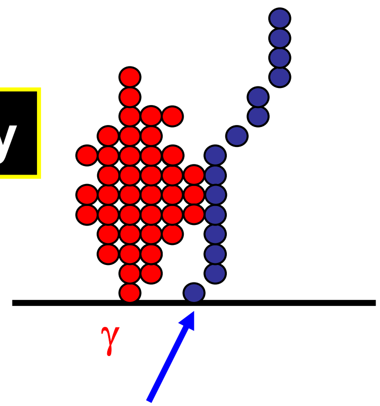
- ★ **Separate energy deposits from different particles**
- ★ **Avoid double counting of energy from same particle**
- ★ **Mistakes drive particle flow jet energy resolution**

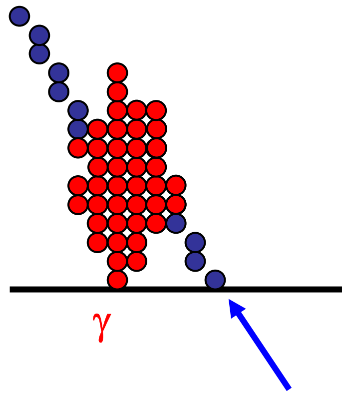
e.g.

- ★ **Need to separate "tracks" (charged hadrons) from photons**

hardware

granularity

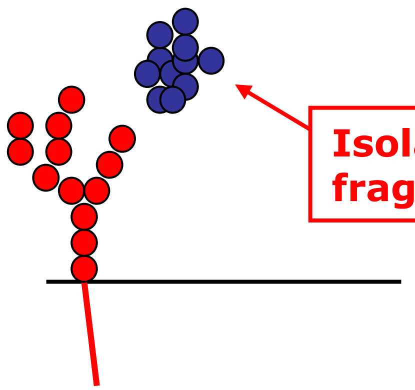




software

PFlow Algorithm

- ★ **Need to separate neutral hadrons from charged hadrons**



Isolated neutral hadron or fragment from shower ?

e.g. Calorimeters for PFlow

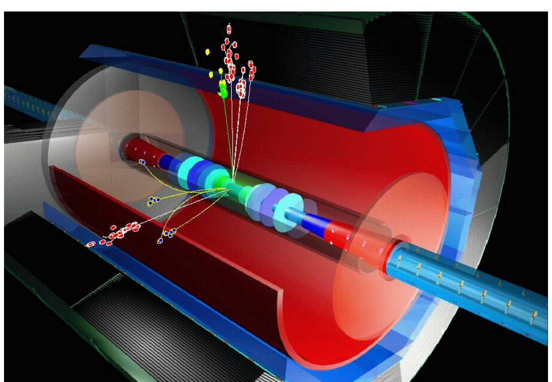
To separate energy deposits from different particles require:

- ★ Very high transverse segmentation
  - ♦ ECAL typically ~1x1 cm^2 — e.g. SiW a la CALICE
  - ♦ HCAL typically ~3x3 cm^2 — e.g. Steel/Scintillator or Steel/RPC
- ★ High longitudinal sampling
  - ♦ ~30 layers in ECAL, ~40 in HCAL

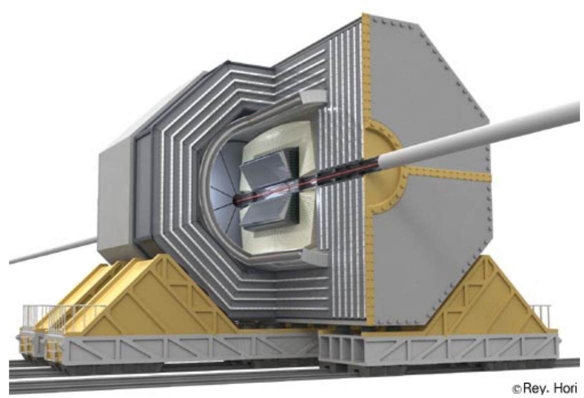
<u>e.g. ILC Detector Concepts:</u>

- ★ ILC Detector Design work centred around 4 detector “concepts”
- ★ 3 of these concepts “optimised” for PFA Calorimetry SiD, LDC, GLD
- ★ PFA Calorimetry has very large impact on the detector designs
- ★ Particle flow calorimetry being extensively studied/developed

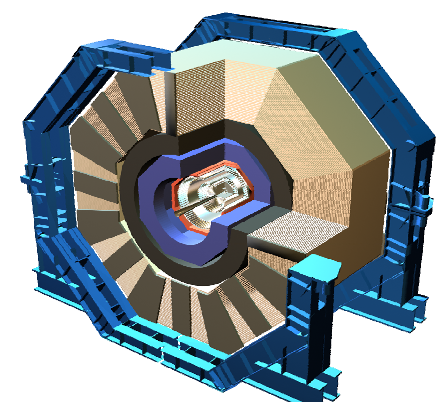
LDC : Large Detector Concept



GLD : Global Large Detector

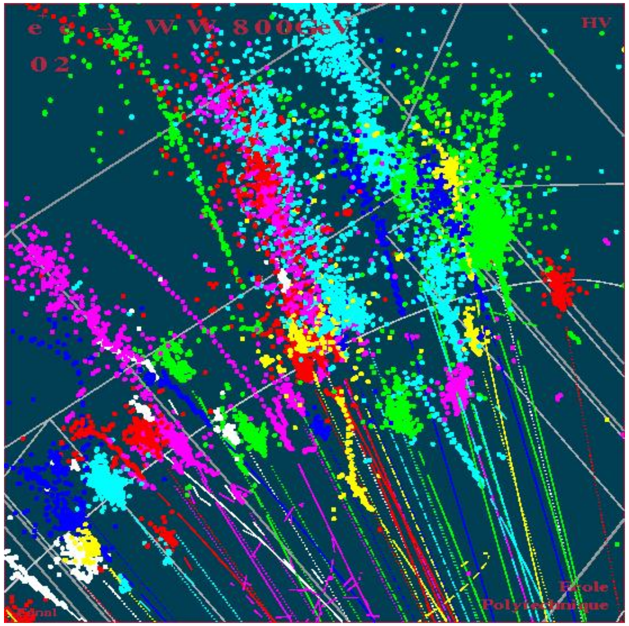


SiD : Silicon Detector



❹ Particle Flow Reconstruction

- ★ High granularity calorimeters – **very different** to previous detectors (exceptions: LEP lumi. calorimeters)
- ★ “Tracking calorimeter” – requires a new approach to ECAL/HCAL reconstruction



- ILC calorimetric performance = **HARDWARE + SOFTWARE**
- Development of sophisticated particle flow algorithms vital to understand ultimate limit of particle flow jet energy resolution

e.g. PandoraPFA Algorithm

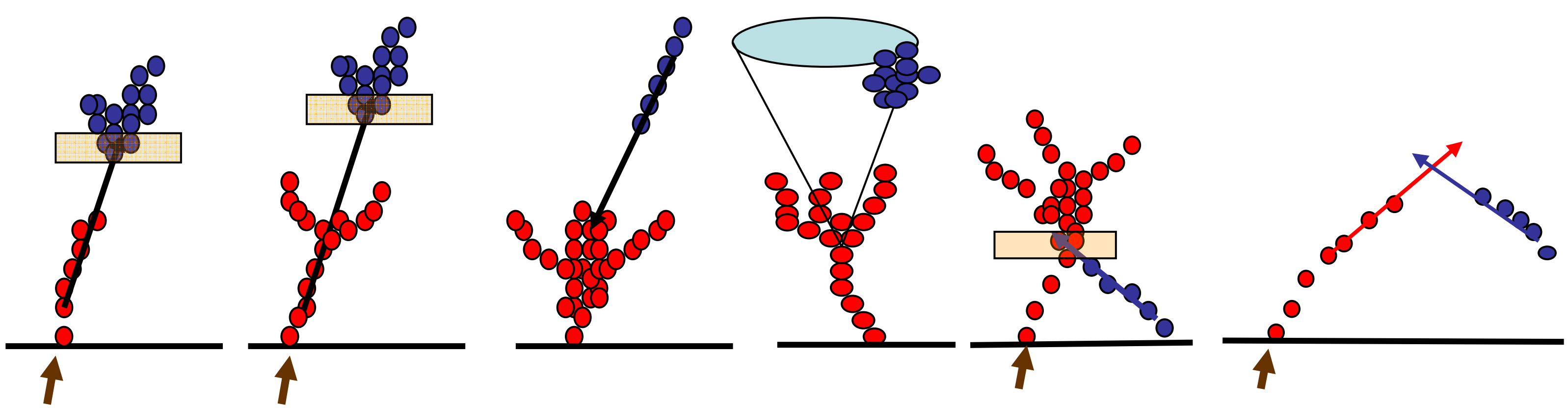
★ Best performing algorithm to date "PandoraPFA"
★ Sophisticated reconstruction – much more than clustering

i. Loose clustering in ECAL and HCAL
ii. Topological association of clusters
iii. Iterative reclustering
iv. Photon Recovery
v. Neutral Fragment ID and Removal
vi. Formation of final Particle Flow Objects

Insufficient time to go into any detail simply try and give flavour

e.g. ii) topological cluster merging

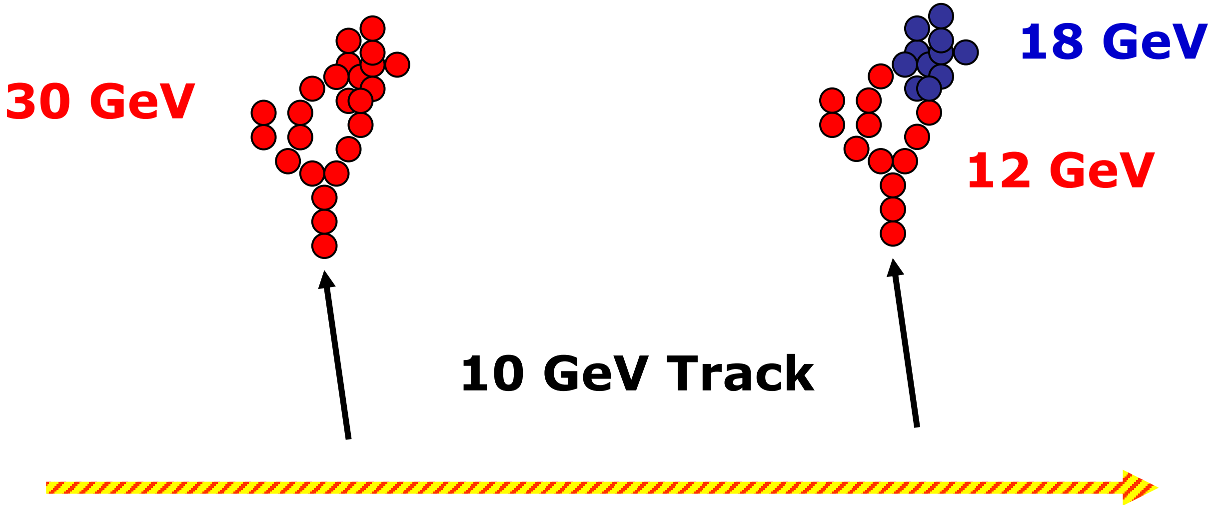
- Join clusters which are clearly associated making use of high granularity + tracking capability: very few mistakes



★ **Particle flow reconstruction is not a pure ECAL/HCAL problem, tracks used extensively to refine reconstruction.**

e.g. iii) iterative reclustering

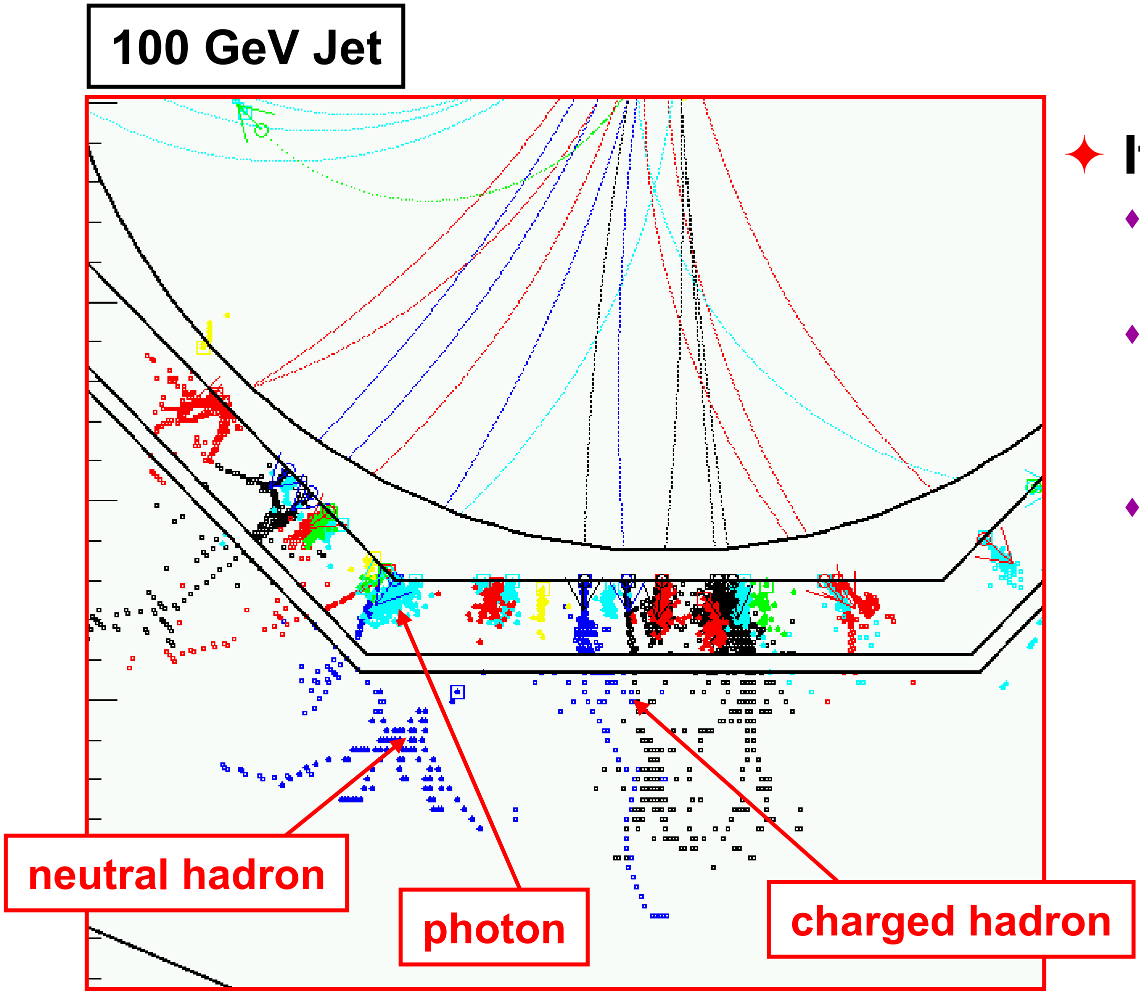
- **If track momentum and matched cluster energy are inconsistent, something has gone wrong… RECLUSTER**



Change clustering parameters until cluster splits and get sensible track-cluster match

★ **Reduces "confusion" and thus improves jet energy resolution**

Putting it all together…



- ✦ **If it all works…**
  - ♦ **Reconstruct the individual particles in the event.**
  - ♦ **Calorimeter energy resolution not critical: most energy in form of tracks.**
  - ♦ **Level of mistakes in associating hits with particles, dominates jet energy resolution.**

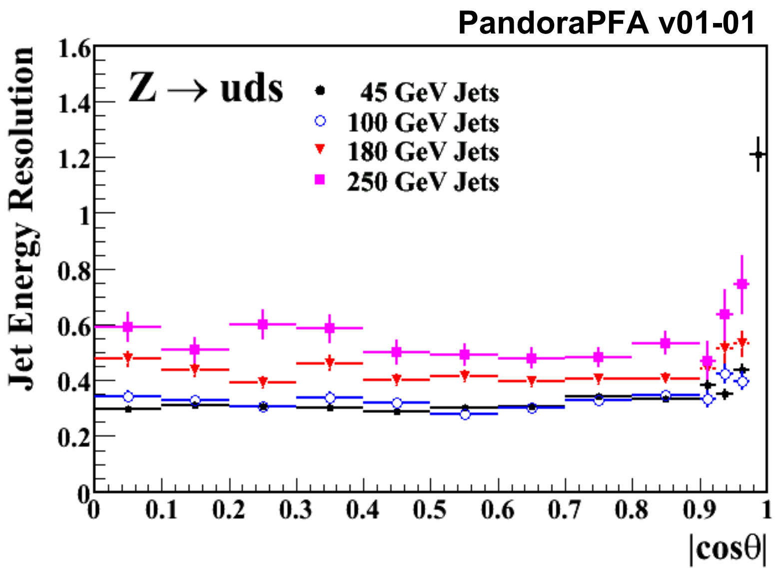
★ **Particle flow reconstruction is an active area of research, new ideas being developed…**

Current performance

★ Full simulation studies using the LDC ILC detector concept with the PandoraPFA algorithm. Use $Z \rightarrow u\bar{u}, d\bar{d}, s\bar{s}$ decays at rest to benchmark performance

rms90*

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E
45 GeV	0.288	4.3 %
100 GeV	0.305	3.0 %
180 GeV	0.418	3.1 %
250 GeV	0.534	3.3 %



★ For jet energies below 100 GeV, particle flow gives a resolution which is a factor 2 better than traditional approaches

❺ Conclusions

★ Physics performance at the ILC will be very dependent on the performance of the detector.

★ A factor 2 improvement in jet energy resolution compared to traditional calorimetric methods is required

★ Particle flow calorimetry with highly segmented calorimeters **can meet** the ILC jet energy resolution goal

★ This is very much “work-in-progress”, ultimate PFA performance unknown…

end

★ **Impact of PFA performance on ILC physics being studied….**

e.g. $\mathrm{HZ} \rightarrow \mathrm{b\bar{b}q\bar{q}}$ **at** $\sqrt{s} = 500\,\mathrm{GeV}$