# Calorimetry and Particle Flow at the ILC

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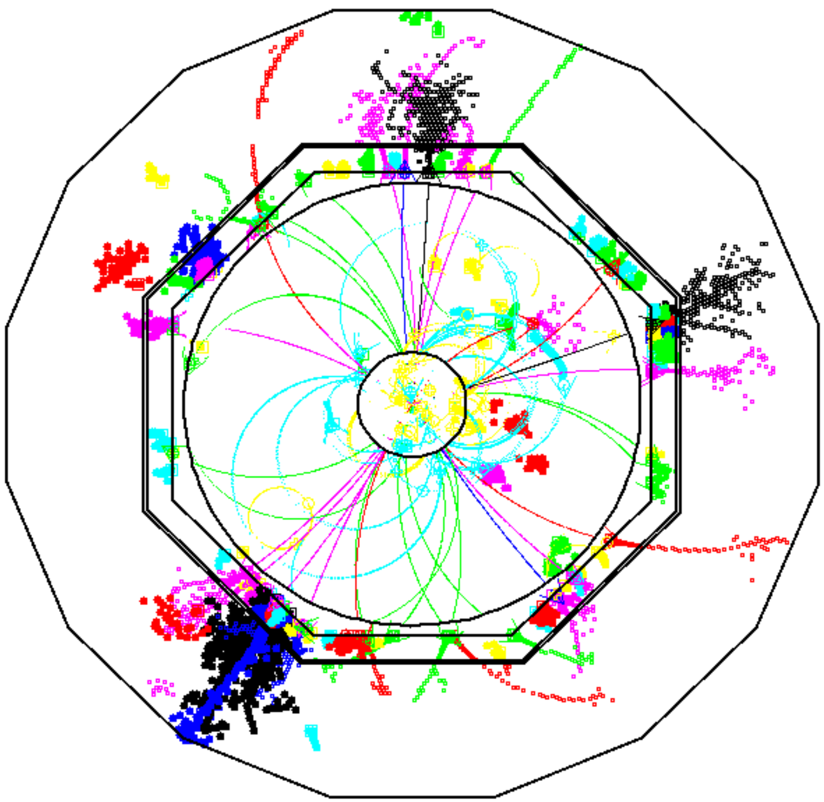


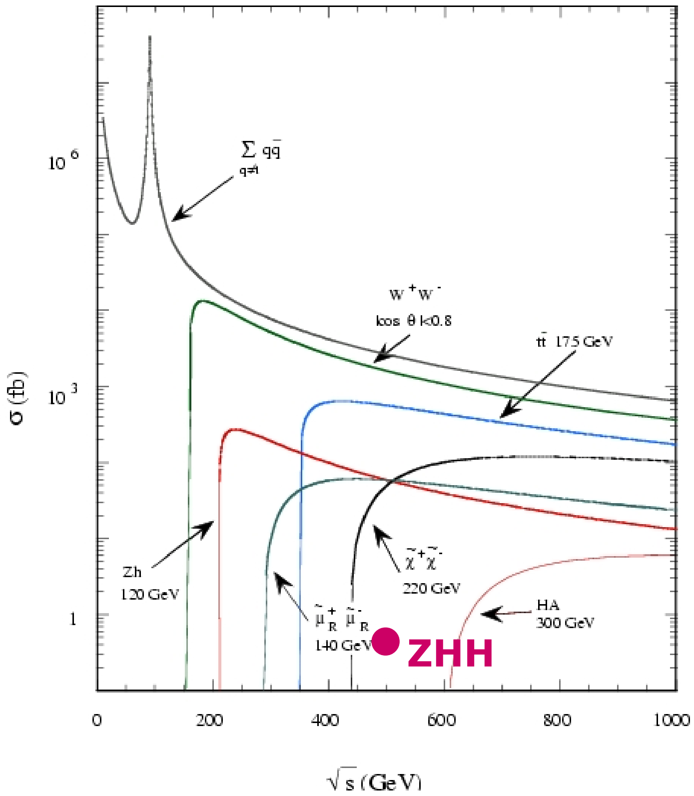
## This Talk:

# ❶ ILC Physics ↔ Calorimetry

**ILC PHYSICS:**

**Precision Studies/Measurements**

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




**Physics characterised by:**

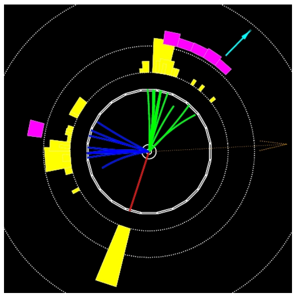
- ★ High Multiplicity final states
  often 6/8 jets
- ★ Small cross-sections
  e.g. $\sigma(e^+e^- \rightarrow ZHH) = 0.3$ fb

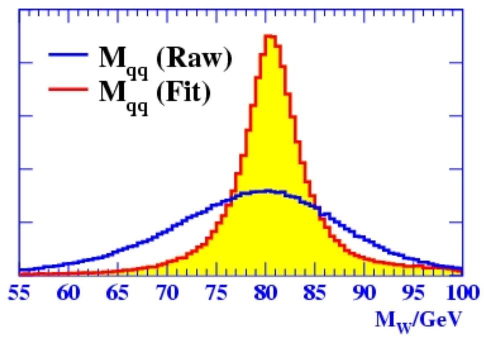
**✸ Require High Luminosity**

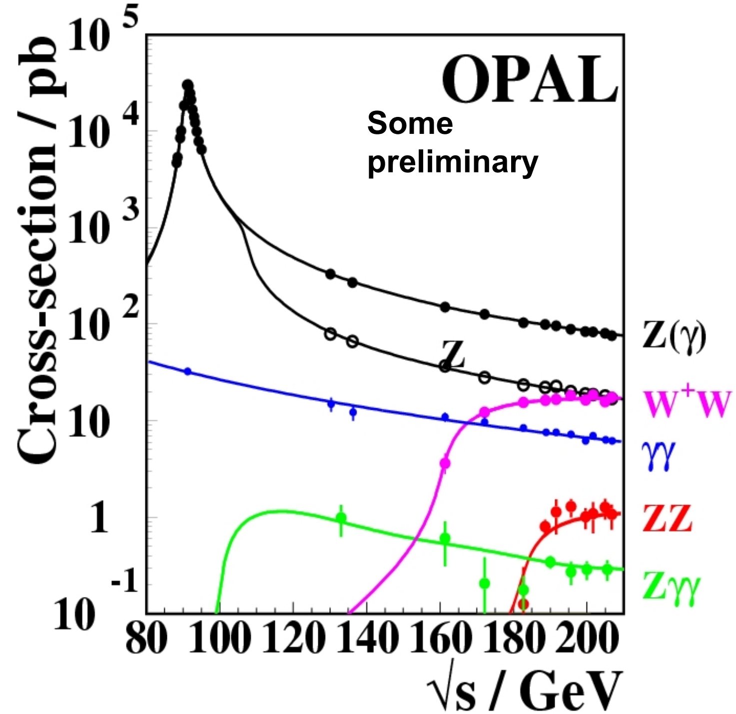
**✸ Detector optimized for precision measurements in difficult multi-jet environment**

# Compare with LEP

- ★ $e^+e^- \to Z$ and $e^+e^- \to W^+W^-$ dominate
  - backgrounds not too problematic
- ★ Kinematic fits used for mass reco.
  - good jet energy resolution not vital






## At the ILC:

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

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

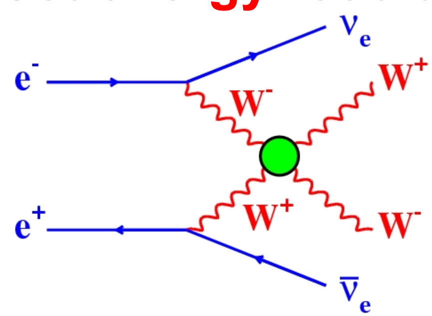
# Calorimetry at the ILC

**Jet energy resolution:**

THIS ISN'T EASY !

| Best at LEP (ALEPH): | ILC GOAL: |
|---|---|
| $\sigma_E/E = 0.6(1+\lvert\cos\theta_{Jet}\rvert)/\sqrt{E(\text{GeV})}$ | $\sigma_E/E = 0.3/\sqrt{E(\text{GeV})}$ |

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

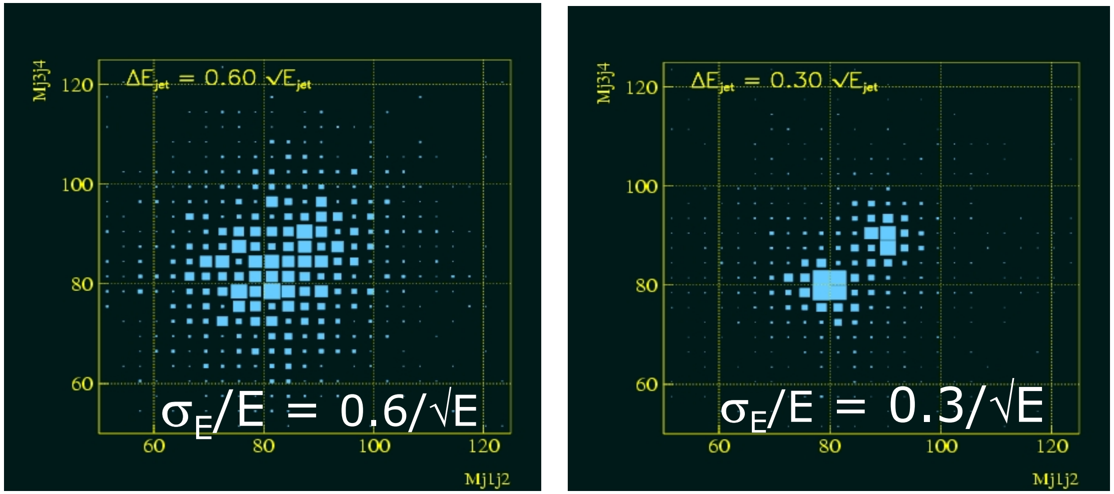



**Often-quoted Example:**

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

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

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



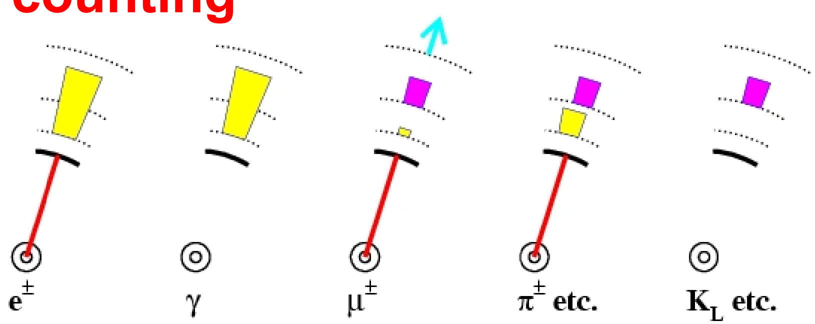

★ **EQUALLY applicable to any final states where want to separate $W \rightarrow qq$ and $Z \rightarrow qq$ !**

# ❷ The Particle Flow Paradigm

★ Much ILC physics depends on reconstructing invariant masses from jets in hadronic final states
★ Often kinematic fits won't help – Unobserved particles (e.g. $\nu$) + Beamsstrahlung, ISR
★ Aim for jet energy resolution ~ $\Gamma_Z$ for "typical" jets
- the point of diminishing return ⟹ $\sigma_E/E \sim 0.3/\sqrt{E(\mathrm{GeV})}$
★ Jet energy resolution is the key to calorimetry at the ILC
★ Widely believed that PARTICLE FLOW is the best way to achieve $\sigma_E/E \sim 0.3/\sqrt{E(\mathrm{GeV})}$

**The Particle Flow Analysis (PFA):**

- Reconstruct momenta of individual particles avoiding double counting




Charged particles in tracking chambers
Photons in the ECAL
Neutral hadrons in the HCAL (and possibly ECAL)

★ Need to separate energy deposits from different particles
★ Not calorimetry in the traditional sense

★ **TESLA TDR resolution (Z→uds at rest) : ~$0.30\sqrt{E_{jet}}$**

| Component | Detector | Frac. of jet energy | Particle Resolution | Jet Energy Resolution |
|---|---|---|---|---|
| Charged Particles($X^{\pm}$) | Tracker | 0.6 | $10^{-4} E_X$ | neg. |
| Photons($\gamma$) | ECAL | 0.3 | $0.11\sqrt{E_\gamma}$ | $0.06\sqrt{E_{jet}}$ |
| Neutral Hadrons($h^0$) | HCAL | 0.1 | $0.4\sqrt{E_h}$ | $0.13\sqrt{E_{jet}}$ |

★ **Energy resolution gives $0.14\sqrt{E_{jet}}$ (dominated by HCAL)**

**Calorimetric performance not the limitation !**

★ **In addition, have contributions to jet energy resolution due to "confusion", i.e. assigning energy deposits to wrong reconstructed particles (double-counting etc.)**

$$\sigma_{jet}^2 = \sigma_{x^{\pm}}^2 + \sigma_{\gamma}^2 + \sigma_{h^0}^2 + \sigma_{confusion}^2 + \sigma_{threshold}^2 + \ldots$$

★ **Single particle resolutions not the dominant contribution to jet energy resolution !**

**granularity more important than energy resolution**

# PFA : Basic issues

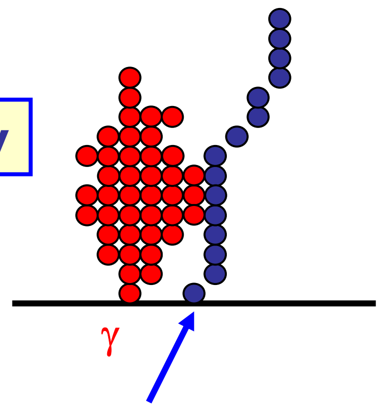
★ What are the main issues for PFA ?

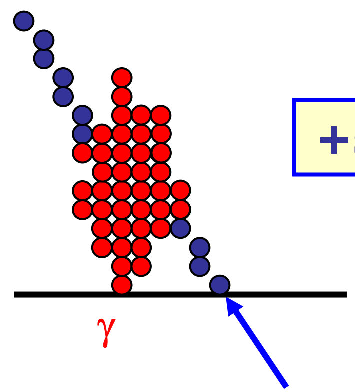
★ Separate energy deposits + avoid double counting

**e.g.**

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

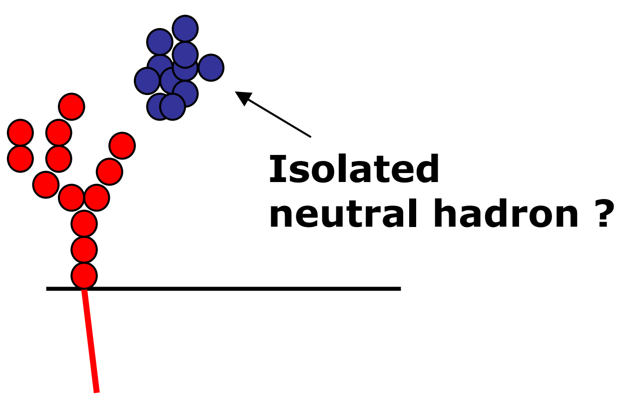
granularity




+software

★ Need to separate neutral hadrons from charged hadrons

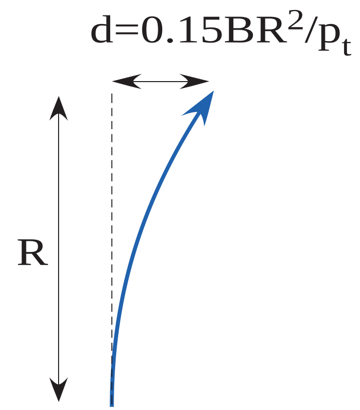


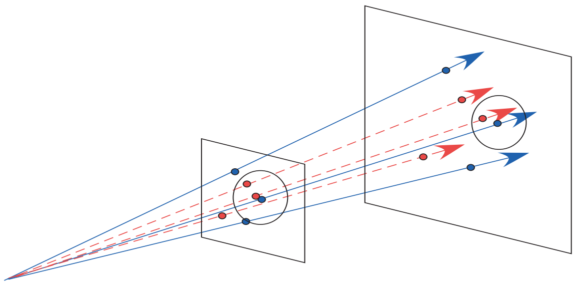

Granularity helps
But less clear…

# PFA : "Figure of Merit"

- For good jet energy resolution need to separate energy deposits from different particles
  - **Large detector** – spatially separate particles
  - **High B-field** – separate charged/neutrals
  - **High granularity ECAL/HCAL** – resolve particles

**HIGH COST**



Often quoted* "figure-of-merit": $\frac{BR^2}{\sigma}$

- $BR^2$ ← Separation of charge/neutrals
- $\sigma$ ← Calorimeter granularity/$R_{Moliere}$

- Physics argues for : large + high granularity + ⇧ B
- Cost considerations: small + lower granularity + ⇩ B

- **Need realistic algorithms to determine what drives PFA performance....**

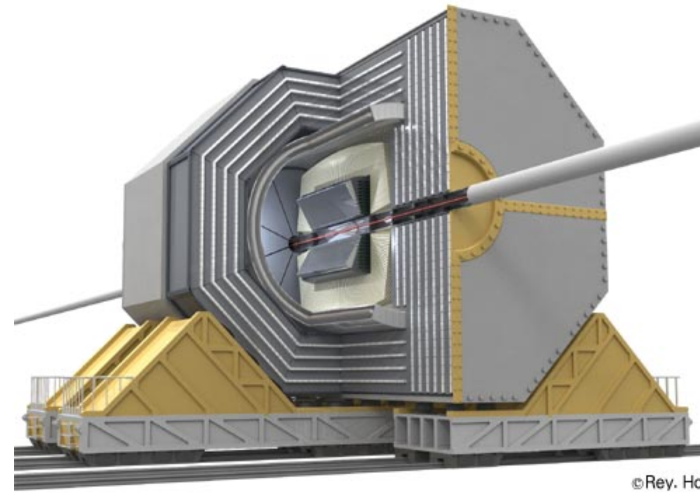
*But wrong

# ❸ The ILC Calorimeter Concepts

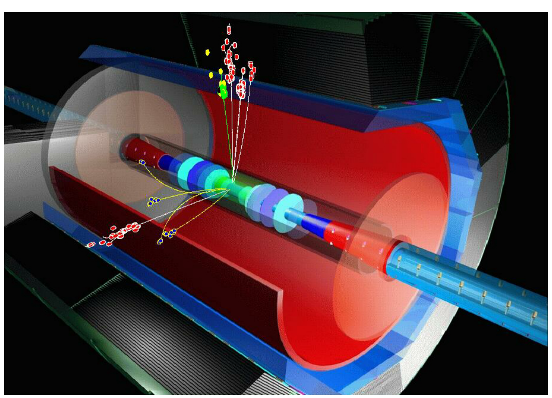
**ILC Detector Concepts:**

- ★ ILC Detector Design work centred around 4 detector "concepts"
- ★ Each will contribute to an ILC detector conceptual design report by end of 2006
- ★ Ultimately may form basis for TDRs
- ★ 3 of these concepts "optimised" for PFA Calorimetry SiD, LDC, GLD

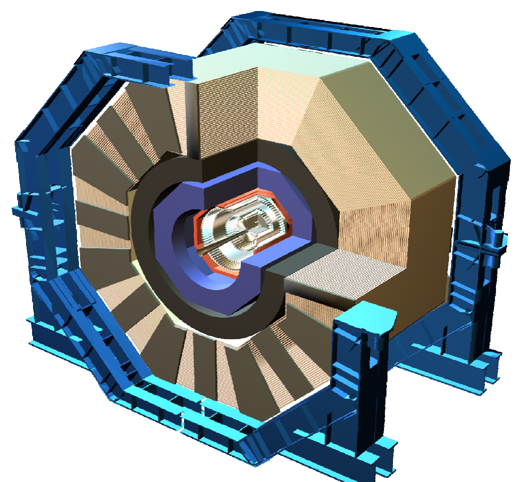
**GLD : Global Large Detector**




**LDC : Large Detector Concept**
**(spawn of TESLA TDR)**



**SiD : Silicon Detector**



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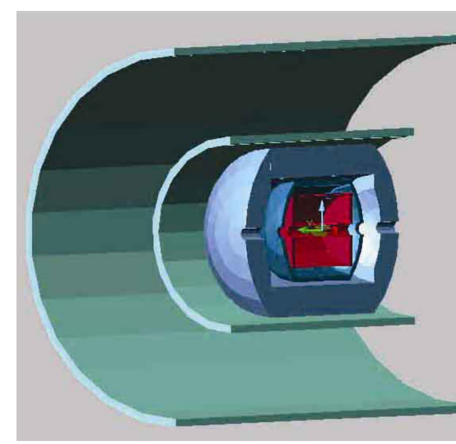
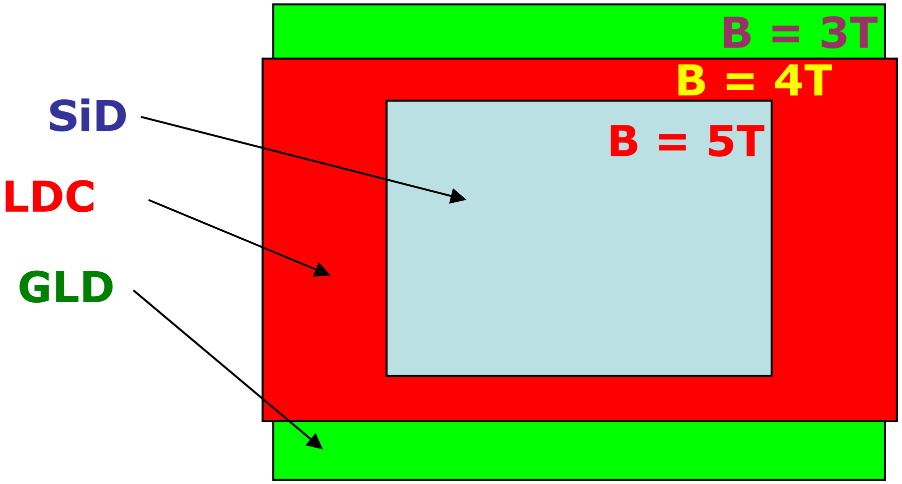


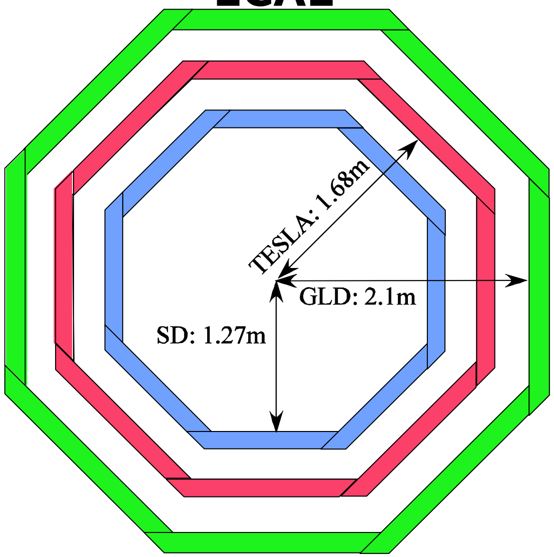
# Main Differences:

- **SIZE + B-Field**

**Tracker**




**ECAL**




- **Central Tracker and ECAL**

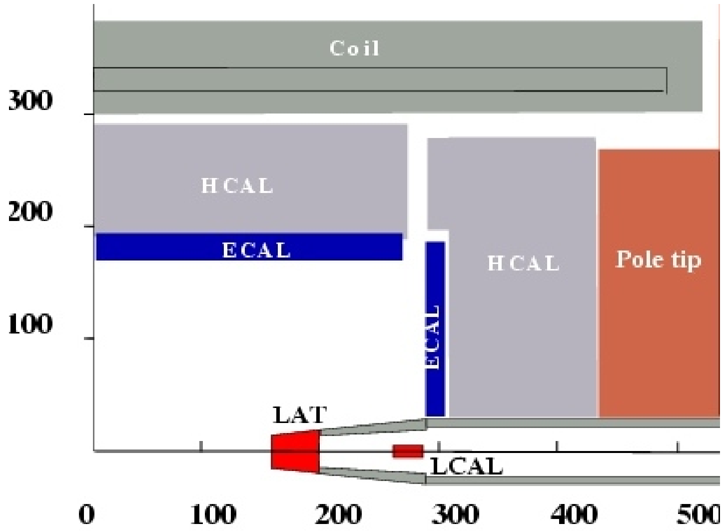
| | SiD | LDC | GLD |
|---|---|---|---|
| Tracker | Silicon | TPC | TPC |
| ECAL | SiW | SiW | Pb/Scint |

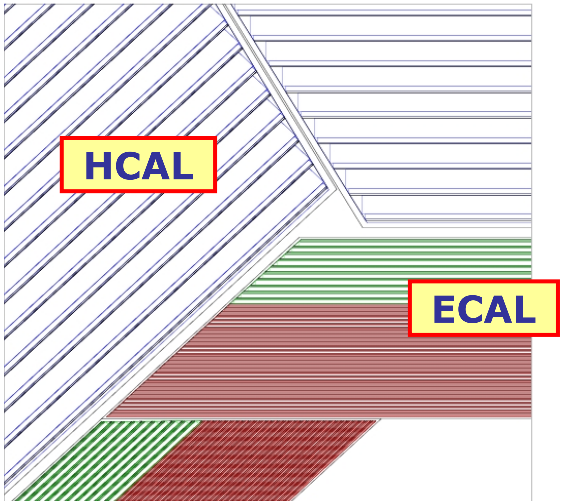
★ **SiD + LDC + GLD all designed for PFA Calorimetry !**

★ **also "4th" concept designed for more "traditional" approach to calorimetry !**

# LDC/SiD Calorimetry

## ECAL and HCAL inside coil




**ECAL: silicon-tungsten (SiW) calorimeter:**

- Tungsten : $X_0\ /\lambda_{had}$ = 1/25, $R_{Moliere}$ ~ 9mm
  (gaps between Tungsten increase effective $R_{Moliere}$)
- Lateral segmentation: ~1cm² matched to $R_{Moliere}$
- Longitudinal segmentation: 40 layers (24 $X_0$, $0.9\lambda_{had}$)
- Resolution: $\sigma_E/E = 0.15/\sqrt{E(\text{GeV})} \oplus 0.01$

  $\sigma_\theta = 0.063/\sqrt{E(\text{GeV})} \oplus 0.024$ mrad

# Hadron Calorimeter

## Highly Segmented – for Particle Flow

- Longitudinal: 40 samples
- 4 – 5 $\lambda$ (limited by cost - coil radius)
- Would like fine (1 $cm^2$ ?) lateral segmentation
- For 10000 $m^2$ of 1 $cm^2$ HCAL = $10^8$ channels – cost !

**Two Main Options:**

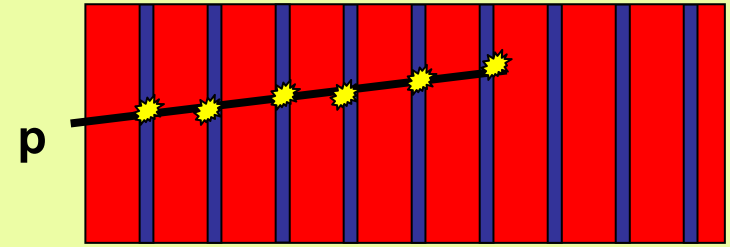
★ Tile HCAL (Analogue readout)
 Steel/Scintillator sandwich
 Lower lateral segmentation
  5x5 $cm^2$ (motivated by cost)

★ Digital HCAL
 High lateral segmentation
  1x1 $cm^2$
 digital readout (granularity)
 RPCs, wire chambers, GEMS…

**The Digital HCAL Paradigm**

- Sampling Calorimeter:

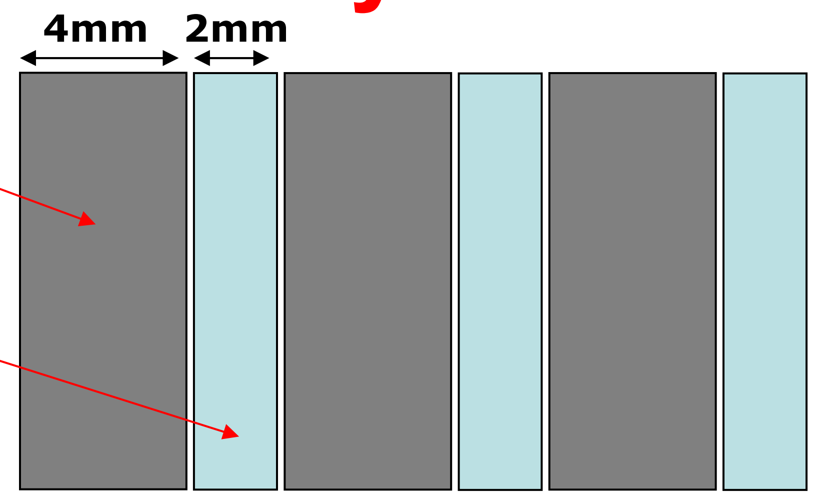
  Only sample small fraction of the total energy deposition

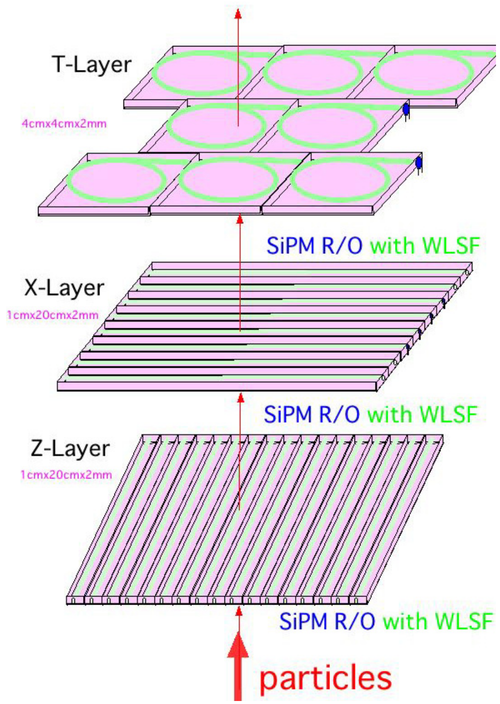



- Energy depositions in active region follow highly asymmetric Landau distribution

# GLD Calorimetry

- ★ ECAL and HCAL inside coil
- ★ W-Scintillator ECAL sampling calo.
- ★ W-Pb HCAL sampling calo.




**Initial GLD ECAL concept:**

- ★ Achieve effective ~1cm x 1cm segmentation using strip/tile arrangement
- ★ Strips : 1cm x 20cm x 2mm
- ★ Tiles : 4cm x 4cm x 2mm

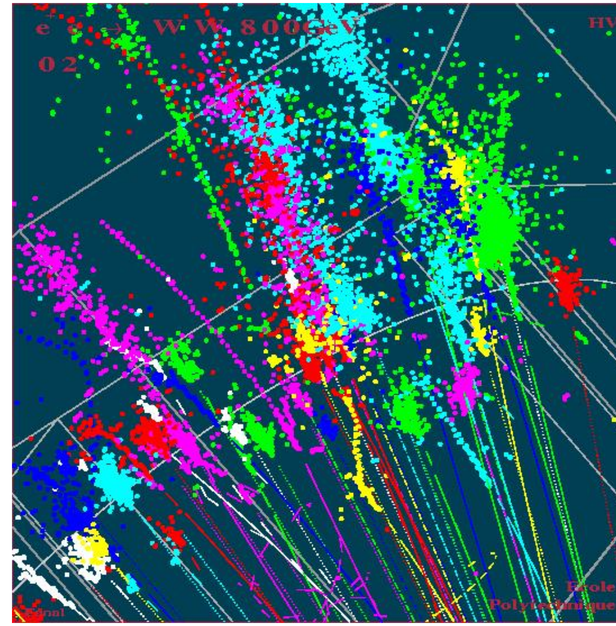
**question of pattern recognition in dense environment**

**SiD/LDC/GLD : Basic design = sampling calorimeter**

# Calorimeter Reconstruction

★ High granularity calorimeters – **very different** from previous detectors

★ "Tracking calorimeter" – requires a new approach to ECAL/HCAL reconstruction



★ **+PARTICLE FLOW**

★ ILC calo. performance = **HARDWARE + SOFTWARE**

★ Performance will depend on the software algorithm

➡ Nightmare from point of view of detector optimisation

★ *a priori* not clear what aspects of hadronic showers are important (i.e. need to be well simulated)

# ❹ PFA and ILC detector design ?

**PFA plays a special role in design of an ILC Detector**

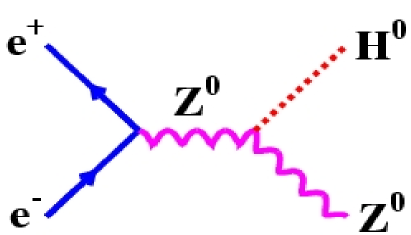
- **VTX** : design driven by heavy flavour tagging, machine backgrounds, <u>technology</u>
- **Tracker** : design driven by $\sigma_p$, track separation
- **ECAL/HCAL** : single particle $\sigma_E$ not the main factor
  - ➡ <u>jet energy resolution</u> ! Impact on particle flow drives calorimeter design + detector size, B field, …

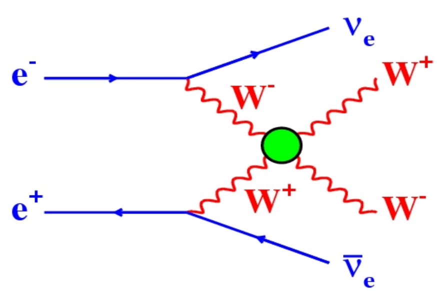
**PFA is a (the?) major $$$ driver for the ILC Detectors**

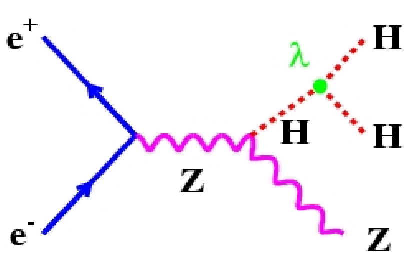
<u>**BUT:**</u> Don't really know what makes a good detector for PFA (plenty of personal biases – but little hard evidence)

<u>**How to optimise/compare ILC detector design(s) ?**</u>

- Need to choose the key "benchmark" processes (EASY)



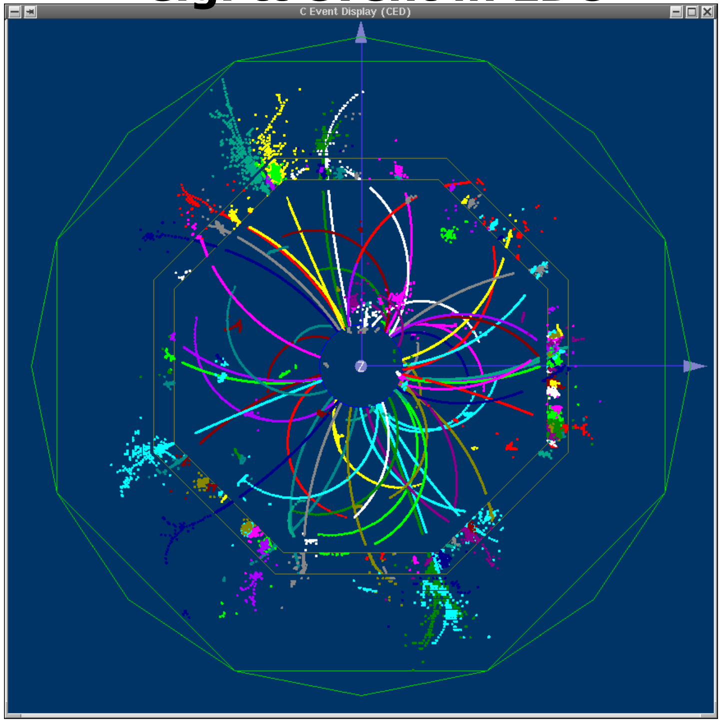



★ The rest is **VERY DIFFICULT** !

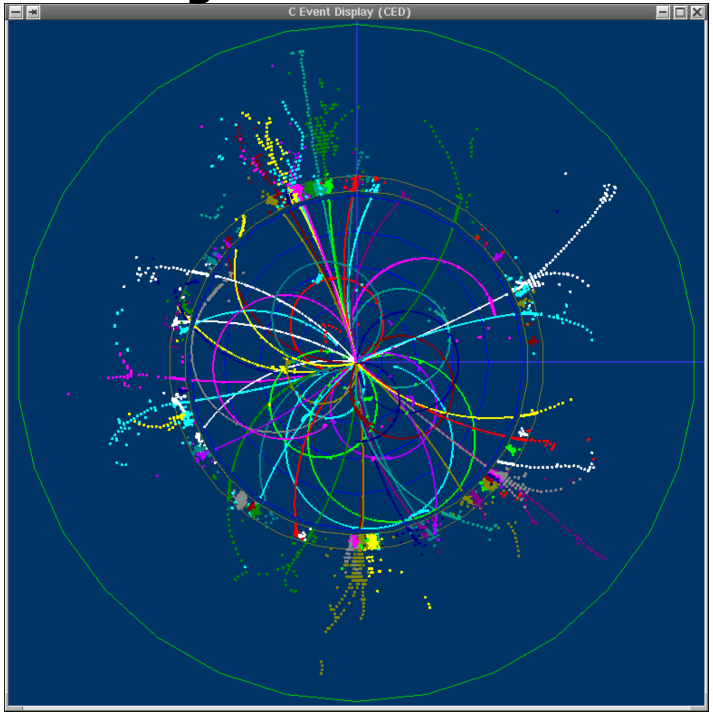
**<u>For example:</u>**

★ Wish to compare performance of say LDC and SiD detector concepts

**e.g. tt event in LDC**




**e.g. tt event in SiD**




★ However performance = DETECTOR + SOFTWARE

★ Non-trivial to separate the two effects

★ NEED REALISTIC SIMULATION + REALISTIC <u>RECONSTRUCTION</u> !

- can't use fast simulation etc.

# ❺ A Realistic(?) Particle Flow Algorithm

- **Need sophisticated reconstruction before it is possible to start full detector design studies**
- **So where are we now ?**
- **Significant effort (~6 groups developing PFA reconstruction worldwide)**

## For this talk concentrate one algorithm: PandoraPFA

- **Work-in-Progress – but does a pretty good job + beginning to get a better feel for what really matters….**
- **Concentrate on general features to indicate how an ultimate particle flow reconstruction might work**
- **Try to highlight the features of hadronic showers that impact PFA calorimetry**

# An Algorithm: PandoraPFA

★ Designed to take advantage of high granularity tracking calorimeter

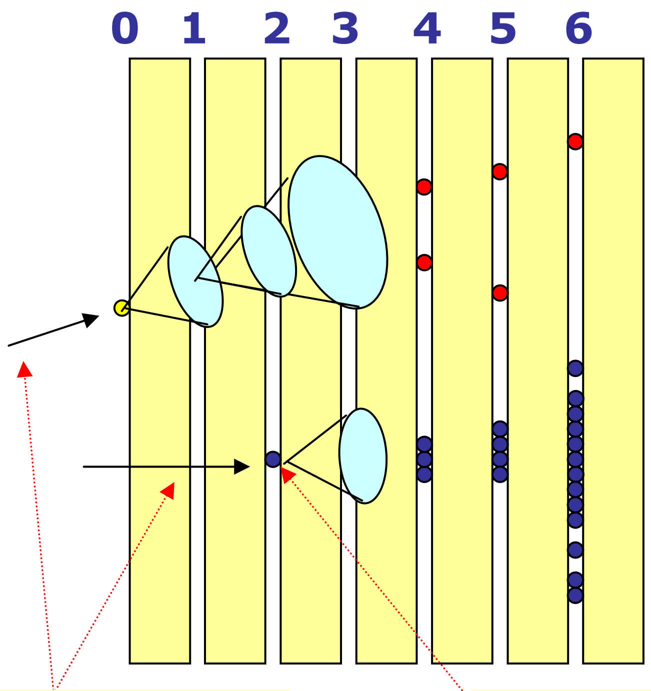
- ★ ECAL/HCAL reconstruction and PFA performed in a single algorithm
- ★ Keep things fairly generic algorithm
  - ★ applicable to multiple detector concepts
- ★ Use tracking information to help ECAL/HCAL clustering

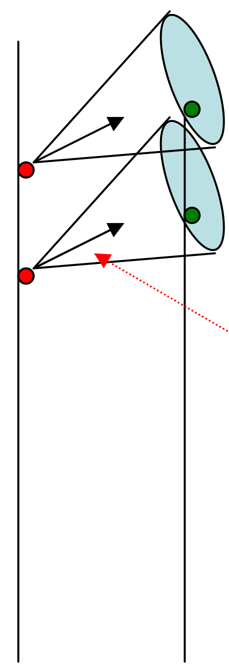
**5 Main Stages:**

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

# i) ECAL/HCAL Clustering

- ★ Start at inner layers and work outward
- ★ Associate Hits with existing Clusters
- ★ Step back **N** layers until associated
- ★ Then try to associate with hits in current layer
- ★ If no association made form new Cluster
- ★ + tracks used to seed clusters



Simple cone algorithm based on current direction + additional N pixels

Cones based on either:
initial PC direction or
current PC direction

Initial cluster direction

Unmatched hits seeds new cluster

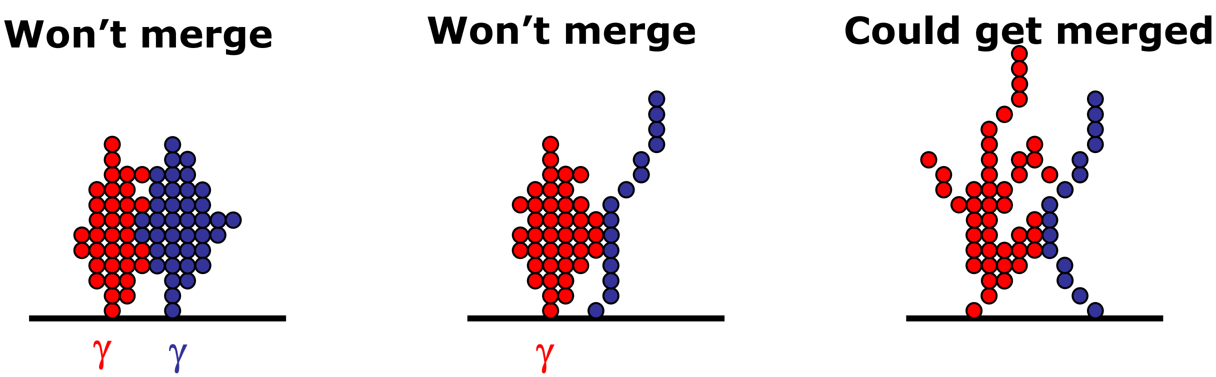
- ★ **NOTE:** TRACKING and CLUSTERING in the calorimeters

# ii) Cluster Association Part I

- ✦By design, clustering errs on side of caution
  i.e. clusters tend to be split
- ✦**Philosophy:** easier to put things together than split them up
- ✦Clusters are then associated together in two stages:
  - 1) Tight cluster association - clear topologies
  - 2) Loose cluster association – catches what's been missed but rather crude

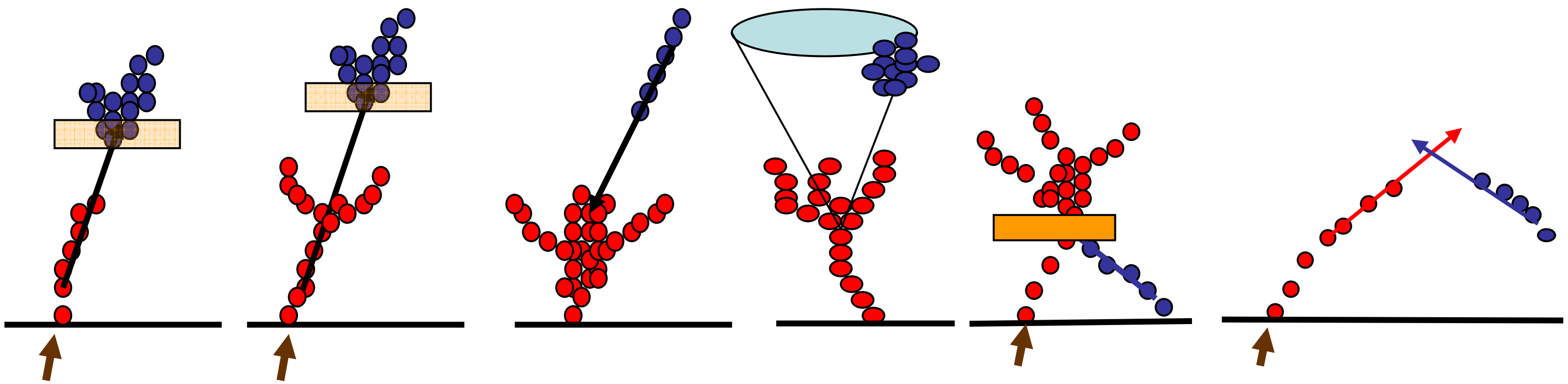
## Photon ID

- ★Photon ID plays important role
- ★Simple "cut-based" photon ID applied to all clusters
- ★Clusters tagged as photons are immune from association procedure – just left alone



# Topological Cluster Association

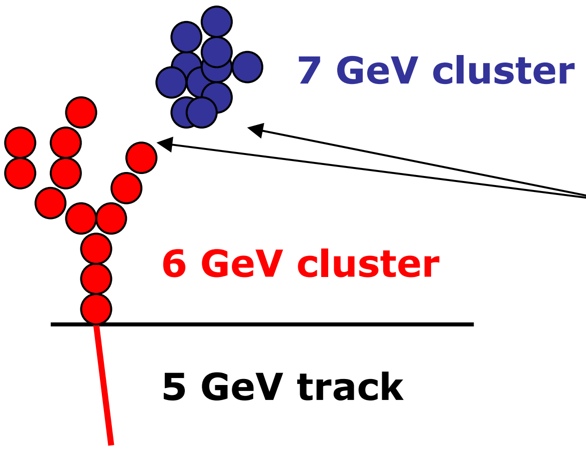
**Join clusters which are clearly associated**
**make use of high granularity + tracking capability**



**Only clear associations – almost no mistakes**

# iii) Cluster Association Part II

- Have made very clear cluster associations
- Now try "cruder" association strategies
- BUT first associate tracks to clusters (temporary association)
- Use track/cluster energies to "veto" associations, e.g.



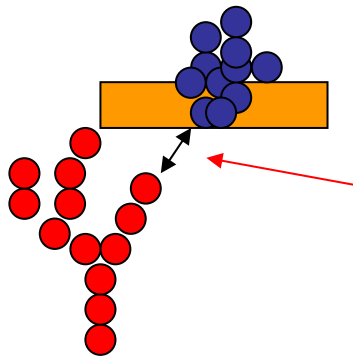

This cluster association would be forbidden if $|E_1 + E_2 - p| > 3\,\sigma_E$

Provides some protection against "dumb" mistakes

★ **Cluster reconstruction and PFA not independent**

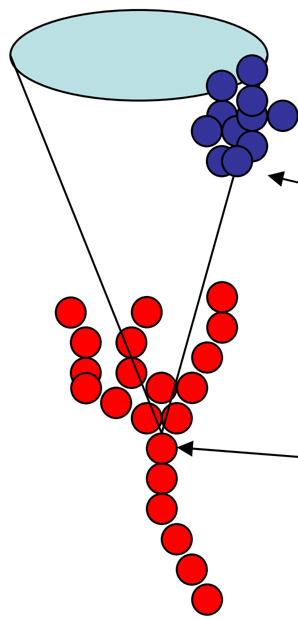
# Course Cluster Association

**<u>Proximity</u>**



**Distance between hits -limited to first layers**

**<u>Shower Cone</u>**



**Associated if fraction of hits in cone > some value**

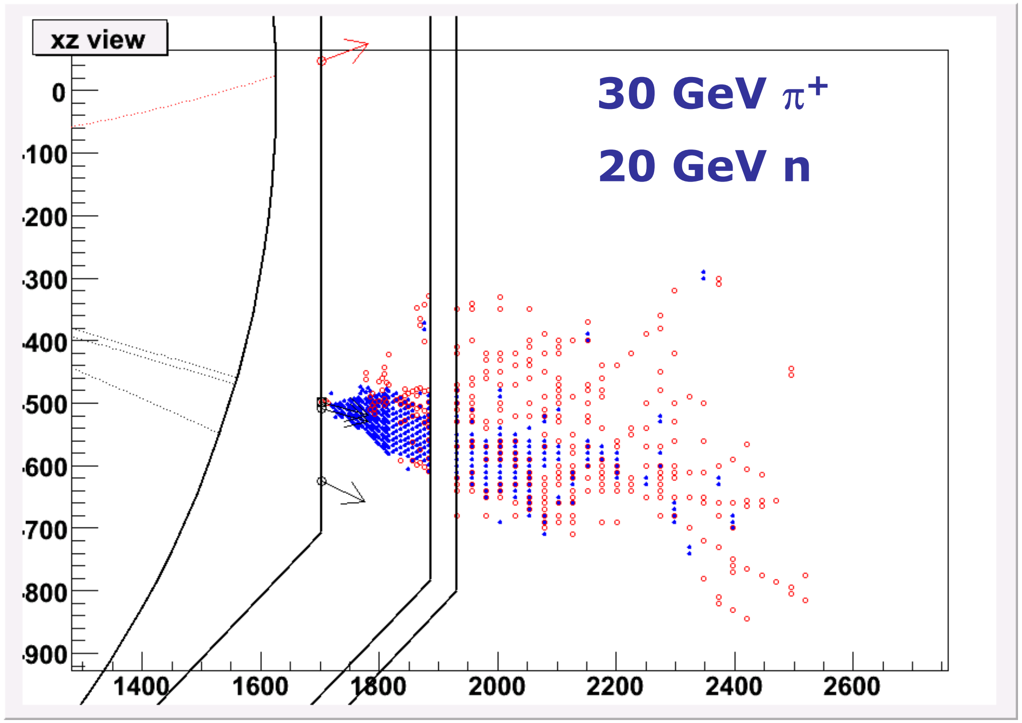
**Shower start identified**

**+<u>Track-Driven Shower Cone</u>**

**Apply looser cuts if have low E cluster associated to high E track**

# iv) Iterative Reclustering

- ★ Generally performance is good – but some difficult cases…




- ★ At some point hit the limit of "pure" particle flow
  - ♦ just can't resolve neutral hadron in hadronic shower

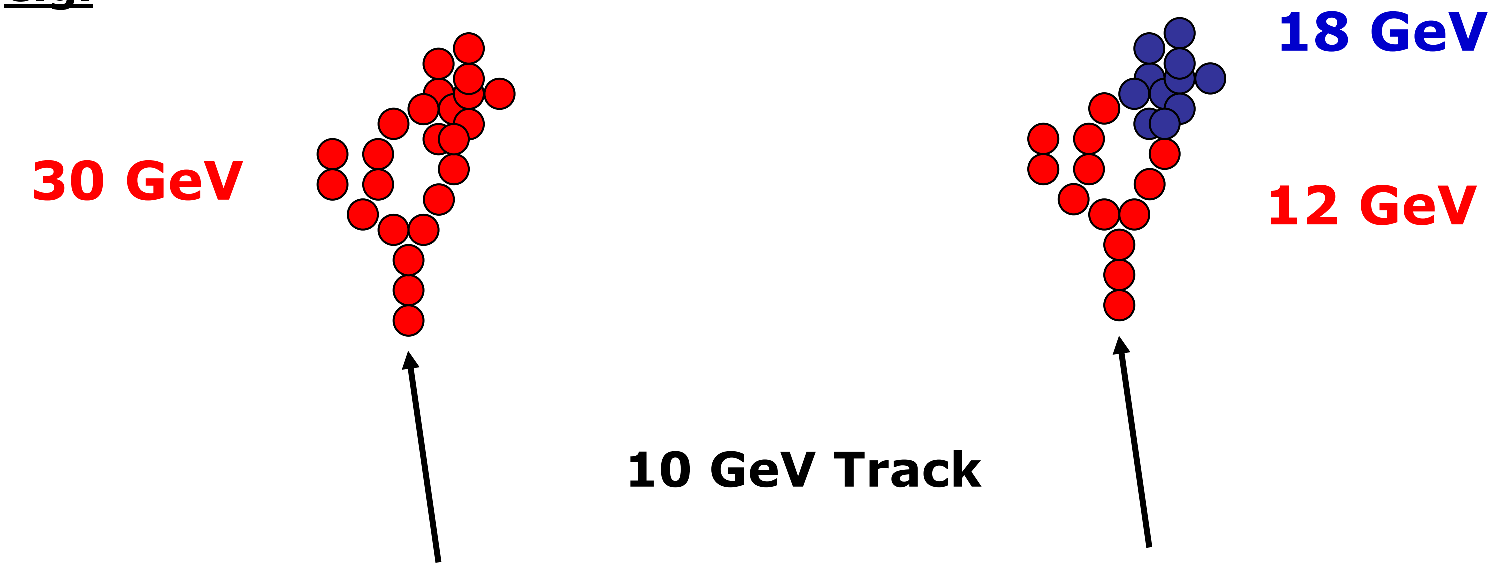
**The ONLY(?) way to address this is "statistically"**

→

**e.g. if have 30 GeV track pointing to 50 GeV cluster SOMETHING IS WRONG**

★ **If track momentum and cluster energy inconsistent : RECLUSTER**

**e.g.**



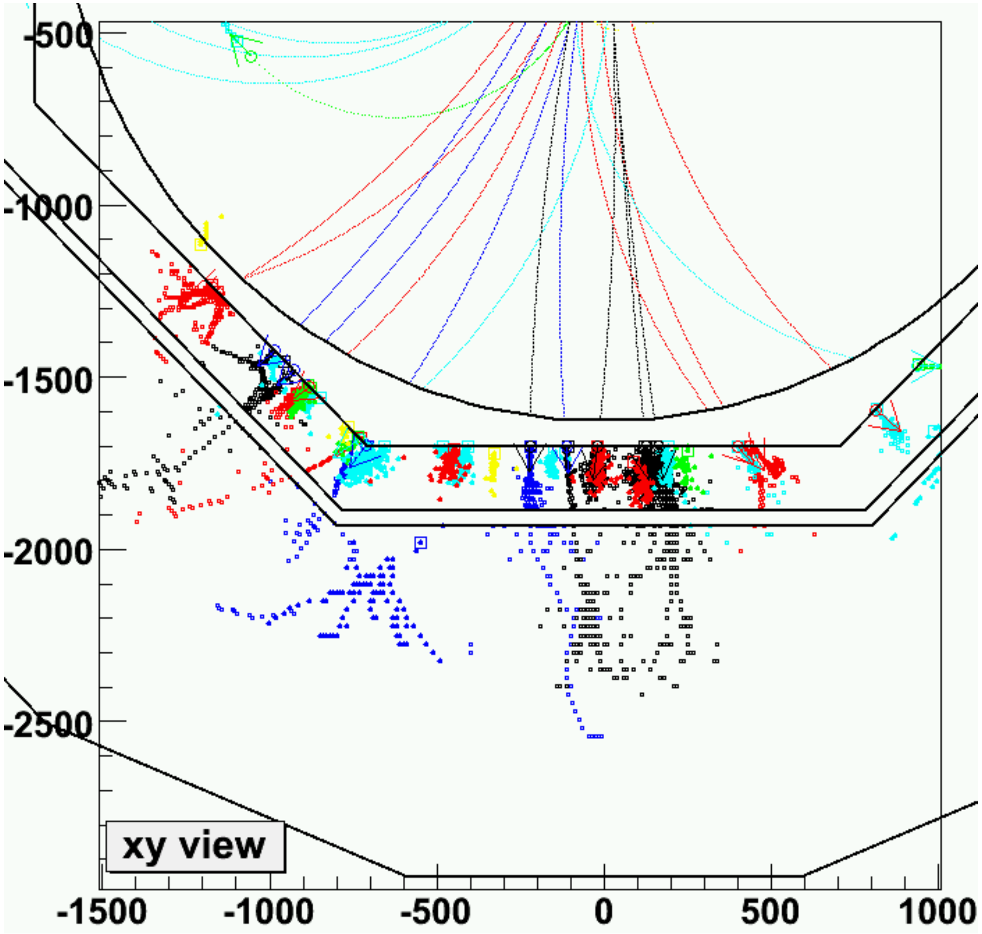

**Change clustering parameters until split cluster + get sensible track-cluster match**

**NOTE:** **NOT FULL PFA as clustering driven by track momentum**

★ Energy Resolution is important here

# ❻ Performance

**Example Reconstruction : 100 GeV Jet**

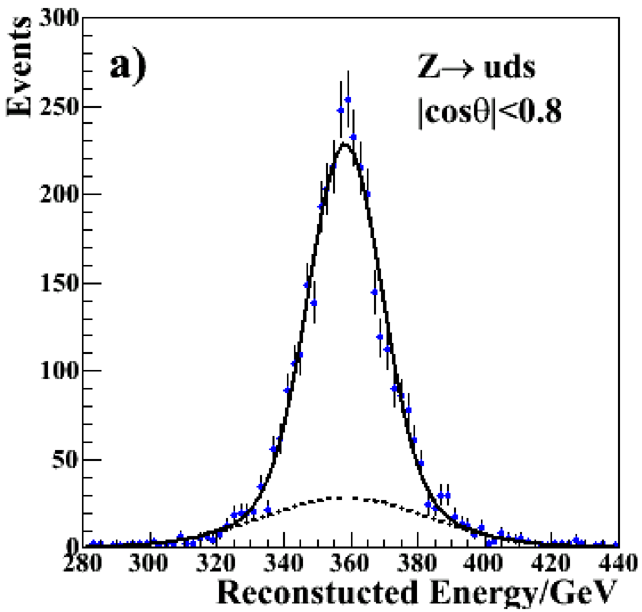


# $Z \rightarrow$ uds jets

**Figures of Merit:**

$\sigma_{75}$

- ★ Fit sum of two Gaussians with same mean. The narrower one is constrained to contain 75% of events
- ★ Quote $\sigma$ of narrow Gaussian




$rms_{90}$

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

| $E_{JET}$ | $\sigma_E/E = \alpha\sqrt{(E/GeV)}$ $\|\cos\theta\|<0.8$ |
|---|---|
| 45 GeV | 0.30 |
| 100 GeV | 0.37 |
| 180 GeV | 0.57 |
| 250 GeV | 0.75 |

**ILC GOAL OF 30 % ACHIEVED !**

- ★ BUT only for Z at 91.2 GeV
- ★ Need to look at performance at higher energies

It is found that $rms_{90} \approx \sigma_{75}$

# Detector Optimisation

★ From point of view of detector design – what do we want to know ?

**Optimise performance vs. cost**

★ Main questions (the major cost drivers):

- Size : performance vs. radius
- Granularity (longitudinal/transverse): ECAL and HCAL
- B-field : performance vs. B

★ To answer them use MC simulation + PFA algorithm

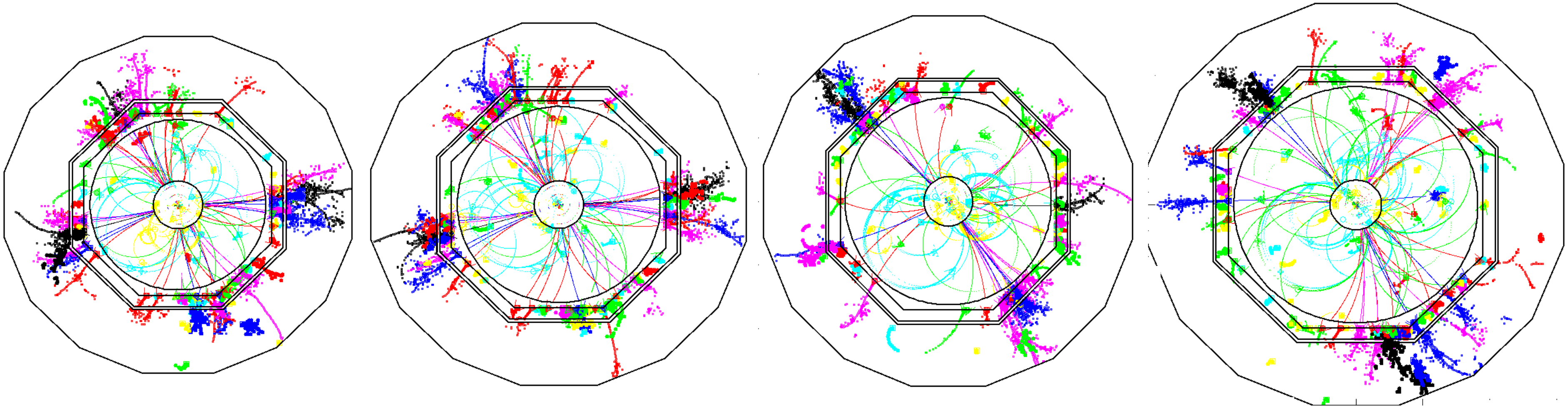
⚠

- Need a good simulation of hadronic showers
- Need realistic PFA algorithm
  (want results from multiple algorithms)

★ This is important – significant impact on overall design of *xxx* **M$** detector !

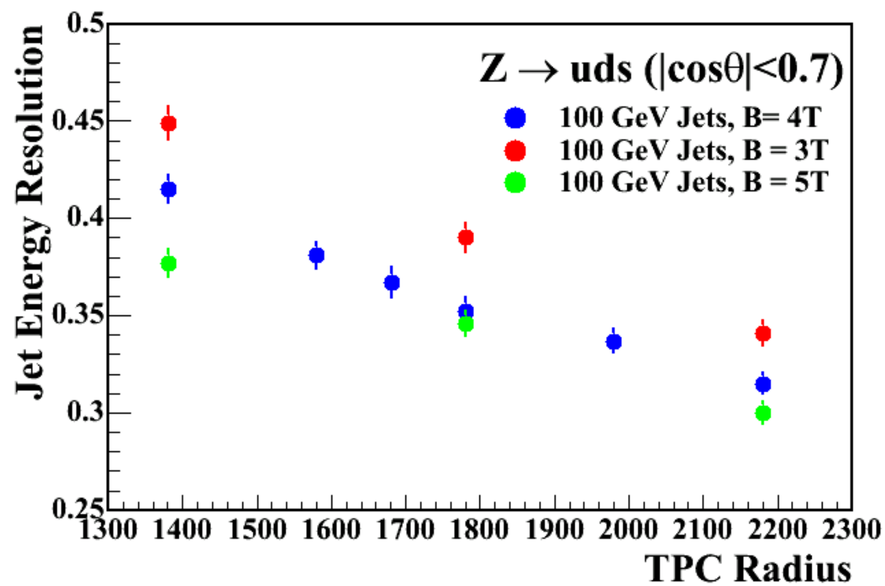
# e.g. Radius/Field

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

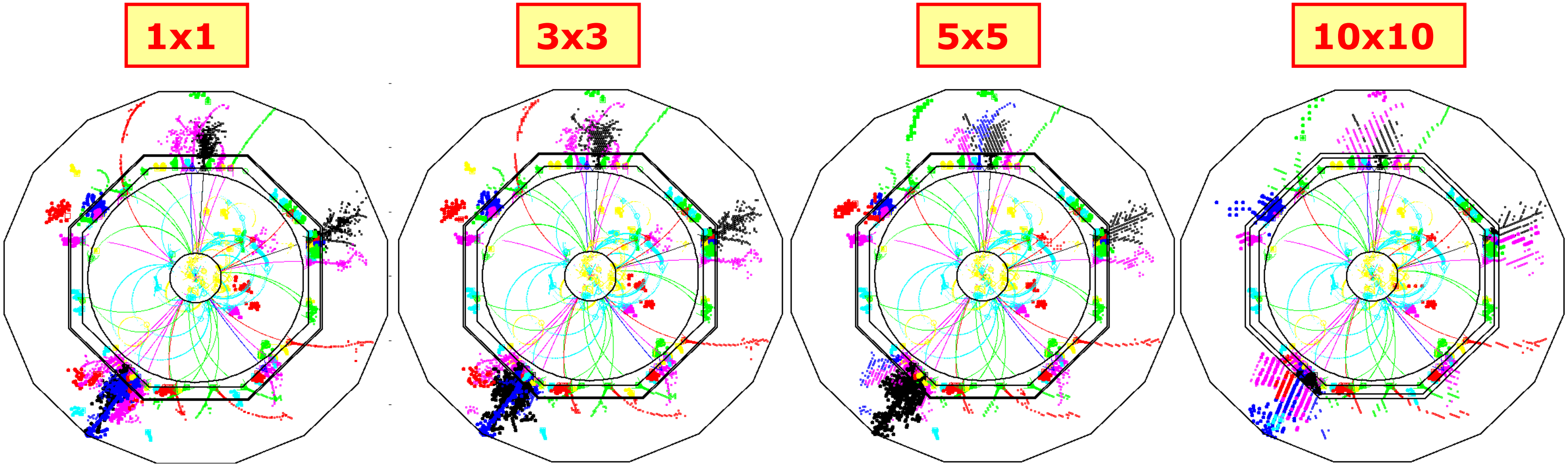


**e.g. 100 GeV Jets in Barrel**

- ★ Performance vs. radius/B (Tesla TDR detector)
- ★ Argues for large high field
- ★ With a reasonable cost model for ECAL+HCAL and Solenoid could identify "optimal" parameters



# e.g. HCAL Transverse Granularity

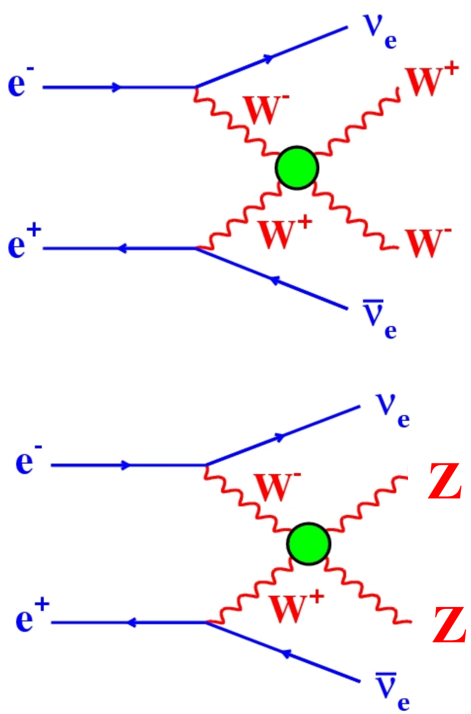


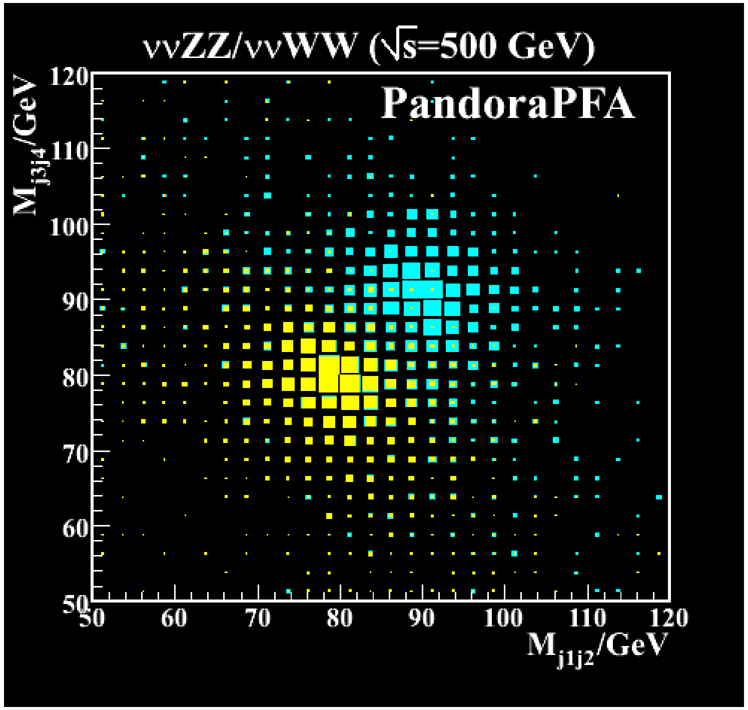

| Detector Model | $\sigma_{E_{vis}}/E = \alpha\sqrt{(E/GeV)}$ | |
|---|---|---|
| | Z @91 GeV | tt@500 GeV |
| LDC00Sc 1cm x 1cm | 31.4 ± 0.3 % | 42 ± 1 % |
| LDC00Sc 3cm x 3cm | 30.6 ± 0.3 % | 45 ± 1 % |
| LDC00Sc 5cm x 5cm | 31.3 ± 0.3 % | 48 ± 1 % |
| LDC00Sc 10cm x 10cm | 33.7 ± 0.3 % | 56 ± 1 %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

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

- Ultimately want to optimise for "physics performance" i.e. di-jet mass resolution in a multi-jet event
- Performance will be degraded by Jet-finding + jet-jet combinatorics
- Need to compare detector performance for analysis chain
  - this work is just starting

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



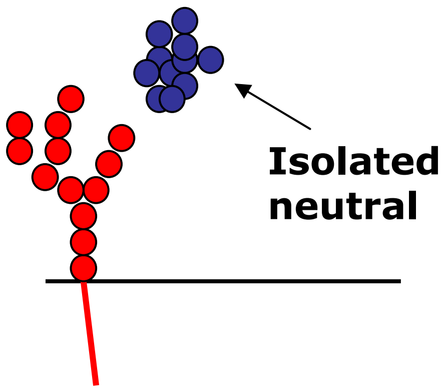



# ❼ Hadron Shower Simulation

★ What aspects of hadronic showers are most important ?
- PFA relies on separating calorimeter deposits from different particles in a dense jet environment

★ Energy Scale
- Mis-assigning a few GeV cluster is a significant effect for jet energy resolutions discussed here

★ NOT CLEAR what is most important !
- NOT energy resolution
- Transverse development is important – how much do showers overlap
- Longitudinal development matters – how well can showers be separated
- Subtle details like rate and $p_T$ distribution of "neutral fragments" may be important




★ BUT, what is important for PFA may well be very different from that for traditional HEP calorimetry

# ❽ Conclusions

- ★ Great deal of effort (worldwide) in the design of the ILC detectors
- ★ Centred around 4 "detector concept" groups: GLD, LDC, SiD + 4th
- ★ Widely believed that calorimetry and, in particular, jet energy resolution drives detector design
- ★ Also believed that it is likely that PFA is the key to achieving ILC goal

**THIS IS HARD – BUT VERY IMPORTANT !**

- ★ Calorimetry at the ILC = HARDWARE + SOFTWARE (new paradigm)
- ★ It is difficult to disentangle detector/algorithm….
- ★ Can only address question with "realistic algorithms"
  - ★ i.e. serious reconstruction 10+ years before ILC turn-on
- ★ With PandoraPFA algorithm already getting to close to ILC goal (for $Z \rightarrow uds$ events)
- ★ More importantly, getting close to being able to address real issues:
  - ⊙ What is optimal detector size/B-field, etc.

**FINAL COMMENT:**

- ★ GLD, LDC, SiD calorimetry "designed" for PFA
  - ★ Need to demonstrate this actually makes sense !
    - ★ not yet proven…!
  - ★ Need Reliable simulation of hadron showers !