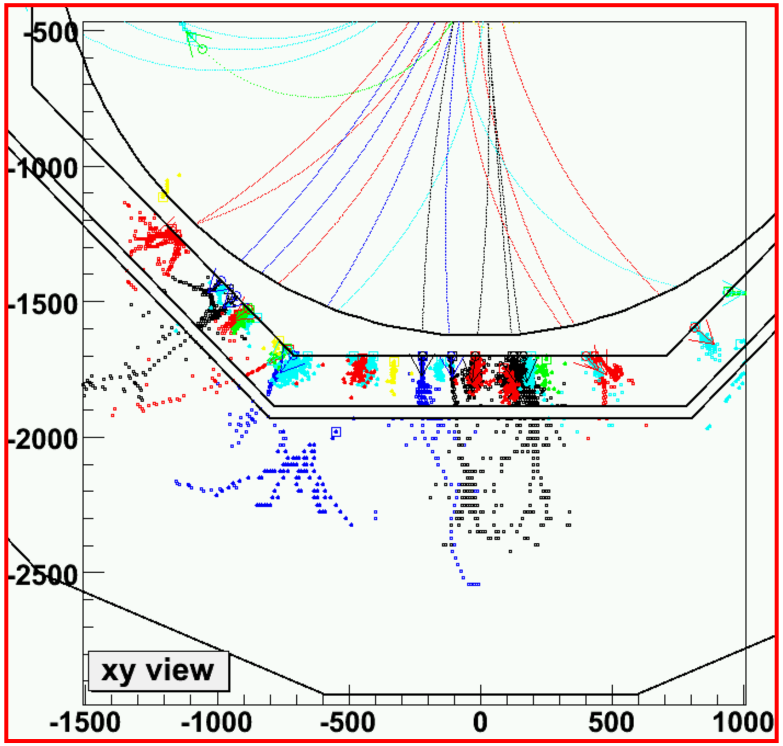
Calorimetry and Particle Flow at the ILC

Mark Thomson
University of Cambridge



This Talk:

➊ ILC Physics ↔ Calorimetry

ILC PHYSICS:

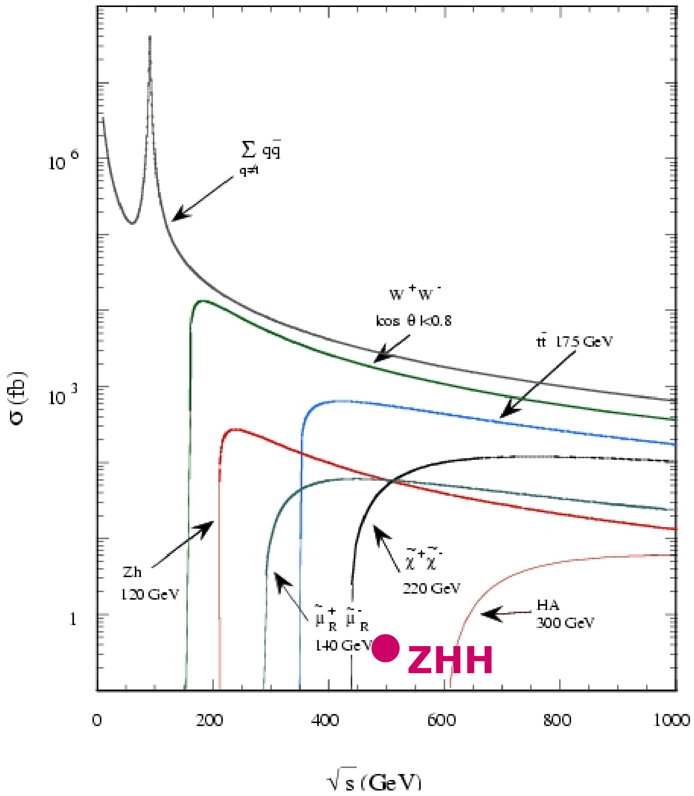
Precision Studies/Measurements

- ★ **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**

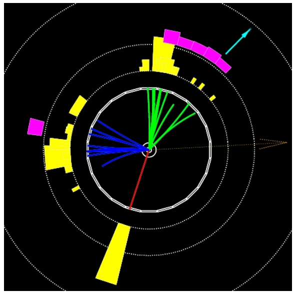
★ **Small cross-sections**
e.g. $\sigma(e^+e^- \rightarrow ZHH) = 0.3$ fb

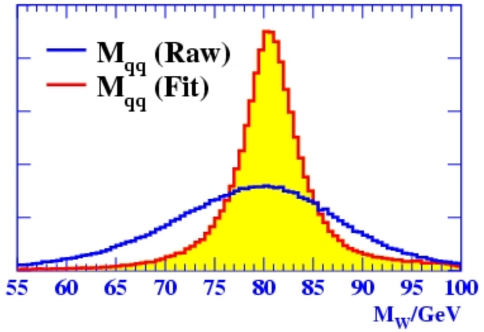


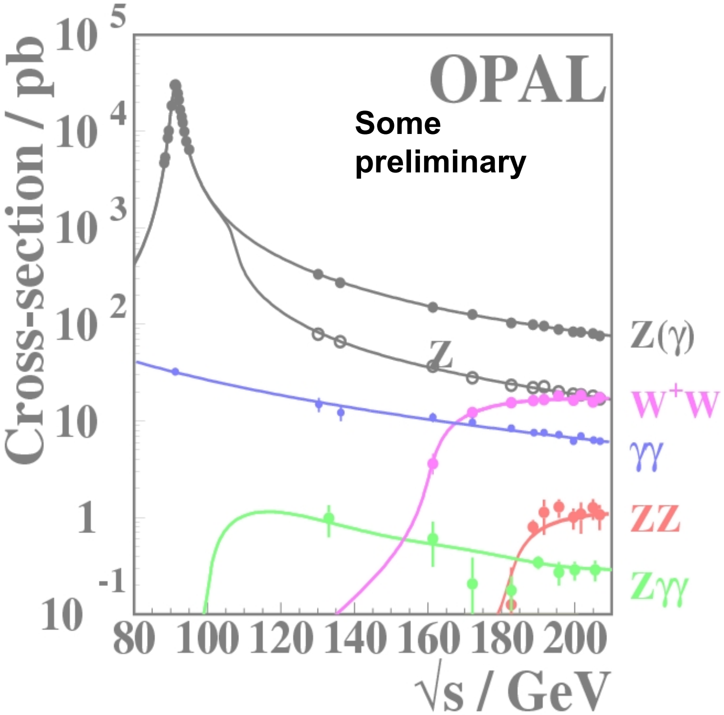
- **Require High Luminosity**
- **Detector optimized for precision measurements in difficult multi-jet environment**

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)

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

Calorimetry at the ILC

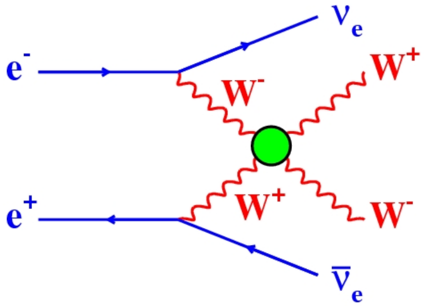
THIS ISN'T EASY !

Jet energy resolution:

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

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

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

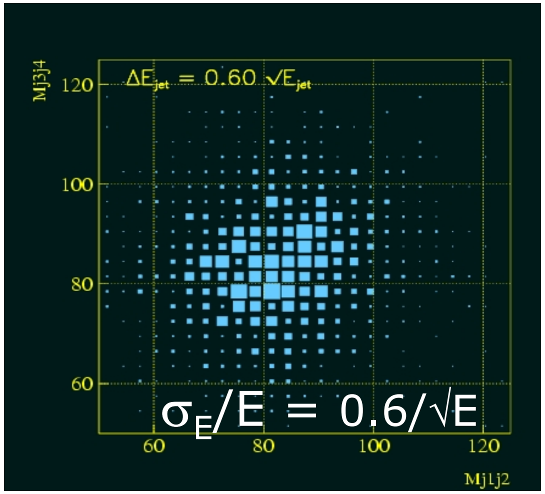


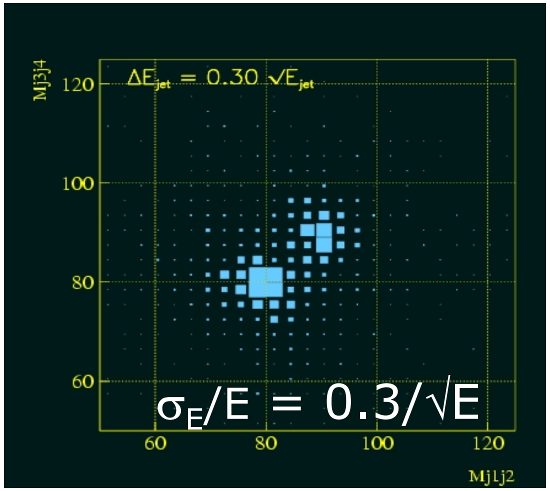
Often-quoted Example:

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





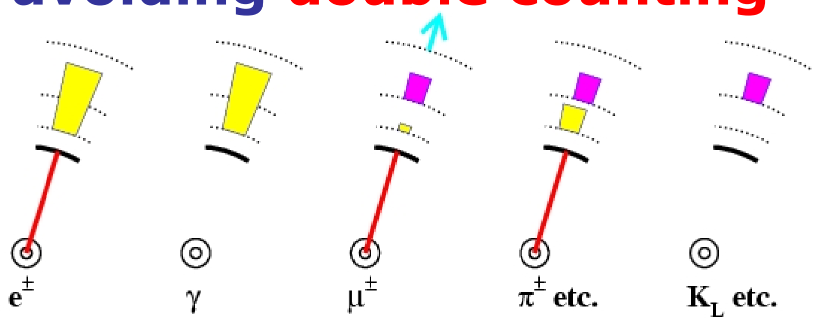
★ **EQUALLY applicable to any final states where want to separate $W \rightarrow qq$ and $Z \rightarrow qq$!**

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. ν) + Beamstrahlung, ISR
★ Aim for jet energy resolution ~ Γ_Z for "typical" jets - the point of diminishing return
★ Jet energy resolution is the key to calorimetry at the ILC
★ Generally (but not uniformly) accepted that PARTICLE FLOW is the only 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 ($Z \rightarrow uds$ at rest) : $\sim 0.30\sqrt{E_{jet}}$

Component	Detector	Frac. of jet energy	Particle Resolution	Jet Energy Resolution
Charged Particles($X^{\pm}$)	Tracker	0.6	$10^{-4}\,E_X$	neg.
Photons(γ)	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)

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

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

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

granularity more important than energy resolution

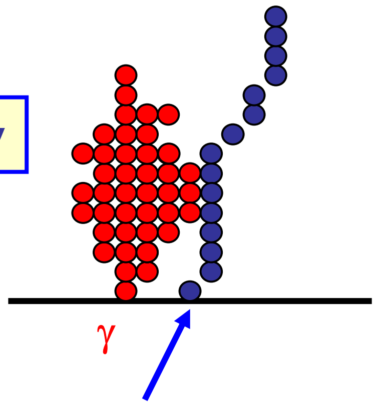
PFA : Basic issues

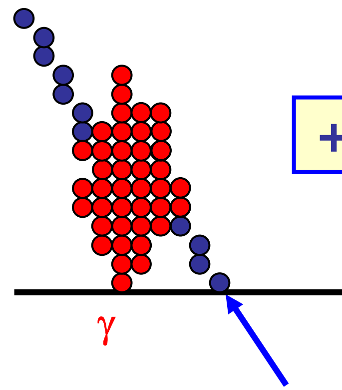
- ★ What are the main issues for PFA ?
- ★ Separate energy deposits + avoid double counting

e.g.

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

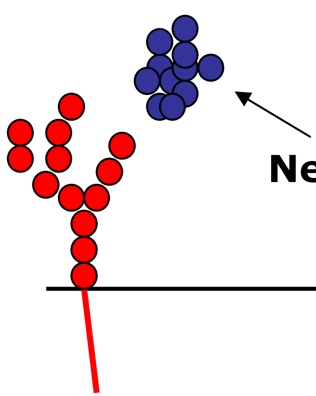
granularity





+software

- ★ Need to separate neutral hadrons from charged hadrons

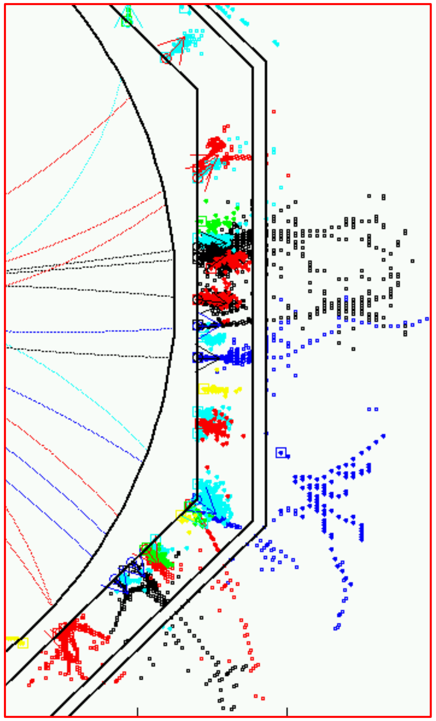


Neutral hadron ?

Granularity helps
But less clear…

Calorimeter Requirements

- Excellent energy resolution for jets – i.e. high granularity
- Good energy/angular resolution for photons – how good ?
- Hermeticity
- Reconstruction of non-pointing photons



Particle flow drives calorimeter design:

★ Separation of energy deposits from individual particles
  - small X_0 and $R_{Moliere}$: compact showers
  - high lateral granularity : $O(R_{Moliere})$

★ Discrimination between EM and hadronic showers
  - small X_0/λ_I
  - longitudanal segmentation

★ Containment of EM showers in ECAL

SiW: sampling calorimeter is a good choice
- Tungsten is great : X_0 $/\lambda_I$ = 1/25, $R_{Moliere}$ ~ 9mm

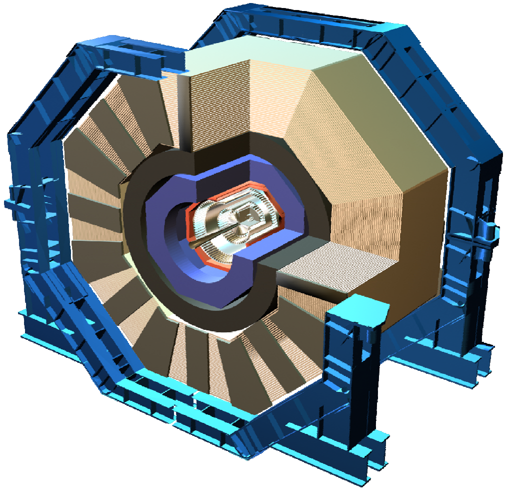
  EM showers are short/Had showers long
  + narrow EM showers
- However not cheap (very significant fraction of total detector cost)!

❸ The ILC Calorimeter Concepts

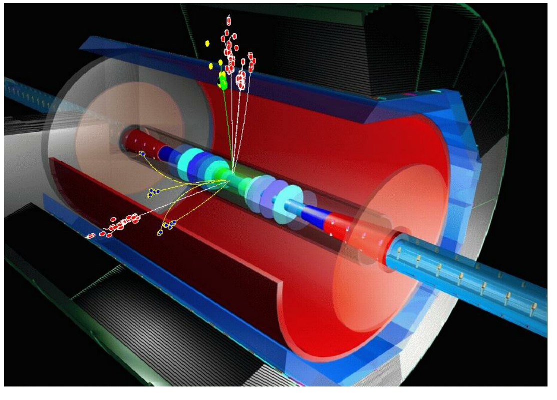
The 3 Main Detector Concepts:

- ★ ILC Detector Design work centred around 3 main detector "concepts"
- ★ Each will contribute to an ILC detector conceptual design report by end of 2006
- ★ Ultimately may form basis for TDRs

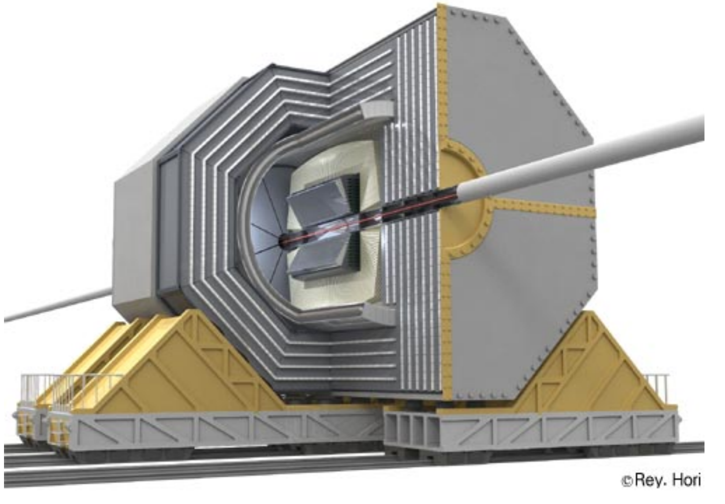
SiD : Silicon Detector



LDC : Large Detector Concept
(spawn of TESLA TDR)

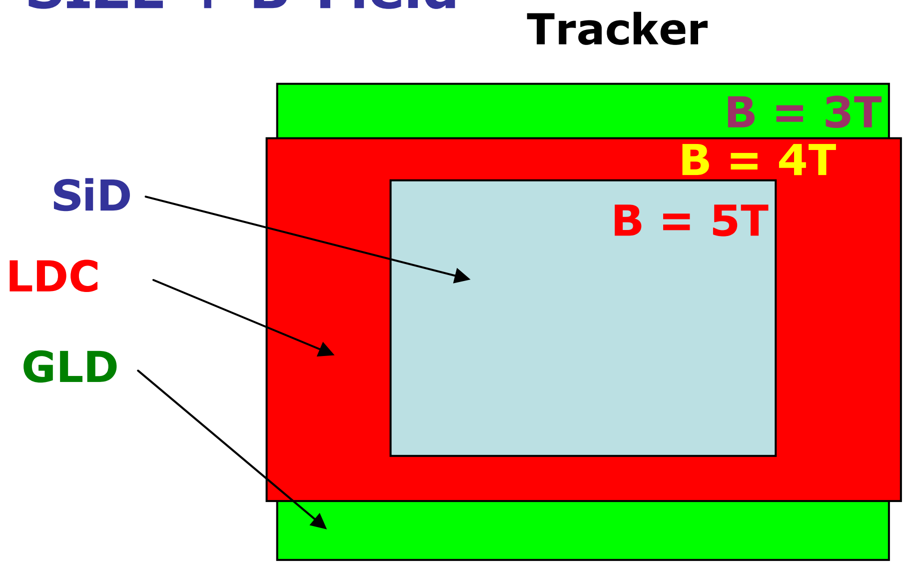


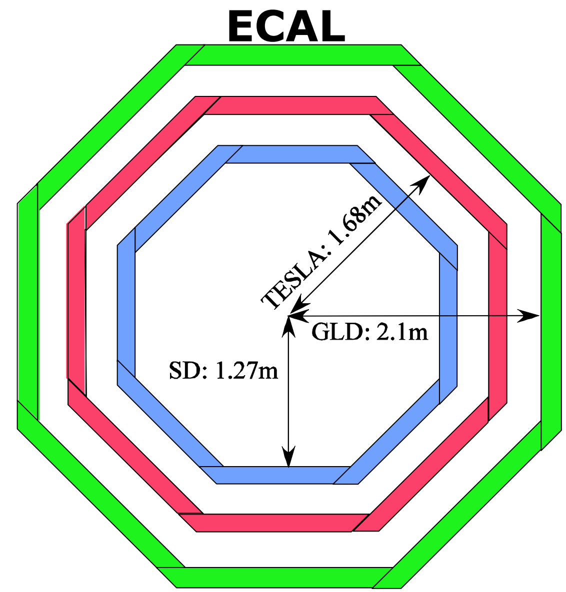
GLD : Global Large Detector



Main Differences:

- **SIZE + B-Field**





- **Central Tracker and ECAL**

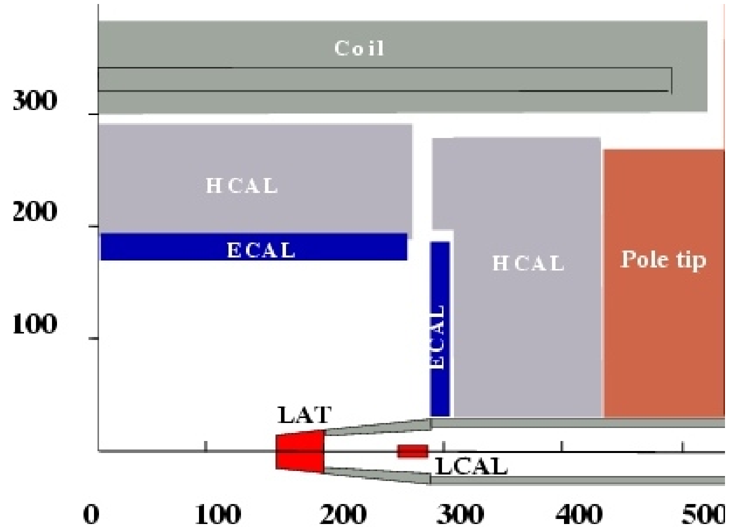
	SiD	LDC	GLD
Tracker	Silicon	TPC	TPC
ECAL	SiW	SiW	Pb/Scint

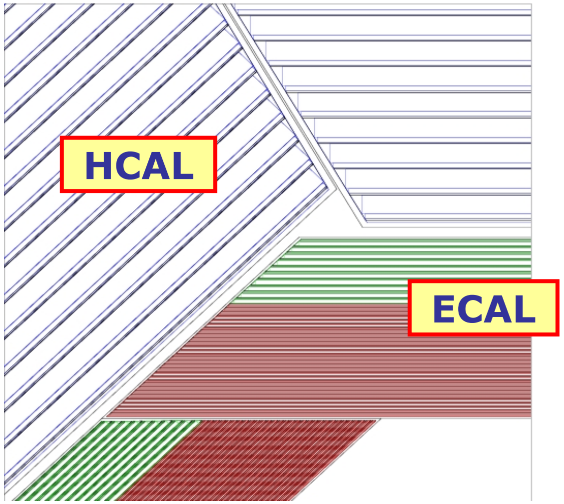
★ **SiD + LDC + GLD all designed for PFA Calorimetry !**

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

LDC/SiD Calorimetry

ECAL and HCAL inside coil





ECAL: silicon-tungsten (SiW) calorimeter:

- Tungsten : $X_0\ /\lambda_{had} = 1/25$, $R_{Moliere} \sim 9$mm
  (gaps between Tungsten increase effective $R_{Moliere}$)
- Lateral segmentation: ~1cm^2 matched to $R_{Moliere}$
- Longitudinal segmentation: 40 layers (24 X_0, 0.9λ_{had})
- Resolution: $\sigma_E/E = 0.11/\sqrt{E(\mathrm{GeV})} \oplus 0.01$

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

Hadron Calorimeter

Highly Segmented – for Particle Flow

- Longitudinal: 40 samples
- 4 – 5 λ (limited by cost - coil radius)
- Would like fine (1 cm² ?) lateral segmentation
- For 10000 m² of 1 cm² HCAL = 10^8 channels – cost !

Two Main Options:

★ Tile HCAL (Analogue readout)

Steel/Scintillator sandwich

Lower lateral segmentation

5x5 cm² (motivated by cost)

★ Digital HCAL

High lateral segmentation

1x1 cm²

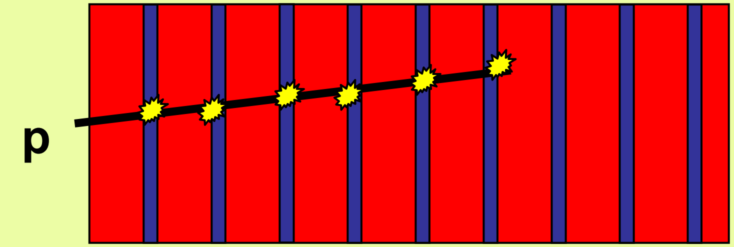
digital readout (granularity)

RPCs, wire chambers, GEMS…

The Digital HCAL Paradigm

- Sampling Calorimeter:

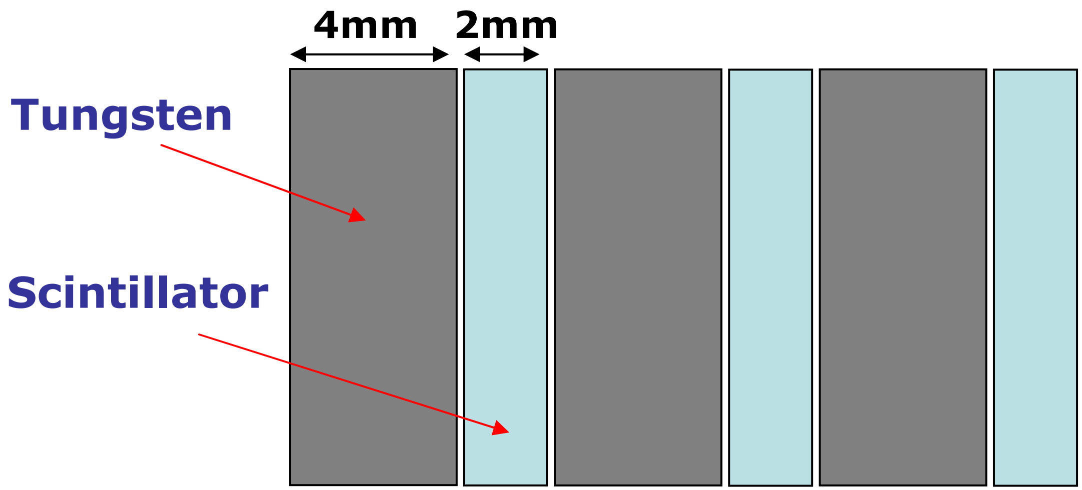
  Only sample small fraction of the total energy deposition

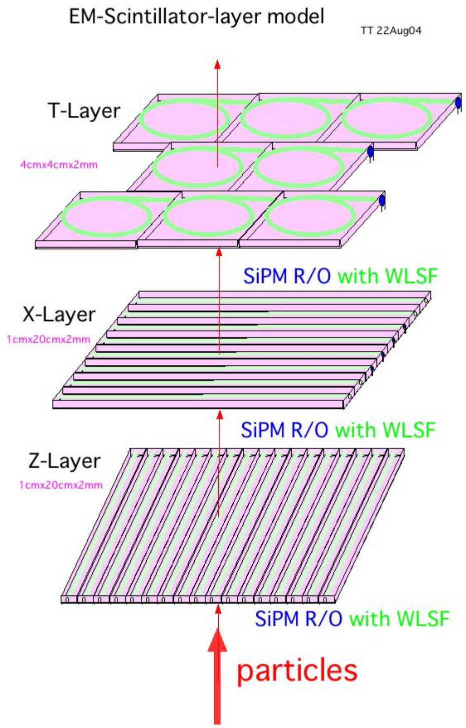


- Energy depositions in active region follow highly asymmetric Landau distribution

GLD Calorimetry

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





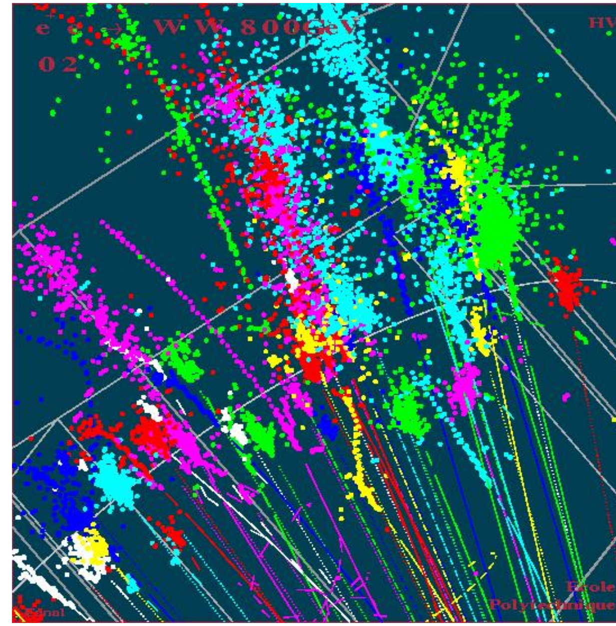
Initial GLD ECAL concept:

- ★ **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

Calorimeter Reconstruction

- ★ High granularity calorimeters – **very different** from previous detectors
- ★ As trad. calorimeters – not great
- ★ "Tracking calorimeter" – requires a new approach to ECAL/HCAL reconstruction



★ **+PARTICLE FLOW**

★ ILC calorimeter performance = **HARDWARE + SOFTWARE**

★ Performance will depend on the software algorithm

➡ Nightmare from point of view of detector optimisation

❹ PFA and ILC detector design ?

PFA plays a special role in design of an ILC Detector

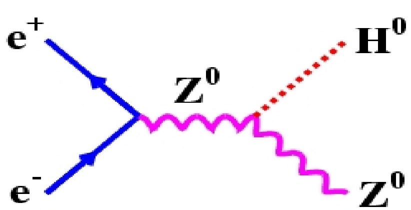
- **VTX : design driven by heavy flavour tagging, machine backgrounds, technology**
- **Tracker : design driven by σ_p, track separation**
- **ECAL/HCAL : single particle σ_E not the main factor**
  ➡ **<u>jet energy resolution</u> ! Impact on particle flow drives calorimeter design + detector size,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

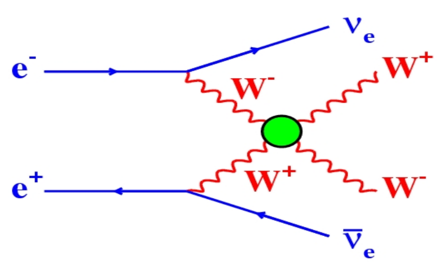
PFA is a (the?) major cost driver for the ILC Detectors

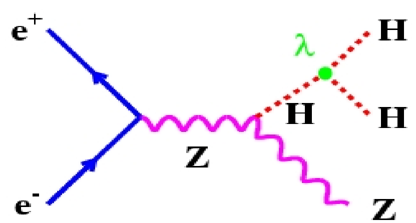
<u>BUT:</u> Don't really know what makes a good detector from point of view of PFA (plenty of personal biases – but little hard evidence)

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

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





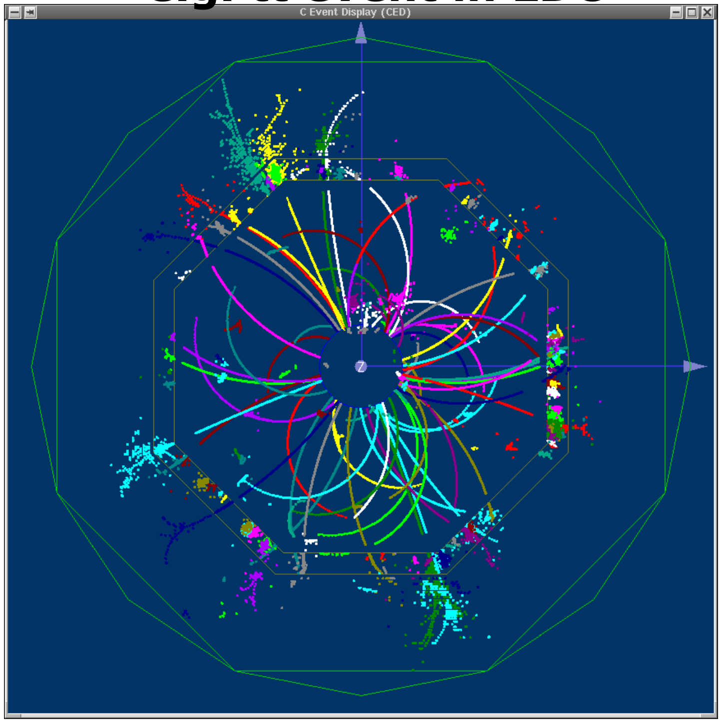


★ The rest is **VERY DIFFICULT** !

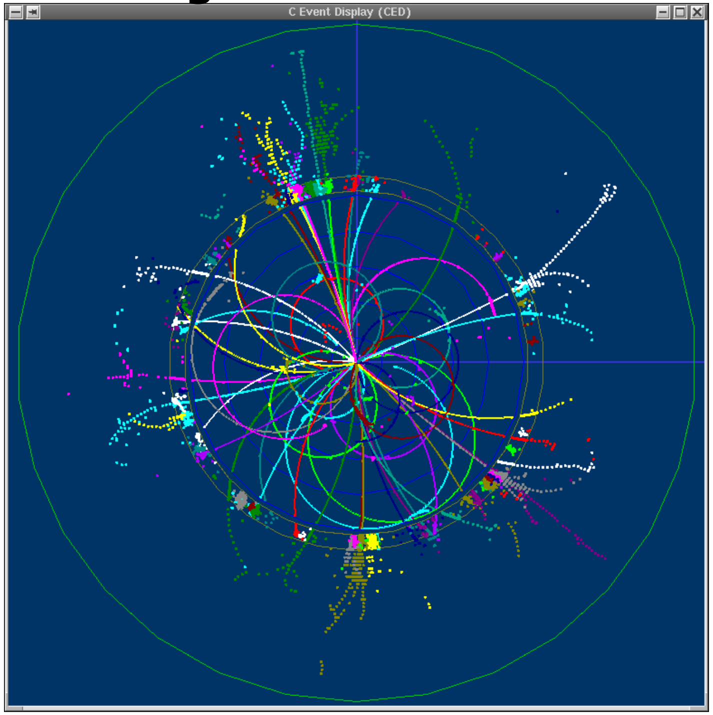
<u>For example:</u>

★ Would like 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/RECONSTRUCTION !**

- 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 (~5 groups developing PFA reconstruction worldwide)**

+ (opinion) to date very little hard evidence that PFA can deliver ILC goals….

For the remainder of this talk concentrate on work in UK

- **Work-in-Progress – but does a pretty good job + much better feel for what really matters….**
- **Concentrate on general features to indicate how an ultimate particle flow reconstruction might work**

An Algorithm: PandoraPFA

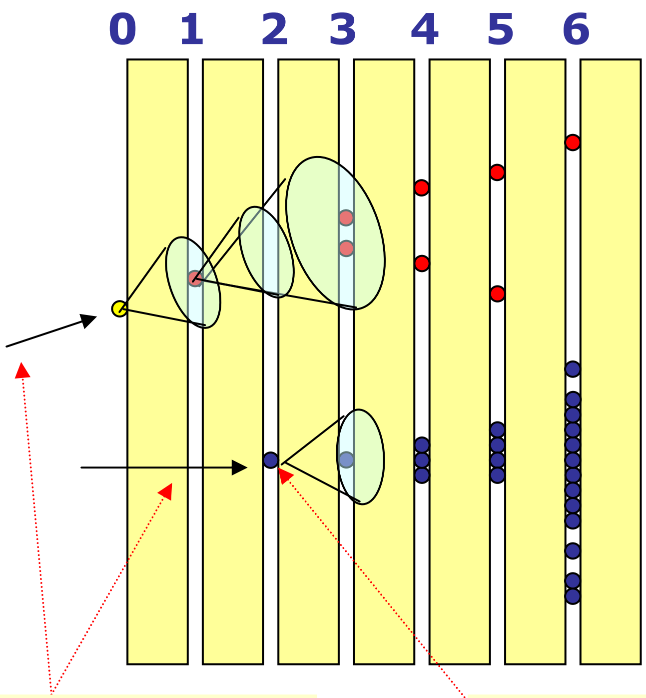
- ★ **ECAL/HCAL reconstruction and PFA performed in a single algorithm**
- ★ **Keep things fairly generic algorithm**
  - ★ **applicable to multiple detector concepts**
- ★ **Use tracking information to help ECAL/HCAL clustering**

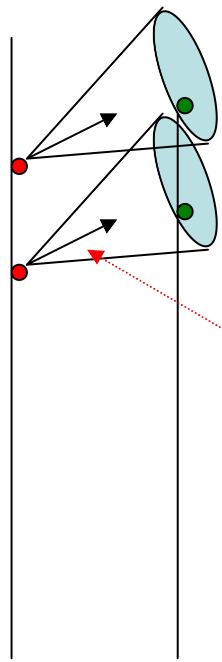
Five Main Stages:

- **i. Loose clustering in ECAL and HCAL**
- **ii. Topological linking of clearly associated clusters**
- **iii. Courser grouping of clusters**
- **iv. 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

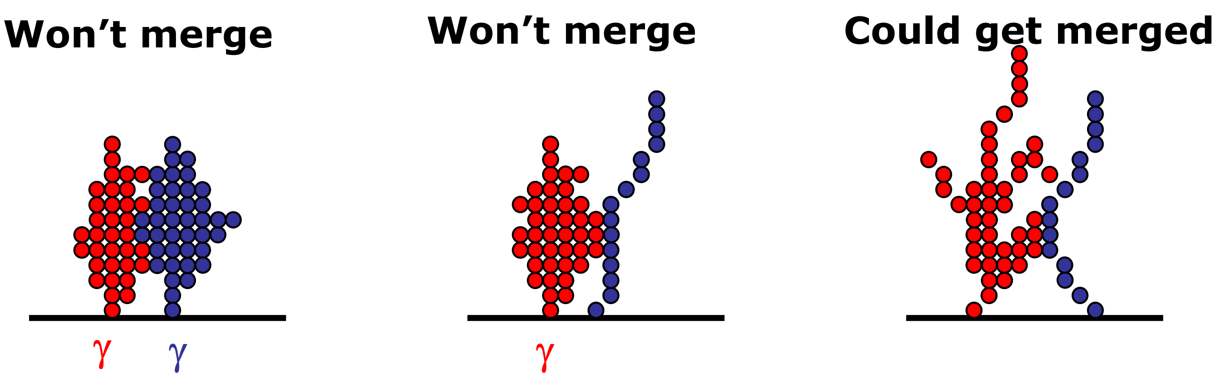
Unmatched hits seeds new cluster

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

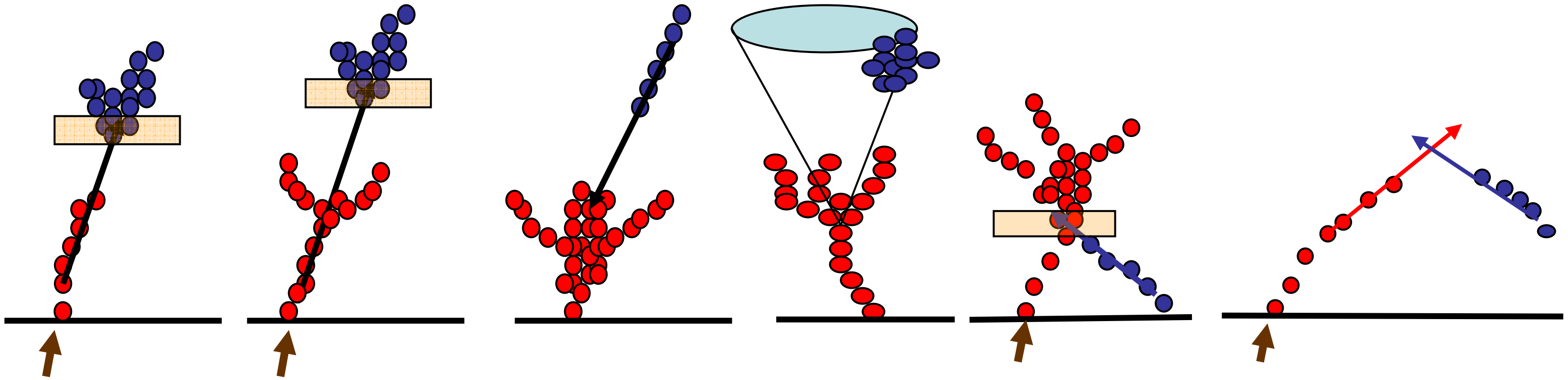
Photon ID

- 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



Cluster Association Part I

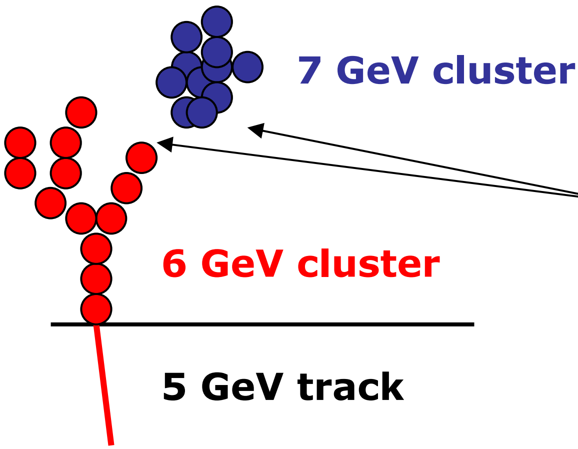
Join clusters which are clearly associated
make use of high granularity + tracking capability



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.



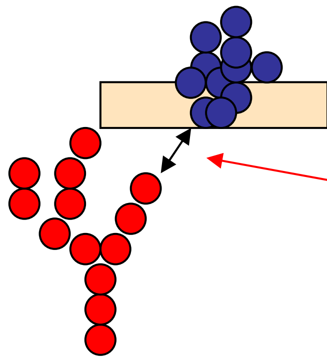
This cluster association would be forbidden if $|E_1 + E_2 - p| > 3\,\sigma_E$

Provides some protection against "silly" mistakes

★ **Cluster reconstruction and PFA not independent**

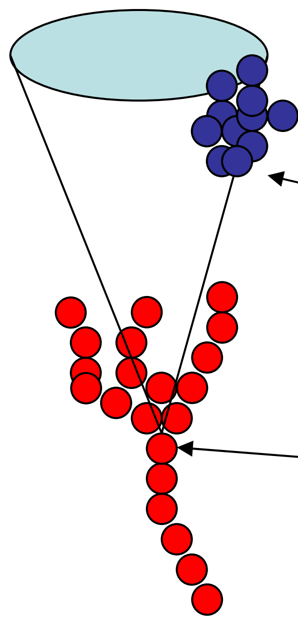
Course Cluster Association

Proximity



Distance between hits -limited to first layers

Shower Cone



Associated if fraction of hits in cone > some value

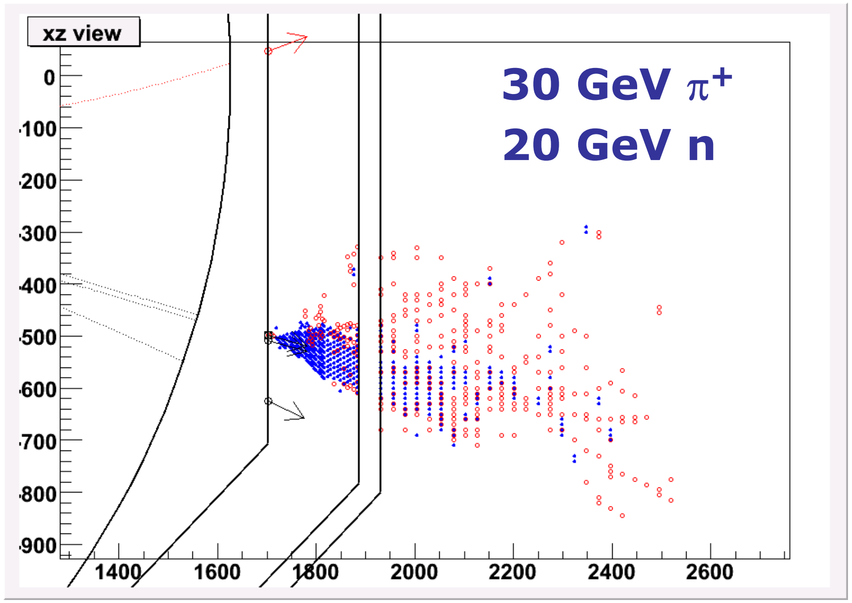
Shower start identified

+Track-Driven Shower Cone

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**

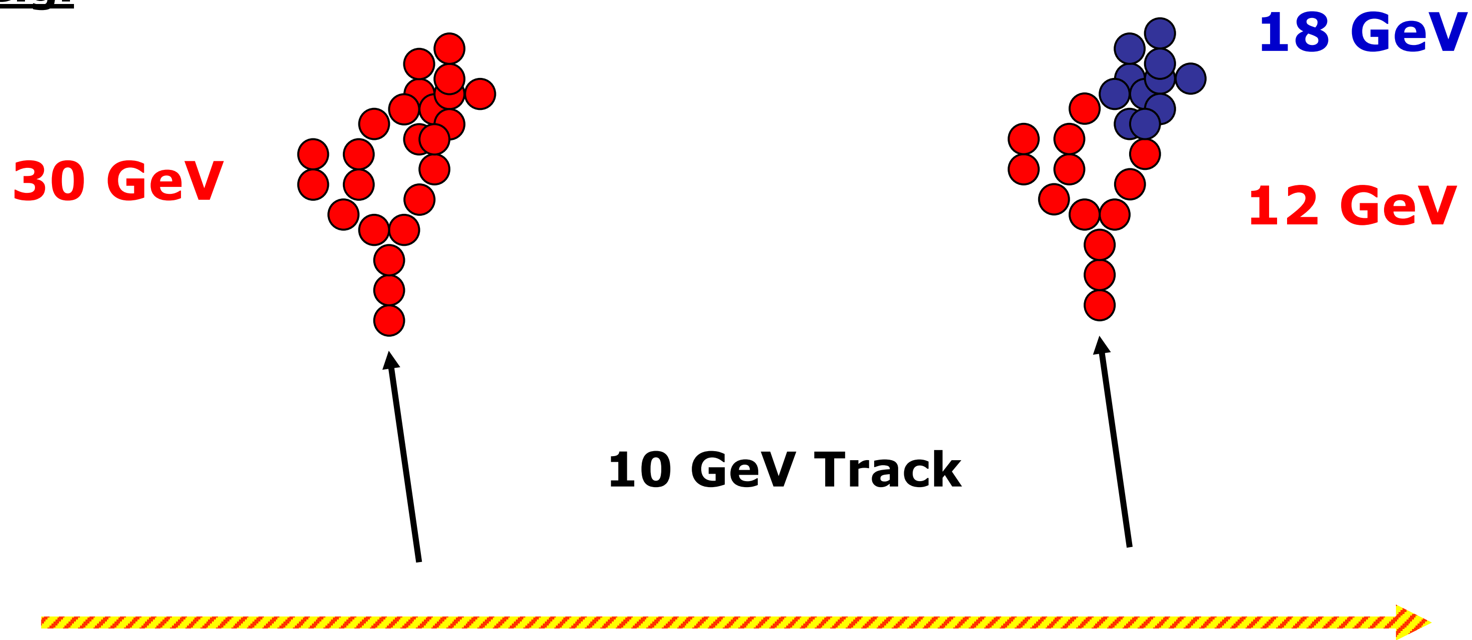
The ONLY(?) way to address this is "statistically"

→

e.g. if have 30 GeV track pointing to 20 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**

★ **If can't find a sensible reclustering use the ultimate sanction i.e. do not use track information**

❻ Current Performance (as of 6/5/06)

Example Reconstruction

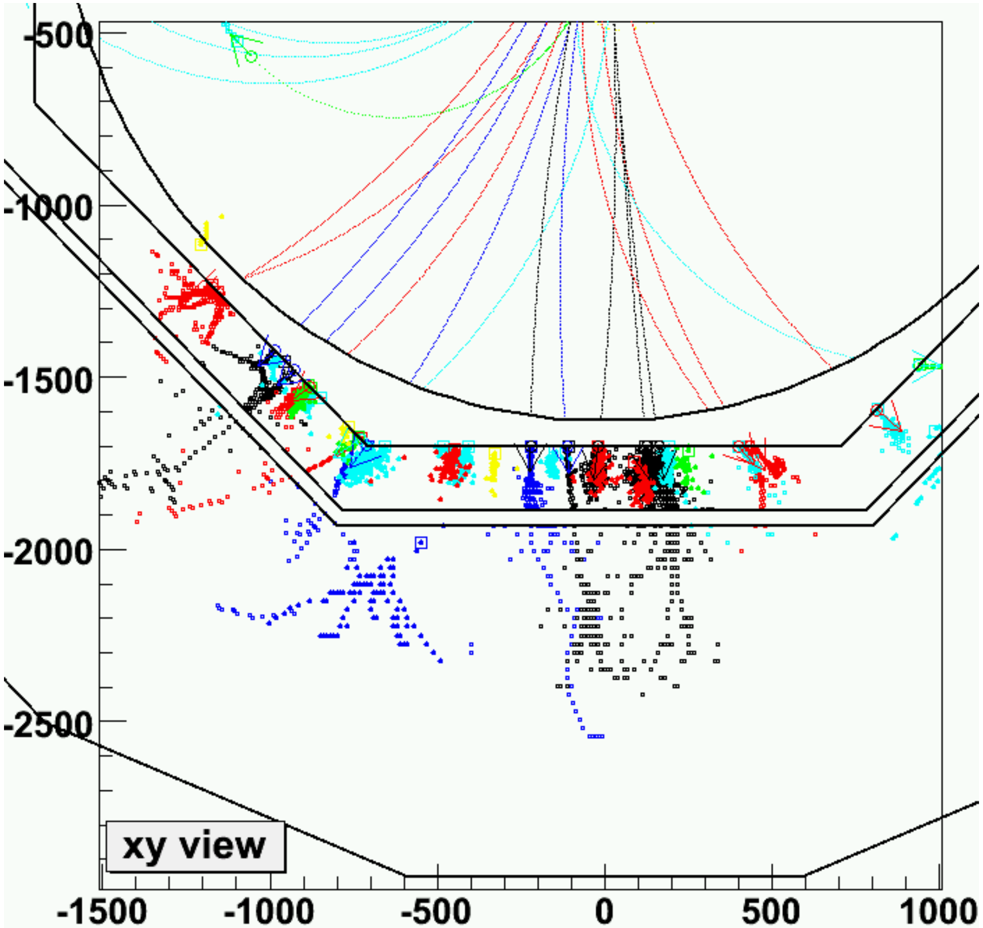
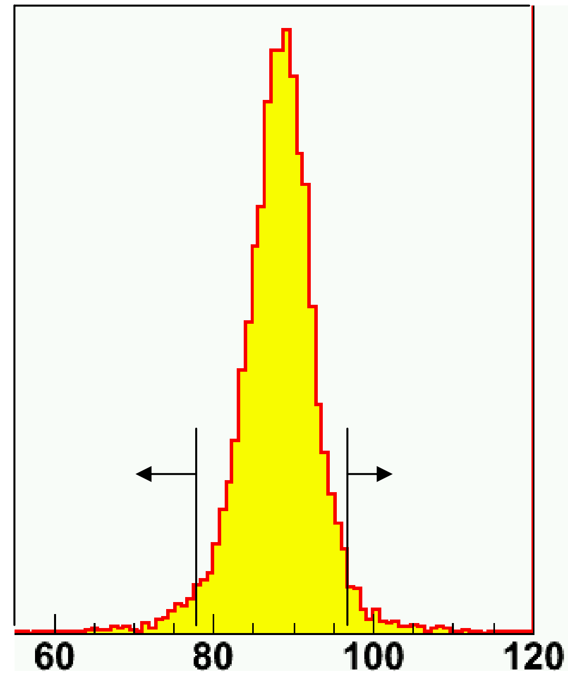
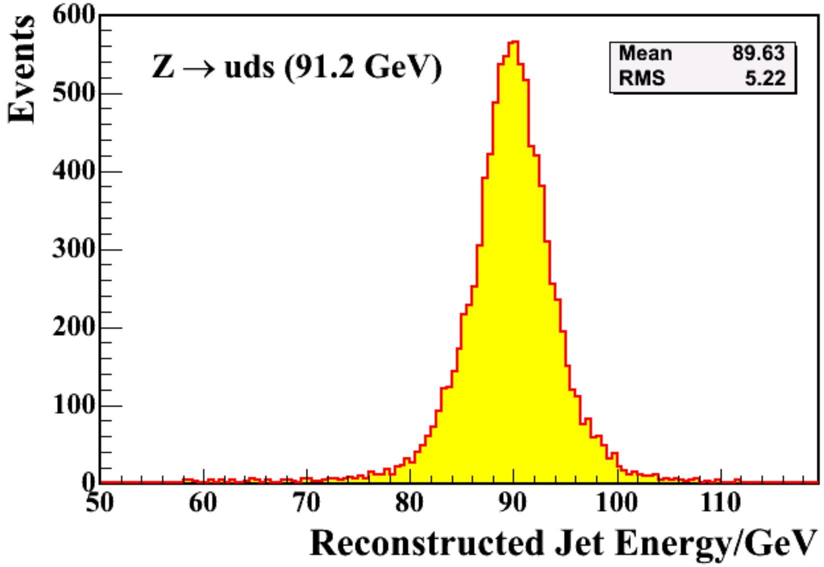


Figure of Merit:

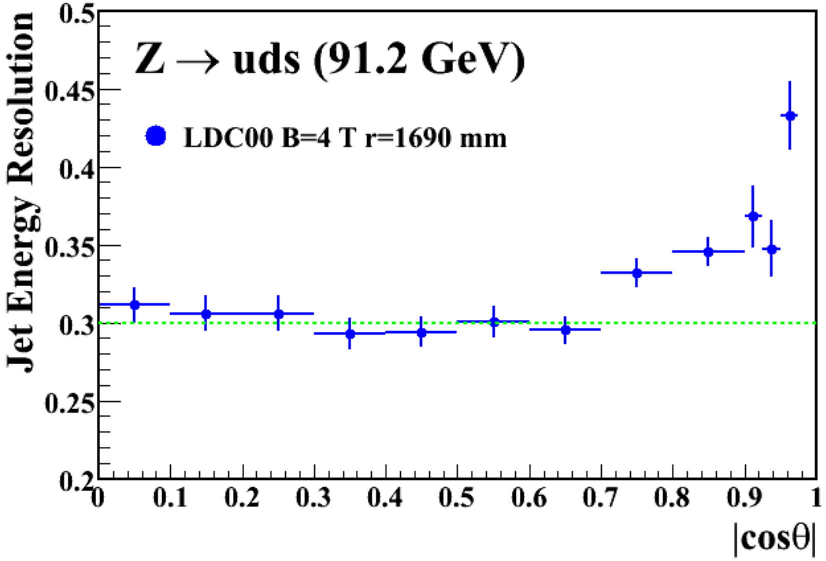


- ★ Find smallest region containing **90 %** of events
- ★ Determine rms in this region

PFA Results ($Z \rightarrow uds$)



$\lvert\cos\theta\rvert$	$\sigma_E/E = \alpha\sqrt{(E/GeV)}$
all	34.3±0.3%
<0.9	30.9±0.3 %
<0.7	30.3±0.3 %



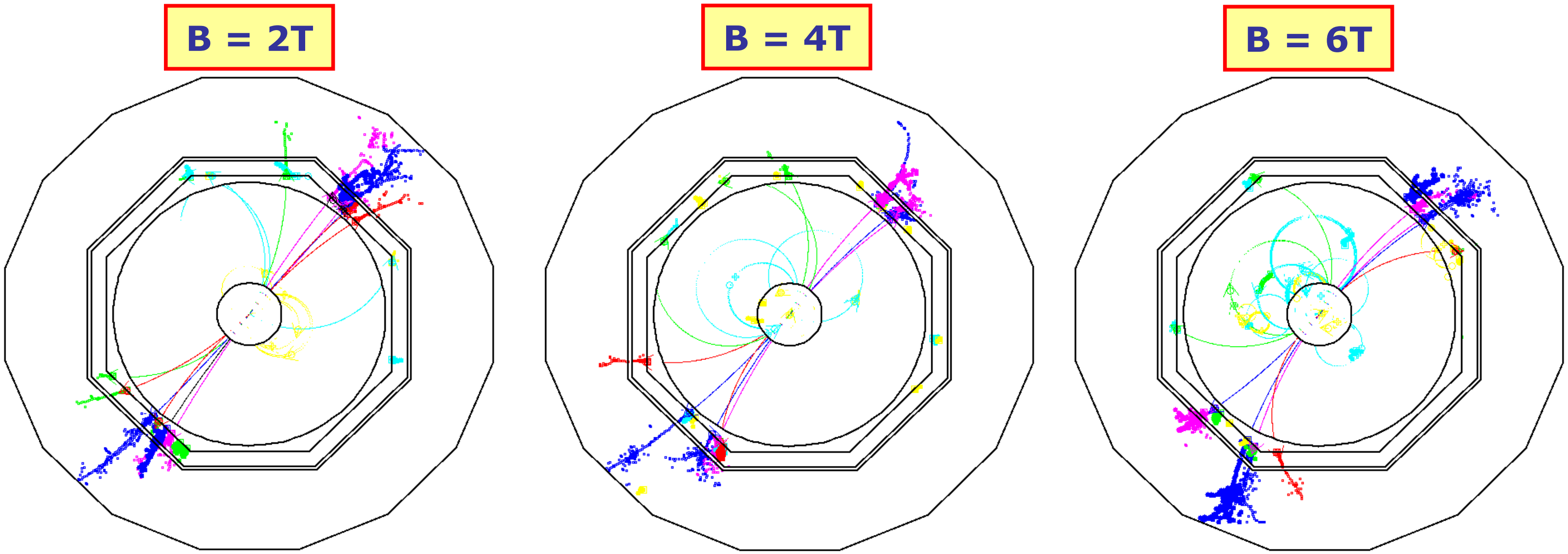
ILC GOAL OF 30 % ACHIEVED !

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

Have realistic (?) PFA code, can start to look at different detectors…

e.g. B-Field

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

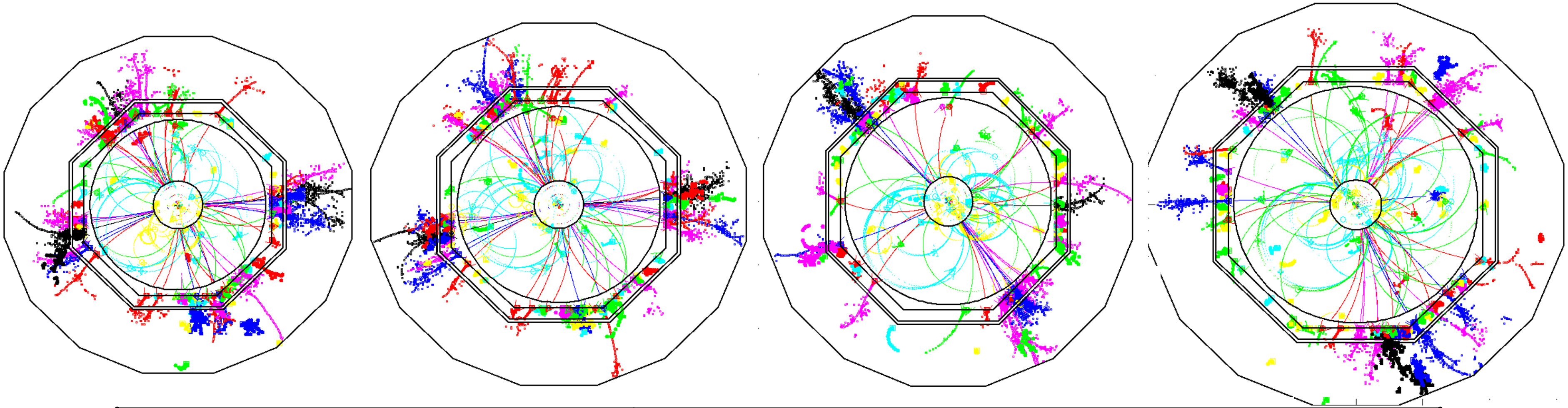


B-Field	$\sigma_E/E = \alpha\sqrt{(E/GeV)}$	
	All angles	$\lvert\cos\theta\rvert<0.7$
2 Tesla	35.6±0.3%	32.1±0.4 %
4 Tesla	34.3±0.3 %	30.3±0.4 %
6 Tesla	34.9±0.3 %	30.3±0.4 %

Only weak B-field dependence

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

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



Detector Model	$\sigma_E/E = \alpha\sqrt{(E/GeV)}$		
	E_{RECO}	$+ E_\nu$	$+E_{FWD}$
LDC01Sc r_{tpc} = 1380mm	89 ± 2 %	59 ± 1 %	56 ± 1 %
LDC01Sc r_{tpc} = 1580mm	84 ± 2 %	56 ± 1 %	52 ± 1 %
LDC00Sc r_{tpc} = 1690mm	78 ± 2 %	49 ± 1 %	45 ± 1 %
LDC00Sc r_{tpc} = 1890mm	76 ± 2 %	45 ± 1 %	42 ± 1 %

- ★ **Strong dependence of performance on Radius**
- ★ **SIZE MATTERS**
- ★ **Can start to address other design issues…**

Some serious PFA-related Detector Design issues

Main questions identified at Snowmass (in some order of priority):

1) **B-field :** Does B help jet energy resolution
2) **Size :** ECAL inner radius/TPC outer radius
3) TPC length/Aspect ratio
4) Tracking efficiency – forward region
5) How much HCAL – how many interactions lengths 4, 5, 6…
6) Longitudinal segmentation – pattern recognition vs sampling frequency for calorimetric performance
7) Transverse segmentation ECAL/HCAL
   ECAL : does high/very high granularity help ?
8) Compactness/gap size
9) Impact of dead material
10) How important are conversions, V^0s and kinks
11) HCAL absorber : Steel vs. W, Pb, U…
12) Circular vs. Octagonal TPC (are the gaps important)
13) HCAL outside coil – probably makes no sense but worth demonstrating this (or otherwise)
14) TPC endplate thickness and distance to ECAL
15) Material in VTX – how does this impact PFA

❼ 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 widely believed that PFA is the key to achieving the 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
  - ⊙ What ECAL/HCAL granularity is needed
  - ⊙ How does material budget impact performance
  - ⊙ ....

FINAL COMMENT:

- ★ GLD, LDC, SiD calorimetry "designed" for PFA
  - ★ Need to demonstrate this actually makes sense !
  - ★ not yet proven...!