Particle Flow Calorimetry and ILC Detector Design

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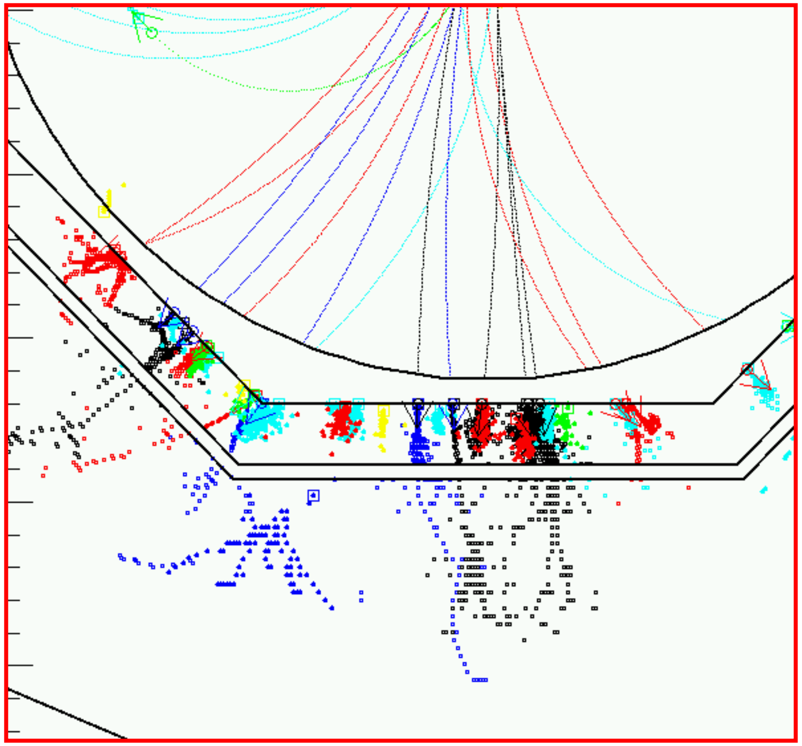


This Talk:

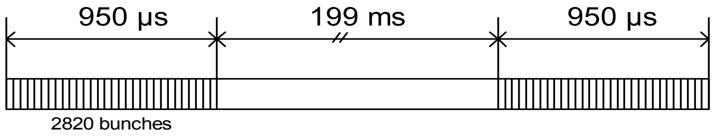
- ❶ The ILC
- ❷ ILC Physics ↔ ILC Calorimetry
- ❸ The Particle Flow Paradigm
- ❹ Calorimetry in the ILC Detector Concepts
- ❺ PFA and Detector Design
- ❻ "Realistic" Particle Flow Reconstruction
- ❼ Current Performance and Detector Optimisation Studies
- ❽ Conclusions

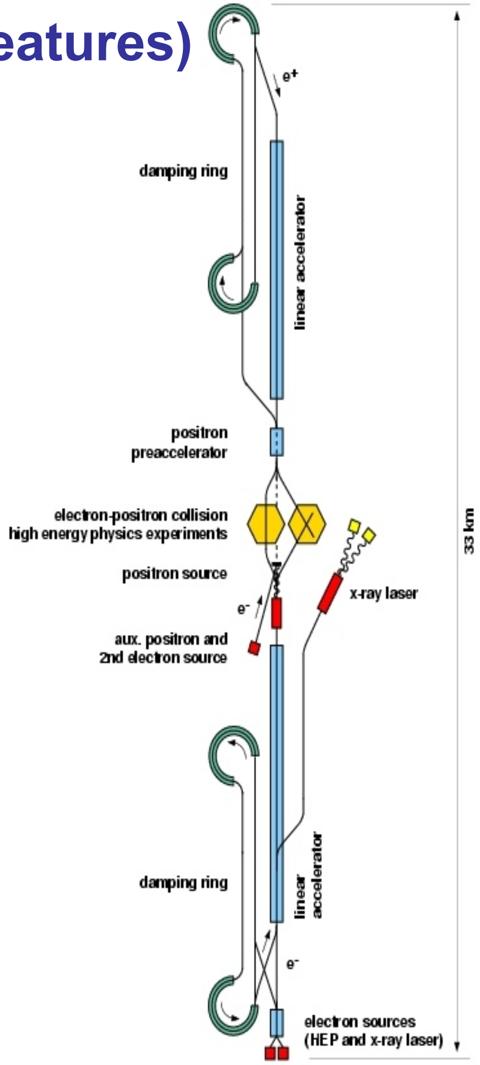
❶The ILC

★ILC baseline parameters (not final but know main features)

- Center-of-Mass Energy : 0.5 – 1.0 TeV
- Luminosity : ~ 10^{34} cm^{-2}s^{-1} (1000xLEP)
- Time Structure : 5 (10?) Bunch-trains/s
  - ♦ Time between collisions: ~ 300 (150) ns

e.g. TESLA TDR





- "Physics" Event Rate (fairly modest):

$e^+e^-\rightarrow qq$ ~100/hr $e^+e^-\rightarrow W^+W^-$ ~1000/hr
$e^+e^-\rightarrow tt$ ~50/hr $e^+e^-\rightarrow HX$ ~10/hr

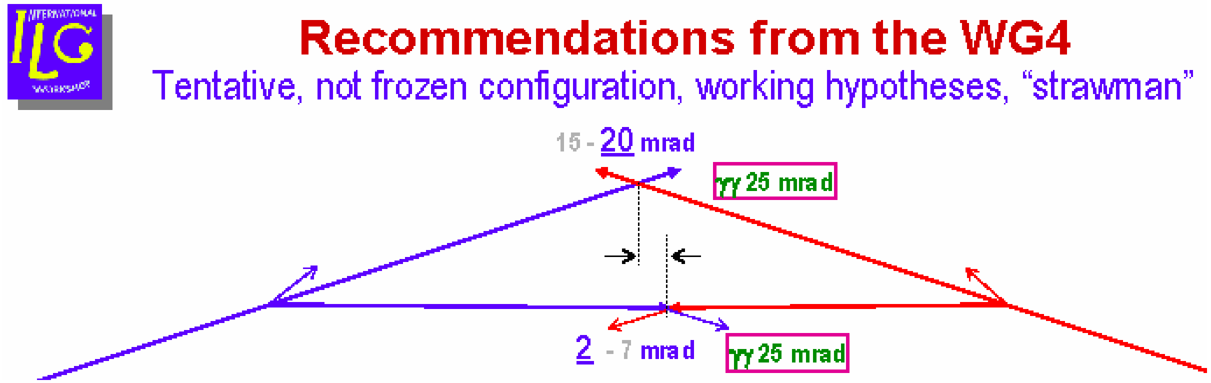
- "Backgrounds" (depends on ILC parameters)

$e^+e^-\rightarrow qq$ ~0.1 /Bunch Train
$e^+e^-\rightarrow\gamma\gamma\rightarrow X$ ~200 /Bunch Train
~500 hits/BX in Vertex det.
~5 tracks/BX in TPC

★ **Event rates/backgrounds modest** (small compared to LHC)

Impact on Detector Design

- **Radiation hardness** does not dictate detector design
- Modest timing requirements (~300 ns)
- Must be able to cope with modest gamma-gamma background
- Impact of non-zero crossing angle ?



Recommendations from the WG4

Tentative, not frozen configuration, working hypotheses, "strawman"

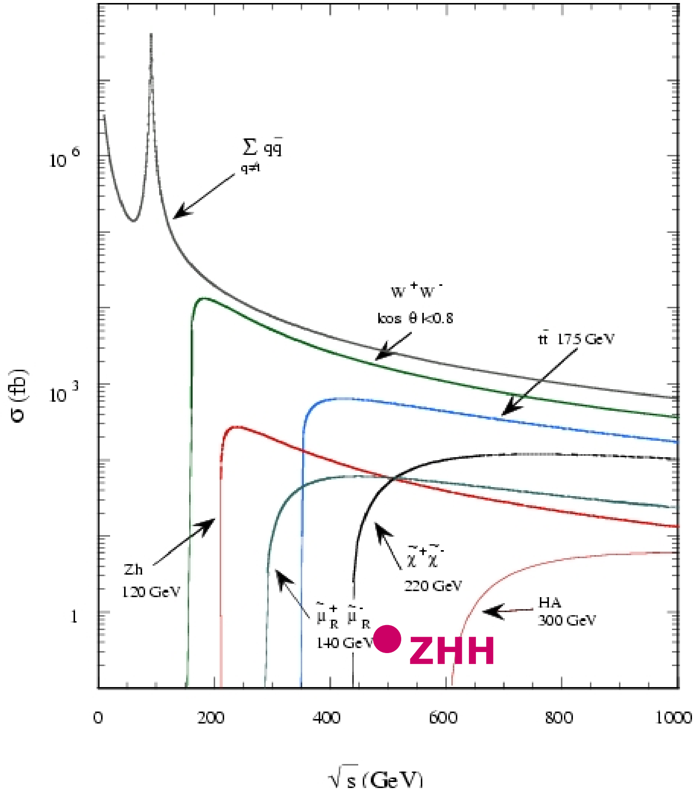
- **PHYSICS not the machine drives ILC Detector design**

❷ 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

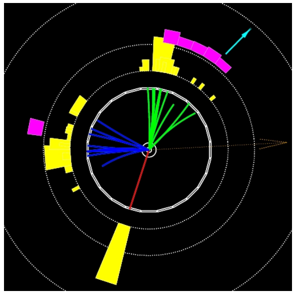
- ★Small cross-sections

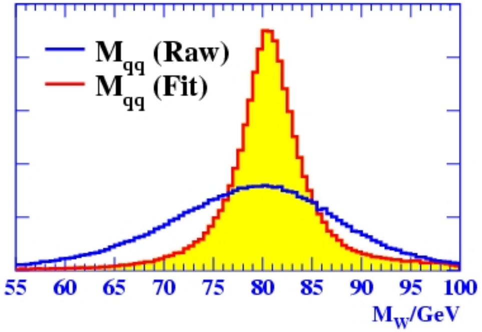
  e.g. $\sigma(e^+e^-\rightarrow ZHH) = 0.3$ fb

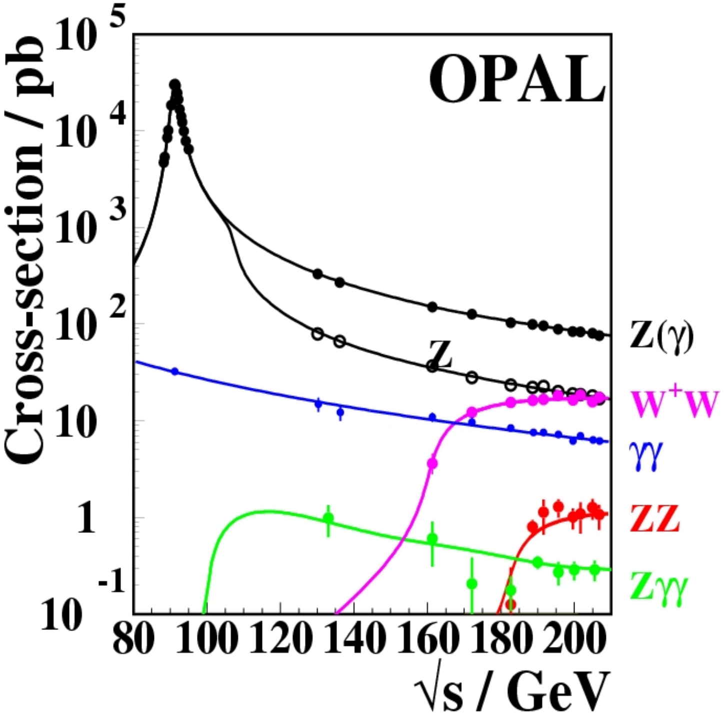
- ✸Require High Luminosity – i.e. the ILC
- ✸Detector optimized for precision measurements in difficult multi-jet environment

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)**
- **Places stringent requirements on the ILC detector**

ILC Detector Requirements

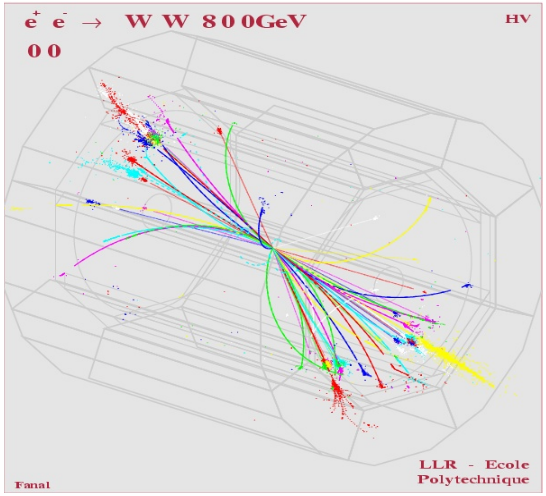
- **momentum:** $\sigma_{1/p} < 7\text{x}10^{-5}/\text{GeV}$ (1/10 x LEP)

  (e.g. mass reconstruction from charged leptons)
- **impact parameter:** $\sigma_{d0} < 5\text{mm} \oplus 5\text{mm}/p(\text{GeV})$ (1/3 x SLD)

  (c/b-tagging in background rejection/signal selection)
- **jet energy:** $\sigma_E/E = 0.3/\sqrt{E(\text{GeV})}$ (1/2 x LEP)

  (invariant mass reconstruction from jets)
- **hermetic down to :** $\theta = 5$ mrad

  (for missing energy signatures e.g. SUSY)
- Radiation hardness not a significant problem, e.g. 1st layer of vertex detector : $10^9\ n\ \text{cm}^{-2}\ \text{yr}^{-1}$ c.f. $10^{14}\ n\ \text{cm}^{-2}\ \text{yr}^{-1}$ at LHC



Must also be able to cope with high track densities due to high boost and/or final states with 6+ jets, therefore require:

- High granularity
- Good two track resolution

- ★ Of the ILC goals the most challenging is (probably) that of jet energy resolution:

$$\boxed{\sigma_E/E = 30\%/\sqrt{E(\mathrm{GeV})}}$$

- ★ So why is this important ?

Calorimetry at the ILC

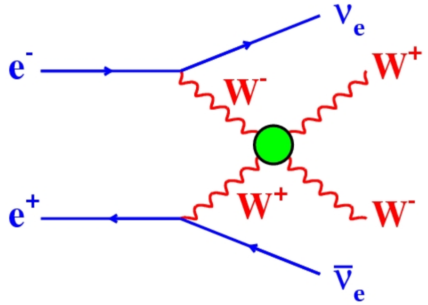
Jet energy resolution:

THIS IS HARD !

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

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

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

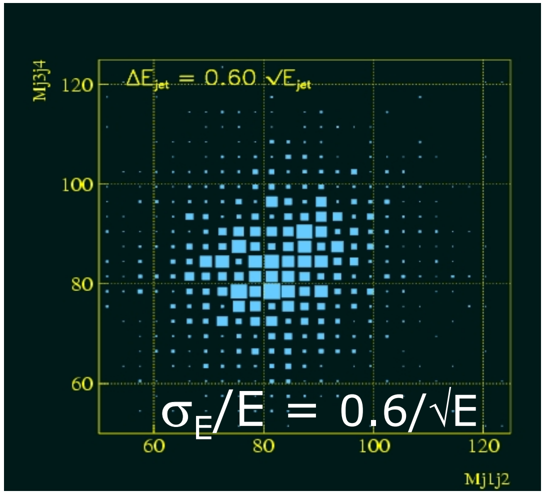


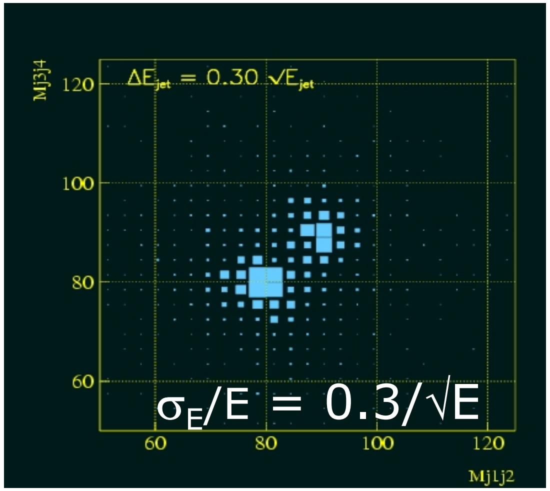
Often-quoted Example:

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

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

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





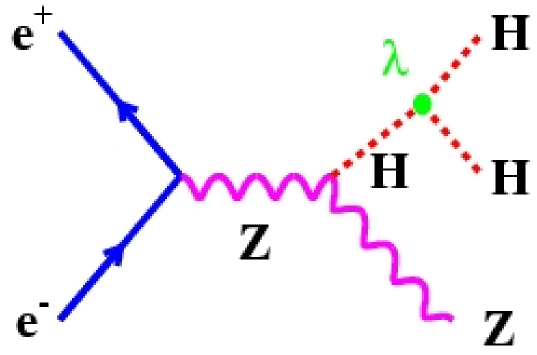
- ★ **EQUALLY applicable to any final states where want to separate $W \to qq$ and $Z \to qq$!**

Another example…..

e.g. measurement of trilinear HHH coupling via

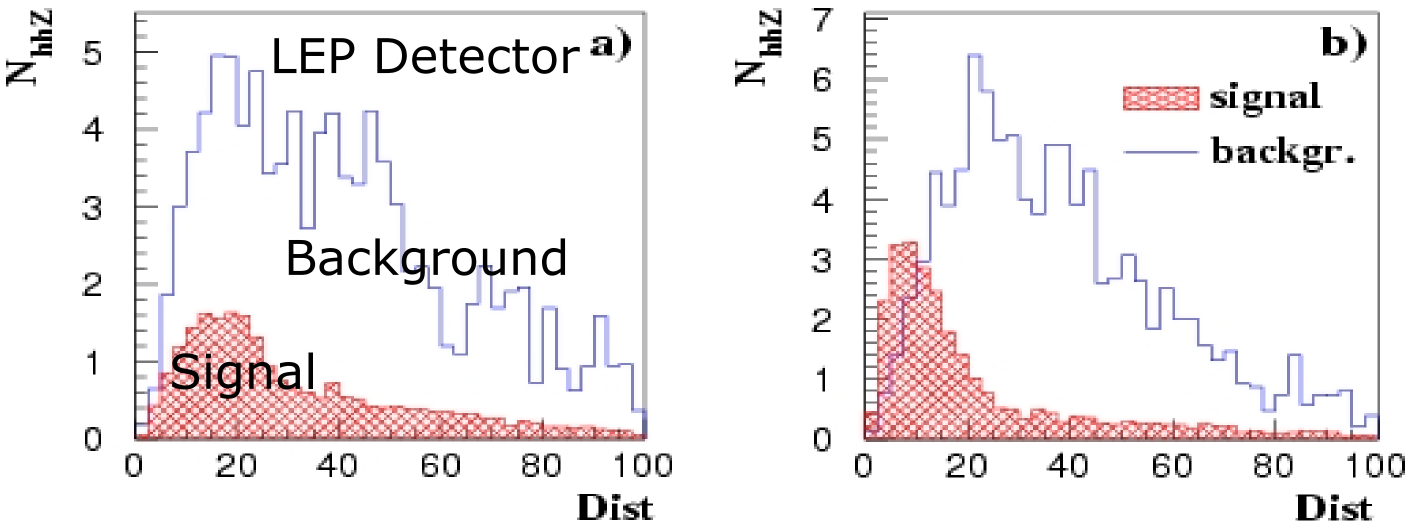
$e^+e^- \rightarrow ZHH \rightarrow qqbbbb$

- ★Probe of Higgs potential
- ★Very small cross-section
- ★Large combinatoric background
- ★6 jet final state



- Use jet-jet invariant masses to extract signal

$$Dist=((M_H - M_{12})^2 + (M_z - M_{34})^2 + (M_H - M_{56})^2)^{1/2}$$



★ Good jet energy resolution gives much improved signal

★ Want $\sigma_E/E \approx 30\%/\sqrt{E(\mathrm{GeV})}$

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

Limited by typical HCAL resolution of $> 50\%/\sqrt{E(\mathrm{GeV})}$

⇨ a new approach to calorimetry

❸ The Particle Flow Paradigm

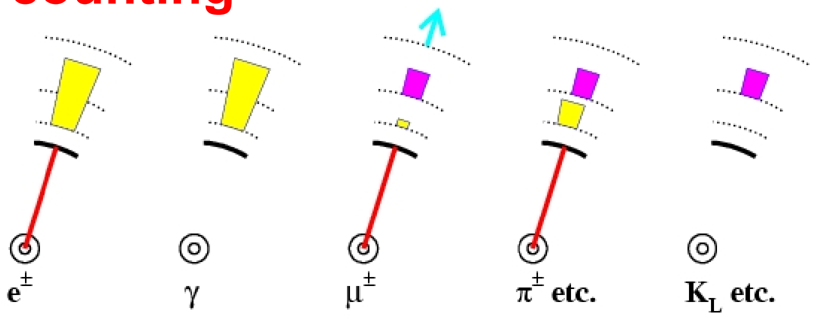
- ★ Much **ILC** physics depends on reconstructing jet-jet invariant masses
- ★ Often kinematic fits won't help – exposed to the detector
- ★ Aim for jet energy resolution ~ Γ_Z for "typical" jets
- ★ If we assume $\sigma_E/E = \alpha/\sqrt{E(\mathrm{GeV})}$

  Di-jet mass resolution is approx. $\sigma_m/m = \alpha/\sqrt{E_{jj}(\mathrm{GeV})}$
- ★ For typical ILC jet pair energies (200 GeV)

  $\Longrightarrow \sigma_E/E \sim 0.3/\sqrt{E(\mathrm{GeV})}$
- ★ Jet energy resolution is the key to calorimetry at the ILC
- ★ Widely believed that PARTICLE FLOW is the best way to achieve this

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 achieved resolution for Z→uds at rest of $\sim 0.30\sqrt{E_{jet}}$

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)

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. This leads to double-counting or incorrectly merging neutrals in to charged showers

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

★ Single particle resolutions not the dominant contribution to jet energy res.

⇨ **granularity more important than energy resolution**

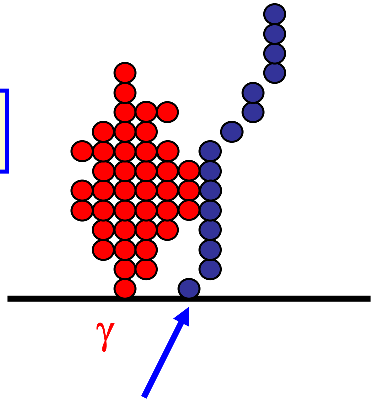
PFA : Basic issues

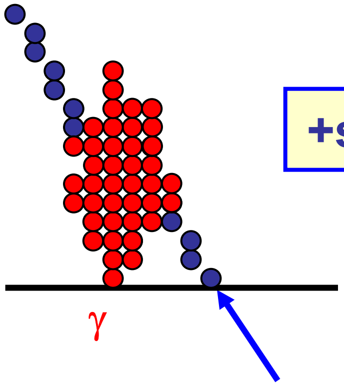
- ★ What are the main issues for PFA ?
- ★ Separate energy deposits + avoid double counting

e.g.

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

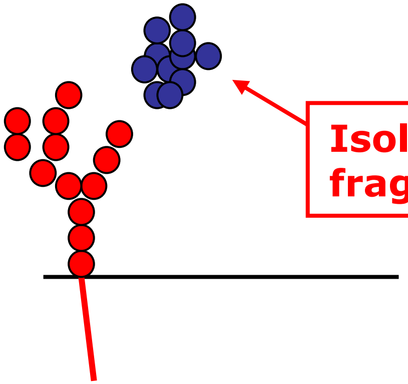
granularity





+software

- ★ Need to separate neutral hadrons from charged hadrons



Isolated neutral hadron or fragment from shower ?

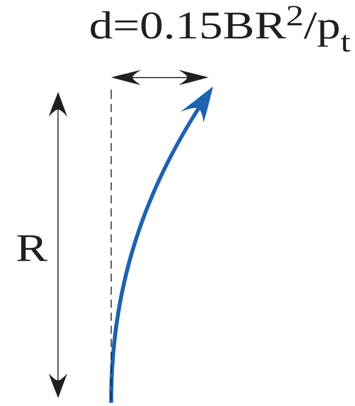
Granularity helps
But less clear…

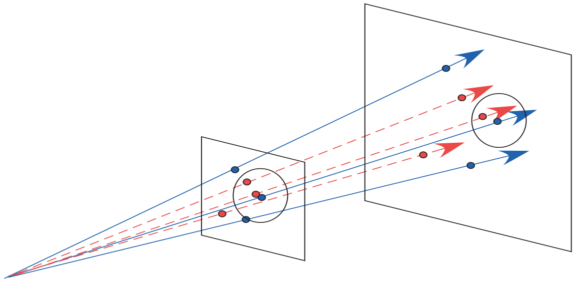
PFA : “Figure of Merit”

★ 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”: $\frac{BR^2}{\sigma}$

Separation of charge/neutrals

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….**

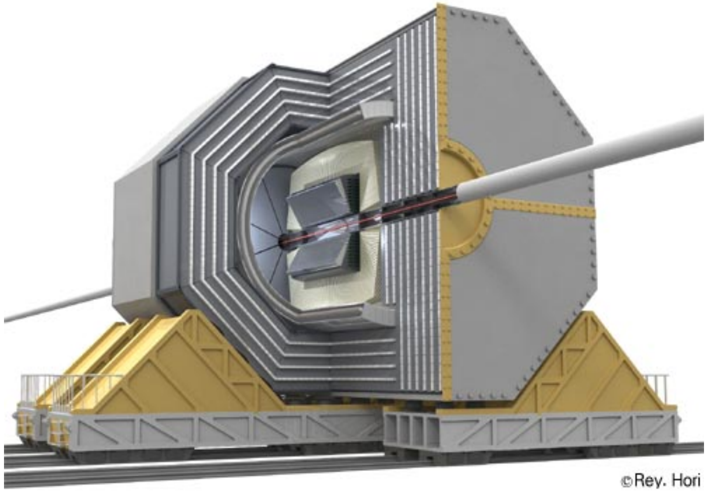
*But almost certainly wrong (see later)

❹ The ILC Detector Concepts

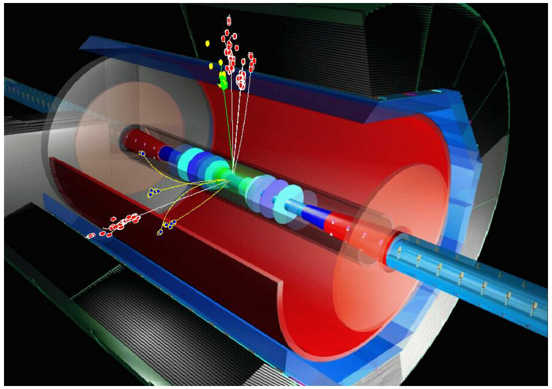
ILC Detector Concepts:

- ★ 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**

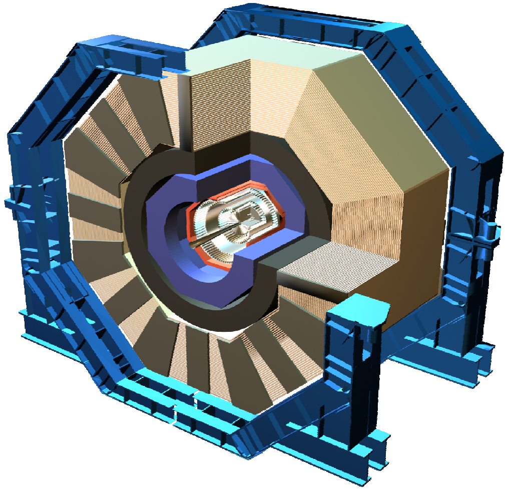
GLD : Global Large Detector



LDC : Large Detector Concept
(spawn of TESLA TDR)



SiD : Silicon Detector



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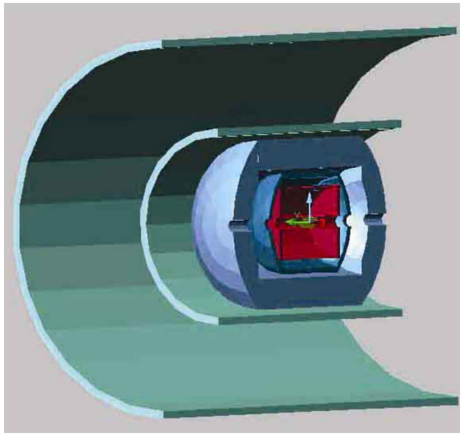
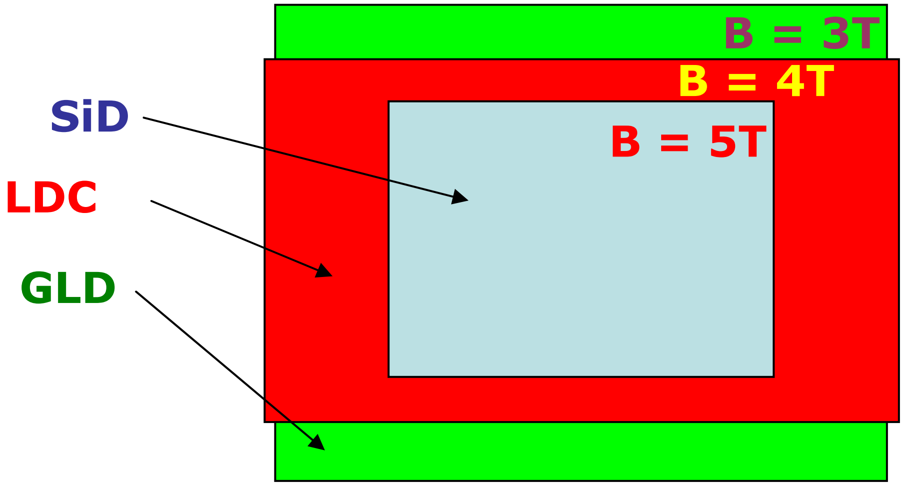


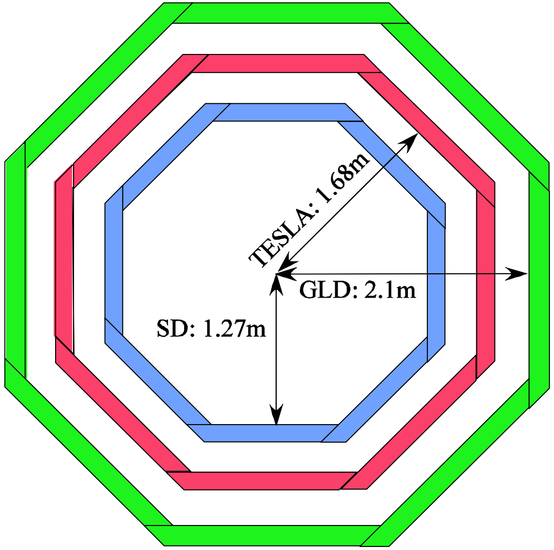
Main Differences:

- SIZE + B-Field

Tracker



ECAL



- **Central Tracker** and **ECAL**

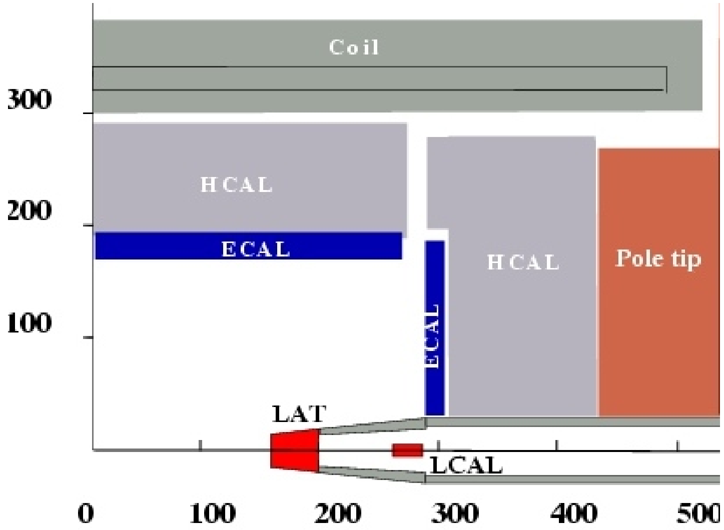
	SiD	LDC	GLD
Tracker	Silicon	TPC	TPC
ECAL	SiW	SiW	Pb/Scint

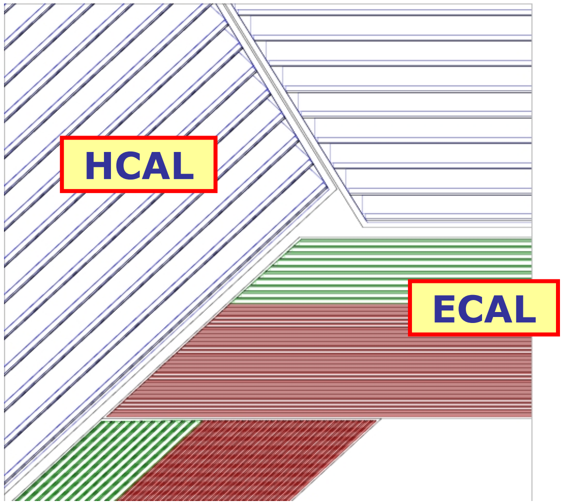
★ **SiD + LDC + GLD** all designed for PFA Calorimetry !

★ also “4th” concept designed for more “traditional” approach to calorimetry !

LDC/SiD Calorimetry

ECAL **and** HCAL inside coil





ECAL: silicon-tungsten (SiW) calorimeter:

- Tungsten : $X_0 / \lambda_{had} = 1/25$, $R_{Moliere} \sim 9mm$
  (gaps between Tungsten increase effective $R_{Moliere}$)
- Lateral segmentation: ~1cm^2 matched to $R_{Moliere}$
- Longitudinal segmentation: 30 layers (24 X_0, 0.9λ_{had})
- Typical resolution: $\sigma_E/E = 0.15/\sqrt{E(GeV)}$

Very high longitudinal and transverse segmentation

Hadron Calorimeter

Again Highly Segmented – for Particle Flow

- Longitudinal: ~40 samples
- 4 – 5 λ (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

~ 3x3 cm^2 (motivated by cost)

★ Digital HCAL

High lateral segmentation

~ 1x1 cm^2

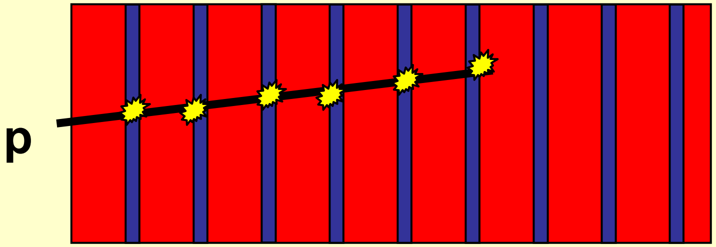
digital readout (granularity)

RPCs, wire chambers, GEMS…

OPEN QUESTION

The Digital HCAL Paradigm

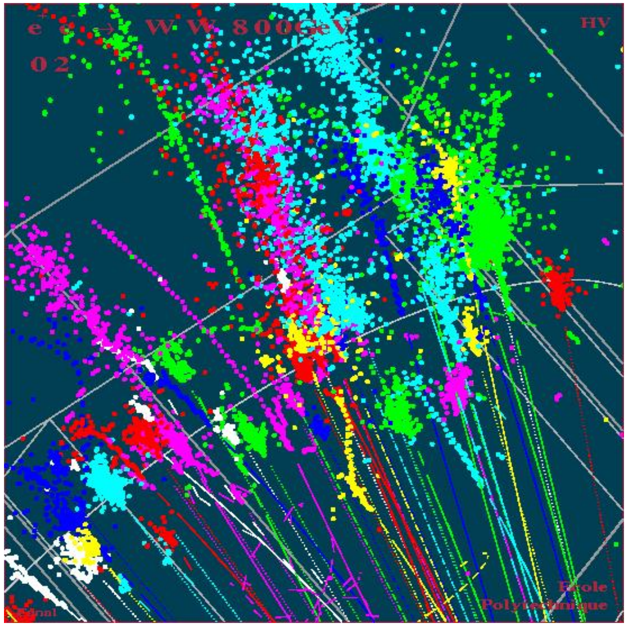
- Sampling Calorimeter:
  Only sample small fraction of the total energy deposition



- Energy depositions in active region follow highly asymmetric Landau distribution

Calorimeter Reconstruction

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



+PARTICLE FLOW

- ILC calorimetric 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)

❺ PFA and ILC detector design ?

PFA plays a special role in design of an ILC Detector

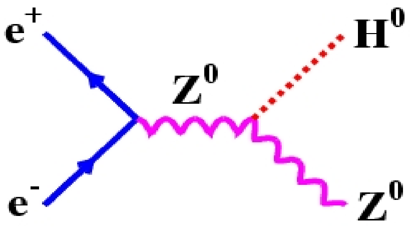
- ★ **VTX** : design driven by heavy flavour tagging, machine backgrounds, technology
- ★ **Tracker** : design driven by σ_p, track separation
- ★ **ECAL/HCAL** : single particle σ_E not the main factor
  - ➡ jet energy resolution ! Impact on particle flow drives calorimeter design + detector size, B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

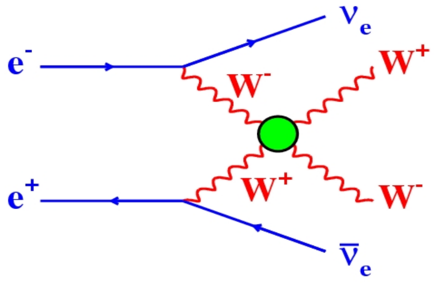
PFA is a (the?) major $$$ driver for the ILC Detectors

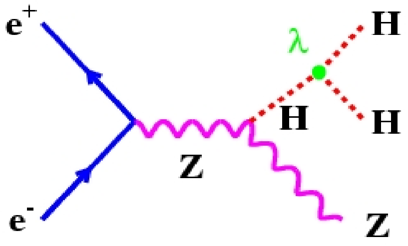
BUT: Don't really know what makes a good detector for PFA (plenty of personal biases – but little hard evidence)

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

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





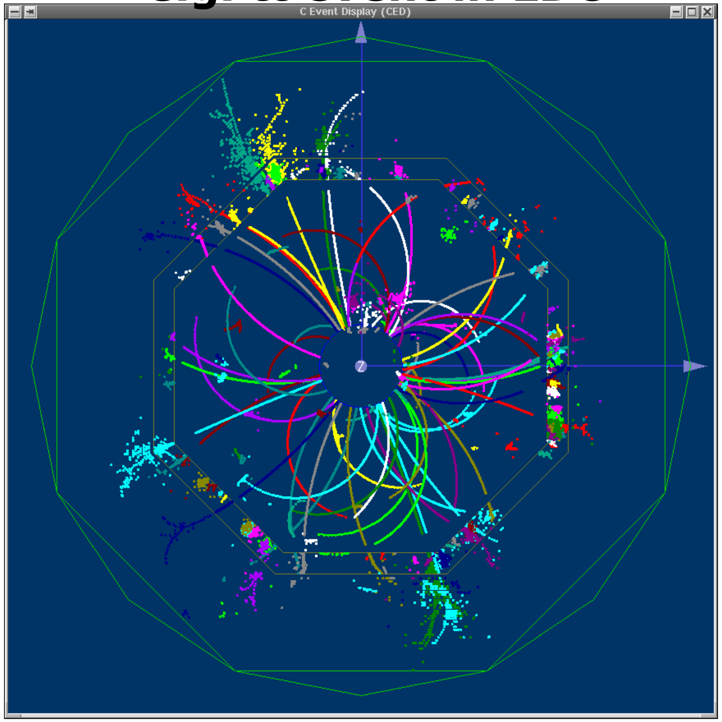


★ The rest is **VERY DIFFICULT** !

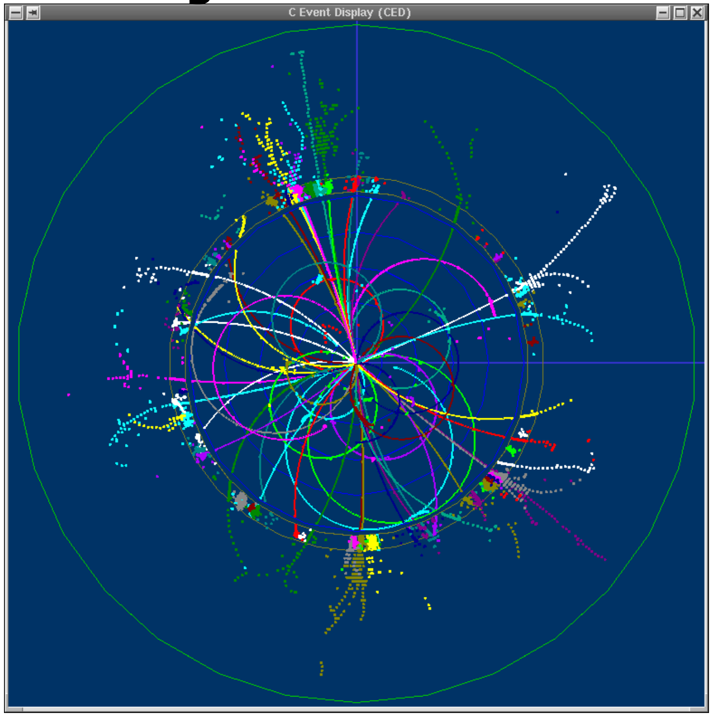
For example:

★ 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 RECONSTRUCTION !

- can't use fast simulation etc.

For design of ILC Calorimetry :

need <u>realistic</u> reconstruction chain

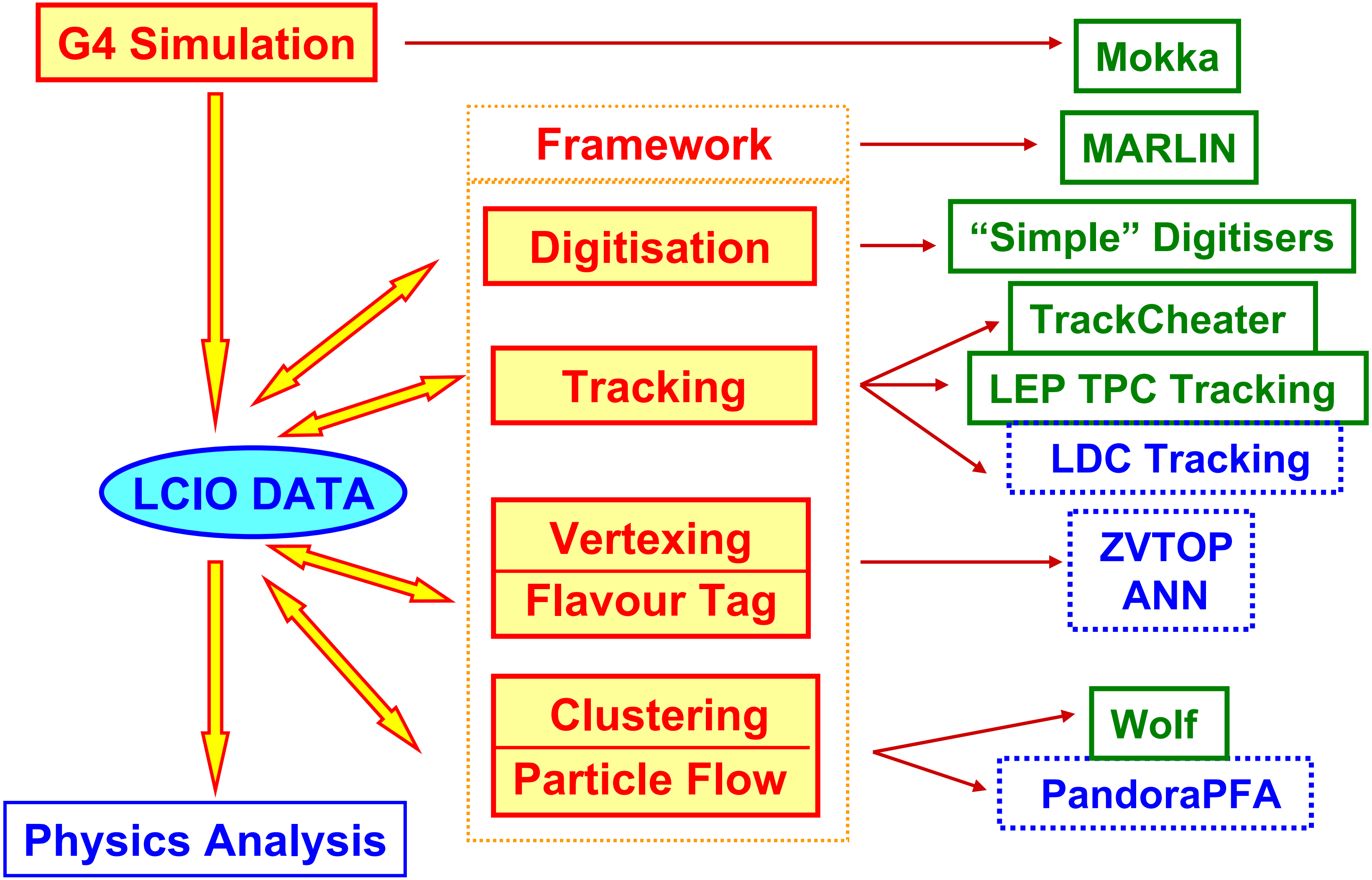
~10 years before start of ILC !!!

(ideally before start of LHC)

(even more challenging: the software has to work for multiple detector design parameters)

Not far off a first version….

European ILC Software Framework



What software is needed?

What exists now?

G4 Simulation

Framework

Digitisation

Tracking

Vertexing

Flavour Tag

Clustering

Particle Flow

LCIO DATA

Physics Analysis

Mokka

MARLIN

"Simple" Digitisers

TrackCheater

LEP TPC Tracking

LDC Tracking

ZVTOP

ANN

Wolf

PandoraPFA

❻ Particle Flow Algorithms

- Need sophisticated Particle Flow reconstruction before it is possible to start full detector design studies
- New paradigm – nobody really knows how to approach this
- So where are we now ?
- Significant effort (~6 groups developing PFA reconstruction worldwide)

For this talk concentrate on: PandoraPFA

- This is still work-in-Progress – but it is the best so far.
- Will give an overview of the algorithm to highlight the most important issues in Particle Flow calorimetry
- Then discuss some first detector optimisation studies

PandoraPFA 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

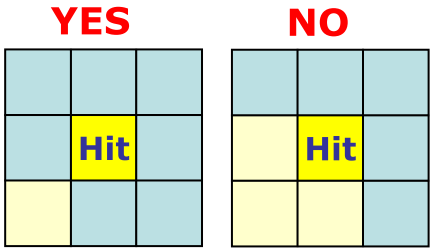
- ★ This is a fairly sophisticated algorithm : ~8000 lines of code

Six Main Stages:

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

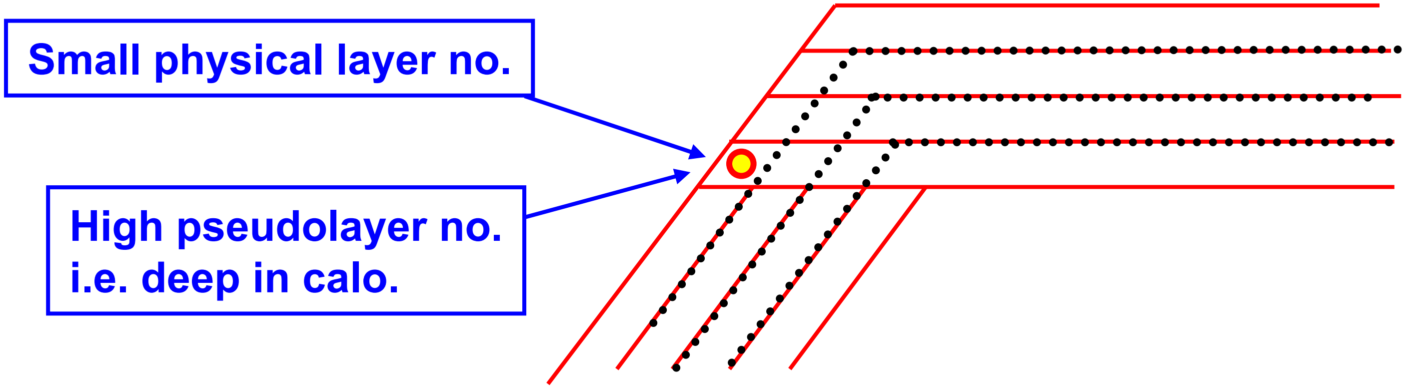
Preparation I: Extended Hits

- Create internal “Clever Hits” from Digitized **Calorimeter Hits**
- **“Extended Hits”** contain extra info:
  - pointer to original hit
  - pseudoLayer (see below)
  - measure of isolation for other hits
  - is it MIP like
  - actual layer (decoded from **CellID**)
  - Pixel Size (from GEAR) – hits are now self describing



(Important decouple from detector geometry)

- Arrange hits into **PSEUDOLAYERS**
  - **i.e.** order hits in increasing depth within calorimeter
  - PseudoLayers follow detector geometry

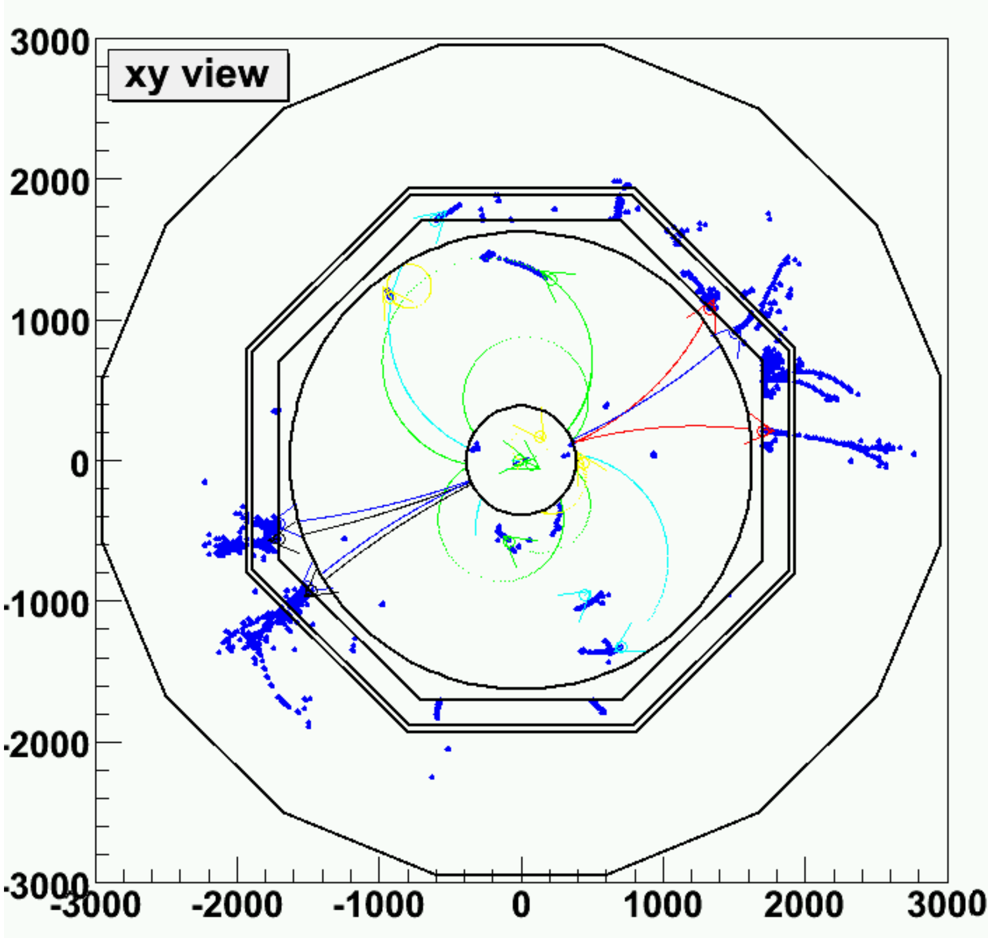


Small physical layer no.

High pseudolayer no.
i.e. deep in calo.

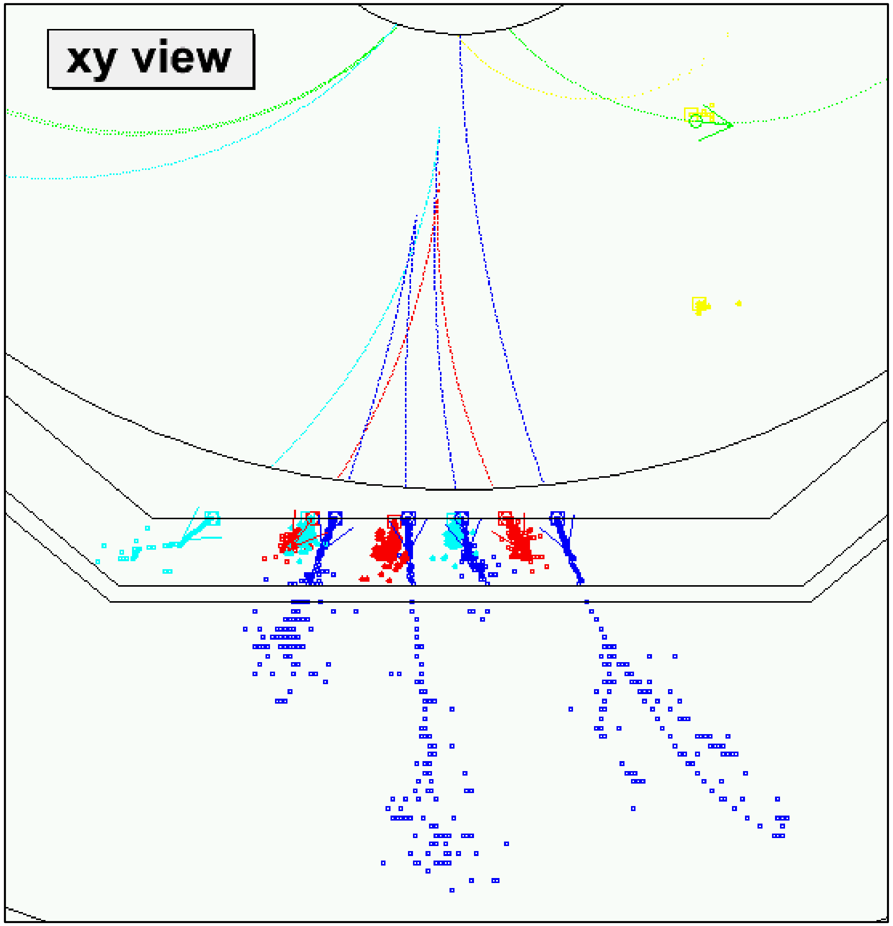
Preparation II: Isolation

- ★Divide hits into isolated and non-isolated
- ★Only cluster **non-isolated** hits
- ★"Cleaner"/Faster clustering
- ★ Significant effect for scintillator HCAL



- ✦ Removal of isolated hits degrades HCAL resolution
- ✦ **e.g. LDC**
  50 %/√E/GeV →
  60 %/√E/GeV

Preparation III: Tracking



- ★Use MARLIN **TrackCheater**
- ★Tracks formed from MC Hits in **TPC/FTD/VTX**
- ★ HelixFit (Alexei R) ⇒ track params
- ★ Cuts (primary tracks):
  - ♦ $|d_0| < 5$ mm
  - ♦ $|z_0| < 5$ mm
  - ♦ >4 non-Si hits

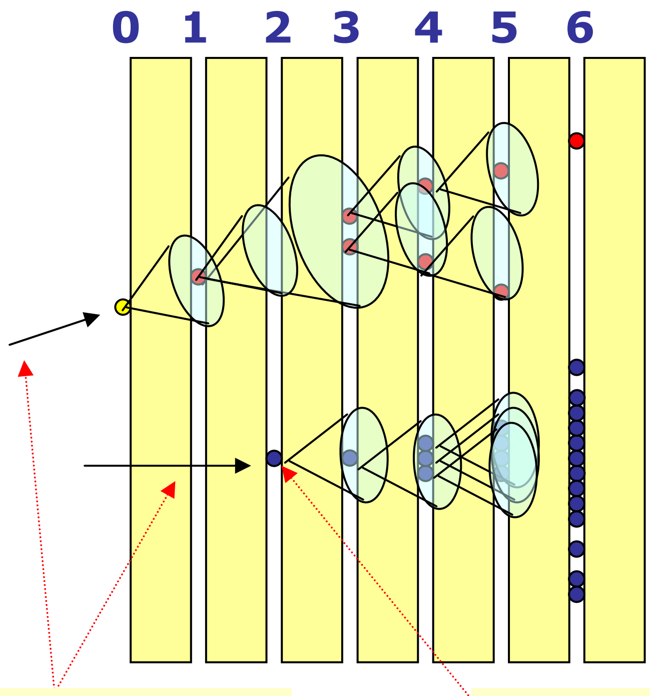
+ V_0 and Kink finding:

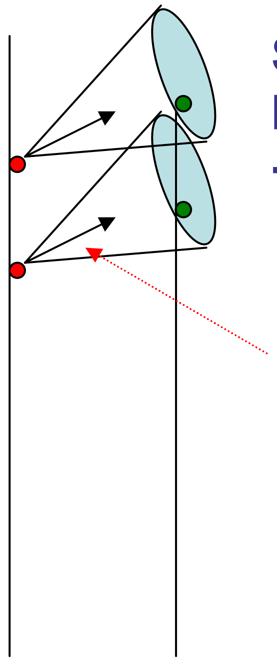
- ✦Track resolution better than cluster
- ✦ Improves PFA performance by ~2 %

Use fully reconstructed tracks when software available

ii) ECAL/HCAL Clustering

- Start at inner layers and work outward
- Tracks can be used to "seed" clusters
- Associate hits with existing Clusters
- If no association made form new Cluster
- Simple cone based algorithm





Simple cone algorithm based on current direction + additional N pixels

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

Parameters:
- cone angle
- additional pixels

Initial cluster direction

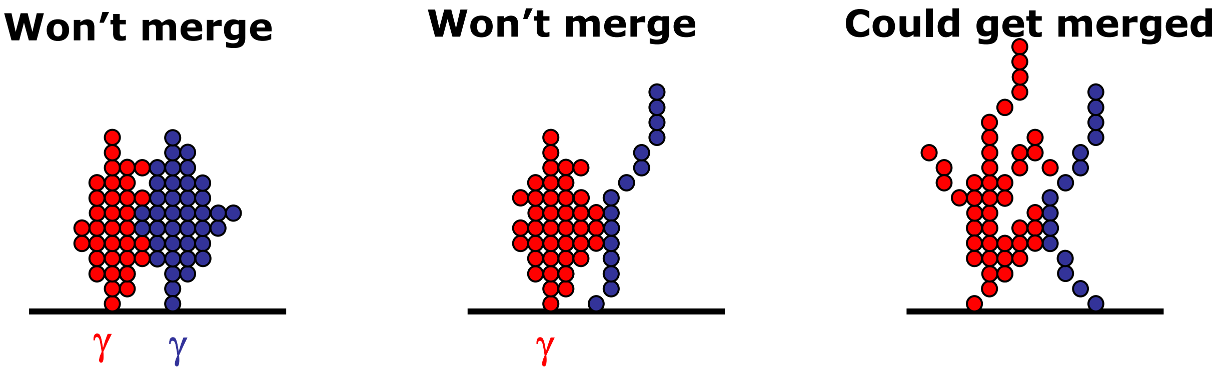
Unmatched hits seeds new cluster

iii) Topological Cluster Association

- 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 – fix what's been missed

Photon ID

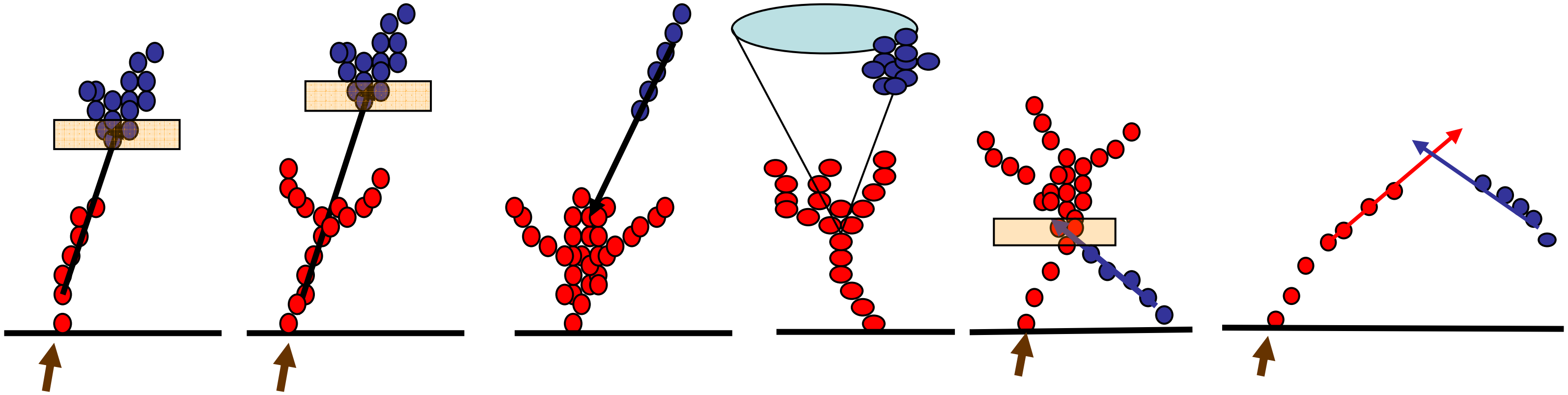
- Photon ID plays important role
- Simple "cut-based" photon ID applied to all clusters
- Clusters tagged as photons are immune from association procedure – just left alone



★ Clusters associated using a number of topological rules

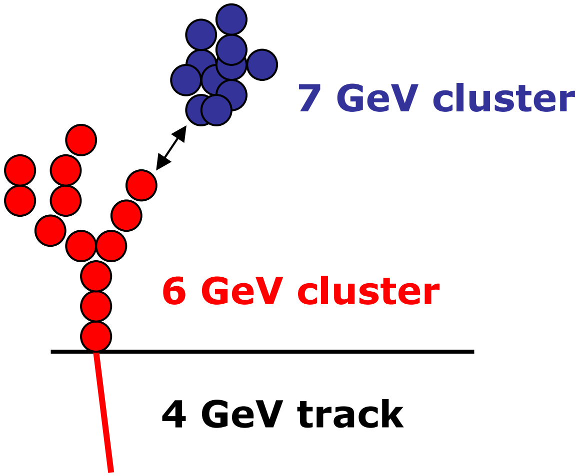
Clear Associations:

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



Less clear associations:

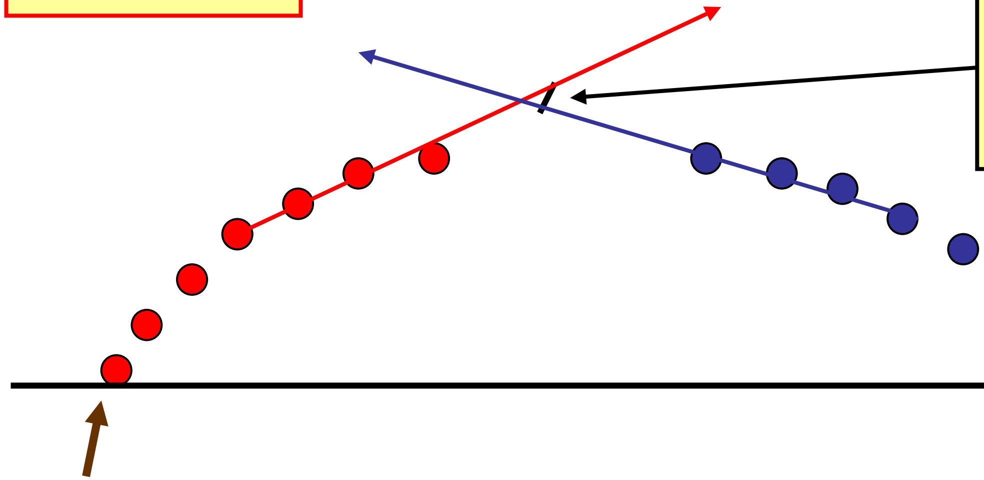
e.g. **Proximity**



Use E/p consistency to veto clear mistakes

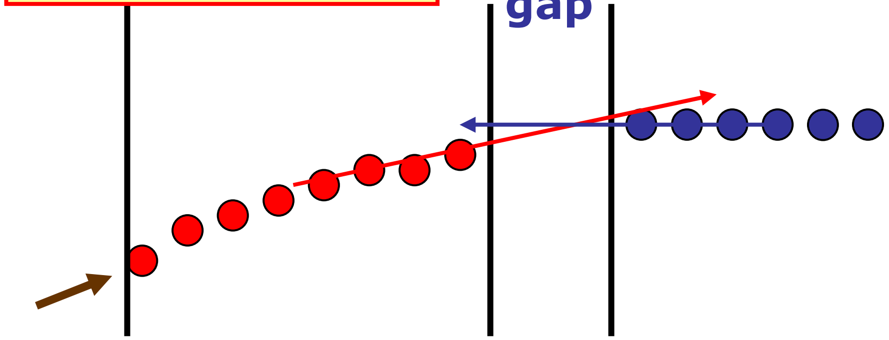
Topological association : track merging

LOOPERS



Tight cut on extrapolation of **distance of closest approach** of fits to ends of tracks

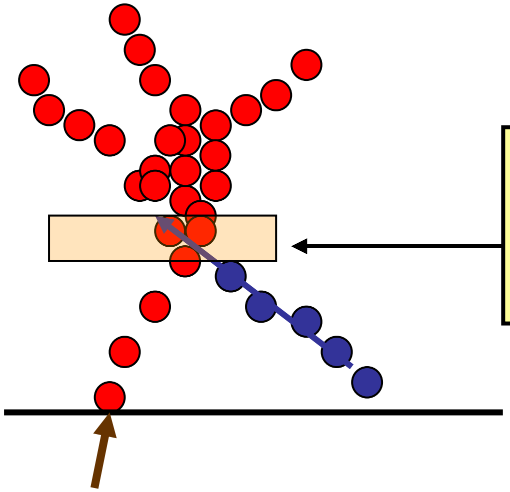
SPLIT TRACKS



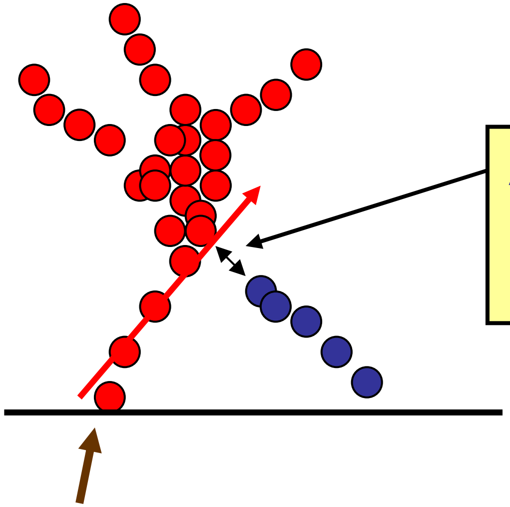
Tight cut on extrapolation of **distance of closest approach** of fits to end of inner tracks and start of outer track

Topological Association II : Backscatters

★ **Forward propagation clustering algorithm has a major drawback: back scattered particles form separate clusters**



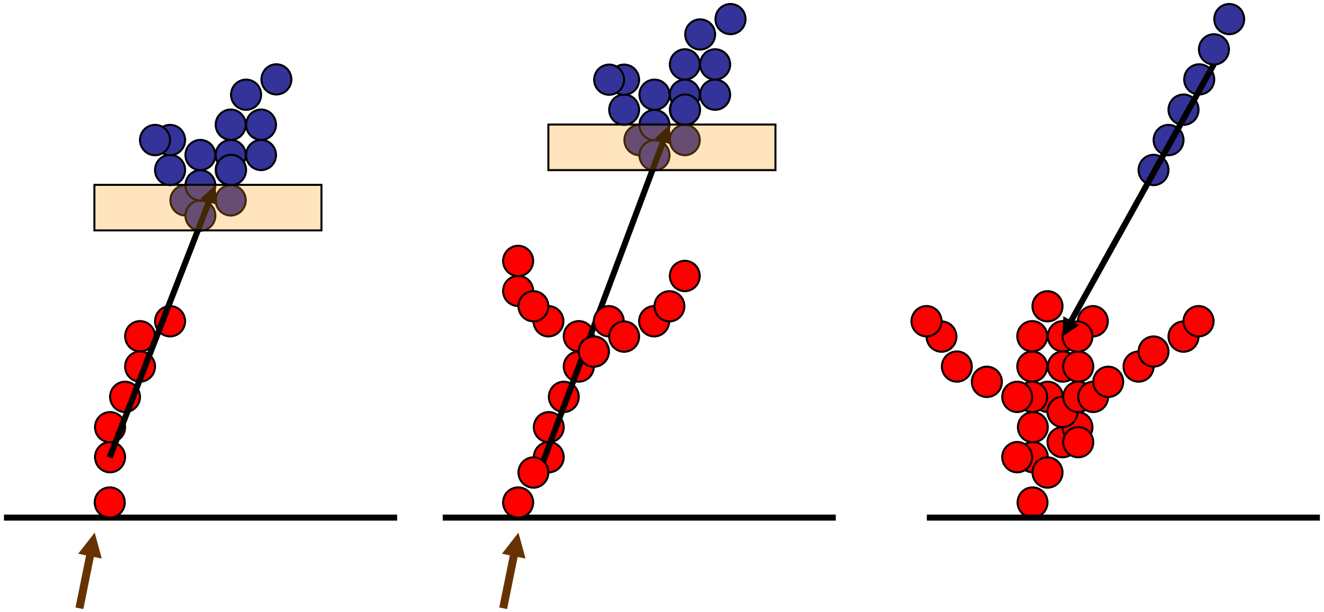
Project track-like clusters forward and check distance to shower centroids in subsequent N layers



Also look for track-like segments at start of cluster and try to match to end of another cluster

Topological association III : MIP segments

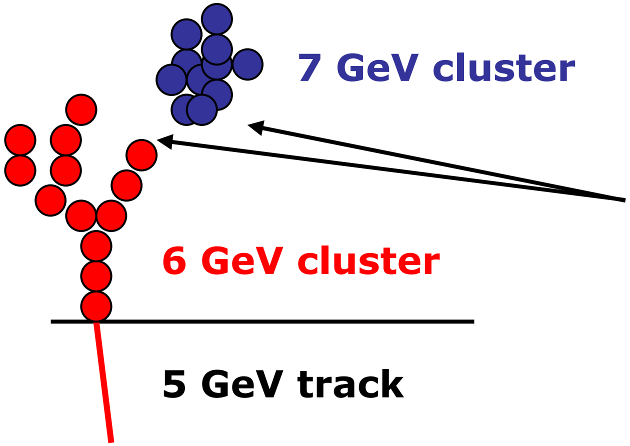
- ★Look at clusters which are consistent with having tracks segments and project backwards/forward (defined using local straight-line fits to hits tagged as MIP-like)



- ★Apply tight matching criteria on basis of projected track [NB: + track quality i.e. chi2]

iv) Cluster Association Part II

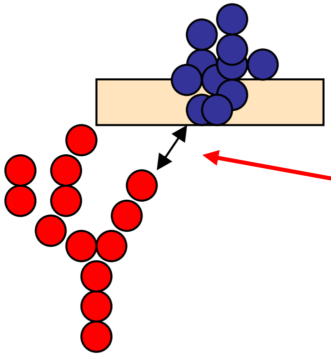
- Have made very clear cluster associations
- Now try "cruder" association strategies
- BUT first associate tracks to clusters (temporary association)
- Use track/cluster energies to "veto" associations, e.g.



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

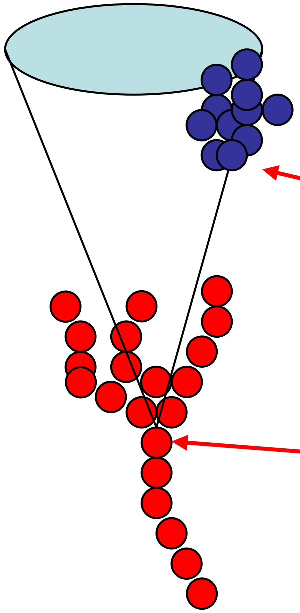
Provides some protection against silly mistakes

Proximity



Distance between hits : limited to first pseudo-layers of cluster

Shower Cone



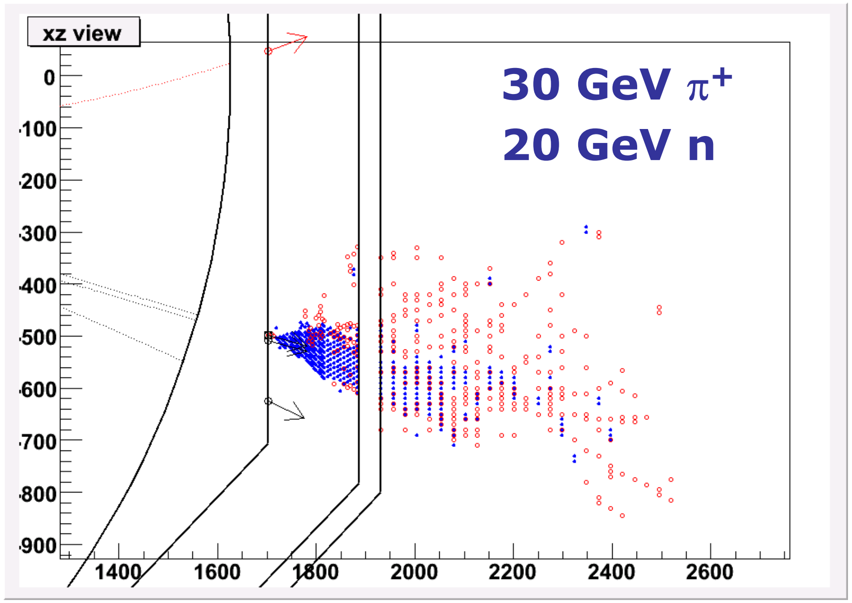
Associated if fraction of hits in cone > some value

Shower start identified

+Track-Driven Shower Cone ⇒ Apply looser cuts if have low E cluster associated to high E track

v) Iterative Reclustering

- ★ Upto this point, in most cases 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

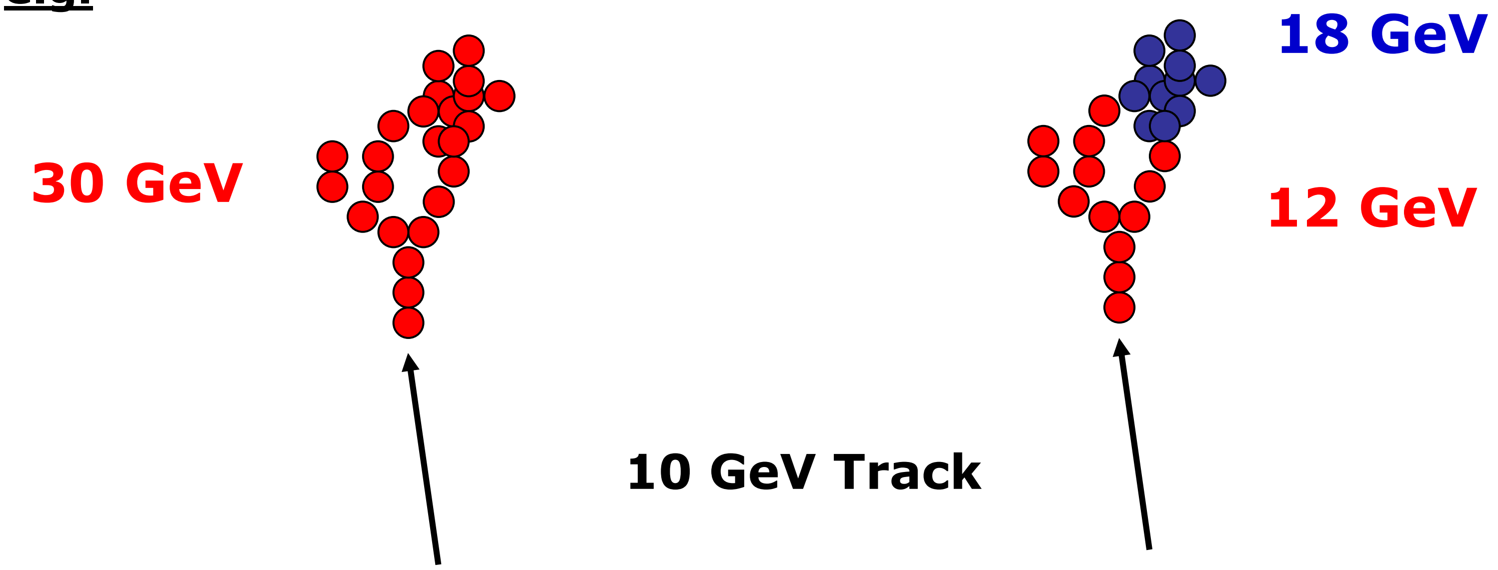
The ONLY(?) way to address this is "statistically"

→

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 cluster splits and get sensible track-cluster match

NOTE: NOT FULL PFA as clustering driven by track momentum

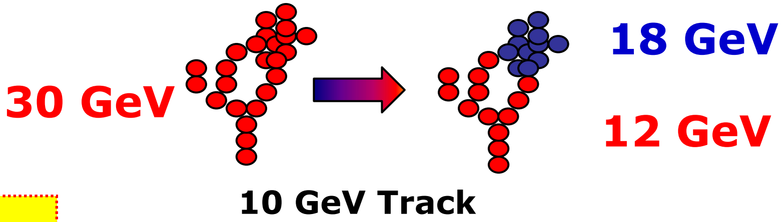
This is very important for higher energy jets

Iterative Reclustering Strategies

① Cluster splitting

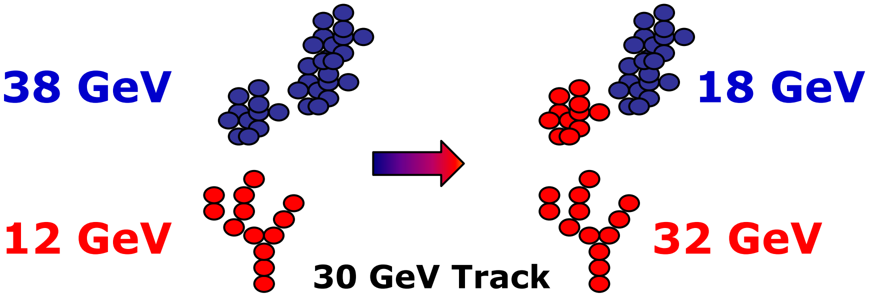
Reapply entire clustering algorithm to hits in “dubious” cluster. Iteratively reduce cone angle until cluster splits to give acceptable energy match to track

★ + plug in alternative clustering algorithms



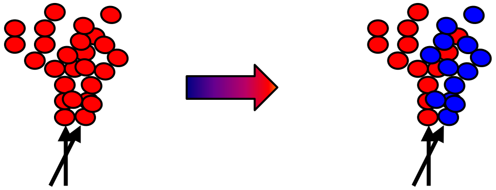
② Cluster merging with splitting

Look for clusters to add to a track to get sensible energy association. If necessary iteratively split up clusters to get good match.



③ Track association ambiguities

In dense environment may have multiple tracks matched to same cluster. Apply above techniques to get ok energy match.



④ “Nuclear Option”

★ If none of above works – kill track and rely on clusters alone

❼ Current Performance

Figures of Merit:

rms_{90}

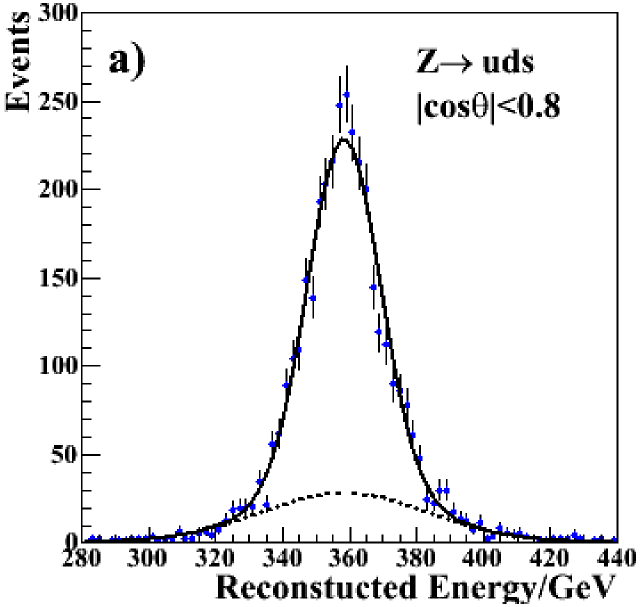
- ★Find smallest region containing 90 % of events
- ★Determine rms in this region

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

For 45 GeV Jets ILC goal achieved. BUT things get worse with increasing energy (more confusion).

σ_{75}

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



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

Recent Detector Optimisation Studies

★ 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

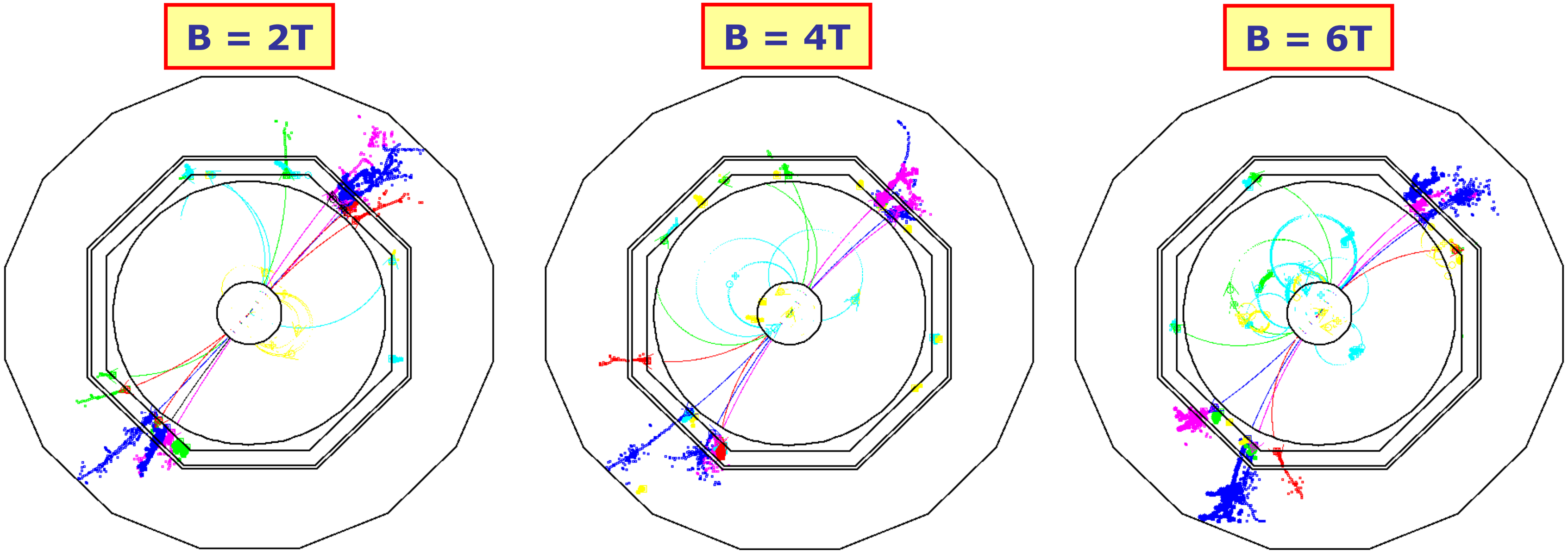
- Need a good simulation of hadronic showers !!!
- Need realistic PFA algorithm
  (want/need results from multiple algorithms)

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

★ Interpretation of results needs care – observing effects of detector + imperfect software

e.g. B-Field at 91.2 GeV

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



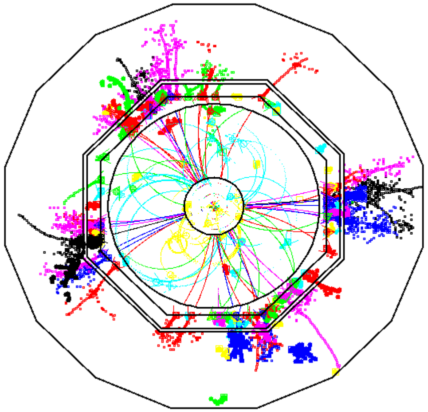
B-Field	$\sigma_E/E = \alpha\sqrt{(E/GeV)}$	
	All angles	$\|\cos\theta\|<0.7$
2 Tesla	34.1±0.3%	30.8±0.4 %
4 Tesla	33.4±0.3 %	29.2±0.4 %
6 Tesla	34.4±0.3 %	29.7±0.4 %

Only weak B-field dependence

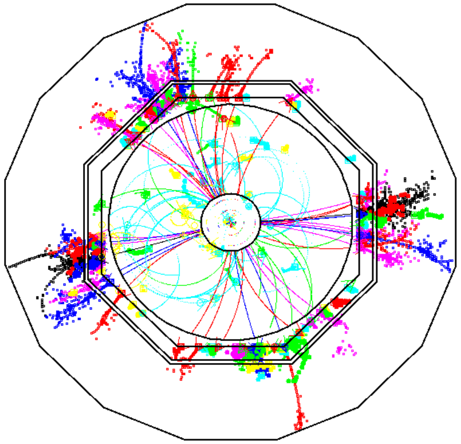
The reason being that confusion is not dominating the resolution for these low energy jets

Radius vs Field

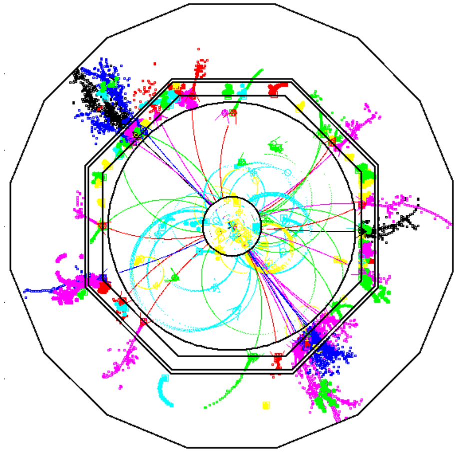
- Now for a more serious study…
- Map out the dependence on B and outer radius of the TPC
- Use LDC00 detector model with:
  - r_{tpc} = 1380-2280 mm
  - B = 3-5 Tesla



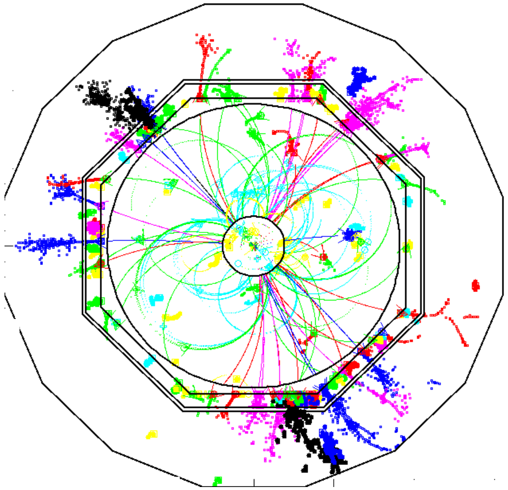
r_{TPC} = 1380 mm



r_{TPC} = 1580 mm



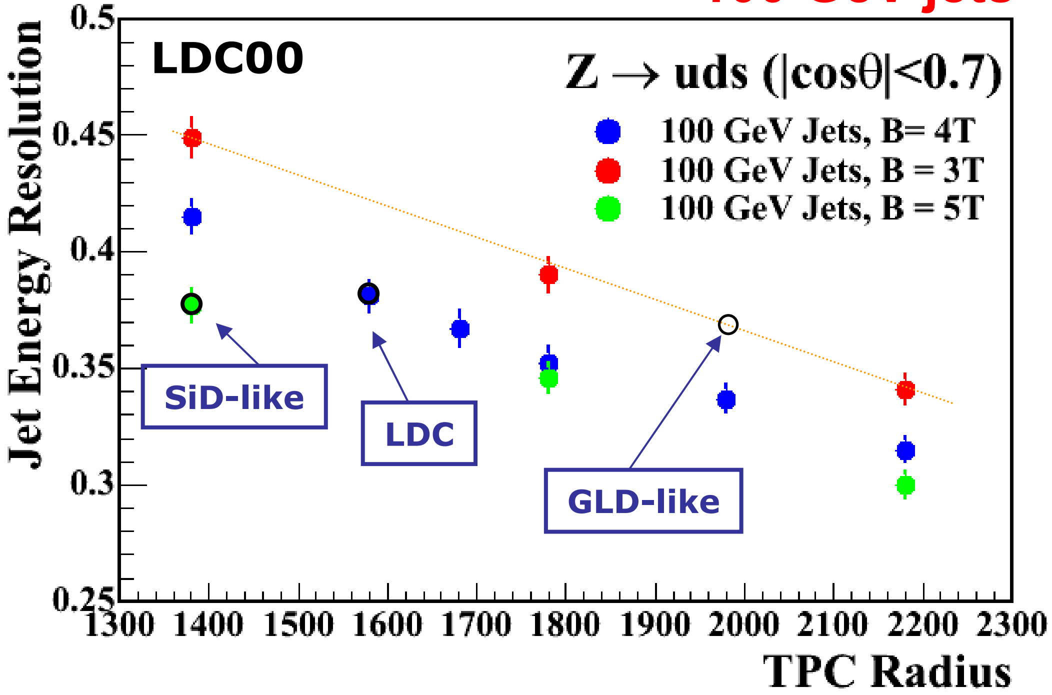
r_{TPC} = 1690 mm



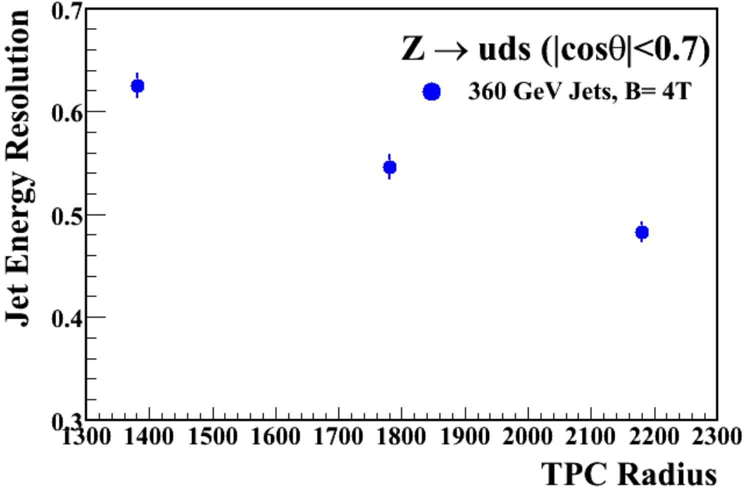
r_{TPC} = 1890 mm

- Look at jet energy resolution for Z→uds events at
  - $\sqrt{s}$ = 200 GeV
  - $\sqrt{s}$ = 360 GeV

100 GeV jets



180 GeV jets



- ★ Results consistent with:

$$\boxed{\frac{\sigma_E}{E} \propto \frac{1}{B^{0.24}R^{0.6}}}$$

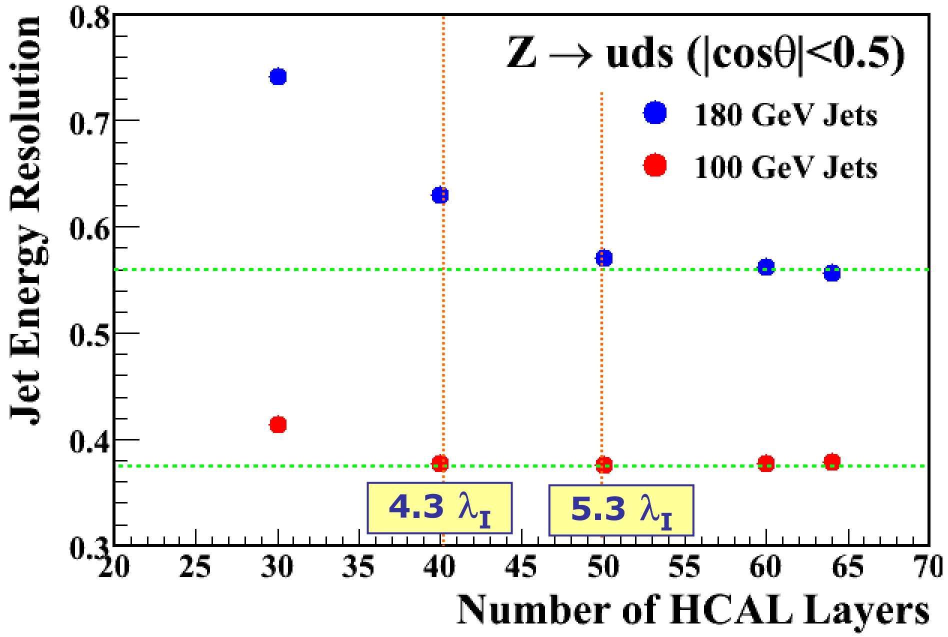
Empirical

- ★ As expected large radius/ large field does best
- ★ But not as strong an effect as might have been expected
- ★ How much due to "intrinsic detector resolution" and how much due to software deficiencies ?

HCAL Depth and Transverse segmentation

★ Investigated HCAL Depth (interaction lengths)

- Generated **Z→uds** events with a large HCAL (63 layers)
    - approx 7 λ_I
- In PandoraPFA introduced a configuration variable to truncate the HCAL to arbitrary depth
- Takes account of hexadecagonal geometry

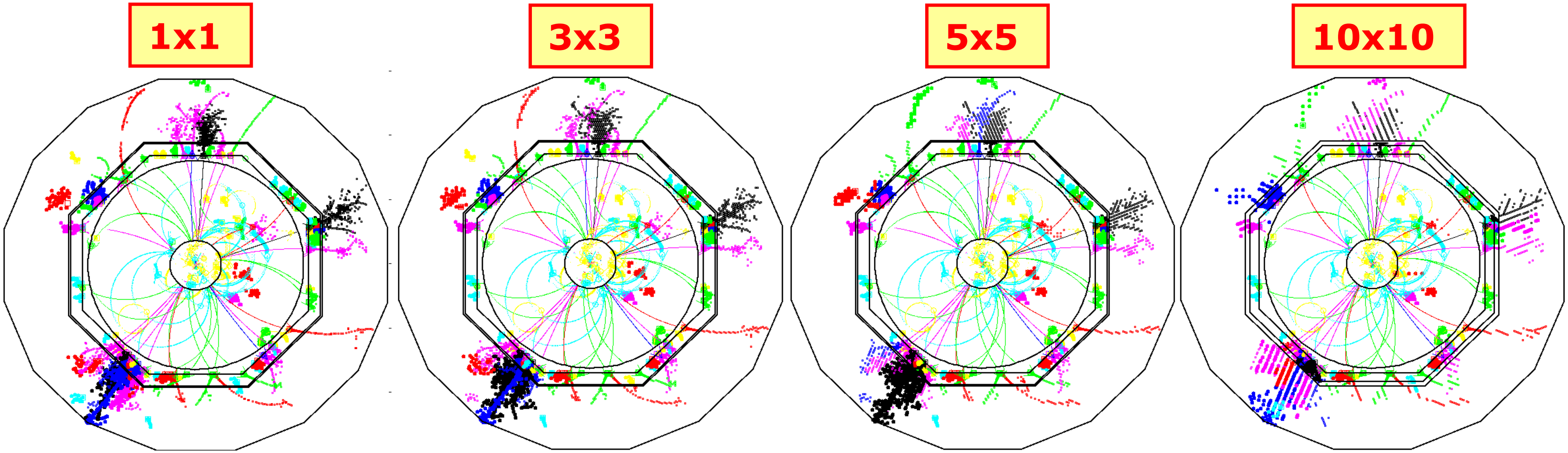


- For **100 GeV** Jets no advantage in going to larger HCAL !

- For **180 GeV** Jets HCAL leakage degrades PFA performance

NOTE: no attempt to account for leakage – i.e. using muon hits - this is a worse case

✶ Analogue scintillator tile HCAL : change tile size 1x1 → 10x10 mm²



Detector Model	$\sigma_{Evis}/E = \alpha\sqrt{(E/GeV)}$	
	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 %

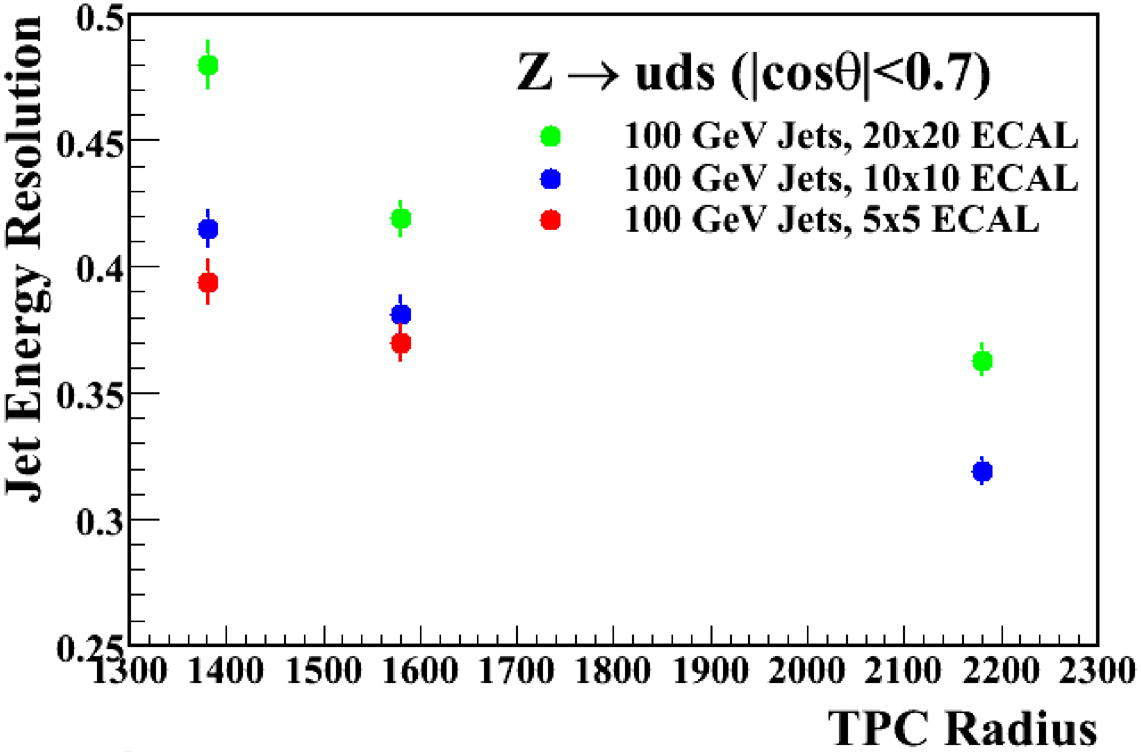
Visible energy resolution

- ★ 10x10 too coarse (can be seen clearly from display)
- ★ Finer granularity helps(?) somewhat at higher energies maybe better tracking of overlapping showers?

ECAL Transverse Granularity

- Use Mokka to generate Z → uds events @ 200 GeV with different ECAL segmentation: 5x5, 10x10, 20x20 [mm^2]

- Detector model: LDC00Sc (~Tesla TDR)
- B = 4 Tesla
- 30x30mm^2 HCAL



With PandoraPFA

- 20x20 segmentation looks too coarse
- For 100 GeV jets, not a big gain going from 10x10 → 5x5mm^2

  [for these jet energies the contributions from confusion inside the ECAL is relatively small – need]

★ For a small detector: finer granularity does help

Caveat Emptor I

- ★ These studies are interesting but not clear how seriously they should be taken
  - how much is due to the detector
  - how much due to imperfect algorithm

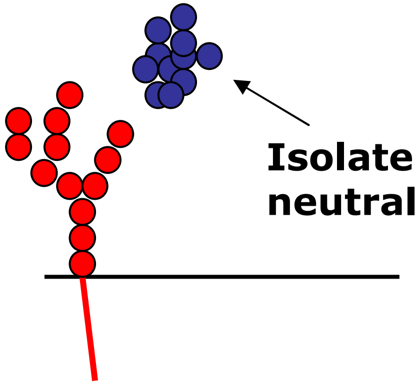
Need results from other algorithms

Caveat Emptor II

★ **Studies rely on MC simulation**
- Simulation of hadronic showers notoriously difficult
- All models in GEANT 4 likely to be quite "wrong"

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

★ **NOT CLEAR what is most important !**
- <u>NOT</u> just 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

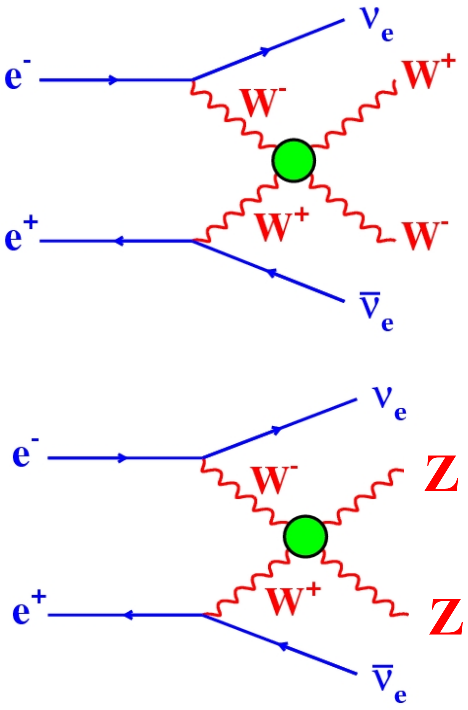


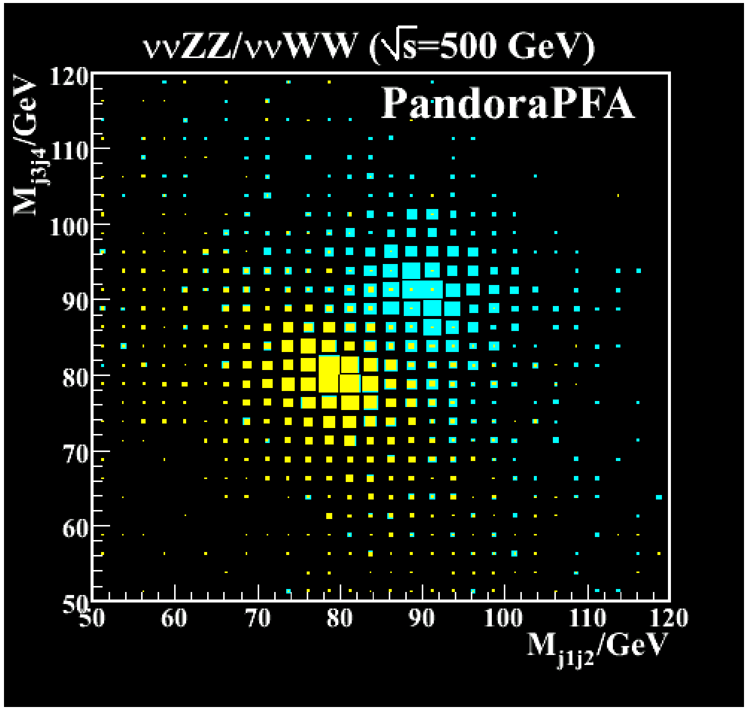
★ **What is important for PFA may well be very different from that for traditional HEP calorimetry**

Caveat Emptor III

- ★ 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 (UK can play a major role)

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





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 →uds events)
- ★ More importantly, getting close to being able to address real issues:
  - ⊙ What is optimal detector size/B-field, etc.

FINAL COMMENT:

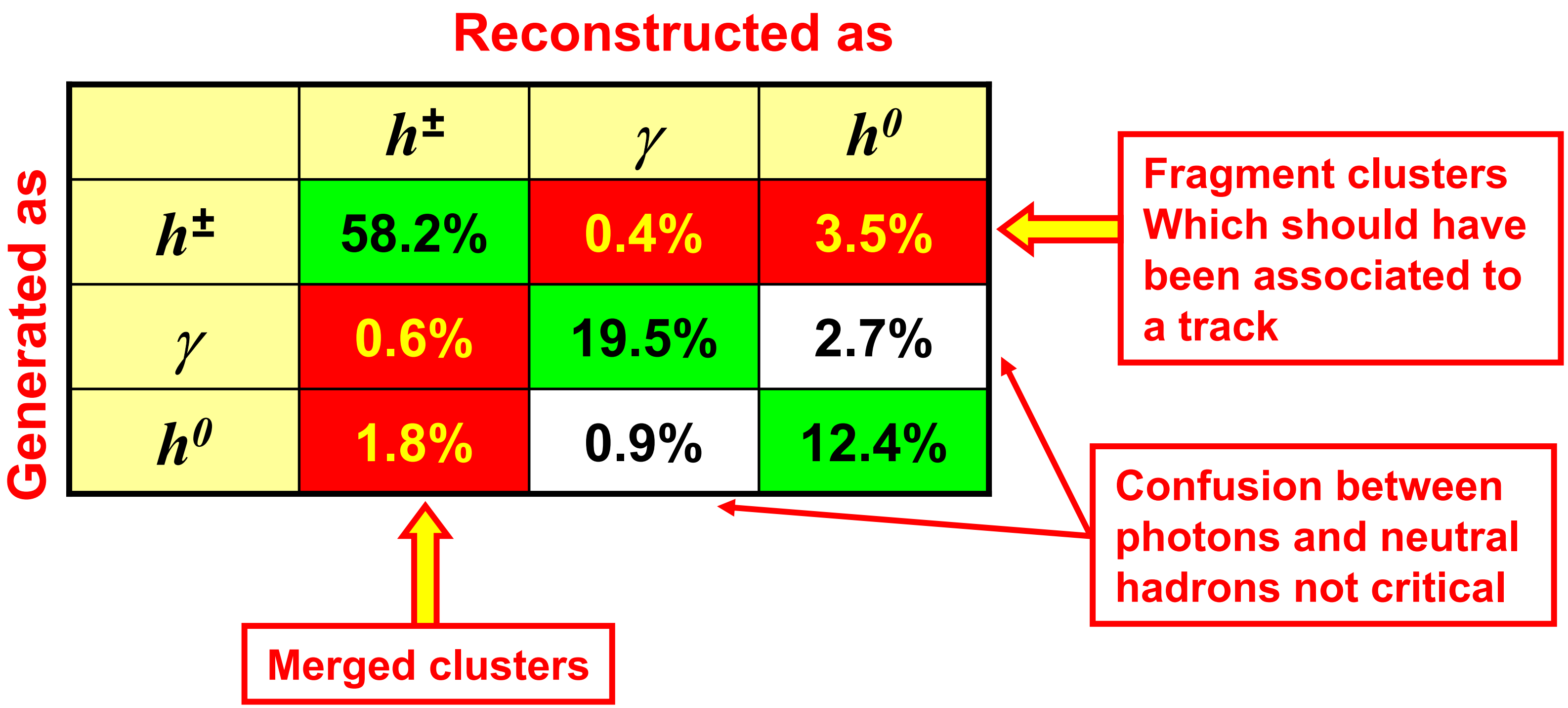
- ★GLD, LDC, SiD calorimetry "designed" for PFA
  - ★ Need to demonstrate this actually makes sense !
    - ★ not yet completely proven…!
  - ★ Need to study in context of physics sensitivity

Fin

RESERVE SLIDES

Current Limitations

- ★ Matrix of Confusion: look MC at fractions of the total energy generated in the different particle types (**$h^{\pm}$, γ, h^0**) and compare to the reconstructed **$h^{\pm}$, γ, h^0** fractions
- ★ For perfect reconstruction this would be diagonal
- ★ e.g. 100 GeV uds jets (all polar angles)



Reconstructed as

Generated as

	$h^{\pm}$	γ	h^0
$h^{\pm}$	🟩 58.2%	🟥 0.4%	🟥 3.5%
γ	🟥 0.6%	🟩 19.5%	2.7%
h^0	🟥 1.8%	0.9%	🟩 12.4%

Fragment clusters Which should have been associated to a track

Confusion between photons and neutral hadrons not critical

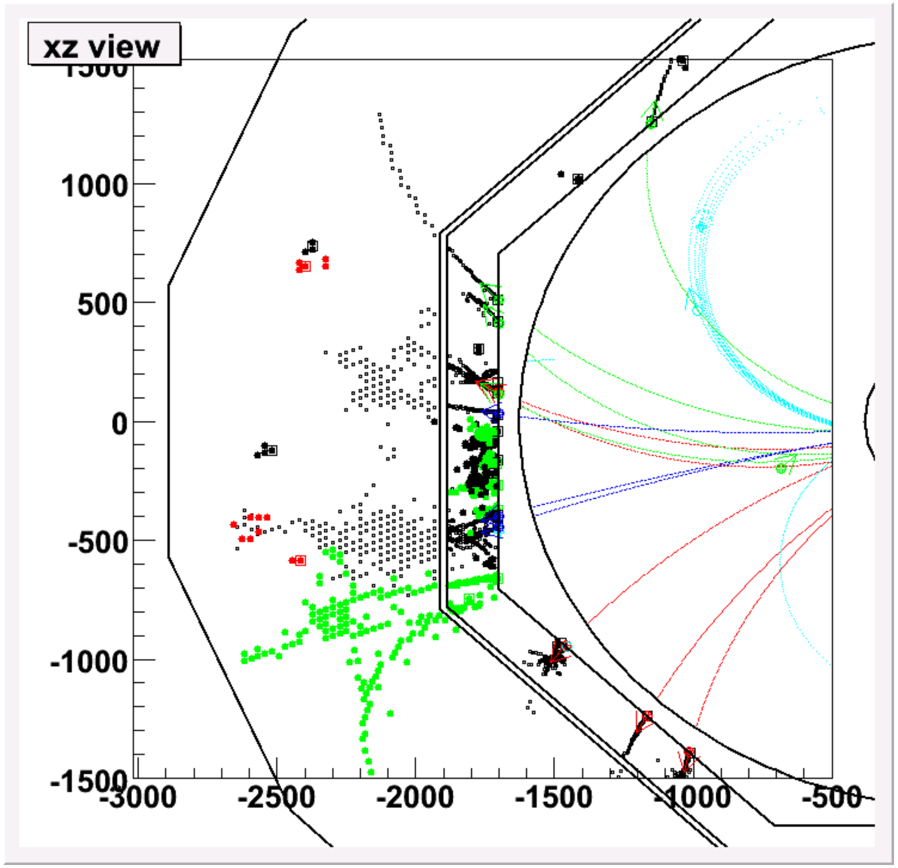
Merged clusters

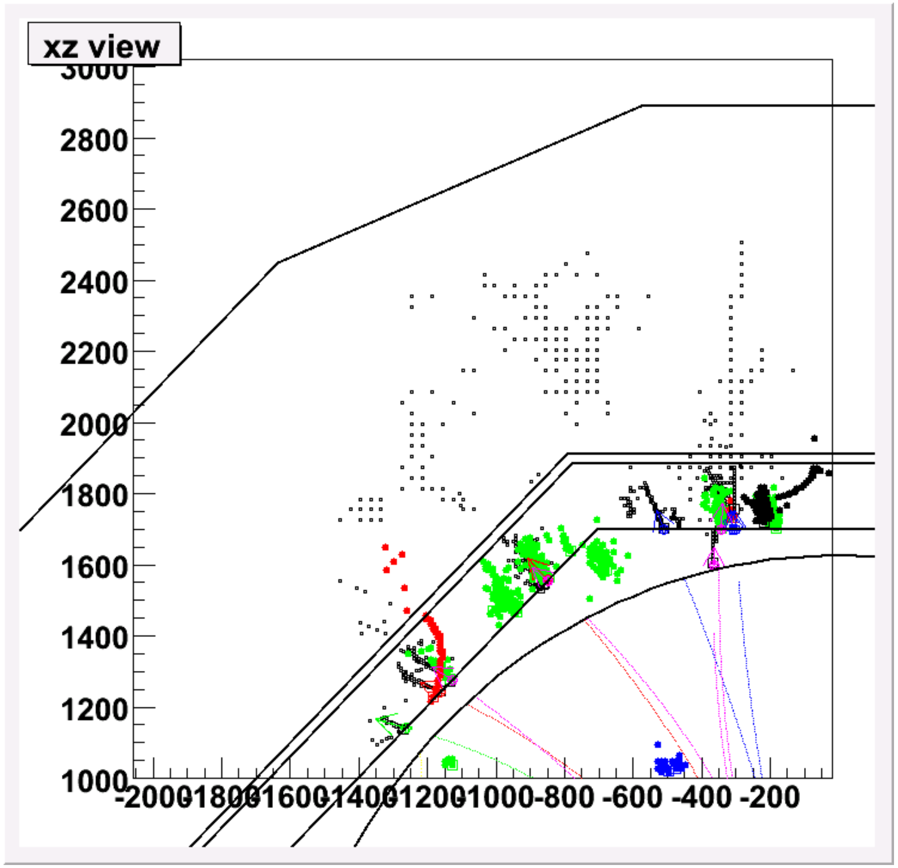
- ★ Fragment clusters are the biggest single problem

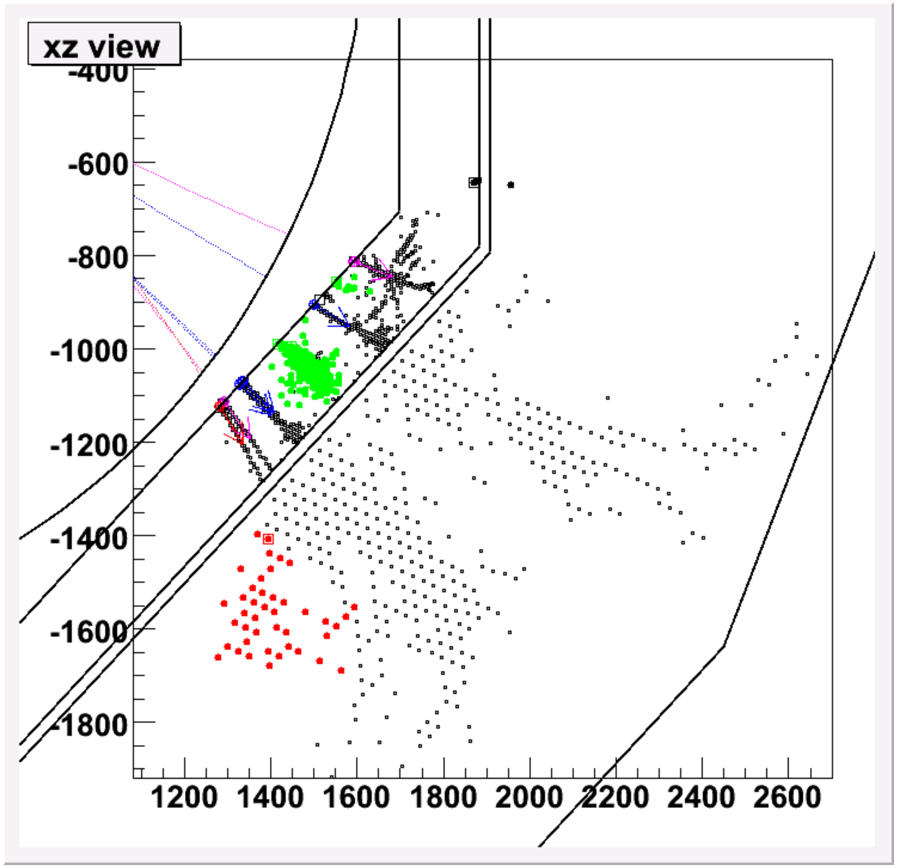
Fragments

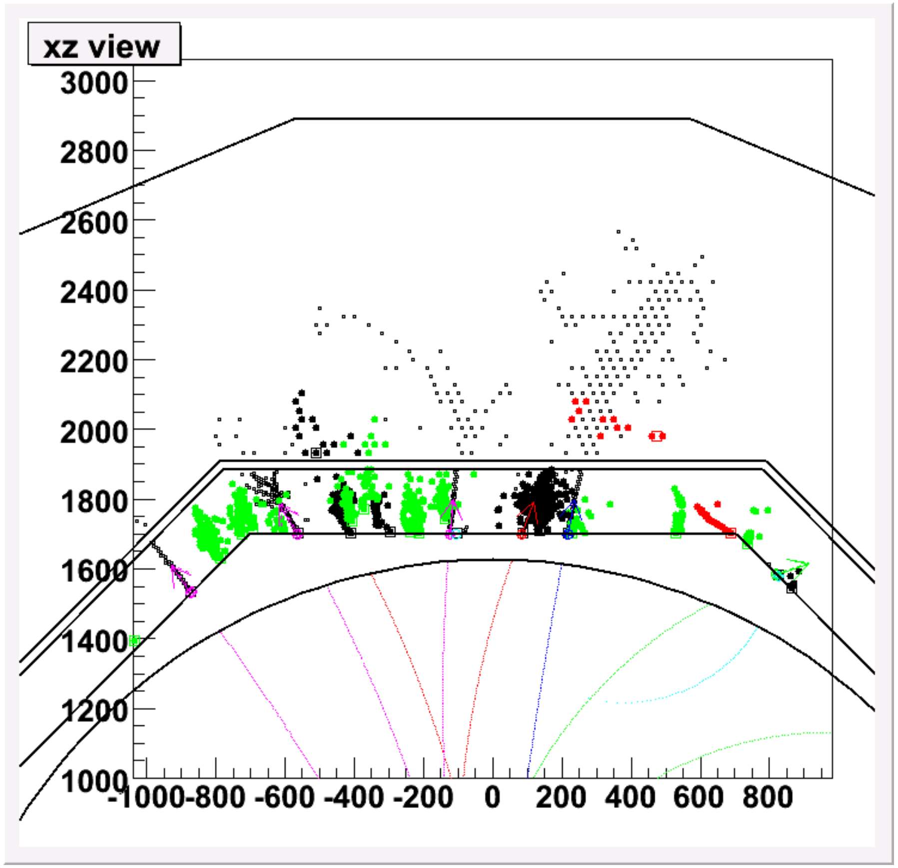
★ **A few example events :**

Green = correctly identified neutral clusters
Red = reconstructed neutral clusters from charged hadron







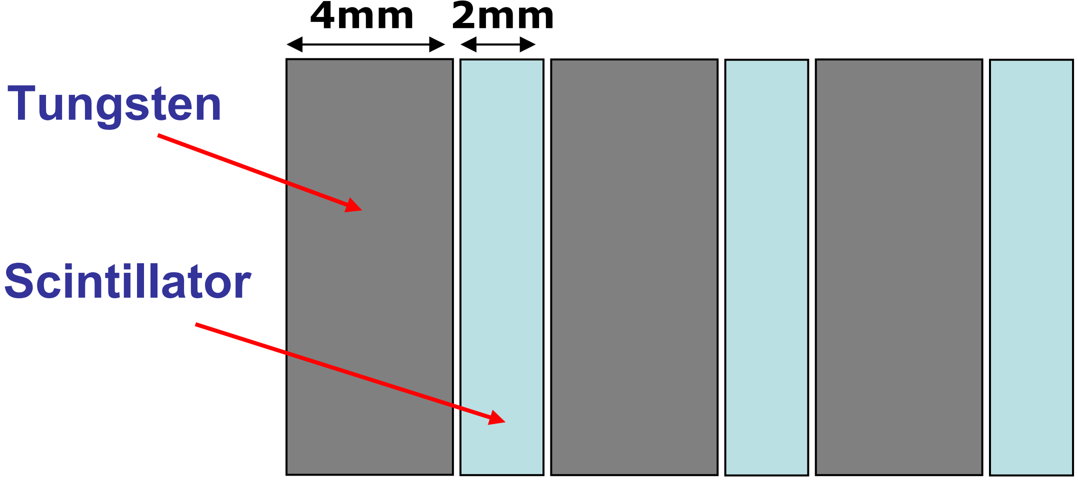


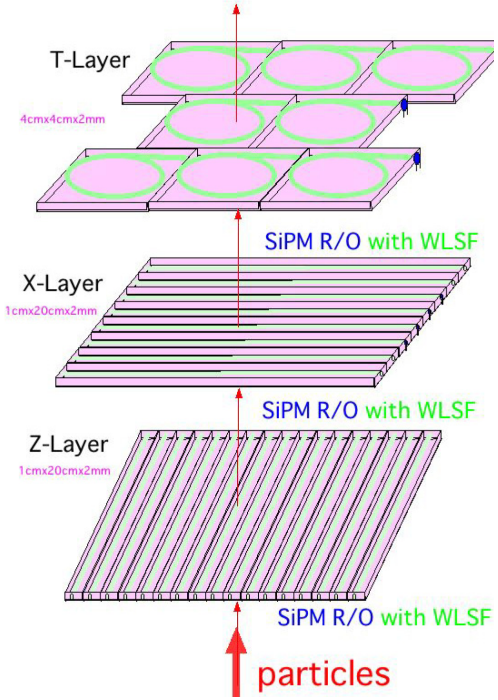
- ★ Work in progress to explicitly identify these fragments as the last stage in the reconstruction based on:
  - ▪ cluster shape, cluster direction, …
- ★ Expect a not insignificant improvement in PFA performance

Also issues with tracking which will improve with new full track reconstruction (better track extrapolation will help)

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**

Big question of pattern recognition in dense environment

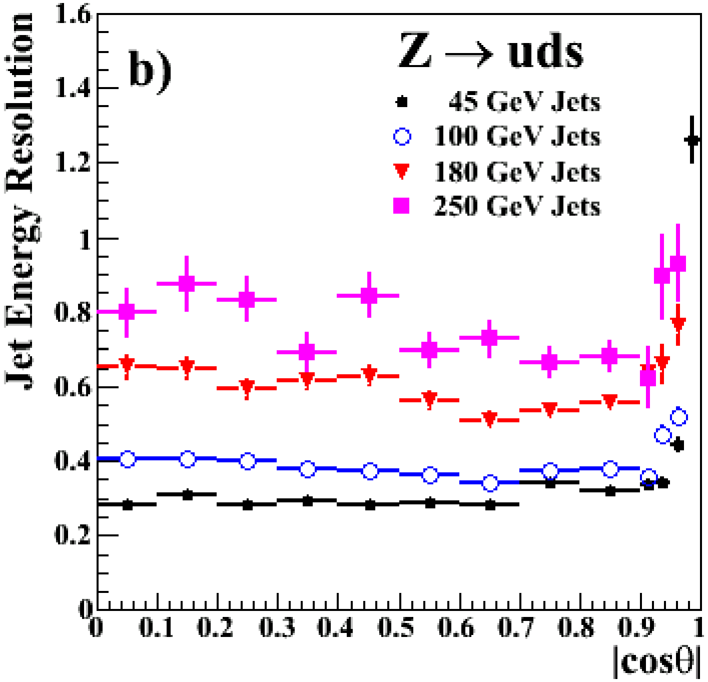
SiD/LDC/GLD : Basic design = sampling calorimeter

- ★ **The current performance of the algorithm is well described by the EMPIRICAL expression:**

$$\boxed{\frac{\sigma_E}{E} = \frac{0.265}{\sqrt{E(\mathrm{GeV})}} + 1.2\times10^{-4}E(\mathrm{GeV})}$$

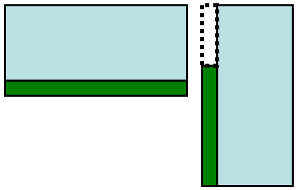
Nothing deep here just current state of play

Angular Dependence



- **Jet energy resolution depends on polar angle**
- **Degradation in endcap : nuclear interactions in TPC endplate have some impact + longer track extrapolation**

+ HCAL ring not currently simulated in Mokka



- **For high energy jets performance in barrel region worse at low values of |cosθ| - leakage (see later)**

PFA-related Detector Design issues

★What aspects of the detector might impact PFA performance?

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