Particle Flow Calorimetry and PandoraPFA

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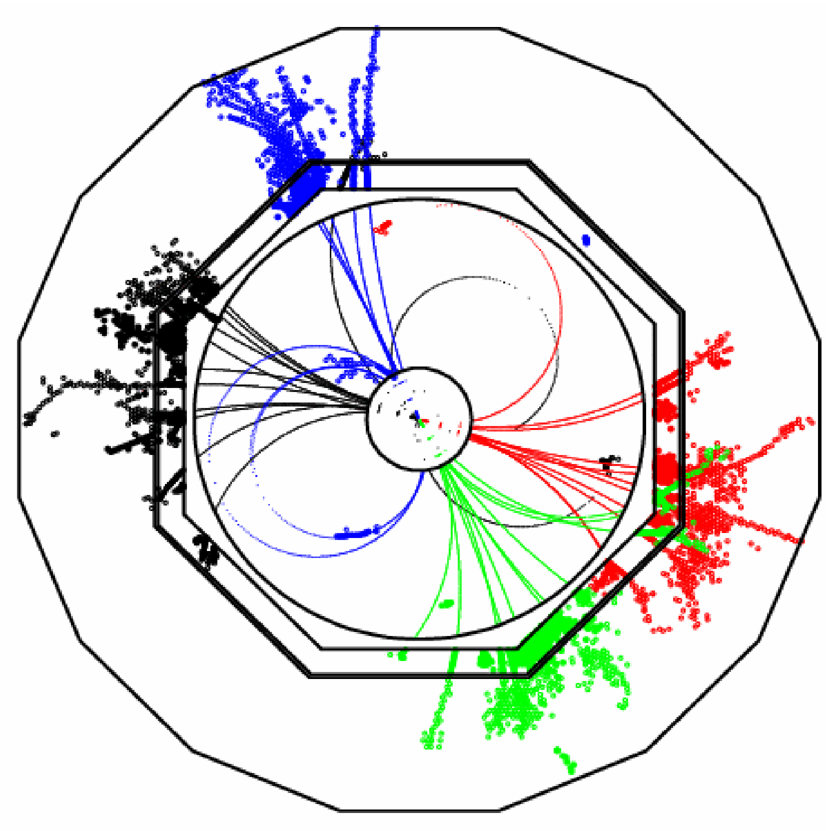


This Talk:

❶ Why 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 PandoraPFA Particle Flow Algorithm (PFA)
❼ Performance and Detector Optimisation Studies
❽ Future Development
❾ Conclusions

❶ Why the ILC ?

★ The LHC and ILC provide a complimentary approach to studying the physics of EWSB and beyond

The LHC

- ★ Will open the door to new physics !
- ★ Pushes the energy frontier with proton-proton collisions at 14 TeV
  - *qq*, *qg* and *gg* collisions in the energy range 0.5-5 TeV

The ILC

- ★ A different approach:
  very high precision as opposed to very high energy
- ★ Electron-positron collisions in the energy range 0.1-1 TeV
- ★ Very clean final states + high resolution detectors
  - ⇨ very precise measurements (as at LEP)
  - ⇨ detailed understanding of new physics + tight constraints on theory (as at LEP)

★ The case for having both the LHC and ILC very well studied:

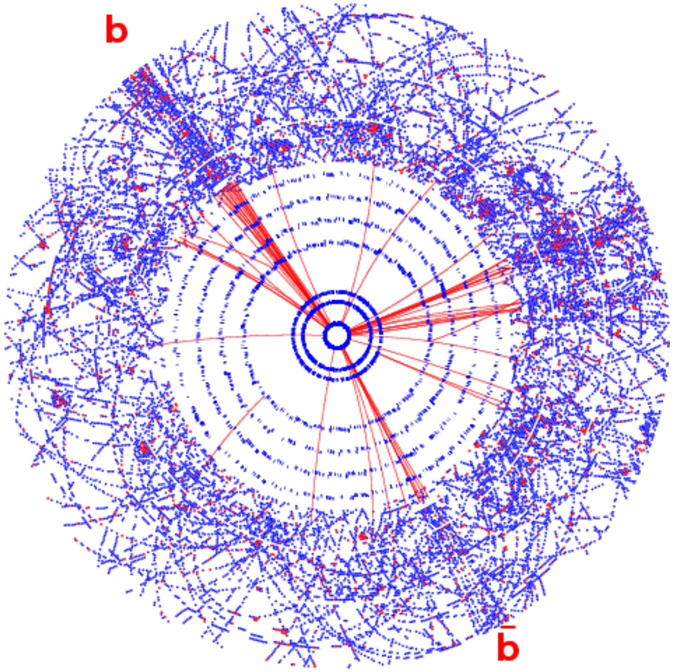
e.g. "Physics Interplay of the LHC and ILC", G. Weiglein et al., Phys. Rept. 426 (2006) 47-358

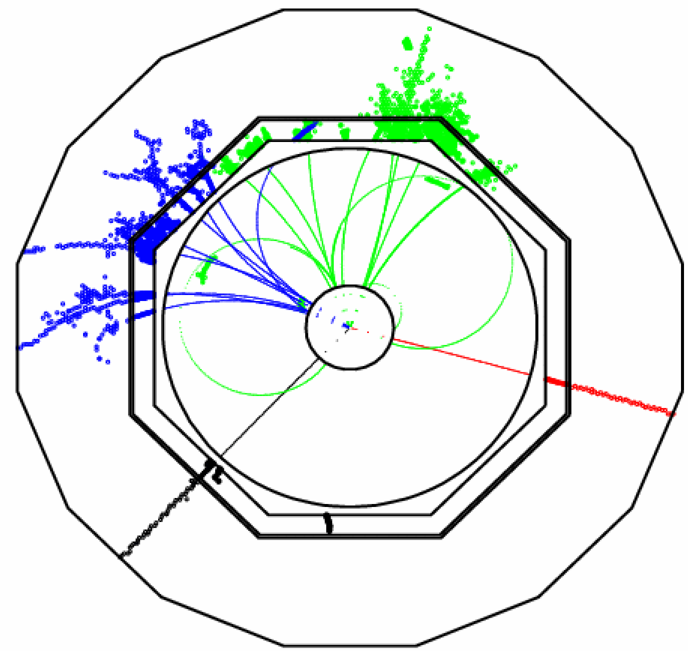
$e^+ e^- \equiv$ precision

★ **Electron-positron colliders provide clean environment for precision physics**

The LHC $\mathrm{pp} \rightarrow \mathrm{H} + X$

The ILC $\mathrm{e}^+\mathrm{e}^- \rightarrow \mathrm{HZ}$





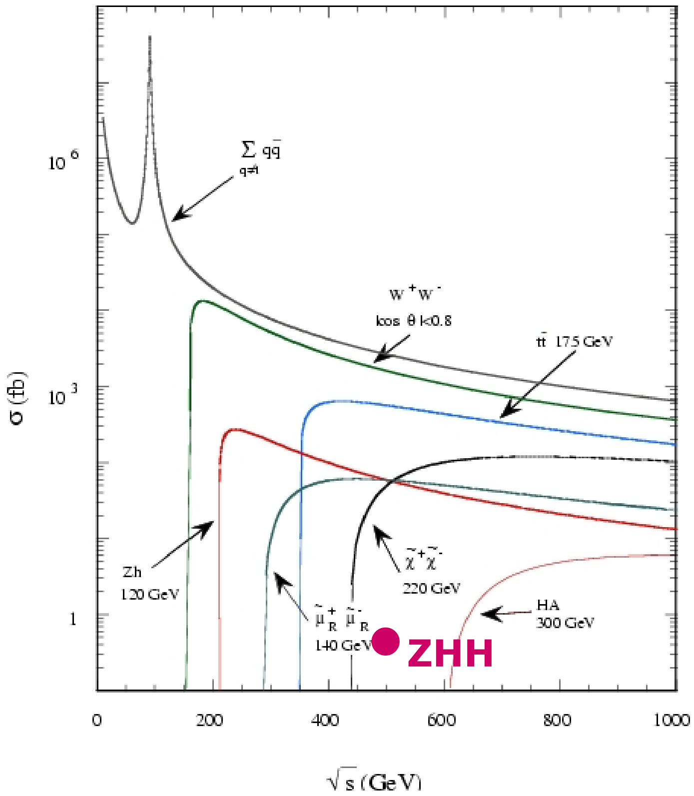
★ **At electron-positron the final state corresponds to the underlying physics interaction, e.g. above see** $\mathrm{H} \rightarrow b\bar{b}$ **and** $\mathrm{Z} \rightarrow \mu^+\mu^-$ **and nothing else…**

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

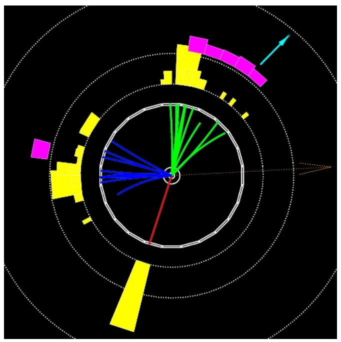
e.g. $\sigma(e^+e^-\rightarrow ZHH) = 0.3$ fb

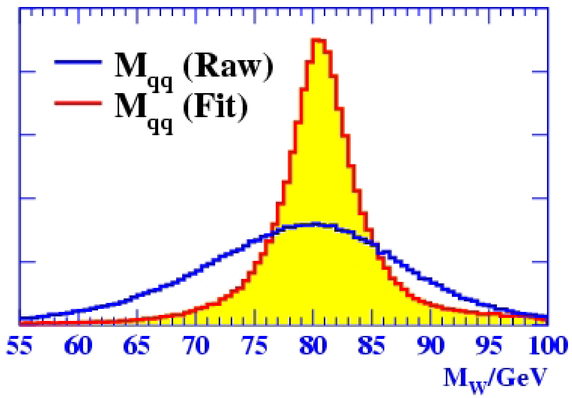
✱ Require High Luminosity – i.e. the ILC

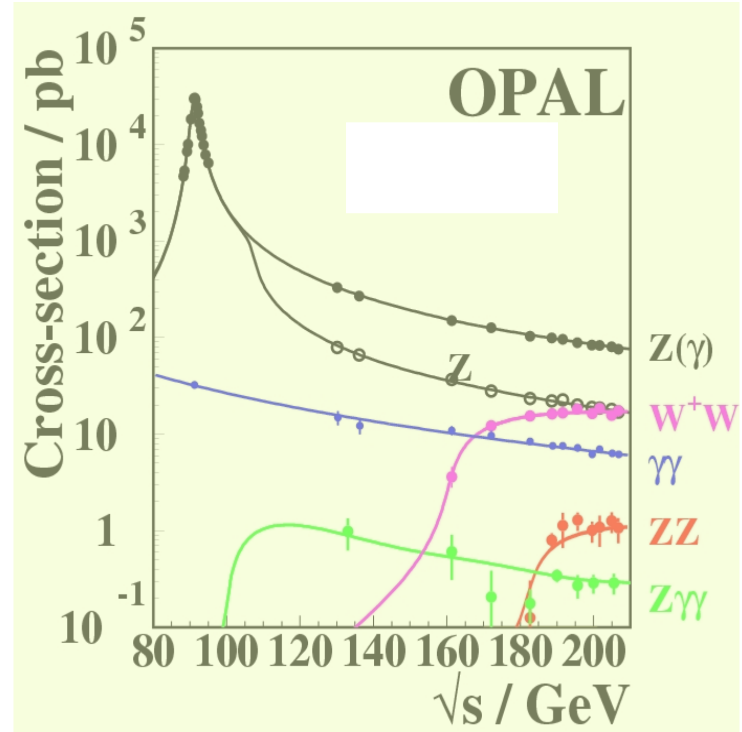
✱ Detector optimized for precision measurements in difficult multi-jet environment

Compare with LEP

- ★ $e^+e^- \rightarrow Z$ and $e^+e^- \rightarrow W^+W^-$ 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

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

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

★ So why is this important ?

Calorimetry at the ILC

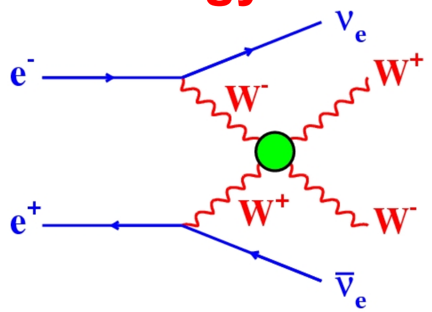
Jet energy resolution:

THIS IS HARD !

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

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

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

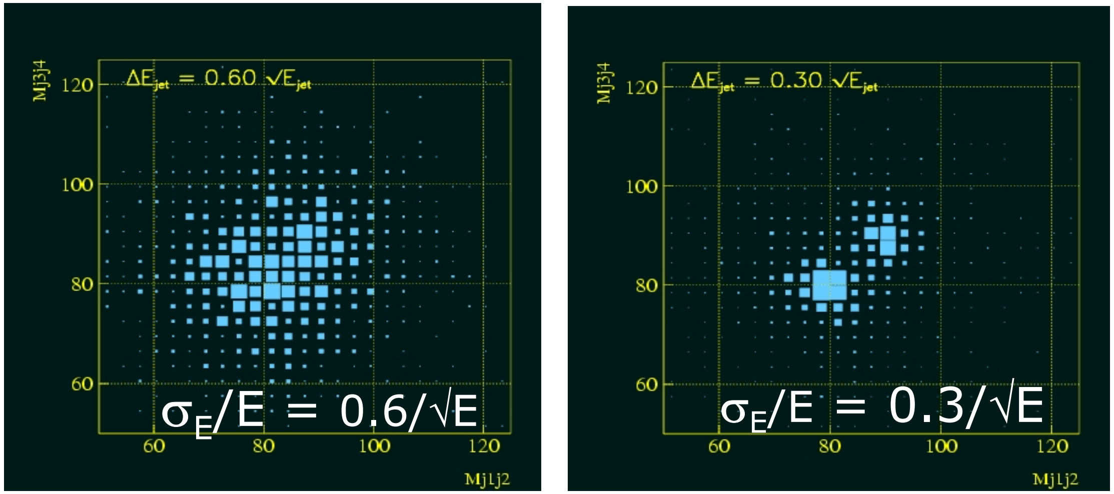


Often-quoted Example:

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

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

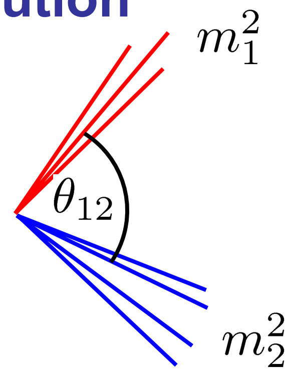
Reconstruction of two di-jet masses allows discrimination of WW and ZZ final states



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

Calorimetry Goals

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



★ For a pair of jets have:

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

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

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

⇒ $\sigma_{E_j}/E_j < 3.8\%$

+ term due to θ_{12} uncertainty

★ Assuming a single jet energy resolution of normal form

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

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

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

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

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

★Want $\sigma_E/E \sim 30\%/\sqrt{E(\text{GeV})}$

or probably more correctly $\sigma_E/E \sim 3.8\ \%$

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

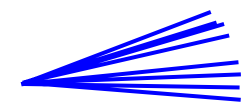
Limited by typical HCAL resolution of $> 50\%/\sqrt{E(\text{GeV})}$

⇒ a new approach to calorimetry

❸ The Particle Flow Paradigm

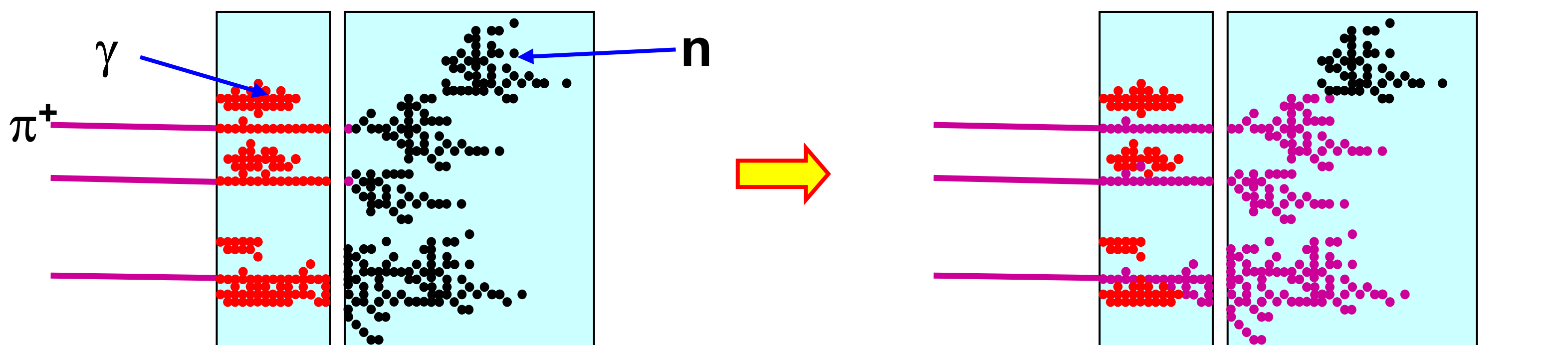
★ **In a typical jet :**

- 60 % of jet energy in charged hadrons
- 30 % in photons (mainly from $\pi^0 \to \gamma\gamma$)
- 10 % in neutral hadrons (mainly n and K_L)



★ **Traditional calorimetric approach:**

- Measure all components of jet energy in ECAL/HCAL !
- ~70 % of energy measured in HCAL: $\sigma_{\mathrm{E}}/\mathrm{E} \approx 60\,\%/\sqrt{\mathrm{E(GeV)}}$
- Intrinsically “poor” HCAL resolution limits jet energy resolution



$E_{JET} = E_{ECAL} + E_{HCAL}$ ⇒ $E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

★ **Particle Flow Calorimetry paradigm:**

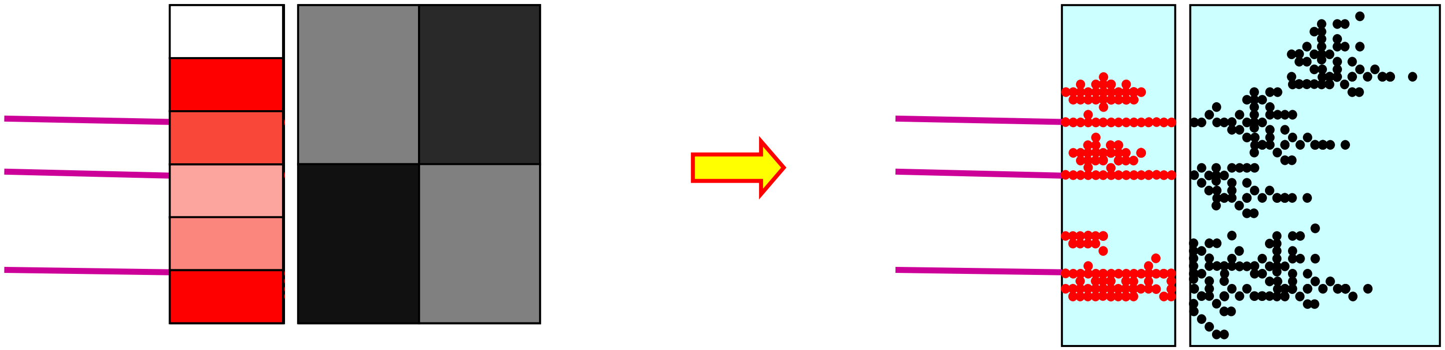
- charged particles measured in tracker (essentially perfectly)
- Photons in ECAL: $\sigma_{\mathrm{E}}/\mathrm{E} < 20\,\%/\sqrt{\mathrm{E(GeV)}}$
- Neutral hadrons (ONLY) in HCAL
- Only 10 % of jet energy from HCAL ⇒ much improved resolution

Particle Flow Calorimetry

Hardware:

★ Need to be able to resolve energy deposits from different particles

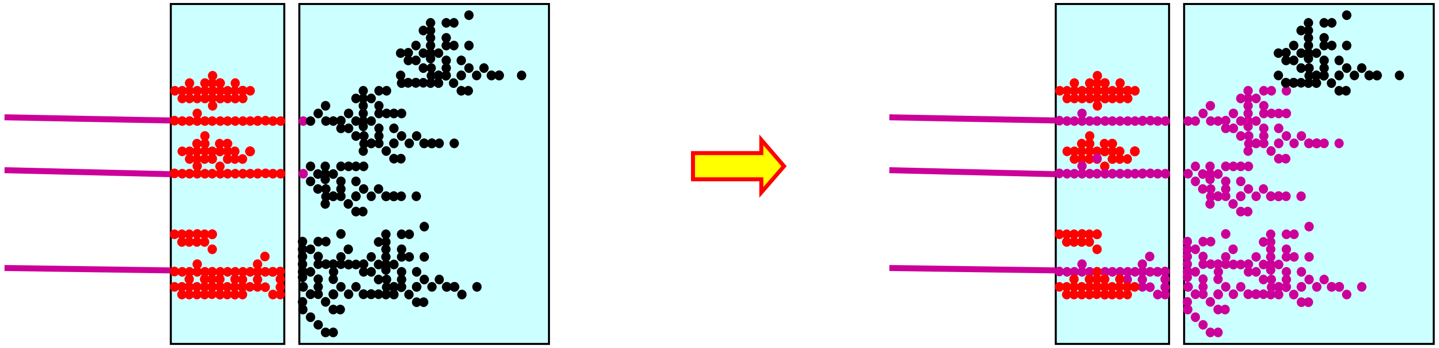
➡ Highly granular detectors (as studied in CALICE)



Software:

★ Need to be able to identify energy deposits from each individual particle !

➡ Sophisticated reconstruction software



★ **Particle Flow Calorimetry = HARDWARE + SOFTWARE**

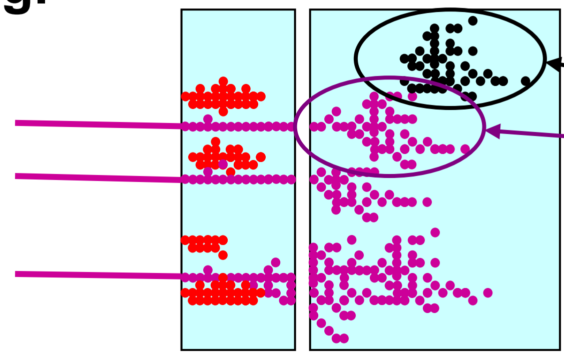
Particle Flow Reconstruction (PFA)

<u>Reconstruction of a Particle Flow Calorimeter:</u>

★ Avoid double counting of energy from same particle

★ Separate energy deposits from different particles

e.g.



<u>If these hits</u> are clustered together with <u>these</u>, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

> Level of mistakes, "confusion", determines jet energy resolution <u>not</u> the intrinsic calorimetric performance of ECAL/HCAL

sounds easy….

★ PFA performance depends on detailed reconstruction

★ Relatively new, still developing ideas (not just software)

★ Studies need to be based on a sophisticated detector simulations

❹ The ILC Detector Concepts

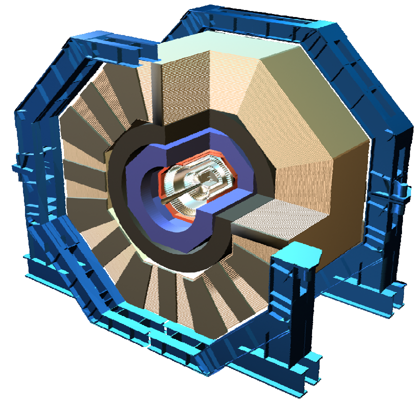
ILC Detector Concepts:

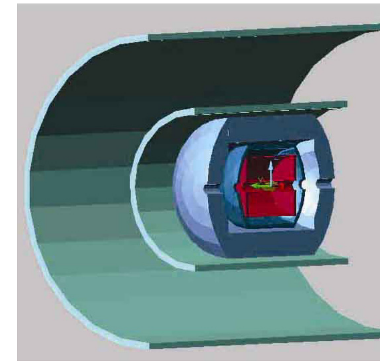
★ ILC Detector Design work centred around 3 detector "concepts"

★ Partial "technical designs" ~ 2010 ?

★ 2 main concepts "optimised" for PFA Calorimetry SiD, ILD

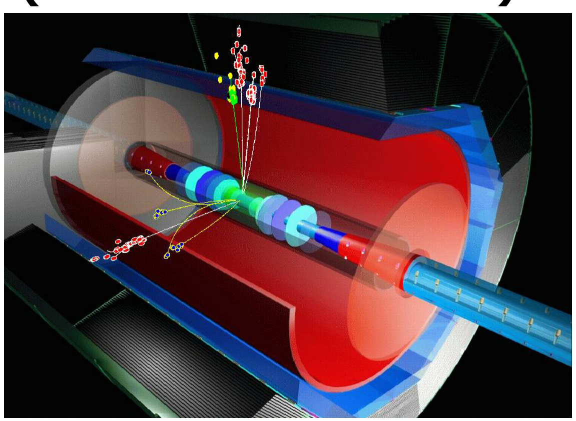
SiD : Silicon Detector **4**





ILD : International Large Detector

LDC : Large Detector Concept
(child of TESLA TDR)



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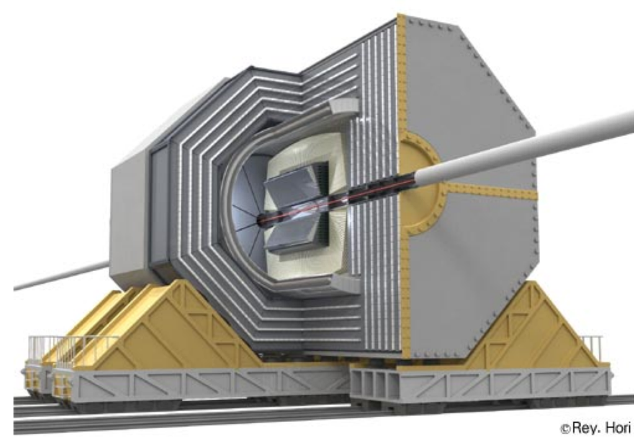
GLD : Global Large Detector

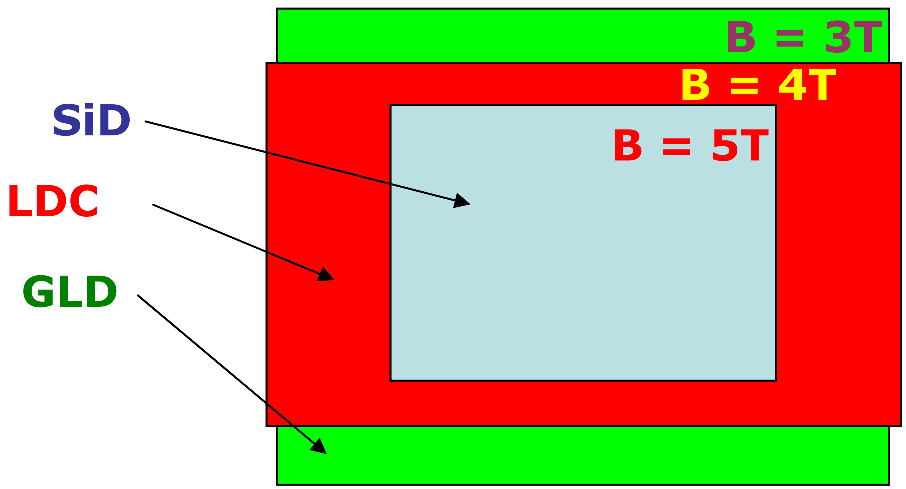


★ **Major ongoing simulation study to define baseline ILD parameters**

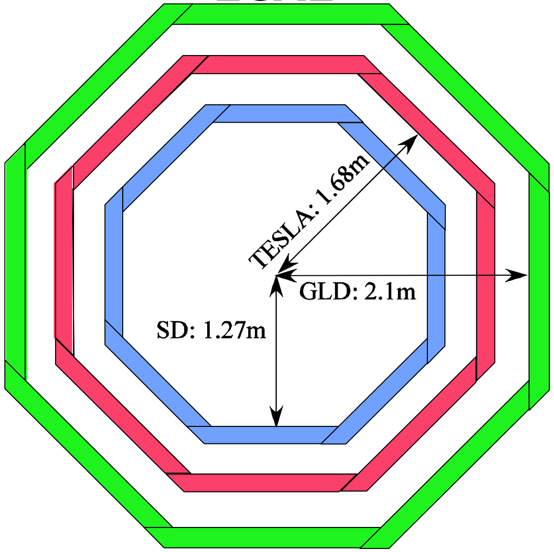
LDC/GLD/SiD

- SIZE + B-Field

Tracker



ECAL



- Central Tracker and ECAL

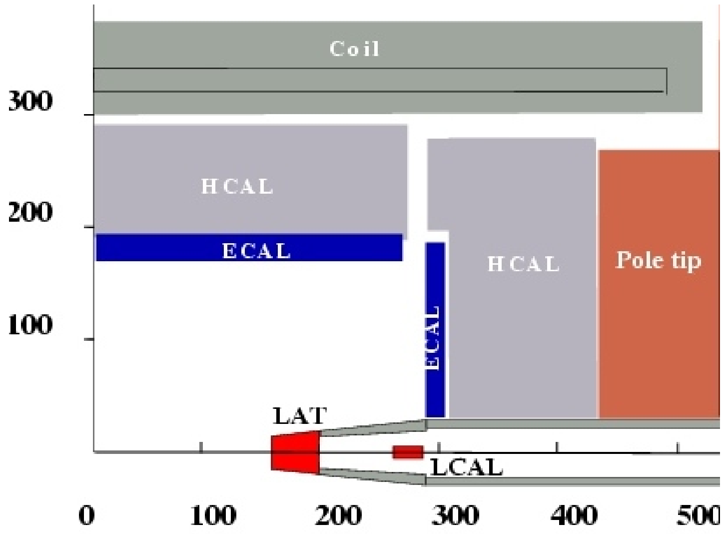
	SiD	LDC	GLD
Tracker	Silicon	TPC	TPC
ECAL	SiW	SiW	Pb/Scint

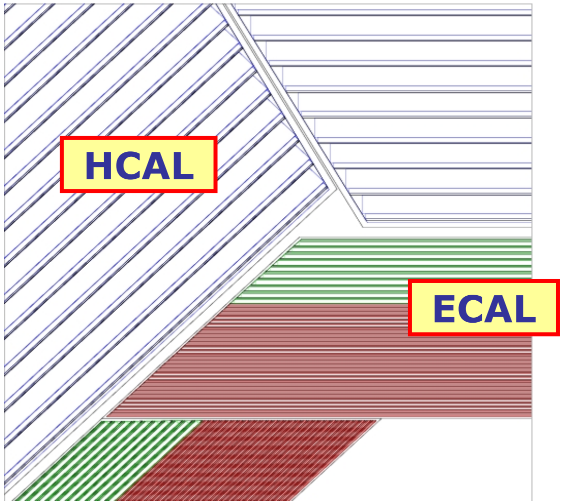
SiD + LDC + GLD all designed for PFA Calorimetry !

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

e.g. LDC/SiD Calorimetry

ECAL and HCAL inside coil





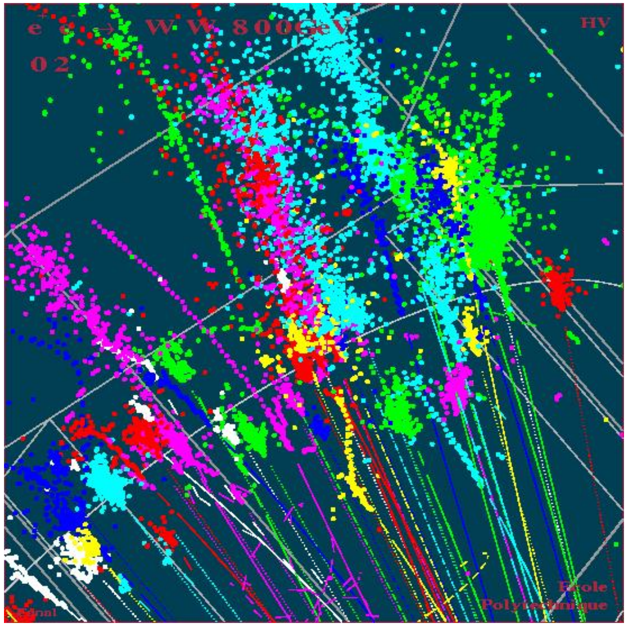
ECAL: silicon-tungsten (SiW) calorimeter:

- Tungsten : X_0 / λ_{had} = 1/25, $R_{Moliere}$ ~ 9mm
  (gaps between Tungsten increase effective $R_{Moliere}$)
- Lateral segmentation: ~1cm² matched to $R_{Moliere}$
- Longitudinal segmentation: 30 layers (24 X_0, 0.9λ_{had})
- Typical resolution: $\sigma_E/E = 0.15/\sqrt{E(\mathrm{GeV})}$

Very high longitudinal and transverse segmentation

Calorimeter Reconstruction

- ★ **High granularity calorimeters – <u>very different</u> 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 design/optimisation**

❺ PFA and ILC detector design ?

PFA plays a special role in design of an ILC Detector

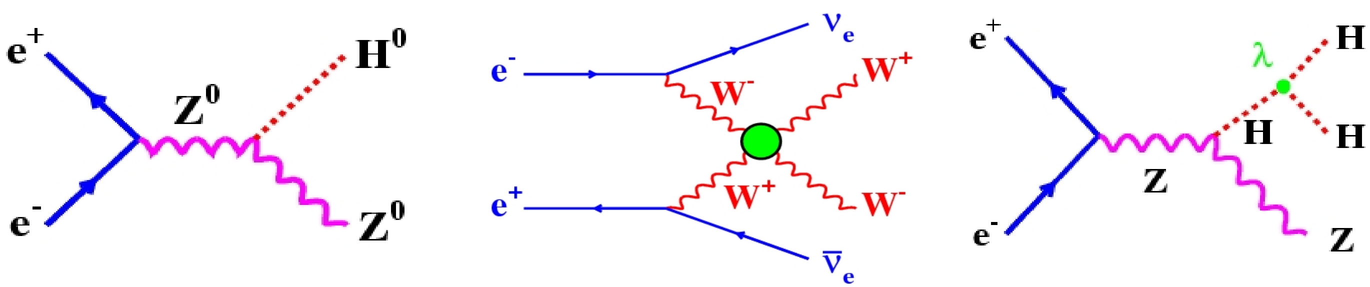
- VTX : design driven by heavy flavour tagging, machine backgrounds, technology
- Tracker : design driven by σ_p, track separation
- ECAL/HCAL : single particle σ_E not the main factor
  - ➡ jet energy resolution ! Impact on particle flow drives calorimeter design + detector size, B field, …

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

BUT: Nobody really knows 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)

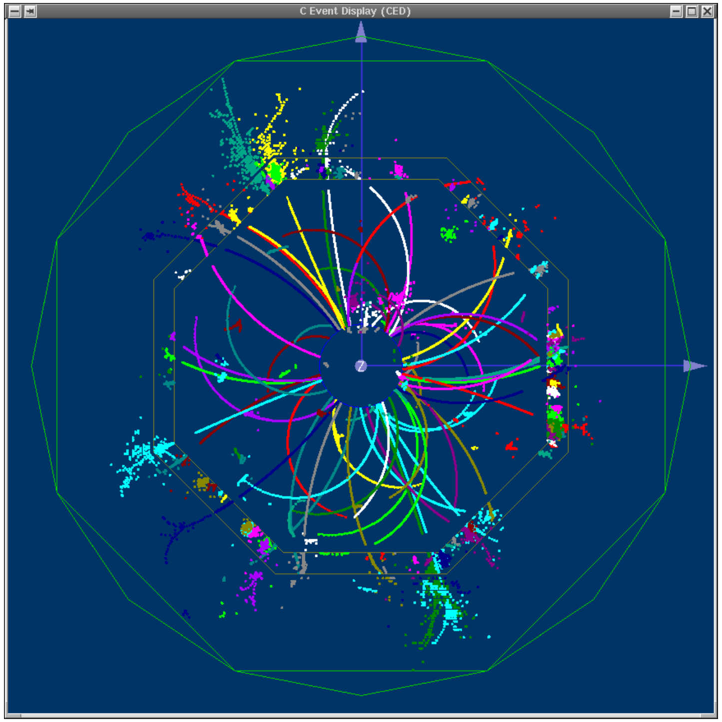


The rest is VERY DIFFICULT !

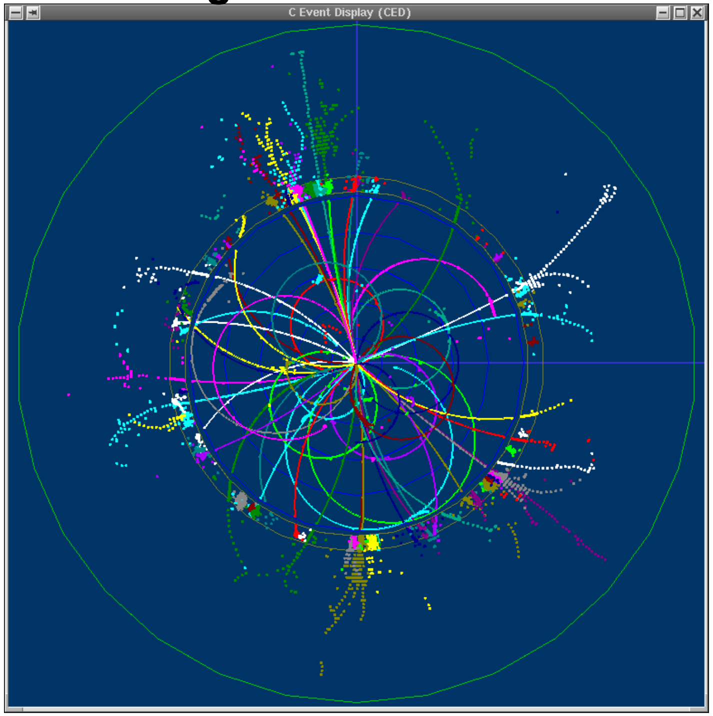
For example:

★ 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 realistic reconstruction chain

~10 years before start of ILC !!!

(ideally before start of LHC)

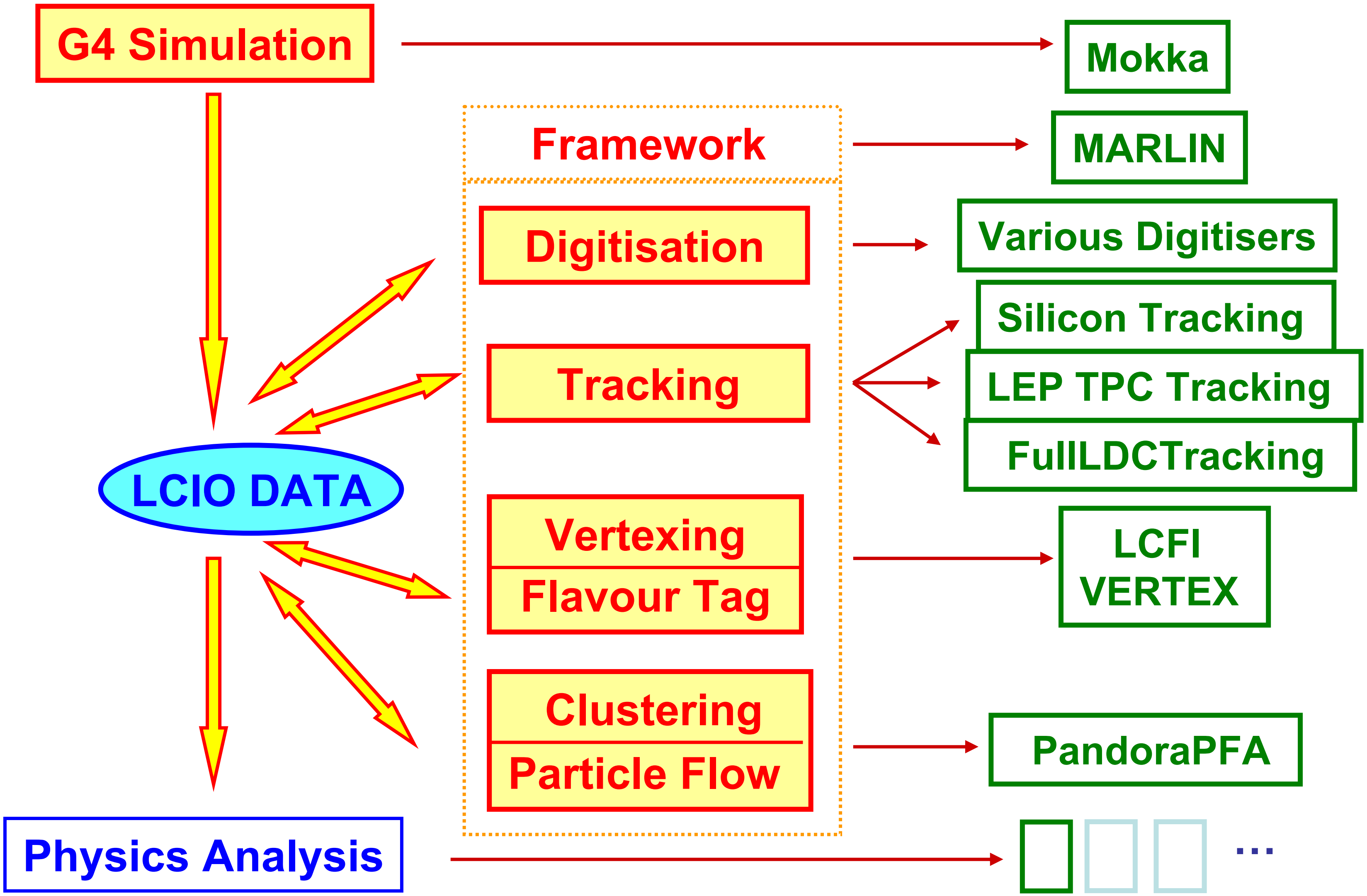
(even more challenging: the software has to work for multiple detector design parameters)

We already have a first version….

(many vital contributions from DESY)

Reconstruction Framework (C++)

★ Everything exists – level of sophistication ~LEP experiment



❻ PandoraPFA

- 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 (~4 groups developing PFA reconstruction worldwide)

For this talk concentrate on: PandoraPFA

- This is still work-in-Progress – currently it gives the best performance
- 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 : 10^4 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. Photon Identification/Recovery
vii. Fragment removal
viii. Formation of final Particle Flow Objects (reconstructed particles)

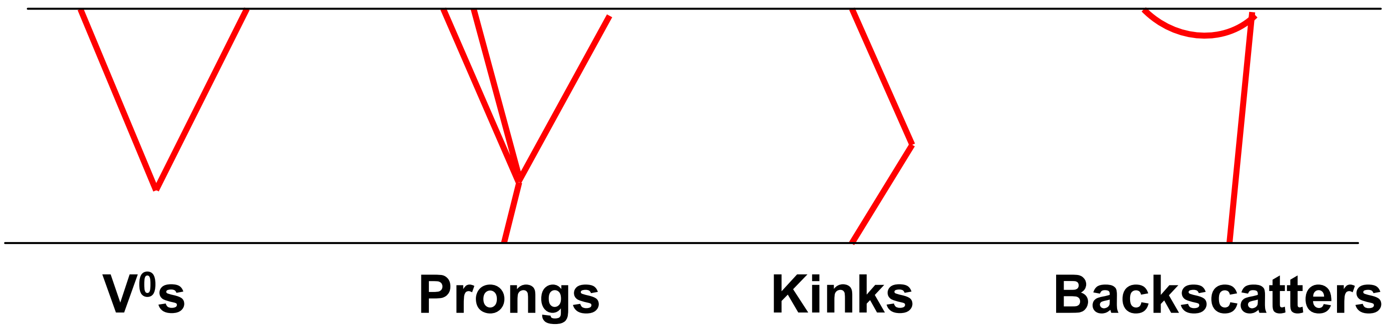
i) Tracking

★ The use of optimal use of tracking information in PFA is essential
★ Non trivial for looping tracks (even in a TPC)
★ Matching of tracks to endcap clusters is non-trivial
★ Use of track information is a major part of PandoraPFA
★ Big effort to use as many tracks in the event as possible
- helps particularly for lower energy jets
- motivation I : better energy resolution
- motivation II : correct measurement of direction

★ **TPC-oriented:** take advantage of pattern recognition capability

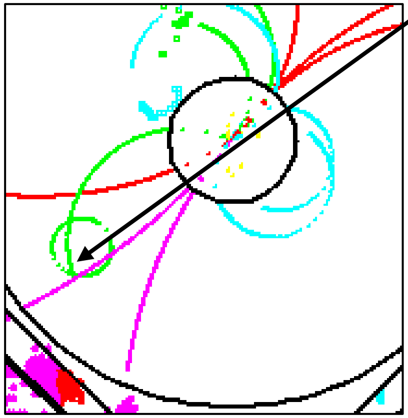
(the algorithm would need modification for Si tracker)

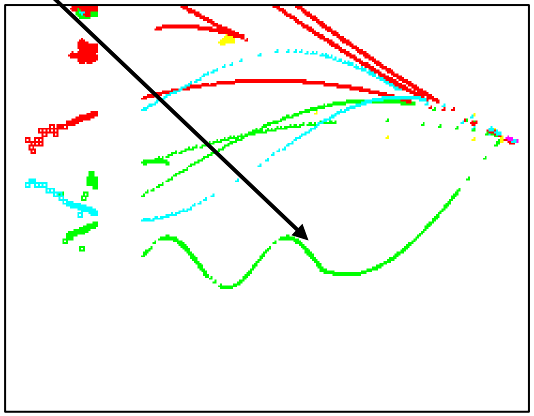
★ From fully reconstructed LDC tracks identify:



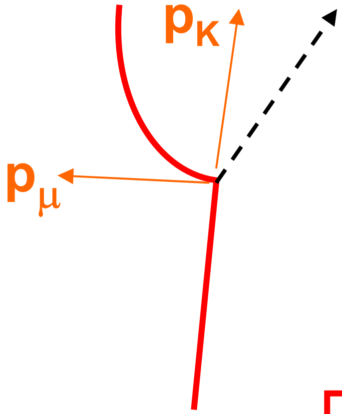
e.g. Kinks

- ★ **Kink finding extends to "loopers"**





- ★ **Can give a measure of missing energy**

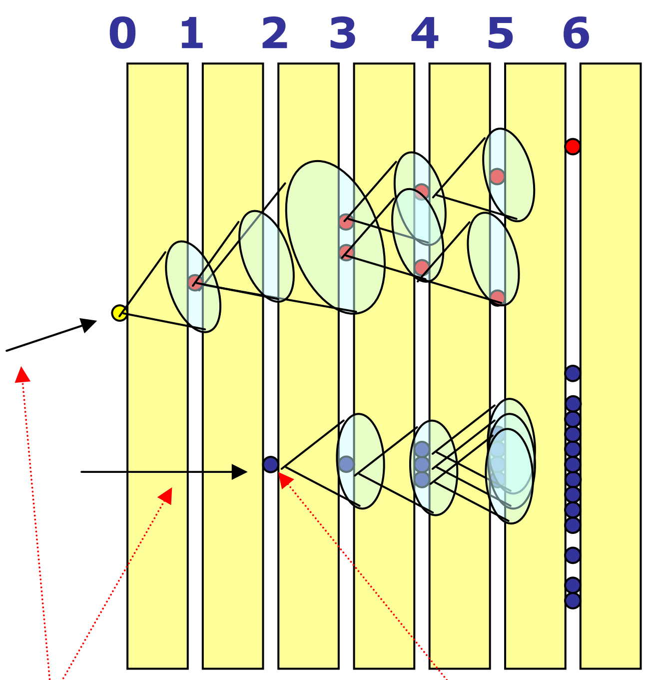


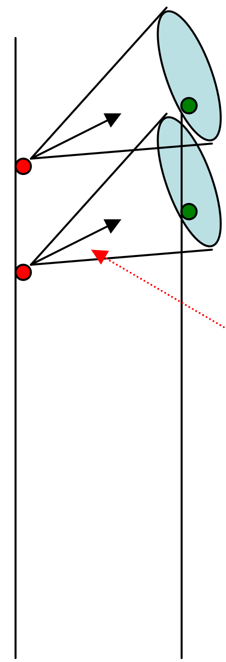
- **Consider physics hypothesis, e.g. $K^\pm \rightarrow \mu^\pm \nu$**
- **Use Helix fits to start and end of tracks to reconstruct missing particle e.g. ν**
- **Can then reconstruct primary mass**
- **If consistent with hypothesis, e.g. m_K use primary track for PFO four-momentum**

PandoraPFA reconstructs (some) neutrinos !

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

Initial cluster direction

Unmatched hits seeds new cluster

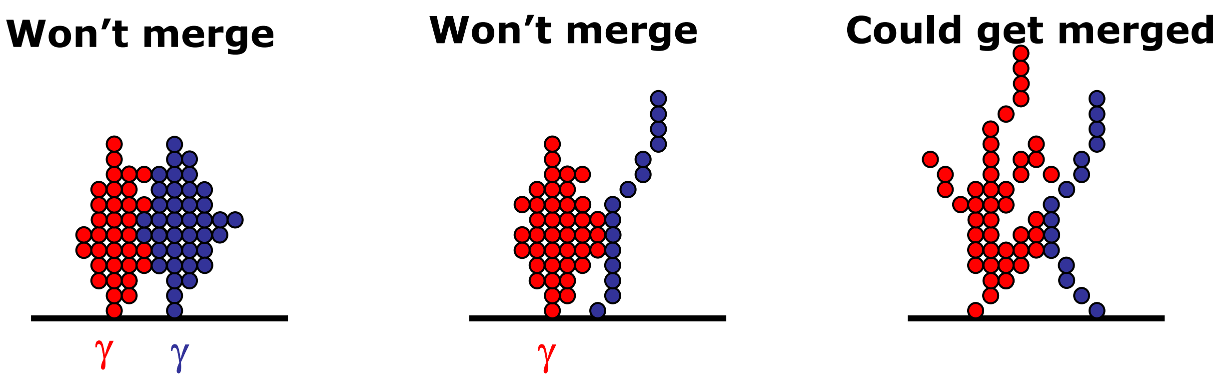
Parameters:
- cone angle
- additional pixels

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

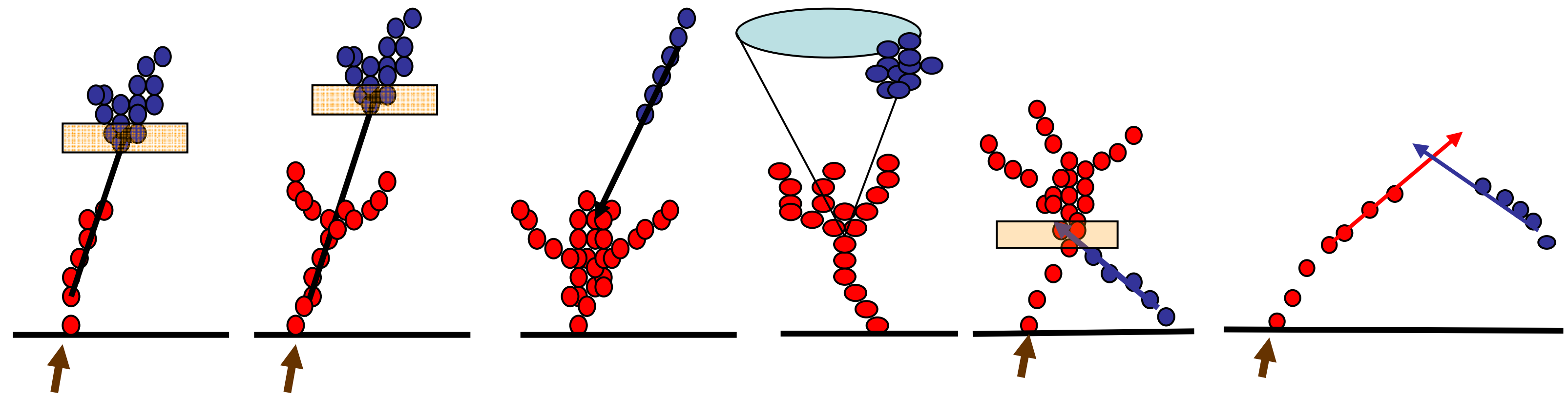
- Photon ID plays important role
- Simple "cut-based" photon ID applied to all clusters
- Clusters tagged as photons are immune from association procedure – just left alone



★ **Clusters associated using a number of topological rules**

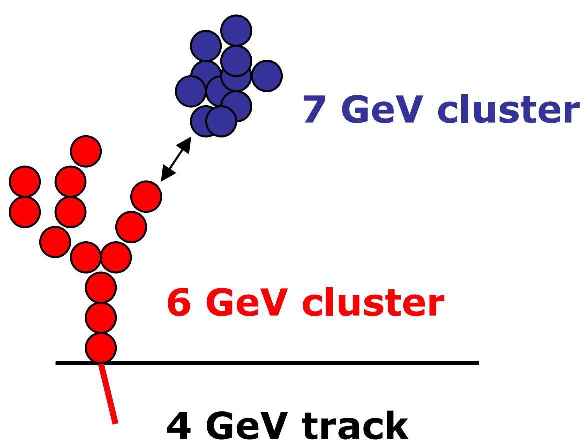
Clear Associations:

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



Less clear associations:

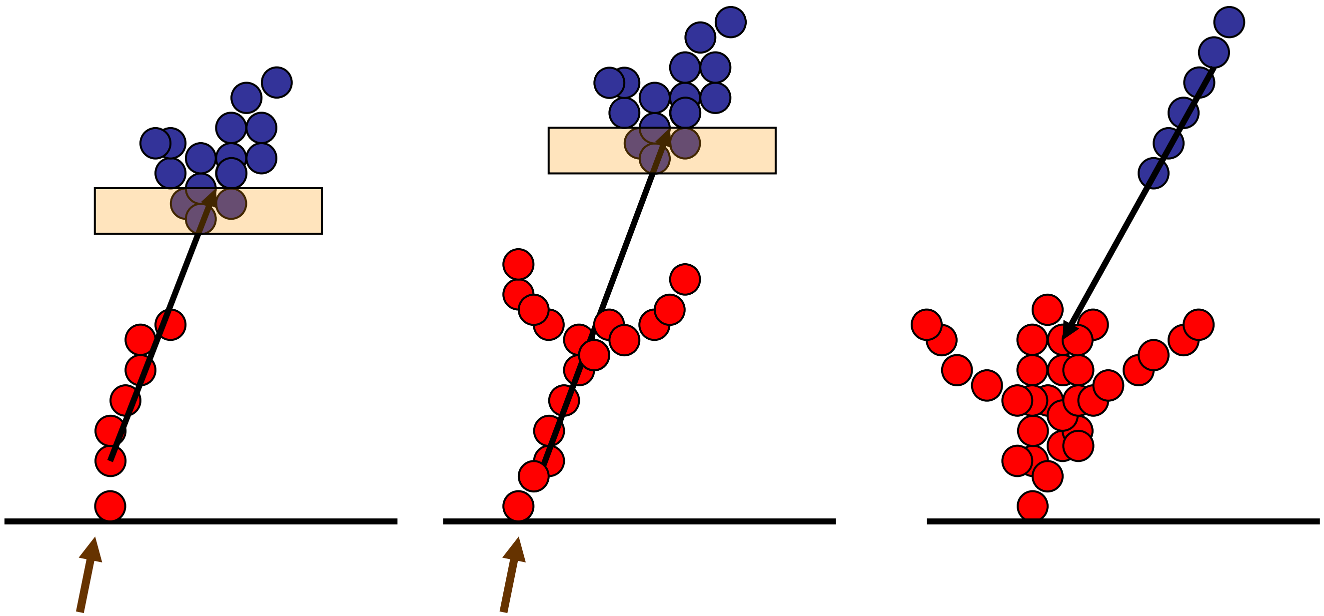
e.g. Proximity



Use E/p consistency to veto clear mistakes

Example : 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)

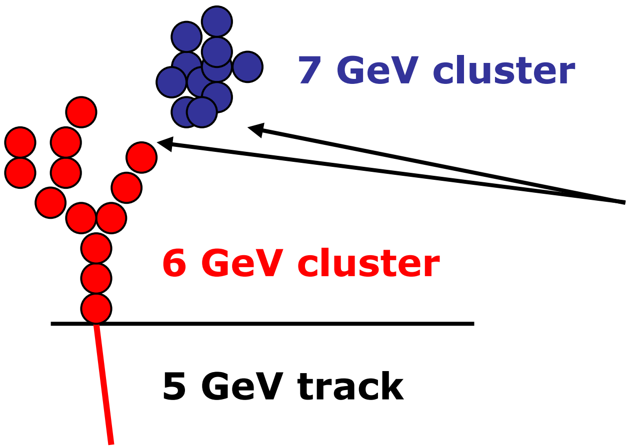


★Apply tight matching criteria on basis of projected track [NB: + track quality i.e. chi2]

★Here, association based on "tracking" in calorimeters

iv) Cluster Association Part II

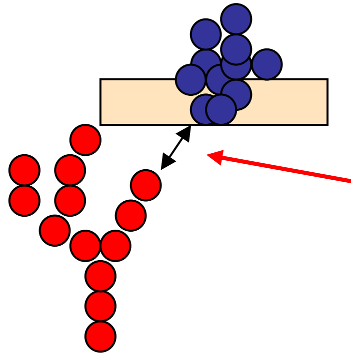
- Have made very clear cluster associations
- Now try "cruder" association strategies
- **BUT** first associate tracks to clusters (temporary association)
- Use track/cluster energies to "veto" associations, e.g.



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

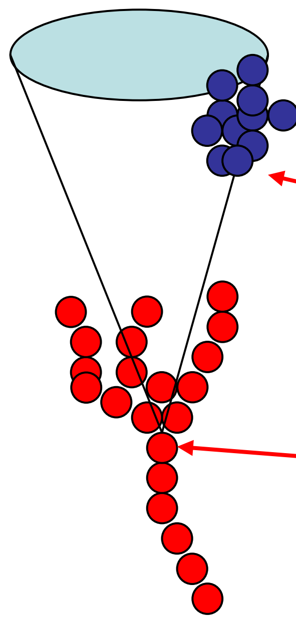
Provides some protection against obvious mistakes

Proximity



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

Shower Cone



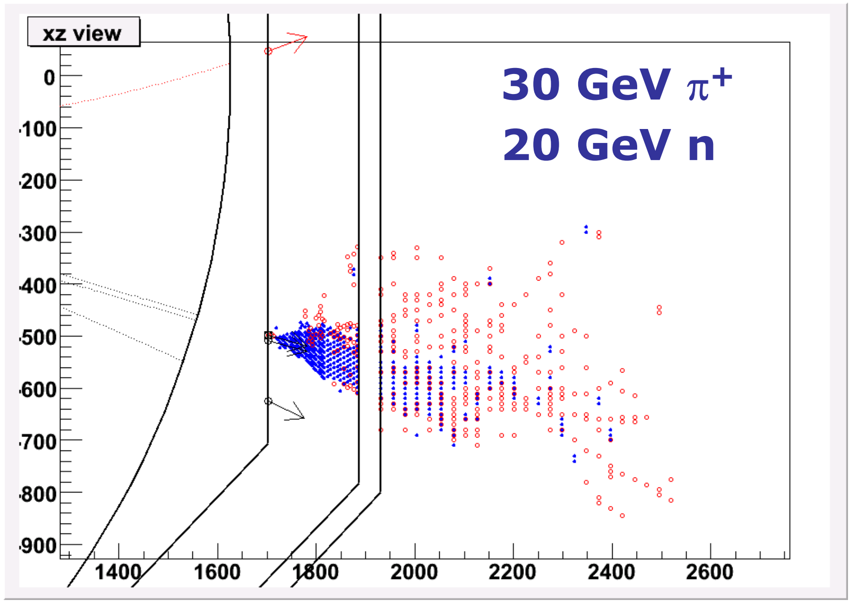
Associated if fraction of hits in cone > some value

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

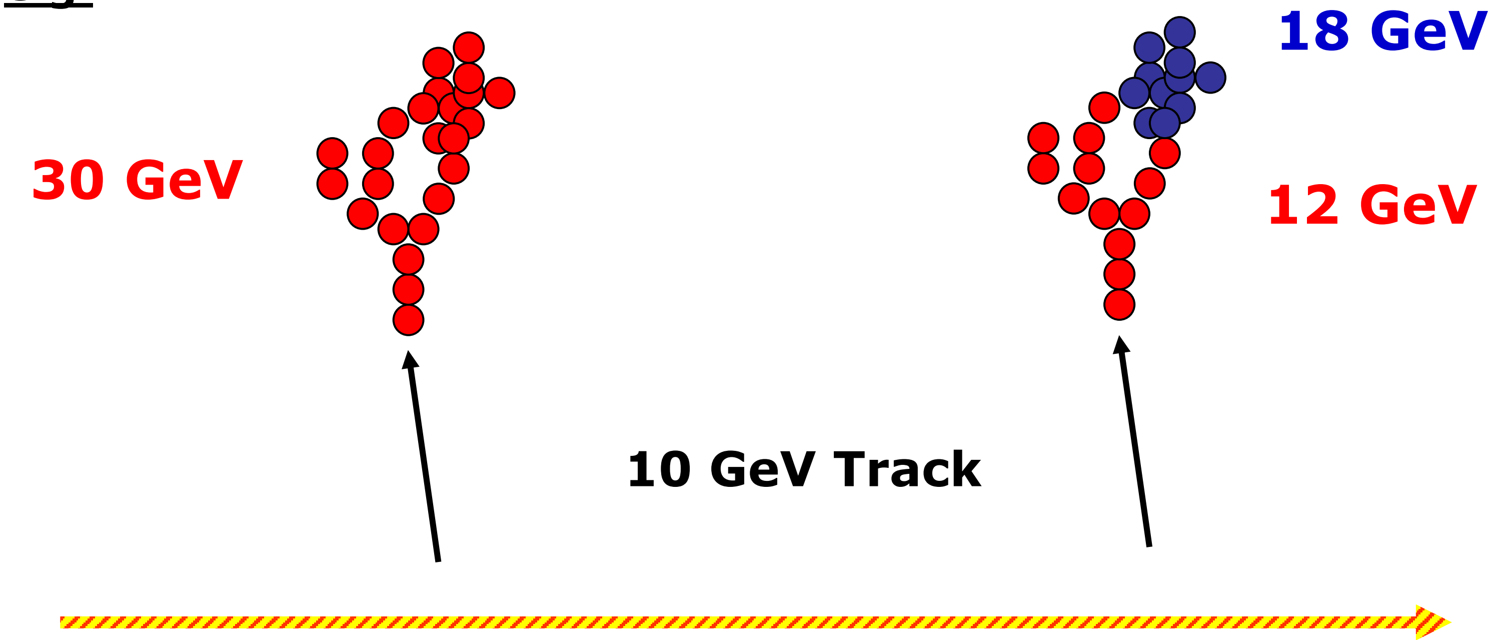
The ONLY(?) way to address this is "statistically"

→

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

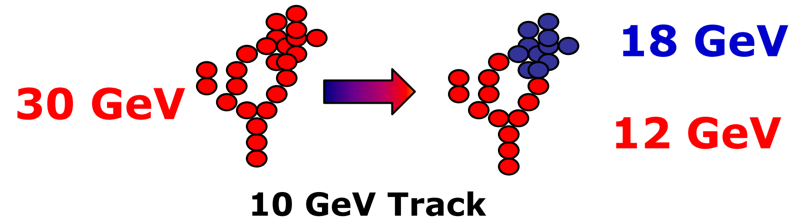
NOTE: NOT FULL PFA as clustering driven by track momentum

This is very important for higher energy jets

Iterative Reclustering Strategies

① Cluster splitting

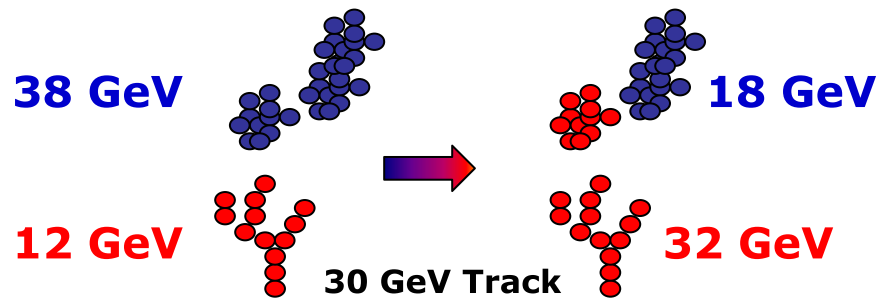
Reapply entire clustering algorithm to hits in "dubious" cluster. Iteratively reduce cone angle until cluster splits to give acceptable energy match to track



★ + plug in alternative clustering algorithms

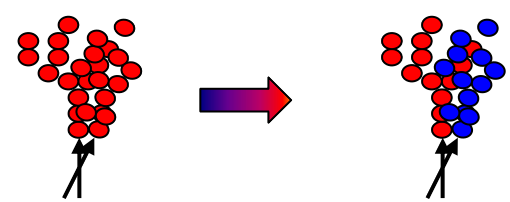
② Cluster merging with splitting

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"

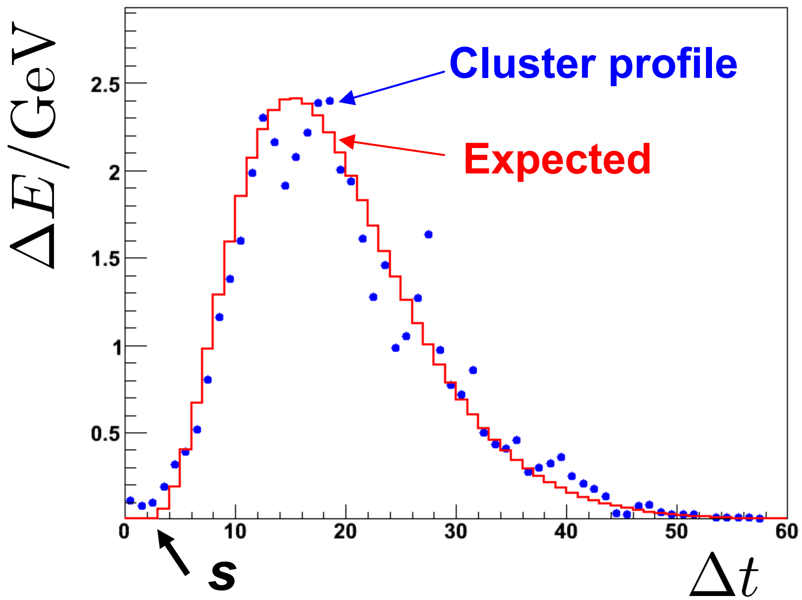
★ **If none of above works – kill track and rely on clusters alone**

vi) Photon ID/Recovery

- ★ Use simple cut-based photon ID in the early (CPU intensive) stages of PandoraPFA
- ★ In the final stages, use improved photon ID based on the expected EM longitudinal profile for cluster energy E_0

$$\Delta E = E_0 \frac{(t/2)^{a-1} e^{-t/2}}{\Gamma(a)} \Delta t \qquad a = 1.25 + \tfrac{1}{2} \ln E_0/E_c$$

- ★ Convert cluster into energy depositions per radiation length
  (use cluster to determine the layer spacing, i.e. geometry indep.)



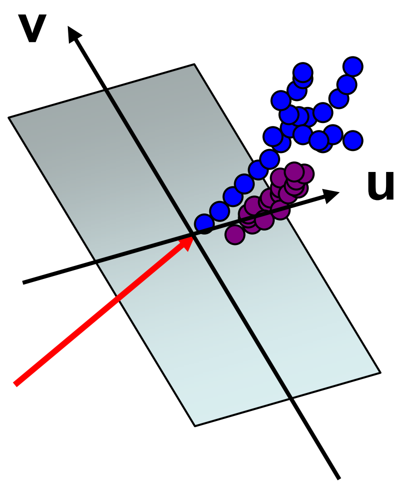
- Shower Profile fixed by cluster energy
- But fit for best shower start, ***s***
- Normalise areas to unity and calc.

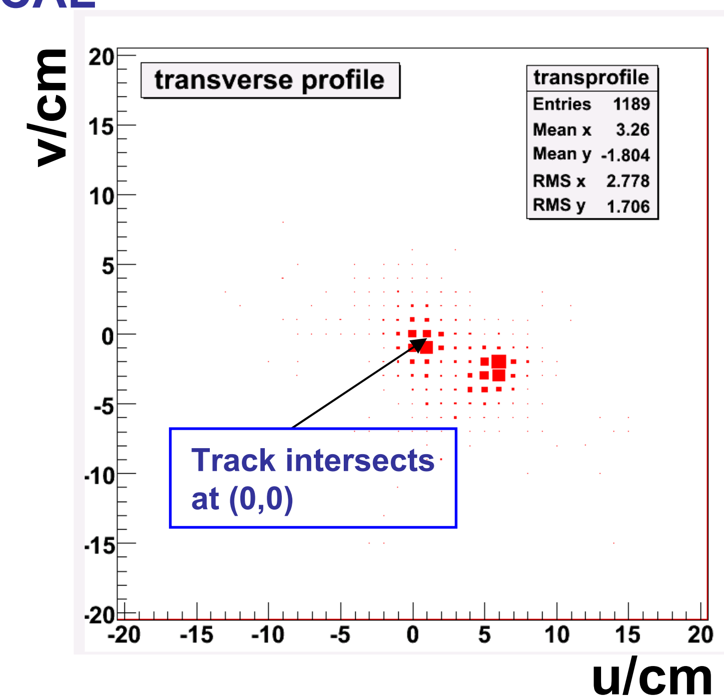
$$f = \sum_i |o_i - e_i|$$

- Gives a measure of fractional
- disagreement in obs/exp profiles
- Use ***f*** and ***s*** to ID photons

Photon Recovery

- ★ With cone clustering algorithm, photons close to early showering charged hadrons can be merged into a single cluster.
- ★ Use longitudinal + transverse profile to recover these
- ★ Essentially, for each cluster associated with a track:
  - project ECAL hits onto plane perpendicular to radial vector to point where track intersects ECAL
  - search for peaks…



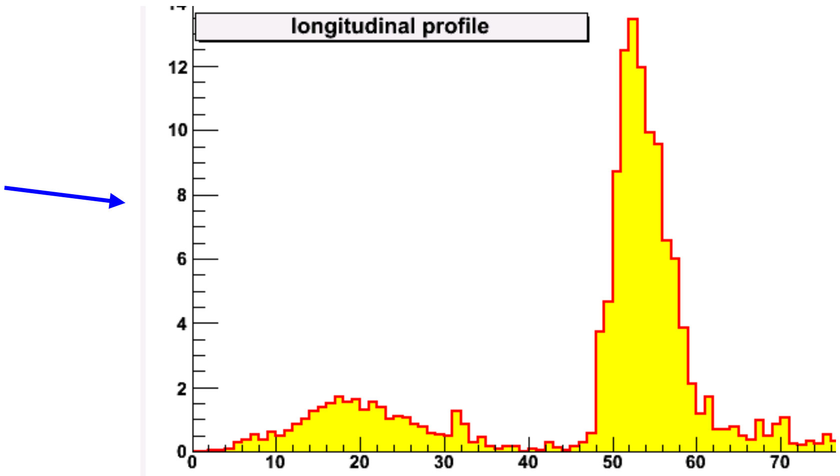


- ★ If there is an isolated peak not associated with "track peak" make new photon cluster if track energy and remaining cluster energy still statistically compatible with track momentum + cluster passes photonID

Use profiles to "dig out" photons overlapping with hadronic clusters:

- Also look for photons where only a single peak is found

- Implemented by looking at longitudinal profile of "shower"

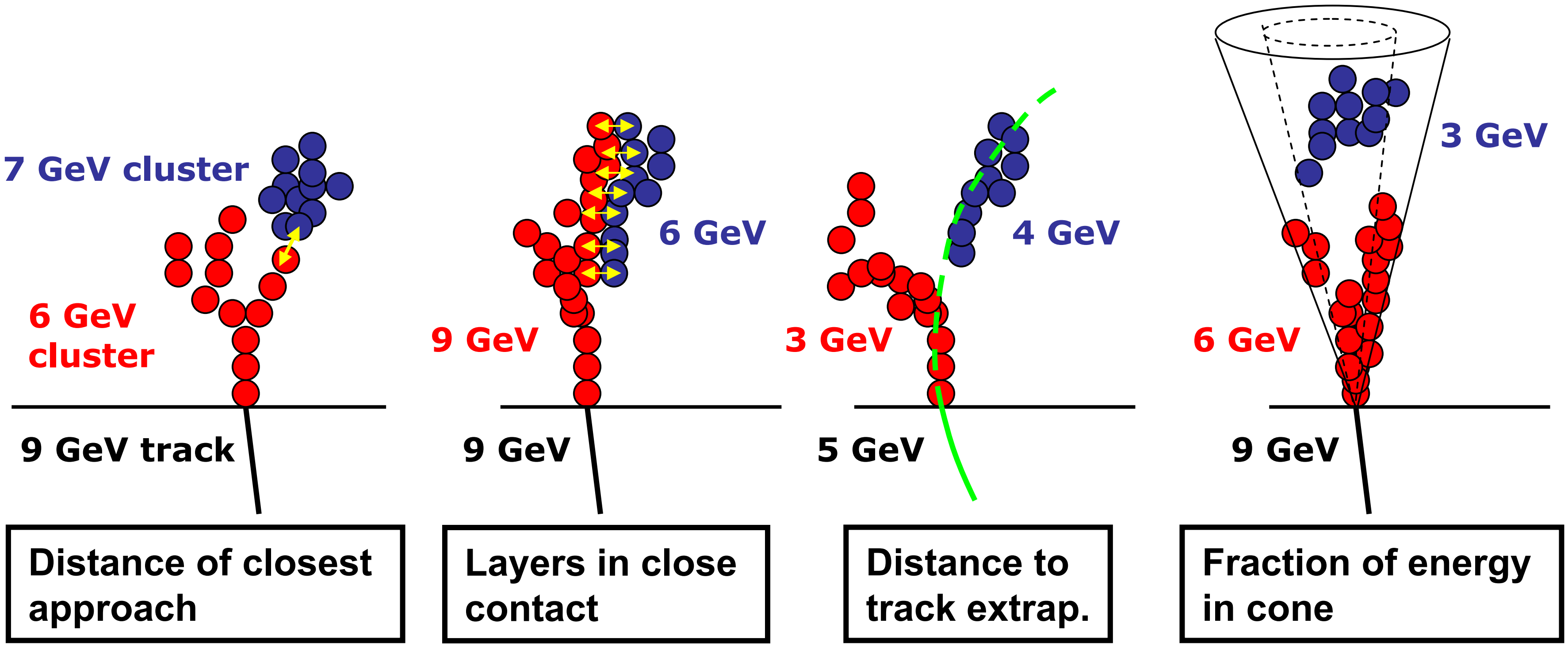


Only allowed if it results in acceptable track-cluster energy consistency…

NOTE: in PandoraPFA, photon identification is an "iterative", rather than one-off process: different levels of sophistication applied at different stages of algorithm

viii) Fragment removal : basic idea

★ Look for "evidence" that a cluster is associated with another



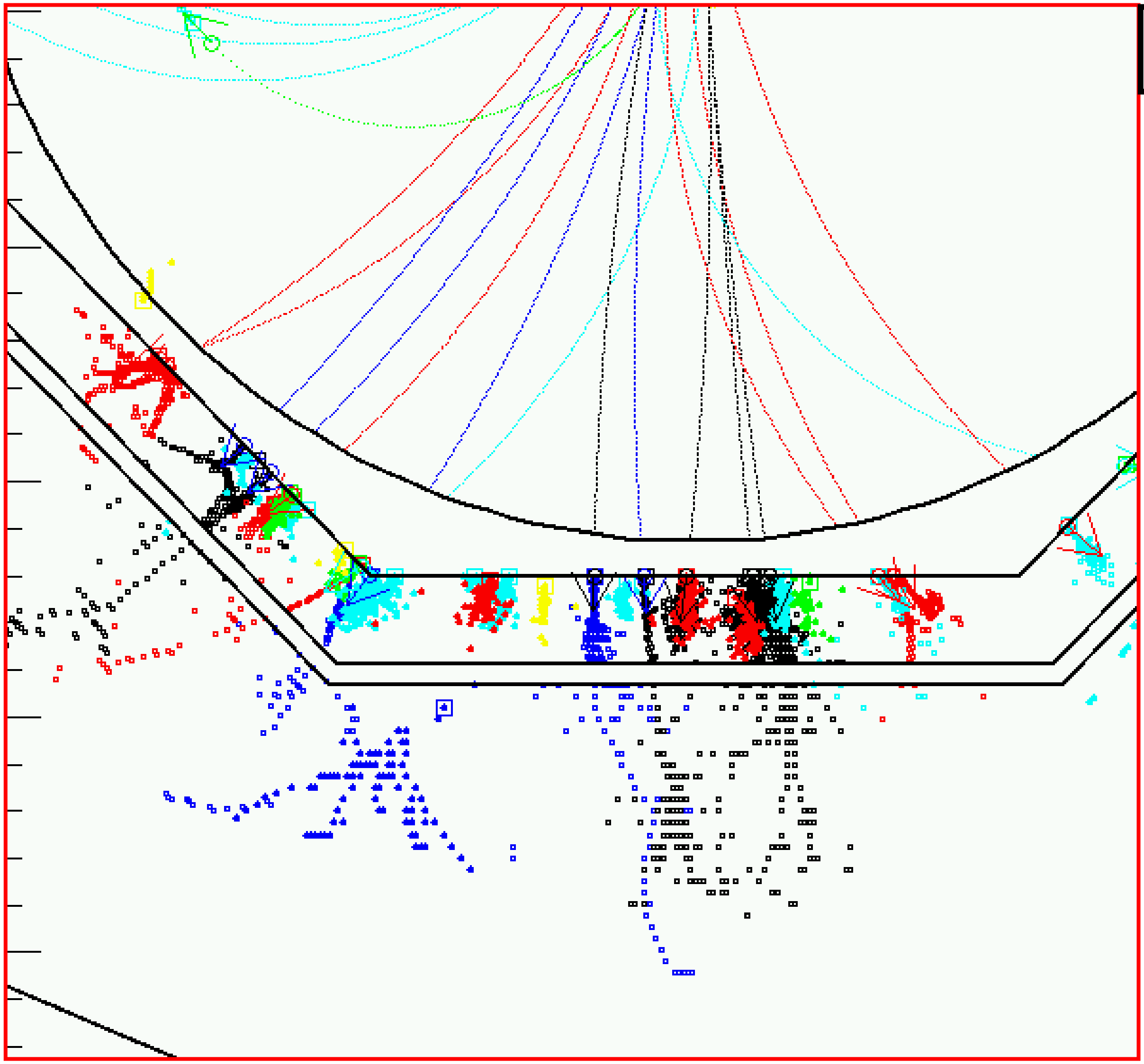
★ Convert to a numerical evidence score **E**

★ Compare to another score "required evidence" for matching, **R**, based on change in E/p chi-squared, location in ECAL/HCAL etc.

★ If **E > R** then clusters are merged

★ Rather *ad hoc* but works well – but works well

Putting it all together…



100 GeV Jet

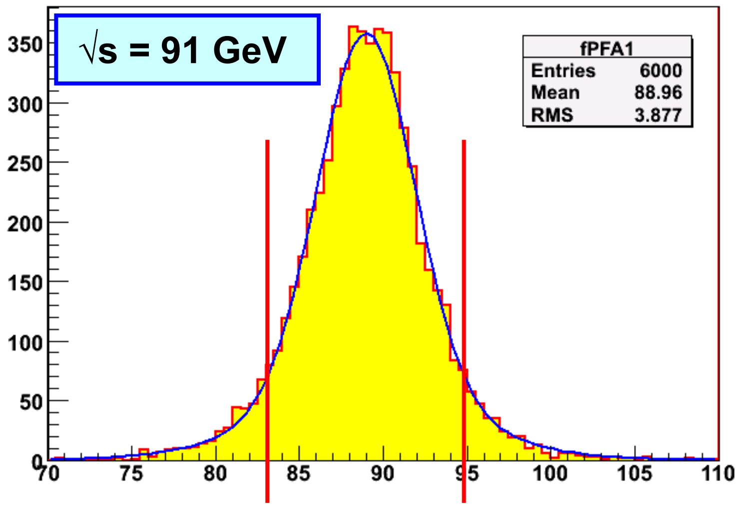
❼ Performance / Detector Studies

Figures of Merit:

rms_{90}

★ Find smallest region containing **90 %** of events

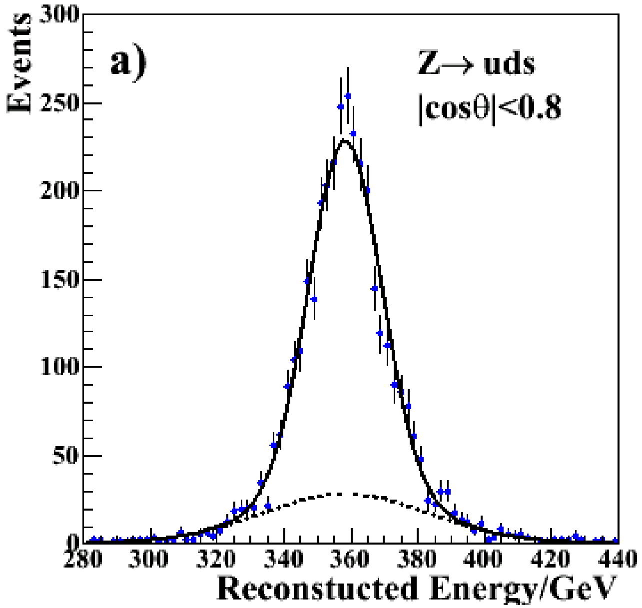
★ Determine rms in this region



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 $rms_{90} \approx \sigma_{75}$

Performance (LDC00)

rms90 PandoraPFA v02-01

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E_j
45 GeV	0.235	3.5 %
100 GeV	0.306	3.1 %
180 GeV	0.427	3.2 %
250 GeV	0.565	3.6 %

NOTE: studies based on ILD detector concept are "work-in-progress"

- Tesla TDR detector model
- Full simulation
- Full reconstruction

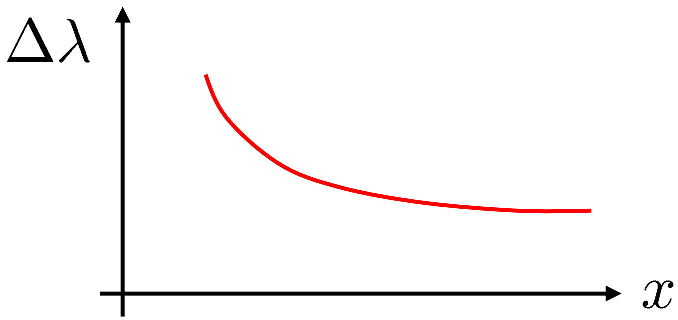
In simulation

★ Particle flow can achieve ILC goal of $\sigma_E/E_j < 3.8\ \%$
★ For lower energy jets Particle Flow gives unprecedented levels of performance, e.g. @ 45 GeV : 3.5% c.f. ~10% (ALEPH)
★ "Calorimetric" performance (α) degrades for higher energy jets
★ + current code is not perfect - can do better

PARTICLE FLOW CALORIMETRY WORKS !

Detector Optimisation : How ?

- ★ Optimise detector based on physics performance vs cost
- ★ First step is to parameterise physics performance vs **R**, **B**, **L**, …



Probably won't see (m)any minima !

- ★ Then fold in cost to motivate baseline ILD design

BUT: non-trivial:

- ★ PFA reconstruction is complex
- ★ Tracking plays a major role in own right and in PFA reconstruction
- ★ Flavour tagging essential to many physics studies

Beware: short-cuts…

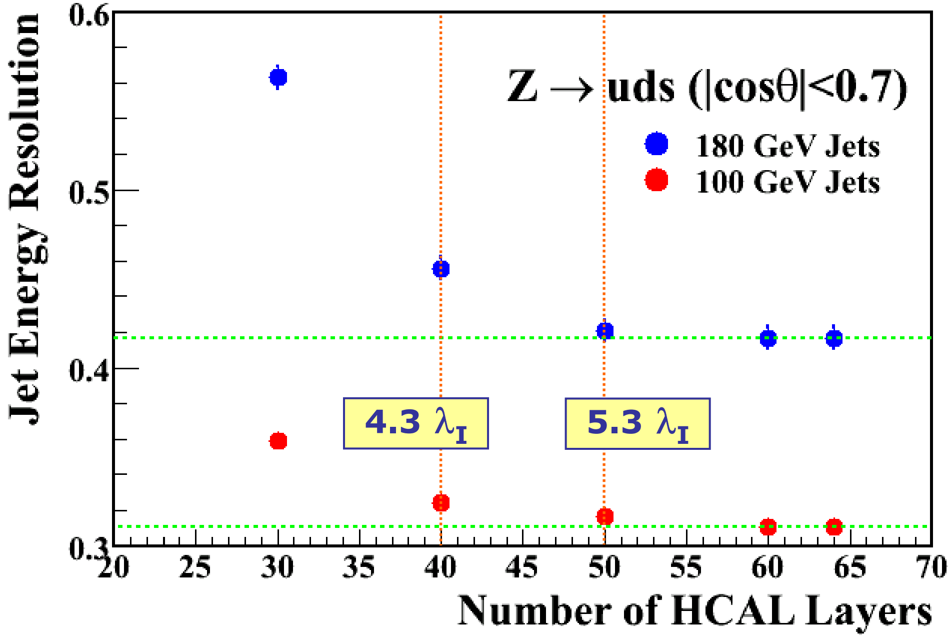
> **Solid** study of ILC detector performance/optimisation **requires** a full detector simulation and REALISTIC reconstruction

Beware: software…

> Interpretation: observing effects of detector + imperfect software

e.g. 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

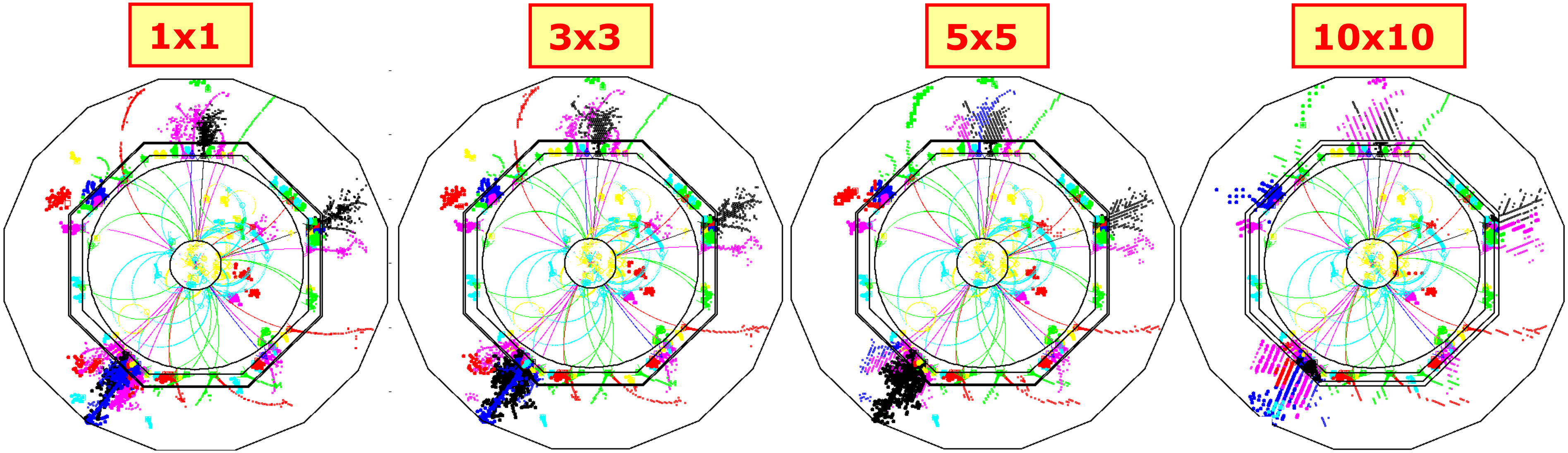


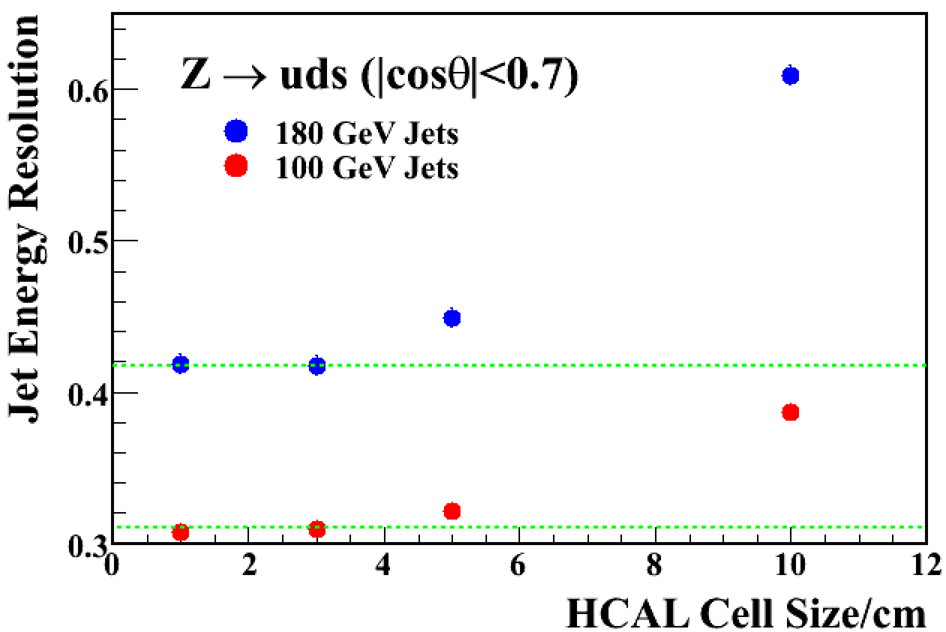
♦ HCAL leakage is significant for high energy

♦ Argues for ~ **5 λ_I HCAL**

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

e.g. change HCAL tile size 1x1 → 10x10 mm^2

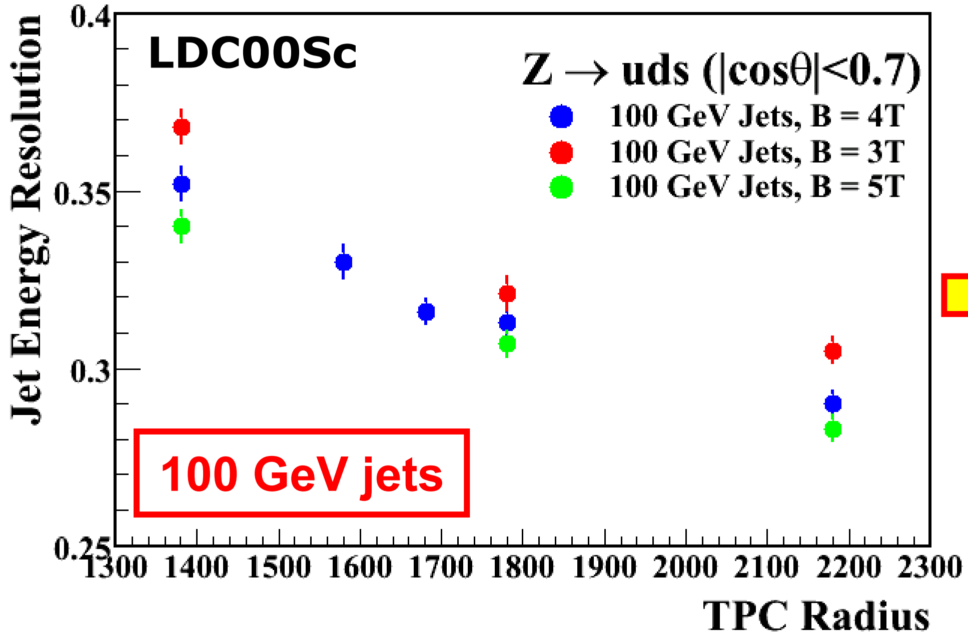




"Preliminary Conclusions"

- 3x3 cm^2 cell size
- No advantage → 1x1 cm^2
  - physics ?
  - algorithm artefact ?
- 5x5 cm^2 degrades PFA
  - Does not exclude coarser granularity deep in HCAL

Radius vs Field



Radius more important than B-field

- ✶ Starting to obtain necessary input to optimise detector design from point of view of Particle Flow Calorimetry
- ✶ Need to extend to physics sensitivity
- ✶ Need to match this with detector cost model
- ✶ In very near future should have a much better idea of the parameters of a cost-performance optimized ILC detector

❽ Random Comments

Deficiencies:

★ PandoraPFA has evolved solely with the aim of improving performance … never overly concerned with niceties…

★ Very little has been optimised:
- Photon ID – good be better
- Photon Recovery – crude
- Fragment Removal – very crude

} Plenty of room for improvement

Why does PandoraPFA work reasonably well ?

★ PFA = much more than clustering
- basic clustering algorithm developed in about a week shortly after Snowmass – essentially unchanged

★ Lessons learnt in developing code:
- advantages in having a single "coherent" approach
- always concentrated on optimising jet E performance, not photonID efficiencies etc.
- extreme care with all stages – avoid unnecessary mistakes
- great care needed in track/cluster matching
- use of track momentum – cluster energy to spot to PFA errors absolutely vital
- PFA reconstruction is an iterative process, use more sophisticated techniques as knowledge of event improves

The Downside

★ PandoraPFA evolved; only initial aspects designed (necessary as didn't know approach when starting out)
★ Consequently PandoraPFA is
- Large ~15000 lines of (partially commented) C++
- Not particularly transparent
- Increasingly difficult to maintain/develop
- Probably slower than necessary

BUT IT WORKS

The Future ?

★ Now have a much better idea of the general approach
★ Could contemplate "starting from scratch"
- Improved structure (i.e. some)
- Improved interfaces, e.g. clustering, to allow easier development of alternative algorithms
- Increase "expert" base for future development

★ BUT would require significant effort
★ Would be helped validation through comparison to existing code
★ Worth the effort…?

❾ Conclusions

- ★ Great deal of effort (worldwide) in the design of the ILC detectors
- ★ Centred around 3 "detector concept" groups: ILD (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

PFA IS HARD – BUT POTENTIALLY 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 have reached the ILC "goal" (for Z →uds events)
- ★ More importantly, getting close to being able to address real issues:
  - ⊙ What is optimal PFA detector size/B-field, etc.

FINAL COMMENT:

- ★ GLD, LDC, SiD calorimetry "designed" for PFA
  - ★ Needed to demonstrate this actually makes sense
    - ▪ until relatively recently not completely proven !
- ★ Now try and understand ultimate reach of PFA calorimetry

The End