Particle Flow Calorimetry

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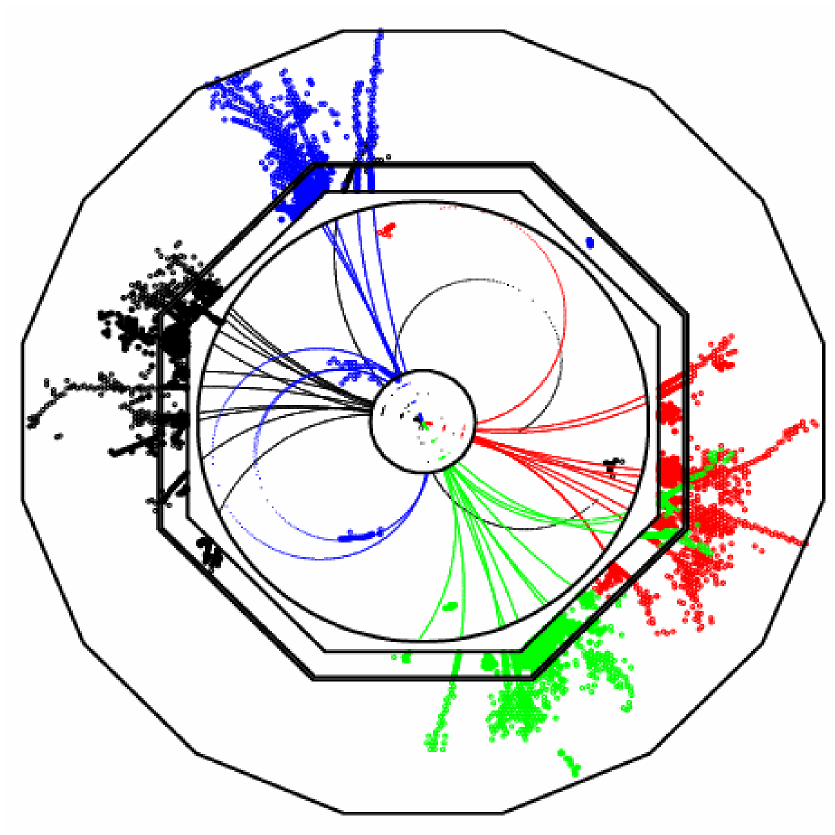


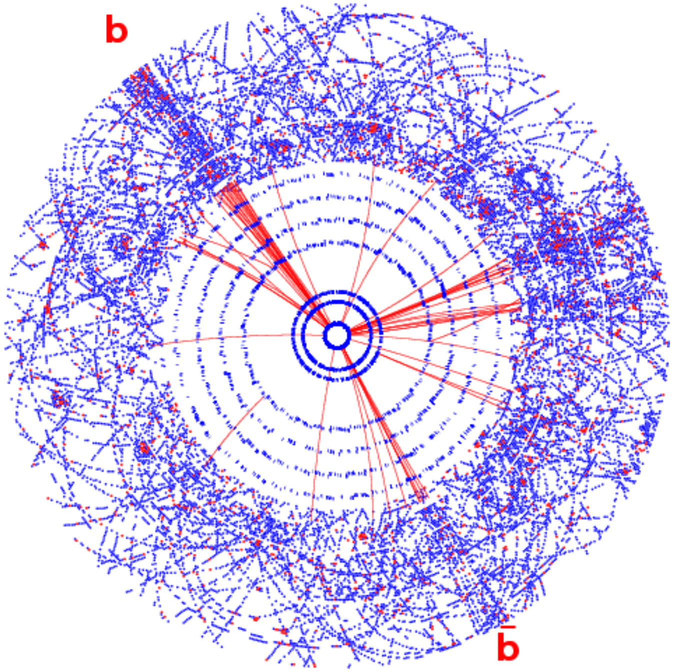
These two lectures:

❶ e^+e^- Collider Physics ↔ Calorimetry
❷ The Particle Flow Paradigm
❸ The ILD Concept
❹ ILC Software
❺ PandoraPFA
❻ Understanding Particle Flow
❼ How to design a PFlow detector
❽ Potential at CLiC
❾ Conclusions

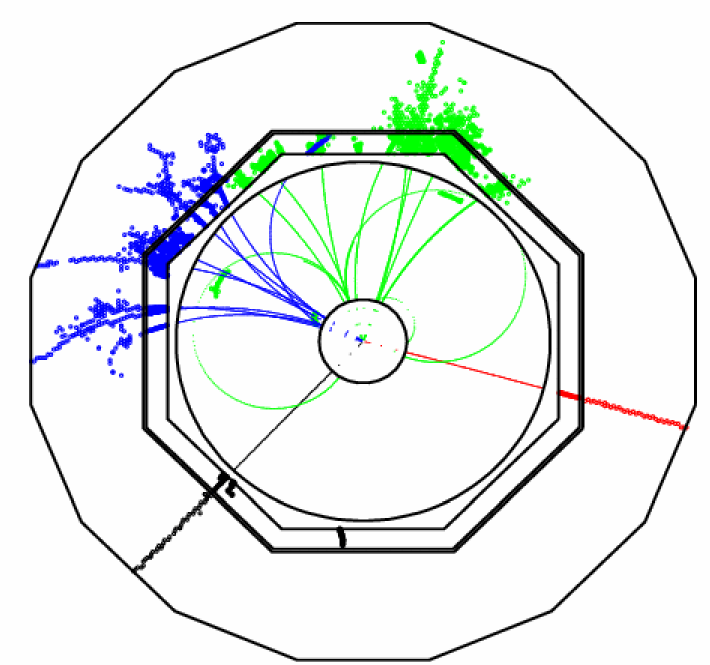
❶ e^+e^- Physics ↔ Calorimetry

★ Electron-positron colliders provide clean environment for precision physics

The LHC $pp \rightarrow H + X$



The ILC $e^+e^- \rightarrow HZ$



★ A detector at a future lepton collider (ILC/CLiC) will be designed to take full advantage of this clean environment

★ Very different detector design requirements c.f. LHC

e.g. ILC Physics

ILC PHYSICS:

Precision Studies/Measurements

★ Higgs sector

★ SUSY particle spectrum (if there)

★ SM particles (e.g. W-boson, top)

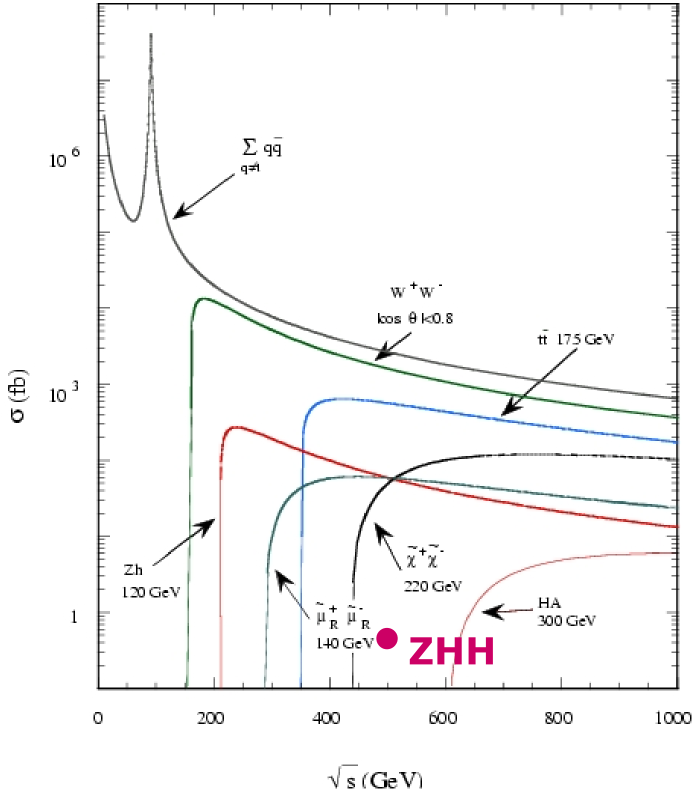
★ and much more...

Physics characterised by:

★ High Multiplicity final states
often 6/8 jets

★ Small cross-sections, e.g.

$$\sigma(e^+e^- \rightarrow ZHH) = 0.3\,\mathrm{fb}$$



✸ **Require High Luminosity – i.e. the ILC/CLiC**

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

Compare with LEP

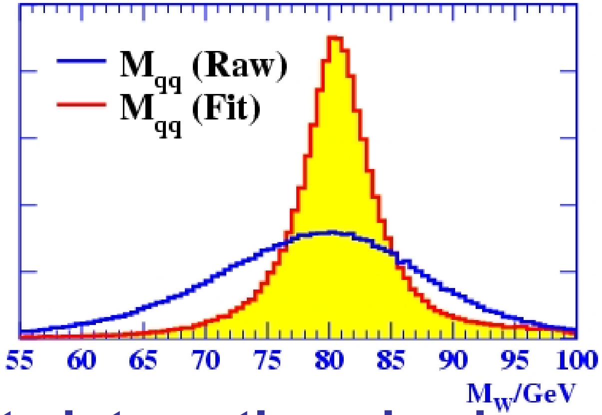
At LEP:

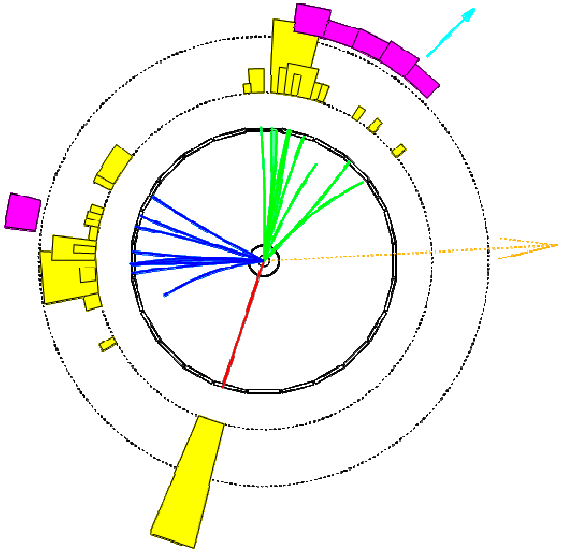
- ★ Signal dominates: $e^+e^- \to Z$ and $e^+e^- \to W^+W^-$
  backgrounds not too problematic
- ★ Even for W mass measurement, **jet energy resolution not too important**

Kinematic Fits

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

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





At the ILC:

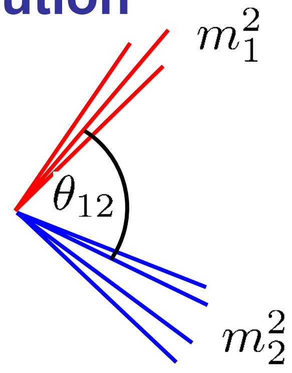
- ★ Backgrounds dominate interesting physics
- ★ Kinematic fitting much less useful: Beamsstrahlung + many final states with > 1 neutrino

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

ILC 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 $\Gamma_{\mathrm{W/Z}}$

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

⇒ $$\boxed{\sigma_{E_j}/E_j < 3.8\%}$$

+ term due to θ_{12} uncertainty

- ★ Assuming a single jet energy resolution with normal stochastic term

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

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

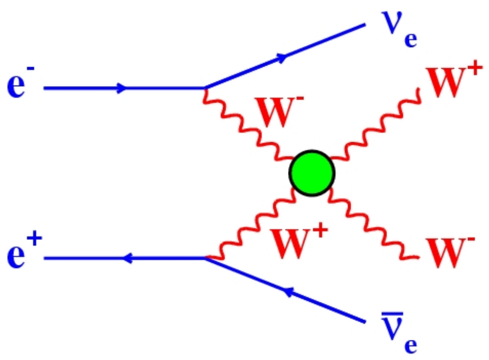
⇒ $$\boxed{\alpha(E_j) < 0.027\sqrt{E_{jj}(\mathrm{GeV})}}$$

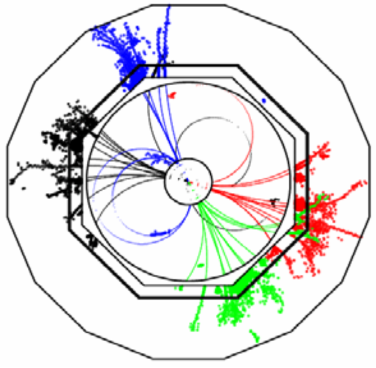
E_{jj}/GeV	$\alpha(E_{jj})$
100	< 27 %
200	< 38 %

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

Why is this important ?

- ★ **Direct impact on physics sensitivity, e.g. "WW-scattering"**

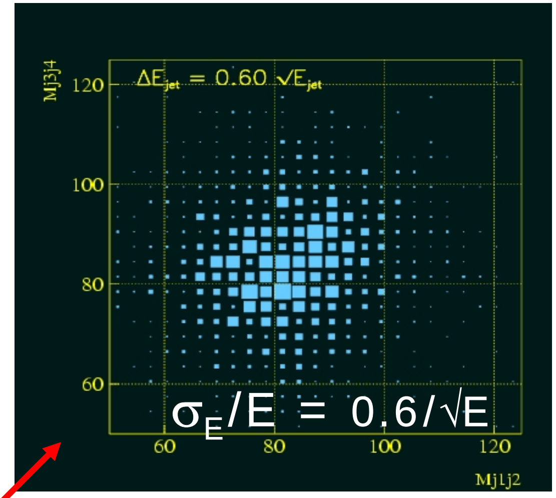


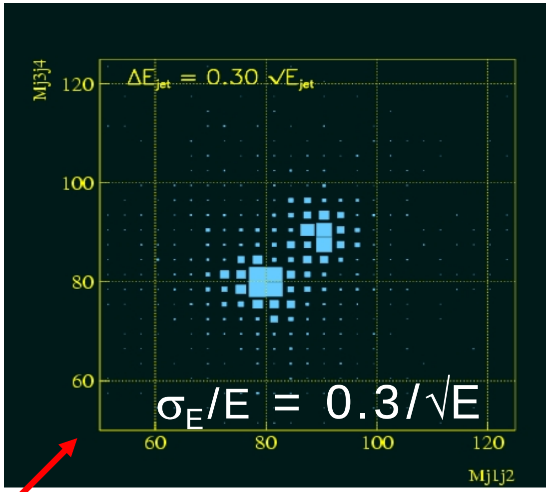


If the Higgs mechanism is not responsible for EWSB then WW fusion processes important

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

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





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

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

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

or more correctly

$\sigma_E/E < 3.8\%$

Remember this number

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

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

⇨ **a new approach to calorimetry**

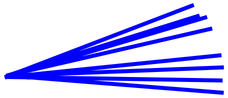
Particle Flow

Dual Readout

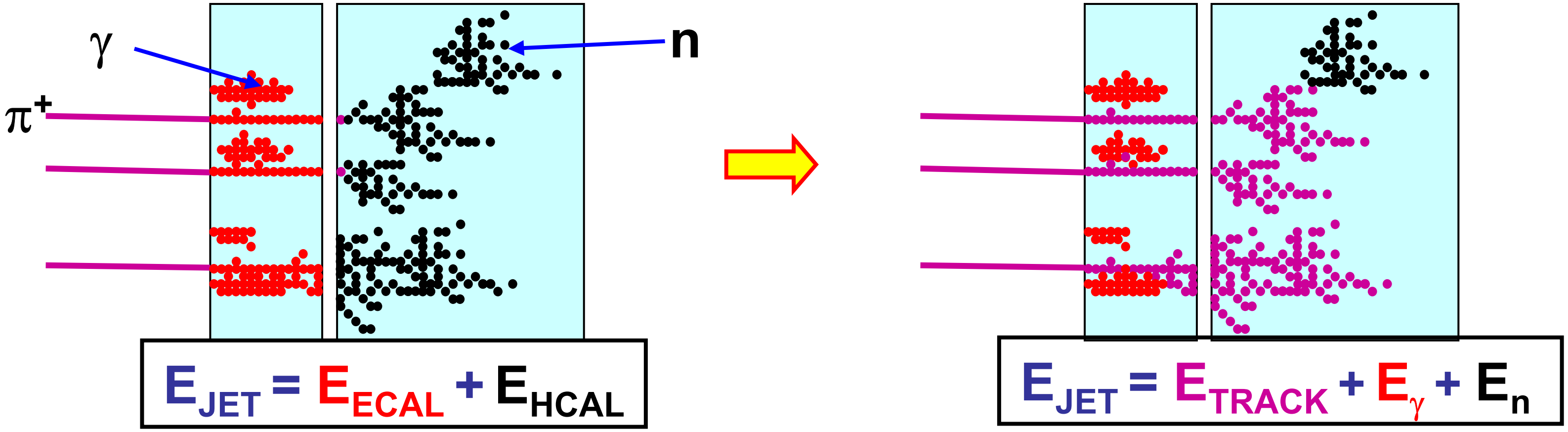
Note: this level of performance wasn't necessary at previous colliders

❷ The Particle Flow Paradigm

- ★ **In a typical jet :**
  - ♦ 60 % of jet energy in charged hadrons
  - ♦ 30 % in photons (mainly from $\pi^0 \rightarrow \gamma\gamma$)
  - ♦ 10 % in neutral hadrons (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



$\mathrm{E_{JET} = E_{ECAL} + E_{HCAL}}$

$\mathrm{E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}}$

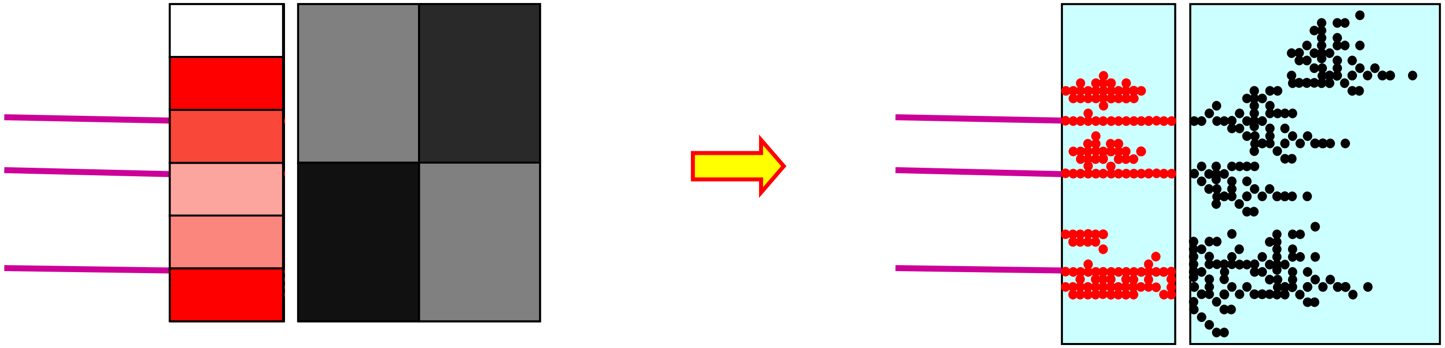
- ★ **Particle Flow Calorimetry paradigm:**
  - ♦ charged particles measured in tracker (essentially perfectly)
  - ♦ Photons in ECAL: $\sigma_{\mathrm{E}}/\mathrm{E} < 20\,\%/\sqrt{\mathrm{E(GeV)}}$
  - ♦ Neutral hadrons (ONLY) in HCAL
  - ♦ Only 10 % of jet energy from HCAL ⟹ much improved resolution

Particle Flow Calorimetry

Hardware:

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

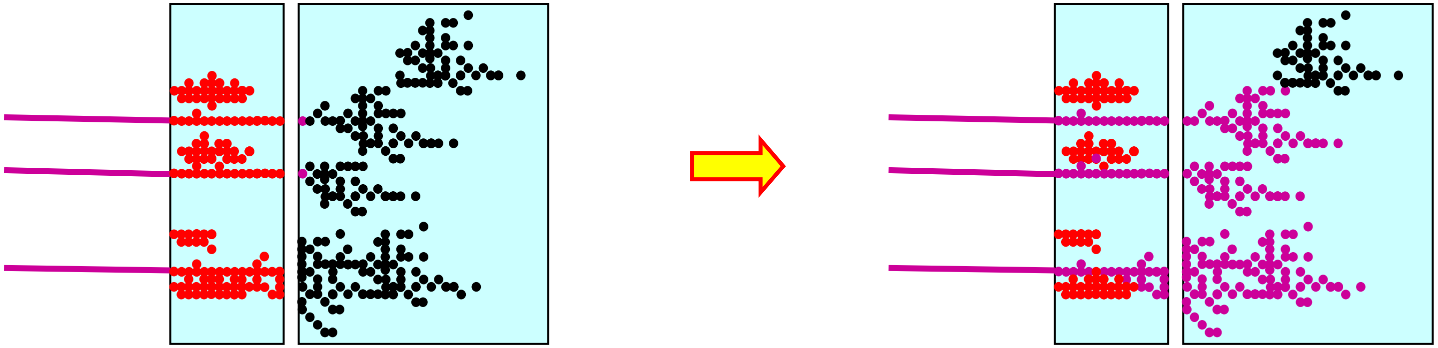
➡ Highly granular detectors (as studied in CALICE)



Software:

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

➡ Sophisticated reconstruction software



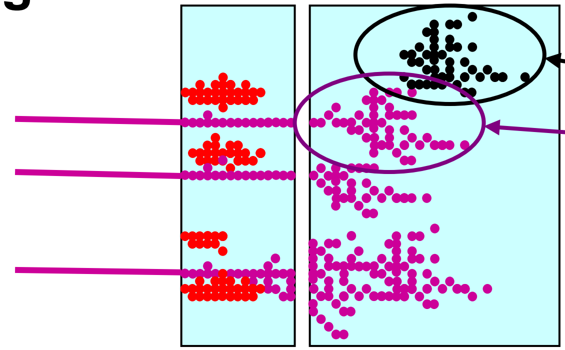
★ **Particle Flow Calorimetry = HARDWARE + SOFTWARE**

Particle Flow Algorithms (PFA)

Reconstruction of a Particle Flow Calorimeter:

- ★ Avoid double counting of energy from same particle
- ★ Separate energy deposits from different particles

e.g.



If these hits are clustered together with **these**, 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 **not** the intrinsic calorimetric performance of ECAL/HCAL

sounds easy….

- ★ PFA performance depends on detailed reconstruction
- ★ Relatively new, still developing ideas
- ★ Output of PFlow is a list of reconstructed particles
  - ★ "Particle Flow Objects" PFOs

❸ The ILD Detector Concept*

NOTE:

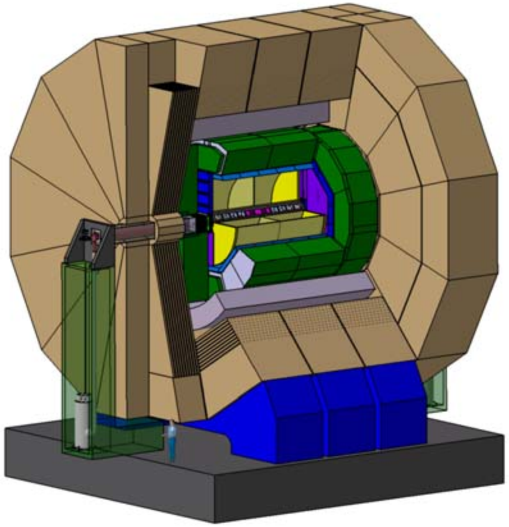
- ★ Particle flow reconstruction involves "whole detector"
- ★ To study potential performance need a detector model, tracking, calorimeters, …

ILC Detector Concepts:

- ★ Here performance of particle flow calorimetry shown in the context of the ILD detector concept for the ILC
- ★ Detailed GEANT 4 detector model exists
- ★ A potential design for an ILC detector
- ★ Designed for Particle Flow calorimetry !

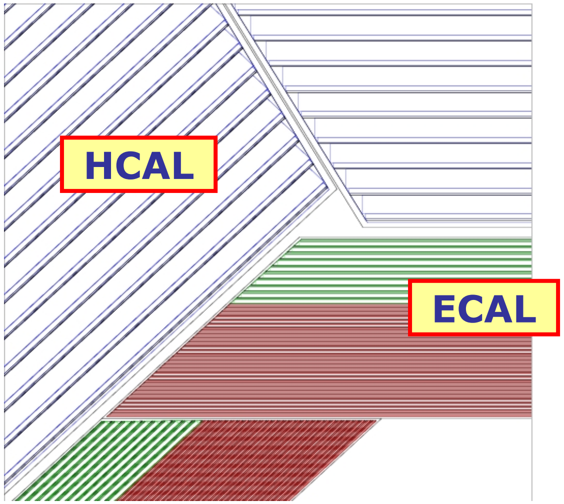
ILD Main Features:

- Large TPC central tracker (R=1.8 m)
- CMS like solenoid (B = 3.5 T)
- ECAL and HCAL inside solenoid
- ECAL/HCAL highly segmented for PFA



ILD calorimetry concept*

Very high longitudinal and transverse segmentation



ECAL:

- SiW sampling calorimeter
- Tungsten: X_0/λ_{had} = 1/25, $R_{Mol.}$ ~ 9mm
  - → Narrow EM showers
  - → longitudinal sep. of EM/had. showers
- longitudinal segmentation: 30 layers
- transverse segmentation: 5x5 mm^2 pixels

HCAL:

- Steel-Scintillator sampling calorimeter
- longitudinal segmentation: 48 layers (6 interaction lengths)
- transverse segmentation: 3x3 cm^2 scintillator tiles

Comments:

★ Technologically feasible (although not cheap)

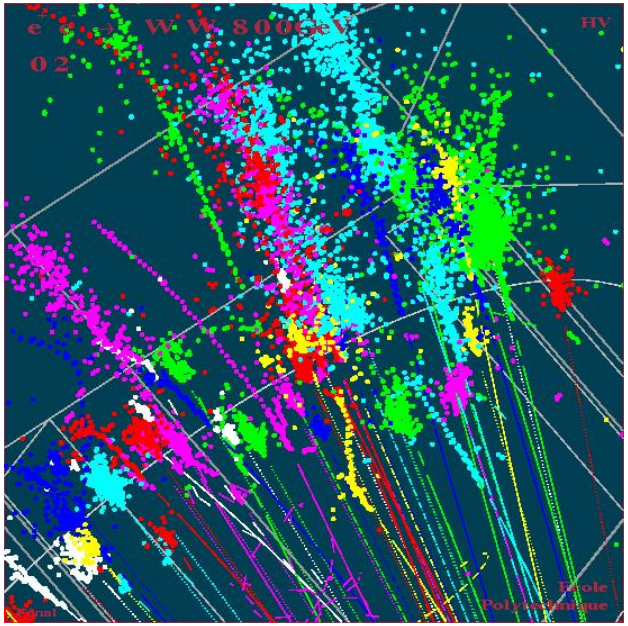
★ Ongoing test beam studies (CALICE collaboration)

*Other ILD calorimetry options being actively studied, e.g. RPC DHCAL, Scintillator strip ECAL

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 Reconstruction



- ★ PFA calorimetric performance = **HARDWARE + SOFTWARE**
- ★ **Performance will depend on the software algorithm**

→ difficult to evaluate full potential

$\sigma_E/E = f\,(\text{software})$

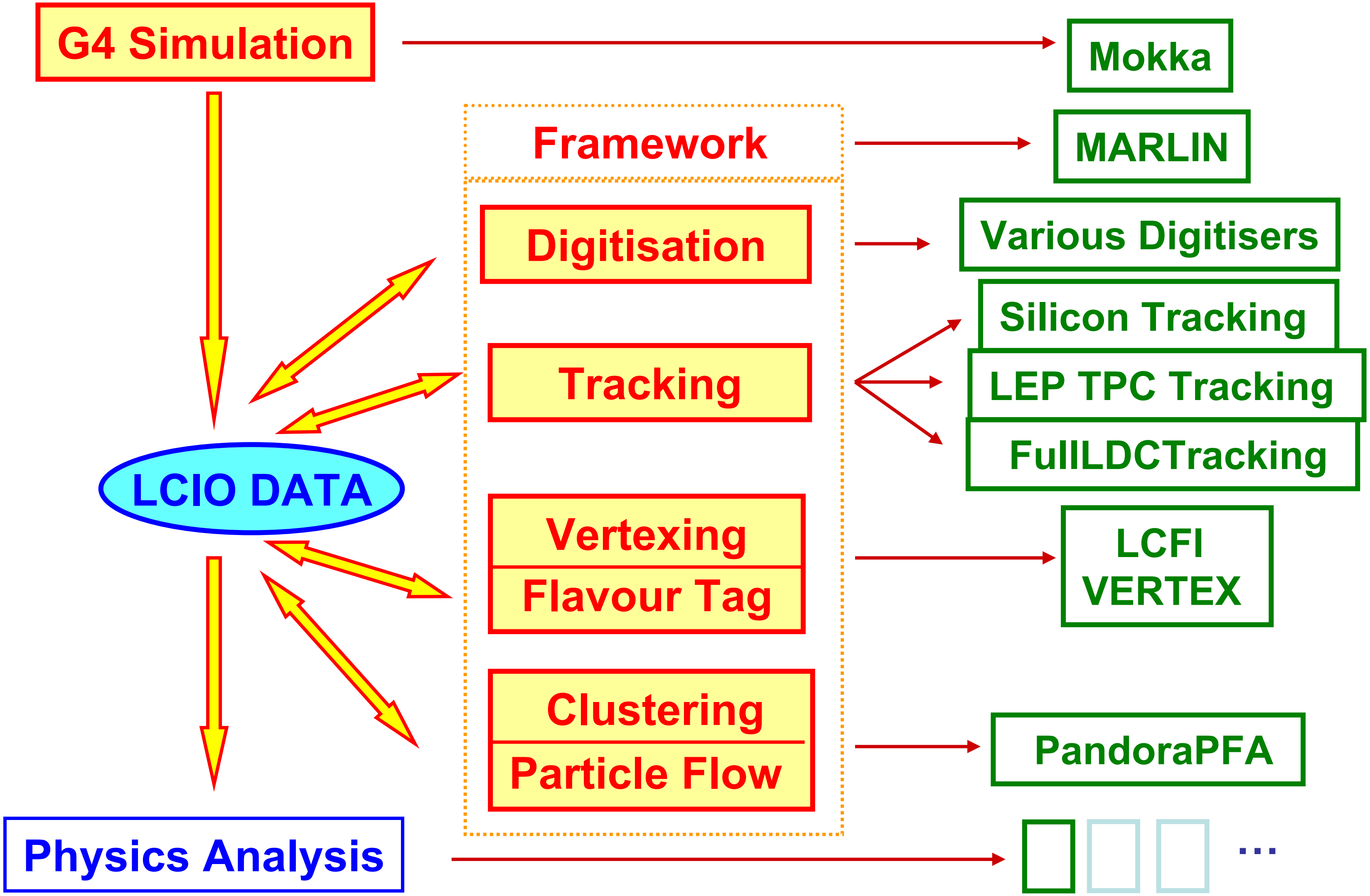
- **There are no short cuts, fast simulation doesn't help…**

To evaluate Particle Flow Calorimetry at ILC:
need realistic reconstruction chain
>10 years before start of ILC !!!

- **But, as a result of a great deal of work within ILC detector community, we already have a first version…**

❹ ILD Software Framework (C++)

★ Everything exists – level of sophistication ~LEP experiment



G4 Simulation

Mokka

Framework

MARLIN

Digitisation

Various Digitisers

Tracking

Silicon Tracking

LEP TPC Tracking

FullLDCTracking

LCIO DATA

Vertexing

Flavour Tag

LCFI VERTEX

Clustering

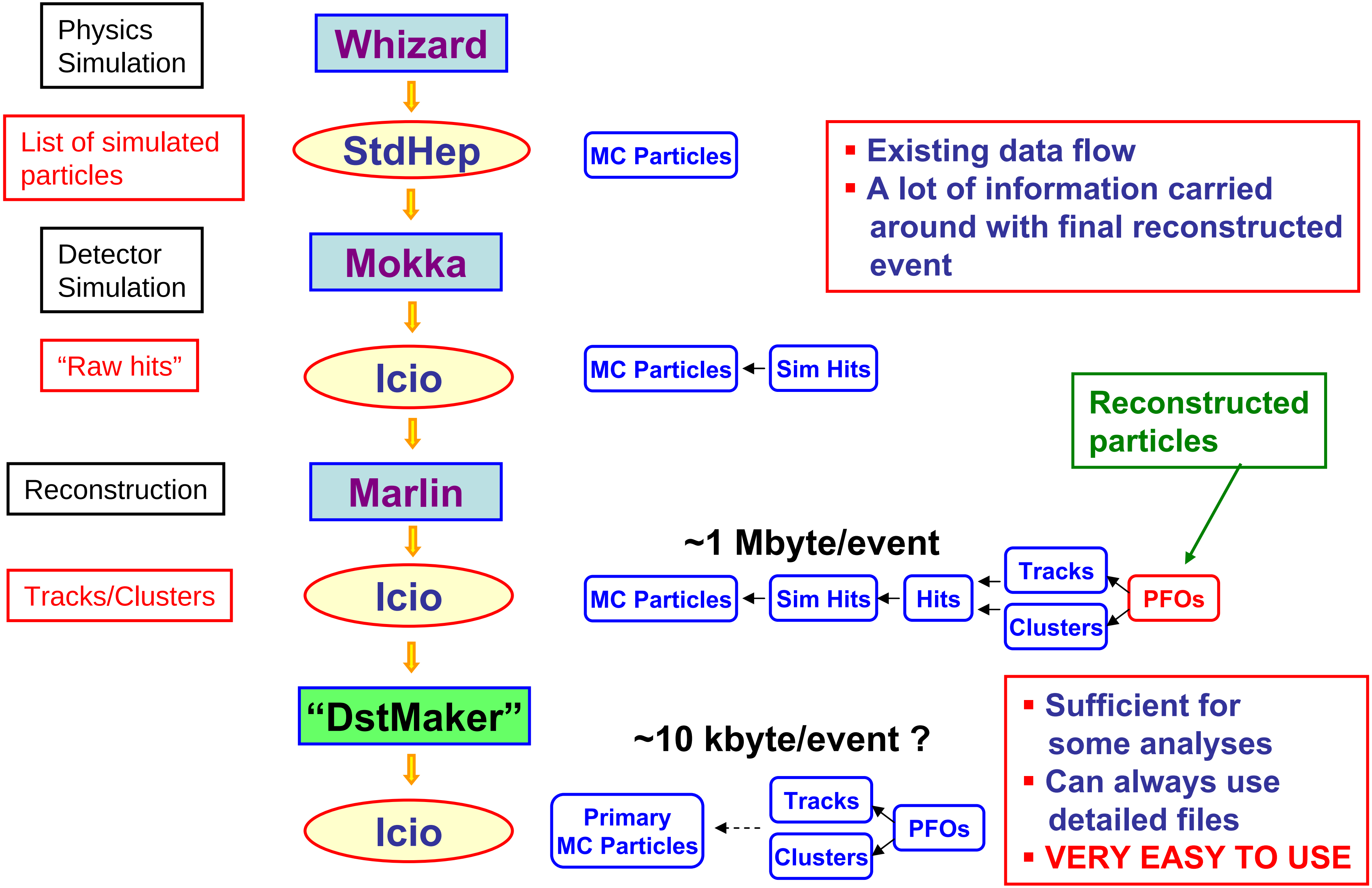
Particle Flow

PandoraPFA

Physics Analysis

…

Simulating an event



Physics Simulation

Whizard

List of simulated particles

StdHep

MC Particles

Detector Simulation

Mokka

"Raw hits"

lcio

MC Particles ← **Sim Hits**

Reconstruction

Marlin

Tracks/Clusters

lcio

~1 Mbyte/event

MC Particles ← **Sim Hits** ← **Hits** ← **Tracks** / **Clusters** ← **PFOs**

Reconstructed particles

"DstMaker"

lcio

~10 kbyte/event ?

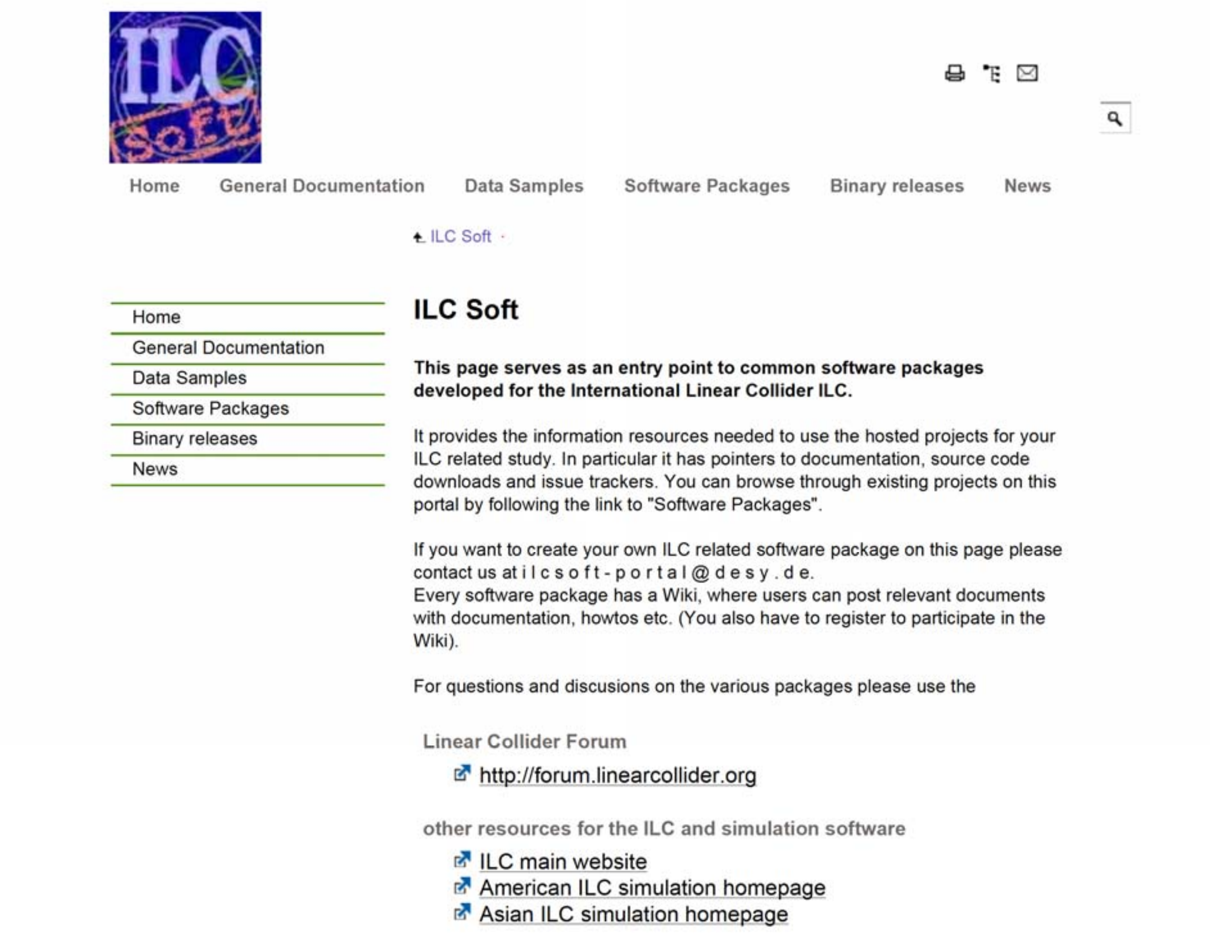
Primary MC Particles ← - - - **Tracks** / **Clusters** ← **PFOs**

- **Existing data flow**
- **A lot of information carried around with final reconstructed event**

- **Sufficient for some analyses**
- **Can always use detailed files**
- **VERY EASY TO USE**

http://ilcsoft.desy.de/portal

- ★ Marlin framework and reconstruction software available from web
- ★ Simple install script “IlcInstall”
- ★ Takes just a few hours to configure and then just run to get all software and associated packages



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ILC Soft

This page serves as an entry point to common software packages developed for the International Linear Collider ILC.

It provides the information resources needed to use the hosted projects for your ILC related study. In particular it has pointers to documentation, source code downloads and issue trackers. You can browse through existing projects on this portal by following the link to "Software Packages".

If you want to create your own ILC related software package on this page please contact us at ilcsoft-portal@desy.de.
Every software package has a Wiki, where users can post relevant documents with documentation, howtos etc. (You also have to register to participate in the Wiki).

For questions and discusions on the various packages please use the

Linear Collider Forum

- http://forum.linearcollider.org

other resources for the ILC and simulation software

- ILC main website
- American ILC simulation homepage
- Asian ILC simulation homepage

❺ PandoraPFA

- Need "realistic" Particle Flow to evaluate potential of method (again no shortcuts)
- New paradigm – nobody really knows how to approach this
- So where are we now ?
- Significant effort in context of ILC detector design (~4 groups developing PFA reconstruction worldwide)

Concentrate on: PandoraPFA

- This is still work-in-Progress – currently it gives the best performance
- Will give an overview of the algorithm to highlight how particle flow reconstruction works

PFA : Basic issues

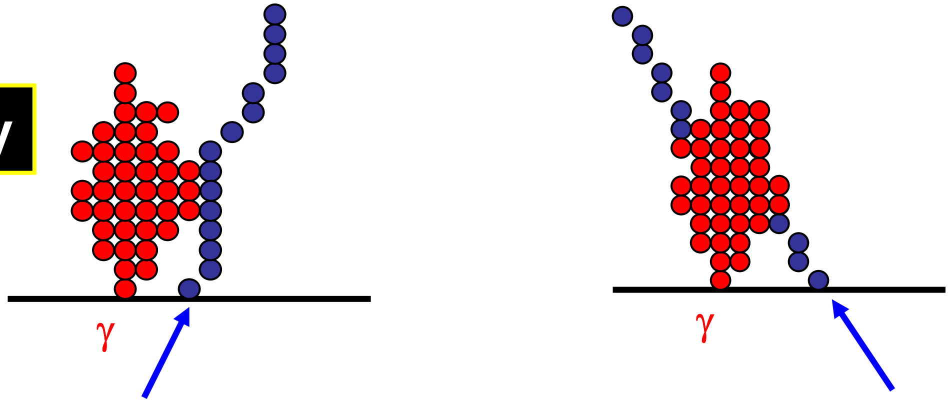
- ★ Separate energy deposits from different particles
- ★ Avoid double counting of energy from same particle
- ★ Mistakes drive particle flow jet energy resolution

e.g.

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

hardware

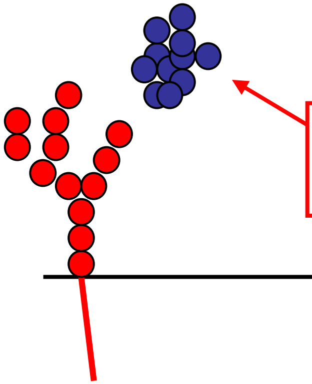
granularity



software

PFlow Algorithm

- ★ Need to separate neutral hadrons from charged hadrons



Isolated neutral hadron or fragment from shower ?

PandoraPFA Overview

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

- This is a sophisticated algorithm : **10^4** lines of code

Eight Main Stages:

1. Track classification/extrapolation
2. Loose clustering in ECAL and HCAL
3. Topological linking of clearly associated clusters
4. Courser grouping of clusters
5. Iterative reclustering
6. Photon Identification/Recovery
7. Fragment removal
8. Formation of final Particle Flow Objects (reconstructed particles)

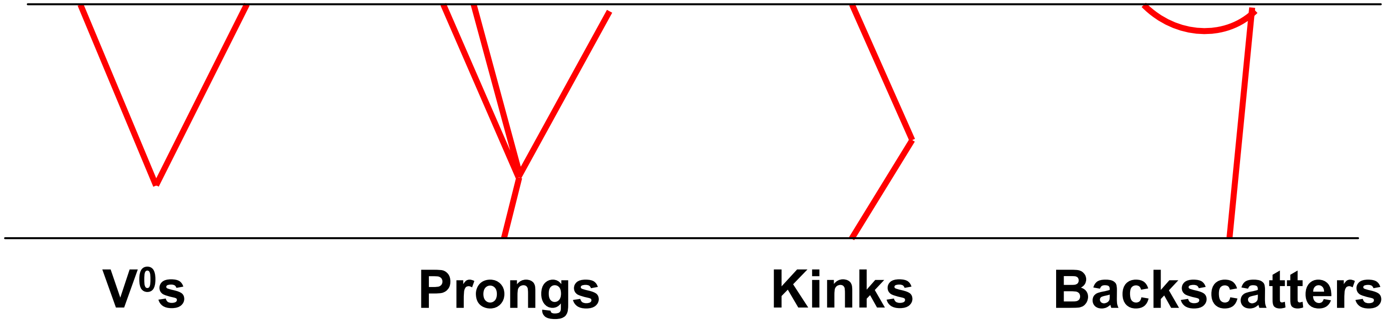
i) Tracking

- ★ 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

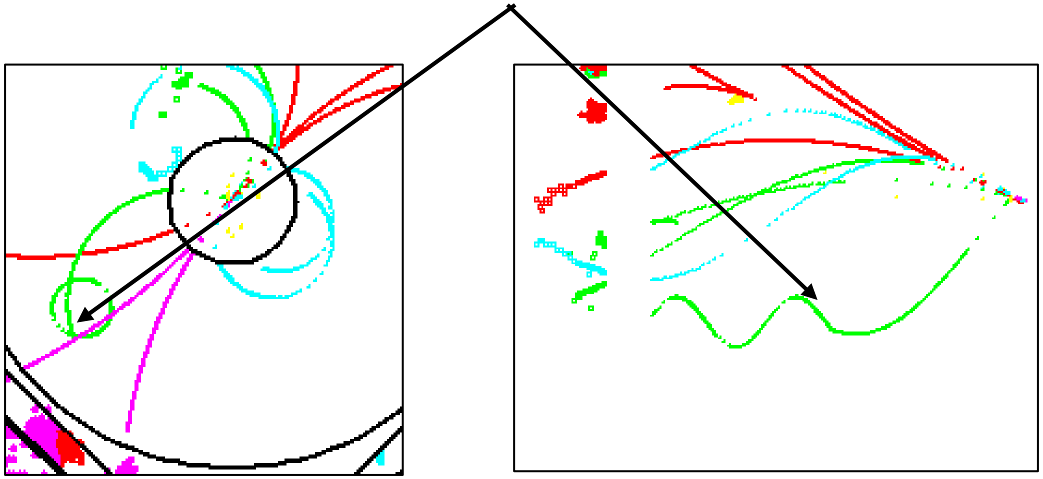
(the algorithm would need modification for Si tracker)

★ From fully reconstructed LDC tracks identify:

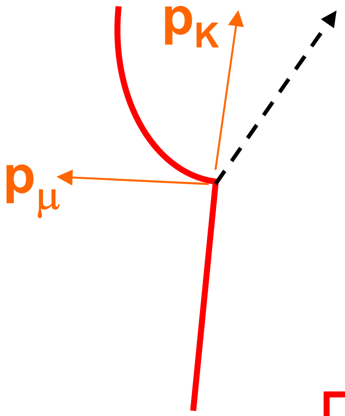


e.g. Kinks

- Kink finding extends to "loopers"



- Can give a measure of missing energy

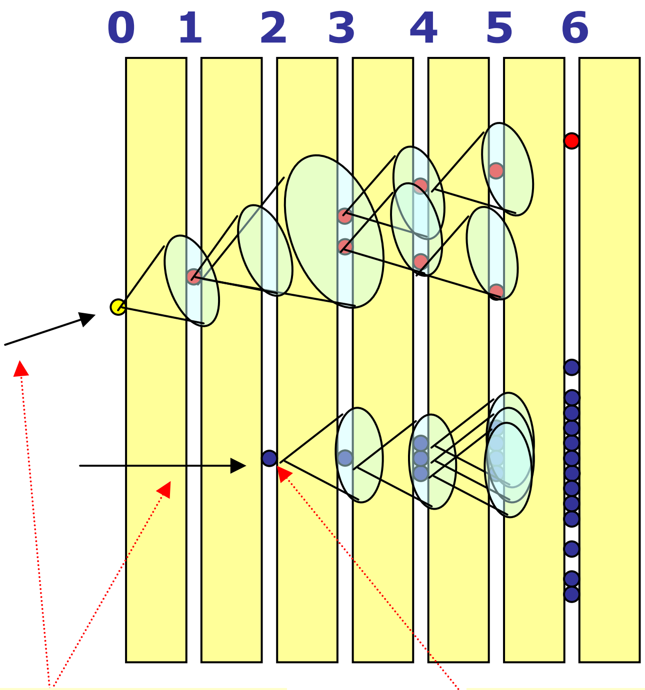


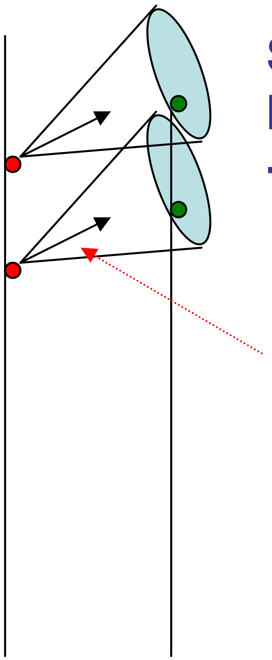
  - Consider physics hypothesis, e.g. $K^\pm \rightarrow \mu^\pm \nu$
  - Use Helix fits to start and end of tracks to reconstruct missing particle e.g. ν
  - Can then reconstruct primary mass
  - If consistent with hypothesis, e.g. m_K use primary track for PFO four-momentum

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:

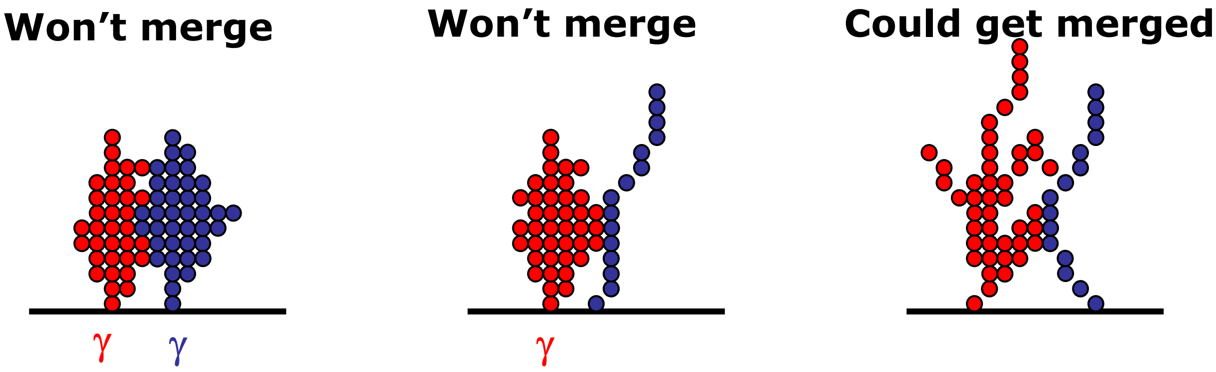
- cone angle
- additional pixels

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

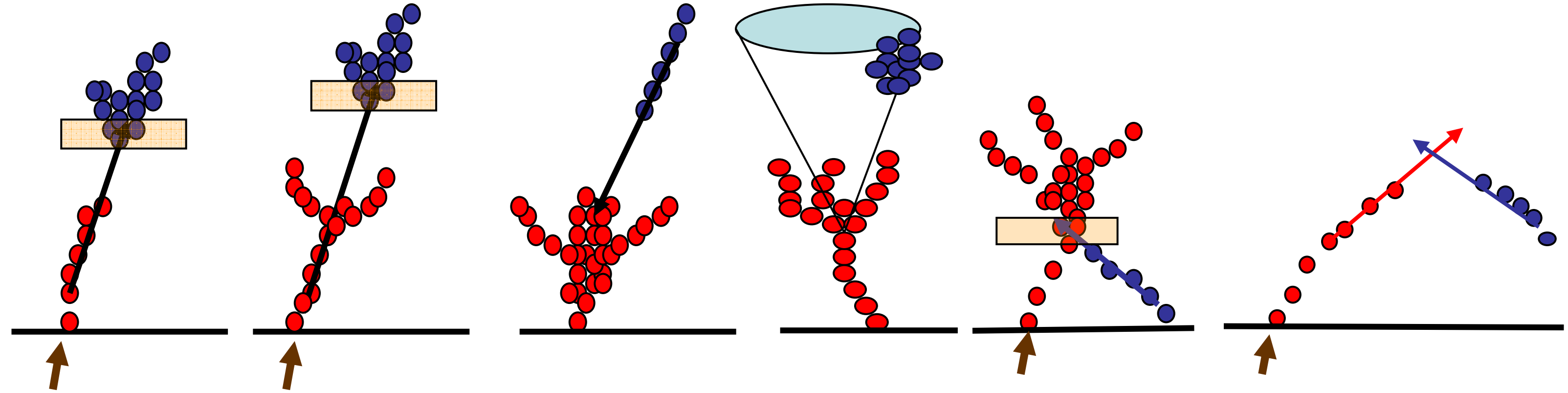
- Photon ID plays important role
- Simple "cut-based" photon ID applied to all clusters
- Clusters tagged as photons are immune from association procedure – just left alone



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

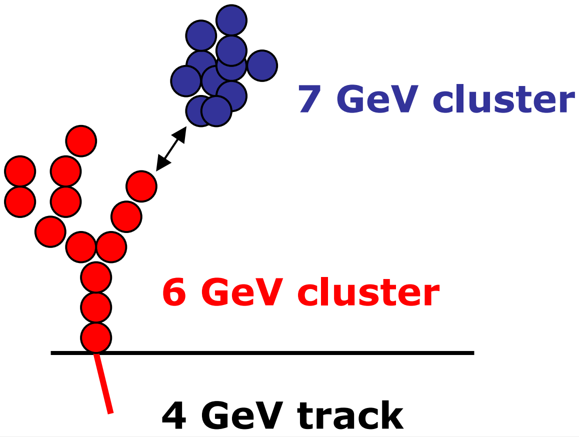
Clear Associations:

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



Less clear associations:

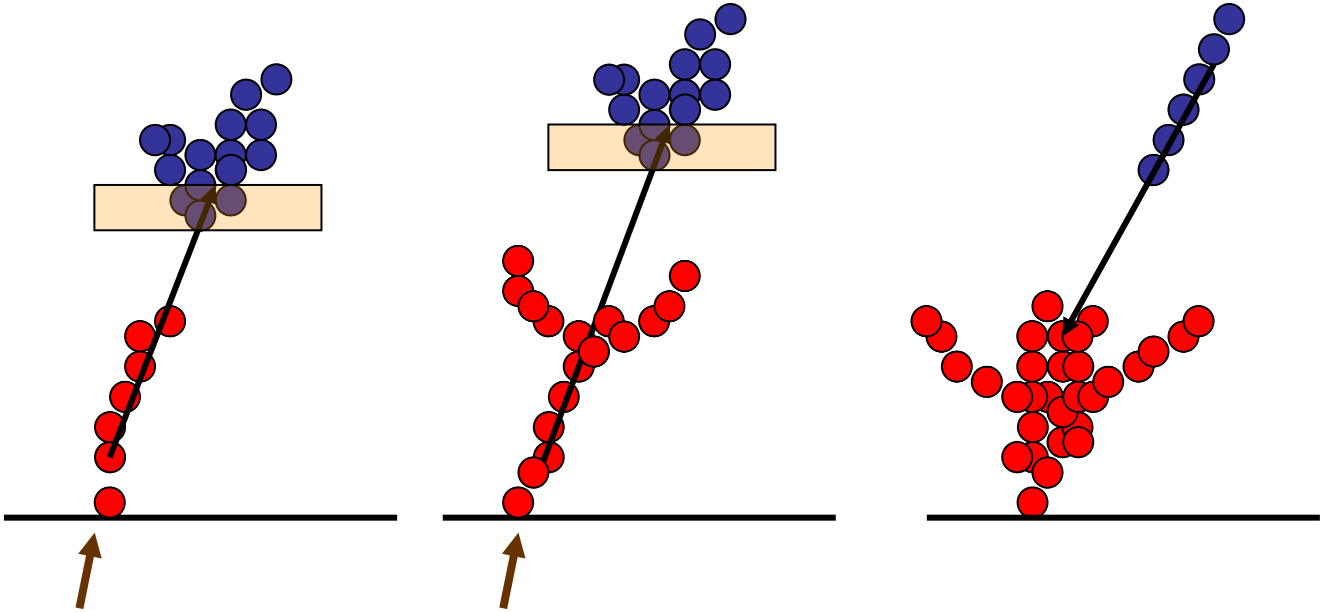
e.g. Proximity



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)

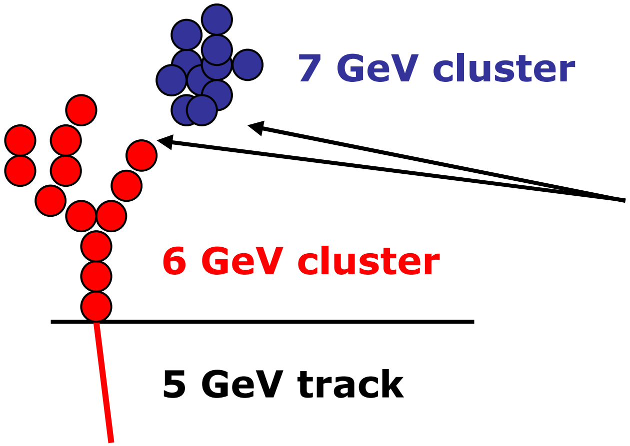


- ★ Apply tight matching criteria on basis of projected track [NB: + track quality i.e. chi2]

- ★ Here, association based on "tracking" in calorimeters

iv) Cluster Association Part II

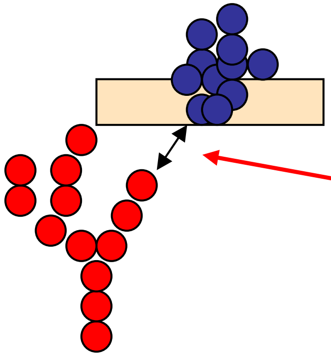
- Have made very clear cluster associations
- Now try “cruder” association strategies
- **BUT** first associate tracks to clusters (temporary association)
- Use track/cluster energies to “veto” associations, e.g.



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

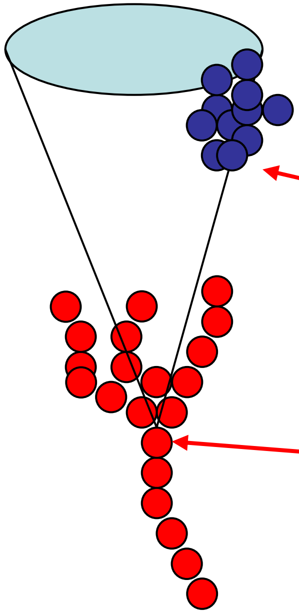
Provides some protection against obvious mistakes

Proximity



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

Shower Cone



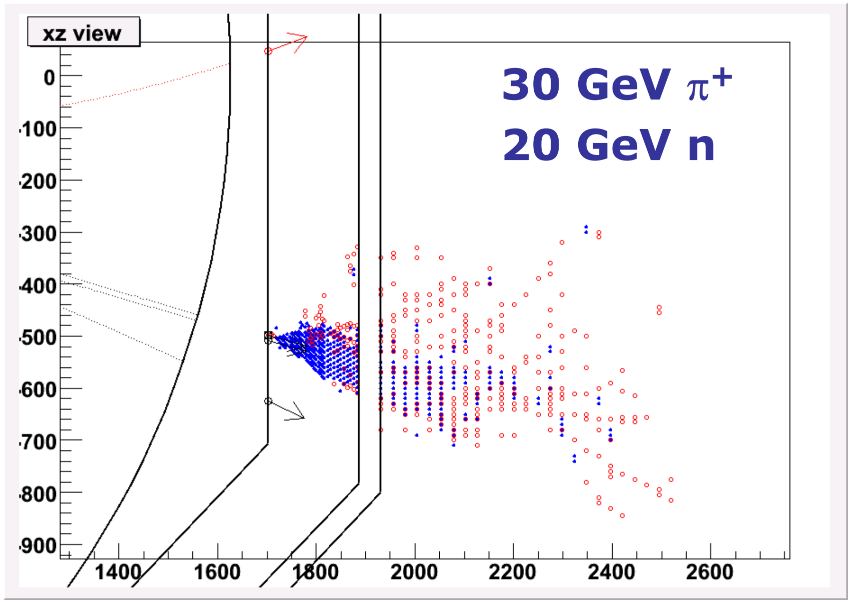
Associated if fraction of hits in cone > some value

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

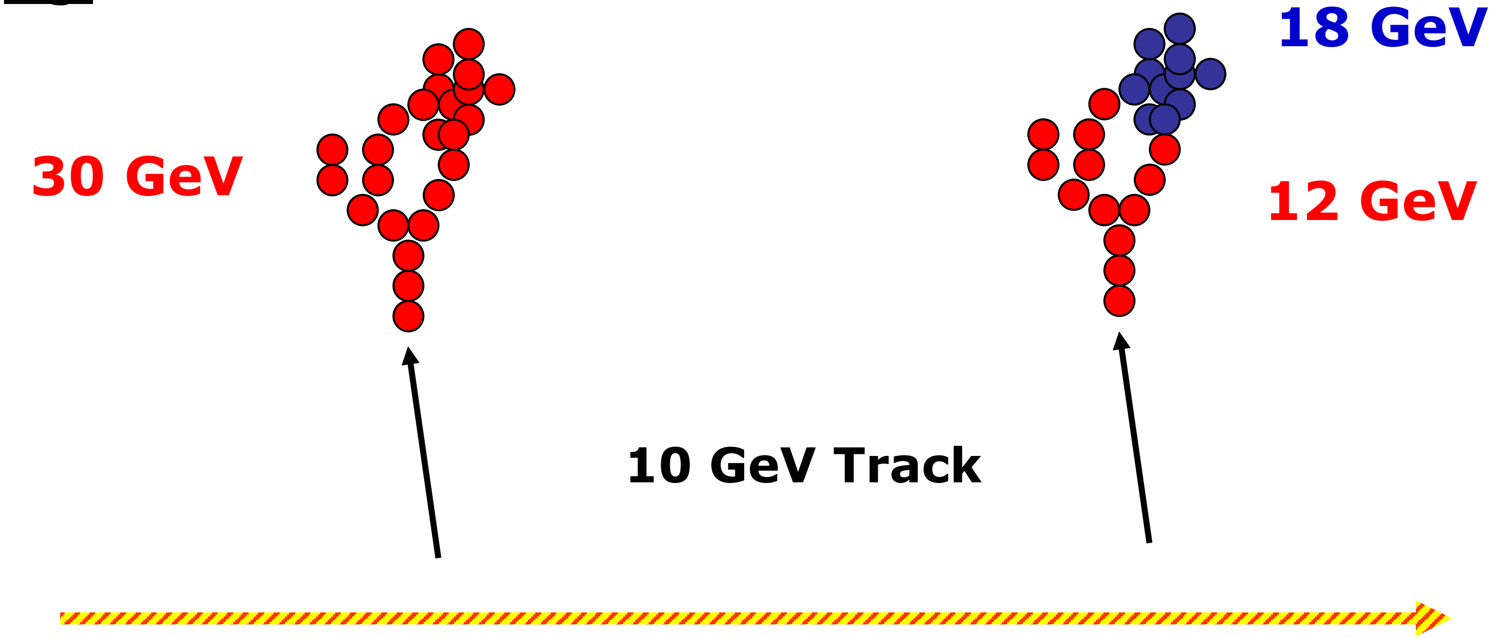
The ONLY(?) way to address this is “statistically”

→

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

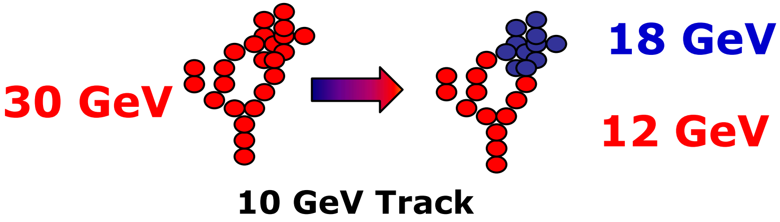
NOTE: NOT FULL PFA as clustering driven by track momentum

This is very important for higher energy jets

Iterative Reclustering Strategies

① Cluster splitting

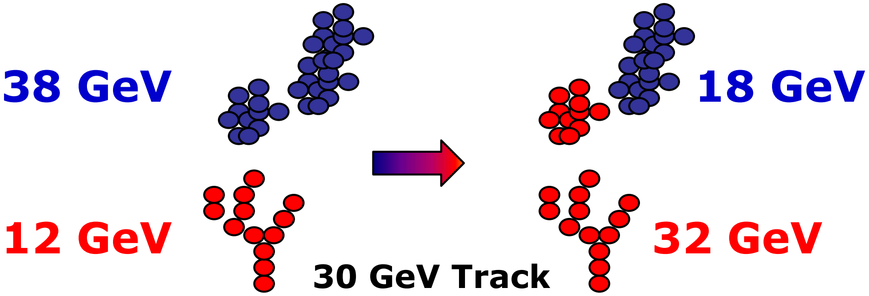
Reapply entire clustering algorithm to hits in "dubious" cluster. Iteratively reduce cone angle until cluster splits to give acceptable energy match to track



★ + plug in alternative clustering algorithms

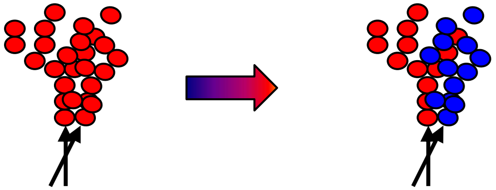
② Cluster merging with splitting

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

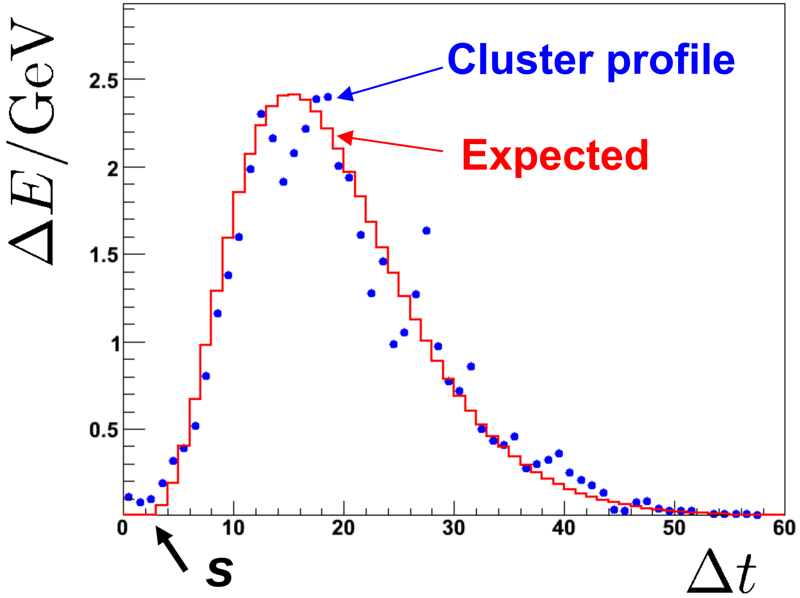
- ★ Use simple cut-based photon ID in the early (CPU intensive) stages of PandoraPFA
- ★ In the final stages, use improved photon ID based on the expected EM longitudinal profile for cluster energy **E_0**

$$\boxed{\Delta E = E_0 \frac{(t/2)^{a-1} e^{-t/2}}{\Gamma(a)} \Delta t}$$

$$a = 1.25 + \frac{1}{2} \ln E_0/E_c$$

- ★ Convert cluster into energy depositions per radiation length

(use cluster to determine the layer spacing, i.e. geometry indep.)



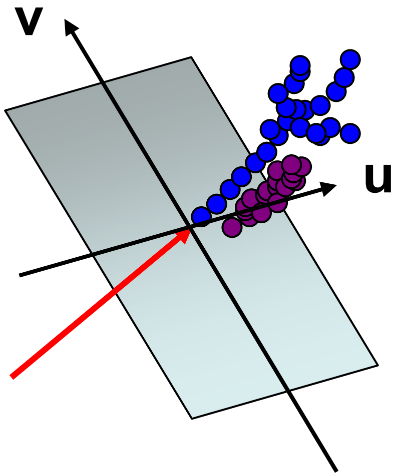
- ♦ Shower Profile fixed by cluster energy
- ♦ But fit for best shower start, ***s***
- ♦ Normalise areas to unity and calc.

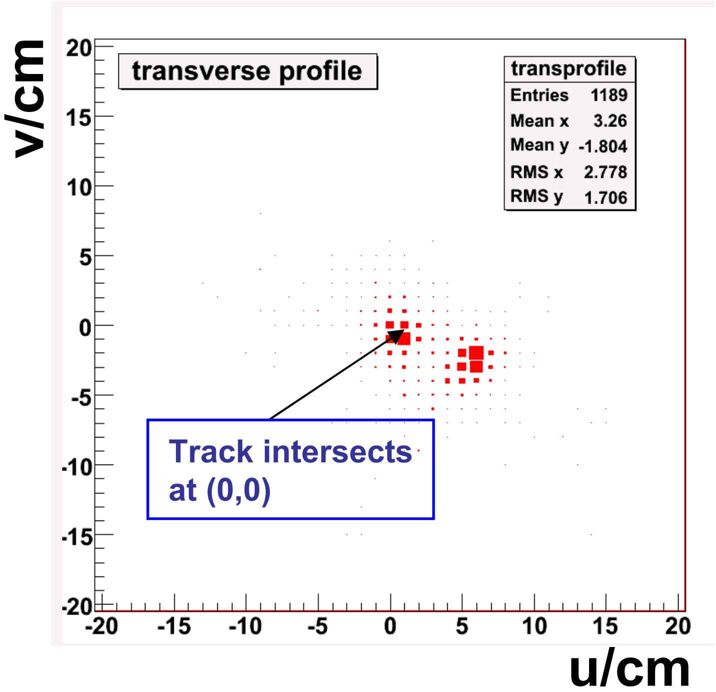
$$f = \sum_i |o_i - e_i|$$

- ♦ 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…





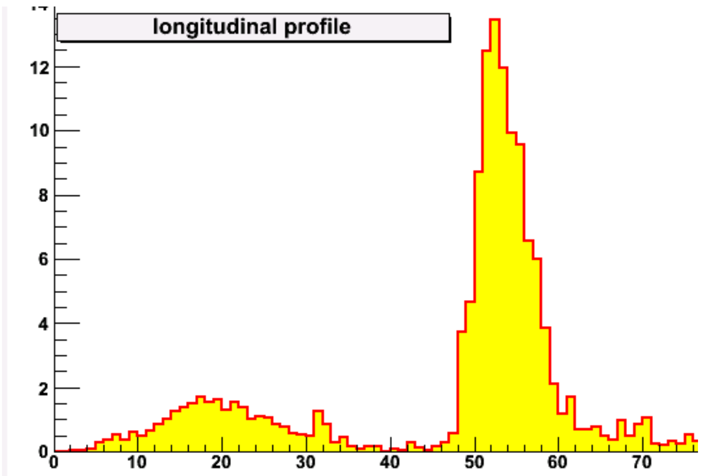
Track intersects at (0,0)

- ★ 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”

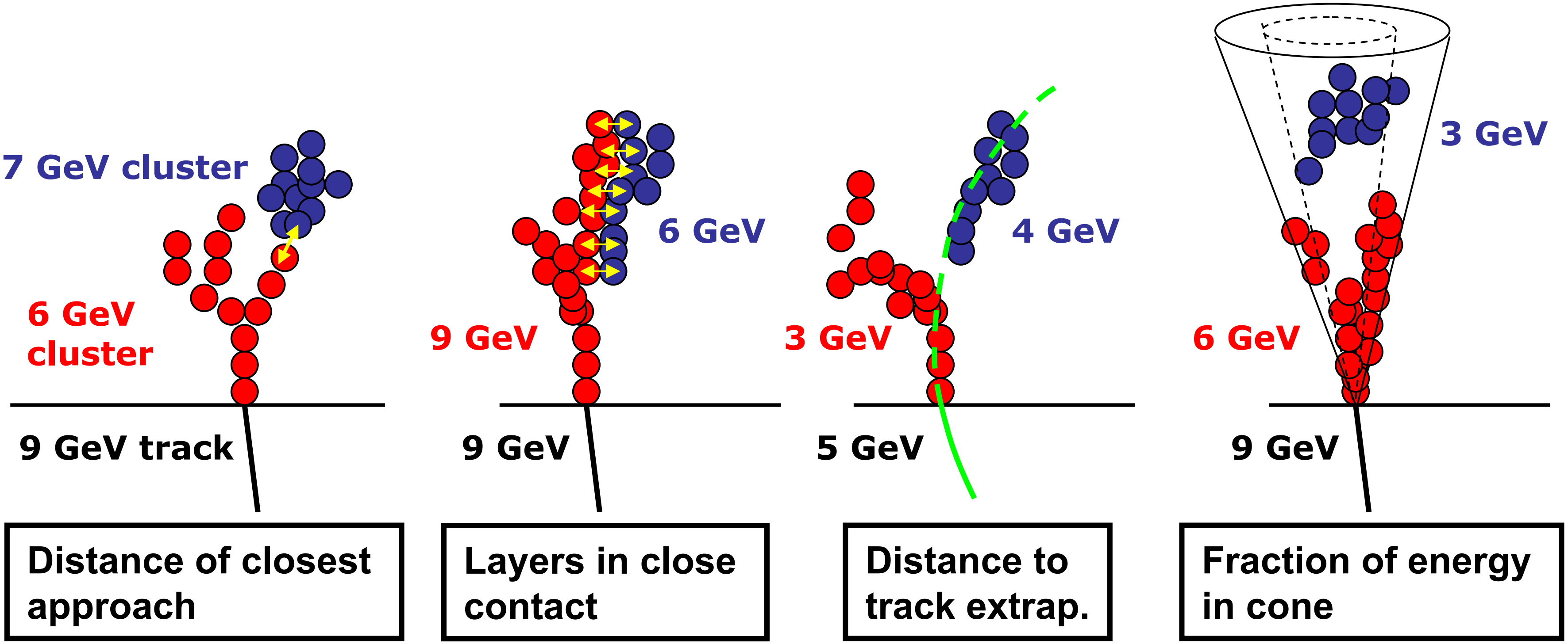


Only allowed if it results in acceptable track-cluster energy consistency…

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



Distance of closest approach

Layers in close contact

Distance to track extrap.

Fraction of energy in cone

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

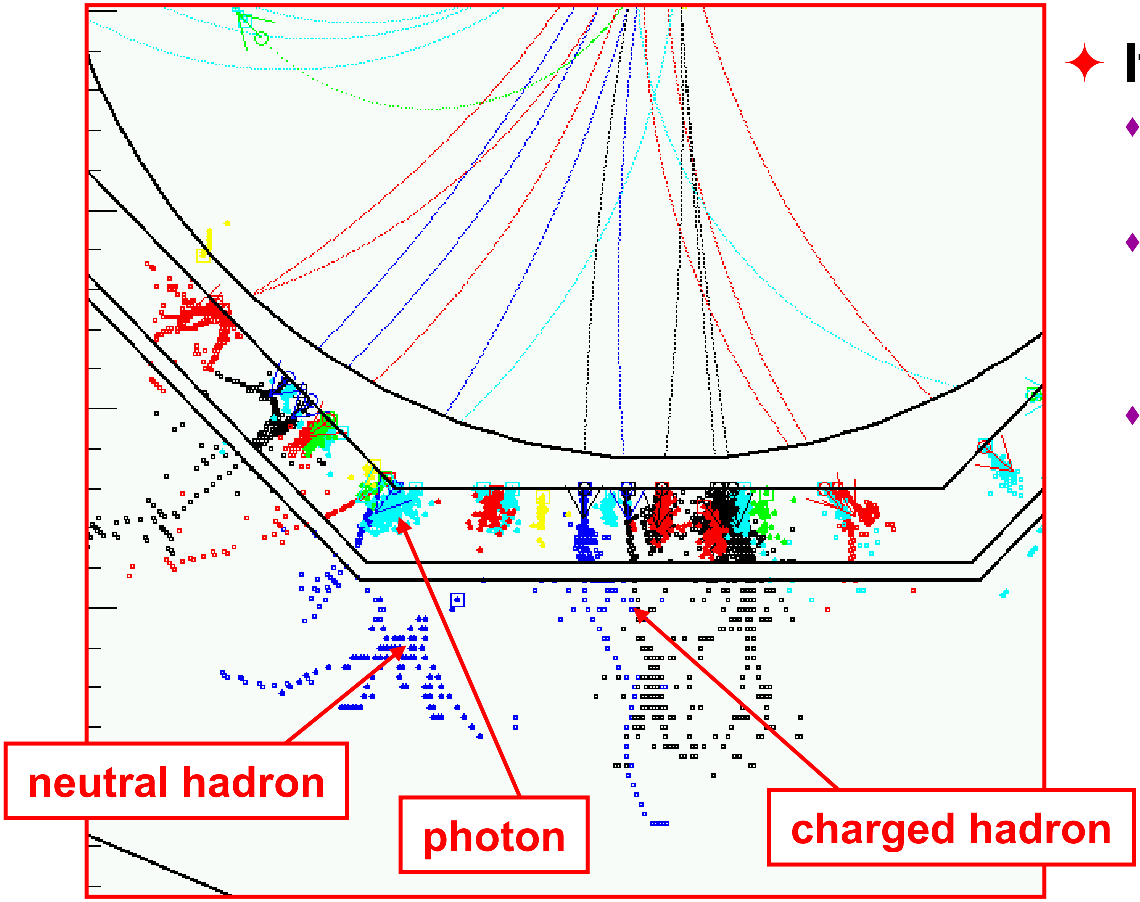
★ Compare to another score “required evidence” for matching, **R**, based on change in E/p chi-squared, location in ECAL/HCAL etc.

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

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

Putting it all together…

100 GeV Jet



neutral hadron

photon

charged hadron

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

Particle Flow Objects

End of Lecture 1

Aside: Analysing PFOs

★ **Within Marlin software framework analysis is very easy:**

```
void ExampleDSTAnalysis::processEvent( LCEvent * evt ) {

  typedef const std::vector<std::string> StringVec ;

  // loop over collections in event
  StringVec* strVec = evt->getCollectionNames() ;
  for(StringVec::const_iterator name=strVec->begin(); name!=strVec->end(); name++){
    LCCollection* col = evt->getCollection(*name);

// find the reconstructed particle flow object collection
   if(*name=="PandoraPFOs"){
        for(unsigned int i=0;i<nelem;i++){
          ReconstructedParticle* recoPart = dynamic_cast<ReconstructedParticle*>(col>getElementAt(i));
// store PFOs in a vector for later analysis
         _pfovec.push_back(recoPart);
        }
}
```

e.g. to calculate total energy in event:

```
for(unsigned int i=0; i<_pfovec.size(); i++)e  += _pfovec[i]->getEnergy();
```

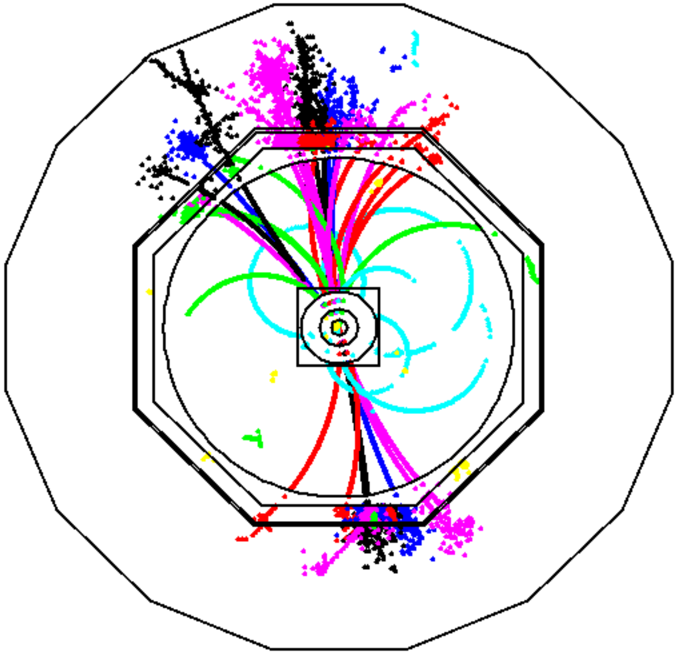
❻ Current performance

★Benchmark performance using $Z \to u\bar{u}$ and $Z \to d\bar{d}$ events (clean, no neutrinos)

★Test at for different energies with Z decays at rest

★OPAL tune of Pythia fragmentation

★Full reconstruction (track + calo) using no Monte Carlo "cheat" information



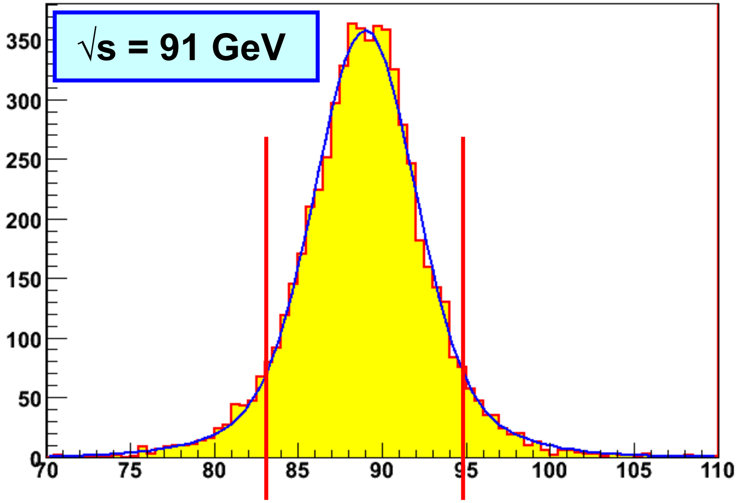
NOTE:

- Quoting rms of reconstructed energy distribution is misleading
- Particle Flow occasionally goes very wrong → tails dominate rms
- Conventional to measure performance using **rms90** which is relatively insensitive to tails

Figures of Merit:

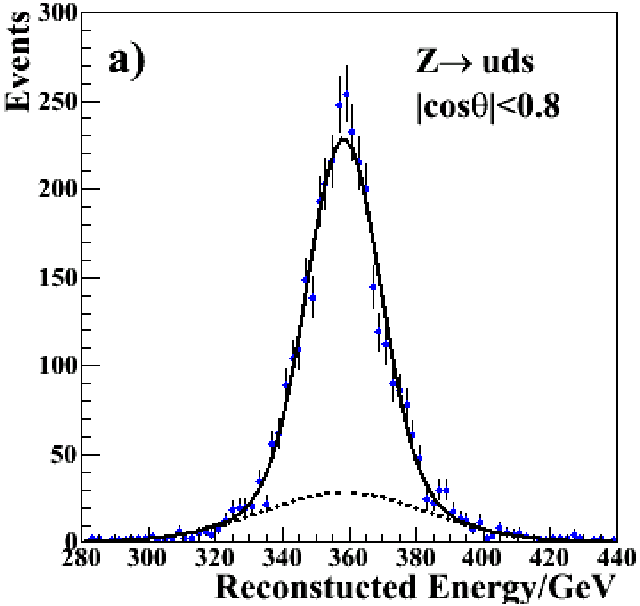
rms_{90}

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



σ_{80}

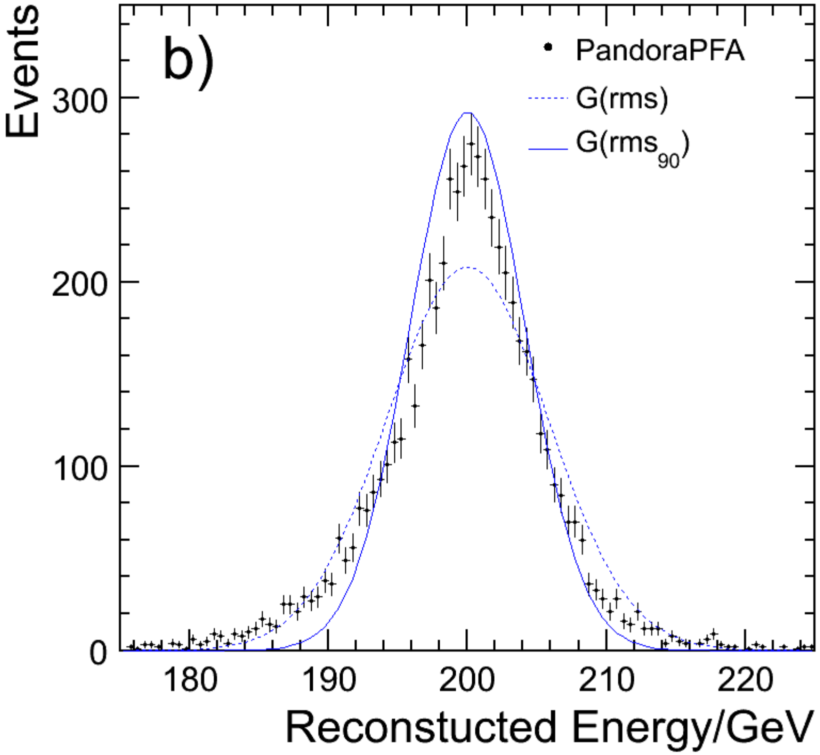
- Fit sum of two Gaussians with same mean. The narrower one is constrained to contain 80 % of events
- Quote σ of narrow Gaussian



It turns out that $\mathrm{rms}_{90} \approx \sigma_{80}$

(need care when comparing to Gaussian resolution)

- ★ **Sligthly confusing but necessary: energy distribution not Gaussian**
- ★ **To illustrate the point compare:**
  - **PFlow reconstructed energy distribution**
  - **Gaussian with raw of energy distribution**
  - **Gaussion with rms$_{90}$**



- ★ **NOTE: FWHM of distribution actually narrower than for G(rms$_{90}$)**

Performance (ILD) $Z \rightarrow d\bar{d}, Z \rightarrow u\bar{u}$

rms90 **PandoraPFA v03-β**

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E_j
45 GeV	23.8 %	3.5 %
100 GeV	29.1 %	2.9 %
180 GeV	37.7 %	2.8 %
250 GeV	45.6 %	2.9 %

- Full G4 simulation
- Full reconstruction

★ Particle flow achieves 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 PFA code is not perfect – lower limit on performance

Proof of principle:

PARTICLE FLOW CALORIMETRY WORKS

At least in simulation

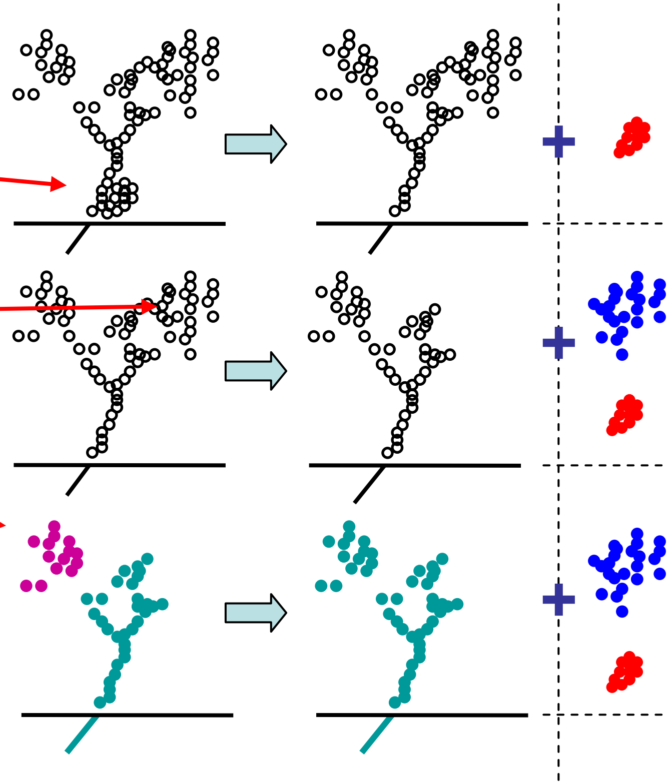
Understanding PFA Performance

What drives Particle Flow performance ?

★ Try to use various “Perfect PFA” algorithms to pin down main performance drivers (resolution, confusion, …)

★ Use MC to “cheat” various aspects of **Particle Flow**

PandoraPFA options:

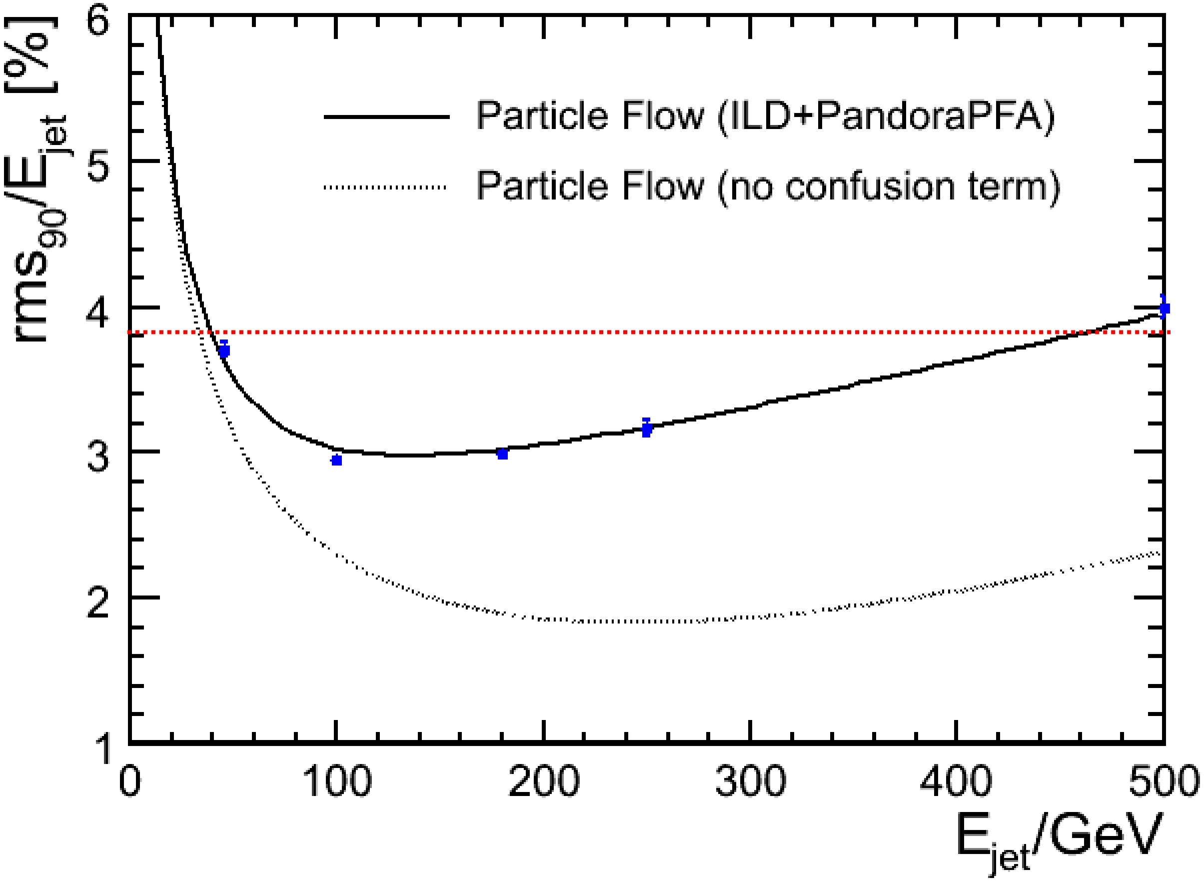


- **PerfectPhotonClustering**
  hits from photons clustered using MC info and removed from main algorithm
- **PerfectNeutralHadronClustering**
  hits from neutral hadrons clustered using MC info…
- **PerfectFragmentRemoval**
  after PandoraPFA clustering “fragments” from charged tracks identified from MC and added to charged track cluster
- **PerfectPFA**
  perfect clustering and matching to tracks

Contribution	σ_E/E			
	45 GeV	100 GeV	180 GeV	250 GeV
Calo. Resolution	3.1 %	2.1 %	1.5 %	1.3 %
Leakage	0.1 %	0.5 %	0.8 %	1.0 %
Tracking	0.7 %	0.7 %	1.0 %	0.7 %
Photons "missed"	0.4 %	1.2 %	1.4 %	1.8 %
Neutrals "missed"	1.0 %	1.6 %	1.7 %	1.8 %
Charged Frags.	1.2 %	0.7 %	0.4 %	0.0 %
"Other"	0.8 %	0.8 %	1.2 %	1.2 %

Comments:

- ★ For 45 GeV jets, jet energy resolution dominated by ECAL/HCAL resolution
- ★ Track reco. not a large contribution (Reco ≈ CheatedTracking)
- ★ "Satellite" neutral fragments not a large contribution
  - ▪ efficiently identified
- ★ Leakage only becomes significant for high energies
- ★ Missed neutral hadrons dominant confusion effect
- ★ Missed photons, important at higher energies

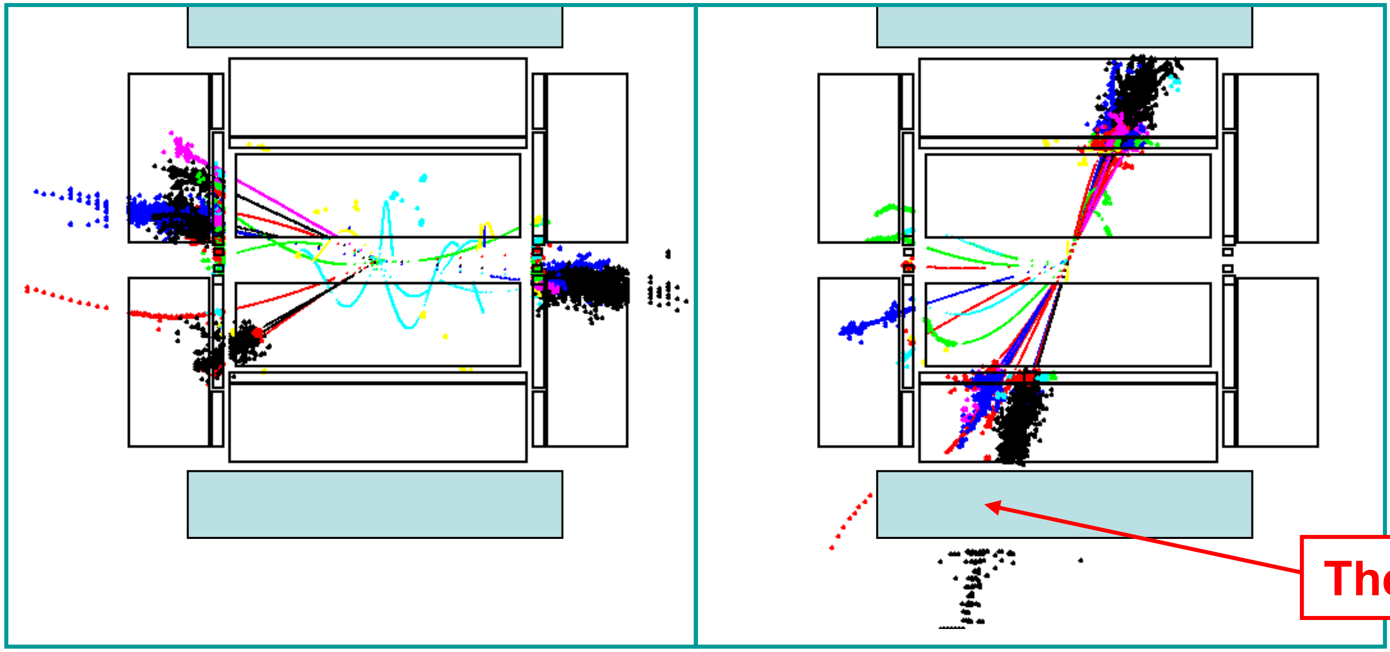

rms$_{90}$/E$_{jet}$ [%]
1
2
3
4
5
6
0
100
200
300
400
500
E$_{jet}$/GeV
Particle Flow (ILD+PandoraPFA)
Particle Flow (no confusion term)

Leakage

<u>Two interesting questions:</u>

- ★ How important is HCAL leakage ?
  - vary number of HCAL layers
- ★ What can be recovered using MUON chambers as a "Tail catcher"
  - PandoraPFA now includes MUON chamber reco.
  - Switched off in default version
  - Simple standalone clustering (cone based)
  - Fairly simple matching to CALO clusters (apply energy/momentum veto)
  - Simple energy estimator (digital) + some estimate for loss in coil

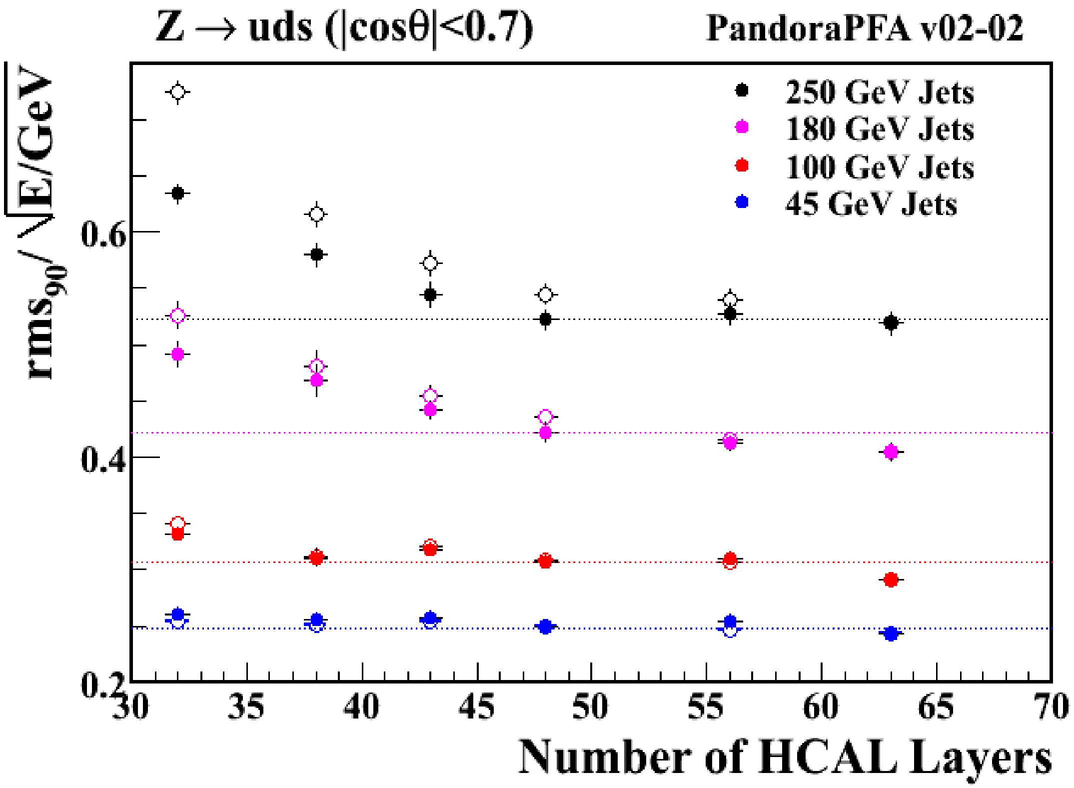
e.g.



The problem

HCAL Depth Results

- **Open circles** = no use of muon chambers as a “tail-catcher”
- **Solid circles** = including “tail-catcher”



HCAL Layers	λ_I HCAL	λ_I +ECAL
32	4.0	4.8
38	4.7	5.5
43	5.4	6.2
48	6.0	6.8
63	7.9	8.7

ECAL : λ_I = 0.8

HCAL : λ_I includes scintillator

★ Little motivation for going beyond a 48 layer (6 λ_I) HCAL

★ Depends on Hadron Shower simulation

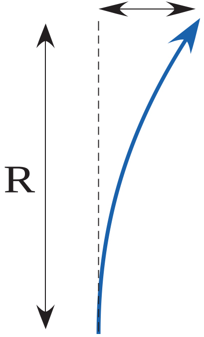
★ “Tail-catcher”: corrects ~50% effect of leakage, limited by thick solenoid

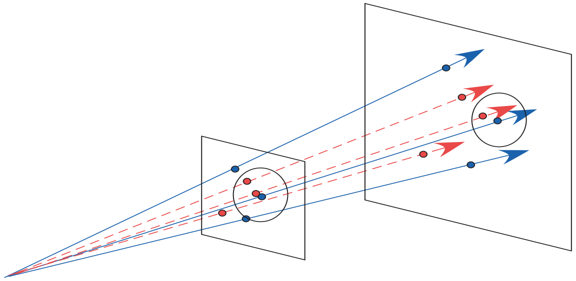
For 1 TeV machine “reasonable range” ~ 40 – 48 layers (5 λ_I - 6 λ_I)

❼ Optimisation of a Particle Flow detector

★ Particle Flow Calorimetry lives or dies on ability to separate energy deposits from individual particles.

- **Large detector** – spatially separate particles
- **High B-field** – separate charged/neutrals
- **High granularity ECAL/HCAL** – resolve particles





Might expect "figure-of-merit": $\frac{BR^2}{\sigma}$

Separation of charge/neutrals

Calorimeter granularity/R_{Moliere}

★ Argues for: large + high granularity + ⇧ B

★ Cost considerations: small + lower granularity + ⇩ B

Optimise detector parameters using PandoraPFA

Interpretation: observing effects of detector + imperfect software

e.g. Radius vs. B-field

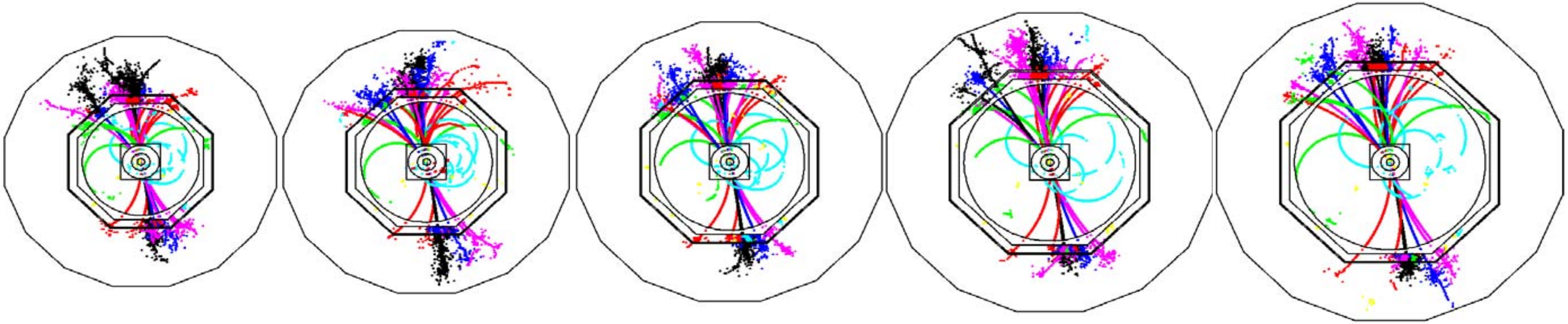
Cost drivers:

- For Particle flow, ECAL and HCAL inside Solenoid
- Calorimeters and solenoid are the main cost drivers of an ILC detector optimised for particle flow
- Cost of calorimeters scales with active area
- Cost of solenoid scales with stored energy, (very approx.)

$$\$\$\$ \propto (B^2R^2L)^{0.66}$$

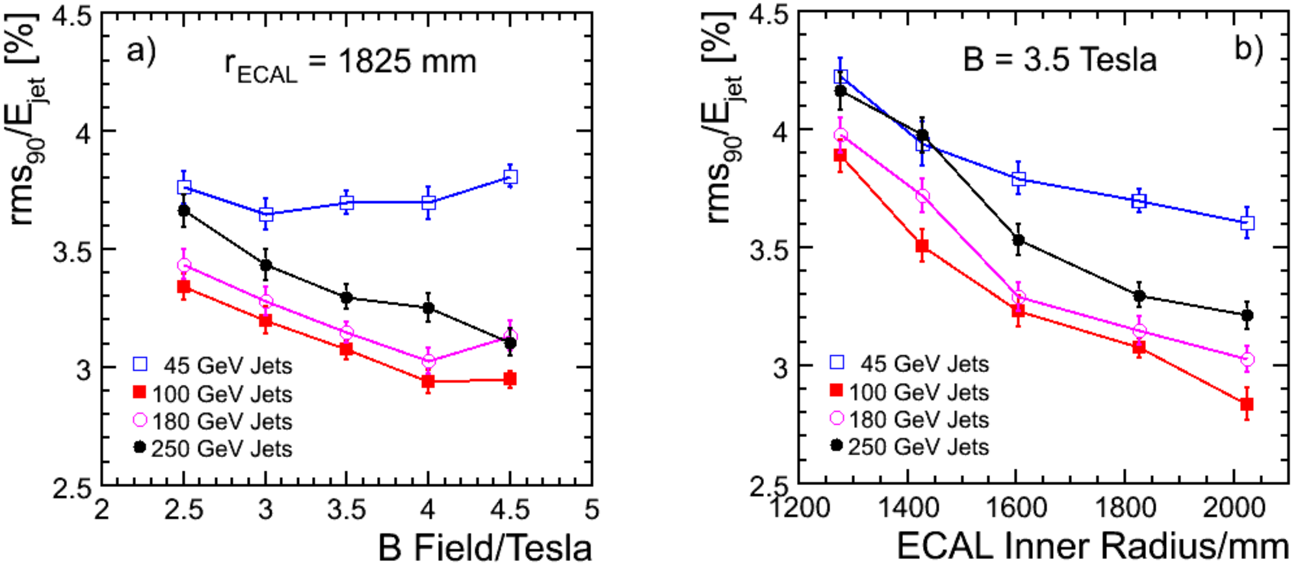
★TPC radius and B-field play major role in total detector cost

- Study jet energy resolution as a function of **B** and **R**



PFA Optimisation: B vs Radius

- ★ Vary B and R



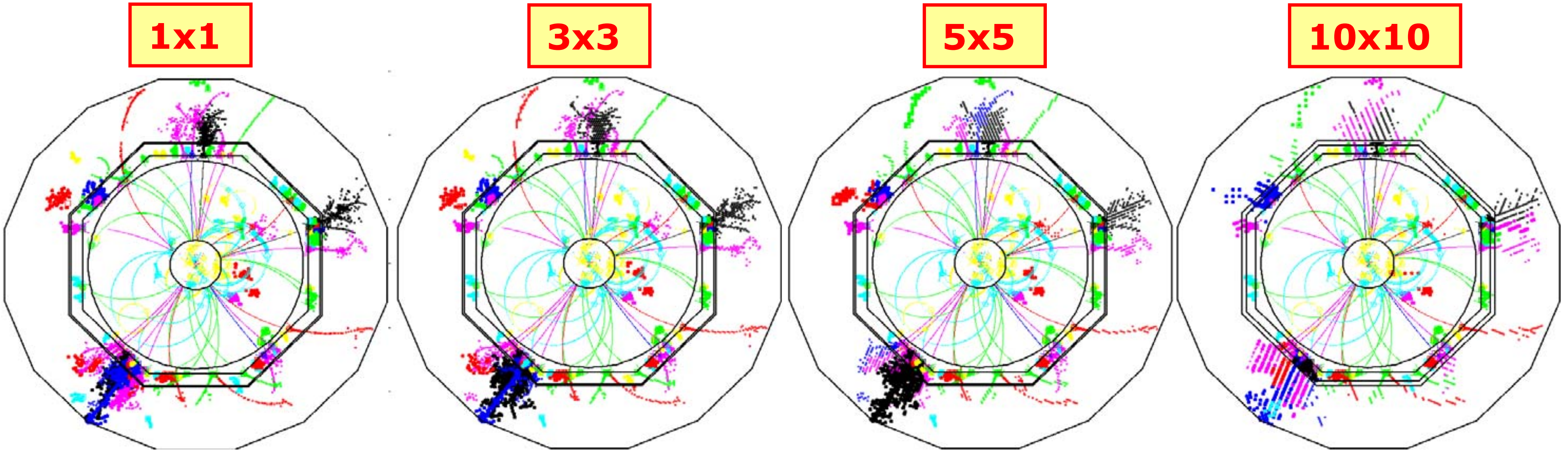
- ★ Empirically find

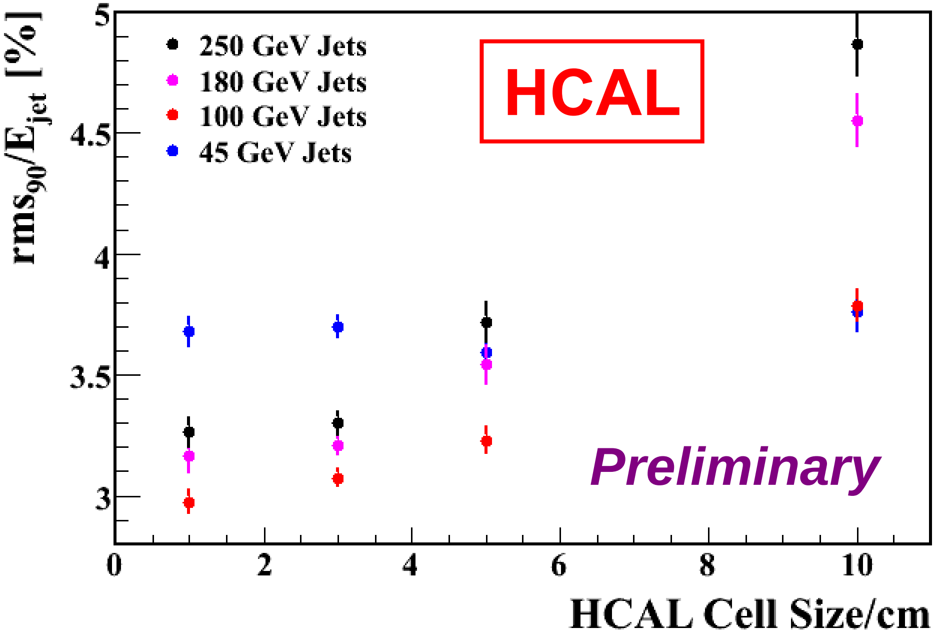
$$\frac{\sigma_E}{E} = \frac{21}{\sqrt{E/\mathrm{GeV}}} \oplus 0.7 \oplus 0.004E \oplus 2.1\left(\frac{R}{1825}\right)^{-1.0}\left(\frac{B}{3.5}\right)^{-0.3}\left(\frac{E}{100}\right)^{+0.3}\%$$

Resolution **Tracking** **Leakage** **Confusion**

- ★ **Conclude:**
  - R is more important than B for PFA performance
  - Confusion term ∝ $B^{-0.3}R^{-1}$
  - 1/R makes sense – it's just geometry

How important is segmentation ?

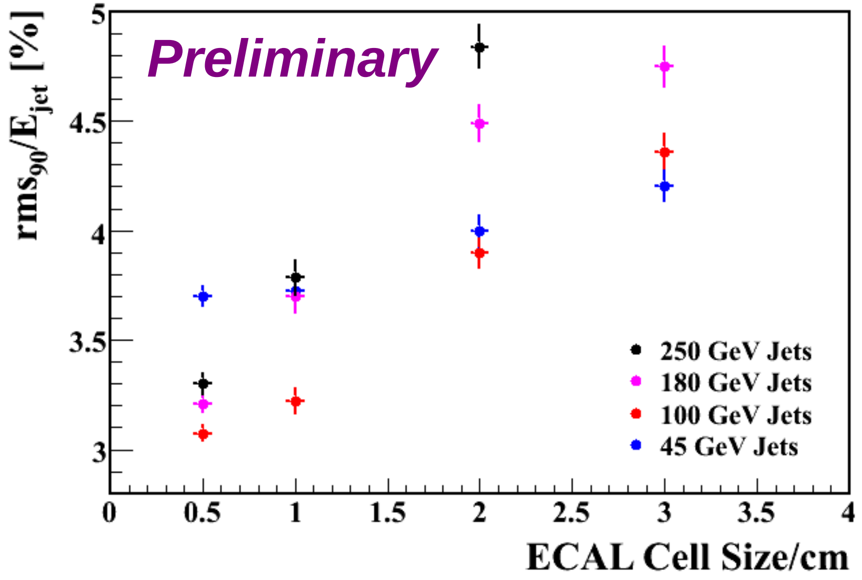




- 3×3cm^2 looks reasonable
- Hint of gain going to 1×1cm^2
- Significant degradation for larger tile sizes, e.g. 5×5cm^2

and ECAL Segmentation ?

- ★ Investigate 10×10mm^2, 20×20mm^2 and 30×30mm^2
  - ▪ Note: retuned PandoraPFA clustering parameters



- ★ Performance is a strong function of pixel size
- ★ High ECAL segmentation is vital for PFA

Caveat:

⚠
- ▪ Remember results are algorithm dependent
- ▪ Could reflect flaw in reconstruction

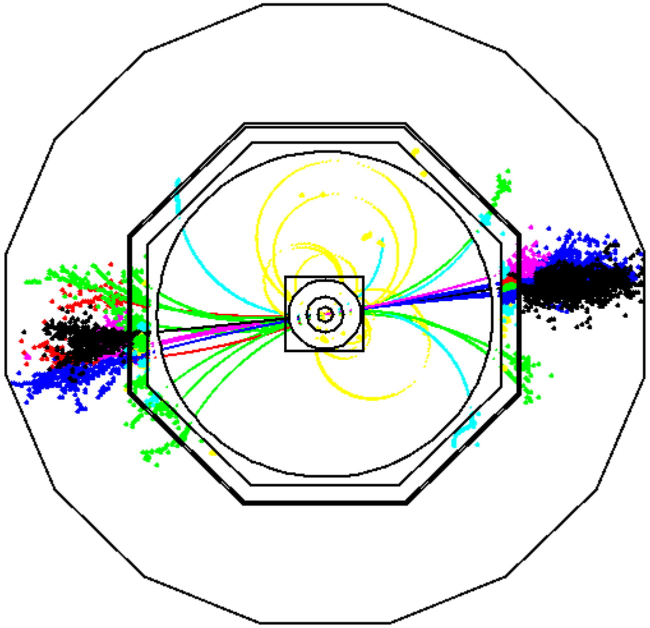
★ **Nevertheless:** highly segmented HCAL/ECAL clearly essential

- ★ **Particle Flow can deliver ILC jet energy goals**
- ★ **Whole detector concepts studied, and (partially) optimised**
  e.g. ILD
- ★ **What about Particle Flow for higher energy machines ?**

❽ Particle Flow at CLIC

- ★ Particle Flow can deliver **ILC** jet energy goals
- ★ Detector concepts studied, and (partially) optimised
  e.g. ILD
- ★ What about Particle Flow for CLIC ?

STEP 1: take ILD and run…



500 GeV Jet

500 GeV Jet

General Considerations

★Traditional calorimetry $\sigma_E/E \approx 60\%/\sqrt{E/\mathrm{GeV}}$

★Does not degrade significantly with energy (but leakage will be important at CLIC)

★Particle flow gives much better performance at "low" energies

- very promising for ILC

What about at CLiC ?

★PFA perf. degrades with energy

★For **500 GeV jets**, current alg. and ILD concept:

$$\sigma_E/E \approx 85\%/\sqrt{E/\mathrm{GeV}}$$

★Crank up field, HCAL depth…

$$\sigma_E/E \approx 65\%/\sqrt{E/\mathrm{GeV}}$$

★**Algorithm not tuned for very high energy jets, so can probably do significantly better**

rms90 PandoraPFA v03-β

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E_j
45 GeV	23.8 %	3.5 %
100 GeV	29.1 %	2.9 %
180 GeV	37.7 %	2.8 %
250 GeV	45.6 %	2.9 %
500 GeV	84.1 %	3.7 %
500 GeV	64.3 %	3.0 %

63 layer HCAL (8 λ_I)
B = 5.0 Tesla

Conclude: for 500 GeV jets, PFA reconstruction not ruled out

- For **1 TeV** jets, particle flow will not give $\sigma_E/E < 60\%/\sqrt{E/\mathrm{GeV}}$
  (probably substantially worse)
- This is probably not a problem for two reasons
  - i) Not interested in 1 TeV jets:
    - most interesting physics likely to be **6, 8, ... fermion final states**
    - For **0.5 TeV** jets, particle flow likely to be comparable or better than a traditional calorimetric approach
  - ii) A PFlow calorimeter still has good calorimetric resolution
    can design algorithm to move away from particle flow at higher energies

Particle Flow → **Energy Flow** → **Calo Energy**

- Could be adapted on event, jet, locality basis
- Energy flow "trivial" to implement in **PandoraPFA**
- An adaptive algorithm should not be too difficult…

But, a particle flow detector is expensive: possible to justify cost ?

Physics Considerations

★ Whether particle flow is appropriate for a **multi-TeV e^+e^-** collider needs detailed study but depends on <u>physics program</u>, e.g.

- CLIC is unlikely to operate solely at the highest energy
- Likely to be a rich physics program below max. energy
  - lower $\sqrt{s}$ to study **Higgs**, **SUSY threshold scans**, etc.
  - Here Particle Flow Calorimetry highly desirable

<u>For high energy running what are the calorimetry goals ?</u>

★ For **ILC** reasonably well defined, wish to separate W/Z

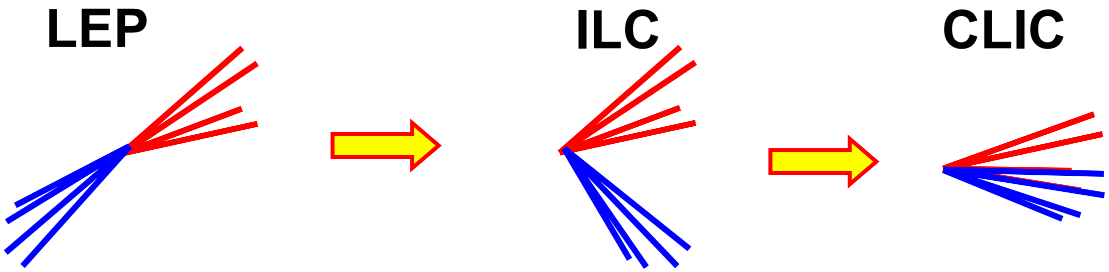
★ For **CLIC**, less clear and again depends on physics program

★ What is most important:

- direct reconstruction of high mass particles
  - What jet energy scale ? Not $\sqrt{s}/2$
  - For 6 fermion final states current PFA already competitive (ILD+)
  - What mass resolution is needed ?
  - For 1TeV particle, e.g. $X \rightarrow q\bar{q}$ decaying at rest current PFA + ILD detector: $\boxed{\frac{\sigma_m}{m_X} \sim 2.7\,\%}$
- Missing transverse energy (i.e. p_T) resolution ?
- W/Z separation ?

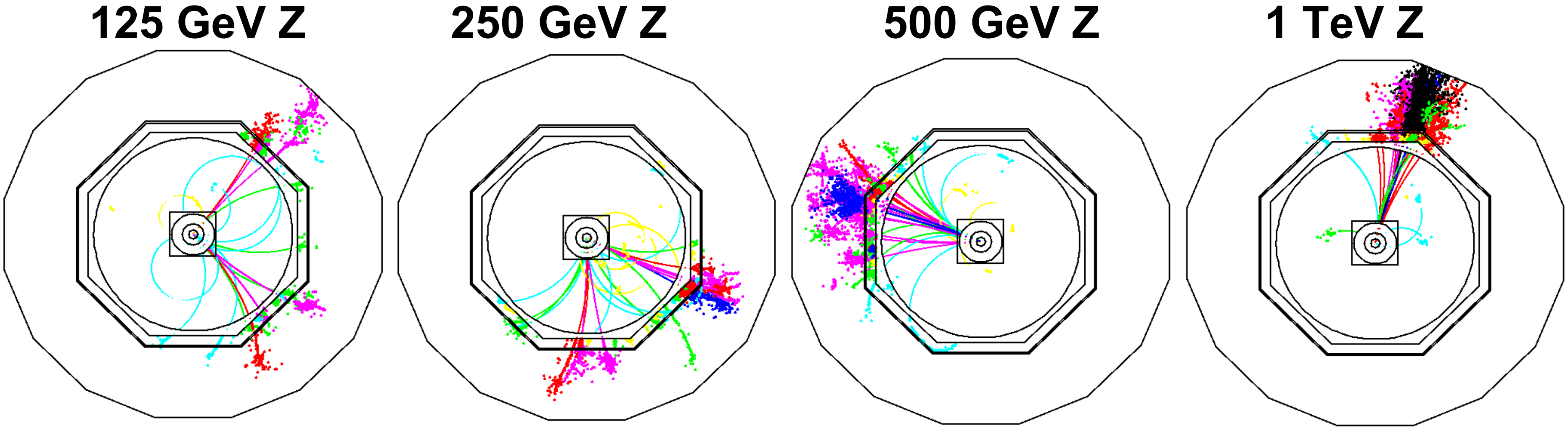
W/Z Separation at high Energies

- On-shell W/Z decay topology depends on energy:

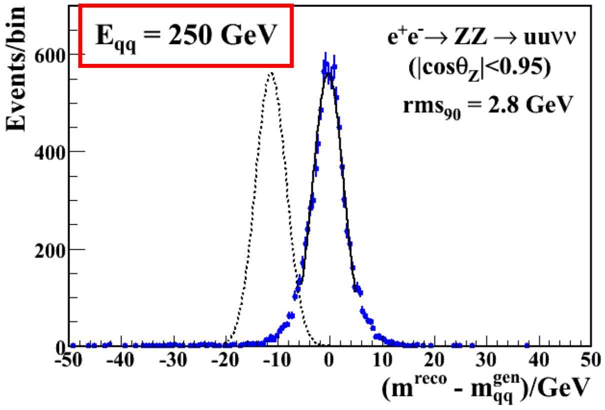


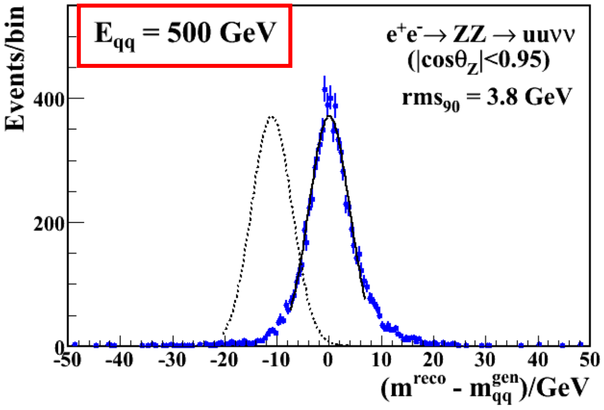
Particle flow reco. might help here

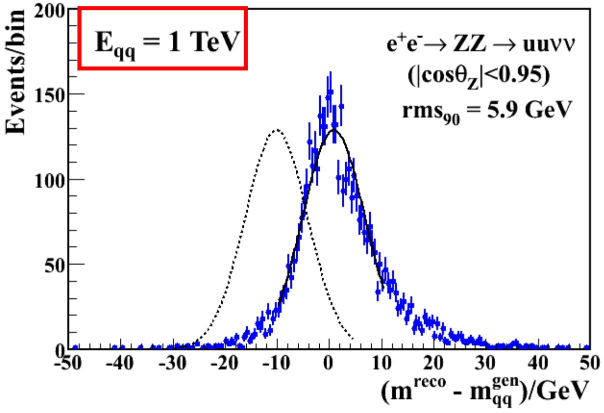
- A few comments:
  - Particle multiplicity does not change
  - Boost means higher particle density
  - PFA could be better for "mono-jet" mass resolution
- PandoraPFA + ILD performance studied for:



- Study Z mass resolution as function of E_Z with ILD detector (TPC based, B=3.5 T, 6 λ_I HCAL)







rms90 **PandoraPFA v03-β**

E_Z	σ_E/E	σ_m/m
125 GeV	2.4 %	2.7 %
250 GeV	2.5 %	3.1 %
500 GeV	3.1 %	4.1 %
1 TeV	4.2 %	6.2 %
1.5 TeV	5.6 %	8.2 %

❽ Conclusions

★ Particle Flow at the ILC

Now have a proof of principle of Particle Flow Calorimetry

⇨ **Unprecedented Jet Energy Resolution**

- Based on full simulation/reconstruction (gaps and all) of ILD detector concept

PFLOW drives design of ILC Detectors: ILD and SiD

★ Particle Flow at CLIC

Particle Flow Calorimetry certainly not ruled out

- Need to consider in context of the full CLIC physics programme
  - what drives jet energy resolution goals at CLIC ?
- For Higgs + threshold studies, CLIC would be likely to run at lower energy: here there is a strong argument for PFA
- For mono-jet mass resolution, PFA may help at high energies (needs study)
- Perhaps surprisingly, ILD detector concept looks like it will give “OK” performance for 500 GeV jets and 1 TeV Zs: i.e. TPC, 3.5 T, 6 λ_I

Thank you