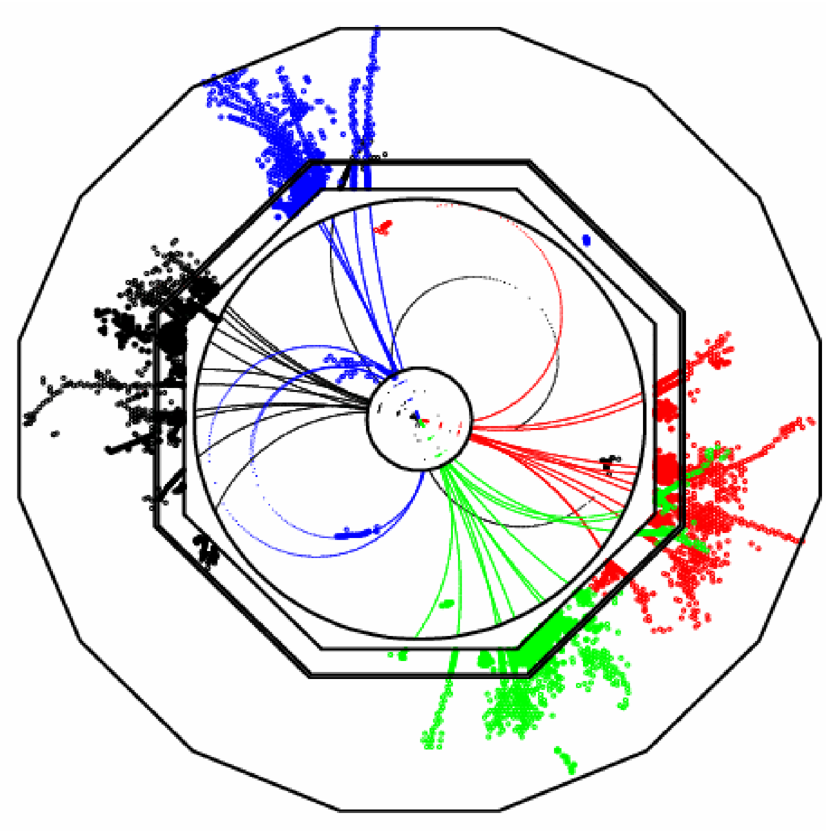
Particle Flow Calorimetry

Mark Thomson
University of Cambridge



This Talk:

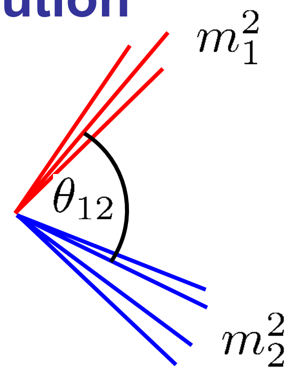
1. Calorimetry at the ILC
2. The Particle Flow Paradigm
3. The ILD Detector Concept
4. PandoraPFA
5. Particle Flow at the ILC
6. Particle flow at CLIC
7. CLIC Detector Considerations
8. Conclusions

❶ Calorimetry at the ILC

★ 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 $\Gamma_{\mathrm{W/Z}}$

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

⇨ $\sigma_{E_j}/E_j < 3.8\%$

+ term due to θ_{12} uncertainty

★ What jet energies are we interested in ?

- Depends on **physics**
- Not $E_{\mathrm{jet}} = \sqrt{s}/2$
- Interested in 4-6+ fermion final states

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

★ Typical di-jet energies at **500 GeV ILC:** (50-150 GeV)

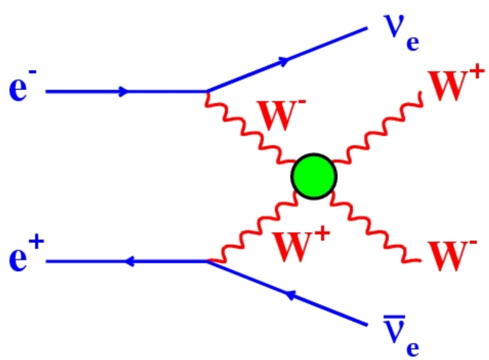
$$\sigma_E/E < 0.20/\sqrt{E_{jj}(\mathrm{GeV})} - 0.33/\sqrt{E_{jj}(\mathrm{GeV})}$$

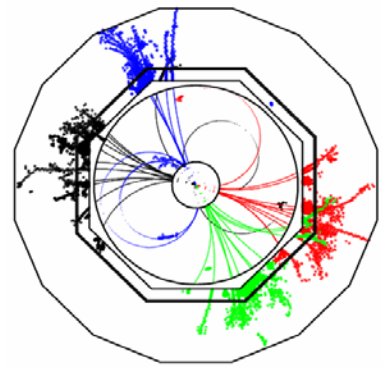
★ Typical di-jet energies at **1 TeV ILC:** (100-300 GeV)

$$\sigma_E/E < 0.27/\sqrt{E_{jj}(\mathrm{GeV})} - 0.46/\sqrt{E_{jj}(\mathrm{GeV})}$$

Why is this important ?

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

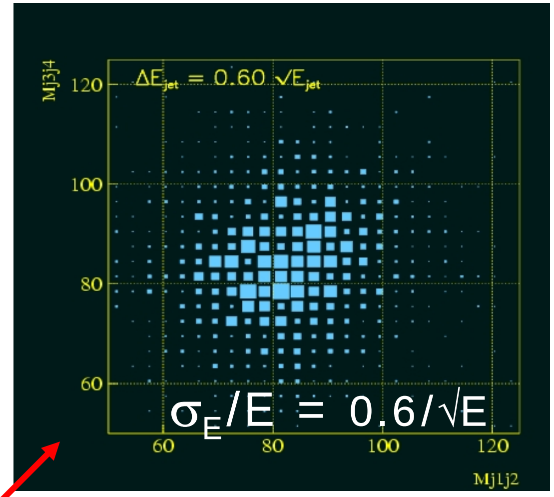


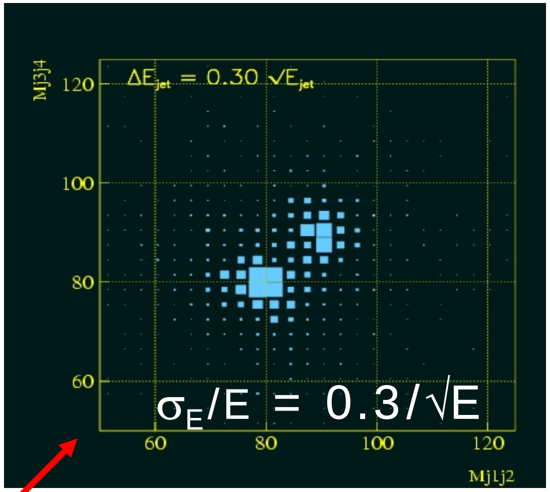


If the Higgs mechanism is not responsible for EWSB then WW fusion processes important

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

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





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

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

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

or more correctly

$\sigma_E/E < 3.8\%$

Remember this number

★Unlikely 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

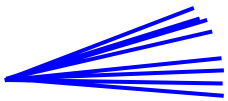
Dual Readout

Within the ILC community, widely believed to be most promising approach

❷ The Particle Flow Paradigm

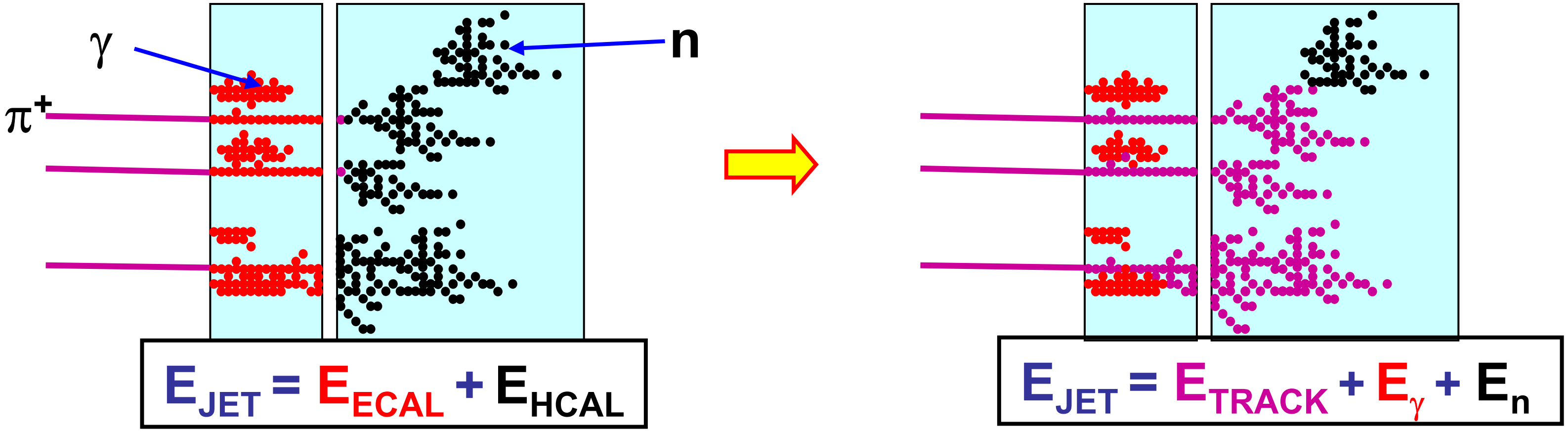
★ **In a typical jet :**

- **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**



★ **Particle Flow Calorimetry paradigm:**

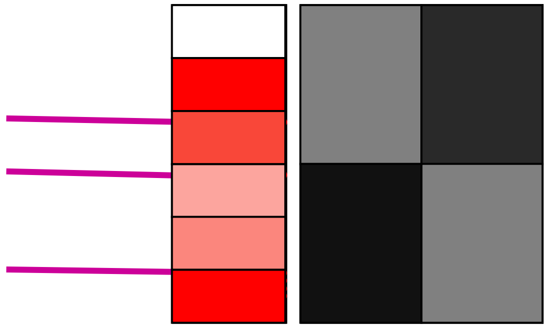
- **charged particles measured in tracker (essentially perfectly)**
- **Photons in ECAL: $\sigma_\mathrm{E}/\mathrm{E} < 20\,\%/\sqrt{\mathrm{E(GeV)}}$**
- **Neutral hadrons (ONLY) in HCAL**
- **Only 10 % of jet energy from HCAL ⇒ much improved resolution**

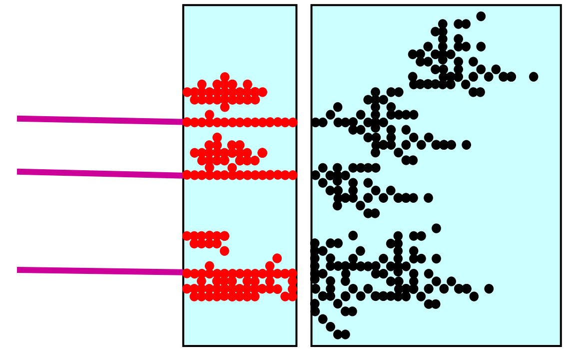
Particle Flow Calorimetry

Hardware:

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

→ Highly granular detectors (as studied in CALICE)

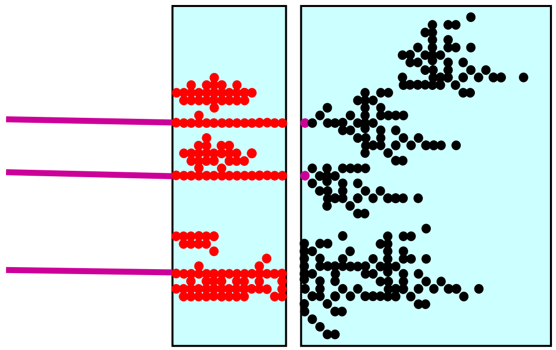


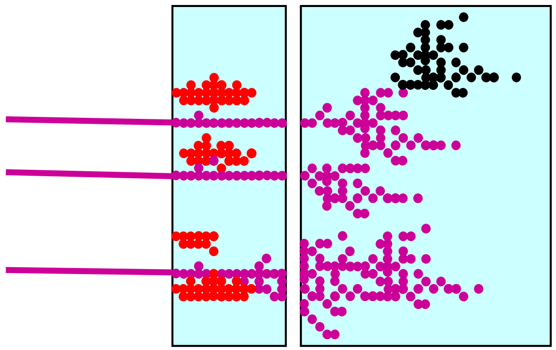


Software:

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

→ Sophisticated reconstruction software





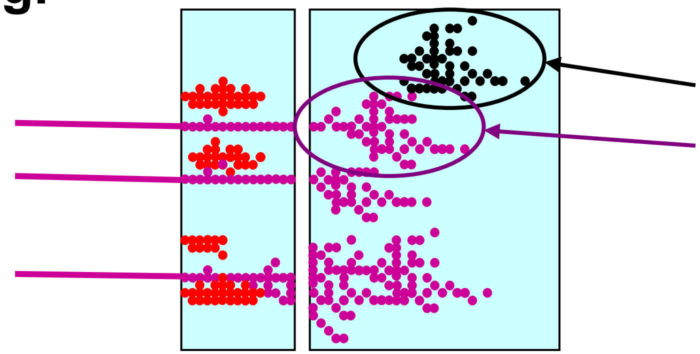
★ **Particle Flow Calorimetry = HARDWARE + SOFTWARE**

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
- ★ Studies need to be based on a sophisticated detector simulations
  - can't use fast simulation

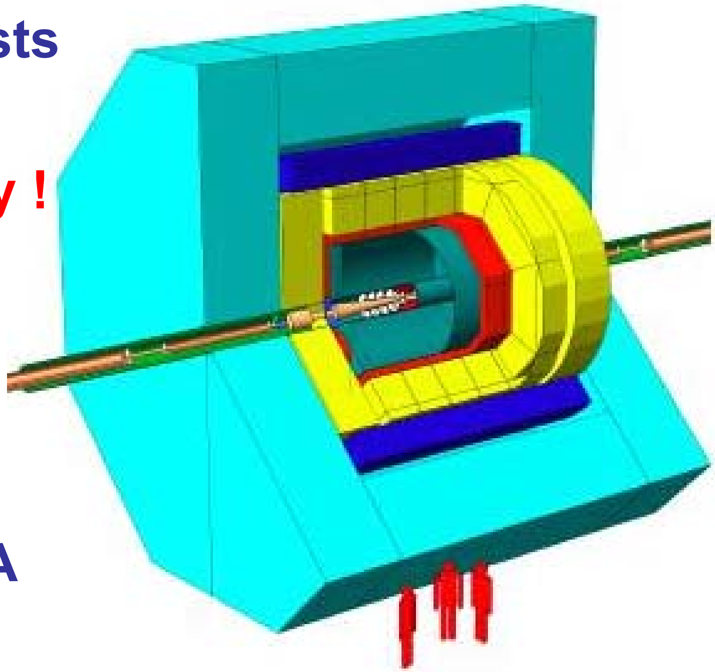
❸ e.g.The ILD Detector Concept*

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:

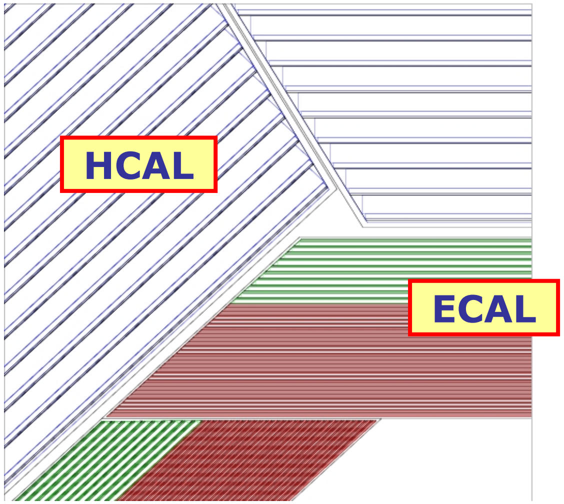
- Large TPC central tracker (R=1.8 m)
- CMS like solenoid (B = 3.5 T)
- ECAL and HCAL inside solenoid
- ECAL/HCAL highly segmented for PFA

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)

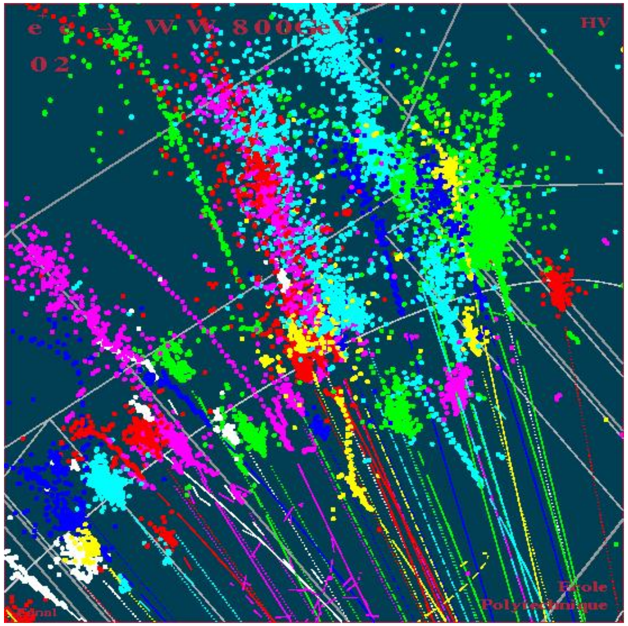
★ Ongoing test beam studies (CALICE) see Nigel Watson's talk

*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**

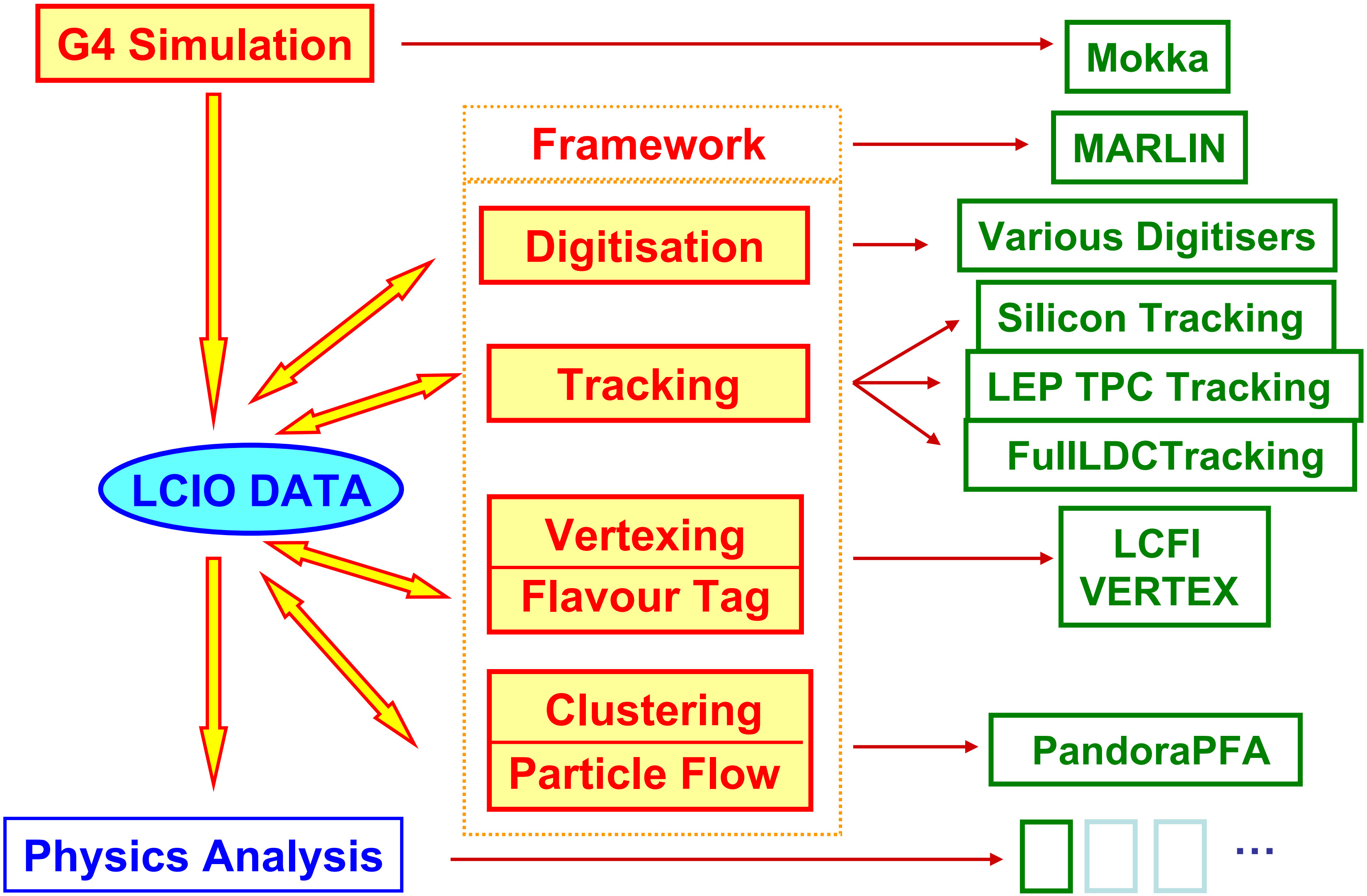
➡ difficult to evaluate full potential of particle flow

$\sigma_E/E = f$ (software)

To evaluate Particle Flow Calorimetry at ILC (or CLIC) need realistic reconstruction chain (PFA, tracking,…)

ILD Reconstruction Framework (C++)

★ Everything exists – level of sophistication ~LEP experiment



❹ The PandoraPFA Algorithm

This is work-in-Progress – currently best algorithm on market

- ★ 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:

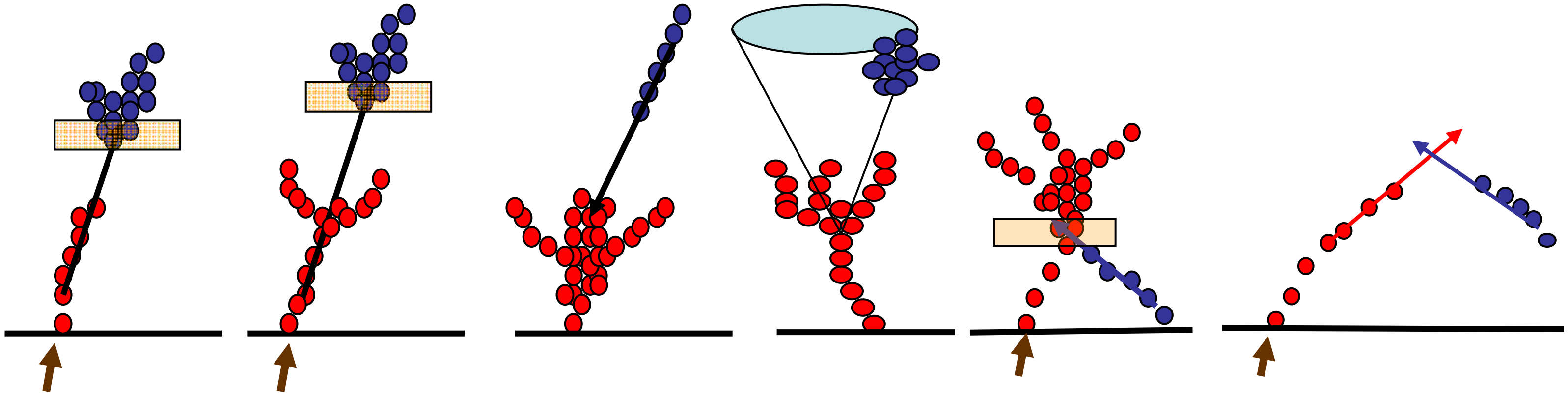
i. Track classification/extrapolation
ii. Loose clustering in ECAL and HCAL
iii. Topological linking of clearly associated clusters
iv. Courser grouping of clusters
v. Iterative reclustering
vi. Photon Identification/Recovery
vii. Fragment removal
viii. Formation of final Particle Flow Objects (reconstructed particles)

iii) Topological Cluster Association

★ Clusters associated using a number of topological rules

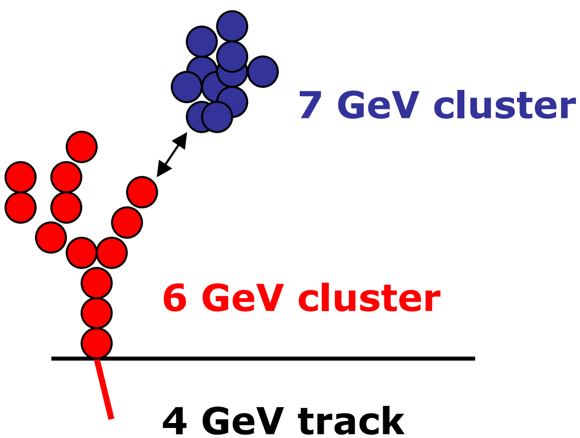
Clear Associations:

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



Less clear associations:

e.g. Proximity

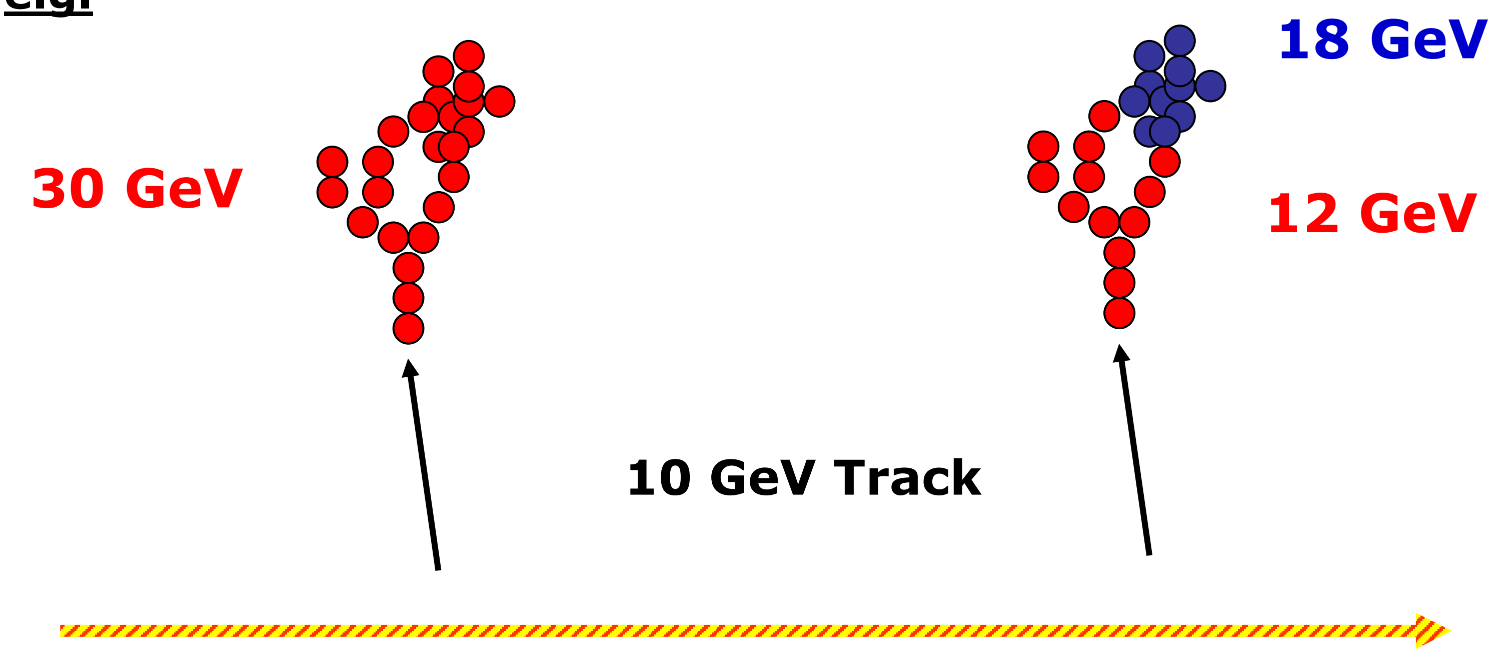


Use E/p consistency to veto clear mistakes

v) Iterative Reclustering

★ If track momentum and cluster energy inconsistent : RECLUSTER

e.g.



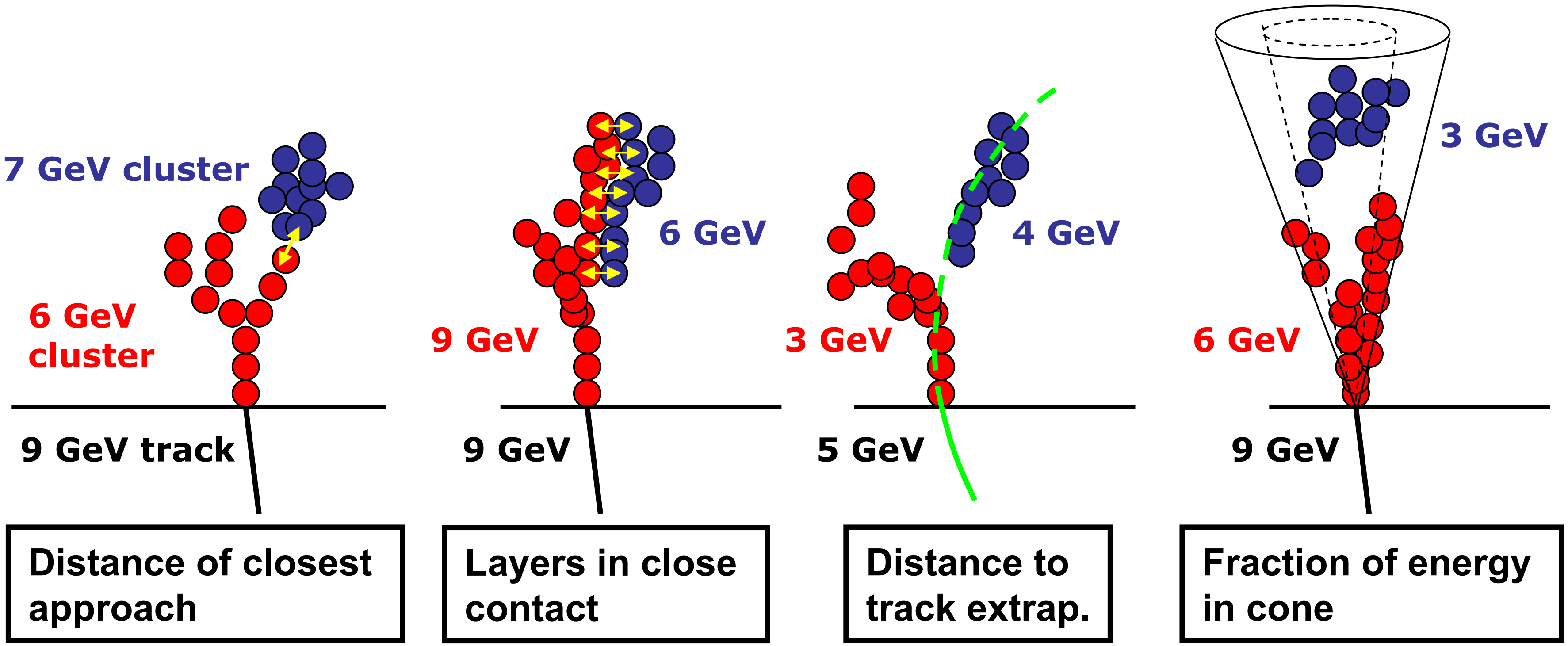
Change clustering parameters until cluster splits and get sensible track-cluster match

NOTE: clustering driven by track momentum (but not subtraction)

This is very important for higher energy jets

viii) Fragment removal : basic idea

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



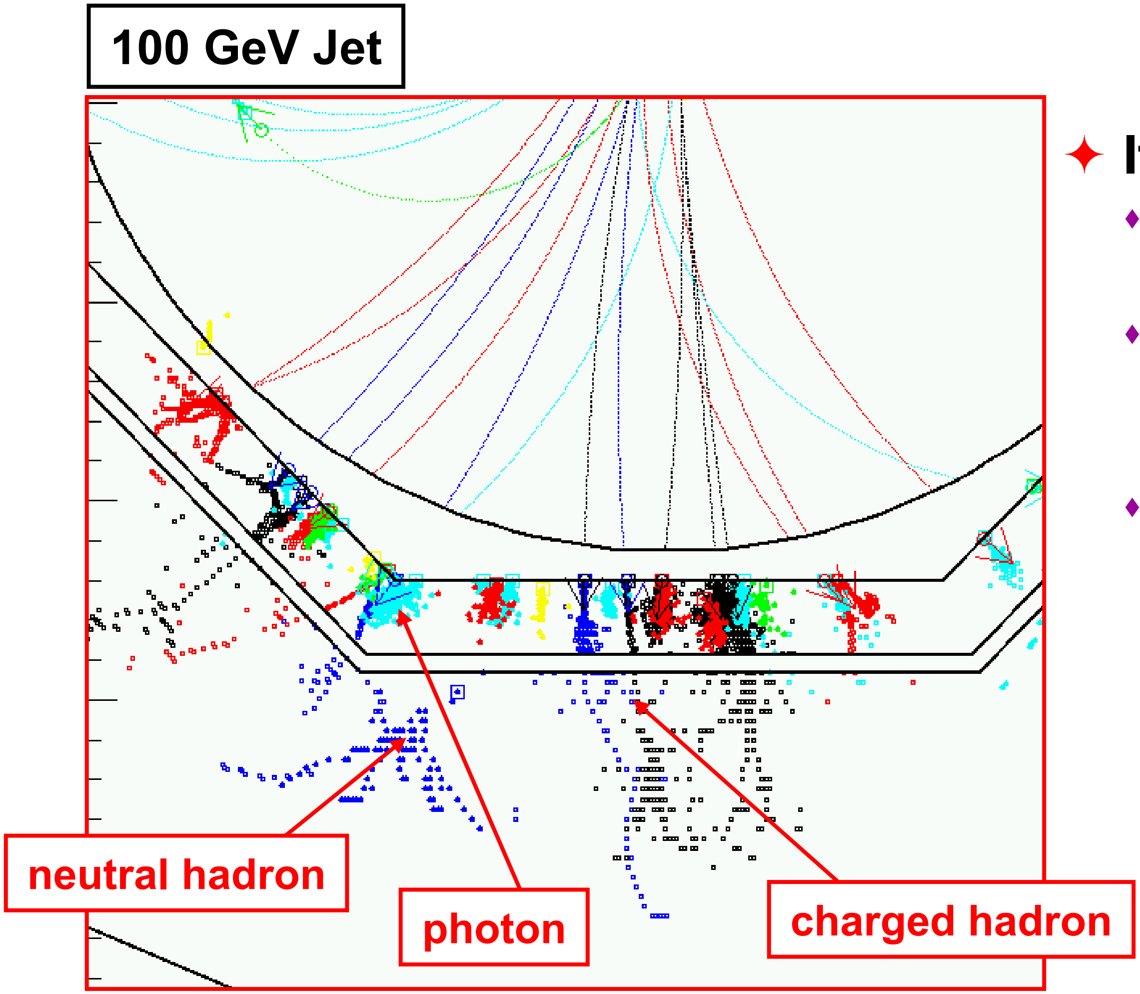
★ Convert to a numerical evidence score **E**

★ 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

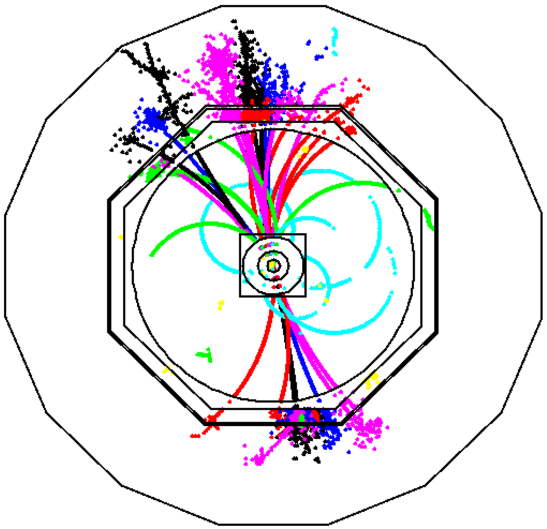
Putting it all together…



- **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.**

❺ Particle Flow at the ILC

- ★ 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

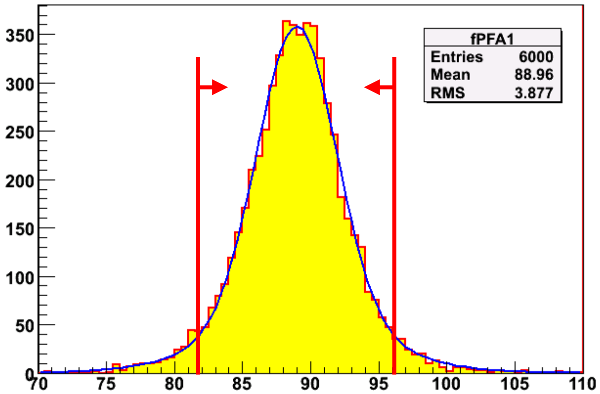


NOTE:

- 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

rms_{90}

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



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

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
- "Realistic" detector, gaps etc.
- 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:

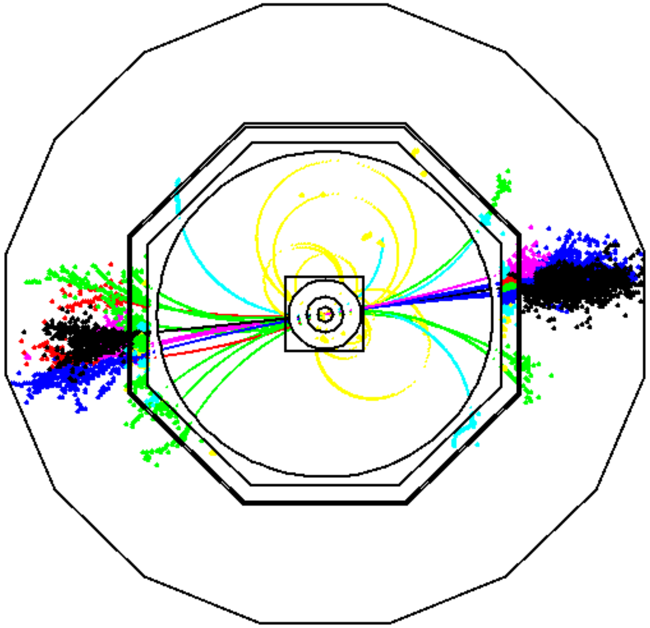
PARTICLE FLOW CALORIMETRY WORKS

At least in simulation

❻ 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 $\sigma_E/E \approx 60\%/\sqrt{E/\text{GeV}}$

★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

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

What about at CLiC ?

★PFA perf. degrades with energy

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

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

★Crank up field, HCAL depth…

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

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

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 physics program, 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

For high energy running what are the calorimetry goals ?

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

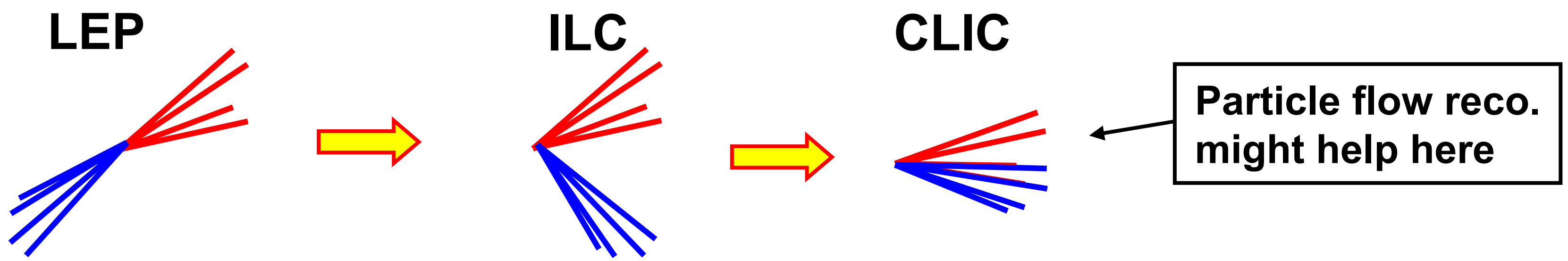
★ For **CLIC**, less clear and again depends on physics program

★ 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: $\frac{\sigma_m}{m_X} \sim 2.7\,\%$
- Missing transverse energy (i.e. p_T) resolution ?
- W/Z separation ?

W/Z Separation at high Energies

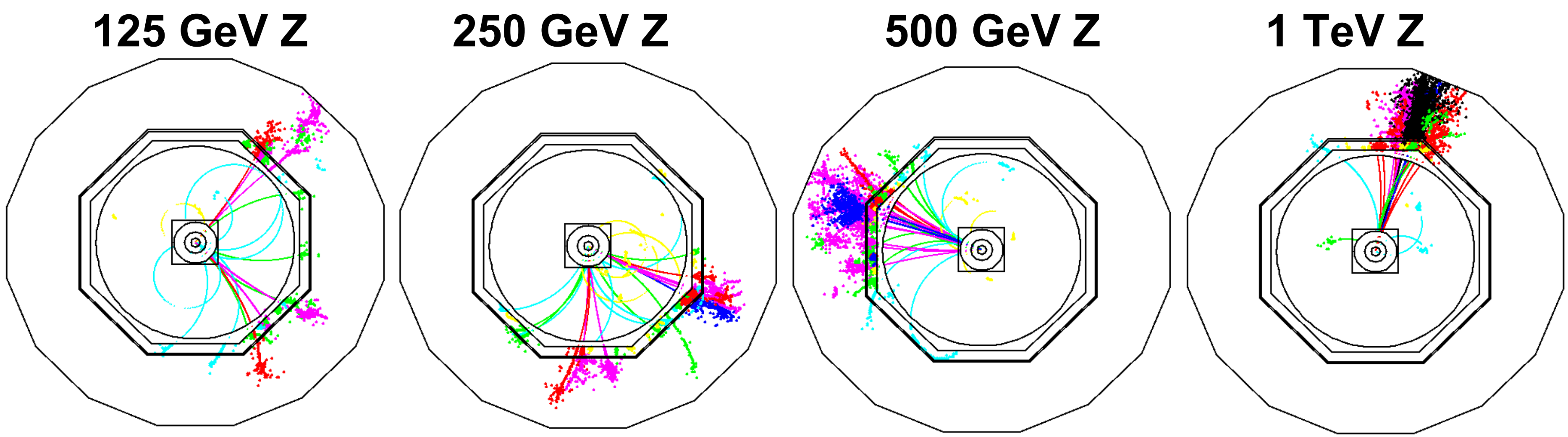
★ On-shell W/Z decay topology depends on energy:



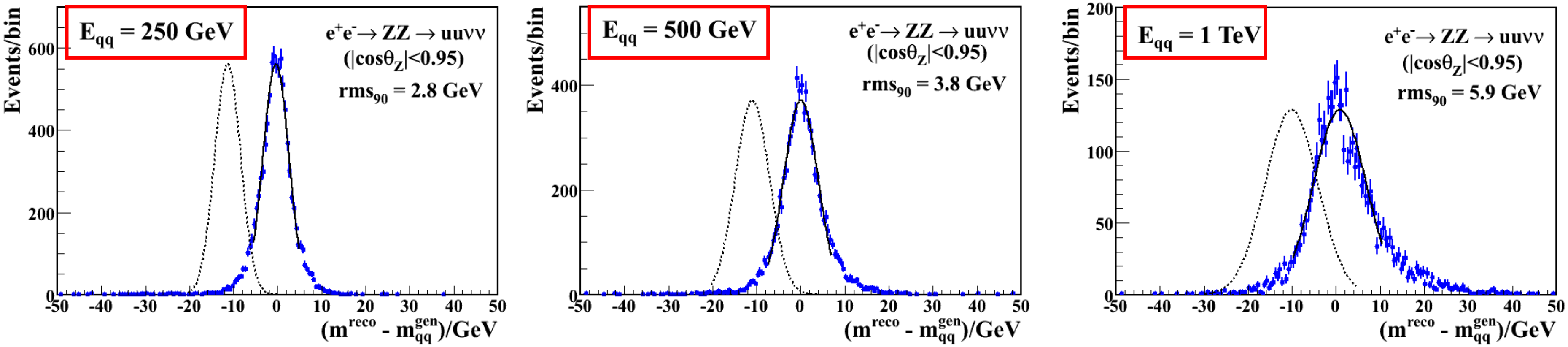
★ A few comments:

- 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)**



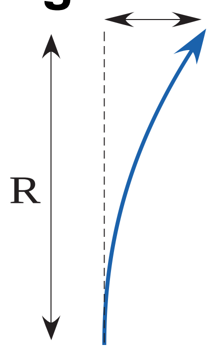
rms90 **PandoraPFA v03-β**

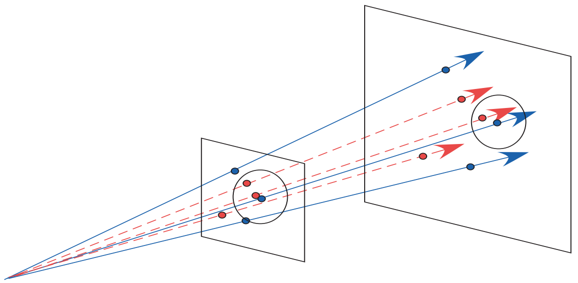
E_Z	σ_E/E	σ_m/m
125 GeV	2.4 %	2.7 %
250 GeV	2.5 %	3.1 %
500 GeV	3.1 %	4.1 %
1 TeV	4.2 %	6.2 %
1.5 TeV	5.6 %	8.2 %

❼ CLIC Detector Considerations

★ 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





WRONG

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

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

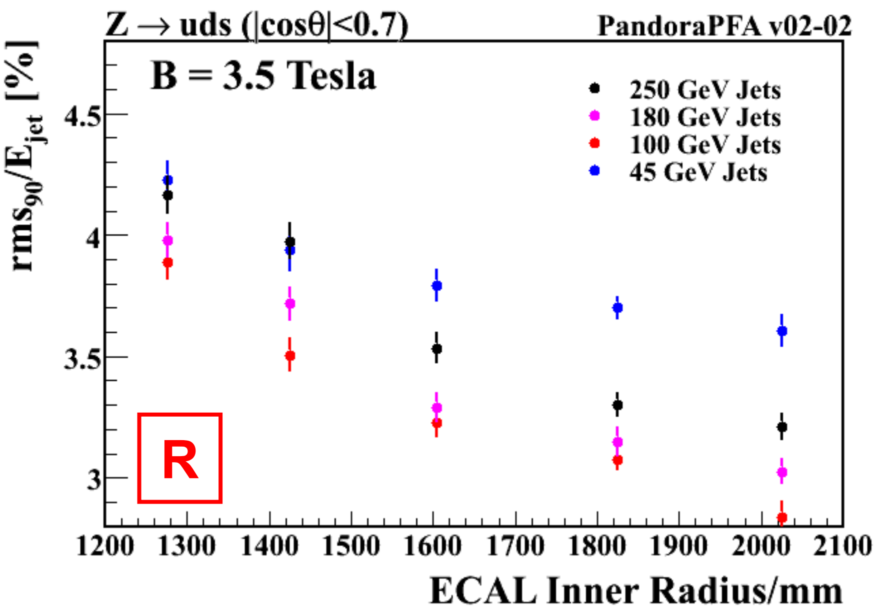
★ Argues for: large + high granularity + ⇧ B

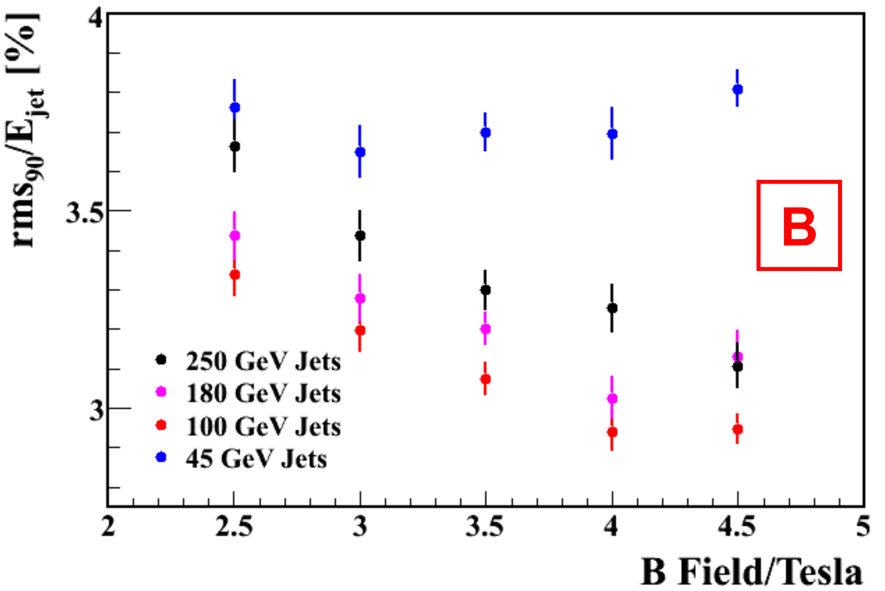
★ Cost considerations: small + lower granularity + ⇩ B

→ Study ILC (CLIC) detector parameters using PandoraPFA

! Interpretation: observing effects of detector + imperfect software

ILC/ILD: vary ECAL Inner Radius





★ Empirically (for current algorithm) find

$$\frac{\sigma_E}{E} = \frac{0.021}{\sqrt{E}} \oplus 0.01 \oplus 0.02 \left(\frac{R}{1825}\right)^{-1.0} \left(\frac{B}{3.5}\right)^{-0.35} \left(\frac{E}{100}\right)^{+0.4}$$

Resolution | Tracking/Leakage/Fragments | Confusion

- As expected, larger + higher field gives best performance
- R more important than B

⇨ motivates choice of ILD detector concept parameters

(SiD concept team investigating small, high B-field option)

B vs R at CLIC

- ★ CLIC energies will push limits of Particle Flow Calorimetry
- ★ Particle Flow argues more strongly for large **R** rather than high **B**
- ★ For high energy jets, estimate (based on ILC/ILD studies)

R: 1.25m → 2.0m : +60 % improvement

B: 5.0 T → 3.5 T : +13 % improvement

Argument for high B-field is not Particle Flow !

B impacts inner radius of Vertex Detector

Dependence not strong

$r_{\text{inner}} \propto \sqrt{B}$

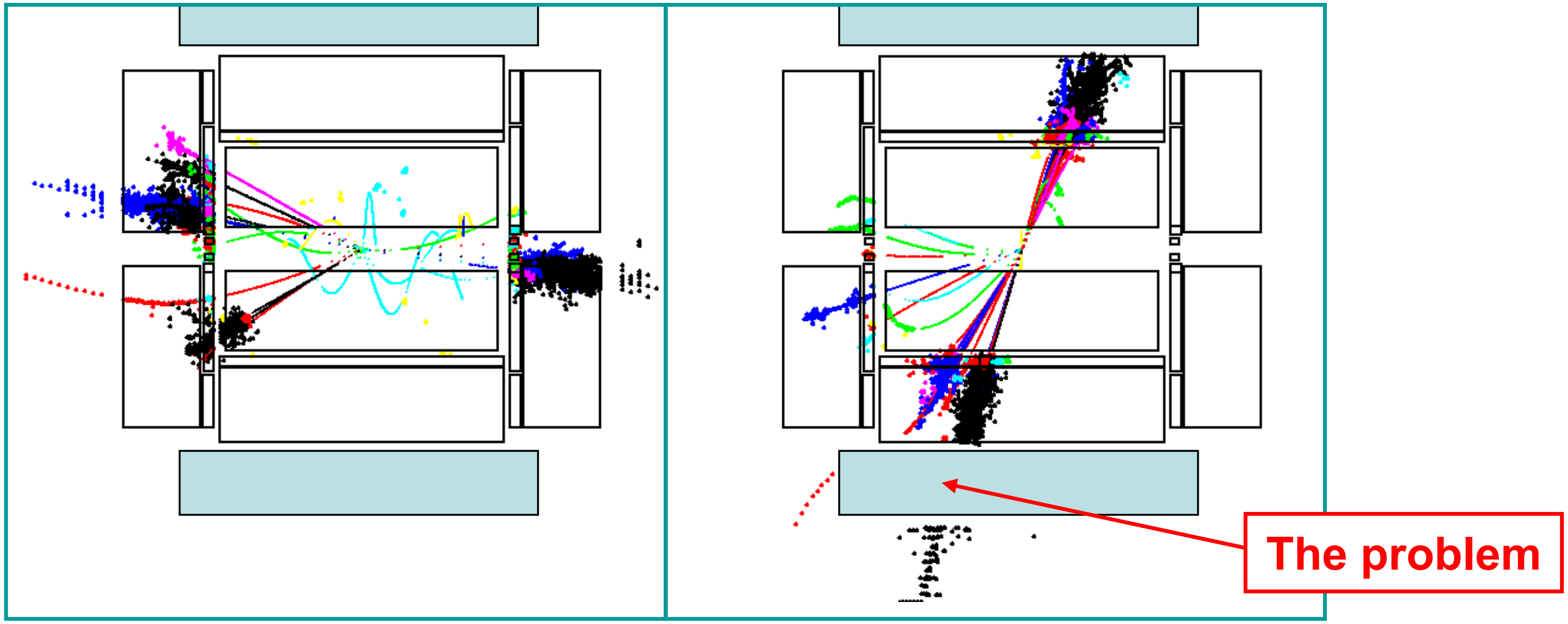
ILC Optimisation Studies: HCAL Depth

Two interesting questions:

★ **How important is HCAL leakage ?**
  - vary number of HCAL layers

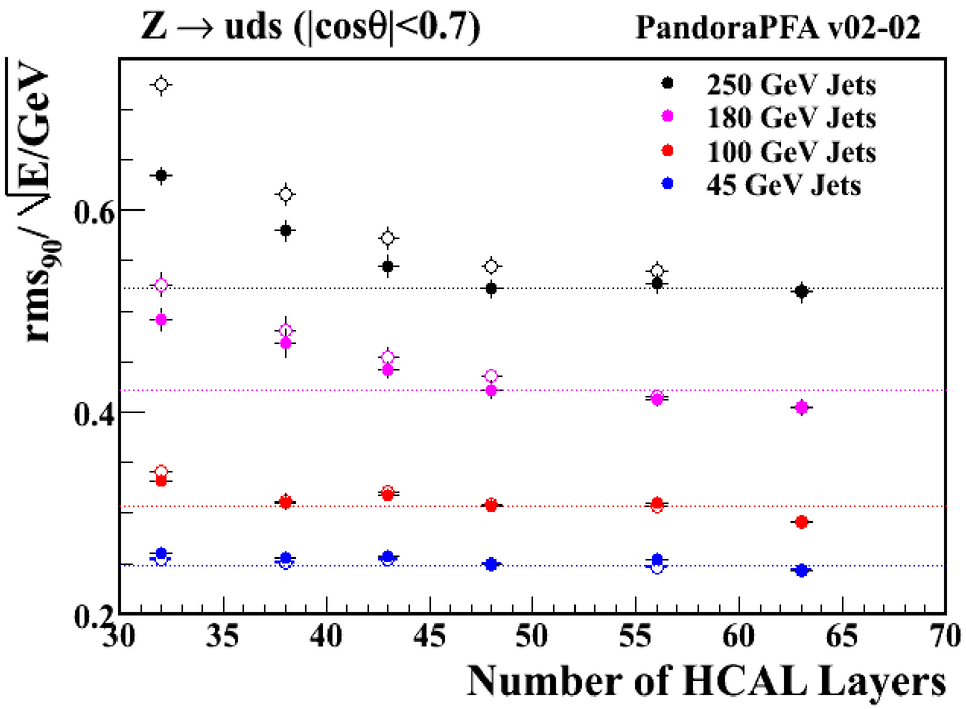
★ **What can be recovered using MUON chambers as a "Tail catcher"**
  - PandoraPFA now includes MUON chamber reco.
  - Switched off in default version
  - Simple standalone clustering (cone based)
  - Fairly simple matching to CALO clusters (apply energy/momentum veto)
  - Simple energy estimator (digital)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

e.g.



ILC/ILD HCAL Depth Results

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

★ Results will depend 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)

HCAL Depth at CLIC

Not much data:

E_{JET}	HCAL	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ |cosθ|<0.7	σ_E/E_j
500 GeV	6 λ_I	84.1 %	3.7 %
500 GeV	8 λ_I	~70 %	3.4 %

63 layer HCAL (8 λ_I)
B = 5.0 T, corrected to B = 3.5 T

For 3 TeV machine: 6 λ_I not sufficient

For 3 TeV machine: 8 λ_I ?

Needs study

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

★ 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

Conclusions cont.

★ A Particle Flow Detector for CLIC

- Tracker should be as large as possible
  - r = 1.25 m, almost certainly too small for CLIC
- Argument for high B is not from Particle Flow
  - momentum resolution/vertex tagging
- Argument for B = 5 T at CLIC may not be that strong
- From ILD studies, no evidence (yet) for problems related to a TPC, don't rule it out yet

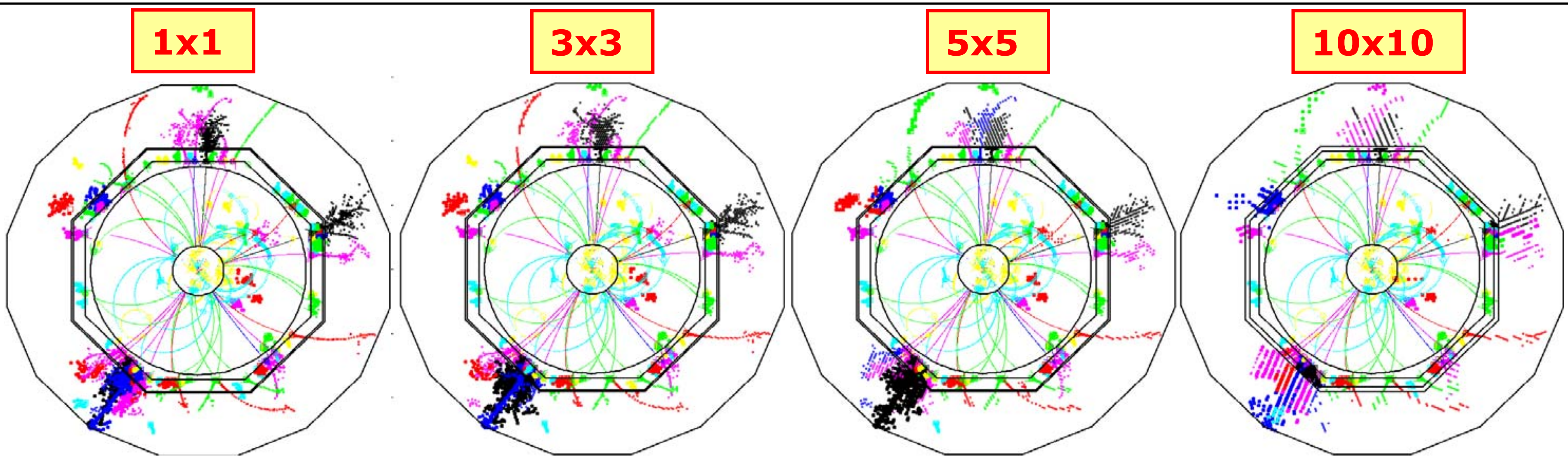
★ A Particle Flow Development for CLIC

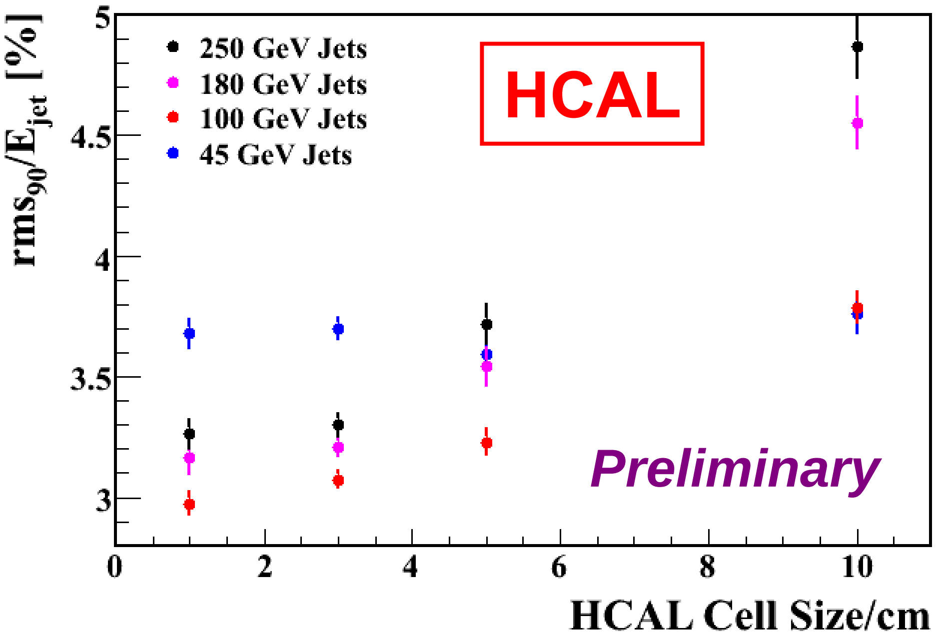
- Not *a priori* obvious that Particle Flow is the right approach for CLIC
- Will require study/development
  - correcting for leakage
  - evolution from PFlow to EFlow to pure calorimetry
  - understanding of jet mass reconstruction…

Requires new effort

End

How important is segmentation ?

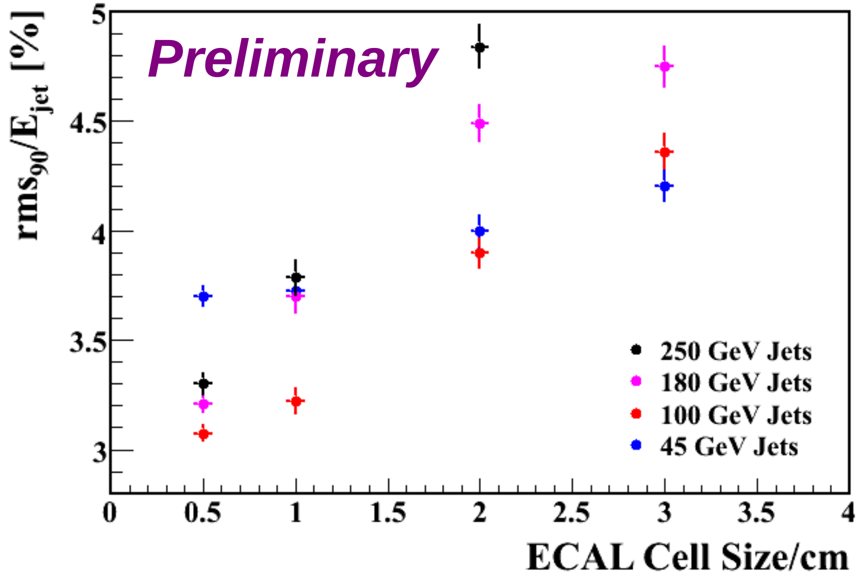




- 3×3cm^2 looks reasonable
- Hint of gain going to 1×1cm^2
- Significant degradation for larger tile sizes, e.g. 5×5cm^2

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