High Granularity Particle Flow Calorimetry at the ILC/CLIC

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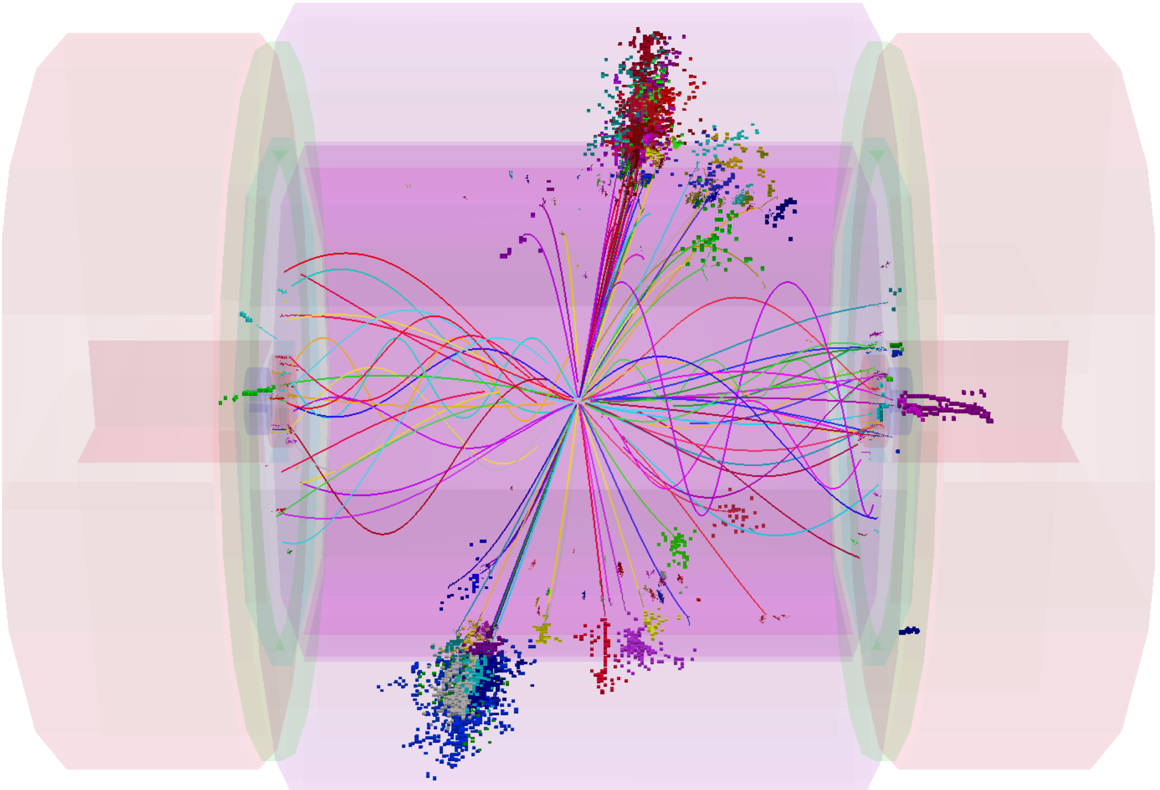
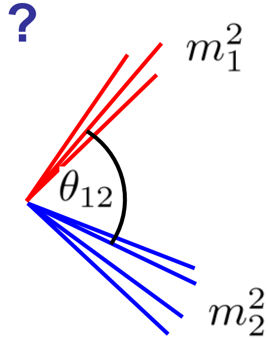


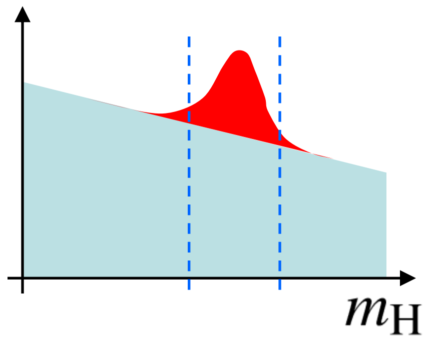
This Talk

★ Primarily and introduction to Particle Flow as developed for the ILC
★ Try and give a broad overview of issues and current status
★ Different from previous approaches to Particle/Energy
  - assume/design detector "optimised" for Pflow Calorimetry

➊ Calorimetry at a Future Lepton Collider

- ★ **What motivates the jet energy requirements at a future LC ?**
  - **in part, depends on physics**
- ★ **Likely to be primarily interested in di-jet mass resolution**
  - **For a narrow resonance, want best possible di-jet mass res.**

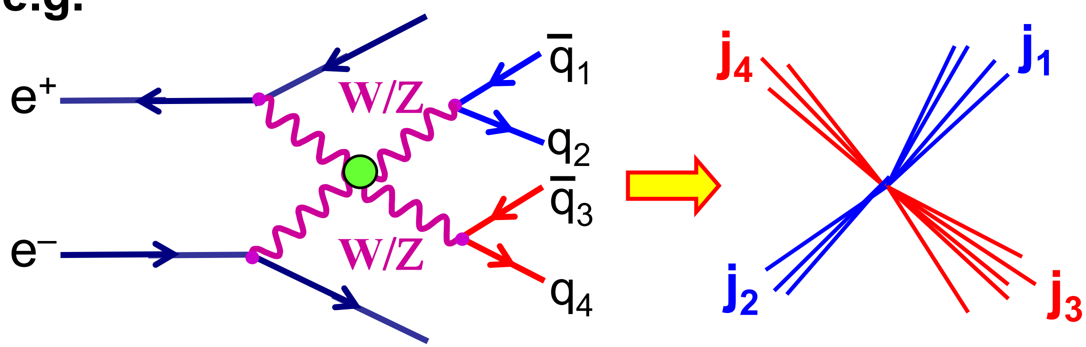


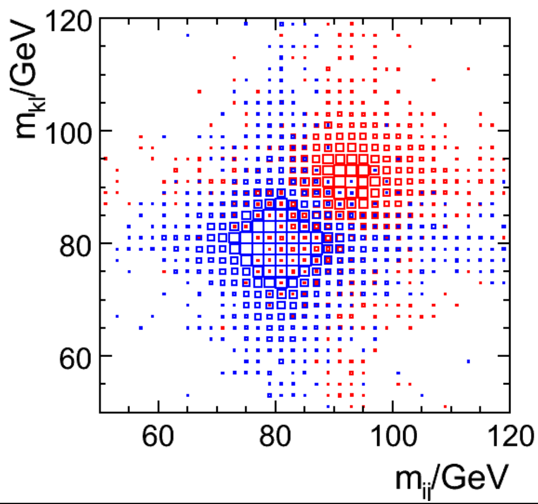


$$\text{signif.} \propto \frac{S}{\sqrt{B}} \quad \propto (\text{resolution})^{-\frac{1}{2}}$$

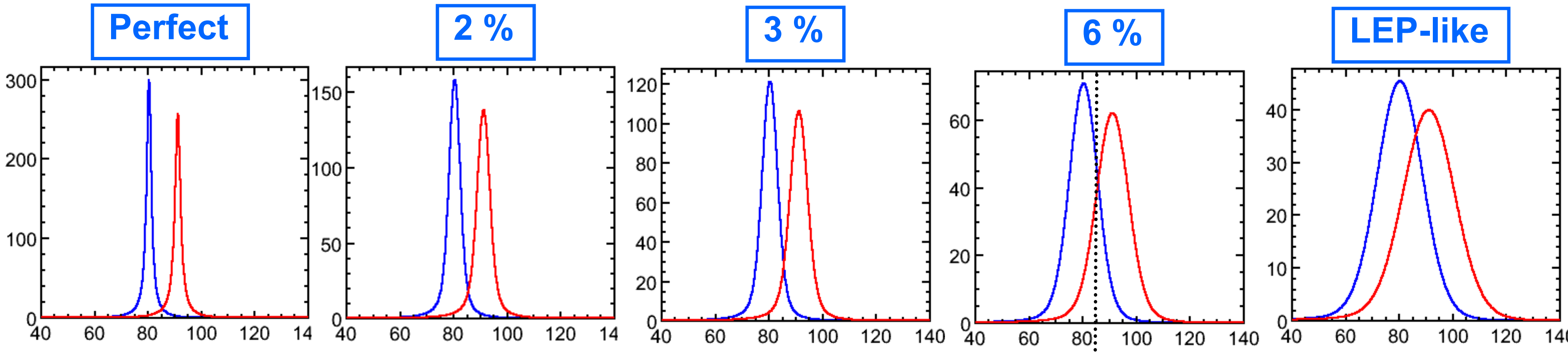
- **At very least, need to separate W/Z hadronic decays**

e.g.





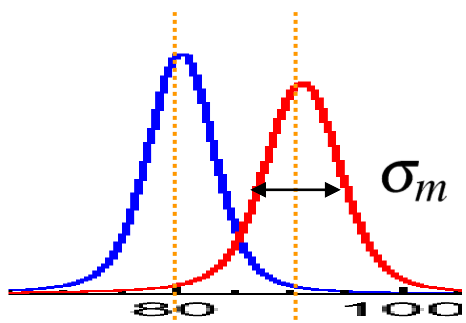
- **Gauge boson width sets “natural” goal for minimum jet energy resolution**



- **Quantify by effective W/Z separation**

$$\mathrm{W/Z\ sep} = (m_Z - m_W)/\sigma_m$$

Jet E res.	W/Z sep
perfect	**3.1 σ**
2%	**2.9 σ**
3%	**2.6 σ**
4%	**2.3 σ**
5%	**2.0 σ**
10%	**1.1 σ**



Defined as effective Gaussian equivalent Mass resolution

- **3 – 4 % jet energy resolution give decent W/Z separation 2.6 – 2.3 σ**
- **sets a reasonable choice for Lepton Collider jet energy minimal goal ~3.5 %**
- **for W/Z separation, not much to gain beyond this as limited by W/Z widths**

Physics Context : LC jet energies

- ★ At **500 GeV** (ILC) primarily interested in **4-fermion/6-fermion** final states
  - e.g. $e^+e^- \to ZH \to q\bar{q}b\bar{b}$ and $e^+e^- \to t\bar{t} \to bq\bar{q}\bar{b}q\bar{q}$
- ★ For higher centre-of-mass energies (CLIC, muon-collider), fermion multiplicities will tend to be higher, e.g. SUSY cascade decays
- ★ Sets scale of typical jet energies:

$\sqrt{s}$	#fermions	Jet energy	
250 GeV	4	~60 GeV	ILC - like
500 GeV	4 – 6	80 – 125 GeV	ILC - like
1 TeV	4 – 6	170 – 250 GeV	ILC - like
3 TeV	6 – 8	375 – 500 GeV	CLIC - like

ILC Goals: ~3.5 % jet energy resolution for 50 – 250 GeV jets

CLIC Goals: ~3.5 % jet energy resolution for 100 – 500 GeV jets

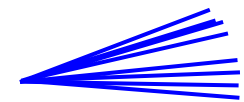
Sets the goal for calorimetry at a future LC

Can be achieved with particle flow technique

❷ Particle Flow Calorimetry

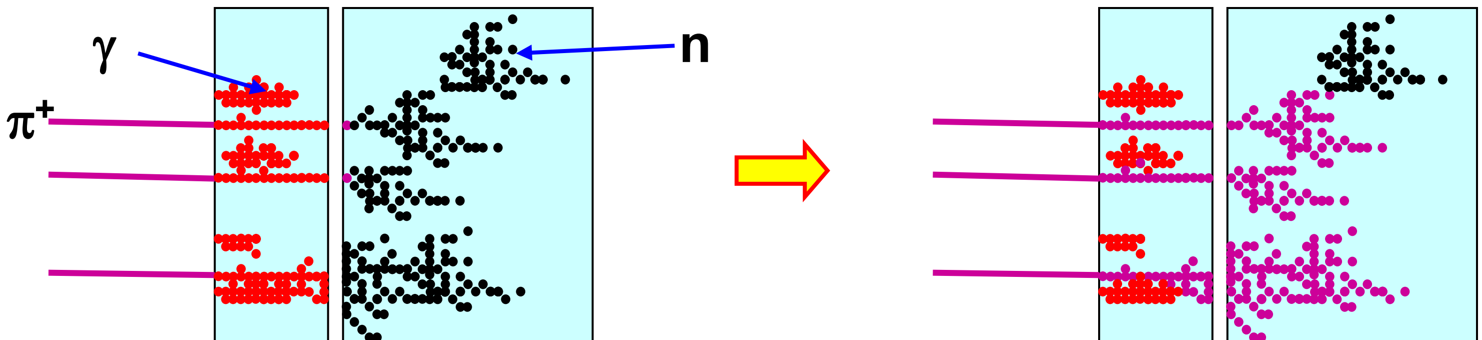
★ **In a typical jet :**

- 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



$\mathrm{E_{JET} = E_{ECAL} + E_{HCAL}}$ $\quad\Rightarrow\quad$ $\mathrm{E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}}$

★ **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 $\Rightarrow$ much improved resolution

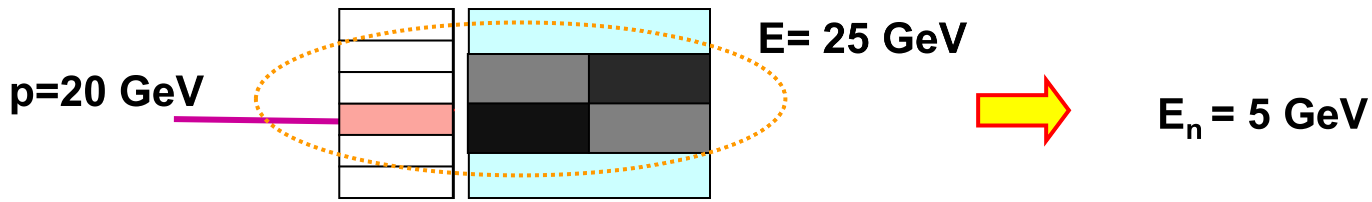
Nomenclature

★ Before moving on, a few words on nomenclature from the LC perspective

"Energy Flow" vs "Particle Flow"

"Energy Flow" vs "Particle Flow"

- The idea *behind* particle flow calorimetry is not new
- a *similar* idea was first (?) used by ALEPH NIM A360:481-506, 1995
  - Jet energies reconstructed using an "ENERGY FLOW" algorithm
  - Remove ECAL deposits from IDed electrons/photons
  - Left (mostly) with charged and neutral hadrons
  - However, insufficient HCAL granularity to identify neutral hadrons
  - Neutral hadrons identified as significant excesses of CAL energy



  - Energy of neutral hadron obtained by subtraction: $E_n = E_{calo} - p_{track}$

⇒ $\sigma_E / E \sim 10\%$ jet E resolution for 45 GeV jets

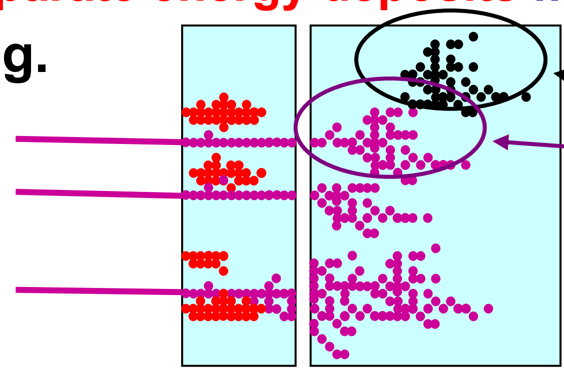
- Similar approach used by a number of other collider experiments
- "PARTICLE FLOW" significantly extends this approach to a high granularity calorimeter
  - Now directly reconstruct neutral hadrons (not subtraction)
  - Potentially much better performance
  - but <u>need</u> highly granular calorimeter + sophisticated software "particle flow algorithm"

Particle Flow Reconstruction

Reconstruction of a Particle Flow Calorimeter:

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

e.g.

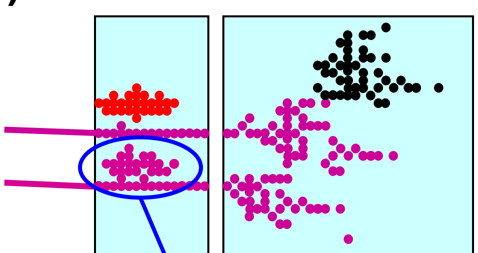


If these hits are clustered together with these, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

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

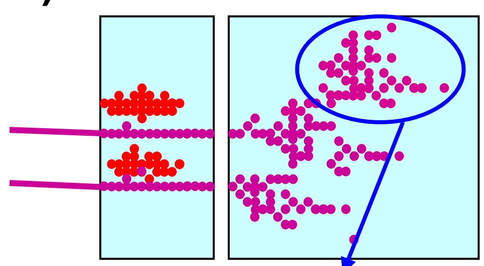
Three types of confusion:

i) Photons



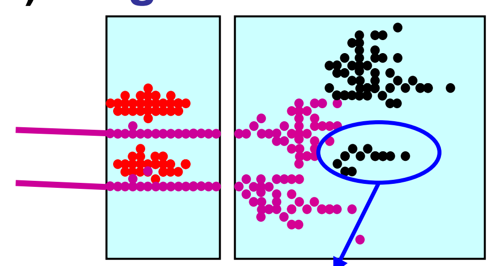
Failure to resolve photon

ii) Neutral Hadrons



Failure to resolve neutral hadron

iii) Fragments

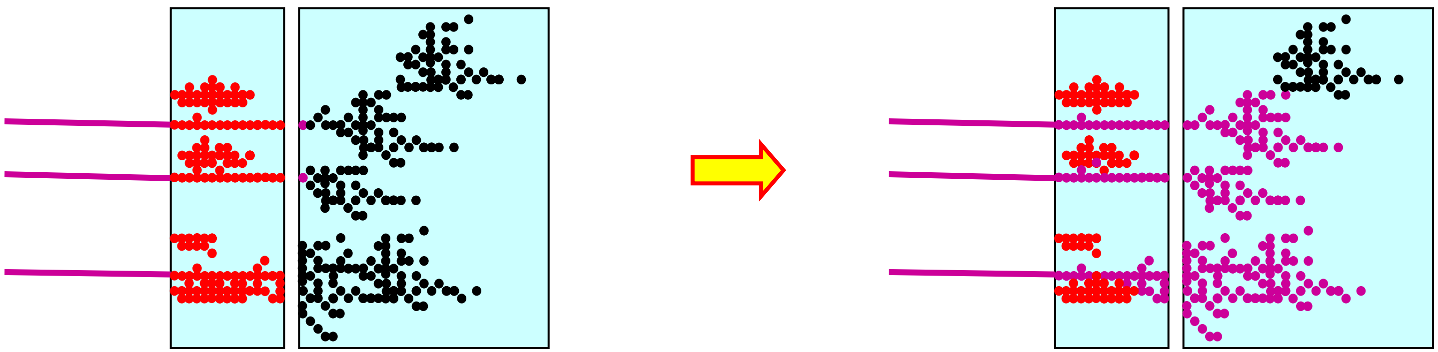


Reconstruct fragment as separate neutral hadron

Towards Particle Flow Calorimetry

- ★ **Particle Flow Calorimetry = HARDWARE + SOFTWARE**
- ★ **Need to study both aspects to demonstrate Pflow concept**
  - ✦ **CALICE studying a number of technological options for a high granularity ECAL/HCAL**
  - ✦ **No obvious show-stoppers…**

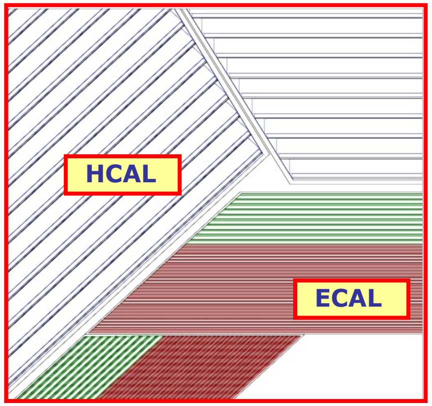
➡ **Then need sophisticated PFlow reconstruction software**



❸ High Granularity Particle Flow Calorimetry motivates LC detector design

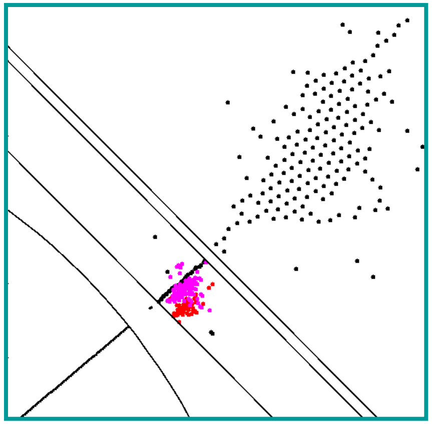
Particle Flow ECAL considerations

★ Require: high longitudinal and transverse segmentation



★ ECAL:

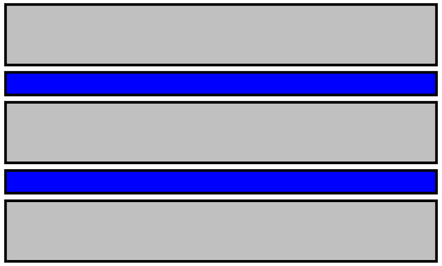
- minimise transverse spread of EM showers
  - ⇨ small Moliere radius
- transverse granularity ~ Moliere radius
- longitudinally separate EM and Hadronic showers
  - ⇨ large ratio of λ_I/X_0
- longitudinal segmentation to cleanly ID EM showers



Material	X_0/cm	ρ_M/cm	λ_I/cm	X_0/λ_I
Fe	1.76	1.69	16.8	9.5
Cu	1.43	1.52	15.1	10.6
W	0.35	0.93	9.6	27.4
Pb	0.56	1.00	17.1	30.5

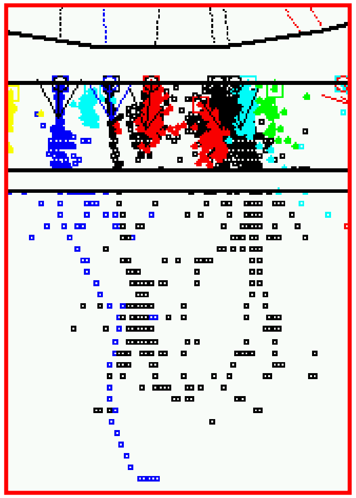
★ Favoured option : Tungsten absorber

- ♦ need to keep sensitive material "thin" to maintain small ρ_M



Particle Flow HCAL considerations

- ★ Require: high longitudinal and transverse segmentation
- ★ HCAL:
  - resolve structure in hadronic showers
    - ⇨ longitudinal and transverse segmentation
  - contain hadronic showers
    - ⇨ small λ_I
  - HCAL will be large: absorber cost/structural properties important



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?

- ★ A number of technological option being studied (mainly) by the CALICE collab: CAlorimetry for the LInear Collider Experiment

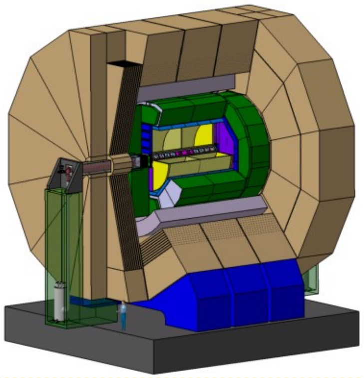
ILC Detector Concepts

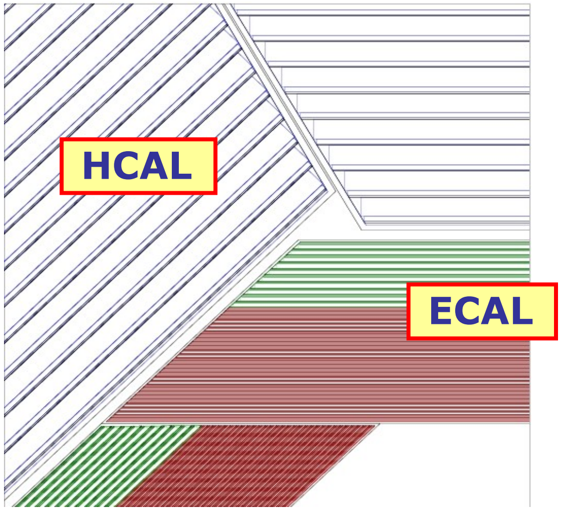
★ Particle Flow needs to be studied in the context of the whole detector
  - tracking is central to particle flow reconstruction

★ Need detailed GEANT 4 simulations of potential detector designs, e.g. the ILC detector concepts (ILD and SiD)

e.g. ILD: International Large Detector

"Large" : tracker radius 1.8m
B-field : 3.5 T
Tracker : TPC
Calorimetry : high granularity particle flow
ECAL + HCAL inside large solenoid





ECAL:

- SiW sampling calorimeter
- longitudinal segmentation: 30 layers
- transverse segmentation: 5x5 mm^2 pixels

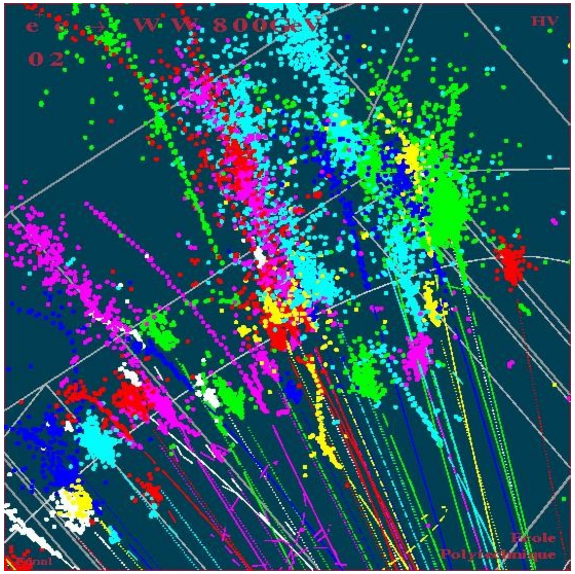
HCAL:

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

Calorimeter Reconstruction

★ **High granularity calorimeters – <u>very different</u> to previous detectors**

★ **"Tracking calorimeter" – requires a new approach to ECAL/HCAL reconstruction – a new problem**



Particle Flow Algorithms (PFA)

★ **To assess full potential of Particle Flow need a "realistic" algorithm**
- **+ full detector reconstruction (no use of Monte Carlo information) many years before project is approved !**

★ **Most sophisticated and best performing Particle Flow Algorithm (PFA) is "PandoraPFA"**

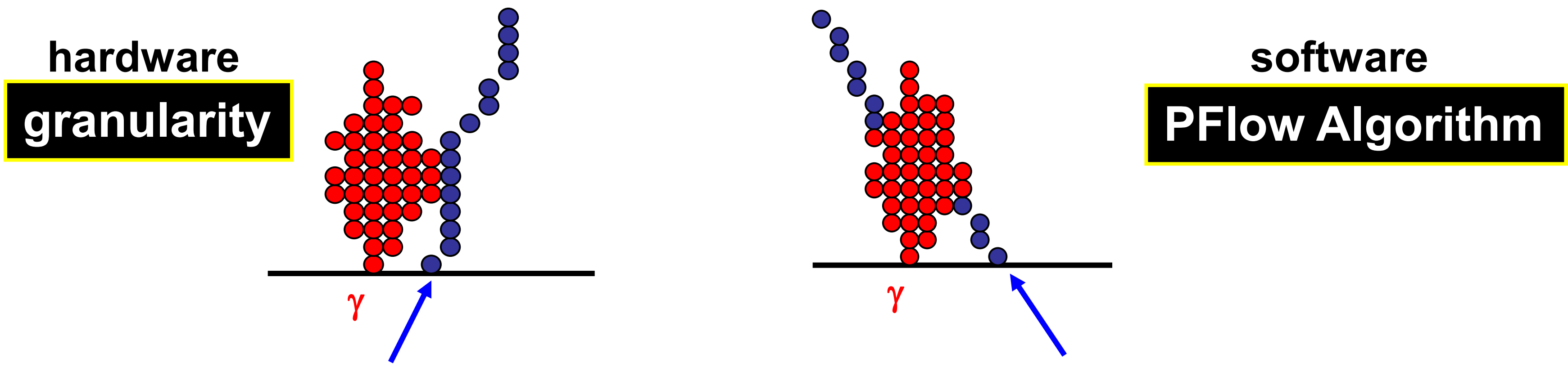
★ **Has been used to:**
- **demonstrate the potential of high granularity Particle Flow Calorimetry**
- **gain an understanding of what drives performance**
- **developing into a flexible clustering/pfa framework/toolkit**

PFA : Basic issues

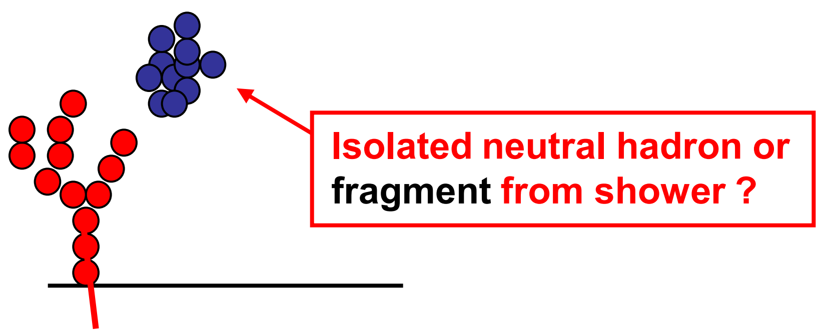
- ★ Separate energy deposits from different particles
- ★ Avoid double counting of energy from same particle
- ★ Mistakes drive particle flow jet energy resolution

<u>**e.g.**</u>

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



- ★ Need to separate neutral hadrons from charged hadrons



- ★ Requires novel/sophisticated reconstruction techniques…

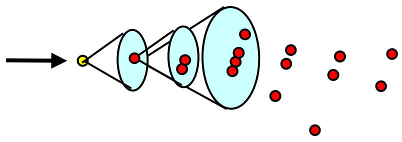
❹ The PandoraPFA Algorithm

★ **High granularity Pflow reconstruction is highly non-trivial !**

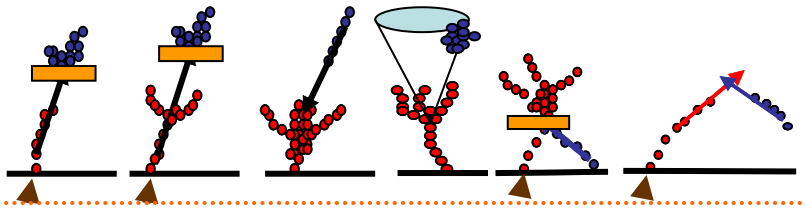
PandoraPFA consists of a many complex steps (not all shown)

❹

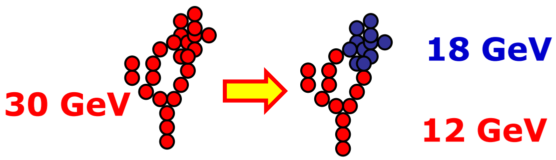
Clustering



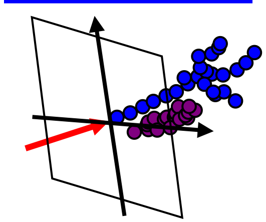
Topological Association



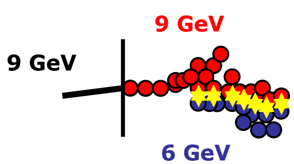
Iterative Reclustering

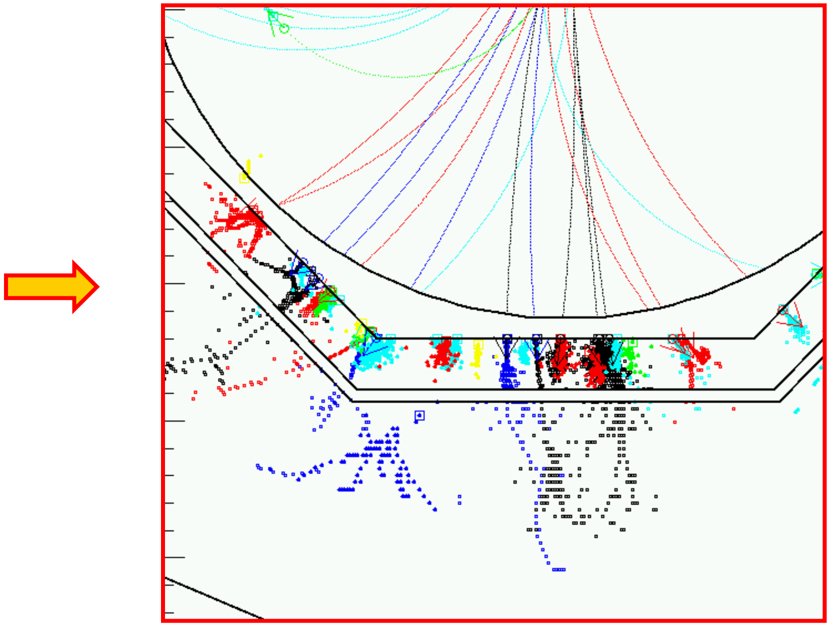


Photon ID



Fragment ID





For more details: MT, NIM 611 (2009) 24-40

PandoraPFA Overview

- ★ ECAL/HCAL reconstruction and PFA performed in a single algorithm
- ★ Applicable to multiple detector concepts
  - ♦ Used to study conceptual designs
- ★ Use tracking information to help ECAL/HCAL clustering

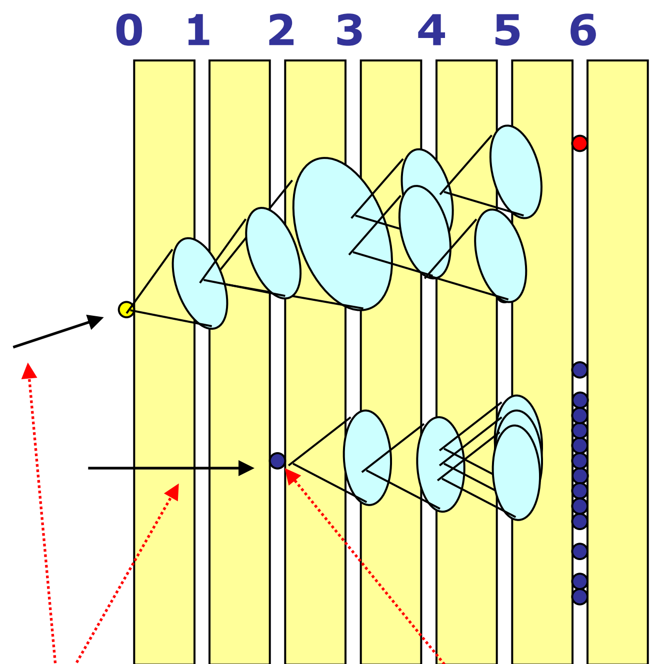
- ★ Originally "rat's nest" software
- ★ Now (thanks to John Marshall) – extremely flexible, reusable, API based framework + algorithm implemetation

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)

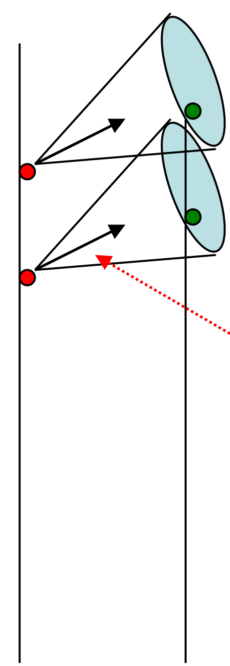
ii) ECAL/HCAL Clustering

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



Initial cluster direction

Unmatched hits seeds new cluster



Simple cone algorithm based on current direction + additional N pixels

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

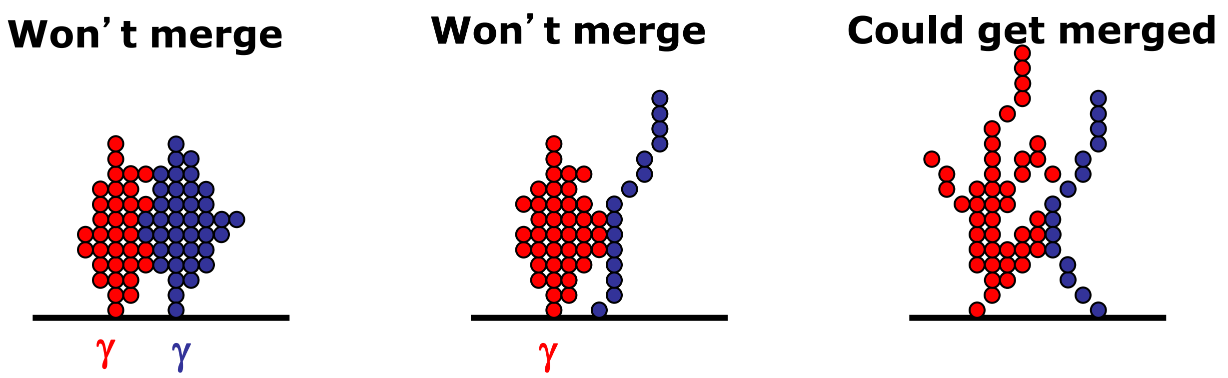
Parameters:
- cone angle
- additional pixels

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

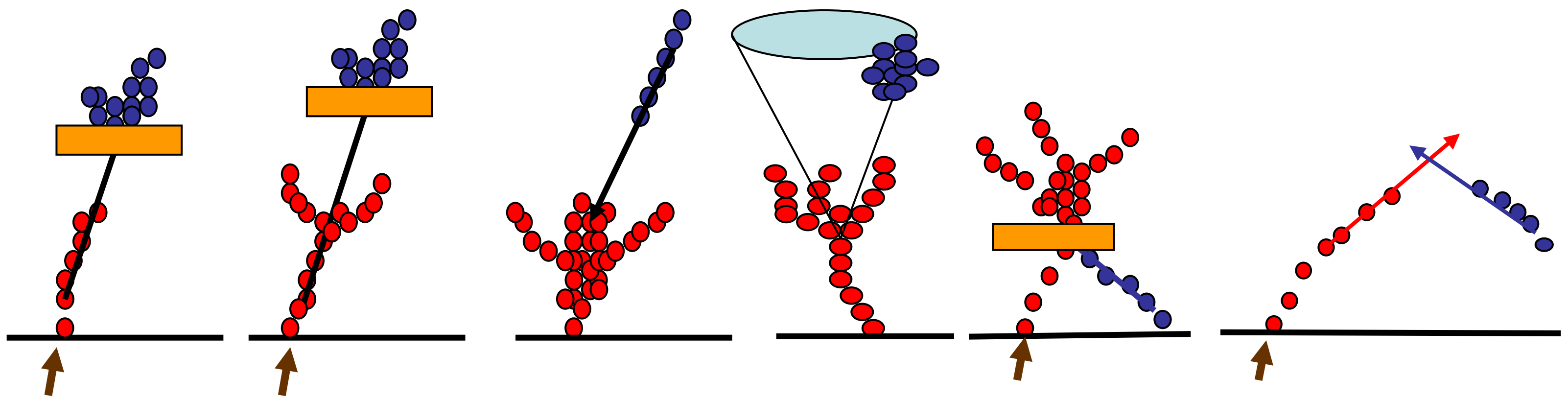
- Photon ID plays important role
- Simple "cut-based" photon ID applied to all clusters
- Clusters tagged as photons are immune from association procedure – just left alone



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

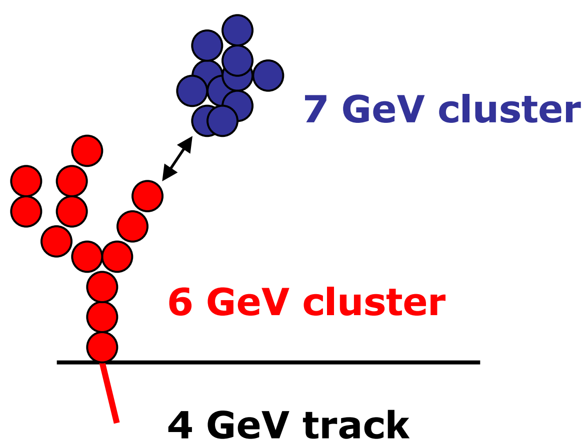
Clear Associations:

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



Less clear associations:

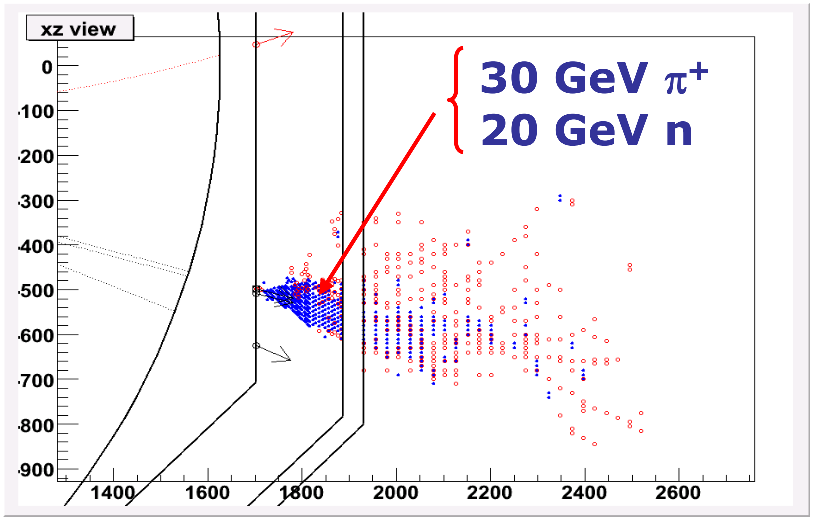
e.g. **Proximity**



Use E/p consistency to veto clear mistakes

v) Iterative Reclustering

★ At some point, in high density jets (high energies) reach the limit of "pure" particle flow
  - ♦ i.e. can't cleanly resolve neutral hadron in hadronic shower

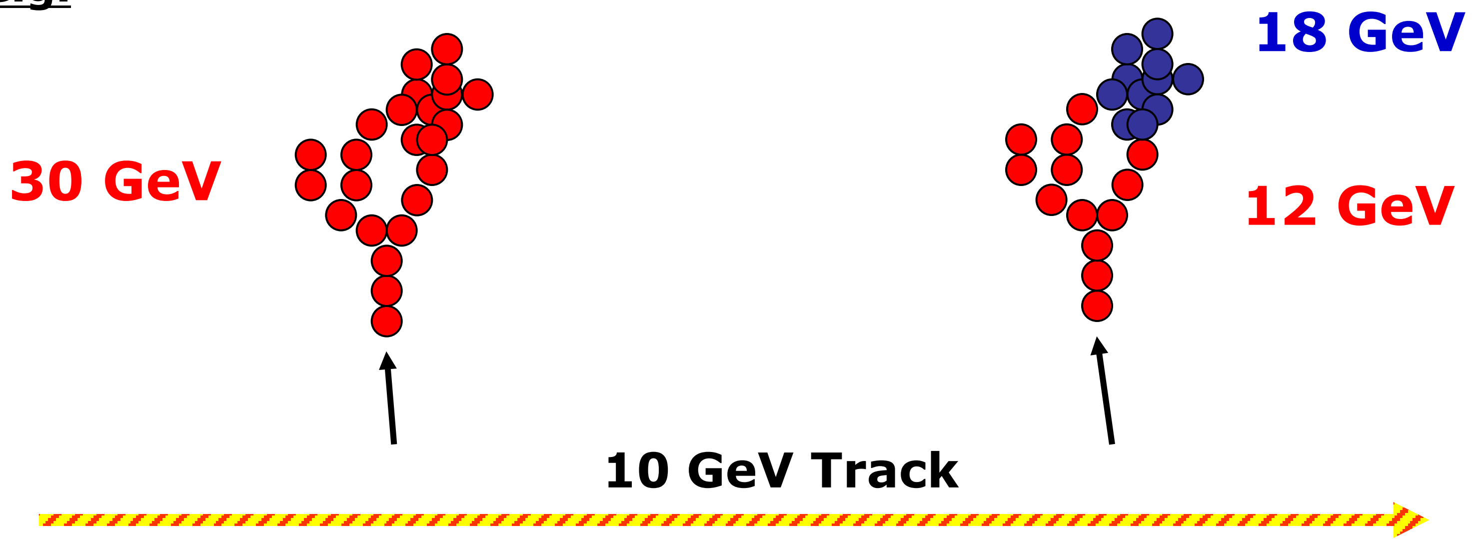


The ONLY(?) way to address this is "statistically"

e.g. if have 30 GeV track pointing to 50 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:

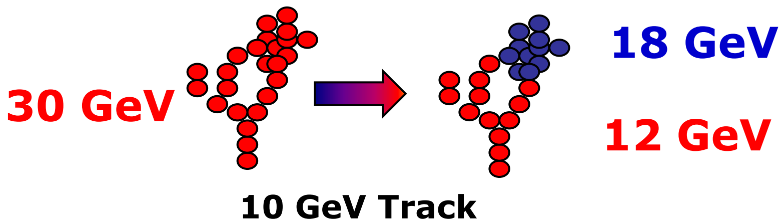
- clustering guided by track momentum
- more powerful than subtraction (Energy Flow)

This is very important for higher energy jets

Iterative Reclustering Strategies

① Cluster splitting

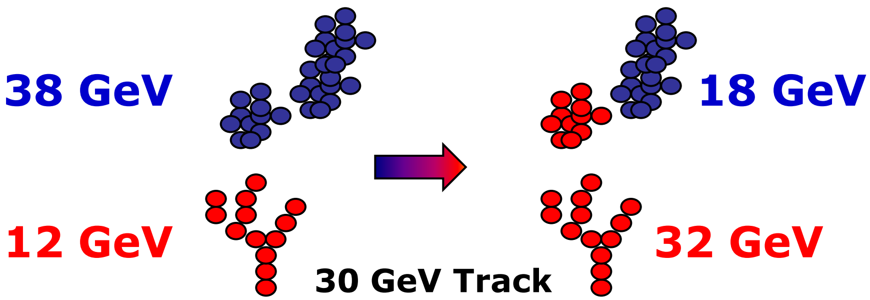
Reapply entire clustering algorithm to hits in "dubious" cluster. Iteratively reduce cone angle until cluster splits to give acceptable energy match to track



★ + plug in alternative clustering algorithms

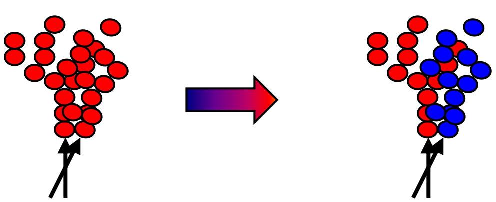
② Cluster merging with splitting

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

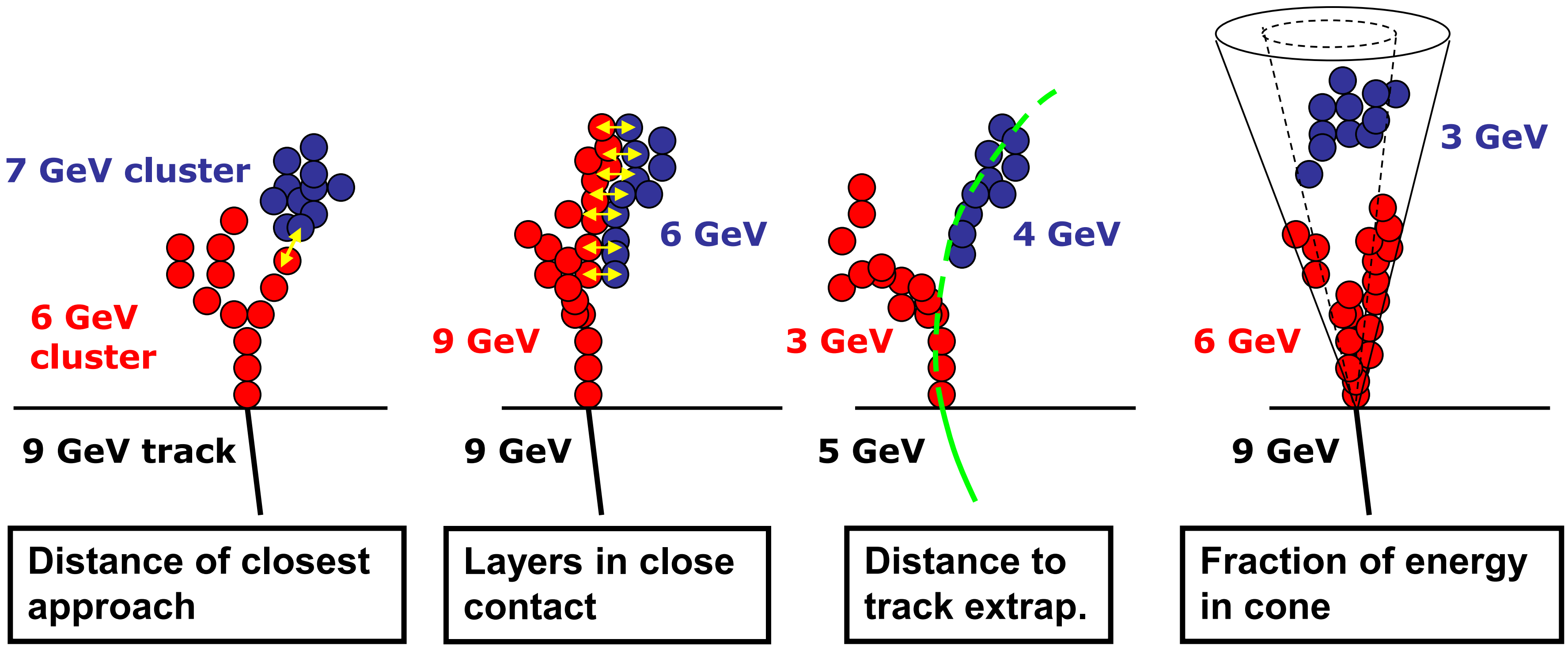
In dense environment may have multiple tracks matched to same cluster. Apply above techniques to get ok energy match.



Reclustering stage enables PandoraPFA to move seamlessly from Pflow to Eflow !!!

viii) Fragment removal : basic idea

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



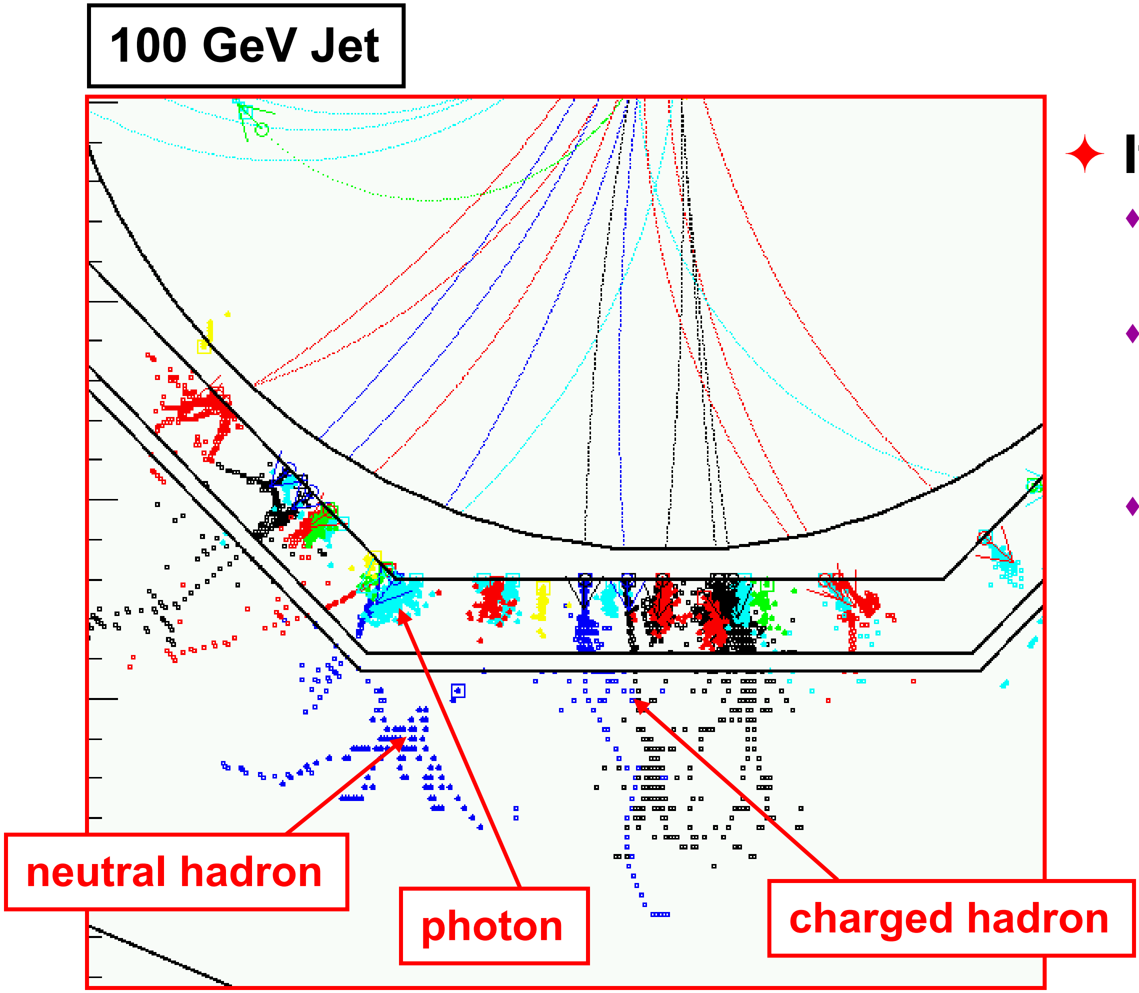
★ Convert to a numerical evidence score **E**

★ 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

The output… reconstructed particles



- 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.

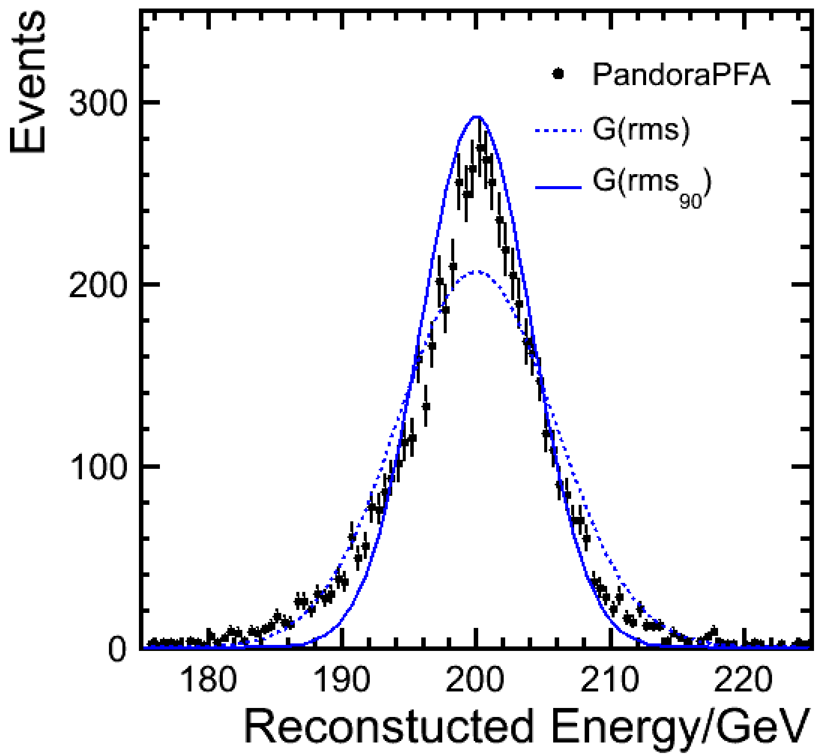
★ Can start to understand performance of a Particle Flow detector…

❺ PFA Resolution: rms_{90}

★ PFA resolution is inherently non-Gaussian
- resolution driven by number of mistakes (confusion)
- leads to narrow core + tails
- rms/Gaussian fits do not give representative resolution
- instead use rms_{90}
- defined as "rms in smallest region containing 90 % of events"

★ How to interpret rms_{90} ?
- analysing power

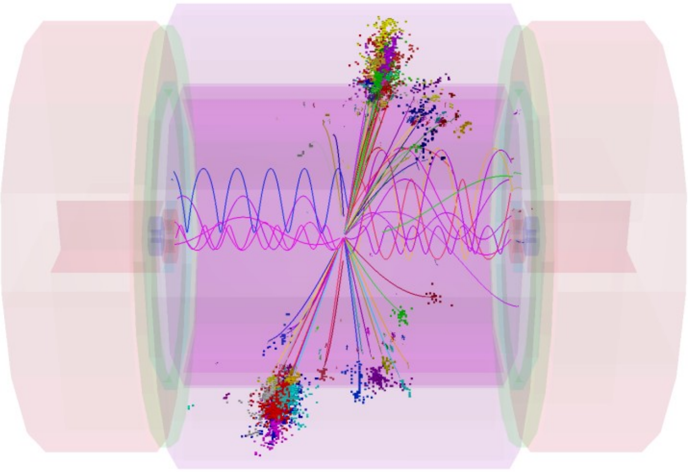
$$\boxed{\mathrm{rms}_{90} \approx 0.9\sigma_{\mathrm{Gaus}}}$$



"ILC" Jet Energy Resolution

★ Recall, motivation for high granularity PFlow Calorimetry

Jet energy resolution: $\boxed{\sigma_E/E < 3.5\%}$



★ Benchmark performance using jet energy resolution in Z decays to light quarks

★ Use total energy to avoid complication of jet finding (mass resolutions later)

★ Current Pflow performance (PandoraPFA + ILD)

- uds jets (full GEANT 4 simulations)

rms$_{90}$

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E_j
45 GeV	25.2 %	3.7 %
100 GeV	29.2 %	2.9 %
180 GeV	40.3 %	3.0 %
250 GeV	49.3 %	3.1 %

★ Equivalent stochastic term shown for comparison, PFA resolution **is not** stochastic, CONFUSION

❻ Understanding PFA Performance

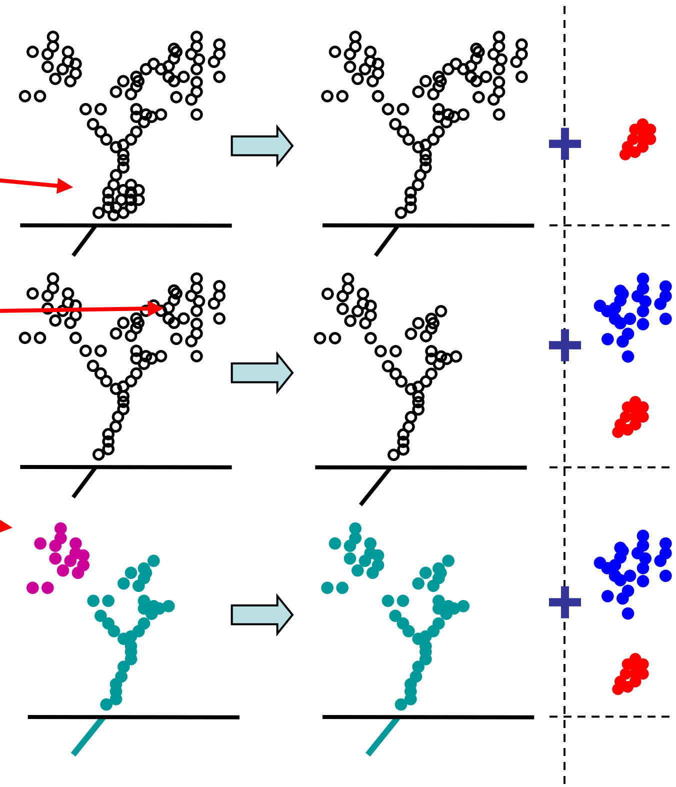
What drives Particle Flow performance ?

★ Treat PFA reconstruction as a black box

★ Empirically determine contributions to jet energy resolution

★ Use MC to "cheat" various aspects of **Particle Flow**

PandoraPFA options:

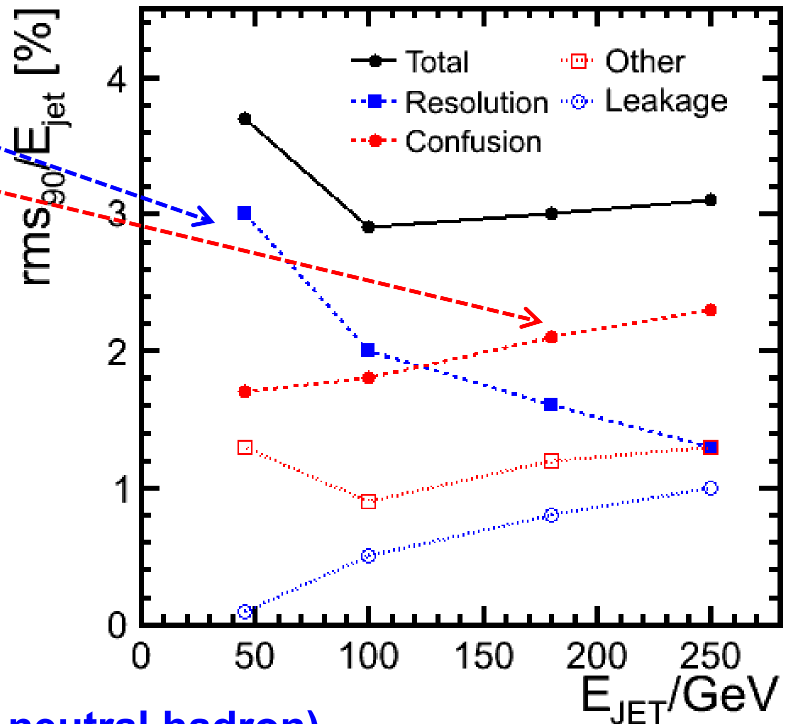


- **PerfectPhotonClustering**
  hits from photons clustered using MC info
  and removed from main algorithm
- **PerfectNeutralHadronClustering**
  hits from neutral hadrons clustered
  using MC info…
- **PerfectFragmentRemoval**
  after PandoraPFA clustering "fragments"
  from charged tracks identified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

★ Also consider leakage (non-containment) of hadronic showers

Contributions to resolution

★ **Answer depends on jet energy**
- Low energy jets: RESOLUTION
- High energy jets: CONFUSION
- Cross-over at ~100 GeV
- Very high energy jets: leakage important



★ **What kind of confusion ?**
- i) photons
  (γ merged into charged had. shower)
- ii) neutral hadrons
  (K_L/n merged into charged had. shower)
- iii) charged hadron fragments
  (fragments of charged had. reconstucted as neutral hadron)

★ **At high energies ii) is the largest contribution, e.g. for 250 GeV jets**

Total Resolution	3.1 %
Confusion	2.3 %
i) Photons	1.3 %
ii) Neutral hadrons	1.8 %
iii) Charged hadrons	0.2 %

Not insignificant

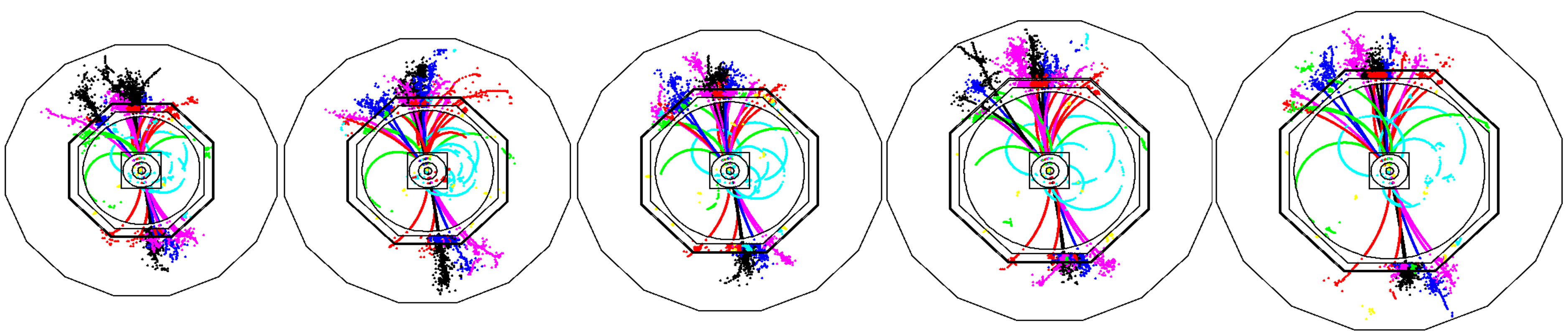
Largest single contribution, but remember, enters in quadrature

❼ Optimising a PFlow Detector

Cost drivers:

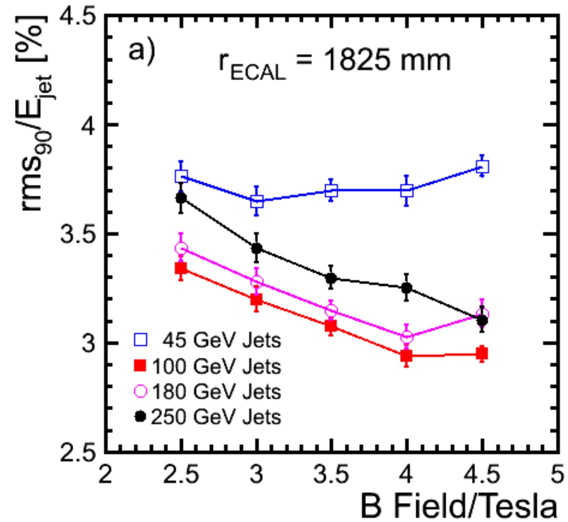
- Calorimeters and solenoid are the main cost drivers of an ILC detector optimised for particle flow
- Most important detector design considerations are:
  - B-field
  - R : inner radius of ECAL
  - L : length, equivalently aspect ratio L/R
  - HCAL thickness : number of interaction lengths
  - ECAL and HCAL segmentation
- Study jet energy resolution as a function of these cost critical issues

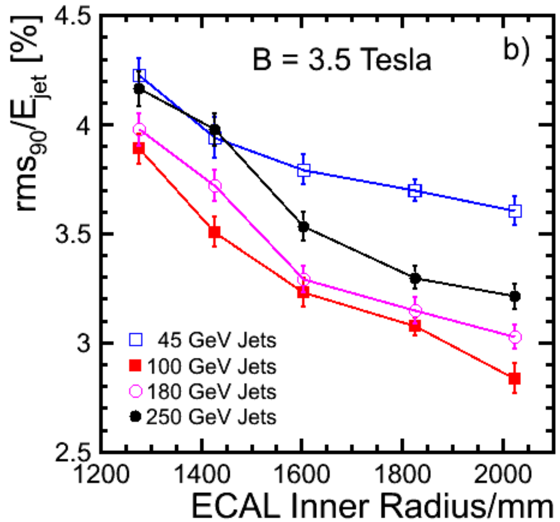
★ e.g. vary ECAL radius and B-field



B vs R

★ **Empirically find** (PandoraPFA/ILD)





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

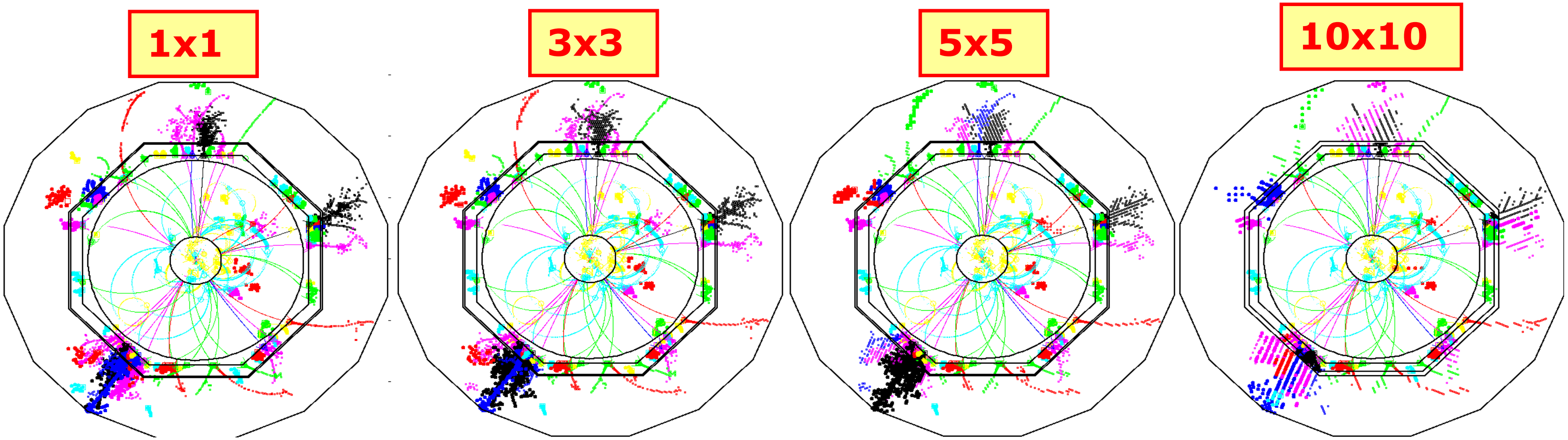
♦ **Confusion $\propto$ B$^{-0.3}$ R^{-1}** **(1/R dependence "feels right", geometrical factor !)**

Conclusions:

Detector should be fairly large
Very high B-field is less important

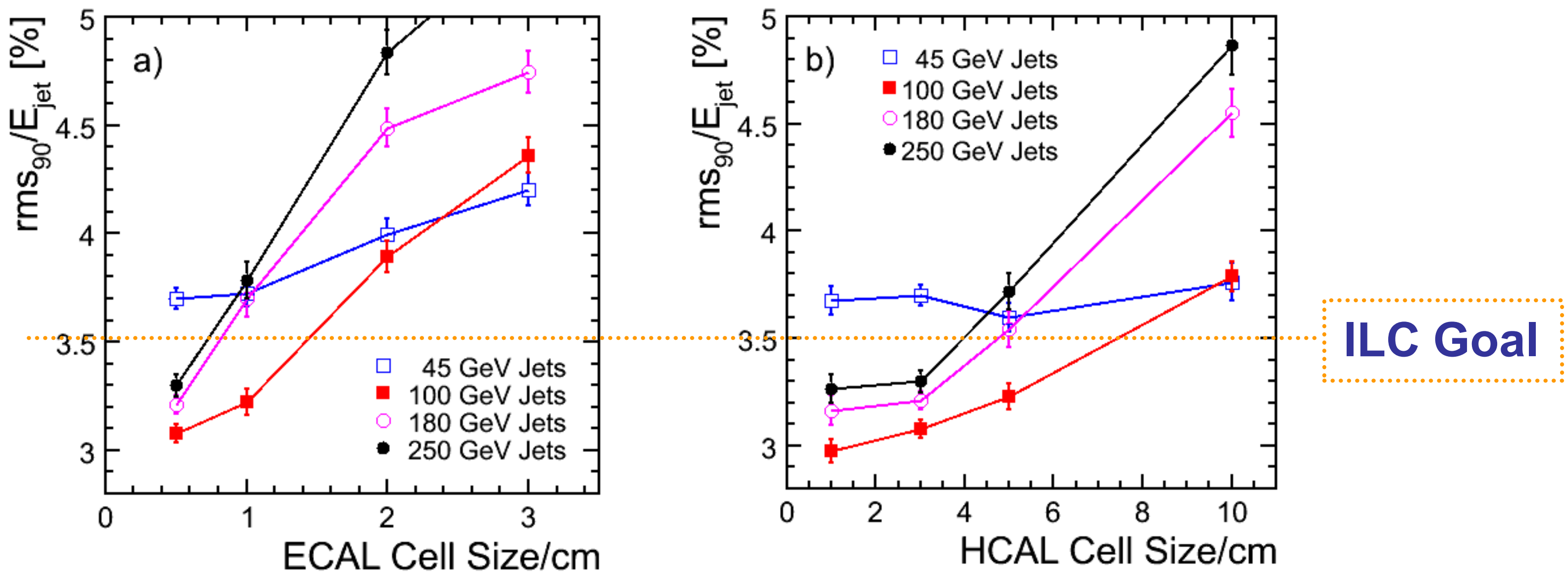
ECAL/HCAL Segmentation

- ★ Assumed particle flow reconstruction requires very highly segmented ECAL and HCAL
- ★ What does "highly segmented" mean ?
- ★ In ILD detector model vary ECAL Si pixel size and HCAL tile size
  - e.g. HCAL tile size [cm^2]



- ★ "By eye" can see that pattern recognition becomes harder for 10x10 cm^2
- ★ Dependence of jet energy resolution on segmentation obtained with full particle flow reconstruction

★ In ILD detector model vary ECAL Si pixel size and HCAL tile size



★ <u>**ECAL Conclusions:**</u>

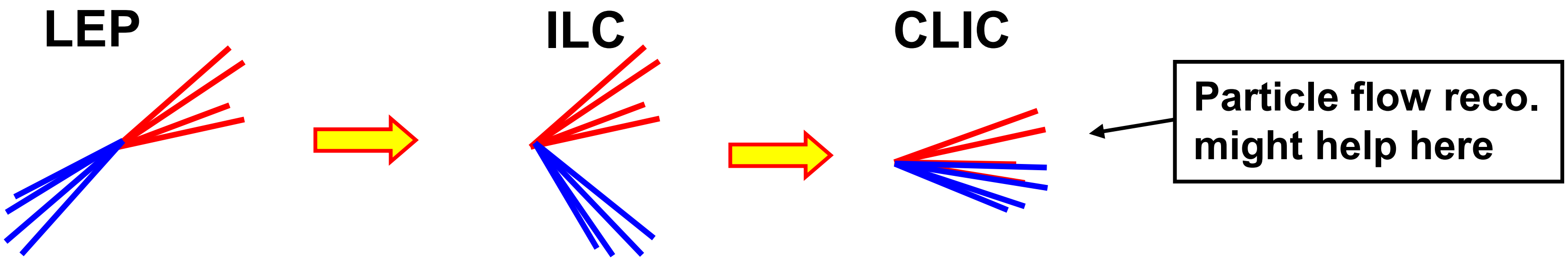
- Ability to resolve photons in current PandoraPFA algorithm strongly dependent on transverse cell size
- Require at least as fine as 10x10 mm^2 to achieve 4.0 % jet E resolution
- Significant advantages in going to 5x5 mm^2

★ <u>**HCAL Conclusions:**</u>

- For current PandoraPFA algorithm and for Scintillator HCAL, a tile size of 3×3 cm^2 looks optimal
- May be different for a digital/semi-digital RPC based HCAL

❽ PFA at high Energies

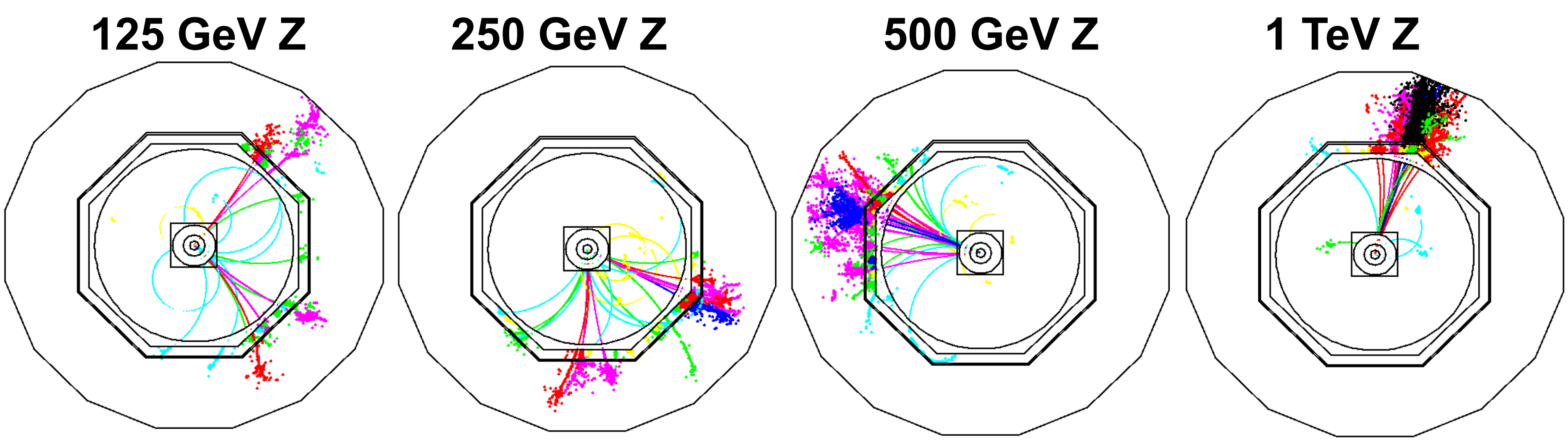
★ On-shell W/Z decay topology depends on energy:



★ A few comments:

- Particle multiplicity does not change
- Boost means higher particle density
- PFA could be better for "mono-jet" mass resolution

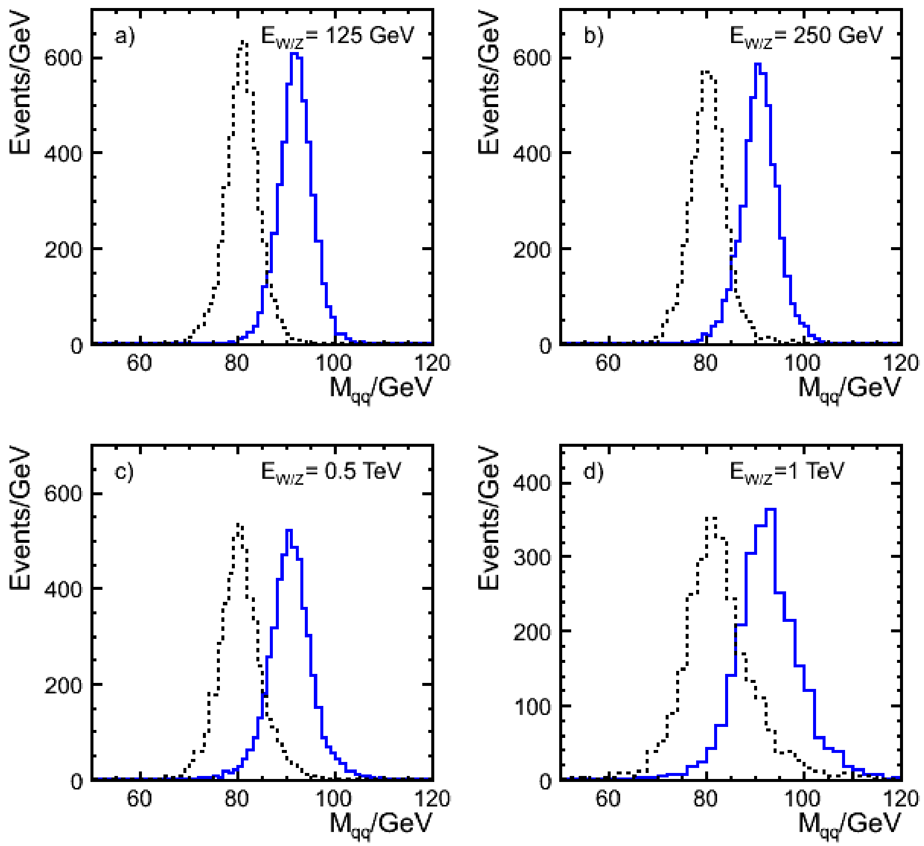
More confusion



W/Z Separation at high Energies

★ Studied W/Z separation using ILD+ (8 λ_I HCAL) samples of

$$e^+e^- \to WW \to u\bar{d}\nu\mu \qquad e^+e^- \to ZZ \to d\bar{d}\nu\bar{\nu}$$



ILC-like energies

Clear separation

CLIC-like energies

There is separation, although less clear for 1 TeV bosons

- Current PandoraPFA/ILD+ gives good W/Z separation for 0.5 TeV bosons
- Still fair separation for 1 TeV bosons
- **NOTE** PandoraPFA not designed/tuned for such high energies

W/Z Di-jet Mass Separation

W/Z Energy GeV	h^0 cut GeV	σ_m/m w.r.t. $m_{W/Z}$	σ_m/m w.r.t. m_{gen}	W/Z Sep. Efficiency
125	0	2.8 %	2.4 %	92 %
250	1.0	2.9 %	2.6 %	91 %
500	2.5	3.4 %	3.2 %	88 %
1000	5.0	5.2 %	5.1 %	80 %

- **Note due to Breit-Wigner tails best possible separation is 96 %**
- **Separation of W and Z bosons up to 500 GeV very good**
- **Still need to work on 1 TeV (di)-jet mass resolution, but not bad**

CLIC Jet Energy Performance

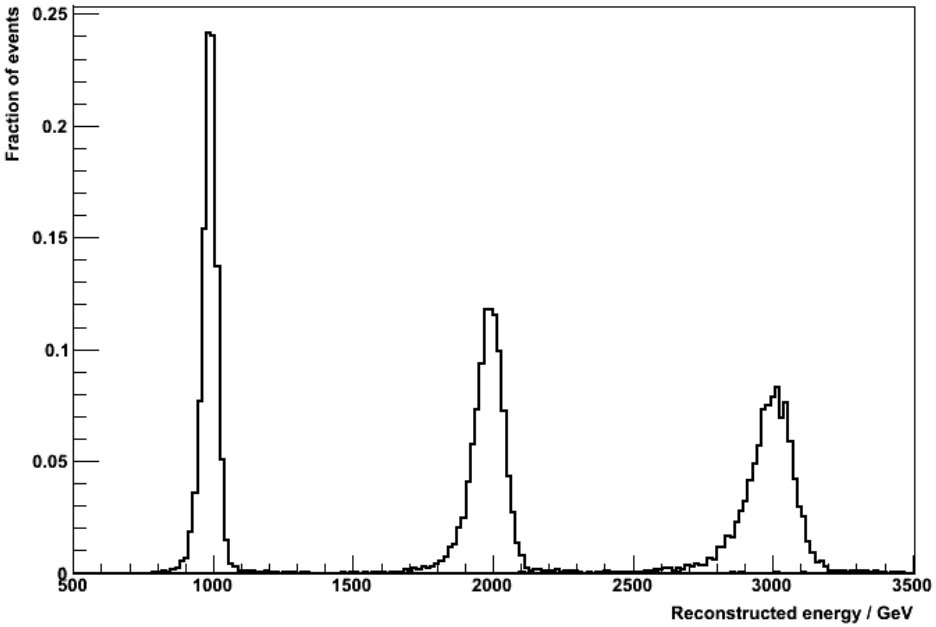
★ Now tested for jets in range 45 GeV – 1.5 TeV

ILD

E_{JET}	RMS_{90}/E_J
45 GeV	3.6 %
100 GeV	3.1 %
180 GeV	3.0 %
250 GeV	3.3 %

CLIC_ILD

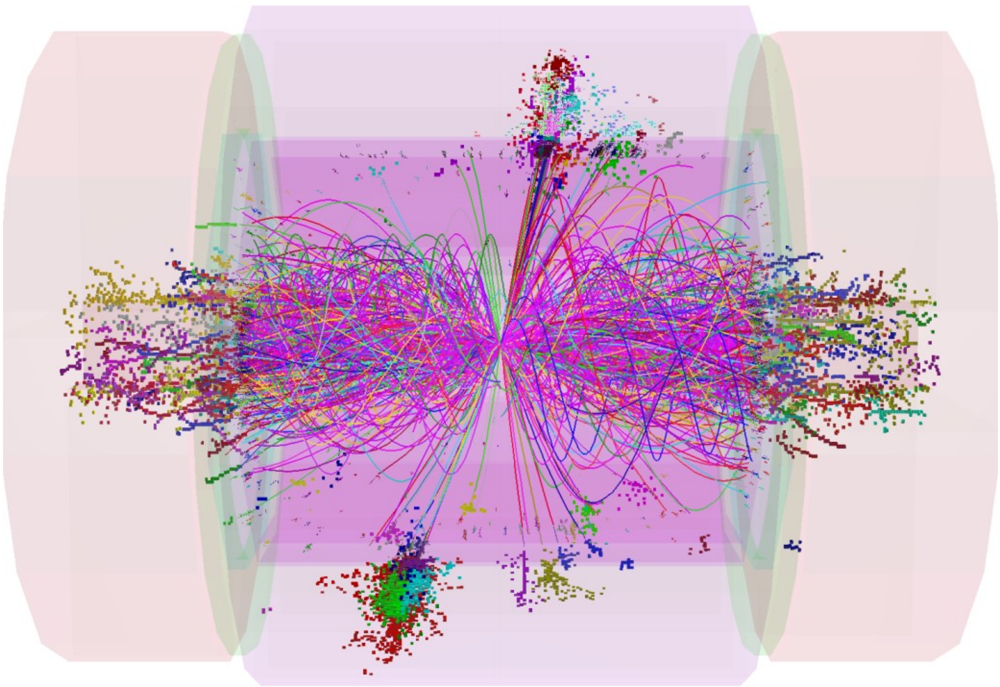
E_{JET}	RMS_{90}/E_J
45 GeV	3.6 %
100 GeV	2.9 %
250 GeV	2.8 %
500 GeV	3.0 %
1 TeV	3.2 %
1.5 TeV	3.2 %



Jet Energy Resolution better than 3.6 % over whole range

❾ Recent work

★ Recent work
- Emphasis on CLIC CDR studies
- Challenge to software: pile-up and use of timing information



★ + spreading our wings…
- CALICE Pandora
- Proto-type LAr calorimeter reconstruction
- …

❿ Conclusions

- ★ High granularity calorimeters being "prototyped" by CALICE
  - ✦ such a detector can be built (at a cost)
  - ✦ basis for default detector concept for ILC and CLIC !
- ★ Clear demonstration that PFA can deliver ILC performance goals
  - ▪ excellent performance for both $\sqrt{s}$ = 500 GeV and $\sqrt{s}$ = 1 TeV
  - ▪ modelling uncertainties do not appear to be large
  - ▪ + remember, not yet reached ultimate PFA performance
- ★ Have developed a reasonably good understanding of Particle Flow
- ★ Initial studies demonstrate the Particle Flow Calorimetry will work (although becomes more like EFlow) at $\sqrt{s}$ = 3 TeV:
  - ▪ For 0.5 – 1.5 TeV jets can achieve ~3.2 % jet energy resolution
  - ▪ For 0.5-1.0 TeV achieve reasonable separation of W/Z bosons
- ★ PandoraPFA – developing into powerful PFA/clustering framework/toolkit
- ★ One day, hope to apply it to real ILC/CLIC data…

fin

Dependence on hadron shower simulation

★ Modelling of hadronic showers in GEANT4 is far from perfect…
- Can we believe PFA results based on simulation ?

★ PandoraPFA/ILD performance for 5 very different Geant4 physics lists…

Physics List	Jet Energy Resolution			
	45 GeV	100 GeV	180 GeV	250 GeV
LCPhys	3.74 %	2.92 %	3.00 %	3.11 %
QGSP_BERT	3.52 %	2.95 %	2.98 %	3.25 %
QGS_BIC	3.51 %	2.89 %	3.12 %	3.20 %
FTFP_BERT	3.68 %	3.10 %	3.24 %	3.26 %
LHEP	3.87 %	3.15 %	3.16 %	3.08 %
χ^2	23.3 / 4	17.8 / 4	16.0 / 4	6.3 / 4
rms	4.2 %	3.9 %	3.5 %	2.5 %

Default (LCPhys)

~GHEISHA (LHEP)

★ Only a weak dependence < 5 %
- **NOTE:** 5 % is on the **total**, not just the **hadronic confusion term**

e.g.

Total Resolution	3.11 %		Total Resolution	3.27 %
Conf: neutral hads	1.80 %	$\times 1.14$	Conf: neutral hads	2.05 %
Other contributions	2.54 %	$\times 1.00$	Other contributions	2.54 %

(Total Resolution: $\times 1.05$)

Suggests **PFA** performance is rather robust
- MC results likely to be reliable, despite shower model uncertainties

CALICE study (Oleg Markin) supports this statement